MONTE CARLO EVENT GENERATION WITH RADIATIVE QED PROCESSES IN DEEP-INELASTIC SCATTERING

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CONTENTS

- Radiative corrections : features and impact.
- The DJANGOH generator for radiative events.
- Results for inclusive and semi-inclusive corrections.

INTRODUCTION TO RADIATIVE CORRECTION

Measure FFs, PDFs, by comparing data with theoretical predictions :

$$\sigma_{\exp} = \sigma_{theory}\left[F_n\left(x,Q^2\right)\right]$$

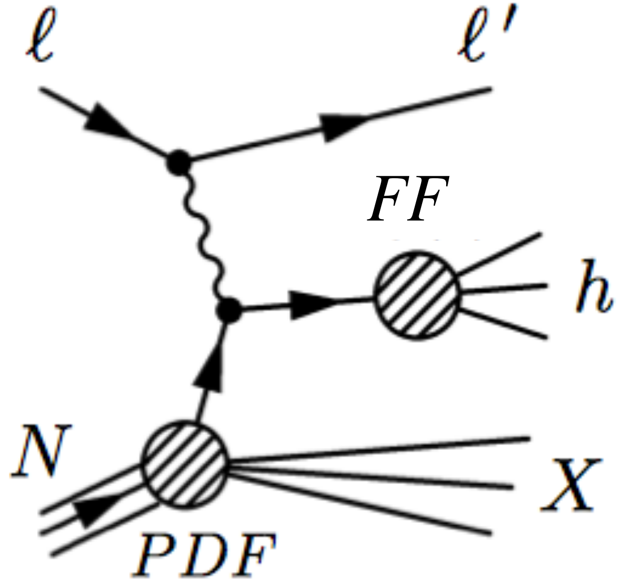
High precision = knowledge of higher order corrections :

$$\sigma_{theory} = \sigma^{(0)}\left[F_n\right] + \alpha_{em}\sigma^{(1)}\left[F_n\right] + \ldots$$

Experimental problem :

cannot distinguish radiative photon from non-radiative ones…

RADIATIVE QED CORRECTIONS IN DIS/SIDIS



One of COMPASS goals : measurement of hadron multiplicities for Fragmentation Functions (FFs) extraction.

DIS = Deep-Inelastic Scattering (Inclusive)

SIDIS = Semi-Inclusive Deep-Inelastic Scattering (Observation of at least one hadron in the final state)

Impact on SIDIS data :

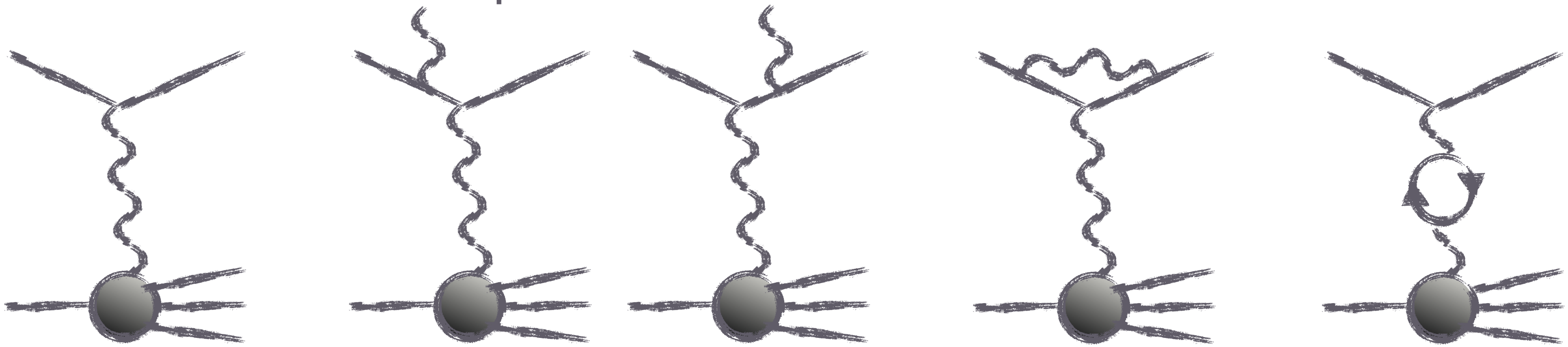
Difference between the hadronic and leptonic kinematic variables

→ some hadrons fall into the wrong kinematic bin.

Correction factor to multiplicities → 'redirects' those hadrons.

RADIATIVE QED CORRECTIONS IN DIS/SIDIS

Born level and one-loop corrections (so-called o(α) corrections) :



Born | Internal Bremsstrahlung | Vertex Correction | Vacuum Polarization

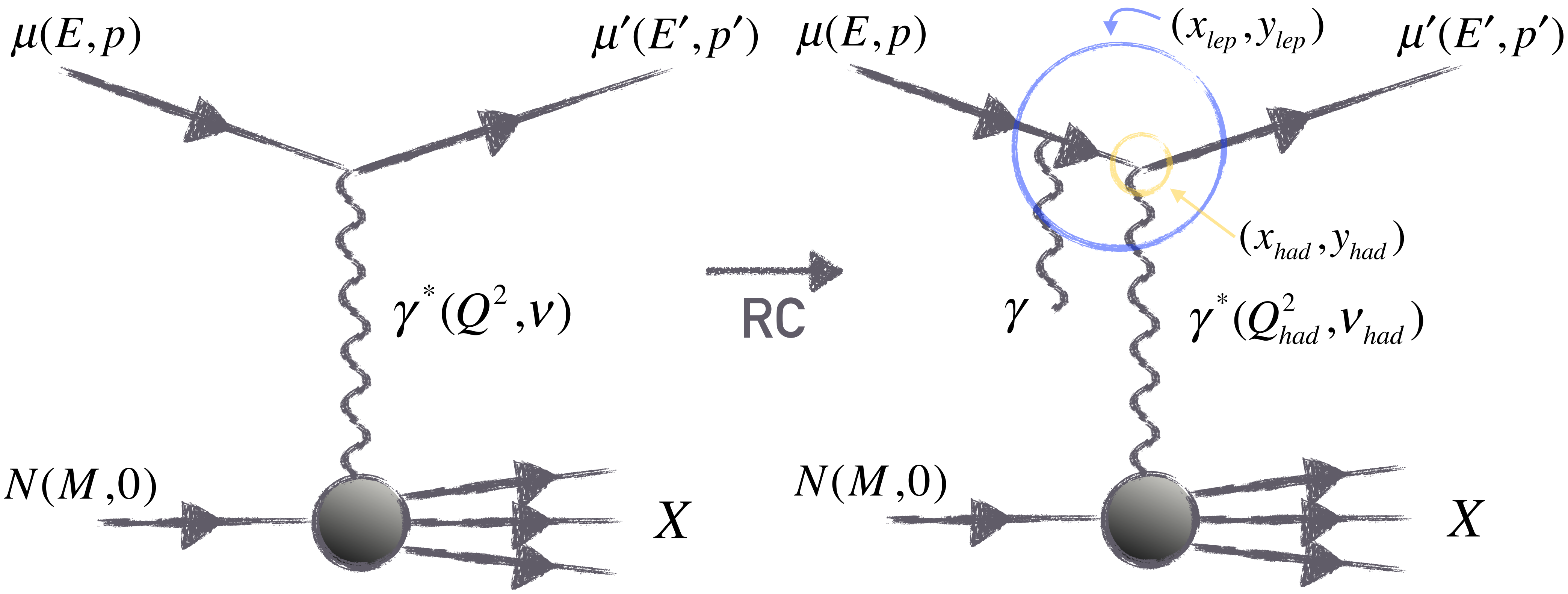
Measurement of DIS cross-section : Inclusive radiative corrections

$$\eta(x,y) = \frac{\sigma_{Born}(x,y)}{\sigma_{Born+o(\alpha)}(x,y)} = \frac{\sigma_{1\gamma}(x,y)}{\sigma_{measured}(x,y)}$$

Measurement of SIDIS cross-section : Semi-Inclusive radiative corrections

$$\eta^{h^\pm}(x,y,z) = \frac{M^{h^\pm}_{Born}(x,y,z)}{M^{h^\pm}_{Born+o(\alpha)}(x,y,z)} = \frac{M^{h^\pm}_{1\gamma}(x,y,z)}{M^{h^\pm}_{measured}(x,y,z)}$$

DEFINITION OF A RADIATIVE EVENT



SIDIS = Semi-Inclusive DIS (obs. of one hadron of the final state)

