Electroweak Processes @ High Energies

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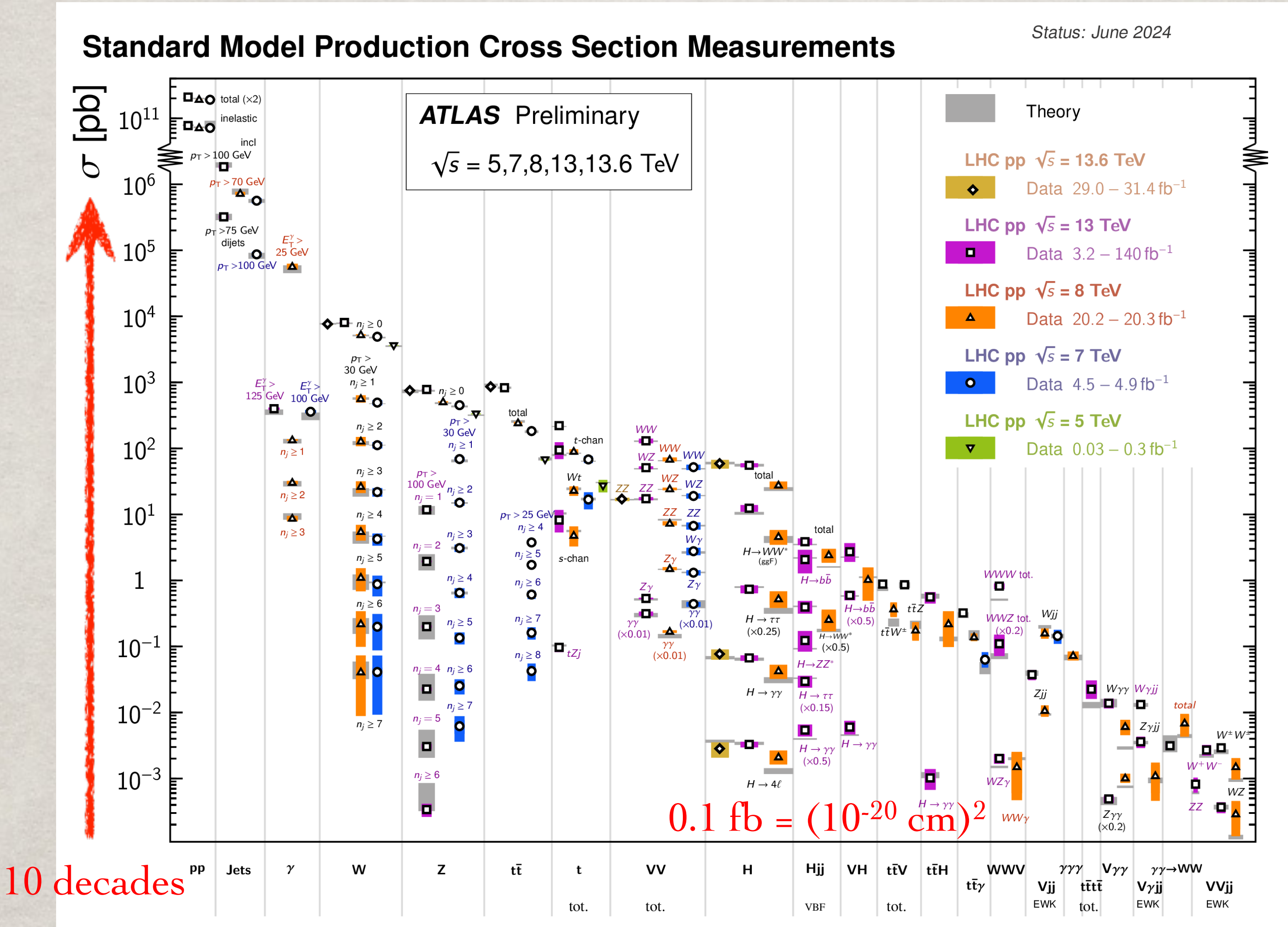
DESY Annual Theory Workshop
"Synergies Towards the Future Standard Model"
September 24, 2025

LHC Rocks!

Energy frontier for the next ~15 years!



Reaching a scale of a few TeV,
Towards the future Standard Model!

Today's Topics:

"Electroweak Processes @ High Energies"

- Longitudinal gauge bosons, electroweak symmetry restoration
- Electroweak splitting: EW PDF and EW showering

Goldstone-boson Equivalence Theorem

At high energies $E >> M_W$, the longitudinally polarized gauge bosons behave like the corresponding Goldstone bosons associated with the gauge symmetry breaking. (They remember their origin!)

$$\mathcal{M}(W_L^i W_L^j \to W_L^i W_L^j) \approx \mathcal{M}(\omega^i \omega^j \to \omega^i \omega^j)$$

W^i_L → Most sensitive to the underlying mechanism for EWSB.

→ "Bad high energy behavior" $\mathcal{M}(W_L^i W_L^j \to W_L^i W_L^j) \propto \frac{E^2}{M_W^2}$

ω^i → Correspond to the broken generators $U = \exp\{i\omega^i \tau^i / v\}$

- Living in a "incomplete representation", nothing to say about the "Higgs boson".
- The "Higgs mechanism" for W mass generation DOES NOT require the existence of a Higgs boson!

Lee, Quigg, Thacker (1977); Chanowitz, Gailard (1984); J. Chen, TH, B. Tweedie, arXiv:1611.00788; Coumo, L. Vecchi, A. Wulzer, arXiv:1911.12366

The Role of the Higgs Boson

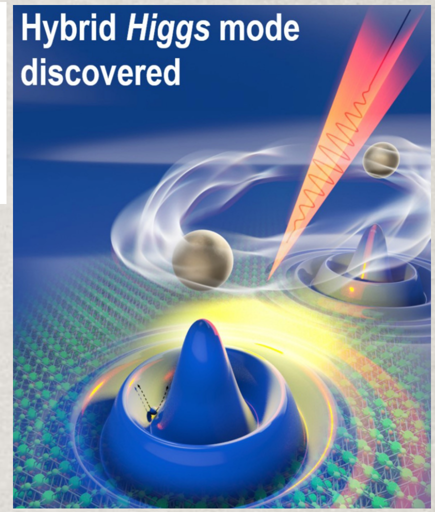
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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]



Laser @ 10^{12} Hz (2021, Ames Lab)

