The nCTEQ PDFs: Improved PDF precision with eA measurements

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Thanks for substantial input from my friends & colleagues







INT Workshop

22-26 October 2018





The QCD Parton Model

$$d\sigma = f_a(x) \otimes \widehat{\sigma}$$

Parameterized in terms of a single variable x, the momentum fraction ... use DGLAP to determine μ dependence

 $f_a(x)$... working in the limit of a spherical horse ...



Nuclear PDFs

... a few simpifications

even more so with nPDFs



Nuclear PDFs are ESSENTIAL for proton PDFs

neutrino DIS

$$F_{2}^{\nu} \sim \begin{bmatrix} d + s + \bar{u} + \bar{c} \end{bmatrix}$$

$$F_{2}^{\bar{\nu}} \sim \begin{bmatrix} \bar{d} + \bar{s} + u + c \end{bmatrix}$$

$$F_{3}^{\nu} \sim 2\begin{bmatrix} d + s - \bar{u} - \bar{c} \end{bmatrix}$$

$$F_{3}^{\bar{\nu}} \sim 2\begin{bmatrix} u + c - \bar{d} - \bar{s} \end{bmatrix}$$

Differentiate flavors of free-proton PDFs:





"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"

Nuclear PDF

The Players The Ingredients

... selected NLO Nuclear PDF Fits





Towards a Neural Network determination of nuclear PDFs

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	EPS09	DSSZ12	ка15	NCTEQ15	EPPs16	nNNPDF1.0
Order in α_s	LO & NLO	NLO	NNLO	NLO	NLO	NLO
Neutral current DIS $\ell + A/\ell + d$	~	~	~	~	~	\checkmark
Drell-Yan dilepton p+A/p+d	 ✓ 	~	~	~	~	
RHIC pions d+Au/p+p	~	~		\checkmark	~	
Neutrino-nucleus DIS		~			\checkmark	
Drell-Yan dilepton $\pi + A$					\checkmark	
LHC p+Pb jet data					~	
LHC p+Pb W, Z data					~	
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV	1.3 GeV
datapoints	929	1579	1479	708	1811	605
free parameters	15	25	16	17	20	73
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Monte
error tolerance $\Delta \chi^2$	50	30	not given	35	52	Carlo rep
Free proton baseline PDFs	стеоб.1	мятw2008	лю9	стеобм-like	ct14NLO	NNPDF3.1
Heavy-quark effects		~		\checkmark	\checkmark	\checkmark
Flavor separation				some	1	
Reference	[JHEP 0904 065]	[PR D85 074028]	[PR D93, 014026]	[PR D93 085037]	[EPJ C77 163]	Preliminary

Nuclear PDFs: The Ingredients ... ~19 nuclei



9



Isospin Symmetry used to generate nPDFs







Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

A Review of Target Mass Corrections. Ingo Schienbein et al, J.Phys.G35:053101,2008.

Data sets & cuts for nPDF fits



proton vs nuclear: fewer data and more DOF ... impose assumptions on nPDFs

Low Q

Hi-X

Higher Twist, many body problem, duality, hi-x, mass corrections ...



EIC can push these boundaries

HI-X

Higher twist mass effects limit $x \rightarrow 1$

CJ Project

Nuclear PDFs: Hi-x Region

0

0.2

0.4

x

0.6

0.8

CJ-15 arXiv: 1602.03154

Challenges at Hi-x

Partonic structure at high-x

- Partonic structure of nucleons/nuclei at high-x (x>0.5) poorly known:
 - >50% uncertainty on d(x) at x>0.6
 - >50% uncertainty on g(x) at x>0.2
 - very large uncertainties on quark sea
- Better understanding provides tests of models of hadron structure
 - ► $d/u \rightarrow 1/2$: SU(6) Spin-Flavor symmetry
 - ► $d/u \rightarrow 0$: Scalar diquark dominance
 - ► $d/u \rightarrow 1/5$: pQCD power counting
 - Local quark hadron duality:

 ${
m d}/{
m u}
ightarrow rac{4 \mu_{
m n}^2/\mu_{
m p}^2 - 1}{4 - \mu_{
m n}^2/\mu_{
m p}^2} \simeq 0.42$

Better understanding important for BSM searches of new heavy states

Ingo Schienbein 2018 Trento Workshop

CJ15 global fit, PRD93(2016)114017

17

PDF Parameterization

1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

$$f_i^{\mathbf{p}/\mathbf{A}}(x_N, Q_0) = R_i(x_N, Q_0, \mathbf{A}) f_i^{free\ proton}(x_N, Q_0)$$

... for example

HKN

$$R_i(x, Q_0, \mathbf{A}) = 1 + \left(1 - \frac{1}{A^{\alpha}}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1 - x)^{\beta_i}}$$

2) Generalized A-parameterization (nCTEQ)

$$f_{i}^{p/A}(x_{N}, \mu_{0}) = f_{i}(x_{N}, A, \mu_{0})$$

$$f \sim \dots x^{c_{1}(A)}(1 - x)^{c_{2}(A)}\dots$$

$$c_{k} \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$
Proton Nuclear

use proton as a Boundary Condition

Nuclear PDFs: Complementary efforts in general agreement

Nuclear PDFs are more complex more DOF than Proton case more "issues" to consider more work to do ...

20

Nuclear PDFs: nCTEQ A-Dependence

$$xf(x) = x^{a_1}(1-x)^{a_2}e^{a_3x}(1+e^{a_4}x)^{a_5}$$

$$a_i \to a_i(A)$$

$$a_k = a_{k,0} + a_{k,1} (1-A^{-ak,2})$$

$$f_{set by}$$
Nuclear
$$dof$$
Nuclear
$$dof$$
Nuclear
$$dof$$

m /

Generalized PDFs

Nuclear Structure & Generalized PDFs

Nuclear Structure & Generalized PDFs

Eur.Phys.J. A52 (2016) no.6, 149

TMD PDFS and Reorganizing the Perturbation Series

Connecting different TMD factorization formalisms in QCD

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In the original Collins-Soper-Sterman (CSS) presentation of the results of transverse-momentumdependent (TMD) factorization for the Drell-Yan process, results for perturbative coefficients can be obtained from calculations for collinear factorization. Here we show how to use these results, plus known results for the quark form factor, to obtain coefficients for TMD factorization in more recent formulations, e.g., that due to Collins, and apply them to known results at order α_s^2 and α_s^3 . We also show that the "nonperturbative" functions as obtained from fits to data are equal in the two schemes. We compile the higher-order perturbative inputs needed for the updated CSS scheme by appealing to results obtained in a variety of different formalisms. In addition, we derive the connection between both versions of the CSS formalism and several formalisms based in soft-collinear effective theory (SCET). Our work uses some important new results for factorization for the quark form factor, which we derive.

