Polarization Effects in Electroweak PDFs at Very High Energies

Bryan Webber



Work in collaboration with Christian Bauer and Nicolas Ferland, LBNL

1703.08562 = JHEP 08(2017)036, 1808.08831

Motivation

- Electroweak corrections becoming essential
 - Fixed order adequate at present energies
 - Enhanced higher orders important for FCC
- SM may be valid up to much higher energies
 - Implications for cosmology and astrophysics
- Need full simulations of VHE interactions: parton shower event generators for full SM
 - First step: event generators need PDFs

Outline

- Electroweak effects at high energies
 - Non-cancelling large logarithms
 - Sudakov factors
- SM parton distributions
 - DGLAP evolution: double log, LL and NLL
 - L-R and isospin asymmetries
- Polarization of gauge bosons
 - Matching to below EW scale
- Conclusions and prospects

Electroweak Effects at High Energies

Electroweak effects: e⁺e⁻



- For massless bosons, IR divergences in each graph, cancel in inclusive sum over SU(2) multiplets
- For massive bosons, divergences become log(m_w²/s), generally two per power of α_w

Electroweak effects: e⁺e⁻



- α_w log²(m_w²/s) from each graph, cancel in inclusive sum over SU(2) multiplets
- But we don't have vv or ev colliders, so cancellation is incomplete

Electroweak effects: qq



- α_w log²(m_w²/s) from each graph, cancel in inclusive sum over SU(2) multiplets
- In pp, u-quark PDF ≠ d-quark PDF, so cancellation is incomplete

Electroweak logarithms



- Electroweak logs get large at high energy
- Virtual corrections exponentiate as Sudakov factor

$$\Delta_i(s) \sim \exp\left[-C_i \frac{\alpha_w}{\pi} \log^2\left(\frac{s}{m_W^2}\right)\right]$$

π / ³⁰⁰ 435 relations between NLO, NNLO and NNNLO te

$Eee C_{43}^{42} \text{At NLL level, which is the logarithmic accuracy at which NNLO Sudakov electron, are known (Perpervice 12-10), the ollowing types of logarithms are available, <math>\delta_{\text{Sud}}^{(3)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(2)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} \end{bmatrix}^2, \quad c^{(1)} = \frac{1}{2} \begin{bmatrix} c^{(1)} \\ b^{(1)} \end{bmatrix}^2, \quad c^{(1)} \end{bmatrix}^2,$

