Electroweak Corrections 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 (double) logarithms
- SM parton distributions
	- ✤ DGLAP and double-log evolution
	- ✤ L-R and isospin asymmetries
	- ✤ Electron PDFs (preliminary)
- Lepton pair production
	- ✤ Matching to fixed order
- Conclusions and prospects

Electroweak Effects at High Energies

Electroweak effects: e^+e^- **ELECTROWED**

- For massless bosons, IR divergences in each graph, cancel in inclusive sum over SU(2) multiplets
- For massive bosons, divergences become log(mw $^{2}/s),$ generally two per power of $\alpha_{\rm w}$ ϵ and two powers per powers per powers per powers per powers per power of alphanet ϵ Start end portugal sensitive to logical sensitive to l

Electroweak effects: e^+e^- **ELECTROWED**

- $\alpha_w \log^2(m_w)$ ²/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 generally have two powers per power of alpha CANCCHACION IS INCOMPLETE

Electroweak effects: qq **ELECTIONS**

- $\alpha_w \log^2(m_w)$ ²/s) from each graph, cancel in inclusive sum over SU(2) multiplets
	- In pp, u-quark PDF \neq d-quark PDF, so cancellation is incomplete generally have two powers per power of alpha Cancellation is incomplete

Parton Distribution Functions

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f_{V}(x) = \frac{2}{\bar{n} \cdot p} \int \frac{dy}{2\pi} e^{-i 2x \bar{n} \cdot py} \bar{n}_{\mu} \bar{n}^{\nu} \langle p | V^{\mu \lambda}(y) V_{\lambda \nu}(-y) | p \rangle \Big|_{\text{spin avg.}}
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$$
J_{i}(\mu) = \frac{2}{n} \int \frac{dy}{2\pi} e^{-i 2x \bar{n} \cdot py} \bar{n}_{\mu} \bar{n}^{\nu} \langle p | V^{\mu \lambda}(y) V_{\lambda \nu}(-y) | p \rangle \Big|_{\text{spin avg.}} \qquad (2)
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• Virtuals have loops on same side

SU(3) Evolution (DGLAP) **F**UCHERE LEAPING \sim \sim \prime $F(11/2)$ $F(1,1)$ $F(2,1)$ $F(3,1)$ $F(4,1)$ **single logarithmic**

• Consider evolution of u quark PDF er evolution of u quark PDF

 \mathcal{L} **Logarity** as \mathcal{L} \mathcal{L} *t* d d*t* $f_q(x,t) = \frac{\alpha C_F}{\alpha}$ $\widehat{\mathbf{\mathcal{Y}}}% _{0}^{\left(1\right) }=\widehat{\mathbf{\mathcal{Y}}}_{0}^{\left(2\right) }$ \int $\frac{1}{2}$ 0 $d^2_{\!Q\!f\!f\!f\!f\!g\!g}(z)\left[f_q(x/z,t)-f_q(x,t)\right]+ \ldots.$ **Combination** *t* d $d\vec{t}$ $f_{\overline{H}}(\overline{f}_{\alpha},(t),q) = \frac{\alpha}{\alpha} \frac{\overline{G}_{\overline{F}}}{\alpha}$ π $\int_{\mathcal{B}}\int_0^z f \mathrm{d} x \, \mathrm{d} \overline{x} \, \mathrm{d} \overline{t}$ 0 $\frac{d^{2}\theta^{q}}{d^{2}\theta^{q}}(f_{a},t_{b}),q) = \frac{\alpha}{\pi} \frac{G_{a}^{q}C_{b}^{q}}{\pi} \int_{0}^{z_{\text{flat}}(x)} d z \text{d}P_{qq}^{p}(z) f_{a}^{p}(x) f_{c}^{p}(x,0) - f_{a}(x) f_{c}^{p}(x,0) f_{c}^{p}(x,0) \text{d}x$ $f_{\hat{i}\hat{i}\hat{k}}(t\hat{r}), \theta \} \stackrel{\alpha}{=} \frac{\mathscr{A}_{\mathcal{F}}C_{\mathcal{F}}}{\sqrt{2\pi}}$ π Z ¹*µ/q* 0 $dP_{qq}f(x)[f_{q}f(x\mathscr{A}|z\mathscr{A},t\mathscr{G})-f_{q}f(x)]$

