nCTEQ PDFs and LHC nuclear scattering data

Challenges and Opportunities for QCD

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nuclear parton distribution functions

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...they are **crucial** for heavy-ion programs at

RHIC (Al, Au, Cu, U, ...)

LHC (pPb, PbPb)



AND, to perform detailed flavor separations:



impact of Nuclear Corrections on Proton PDFs



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

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nPDFs are informative of the **dynamics** at work in the nuclear medium!

 \rightarrow short-range correlations?

→ mean-field picture?



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... the motivation for nCTEQ



nPDFs of Current Interest





Heavy lons at the LHC







nuclear PDFs

...the Ingredients

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Data sets & cuts for nPDF fits



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

... selected NLO Nuclear PDF Fits



nuclear parton distribution functions

HKN'07: Hirai, Kumano, Nagai [PRC 76, 065207 (2007)]

EPS'09: Eskola, Paukkunen, Salgado [JHEP 04 (2009)] EPPS'16: Eskola, Paakkinen, Paukkunen, Salgado Eur.Phys.J. C77 (2017) no.3, 163 (supersedes EPS'09)

DSSZ'11: de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012)]

nCTEQ'15: nCTEQ Collaboration [PRD 93, 085037 (2016)]

nNNPDF1.0: NNPDF Group [arXiv:1904.00018]

(talk by J. Ethier later this session)



nPDF framework and parametrization

1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ) $f_i^{p/A}(x_N, Q_0) = R_i(x_N, Q_0, A) f_i^{free\ proton}(x_N, Q_0) \stackrel{1.5}{\underset{y_a}{\models}}$ Fermiantishadowing motion 1.0 R^A_i ... for example EMC 0.6 .y_e effect y₀ shadowing **HKN** $R_i(x, Q_0, \mathbf{A}) = 1 + \left(1 - \frac{1}{A^{\alpha}}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1 - x)^{\beta_i}}$ 0.2 FPS Xa Xe 10^{-3} 10^{-2} 10^{-1} 1 x

0.9

0.8

d

2) Generalized A-parameterization (nCTEQ)

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

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

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

$$Nuclear$$

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$$use proton as a Boundary Condition$$

A=9 A=12 A=27 A=40 A=56 A=84 A=119 A=131 A=197 A=207

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Nuclear PDFs: Complementary efforts in general agreement ¹²



Nuclear PDFs are more complex more DOF than Proton case more complicated dynamically (much) more work to do...



recent progress on strangeness



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strange

constraints on nucleon strangeness remain fairly loose





strangeness suppression ratio,

 $\kappa_s(\mu^{\text{lat}}) \equiv \langle x \rangle_{s+\bar{s}} / \langle x \rangle_{\bar{u}+\bar{d}} |_{\mu=2 \,\text{GeV}}$

preliminary CT results

| PDF moment | CT18 | CT18Z | CT14H2 | | |
|-----------------------------|-------------------|-------------------|-------------------|--|--|
| $\langle x \rangle_{u-d}$ | 0.163 ± 0.009 | 0.163 ± 0.009 | 0.166 ± 0.008 | | |
| $\langle x^2 \rangle_{u-d}$ | 0.054 ± 0.003 | 0.054 ± 0.003 | 0.054 ± 0.003 | | |
| $\langle x^3 \rangle_{u-d}$ | 0.022 ± 0.002 | 0.022 ± 0.001 | 0.022 ± 0.002 | | |
| $\langle x \rangle_g$ | 0.413 ± 0.014 | 0.402 ± 0.012 | 0.415 ± 0.013 | | |
| κ_s | 0.496 ± 0.112 | 0.643 ± 0.206 | 0.459 ± 0.217 | | |

models may also enlighten PDF parametrization dependence



Di-muon production \rightarrow Extract s(x) Parton Distribution





Neutrino DIS

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(...see talk by Jorge Morfin!)

W/Z Production at LHC and the strange PDF



$p Pb \rightarrow W/Z$: Impact of {s,c,b} PDF



Could p Pb \rightarrow W/Z Help?



...but how can we include these new processes into the fit **directly**???



what is nCTEQ++?



- a complete re-write 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: 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 be compared to data and used in nCTEQ++ as theory predictions



MCFM Processes Library (v6.8)

 $\begin{array}{l} \nu(p_3) + e^{-}(p_4)) + H (\to \delta(p_5) + \delta(p_6)) \\ \nu(p_3) + e^{+}(p_4)) + H (\to W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8))) \\ \nu(p_3) + e^{+}(p_4)) + H (\to Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu(p_8))) \\ \nu(p_3) + e^{+}(p_4)) + H (\to \gamma(p_5) + \gamma(p_6)) \end{array}$

 $\begin{array}{l} \sum_{q=q_1, r \in \{q_4\}_1} + rt (\rightarrow w^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8))) \\ p_3) + \bar{\nu}(p_4)) + H(\rightarrow Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu^+(p_8))) \\ p_3) + \bar{\nu}(p_4)) + H(\rightarrow \gamma(p_5) + \gamma(p_6)) \end{array} \right| \begin{array}{l} \text{NLO} \\ \end{array}$

 $(n_2) + \bar{\nu}(n_4) + H(\rightarrow b(n_5) + \bar{b}(n_6))$

NLO NLO

NLO NLO

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.

