Limits on the Effective Quark Charge Radius

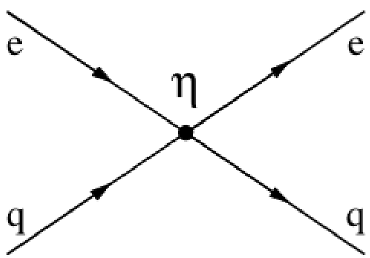
O. Turkot, K. Wichmann, A.F. Żarnecki

ZEUS paper presentation.

- Quark charge radius model
- Limits setting procedure including PDFs fit
- Probability and χ^2 methods results
- Model and parameterization variations
- Second analysis
- Plots for publication

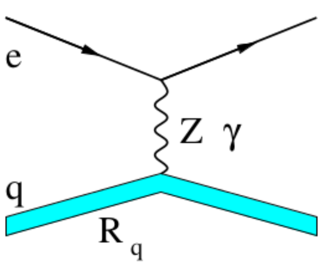
Introduction to contact interactions

An investigation of possible effects due to the virtual exchange allows to search for evidance of new particles with mass much higher than center of mass energy.



Four-fermion *eeqq* contact interactions provide a convenient method for such search and can be represented by additional terms in the Standard Model Lagrangian:

$$\mathscr{L}_{CI} = \sum_{i,j=L,R;q=u,d} \eta_{ij}^{eq} (\bar{e}_i \gamma^{\mu} e_i)(\bar{q}_j \gamma_{\mu} q_j)$$



For now we are working on quark form factor model:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left(1 - \frac{R_q^2}{6} Q^2\right)^2$$

Motivation for new limit setting procedure

- In HERA I analyses we compared our measurements to SM predictions based on CTEQ5D PDFs. As CTEQ5D included only 1994 HERA data with large statistical uncertainties, and high-Q^2 predictions were determined mainly by fixed-target measurements, we could treat PDFs uncertainty as an additional, independent source of systematics.

- Now we have much more precise high-Q^2 data and our own more flexible PDFs set HERAPDF2.0. This mean that possible contribution from the BSM processes could be reflected in PDFs.

- We propose a new procedure which include possible contribution from the BSM processes in the QCD fit to the data .

Probability method of limits setting

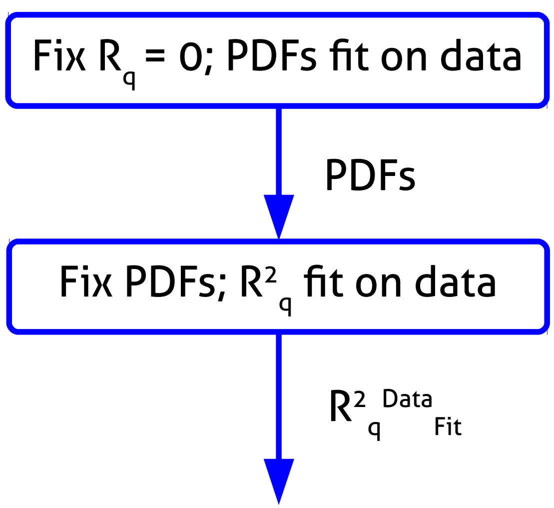
Two procedures for limit setting:

R_q-only Monte Carlo replicas generated for R_q^{True} using **SM PDFs** and R_q parameter fited with PDFs **fixed to SM PDFs**.

QCD+R_q Monte Carlo replicas generated for R_q^{True} using **SM PDFs** and R_q parameter fited **simultaneously** with PDFs.