• z=1 singularity cancels → single-log evolution

SU(2) Evolution **Formula Formula F**undultion **single contract of the single state** For **Formula** \mathbf{F} **single single sing**

● z=1 doesn't cancel **→** double-log evolution

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

Bryan Webber, EW Corrections at HE 2018

Electroweak logarithms $\mathbf{F} = \mathbf{F} \mathbf{$ **lactrow**

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

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\Delta_i(s) \sim \exp\left[-C_i \frac{\alpha_w}{\pi} \log^2\left(\frac{s}{m_W^2}\right)\right]
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Bryan Webber, EW Corrections at HE¹¹ DC 1114 $\Delta_{h_{11}}^{\vee}$ 2 η_{∞}^{\vee} + π Ξ_{∞}^{\vee} + Ξ_{∞}^{\vee} + π H G \otimes + Ξ_{∞}^{\vee} + Ξ_{∞}^{\vee} + Ξ_{∞}^{\vee} + Ξ_{∞}^{\vee} + Ξ_{∞}^{\ve S M F This gives contributions at the top quark PDF, as well as the †₹ **Before Life VII usuar-spring organ Culture This gives contribute section of the top quark PDF, as well as the leftquark pdf as an example** $\mathbf{S}_{\mathbf{r}}$ $\left[\begin{array}{cc} \mathscr{L} & \mathscr{D} & \mathscr{D} & \mathscr{D} \mathscr{D} \rightarrow \mathscr{D} & \mathscr{D} & \mathscr{D} \mathscr{D} \rightarrow \mathscr{D} & \mathscr{D} & \mathscr{D} & \mathscr{D} \end{array} \right]$ $\left(\frac{1}{1} \right)$ or cultures and it for $\frac{1}{2} \left(\frac{1}{2} \right)$ interaction of $\frac{1}{2} \left(\frac{1}{2} \right)$ interaction case of $\frac{1}{2} \left(\frac{1}{2} \right)$ interactions. The relevant degrees of $\frac{1}{2} \left(\frac{1}{2} \right)$ or $\frac{1}{2} \left(\frac{$ Γ for the W^{\dagger} and W^{\dagger} bosons we have ℓ as ℓ and P and ℓ is ℓ \overline{O} $\frac{d}{dx}$, $\frac{\partial}{\partial q}$ $\frac{\partial}{\partial t} f_L \neq \frac{d}{dx}$ $\frac{d}{dx}$ $\frac{\partial}{\partial q}$ $\frac{\partial}{\partial q}$ $\frac{\partial}{\partial q}$ $\frac{\partial}{\partial r}$ $\frac{\partial}{\partial r} f_W$ $\frac{\partial}{\partial r}$ $\frac{\partial}{\partial r} F_W$ $\frac{\partial}{\partial r} G \otimes \frac{\partial}{\partial r} f_H$ where we have used in the second $\lim_{\epsilon \to 0} \frac{1}{\epsilon} \int_{0}^{\epsilon} f(x) e^{-\frac{1}{2} \epsilon^2} dx$ \int Δq ,3 q ∂ $\emph{D}\hspace{-1.4pt}\rule{0pt}{1.4pt}\,\rho$ *fq q,*³ ֺֺֺ֘֞֞֞׀֘֞
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14 $\tilde{\mathcal{C}}$ **er 12 in (**
arithmic
ancel**os** ϕ_1 *Yf* $\stackrel{\mathsf{U}}{\mathsf{X}}$ \Pr^{108V11}_{R} **fonce as in the evolution pased on l** $\frac{1}{\sqrt{1}}$ *BW q* @ \overline{a} *fBW* Bection
Particle n_u ef .ւշ է
՝∄հ $\frac{1}{\alpha}$ f_{ik} SU $\overline{2}$ *Yf* $\frac{1}{2}$ $\frac{8}{11}$ $\frac{1}{2}$ *f*
PV fApternata vel *fd J* ∪
C^{*f*} <u>้สู</u> **P** $\frac{1}{2}$ *r*