 π Suu

 $Q^2 \rightarrow 38$ Based on these relations, we estimate the unce) \hbar^2 jet $\underbrace{@is}_{M^2}$ $\downarrow V_+ C_1^{(1)} \ln^1$ $\delta^{(1)}_{
m Sud}$ $\frac{1}{M^2}$ as EW effects beyind \mathbb{E}^{39} EW effects beyind \mathbb{E}^{39} 405 $\begin{bmatrix} 10^1 \\ 10 \end{bmatrix}$ 10 $\begin{pmatrix} Q_{ij}^2 \\ M^2 \end{pmatrix} + C_3^{(2)} \ln^3 \left(\frac{Q^2}{M^2} \right)^{440} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ Q^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{$ 406 $\overline{Z^{j}}$ +iet effects from angular integration and multiplyin where $M = M_W \sim M_Z$, $Q_{ij}^2 = |(\hat{p}_i \pm \hat{p}_j)^2|$ are the various Mandelstaneinovasiavative. This rough estimate 407 built from the hard momenta \hat{p}_i of the V + jet prodeet is \hat{h}^e prodeets introduce 20 missing NNLO Sudakov 408 exponentiation approach, $Q_{12}^2 = \hat{s}^{-6}$ 409 In this work we will employ the explicit NLL Sudakov results of (12(416)) which have been implemented, finaddition to exact NLO QCD NLO EW am- $= \ \delta \kappa_{\rm NLO\,EW}^{(V)}(x) =$ 410 411 plitudes, In the OPENLOOPS matrix-element generator kan be compared to ded known NLL Sudakov res 412 that the results of [12–16] are based on the high-energy limit Fight which demonstrates that eq. (35) (s 413 two-loop $2c_{\text{prections' regularised' with a fictitious photon mass of order <math>M_W$. The corrections. The 414 This generates logarithms of the form $\alpha^n \ln^k(\hat{s}/M_W^2)$ that correspond to the (34) turn out to be 415 combination of virtual one- and two-loop EW corrections plus corresponding provide the provided of the state 416 photon vadiation contributions up to an effective cut aff scale value of the full NLO EW 417 the case of V+ jet production, for physical observables that are inclusive with respect to photon radiation, this approximation is accurate at the one-percent $\kappa_{\rm EW}^{(V)}(x) = 0.05 \kappa_{\rm NLO\,E}^{(V)}$ 418 419 level [130.4]6, 18]. ⁴⁵⁵ This type of uncertainty has a twofold motivat 420 In this work we will employ full EW results at NLQ and NIOW Storaks of logar $\alpha^2 \ln^2 \left(\frac{Q^2}{M^2}\right)$ that can 421 rithms at NNLO. In the provide of eq. (24)-(26), for fully-differential partonic cross sections, this implies $\frac{p_{T,V} [\text{GeV}]}{457} \left(\frac{\alpha}{\pi}\right)^2 \delta_{\text{hard}}^{(1)} \delta_{\text{Sud}}^{(1)} = \kappa_{\text{NLO hard}} \kappa_{\text{NLO Sud}} \simeq$ 422 423 $\kappa_{\text{NLOEW}}(\hat{s}, \hat{t}) = \prod_{\kappa_{\text{NLOSUd}}} \left[\delta_{\text{hard}}^{(1)} + \delta_{\text{Strd}}^{(1)} \right] \text{Here, in general, the hon-Sudakov factor } \kappa_{\text{NLO}} + \delta_{\text{Strd}}^{(1)} + \delta_{\text{Strd}}^{(1)}$ 424 425 ⁴⁶¹ per, the quality of the Sudakov approximation Transverse-momentum distributions including exact NLO FWh Gorie versions and Nevertheless, to be co 426 Bryan Webber, Polarization in Even HDEs logarithms at NLO and NNLO are shown in Fign 4, control Control Control are shown in Fign 4, control Control Control and NNLO are shown in Fign 4, control Control Control and NNLO are shown in Fign 4, control Control and NNLO are shown in Fign 4, control and A a a magned motivation bogidag unimour

Parton Distribution Functions

f a bi-local operator, separated along the lightconer For lemmons, one finds the standard efinition, but without spin averaging as we are separating the fermions into left and right include all gauge interactions of the standard model, one needs to include shanded, thus each fermion has only one possible spin determined by its helicity and the parton distribution functions for left- and right-handed fields. This implies that for of 42 ferm
$$f_i(x) = x \int \frac{dy}{2\pi} e^{-i2x\bar{n}\cdot p \cdot y} \langle p | \bar{\psi}^{(i)}(y) \, \bar{n} \, \psi^{(i)}(-y) | p \rangle$$

he standard definition of an x-weighted parton distribution is given by the patrix elem

Parto

To include all gauge interactions of the standard model, one needs to include field at the symmetry on the other hand, one needs to take the symmetry break of a count. For the H+ and W⁻ boson we simply include reprint point of the total of 8 quark PDFs and 6 leptons PDFs to consider, for a total of 8 quark PDFs and 6 leptons to be more careful to take the between these two bosons ato account. This implies that besides PDFs for each of two particles, one needs to include a mixed PDF, which is given by χ

$$\int_{BW}^{V(\omega)} = \bar{n} \frac{1}{2} p \left(\int_{\bar{n} \cdot p}^{2\pi} \int_{2\pi}^{\pi} \frac{dy}{2\pi} e^{-i 2x \bar{n}^{\mu} p \cdot y} \bar{n}_{\mu} \bar{n}^{\nu} \langle p | B^{\mu \lambda}(y) W^{3}_{\lambda \nu}(-y) | p \cdot p \rangle \right) | \text{avg.} + \text{h.c.}$$

$$J(3) \text{ is unbroken, we consider a single PDF to describe the gluon field. For the second secon$$

