Electroweak Symmetry Restoration @ High Energies

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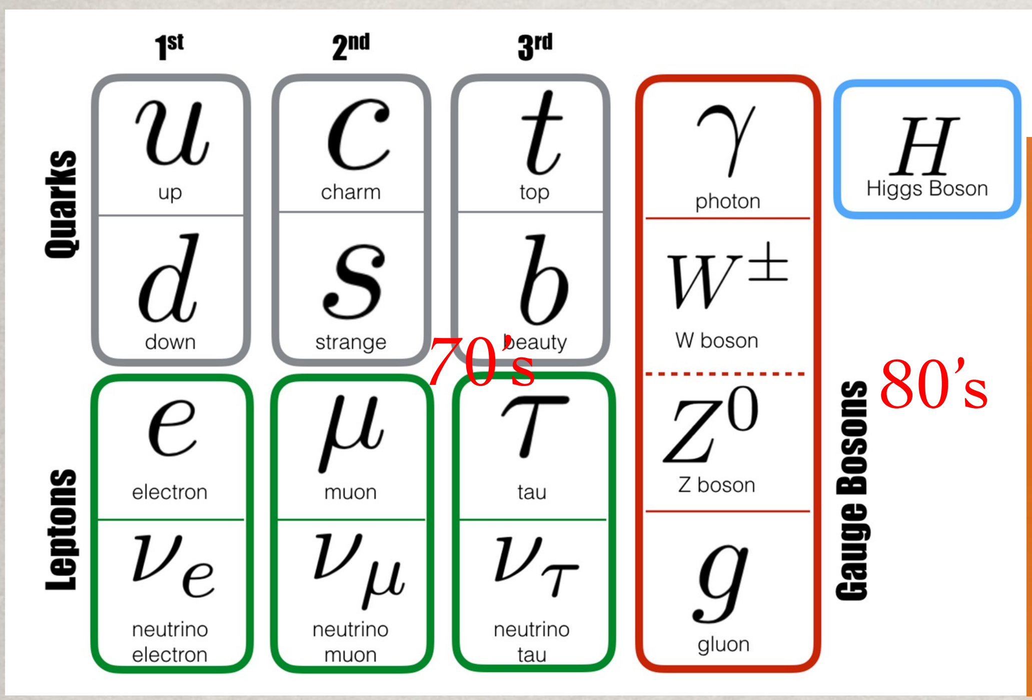
HEP: Uninterrupted discoveries for more than half a century!

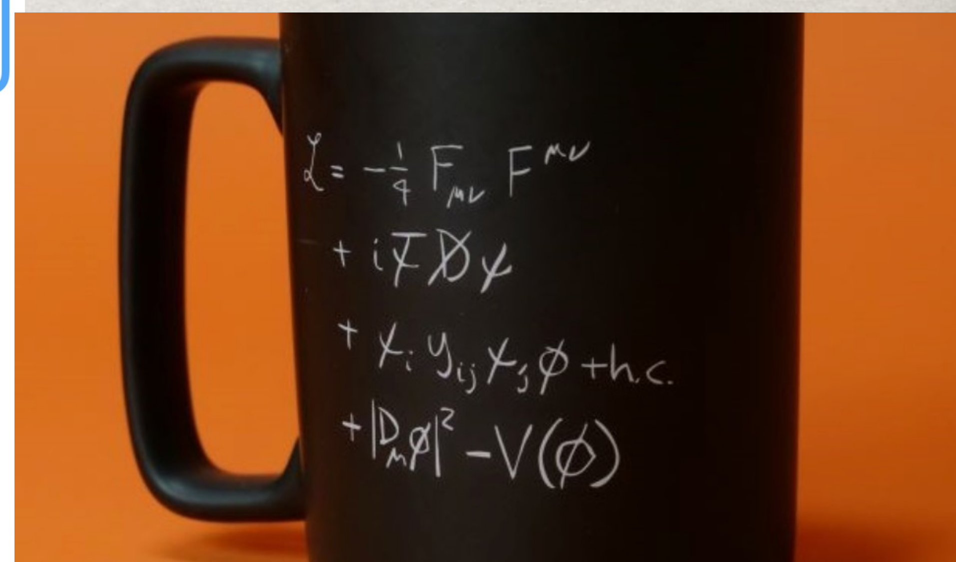
From quarks to the Higgs boson, with heroic efforts in theory and experiments:

60's 70's 90's 2012



ν's: 1930/1956 1962 2000

The Standard Model of particle physics

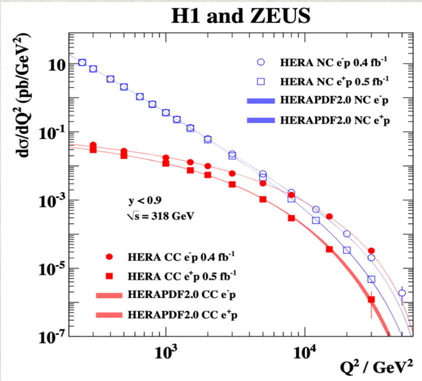


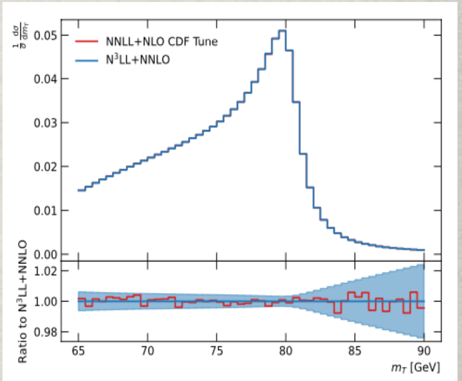
• Electroweak Gauge Theory

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

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

- At the EW scale ~O(100 GeV)
  - o Non-Abelian gauge structure
  - o Gauge coupling universality
  - o Spontaneous symm breaking





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

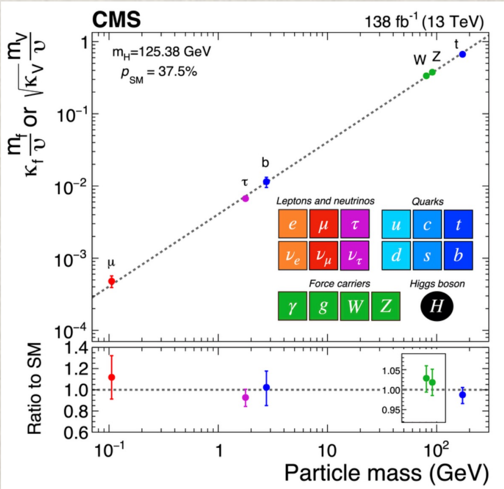
Yet, we are still in a **broken phase:**

massive bosons:

$$M^2W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H\partial_\mu H - \tfrac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$

massive fermions & flavor mixing:

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

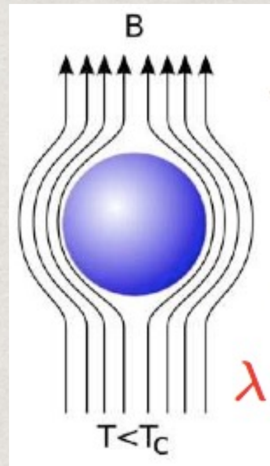


$\Delta m_h/m_h \sim 10^{-3}$

• Spontaneous Symmetry Breaking

- In a **broken or superconducting phase:**

London penetration depth -- the Meissner effect:



⇐Superconducting phase

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

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

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

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

The SM scalar sector:

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

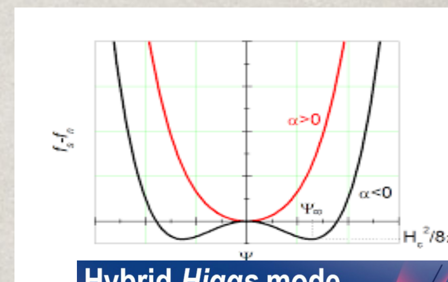
$$v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

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

Landau-Ginzburg Theory:

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

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

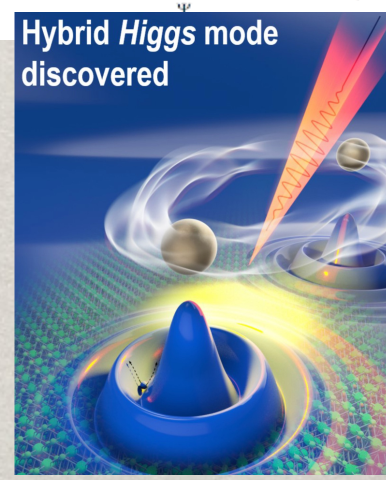


In CM, **BCS** as the underlying theory to calculate $\boldsymbol{\alpha}$(T) & $\boldsymbol{\beta}$(T)!

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.**



Laser @ 10^{12} Hz (2021)

• Longitudinal gauge bosons

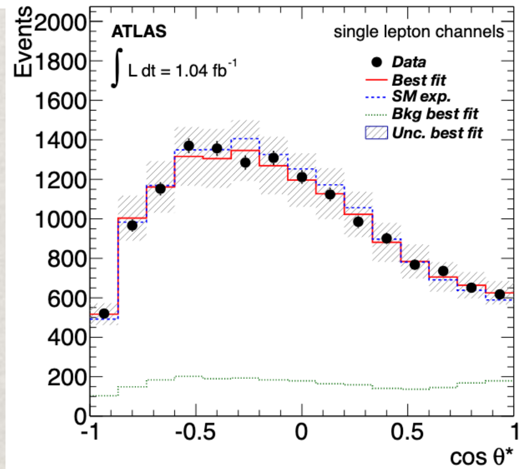
- 1^{st} observation of W_L in top decay (CDF/D0, 2000)

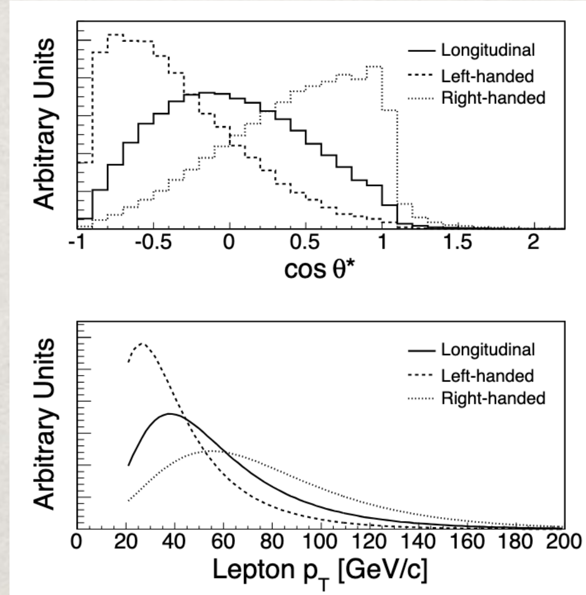
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

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

W_L dominant!

CDF: hep-ex/0511023;
ATLAS: 1205.2484;
CMS: 1308.3879

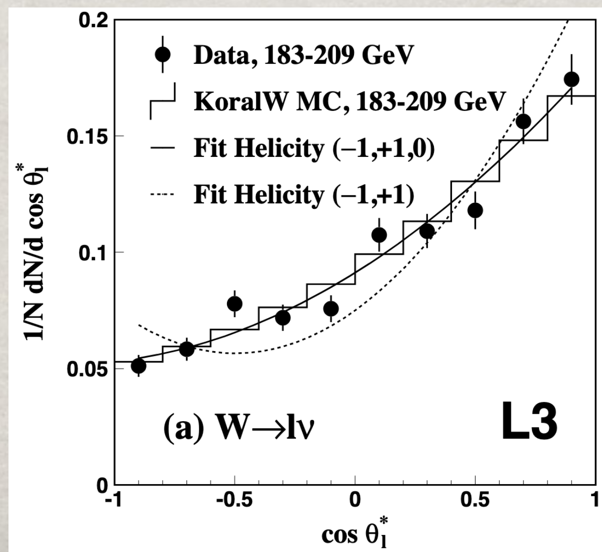


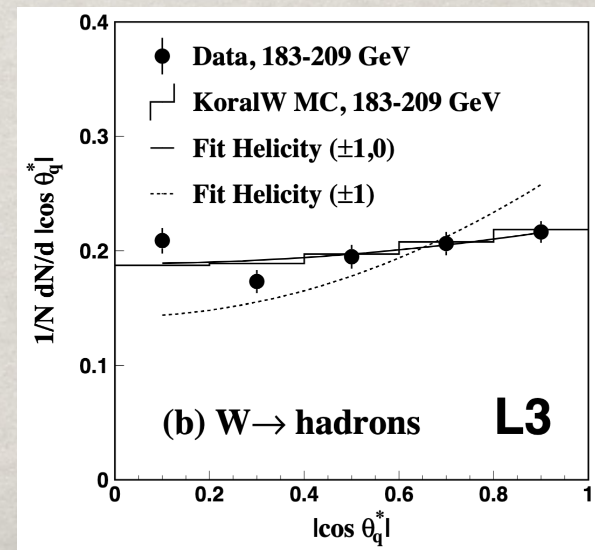


- 2^{nd} observation: $e^+e^- \to W^+W^-$ at LEP (L3, 2003)

W_L fits at 3σ

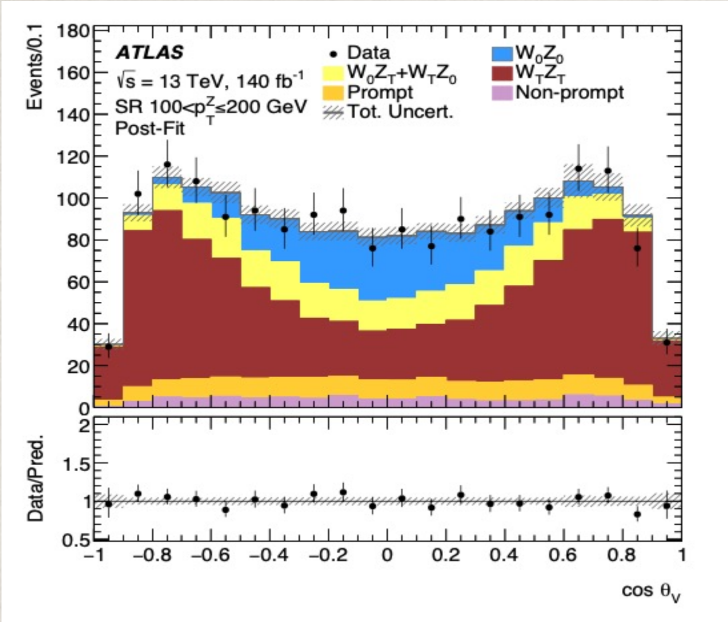
PLB557, 147(2003)





