

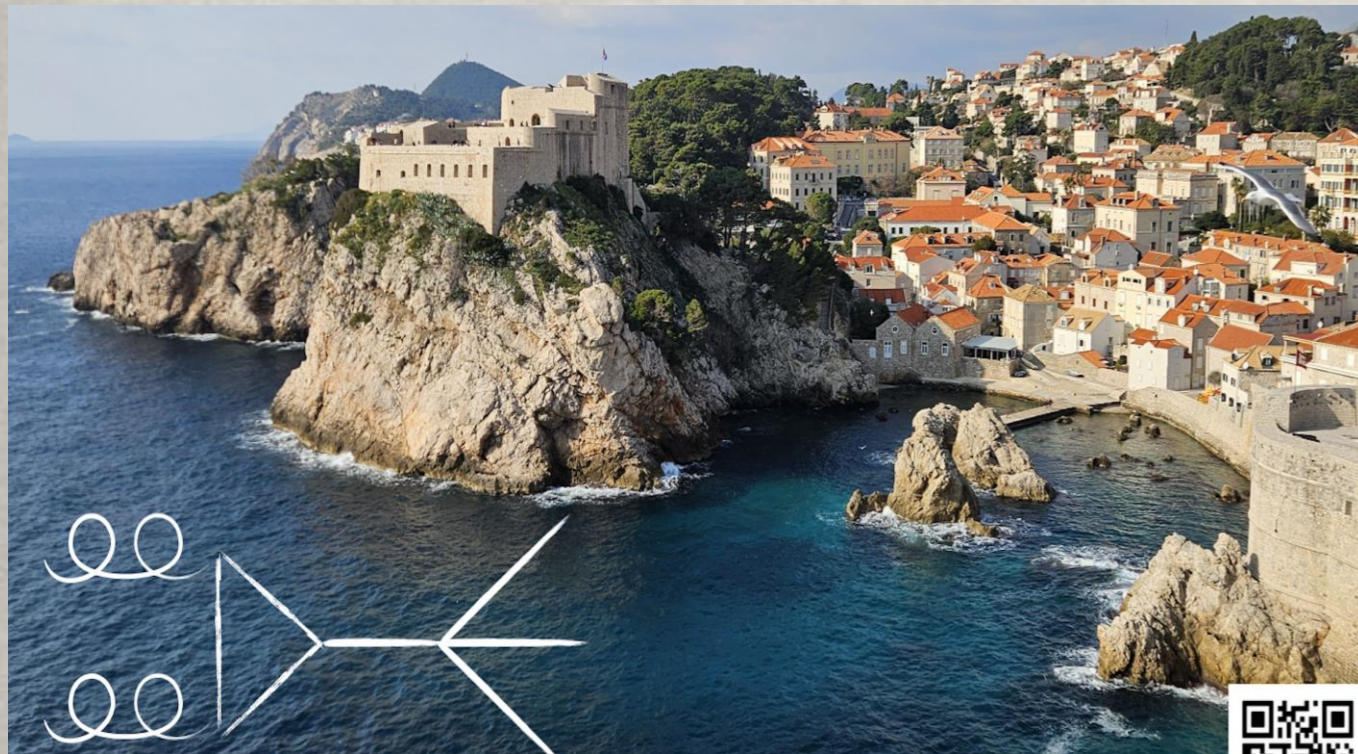
Electroweak Symmetry Restoration @ High Energies

Tao Han

Pitt PACC, University of Pittsburgh

HHH Workshop, Dubrovnik

September 29, 2025



Today's Topics:

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

• Longitudinal gauge bosons

V_L wavefunction for a massive vector :

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

trivial “scalarization”
(for any vector state)

symmetry
breaking residual

- 1st observation of W_L in top decay

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

- 2nd observation: $e^+e^- \rightarrow W^+W^-$ at LEP

Angular distribution fit PLB557, 147(2003)

- 3rd observation: $q\bar{q} \rightarrow W_L^\pm Z_L @ 5.2\sigma$

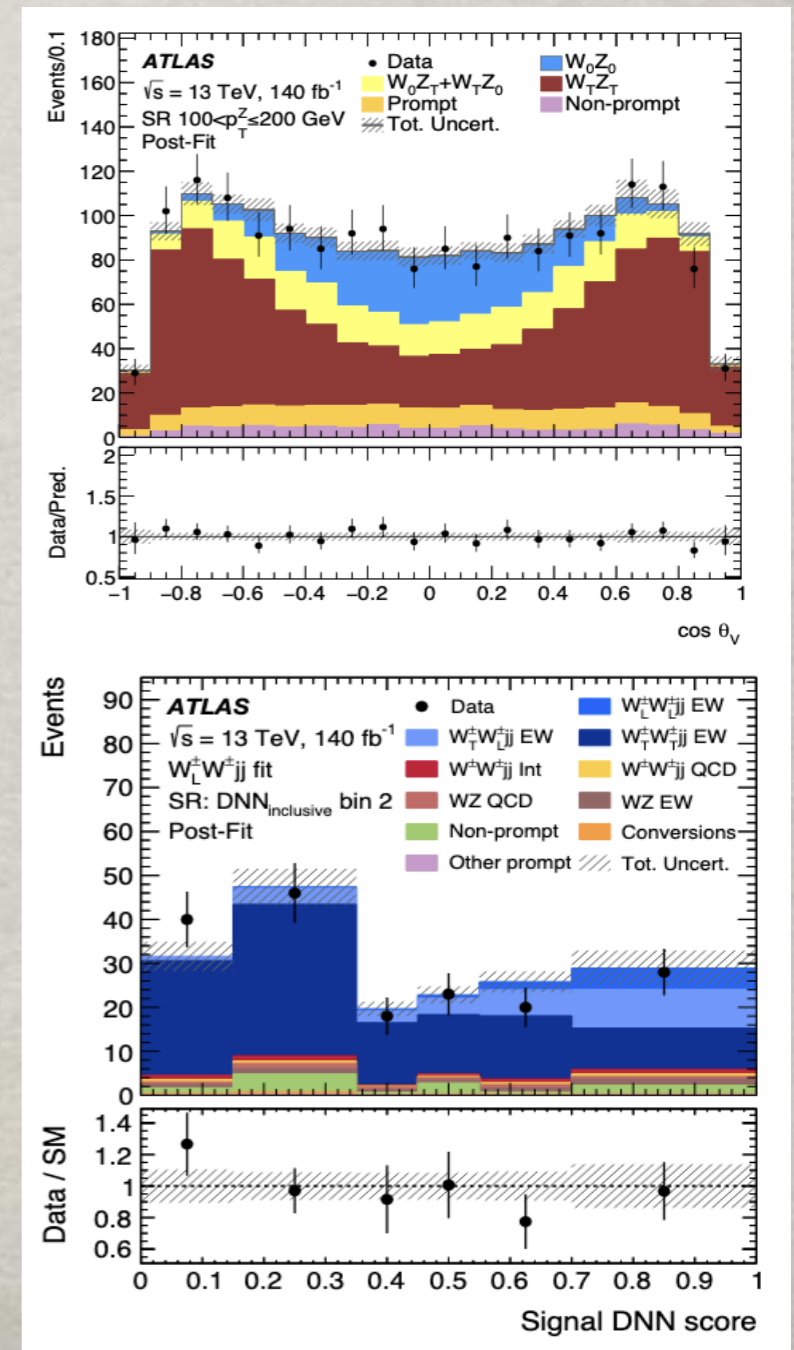
at LHC: ATLAS: arXiv:2402.16365, PRL

- 4th observation (?): $W^\pm W^\pm \rightarrow W_L^\pm W_L^\pm$

at the LHC: at least one $W_L @ 3.3\sigma$

CMS: arXiv:2009.09429, ATLAS: arXiv:2503.11317

Great step to scrutinizing EWSB !

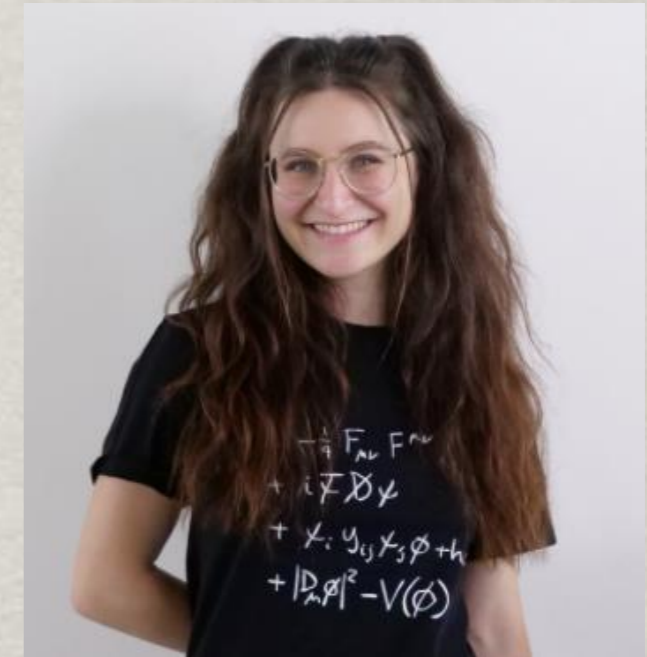


EW Symmetry Restoration (EWSR)

