HIGH-PT PROCESSES IN MANY-TEV ION COLLISIONS

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OUTLINE

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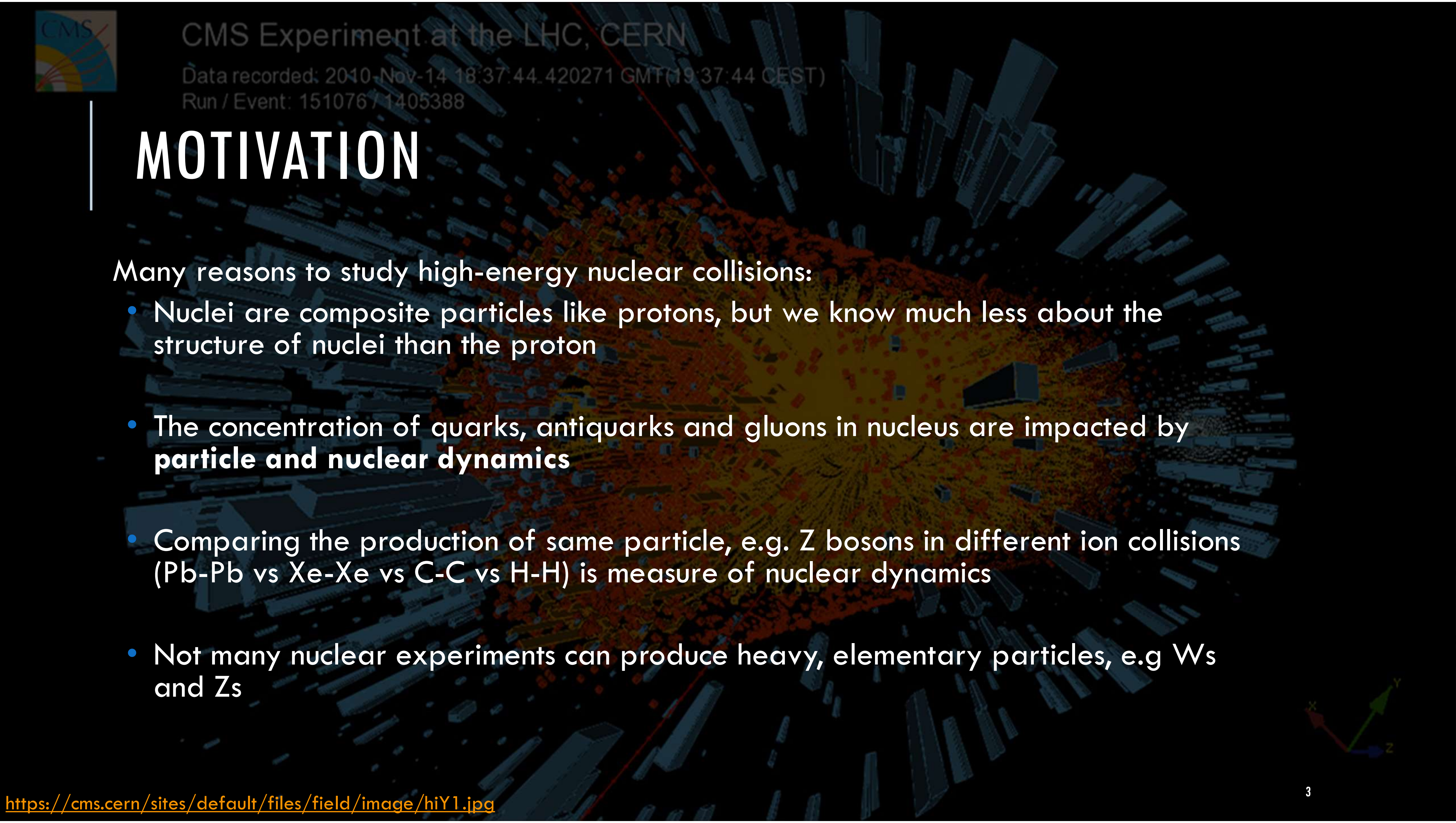


