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

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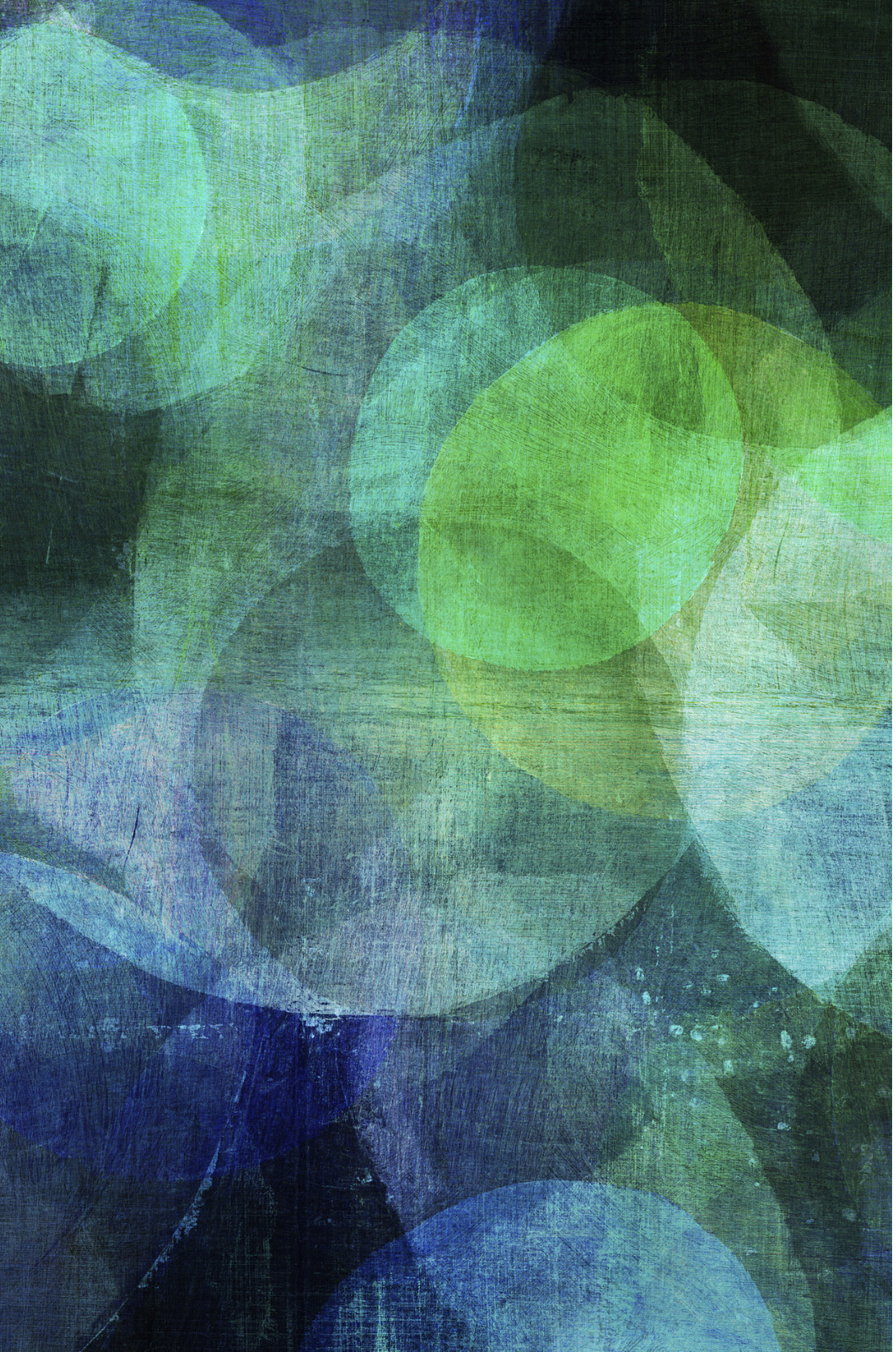
December 5, 2017 – GDR'17



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 :

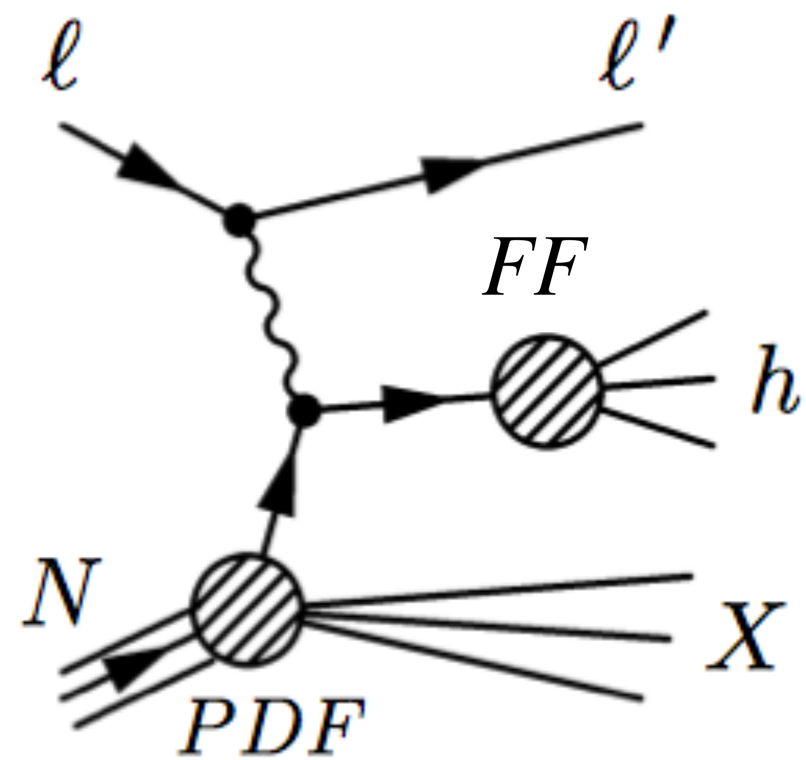
$$\sigma_{theory} = \sigma^{(0)}\left[F_n\right] + \alpha_{em}\sigma^{(1)}\left[F_n\right] + \ldots$$

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 :

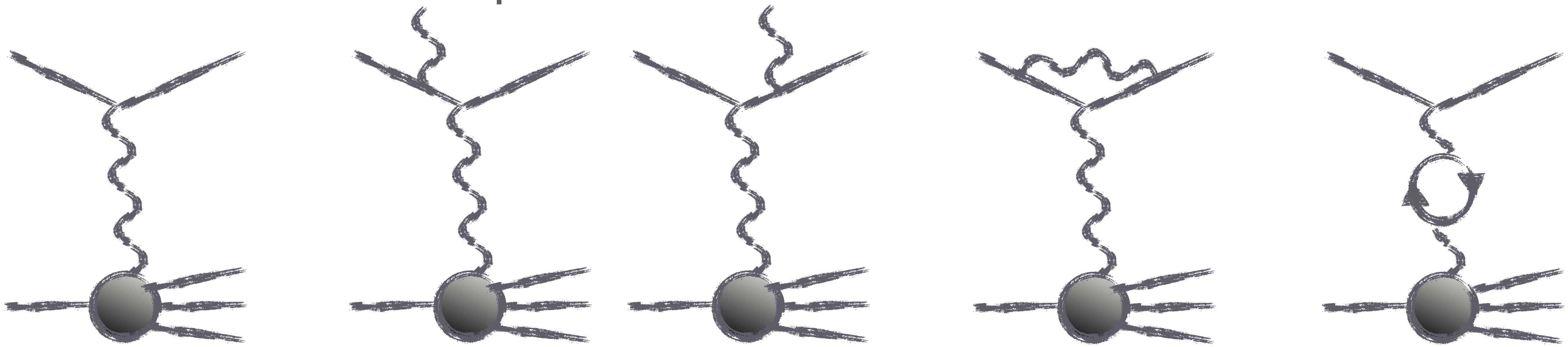
Difference between the hadronic and leptonic kinematic variables

→ 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

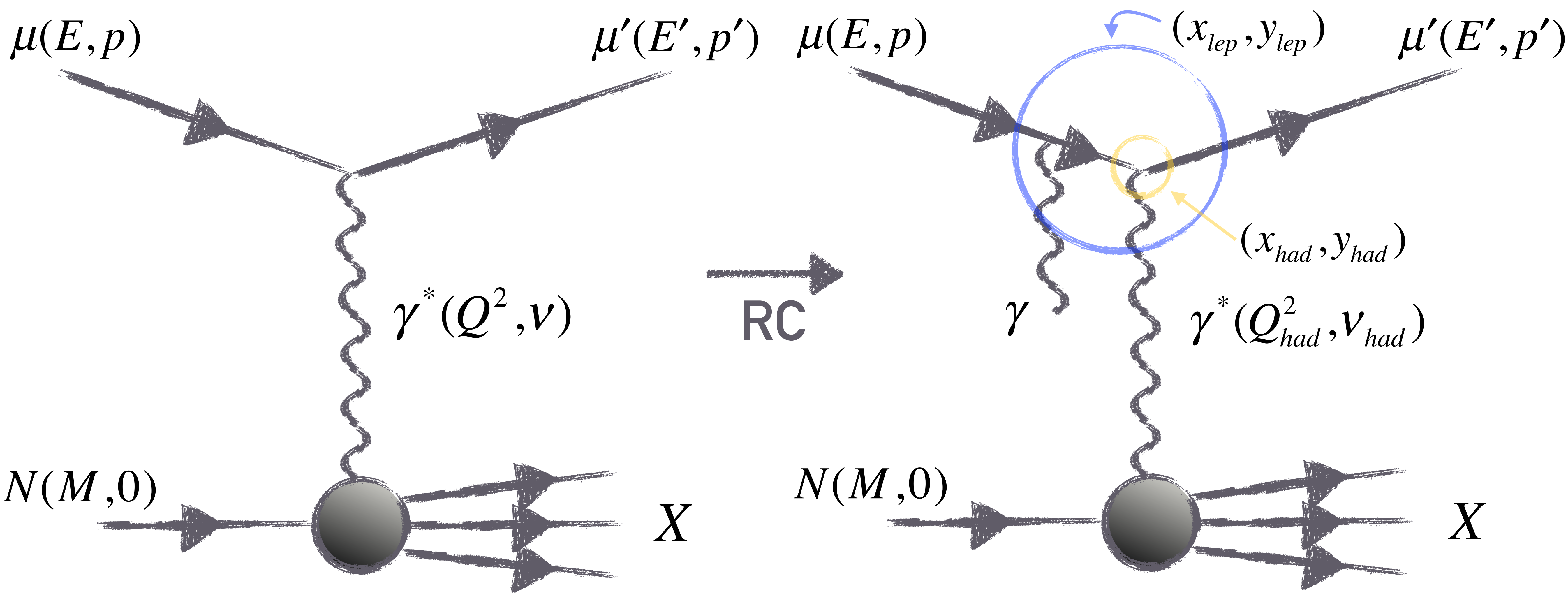
Measurement of DIS cross-section : Inclusive radiative corrections