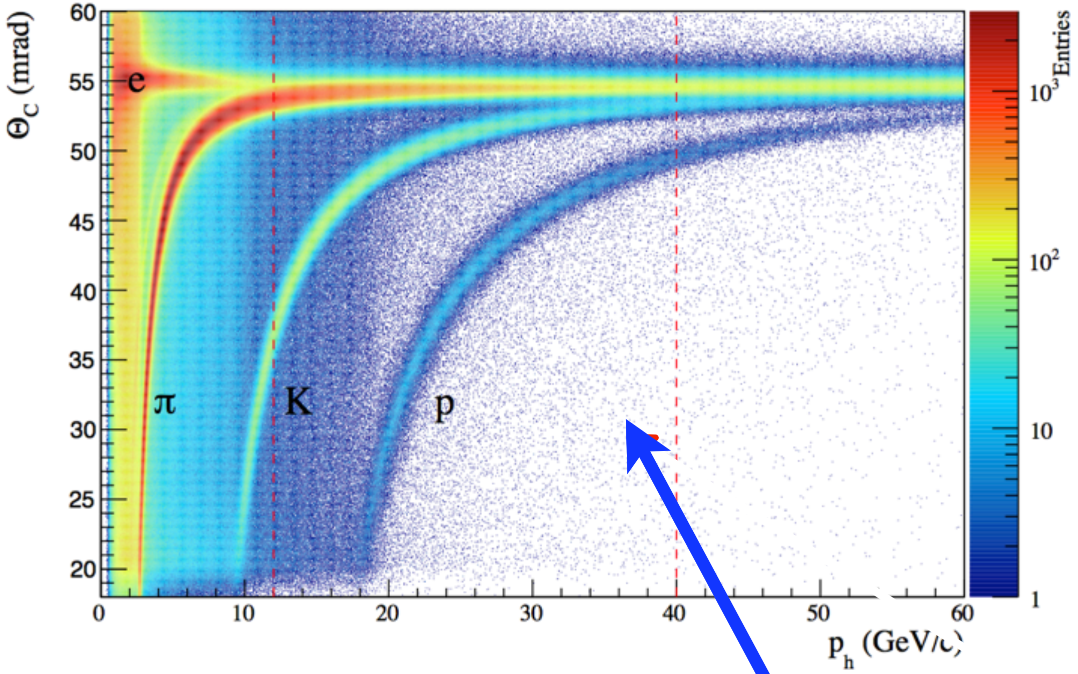
$$x \stackrel{lab}{=} \frac{Q^2}{2M\nu} \qquad y \stackrel{lab}{=} \frac{E-E'}{E} = \frac{\nu}{E} \qquad z \stackrel{lab}{=} \frac{E_h}{\nu}$$

Radiative event

=

Event containing a real radiated photon

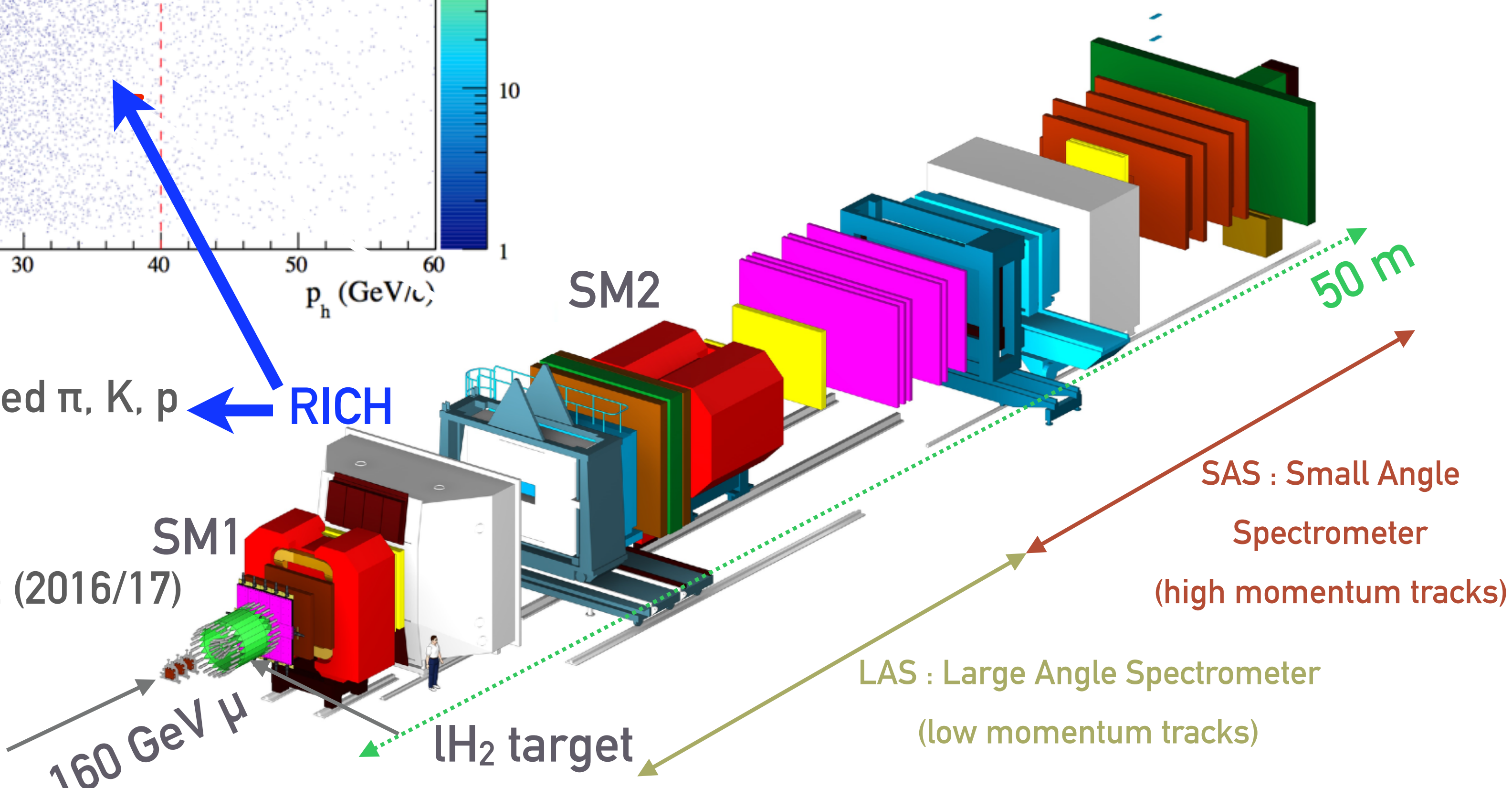
COMPASS EXPERIMENT



- Fixed target experiment at CERN SPS
- Two-staged spectrometer (LAS/SAS)
- Can operate with muon or hadron beams

- RICH : excellent charged π, K, p discrimination

- Unpolarized lH_2 target (2016/17)



RC @ COMPASS

Used program for RC calculation : TERAD composed by Dubna group (A.A.Akhundov, et al., Fortschr. Phys. 44 (1996) 373).

However, still do not know where the radiative photon goes…

→ need a radiative event generator

COMPASS used RADGEN generator (I.Akushevich, H.Böttcher, D.Ryckbosch, arXiv:hep-ph/9906408) in previous analyses.

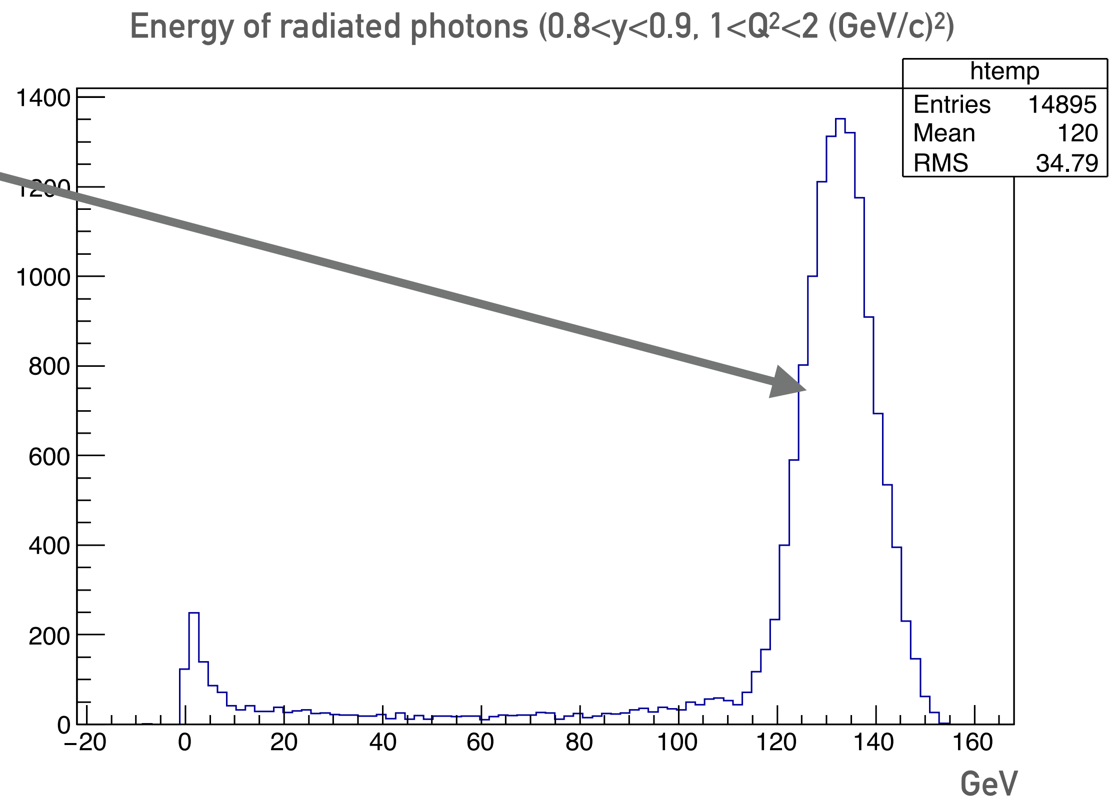
Important note : all further results are at generator level !

