Electroweak Fragmentations/Parton Showers at high energies

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EW physics at high energies

- At high energies, every particle become massless, the splitting behavior dominate due to the largely logarithmic enhancement.

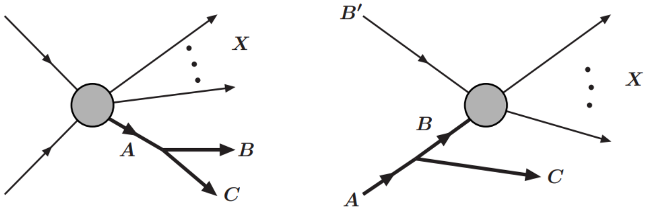
$$\frac{v}{E} : \frac{v}{10\ \mathrm{TeV}} \sim \frac{\Lambda_{\mathrm{QCD}}}{10\ \ \mathrm{GeV}},\ \frac{v}{E}, \frac{m_t}{E}, \frac{M_W}{E} \to 0!$$

- The EW symmetry is restored: $SU(2)_L \times U(1)_Y$ unbroken $(v/E \to 0)$.
- Goldstone Boson Equivalence:

$$\varepsilon_L^{\mu}(k) = \frac{E}{M_W}(\beta_W, \hat{k}) \simeq \frac{k^{\mu}}{M_W} + \mathscr{O}(\frac{E}{M_W})$$

  The violation terms is power counted as $v/E \to$ Higher twist effects in QCD $(\Lambda_{\mathrm{QCD}}/Q)$ [T. Han et al. 1611.00788, G. Cuomo, A. Wulzer, 1703.08562; 1911.12366].
- We mainly focus on the splitting phenomena, which can be factorized and resummed as the EW PDFs in the ISR, and the Fragementaions/Parton Showers in the FRS.
- Other interesting effects, e.g. the polarized EW boson scattering.

Splitting phenomena



$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathscr{P}_{A\to B+C}, \quad E_B \approx zE_A, \quad E_C \approx \bar{z}E_A, \quad k_T \approx z\bar{z}E_A\theta_{BC}$$

$$\frac{d\mathscr{P}_{A\to B+C}}{dz dk_T^2} \simeq \frac{1}{16\pi^2}\frac{z\bar{z}|\mathscr{M}^{(\mathrm{split})}|^2}{(k_T^2+\bar{z}m_B^2+zm_C^2-z\bar{z}m_A^2)^2}, \quad \bar{z}=1-z$$

- On the dimensional ground: $|\mathscr{M}^{(\mathrm{split})}|^2 \sim k_T^2$ or m^2
- Integrating out the k_T ends up with $\alpha_W \log\left(Q^2/M_V^2\right) P_{A\to B+C}$
- To validate the fractorization formalism
  - The observable σ should be infra-red safe;
  - Leading behavior comes from the collinear splitting.

[Ciafaloni et al., hep-ph/0004071; 0007096; C. Bauer, Ferland, B. Webber et al., arXiv:1703.08562;1808.08831]

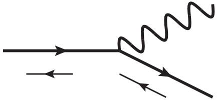
[A. Manohar et al., 1803.06347; T. Han, J. Chen & B. Tweedie, arXiv:1611.00788]

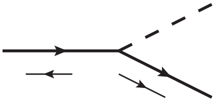
EW Splitting functions

- Starting from the unbroken phase: all massless

$$\mathscr{L}_{SU(2)\times U(1)} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\phi} + \mathscr{L}_{f} + \mathscr{L}_{\text{Yukawa}}$$

- Particle contents:
  - Chiral fermions $f_{L,R}$
  - Gauge bosons: B, $W^{0,\pm}$
  - Higgs $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(h - i\phi^0) \end{pmatrix}$
- Splitting functions [See Ciafaloni et al. hep-ph/0505047, Chen et al. 1611.00788 for complete lists.]