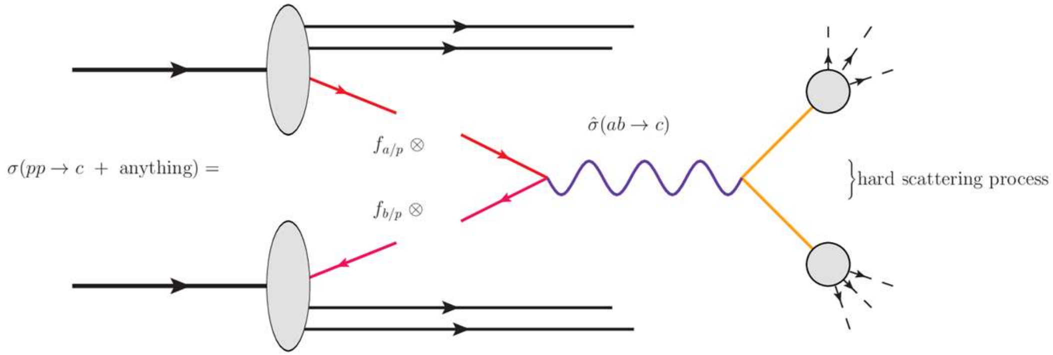
MOTIVATION

Many reasons to study high-energy nuclear collisions:

- Nuclei are composite particles like protons, but we know much less about the structure of nuclei than the proton
- The concentration of quarks, antiquarks and gluons in nucleus are impacted by **particle and nuclear dynamics**
- Comparing the production of same particle, e.g. Z bosons in different ion collisions (Pb-Pb vs Xe-Xe vs C-C vs H-H) is measure of nuclear dynamics
- Not many nuclear experiments can produce heavy, elementary particles, e.g Ws and Zs

https://cms.cern/sites/default/files/field/image/hiY1.jpg

PERTURBATION THEORY



Idea: start with simplified version of problem, then add a perturbation

Get close to the answer: leading order – LO, then add perturbation

Get closer to the answer: next-to-leading order - NLO= LO + 2nd order correction

Colinear factorisation theorem (proton)

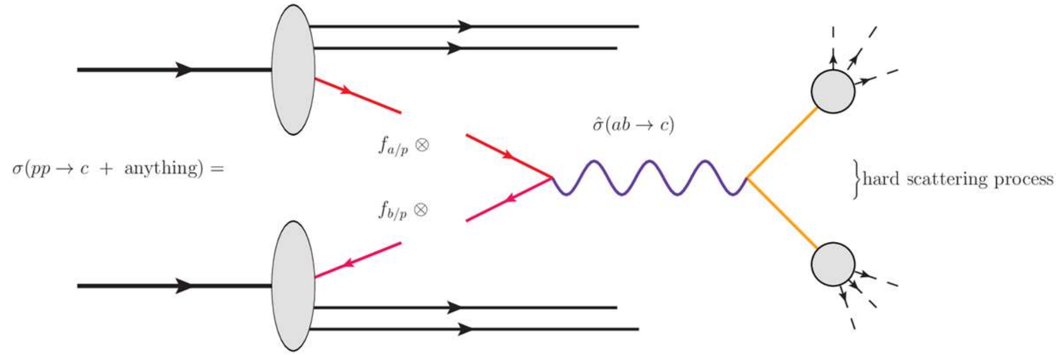
$$\sigma(pp \to V + x) = f_i \otimes f_j \otimes \hat{\sigma}(ij \to V)$$

σ - *hadronic cross-section*

f - *PDF*

$\hat{\sigma}$- partonic cross-section; (matrix element)^2

PERTURBATION THEORY



Idea: start with simplified version of problem, then add a perturbation

Get close to the answer: leading order – LO, then add perturbation

Get closer to the answer: next-to-leading order - NLO= LO + 2nd order correction

Colinear factorisation theorem (ion)

