Standard Model Parton Distributions at Very High Energies

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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 and double-log evolution
 - L-R and isospin asymmetries
- Lepton pair production
 - Matching to fixed order
- 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

 π but

 $Q^2 \rightarrow 38$ Based on these relations, we estimate the unce) \underline{h}^{2} jet $\underbrace{@ii}_{M2}$ TeV+ $C_{1}^{(1)} \ln^{1}$ M^2 AND EW effects beyind EV tas PSR2017 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 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{\text{which}} \begin{bmatrix} n^2 \\ M^2 \\ M^2 \end{bmatrix} + \mathcal{O}_{$ 406 $\overline{7^{i}}$ +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(16)) 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 $\kappa_{\text{NLOEW}}(\hat{s}, \hat{t}) = \prod_{\kappa_{\text{NLOSU}}(\hat{s}, \hat{t})}^{\alpha} \left[\delta_{\text{hard}}^{(1)} + \delta_{\text{Sud}}^{(1)} \right] \text{Here, in general, the hon-Sudakov factor } \kappa_{\text{NLOSU}} + \delta_{\text{Sud}}^{(1)} +$ 424 425 ⁴⁶¹ per, the quality of the Sudakov approximation momentum distributions including exact NLO EW against including exact be constant of the state o 426 Bryan Webber, SM PDFs at VHS udakov logarithms at NLO and NNLO are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in Fign 4; connectate of the first as Parge as which are shown in the first as t A a a grand mating basides unly own

Parton Distribution Functions

The s

dard definition of an x-

f a bi-local operator, separated along the lightconer

general of 42 f
$$f_i(x) = x \int \frac{dy}{2\pi} e^{-i 2x \bar{n} \cdot p \, y} \langle p | \, \bar{\psi}^{(i)}(y) \, \vec{n} \, \psi^{(i)}(-y) | p \rangle$$
 consider, for (2)

$$P_{i} f_{V}(x) = \frac{2}{\bar{n} \cdot p} \int \frac{dy}{2\pi} e^{-i 2x \bar{n} \cdot p \cdot y} \bar{n}_{\mu} \bar{n}^{\nu} \langle p | V^{\mu\lambda}(y) V_{\lambda\nu}(-y) | p \rangle \Big|_{\text{spin avg.}} \int \frac{dy}{2\pi} e^{-i 2x \bar{n} \cdot p \cdot y} \bar{n}_{\mu} \bar{n}^{\nu} \langle p | V^{\mu\lambda}(y) V_{\lambda\nu}(-y) | p \rangle \Big|_{\text{spin avg.}}$$
(4)

eighted parton distribution is given by the partrix elemetric $a_{ij}^{ij} = \frac{i 2x \overline{n} \cdot p y}{i 2x \overline{n} \cdot p y}$ (i) for the standard of th

To include all gauge interactions of the standard model, one fields to include separation $SU(2) \otimes U(1)$ symmetry on the other hand, one needs to take the symmetry break account. For the W^+ and W^- boson we simply include separate PDFs for each of account. For the W^+ and W^- boson we simply include for the properties that for each of account. For the W^+ and W^- boson we simply include for W^+ and W^- boson W^-

$$f_V(x) = -\frac{1}{\bar{n}\cdot p} \left(\int \frac{2\pi}{2\pi} \int \frac{dy}{2\pi} e^{-i2xn \cdot p \cdot y} \bar{n}_{\mu} \bar{n}_{\nu} \langle p | V^{\mu\lambda}(y) V_{\lambda\nu}(-y) | p \rangle \right|_{\text{spin avg.}} + \text{h.c.}$$

Since SU(3) is unbroken, we consider a single PDF to describe the gluon field. For the $Z_{\rm L}$ the photon and their 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 at a spectra transformation of the PDF for the B, the W^3 and their provide state of the W spectra the symmetry become the symmetry breaking is count. For the W^4 and W^- boson we simply include separate PDFs for each of the t