FINDING THE BEST RC GENERATOR

RADGEN : high amount of hard photons (high energy photons)

Naïve thinking : in theory, more soft than hard photons.

But : MC simulation + RADGEN do not describe COMPASS data : hard photons leading to high production of electrons not seen in COMPASS data..



Can we find a better MC generator ?

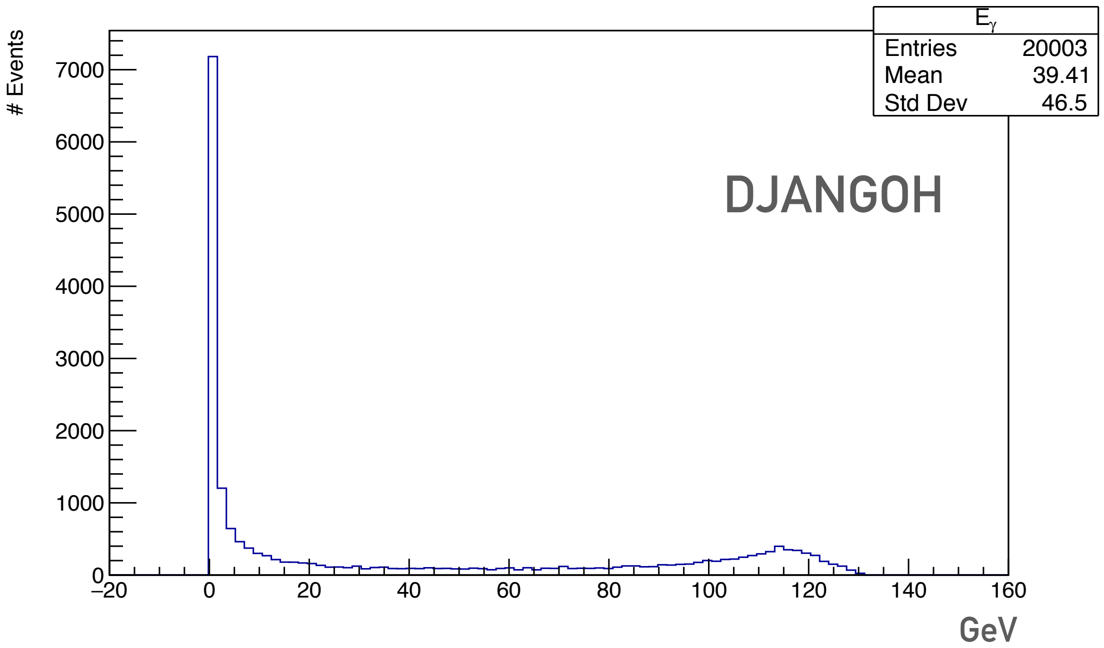
DJANGOH

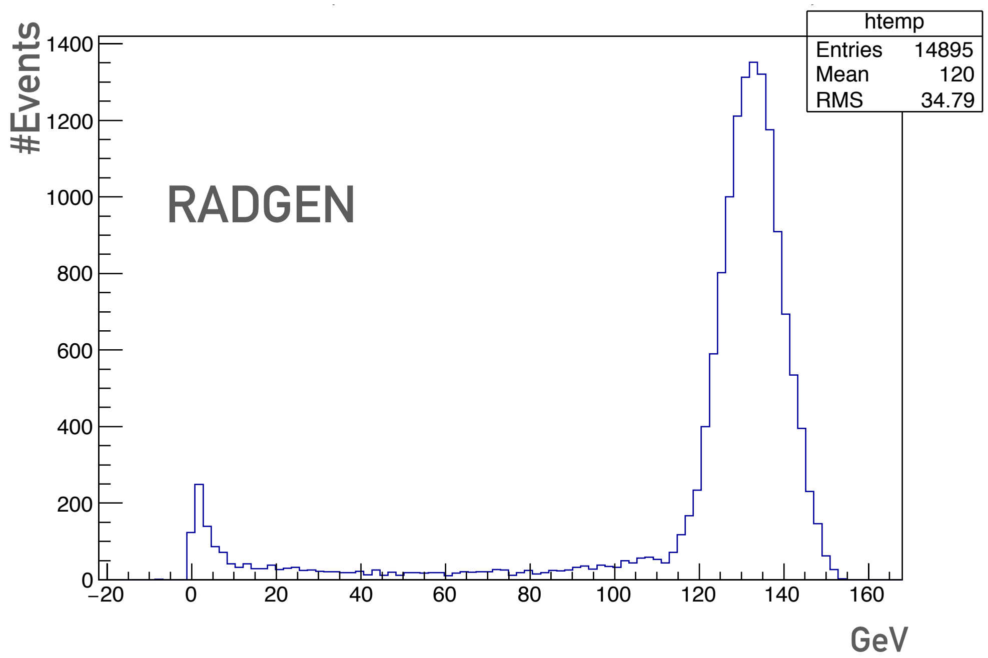
DJANGOH, concatenation of DJANGO and HERACLES :

- Event generator for neutral/charged current ep interactions at HERA by H. Spiesberger (http://wwwthep.physik.uni-mainz.de/~hspiesb/djangoh/djangoh.html, arXiv:1309.5327)
- Simulates DIS including both QED and QCD radiative effects.
- Includes single photon emission from lepton/quark line, self energy corrections and complete set of one-loop weak corrections (o(α) corrections).
- Includes also the background from radiative elastic scattering $\mu p \to \mu p \gamma$.
- Capable of obtaining hadronic final state via the use of JETSET.
- Modified to work for μp interactions.
- Uses exact calculations and no approximations.
- FORTRAN framework.

DJANGOH/RADGEN COMPARISON

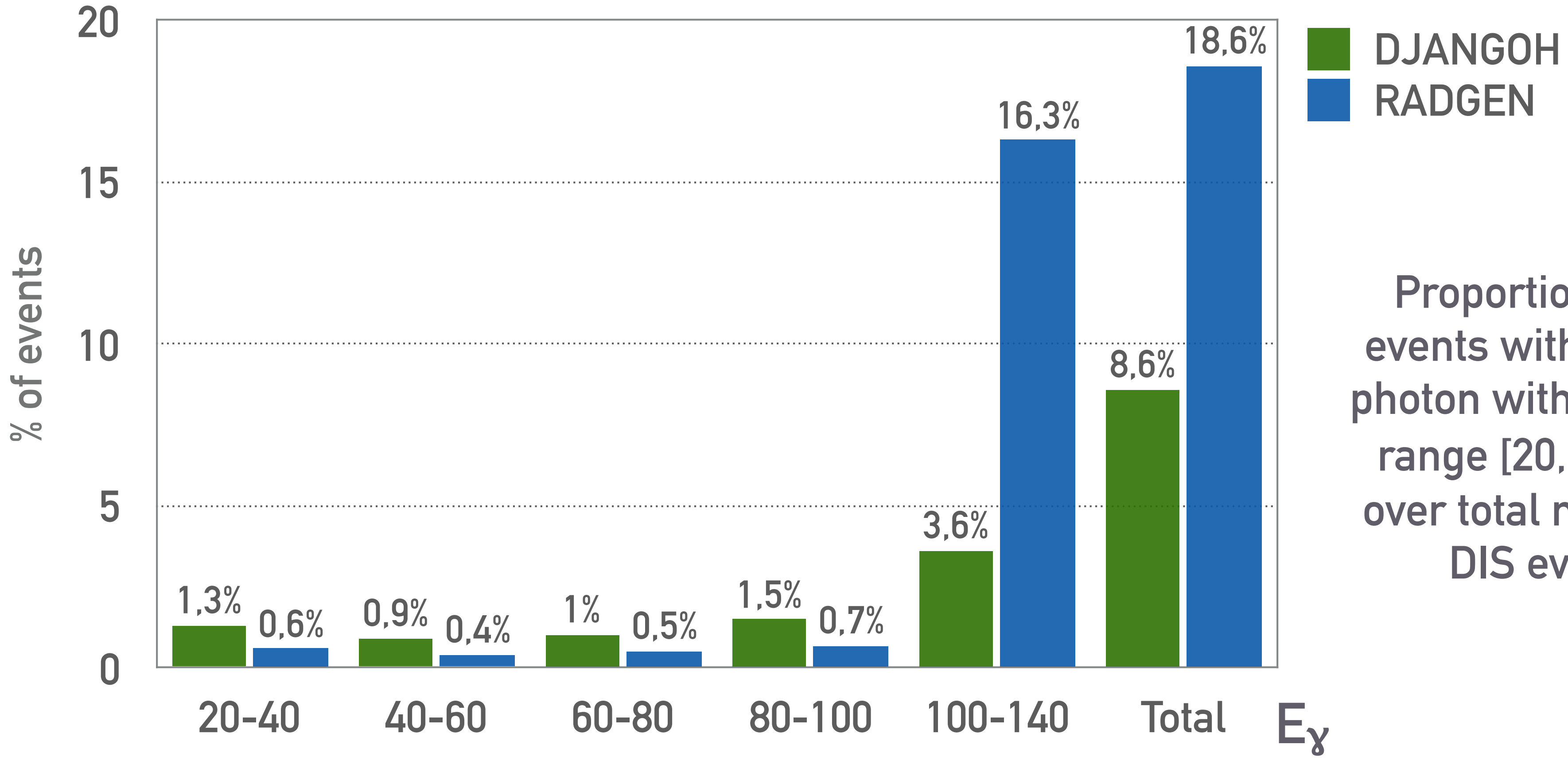
Energy of radiated photons (0.8<y<0.9, 1<Q^2<2 $(GeV/c)^2$)





First observation : DJANGOH produces more soft photons than hard photons

DJANGOH/RADGEN COMPARISON



Proportion of DIS events with radiated photon with energy in range [20,140] GeV over total number of DIS events.