Since SU(3) is unbroken, we consider a single PDF to describe the gluon field. For the From these PDFs one can then construct the PDF for the Z, the photon and their $U(2) \otimes U(1)$ symmetry, on the other hand, one needs to take the symmetry breaking in Bryan West are the symmetry breaking in the poson we simply include separate PDFs for each of the take the symmetry of the take the symmetry become to the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we simply include separate PDFs for each of the take the poson we provide the

PDF Evolution



q d/dq f = $P_{ff} \otimes f$

q d/dq f =
$$P_{fV} \otimes V$$

 $q d/dq f = P_{fH} \otimes H$



Reals have loops from one side to the other



Virtuals have loops on same side



SU(3) Evolution (DGLAP)

Consider evolution of u quark PDF







 $t\frac{\mathrm{d}}{\mathrm{d}t} f_q(x,t) = \frac{\alpha C_F}{\alpha \mathcal{Q}_F} \int_{0}^{z_{\mathrm{frax}}(y)q} \int_{0}^$

z=1 singularity cancels → single-log evolution

SU(2) Evolution

 $t \frac{\mathrm{d}}{\mathrm{d}t} f_q(x,t) = \frac{\alpha C_F}{\pi} \int_{0}^{\infty} \int_{0}^{\infty} \frac{\mathrm{d}z P_{qq}(z) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z,x)} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) P_{qq}(x) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots}{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d}z P_{ff}(z) \left[f_{qq}(x/z,t)\right] + \dots} \int_{0}^{\infty} \frac{\mathrm{d$

z=1 doesn't cancel double-log evolution

M Ciafaloni, P Ciafaloni, D Comelli, hep-ph/9809321, 0001142, 0111109, 0505047

SU(2) Evolution



z=1 doesn't cancel double-log evolution

M Ciafaloni, P Ciafaloni, D Comelli, hep-ph/9809321,0001142,0111109,0505047

eneralized DGLAP equations presented below. We consider the *x* weighted PCFF oppart in secret is in interval fraction *x* and sc 21 General gaperates the set of the solution of the following forms: as considering the Sudakoved actor of the construction of the second sec etl, al fiperical Storker (1) $F_{i} = \frac{1}{2} \int_{i} \frac{1}{i} \int_{i} \frac{1}{i$ as a partial Sudakovi factor for leach the second $\tilde{k}_{i,T}^{j}$ \tilde{k}_{I}^{j} \tilde{k}_{D}^{j} $\tilde{$ interaction $dz \mathbf{H}_{i}^{R} = z \cdot f_{i}^{2} \cdot f_{i}^{2} \cdot z \cdot q$ $\operatorname{vrit} \mathcal{Q}_{\overline{\mathfrak{D}}} f_i(x,q)$ conversion we set equal to m_V . This a oitrany curop which kelpaispaptinblinger for the second of the second mrite They are on the product of the offer of the one of the other other of the other f_{q_0} f_{q_0} f_{q_0} f_{π} π f_{π} $f_$ SETTES are only produced through insertio cangaine no bottony ($\partial q \Delta_{i a I} q$ $G_{ij,T} = f_{ij,T} = f_{j}$; nteraction (ig) मिं gain the not $p_{i}(x, q)$ $A_I(\underline{q})$ $C_{ii,I}P_{ii,I}^{R}\otimes f_{j}$ *v*es eregain the hermotation ∂q . I Any les that only terms from the interaction A A $f_i(x,q)$ **Seve**ives $\Delta_i(q) q$ z_{max} Bryan Webber, Polarization in EW PDF? -IPPP Workshop 2018