Strange PDF

Case Study: The Strange PDF

Strange PDF: *v* N di-muon Production ... (Fe,Pb)

29

Puzzle: What is the Nuclear Correction

30

Propagation of γ/W thru nuclei

What's the Solution??? ... high energy does not always help

Intrinsic Charm (IC)

Probe IC via charm contributions to DIS σ , F_L^C , or angular distributions

also F_2^{c} for charm PDF...

 $gs \rightarrow cW$ at LHC and s(x)

T. Stavreva, I. Schienbein, F. Arleo, K. Kovarik, F. Olness, J.Y. Yu, J.F. Owens, JHEP 1101 (2011) 152

nCTEQ++ xFitter PDFSense

nCTEQ++

... the motivation for nCTEQ

What is nCTEQ++?

- A complete rewrite of the nCTEQ FORTRAN fitting code in C++
- Changed the code to allow for modules when building a PDF

Evolution

Interpolation

Parameterization

- Use external programs
 - Minuit
 - HOPPET
 - MCFM
 - APPLgrid

Special thanks to: Eric Godat Florian Lyonnet Tomas Jezo Aleksander Kusina

Use MCFM + APPLgrid for pPb

- (1)Data matched to pA-FEWZ in reweighting
- (2)Run FEWZ in symmetric pp mode
- (3)Compare pp FEWZ to pp MCFM
- (4)Generate APPLgrid grids
- Using mcfm-bridge
- Different Monte Carlo seeds
- (5)Combine replica grids into a single PDF independent grid
- Using applgrid-combine
- (6)Convolute PDF independent grid with asymmetric PDFs to compare to pAFEWZ
- (7)Add data and grid in nCTEQ++ to fit W/Z LHC data

Grids generated for pp can be used for pPb !!!

Convoluted grids can then be compared to data and

used in nCTEQ++ as theory predictions

nCTEQ++ ... can now access all MCFM Processes

MCFM Processes Library (v6.8)

MCFM: Vector boson pair production at the LHC, J. M.Campbell, R. K.Ellis and C.Williams, JHEP 1107, 018 (2011)

The APPLGRID Project: Tancredi Carli, Dan Clements, Amanda Cooper-Sarkar, Claire Gwenlan, Gavin P. Salam, Frank Siegert, Pavel Starovoitov, Mark Sutton. Eur.Phys.J. C66 (2010) 503-524