| | 1 | | | | | | | | | | |
|--|--|------------------|---|--|------------|---|-------------------------------------|----------------|--|--|---|
| nproc | $f(p_1) + f(p_2)$ | ightarrow . | | | | | Order | r | | | |
| 1 | $W^+(\rightarrow \nu(p_3))$ | $+ e^{+}$ | $(p_{4}))$ | | | | NLO | 27 | $0 H(\gamma(p_8) + \gamma(p_4)) + f(p_5) + f(p_6)[in heavy top limit]$ | NLO | $540 \mid H(b(n_{0}) + \tilde{b}(n_{1})) + t(n_{0}) + a(n_{0})$ [NIO] |
| 6 | $W^{-} (\rightarrow e^{-} (n_{0}))$ | $+ \overline{i}$ | (n_{1}) | | | | NLO | 27 27 27 | 1 $H(b(p_3) + b(p_4)) + f(p_5) + f(p_6)[in heavy top limit]$ 2 $H(\tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6)[in heavy top limit]$ 3 $H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \overline{\nu}(p_6))) + f(p_7) + f(p_8)$ | NLO NLO NLO | $\begin{array}{c} 510 & H^{-}(q^{+}g^{+}) + q^{+}g^{+}(p_{5}) + q^{+}g^{+}(p_{5}) \\ 541 & H^{+}(b_{5}) + b_{5}(p_{4}) + t_{5}(p_{5}) + q^{+}(p_{6}) \\ 544 & H^{+}(p_{5}) + b_{5}(p_{4}) + t_{5}(p_{5}) + t_{5}(p_{5}) + t_{5}(p_{5}) \\ \end{array}$ NLO |
| | $\frac{\mathbf{v}}{\mathbf{v}} = \frac{\mathbf{v}}{\mathbf{v}} + \frac{\mathbf{v}}{\mathbf{v}$ | | (P4)) | | | | | - 27 | $\begin{array}{l} H \rightarrow Z(e^{-}(p_{3}), e^{+}(p_{4})) Z(\mu^{-}(p_{5}), \mu^{+}(p_{6}))) + f(p_{7}) + f(p_{8}) \\ 5 & H(b(p_{3}) + \bar{b}(p_{4})) + f(p_{5}) + f(p_{6}) + f(p_{7}) [\text{in heavy top limit}] \end{array}$ | NLO LO | $ \begin{array}{c} 547 \\ 547 \\ H(b(p_3) + \bar{b}(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9) \\ \end{array} \right. \tag{ADC} \\ \hline \\ 547 \\ H(b(p_3) + \bar{b}(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9) \\ \end{array} $ |
| 11 | $ W^+ (\rightarrow \nu(p_3) \cdot$ | $+ e^{+}$ | $(p_4))$ | $+ f(p_5)$ | | | NLO | 270 | $ \begin{array}{l} & 6 & H(\tau^{-}(p_{3}) + \tau^{+}(p_{4})) + f(p_{5}) + f(p_{6}) + f(p_{7}) [\text{in heavy top limit}] \\ & 8 & H(\rightarrow W^{+}(\nu(p_{3}), c^{+}(p_{4}))W^{-}(c^{-}(p_{3}), \bar{\nu}(p_{6}))) + f(p_{7}) + f(p_{7}) + f(p_{8}) + f(p_{8}) \\ & 0 & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) + f(a_{7}) \\ & H(-, Z^{-}(a_{7}), c^{+}(a_{7}))W^{-}(a_{7}) \\ & H(-, Z^{-}(a_{7}))W^{-}(a_{7}) \\ &$ | LO LO | $\begin{array}{c} 550 & H(\gamma(p_3) + \gamma(p_4)) + t(p_5) + q(p_6) \\ 551 & H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(p_5) + q(p_6) \end{array} \\ \end{array} \qquad \qquad$ |
| 12 | $W^+(\rightarrow \nu(p_3))$ | $+ e^{+}$ | $(p_4))$ | $+ \bar{b}(p_5)$ | | | NLO | 28 28 | $ \begin{array}{l} \sigma & 1 \\ (\neg c_2) + (c_2) \\ (\neg p_3) + f(p_4) \\ \end{array} \\ (2) & f(p_1) + f(p_2) \\ (2) & f(p_1) + f(p_2) \\ \end{array} \\ (2) & f(p_1) + f(p_2) \\ (2) & f(p_1) + f(p_2) \\ \end{array} $ | NLO+F LO | $\begin{array}{l} 554 & H(\gamma(p_3) + \gamma(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + q(p_9) \\ 557 & H(\gamma(p_3) + \gamma(p_4)) + \tilde{t}(e^-(p_4) + \tilde{\nu}(p_6) + b(p_7)) + q(p_9) \end{array} \\ \begin{array}{l} \text{NLO} \\ \text{NLO} \end{array}$ |
| 13 | $W^+(\rightarrow \nu(n_2))$ | $+ e^+$ | $(n_{4}))$ | $+ \bar{c}(n_{\rm E})$ | | | NLO | 28 28 28 | $3 f(p_1) + f(p_2) \rightarrow \gamma(p_3) + b(p_4)$ $4 f(p_1) + f(p_2) \rightarrow \gamma(p_3) + c(p_4)$ $5 f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4)$ | LO LO NLO+F | $\frac{560}{561} \frac{Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6)}{Z(e - (p_3) + e + (p_4)) + \tilde{t}(p_5) + q(p_6)} $ NLO |
| 10 | $ \mathbf{U} + (\mathbf{V} + \mathbf{V} + \mathbf{V}) $ | | (P4) | (P_3) | | | | 28 28 | $\begin{array}{l} 6 f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) + f(p_5) \\ 7 f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) + \gamma(p_5) \end{array}$ | NLO+F NLO+F | $562 Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6) + f(p_7) \qquad \text{LO}$ |
| 14 | $ W^{+}(\rightarrow \nu(p_3) \cdot$ | $+e^{-}$ | $(p_4))$ | $+ c(p_5)$ [massless] | | | LO | 290 | $\begin{array}{l} 0 W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) \\ 2 W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6) \\ \vdots W^-(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6) \end{array}$ | NLO+F LO | $\begin{array}{c} 503 Z(e-(p_3)+e+(p_4))+t(p_5)+q(p_6)+f(p_7) \\ 564 Z(e-(p_3)+e+(p_4))+t(\rightarrow\nu(p_5)+e^+(p_6)+b(p_7))+q(p_8) \end{array} \qquad \text{LO}$ |
| 16 | $W^{-}(\rightarrow e^{-}(p_{2}))$ | $+ \overline{i}$ | $i(p_{4}))$ | $+ f(p_5)$ | | | NLO | 29 | $0 W (\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + \gamma(p_5)$ $T W^-(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + f(p_6)$ $0 Z^0(\rightarrow e^{-}(p_3) + e^{+}(p_4)) + \gamma(p_5)$ | LO NLO+F | $\begin{bmatrix} 566 \\ 2(e - (p_3) + e + (p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8) + f(p_9) \end{bmatrix} LO$ $\begin{bmatrix} 567 \\ 2(e - (p_3) + e + (p_2)) + \bar{t}(\rightarrow e^-(p_3) + \bar{t}(p_3) + \bar{t}(p_3)) + q(p_8) \end{bmatrix} + q(p_8)$ NLO |
