#### nCTEQ and PDFs at LHC

Challenges and Opportunities for QCD

#### Fred Olness SMU



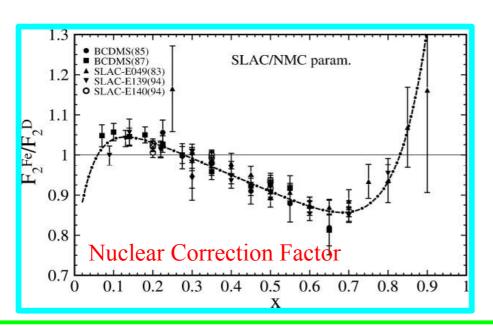
#### Thanks to my nCTEQ colleagues

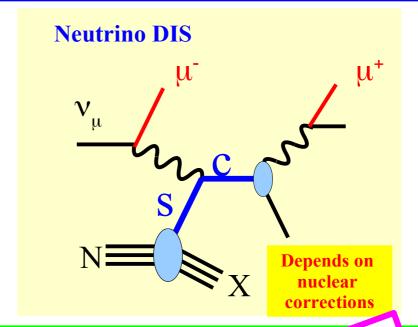
**A.** Kusina, B. Clark, E. Godat, T.J. Hobbs, **T. Jezo, C. Keppel,** J.Kent F. Lyonnet, J.G. Morfin, K. Kovarik, J.F. Owens, I. Schienbein, J.Y. Yu,

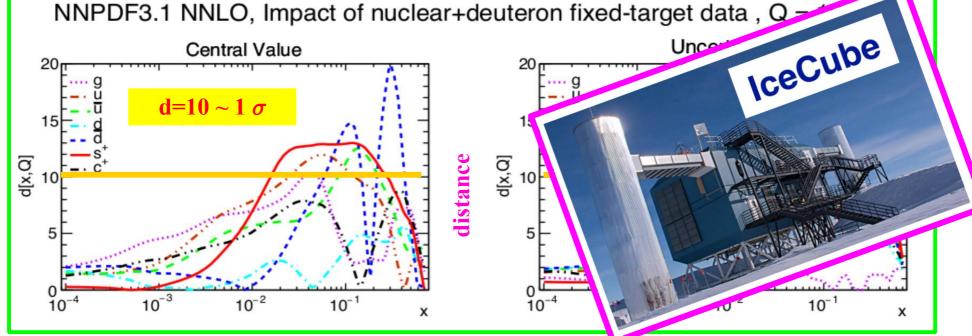


DIS2019 Torino, Italy April 18-12, 2019

#### **Impact of Nuclear Corrections on Proton PDF**







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

# Nuclear PDFs

# The Cast

#### nPDFs

nuclear parton distribution functions

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

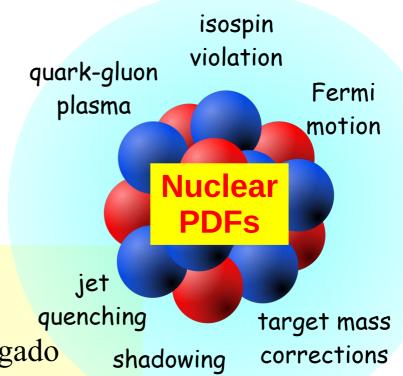
EPPS'16: Eskola, Paakkinen, Paukkunen, Salgado Eur. Phys. J. C77 (2017) no.3, 163 (supersedes EPS'09)

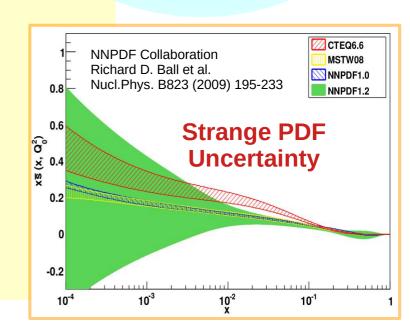
DSSZ'11: de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012)]

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

nNNPDF1.0: Khalek, Ethier, Rojo,

[arXiv:1904.00018]





# Nuclear PDF

# The Ingredients

#### Data sets & cuts for nPDF fits

#### NC DIS & DY

SLAC E-139 & E-049

N = (D, Ag, Al, Au, Be, C, Ca, Fe, He)

CERN BCDMS & EMC & NMC

N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)

DIS Cuts:

nCTEQ: Q>2.0 & W>3.5

EPPS16: Q>2.0 & W>3.5

EPS09: Q>1.3

HKN: Q>1.0

DSSZ: Q>1.0

**DESY Hermes** 

N = (D, He, N, Kr)

**FNAL E-665** 

N = (D, C, Ca, Pb, Xe)

FNAL E-772 & E-886

N = (D, C, Ca, Fe, W)

#### **Neutrino DIS\***

NuTeV CHORUS CCFR & NuTeV

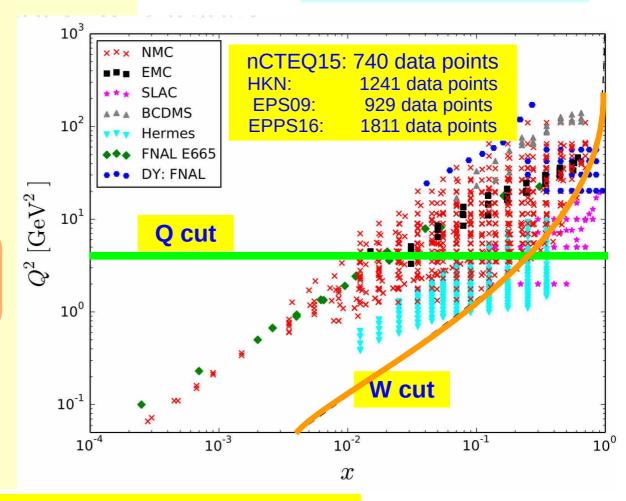
N = Pb & Fe

#### **Pion Production:**

RHIC: PHENIX & STAR

N = Au

will show comparision w/ LHC pPb



#### Data sets & cuts for nPDF fits

#### NC DIS & DY

SLAC E-139 & E-049

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N = (D, C, Ca, Fe, W)

# [GeV]

#### **Neutrino DIS\***

NuTeV CHORUS CCFR & NuTeV

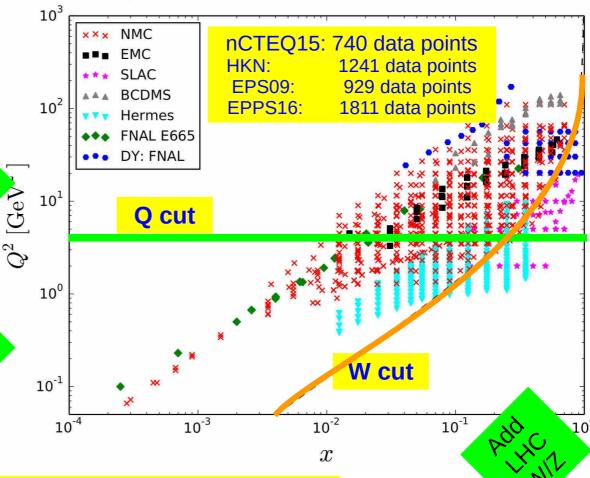
N = Pb & Fe

#### **Pion Production:**

**RHIC: PHENIX & STAR** 

N = Au

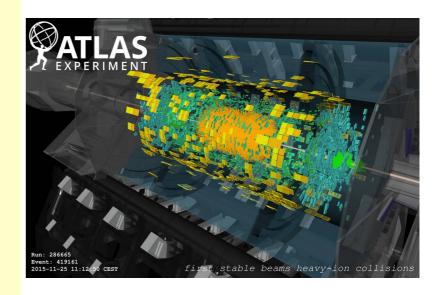
will show comparision w/ LHC pPb

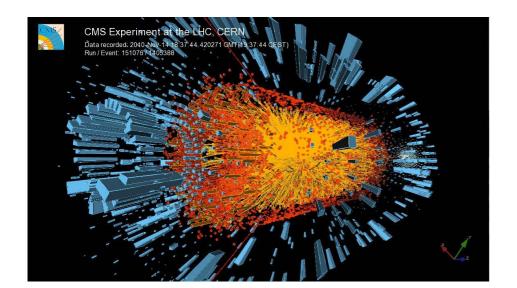


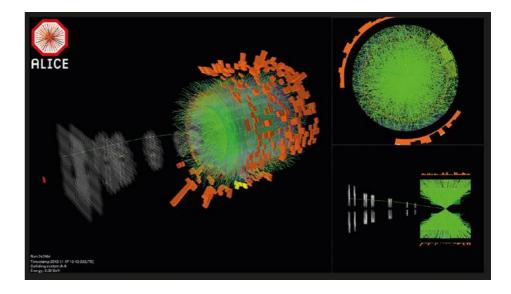
proton vs nuclear: fewer data and more DOF ... impose assumptions on nPDFs

#### **Heavy Ions at the LHC** CMS LHC LHCb ALICE SPS **ATLAS** AWAKE ΑD **ISOLDE** LINAC 2 LINAC 3 Antiproton Decelerator Proton Synchrotron n-TOF Neutron Time Of Flight Super Proton Synchrotron protons antiprotons AWAKE Advanced Wakefield Experiment LHC Large Hadron Collider electrons CTF3 CLIC Test Facility 3 neutrinos

#### ... focus on pPb Production





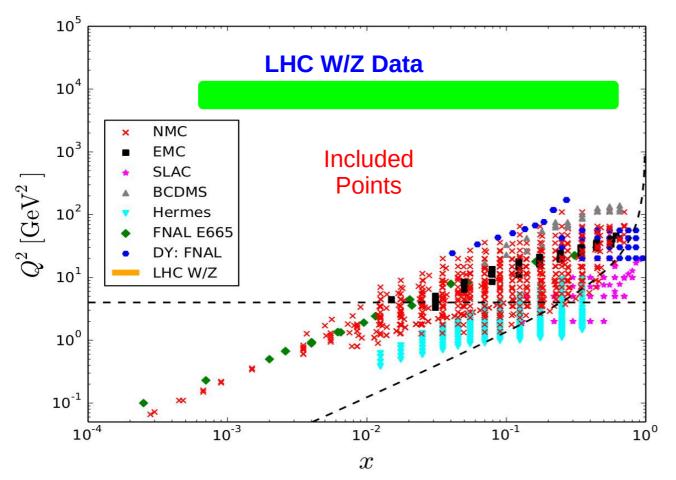


#### pPb Data for nCTEQ+LHC

# TM

#### No LHC data in any previous nCTEQ fit

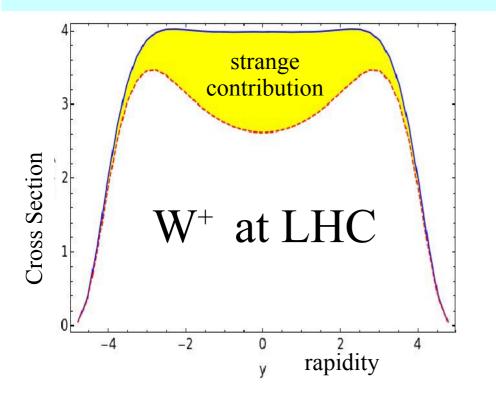
• New nCTEQ++ code using ApplGrid predictions make this possible

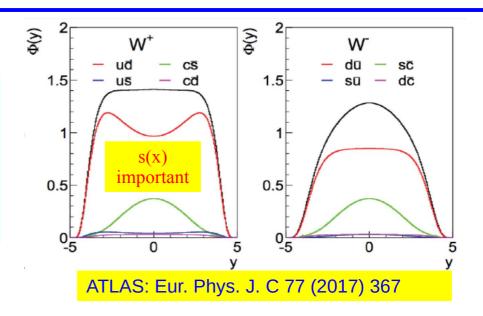


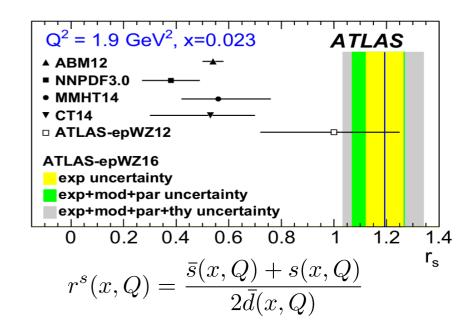
CMS	W+
CMS	W-
CMS ATLAS	Z W+
ATLAS	W-
ATLAS ALICE	Z W+
ALICE LHCb	W- Z
CMS_II	W+
CMS_II	W-

Fred Olness - SMU

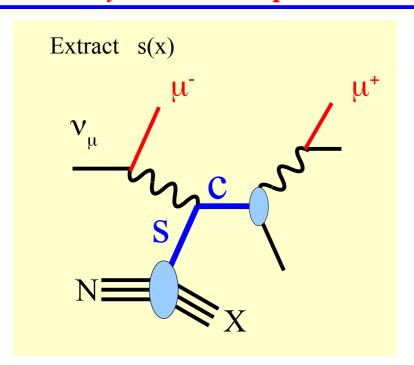
#### W/Z Production Channels

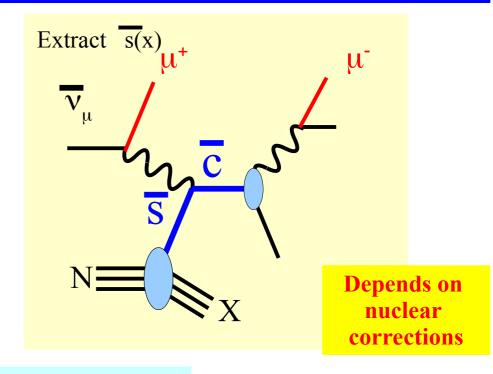






"The ATLAS and CMS inclusive W and Z differential cross section data... support unsuppressed strangeness... The result is dominated by the ATLAS data but is not in contradiction with the CMS data."