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

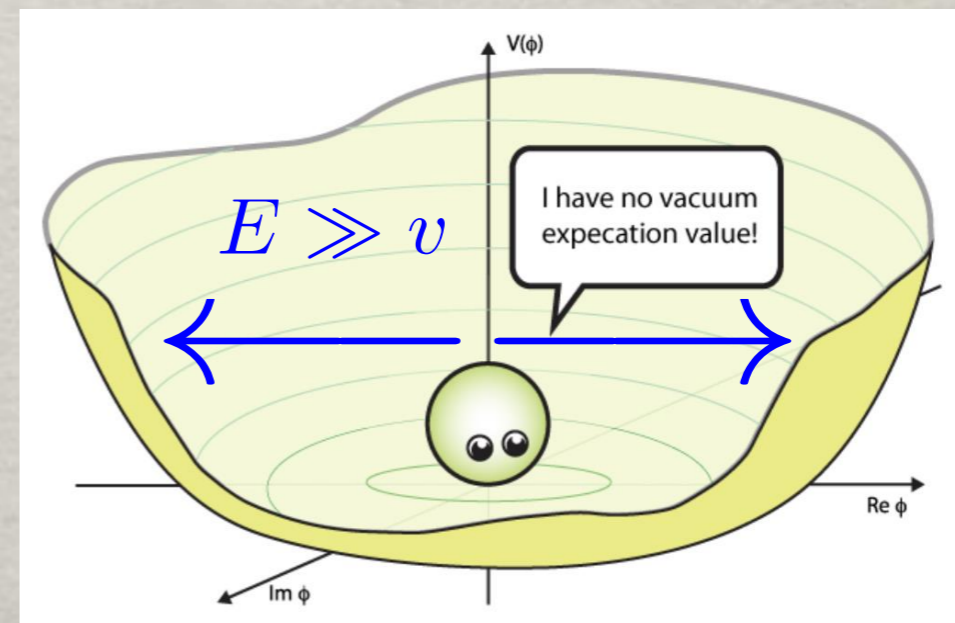
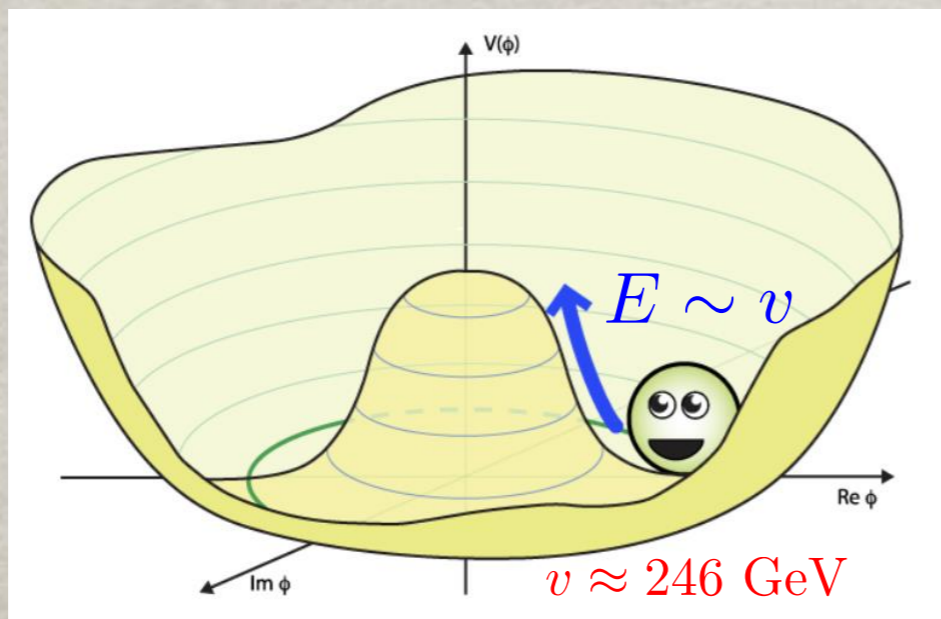
(i) the physics of the transverse gauge bosons (W_T^\pm, Z_T, γ) and fermions is described by a massless theory in the unbroken phase;

(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 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

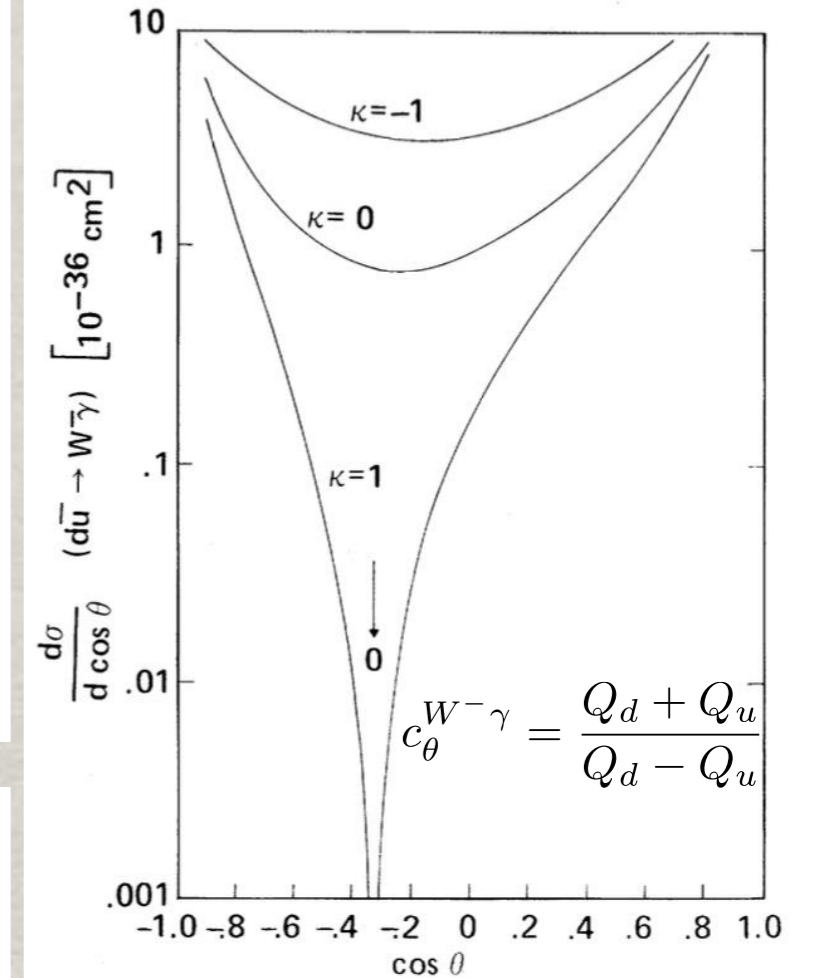
and

D. Sahdev

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

(Received 5 June 1979)

We suggest that the reactions $pp \rightarrow W^\pm \gamma X$ 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.



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

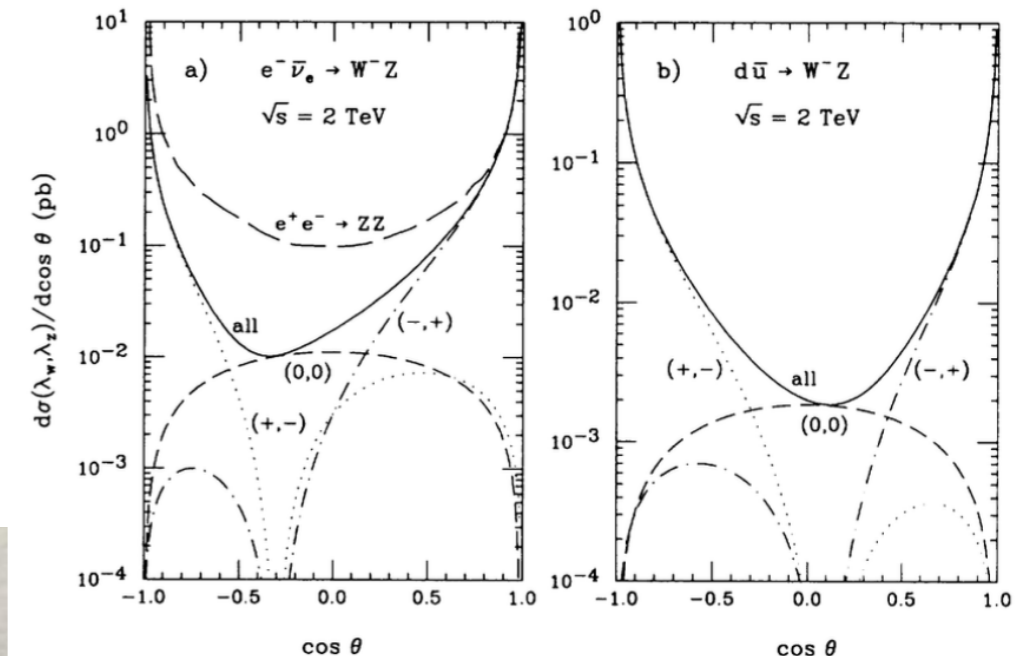
T. Han and J. Ohnemus

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, 2025)

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

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

- Gauge sector: Radiation Amplitude Zeros (RAZs)

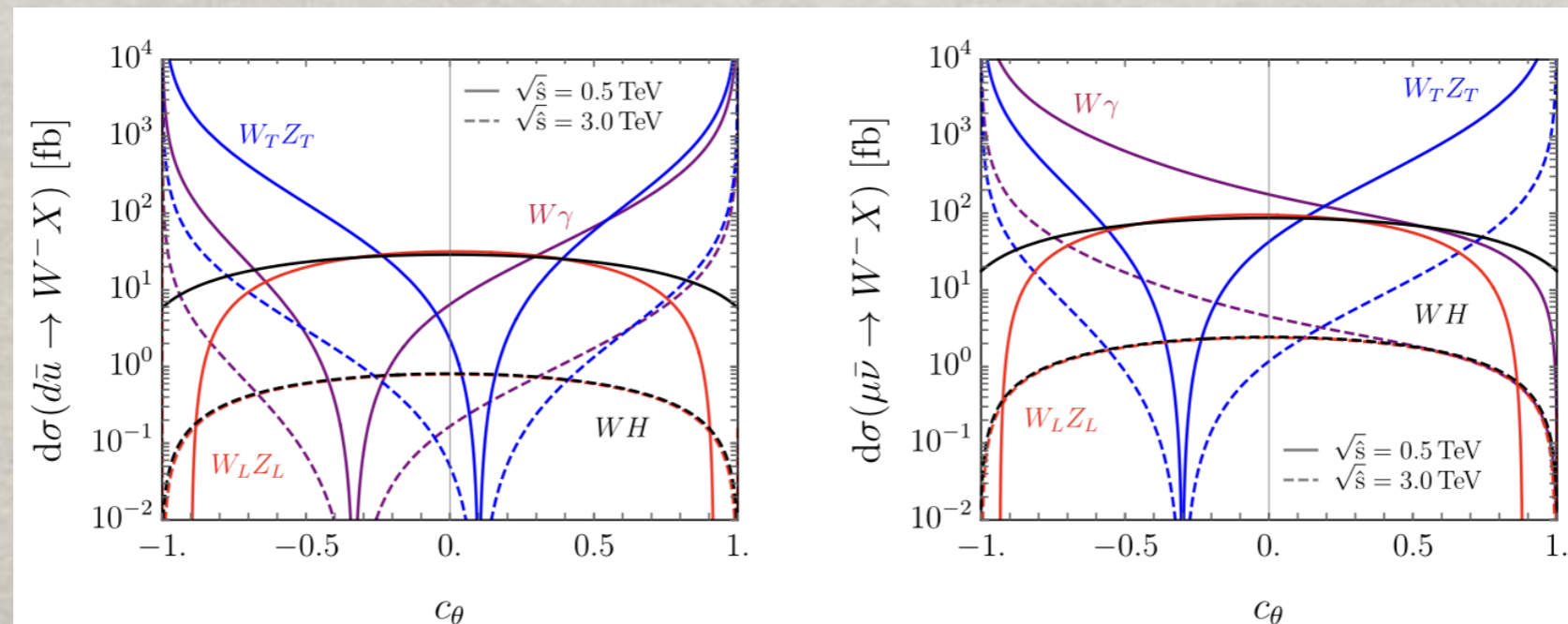
EM: $c_\theta^{W^- \gamma} = \frac{Q_d + Q_u}{Q_d - Q_u}$ EW (transverse): $c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$