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

Consider evolution of u_L quark PDF Virtual Rea $t \frac{\mathrm{d}t}{\mathrm{d}t} \frac{d}{f_{u}} \underbrace{f_{u}}{g_{u}}(x,t) = \alpha \frac{\alpha C_{F}}{C_{Q2}} P_{V}^{V}(t) f_{u}(x,t) \qquad q \frac{\partial \mathrm{d}t}{\partial q} \frac{\mathrm{d}t}{f_{u}} \underbrace{f_{u}}{g_{q}} \underbrace{f_{u$ $q \frac{\partial}{\partial qt} \frac{d}{dt} f_q(x,t) = \frac{\partial 2C_F}{\partial qt} \int_x^{\pi} \int_x^{\pi} \int_x^{\pi} \frac{\partial 2C_F}{\partial x} \int_x^{\pi} \int_x^{\pi} \frac{\partial 2C_F}{\partial x} \int_x^{\pi} \int_x^{\pi} \frac{\partial 2C_F}{\partial x} \int_x^{\pi}$ $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_{f} \mathfrak{C}(z) t} \frac{\alpha_2 \mathcal{C}_F}{f_q(x,t)} \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_{f} \mathfrak{C}(z) P_{qq}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{qq}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{qq}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_q(x/z,t) - f_q(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{qq}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) P_{q}(x) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t) - f_{q}(x,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) \left[f_{q}(x/z,t)\right] + \dots}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{C}(z) t}{\mathrm{d}z P_{f} \mathfrak{C}(z) t} \int_{0}^{\infty} \frac{\mathrm{d}z P_{f} \mathfrak{$

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 Inpential Statistic for $F_{i} = \frac{1}{2} \int_{i} \frac{1}{i} \int_{i} \frac{1}{i$ as a partial Sudakovi factor for leach the second (i, I) (interaction $dz \mathbf{H}_{i}^{R} = z \cdot f_{i}^{2} \cdot f_{i}^{2} \cdot z \cdot q$ $\operatorname{vrit} \mathcal{Q}_{\overline{\mathfrak{Q}}} f_i(x,q)$ converses we set equal to m_V . This a bitrary curof of the states ketpaispaptinbhughetontoft mrite They are on the order of the offer of the order of t f_{q_0} f_{q_0} f_{q_0} f_{π} π f_{π} $f_$ SETTES are only produced through insertion cangaine neo battany 19. $\partial q \Delta_{\dot{R}} I q$ $G_{i}F_{j}F_{j}F_{j}$ (ig) मिं gain the not $p_{i}(x, q)$ $\neg \overline{\alpha}_I(\underline{q})$ $C_{ii,I}P_{ii,I}^{K}\otimes f_{j}$ *v*es eregain the hermotation ∂q . I Any les that only terms from the interaction A A $f_i(x,q)$ **Seve**ives $\Delta_i(q) q_{\frac{1}{\xi}}$ z_{max} Bryan Webber, SM PDFs at VHE $i \Delta q$ -IPPP Workshop 2017

Couplings



Th<u>e</u> vi red tit de tor the Sudakov, Ga $\mathcal{O}q \mathcal{I}_{g;3}$ where u_L and d_L stand for left handed jup and down-type fermions and as U(1) or quarks as una to the second secon E = For 2t g = WT hand W = b d sons we have R $\begin{bmatrix} \Delta_{F_{L}} \\ \Delta_{F_{L}} \\ A_{W,2} \\ q \\ \hline \partial q \\ \hline \partial q \\ \hline \partial Q \\ A_{W,2} \\ Q \\ q \\ \hline \partial q \\ \hline \partial Q \\ A_{W,2} \\ Q \\ q \\ \hline \partial q \\ A_{W,2} \\ Q \\ q \\ \hline \partial q \\ A_{W,2} \\ Q \\ Q \\ \hline \partial q \\ A_{W,2} \\ \hline \partial q \\ \hline \partial q \\ A_{W,2} \\ \hline \partial q \\ \hline$ $z \, \mathrm{d} z \, P^R_{VH,G}(z)$ SU(2): $f_{H_{H}G}\otimes [f_{H^+}]$ where we have used in the second line that for each generation there are (one needs to couply particles and antiparticles separately) The particles and antiparticles separately The particles and antiparticles and antiparticles are the particles and antiparticles are the particles ar SU(3): 2 right-handed down type quarks C_F left-handed lept p_R and f_g right-handed with type $q_{M,2}$ and f_g right-handed lept p_R and f_g right-handed with the reference of $M_{M,2}$ and f_g right-handed lept p_R right p_R and f_g right handed p_R right p_R Yukawa: 2.7 T = 1EThe SU(2) Tinteractions are more complicated since the emission of VMixed(2.56) flavor of the emitting particle R This combined in the equation for the W Transformed of the same ast line is over all lenote any a instants are (where ans evolution equal Termion Which Ca. Bryan Webber, SM PDFs at VHE