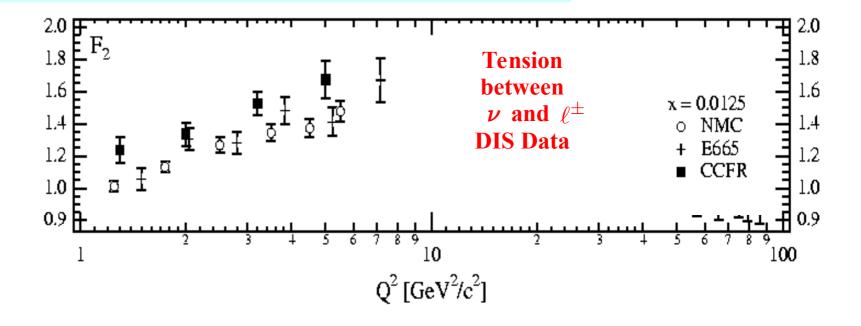


Can extract s(x) and  $\overline{s}(x)$  separately

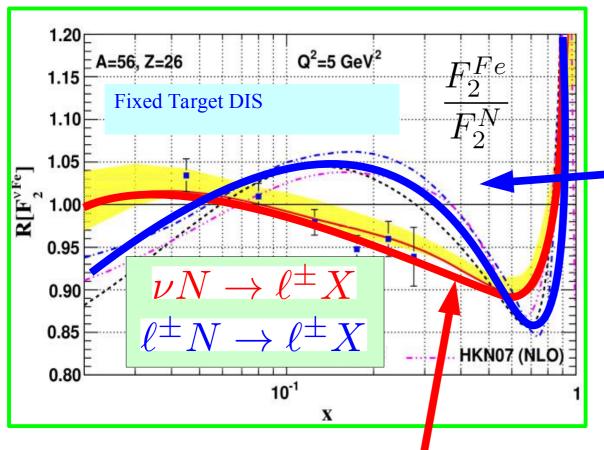
Used in CTEQ Fits

The CTEQ List of Challenges in Perturbative QCD

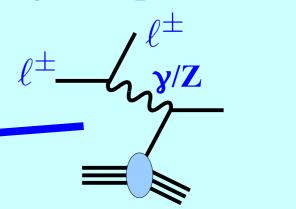
~1995



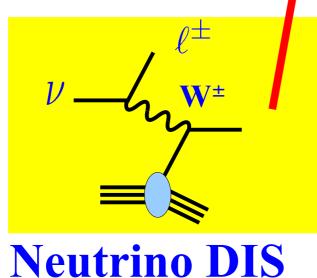
CTEQ



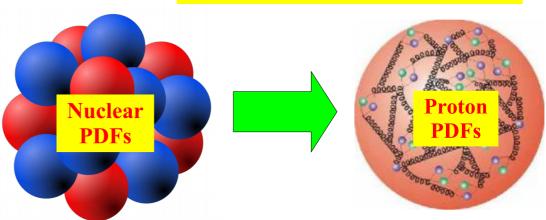
#### **Charged Lepton DIS**



some caveats
... correlated errors

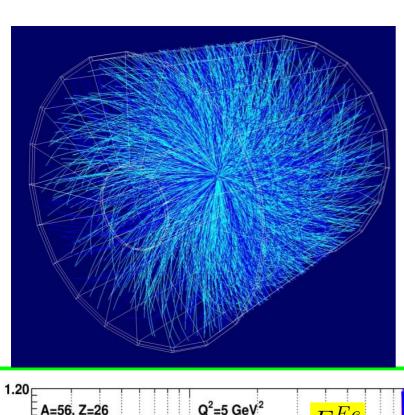


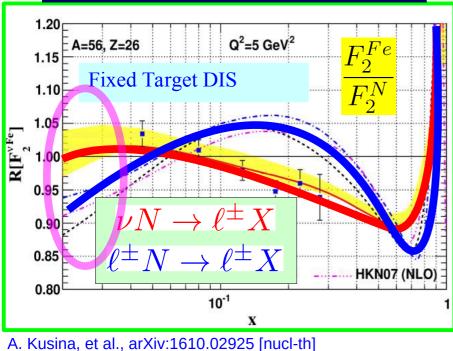


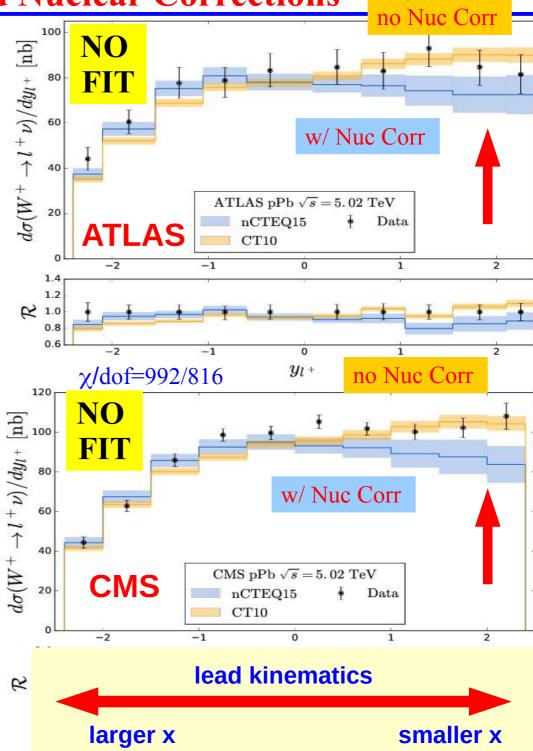


# Including W/Z Heavy Ion Data

#### $p Pb \rightarrow W/Z$ and Nuclear Corrections







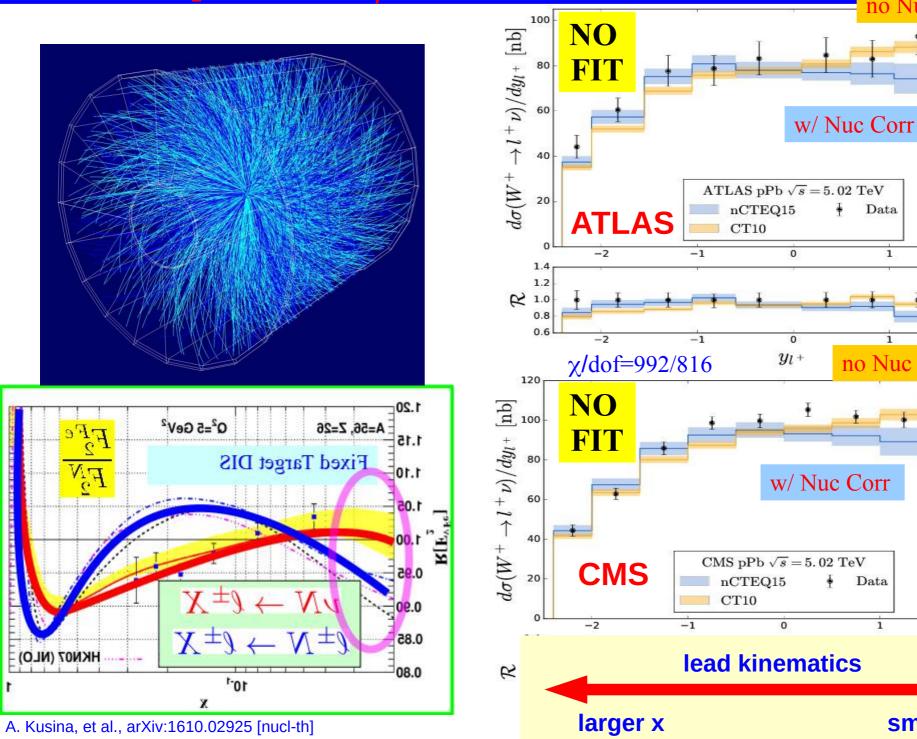
Data

no Nuc Corr

Data

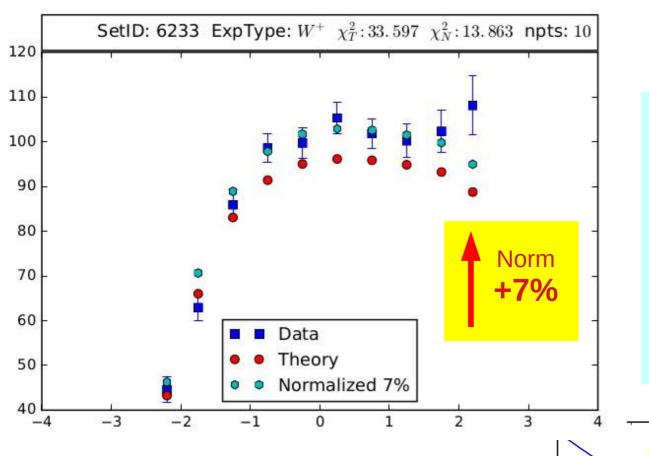
smaller x

#### $p Pb \rightarrow W/Z$ and Nuclear Corrections



#### Fit to LHC W/Z Data w/ Normalization

Frec

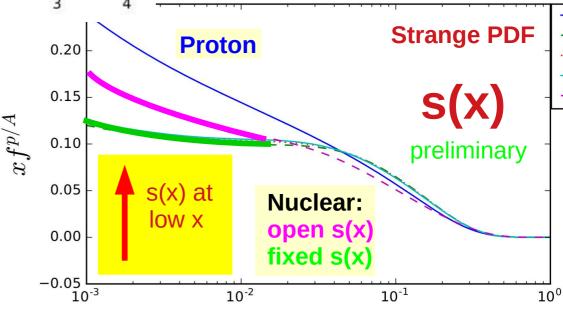




#### Fit + Normalization

- Improved  $\chi^2/d.o.f.$
- Seems to prefer larger strange PDF

The <u>preliminary</u> result is if we fit strange, the data prefers a larger s(x)



# include in fit w/ nCTEQ++

(using ApplGrids)