| | $ \mathbf{U} - (\mathbf{U} - \mathbf{U}) \rangle$ | | (P_{4}) | J(P3) | | | NIO | 30 30 | 11 $Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6)$ 12 $Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6)$ | $\frac{\text{NLO +F}}{\text{NLO + F}}$ | $\frac{2(e - (p_3) + e + (p_4)) + i(-e - (p_5) + i(p_6) + i(p_7)) + q(p_8)}{569 Z(e - (p_3) + e + (p_4)) + i(-e - (p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8) + f(p_9)}$ IO |
| 17 | $ W (\rightarrow e (p_3))$ | $+ \iota$ | $(p_4))$ | $+ o(p_5)$ | | | NLO | 303 304 | $\begin{array}{ccc} 13 & Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + \gamma(p_{6}) + f(p_{7}) \\ 4 & Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + f(p_{6}) + f(p_{7}) \end{array}$ | LO LO | $\begin{array}{c} 601 & H(b(p_3) + b(p_4)) + H(\tau^-(p_5) + \tau^+(p_6)) \\ 602 & H(b(p_1) + \bar{b}(p_4)) + H(\gamma(p_5) + \gamma(p_6)) \\ \end{array}$ |
| 18 | $W^{-}(\rightarrow e^{-}(p_{2}))$ | +i | $\overline{p}(p_A)$ | $+ c(p_5)$ | | | NLO | 30 | $b_{1} Z^{0}(\rightarrow 3(\nu(p_{3}) + \nu(p_{4}))) + \gamma(p_{5})$ $b_{2} Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6})$ $f_{2} Z^{0}(\rightarrow 2(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6})$ | NLO + F NLO + F | $\begin{array}{c} 640 & t(p_3) + \bar{t}(p_4) + H(p_5) \\ 100 & t(p_4) + H(p_5) \\ 100 & t(p_5) + H(p_5) \\$ |
| 10 | $\mathbf{I}\mathbf{U}$ | | $(\Gamma 4)$ | (r_{0}) | | | TO | 30 | $\begin{array}{l} u & Z^{-}(\rightarrow 3(\nu(p_{3}) + \nu(p_{4}))) + \gamma(p_{5}) + f(p_{6}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) + f(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{7}) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) \\ u & Z^{0}(\rightarrow 3(\nu(p_{3}$ | LO LO | $\begin{bmatrix} b41 & t(\rightarrow \nu(p_3) + e^-(p_4) + b(p_5)) + t(\rightarrow \nu(p_7) + e^-(p_8) + b(p_6)) + H(b(p_8) + b(p_{10})) \\ b44 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + b(p_6)) + H(b(p_8) + b(p_{10})) \end{bmatrix} LO$ |
| 19 | $W (\rightarrow e (p_3))$ | + l | $(p_4))$ | $+ c(p_5)$ massless | | | LO | 31 | $\begin{array}{c} 0 \\ f(p_1) + b(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6) \\ f(p_1) + b(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) \\ \end{array}$ | LO LO | 647 $t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_8) + \bar{b}(p_{10}))$ LO |
| nproc $f(p_1) + f(p_2)$ | $\rightarrow \dots$ | Order | $101 Z^0 (\rightarrow e^-)$ $102 Z^0 (\rightarrow 3 \times 103) Z^0 (\rightarrow b(r_0))$ | $p_3) + e^{-r}(p_4) + H (\rightarrow b(p_5) + b(p_6))$ $: (\nu(p_3) + \bar{\nu}(p_4))) + H (\rightarrow b(p_5) + \bar{b}(p_6))$ $: b_{(n_1)} + b_{(n_2)} $ | NLO NLO | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | W intf. LO +WW intf.] LO | 32 32 | 11 $f(p_1) + c(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + c(p_5) + f(p_6)$ 16 $f(p_1) + c(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5) + f(p_6)$ | LO LO | $\begin{array}{c} 051 & t(\rightarrow \nu(p_3) + e^-(p_4) + b(p_5)) + t(\rightarrow \nu(p_7) + e^-(p_8) + b(p_6)) + H(\gamma(p_6) + \gamma(p_{10})) \\ 654 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \overline{t}(\rightarrow \overline{q}(p_7) + q(p_8) + \overline{b}(p_6)) + H(\gamma(p_8) + \gamma(p_{10})) \\ \end{array} $ |
| $\begin{array}{c} 1 \\ 0 \\ W^-(\rightarrow e^-(p_3)) \\ \hline \end{array}$ | $+ \bar{\nu}(p_4))$ $+ \bar{\nu}(p_4))$ $+ e^+(p_4)) + f(p_5)$ | NLO | 105 $Z^{0}(\rightarrow e^{-})$ 104 $Z^{0}(\rightarrow e^{-})$ 105 $Z^{0}(\rightarrow \rightarrow 3)$ | $(1 \to (p_1)) + n (\to (p_5) + o(p_5))$ $p_3) + e^+(p_4)) + H(\to \gamma(p_5) + \gamma(p_6))$ $3 \times (\nu(p_5) + \bar{\nu}(p_4))) + H(\to \gamma(p_5) + \gamma(p_6))$ | NLO NLO | $\frac{126}{128} \frac{W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6))}{W^+(\nu_1p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6))} [gg \text{only}, (H + gg \rightarrow WV)]}{128} \frac{W(\nu_1p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6))}{W^+(\nu_1p_3) + e^+(\nu_1p_3) + e^+(\nu_1p_3))} \frac{W(\nu_1p_3)}{W^+(\nu_1p_3) + e^+(\nu_1p_3)} \frac{W(\nu_1p_3)}{W^+(\nu_1p_3)} \frac{W(\nu_1p_3)}{W^+(\nu_$ | V) squared] LO LO | 33 33 | $\begin{array}{l} W^+(\rightarrow \nu(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[c-s interaction] \\ 6 & W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5) + f(p_6)[c-s interaction] \end{array}$ | LO LO | $\begin{bmatrix} 657 & t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_3)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10})) \\ 661 & t(\rightarrow \nu(p_1)e^+(p_1)b(p_1)) + \bar{t}(\rightarrow \bar{\nu}(p_2)e^-(p_2)\bar{b}(p_3)) + H(W^+(p_2, p_2)W^-(p_1, p_2)) \end{bmatrix} IO$ |