DJANGOH produces less hard photons than RADGEN

Motivated implementation in MC chain and further tests

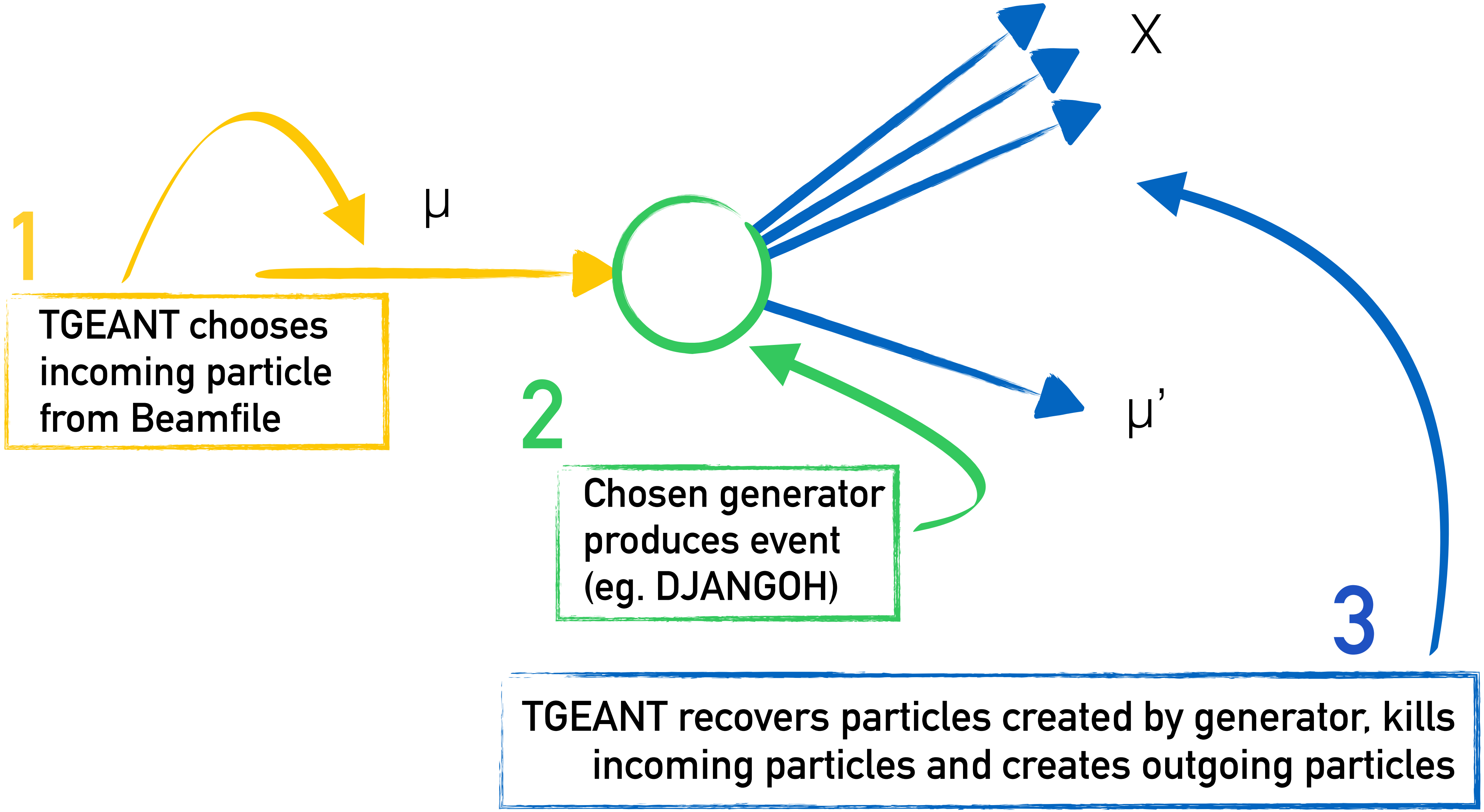
TGEANT

GEANT4 : A **835** (2016) 186-225

« *A GEANT4-based Monte-Carlo simulation for the COMPASS-II experiment.*

- C++ framework
- Modular
- Can handle event generators for specific interaction simulation

EVENT GENERATION HANDLING IN TGEANT



INTERNAL IMPLEMENTATION OF DJANGOH

Interface Class : TDjangoh

- Is a standalone class
- Creates instance of Djangoh that can be manipulated in any C/C++ environment
- Able to generate bunch of events with different input energies
- TDjangoh can be used within any C++ framework

Process Class : T4DjangohProcess

- Is a TGEANT class
- Manipulates instance of TDjangoh
- Do the I/O transfer of TGeant to TDjangoh

INCLUSIVE RADIATIVE CORRECTIONS

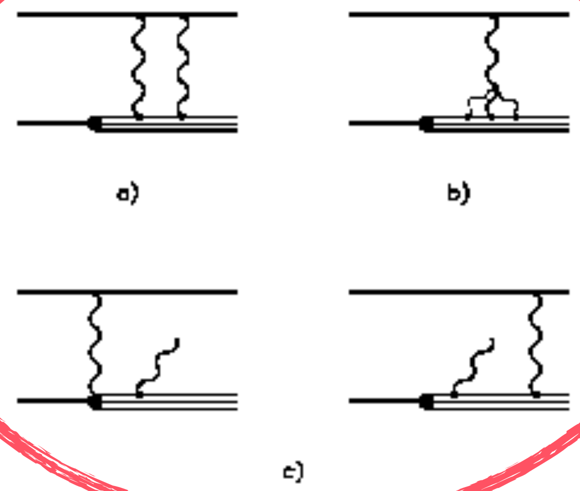
- To fix the definition of radiative correction :

$$\eta(x,y)=\frac{\sigma_{Born}(x,y)}{\sigma_{Born+o(\alpha)}(x,y)}=\frac{\sigma_{1\gamma}(x,y)}{\sigma_{measured}(x,y)}$$

- This definition will be used in the following.

- o(α) corrections for DJANGOH, o(α) and some hadron currents corrections for TERAD.

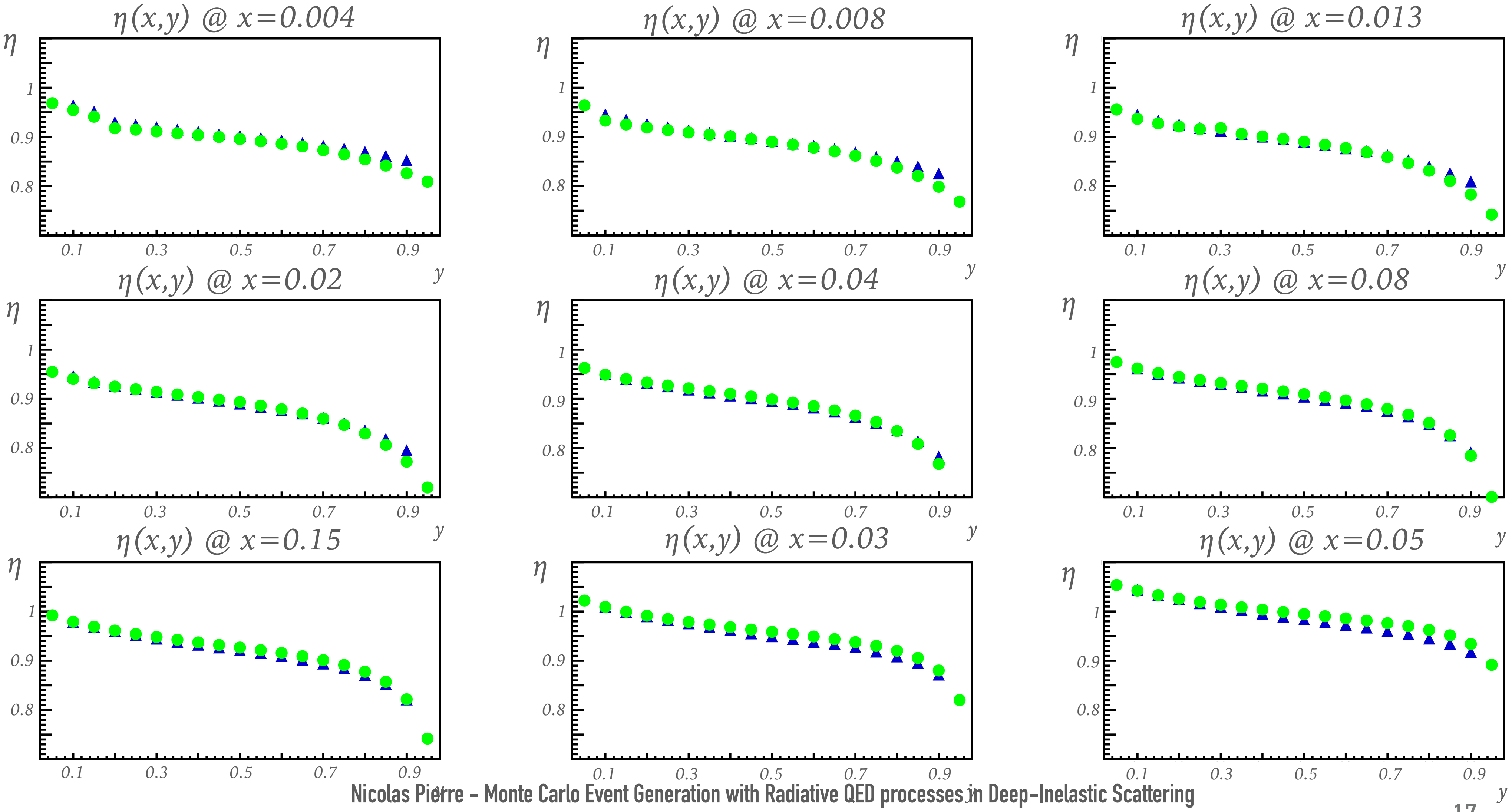
- TERAD uses parametrization for structure functions. Same F_2 and R used in DJANGOH.