#### 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

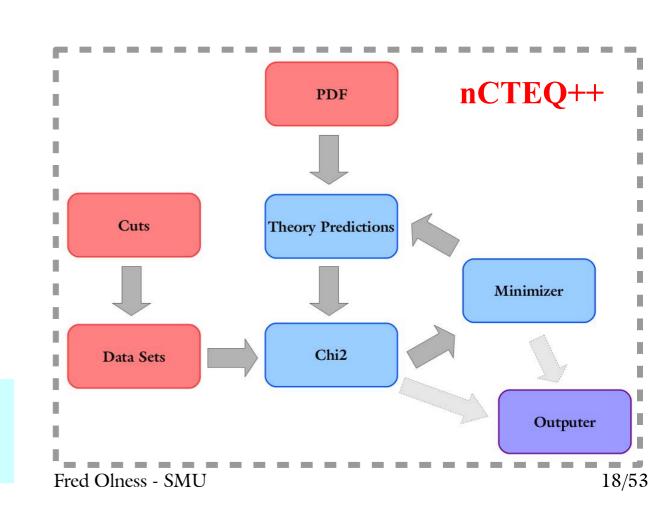
**Evolution** 

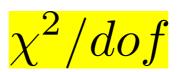
Interpolation

Parameterization

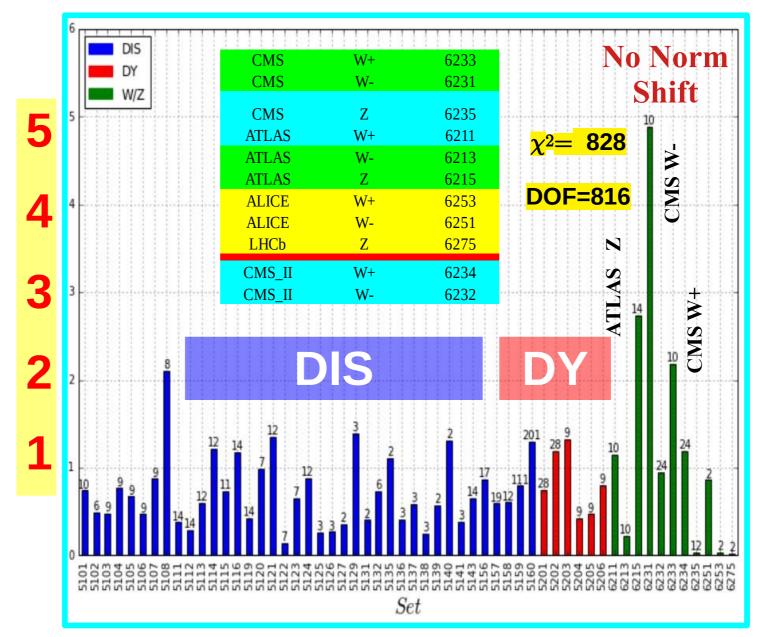
- Use external programs
  - Minuit
  - HOPPET
  - MCFM
  - APPLgrid