| 11 12 13 $W^+(\rightarrow \nu(p_3))$ $W^+(\rightarrow \nu(p_3))$ $W^+(\rightarrow \nu(p_3))$ | $+ e^{+}(p_4)) + \bar{p}(p_5)$ + $e^{+}(p_4)) + \bar{b}(p_5)$ + $e^{+}(p_4)) + \bar{c}(p_5)$ | NLO | 106 $Z^0(\rightarrow e^-)$ 107 $Z^0(\rightarrow 3 \times$ | $p_3) + e^+(p_4)) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8))))$: $(\nu(p_3) + \bar{\nu}(p_4))) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8))))$ | NLO NLO | 129 $H(\rightarrow Z^0(e^-(p_3) + e^+(p_4)) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ [ody, bottom to 129 $H(\rightarrow Z^0(e^-(p_3) + e^+(p_4)) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ [m] H , ag H, gg $\rightarrow ZJ$ 130 $H(\rightarrow Z^0(e^-(p_3) + e^+(p_4)) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ [m] H and H, gg. | Jintf.] LO →ZZ intf.] LO | 34 34 | $\begin{array}{c} 1 & f(p_1) + b(p_2) \rightarrow Z^0 (\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) [+f(p_7)] \\ 2 & f(p_1) + b(p_2) \rightarrow Z^0 (\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) [+\bar{b}(p_7)] \end{array}$ | NLO (REAL) | $\begin{array}{c} 001 & (\neg \nu p_3)e^{-}(p_4)o(p_5)) + (\neg \nu (p_7)e^{-}(p_8)o(p_6)) + H(w^{-}(p_9,p_{10})w^{-}(p_{11},p_{12})) \\ 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} $ |
| 14 $W^+(\rightarrow \nu(p_3))$ $W^-(\rightarrow e^-(p_2))$ | $+ \bar{v}(p_4) + \bar{c}(p_5)$ [massless] $+ \bar{v}(p_4) + \bar{f}(p_5)$ [massless] | LO | 108 $Z^0(\rightarrow b(p_3)$ 109 $Z^0(\rightarrow e^-(p_3))$ | $_{3}) + \bar{b}(p_{4})) + H(\rightarrow W^{+}(\nu(p_{5}), e^{+}(p_{6}))W^{-}(e^{-}(p_{7}), \bar{\nu}(p_{8}))))$ $p_{3}) + e^{+}(p_{4})) + H(\rightarrow Z(e^{-}(p_{5}), e^{+}(p_{6})) + Z(\mu^{-}(p_{7}), \mu^{+}(p_{8})))$ | NLO NLO | $ \begin{array}{ c c c c c c c c c c c c c c c c c c c$ | I squared LO LO | 34 34 | $\begin{array}{l} 6 \\ f(p_1) + b(p_2) \rightarrow Z^0 (\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) + f(p_7) \\ 7 \\ f(p_1) + b(p_2) \rightarrow Z^0 (\rightarrow e^-(p_3) \$4e^+(p_4)) + b(p_5) + f(p_6) + \bar{b}(p_7) \end{array}$ | LO LO | $ \begin{array}{ $ |
| 17 $W^-(\rightarrow e^-(p_3))$ 18 $W^-(\rightarrow e^-(p_3))$ | $(+\bar{\nu}(p_4)) + b(p_5)$ $(+\bar{\nu}(p_4)) + c(p_5)$ | NLO NLO | 111 $H(\rightarrow b(p_3))$ 112 $H(\rightarrow \tau^-(p_3))$ 112 $H(\rightarrow \psi^+(p_3))$ | $(b_{1}(a_{1}) + b(p_{4}))$ $p_{3}(b_{1} + c^{+}(p_{4}))$ $(b_{1}(a_{2}) + c^{+}(p_{4})) + W^{-}(c^{-}(p_{4}) + \bar{p}(p_{4})))$ | NLO NLO | 1281 $H \rightarrow e^{-}(p3) + e^{-}(p4)\nu_e(p5) + \nu_e(p6)$ (top, bottom loops, exact] 1311 $e^{-}(p3) + e^{+}(p4) + \nu_e(p5) + \bar{\nu}_e(p6)$ [gg only, (H + gg \rightarrow ZZ) squared 1321 $e^{-}(p3) + e^{+}(p4) + \nu_e(p5) + \bar{\nu}_e(p6)$ [gg \rightarrow ZZ) squared | LO LO | 351 | $[f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+f(p_7)]$ $[f(p_1) + c(p_3) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_3) + f(p_5)[+f(p_7)]$ | NLO (REAL) | 800 $V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Vector Mediator] NLO |
| 19 $W^-(\rightarrow e^-(p_3))$ 20 $W^+(\rightarrow \nu(p_3))$ | $(+ \overline{\nu}(p_4)) + c(p_5)$ [massless] + $e^+(p_4)) + b(p_5) + b(p_6)$ [massive] | LO NLO | 113 $H \rightarrow W^+$ 114 $H \rightarrow W^+$ 115 $H \rightarrow W^+$ | $(\nu(p_3) + e^+(p_4)) + W = (e^-(p_5) + \nu(p_6)))$ $(\nu(p_3) + e^+(p_4)) + W^-(q(p_5) + \bar{q}(p_6)))$ $(\nu(p_3) + e^+(p_4)) + W^-(q(p_5) + \bar{q}(p_6)))$ | NLO | $\begin{array}{ c c c c c c c c c c c c c c c c c c c$ | LO LO | 356 | $\begin{array}{c} f(p_1) + c(p_2) \rightarrow 2 (\neg e^{-}(p_3) + e^{-}(p_1)) + c(p_3) + f(p_6) + f(p_7) \\ f(p_1) + c(p_2) \rightarrow 2^0 (\neg e^{-}(p_3) + e^{+}(p_1)) + c(p_3) + f(p_6) + f(p_7) \\ f(p_1) - c(p_1) - 2^0 (\neg e^{-}(p_3) + e^{+}(p_1)) + c(p_3) + f(p_6) + f(p_7) \end{array}$ | LO | 801 $A \rightarrow (\chi(p_3) + \ddot{\chi}(p_4)) + f(p_5)$ [Axial Vector Mediator] NLO 802 $S \rightarrow (\chi(p_3) + \ddot{\chi}(p_4)) + f(p_5)$ [Scalar Mediator] NLO |
| 21 $W^+(\rightarrow \nu(p_3) -$ 22 $W^+(\rightarrow \nu(p_3) -$ | $+ e^+(p_4)) + b(p_5) + \bar{b}(p_6)$ + $e^+(p_4)) + f(p_5) + f(p_6)$ | NLO NLO | 116 $H \rightarrow Z^0(e)$ 117 $H \rightarrow Z^0(e)$ | $(\nu(p_3) + c - (p_4)) + W - (p_5) + q(p_6)))(\nu(a_3Ma_4)) = 1$ $(p_5) + c^+(p_4)) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ $3 \times (\nu(p_3) + \tilde{\nu}(p_4))) + Z^0(\mu^-(p_5) + \mu^+(p_6))$ | NLO NLO | $\begin{bmatrix} 1322 & e^{-}(p3) + e^{+}(p4) + \nu(p5) + \bar{\nu}(p6) & [(gg \rightarrow ZZ) \text{ squared}] \\ \hline 133 & H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6) + f(p7)) & [\text{intf,no} \\ \hline 12e & H(\mu^{-},\mu^{-}) + \mu^{-}(\mu^{-},\mu^{-}) + \mu^{-}(\mu^{-},\mu^{-}) + \mu^{-}(p6) & - f(p7) \\ \hline 12e & H(\mu^{-},\mu^{-}) + \mu^{-}(\mu^{-},\mu^{-}) + \mu^{-}(\mu^{-},\mu^{-}) \\ \hline 12e & H(\mu^{-},\mu^{-}) \\ \hline 12e$ | p ₇ cut] LO | 361 | $J(p_1) + c(p_2) \rightarrow Z^*(\rightarrow e^-(p_3) + e^-(p_4)) + c(p_5) + J(p_6) + c(p_7)$ $c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))[mc=0 \text{ in NLO}]$ | NLO | 803 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_i)) + f(p_5)$ [Pseudo Scalar Mediator] NLO |