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:

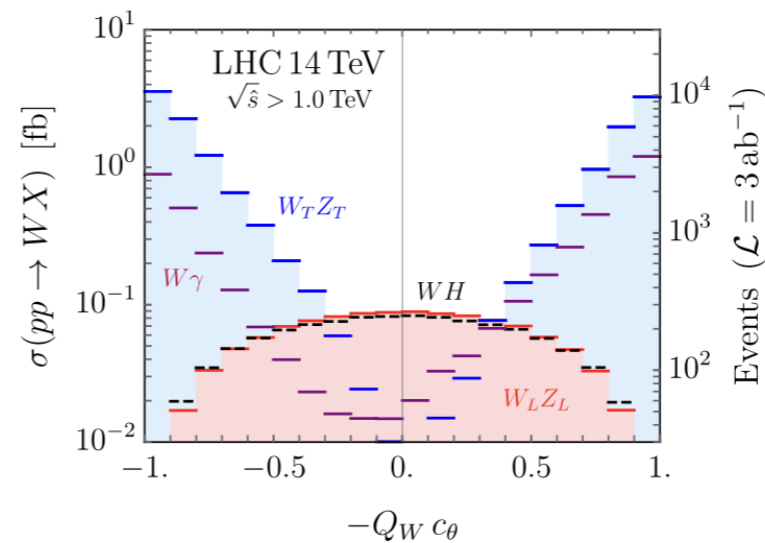
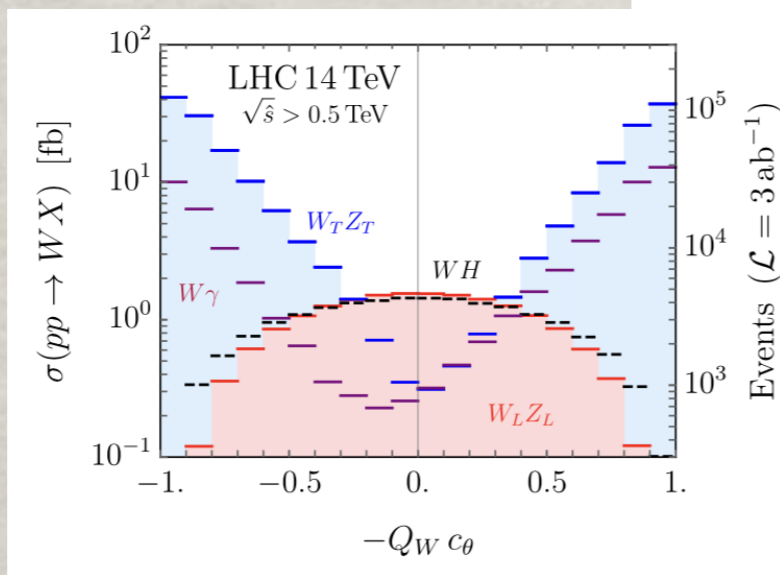
$$r_{Z\gamma} = \frac{\sigma(WZ)}{\sigma(W\gamma)}, \quad r_{ZH} = \frac{\sigma(WZ)}{\sigma(WH)}$$

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

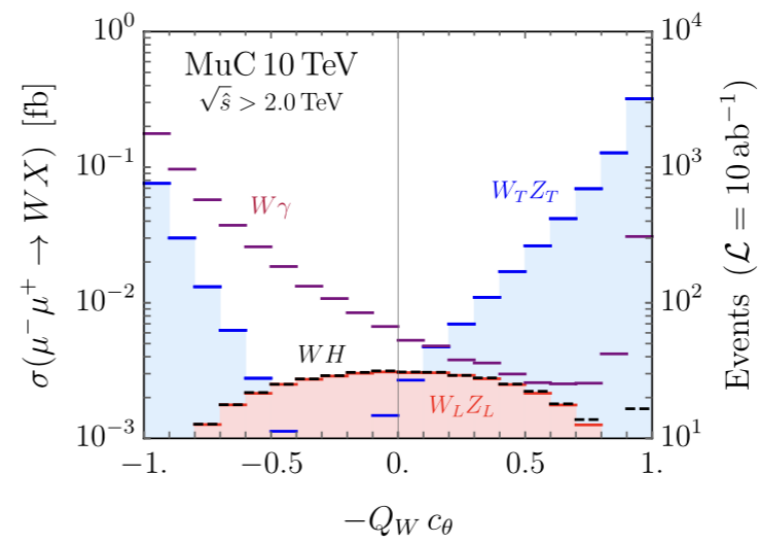
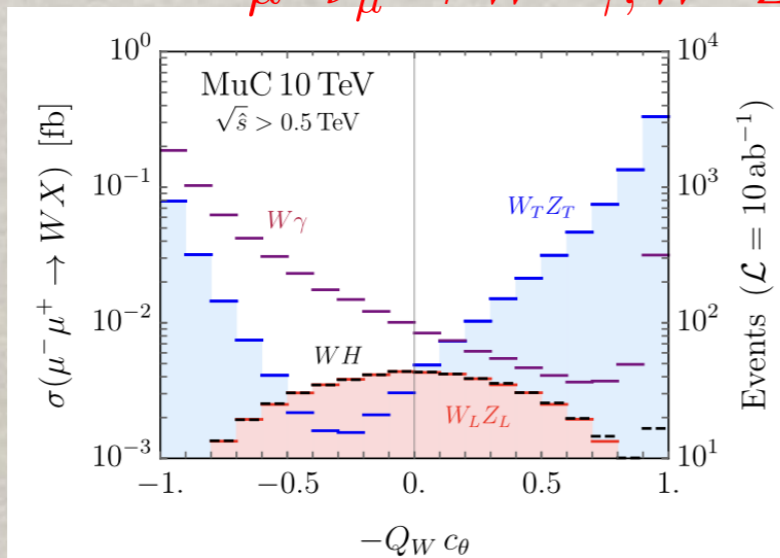
$$\frac{\sigma(W_T Z_T)}{\sigma(W_T \gamma)} \approx \frac{g_z^2 (g_-^{f_1})^2 + (g_-^{f_2})^2}{e^2 (Q_1^2 + Q_2^2)}$$

$$\sigma(W_L^\pm Z_L) \sim \sigma(W_L^\pm H),$$

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



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



Next target: $W_L W_L \rightarrow W_L W_L @ \text{HE}$

Talk by
Steven Lowette

What do we learn in testing EWSR?

“endlessly confirm the correctness of SM” ?!

- Carlo Rubia

SMEFT BSM

vs.

HEFT BSM

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

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

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

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

weakly coupled (SUSY)

strongly coupled (composite)

new scale $\sim \Lambda$

nearby scale $\sim 4\pi v$

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

(light) Fermion Yukawa's wide open:

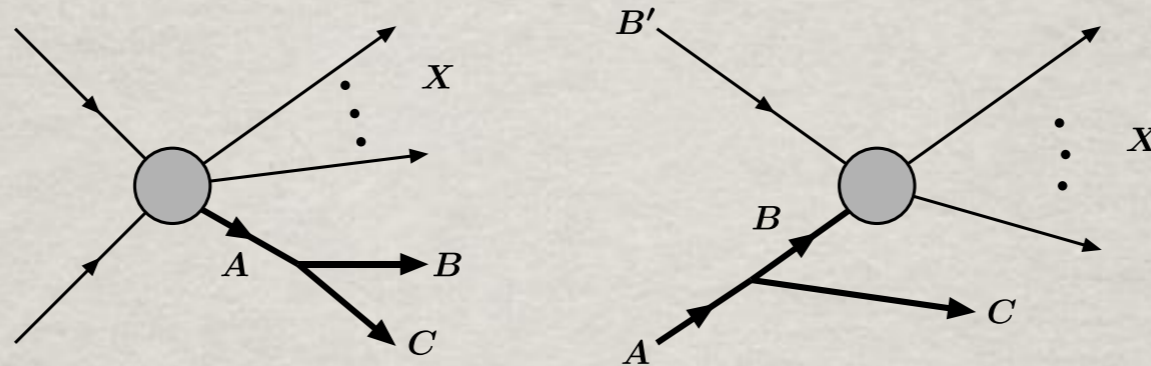
$$- \sum_{n=1}^{\infty} \frac{c_{l\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n (\bar{\ell}_L \varphi \mu_R + \text{h.c.})$$

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

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

• Other Aspects of EWSR

Colinear splitting: the dominant phenomena

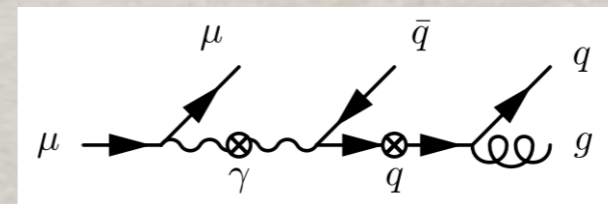


$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A \rightarrow B+C}$$

- 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

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



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

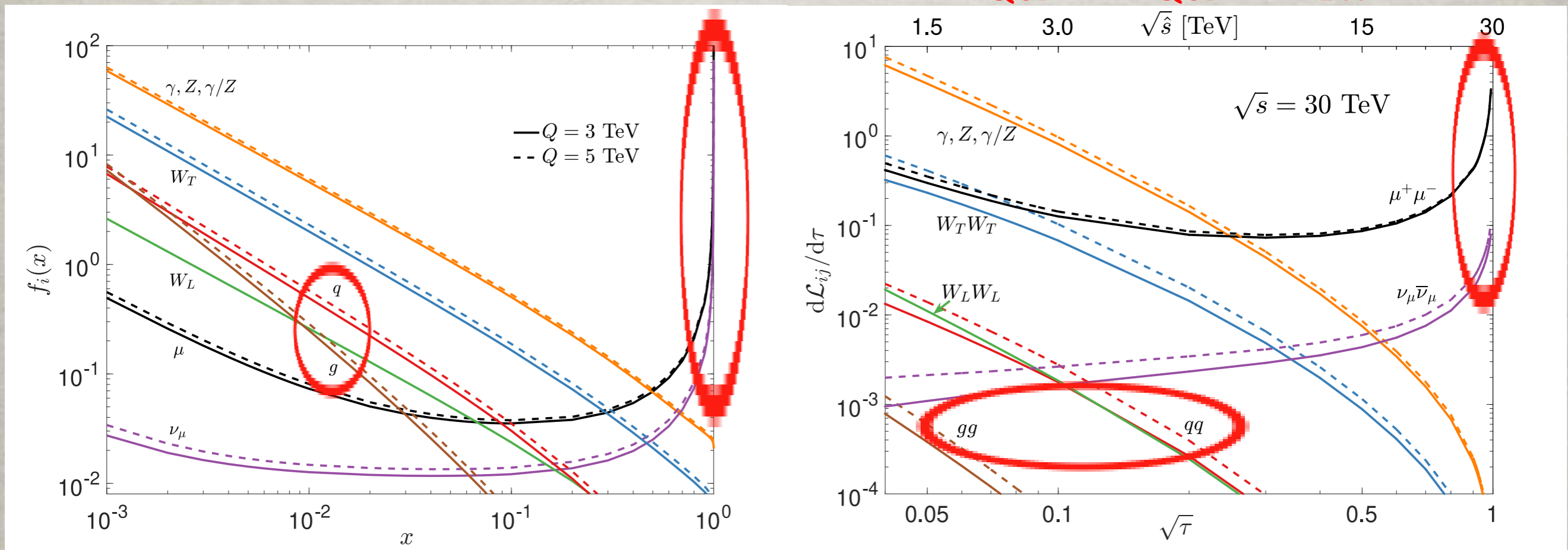
EW PDFs @ a Muon Collider

TH, Yang Ma, Keping Xie, arXiv:2007.14300

DGLAP evolution in full SM:

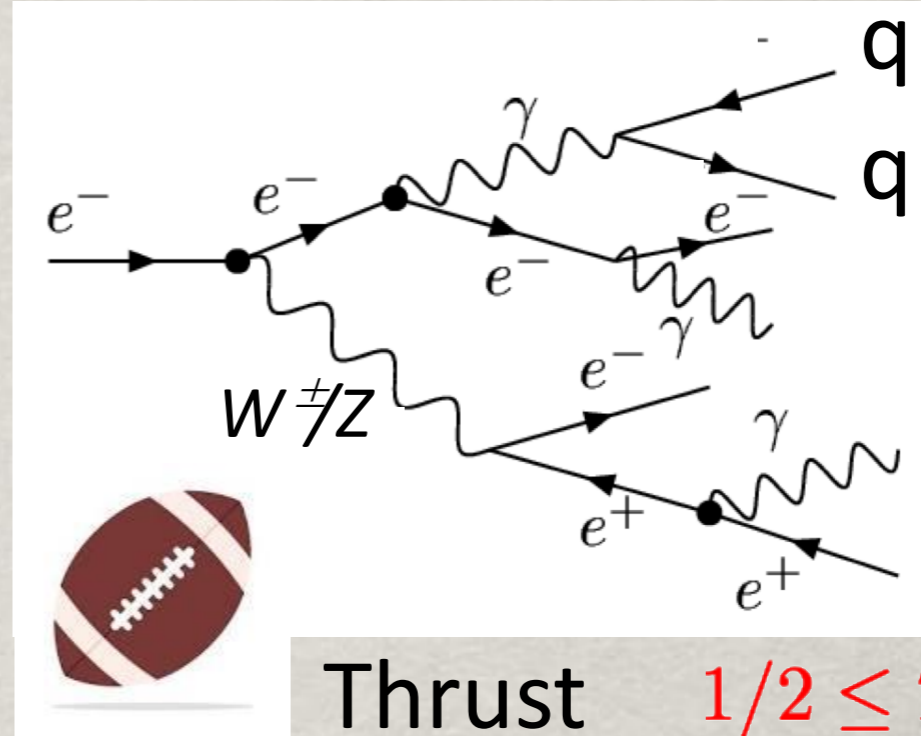
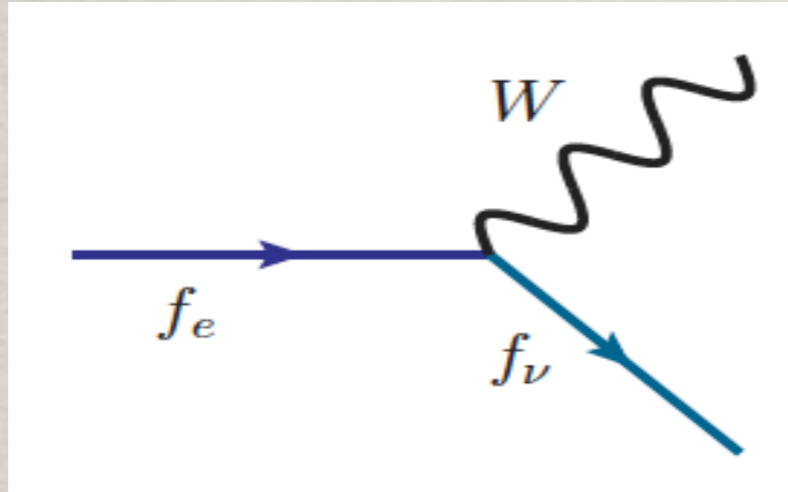
$$\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \frac{d}{d \log Q^2} \begin{pmatrix} P_{ll} & 0 & 0 & 2N_l P_{l\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma l} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma}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

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



μ^\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



How jetty is it?

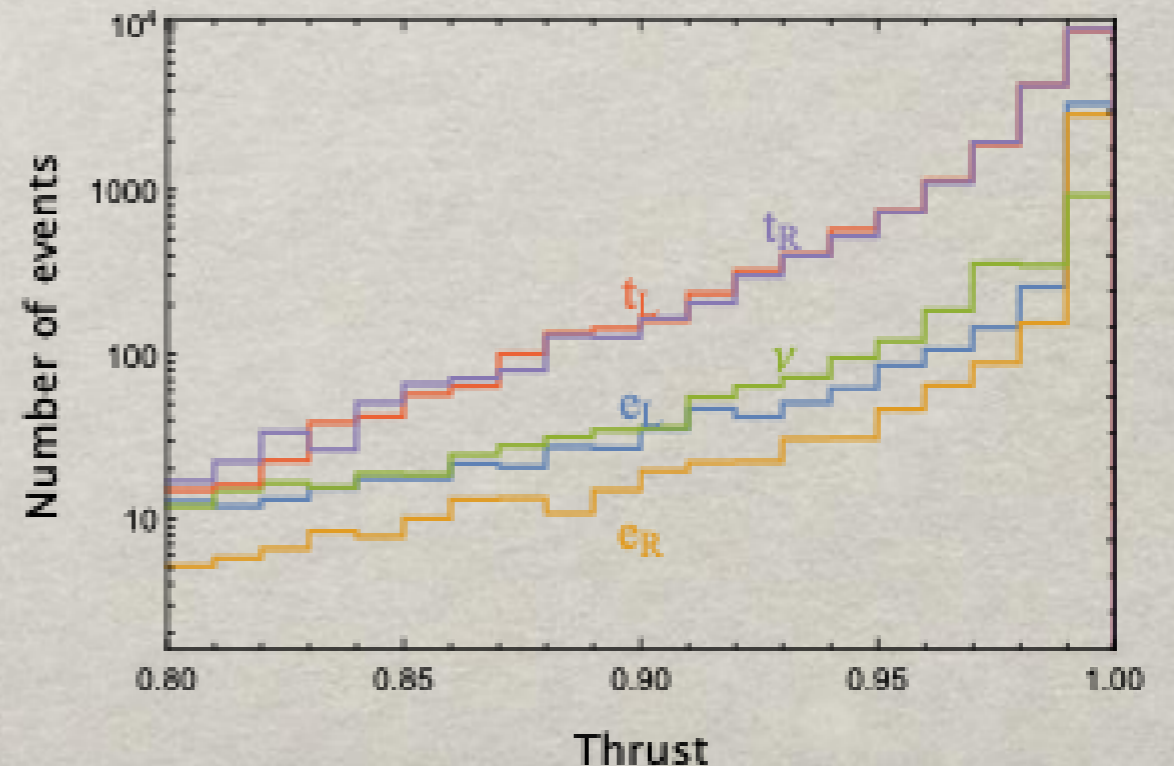
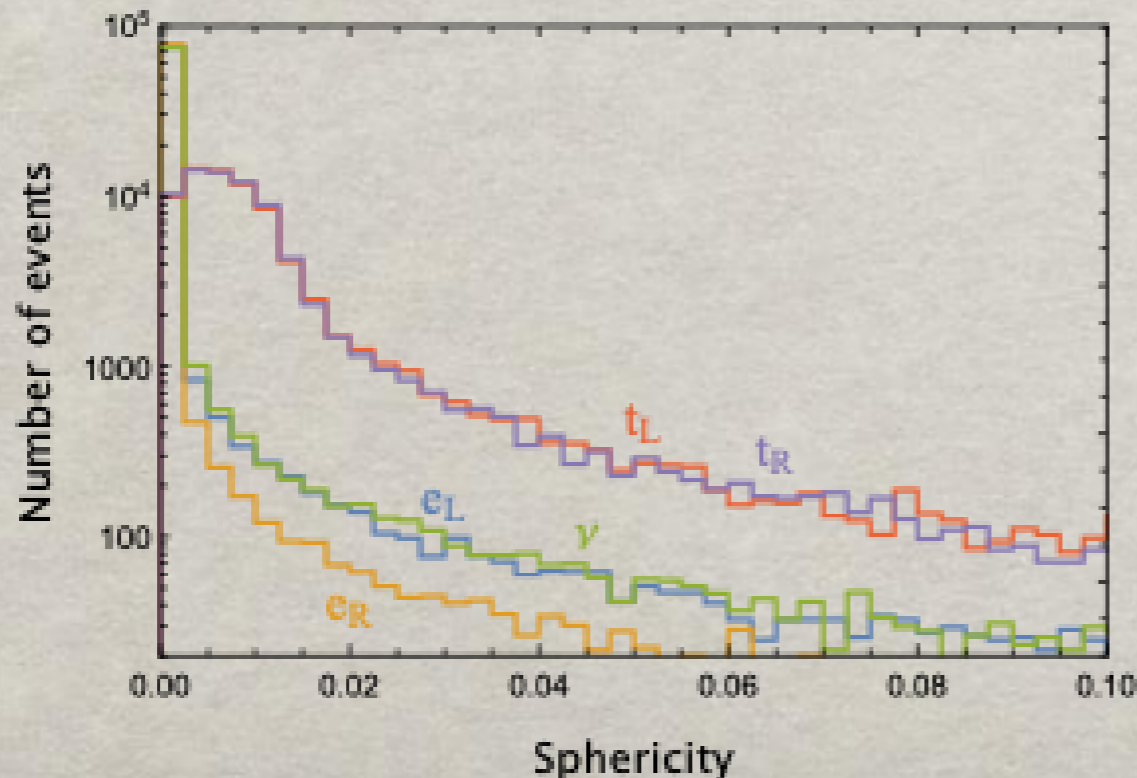
Sphericity $0 \leq S \leq 1$