Special thanks to:
Florian Lyonnet
Tomas Jezo
Aleksander Kusina

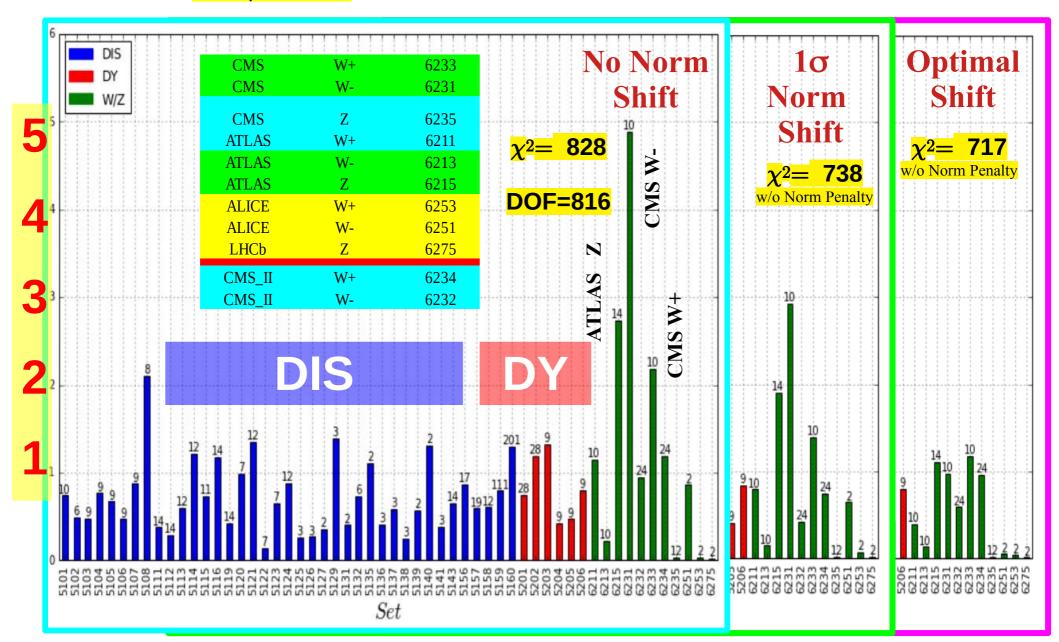


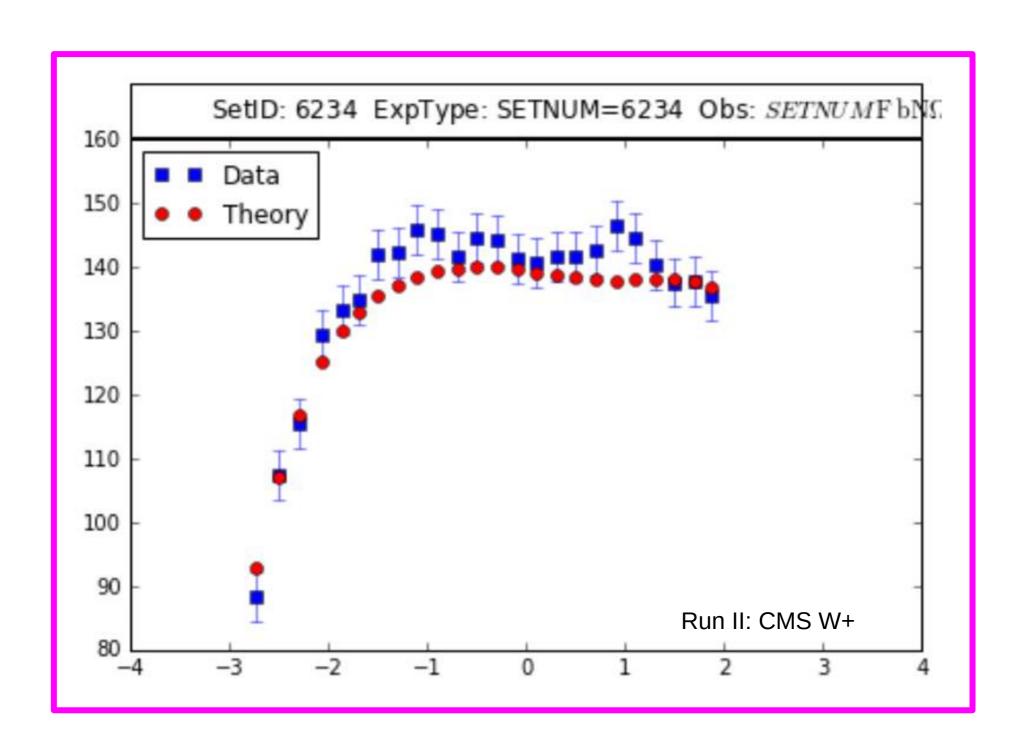


 $\chi^2$  992  $\rightarrow$ 828

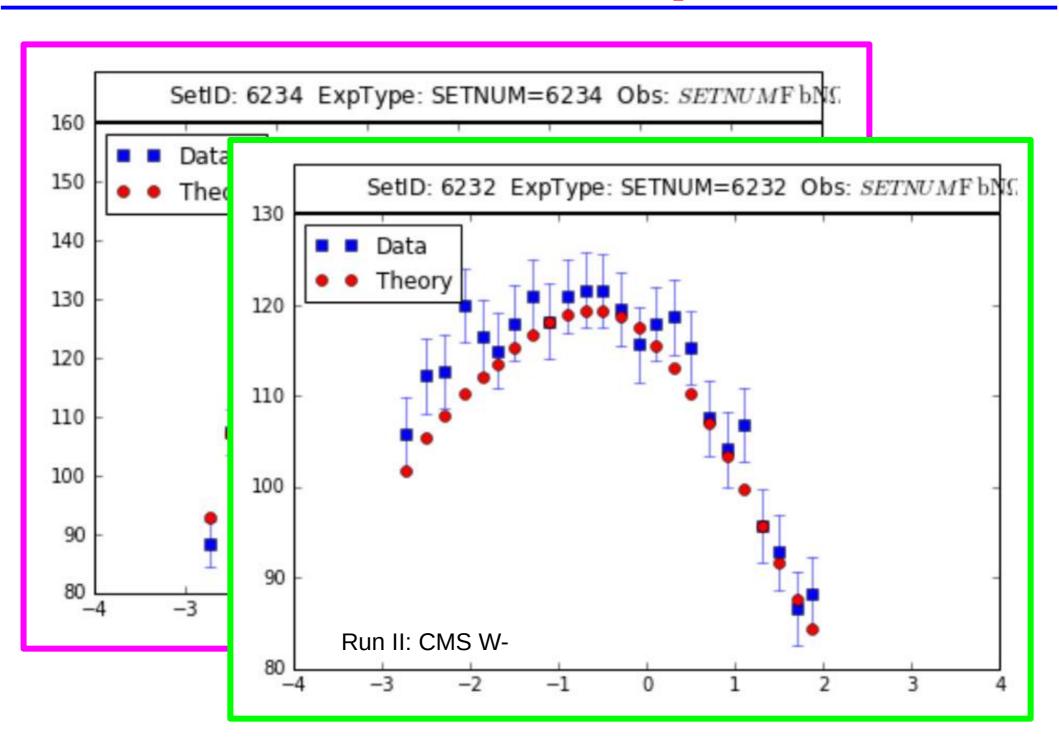


#### $\chi^2/dof$

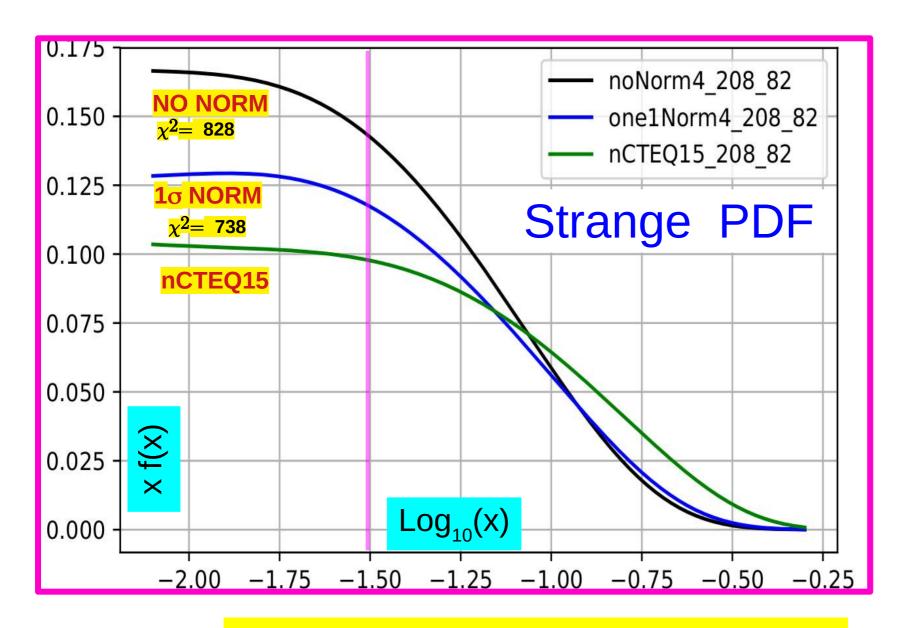




#### W/Z Data in fit: LHC p-Pb

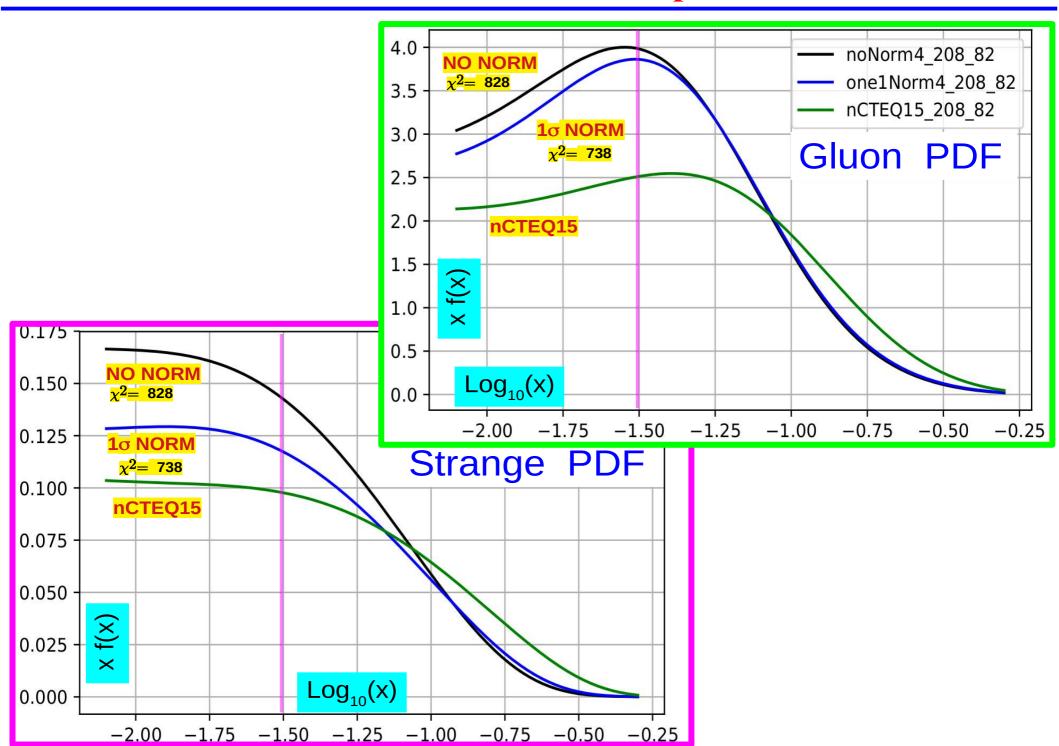


#### W/Z Data in fit: LHC p-Pb



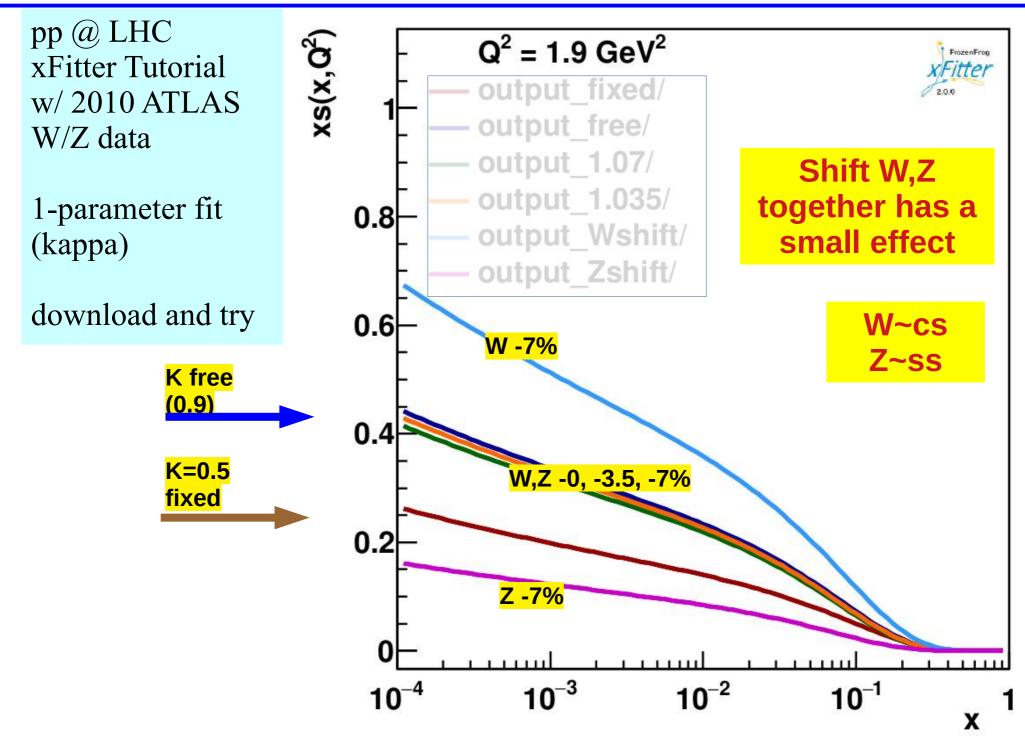
Is the strange PDF driving the data .... Or is the data driving the strange ???

#### W/Z Data in fit: LHC p-Pb



# a "toy" fit with xFitter

#### A Toy Fit with xFitter: (only 1 free parameter: κ)

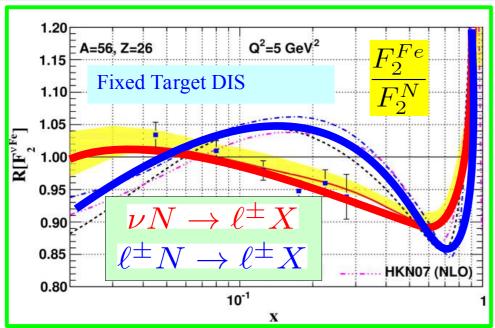


### Disentangling

S(X)

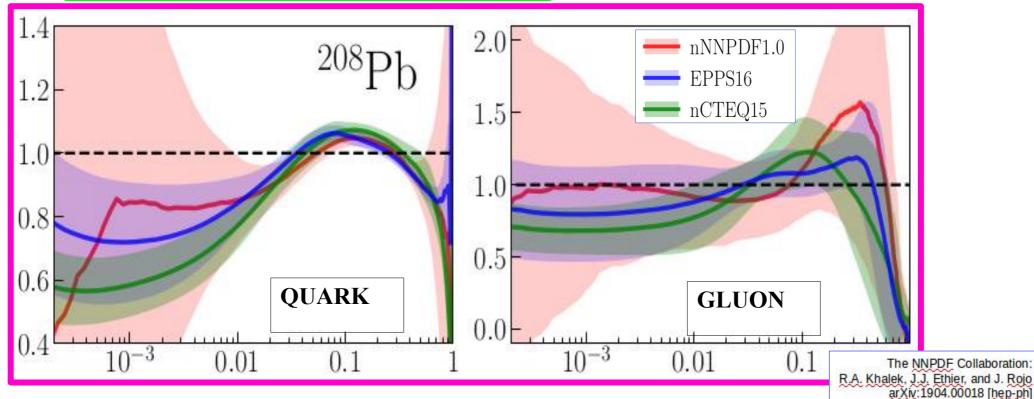
and the

nuclear corrections

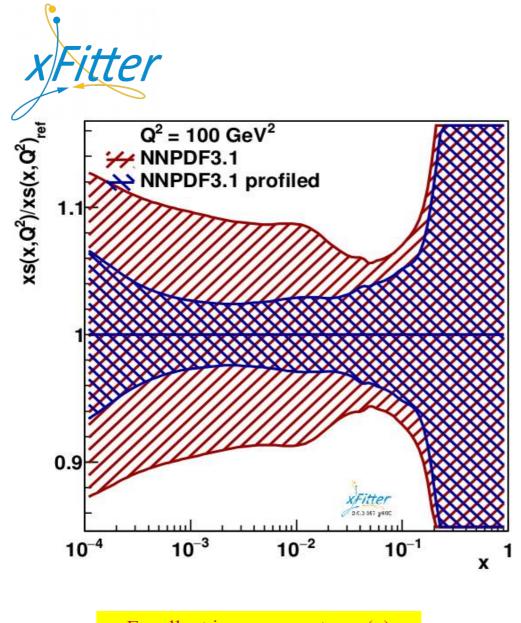


NCTEQ15 fit uses NC DIS

... interesting to try with Neutrino-DIS



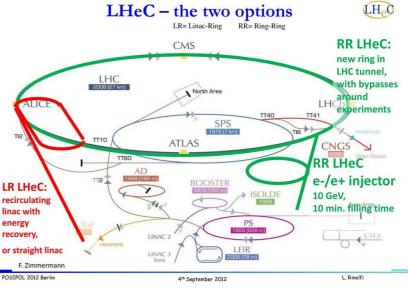
# Future Facilities



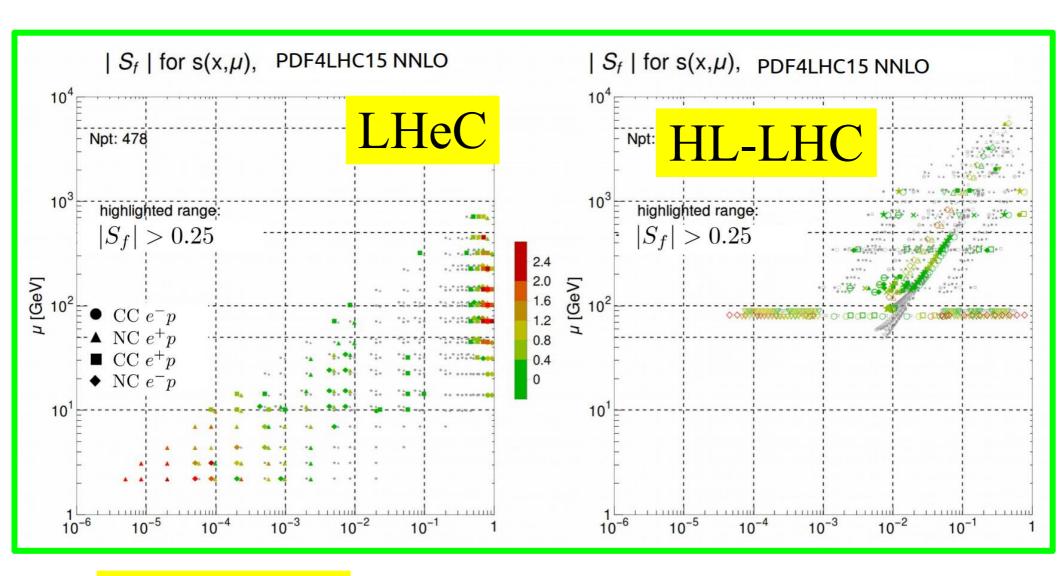
Excellent improvement on s(x) Additional improvement on g(x)







Sensitivity  $S_t$ : Extend concept of correlation (C) to include both pull and precision of experiment. (Technically, weight by scaled residual.)



See Talk By: Pavel Nadolsky (SMU)

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

#### **DIS** at **DUNE**

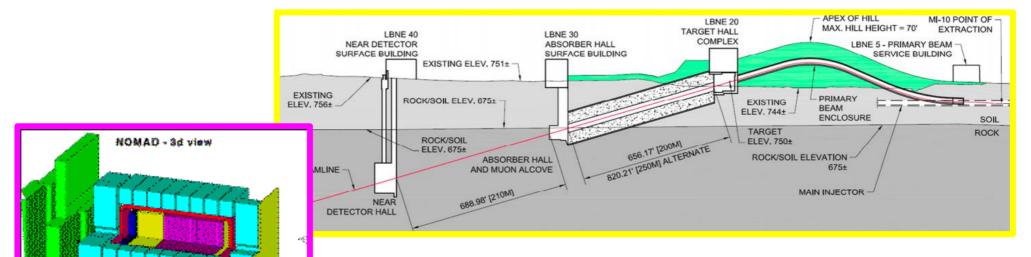
#### Extract vH from C and CH2 targets:

$$\nu H \to \ell^{\pm} X$$

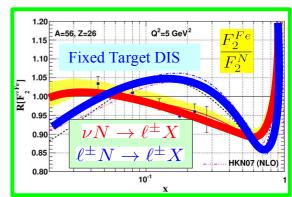
#### Enhancing the LBNF/DUNE Physics Program

**EPPSU 2020 Contribution** 

P. Bernardini<sup>1</sup>, S. Bertolucci<sup>2</sup>, M. Bhattacharjee<sup>3</sup>, B. Bhuyan<sup>3</sup>, S. Biagi<sup>11</sup>,
A. Caminata<sup>13</sup>, A. Cervelli<sup>6</sup>, S. Davini<sup>13</sup>, S. Di Domizio<sup>13</sup>, L. Di Noto<sup>13</sup>,
M. Diwan<sup>4</sup>, C. Distefano<sup>11</sup>, H. Duyang<sup>5</sup>, F. Ferraro<sup>13</sup>, A. Gabrielli<sup>2</sup>, M. Guerzoni<sup>6</sup>,
B. Guo<sup>5</sup>, M.A. Iliescu<sup>12,14</sup>, G. Laurenti<sup>6</sup>, G. Mandrioli<sup>6</sup>, N. Mauri<sup>2</sup>, S.R. Mishra<sup>5</sup>,
N. Moggi<sup>2</sup>, A. Montanari<sup>6</sup>, M. Pallavicini<sup>13</sup>, L. Pasqualini<sup>2</sup>, L. Patrizii<sup>6</sup>, R. Petti<sup>5</sup>,\*
M. Pozzato<sup>6</sup>, P. Sapienza<sup>11</sup>, F. H. Sawy<sup>7</sup>, G. Sirri<sup>6</sup>, L. Stanco<sup>8</sup>, A. Surdo<sup>9</sup>, M. Tenti<sup>10</sup>,
F. Terranova<sup>10</sup>, G. Testera<sup>13</sup>, M. Torti<sup>10</sup>, N. Tosi<sup>6</sup>, R. Travaglini<sup>6</sup>, and S. Zucchelli<sup>2</sup>

