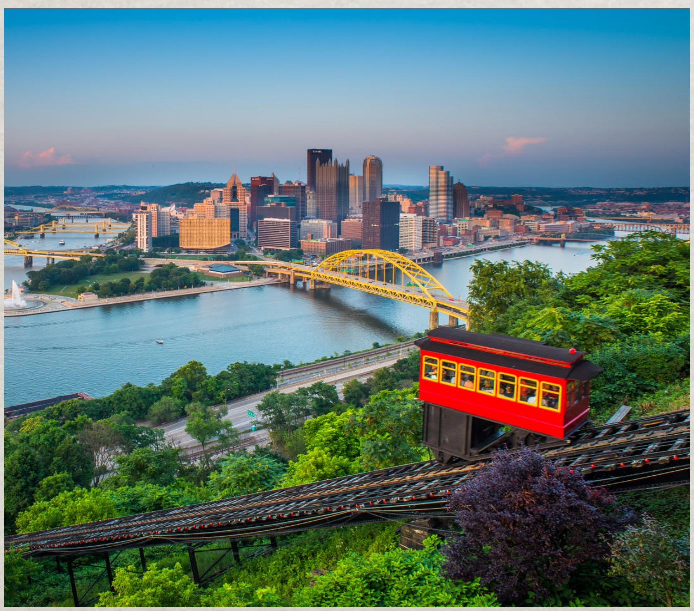
EW physics at very high energies -- Splitting & Showering

Tao Han
University of Pittsburgh

International Workshop on
New Opportunities for Particle Physics
IHEP, Aug. 15, 2026



PITTPACC
Pittsburgh Particle Physics Astrophysics Cosmology Center

EW Physics at Higher Energies

Some numerology w.r.t. the weak scale:

$$(1).\ \frac{E}{v}:\quad G_F E_\beta^2 \sim \left(\frac{\text{MeV}}{M_W}\right)^2 \sim 10^{-8}, \quad \left(\frac{10\ \text{TeV}}{M_W}\right)^2 \sim 10^4\ !$$

$$\epsilon_L^\mu(p) \sim \frac{p^\mu}{M_W}$$ → sensitive to HE/UV physics.

$$(2).\ \frac{v}{E}:\quad \frac{v\ (250\ \text{GeV})}{10\ \text{TeV}} \approx \frac{\Lambda_{QCD}\ (300\ \text{MeV})}{10\ \text{GeV}}$$

At E>>v , $v/E,\ m_t/E,\ M_W/E \to 0!$

→ massless theory; EW symmetry restored!

v/E as power corrections:

- Like QCD: higher-twist terms Λ^2_{QCD}/Q^2.
- Unlike QCD: perturbatively defined!

Some numerology:

(3). EW logarithms

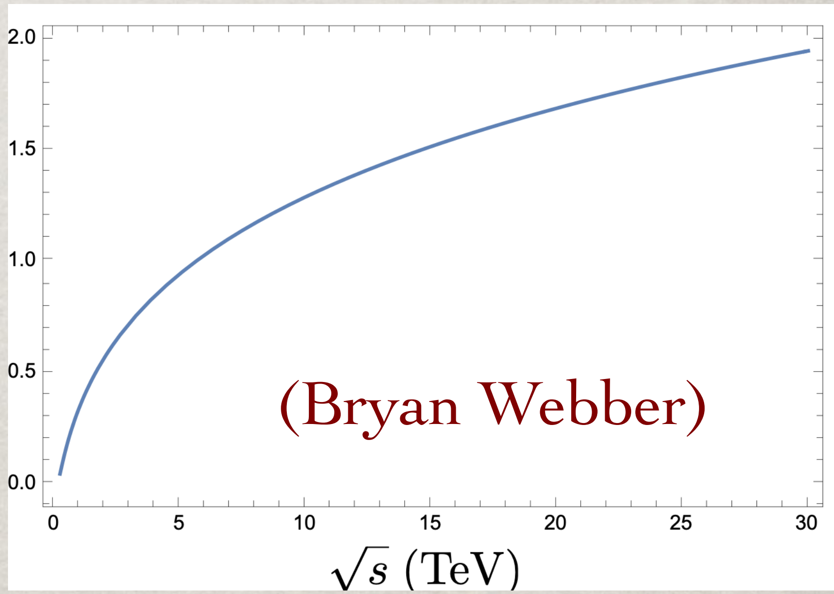
At scale Q : $\frac{\alpha_2}{\pi} C_w \ln^2 \frac{Q^2}{M_W^2} \sim \delta$

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

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

$Q \approx 30 M_W \Rightarrow 2.5$ TeV.



- Virtual Sudakov suppression;
- Real emission enhancement.

SU(2) versus SU(3):
Gauge boson splitting

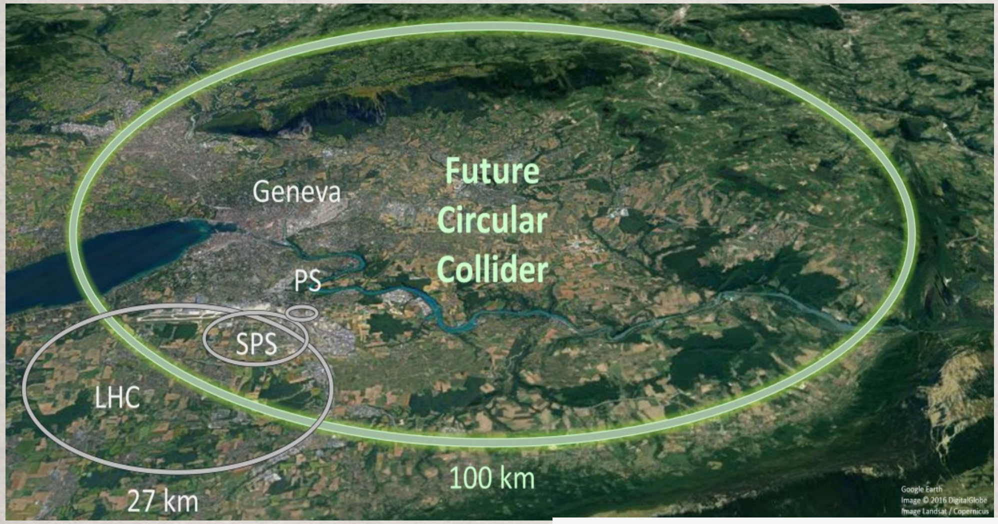
"Color factors" : $\frac{C_A}{C_F} = \frac{2N^2}{N^2-1} \Rightarrow (\frac{9}{4})_{N=3}$ and $(\frac{8}{3})_{N=2}$.

