Electroweak Parton Distributions and Fragmentations at Ultra-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.

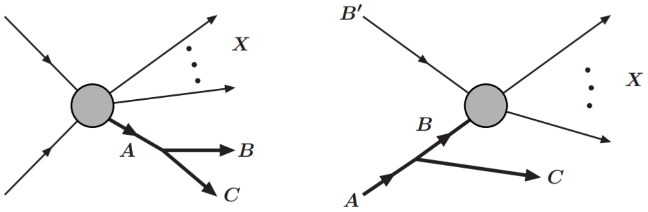
$$\frac{v}{E} : \frac{v}{100\ \mathrm{TeV}} \sim \frac{\Lambda_{\mathrm{QCD}}}{100\ \mathrm{GeV}},\ \frac{v}{E}, \frac{m_t}{E}, \frac{M_W}{E} \to 0!$$

- 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 $(\Lambda_{\mathrm{QCD}}/Q)$ [G. Cuomo, A. Wulzer, arXiv: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 Shower in the FRS.
- For other interesting effects, e.g. the polarized EW boson scattering, see Richard Ruiz's talk.

The EW splittings



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

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

- The dimensional behavior: $|\mathscr{M}^{(\text{split})}|^2 \sim k_T^2$ or m^2
- 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]

PDFs and Fragmentations

- Initial state radiation (ISR), PDF (DGLAP):

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

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

- Final state radiation (FSR): Fragmentations (parton showers):

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

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

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

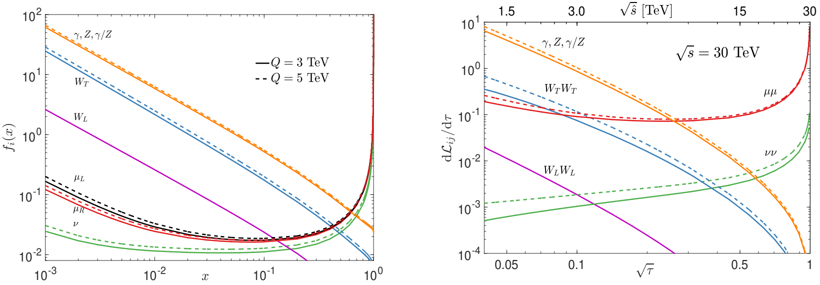
EWPDFs at a muon collider

- Production cross sections

$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^{1} d\tau \sum_{ij} \frac{d\mathscr{L}_{ij}}{d\tau}\ \hat{\sigma}(ij \to F),\ \ \tau = \hat{s}/s$$

- Partonic luminosities

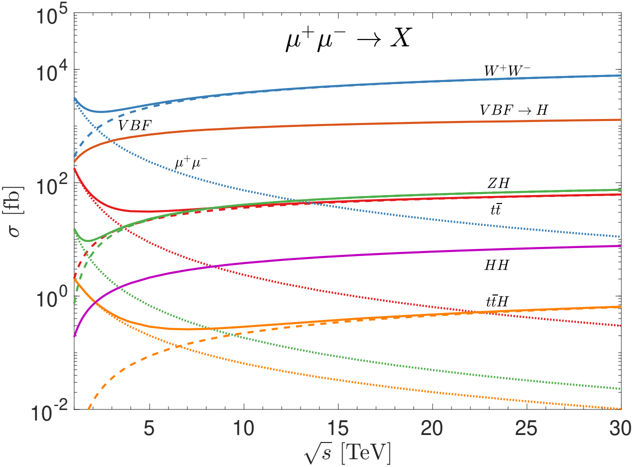
$$\frac{d\mathscr{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$



- W_L does not evolve, reflecting the residue of the EW broken (high-twist) effects
- We have neutrinos, and everything as partons [Tao, Yang, Xie, 2007.14300].

Semi-inclusive processes

Just like in hadronic collisions:
$\mu^+\mu^- \to$ exclusive particles + remnants



Summary and prospects

- At high energies, the EW splitting phenomena dominate.
- The ISR can be factorized as the PDF, the FSR as Fragmentations (parton shower).
- the EW PDF approach allows for decomposition of polarized partonic subprocesses, including the γZ_T and hZ_L mixing.
- Near the threshold (at low energies), the factorization breaks down. We need to match to fixed-order calculation.
- Fragmentation/FSR as a next target.
- EW splitting at the hadronic colliders as another target.
- Bloch-Nordsieck theorem violation: Factorization breaks down for the insufficiently inclusive processes.
  - Cutoff (M_W) to regulate the divergence,
  - Fully inclusive to cancel all the divergence.