| 23 $W^+(\rightarrow \nu(p_3) -$ 24 $W^+(\rightarrow \nu(p_3) -$ | $+ e^{+}(p_{4})) + f(p_{5}) + f(p_{6}) + f(p_{7})$ $+ e^{+}(p_{4})) + b(p_{5}) + \bar{b}(p_{6}) + f(p_{7})$ | LO LO | 118 $H \rightarrow Z^0(\mu)$ 119 $H \rightarrow \gamma(p_3)$ | $\mu^{-}(p_{3}) + \mu^{+}(p_{4})) + Z^{0}(b(p_{5}) + \bar{b}(p_{6}))$ (1) (2) (2) (2) (3) (2) (3) | NLO NLO | $\begin{array}{cccc} 130 & H(\rightarrow b(p_3) + b(p_4)) + \bar{b}(p_5)(+ b(p_6)) \\ 137 & H(\rightarrow b(p_3) + \bar{b}(p_4)) + \bar{b}(p_5)(+ b(p_6)) \\ 138 & H(\rightarrow b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6) \\ \end{array}$ | (REAL) (REAL) | 362 363 | $\begin{array}{l} 2 c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) \text{[massless corrections only]} \\ 3 c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) \text{[massive charm in real]} \end{array}$ | NLO NLO | 804 GG $\rightarrow (\chi(p_3) + \chi(p_4)) + f(p_5)$ [Guome DAI operator] 805 $S(\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator, mt loops] NLO |
| 25 $W^-(\rightarrow e^-(p_3))$ 26 $W^-(\rightarrow e^-(p_3))$ | $(+\bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ [massive] $(+\bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ | NLO NLO | 120 $H(\rightarrow Z^0)$ 121 $H(\rightarrow Z^0)$ | $\chi^{-}(p_{3}) + \mu^{+}(p_{4})) + \gamma(p_{5}))$ $3 \times (\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}))$ [1] | NLO NLO | 141 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8))$ | NLO | 370 371 | $\begin{array}{l} U & W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6) \\ U & W^-(\rightarrow e^-(p_3) + \overline{\nu}(p_4)) + \gamma(p_5) + \gamma(p_6) \end{array}$ | LO LO | 820 $V \rightarrow (\chi(p_3) + \bar{\chi}(p_i)) + \gamma(p_5)$ [Vector Mediator] NLO + F 821 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_i)) + \gamma(p_5)$ [Axial Vector Mediator] NLO + F |
| 27 $W^-(\rightarrow e^-(p_3))$ 28 $W^-(\rightarrow e^-(p_3))$ | $(+\bar{\nu}(p_4)) + f(p_5) + f(p_6)$ $(+\bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ | NLO LO | 56 $Z^0(\rightarrow e^-(p_3$ | $r_3) + e^+(p_4)) + c(p_5) + \bar{c}(p_6)$ N | NLO | $ \begin{array}{ c c c c c c c c c c c c c c c c c c c$ | Lin.dk] NLO (p ₉) LO | 401 402 | $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS] $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS] | NLO NLO | 822 $S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Scalar Mediator] NLO + F |
| $\frac{29}{31} \qquad W^-(\rightarrow e^-(p_3))$ | $(+ \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$ + $e^+(p_4))$ | LO NLO | $\begin{array}{c c} 61 & W^+(\rightarrow \nu(p_3 \\ 62 & W^+(\rightarrow \nu(p_3 \\ \end{array})) \end{array}$ | $_{1}) + e^{+}(p_{4})) + W^{-}(\rightarrow e^{-}(p_{5}) + \bar{\nu}(p_{6}))$ N $_{3}) + e^{+}(p_{4})) + W^{-}(\rightarrow q(p_{5}) + \bar{q}(p_{6}))$ N | NLO NLO | 144 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + t(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ (ur 145 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 146 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 147 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 148 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 149 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$] [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_8) + \bar{t}(\rightarrow b(p_8) + e^-(p_7) + \bar{\nu}(p_8))$] [ran 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_8) + \bar{t}(\rightarrow b(p_8) + e^-(p_7) + \bar{\nu}(p_8))$] [ran 140 $t(\rightarrow \nu(p_3) + b(p_8) + b(p_8) + \bar{t}(\rightarrow b(p_8) + e^-(p_7) + \bar{\nu}(p_8))$] [ran 140 $t(\rightarrow \nu(p_8) + b(p_8) + b(p_8) + \bar{t}(\rightarrow b(p_8) + e^-(p_8) + \bar{\mu}(p_8) + \bar{\mu}(p_8$ | corr) NLO Lin.dk],uncorr NLO | 403 | 3 $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$ [2 or 3 jets, 4FNS] $W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$ [1 2 or 3 jets, 4FNS] | NLO NLO | 823 $PS \rightarrow (\chi(p_3) + \chi(p_4)) + \gamma(p_5)[Pseudo Scalar Mediator] NLO + P 840 V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6) [Vector Mediator] LO$ |