C *fJer* fon S
E Workshop lar $U(1)$: SU(2): $\mathsf{SU}(3)$: $2 \text{ right-hapdeq}\left\{q\right\}$ Yukawa: $\frac{1}{21}$ *q*,3 *q* @*q* **p,s, t,u**
bdq:13 3 $\overline{10}$ $\frac{1}{2}$ The virtual splitting functions, required for the Sudakov factor lare \bm{r} Ï *g,*³ *q* $\partial\!\!\!\!{}^{\!\!\!~}$ $\partial q \rightarrow 3 \, g/3 \, g$ *fg* 1 $=$ $\alpha \AA$ $\overline{\pi}$ **/** ⁴*CA^P ^R* W F V X Q *C^F P ^R V f,G* ⌦ *f^q* The Sudator factor of the constant of the constant of the constants of the constants in the constant of the constants in the constant of the c Eq. (2.34) W⁺ hand W3 bosons we have *P^V q,*3(*q*) = *C^F* π^R_{II} l $Z dZ$ $H H + T$ $J W_3$ $F K T V H$
f f,G(z) $F T V f, G(z)$ $\operatorname{\mathbb{C}}_{\mathsf{n}}$ *P^V g,*3(*q*) = \int_{Π} (one needs to count particles $\dim_{\mathcal{C}} \dim_{\mathcal{C}} \$ where $\frac{1}{2}$ we have a testally of the Happen line extraction of the 8 chiral quarks p generation. enters the Sudakov factors. q, q, and a string dependence in the sycle of the string of the string of the stri
erwisere . The sum over a in the 12st line is nyer all left-handed fermions that only single togaritme actual center as in the evolution paset on t
the native evergences cancel in the evening to the actor of the evolutions, as \exp and $\frac{d}{dt}$ in Section 3, one obtains evolution equations that are free of an which can be implemented <u>numerically.</u> Apternative that on showe one can impose a cuto $\mathcal{O}(l^2 \lambda \hbar 2 \ln 2 \ln m)$ \mathbb{F}_{q} (2.19) with \mathcal{L}_{m} still each by $P_{\mathbf{X}_{\alpha}}^{V}$ $f_{\rm g1}^{V}$ $f_{\rm g2}^{V}$ $f_{\rm g3}^{V}$ $\prod_{i=1}^n$ *q* 0 @*q q*³ *L,Y* # *Y z* d*z P ^R f f,G*(*z*) + ^Z ¹ $\overline{0}$ *z* d*z P ^R V f,G*(*z*) $\overline{1}$ **P**^{*P*}_B, *Y d*², *a*^{2, *b*}_d, *n*^{*i*}q
EOOQQQQQDPFCaH <u>hoppe</u> \boldsymbol{Q} **led** futh and d \emptyset *z* dz *P RP K Z K*
n Eq. 12437 us \mathcal{L} $\boldsymbol{\vartheta}$ $\frac{1}{2}$ dz *P_H*
702 c*H HV,G*(*z*) *P^V* $\frac{H_{1}^{2}}{H_{1}}\frac{H_{2}^{2}}{H_{2}}$ 4 $\begin{bmatrix} \mathbf{u} & \mathbf{w} & \mathbf{w} \\ \mathbf{v} & \mathbf{w} & \mathbf{w} \\ \mathbf{v} & \mathbf{w} & \mathbf{w} \end{bmatrix}$ $\pmb{\psi}$ $P_{ff,Y}^{n} \otimes f_{\text{FR}} + N_C P_{f\text{/H},Y} \approx P_{ff,\text{G}} R_{f\text{H},\text{G}} + \frac{N_{f\text{H},Y}}{N_{f\text{H},\text{G}}} \approx P_{ff,\text{G}} + \frac{N_{f\text{H},Y}}{N_{f\text{H},\text{G}}} \approx P_{f\text{H},\text{G}} + \frac{N_{f\text{H},Y}}{N_{f\text{H},\text{G}}} \approx P_{f\text{H},\text{G}} + \frac{N_{f\text{H},Y}}{N_{f\text{H},\text{G}}} \approx P_{f\text{H},\text{G$ \overline{Q} $z \frac{dz}{R} P_{VH,G}^{R}(z)$ $\overline{}$ 2 right-handed down-type quarks \tilde{C}_F^T left-handed leptons, and 2 right-hand that there are a total of 4 He the pasons 2.7 $T = 2.4$ _gs, $V_1(2)$ $\frac{1}{2}$ the ractions The $SU(2)$ interactions are more complicated, since the emission of μ $t\log\frac{q}{\log$ who equatives for which be populatived it out that of the M DG on car in