nproc	$f(p_1) + f(p_2) \to .$			Order	$H(\gamma(p_3) + \gamma(p_4)) + f(p_5) + f(p_6) [in heavy top limit]$ $H(b(p_4) + \tilde{b}(p_4)) + f(p_5) + f(p_6) [in heavy top limit]$ $H(\tau^-(p_5) + \tau^+(p_4)) + f(p_5) + f(p_6) [in heavy top limit]$ $H(\tau^-(p_5) + \tau^+(p_4)) + f(p_5) + f(p_6) [in heavy top limit]$	NLO NLO NLO	$ \begin{array}{l} 540 H(b(p_3)+\bar{b}(p_4))+t(p_5)+q(p_6)\\ 541 H(b(p_3)+\bar{b}(p_4))+\bar{t}(p_5)+q(p_6)\\ \end{array} $	NLO NLO
1	$W^+(\rightarrow \nu(p_3) + e^-)$	$(p_4))$		NLO	$ \begin{array}{c} 1 & H(-Y, H'(e^{-}(p_{3}), e^{-}(p_{4}))H'(e^{-}(p_{3}'), e^{+}(p_{6}))) + f(p_{7}) + f(p_{8}) \\ 1 & H(-Z(e^{-}(p_{3}), e^{+}(p_{4}))Z(\mu^{-}(p_{5}), \mu^{+}(p_{6}))) + f(p_{7}) + f(p_{8}) \\ 2 & H(b(p_{3}) + b(p_{4})) + f(p_{5}) + f(p_{6}) + f(p_{7}) [in heavy top limit] \\ 1 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(e^{-}(p_{3}) + e^{+}(p_{3})) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(p_{3}) + f(p_{3}) + f(p_{3}) + f(p_{3}) + f(p_{3}) + f(p_{3}) [in heavy top limit] \\ 2 & H(p_{3}) + f(p_{3}) + f(p$	NLO LO	$\frac{544}{547} \frac{H(b(p_3) + b(p_4)) + t(\nu(p_5) + e^-(p_6) + b(p_7)) + q(p_9)}{H(b(p_3) + \bar{b}(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9)}$ $\frac{550}{550} \frac{H(b(p_3) + c(p_3) + d(p_3)) + d(p_3)}{H(b(p_3) + b(p_3)) + d(p_3) + d(p_3)}$	NLO
6	$W^{-}(\rightarrow e^{-}(p_3) + i$	$\overline{p}(p_A))$		NLO	$\begin{array}{c} 3 & H(\gamma (r_3) + \gamma (r_4)) + f(r_5) + f(r_6) + f(r_7) \text{in newy cop finite} \\ 3 & H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8) + f(p_8) \\ 0 & H(\rightarrow Z(e^-(p_4), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8) + f(p_8) \\ \end{array}$	LO LO	550 $H(\gamma(p_3) + \gamma(p_4)) + t(y_5) + q(p_6)$ 551 $H(\gamma(p_3) + \gamma(p_4)) + \tilde{t}(p_5) + q(p_6)$ 554 $H(\gamma(p_3) + \gamma(p_4)) + t(y(p_3) + q^+(p_3) + b(p_3)) + q(p_3)$	NLO
11	\mathbf{W}^+	(f + f(r - r)) + f(r - r)		NIO	$\begin{array}{c} \begin{array}{c} & \gamma(p_3) + f(p_4) \rightarrow \gamma(p_3) \\ \hline \\ & f(p_1) + f(p_2) \rightarrow \gamma(p_3) + f(p_4) + f(p_5) \\ & f(p_1) + f(p_3) \rightarrow \gamma(p_4) + b(p_4) \end{array}$	LO	$ 557 H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(e^-(p_5) + \bar{e}^-(p_6) + b(p_7)) + q(p_9) $ $ 557 H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9) $	NLO
	$W' (\rightarrow \nu(p_3) + e)$	$(p_4)) + J(p_5)$		NLO	$\begin{array}{c} f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) \\ 1 + f(p_1) + f(p_2) \rightarrow \gamma(p_3) + c(p_4) \\ 1 + f(p_1) + f(p_2) \rightarrow \gamma(p_1) + \gamma(p_4) \end{array}$	LO NLO+F	$\begin{vmatrix} 560 \\ 561 \\ Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6) \\ 561 \\ Z(e - (p_3) + e + (p_1)) + \bar{t}(p_5) + q(p_6) \end{vmatrix}$	NLO
12	$W^+(\rightarrow \nu(n_2) + e^-)$	$(n_{4}) + \overline{b}(n_{5})$		NLO	$\begin{array}{c} i \\ f(p_1) + f(p_2) \to \gamma(p_3) + \gamma(p_4) + f(p_5) \\ f(p_1) + f(p_2) \to \gamma(p_3) + \gamma(p_4) + \gamma(p_5) \end{array}$	NLO+F NLO+F	$562 Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6) + f(p_7)$ $562 Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6) + f(p_7)$	LO
12	$(- \nu (p_3) + c)$	$(P_4)) + o(P_5)$		NIC) $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5)$ 2 $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6)$	NLO+F LO	$\begin{array}{c c} 563 & Z(e - (p_3) + e + (p_4)) + \tilde{t}(p_5) + q(p_6) + f(p_7) \\ 564 & Z(e - (p_1) + e + (p_1)) + t(\rightarrow y(p_1) + e^+(p_1) + h(p_1)) + q(p_1) \end{array}$	LO
13	$W^+(\rightarrow \nu(p_3) + e^-)$	$(p_4)) + \bar{c}(p_5)$		NLO	5 $W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5)$ 7 $W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + f(p_6)$	NLO+F LO	$\begin{array}{c} 5051 \\ 566 \\ Z(e - (p_3) + e + (p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q_4p_8) \\ 566 \\ Z(e - (p_3) + e + (p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8) + f(p_9) \end{array}$	LO
14	$14 \qquad W^+(\rightarrow u(n) + c^+(n)) + \bar{c}(n) [mag] aga$			IO) $Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5})$ $Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + \gamma(p_{6})$	NLO+F NLO+F	567 $Z(e - (p_3) + e + (p_4)) + \bar{t}(\rightarrow e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8)$ 560 $Z(e^-(p_3) + e^-(p_3)) + \bar{t}(-e^-(p_3) + \bar{t}(p_3)) + q(p_8)$	NLO
14	14 $VV^{*}(\rightarrow \nu(p_{3}) + e^{*}(p_{4})) + c(p_{5})[\text{massless}]$				2 $Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6)$ 3 $Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6) + f(p_7)$	NLO + F LO	$\frac{505}{601} \frac{2(e - (p_3) + e + (p_4)) + e(-e - (p_5) + \nu(p_6) + o(p_7)) + q(p_8) + f(p_9)}{601} = \frac{601}{H(b(p_3) + b(p_4)) + H(\tau^-(p_5) + \tau^+(p_6))}$	LO
$16 \qquad W^{-}(\to e^{-}(p_{3}) + \bar{\nu}(p_{4})) + f(p_{5})$			NLO	1 $Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6) + f(p_7)$ 5 $Z^0(\rightarrow 3(\nu(p_3) + \overline{\nu}(p_4))) + \gamma(p_5)$	LO NLO + F	$\begin{array}{c c} 602 & H(b(p_3) + \bar{b}(p_4)) + H(\gamma(p_5) + \gamma(p_5)) \\ 640 & H(p_1) + \bar{J}(p_2) + H(p_3) \end{array}$	LO	
17	$ \begin{array}{c} \\ \\ \\ \\ \\ \\ \\$			NIO	$\begin{array}{c} i \\ Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6}) \\ \bar{i} \\ Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + f(p_{6}) \end{array}$	NLO + F NLO + F	$\begin{bmatrix} 040 & t(p_3) + t(p_4) + H(p_5) \\ 641 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) \\ \end{bmatrix}$	$\hat{b}(p_{10}))$ LO
11	$11 \qquad W (\rightarrow e (p_3) + \nu(p_4)) + b(p_5)$			NLO	$\begin{array}{c} S \\ Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6}) + f(p_{7}) \\ D \\ Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + f(p_{6}) + f(p_{7}) \\ D \\ $	LO LO	$644 t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(b(p_9) + H(b(p_9) + \bar{b}(p_6)) + H(b(p_9) + H(b(p_9) + \bar{b}(p_6)) + H(b(p_6) + H(b(p_6) + H(b(p_6))) + H(b(p_6) + H(b(p_6) + H(b(p_6))) + H(b(p_6) + H(b(p_6) + H(b(p_6))) + H(b(p_6) + H(b(p_6) + H(b(p_6) + H(b(p_6))) + H(b(p_6) + H(b(p_6)$	p ₁₀)) LO