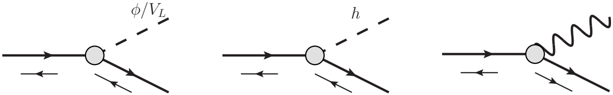




	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\frac{1+\bar{z}^2}{z}$		$\frac{1}{8\pi^2}\frac{1}{k_T^2}\frac{z}{2}$	
$f_{s=L,R} \to$	$V_T f_s^{(\prime)}$	$[BW]^0_T f_s$	$H^{0*} f_{-s}$	$\phi^\pm f'_{-s}$
	$g_V^2 (Q^V_{f_s})^2$	$g_1 g_2 Y_{f_s} T^3_{f_s}$	$y^2_{f_R^{(\prime)}}$	
	Infrared, collinear singularites (P_{gq})		Collinear singularity chirality-flip, Yukawa	

Corrections to the GET in the EWSB

- New fermion splitting: $P \sim \frac{v^2}{k_T^2}\frac{\mathrm{d}k_T^2}{k_T^2}$
- V_L is of IR, h has no IR



	$\frac{1}{16\pi^2}\frac{v^2}{k_T^4}\frac{1}{z}$	$\frac{1}{16\pi^2}\frac{v^2}{k_T^4}$	$\frac{1}{16\pi^2}\frac{v^2}{k_T^4}$
$f_s \to$	$V_L f_s^{(\prime)} (V \neq \gamma)$	$h f_s$	$V_T f_{-s}^{(\prime)}$
	Chirality conserving		Chirality flipping
	non-zero for massless f		$\sim m_f$

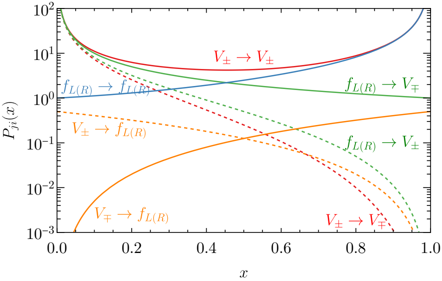
- The PDFs for W_L/Z_L behaves as constants, which does not run at the leading log: "Bjorken scaling" restoration

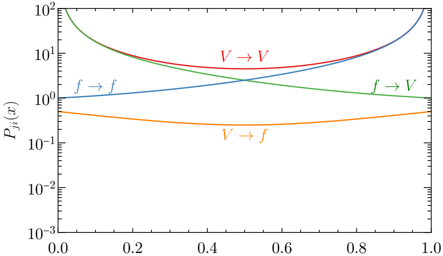
$$f_{V_L/f}(x, Q^2) \sim \alpha \frac{1-x}{x}$$

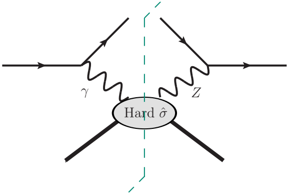
Residuals of the EWSB, v^2/E^2, similar to higher-twist effects (not evolve)

Polarization of splitting functions

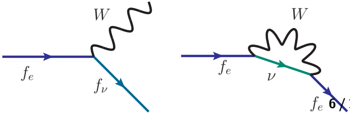
- The chiral nature of EW theory
  $\alpha_R P_{V_+/f_R} \neq \alpha_L P_{V_-/f_L}, \quad \alpha_L P_{V_+/f_L} \neq \alpha_R P_{V_-/f_R}.$







- The interference gives the mixed matrix elements: $P_{\gamma Z} \sim \langle \Omega | A^{\mu\nu} Z_{\mu\nu} | \Omega \rangle + \text{h.c.}$ similarly for P_{hZ_L} [Bauer '17, '18, Manohar '18 , Tao '16.].
- Bloch-Nordsieck theorem violation due to the non-cancelled divergence in $f \to f' V$: cutoff M_V/Q or redefinition



Resummation of collinear logarithms

- Initial state radiation (ISR), PDF (DGLAP) [Han, Ma, Xie, 2007.14300, 2103.09844]

$$f_B(z,\mu^2) = \sum_A \int_z^1 \frac{d\xi}{\xi} f_A(\xi) \int_{m^2}^{\mu^2} d\mathscr{P}_{A\to B+C}(z/\xi, k_T^2)$$

$$\frac{\partial f_B(z,\mu^2)}{\partial \mu^2} = \sum_A \int_z^1 \frac{d\xi}{\xi} \frac{d\mathscr{P}_{A\to B+C}(z/\xi,\mu^2)}{dz dk_T^2} f_A(\xi,\mu^2)$$