| 32 $Z^0(\rightarrow 3 \times (\nu))$ 33 $Z^0(\rightarrow b(p_3) +$ | $p_3) + \bar{\nu}(p_4)))$ $\bar{b}(p_4))$ | NLO NLO | $\begin{array}{c} 63 \\ 64 \end{array} W^+(\rightarrow \nu(p_3) \\ W^-(\rightarrow e^-(p_3)) \\ W^+(\rightarrow e^-(p_3)) $ | $_{1}) + e^{+}(p_{4})) + W^{-}(\rightarrow q(p_{5}) + \bar{q}(p_{6})) [rad.in.dk]$ N $p_{3}) + \bar{\nu}(p_{4}))W^{+}(\rightarrow q(p_{5}) + \bar{q}(p_{6}))$ N | NLO NLO | 140 $t(\rightarrow \nu(p_3) + e^+(p_4) + \delta(p_5)) + \bar{t}(\rightarrow o(p_6) + q(p_7) + q(p_8))$ 147 $t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + \bar{q}(p_8))$ [rad. 148 $t(\rightarrow \nu(p_3) + e^+(p_3) + b(p_7)) + \bar{t}(\rightarrow b(p_7) + q(p_7) + \bar{q}(p_7))$ [rad. | n.top.dk] NLO | 407 | $W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + (b + \bar{b})(p_{5}) [1 \text{ or } 2 \text{ jets}, 4\text{FNS}]$ $W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + b(p_{3}) + \bar{b}(p_{3}) [2 \text{ or } 2 \text{ jets}, 4\text{FNS}]$ | NLO | 841 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Axial Vector Mediator] LO |
| $\begin{array}{ccc} 34 & Z^0(\rightarrow 3 \times (d)) \\ 35 & Z^0(\rightarrow 2 \times (u)) \end{array}$ | $p_5) + \bar{d}(p_6)))$ $p_5) + \bar{u}(p_6)))$ | NLO NLO | $\begin{array}{c c} 65 & W & (\rightarrow c \ (p \\ 66 & W^+ (\rightarrow \nu (p_3 \\ co \ W^+ (\rightarrow (p_3 \\ co \ W^+ (\gamma (p_3 \\ $ | $p_3) + \nu(p_4))W^+ (\rightarrow q(p_5) + q(p_6))[rad.m.dk]$ [N $3) + e^+(p_4)) + W^- (\rightarrow e^-(p_5) + \bar{\nu}(p_6)) + f(p_7)$ [L $y + e^+(p_4) + W^- (\rightarrow e^-(p_5) + \bar{\nu}(p_6)) + f(p_7)$ [L | LO | 149 $t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ 150 $t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad. | n.top.dk] NLO | 411 | $f(p_1) + b(p_2) \to W(\to \nu(p_3) + e(p_4)) + b(p_3) + e(p_4) + b(p_4) + b(p_3) + e(p_4) + b(p_4) + b(p_4$ | NLO | 843 $PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Pseudo Scalar Mediator] LO |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $b_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ + $e^+(p_4)) + f(p_5)$ | LO NLO | $09 W^+ (\rightarrow \nu (p_3)$ $71 W^+ (\rightarrow \nu (p_3)$ $72 W^+ (\rightarrow \nu (p_3))$ | $(y_1) + e^+(p_4)) + W \rightarrow e^-(p_5) + \nu(p_6)) \text{ [In Poi]}$ $(y_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_5) + e^+(p_6)) \text{ [N]}$ | NLO | $\frac{151}{157} \frac{t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b \ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \text{ [rad.}}{157} \frac{t\bar{t}_{[\text{for total Xsect}]}}{t\bar{t}_{[\text{for total Xsect}]}}$ | n.W.dk] NLO NLO | 421 | $W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS] | NLO | 844 $[GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)]$ [Gluonic DM operator] LO 845 $[V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)]$ [Vector Mediator] LO |
| 42 $Z_0(\rightarrow 3 \times (\nu q)$ 43 $Z^0(\rightarrow b(p_3) +$ | $p_3) + \bar{\nu}(p_4))) + f(p_5)$ $\bar{b}(p_4)) + f(p_5)$ | NLO NLO | $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $\begin{array}{ll} 1) + \mu^{-}(p_4) + z^{0} (\rightarrow 3 \wedge (e_c(p_5) + b_c(p_6))) \\ 3) + \mu^{+}(p_4)) + z^{0} (\rightarrow b(p_5) + \overline{b}(p_6)) \\ N \end{array}$ | NLO | 158 bb[for total Xsect] 159 cc[for total Xsect] | NLO NLO | 426 | $ \begin{array}{c} W^{-}(\rightarrow e^{-}(p_{3}) + \nu(p_{4})) + b(p_{5}) \ [1,2 \ {\rm or} \ 3 \ {\rm jets}, \ 4FNS+5FNS] \\ W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + b(p_{5}) + b(p_{6}) + f(p_{7}) \ [{\rm massive}] \end{array} $ | LO | 846 $A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Axial Vector Mediator] LO |
| 44 $Z^0(\rightarrow e^-(p_3) \rightarrow Z^0(\rightarrow E^0(\rightarrow e^-(p_3) \rightarrow Z^0(\rightarrow E^0(\rightarrow e^-(p_3) \rightarrow Z^0(\rightarrow E^0(\rightarrow e^-(p_3) \rightarrow Z^0(\rightarrow E^0(\rightarrow E^$ | $+ e^+(p_4)) + f(p_5) + f(p_6)$ $+ e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$ | | | 1 1 1 | | • | | | | | |
| 46 $Z^0(\rightarrow 3 \times (\nu))$ 47 $Z^0(\rightarrow 3 \times (\nu))$ | $p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$ $p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ | -hi | s m | iodularity n |) | omises many | | D | ortunities to |) L (| יחסוצחהמצי |
| 50 $Z^0(\rightarrow e^-(p_3) \rightarrow Z^0(\rightarrow E^0(p_3) \rightarrow Z^0(\rightarrow Z^0(p_3) \rightarrow Z^0(p_3) $ | $+ e^+(p_4)) + b(p_5) + b(p_6)[massive]$ $+ e^+(p_4)) + b(p_5) + \bar{b}(p_6)$ | | | louddiney p | | | , e | Μ | oredificies re | | |