Couplings



Far above EW scale ~ unbroken SU(3)xSU(2)xU(1)

Polarized Splitting Functions

$$\begin{split} P_{f_L f_L,G}^R(z) &= P_{f_R f_R,G}^R(z) = \frac{2}{1-z} - (1+z) \,, \\ P_{V+f_L,G}^R(z) &= P_{V-f_R,G}^R(z) = \frac{(1-z)^2}{z} \,, \\ P_{V-f_L,G}^R(z) &= P_{V+f_R,G}^R(z) = \frac{1}{z} \,, \\ P_{f_L V+,G}^R(z) &= P_{f_R V-,G}^R(z) = \frac{1}{2} (1-z)^2 \,, \\ P_{f_L V-,G}^R(z) &= P_{f_R V+,G}^R(z) = \frac{1}{2} z^2 \,, \\ P_{V+V+,G}^R(z) &= P_{V-V-,G}^R(z) = \frac{2}{1-z} + \frac{1}{z} - 1 - z(1+z) \,, \\ P_{V+V-,G}^R(z) &= P_{V-V+,G}^R(z) = \frac{(1-z)^3}{z} \,, \end{split}$$

- L and R fermions evolve differently
 - Gauge bosons get polarized

Altarelli & Parisi, NP B126 (1977) 298 Manohar & Waalewijn, arXiv:1802.08687

Isospin (T) + CP PDFs

$$\begin{split} f_{f_L}^{0\pm} &= \frac{1}{4} \left[(f_{u_L} + f_{d_L}) \pm \left(f_{\bar{u}_L} + f_{\bar{d}_L} \right) \right], \\ f_{f_L}^{1\pm} &= \frac{1}{4} \left[(f_{u_L} - f_{d_L}) \pm \left(f_{\bar{u}_L} - f_{\bar{d}_L} \right) \right], \\ f_W^{0\pm} &= \frac{1}{3} \left[\left(f_{W_+^+} + f_{W_+^-} + f_{W_+^3} \right) \pm \left(f_{W_-^+} + f_{W_-^-} + f_{W_-^3} \right) \right], \\ f_W^{1\pm} &= \frac{1}{2} \left[\left(f_{W_+^+} - f_{W_-^-} \right) \mp \left(f_{W_-^+} - f_{W_-^-} \right) \right], \\ f_W^{0}(\underline{x}_{\pm}, \underline{t}) &= \frac{4}{6} \left[\left(f_{W_+^+} + 2f_{W_+^-} - 2f_{W_+^3} \right) \pm \left(f_{W_-^+}^{1+} + f_{W_-^-} - 2f_{W_-^3} \right) \right] \right]. \end{split}$$



Next-to-leading log accuracy

$$\Delta_2(q) = \exp\left[Lg_1(\alpha_2 L) + g_2(\alpha_2 L) + \ldots\right] \sim \exp\left[-C\alpha_2 L^2\right]$$

where $\alpha_2 = \alpha_2(q)$, $L = \log(q/m_W)$

 Can get the whole of g₁ and g₂ by the following change in evolution equations:

* **Replace**
$$\alpha_2(q) \rightarrow \alpha_2 \left(k_{\text{CKW}} (1-z)q \right)$$

where $k_{\text{CMW}} = \exp\left(-\frac{1}{\beta_0^{(2)}} \frac{\Gamma_{\text{cusp},f}^{(2)}}{\Gamma_{\text{cusp},f}^{(1)}} \right) = \exp\left(\frac{6\pi^2 - 70}{57} \right) = 0.828$.