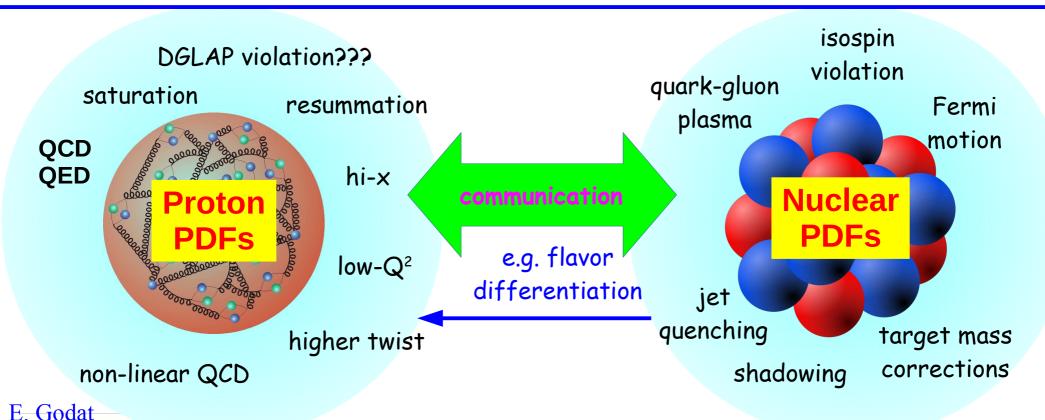


See Presentation by R. Petti Wednesday WG7



# Conclusions

#### ... the motivation for nCTEQ



T.J. Hobbs
T. Jezo,
J. Kent
C. Keppel,
K. Kovarik
A Kusina,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein.

J. Yu

Data from nuclear targets play a key role in the flavor differentiation



nuclear parton distribution functions



#### Thanks to my nCTEQ & xFitter colleagues

nctear parton distribution functions

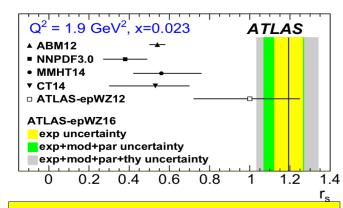




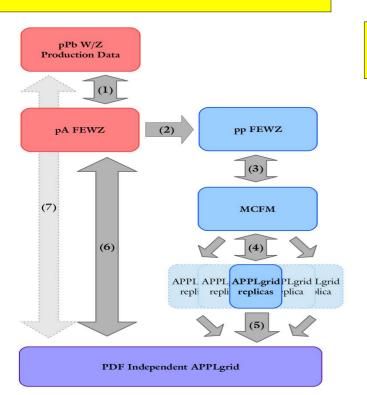




#### **New Data & New Theoretical Tools**



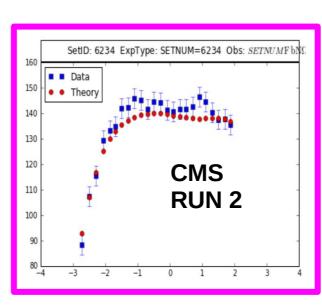
#### **The Strange PDF Puzzle**



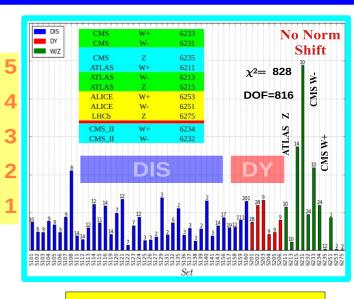
**New Theory Tools** 



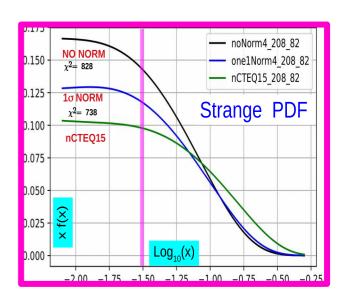
Nuclear Data Essential for PDFs



**New Analyses** 



#### **Tensions Evident**



**New Perspectives** 

F. Olness DIS April 2019 36

# Extras

How can we include these new processes into the fit directly???

### 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

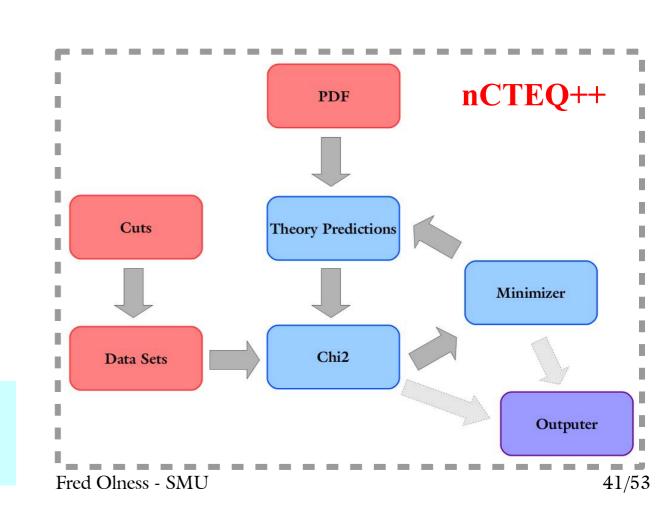
**Evolution** 

Interpolation

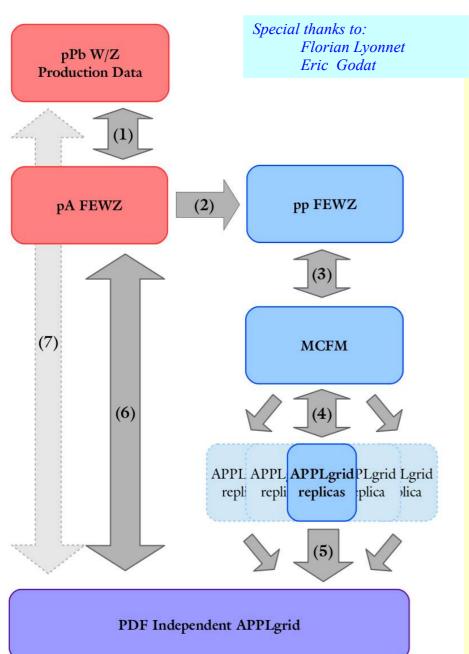
Parameterization

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

Special thanks to:
Florian Lyonnet
Tomas Jezo
Aleksander Kusina



### Use MCFM + APPLgrid for pPb





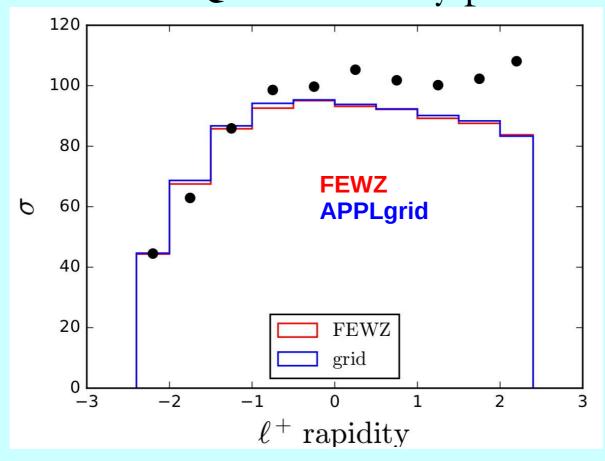
- (1)Data matched to pA-FEWZ in reweighting
- (2) Run FEWZ in symmetric pp mode
- (3)Compare pp FEWZ to pp MCFM
- (4) Generate APPLgrid grids
  - · Using mcfm-bridge
- · Different Monte Carlo seeds
- (5) Combine replica grids into a single PDF independent grid
- · Using applgrid-combine
- (6)Convolute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

### They Match!!!

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



Convoluted grids can then be compared to data and used in nCTEQ++ as theory predictions



### 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	$f(p_1) + f(p_2) \rightarrow \dots$	Order
1	$W^+(\to \nu(p_3) + e^+(p_4))$	NLO [
6	$W^-(\to e^-(p_3) + \bar{\nu}(p_4))$	NLO
11	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5)$	NLO
12	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{b}(p_5)$	NLO
13	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$	NLO
14	$W^{+}(\to \nu(p_3) + e^{+}(p_4)) + \bar{c}(p_5)$ [massless]	LO
16	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
17	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$	NLO
18	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$	NLO
19	$W^-( o e^-(p_3) + ar{ u}(p_4)) + c(p_5)[{ m massless}]$	LO

	, , , , ,	
nproc	$f(p_1) + f(p_2) \rightarrow$	Order
1	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4}))$	NLO
6	$W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}))$	NLO
11	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + f(p_5)$	NLO
12	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + \tilde{b}(p_{5})$	NLO
13	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + \bar{c}(p_{5})$	NLO
14	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$ [massless]	LO
16	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
17	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + b(p_5)$	NLO
18	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + c(p_5)$	NLO
19	$W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + c(p_{5})[\text{massless}]$	LO
20	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + b(p_{5}) + b(p_{6})$ [massive]	NLO
21	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
22	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + f(p_5) + f(p_6)$	NLO
23	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
24	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
25	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)[massive]$	NLO
26	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
27	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$	NLO
28	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
29	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
31	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4}))$	NLO
32	$Z^0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4)))$	NLO
33	$Z^0(\rightarrow b(p_3) + \bar{b}(p_4))$	NLO
34	$Z^0(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
35	$Z^0(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
36	$Z \rightarrow t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{b}(p_6) + e^-(p_7) + \bar{\nu}(p_8))$	LO
41	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + f(p_{5})$	NLO
42	$Z_0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + f(p_5)$	NLO
43	$Z^{0}(\rightarrow b(p_{3}) + \bar{b}(p_{4})) + f(p_{5})$	NLO
44	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + f(p_{5}) + f(p_{6})$	NLO
45	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + f(p_{5}) + f(p_{6}) + f(p_{7})$	LO
46	$Z^{0}(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$	NLO
47	$Z^{0}(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
50	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + b(p_{5}) + b(p_{6})[massive]$	LO
51	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + b(p_{5}) + \bar{b}(p_{6})$	NLO
52	$Z_0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + b(p_5) + \bar{b}(p_6)$	NLO
53	$Z^{0}(\rightarrow b(p_{3}) + \bar{b}(p_{4})) + b(p_{5}) + \bar{b}(p_{6})$	NLO
54	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + b(p_{5}) + \bar{b}(p_{6}) + f(p_{7})$	LO