hadron PRTs, leads to double logarithmic dependence in the DGLAP. MWILCLC. I LIC SUIT OVCL, J III the IdSULLILE 15 OVCL, ALL ICLUTILATIQUE I CLITILOIR
Unain only single logarithmic dependence as in the evolution based on U The relevant coupling constants are (where *u* and *d* denote any fermion, and *W_i* any of the SU(2) gauge bosons) $\mathbf{1}^{\mathbf{1}}$ *f* @*q* **g** film $\mathbf{\hat{2}}$ \overline{m} ⇡ #7# *f dG* (G) 2 Sudak +*NfPfV,G* ⌦ T *fW* $\frac{1}{2}$ $\frac{f_W}{\sqrt{2R}}$)
【
〔 \bigcap *,* (2.49) where u_L and d_L stand for left-handed (up and down-type fermions and as for quarks and 1 for the correct $\sqrt{ }$ $\Delta_{W,2} q$ ∂ ∂q *fW*⁺ $\Delta\!R_{\!V\!,2}^V$ $\boldsymbol{\varPsi}$ $\frac{2}{7}$ \vec{Q}^{\pm}_2 ⇡ ⇢ P_T^R $\mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] = \begin{cases} \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] & \text{if } \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[f] \rightarrow \mathcal{F}_{\mathcal{F}}^{\mathcal{D}}[$ ริว
74 P^R_{VH} $\mathcal{F} \overset{\text{VH,VY}}{\otimes}$ $[f_{H^+}]$.|
ที่7 b we have used in the second line phare preced $\frac{20}{4}$ or $\frac{1}{4}$ or $\frac{$ gen Φ P ^{*l*} + *f*_{*v*} + *f*_{*l*} + *f*^{*l*} + *f*^{*l*}_{*f^d*} + *f*^{*l*}_{*fd*} + *f*^{*l*}^{*fd*}_{*fd*} $f(x) = \frac{2}{\sqrt{2}} \int_{0}^{1} \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} \int_{0}^{1} \frac$ \uparrow *W,*² *q* $\partial\overline{\partial}$ ∂q *fW*³ *W,*² $\mathbb T$ 2 ∫ }
17 $\vec{q}_{\rm R}$ $\overline{\pi}$ ⇢ *P ^R* V ^{*P*}^{*I*} *ff*,*G* ∞ *J*_{*q*}² | - *1R*₁ - *f*_{*V*},
MigeO@S[*fwtherefwre]* & *q* $\ddot{4}$ P_R^R , q $\sqrt{2}$ \sum_{S} *h fh* $\,mathcal{H}$ $f_{f} \times \mathcal{D} f_{t_{B}} + N_C P_{fH}$ *f^L* \bigcap $\mathfrak{gl}\Gamma\mathfrak{t}$ he z integration and the equation for the *W* acan be obtained from that of the William Spile.
and the equation for the W acan be obtained from that of the W+ bow takin re stablished the stablished of the stabli Finally UPVELGEIGES Cancel IN WE have $\rm V_{\rm r}$ *hu,*² *q* $\hat{\beta}$ ∂q *fh^u h,*² $\prod\limits_{k\in\mathbb{N}}% \left\vert k\right\vert$ $\hat{\mathbf{r}}$ \overline{c} **刊2** $\overline{\textbf{t}}$ $\Im \widetilde{\Phi}$ $\mathcal{P}^{\rm \textit{R}}_{H}$ $HH, G \otimes$ \int *fh^d* :
h_dfor f<i>bu
2 m- ray $\breve{\mathcal{A}}$ $\overline{1}$ This gives contributions; ∂ the top quark PDF, as well as the left-handed both **1 in 1999** *^L,Y q* $\partial\!\!\!\!/\,$ f <u>—</u>