The Future Energy Frontier: toward 10 TeV partonic C.M. Energy (pCM)

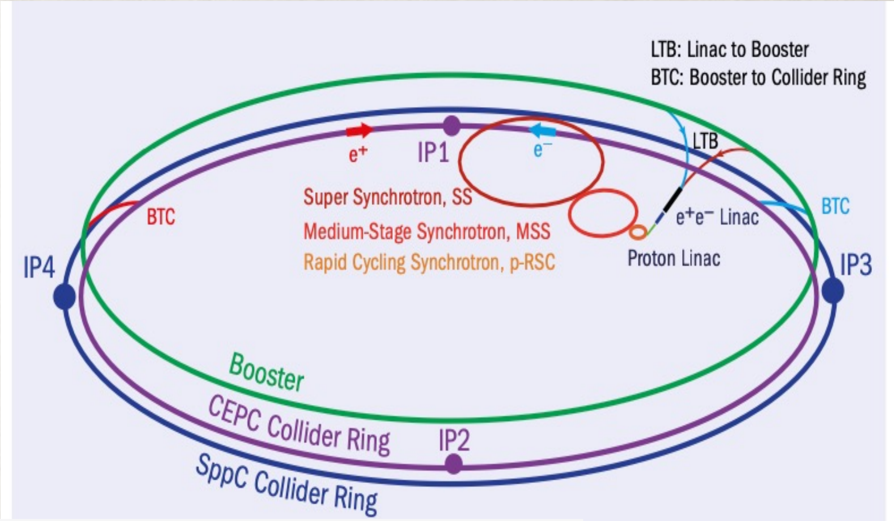
Fully explore the Higgs sector/mechanism & beyond