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	101	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + H(\rightarrow b(p_{5}) + b(p_{6}))$	NLO
	102	$Z^{0}(\rightarrow 3 \times (\nu(p_{3}) + \bar{\nu}(p_{4}))) + H(\rightarrow b(p_{5}) + \bar{b}(p_{6}))$	NLO
	103	$Z^{0}(\rightarrow b(p_{3}) + \bar{b}(p_{4})) + H(\rightarrow b(p_{5}) + \bar{b}(p_{6}))$	NLO
	104		NLO
	105		NLO
	106		NLO
	107		NLO
	108		NLO
ı	109		NLO
ŀ	111		NLO
ı	112		NLO
	113		NLO
	114		NLO
H	115		NLO
H	116		NLO
	117		NLO
			NLO
	118		NLO
	120		NLO
-			
Į	121	$H(\rightarrow Z^{0}(3 \times (\nu(p_{3}) + \bar{\nu}(p_{4})))) + \gamma(p_{5}))$	NLO
_			
	56	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + c(p_{5}) + \bar{c}(p_{6})$	NLO
	61	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + W^{-}(\rightarrow e^{-}(p_5) + \bar{\nu}(p_6))$	NLO
ŀ	62	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + W^{-}(\rightarrow q(p_5) + \bar{q}(p_6))$	NLO
ŀ	63	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + W^{-}(\rightarrow q(p_5) + \bar{q}(p_6))[rad.in.dk]$	NLO
Į,	64	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4))W^{+}(\rightarrow q(p_5) + \bar{q}(p_6))$	NLO
١,	65	$W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}))W^{+}(\rightarrow q(p_{5}) + \bar{q}(p_{6}))[rad.in.dk]$	NLO
١,	66	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + W^{-}(\rightarrow e^{-}(p_5) + \bar{\nu}(p_6)) + f(p_7)$	LO
	69	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + W^{-}(\rightarrow e^{-}(p_{5}) + \bar{\nu}(p_{6}))[\text{no pol}]$	LO
	71	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z^0(\rightarrow e^-(p_5) + e^+(p_6))$	NLO
	72	$W^{+}(\rightarrow \nu(p_{3}) + \mu^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu_{e}(p_{5}) + \bar{\nu}_{e}(p_{6})))$	NLO
	73	$W^+(\rightarrow \nu(p_3) + \mu^-(p_4)) + Z^-(\rightarrow 3 \times (\nu_e(p_5) + \nu_e(p_6)))$ $W^+(\rightarrow \nu(p_4) + \mu^+(p_4)) + Z^0(\rightarrow b(p_5) + \bar{b}(p_e))$	NLO
	74		NLO
		$W^{+}(\rightarrow \nu(p_3) + \mu^{+}(p_4)) + Z^{0}(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	
	75	$W^{+}(\rightarrow \nu(p_3) + \mu^{+}(p_4)) + Z^{0}(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
	76	$W^-(\rightarrow \mu^-(p_3) + \bar{\nu}(p_4)) + Z^0(\rightarrow e^-(p_5) + e^+(p_6))$	NLO
	77	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + Z^{0}(\rightarrow 3 \times (\nu_e(p_5) + \bar{\nu}_e(p_6)))$	NLO
l.	78	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + Z^{0}(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
l.	79	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z^0(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
1.	80	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + Z^{0}(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
T.	81	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow \mu^{-}(p_{5}) + \mu^{+}(p_{6}))$	NLO
	82	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))$	NLO
	83	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow b(p_{5}) + \bar{b}(p_{6}))$	NLO
	84	$Z^{0}(\rightarrow b(p_{3}) + \bar{b}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))$	NLO
	85	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6}))) + f(p_{7})$	LO
	86	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{-}(p_{4})) + Z^{0}(\rightarrow e^{-}(p_{5}) + e^{+}(p_{6}))) + J(p_{7})$ $Z^{0}(\rightarrow \mu^{-}(p_{3}) + \mu^{+}(p_{4})) + Z^{0}(\rightarrow e^{-}(p_{5}) + e^{+}(p_{6}))[\text{no gamma*}]$	NLO
	87		
		$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))[\text{no gamma*}]$	NLO
	88	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow b(p_{5}) + \bar{b}(p_{6}))[\text{no gamma*}]$	NLO
	89	$Z^{0}(\rightarrow b(p_{3}) + \bar{b}(p_{4})) + Z^{0}(\rightarrow 3 \times (\nu(p_{5}) + \bar{\nu}(p_{6})))[\text{no gamma*}]$	NLO
	90	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + Z^{0}(\rightarrow e^{-}(p_{5}) + e^{+}(p_{6}))$	NLO
	91	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
	92	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + H(\rightarrow W^{+}(\nu(p_5), e^{+}(p_6))W^{-}(e^{-}(p_7), \bar{\nu}(p_8)))$	NLO
1	93	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + H(\rightarrow Z(e^{-}(p_5), e^{+}(p_6)) + Z(\mu^{-}(p_7), \mu(p_8)))$	NLO
1	94	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + H(\rightarrow \gamma(p_5) + \gamma(p_6)$	NLO
1	96	$W^{-}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4})) + H(\rightarrow b(p_{5}) + \bar{b}(p_{6}))$	NLO
	97	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + H(\rightarrow W^{+}(\nu(p_5), e^{+}(p_6))W^{-}(e^{-}(p_7), \bar{\nu}(p_8)))$	NLO
	98	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + H(\to Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu^+(p_8)))$	NLO
		$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + H(\to \gamma(p_5) + \gamma(p_6))$	NLO
	99		

123	$H(\rightarrow W^{+}(\nu(p_{3}) + e^{+}(p_{4})) + W^{-}(e^{-}(p_{5}) + \bar{\nu}(p_{6})))$ [top, bottom loops, exact]	LO
124	$H(\rightarrow W^{+}(\nu(p_{3}) + e^{+}(p_{4})) + W^{-}(e^{-}(p_{5}) + \bar{\nu}(p_{6})))$ [only H, gg $\rightarrow$ WW intf.	LO
125	$H(\rightarrow W^{+}(\nu(p_{3}) + e^{+}(p_{4})) + W^{-}(e^{-}(p_{5}) + \bar{\nu}(p_{6})))$ [ $ H ^{2}$ and $H,gg\rightarrow WW$ intf.]	LO
126	$W^{+}(\nu(p_3) + e^{+}(p_4)) + W^{-}(e^{-}(p_5) + \bar{\nu}(p_6))$ [gg only, (H + gg $\rightarrow$ WW) squared]	LO
127	$W^{+}(\nu(p_3) + e^{+}(p_4)) + W^{-}(e^{-}(p_5) + \bar{\nu}(p_6))$ [(gg $\rightarrow$ WW) squared]	LO
128	$H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6))$ [top, bottom loops, exact]	LO
129	$H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6))$ [only H, gg $\rightarrow$ ZZ intf.]	LO
130	$H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6))$ [ $ H ^{2}$ and H,gg $\rightarrow$ ZZ intf.]	LO
131	$Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6))$ [gg only, (H + gg $\rightarrow$ ZZ) squared]	LO
132	$Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6))$ [(gg $\rightarrow$ ZZ) squared]	LO
1281	$H(\rightarrow e^{-}(p3) + e^{+}(p4)\nu_{e}(p5) + \bar{\nu}_{e}(p6)$ [top, bottom loops, exact]	LO
1311	$e^-(p3) + e^+(p4) + \nu_e(p5) + \bar{\nu}_e(p6)$ [gg only, (H + gg $\rightarrow$ ZZ) squared]	LO
1321	$e^{-}(p3) + e^{+}(p4) + \nu_{e}(p5) + \bar{\nu}_{e}(p6)$ [(gg $\to$ ZZ) squared]	LO
1282	$H(\rightarrow e^{-}(p3) + e^{+}(p4) + \nu(p5) + \bar{\nu}(p6)$ [top, bottom loops, exact]	LO
1312	$e^{-}(p3) + e^{+}(p4) + \nu(p5) + \bar{\nu}(p6)$ [gg only, (H + gg $\rightarrow$ ZZ) squared]	LO
1322	$e^{-}(p3) + e^{+}(p4) + \nu(p5) + \bar{\nu}(p6)$ [(gg $\to$ ZZ) squared]	LO
133	$H(\rightarrow Z^{0}(e^{-}(p3) + e^{+}(p4)) + Z^{0}(\mu^{-}(p5) + \mu^{+}(p6) + f(p7))$ [intf,no $p_{7}$ cut]	LO
136	$H(\rightarrow b(p_3) + b(p_4)) + b(p_5)(+g(p_6))$	NLO
137	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + \bar{b}(p_5)(+b(p_6))$	(REAL)
138	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)[both observed]$	(REAL)
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
142	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.dk]	NLO
143	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + f(p_9)$	LO
144	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8))$ (uncorr)	NLO
	4( - u(u ) + u+(u ) + U(u ) + T( - U(u ) + u-(u ) + T(u ) (u	- 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
142		NLO
143		LO
144		NLO
145		NLO
146		NLO
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.in.top.dk]	NLO
148	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b\ (p_6) + q(p_7) + \bar{q}(p_8))$ [rad.in.W.dk]	NLO
149	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8))$	NLO
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.in.top.dk]	NLO
151	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.W.dk]	NLO
157	$t\bar{t}$ [for total Xsect]	NLO
158	$b\bar{b}[\text{for total Xsect}]$	NLO
159	cc[for total Xsect]	NLO
160	$t\bar{t} + g[\text{for total Xsect}]$	LO
161	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)[t\text{-channel}]$	NLO
162		NLO
163		NLO
166		NLO
167	$\bar{t}(\rightarrow e^{-}(p_{5}) + \bar{\nu}(p_{4}) + \bar{b}(p_{5})) + q(p_{6})[rad.in.dk]$	NLO
168	$\bar{t}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)[\text{t-channel}]mb > 0$	NLO
171	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6))$ [s-channel]	NLO
172		NLO
176	$\bar{t}(\rightarrow e^{-}(p_{3}) + \bar{\nu}(p_{4}) + \bar{b}(p_{5})) + b(p_{6}))$ [s-channel]	NLO
177	$\bar{t}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6))$ [rad.in.dk]	NLO
180	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + t(p_5)$	NLO
181	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$	NLO
182	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$ [rad.in.dk]	NLO
183	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + b(p_8)$	LO
184	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + b(p_6)$ [massive b]	LO
185	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + \bar{t}(p_{5})$	NLO
186	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + \bar{t}(e^{-}(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)$	NLO
187	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + \bar{t}(e^{-}(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)[rad.in.dk]$	NLO

270	$H(\gamma(p_3) + \gamma(p_4)) + f(p_5) + f(p_6)$ in heavy top limit	NLO	Г
271	$H(b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6) in \text{ heavy top limit} $	NLO	
272		NLO	
273	$H(\rightarrow W^{+}(\nu(p_3), e^{+}(p_4))W^{-}(e^{-}(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8)$	NLO	ı
274	$H(\rightarrow Z(e^{-}(p_3), e^{+}(p_4))Z(\mu^{-}(p_5), \mu^{+}(p_6))) + f(p_7) + f(p_8)$	NLO	
275	$H(b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [in heavy top limit]	LO	
276		LO	Γ
278	$H(\rightarrow W^{+}(\nu(p_3), e^{+}(p_4))W^{-}(e^{-}(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8) + f(p_9)$	LO	
279	$H(\rightarrow Z(e^-(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8) + f(p_9)$	LO	
280		NLO+F	
282		LO	- 1
283		LO	ŀ
284		LO	
285		NLO+F	
286		NLO+F	
287		NLO+F	
290		NLO+F	
292	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + \gamma(p_5) + f(p_6)$	LO	- 1
295	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + \gamma(p_5)$	NLO+F	
297		LO	
300	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5})$	NLO+F	
301	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + \gamma(p_{6})$	NLO +F	
302	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + f(p_{6})$	NLO + F	ŀ
303	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + \gamma(p_{6}) + f(p_{7})$	LO	
304	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + \gamma(p_{5}) + f(p_{6}) + f(p_{7})$	LO	- 1
305		NLO + F	
306		NLO + F	
307	$Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + f(p_{6})$	NLO + F	
308	$Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + \gamma(p_{6}) + f(p_{7})$	LO	
309	$Z^{0}(\rightarrow 3(\nu(p_{3}) + \bar{\nu}(p_{4}))) + \gamma(p_{5}) + f(p_{6}) + f(p_{7})$	LO	
311	$f(p_1) + b(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$	LO	
316	$f(p_1) + b(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6)$	LO	- 1
321	$f(p_1) + c(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + c(p_5) + f(p_6)$	LO	
326		LO	
331	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + c(p_{5}) + f(p_{6})[c-s interaction]$	LO	
336	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5) + f(p_6)$ [c-s interaction]	LO	
341	$f(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)[+f(p_7)]$	NLO	
342		(REAL)	
346		LO	- 1
347	$f(p_1) + b(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) \ 84e^+(p_4)) + b(p_5) + f(p_6) + \bar{b}(p_7)$	LO	Ļ
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) $	NLO	
352		(REAL)	
	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+\bar{c}(p_7)]$		
356	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + f(p_7)$	LO	