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

Benjamin W. Lee,* C. Quigg,† and H. B. Thacker

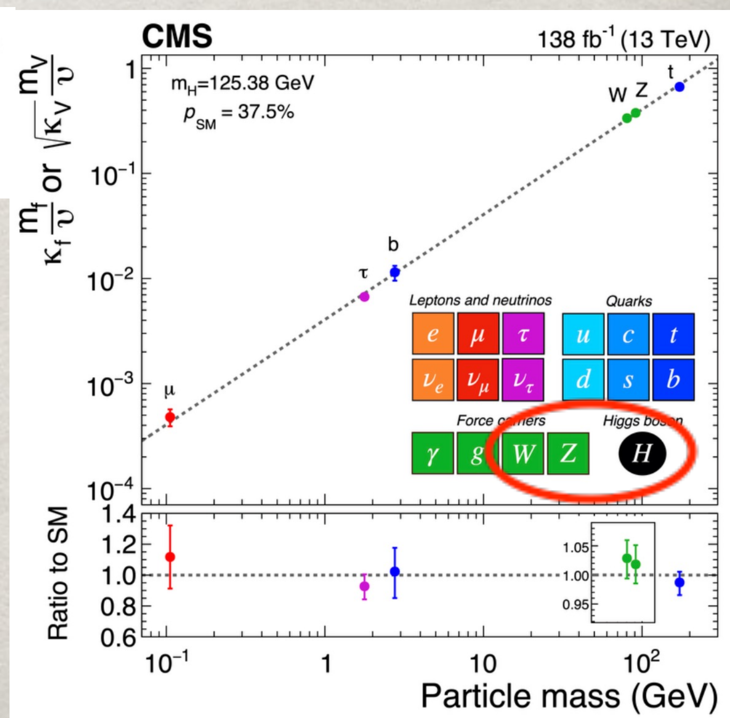
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510

(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 $U = \exp\{i\omega^i\tau^i/v\} + h$



• Longitudinal gauge bosons

V_L wavefunction for a massive vector :

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

trivial "scalarization" (for any vector state)

symmetry breaking residual

- 1^{st} observation of W_L in top decay

$$\frac{d\Gamma(t\to bW_{T,L})}{d\cos\theta^*} \sim 1 \pm \cos^2\theta^* \qquad \Gamma_{W_L}/\Gamma_{W_T} \approx m_t^2/2M_W^2 \approx 2.$$

- 2^{nd} observation: $e^+e^- \to W^+W^-$ at LEP

  Angular distribution fit PLB557, 147(2003)

- 3^{rd} observation: $q\bar{q} \to W^\pm_L Z_L$ @ 5.2**σ**

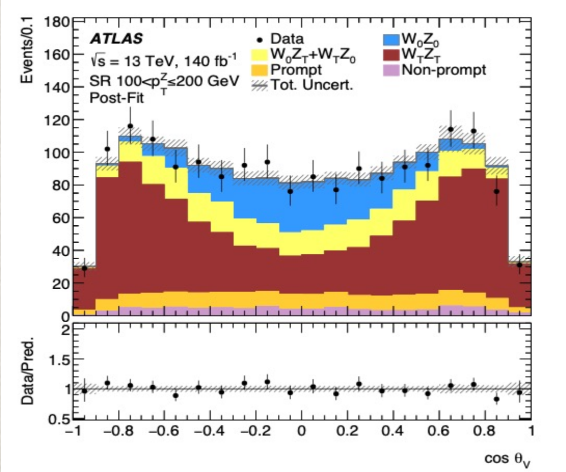
  at LHC: ATLAS: arXiv:2402.16365, PRL

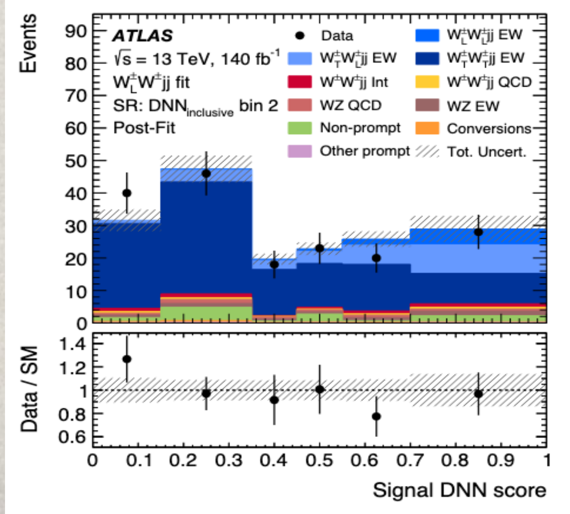
- 4^{th} observation (?): $W^\pm W^\pm \to W^\pm_L W^\pm_L$

  at the LHC: at least one W_L @ 3.3**σ**

CMS: arXiv:2009.09429, ATLAS: arXiv:2503.11317

Great step to scrutinizing EWSB !





EW Symmetry Restoration (EWSR)

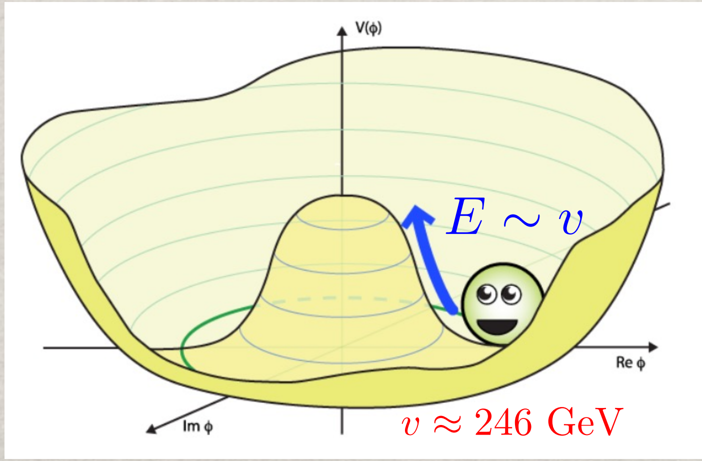
$$\frac{v}{E}: \quad \frac{v\ (250\ \text{GeV})}{10\ \text{TeV}} \approx \frac{\Lambda_{QCD}\ (300\ \text{MeV})}{10\ \text{GeV}} \qquad v/E,\ m_t/E,\ M_W/E \to 0!$$

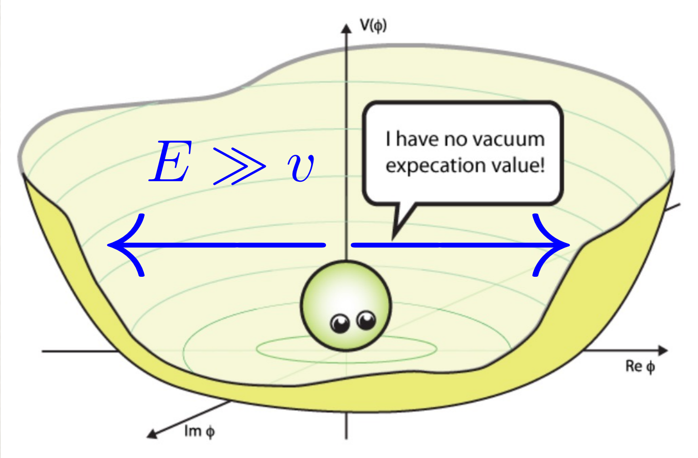
(*i*) the physics of the transverse gauge bosons $(W_T^\pm, Z_T, \gamma)$ and fermions is described by a massless theory in the unbroken phase;