INCLUSIVE CORRECTIONS

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.

Corrections within 10%, going to 40% at high y. Discrepancy smaller than 3%.



SEMI-INCLUSIVE RADIATIVE CORRECTIONS

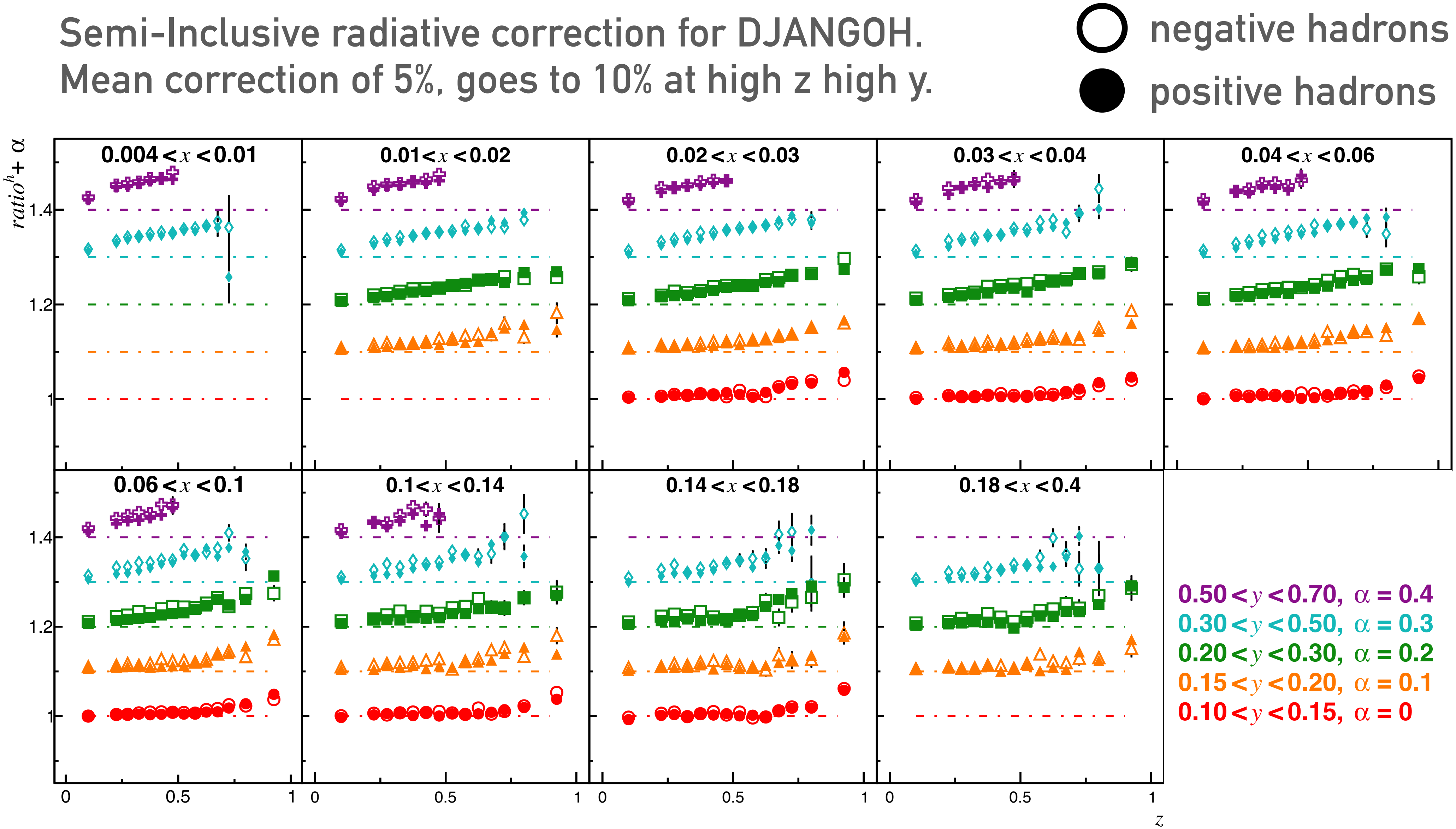
- To fix the definition of radiative correction :

$$\eta^{h^\pm}(x,y,z) = \frac{M^{h^\pm}_{Born}(x,y,z)}{M^{h^\pm}_{Born+o(\alpha)}(x,y,z)}$$

- This definition will be used in the following.
- 'True' DJANGOH used with PDFs and no parametrization for SFs : comparison with TERAD will be difficult.

SEMI-INCLUSIVE CORRECTIONS

Semi-Inclusive radiative correction for DJANGOH.
Mean correction of 5%, goes to 10% at high z high y.



WORK STILL IN PROGRESS

- Comparison with TERAD is difficult for semi-inclusive :
  - TERAD : special parametrization of SFs.
  - DJANGOH : SFs extracted from PDFs.
- Possible investigation : apply a correction to extracted SFs to match TERAD SFs.

- Comparison of MC and COMPASS data
  - Test production done
  - Reconstruction of the production is ongoing

CONCLUSION & PROSPECTS

- RCs needed for cross-sections. Impact of these corrections on SIDIS are not negligible : corrections goes up to 40%, average at ~10% for inclusive, up to 10%, average at ~5% for semi-inclusive.
- Inclusive corrections calculated by DJANGOH consistent with TERAD inclusive corrections : discrepancy smaller than 3%.
- TDJANGOH : C++ wrapper of DJANGOH, can be used easily as physics generator MC simulation as in TGEANT.
- Production of MC with DJANGOH as event generator has begun for 2016 setup, hopefully giving better agreement than RADGEN. Presently in the reconstruction step.

BACKUP

UNFOLDING

Determination of the true cross-sections from the measured ones :

$$d\sigma^{obs}(p,q) = \int \frac{d^3k}{2k^0} R(l,l',k)\, d\sigma^{true}(p,-q,k)$$

Typical answer : an iterative solution !

But, ill defined :
- no unique solution
- large uncertainties
- numerically unstable

However, with partial functioning : $R(l,l',k) = \frac{I}{k \cdot l} + \frac{F}{k \cdot l'} + \frac{C}{\tilde{Q}^2}$

- Initial state radiation : k.l small for $\sphericalangle(l_{in},\gamma) \to 0$
- Final state radiation : k.l' small for $\sphericalangle(l_{out},\gamma) \to 0$
- Compton peak : Q^2 small for $p_T(l_{out}) \sim p_T(\gamma)$

SOME WORDS ON HADRONIC RADIATION

Cancels with loops, collinear emission give rise to correction of type :

$$\frac{\alpha}{2\pi}\log\left[m_q^2\right] \quad where \quad m_q = 0$$

Solution is to factorize and absorb the divergences into PDF.

$$d\sigma = \sum_f d\hat{\sigma}_f\left[1+\delta_f\left(Q^2,m_q^2\right)\right]q_f(x) = \sum_f d\hat{\sigma}_f \hat{q}_f\left(x,Q^2\right)$$

However, due to the difference of charge between quarks, there's an isospin violating effect.

INTERFACE CLASS

Changed input method of Djangoh :

- Standard method ⟶ input file.
- But : input file is not efficient when producing 1M events changing input between each generation.
- Solution : drawing correspondence between struct in C++ and COMMON blocks in Fortran.
- Defined input values necessary for Djangoh in Interface.

Struct in C++

```
extern "C" struct ihscut
{
  float ixmin;
  float ixmax;
  float iq2min;
  float iq2max;
  float iymin;
  float iymax;
  float iwmin;
} ihscut_;
```

Corresponding COMMON block in Fortran

```
      COMMON /IHSCUT/ IXMIN,IXMAX,IQ2MIN,IQ2MAX,IYMIN,IYMAX,IWMIN
      REAL            IXMIN,IXMAX,IQ2MIN,IQ2MAX,IYMIN,IYMAX,IWMIN
```

When a value is given to a member of the block in C++, we retrieve the same value in its Fortran counterpart and vice-versa.