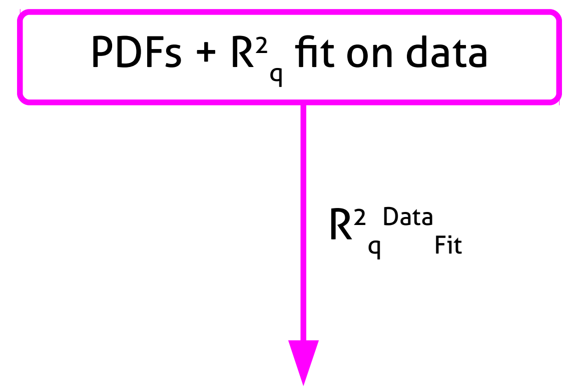
Two limits estimation procedures

R_q-only



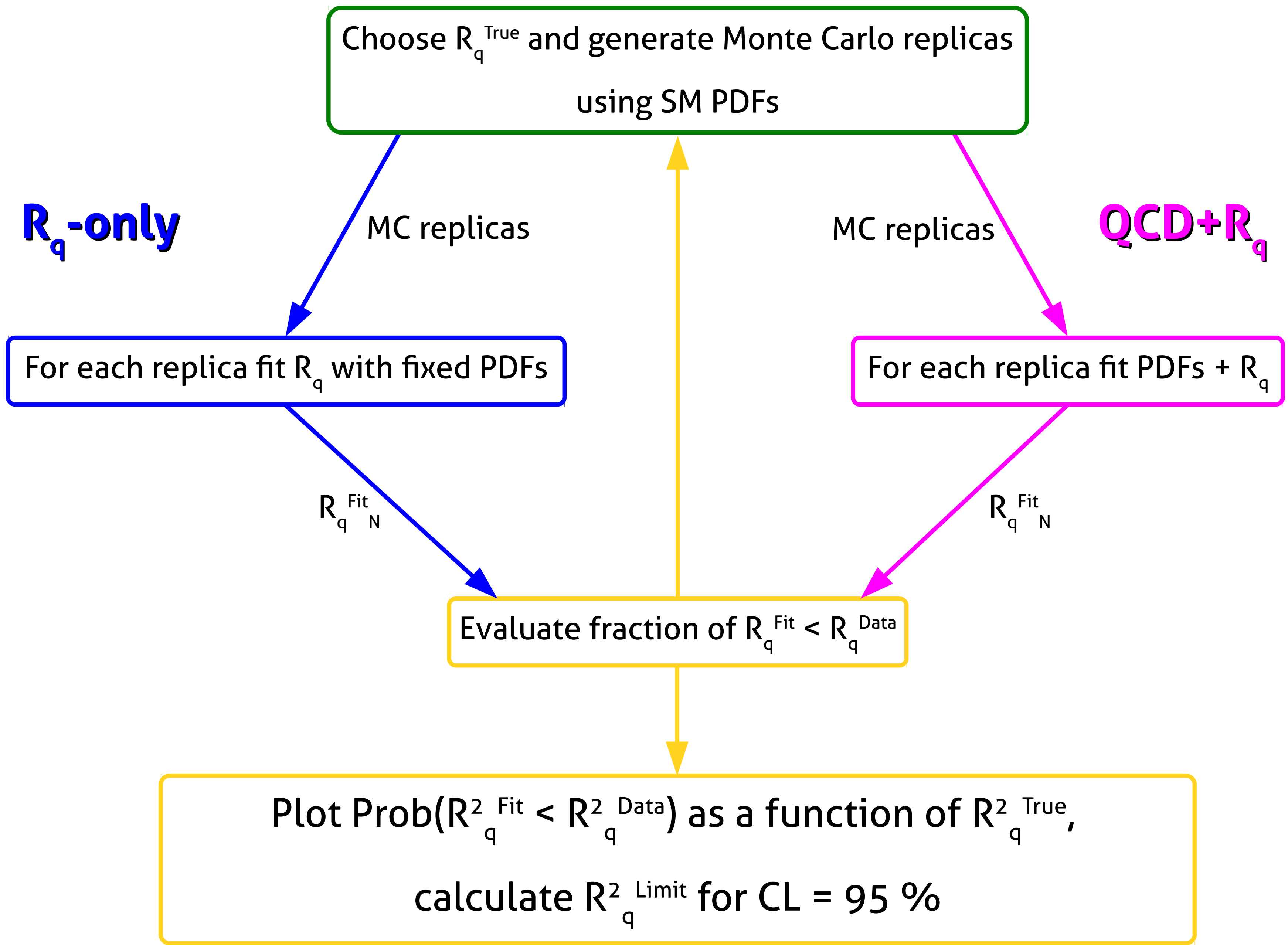
$R^{2\ Data}_q = (-\ 0.355 \pm 2.67) \cdot 10^{-6}\ GeV^{-2}$

QCD+R_q



$R^{2\ Data}_q = (-\ 0.479 \pm 3.06) \cdot 10^{-6}\ GeV^{-2}$

Full H1-ZEUS HERA I+II combined inclusive NC and CC data used, Q^2_{min} = 3.5 GeV^2