(*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 2025





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

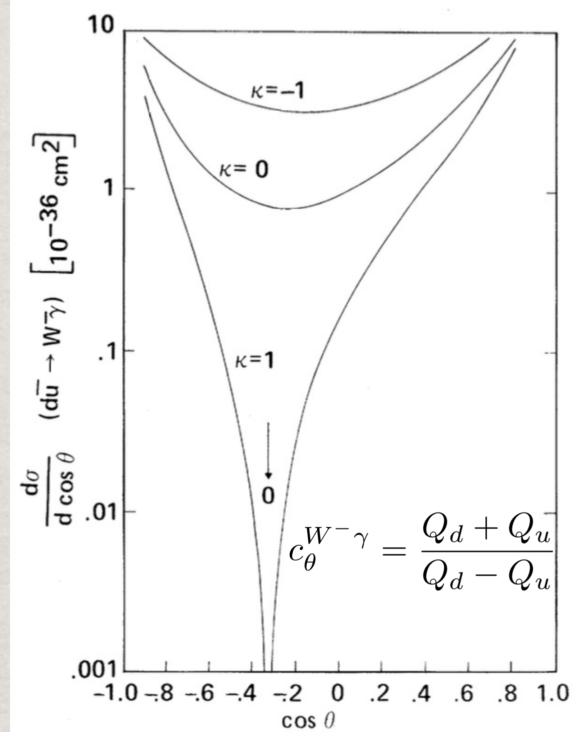
K. O. Mikaelian and M. A. Samuel
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74074

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

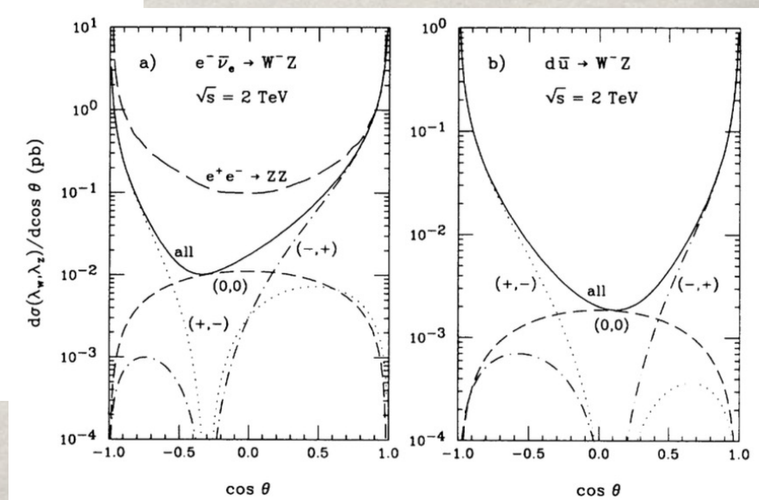
Amplitude Zeros in $W^{\pm}Z$ Production

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 nonstandard 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, 2025)

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

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

- Gauge sector: Radiation Amplitude Zeros (RAZs)

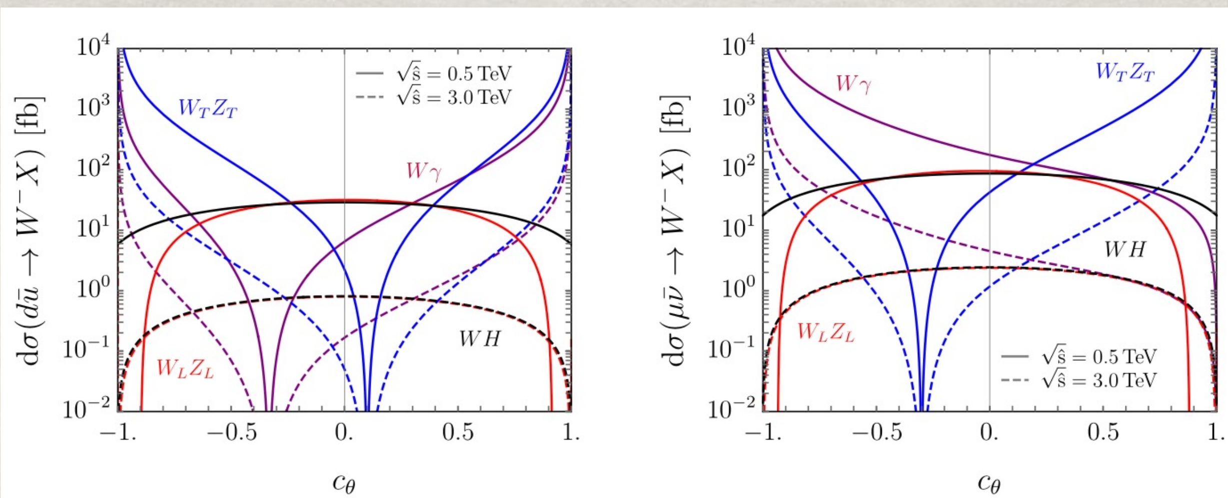
EM: $c_\theta^{W^-\gamma} = \dfrac{Q_d+Q_u}{Q_d-Q_u}$; EW (transverse): $c_\theta^{W^-Z_T} = \dfrac{g_-^d+g_-^u}{g_-^d-g_-^u}$