• Longitudinal gauge bosons

- 3[rd] observation: $q\bar{q} \to W_L^{\pm} Z_L$@ 7.1**σ** at ATLAS:

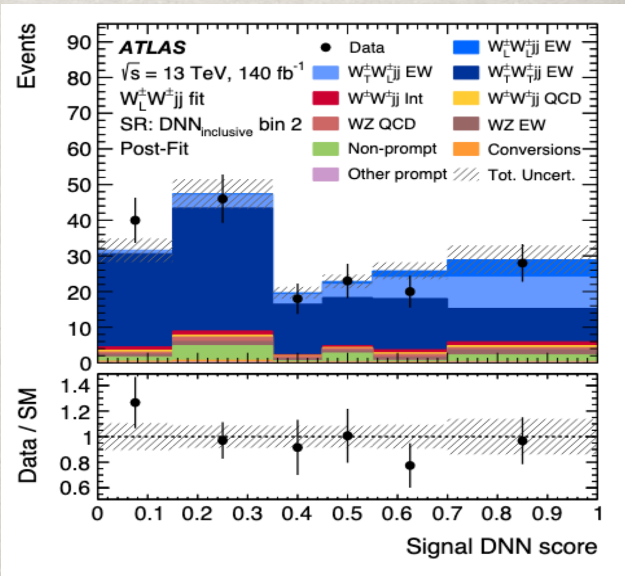


W_LZ_L observation & utilization of the "Radiation Amplitude Zero"

ATLAS:
arXiv:2211.09435: PLB 2023
arXiv:2402.16365: PRL 2024

- 4[th] observation (?): $W^{\pm}W^{\pm} \to W_L^{\pm}W_L^{\pm}$ at the LHC: at least 1 W_L @ 3.3**σ**

CMS: arXiv:2009.09429, ATLAS: arXiv:2503.11317



Great step to scrutinizing EWSB !

Goldstone-boson Equivalence Theorem (GET):

Lee, Quigg, Thacker (1977); M. Chanowitz, M. 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!)

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) ← $\frac{p^\mu}{M}$

$\frac{1}{1+\beta}\frac{M}{E}n^\mu$ → symmetry breaking residual

- Goldstone-bosons Equivalence Theorem:

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

W_L^i → Correspond to the broken generators

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

→ 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]

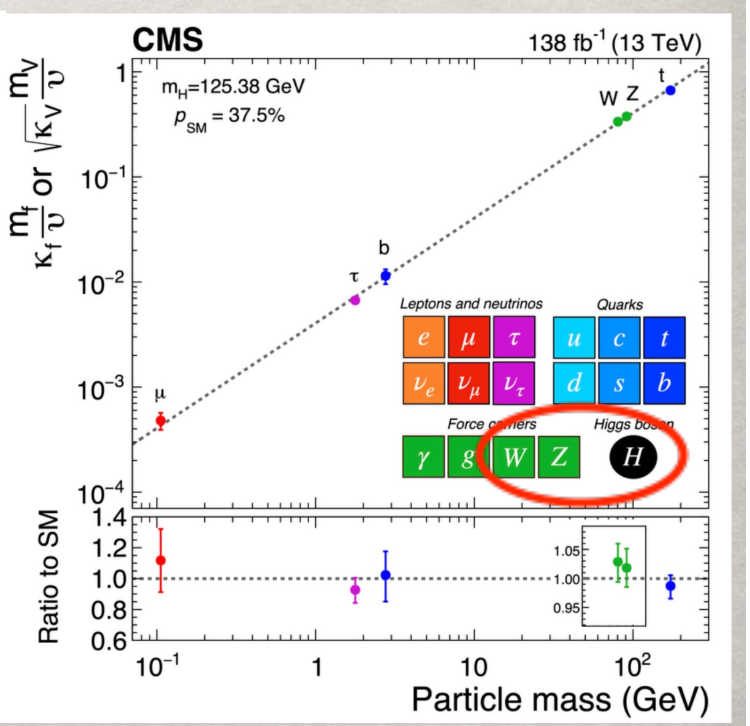
Weak interactions at very high energies: The role of the Higgs-boson mass

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

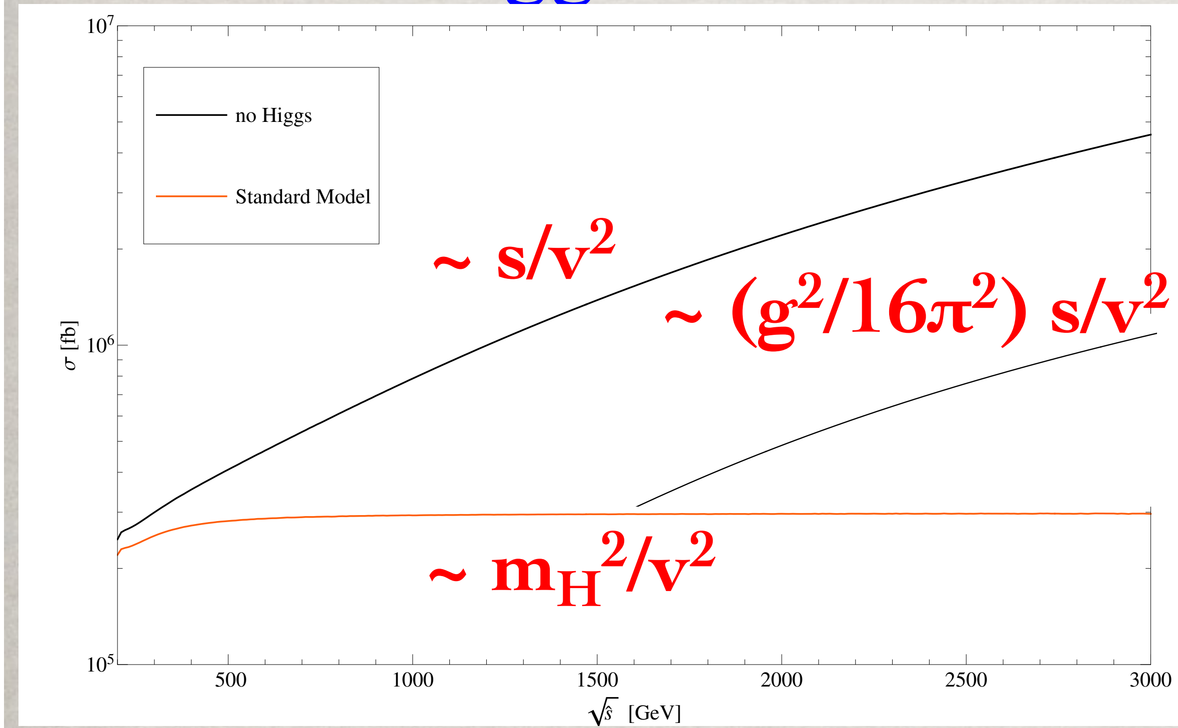
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} w_1 \\ w_2 \\ z \\ h \end{pmatrix}$$