- Proton + Proton @ 100 TeV

FCC-hh @ CERN



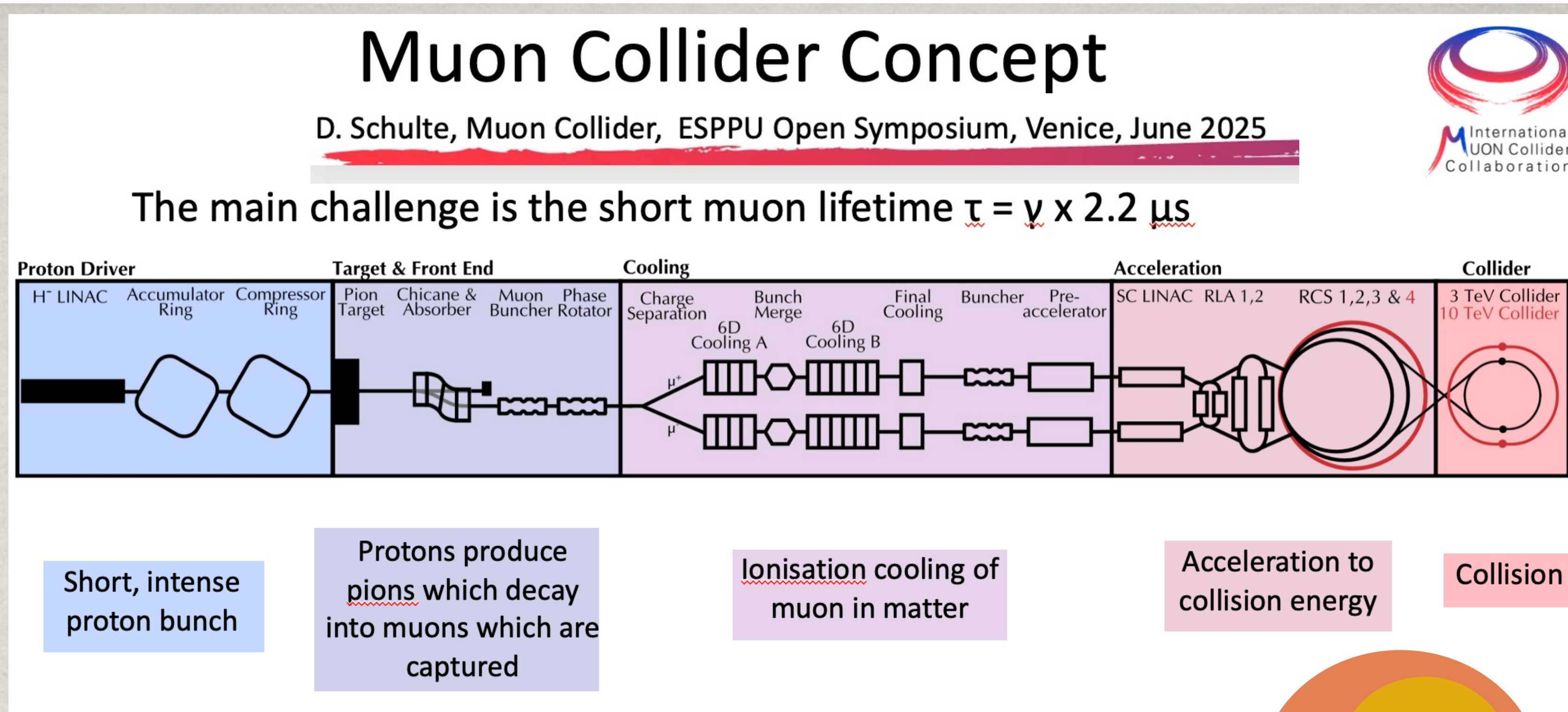
SppC in China

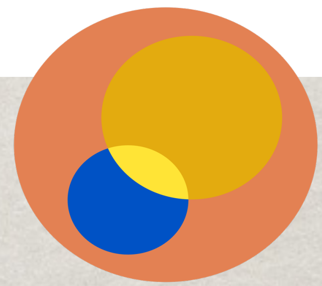


May 22, 2026

The CERN Council decided to update the European Strategy for Particle Physics

"The Strategy process has seen a very strong engagement of the particle physics community and has led to a very clear conclusion: the FCC-ee, if approved, would deliver the world's broadest high-precision particle physics programme, its technical feasibility has been demonstrated by the comprehensive FCC Feasibility Study and its scope and cost are well defined," said Karl Jakobs, Strategy Secretary. "It would also pave the way for a possible future hadron collider reusing the tunnel and much of the infrastructure, providing direct discovery reach well beyond the 10 TeV parton energy scale."

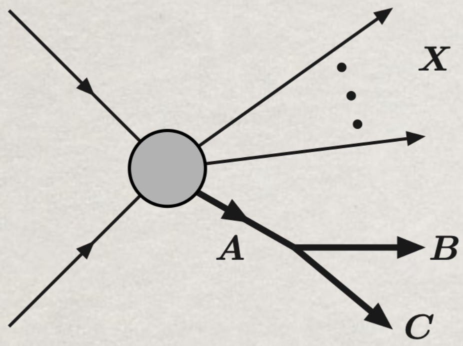


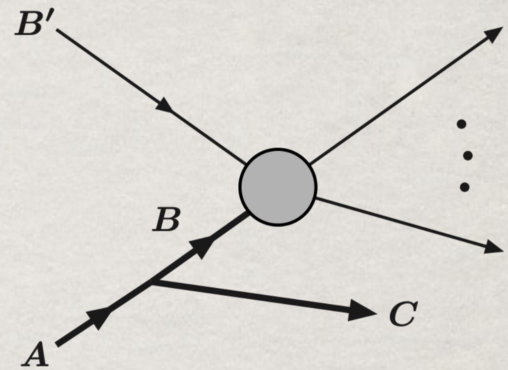


- An enthusiastic engaging community
  IMCC, USMCC
- Strong supporting reports from P5 and NAS EPP

> Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

Splitting: the dominant phenomena





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

$$E_B \approx zE_A, \quad E_C \approx \bar{z}E_A, \quad k_T \approx z\bar{z}E_A\theta_{BC}$$

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

- On the dimensional ground: $|\mathcal{M}_{split}|^2 \sim k_T^2$ or m^2
- For the factorization formalism to be valid: infra-red safe & leading behavior

Ciafaloni et al., hep-ph/0004071, 0007096; J.M. Chen, TH & B. Tweedie, arXiv:1611.00788; C. Bauer, Ferland, B. Webber et al., arXiv:1703.08562; 1808.08831; A. Manohar et al., 1803.06347.

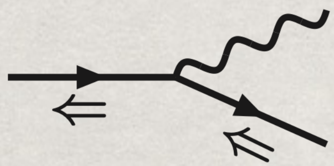
EW Splitting functions

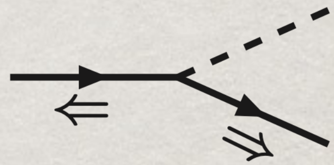
Start from the unbroken phase – all massless.

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{gauge} + \mathcal{L}_{\phi} + \mathcal{L}_{f} + \mathcal{L}_{Yuk}$$

Chiral fermions: f_s, gauge bosons: $B, W^0, W^{\pm}$; $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(h - i\phi^0) \end{pmatrix}$

e.g.: fermion splitting:





	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$		$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z}{2}\right)$
	$\to\ V_T\ f_s^{(\prime)}$	$[BW]_T^0\ f_s$	$H^{0(*)}\ f_{\text{-}s}$ or $\phi^{\pm}\ f'_{\text{-}s}$
$f_{s=L,R}$	$g_V^2 (Q_{f_s}^V)^2$	$g_1 g_2 Y_{f_s} T_{f_s}^3$	$y^2_{f_R^{(\prime)}}$

Ciafaloni et al., Hep-ph/0505047.