- Final state radiation (FSR): Fragmentations (parton showers) [2203.11129]

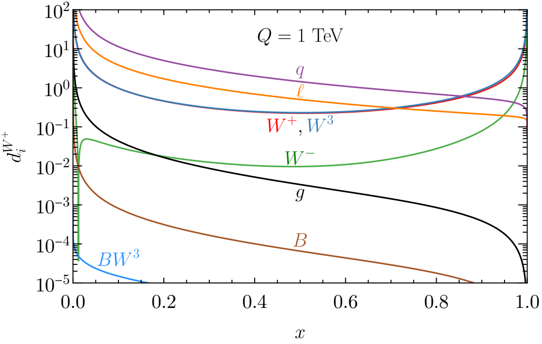
$$\Delta_A(t) = \exp\left[-\sum_B \int_{t_0}^t \int dz \, \mathscr{P}_{A\to B+C}(z) \right],$$

$$f_A(x,t) = \Delta_A(t) f_A(x,t_0) + \int_{t_0}^t \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \mathscr{P}_{A\to B+C}(z) f_A(x/z,t')$$

- Very important formulation for the LHC physics, and future colliders.

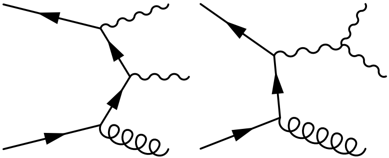
FSR Resummation: Fragmentation functions

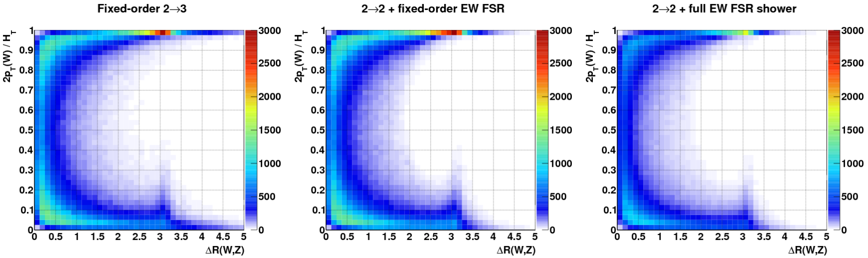
- At future high-energy colliders, collinear splittings also happen to energetic final state particles ⇒ **EW jets**
- One treatment is the electroweak fragmentation functions (EW FFs)
- Both parton distributions (f_i) and fragmentations (d_i) are controlled by the DGLAP equations.
- The evolutions (splittings) are in opposite directions.



Probabilities of finding a W^+ in the mother particle i (i.e., $i \to W$) at 1 TeV [Han, Ma, Xie, 2203.11129]

Applications: $pp \to WZj$





[Han et al. 1611.00788]

- $(\Delta R_{WZ}, 2p_T^W/H_T) \sim (\pi, 0), (\pi, 1)$ due to the back-to-back of W, Z
- $\Delta R_{WZ} \sim 0$ due to $W \to WZ$ splitting
- The comparison between fragmentation and parton shower is still ongoing.

Summary and prospects

- At high energies, all SM particle essentially become massless. The EW symmetry is asymptotically restore.
- The EW splitting phenomena dominate, due to the logarithm enhancement.
- The ISR can be factorized as the PDF, the FSR as Fragmentations (parton shower).
- the EW factorization approach allows for decomposition of polarized partonic subprocesses, including the γZ_T and hZ_L mixing.
- Bloch-Nordsieck theorem violation: Factorization breaks down for the insufficiently inclusive processes.
  - Cutoff (M_W) to regulate the divergence (easy to implement),
  - Fully inclusive to cancel all the divergence (consistent treatment).
- High-energy behavior of longitudinal gauge boson $\varepsilon_L^\mu = \frac{E}{m}(\beta, \hat{k})$.
  - Goldstone equivalence gauge: $\varepsilon_n^\mu(k) \equiv \frac{-\sqrt{|k^2|}}{n(k)\cdot k} n^\mu(k) \overset{\text{on-shell}}{\rightarrow} \frac{m_W}{E+|\vec{k}|}(-1, \hat{k})$, [Han et al. 1611.00788]