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

@ 5 TeV

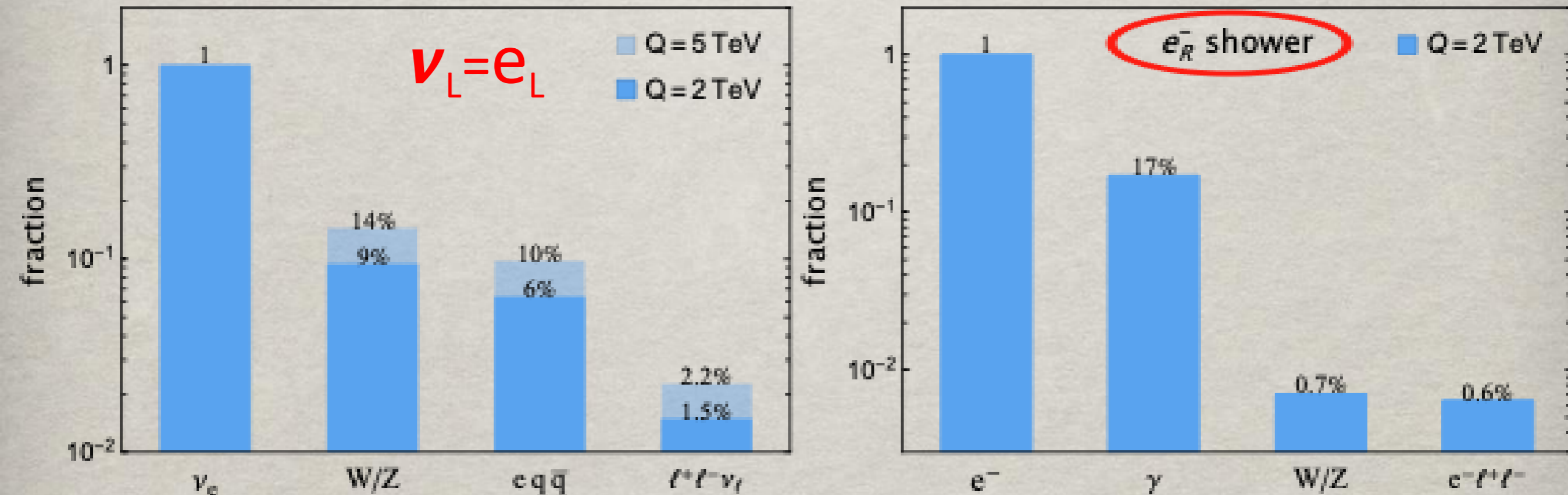
Thrust $1/2 \leq T \leq 1$

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



EW Showering @ high energies

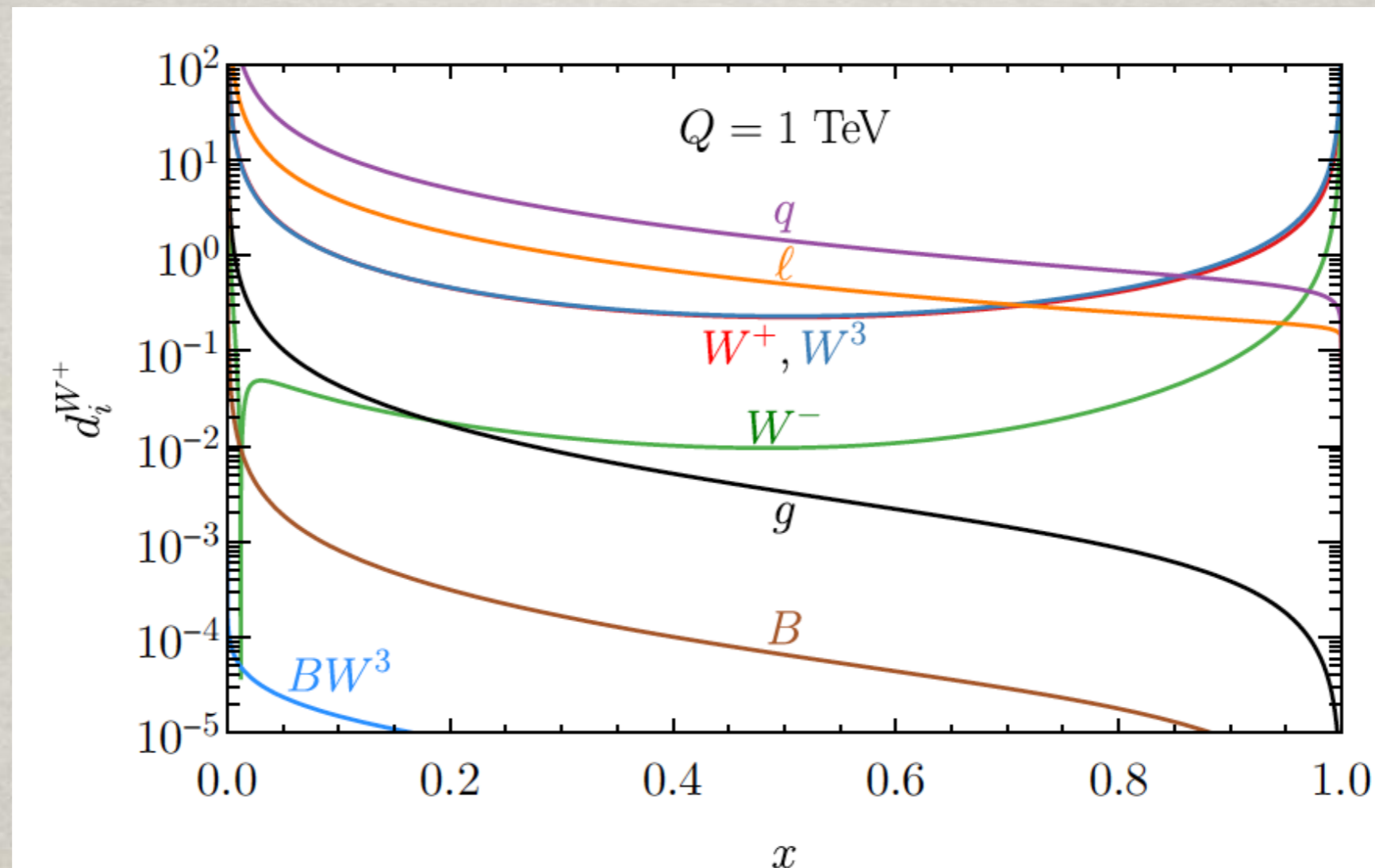
- With W/Z showers, all leptons/neutrino components exist!
- (ν_L, e_L) indistinguishable in the symmetric phase.
- EW “jets”: *e.g.*, a HE $\nu \rightarrow$ an observable jet!



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

Fragmentation to a final state particle

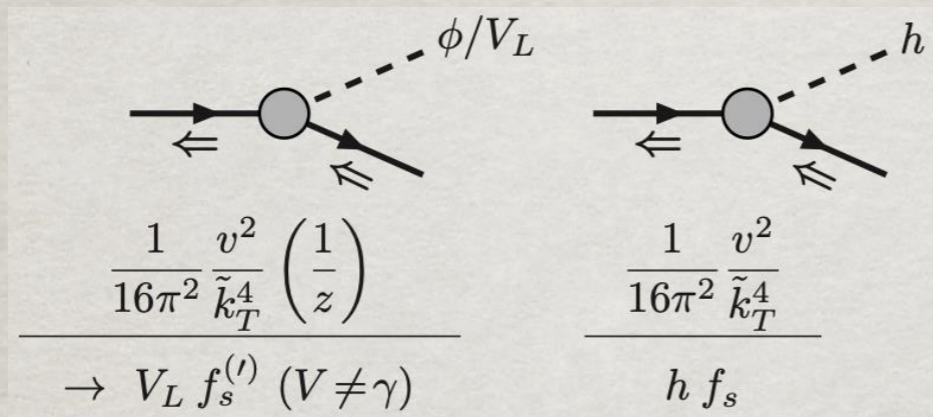
finding a W^+ in the mother particle i (i.e., $i \rightarrow W$)



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

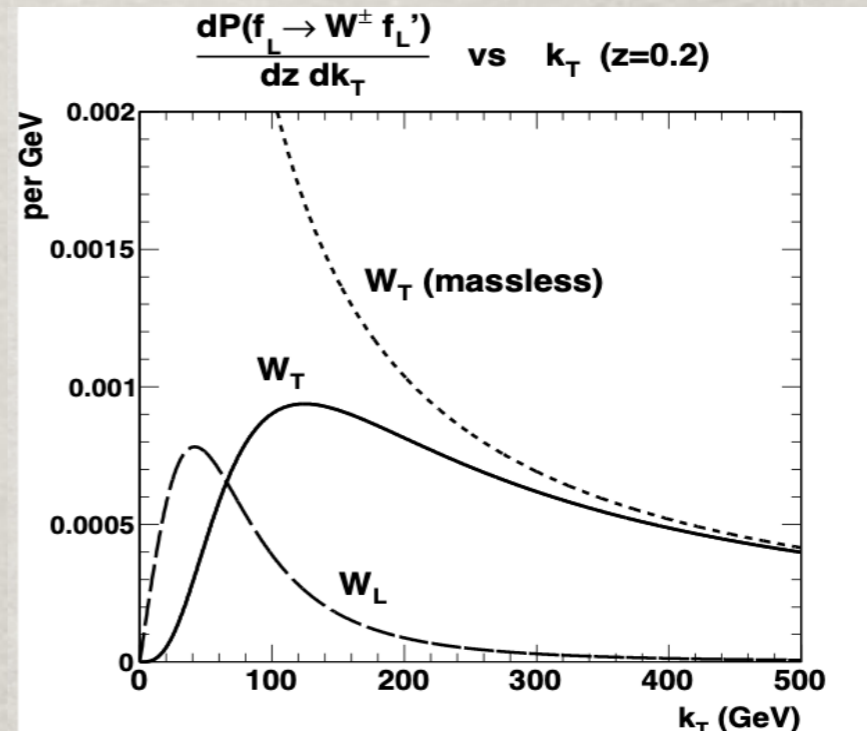
“Ultra collinear behavior”

New characteristics with the mass:



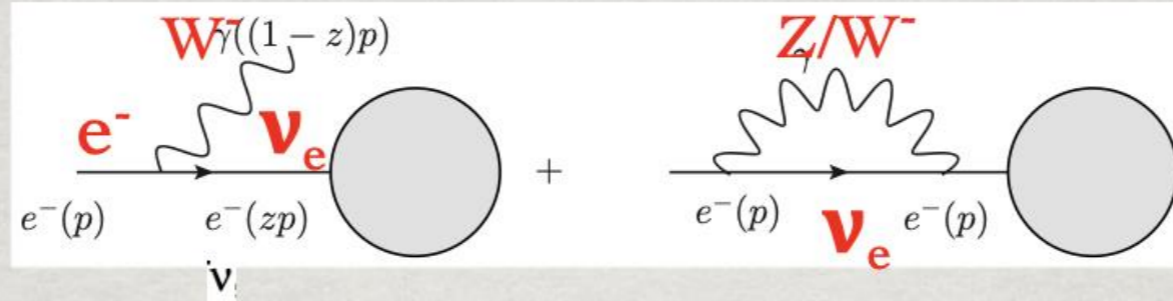
$$\frac{v^2}{k_T^2} \frac{dk_T^2}{k_T^2} \sim \left(1 - \frac{v^2}{Q^2}\right)$$

$k_T^2 > m_W^2$, it shuts off;
 $k_T^2 < m_W^2$, flattens out!