Infrared & collinear singularities (P_{gq})

Only collinear (new) Chirality-flip, Yukawa

EW gauge bosons from splitting@Fcc-hh

(2). W radiation costs ~ 1/10

At 100 TeV:

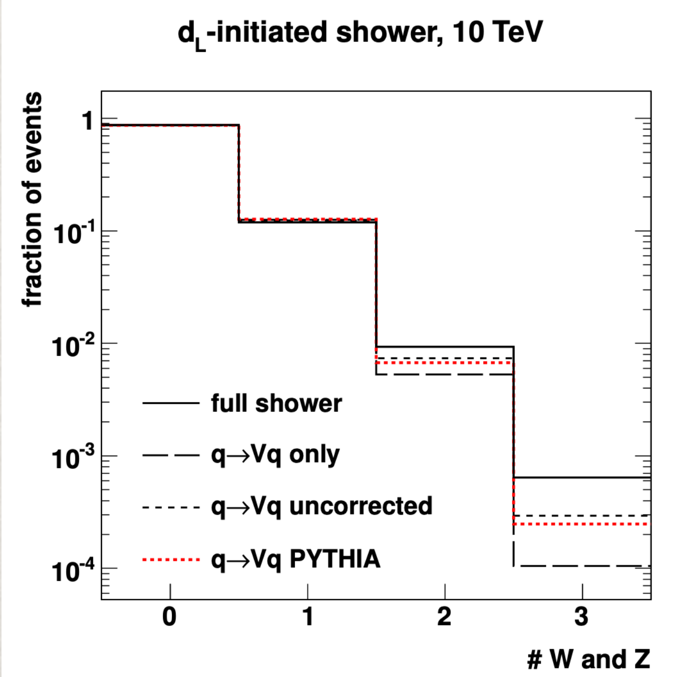
M. Mangano

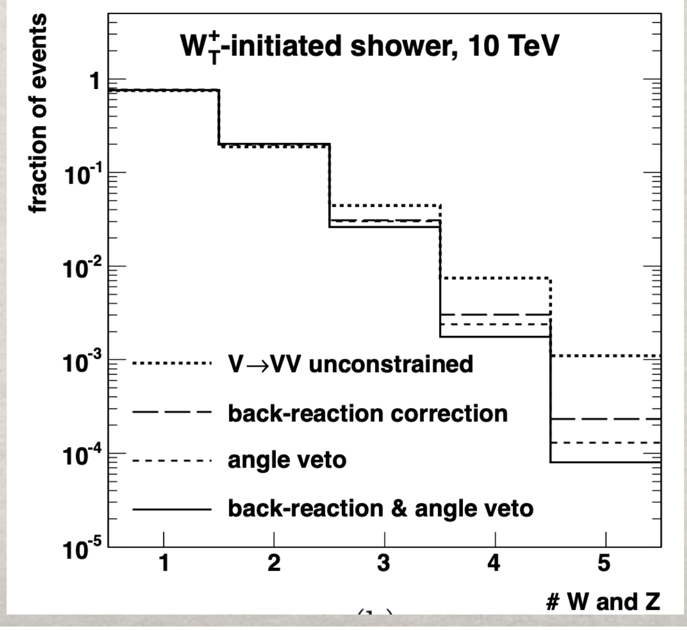
Diagramatic calculations

W W	σ=770 pb
W W W	σ=2 pb
W W Z	σ=1.6 pb
W W W W	σ=15 fb
W W W Z	σ=20 fb

....

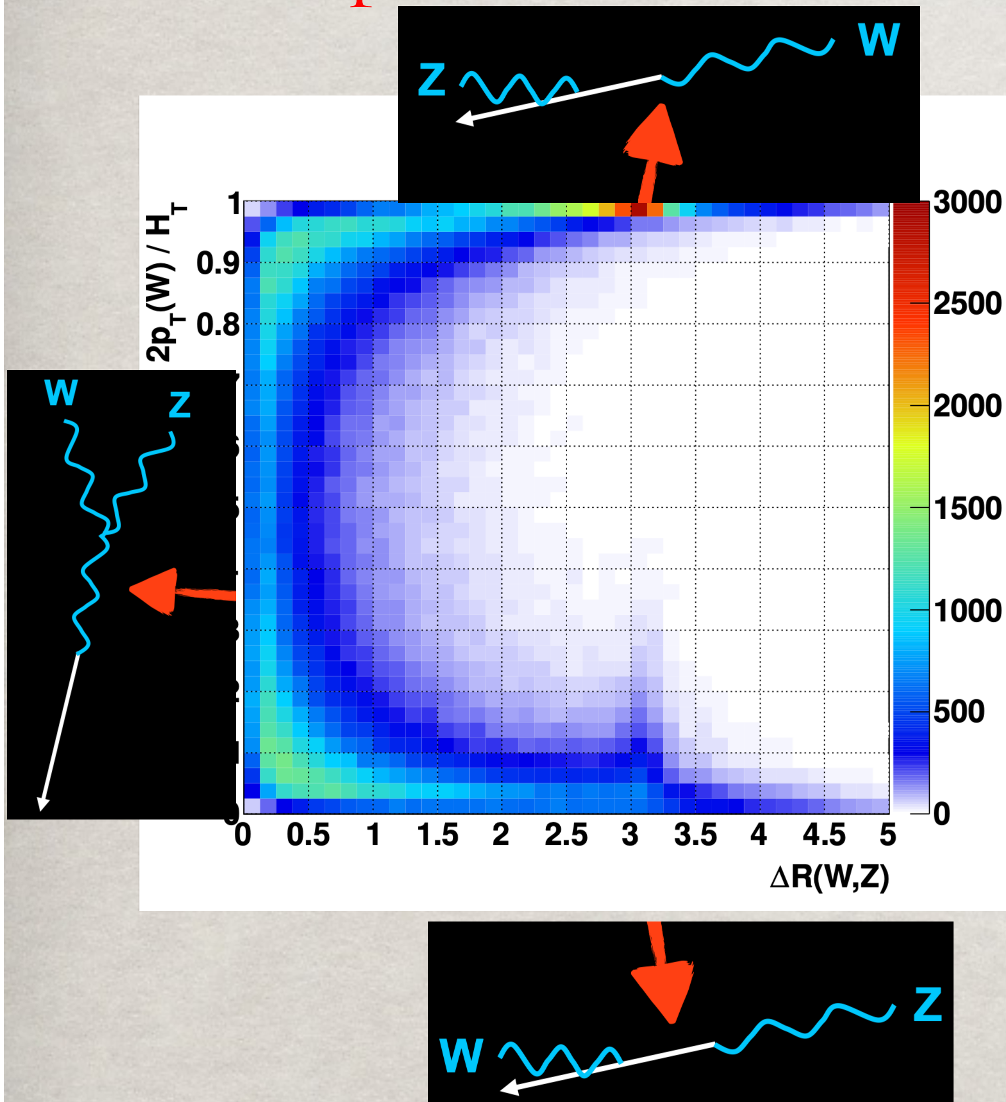
(1). Each *W* costs you a factor of ~ 1/100 (EW coupling)