| 52 $Z_0(\rightarrow 3 \times (\nu))$ 53 $Z^0(\rightarrow b(p_3) + Z^0(\rightarrow b(p_3))$ | $p_3 + \nu(p_4)) + b(p_5) + b(p_6)$ $\bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)$ | NLO | 81 $Z^0(\rightarrow e^-(p_3)$ 82 $Z^0(\rightarrow e^-(p_3))$ | $s_{3}^{-} + e^{+}(p_{4})) + Z^{0}(\rightarrow \mu^{-}(p_{5}) + \mu^{+}(p_{6}))$ N $s_{3}^{-} + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))$ N | NLO NLO | $\begin{array}{ccc} 171 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6)) s-\text{channel} \\ 172 & t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6)) decay \\ 176 & \mu^{-1}(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6)) decay \\ 176 & \mu^{-1}(p_3) + b(p_3) + b(p_3) + b(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_3) + b(p_6) + b(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_3) + b(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) \\ 176 & \mu^{-1}(p_6) + b(p_6) + b(p_6) \\ 186 & \mu^{-1}(p_6) \\ 186 & \mu^{-1}(p_6) + b(p_6) \\ 186 & \mu^{-1}(p_6) $ | NLO NLO | 510 511 | $\frac{W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + \bar{t}(p_6)[\text{massive}]}{t(\rightarrow \nu(p_5) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_6)) + W^-(\mu^-(p_6), \bar{\nu}(p_6))}$ | NLO NLO | 906 Check of Volume of 6 particle phase space |
| $z_{-}(\rightarrow e^{-}(p_3) -$ | $+ e \cdot (p_4) + o(p_5) + o(p_6) + J(p_7)$ 79 | 10 | $\begin{array}{c c} 83 \\ 84 \\ Z^0 (\rightarrow e^-(p_3) \\ Z^0 (\rightarrow b(p_3)) \end{array}$ | $_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow b(p_{5}) + \bar{b}(p_{6}))$ N + $\bar{b}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))$ N | NLO NLO | $\frac{170}{\overline{t}(\rightarrow e^-(p_1) + \overline{\nu}(p_4) + \overline{o}(p_5)) + \overline{o}(p_6))[\text{s-cnannel}]}{177} \frac{1}{\overline{t}(\rightarrow e^-(p_1) + \overline{\nu}(p_4) + \overline{b}(p_5)) + b(p_6))[\text{rad.in.dk}]}$ $\frac{180}{180} \frac{W^-(\rightarrow e^-(p_1) + \overline{\mu}(p_4) + \overline{b}(p_5)) + t(p_1)}{180}$ | NLO | 512 513 | (same as process 511 but with radiation in decay) $t \rightarrow u(p_1) + e^+(p_2) + b(p_1) + \overline{t} \rightarrow b(p_2) + a(p_2) + a(p_2)) + W^-(u^-(p_2)) \overline{u}(p_2)$ | NLO NLO | 908 Check of Volume of 8 particle phase space 909 Check of Volume of 4 particle massive phase space |
| | | | 85 $Z^0(\rightarrow e^-(p_3)$ 86 $Z^0(\rightarrow \mu^-(p_3))$ | $\begin{array}{ll} \underbrace{_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{3}) + \bar{\nu}(p_{6}))) + f(p_{7}) & L \\ \underbrace{_{3}) + \mu^{+}(p_{4})) + Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{6}))[\text{no gamma}^{*}] & N \end{array}$ | LO NLO | $\begin{array}{cccc} & & & & & & & & & & & & & & & & & $ | NLO NLO | 516 | $\begin{array}{l} r(r + qr_{3}) + c(r_{4}) + v(r_{5})) + \bar{r}(r - b(p_{5}) + q(p_{7}) + q(r_{5})) + W & (\mu - (p_{5}), \rho(p_{6})) \\ \bar{r}(r - q(p_{3}) + q(p_{4}) + b(p_{5})) + \bar{\ell}(r - b(p_{5})) + e^{-}(p_{7}) + \bar{\nu}(p_{8})) + W^{-}(\mu^{-}(p_{9}), \bar{\nu}(p_{6})) \\ r(r - p_{1}) + r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) + \bar{\ell}(r - b(p_{1})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) + \bar{\ell}(r - b(p_{1})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) + \bar{\ell}(r - b(p_{1})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) + \bar{\ell}(r - b(p_{1})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) + \bar{\ell}(r - b(p_{1})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) \\ r(r - p_{1}) + r(r - b(p_{1}) + b(p_{2})) \\ r(r - b(p_{1}) + b(p_$ |)) NLO | 910 Check of Volume of 3 particle (2 massive) phase space |
| | | | $\begin{array}{c c} 87 \\ 88 \\ Z^0(\rightarrow e^-(p_3) \\ Z^0(\rightarrow e^-(p_3)) \end{array}$ | $_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{3}) + \bar{\nu}(p_{6})))[\text{no gamma}^{*}]$ [N $_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow b(p_{5}) + \bar{b}(p_{6}))[\text{no gamma}^{*}]$ [N | NLO NLO | $\begin{array}{c} 183 & W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + b(p_8) \\ 184 & W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + b(p_6) [\text{massive b}] \end{array}$ | LO | 529 | $\begin{array}{l} p \geq (-e^-(p_3) + e^+(p_4)) + t(p_0) + t(p_0) \\ 1 = (-e^-(p_1) + e^+(p_4) + b(p_3)) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + b(p_0)) + Z(e^-(p_3), e^+(p_{10}) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{\nu}(p_3) + \bar{t}(-e^-(p_1) + \bar{\mu}(p_3))) \\ + (-e^-(p_1) + e^-(p_1) + \bar{t}(-e^-(p_1) + \bar{t}(-e^-(p$ |)) LO | 911 Cneck of volume of 5 particle W+t (with decay) massive phase space 912 Check of Volume of 5 particle W+t (no decay) massive phase space |
| | | | 89 $Z^0(\rightarrow b(p_3))$ 90 $Z^0(\rightarrow e^-(p_3))$ | $+ b(p_4)) + Z^0(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6)))[\text{no gamma*}]$ N $y_3) + e^+(p_4)) + Z^0(\rightarrow e^-(p_5) + e^+(p_6))$ N | NLO NLO | $ \begin{array}{ c c c c c c c c c c c c c c c c c c c$ | NLO NLO | 531 532 | $\frac{1}{2} t(\rightarrow \nu(p_3) + e^-(p_4) + b(p_5)) + t(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10}))}{t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow q(p_7) + \bar{q}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))}$ | TO TO | 913 Check of Volume of 5 particle W+t+g (in decay) massive phase space 014 Check of Volume of 5 particle W+t+g (in production) massive phase space |