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

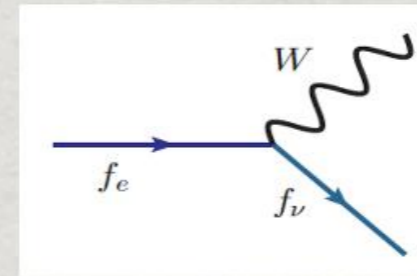
EW Evolution beyond Leading Log



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

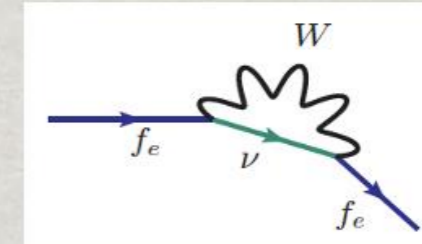
$$d\mathcal{P}_{\nu \leftarrow e} = d\mathcal{P}_{e \leftarrow \nu} \sim \frac{(T^\pm)^2}{1-z} = \frac{(1/\sqrt{2})^2}{1-z}$$

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



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

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



→ 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

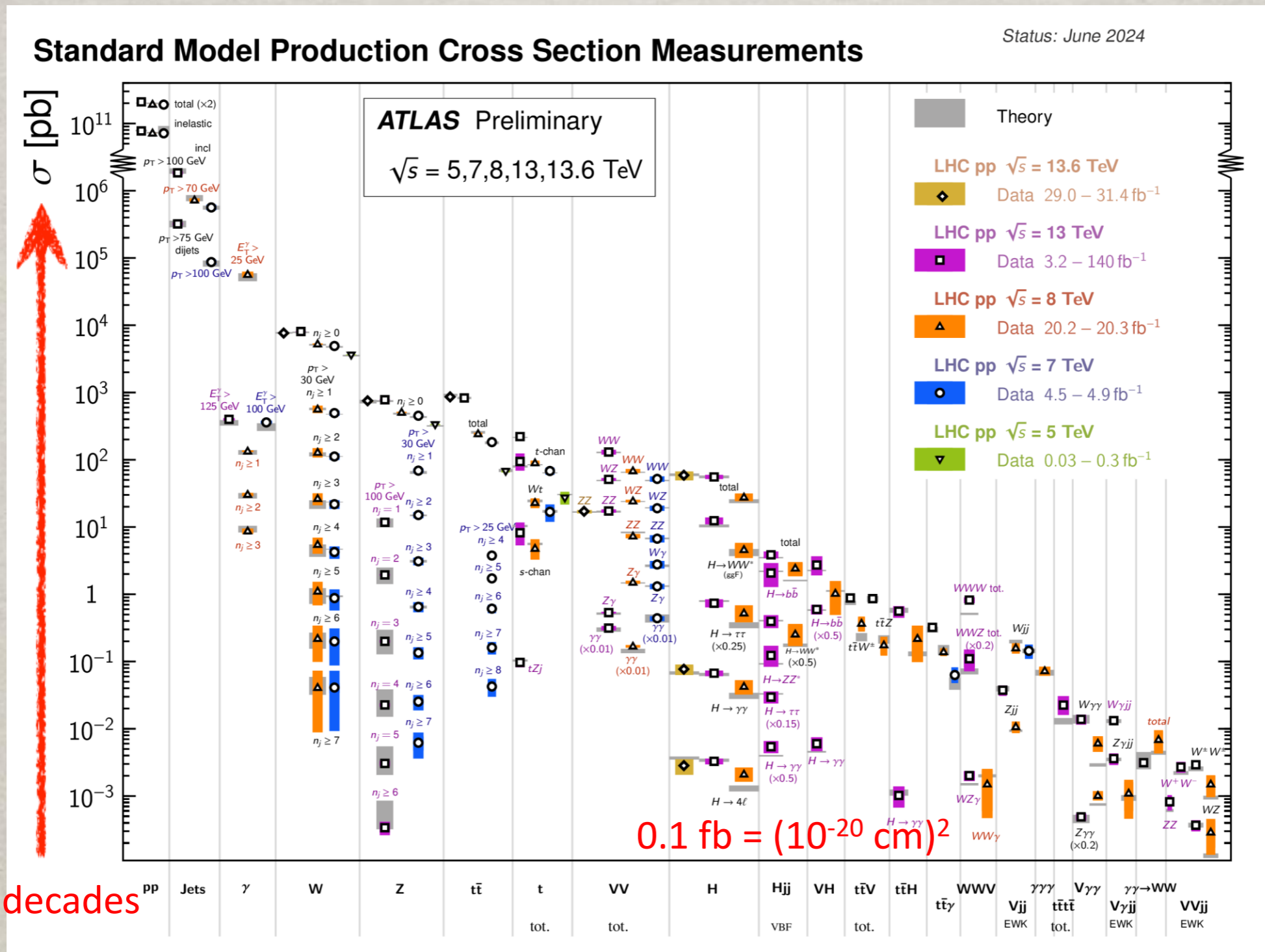
Electroweak physics rich!

Energy frontier drives!

Thank you!

LHC Rocks!

Energy frontier for the next ~15 years!



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

Goldstone-boson Equivalence Theorem

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

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

$W_L^i \rightarrow$ Most sensitive to the underlying mechanism for EWSB.

\rightarrow “Bad high energy behavior” $\mathcal{M}(W_L^i W_L^j \rightarrow W_L^i W_L^j) \propto \frac{E^2}{M_W^2}$

$\omega^i \rightarrow$ 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

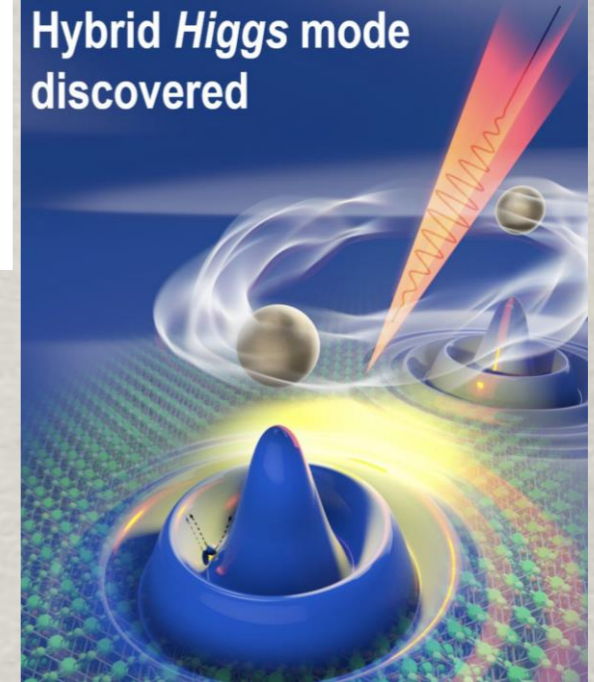
The Role of the Higgs Boson

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 @ 10¹² 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

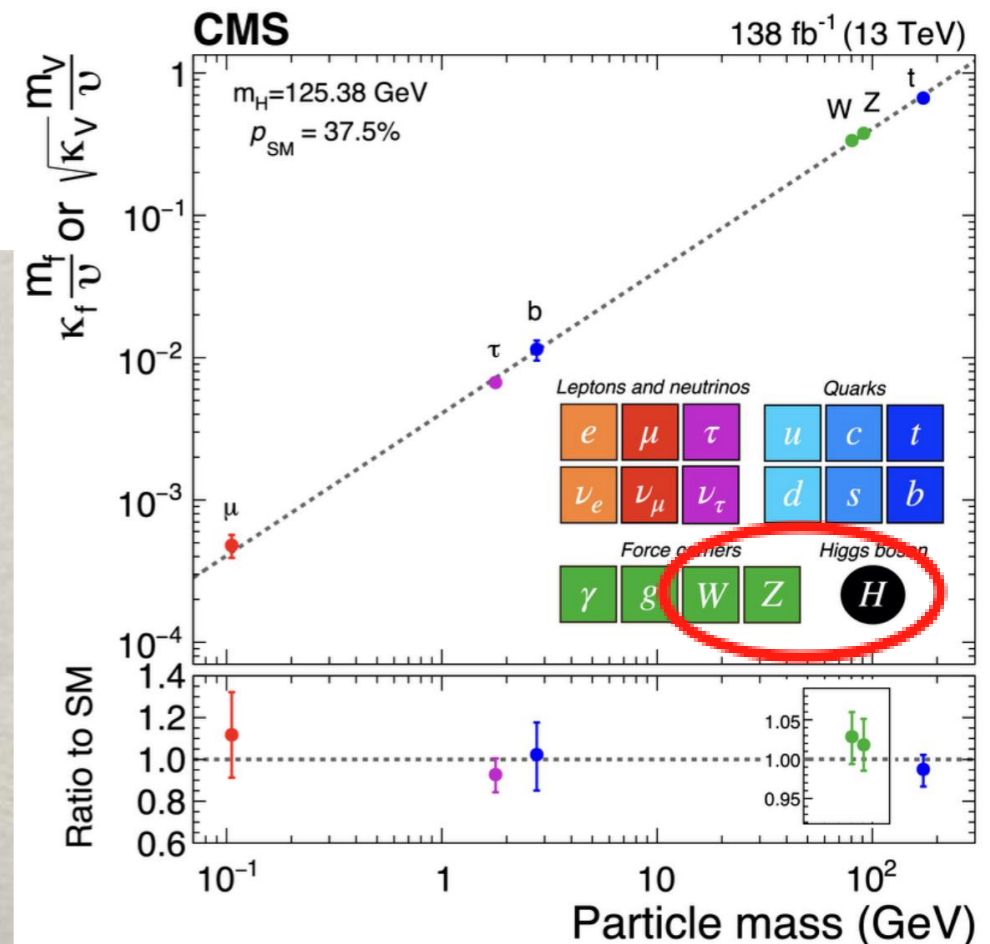
Fermi National Accelerator Laboratory,[‡] Batavia, Illinois 60510