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

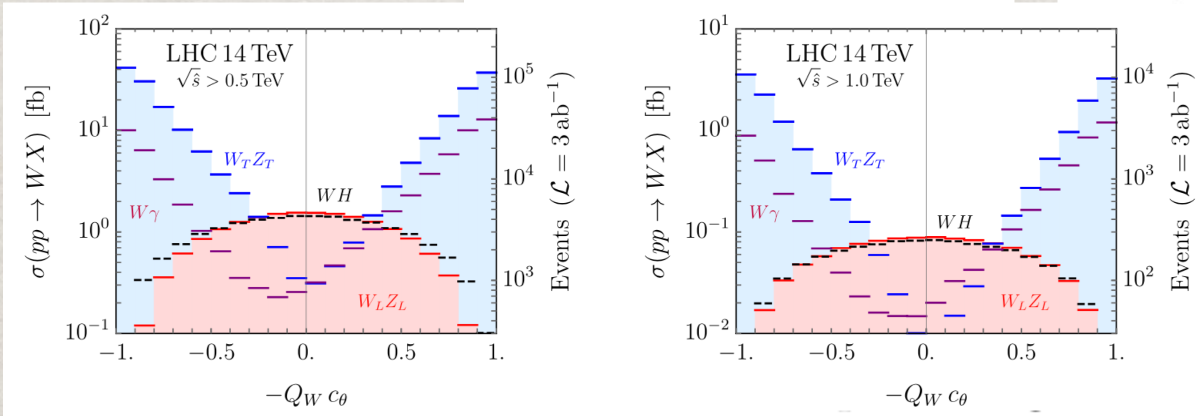


Test EWSR @ LHC / muon Collider

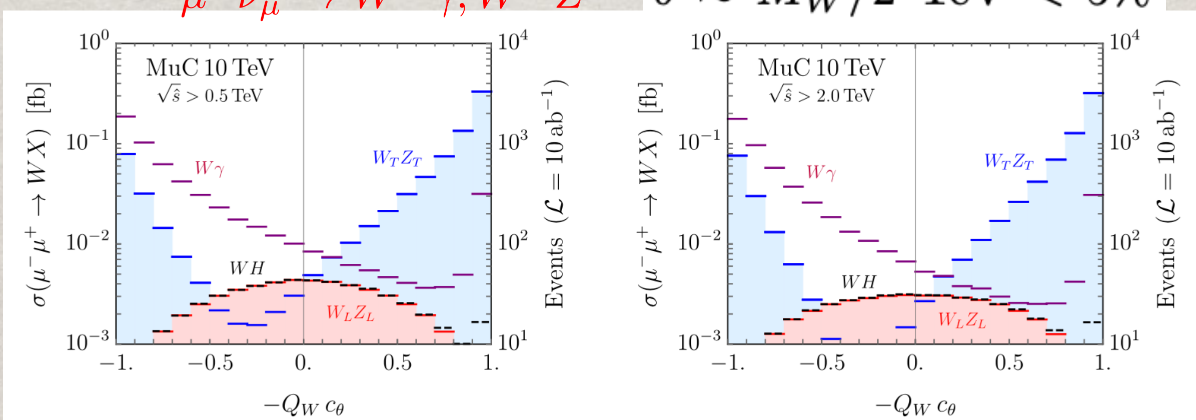
R. Capdevilla, TH, arXiv:2412.12336; Huang, Lewis, Lane, Liu, arXiv:2009.09429

Massless gauge sector & Higgs sector: $r_{Z\gamma} = \dfrac{\sigma(WZ)}{\sigma(W\gamma)}\,, \quad r_{ZH} = \dfrac{\sigma(WZ)}{\sigma(WH)}$

For **δ** = $M_W/2E$ << 1: $\dfrac{\sigma(W_T Z_T)}{\sigma(W_T\gamma)} \approx \dfrac{g_z^2}{e^2}\dfrac{(g_-^{f_1})^2+(g_-^{f_2})^2}{Q_1^2+Q_2^2}$ $\quad \sigma(W_L^\pm Z_L) \sim \sigma(W_L^\pm H)$, or $\sigma(\omega^\pm\omega^0) \sim \sigma(\omega^\pm H)$



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



Next target: $W_L W_L \to W_L W_L$ @ HE

Talk by Steven Lowette

What do we learn in testing EWSR?

"endlessly confirm the correctness of SM" ?!

- Carlo Rubia

SMEFT BSM vs. HEFT BSM

Talks by E. Vryonidou, R. Grober

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

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

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

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

weakly coupled (SUSY) — strongly coupled (composite)

new scale ~ **Λ** — nearby scale ~ **4π υ**

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

(light) Fermion Yukawa's wide open:

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

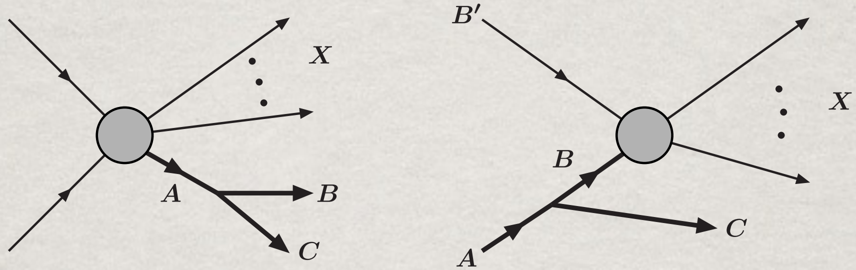
$$-\frac{v}{\sqrt{2}} \left[\bar{\ell}_L Y_\ell(H) U P_- \ell_R + \mathrm{h.\,c.}\right]$$

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

TH, Kilian, Kreher, Ma, Maltoni, Pagani, Reuter, Striegl, Xie, arXiv:2108.05362, arXiv:2312.13082

• Other Aspects of EWSR

Colinear splitting: the dominant phenomena



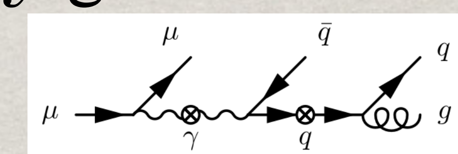
$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A\to B+C}$$

- Power corrections suppressed: $M_W^2/Q^2 \ll 1$
- Log corrections (RGE) large: $\alpha_2 \ln^2(Q^2/M_W^2) \sim \mathcal{O}(1)$
- Virtual Sudakov suppression;
- Real emission enhancement.

S. Frixione, F. Maltoni, D. Pagani, M. Zaro, arXiv:2506.10733.

EW "partons" dynamically generated

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



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

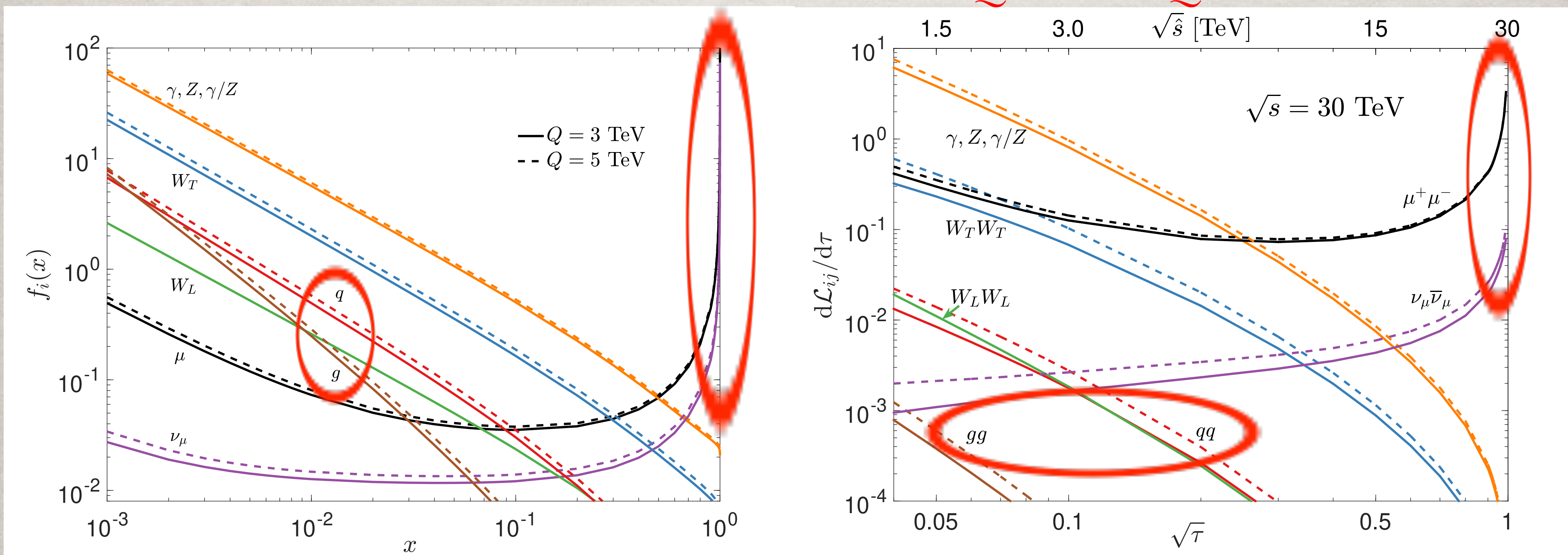
EW PDFs @ a Muon Collider

TH, Yang Ma, Keping Xie, arXiv:2007.14300

DGLAP evolution in full SM:

$$\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \frac{\mathrm{d}}{\mathrm{d}\log Q^2} \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma} & 0 \\ 0 & P_{gu} & P_{gd} & 0 & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix}$$