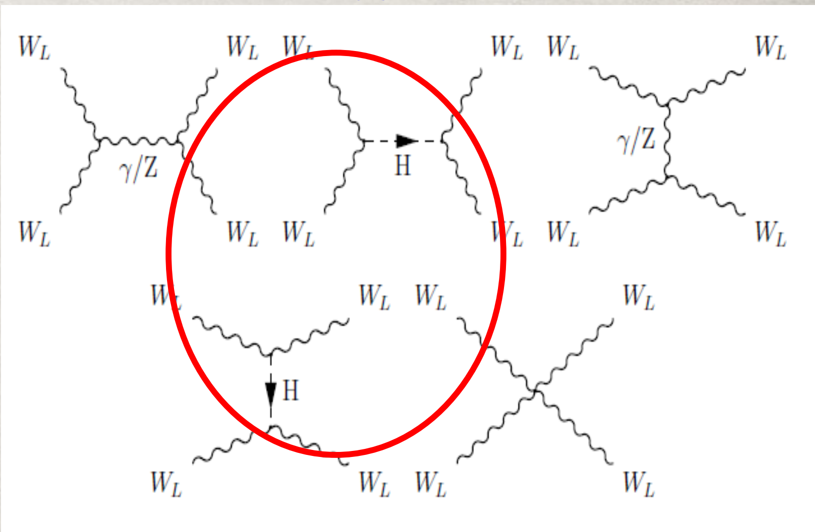
or $U = \exp\{i\omega^i\tau^i/v\}$



$V_L V_L \to V_L V_L$ Scattering

- "Bad high-energy behavior" $\epsilon(k)^\mu_L = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$
- The Higgs boson unitarize the amplitude:





Lee, Quigg, Thacker (1977)
Chanowitz, Furman, Hinchliffe (1978)
Chanowitz, Gailard (1984)

- Consistent perturbative theory up to Λ (?)
- New strong dynamics effects may still exist, but "delayed" to v^2/Λ^2.

• EW Symmetry Restoration (EWSR)

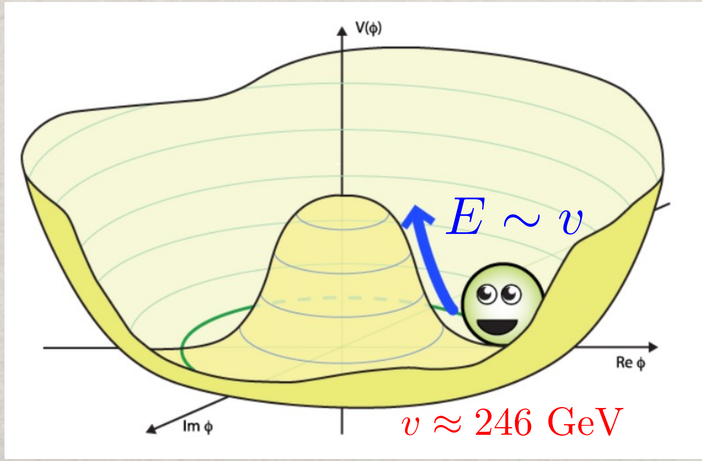
$$\frac{v}{E}: \quad \frac{v\ (250\ \text{GeV})}{10\ \text{TeV}} \approx \frac{\Lambda_{QCD}\ (300\ \text{MeV})}{10\ \text{GeV}} \qquad v/E,\ m_t/E,\ M_W/E \to 0!$$

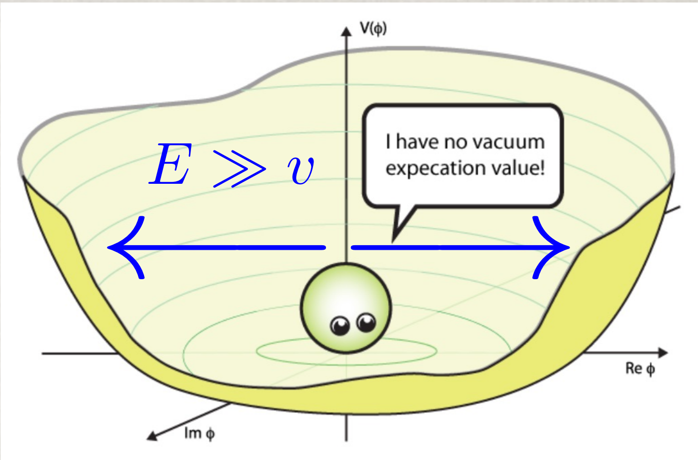
(i) the physics of the transverse gauge bosons $(W_T^{\pm}, Z_T, \gamma)$ and fermions is described by a massless theory in the unbroken phase;