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

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

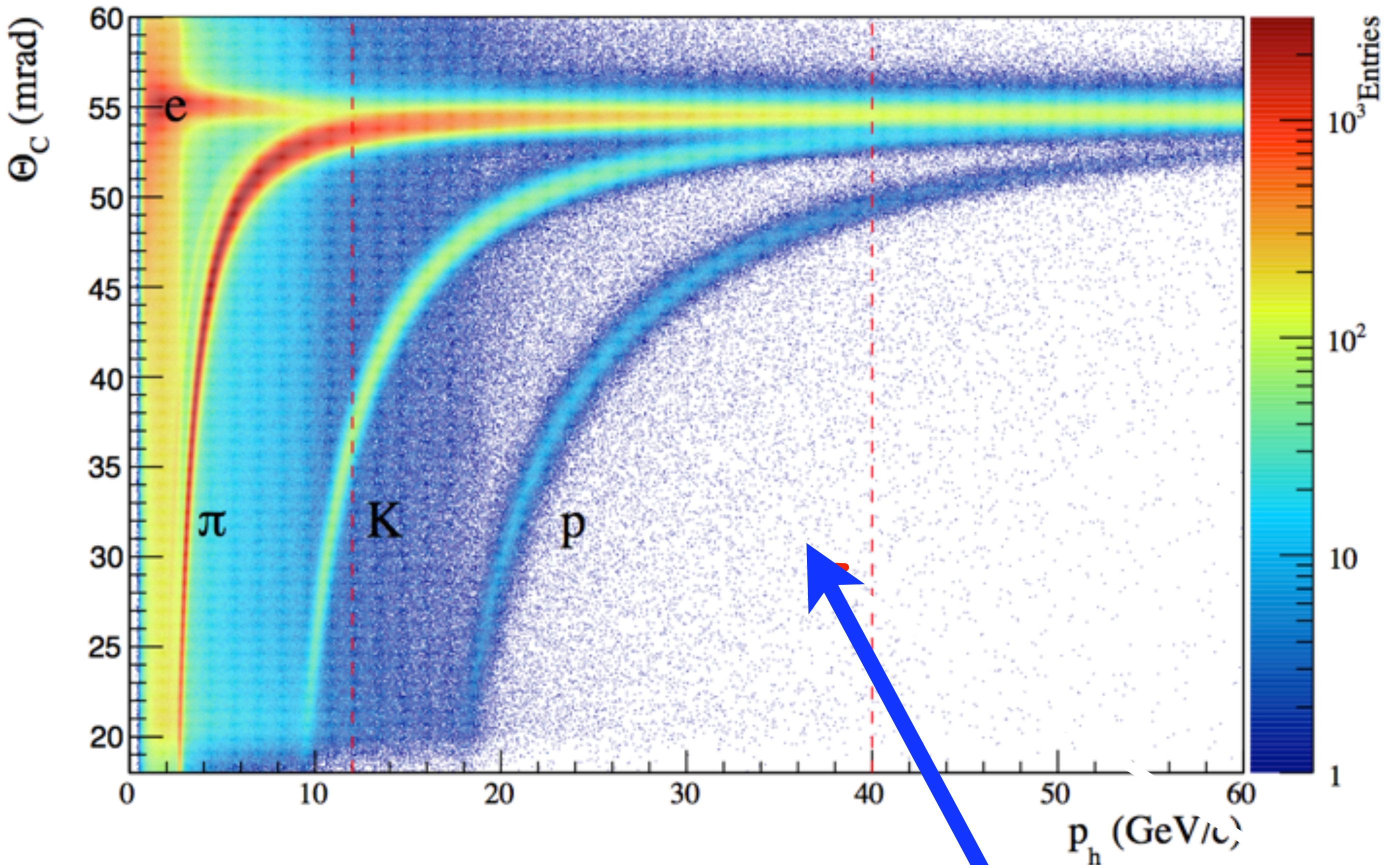


SIDIS = Semi-Inclusive DIS (obs. of one hadron of the final state)

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

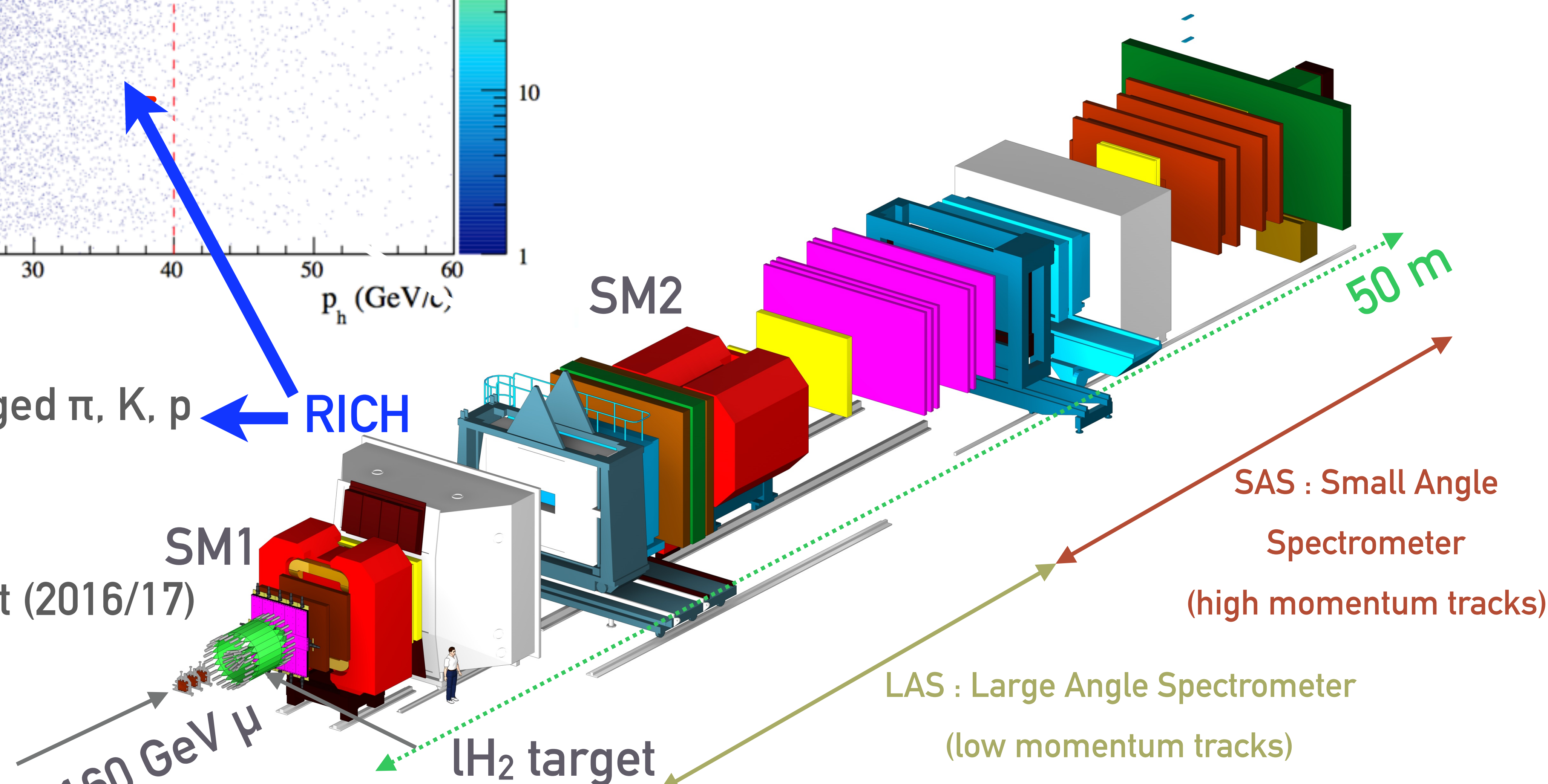
Radiative event
=
Event containing a real radiated photon

COMPASS EXPERIMENT



- Fixed target experiment at CERN SPS
- Two-staged spectrometer (LAS/SAS)
- Can operate with muon or hadron beams (2016/17 160 GeV muon beam)

- 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

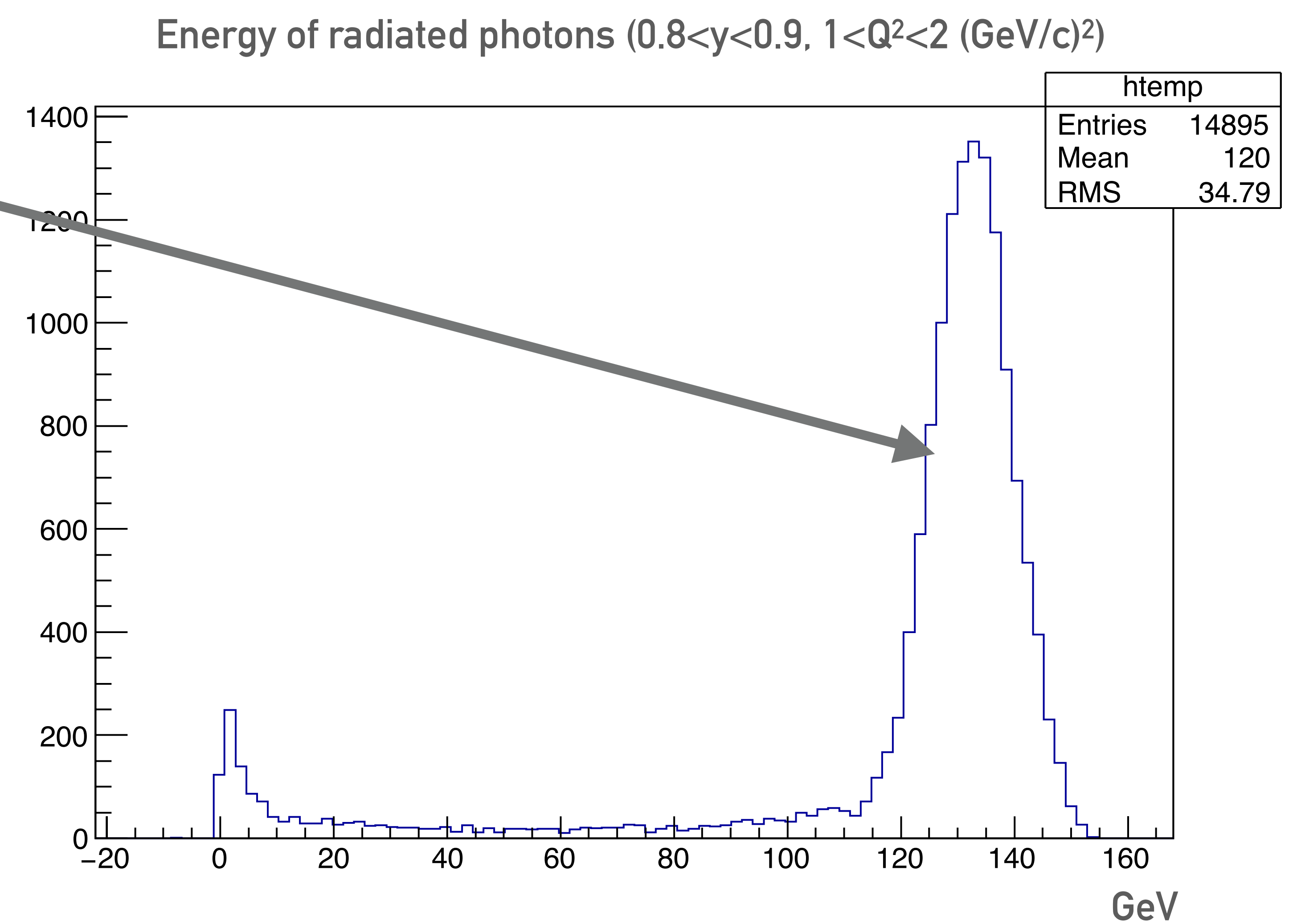
COMPASS used RADGEN generator (I.Akushevich, H.Böttcher, D.Ryckbosch, arXiv:hep-ph/9906408) in previous analyses.

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 ?