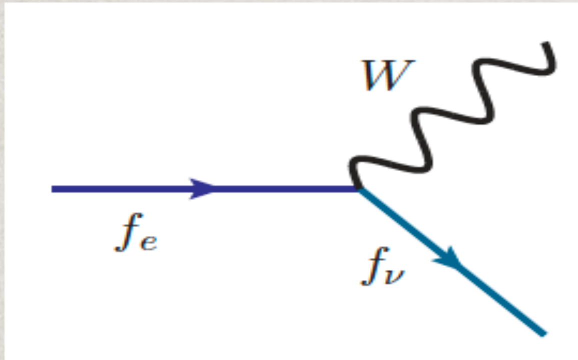
Take into account two scales: $\mu_{QCD} \sim \Lambda_{QCD}$, $\mu_{EW} \sim v$

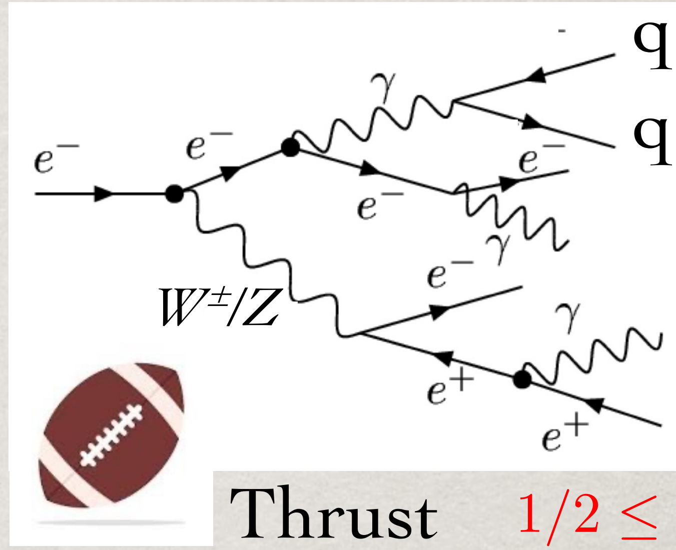


$\mu^\pm$, ν_μ : the valance. ℓ_R, ℓ_L, ν_L and $B, W^{\pm,3}$: LO sea.

Quarks: NLO; gluons: NNLO.

EW Showering @ high energies





Talk by
Silvia Ferrario
Ravasio

How jetty is it?