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

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

R. Capdevilla, TH, arXiv:2412.12336 (PRL)

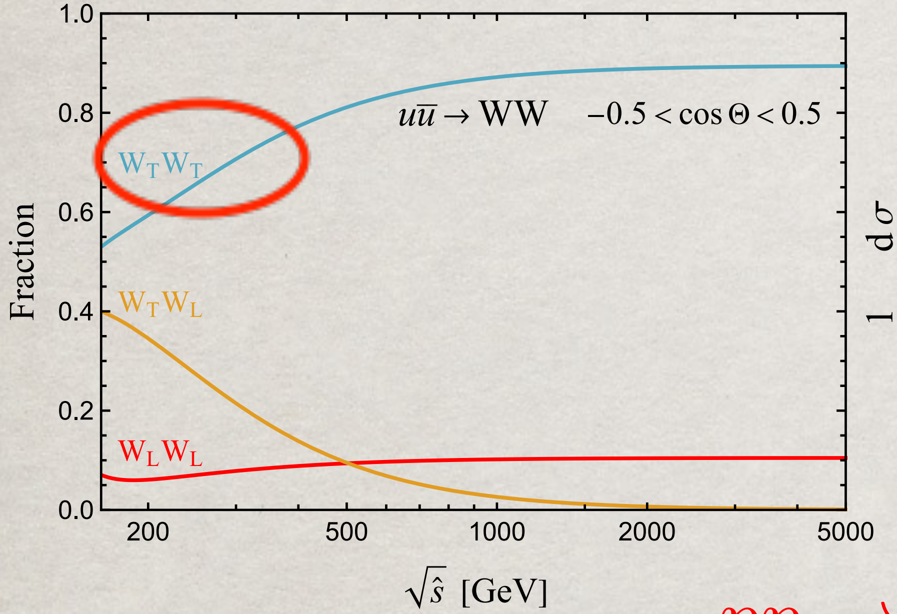


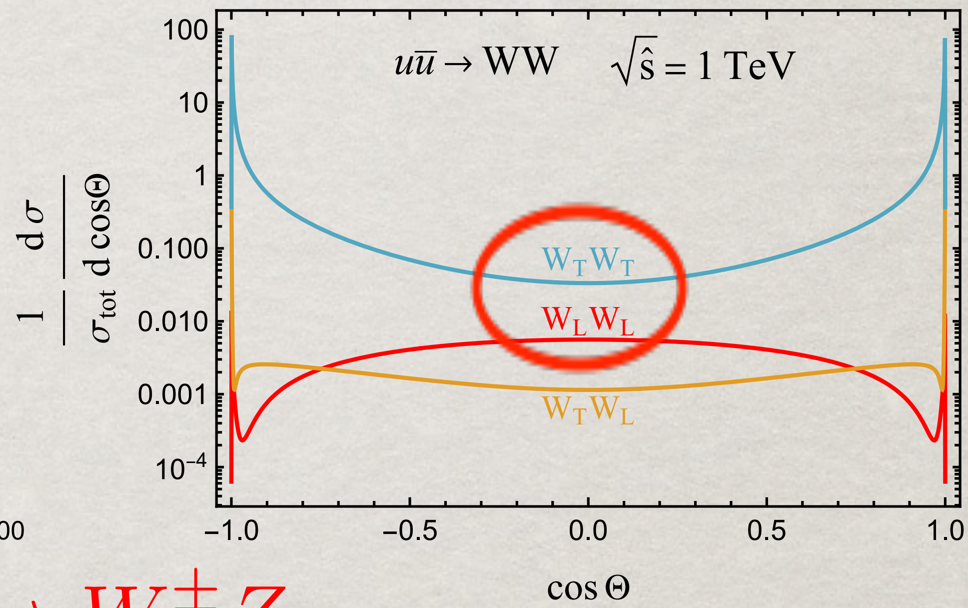


• Physics with Gauge Boson Pairs

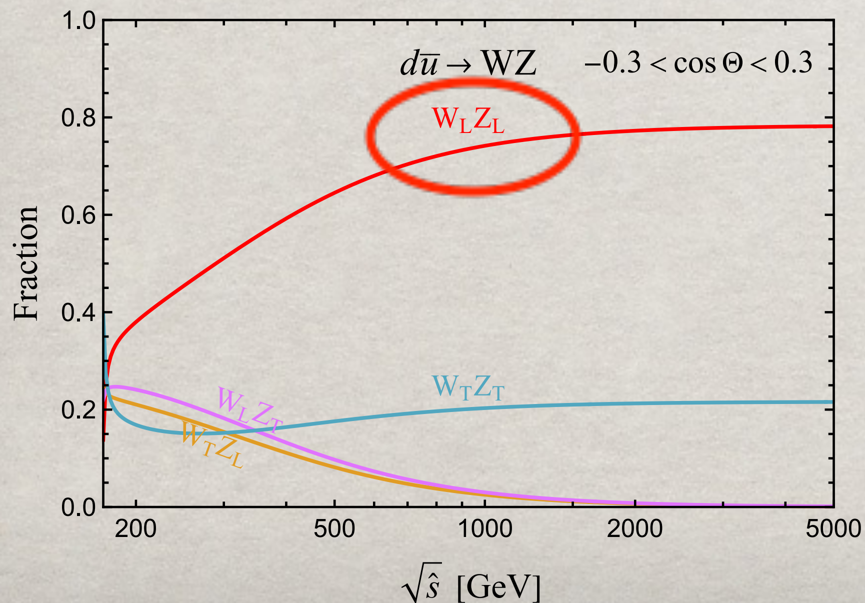
$pp \to W^+W^-$

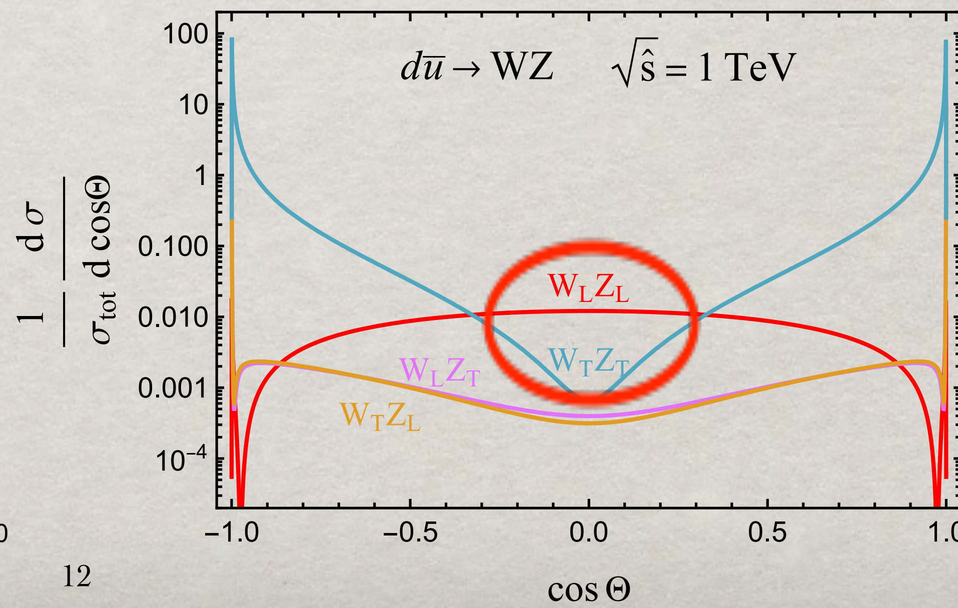
K. Cheng, TH, T. A. Wu, to appear





$pp \to W^{\pm}Z$





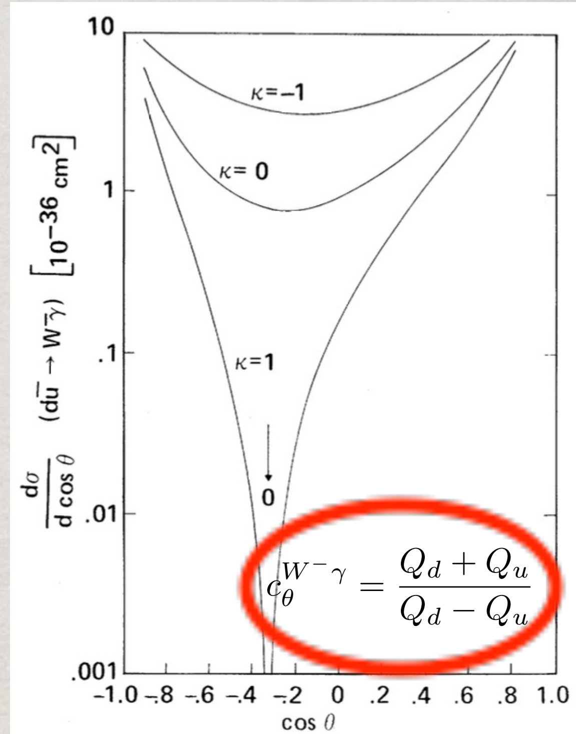
• Radiation Amplitude Zeros (RAZs)