18	$W^{-}(\rightarrow e^{-}(n_2) + i$	$\overline{\nu}(n_A)) + c(n_E)$		NLO	$\begin{array}{c} 1 f(p_1) + b(p_2) \to W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6) \\ \vdots f(p_1) + b(p_2) \to W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6) \\ \end{array}$	LO LO	$\begin{array}{c} 647 & t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + t(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + b(p_6)) + H(b(p_9) + b(p_6)) \\ 651 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_6) + b(p_6)) \\ \end{array}$	$p_{10}))$ LO $\gamma(p_{10}))$ LO
10	(1) (1)	$(P_4)) + O(P_5)$			$\begin{array}{c} f(p_1) + c(p_2) \to W^+(\to \nu(p_3) + e^+(p_4)) + c(p_8) + f(p_6) \\ \vdots & f(p_1) + c(p_2) \to W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_8) + f(p_6) \\ \end{array}$	LO	$654 t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_9) + q(p_8) + \bar{b}(p_8)) + H(\gamma(p_9) + q(p_8) + q(p_8) + \bar{b}(p_8)) + H(\gamma(p_9) + q(p_8) + q(p_8) + \bar{b}(p_8)) + H(\gamma(p_9) + q(p_8) + \bar{b}(p_8)) + H(\gamma(p_8) + $	(p ₁₀)) LO
19	$W^-(\rightarrow e^-(p_3) + i$	$\overline{\nu}(p_4)) + c(p_5)$ massless		LO	$W^{-}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + c(p_{5}) + f(p_{6})[c-s \text{ interaction}]$ $W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + c(p_{5}) + f(p_{6})[c-s \text{ interaction}]$	LO	$\begin{array}{c} 657 & t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + t(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + b(p_6)) + H(\gamma(p_9) + \gamma(p_6)) \\ 661 & t(\rightarrow \nu(p_2)e^+(p_1)b(p_2)) + \bar{t}(\rightarrow \bar{\nu}(p_2)e^-(p_8)\bar{h}(p_6)) + H(W^+(p_8, p_9)W^-(p_9)) \\ \end{array}$	(<i>p</i> ₁₀)) LO
12 $W^+(\rightarrow \nu(p_3) - W^+(\rightarrow \nu(p_3)))$ 13 $W^+(\rightarrow \nu(p_3) - W^+(\rightarrow \nu(p_3)))$	$e^{+}(p_4)) + b(p_5)$ $e^{+}(p_4)) + \bar{e}(p_2)$ NLO NLO	$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	zz mt.] LO g→ZZ intf.] LO	$\begin{array}{c} 1 \\ 342 \\ f(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+f(p_7)] \\ 342 \\ f(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_5) + e^+(p_5)) + b(p_5) + f(p_6)[+\bar{b}(p_7)] \\ g(p_1) + b(p_2) - Z^0(\rightarrow e^-(p_5) + e^+(p_5)) + b(p_5) +$	(REAL)	$ \begin{array}{c} 664 \\ 664 \\ t(\rightarrow \nu p_3)e^+(p_4)b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7)q(p_8)\bar{b}(p_6)) + H(W^+(p_9,p_{10})W^-(p_{11},p_{12})) \\ \end{array} $	p ₁₂)) LO
14 $W^+(\rightarrow \nu(p_3))$ 16 $W^-(\rightarrow e^-(p_2))$	$-e^{+(p_4)} + \bar{c}(p_5)$ [massless] LO $+\bar{\nu}(p_4) + \bar{f}(p_5)$ [massless] NLO	$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$\begin{array}{c c} O \\ 131 & Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6)) \ [\text{gg only}, (\text{H} + \text{gg} - \\ 132 & Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6)) \ [\text{gg} \rightarrow \text{ZZ}) \ \text{squared} \end{array}$	ZZ) squared] LO LO	$ \begin{array}{l} 340 \\ 347 \\ \hline f(p_1) + b(p_2) \rightarrow Z^{\circ}(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) + f(p_7) \\ 347 \\ \hline f(p_1) + b(p_2) \rightarrow Z^{0}(\rightarrow e^-(p_3) \$4e^+(p_4)) + b(p_5) + f(p_6) + \bar{b}(p_7) \\ \end{array} $	LO	$667 t(\rightarrow q(p_3)\bar{q}(p_4)b(p_5)) + \bar{t} \rightarrow (\bar{\nu}(p_7)e^-(p_8)\bar{b}(p_5)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{$	p ₁₂)) LO
17 $W^-(\rightarrow e^-(p_3))$ 18 $W^-(\rightarrow e^-(p_3))$	$+ \bar{v}(p_4) + f(p_5)$ $+ \bar{v}(p_4) + b(p_5)$ NLO NLO	$\begin{array}{c} 111 & H(\rightarrow b(p_3) + b(p_4)) \\ 112 & H(\rightarrow \tau^-(p_3) + \tau^+(p_4)) \end{array} \\ \end{array} \qquad \qquad$	O 1281 $H(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})\nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{6})$ [top, bottom loops, exact] 1311 $e^{-}(p_{3}) + e^{+}(p_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{6})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1321 $e^{-}(n_{3}) + e^{+}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1422 $e^{-}(n_{3}) + e^{-}(n_{4}) + \nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{5}) + \bar{\nu}_{e}(p_{5})$ [gg only, (H + gg \rightarrow ZZ) squar 1422 $e^{-}(n_{5}) + e^{-}(n_{5}) + \bar{\nu}_{e}(p_{5}) + \bar{\nu}_$	ed] LO LO LO	$351 f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_3) + f(p_6)[+f(p_7)]$	NLO	800 $V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Vector Mediator]	NLO
$10 W^-(\to e^-(p_3))$ $19 W^-(\to e^-(p_3))$ $20 W^+(\to w(p_3))$	$+ \bar{\nu}(p_4)) + c(p_5)$ [massless] LO $-c^{+}(p_4)) + c(p_5)$ [massless] NIO	113 $H \rightarrow W^{+}(\nu(p_{3}) + e^{+}(p_{4})) + W^{-}(e^{-}(p_{5}) + \bar{\nu}(p_{6})))$ 114 $H \rightarrow W^{+}(\nu(p_{3}) + e^{+}(p_{4})) + W^{-}(q(p_{5}) + \bar{q}(p_{6})))$ NI NI	$\begin{array}{c c c c c c c c c c c c c c c c c c c $		$\begin{array}{l} 352 & f(p_1) + c(p_2) \rightarrow Z^*(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f^-(p_6)[+c(p_7)] \\ 356 & f^-(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f^-(p_6) + f^-(p_7) \end{array}$	LO	801 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Axial Vector Mediator] 802 $S \rightarrow (\chi(p_3) + \bar{\chi}(p_3)) + f(p_5)$ [Scalar Madiator]	NLO
20 $W^+(\rightarrow \nu(p_3))$ $W^+(\rightarrow \nu(p_3))$	$e^{-(p_4))} + b(p_5) + b(p_6)$ [massive] NLO $e^{+(p_4))} + b(p_5) + \bar{b}(p_6)$ NLO	115 $H (\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(q(p_5) + \bar{q}(p_6)))[rad in.dk]$ N1 116 $H (\rightarrow Z^0(e^-(p_3) + e^+(p_4)) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ N1	$\begin{array}{c} 0 \\ 0 \\ 1322 \\ e^{-}(p3) + e^{+}(p4) + \nu(p5) + \bar{\nu}(p6) \\ 133 \\ H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6) + f(p7)) \\ \end{array}$	LO LO LO	$\frac{357}{361} \frac{f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + \bar{c}(p_7)}{(c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) mc=0 \text{ in NLO}}$	LO	803 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator] 803 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Pseudo Scalar Mediator]	NLO