$$\sigma(A_1A_2 \to V + x) = A_1 \times A_2 \times \sigma\ (NN \to V + x)$$

A_i - Atomic #

σ_{NN} is σ_{pp} but with nucleic PDFs

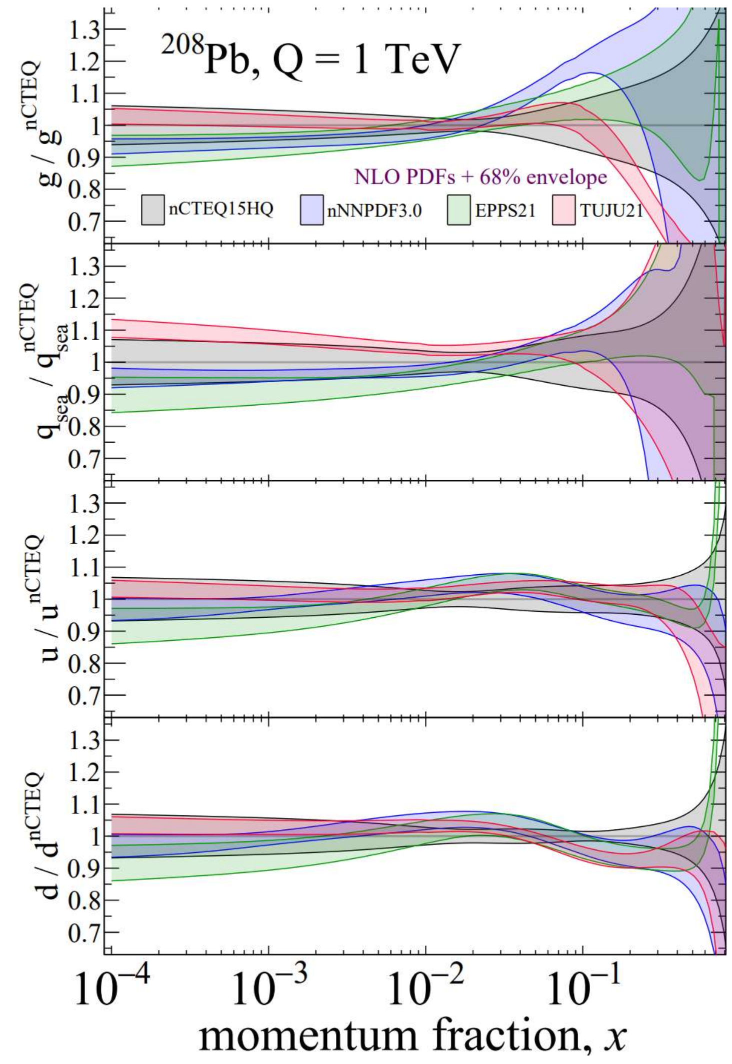
PDF CHOICE

Parton distribution functions give the probability to find partons (quarks and gluons) in a hadron as a function of the fraction x of the hadron's momentum carried by the parton.

Sets of nuclear PDFs compared to nCTEQ15HQ

- nNNPDF3.0
- EPPS21
- TUJU21

for x<0.1, various nPDFs family are consistent ⇒ $O(10\%)$ systematic uncertainties in our numbers