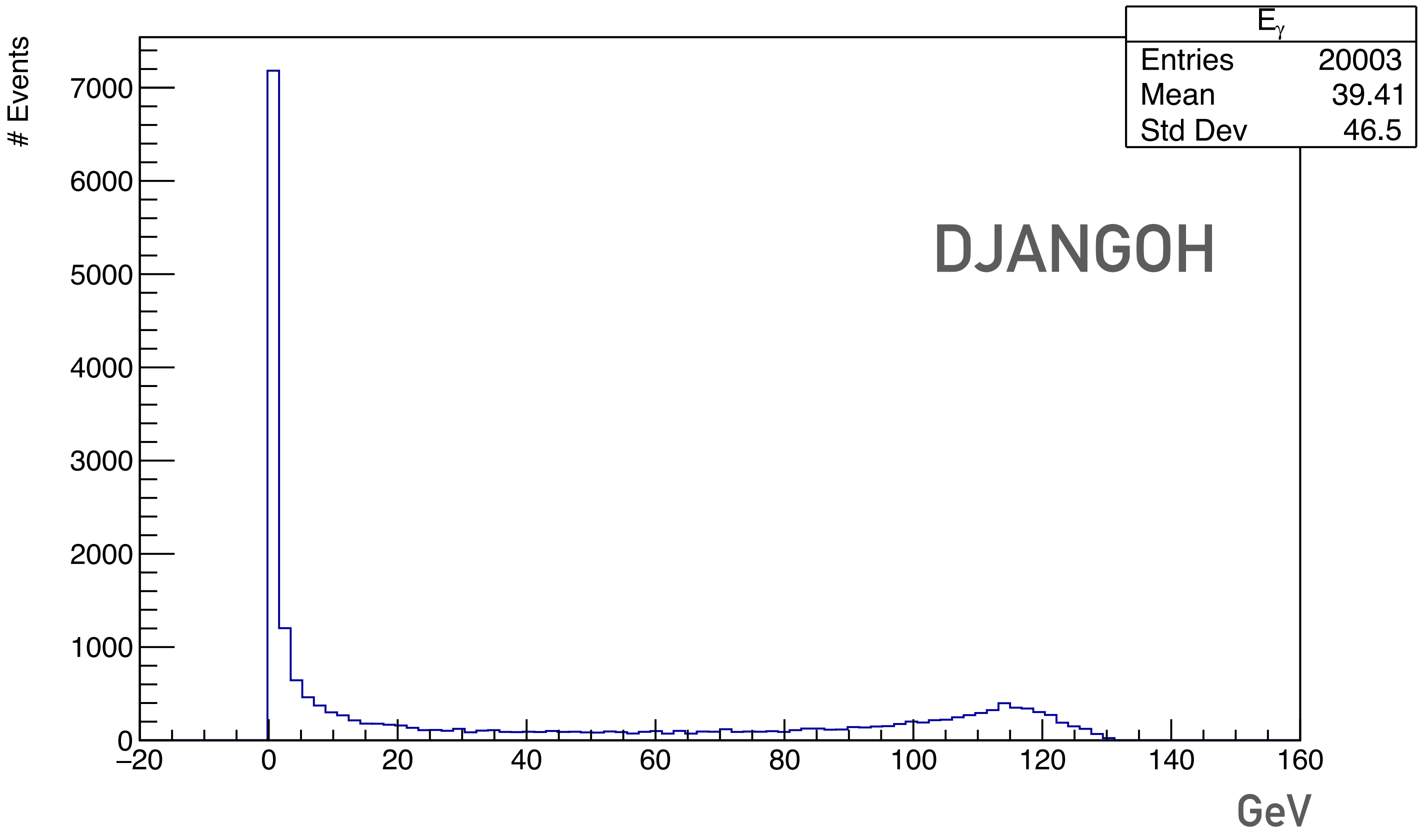
DJANGOH

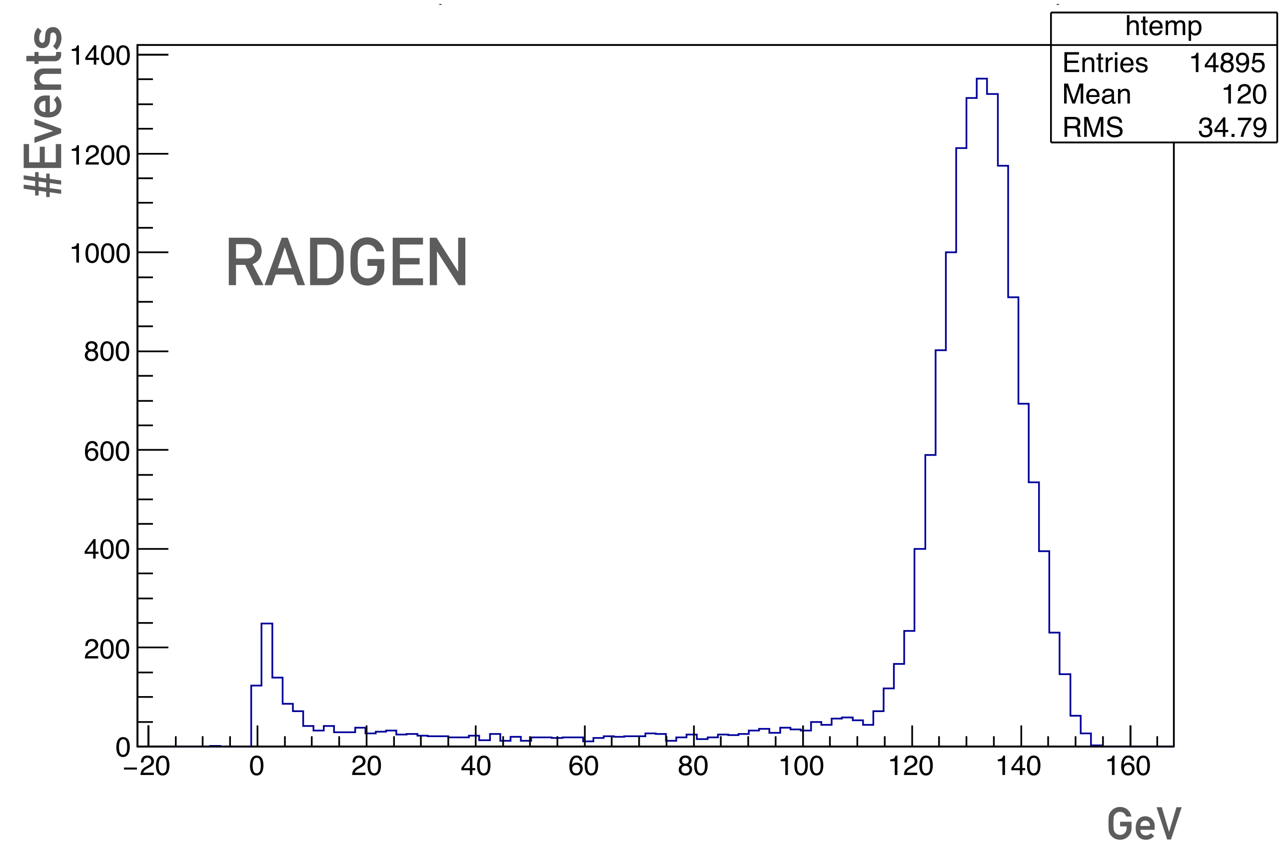
DJANGOH, concatenation of DJANGO and HERACLES :

- 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). Will be used for EIC (arXiv:1309.5327v1)
- 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

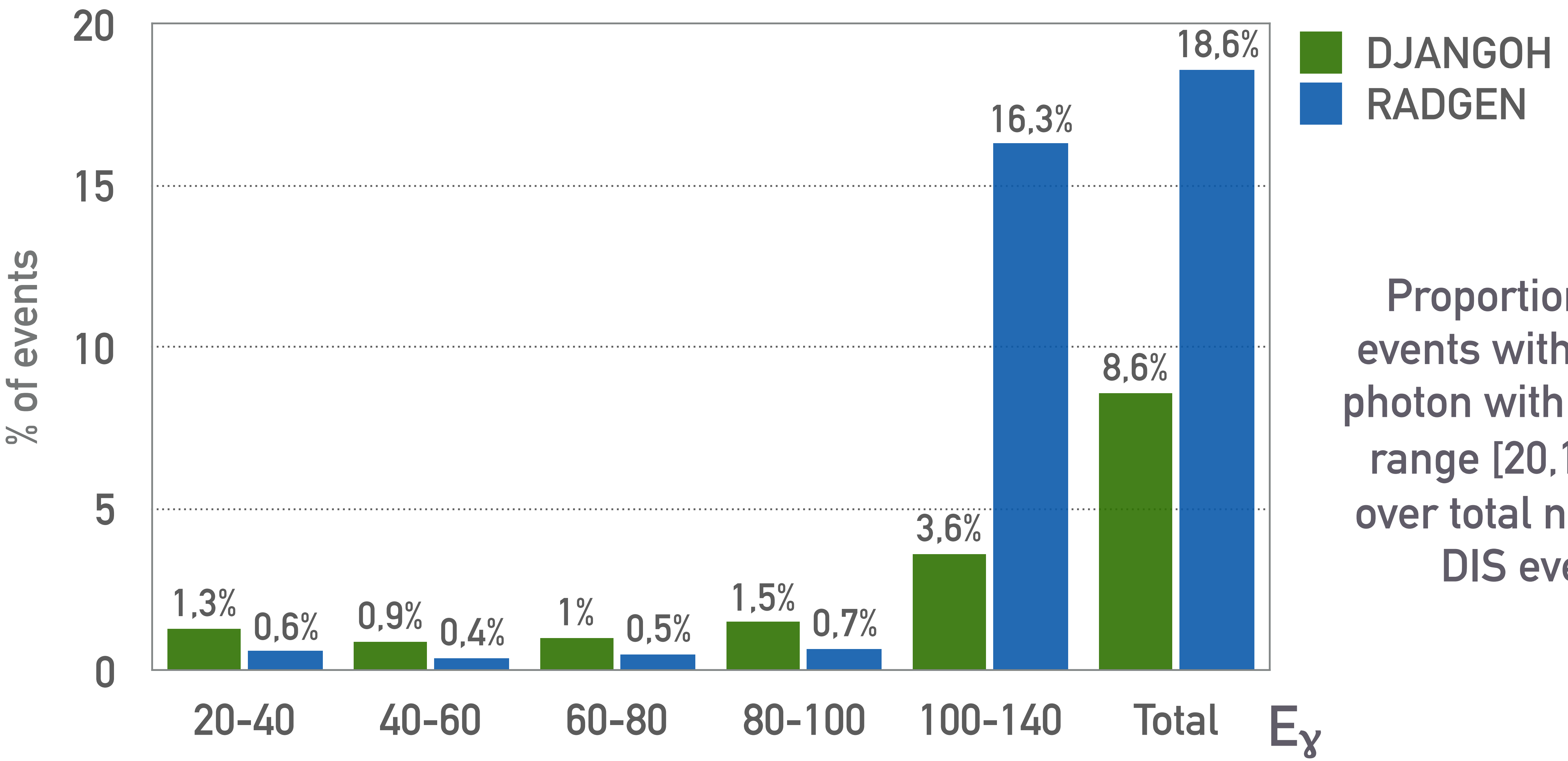
Energy of radiated photons ($0.8<y<0.9$, $1<Q^2<2$ $(GeV/c)^2$)