= ↵*^Y* $\overline{\pi}$ \mathcal{L} $P^{\mathcal{B}}_T$ *f f,Y* ⌦ *ft^R* + *NCPfH,Y* ⌦ *fH*¯ ⁰ $\sharp_{{\bf l}}$ $\frac{\partial}{\partial t}$ _R^{*q*} *for lest* - h \overline{E} ⇡ *P ^R* $f^T_{\mathcal{B}}(f) = \frac{1}{2} \int_{\mathcal{B}} f^T_{\mathcal{B}}(f) \, d\mathcal{B} = \int_{\mathcal{$.
|
| *q* $\left[\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}\right]$ ∂ ^{*b*}*bb*₂^{*l*} $\frac{\lambda}{\sqrt{2}}$ ↵*^Y* ⇢ $\mathcal{F}_f^{\text{ref}}(X) = \mathcal{F}_f^{\text{ref}}(X)$ $\mathcal{F}_f^{\text{ref}}(X) = \mathcal{F}_f^{\text{ref}}(X)$ $\mathcal{F}_f^{\text{ref}}(X) = \mathcal{F}_f^{\text{ref}}(X)$ $\mathcal{F}_f^{\text{ref}}(X) = \mathcal{F}_f^{\text{ref}}(X)$ $\mathcal{F}_f^{\text{ref}}(X) = \mathcal{F}_f^{\text{ref}}(X)$ $\bigoplus_{f \mid f} R$ γ *CBWhu,M* = *ChuBW,M* = *CBWhd,M* = *ChdBW,M* = \mathfrak{a} $\left\lfloor \frac{\sqrt{3}}{D} \right\rfloor$ $\left[\begin{array}{c} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{array} \right]$ $\left[\begin{array}{c} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{array} \right]$ $\frac{1}{4}$ *q* £
ረጋ $\frac{1}{2}$ $\frac{1}{2}$ *ff^u* ।
क्रि $\frac{1}{2}a$ ↵*^M Yf Nor* quarks shidakowlade the and two brained flom Eq. (2.43) using the cot \vec{p} 究
明夏 ff^d $\overline{\hbar}$ $^{\mathsf{r}}$ L $\frac{1}{4}$ $\frac{1$ \overline{I} *Yf* |
|
|
| $P_{\mathcal{F}}^{R}$ *f*_{*f*}^{*g*}*f*_{*f*}^{*f*}*f*_{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*}^{*f*}_{*f*} $Qq \Delta W_{q,3}(\mathbf{q}) = \pi Q_F \int_{\mathbb{R}^n} \mathbf{z} d\mathbf{z}$ α count particles: $\frac{\Delta W_{V,3}^{\prime}}{1}$ and $\frac{10}{1}$ $\alpha = \pi C \psi$
 $\alpha = 2C \sin \left(\frac{F}{2} \right)$
 $\alpha = 2C \sin \left(\frac{F}{2} \right)$
 $\alpha = 2C \sin \left(\frac{F}{2} \right)$ *fu* 上
二 *fd* . –
|- $\begin{bmatrix} 3 & 1 \\ 1 & 6 \end{bmatrix}$ for $\begin{bmatrix} 3 & 4 \\ 1 & 6 \end{bmatrix}$ \mathcal{L} $\sum_{i=1}^{n}$)
ጋር $\stackrel{\centerdot}{\models} \stackrel{\centerdot}{\not\in} \{$ *hu* $P_{f,G}^{A \to V} V_{g}^{A \to V} C_{f}^{B}$ $\frac{1}{1}$ $\lim_{\epsilon\to 0}$ *hd* $\frac{1}{2}$ *f*_g^{*f*} *f*_g^{*f*} *f*_g^{*f*} *f*_{*f*} *f*_{*f*} *f*_{*f*} *f*_{*f*} $\bigcup_{Q} \bigoplus_{f} W, \bigoplus_{f} \bigoplus_{f}$ \bigcup $\overline{\mathcal{L}}$ @*q* $\frac{1}{\sqrt{10}}$ *M* $\overline{\mathbf{d}}$ ↵*^M* ー
尽 $\frac{1}{2}$ э4
Ц $P_{\text{Ff}}^R \otimes f_{\text{Lg}} + N_C P_{\text{f}_1 H, Y} \otimes f_{\text{r}} =$ nteractions are more $\frac{1}{1}$ \mathbf{F} *fh^d* ti<u>ff^y f</u>afrtycle
11LS HÖWCVE $P_{\text{H}}^{\text{W}}(Q) = \int_{f,f,G}^{f,f,G} \int_{g}^{f} \mathbf{a} \mathbf{r} \mathbf{d} \mathbf{r} \mathbf{d} \mathbf{r} \mathbf$ that the divergences can cell my the overation at the action in Biblion Systhe^r \mathbb{R}^3 : \mathbb{R}^3 Yukawa: Thu the evenit fou attract action in present