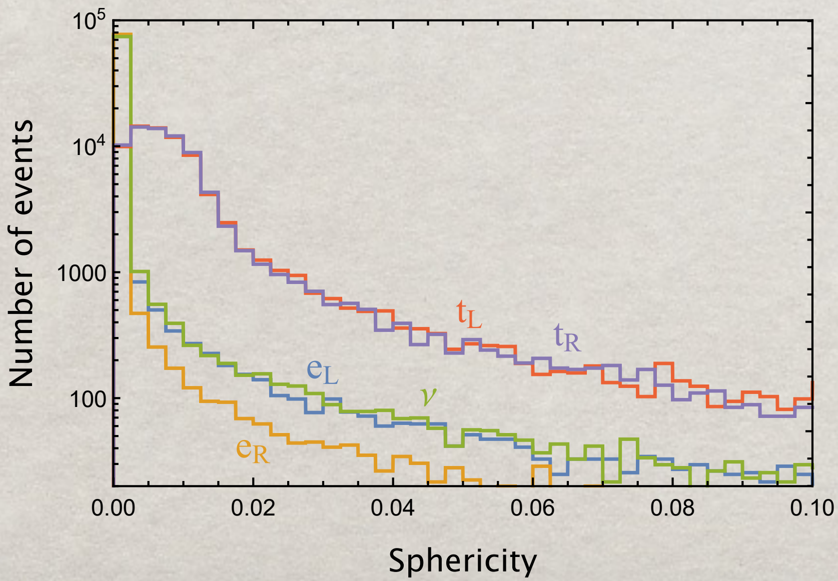
Sphericity $0 \leq S \leq 1$

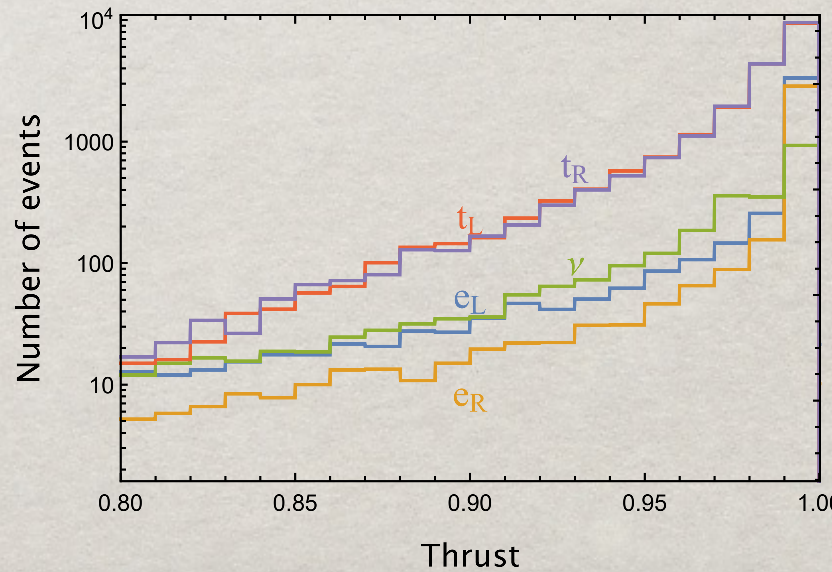
Thrust $1/2 \leq T \leq 1$

$$S = \frac{3}{2}\min\left(\frac{\sum_i p_{iT}^2}{\sum_i p_i^2}\right)$$

$$T = \max\left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}\right)$$

@ 5 TeV

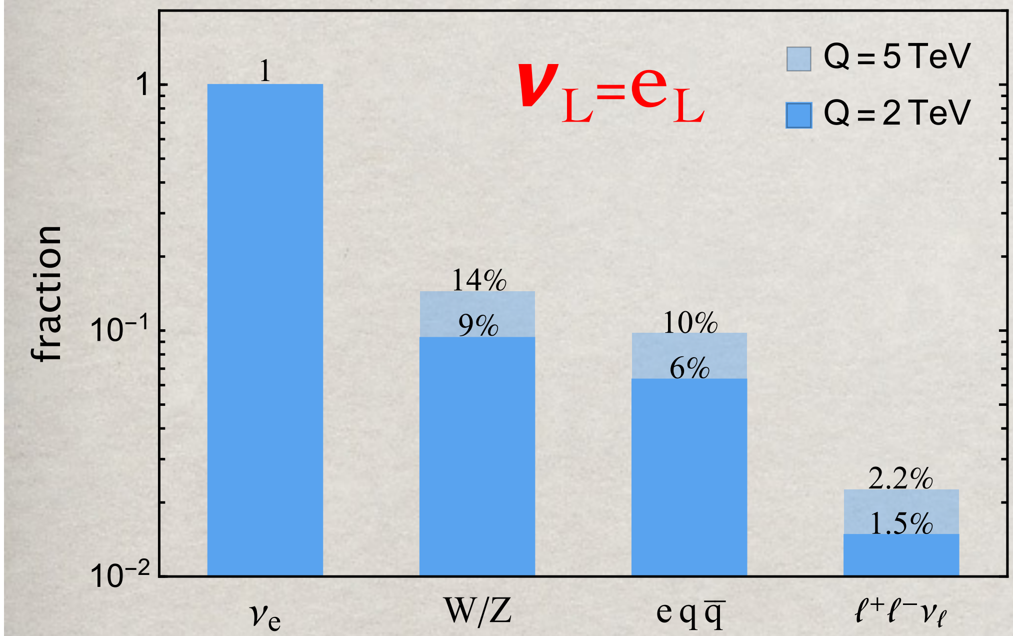


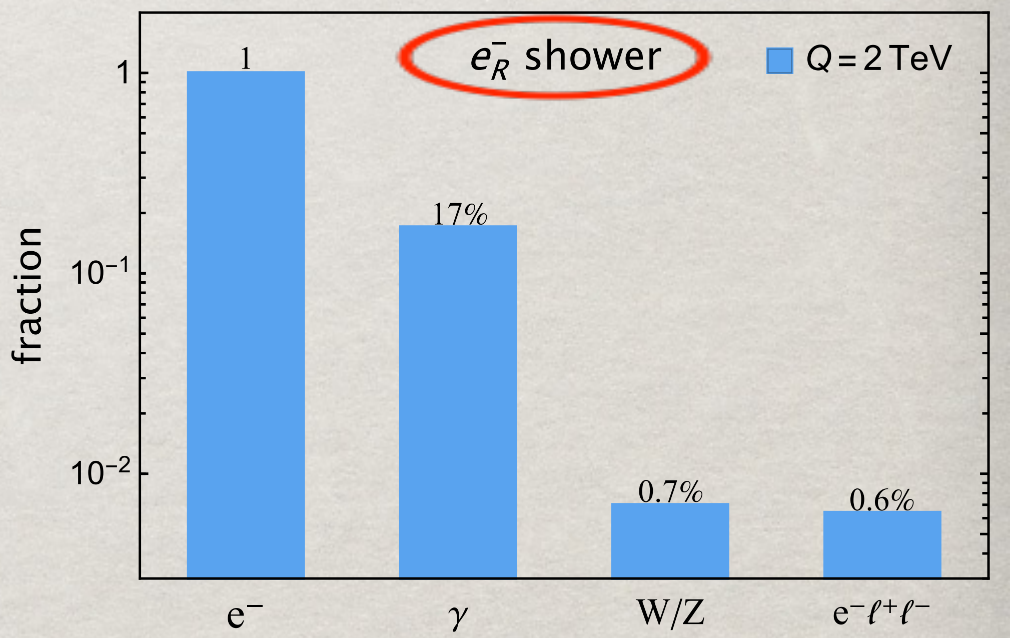


 TH, K. Xie, Y. Ma & A. Wu, … ; VINCIA

EW Showering @ high energies

- With W/Z showers, all leptons/neutrino components exist!
- (ν_L, e_L) indistinguishable in the symmetric phase.
- EW "jets": *e.g.*, a HE ν → an observable jet!

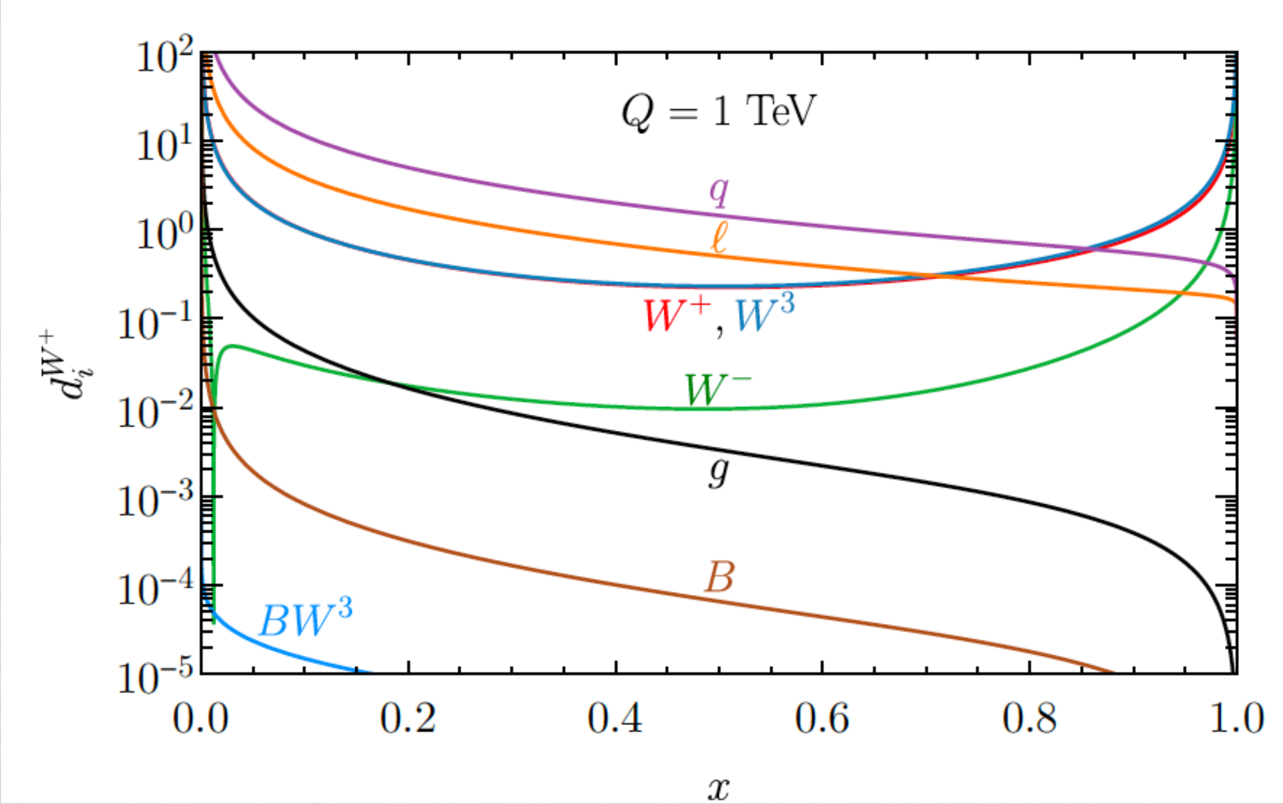




TH, K. Xie, Y. Ma & A. Wu, …, in preparation.
VINCIA used.