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

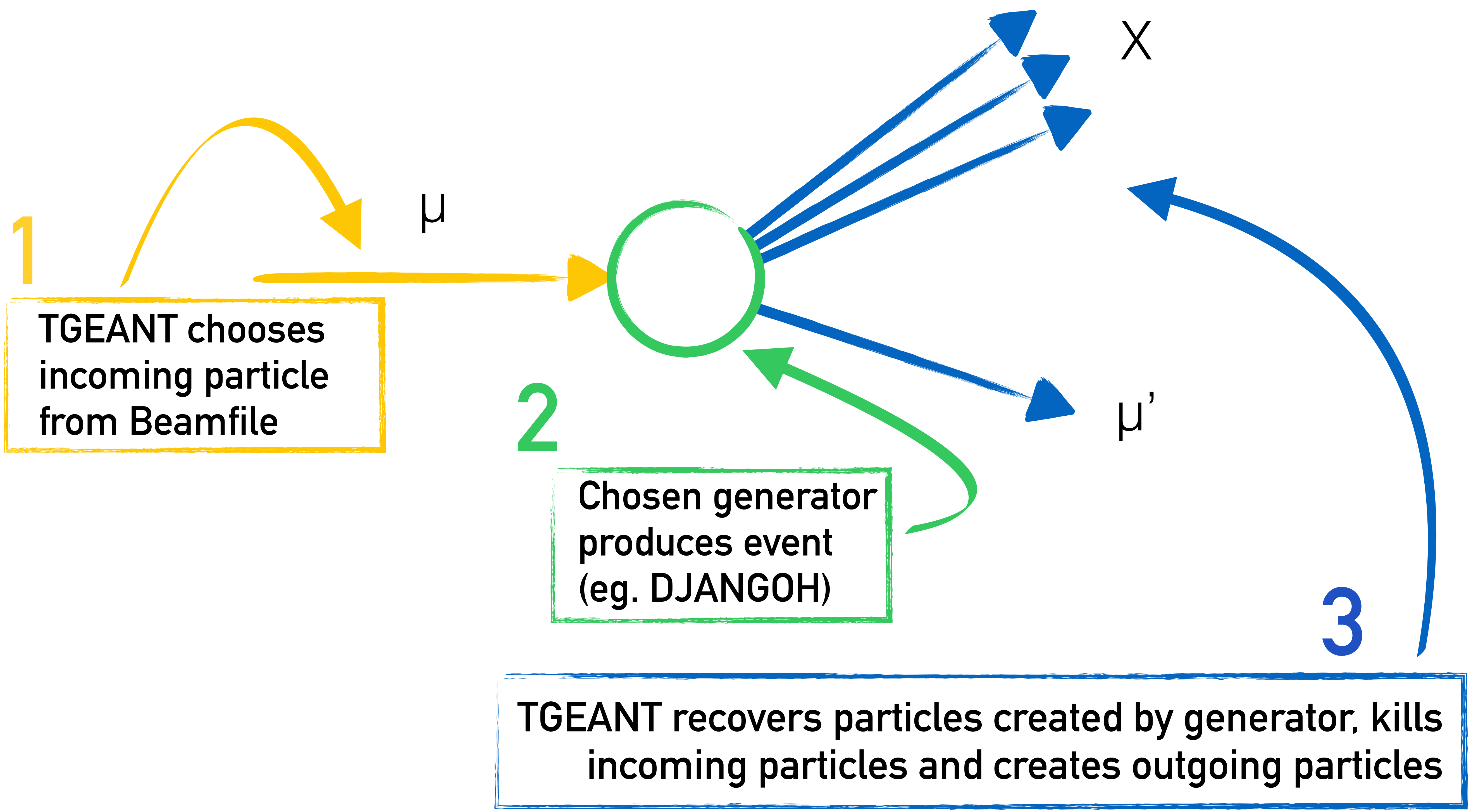
Motivated implementation in MC chain and further tests

TGEANT

> *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

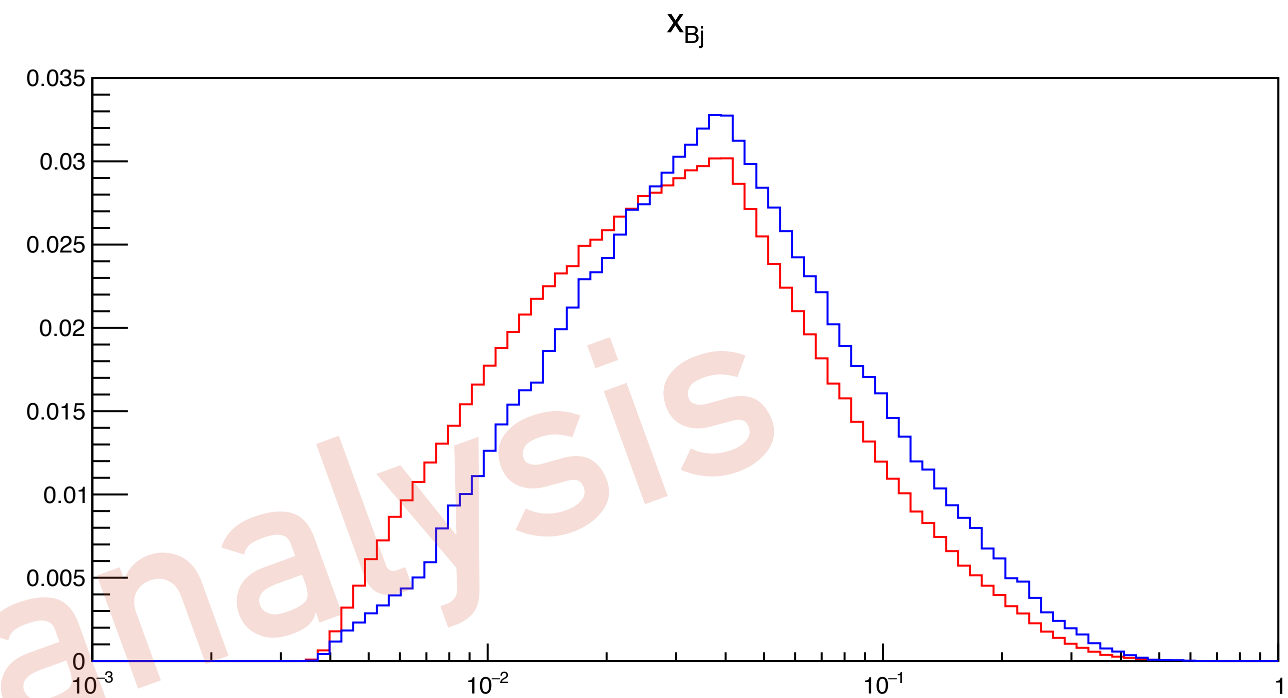
- Is a TGEANT class
- Manipulates instance of TDjangoh
- Do the I/O transfer of TGeant to TDjangoh

→ TDJANGOH GitHub Repo : https://github.com/nipierre/TDJANGOH

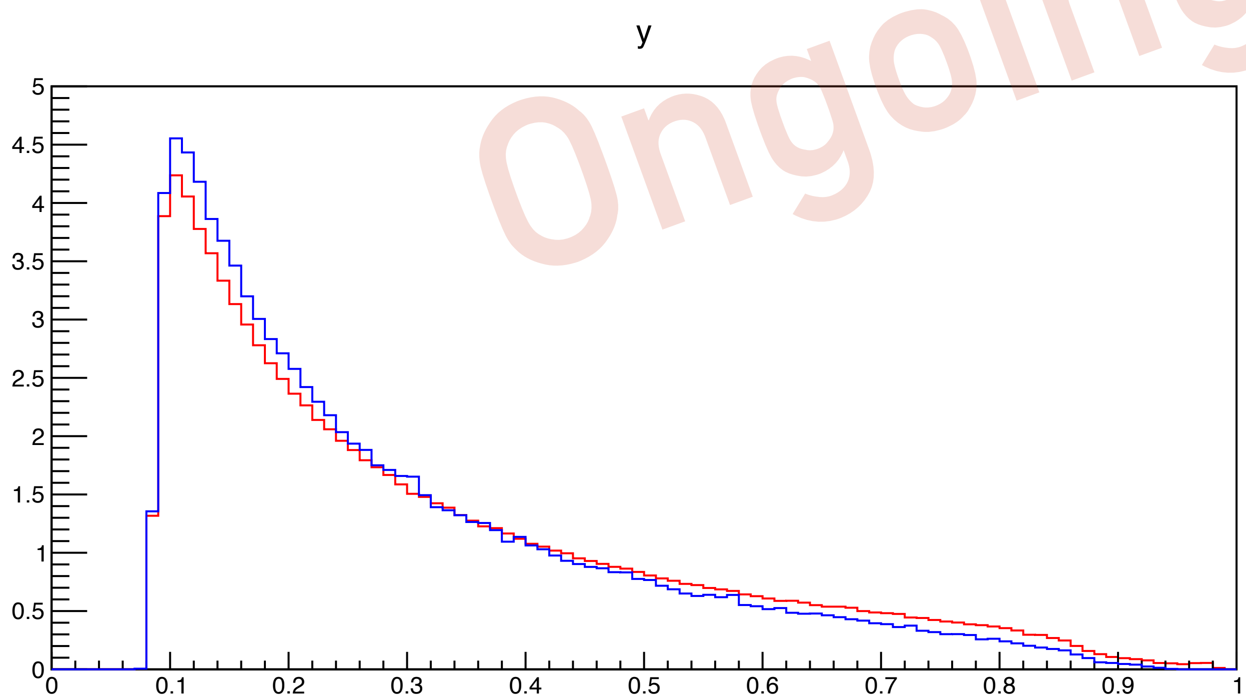
RECONSTRUCTED MONTE-CARLO

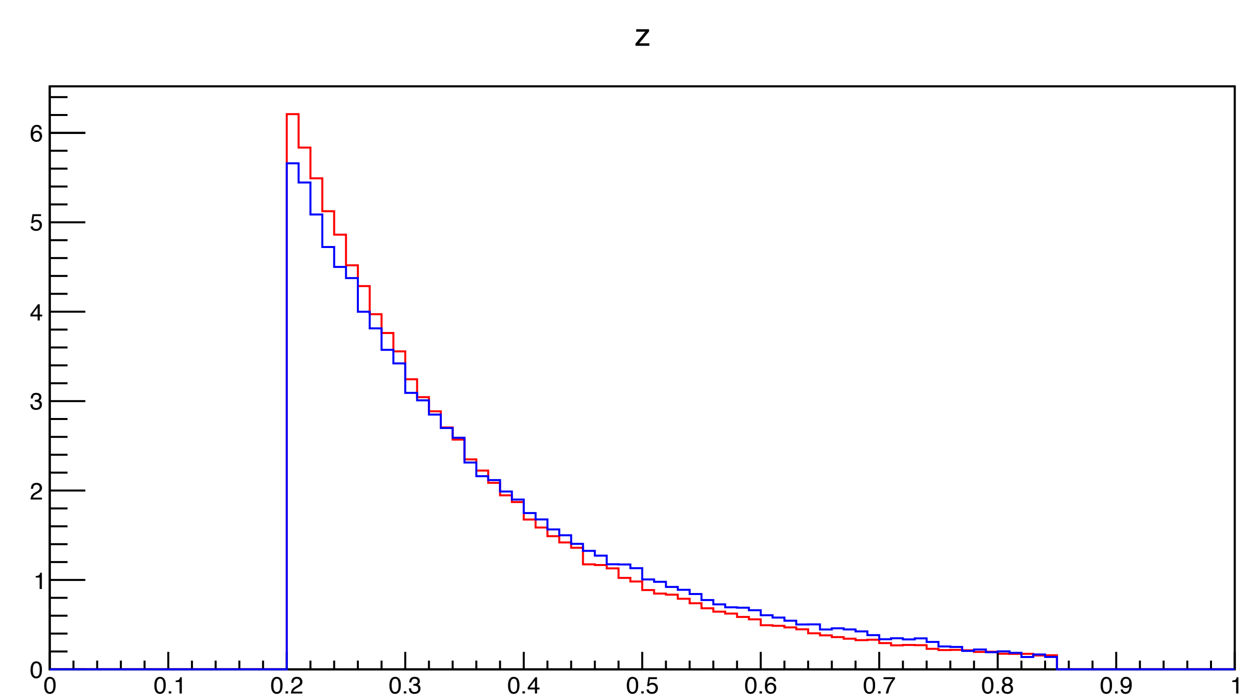
Comparison between real Data and MC for x, y and z.
Ok for y and z, still some problems with x (not enough low x events) : **under investigation** !