• Effect is small as long as
$$\alpha_2 L \ll 1$$

Counting PDFs

$\{\mathbf{T},\mathrm{CP}\}$	fields	
$\{0,\pm\}$	$2n_g \times q_R, n_g \times \ell_R, n_g \times q_L, n_g \times \ell_L, g, W, B, H$	38
$\{1,\pm\}$	$n_g \times q_L, n_g \times \ell_L, W, BW, H, HH$	20
$\{2,\pm\}$	W	2
		60

- 60 SM PDFs for unpolarised proton (48 distinct)
- Only those with same {T,CP} can mix
- Only {0,+} contribute to momentum
- Momentum conserved for each interaction

- Left-handed quarks have isospin and hypercharge, so they can generate f_{BW}
- This means in broken basis we have $f\gamma$, f_Z and $f_{\gamma Z}$

Mixed Higgs PDF

$$\begin{array}{c} H^{0} \swarrow & \overline{H}^{0} & \overline{H}^{0} \swarrow & H^{0} \swarrow & H^{0} & H^{0} \swarrow & H^{0} & \overline{H}^{0} & \overline{H}^{0} \\ f_{H}^{0} & f_{H}^{0} & f_{H}^{0} & f_{H}^{0} \overline{H}^{0} & f_{H}^{0} H^{0} \\ H^{0} & = \frac{1}{\sqrt{2}} \left(h - iZ_{L} \right), \quad \overline{H}^{0} = \frac{1}{\sqrt{2}} \left(h + iZ_{L} \right) \\ h & = \frac{1}{\sqrt{2}} \left(H^{0} + \overline{H}^{0} \right), \quad Z_{L} = \frac{i}{\sqrt{2}} \left(H^{0} - \overline{H}^{0} \right) \\ f_{HH}^{1\pm} & = \frac{1}{2} \left(f_{H^{0}\overline{H}^{0}} \pm f_{\overline{H}^{0}H^{0}} \right)$$

• f_{HH}^{1+} distinguishes between Higgs and Z_L

$$f_{Z_L} = f_H^{0+} - f_H^{1+} - f_{HH}^{1+},$$

$$f_h = f_H^{0+} - f_H^{1+} + f_{HH}^{1+}.$$

Matching at 100 GeV

$$\begin{pmatrix} f_{\gamma} \\ f_{Z} \\ f_{\gamma Z} \end{pmatrix} = \begin{pmatrix} c_{W}^{2} & s_{W}^{2} & c_{W}s_{W} \\ s_{W}^{2} & c_{W}^{2} & -c_{W}s_{W} \\ -2c_{W}s_{W} & 2c_{W}s_{W} & c_{W}^{2} - s_{W}^{2} \end{pmatrix} \begin{pmatrix} f_{B} \\ f_{W_{3}} \\ f_{BW} \end{pmatrix}$$

- At q=100 GeV, match to:
 - CTI4 QCD partons Schmidt, Pumplin, Stump, Yuan, 1509.02905
 - LUX photon Manohar, Nason, Salam, Zanderighi, 1708.01256
 - FMW Z⁰ & W[±]
 Fornal, Manohar, Waalewijn, 1803.06347
- Project back on f_{γ} , f_Z and $f_{\gamma Z}$ at higher scales
- $f_h=0$ at $q \le 100$ GeV, $f_t=0$ at $q \le m_t(m_t)=163$ GeV



Quarks relative to QCD



EW bosons relative to gluon



IPMU-KIAS-IPPP Workshop 2018

EW boson polarization



IPMU-KIAS-IPPP Workshop 2018

EW bosons relative to gluon



Longitudinal + h

Conclusions and Prospects

- Rich SM structure inside the proton
 - 60 parton distributions (48 distinct)
- Symmetries restored double-logarithmically, distinct left and right-handed PDFs
 - Onset of large effects around 10 TeV
 - Significant for ~100 TeV collider
 - Large EW boson polarizations
- Next step: complete SM event generator
 - Electroweak jets, ISR, MET, …

Thanks for your attention!



Leptons relative to gluon



Masses neglected
 → all generations equal

Lepton Pair Production at 100 TeV Collider

Lepton Pair Production



Lepton Pair Production



PeV Collider!

Lepton Pair Production