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533 $t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(e^-(p_9),$

we are now positioned to include LHC data directly into nPDF fits



Fit to LHC W/Z Data w/ Normalization



pPb Data for nCTEQ+LHC

No LHC data in any previous nCTEQ fit

• New gridded theory predictions make this possible



```
\sqrt{s} = 5.02 \,\text{TeV}
```

ATLAS:

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

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Fit to LHC W/Z Data w/ Normalization



unlike the gluon, strangeness is very sensitivity to our treatment of the LHC W/Z data

0.175

0.150

0.100

0.075

0.050

0.025

0.000





future facilities will be well-poised to constrain nucleon (nuclear) strangeness

Wang, TJH, Doyle, Gao, Hou, Nadolsky, Olness, LHeC, HL-LHC, EIC, AFTER@CERN, ... PRD98, 094030 (2018). → for more, **later today** (PDF-lattice) AND http://metapdf.hepforge.org/PDFSense/ Session **C09**: Sat., April 13th – 1:30pm $|S_f|$ for s(x, μ), PDF4LHC15 NNLO $|S_f|$ for s(x, μ), PDF4LHC15 NNLO 10⁴ 10 LHeC HL-LHC Npt: 749 Npt: 478 10^{3} 10^{3} highlighted range: highlighted range: $|S_f| > 0.25$ $|S_f| > 0.25$ 2.4 [ЛеО] и µ [GeV] 2.0 1.6 $CC e^- p$ 1.2 \blacktriangle NC e^+p 0.8 \blacksquare CC e^+p 0.4 • NC e^-p 0 10 10 10^{-2} 10^{-5} 10^{-3} 10^{-2} 10^{-1} 10^{-5} 10^{-4} 10^{-3} 10^{-6} 10^{-6} 10^{-4} 10^{-1}

can make projections for PDF impact of

conclusions: we face **new data**, but with **new theoretical tools**







New Analyses in progress



New Perspectives – e.g., on nucleon strangeness

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BACKUP



Nuclear PDFs: DIS, DY, π **Prod,** (new) **Di-Jet**

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... on Monday we heard ...

Recap: LHC data and the strange sea



- HERMES 2014: r_s is x-dependent (leading-order analysis)
- ATLAS 2012 fit of W and Drell-Yan +HERA: "unsuppressed" strange sea r_s=1
- CMS 2013 data on W asymmetry plus PDF fit: "suppressed" strange sea
- CMS 2013 data on c+W compatible with "suppressed" strange sea
- ATLAS 2014 data on c+W compatible with with "unsuppressed" ATLAS fit

HERMES: Phys.Rev. D89 (2014) 097101 [arXiv:1312.7028] ATLAS fit: Phys.Rev.Lett. 109 (2012) 012001 [arXiv:1203.4051] CMS c+W: JHEP 1402 (2014) 013 [arXiv:1310.1138] CMS W asym: Phys.Rev. D90 (2014) 032004 [arXiv:1312.6283] ATLAS c+W: JHEP 1405 (2014) 068 [arXiv:1402.6263]



S.Schmitt, Parton density results

DIS conference, April 2018

T.J. Hobbs - SMU/EIC Center@JLab



 $Q^2 = 1.9 \text{ GeV}^2$





F. Olness

KEK 13 April 2018

EPPS16

- EPPS fits nuclear ratios, not nuclear PDFs
 - EPPS16 includes LHC data
 - CMS Di-jets
 - W/Z Production from CMS, Z Production from ATLAS
 - Also includes large number of CHORUS Pb Fixed Target DIS points (824)
- More than double the data points in nCTEQ15 (1789)





Fit to LHC W/Z Data w/ Normalization





2σ normalization applied to LHC sets

- Improved χ²/d.o.f.
- Additional normalization could improve χ^2 more

| | | Data ID: | 6211 | 6231 | 6233 | 6215 |
|--------------|--|---------------------|-------------|-------------|-------------|-------------|
| | nCTEQ15-np | χ^2 per d.o.f: | 1.55 | 6.91 | 7.73 | 3.16 |
| | Reweighting | χ^2 per d.o.f: | 0.87 | 3.27 | 2.95 | 1.76 |
| | nCTEQ+LHC | χ^2 per d.o.f: | 1.30 | 5.30 | 3.36 | 2.75 |
| Normalized { | ncteq+lhc $(1 \times \sigma_N)$ | χ^2 per d.o.f: | 0.92(+0.10) | 2.77(+0.10) | 1.66(+0.10) | 1.96(+0.07) |
| | $\texttt{nCTEQ+LHC} \; \left(4\sigma_N^{ATLAS}, \; 2\sigma_N^{CMS} \right)$ | χ^2 per d.o.f: | 0.42(+1.60) | 1.33(+0.40) | 1.39(+0.40) | 0.94(+1.14) |
| | T.J. Hobbs - SMU | Penalty | | 41/46 | | |

... earlier this week we heard ...

LHC Physics and EIC

 W^+

Shima Shimizu (KEK 協力研究員)

Charm-tagged Charged Current DIS

- If a charm is tagged in CC DIS, the cross section has a sensitivity to the <u>intrinsic strange</u>.
- Strange quark distribution is not well determined.
 - ATLAS data prefers more strangeness than fixed target data?

ATLAS d,s,b JHEP05(2014)068 Ldt = 4.6 fbaMC@NLO s = 7 TeVCT10 W^c-jet Asymmetric s and sbar, ▲ MSTW2008 derived from CCFR and NuTeV ▼ NNPDF2.3 (neutrino-nucleon DIS) 20000 O HERAPDF1.5 Data 37.3 ± 0.8 ± 1.9 [pb] ATLAS-epWZ12 LHC data included g С Stat NNPDF2.3col Stat+syst 30 20 40 50 60 70 σ^{OS-SS} [pb]

- Charm-tagged CC DIS at EIC would be interesting.
 - Free from the nuclear/target correction.
 - Requires charm tagging in the Central-Forward region.

At EIC ($\int s \sim 70 \text{ GeV}, Q^2 > 100 \text{ GeV}^2$): $\sigma(e^+p \rightarrow v_e + c + X) \sim 0.1 \text{ pb}$ $\Rightarrow \text{ with } 10 \text{ fb}^{-1} / \text{year}$ $\Rightarrow \sim 1000 \text{ events} / \text{year}$

Y. Furletova



at DIS2017 we heard.



Electroweak and QCD Measurements at the Large Hadron Collider **Strangeness in the Proton**

arXiv:1612.03016



João Guimarães da Costa **IHEP, Chinese Academy of Sciences**

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}} = 1.13 \pm 0.05 \,(\text{exp}) \pm 0.02 \,(\text{mod}) \stackrel{+0.01}{_{-0.06}} \,(\text{par})$$

Do it yourself!!!



Fits using ATLAS and CMS W+DY data



T.J. Hobbs - SMU/EIC Center@JLab

The Future Frontier: Pushing Kinematic Boundaries + Innovative Ideas⁴⁵



Precise knowledge of the PDFs are essential for predictions

QCD factorization:

$$\sigma = \widehat{\sigma} \otimes PDF$$

Experimental Data:

→ requires a large variety of data from fixed-target and collider experiments

Theory:

→ intense theoretical developments

Tevatron + HERA essential complementary components

LHC alone cannot maximize PDF precision



" PDF uncertainties are among the leading uncertainties in the first LHC precision measurements by CMS" *Jan Kretzschmar*

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