Real Data — MC



Ongoing analysis





INCLUSIVE RADIATIVE CORRECTIONS

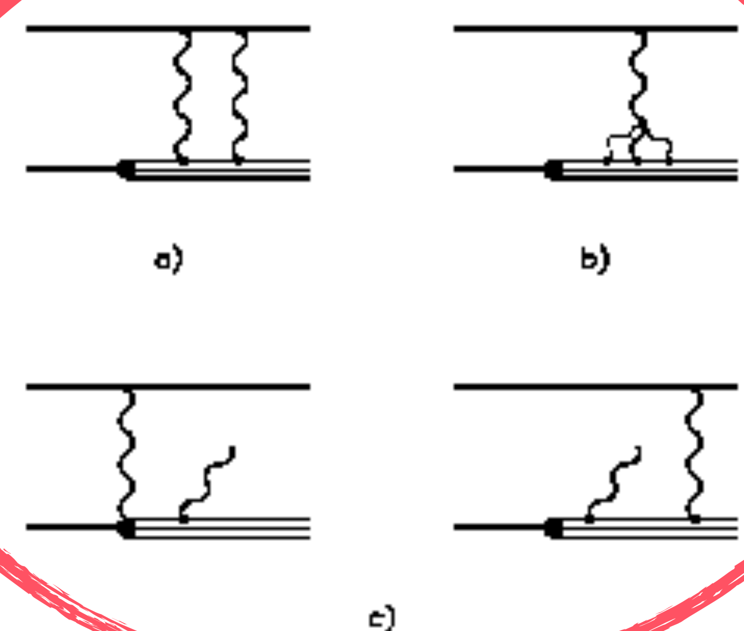
- To fix the definition of radiative correction :

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

- This definition will be used in the following.

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

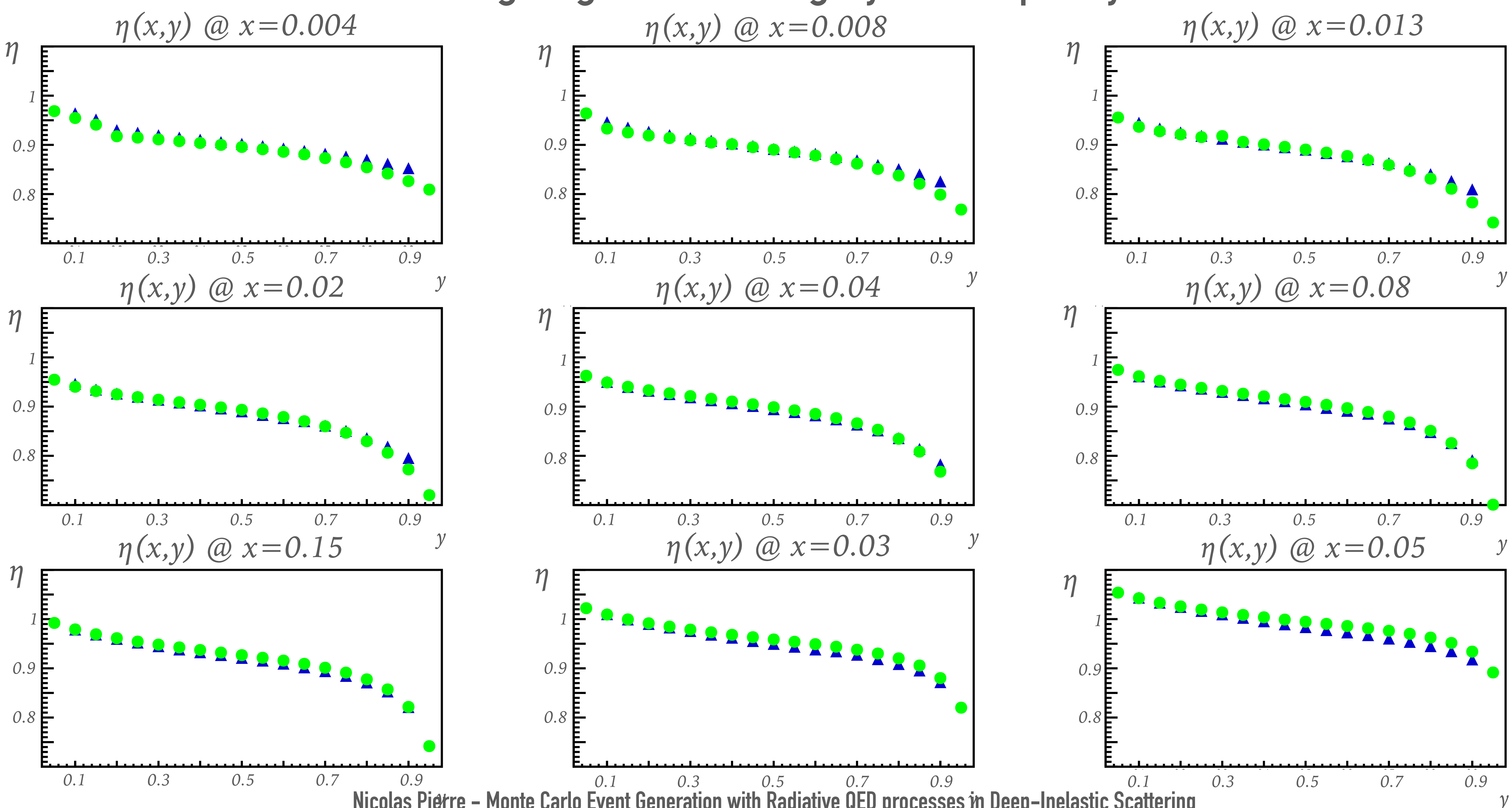
- TERAD uses parametrization for structure functions. Same F_2 and R used in DJANGOH.



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 :

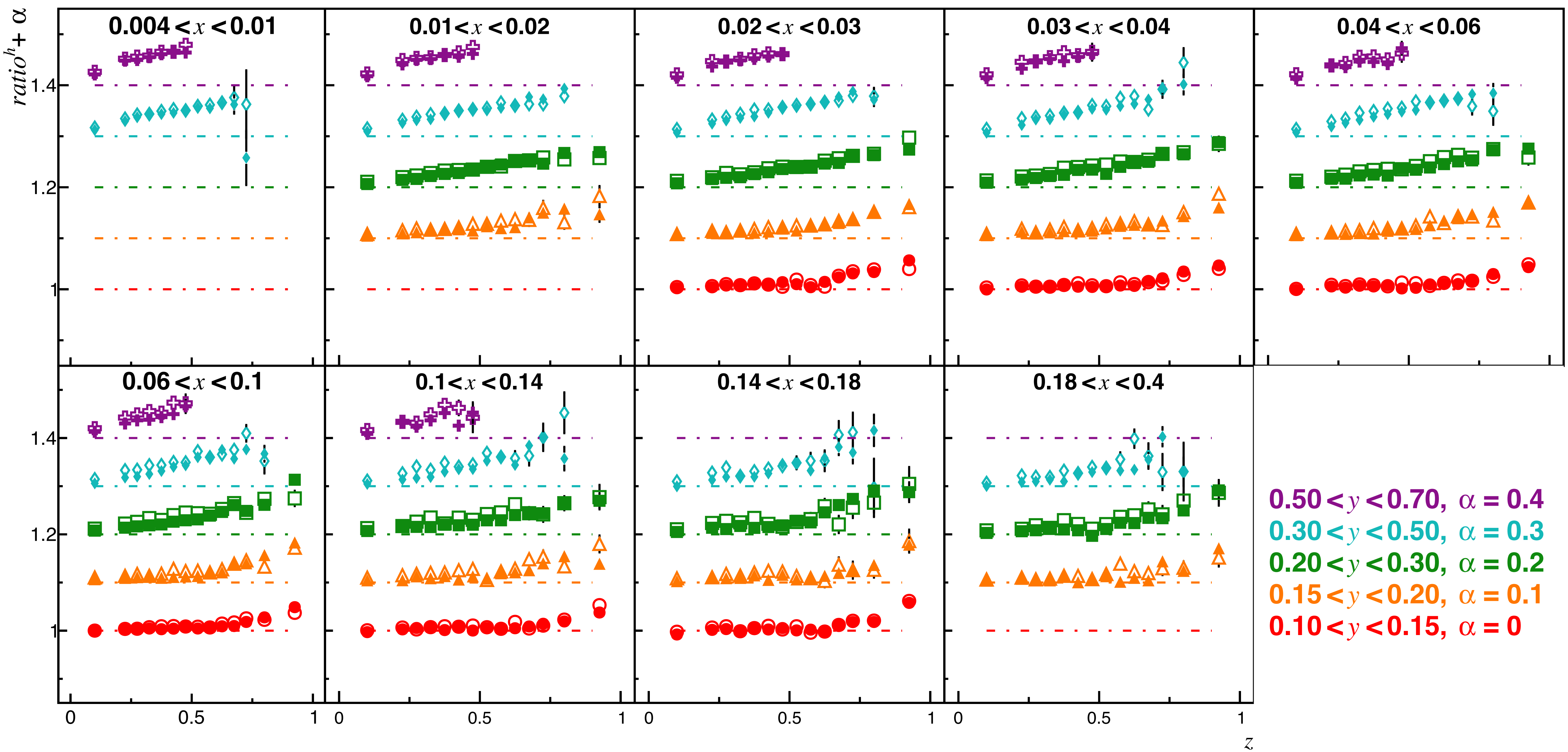
$$\eta^{h^{\pm}}(x,y,z) = \frac{M^{h^{\pm}}_{Born}(x,y,z)}{M^{h^{\pm}}_{Born+o(\alpha)}(x,y,z)}$$

- 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.