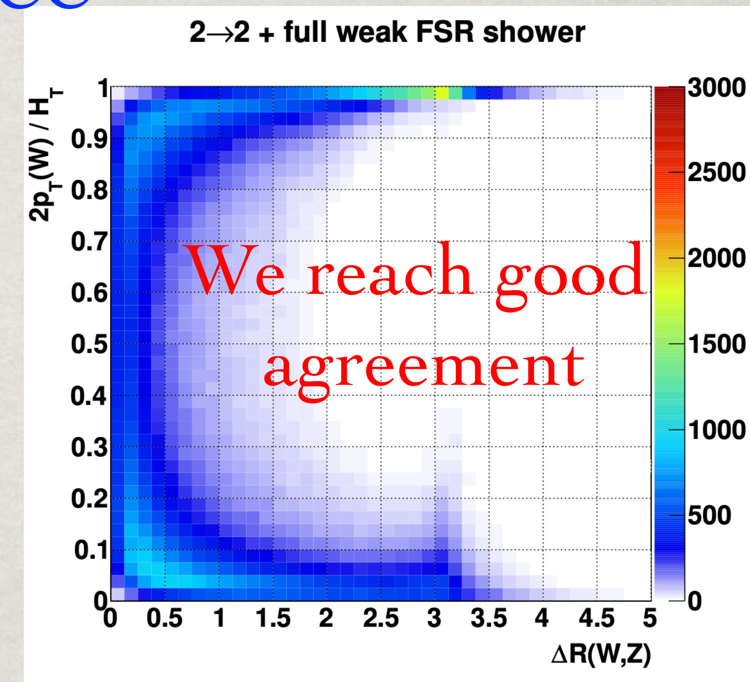


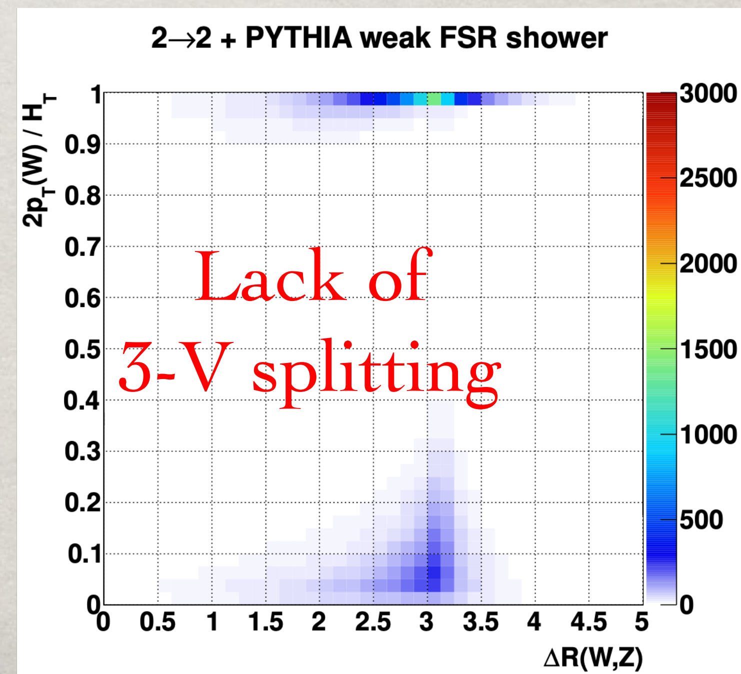


WZ+1 jet @ F_{CC}: 100 TeV

MadGraph 2→3 fixed order







P. Richardson et al., arXiv:2108.10817;
P. Skands, VINCIA Update.

Longitudinal Gauge Boson & Goldstone-boson Equivalence Theorem (GET):

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

"Scalarization" to implement the Goldstone-boson Equivalence Theorem (GET):

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

trivial "scalarization"
(for any vector state)

symmetry
breaking residual

Puzzle of massless fermion radiation

V_L contributions dominant at high energies:

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

Then, massless fermion splitting

$f \rightarrow f\, V_L$

would be zero, in accordance with GET for

$f \rightarrow f\, \phi \quad (y_f \rightarrow 0)$.

GET ignored the EWSB effects at the order M_W/E
→ QCD analogue: the power-corrections Λ_{QCD}/Q,
higher twist effects

Corrections to GET
1st example: "Effective W-Approximation"

G. Kane, W. Repko, W. Rolnick (1984);
S. Dawson (1985); Chanowitz & Gailard (1984)

At colliding energies $E >> M_W$,

$$P_{q\to qV_T} = (g_V^2 + g_A^2)\,\frac{\alpha_2}{2\pi}\,\frac{1+(1-x)^2}{x}\,\ln\frac{Q^2}{\Lambda^2}$$