Fragmentation to a final state particle

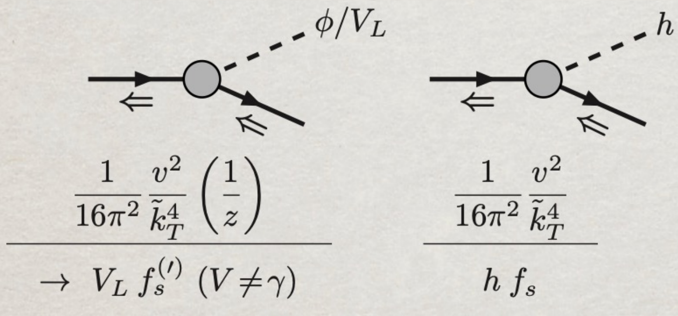
finding a W^+ in the mother particle i (i.e., $i \to W$)



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

"Ultra collinear behavior"

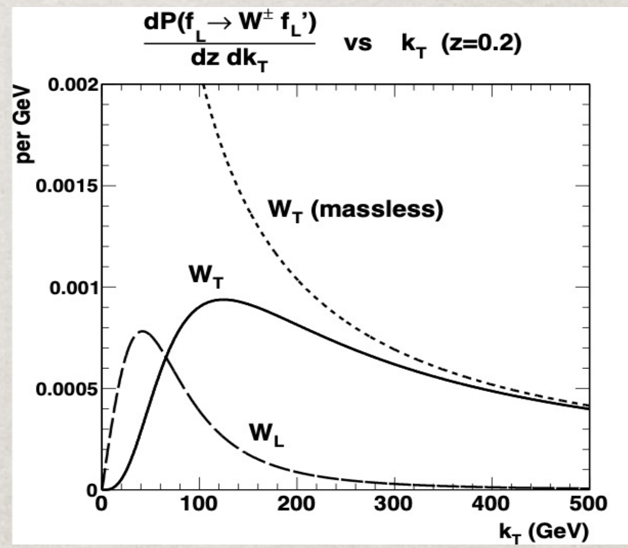
New characteristics with the mass:



$$\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1-\frac{v^2}{Q^2})$$

$k_T^2 > m_W^2$, it shuts off;

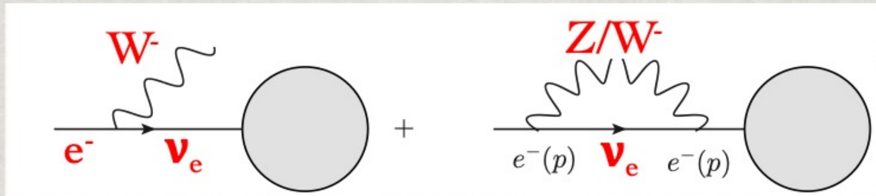
$k_T^2 < m_W^2$, flattens out!



- EWSB residual effect, Goldstone Eq. Th. violation!
- The PDFs for W_L no $\log(Q^2/M^2)$: M_W/E > Yukawa!
- Kinematic basis for "forward jet-tagging, central jet-vetoing".

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

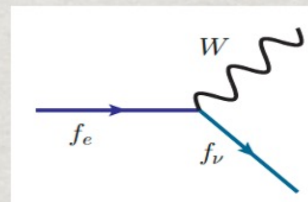
EW Evolution beyond Leading Log



Incomplete cancellation for non-inclusive process in SU(2):
SU(2) "color" (e,ν) distinguishable, unlike QCD!

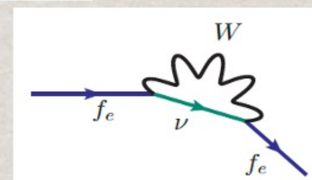
$$d\mathcal{P}_{\nu\leftarrow e} = d\mathcal{P}_{e\leftarrow\nu} \sim \frac{(T^{\pm})^2}{1-z} = \frac{(1/\sqrt{2})^2}{1-z}$$

$$d\mathcal{P}_{e\leftarrow e} = d\mathcal{P}_{\nu\leftarrow\nu} \sim \frac{(T^{3})^2}{1-z} = \frac{(1/2)^2}{1-z}$$



$$dV_{\nu\leftarrow e} = dV_{e\leftarrow\nu} = 0$$

$$dV_{e\leftarrow e} = dV_{\nu\leftarrow\nu} \sim -\int dz\, \frac{C_2(\mathbf{2})}{1-z} = -\int dz\, \frac{3/4}{1-z}$$



→ Bloch-Nordsieck theorem violation!

→"Factorization theorem":

- sufficiently inclusive **processes,**
- and infrared safe-**observables**

Not there yet! Much more to learn @ HE !

Conclusions

- EW physics @ high energies remains exciting and challenging!
- We are approaching the EW symmetric phase measured by $M_W/2E$.
- Longitudinal gauge bosons + Higgs form an O(4) multiplet: sensitive to underlying EWSB & BSM
- Colinear splitting is the dominant behavior:
  - Initial state EW PDF
  - Final state EW showering & fragmentation

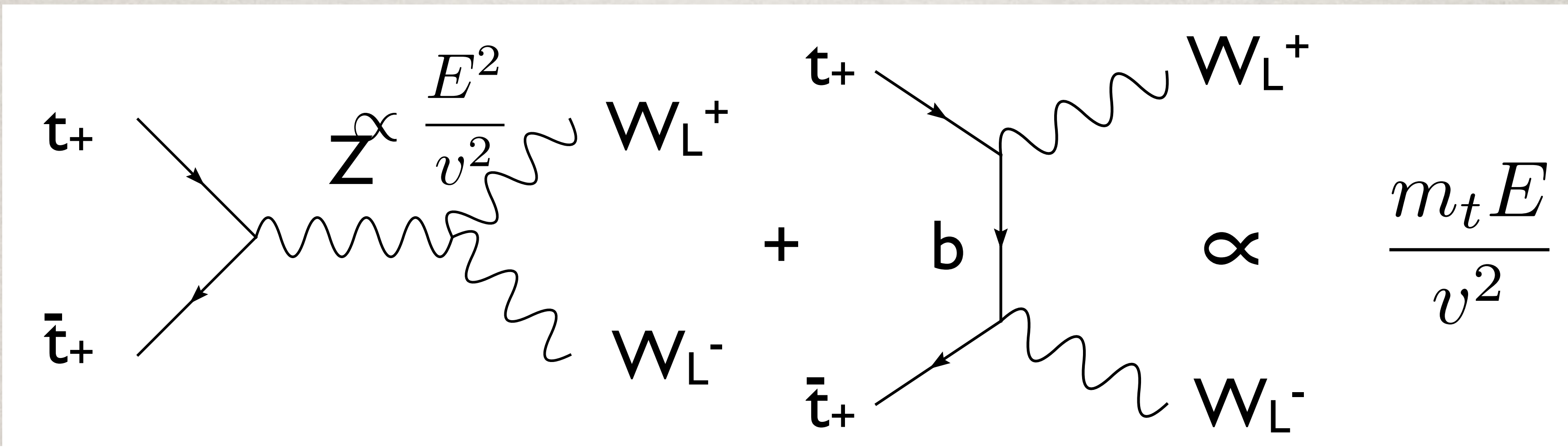
Electroweak physics rich!