○ negative hadrons
● positive hadrons



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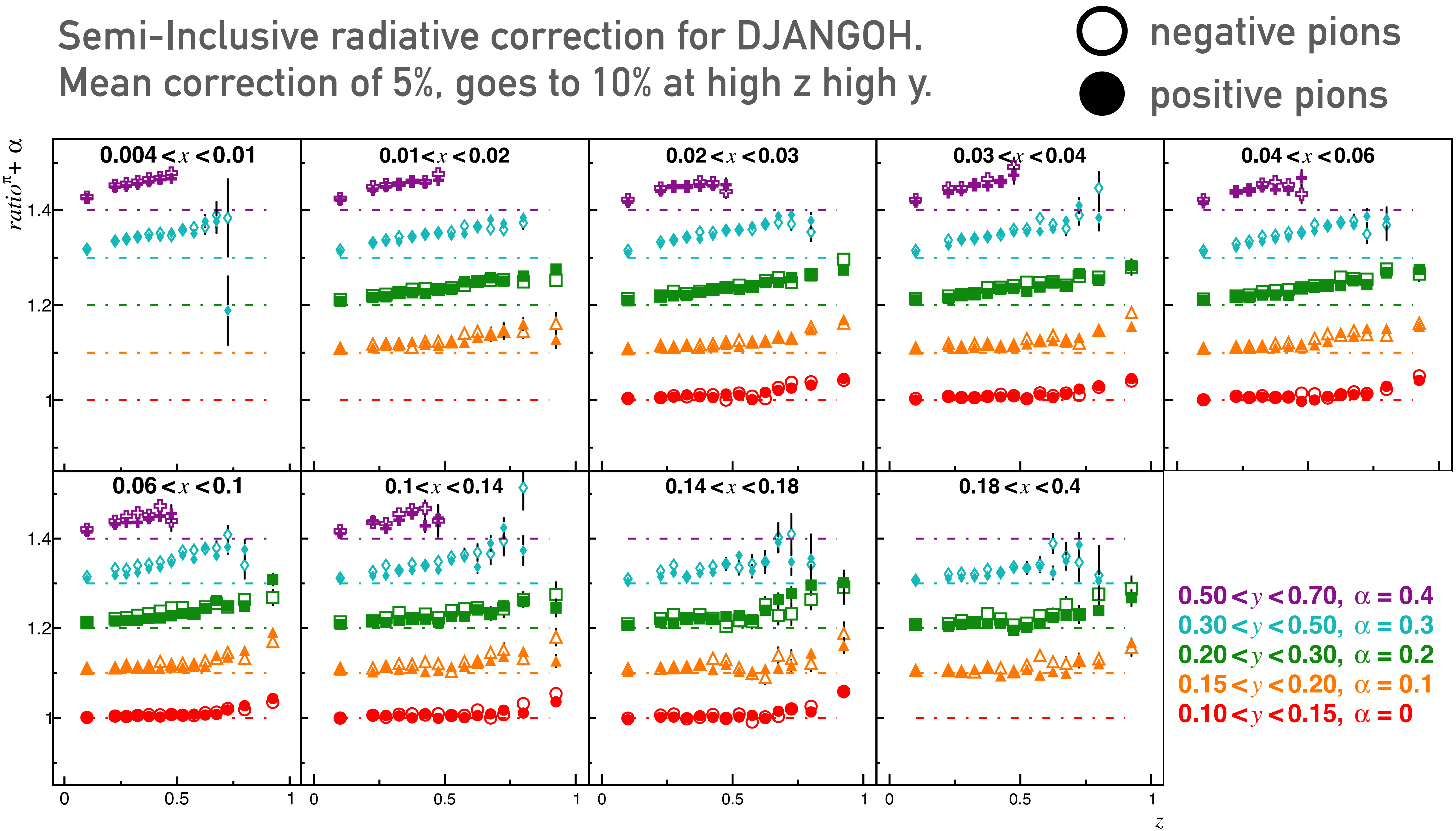

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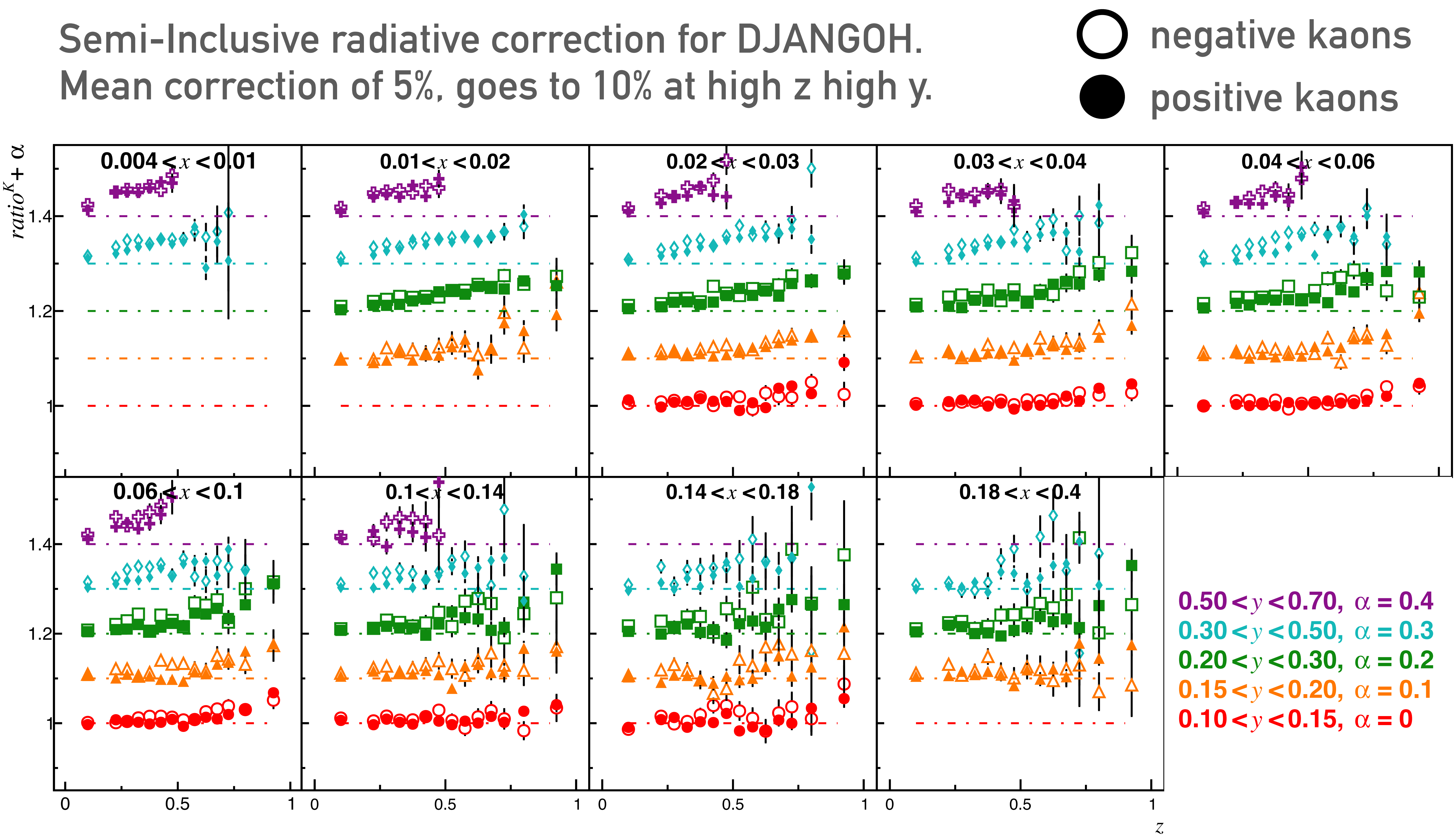


WORK STILL IN PROGRESS

- 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
  - Tuning of MC

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.

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 :

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

Solution is to factorize and absorb the divergences into PDF.

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

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),NDO2,
     +                NTOT2,NCAL2,NCA12,NCA22,IBIM2,JCOR2,
     +                LGLO2,LLOC2
```

```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 :: NDO2
    DOUBLE PRECISION :: NTOT2
    REAL :: NCAL2
    REAL :: NCA12
    REAL :: NCA22
    REAL :: IBIM2
    REAL :: JCOR2
    LOGICAL :: LGLO2
    LOGICAL :: LLOC2
  END TYPE
```

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)

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-----------------------
```

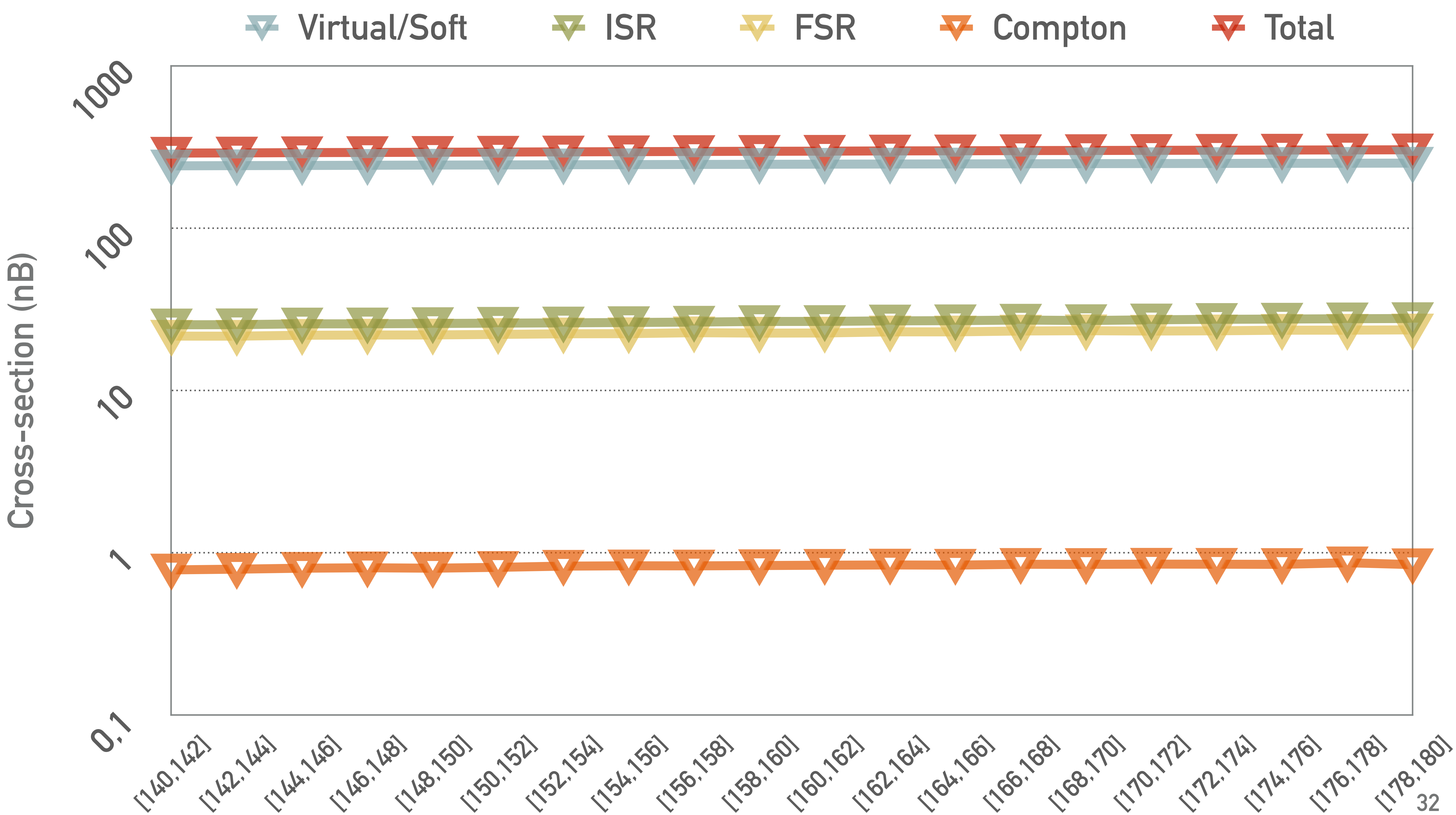
Then declaration of COMMON Block that consists of tables of types

=

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 Distribution
hep-ph/9412286