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 $pp \to W^{\pm}\gamma X$ and $p\bar{p} \to W^{\pm}\gamma X$ 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 $p\bar{p} \to W^{\pm}\gamma X$ is particularly sensitive to this parameter. For the gauge-theory value of $\kappa = 1$, we have found a peculiar zero in $d\sigma(d\bar{u} \to W^-\gamma)/d\cos\theta$ 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 $d\sigma(u\bar{d} \to W^+\gamma)/d\cos\theta$. We can offer no explanation for this behavior.



$$c_\theta^{W^-\gamma} = \frac{Q_d + Q_u}{Q_d - Q_u}$$

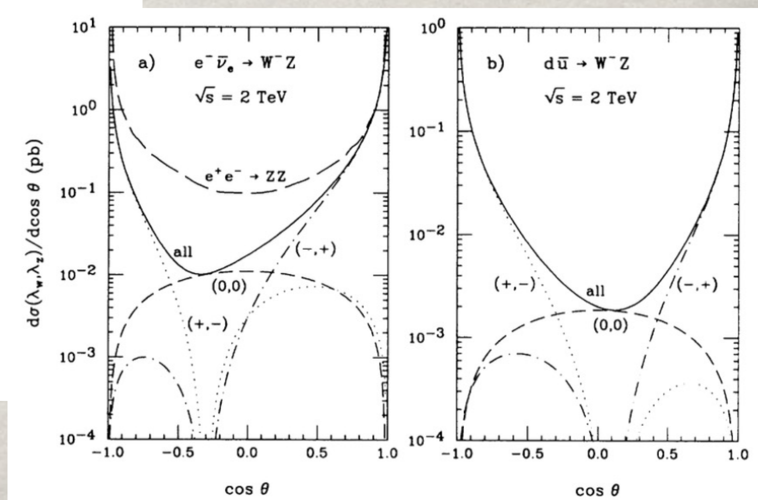
VOLUME 72, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1994

Amplitude Zeros in $W^{\pm}Z$ Production

U. Baur
Department of Physics, Florida State University, Tallahassee, Forida 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 $f_1\bar{f}_2 \to W^{\pm}Z$ 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)

$$f_1\bar{f}_2 \to W^\pm\gamma,$$
$$f_1\bar{f}_2 \to W^\pm Z,$$
$$f_1\bar{f}_2 \to W^\pm H.$$

$$\mathcal{M}^{W\gamma}_{\pm\mp} \approx -\frac{geV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[Q_{(1-2)}c_\theta - Q_{(1+2)}\right],$$
$$\mathcal{M}^{WZ}_{\pm\mp} \approx \frac{gg_zV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[g_-^{(1-2)}c_\theta - g_-^{(1+2)}\right],$$
$$\mathcal{M}^{WZ}_{00} \approx -\frac{g_z^2V_{12}}{2\sqrt{2}}s_\theta g_-^{(1-2)} = \frac{g^2V_{12}}{2\sqrt{2}}s_\theta,$$
$$\mathcal{M}^{WH}_{0} \approx \frac{g^2V_{12}}{2\sqrt{2}}s_\theta,$$

- Gauge sector: Radiation Amplitude Zeros (RAZs)

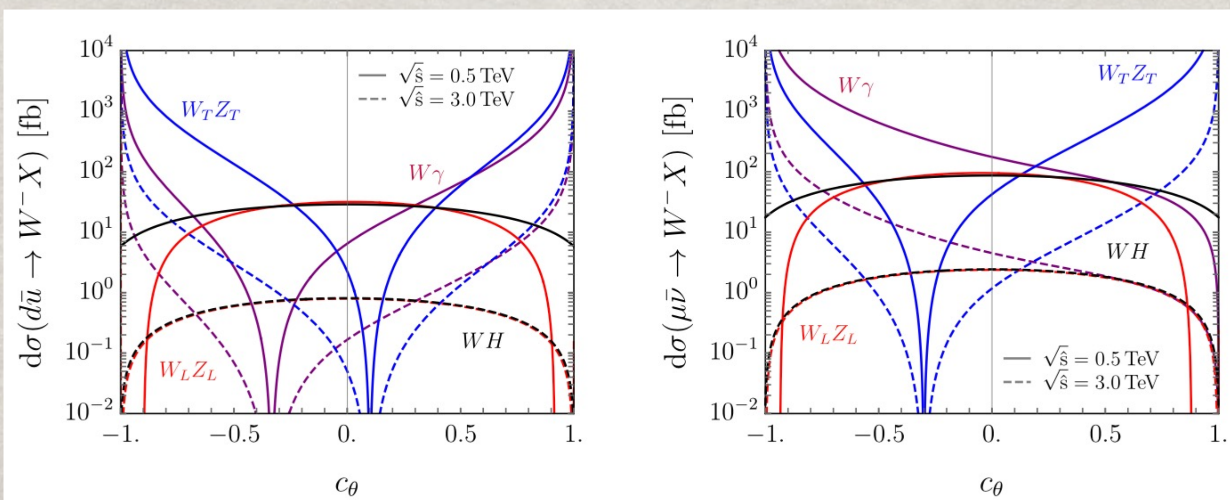
EM: $c_\theta^{W^-\gamma} = \dfrac{Q_d+Q_u}{Q_d-Q_u}$; EW (transverse): $c_\theta^{W^-Z_T} = \dfrac{g_-^d+g_-^u}{g_-^d-g_-^u}$

Mikaelian, Samual (1979)

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

U. Baur, TH, JO, (1994)

- Higgs scalar sector: $\mathcal{M}^{W_LZ_L}(\delta \ll 1) \approx \mathcal{M}^{W_Lh}(\delta \ll 1)$



Test EWSR @ LHC / muon Collider

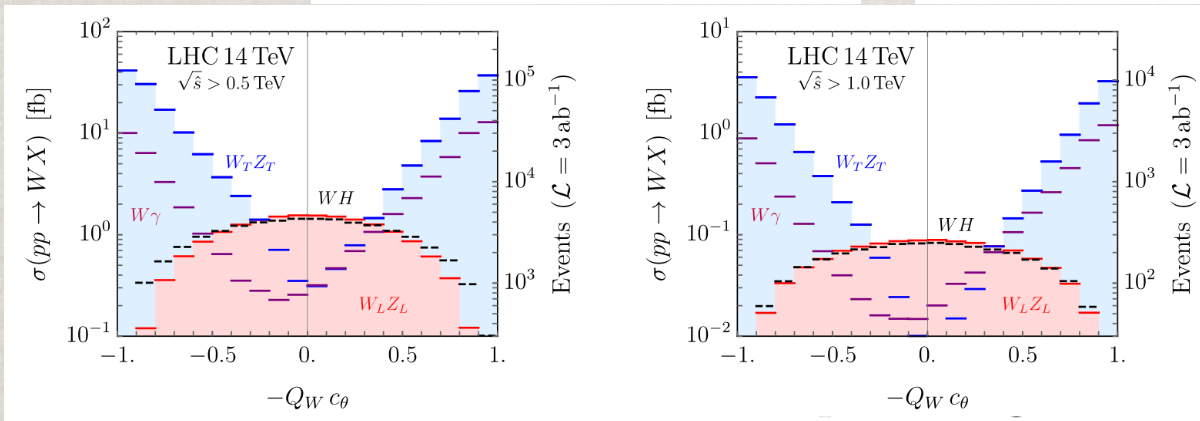
R. Capdevilla, TH, arXiv:2412.12336; Huang, Lewis, Lane, Liu, arXiv:2009.09429