METHODOLOGY

- Theory inputs
  - Standard model
  - Proton PDF CT18NLO
  - Nuclear PDFs
    - nCTEQ15HQ_FullNuc_208_82,
    - nCTEQ15HQ_FullNuc _131_54,
    - nCTEQ15HQ_FullNuc _12_6
- MadGraph5_aMC@NLO to calculate cross-sections for different ion collisions
- Python3 script to harvest data
- C++ script to plot in ROOT6

```
INFO: Doing fixed order LO
INFO: Setting up grids
INFO:  Idle: 0,  Running: 0,  Completed: 4 [ current time: 19h04 ]
sum of cpu time of last step: 0 second
INFO:
      Results after grid setup:
      Total cross section:      1.722e+01 +- 1.4e-01 pb

INFO: Refining results, step 1
INFO:  Idle: 0,  Running: 4,  Completed: 0 [ current time: 19h04 ]
INFO:  Idle: 0,  Running: 3,  Completed: 1 [  8.8s  ]
INFO:  Idle: 0,  Running: 2,  Completed: 2 [  8.9s  ]
INFO:  Idle: 0,  Running: 1,  Completed: 3 [  8.9s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 4 [  9s  ]
sum of cpu time of last step: 0 second
INFO:
   --------------------------------------------------------------
      Final results and run summary:
      Process p p > z  z  QED=2 QCD=0 [QCD]
      Run at p-p collider (10000.0 + 10000.0 GeV)
      Total cross section: 1.725e+01 +- 8.0e-02 pb
   --------------------------------------------------------------
      Scale variation (computed from histogram information):
          Dynamical_scale_choice -1 (envelope of 9 values):
              1.725e+01 pb  +7.3% -8.5%
      PDF variation (computed from histogram information):
          nCTEQ15_12_6 (33 members; using hessian method):
              1.725e+01 pb  +2.1% -2.4%
   --------------------------------------------------------------
```

```
# xsec@NLO with scale uncertainty
if(setDebug): print('xsec@NLO with RG scale and PDF uncertainties')
cenOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr]+'_Cen['+str(binNr)+'] = '+xSecCenList[beamBinNr]+';\t // [pb]'# mass names have to be the same for fill func
maxOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr]+'_Max['+str(binNr)+'] = '+xSecMaxList[beamBinNr]+';\t // [pb]'
minOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr]+'_Min['+str(binNr)+'] = '+xSecMinList[beamBinNr]+';\t // [pb]'
xSecNLOCenOutList_ZeeBabu.append(cenOut)
xSecNLOMaxOutList_ZeeBabu.append(maxOut)
xSecNLOMinOutList_ZeeBabu.append(minOut)
if(setDebug):
    print('L%d:\txsec+RGunc:\ncenOut=%s\nmaxOut=%s\nminOut=%s' % (debug_getLineNo(setDebug),cenOut,maxOut,minOut))

# xsec@NLO with PDF uncertainty
cenOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr]+'_Cen['+str(binNr)+'] = '+xSecCenList[beamBinNr]+';\t // [pb]'
maxOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr]+'_Max['+str(binNr)+'] = '+xPDFMaxList[beamBinNr]+';\t // [pb]'
minOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr]+'_Min['+str(binNr)+'] = '+xPDFMinList[beamBinNr]+';\t // [pb]'
xPDFNLOCenOutList_ZeeBabu.append(cenOut)
xPDFNLOMaxOutList_ZeeBabu.append(maxOut)
xPDFNLOMinOutList_ZeeBabu.append(minOut)
if(setDebug):
    print('L%d:\txsec+PDFunc:\ncenOut=%s\nmaxOut=%s\nminOut=%s' % (debug_getLineNo(setDebug),cenOut,maxOut,minOut))