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



Some numerology:

(4). EW logarithms

At scale Q : $\frac{\alpha_2}{\pi} C_w \ln^2 \frac{Q^2}{M_W^2} \sim \delta$

$$Q \approx M_W \cdot \exp\left(\frac{\pi\delta}{4\alpha_2 C_w}\right)^{\frac{1}{2}}$$

J. Chiu, A. Manohar et al., 2005;
Manohar, Bauer et al. (SCET);
M. Chiesa et al., PRL (2013);
T. Becher et al., 1305.4202;
Bauer, Ferland, 1601.07190;

For $\delta = 50\%$, $\alpha_2 \sim 0.035$,

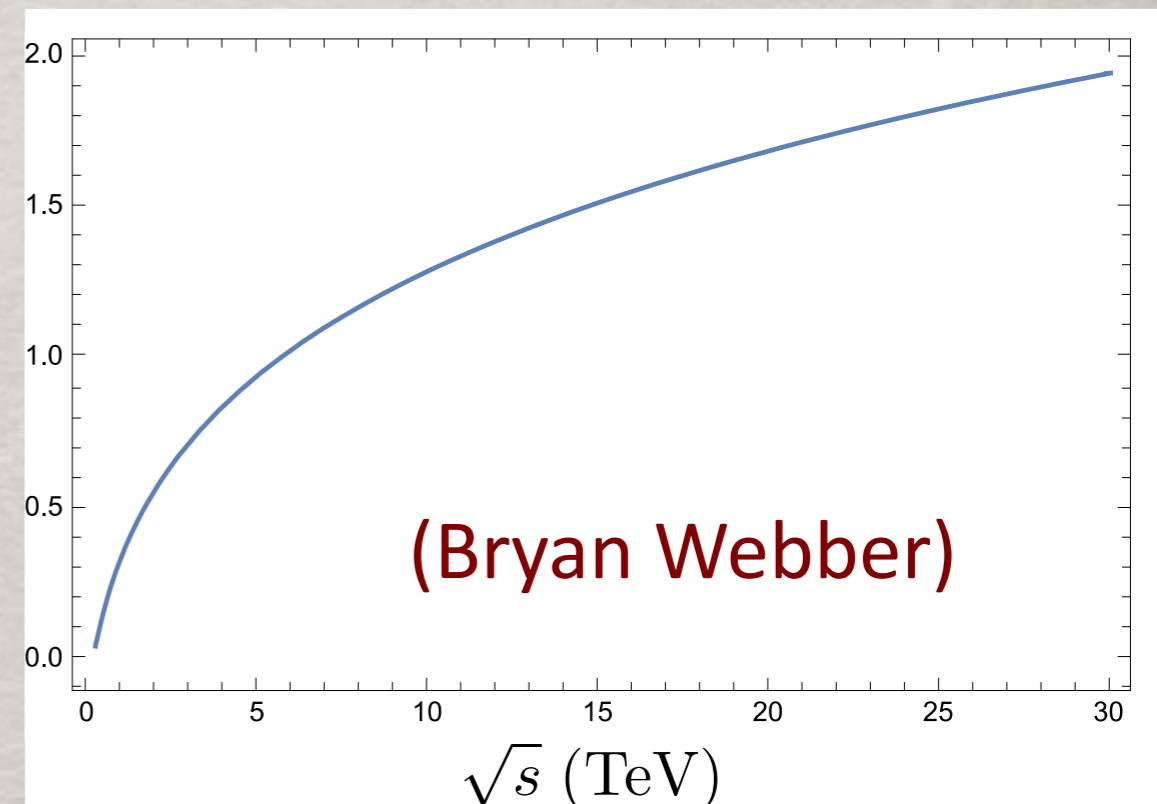
$$Q \approx 30 M_W \Rightarrow 2.5 \text{ TeV.}$$

- Virtual Sudakov suppression;
- Real emission enhancement.

SU(2) versus SU(3):

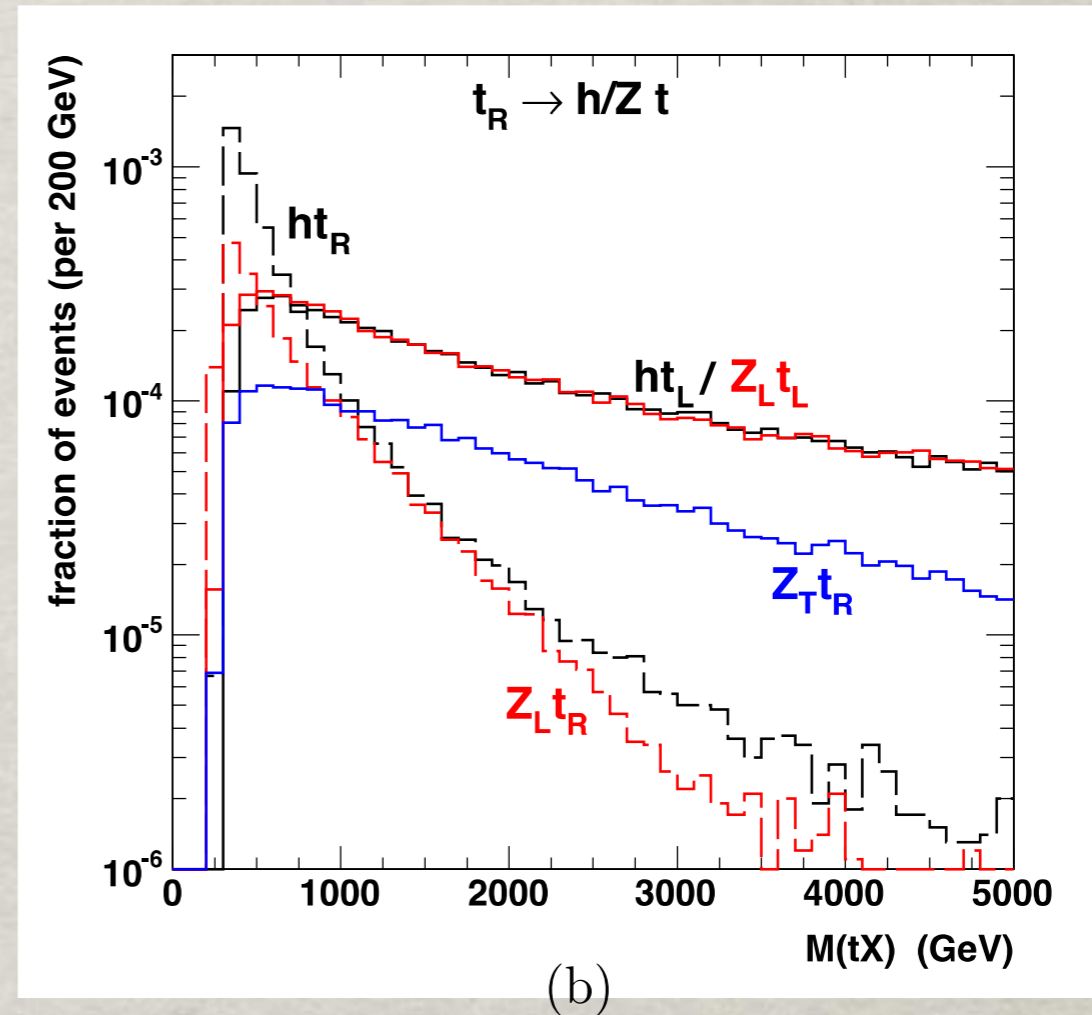
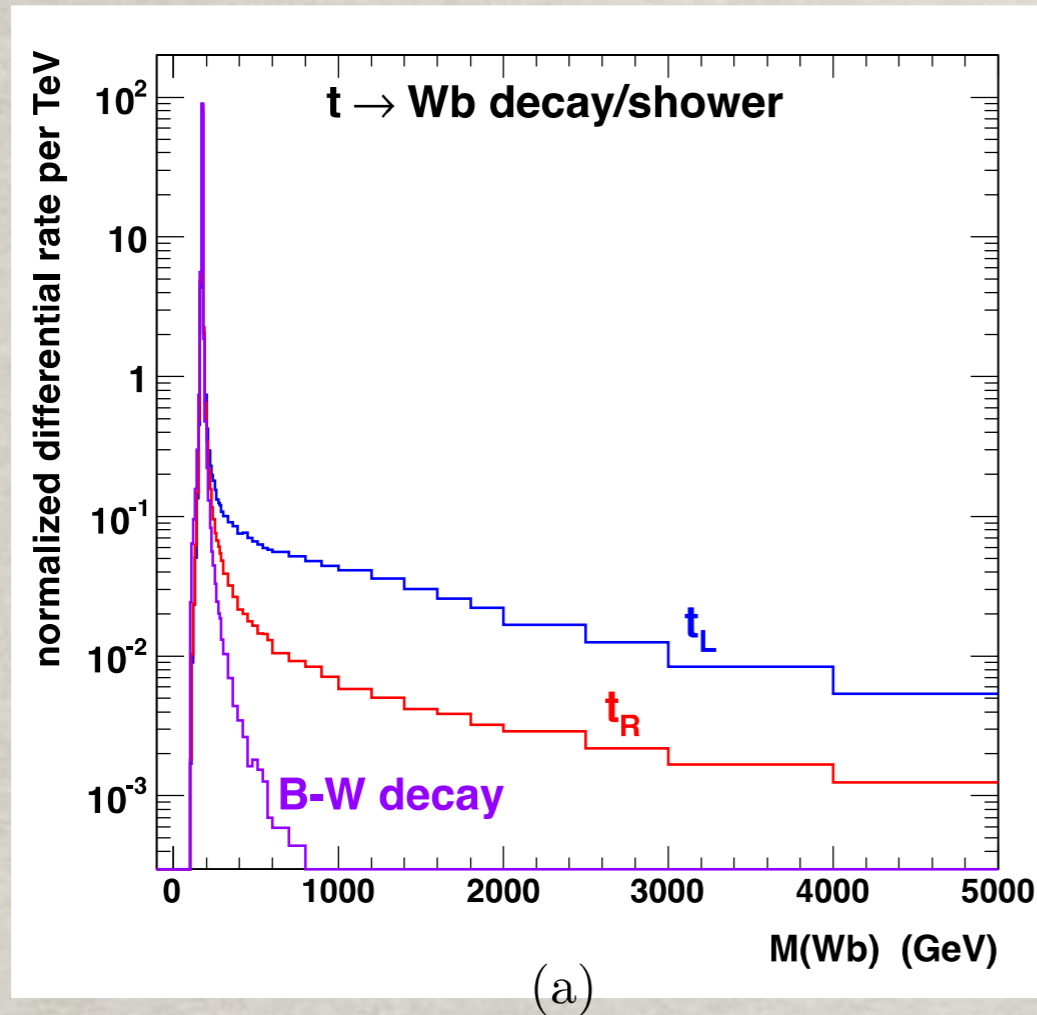
Gauge boson splitting

“Color factors” : $\frac{C_A}{C_F} = \frac{2N^2}{N^2 - 1} \Rightarrow \left(\frac{9}{4}\right)_{N=3}$ and $\left(\frac{8}{3}\right)_{N=2}$.