⇤

*C*_h**u***h*_u*h*_u*,*2 = *C*_{*h*}_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*_u*h*</sub>^{*n*}

- Left-handed quarks have isospin and hypercharge, so they can generate f_{BW} –3– *w f*₂ *f*²
- This means in broken basis we have fy, fz and $f_{\gamma Z}$ $\frac{1}{2}$ $A = 3 - \frac{1}{2}$ **P** in the means in proken basis we have ty, the and $I_{\gamma Z}$

Isospin (T) + CP PDFs

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

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

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

• **Double**
$$
\log_2 \frac{f_u(x,t) + f_d(x,t)}{\log_2 \omega}
$$
 appear¹ (*int*) $\sqrt{f} + \sqrt{\log_2 f}$

Bryan Webber, EW Corrections at HE

Counting PDFs

- 52 SM PDFs for unpolarised proton (36 distinct) **6** 52 SM PDFs for unpolarised proton (36 distinct) to each to the *{*1*,* +*}* and *{*1*, }* and 1 to the *{*2*,* +*}*.
	- Only those with same {T,CP} can mix The sum of \mathcal{L} momenta of all non-mixed \mathcal{L} is conserved, since it cons
- Only {0,+} contribute to momentum \bullet Only $\{0, +\}$ contribute to momentum
	- Momentum conserved for each interaction $\overline{\mathbf{m}}$ *c* cons $\overline{}$ @*q fi*(*x, q*) \overline{a} $\hat{ }$ each interaction

SMevol Implementation

- Input at 10 GeV: CT14qed partons with LUXqed photon
	- ✤ Photon PDFs consistent, LUX much more precise CT14: Schmidt, Pumplin, Stump, Yuan, 1509.02905 LUX: Manohar, Nason, Salam, Zanderighi, 1607.04266, 1708.01256
- SU(3)xU(1)_{em} LO evolution (inc. leptons) up to 100 GeV
	- ✤ Provides LO PDFs to match to LO SM evolution beyond
- SU(3)xSU(2)xU(1) LO evolution from 100 to 10⁸ GeV
	- ✤ Also evolution due to Yukawa interaction of top quark
	- ✤ Neglect all power-suppressed effects

SMevol: Bauer, Ferland, BW, 1703.08562

Bryan Webber, EW Corrections at HE 2018

Matching at 100 GeV $F = F \cdot P$ <u>zo and the state as a transformation of the PDF for the B, the B</u> F rom the construction then construct the photon, then construct the photon, the photon, the transversely-polarized the photon, the photon, the transversely-polarized the photon, the transversely-polarized the transverse **Z0 and the state state state state state state state as a transformation of the PDF for the PDF for the PDF for the state sta** state. Using *^A* ⁼ *^c^W ^B* ⁺ *^s^W ^W*³ and *^Z*⁰ ⁼ *s^W ^B* ⁺ *^c^W ^W*³ one finds

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

- At $q=100$ GeV: $f_\gamma \neq 0$, $f_Z = f_\gamma Z = 0$, hence C_1 and C_2 $f_{B} = c_{W}^{2} J_{\gamma} , \quad f_{W_{3}} = s_{W}^{2} J_{\gamma} , \quad f_{BW} = 2 c_{W} s_{W} J_{\gamma} .$ For the electroweak input at scale *µ* = *q*⁰ we have *f* 6= 0 and *f^Z* = *f^Z* = 0, so the input \bullet At q=1 $f_B = c_W^2 f_\gamma \, , \quad f_{W_3} = s_W^2 f_\gamma \, , \quad f_{BW} = 2 c_W s_W f_\gamma$
- Project back on f_{γ} , f_Z and $f_{\gamma Z}$ at higher scales **•** Project back on f_γ , f_Z and $f_\gamma Z$ at higher scales
	- $f_W=f_H=0$ at $q \le 100$ GeV PDFs are reconstructed there using the corresponding running values of *c^W* and *s^W* . • $t_W = t_H = 0$ at $q \le 100$ GeV

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

Quarks relative to QCD

Bryan Webber, EW Corrections at HE

Bosons relative to gluon

Bryan Webber, EW Corrections at HE

Leptons relative to gluon

Masses neglected \rightarrow all generations equal

Asymmetries (fi-fj)/(fi+fj)

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Electron PDFs (preliminary)