# xsec@LO with RG scale uncertainty
if(totPQCDOrders > 1):
    if(setDebug): print('xsec@XLO with RG scale and PDF uncertainties')
    cenOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr+binOffset]+'_Cen['+str(binNr)+'] = '+xSecCenList[beamBinNr+binOffset]+';\t // [pb]'
    maxOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr+binOffset]+'_Max['+str(binNr)+'] = '+xSecMaxList[beamBinNr+binOffset]+';\t // [pb]'
    minOut = 'k'+procName+'_XSec_'+pQCDList[beamBinNr+binOffset]+'_Min['+str(binNr)+'] = '+xSecMinList[beamBinNr+binOffset]+';\t // [pb]'
    xSecXLOCenOutList_ZeeBabu.append(cenOut)
    xSecXLOMaxOutList_ZeeBabu.append(maxOut)
    xSecXLOMinOutList_ZeeBabu.append(minOut)
    if(setDebug):
        print('L%d:\txsec+RGunc:\ncenOut=%s\nmaxOut=%s\nminOut=%s' % (debug_getLineNo(setDebug),cenOut,maxOut,minOut))
    # xsec@NLO with PDF uncertainty
    cenOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr+binOffset]+'_Cen['+str(binNr)+'] = '+xSecCenList[beamBinNr+binOffset]+';\t // [pb]'
    maxOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr+binOffset]+'_Max['+str(binNr)+'] = '+xPDFMaxList[beamBinNr+binOffset]+';\t // [pb]'
    minOut = 'k'+procName+'_XPDF_'+pQCDList[beamBinNr+binOffset]+'_Min['+str(binNr)+'] = '+xPDFMinList[beamBinNr+binOffset]+';\t // [pb]'
    xPDFXLOCenOutList_ZeeBabu.append(cenOut)
    xPDFXLOMaxOutList_ZeeBabu.append(maxOut)
    xPDFXLOMinOutList_ZeeBabu.append(minOut)
    if(setDebug):
        print('L%d:\txsec+PDFunc:\ncenOut=%s\nmaxOut=%s\nminOut=%s' % (debug_getLineNo(setDebug),cenOut,maxOut,minOut))
```

```
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->SetTitle("");
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->SetTitleFont(132);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->SetTitle("");
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get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->SetLabelFont(132);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->SetRangeUser(xRangeMin,xRangeMax);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->SetNdivisions(717,kTRUE);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetXaxis()->CenterTitle();

get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetTitleFont(132);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetTitle("#it{#sigma}(#it{AA#rightarrow VV+X}) [pb] ");
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetTitleSize(0.07) ;
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetTitleOffset(.83);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetLabelSize(0.07);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetLabelFont(132);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetRangeUser(0.5e1,2e5);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->SetNdivisions(305,kTRUE);
get_IonsNLO_pp_WmZx_NLOQCD_nCT15Pb208_XSec_NLO_Cen->GetYaxis()->CenterTitle();
```
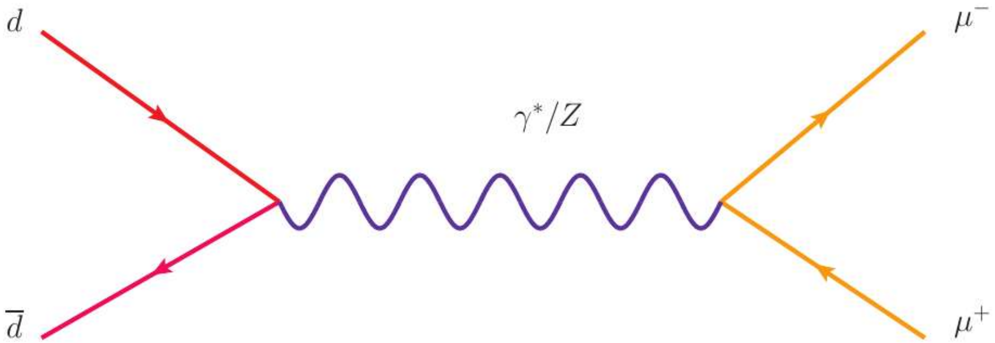
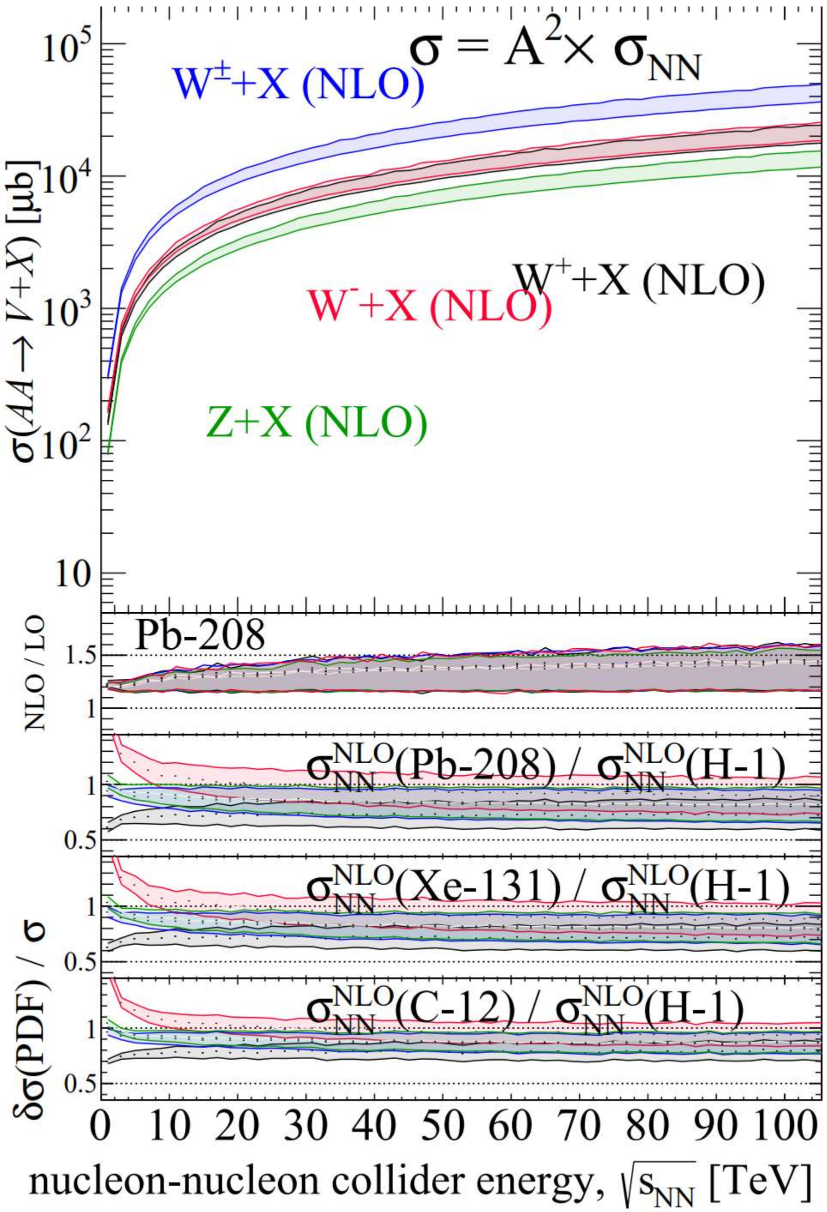