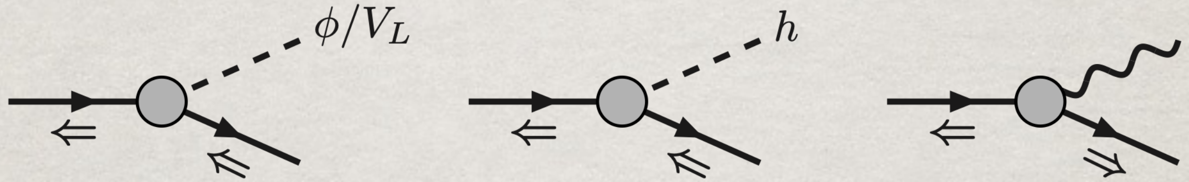
$$P_{q\to qV_L} = (g_V^2 + g_A^2)\,\frac{\alpha_2}{\pi}\,\frac{1-x}{x}$$

- $f \to f\,W_L$, $f\,Z_L$ do not vanish; no collinear-log!
  - Vector boson fusion observed at the LHC
    $WW, ZZ \to h$ & W^+W^+ scattering

EW Splitting functions in the broken phase

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

V_L is of IR, h no IR



$$\frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z}\right)}{\to\ V_L\ f_s^{(\prime)}\ (V \neq \gamma)} \qquad \frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}}{h\ f_s} \qquad \frac{\frac{1}{16\pi^2}\,\frac{v^2}{\tilde{k}_T^4}}{V_T\ f_{\text{-}s}^{(\prime)}}$$

Chirality conserving:
Non-zero for massless f

Chirality flipping:
$\sim m_f$

The PDFs for W_L thus don't run at leading log

→ A broken gauge

→ "Bjorken scaling" restored,

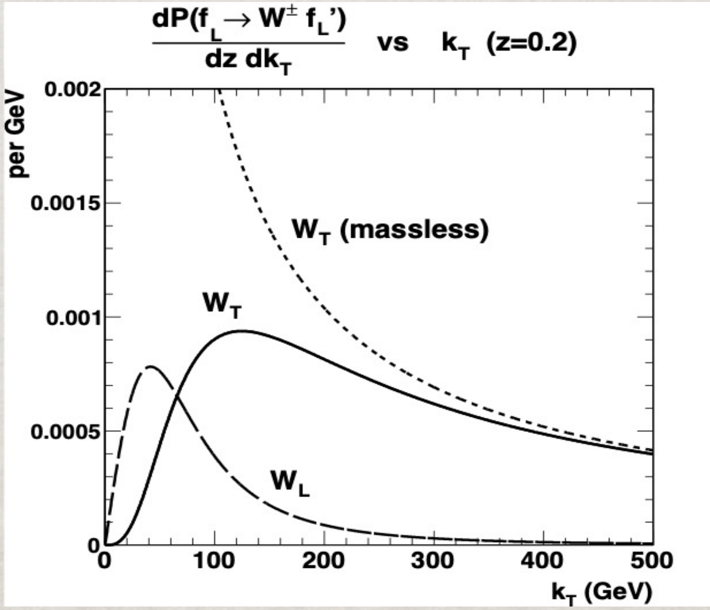
→ or higher-twist effects like Λ^2_{QCD}/Q^2.

“Ultra collinear behavior”

New characteristics with the mass:

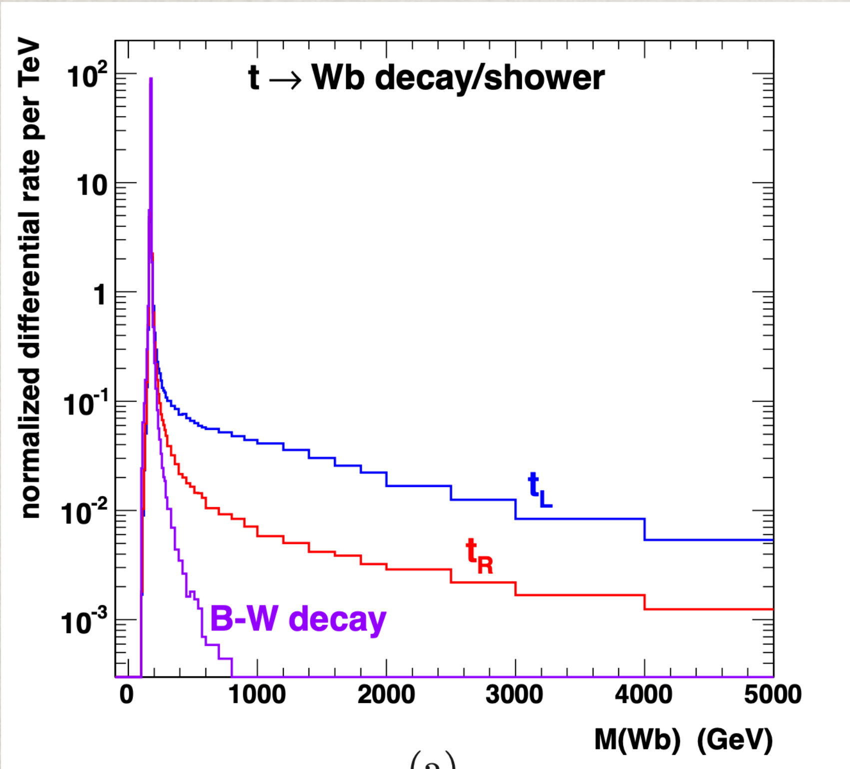
$k_T^2 > m_W^2$, it shuts off; $\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$