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

Isospin (T) + CP PDFs

$$f_{q_L}^{0+} = \frac{1}{4} \left(f_{u_L} + f_{d_L} + f_{\bar{u}_L} + f_{\bar{d}_L} \right), \quad f_{q_L}^{0-} = \frac{1}{4} \left(f_{u_L} + f_{d_L} - f_{\bar{u}_L} - f_{\bar{d}_L} \right),$$

$$f_{q_L}^{1+} = \frac{1}{4} \left(f_{u_L} - f_{d_L} + f_{\bar{u}_L} - f_{\bar{d}_L} \right), \quad f_{q_L}^{1-} = \frac{1}{4} \left(f_{u_L} - f_{d_L} - f_{\bar{u}_L} + f_{\bar{d}_L} \right),$$

$$f_W^{0+} = \frac{1}{3} \left(f_{W^+} + f_{W^-} + f_{W^3} \right), \quad f_W^{1-} = \frac{1}{2} \left(f_{W^+} - f_{W^-} \right), \quad f_W^{2+} = \frac{1}{6} \left(f_{W^+} + f_{W^-} - 2f_{W^3} \right)$$

• Double logs only appear int
$$f_u(x,t) + f_d(x,t)$$



Counting PDFs

$\{T, CP\}$	fields	
$\{0, +\}$	$2n_g \times q_R, n_g \times \ell_R, n_g \times q_L, n_g \times \ell_L, g, W, B, H$	19
$\{0, -\}$	$2n_g \times q_R, n_g \times \ell_R, n_g \times q_L, n_g \times \ell_L, H$	16
$\{1, +\}$	$n_g \times q_L, n_g \times \ell_L, BW, H$	8
$\{1, -\}$	$n_g \times q_L, n_g \times \ell_L, W, H$	8 1
$\{2,+\}$	W	I

Counting PDFs

$\{T, CP\}$	fields	
$\{0, +\}$	$2n_g \times q_R, n_g \times \ell_R, n_g \times q_L, n_g \times \ell_L, g, W, B, H$	19
$\{0, -\}$	$2n_g \times q_R, n_g \times \ell_R, n_g \times q_L, n_g \times \ell_L, H$	16
$\{1, +\}$	$n_g \times q_L, n_g \times \ell_L, BW, H$	8
$\{1, -\}$	$n_g \times q_L, n_g \times \ell_L, W, H$	8 1
$\{2,+\}$	W	
		52

- 52 SM PDFs for unpolarised proton (36 distinct)
- Only those with same {T,CP} can mix
- Only {0,+} contribute to momentum
- Momentum conserved for each interaction

SMevol Implementation

- Input at 10 GeV: CT14qed partons with LUXqed photon
- SU(3)xU(1)_{em} LO evolution (inc. leptons) up to 100 GeV
- SU(3)xSU(2)xU(1) LO evolution from 100 to 10⁸ GeV
- Evolution due to Yukawa interaction of top quark
- Neglect all power-suppressed effects



SMevol: Bauer, Ferland, BW, 1703.08562

CT14: Schmidt, Pumplin, Stump, Yuan, 1509.02905

LUX: Manohar, Nason, Salam, Zanderighi, 1607.04266

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: $f_{\gamma} \neq 0$, $f_{Z}=f_{\gamma Z}=0$, hence $f_{B} = c_{W}^{2}f_{\gamma}, \quad f_{W_{3}} = s_{W}^{2}f_{\gamma}, \quad f_{BW} = 2c_{W}s_{W}f_{\gamma}$
- Project back on f_{γ} , f_Z and $f_{\gamma Z}$ at higher scales
- $f_W=f_H=0$ at $q \le 100$ GeV

•
$$f_t=0$$
 at $q \le m_t(m_t)=163$ GeV



Quarks relative to QCD



Bosons relative to gluon



Leptons relative to gluon



Masses neglected
 → all generations equal

Asymmetries (f_i-f_j)/(f_i+f_j)



Asymmetries (f_i-f_j)/(f_i+f_j)



Lepton Pair Production at 100 TeV Collider









Matching to Fixed Order

Matching to $O(\alpha)$ EW

C Bauer, N Ferland, BW, in preparation

$$q\frac{\partial}{\partial q}f_i^{\rm SM}(x,q) = \sum_I \frac{\alpha_I(q)}{\pi} \left[P_{i,I}^V(q) f_i^{\rm SM}(x,q) + \sum_j C_{ij,I} \int_x^{z_{\rm max}^{ij,I}(q)} dz P_{ij,I}^R(z) f_j^{\rm SM}(x/z,q) \right]$$