SINGLE BOSON INCLUSIVE

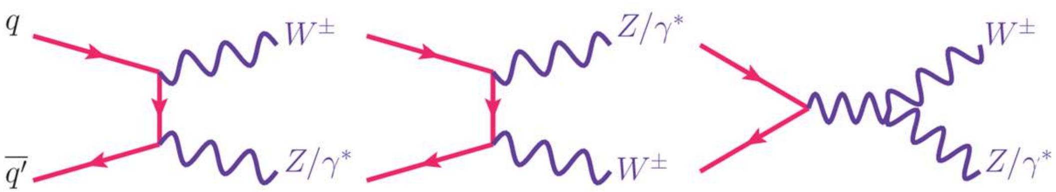
- Upper panel- nuclei level scattering for lead
- Second panel- NLO rate over LO rate for lead
- Three lower panels- nucleon level cross-section divided by hydrogen

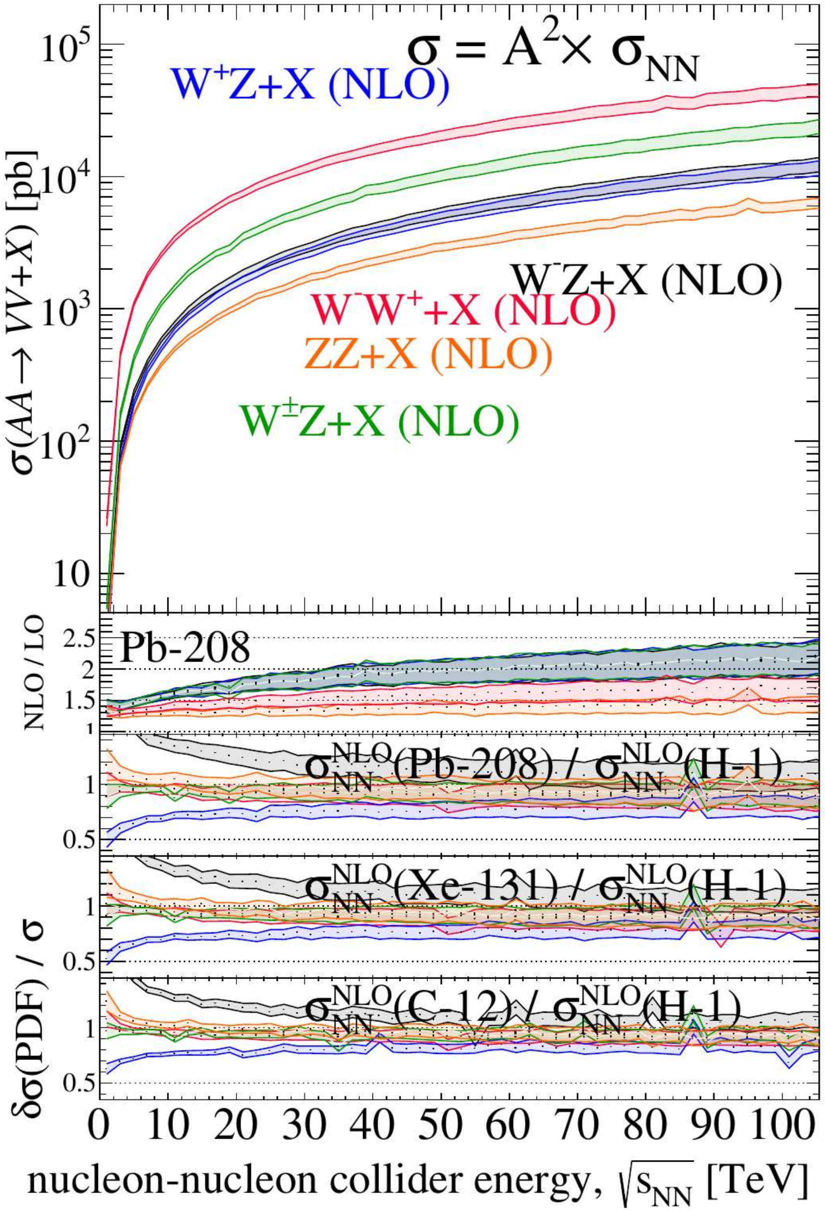




DIBOSON PRODUCTION

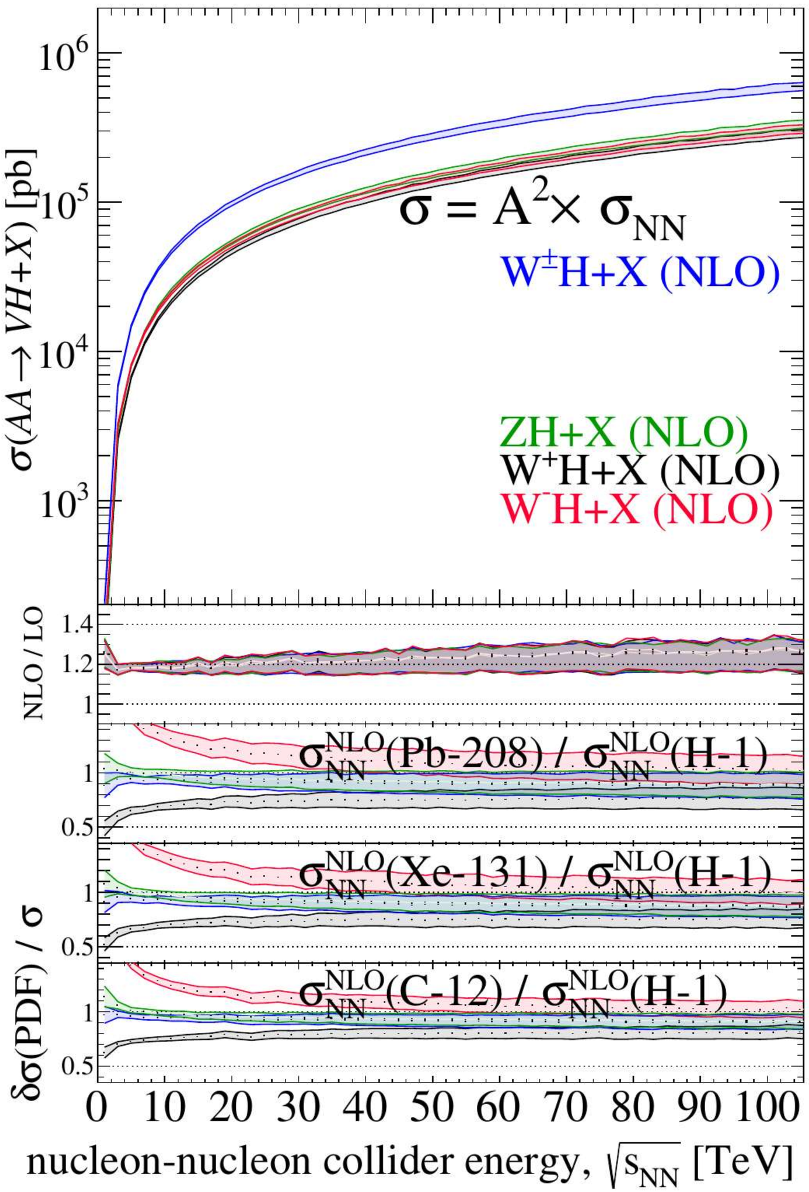
- Upper panel- nuclei level scattering for lead
- Second panel- NLO rate over LO rate for lead
- Three lower panels- nucleon level cross-section divided by hydrogen