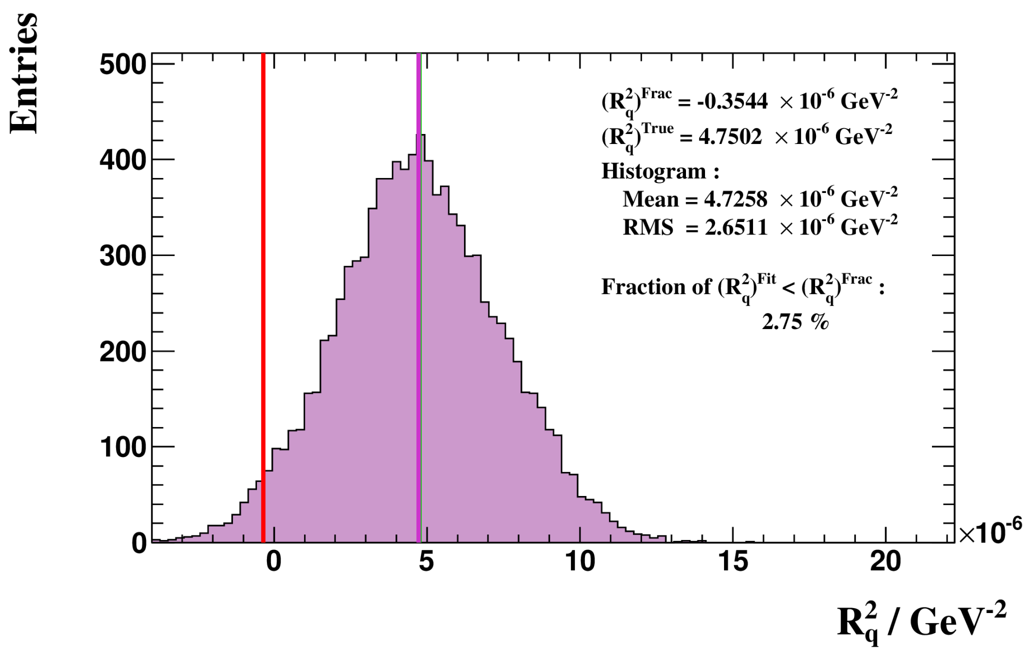
Choose R_q^{True} and generate Monte Carlo replicas using SM PDFs
R_q-only
MC replicas
MC replicas
QCD+R_q
For each replica fit R_q with fixed PDFs
For each replica fit PDFs + R_q
$R_q^{Fit}{}_N$
$R_q^{Fit}{}_N$
Evaluate fraction of $R_q^{Fit} < R_q^{Data}$
Plot Prob($R^2_q{}^{Fit} < R^2_q{}^{Data}$) as a function of $R^2_q{}^{True}$,
calculate $R^2_q{}^{Limit}$ for CL = 95 %

Monte Carlo replicas of cross sections calculated as:

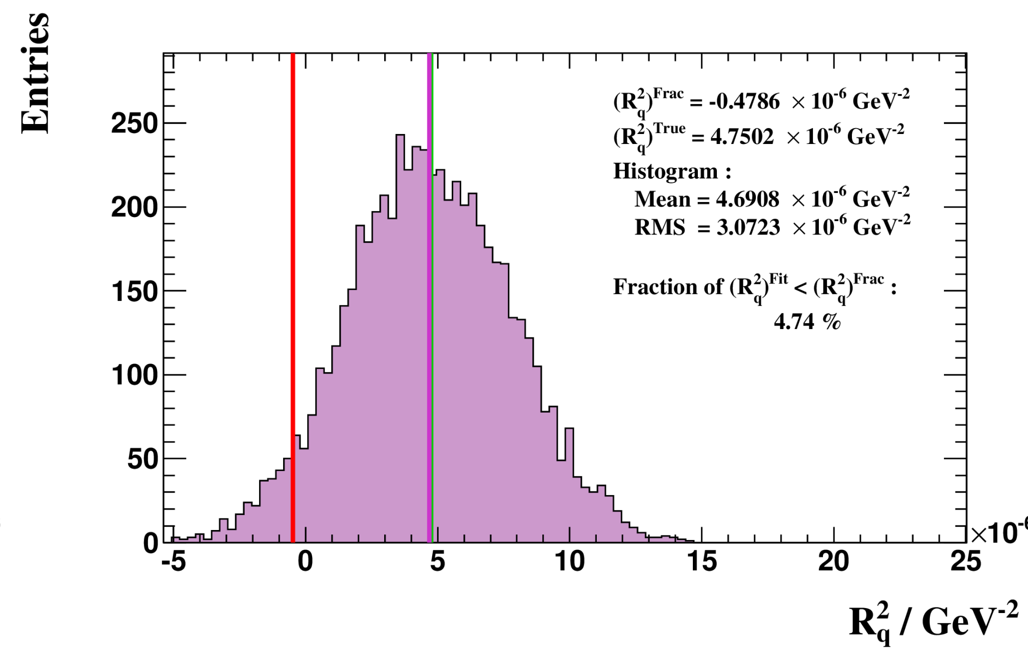
$$\mu^i = [M^i + \delta^i_{tot.uncor.} \cdot R^i_{tot.uncor.} \cdot D^i] \cdot (1 + \sum_j \gamma^j \cdot R^j_{sys.sh.})$$