	351	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+f(p_7)]$	NLO
- 1	352	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+\bar{c}(p_7)]$	(REAL)
	356	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + f(p_7)$	LO
- 1	357	$f(p_1) + c(p_2) \rightarrow Z^0(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + \bar{c}(p_7)$	LO
Ì	361	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))[mc=0 \text{ in NLO}]$	NLO
- 1	362	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))$ [massless corrections only]	NLO
	363	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4))$ [massive charm in real]	NLO
Ī	370	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + \gamma(p_5) + \gamma(p_6)$	LO
	371	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + \gamma(p_6)$	LO
Ī	401	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS]	NLO
- 1	402	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + (b + \bar{b})(p_{5})$ [1 or 2 jets, 4FNS]	NLO
	403	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5) + \bar{b}(p_6)$ [2 or 3 jets, 4FNS]	NLO
	406	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS]	NLO
	407	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS]	NLO
	408	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ [2 or 3 jets, 4FNS]	NLO
Î	411	$f(p_1) + b(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$ [5FNS]	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
Ī	421	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS]	NLO
	426	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS]	NLO
Ī	431	$W^{+}(\rightarrow \nu(p_3) + e^{+}(p_4)) + b(p_5) + b(p_6) + f(p_7)$ [massive]	LO
	436	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$ [massive]	LO
ſ	500	$W^{+}(\rightarrow \nu(p_{3}) + e^{+}(p_{4})) + t(p_{5}) + \bar{t}(p_{6})[\text{massive}]$	NLO
	501	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
	502	(same as process 501 but with radiation in decay)	NLO
	503	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b\ (p_6) + q(p_7) + q\ (p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
	506	$t(\rightarrow q(p_3) + q(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
ſ	510	$W^{-}(\rightarrow e^{-}(p_3) + \bar{\nu}(p_4)) + t(p_5) + \bar{t}(p_6)[massive]$	NLO
- 1	511	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
	512	(same as process 511 but with radiation in decay)	NLO
	513	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b (p_6) + q(p_7) + q (p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
	516	$t(\rightarrow q(p_3) + q^-(p_4) + b(p_5)) + \bar{t}(\rightarrow b^-(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
	529	$Z^{0}(\rightarrow e^{-}(p_{3}) + e^{+}(p_{4})) + t(p_{5}) + \bar{t}(p_{6})$	LO
	530	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO
	531	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10}))$	LO
	532	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow q(p_7) + \bar{q}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO
Į	533	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO

540	$H(b(p_3) + \bar{b}(p_4)) + t(p_5) + q(p_6)$	NL
541	$H(b(p_3) + \bar{b}(p_4)) + \bar{t}(p_5) + q(p_6)$	NL
544	$H(b(p_3) + \bar{b}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + q(p_9)$	NL
547	$H(b(p_3) + \bar{b}(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9)$	NL
550	$H(\gamma(p_3) + \gamma(p_4)) + t(p_5) + q(p_6)$	NL
551	$H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(p_5) + q(p_6)$	NL
554	$H(\gamma(p_3) + \gamma(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + q(p_9)$	NL
557	$H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9)$	NL
560	$Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6)$	NL
561	$Z(e - (p_3) + e + (p_4)) + \bar{t}(p_5) + q(p_6)$	NL
562	$Z(e - (p_3) + e + (p_4)) + t(p_5) + q(p_6) + f(p_7)$	LO
563	$Z(e - (p_3) + e + (p_4)) + \bar{t}(p_5) + q(p_6) + f(p_7)$	LO
564	$Z(e - (p_3) + e + (p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8)$	NL
566	$Z(e - (p_3) + e + (p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8) + f(p_9)$	LO
567	$Z(e - (p_3) + e + (p_4)) + \bar{t}(\rightarrow e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8)$	NL
569	$Z(e - (p_3) + e + (p_4)) + \bar{t}(\rightarrow e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8) + f(p_9)$	LO
601	$H(b(p_3) + \bar{b}(p_4)) + H(\tau^-(p_5) + \tau^+(p_6))$	LO
602	$H(b(p_3) + \bar{b}(p_4)) + H(\gamma(p_5) + \gamma(p_6))$	LO
640	$t(p_3) + \bar{t}(p_4) + H(p_5)$	LO
641	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
644	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
647	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
651	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
654	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
657	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
661	$t(\rightarrow \nu(p_3)e^+(p_4)b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7)e^-(p_8)\bar{b}(p_6)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{12}))$	LO
664	$t(\rightarrow \nu(p_3)e^+(p_4)b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7)q(p_8)\bar{b}(p_6)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{12}))$	LO
667	$t(\rightarrow q(p_3)\bar{q}(p_4)b(p_5)) + \bar{t} \rightarrow (\bar{\nu}(p_7)e^-(p_8)\bar{b}(p_6)) + H(W^+(p_9,p_{10})W^-(p_{11},p_{12}))$	LO

107	$t(\rightarrow q(p_3)q(p_4)b(p_5)) + t \rightarrow (\nu(p_7)e^-(p_8)b(p_6)) + H(W^+(p_9,p_{10})W^-(p_{11},p_{12}))$	) LO
800	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Vector Mediator]	NLO
801	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Axial Vector Mediator]	NLO
802	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator]	NLO
803	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Pseudo Scalar Mediator]	NLO
804	$GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Gluonic DM operator]	NLO
805	$S(\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator, mt loops]	NLO
820	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Vector Mediator]	NLO + F
821	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)[\text{Axial Vector Mediator}]$	NLO + F
822	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)[\text{Scalar Mediator}]$	NLO + F
823	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Pseudo Scalar Mediator]	NLO + F
840	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Vector Mediator]	LO
841	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Axial Vector Mediator]	LO
842	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Scalar Mediator]	LO
843	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Pseudo Scalar Mediator]	LO
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
846	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Axial Vector Mediator]	LO
847	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Scalar Mediator]	LO
848	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Pseudo Scalar Mediator]	LO
902	Check of Volume of 2 particle phase space	
903	Check of Volume of 3 particle phase space	
904	Check of Volume of 4 particle phase space	
905	Check of Volume of 5 particle phase space	
906	Check of Volume of 6 particle phase space	
908	Check of Volume of 8 particle phase space	
909	Check of Volume of 4 particle massive phase space	
910	Check of Volume of 3 particle (2 massive) phase space	
911	Check 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	
913	Check of Volume of 5 particle W+t+g (in decay) massive phase space	
914	Check of Volume of 5 particle W+t+g (in production) massive phase space	

LHC

RR LHeC:

new ring in LHC tunnel,

LHCberperiments

10 min. filling time

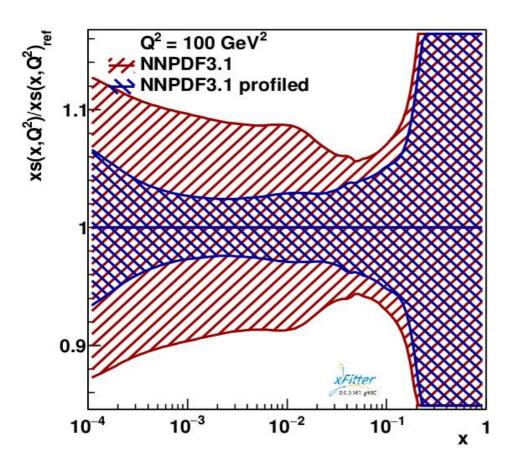
RR LHeC e-/e+ injector

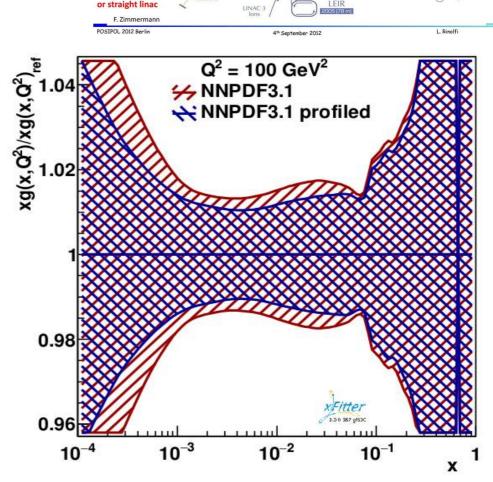
10 GeV,

with bypasses



Additional improvement on g(x)





LHeC - the two options

CMS

**ATLAS** 

LINAC 2

LHC 2008 (27 km)

LR LHeC:

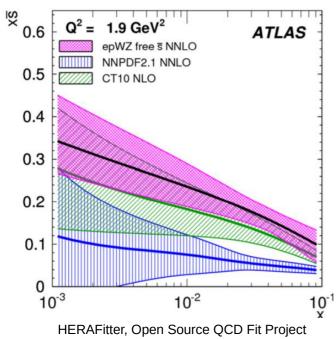
recirculating

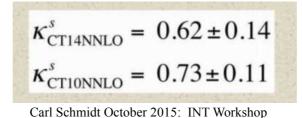
#### ... I want a second opinion, ...

$$\kappa(Q) = \frac{\int_0^1 x \left[ s(x,Q) + \bar{s}(x,Q) \right] dx}{\int_0^1 x \left[ \bar{u}(x,Q) + \bar{d}(x,Q) \right] dx} \quad r^s(x,Q) = \frac{\bar{s}(x,Q) + s(x,Q)}{2\bar{d}(x,Q)} \quad R^s(x,Q) = \frac{s(x,Q) + \bar{s}(x,Q)}{\bar{u}(x,Q) + \bar{d}(x,Q)}$$

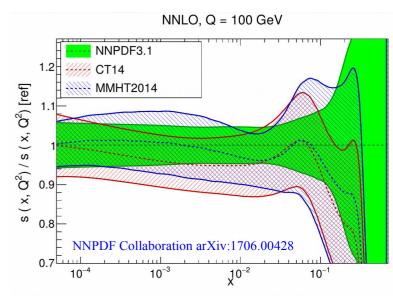
$$r^{s}(x,Q) = \frac{\overline{s}(x,Q) + s(x,Q)}{2\overline{d}(x,Q)}$$

$$R^{s}(x,Q) = \frac{s(x,Q) + \overline{s}(x,Q)}{\overline{u}(x,Q) + \overline{d}(x,Q)}$$





... whatever you want it to be



NuTeV 
$$\kappa = 0.477^{+0.063}_{-0.053}$$

Z.Phys.C65:189-198,1995

NOMAD 
$$\kappa = 0.591 \pm 0.019$$

arXiv:1308.4750

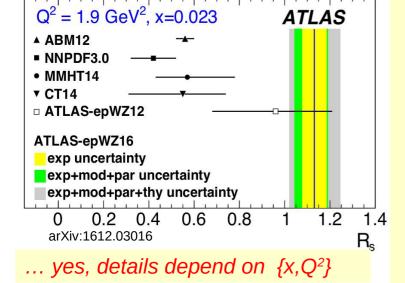
CMS 
$$\kappa = 0.52^{+0.12+0.05+0.13}_{-0.10-0.06-0.10}$$
 Q<sup>2</sup>=20 GeV<sup>2</sup>

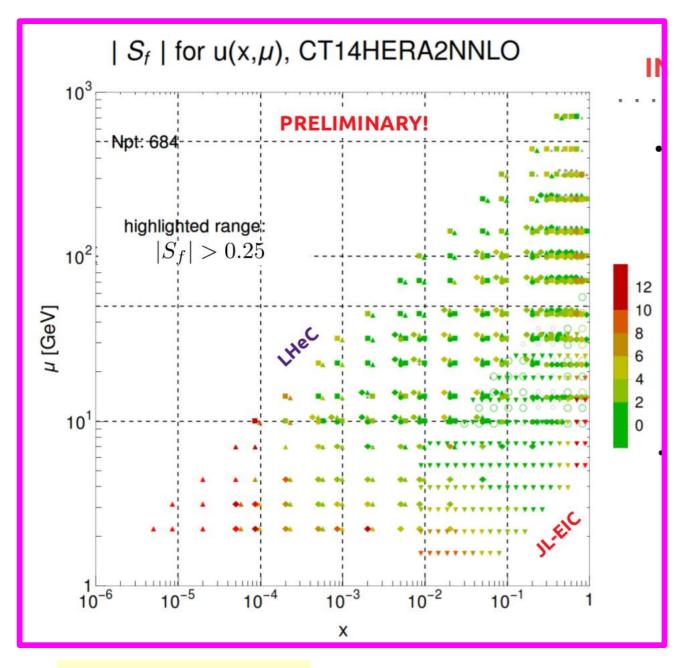
PhysRevD.90.032004 (exp)(model)(param)

ATLAS 
$$R_s = 1.13 \pm 0.05 \pm 0.02 +0.01 -0.06$$

$$Q_0^2 = 1.9 \text{ GeV}^2 \text{ at } x = 0.023$$

EPJC (2107) 77:367 (exp)(model)(param)





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

Sensitivity S,

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

(Technically, weight by scaled residual.)