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

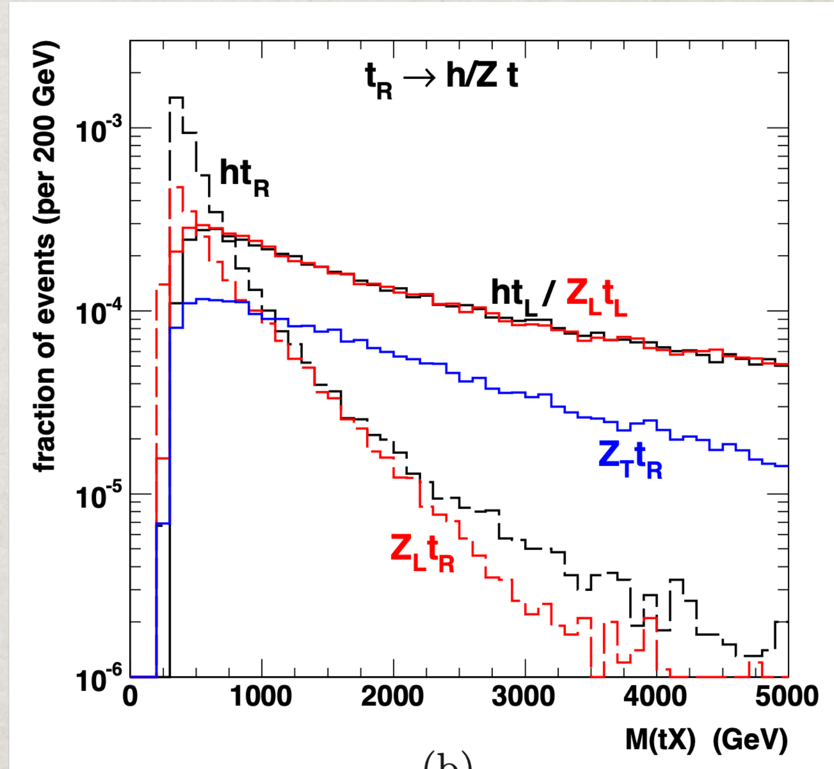


- Kinematic basis for
  “forward jet-tagging, central jet-vetoing” !
- The PDFs for W_L: no $\log(Q^2/M^2)$.

Top decay/showering (10 TeV):



(a)



(b)

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

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

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

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

EW PDFs at a muon collider: "partons" dynamically generated

Initially, the "valence parton": $f_\ell(\xi, m_\ell^2) = \delta(1-\xi)$ + …

Leading order "sea parton": $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$

Beyond leading order with DGLAP evolution:

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

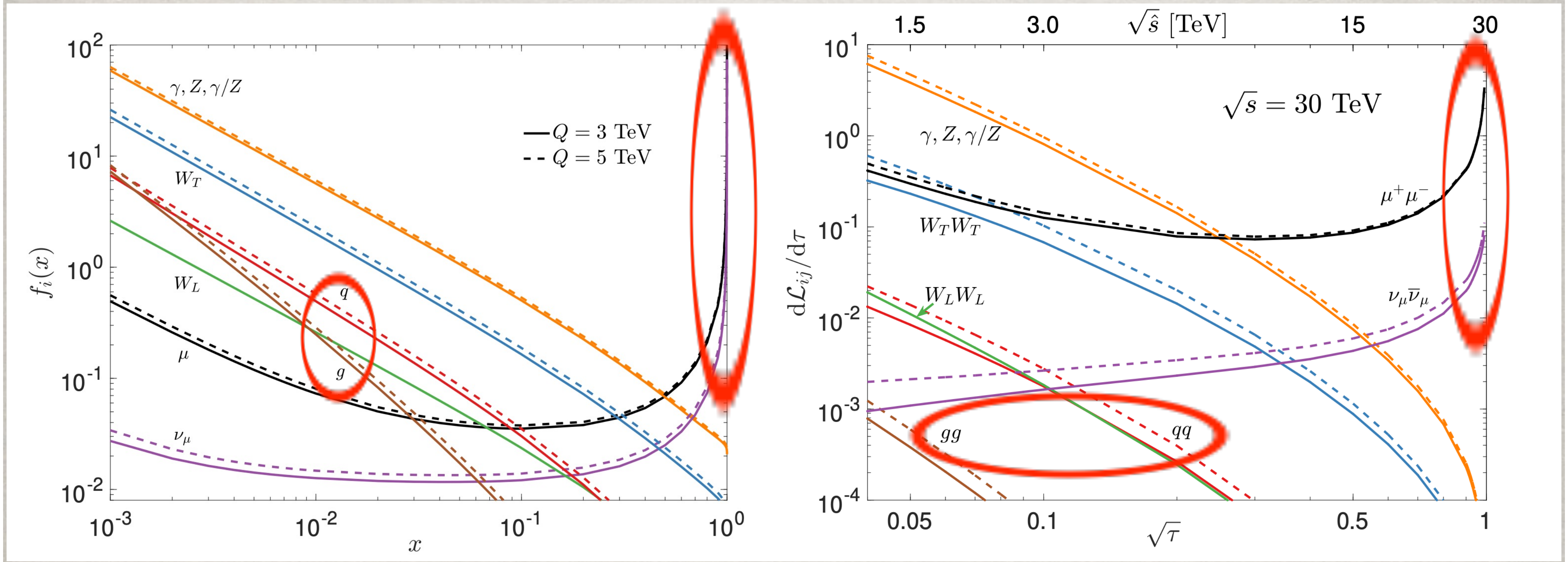
$$\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \frac{\mathrm{d}}{\mathrm{d}\log Q^2} \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma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

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

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

- **EW PDFs at a muon collider:**

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



$\mu^\pm$: the valance. $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$: LO sea.

Quarks: NLO; gluons: NNLO.