- Top decay/showering @ 10 TeV

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



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

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

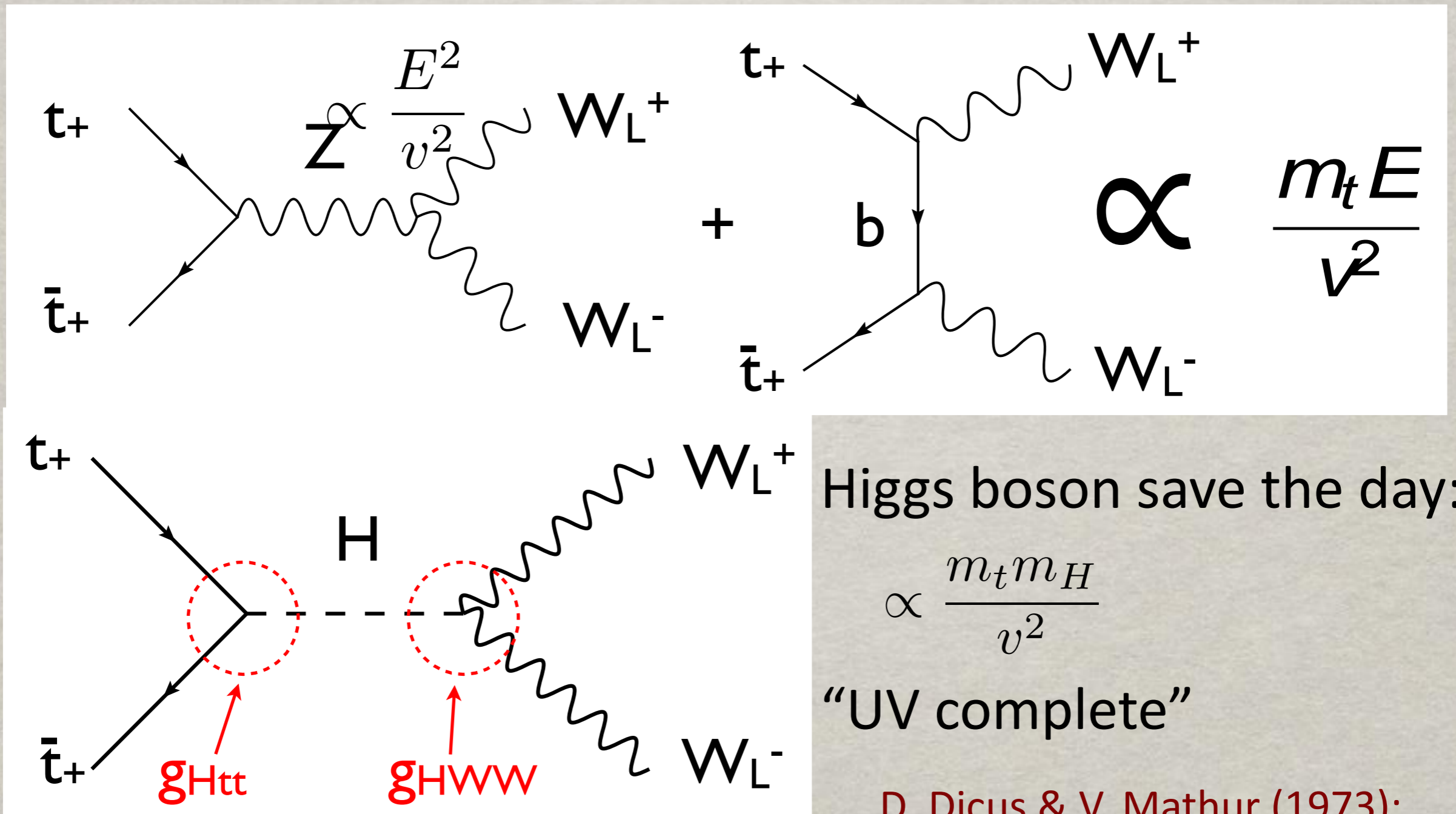
Yukawa: $\mathcal{P}(t_R \rightarrow ht_L) \simeq \mathcal{P}(t_R \rightarrow Z_L t_L) \approx 7.2 \times 10^{-3}$

**EW theory still puzzling:
both conceptually & technically !**

High-energy behavior: V_L & the role of H

$$\epsilon(k)_L^\mu = \frac{E}{m_W} (\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$$

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).

EW PDFs at a muon collider

“partons” dynamically generated

Initially, the “valence parton”: $f \cdot (\leftarrow; \dot{m}^2) = \delta(1 - \leftarrow) + \dots$

Leading order “sea parton”: ℓ_R, ℓ_L, ν_L and $B, W^{\pm,3}$

Beyond leading order with DGLAP evolution:

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

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

$$f_L = \sum_{i=e,\mu,\tau} (f_{l_i} + f_{\bar{l}_i}), \quad f_U = \sum_{i=u,c} (f_{u_i} + f_{\bar{u}_i}), \quad f_D = \sum_{i=d,s,b} (f_{d_i} + f_{\bar{d}_i})$$

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

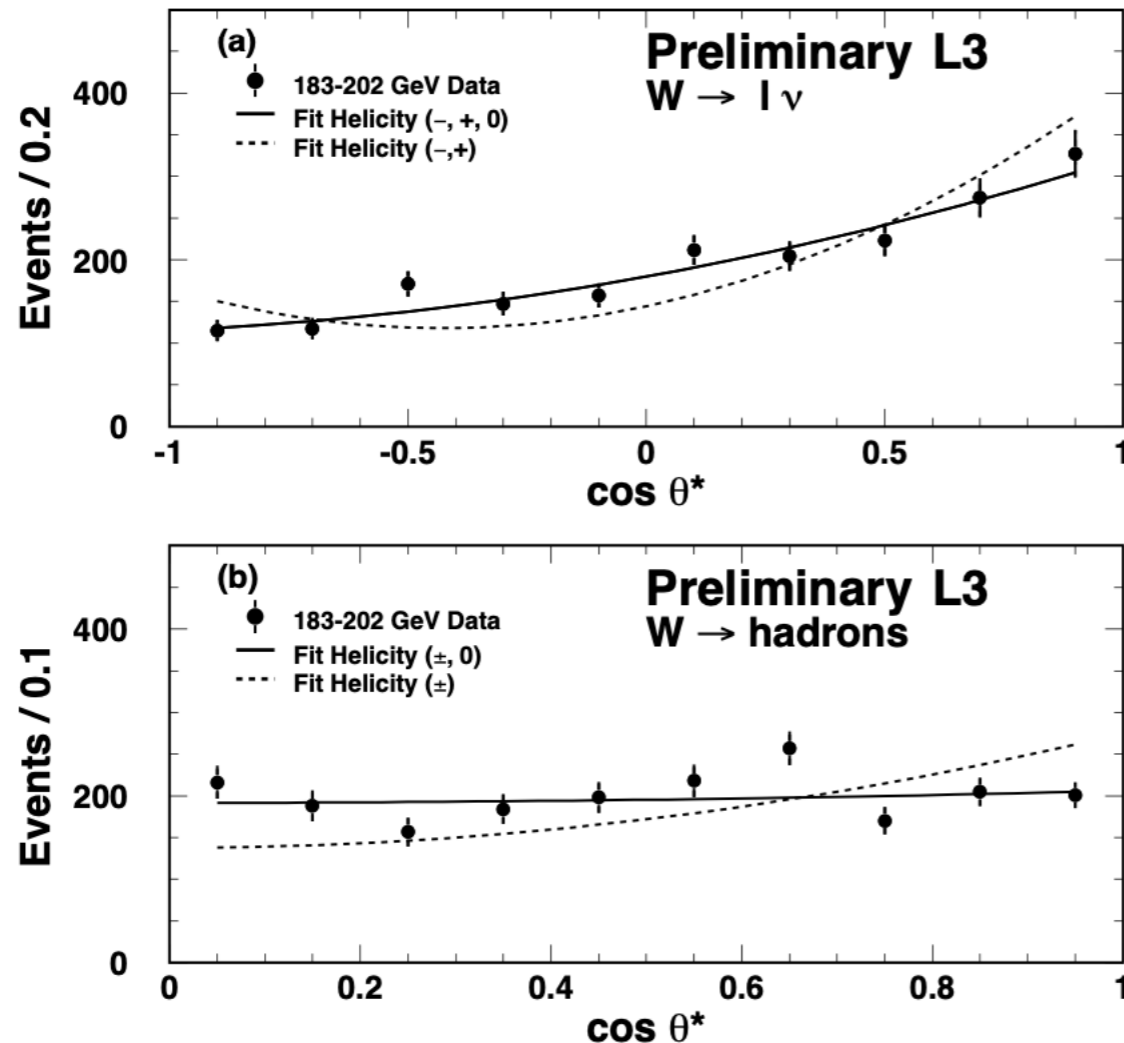


Figure 34: Polar angle of the charged lepton (top) and of the jet (bottom) in the W rest frame for leptonic and hadronic W decays in WW events. The curves indicate the expectations allowing different polarization states, as indicated [1].

$(1 + \cos \theta^*)^2$ while for longitudinally polarized W 's the distribution is proportional to $\sin^2 \theta^*$.

All the LEP collaborations are studying this topic. Data from L3 are shown in Fig. 34.

The measured fraction of longitudinally polarized W 's is $0.285 \pm 0.053 \pm 0.03$ which is in agreement with the SM prediction at the 1σ level.

1. J. Mnich, "Tests of the Standard Model", EPS-HEP-99. Proceedings of the International Europhysics Conference on High Energy Physics, held in Tampere, Finland, July 1999. Edited by K. Huitu, H. Kurki-Suonio and J. Maalampi, Institute of Physics Publishing, 2000.