MODIFICATION OF DJANGOH

Before

SUBROUTINE HSMAIN()

Initialisation step

Receive input from Interface

X-section calculation step

For one energy calculates corresponding X-sections for radiative processes

Event generation step

Generate events according to calculated X-sections for radiative processes

After

SUBROUTINE HSINIT()

Receive input from Interface

For a GIVEN RANGE of energy calculates corresponding X-sections GRID for radiative processes

SUBROUTINE HSEVTG()

Generate events according to calculated X-sections for radiative processes picked in the GRID wrt. INPUT ENERGY

THE CROSS-SECTION GRID

The actual container / The type mimic

```fortran
C---                        NREG2N=NBIN2**NDIM2
      LOGICAL LGLO2,LLOC2
      double precision ntot2
      COMMON /HSSNC2/ SIG2,SIG2E,T2GGMA,T2GMAX(NREG2N),
     +                XX2(50,2),
     +                FFGO2,DNCG2,FFLO2,DNCL2,GOLD2,
     +                NM2(NREG2N),ND02,
     +                NTOT2,NCAL2,NCA12,NCA22,IBIM2,JCOR2,
     +                LGLO2,LLOC2
```

The type mimic is placed in a Module in order to be used and recognised as the same type in every in every subroutine (because fortran)

```fortran
MODULE xSectionModule

  USE ISO_C_BINDING

  TYPE, BIND(C) :: xSection2
    REAL :: SIG2
    REAL :: SIG2E
    REAL :: T2GGMA
    REAL :: T2GMAX(2500)
    REAL :: XX2(50,2)
    REAL :: FFGO2
    REAL :: DNCG2
    REAL :: FFLO2
    REAL :: DNCL2
    REAL :: GOLD2
    REAL :: NM2(2500)
    REAL :: ND02
    DOUBLE PRECISION :: NTOT2
    REAL :: NCAL2
    REAL :: NCA12
    REAL :: NCA22
    REAL :: IBIM2
    REAL :: JCOR2
    LOGICAL :: LGLO2
    LOGICAL :: LLOC2
  END TYPE
```

THE CROSS-SECTION GRID

```fortran
C------------------------
      TYPE(xSection2) :: HSXNC2
      TYPE(xSection2C) :: HSXCC2
      TYPE(xSection2E) :: HSXEL2
      TYPE(xSection31) :: HSXN31
      TYPE(xSection32) :: HSXN32
      TYPE(xSection33) :: HSXN33
      TYPE(xSection34) :: HSXN34
      TYPE(xSection31C) :: HSXC31
      TYPE(xSection32C) :: HSXC32
      TYPE(xSection33C) :: HSXC33
      TYPE(xSection31E) :: HSXE31
      TYPE(xSection32E) :: HSXE32
      TYPE(xSection33E) :: HSXE33
      COMMON /HSXSEC/ HSXNC2(100),HSXCC2(100),HSXEL2(100),
     +                HSXN31(100),HSXN32(100),HSXN33(100),HSXN34(100),
     +                HSXC31(100),HSXC32(100),HSXC33(100),
     +                HSXE31(100),HSXE32(100),HSXE33(100)
      COMMON /HSGRID/ GDSIZE, GDMEAN, GDSDDV
C------------------------
```

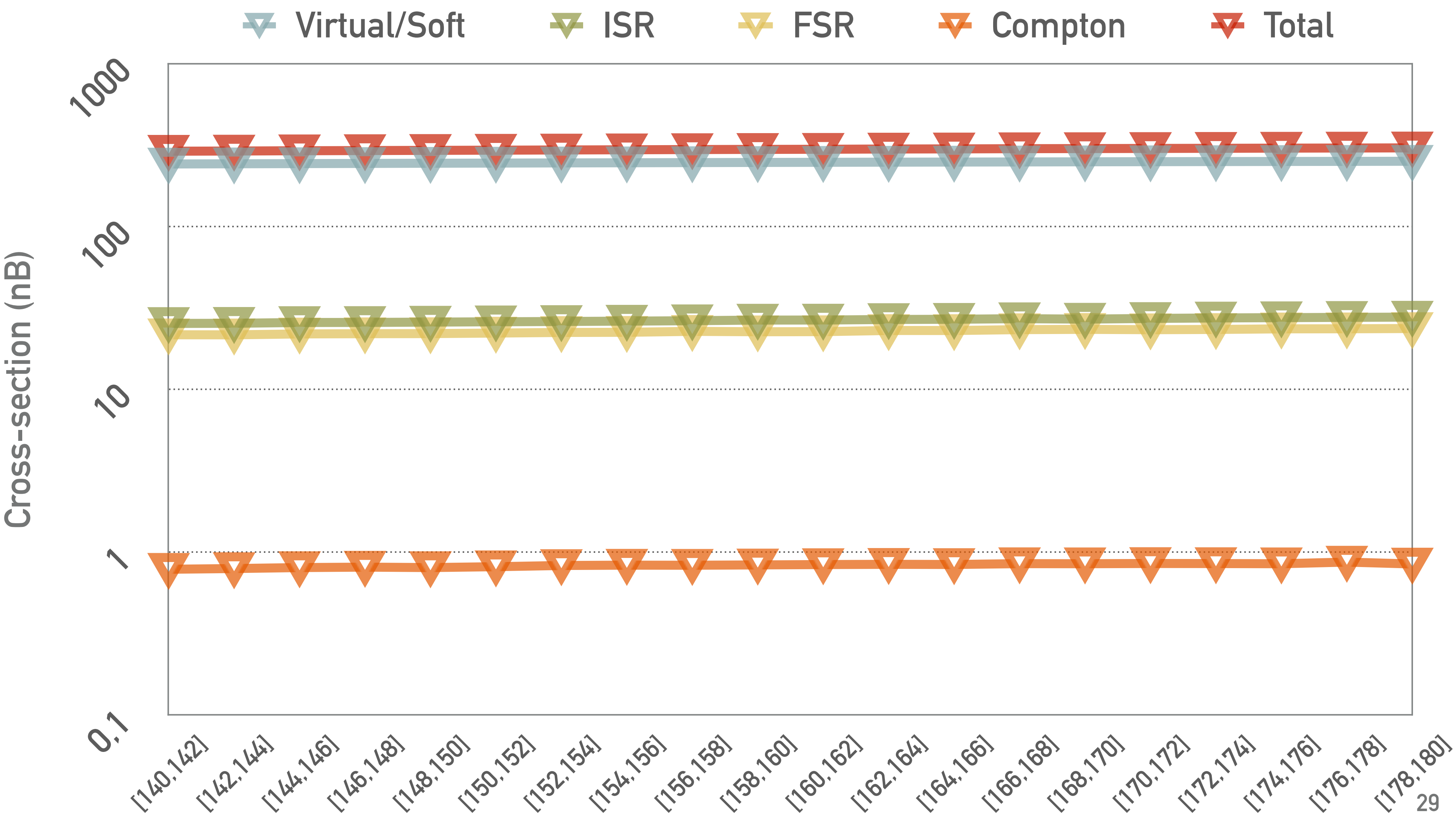
Then declaration of COMMON Block that consists of tables of types

=

COMMON Block of GRIDS

VARIATION OF CROSS-SECTION WITH ENERGY

Diff. on [140,180] : *9.5 nB* *2.38 nB* *2.0 nB* *0.06 nB* *13.9 nB*



QED CORRECTIONS TO F_2

- Typically quark line radiation corrections
- Negligible except at extremely large Q^2 and large x (see next slide)
- Often not subtracted inside the parametrization, thus already taken into account.
- Decided not to use it in DJANGOH for those reasons. Thus $o(\alpha)$ corrections does not take into account quark line radiation corrections.