Massless gauge sector & Higgs sector:

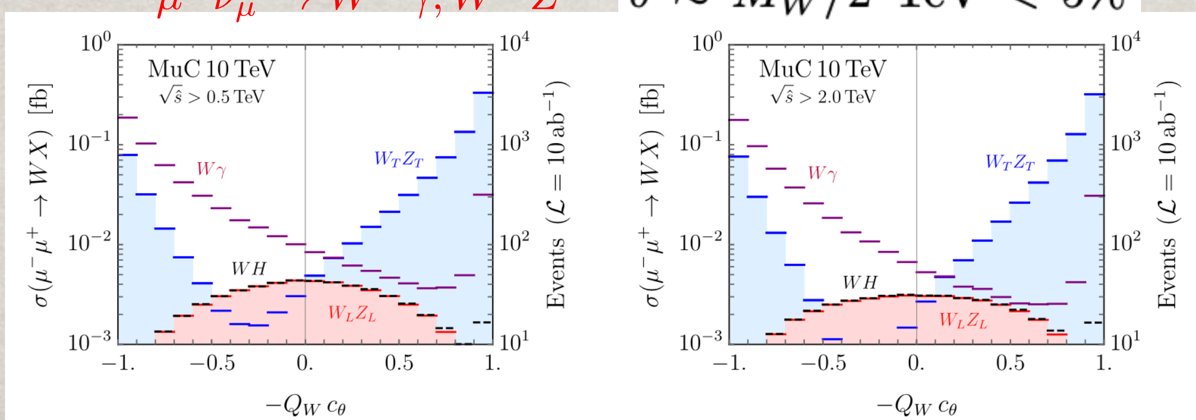
$$r_{Z\gamma} = \frac{\sigma(WZ)}{\sigma(W\gamma)}\,, \quad r_{ZH} = \frac{\sigma(WZ)}{\sigma(WH)}$$

For **δ** = $M_W/2E \ll 1$: $\dfrac{\sigma(W_T Z_T)}{\sigma(W_T\gamma)} \approx \dfrac{g_z^2}{e^2}\dfrac{(g_-^{f_1})^2 + (g_-^{f_2})^2}{Q_1^2 + Q_2^2}$

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



$\mu^\pm \nu_\mu \to W^\pm\gamma, W^\pm Z$ $\quad \delta \approx M_W/2\ \text{TeV} < 5\%$



What do we learn in testing EWSR?

"endlessly confirm the correctness of SM" - Carlo Rubia

SMEFT BSM vs. HEFT BSM

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

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

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

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

weakly coupled (SUSY, 2HDM) — strongly coupled (composite)

new scale ~ Λ — nearby scale ~ 4π υ

At the LHC: Higgs coupling SM-like ~ 10%

Z. Liu, I. Lewis, I. Mahbub, arXiv:2605.08433

(light) Fermion Yukawa's wide open:

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

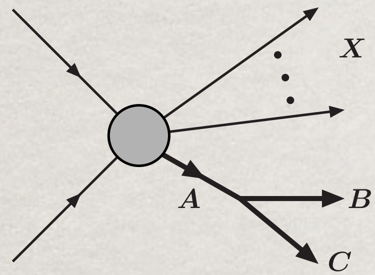
E. Celada, TH et al., arXiv:2312.13082

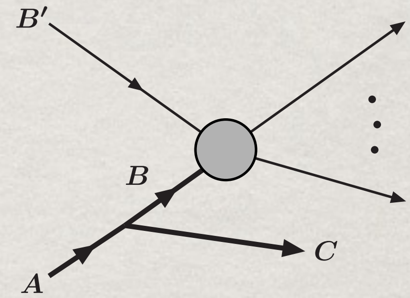
$$-\frac{v}{\sqrt{2}} \left[\bar{\ell}_L Y_\ell(H) U P_- \ell_R + \mathrm{h.\,c.}\right]$$

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

Other Aspects of EWSR

Splitting: the dominant phenomena





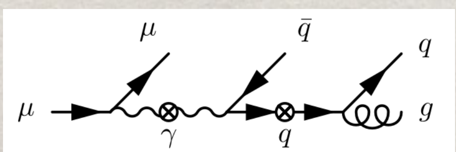
$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A\to B+C}$$

J.M. Chen, TH & B. Tweedie, arXiv:1611.00788

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



$$\frac{\mathrm{d} f_i}{\mathrm{d}\ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{i,j} \otimes f_j$$

C. Bauer, N. Ferland, B. Webber, arXiv:1703.08562

EW shower/jets:

$$W^* \to q\bar{q}g\ ...,\ \ell^\pm\nu\gamma\ ...$$
$$t^* \to b\bar{b}W^*,\ tZ^*,\ th^*\ ...$$
$$\nu^* \to \ell^\pm W^*\ ... \qquad \to \text{EW jets}$$