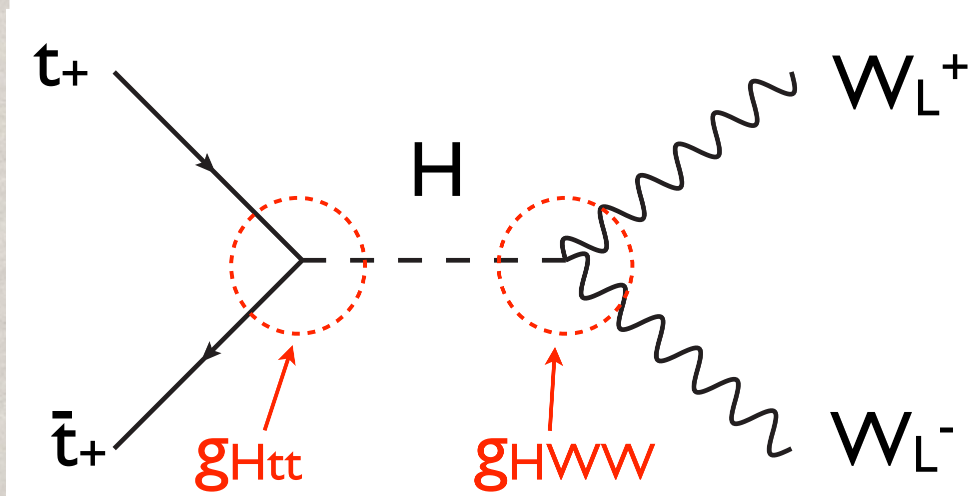
Energy frontier drives!

Thank you!

High-energy behavior: V_L & the role of H

$$\epsilon(k)^{\mu}_{L} = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^{\mu}}{m_W}$$ bad high-energy behavior!





Higgs boson save the day:

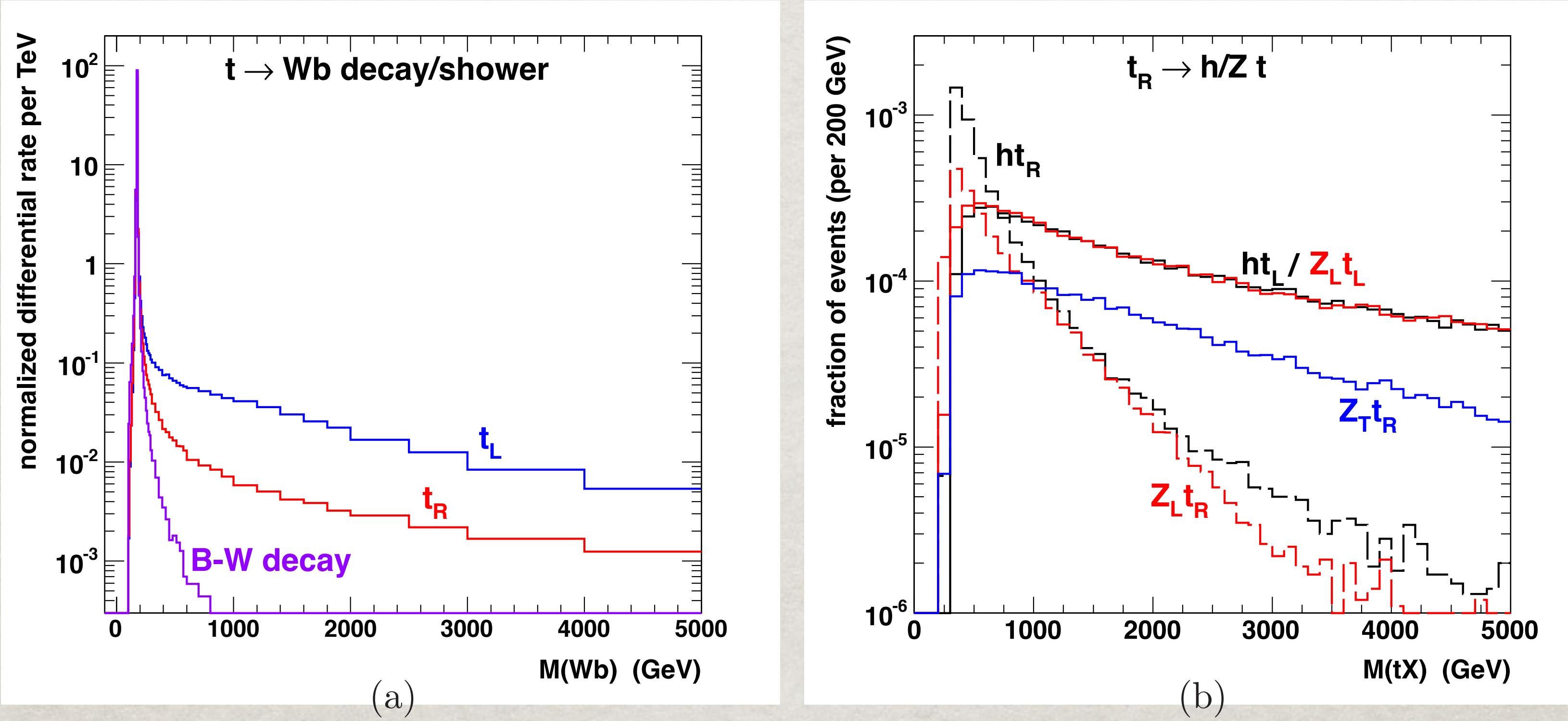
$$\propto \frac{m_t m_H}{v^2}$$

"UV complete"

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

- Top decay/showering @ 10 TeV

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



Leading ultra-collinear: $t_R \to ht_R,\ Z_L t_R$

U(1) gauge: $\mathcal{P}(t_R \to Z_T t_R) \approx 4.5 \times 10^{-3}$

Yukawa: $\mathcal{P}(t_R \to ht_L) \simeq \mathcal{P}(t_R \to Z_L t_L) \approx 7.2 \times 10^{-3}$

EW theory still puzzling:

both conceptually & technically !