22 $W^+(\rightarrow \nu(p_3) -$ 23 $W^+(\rightarrow \nu(p_3) -$	$-e^{+}(p_4)) + f(p_5) + f(p_6)$ NLO $-e^{+}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ LO	$\begin{array}{ccc} 117 & H (\rightarrow Z^0(3 \times (\nu(p_3) + \bar{\nu}(p_4))) + Z^0(\mu^-(p_5) + \mu^+(p_6)) \\ 118 & H (\rightarrow Z^0(\mu^-(p_3) + \mu^+(p_4)) + Z^0(b(p_5) + \bar{b}(p_6)) \end{array} \\ \end{array} \qquad \qquad$	$\begin{array}{c} O \\ O \\ I \\$	NLO (REAL)	362 $c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))$ [massless corrections only] 362 $(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))$ [massless corrections only]	NLO	804 $GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Gluonic DM operator] 805 $S = (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator and logical	NLO
24 $W^+(\rightarrow \nu(p_3) - \psi(p_3) - \psi$	$-e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$ LO + $\bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ [massive] NLO	$\begin{array}{c} 119 & H(\rightarrow \gamma(p_3) + \gamma(p_4)) \\ 120 & H(\rightarrow Z^0(\mu^-(p_3) + \mu^+(p_4)) + \gamma(p_5)) \end{array} \\ \end{array} $ NI	O $I_{138} H(\rightarrow b(p_3) + \overline{b}(p_4)) + b(p_5) + \overline{b}(p_6)[both observed]$ O	(REAL)	$\frac{303}{370} = \frac{c(p_1) + s(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))[\text{massive charm in real}]}{W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6)}$	LO	$\frac{805}{820} \left[S(\chi(p_3) + \chi(p_4)) + f(p_5) \right] \left[\text{Scalar Mediator, int loops} \right]$ $\frac{820}{820} \left[V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) \right] \left[\text{Vector Mediator} \right]$	NLO + F
26 $W^-(\rightarrow e^-(p_3))$ 27 $W^-(\rightarrow e^-(p_5))$	$+ \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ NLO $+ \bar{\nu}(p_4)) + f(p_5) + f(p_6)$ NLO	121 $H(\rightarrow Z^0(3 \times (\nu(p_3) + \bar{\nu}(p_4)))) + \gamma(p_5))$ NI	$ \underbrace{0}_{141} \begin{array}{c} 141 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \overline{t}(\rightarrow b \ (p_6) + e^-(p_7) + \overline{\nu}(p_8)) \\ 142 & t(\rightarrow \nu(p_3) + e^+(p_3) + b(p_5)) + \overline{t}(\rightarrow b \ (p_6) + e^-(p_7) + \overline{\nu}(p_8)) \end{array} $	rad in dkl NLO	$371 W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + \gamma(p_6)$ $401 W^+(\rightarrow \nu(p_5) + e^+(p_5)) + b(p_5) + 12 \text{ or } 3 \text{ integ} \text{ 4FNS}$	LO	821 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Axial Vector Mediator]	NLO + F
28 $W^-(\rightarrow e^-(p_3))$ 28 $W^-(\rightarrow e^-(p_3))$	$+ \bar{\nu}(p_4)) + f(p_5) + f(p_6)$ $+ \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ LO	$\frac{56}{c1} \frac{Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + \bar{c}(p_6)}{W^+(-v_1(p_2) + v_2(p_3)) + W^-(-v_2(p_3)) + \bar{c}(p_3)}$ NIL	$\begin{array}{c} 142 & (-v(p_3) + v(p_3) + v(p_3) + v(-v(p_3)) + v(-v(p_3) + v(p_3)) + v(-v(p_3) + v(p_3)) + v(-v(p_3) + v(p_3) + v(p_3) + v(-v(p_3) + v(p_3)) + v(-v(p_3) + v(-v(p_3) + v(p_3) + v(-v(p_3) + v(p_3)) + v(-v(p_3) + v(-v(p_3) + v(p_3) + v(-v(p_3) + v(p_3) + v(-v(p_3) + v(-v(p_3) + v(p_3) + v(-v(p_3) + v(-v(p_3) + v(p_3) + v(-v(p_3) + v(-v(p_$	$-f(p_9)$ LO NLO	401 W $(\rightarrow \nu(p_3) + e^-(p_4)) + (\nu_1p_5)$ [1,2 of 5 Jets, 4FA5] 402 W $^+(\rightarrow \nu(p_3) + e^+(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS]	NLO	822 $S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Scalar Mediator] 823 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Beaudo Scalar Mediator]	NLO + F
$29 W^-(\rightarrow e^-(p_3))$ $31 Z^0(\rightarrow e^-(p_3))$	$+ \bar{\nu}(p_4)) + b(p_5) + b(p_6) + f(p_7)$ LO $- e^+(p_4))$ NLO	$\begin{array}{cccc} 61 & W & (\rightarrow \nu(p_3) + e^+(p_4)) + W & (\rightarrow e^-(p_5) + \nu(p_6)) \\ 62 & W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow q(p_5) + \bar{q}(p_6)) \\ & & \text{NL} \end{array}$	$ \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ \end{array} \begin{array}{c} 144 \\ 145 \\ 1(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + i(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) \\ 145 \\ 1(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + i(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) \\ \end{array} $	rad.in.dk],uncorr NLO	403 $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + b(p_6)$ [2 or 3 jets, 4FNS] 406 $W^-(\rightarrow e^-(p_5) + \bar{\mu}(p_5)) + b(p_5)$ [1 2 or 3 jets, 4FNS]	NLO	(25) $1.5 \rightarrow (\chi(p_3) + \chi(p_4)) + \gamma(p_5)(1$ sector Schall Methator 840 $V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Vector Mediator]	LO
32 $Z^0(\rightarrow 3 \times (\nu(j)))$ 22 $Z^0(\rightarrow k(m))$	$b_3 + \bar{\nu}(p_4)))$ NLO	$\begin{bmatrix} 63 \\ W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow q(p_5) + \bar{q}(p_6)) [rad.in.dk] \\ 64 \\ W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4))W^+(\rightarrow q(p_5) + \bar{q}(p_6)) \end{bmatrix}$ NL($\begin{array}{c} 140 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + t(\rightarrow b^-(p_6) + q(p_7) + q(p_8)) \\ 147 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b^-(p_6) + q(p_7) + \bar{q}(p_8)) \end{array}$ (rate	d.in.top.dk] NLO	407 $W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS]	NLO	841 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Axial Vector Mediator]	LO
$Z^{0}(\rightarrow 0(p_{3}) + Z^{0}(\rightarrow 3 \times (d)))$	$(p_4)) = (p_6)))$ NLO NLO	$\begin{array}{cccc} 65 & W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}))W^{+}(\rightarrow q(p_{3}) + \bar{q}(p_{6}))[\text{rad.in.dk}] \\ 66 & W^{+}(\rightarrow u(p_{3}) + e^{-}(p_{3})) + W^{-}(\rightarrow e^{-}(p_{3})) + \bar{\nu}(p_{3})) + f(p_{3}) \end{array}$	$D = \begin{bmatrix} 148 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + q(p_7) + \bar{q}(p_8)) \\ 149 & t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \end{bmatrix}$ (ratio	d.in.W.dk] NLO NLO	408 $W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + b(p_6)$ [2 or 3 jets, 4FNS] 411 $f(p_6) + b(p_6) \rightarrow W^+(\rightarrow \nu(p_6) + e^+(p_6)) + b(p_6) + f(p_6)$ [5FNS]	NLO	842 $S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Scalar Mediator] 843 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Decado Scalar Mediator]	LO