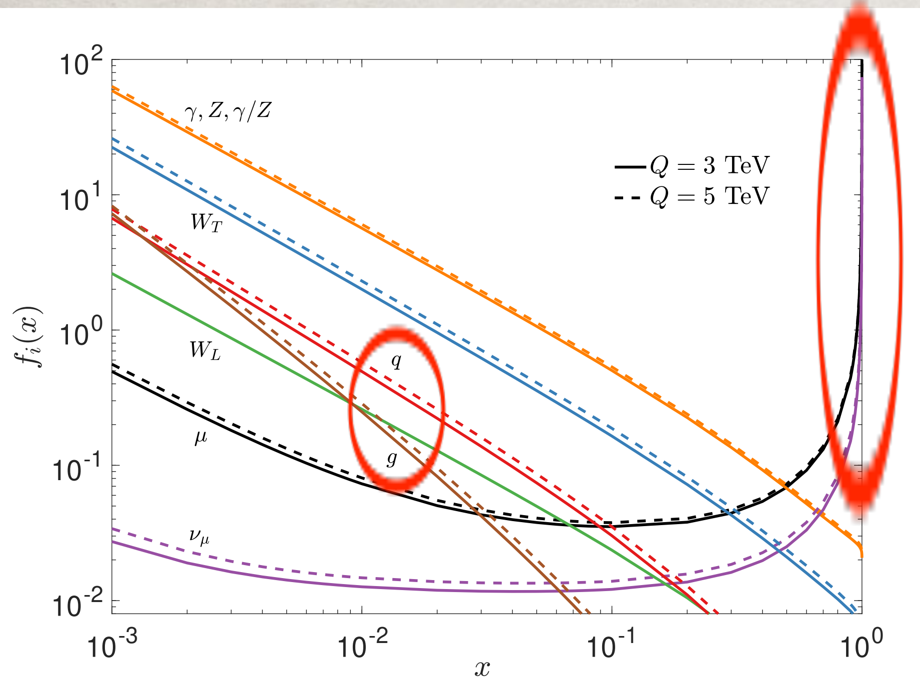
A Multi-TeV $\mu^+\mu^-$ Collider

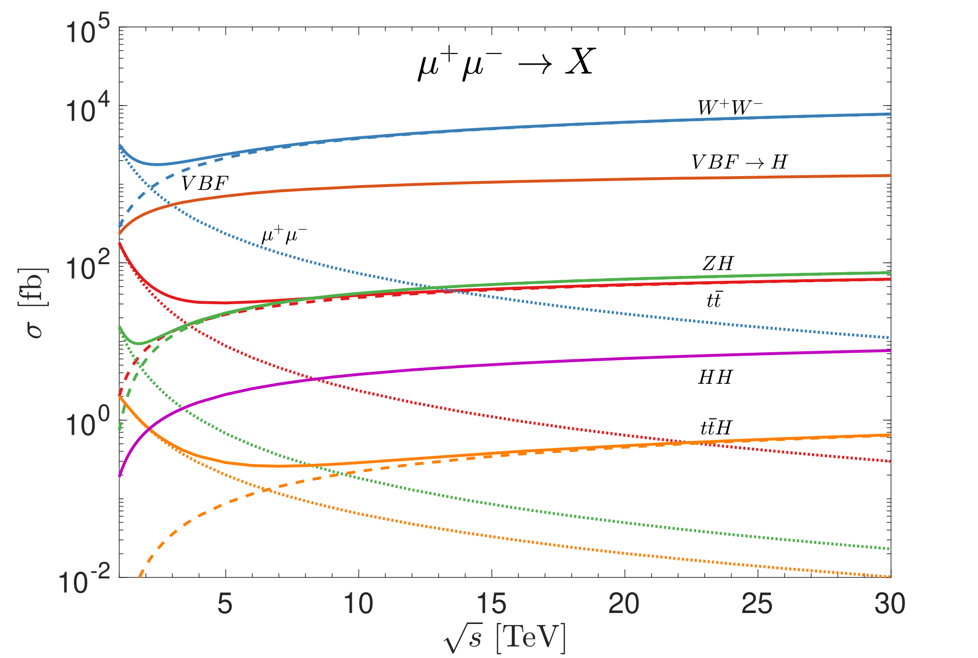
EW PDF's via DGLAP

$$\frac{d f_i}{d \ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{i,j} \otimes f_j$$

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

VBF $\sigma \sim \frac{1}{M^2_{VV}} \ln \frac{Q^2}{M^2_W}$

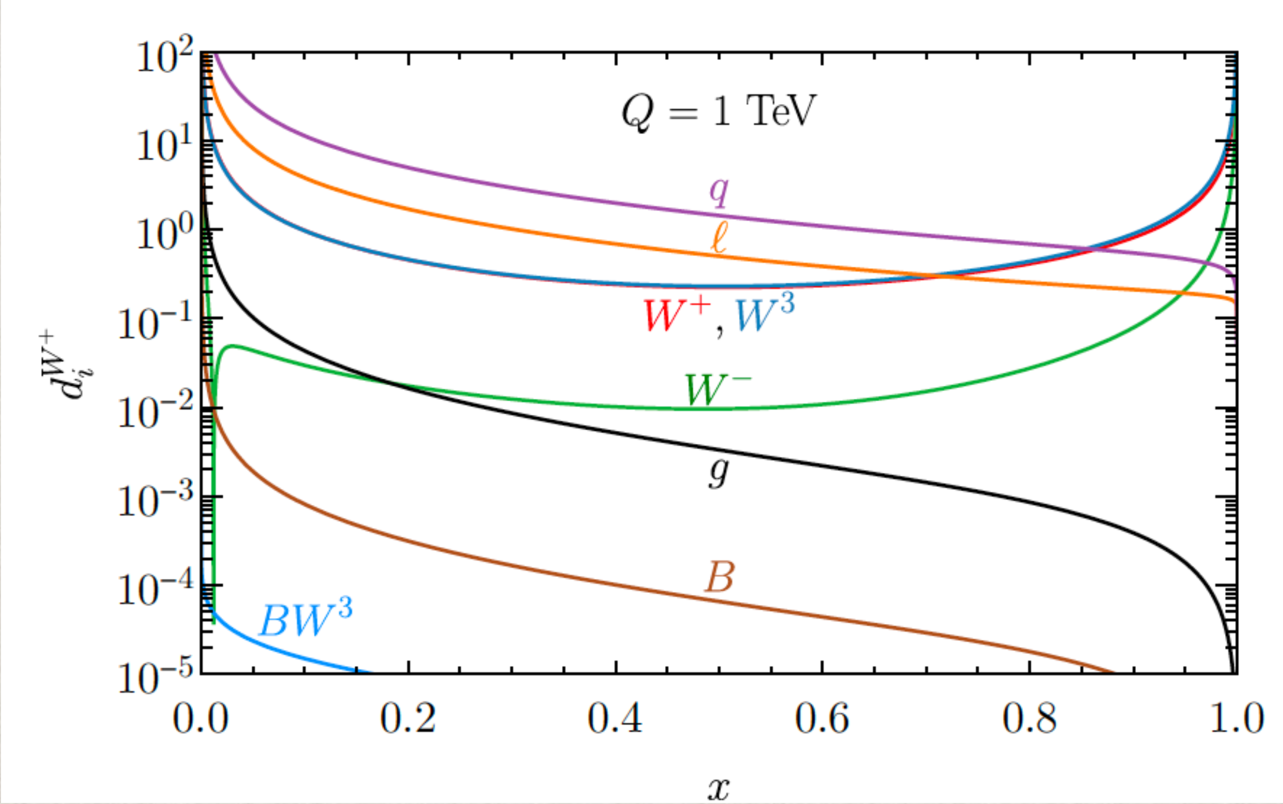




TH, Ma, Xie, arXiv:2203.11129
J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;
C. Bauer, N. Ferland, B. Webber, arXiv:1703.08562

"Leptonic showering"

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



- With W/Z showers, all leptons/neutrino components exist!
- EW "jets": *e.g.*, a HE $\boldsymbol{\nu}$ → an observable jet!

J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;
C. Bauer, D. Provasoli, B. Webber, arXiv:1806.10157

Further Remarks

In approaching EWSR,
how much the SM "UV completion" tells us?

- QED is ~UV complete, but doesn't go beyond O(GeV):
  e.g. $(g\text{-}2)_e$ versus $(g\text{-}2)_\mu$
- QCD IS UV complete, could be dynamically extrapolated to an exponentially high scale Q:

$$\alpha_s(Q^2) \approx 1/\ln(Q^2/\Lambda^2_{QCD}) \Rightarrow \Lambda_{QCD} \approx Q\exp(-1/2\alpha_s)$$

but new physics comes in at $v \sim 250$ GeV

- The SM with the Higgs is ~UV complete,
  --- to be tested by EWSR

but what confidence do we have to extrapolate it to $O(M_{PL})$?

→"UV completion" needs NOT to be a completion!

***i.e.* Go for BSM & beyond EWSR!**

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;
the symmetry could be larger or smaller than O(4).

- EW PDF's & EW jets to emerge @ high energies!

Electroweak physics @ high energies is rich!