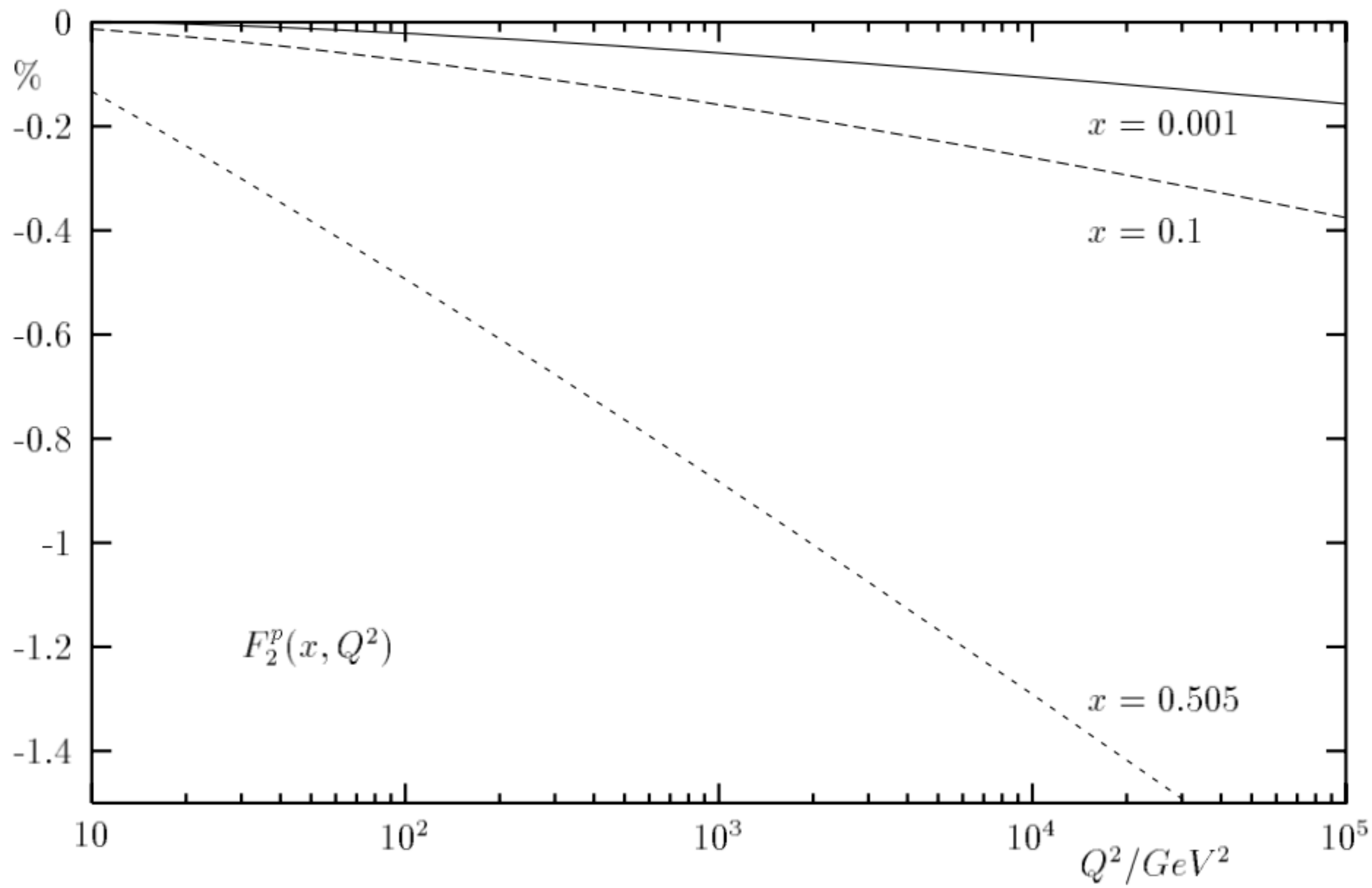
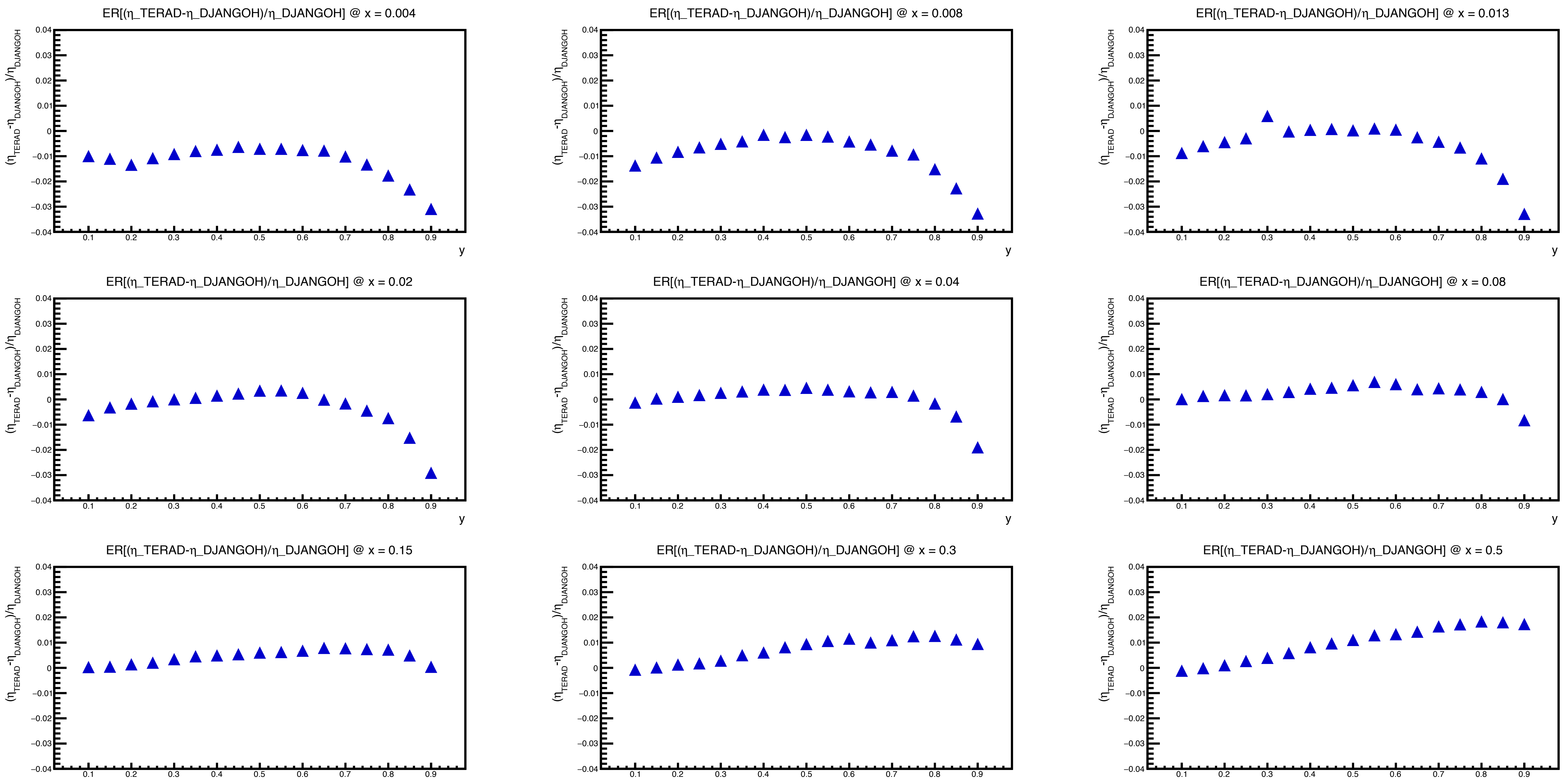


Figure 3: *Q^2 dependence of the QED corrections (in per cent, see text) to the structure function F_2^p for deep inelastic lepton–proton scattering at $x = 0.001$, $x = 0.1$ and $x = 0.505$. Input parton distributions were taken from [12].*

INCLUSIVE CORRECTIONS

$$\frac{\eta_T}{\eta_D} - 1$$

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

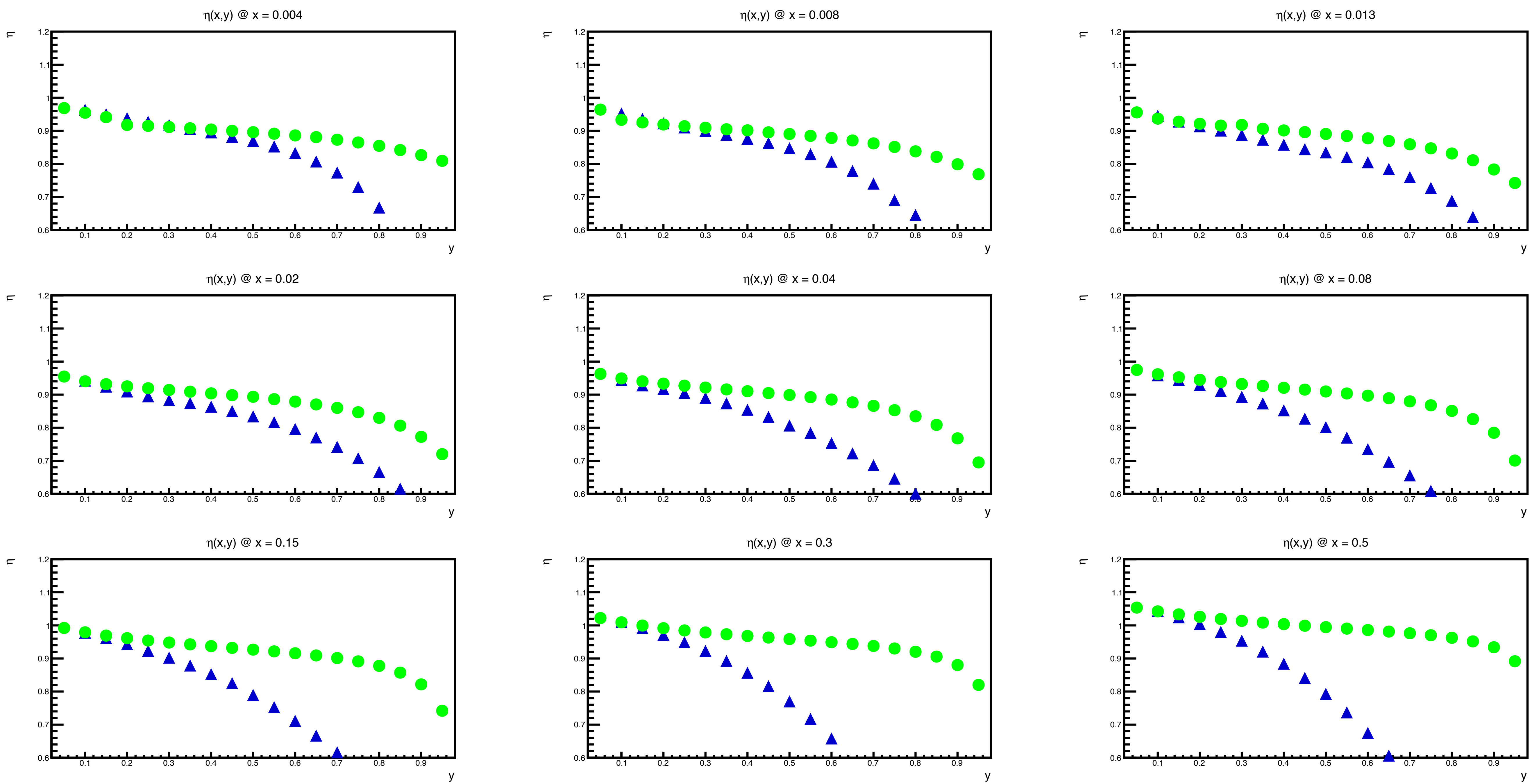


DIGRESSION ON PDF SETS, SF

- 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.