ASSOCIATED HIGGS

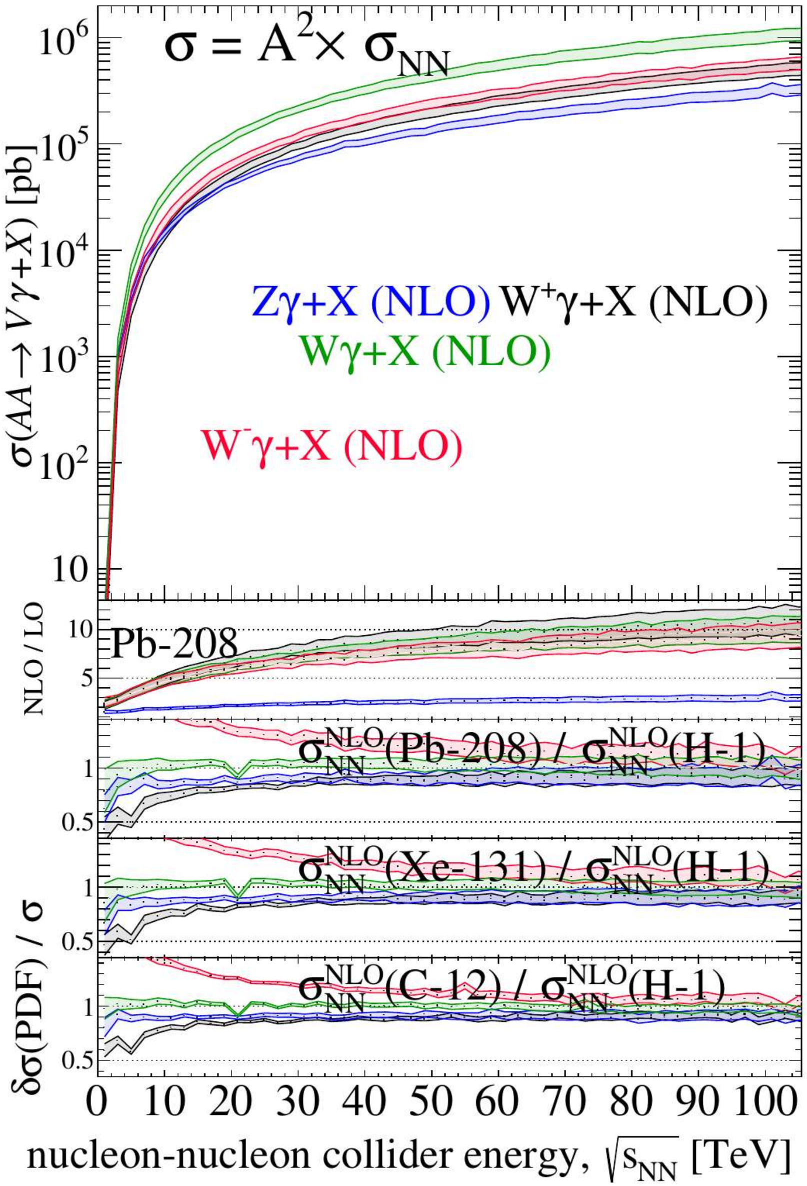
- Upper panel- nuclei level scattering for lead
- Second panel- NLO rate over LO rate for lead
- Three lower panels- nucleon level cross-section divided by hydrogen



ASSOCIATED PHOTON

Photon cuts:

- $P_T^{\gamma} > 150 \text{ GeV}$
- Pseudorapidity $|\eta| < 2.4$



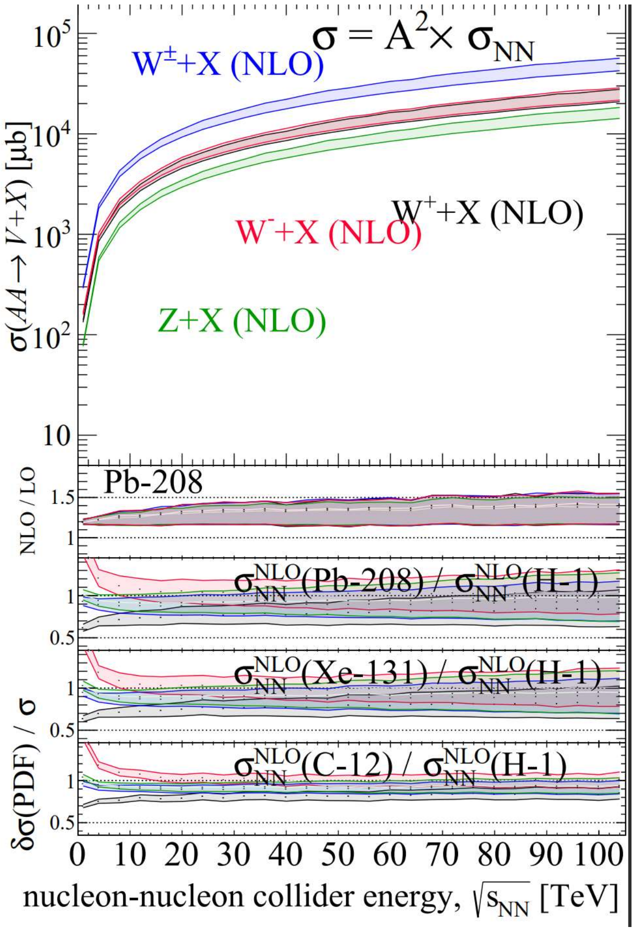
CONCLUSION

- nuclear dynamics modify parton distributions
- changes in PDFs at low- and high-x have impact on production of high-pT objects
- quantifying this is in progress (nearly ready for publication)

THANK YOU

CHANGE OF NPDF RELEASE

nCTEQ15WZSIH_FullNuc_208_82



nCTEQ15HQ_FullNuc_208_82