INCLUSIVE CORRECTIONS

H. Spiesberger,
QED Radiative Corrections for Parton Distributions
hep-ph/9412286

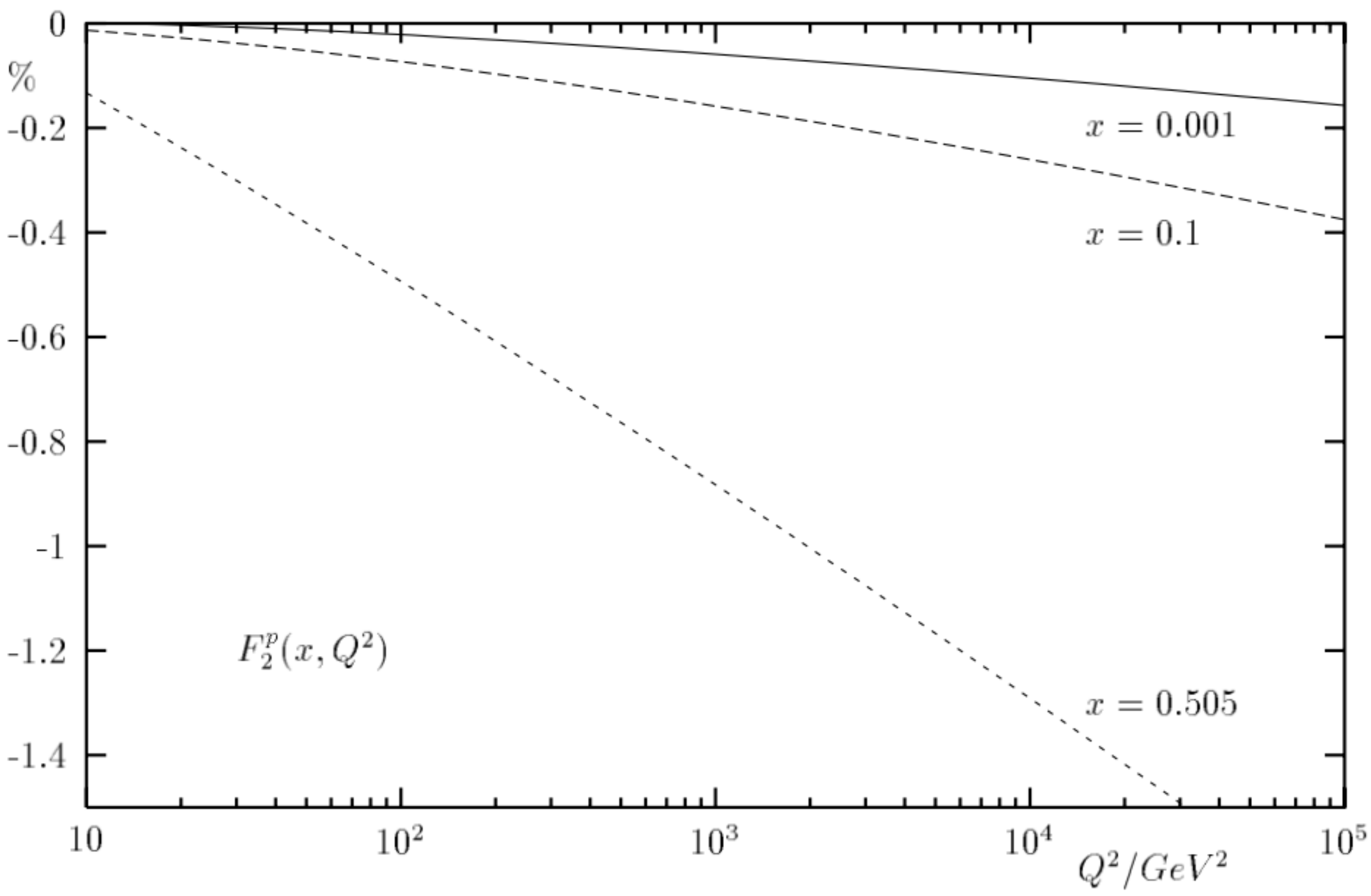
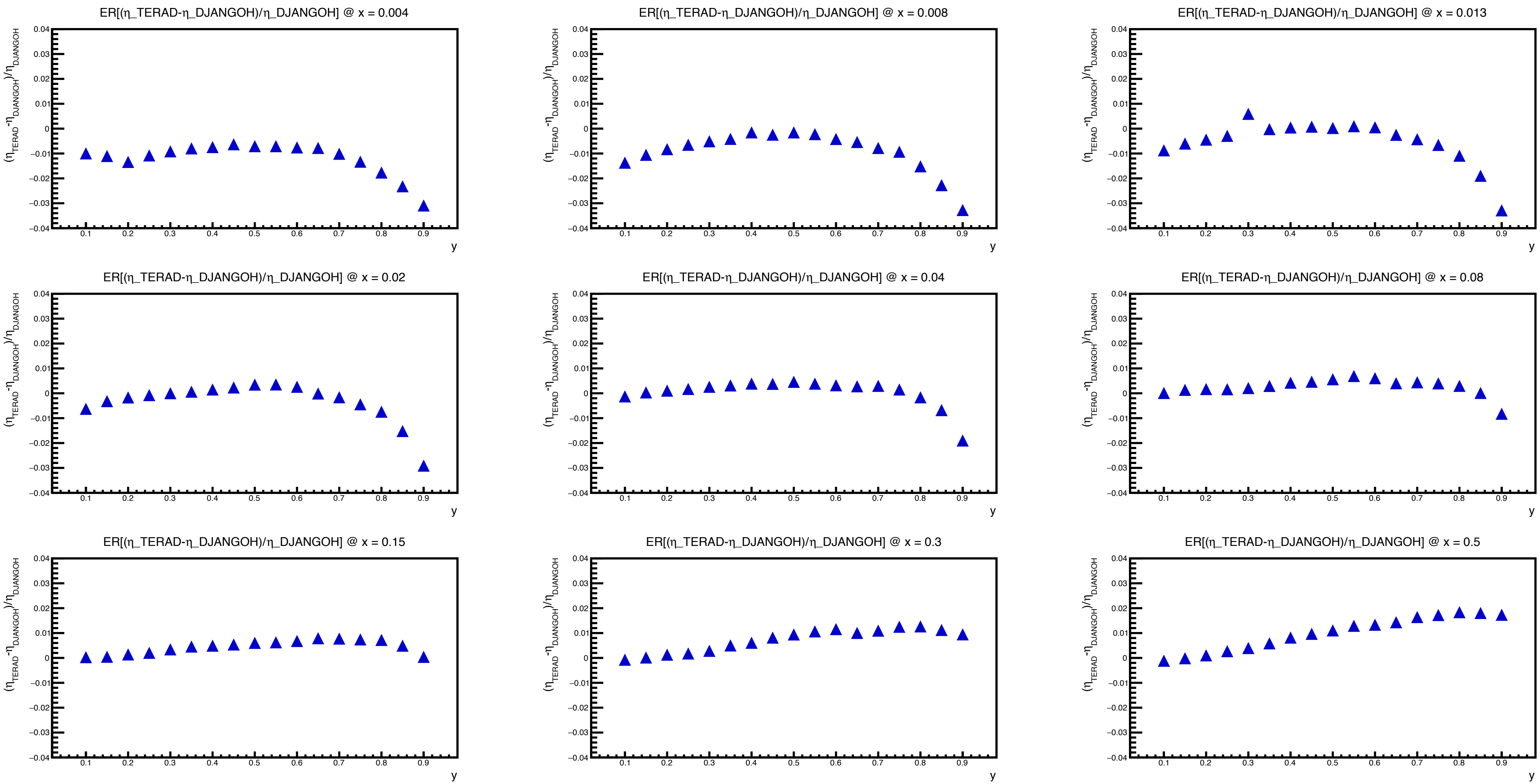


Figure 3: *Q^2 dependence of the QED corrections (in per cent, see text) to the structure function F_2^p for deep inelastic lepton–proton scattering at $x = 0.001$, $x = 0.1$ and $x = 0.505$. Input parton distributions were taken from [12].*