35 $Z^0(\rightarrow 2 \times (u))$ 36 $Z \rightarrow t(\rightarrow \nu)p_3$	$b_5 + \bar{u}(p_6)))$ $) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{b}(p_6) + e^-(p_7) + \bar{\nu}(p_8)))$ IO LO	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\frac{150}{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{t}(p_4) + b(p_5) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{t}(p_4) + b(p_5) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \ [rate{151} t(\rightarrow q(p_3) + \bar{t}(p_4) + \bar{t}(p_4$	d.in.top.dk] NLO d.in.W.dk] NLO	416 $f(p_1) + b(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6)$ [5FNS]	NLO	844 $[GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)]$ [I scato Scalar Archaeol] 844 [$GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Gluonic DM operator]	LO
41 $Z^0(\rightarrow e^-(p_3) \rightarrow Z^-(p_3) \rightarrow $	$-e^+(p_4)) + f(p_5)$ NLO NLO	$ \begin{array}{l} 71 & W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_5) + e^+(p_6)) \\ 72 & W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow 3 \times (\nu_e(p_5) + \bar{\nu}_e(p_6))) \end{array} \right. \qquad NLi $	D 157 tt[for total Xsect] 158 bb[for total Xsect]	NLO	421 $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS] 426 $W^-(\rightarrow e^-(p_2) + \bar{\nu}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS]	NLO	845 $V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Vector Mediator]	LO
43 $Z^0(\rightarrow b(p_3) +$	$b(p_4)) + f(p_5)$ NLO	$\begin{bmatrix} 73 \\ 74 \end{bmatrix} W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow b(p_5) + \bar{b}(p_6)) \\ W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow 3 \times (d(p_2) + \bar{d}(p_2))) \\ NL(0, 0) = 0 \\ NL(0, 0) = $	D 159 $c\bar{c}$ [for total Xsect] 160 $t\bar{b}$ + s[for total Xsect]	NLO	431 $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + b(p_6) + f(p_7)$ [massive]	LO	846 $ A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Axial Vector Mediator] 847 $ S \rightarrow (\chi(p_1) + \bar{\chi}(p_2)) + \gamma(p_5) + f(p_5)$ [Scalar Mediator]	LO
44 $Z^0(\rightarrow e^-(p_3) - Z^0(\rightarrow e^-(p_3) - Z^0(\rightarrow e^-(p_3) - Z^0(\rightarrow e^-(p_3) - Z^0(\rightarrow e^-(p_3) - Z^0)))$	$-e^+(p_4)) + f(p_5) + f(p_6)$ NLO $-e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$ LO	75 $W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$ NL 76 $W^-(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow \nu(p_5) + \bar{u}(p_6)))$ NL	$\frac{160}{161} \frac{[t + q[at \text{ total } Acce]]}{t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)[t-\text{channel}]}$	NLO	$\begin{array}{c} 436 & W & (\rightarrow e \ (p_3) + \nu(p_4)) + b(p_5) + b(p_6) + f(p_7) \ [massive] \\ \hline 500 & W^+(\rightarrow \nu(p_3) + e^+(p_4)) + t(p_5) + \bar{t}(p_6) \ [massive] \end{array}$	NLO	848 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Pseudo Scalar Mediator]	LO
46 $Z^0(\rightarrow 3 \times (\nu))$ 47 $Z^0(\rightarrow 3 \times (\nu))$	$p_3 + \bar{\nu}(p_4) + f(p_5) + f(p_6)$ NLO $p_4 + \bar{\nu}(p_4) + f(p_5) + f(p_6) + f(p_7)$ LO	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} D \\ D \\ \end{array} \begin{bmatrix} 102 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)[\text{decay}] \\ 163 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)[\text{t-channel}]mb > 0 \\ \end{array}$	NLO	501 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_7)) + W^+(\nu(p_7), \mu^+(p_7)) + W^+(\mu(p_7), \mu^+(p_7)) + W^+(\mu(p_7)) $	(h10)) NLO	902 Check of Volume of 2 particle phase space	
50 $Z^0(\rightarrow e^-(p_3) \rightarrow $	$-e^+(p_4)) + b(p_5) + b(p_6)$ [massive] LO	$\begin{bmatrix} 78 \\ W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + Z^0(\to b(p_5) + b(p_6)) \\ W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + Z^0(\to 3 \times (d(p_5) + \bar{d}(p_6))) \\ NL \end{bmatrix}$	$\begin{array}{c} 166 & t(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}) + b(p_{5})) + q(p_{6})[t-channel] \\ 167 & \bar{t}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}) + \bar{b}(p_{5})) + q(p_{6})[rad.in.dk] \end{array}$	NLO NLO	502 (same as process 501 but with radiation in decay) 503 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + q(p_7) + q (p_8)) + W^+(\nu(p_9), \mu^+(p_1))$	(0)) NLO	903 Check of Volume of 3 particle phase space 904 Check of Volume of 4 particle phase space	
51 $Z^{\circ}(\rightarrow e^{-}(p_3) \rightarrow Z_0(\rightarrow 3 \times (\nu p_3)))$	$-e^{+}(p_4)) + b(p_5) + b(p_6)$ NLO $b_3) + \bar{\nu}(p_4))) + b(p_5) + \bar{b}(p_6)$ NLO	80 $W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + Z^{0}(\rightarrow 2 \times (u(p_{5}) + \bar{u}(p_{6})))$ NL 81 $Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{3})) + Z^{0}(\rightarrow u^{-}(p_{3}) + u^{+}(p_{6}))$	$\frac{168}{171} \frac{\bar{t}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4) + b(p_5)) + q(p_6)[t-channel]mb > 0}{171} \frac{1}{t(\rightarrow \nu(p_3) + e^{+}(p_4) + b(p_5)) + b(p_6))[s-channel]}$	NLO	506 $t(\rightarrow q(p_3) + q(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_1)) + \bar{t}(\rightarrow b(p_6) + \bar{t}(p_1)) + \bar{t}(\rightarrow b(p_6) + \bar{t}(p_1)) + \bar{t}(p_1) + \bar{t}(p_2) $	(0)) NLO	905 Check of Volume of 5 particle phase space	
53 $Z^0(\rightarrow b(p_3) +$ 54 $Z^0(\rightarrow e^-(p_3))$	$\bar{b}(p_4)) + \bar{b}(p_5) + \bar{b}(p_6)$ NLO = $e^+(p_4)) + \bar{b}(p_5) + \bar{f}(p_7) + f(p_7)$ LO	$\begin{array}{cccc} 81 & Z & (\rightarrow e^{-}(p_{3}) + e^{-}(p_{4})) + Z & (\rightarrow \mu^{-}(p_{5}) + \mu^{-}(p_{6})) \\ 82 & Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6}))) \\ & \text{NL} \end{array}$	$\begin{bmatrix} 172 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6)) \\ 176 & \bar{t}(\rightarrow e^-(p_2) + \bar{\nu}(p_3) + \bar{b}(p_5)) + b(p_6)) \\ [schannel] \end{bmatrix}$	NLO	510 $W \rightarrow e^{-}(p_3) + \nu(p_4) + \bar{t}(p_5) + \bar{t}(p_6)[massave]$ 511 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_8))$	(NLO (NLO	906 Check of Volume of 6 particle phase space	