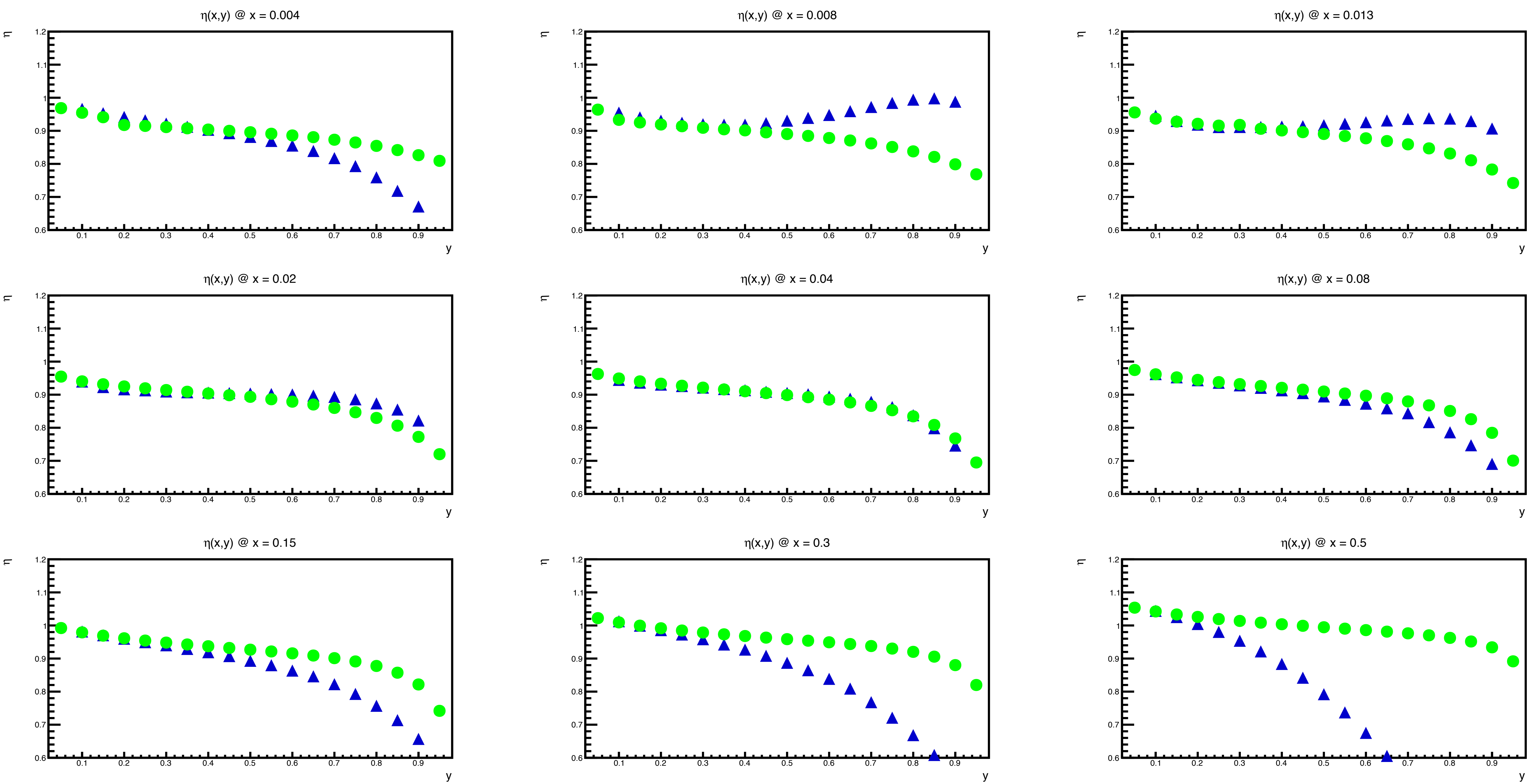
CTEQ6.1

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.



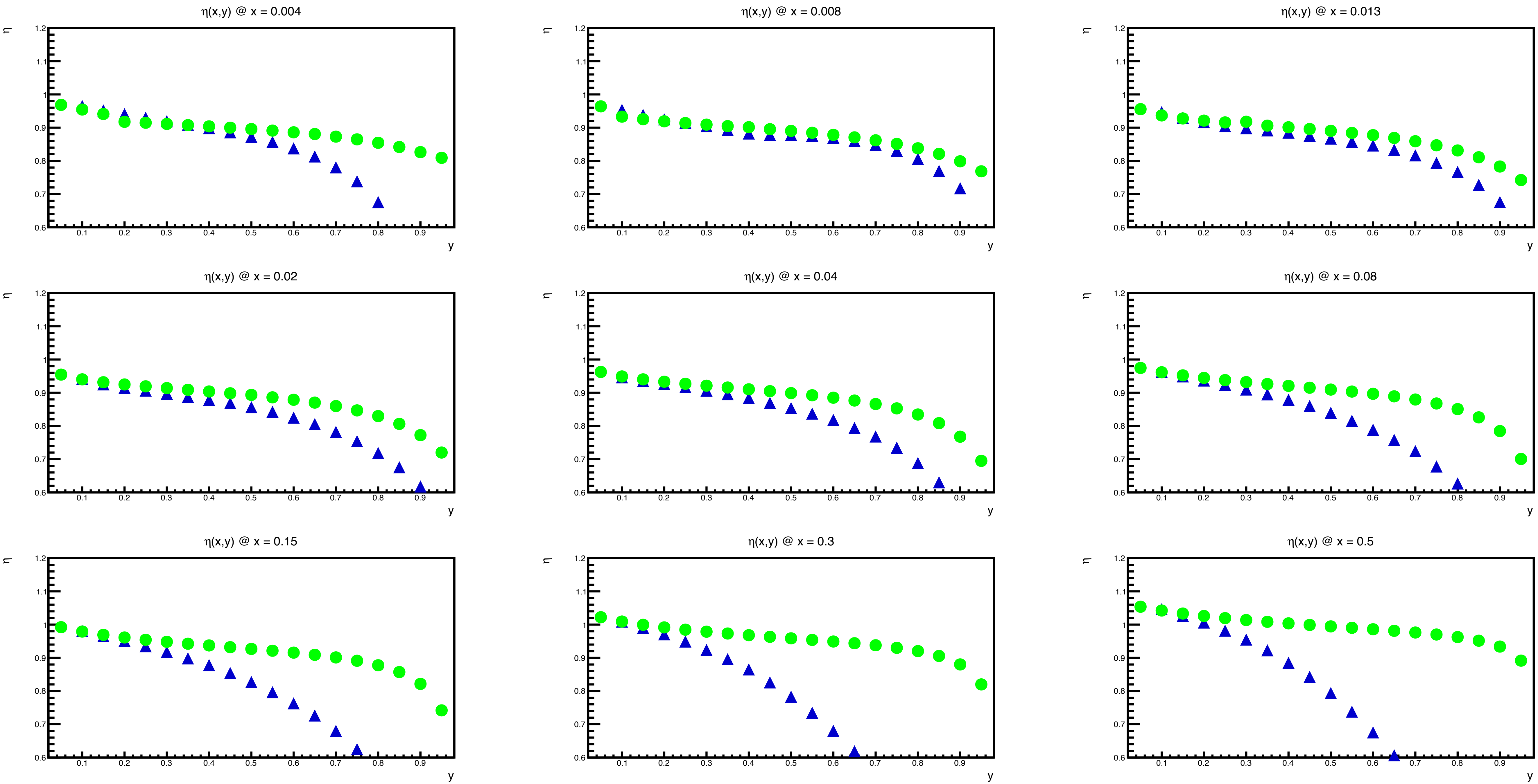
MSTW08

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.



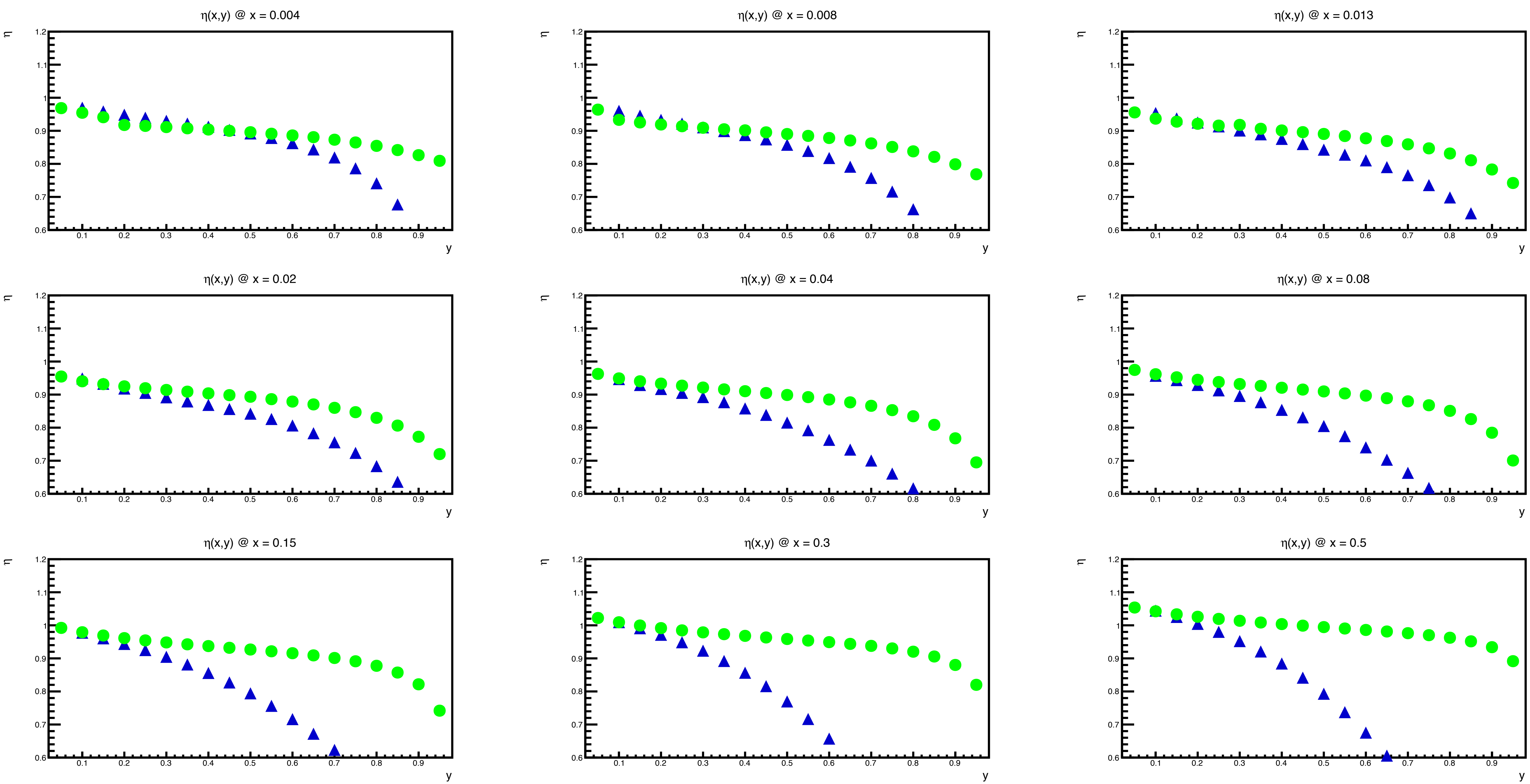
HERAPDF15

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.



NNPDF21DIS

Inclusive radiative corrections for TERAD ● and DJANGOH ▲.



SEMI-INCLUSIVE CORRECTIONS

Semi-Inclusive radiative correction for DJANGOH.
Correction goes from +5% at low y to -10% at high p_T high y.
Strong impact in p_T, stronger than with z.

○ negative hadrons
● positive hadrons