INCLUSIVE CORRECTIONS

$$\eta_T / \eta_D - 1$$

Relative difference between TERAD and DJANGOH. Difference of at most 3%

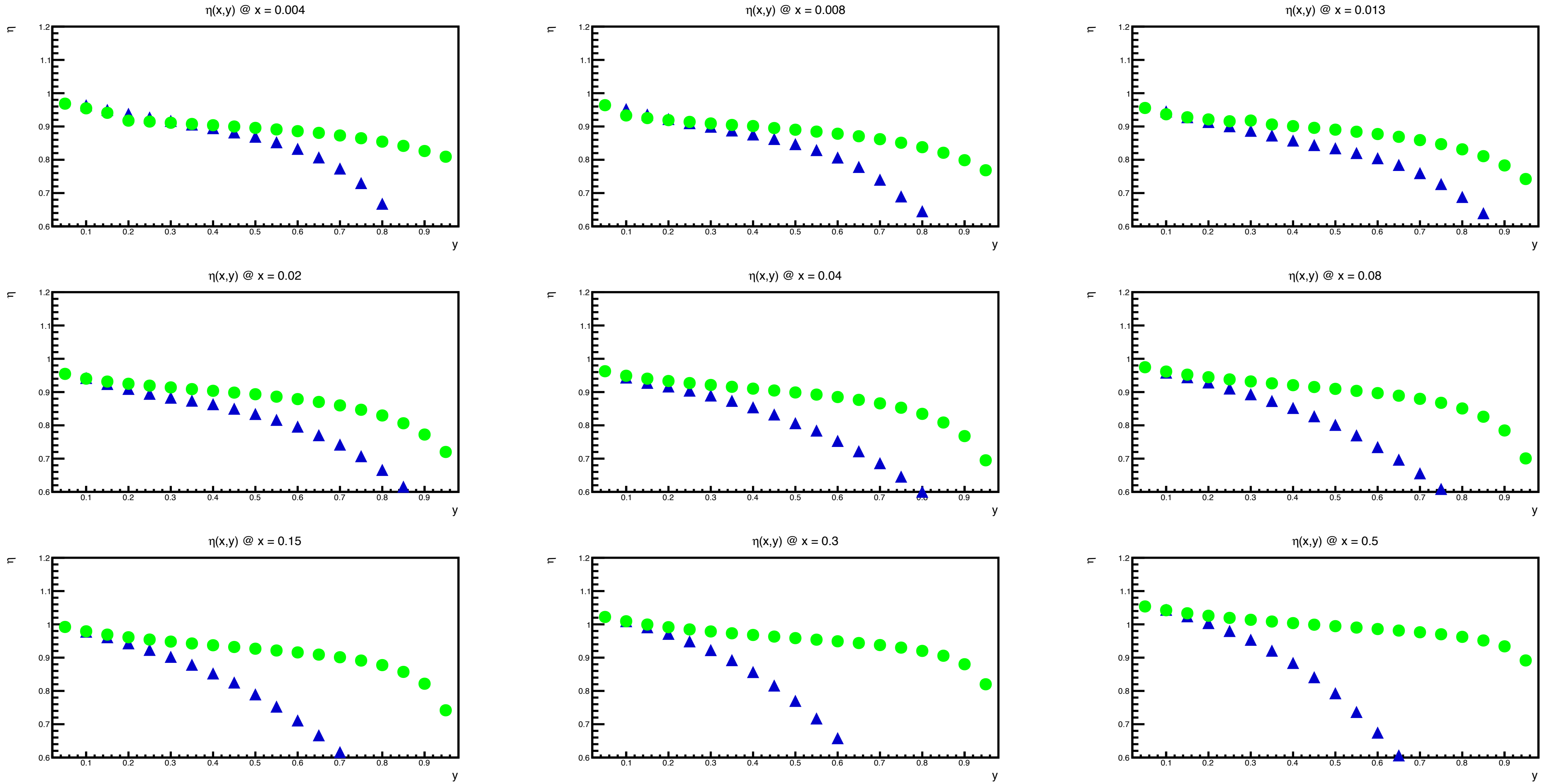


DIGRESSION ON PDF SETS, SF

- Previous results on Inclusive correction show great concordance between DJANGOH and TERAD with TERAD structure functions.
- HOWEVER : for hadronization, DJANGOH needs PDFs and thus cannot use TERAD structure functions for cross-section calculation.
- Game is to find the right PDF set that give structure functions which are not to far from the one from TERAD.
- PROBLEM : for the moment could not find something acceptable.
- ENVISAGED SOLUTION (if time) : might be possible to define a new 'model': use a reasonable set of PDFs and introduce an additional overall correction or scaling factor which gives structure functions in agreement with TERAD structure functions.

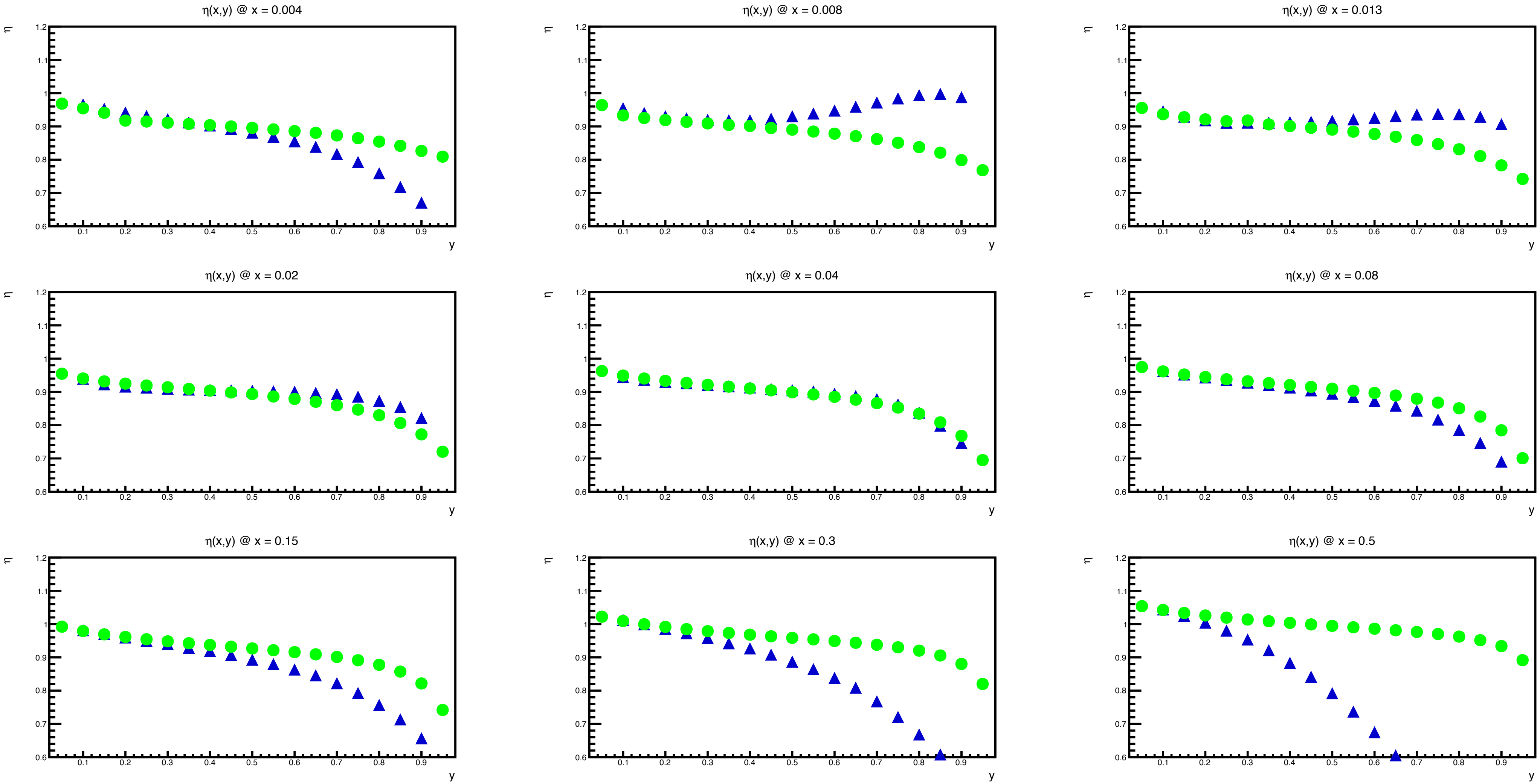
CTEQ6.1

Inclusive radiative corrections for TERAD and DJANGOH .



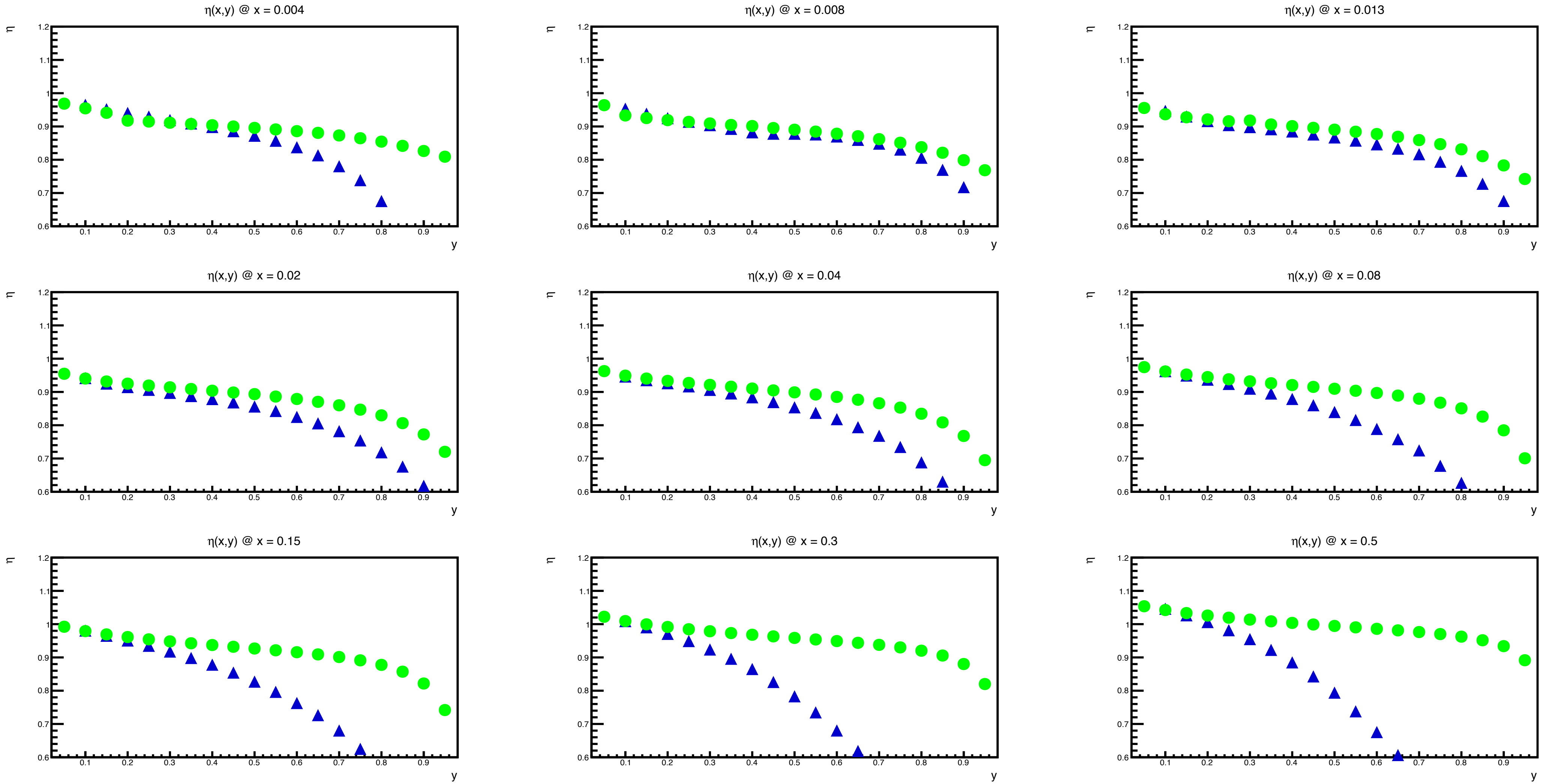
MSTW08

Inclusive radiative corrections for TERAD and DJANGOH .



HERAPDF15

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.



NNPDF21DIS

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.