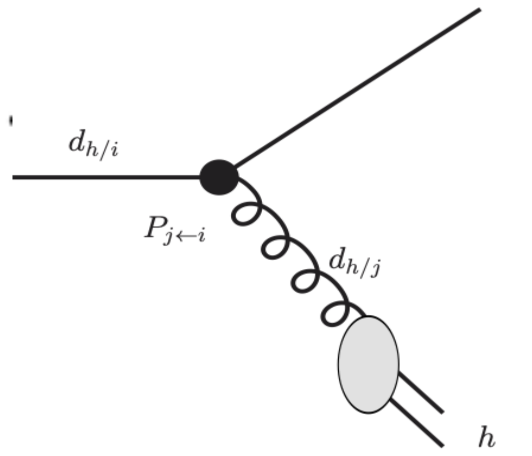
TH, Yang Ma, Keping Xie, arXiv:2007.14300

• **EW fragmentation:**

Parton "i" to an exclusive final state "h"

$$\sigma_{2\to 3} = \int \mathrm{d}z D(z, Q^2)\hat{\sigma}_{2\to 2}$$

$$\frac{\mathrm{d}d_{h/i}}{\mathrm{d}\log\mu^2} = d_{h/j} \otimes P_{ji}$$

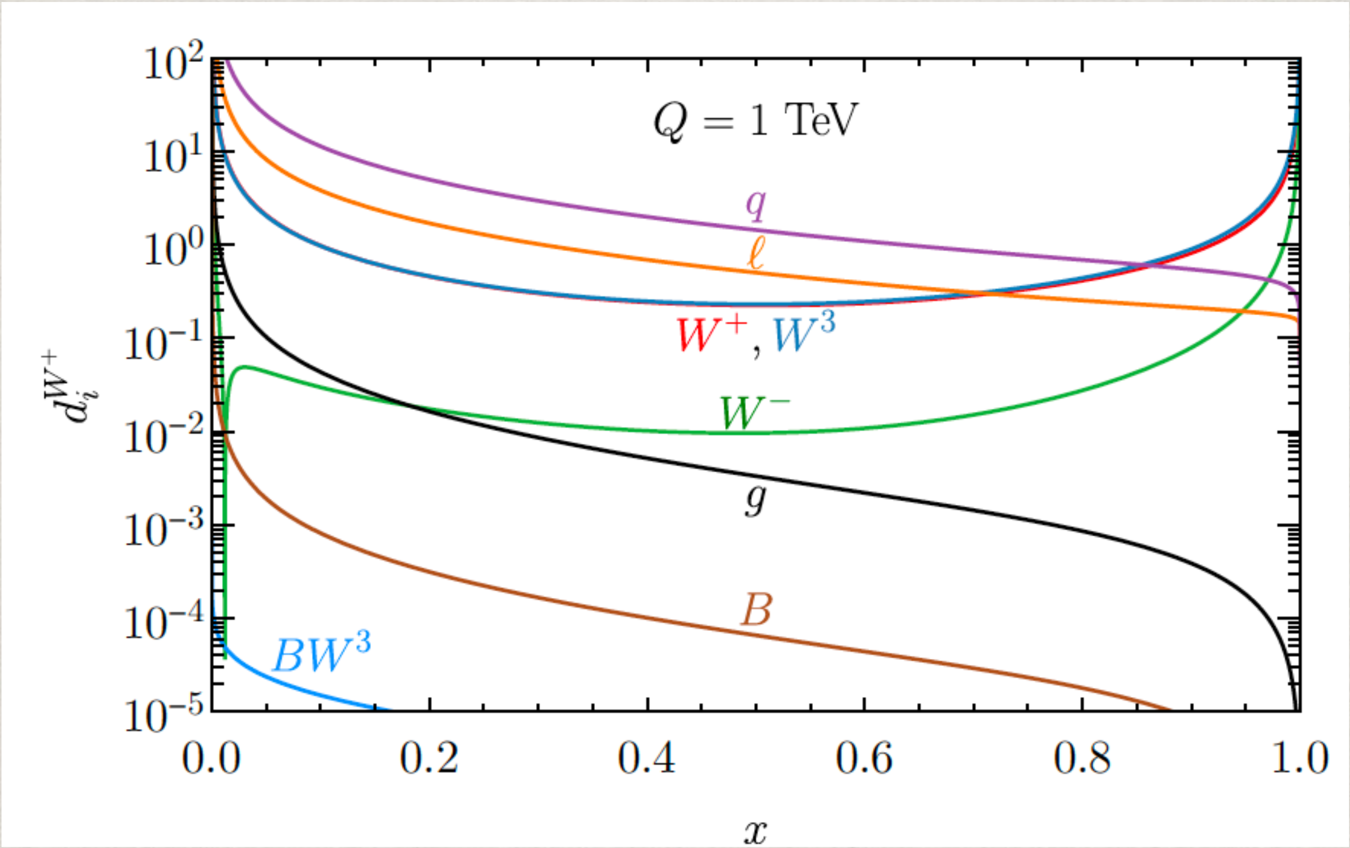


e.g. EW gauge boson production
via fragmentation:

$$\sigma^{\mathrm{FSR}}_{pp\to VVj} \simeq \sigma_{pp\to Vj} \otimes D_{V\to VV} + \sigma_{pp\to Vq} \otimes D_{f\to fV}$$

TH, Ma, Xie, arXiv:2203.11129;
TH, Y. Ma, A. Wu, K. Xie, to appear

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 ν → an observable jet!

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

Many Topics:

- EW physics @ high energies: conceptual new
- Splitting functions, EW showering
- Longitudinal & Goldstone bosons
- Splitting in the broken phase: Ultra collinear
- EW evolution beyond the leading log
- EW fragmentation, EW jets

J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;
TH, Y. Ma & K. Xie, arXiv:2007.14300; 2103.09844;
TH, Y. Ma, A.T. Wu, K. Xie. to appear

Conclusions

- EW splitting/showering will become an increasingly important part at higher energies.

- It still has technical & conceptual challenges at higher energies.

- Be prepared:
  Very high-energy W, Z, h, t may serve as tools for the next discovery !