**New insights** on experimental impacts

https:// metapdf.hepforge.org/

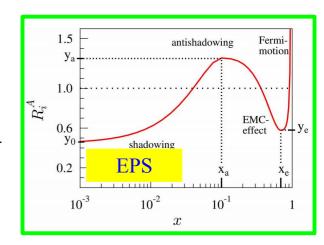
#### 1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... for example

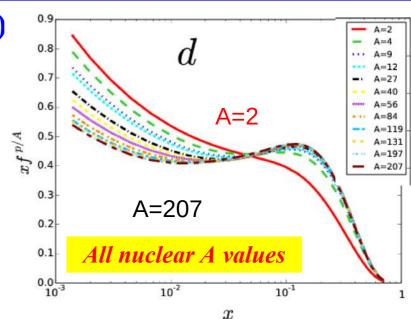
**HKN** 

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



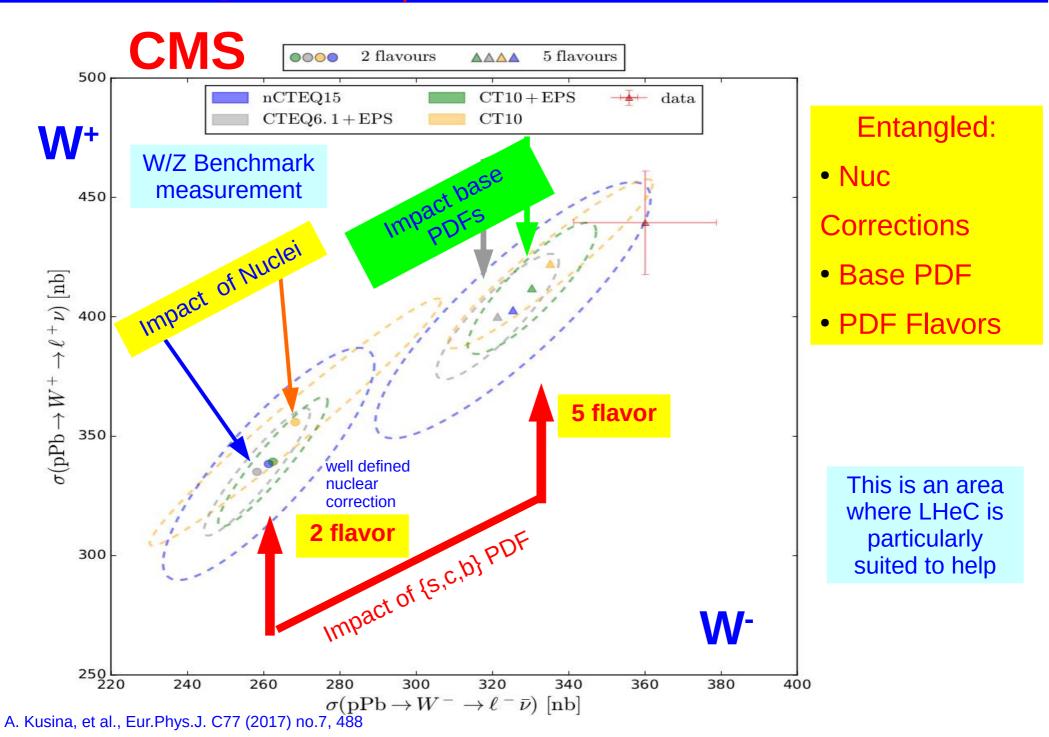
#### 2) Generalized A-parameterization (nCTEQ)

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$
 $f \sim ...x^{c_1(A)}(1-x)^{c_2(A)}...$ 
 $c_k \sim c_{k,0} + c_{k,1} \left(1 - A^{-c_{k,2}}\right)$ 
Proton Nuclear

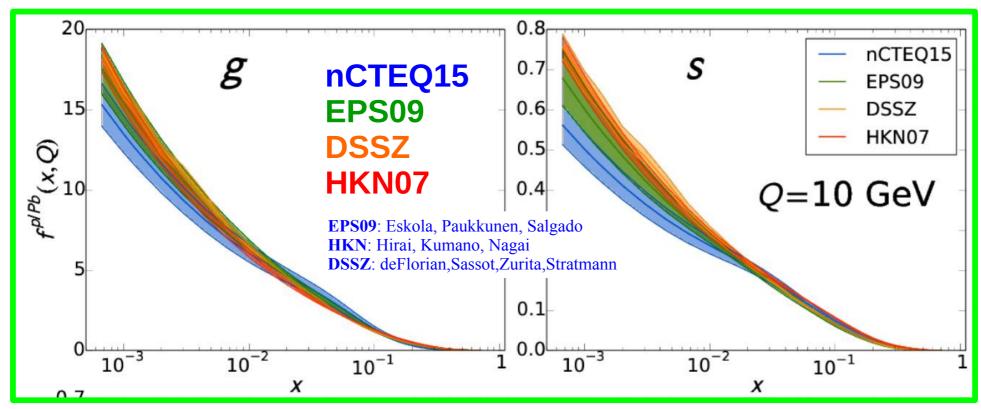


use proton as a Boundary Condition

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

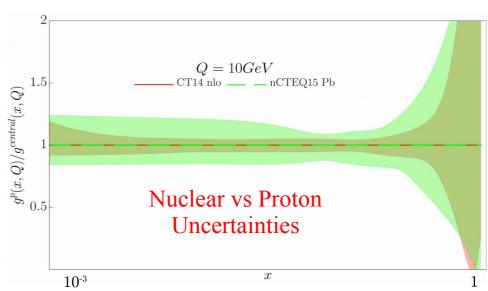


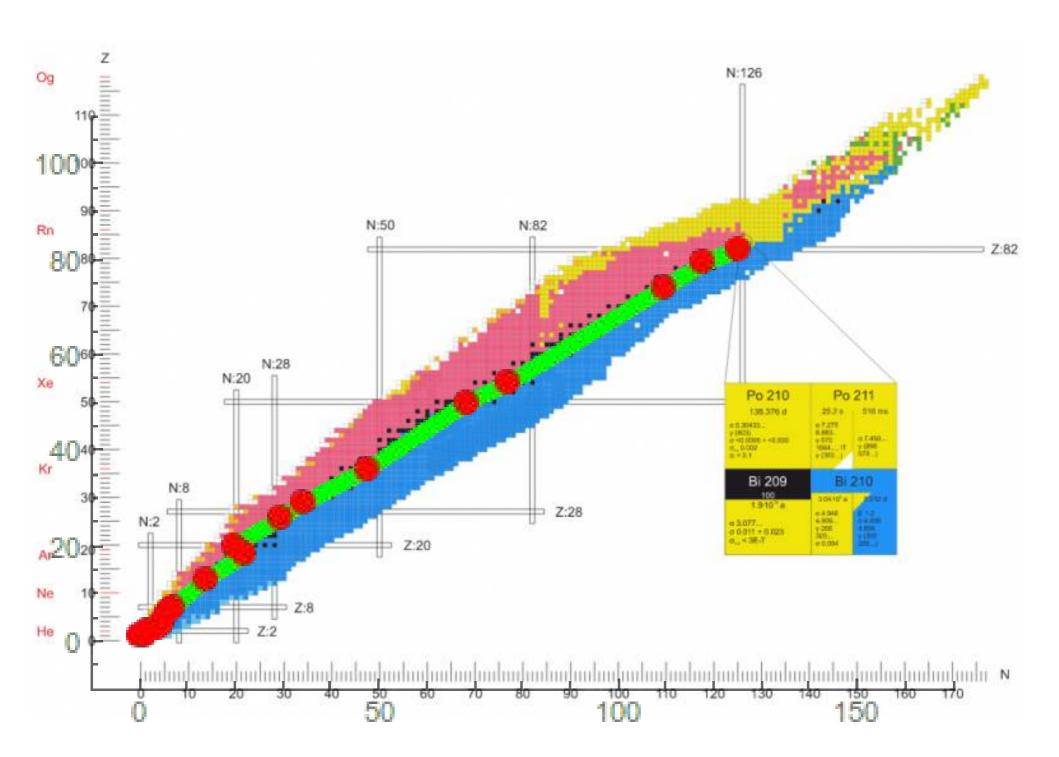
#### **Nuclear PDFs: Complementary efforts in general agreement**

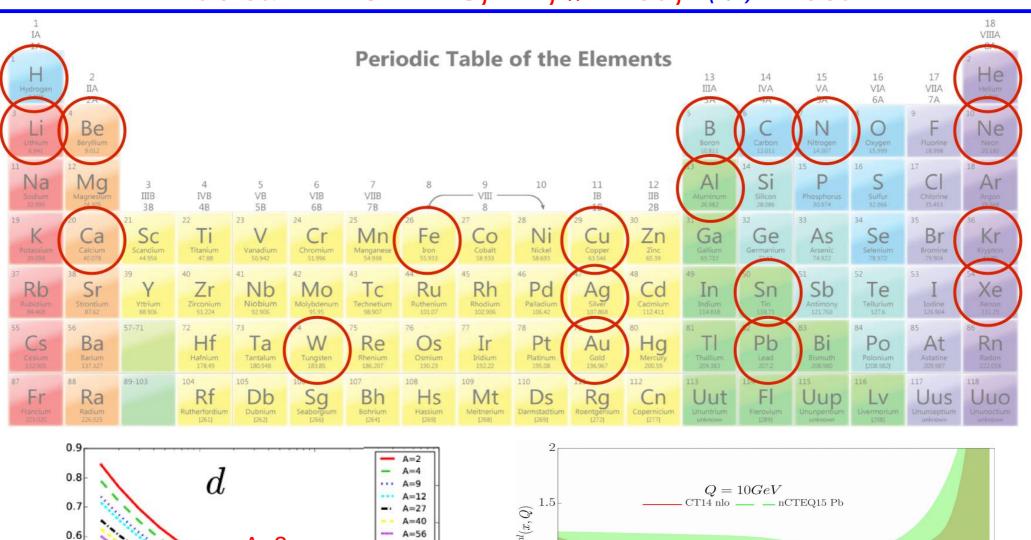


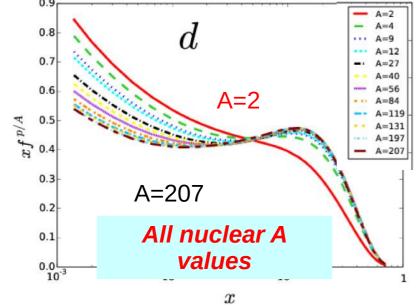
#### **Nuclear PDFs are more complex**

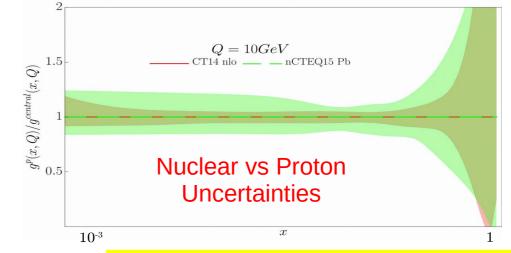
more DOF than Proton case more "issues" to consider more work to do ...



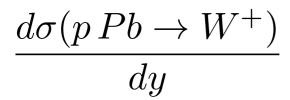


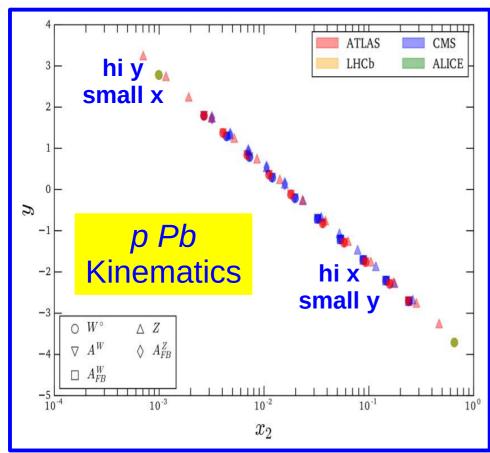






EIC can expand our knowledge of the nuclear A dimension





Vector boson production in pPb & PbPb A. Kusina, F. Lyonnet, D. B. Clark, E. Godat, T. Jezo, K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu, Eur.Phys.J. C77 (2017) no.7, 488