04 D (· C (03)	70 (p4)) + 0(p3) + 0(p6) + 7(p7)	$\begin{array}{c} 83 \\ 84 \\ Z^0(\rightarrow b(p_3) + \bar{e}^+(p_4)) + Z^0(\rightarrow b(p_5) + b(p_6)) \\ 84 \\ Z^0(\rightarrow b(p_3) + \bar{b}(p_4)) + Z^0(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6))) \end{array}$	$\begin{array}{c} 0 \\ 177 \\ \hline t(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}) + \bar{b}(p_{5})) + b(p_{6}))[\text{rad.in.dk}] \\ \end{array}$	NLO	512 (same as process 511 but with radiation in decay) 513 $4(-w(n)) + e^{\frac{1}{2}(n)} + b(n)) + b(-b(n)) + a(n)) + w^{-}(w^{-}(n)) = w^{-}(n)$	NLO NLO	908 Check of volume of 8 particle phase space 909 Check of Volume of 4 particle massive phase space	
		$\frac{85}{86} \frac{Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + Z^0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_6))) + f(p_7)}{86} \frac{L0}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \nu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{L0}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{L0}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{L0}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{L0}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + e^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + \mu^+(p_4))}{86} \frac{Z^0(\rightarrow \nu^-(p_4) + e^+(p_4))}{86} Z^0(\rightarrow \nu$	$\frac{130}{181} \frac{W}{W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \iota(p_5)}{181} \frac{W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \iota(\nu(p_5) + e^+(p_6) + b(p_7))}{W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \iota(\nu(p_5) + e^+(p_6) + b(p_7))}$	NLO	$\begin{array}{c} 515 \\ 516 \\ t(\rightarrow q(p_3) + q(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + \bar{q}(p_8)) + W & (\mu^-(p_9), \nu(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{t}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{t}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{t}(p_8)) + W^-(\mu^-(p_9), \bar{t}(p_1) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{t}(p_8)) + W^-(\mu^-(p_9), \bar{t}(p_1) + \bar{t}(p_1) + \bar{t}(p_1) + \bar{t}(p_2) + \bar$	(0)) NLO	910 Check of Volume of 3 particle (2 massive) phase space	
		87 $Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu/p_{3}) + \bar{\nu}(p_{6})))$ [no gamma*] NL($\begin{bmatrix} 182 \\ 183 \\ W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) \text{[ratin,dk]} \\ W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + b(p_8) \end{bmatrix}$	LO	$\begin{vmatrix} 529 \\ 530 \\ t(\rightarrow \nu(p_t) + e^+(p_t)) + t(p_5) + \bar{t}(p_6) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) + Z(e^-(p_0), e^+(p_0)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) + Z(e^-(p_0), e^+(p_0)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow \nu(p_t) + e^+(p_t) + b(p_t)) + \bar{t}(\rightarrow e^-(p_t) + \bar{\nu}(p_t) + b(p_t)) \\ t(\rightarrow e^-(p_t) + b(p_t) + b(p_$		911 Check of Volume of 5 particle W+t (with decay) massive phase space 012 Check of Volume of 5 particle W+t (so decay) massive phase space	
		$\begin{bmatrix} \infty & Z & (\rightarrow e & (p_3) + e^* (p_4)) + Z & (\rightarrow b(p_5) + b(p_6)) [\text{ino gamma}^*] \\ 89 & Z^0 (\rightarrow b(p_3) + \bar{b}(p_4)) + Z^0 (\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6))) [\text{ino gamma}^*] \\ NLe$	$\begin{array}{c} D \\ D \\ D \\ \end{array} \begin{bmatrix} 184 & W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + t(p_{5}) + b(p_{6}) \\ 185 & W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + \bar{t}(p_{5}) \\ \end{array}$	LO NLO	$531 t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{t}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + \bar{t}(\rightarrow e^-(p_7) + \bar{t}(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + Z(b(p_8) + b(p_8)) + Z(b(p_9), b(p_{10})) + Z(b(p_8) + b(p_8)) + Z(b(p_8) + b(p_8) + D(p_8)) + Z(b(p_8) + D(p_8)) + Z(b(p_8) + b(p_8) +$	LO	912 Uneck of Volume of 5 particle W+t (no decay) massive phase space 913 Check of Volume of 5 particle W+t+g (in decay) massive phase space	
		$\frac{90}{91} \frac{Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow e^{-}(p_{5}) + e^{+}(p_{6}))}{W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + H(\rightarrow b(p_{5}) + b(p_{6}))} NL$	$\frac{\partial}{\partial 1} = \begin{bmatrix} 186 \\ W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7) \\ 187 \\ W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7) \\ rad.in.dk \end{bmatrix}$	NLO NLO	$\begin{vmatrix} 532 \\ 533 \\ t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + t(\rightarrow q(p_7) + \bar{q}(p_8) + b(p_6)) + Z(e^-(p_8), e^+(p_{16}) \\ 533 \\ t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_6) + b(p_6)) + Z(e^-(p_8), e^+(p_{16}) \\ - E(p_7) + E(p_7) \\ - E(p_7) + E(p_7) \\ - E(p_7) + E(p_7) \\ - E(p_7) + E($) LO LO	914 Check of Volume of 5 particle W+t+g (in production) massive phase spa	ice
		$\begin{array}{ c c c c c c c c c c c c c c c c c c c$			f − − 1 − f = man + anal + -nami + − f = fk() + afbal + afbal) + afc (hal)ip (h(0)	/ L = #		
		$\begin{array}{c} 94 \\ 94 \\ W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + H(\rightarrow \nu(p_{5}) + \nu(p_{6})) + 2 (\mu^{+}(p_{7}), \mu(p_{8}))) \\ NL \\$						
		$ \begin{array}{ c c c c c } & y_0 & w & (\to e^-(p_3) + \nu(p_4)) + H (\to b(p_5) + b(p_6)) \\ & y_7 & W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + H (\to W^+(\nu(p_5), e^+(p_6)) W^-(e^-(p_7), \bar{\nu}(p_8))) \\ & & \text{NL} \end{array} $						
		$ \begin{array}{ c c c c c } & & & W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + H(\to Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu^+(p_8))) \\ & & & & \\ & & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & & \\ & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\$	2					