• **Define** $f_i^{\text{SM}}(x,q) = f_i^{\text{QCED}}(x,q) + g_i(x,q) + \mathcal{O}(\alpha^2)$

$$\begin{split} q \frac{\partial}{\partial q} g_i(x,q) &= \frac{\alpha_3(q)}{\pi} \left[P_{i,3}^V(q) \, g_i(x,q) + \sum_j C_{ij,I} \int_x^1 dz \, P_{ij,3}^R(z) g_j(x/z,q) \right] \\ &+ \sum_{I \in 1,2,M} \frac{\alpha_I(q)}{\pi} \left[P_{i,I}^V(q) \, f_i^{\text{QCED}}(x,q) + \sum_j C_{ij,I} \int_x^{z_{\max}^{ij,I}(q)} dz \, P_{ij,I}^R(z) f_j^{\text{QCED}}(x/z,q) \right] \\ &- \frac{\alpha_{\text{em}}(q)}{\pi} \left[P_{i,\text{em}}^V(q) \, f_i^{\text{QCED}}(x,q) + \sum_j C_{ij,\text{em}} \int_x^1 dz \, P_{ij,\text{em}}^R(z) f_j^{\text{QCED}}(x/z,q) \right] \end{split}$$

Matching to $O(\alpha)$ EW

$$f_i^{\rm SM}(x,q) = f_i^{\rm QCED}(x,q) + g_i(x,q) + \mathcal{O}(\alpha^2)$$

$$\sigma_{ij}^{\text{QCED}} = f_i^{\text{QCED}} \otimes \hat{\sigma}_{ij} \otimes f_j^{\text{QCED}}, \quad \sigma_{ij}^{\text{SM}} = f_i^{\text{SM}} \otimes \hat{\sigma}_{ij} \otimes f_j^{\text{SM}}$$

$$\sigma_{ij}^{\text{SMexp}} = \sigma_{ij}^{\text{QCED}} + f_i^{\text{QCED}} \otimes \hat{\sigma}_{ij} \otimes g_j + g_i \otimes \hat{\sigma}_{ij} \otimes f_j^{\text{QCED}}$$

• Define
$$\sigma_{ij}^{\text{SMexp2}} = \sigma_{ij}^{\text{SMexp}}$$
 when $\sigma_{ij}^{\text{SMexp}} \neq 0$, else
 $\sigma_{ij}^{\text{SMexp2}} = g_i \otimes \hat{\sigma}_{ij} \otimes g_j$ (e.g. WW fusion)

• Then $\sigma_{ij}^{SM} - \sigma_{ij}^{SMexp2}$ is resummation of (IS) HO logs

Preliminary Results



Preliminary Results



Overall HO contribution is smaller (few %)

Bryan Webber, SM PDFs at VHE

Conclusions and Prospects

- Rich SM structure inside the proton
 - 52 parton distributions (36 distinct)
- Symmetries restored double-logarithmically, distinct left and right-handed PDFs
 - Onset of large effects around 10 TeV
 - Significant for ~100 TeV collider
 - Matching to FO almost ready
- Next step: complete SM event generator
 - Electroweak jets, ISR, MET, …

Thanks for listening!



PDFs and Parton Luminosity

• Factorization

$$\sigma_{pp\to X}(s) = \sum_{i,j} \int_0^1 \frac{\mathrm{d}x_1}{x_1} \frac{\mathrm{d}x_2}{x_2} f_i(x_1, q) f_j(x_2, q) \hat{\sigma}_{ij\to X}(x_1 x_2 s, q)$$

• Momentum sum rule

$$\sum_{i} \int_0^1 \mathrm{d}x \, f_i(x,q) = 1$$

• Luminosity

$$\frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}M^2} = \int_0^1 \frac{\mathrm{d}x_1}{x_1} \frac{\mathrm{d}x_2}{x_2} f_i(x_1, M) f_j(x_2, M) \,\delta(M^2 - x_1 x_2 s)$$

$$\sigma_{pp\to X}(s) = \sum_{i,j} \int_0^s \mathrm{d}M^2 \frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}M^2} \hat{\sigma}_{ij\to X}(M^2, M)$$

Left-handed quarks



Bryan Webber, SM PDFs at VHE

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Right-handed quarks



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Higgs PDFs



Higgs relative to gluon



Luminosities at 100 TeV



Luminosities at 100 TeV



Gauge boson PDFs



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Higgs PDFs



SMevol/LUX yy luminosity



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PeV Collider!







Preliminary Results

Large HO contributions to VBF (note scales)