- Electron+photon (Weizsacker-Williams) at 1 GeV
	- ✤ SU(3)xU(1)em evolution up to 100 GeV
	- ✤ Then unbroken SU(3)xSU(2)LxU(1)Y
	- ✤ No beam-beam effects

100 TeV pp Collider

Lepton Pair Production

Lepton Pair Production

Matching to Fixed Order

Matching to $O(\alpha)$ EW

C Bauer, N Ferland, BW, 1712.07147

$$
q \frac{\partial}{\partial q} f_i^{\text{SM}}(x, q) = \sum_{I} \frac{\alpha_I(q)}{\pi} \left[P_{i, I}^V(q) f_i^{\text{SM}}(x, q) + \sum_{j} C_{i j, I} \int_x^{z_{\text{max}}^{i, I}(q)} dz P_{i j, I}^R(z) f_j^{\text{SM}}(x/z, q) \right]
$$
\n
$$
\bullet \quad \text{Define} \quad f_i^{\text{SM}}(x, q) = f_i^{\text{noEW}}(x, q) + g_i(x, q) + \mathcal{O}(\alpha^2)
$$
\n
$$
\bullet \quad \text{Then}
$$
\n
$$
q \frac{\partial}{\partial q} g_i(x, q) = \frac{\alpha_3(q)}{\pi} \left[P_{i, 3}^V(q) g_i(x, q) + \sum_{j} C_{i j, 3} \int_x^1 dz P_{i j, 3}^R(z) g_j(x/z, q) \right]
$$
\n
$$
+ \sum_{I \in 1, 2, M} \frac{\alpha_I(q)}{\pi} \left[P_{i, I}^V(q) f_i^{\text{noEW}}(x, q) + \sum_{j} C_{i j, I} \int_x^{z_{\text{max}}^{i, I}(q)} dz P_{i j, I}^R(z) P_{i j, I}^R(z) f_j^{\text{noEW}}(x/z, q) \right]
$$

Bryan Webber, EW Corrections at HE 2018 and ECC Workshop, Jan 2018

Matching to $O(\alpha)$ EW

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

$$
\sigma_{ij}^{\rm noEW} = f_i^{\rm noEW} \otimes \hat{\sigma}_{ij} \otimes f_j^{\rm noEW}, \ \ \, \sigma_{ij}^{\rm SM} = f_i^{\rm SM} \otimes \hat{\sigma}_{ij} \otimes f_j^{\rm SM}
$$

$$
\sigma_{ij}^{[\text{SM}]_{\alpha}} = \sigma_{ij}^{\text{noEW}} + f_{i}^{\text{noEW}} \otimes \hat{\sigma}_{ij} \otimes g_j + g_i \otimes \hat{\sigma}_{ij} \otimes f_{j}^{\text{noEW}}
$$

• Define
$$
\sigma_{ij}^{[\text{SM}]^{\text{mod}}_{\alpha}} = \sigma_{ij}^{[\text{SM}]_{\alpha}}
$$
 when $\sigma_{ij}^{[\text{SM}]_{\alpha}} \neq 0$, else

$$
\sigma_{ij}^{[\text{SM}]^{\text{mod}}_{\alpha}} = g_i \otimes \hat{\sigma}_{ij} \otimes g_j \text{ (e.g. WW fusion)}
$$

• Then
$$
\sigma_{ij}^{\text{SM}} - \sigma_{ij}^{\text{[SM]}^{\text{mod}}}
$$
 is resummation of HO logs

Bryan Webber, EW Corrections at HE 2018 and 2018 and 2nd FCC Workshop, Jan 2018

Results for matching

2nd FCC Workshop, Jan 2018

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
	- ✤ Ready for matching to FO
- Next step: complete SM event generator
	- ✤ Electroweak jets, ISR, MET, …

PDFs and Parton Luminosity

• Factorization

$$
\sigma_{pp \to X}(s) = \sum_{i,j} \int_0^1 \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_i(x_1, q) f_j(x_2, q) \hat{\sigma}_{ij \to X}(x_1 x_2 s, q)
$$

• Momentum sum rule

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

• Luminosity

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

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

Bryan Webber, EW Corrections at HE 2nd FCC Workshop, Jan 2018

Luminosities at 100 TeV

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Lepton Pair Production

Lepton Pair Production

Higgs PDFs

Higgs relative to gluon

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Lepton Pair Production at I PeV

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