nCTEQ++ ... can now access all MCFM Processes

MCFM Processes Library (v6.8)

MCFM: Vector boson pair production at the LHC, J. M.Campbell, R. K.Ellis and C.Williams, JHEP 1107, 018 (2011).

The APPLGRID Project: Tancredi Carli, Dan Clements, Amanda Cooper-Sarkar, Claire Gwenlan, Gavin P. Salam, Frank Siegert, Pavel Starovoitov, Mark Sutton. Eur.Phys.J. C66 (2010) 503-524

xFitter

xFitter release xfitter-2.0.0

xFitter/xFitterTalks » xFitter/../xFitterDevel.. » xFitter/../Meeting2017-.. » xFitter » xFitter/DownloadPage

Sample data files: LHC: ATLAS, CMS, LHCb Tevatron: CDF, D0 HERA: H1, ZEUS, Combined Fixed Target: ... User Supplied: ...

Features & Recent Updates:

xFitter

Photon PDF & QED Pole & MS-bar masses Profiling and Re-Weighting Heavy Quark Variable Treshold Improvements in χ^2 and correlations TMD PDFs (uPDFs) ... and many other

xFitter 2.0.0 FrozenFrog

Versatility of xFitter

New Tools

PDFSense & & ... borrowing from AI

See Talk By: Tim Hobbs (SMU) A new measure:

Sensitivity S_f

Extend concept of correlation (C) to include both pull and precision of experiment.

(Technically, weight by scaled residual.)

New insights on experimental impacts

Linked from: https://metapdf.hepforge.org/

Artificial Intelligence Tools: Projector tool of Google TensorFlow

Dynamical projections for the visualization of PDFSense data Dianne Cook, Ursula Laa, German Valencia arXiv:1806.09742

Conclusion

Thanks to my nCTEQ & xFitter colleagues

nuclear parton distribution functions

xFitter Meeting: Krakow March 2018

"EIC would unlock scientific mysteries" NAP Report

What is s(x) ... I want a second opinion, ...

... yes, details depend on $\{x, Q^2\}$

53

Reweighting: Add $p Pb \rightarrow W/Z$

Fit to LHC W/Z Data w/ Normalization

High Energy Insight: *W*/*Z Production at LHC and the strange PDF* ⁵⁶

2018 CTEQ School Tutorial

ATLAS: Eur. Phys. J. C 77 (2017) 367

Add LHC Heavy Ion:

A. Kusina, et al., Eur. Phys. J. C77 (2017) no.7, 488

Photon

PDFs

Photon PDF using xFitter

Determination of the photon PDF from fits to recent ATLAS measurements of high-mass Drell-Yan dilepton production at $\sqrt{s=8}$ TeV

Fit photon PDF at Q₀
$$x\gamma(x) = A_{\gamma} x^{B_{\gamma}} (1-x)^{C_{\gamma}} (1+D_{\gamma} x+E_{\gamma} x^2)$$

L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, Eur. Phys. J. C76 (2016)

Let's include LHC data into the fit directly

pPb Data for nCTEQ+LHC

No LHC data in any previous nCTEQ fit

• New gridded theory predictions make this possible

ATLAS:

- $d\sigma(W^- \to \ell^- \nu)/dy$
 - ID: 6211 Npts: 10
- $d\sigma(Z \to \ell^+ \ell^-)/dy$
 - ID: 6215 Npts: 14

CMS:

- $d\sigma(W^- \to \ell^- \nu)/dy$
 - ID: 6231 Npts: 10
- $d\sigma(W^+ \to \ell^+ \nu)/dy$

ID: 6233 Npts: 10

Fit to LHC W/Z Data w/ Normalization

Fit to LHC W/Z Data w/ Normalization

... the motivation for nCTEQ

64

The ratio of iron (Fe) to Deuterium (D)

Discovered by the French in 1799 at Rosetta, a harbor on the Mediterranean coast in Egypt. Comparative translation of the stone assisted in understanding many previously undecipherable examples of hieroglyphics. Ideally suited to " ... glean the fundamental insights into QCD"

Nucleon Structure:

protons, hadrons, nuclear tomography, ...

Hadron/Parton Transition:

Higher Twist, many body, duality, ...