For central variant with $R_q^{True} = 2.1795 \cdot 10^{-3}\ \mathrm{GeV}^{-1}$:

R_q-only

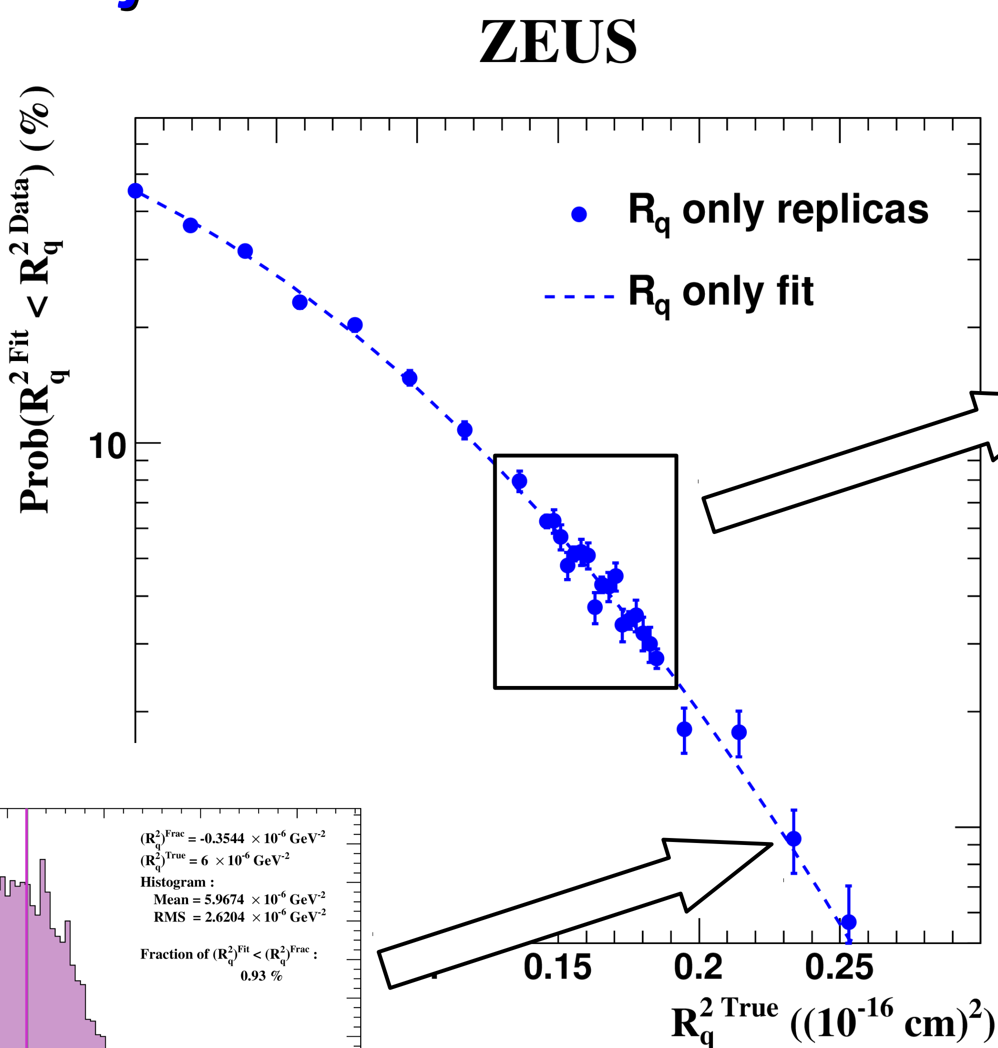


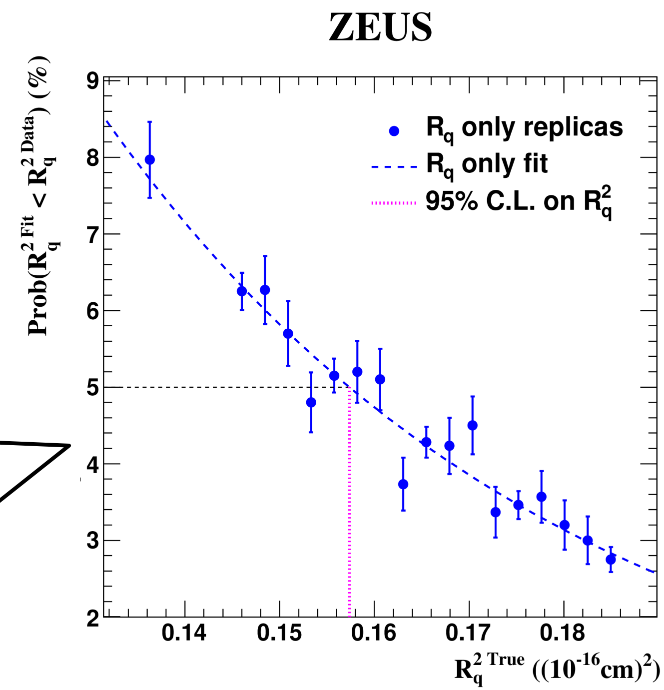
QCD+R_q



For central variant:

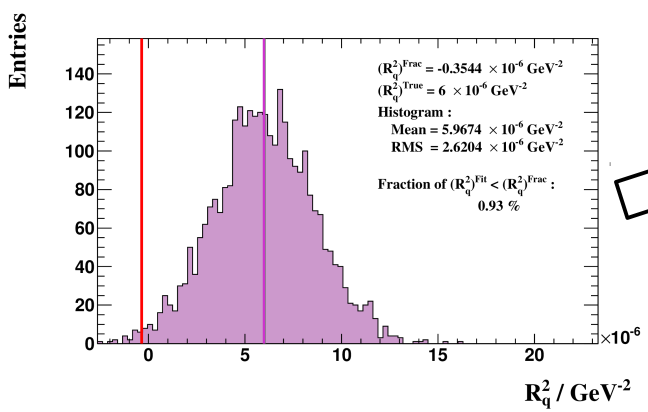
R_q-only





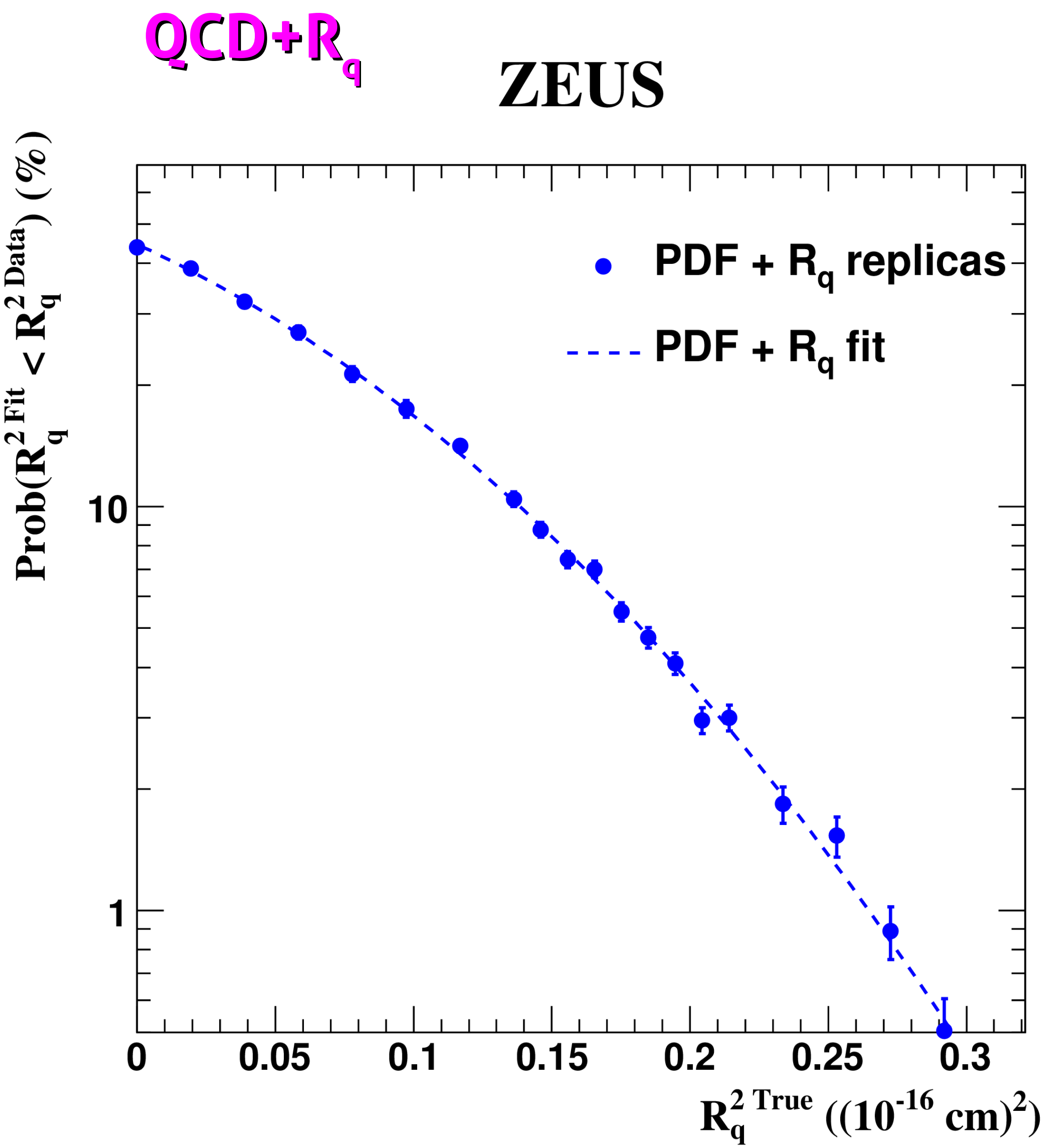
Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



$$R_q^{Limit} = 0.397 \pm 0.002 \cdot 10^{-16}\ \text{cm}$$

For central variant:



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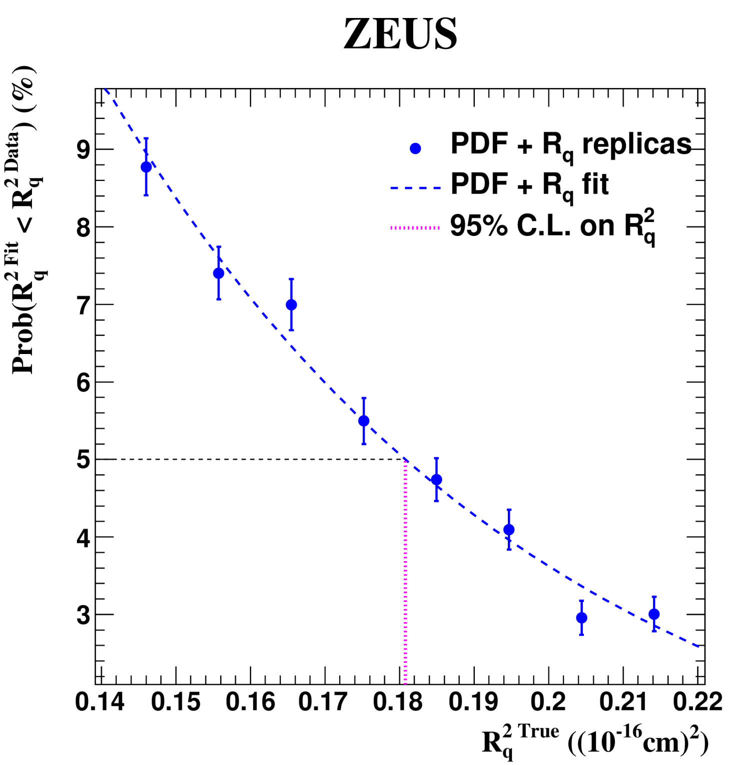
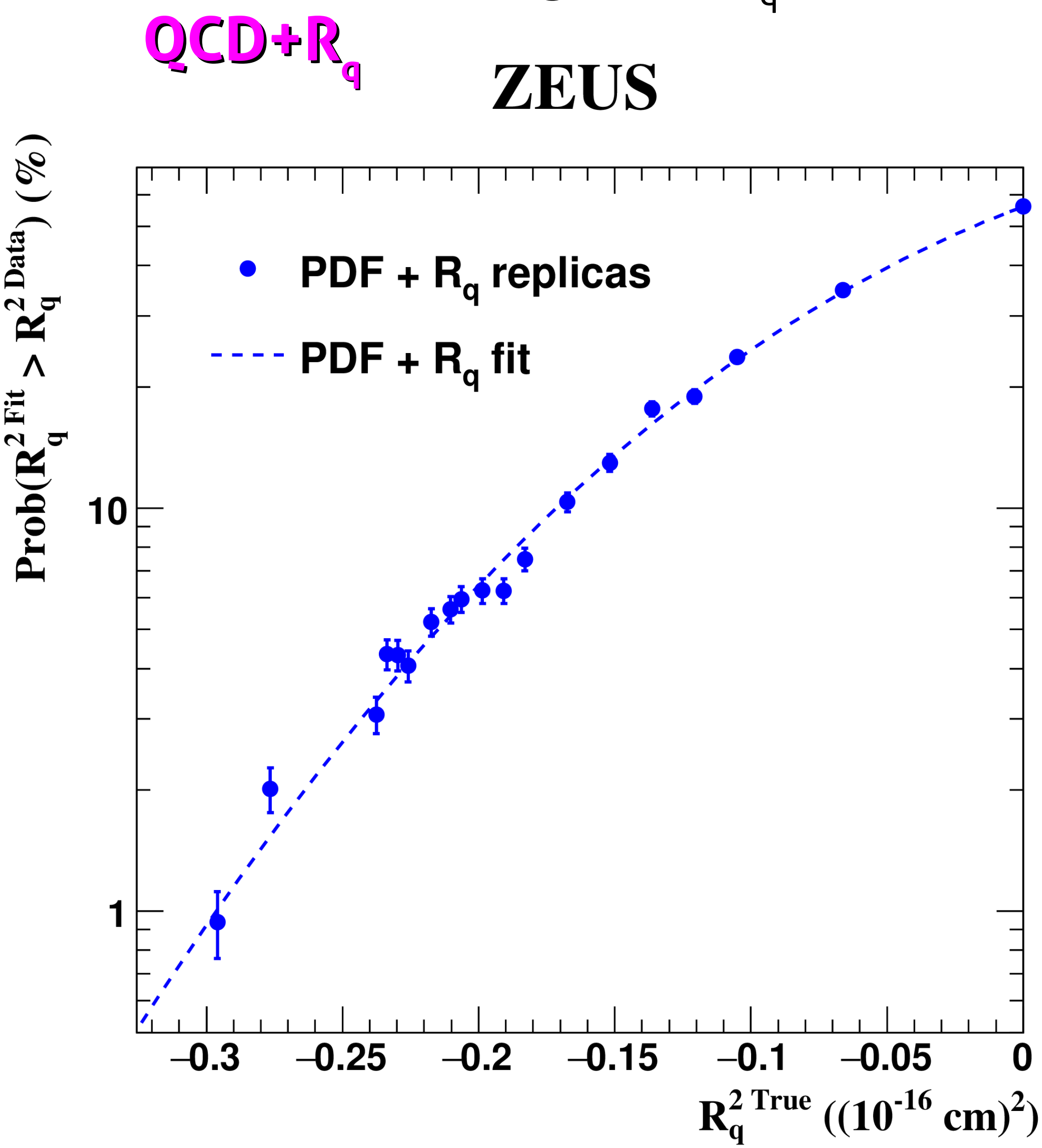


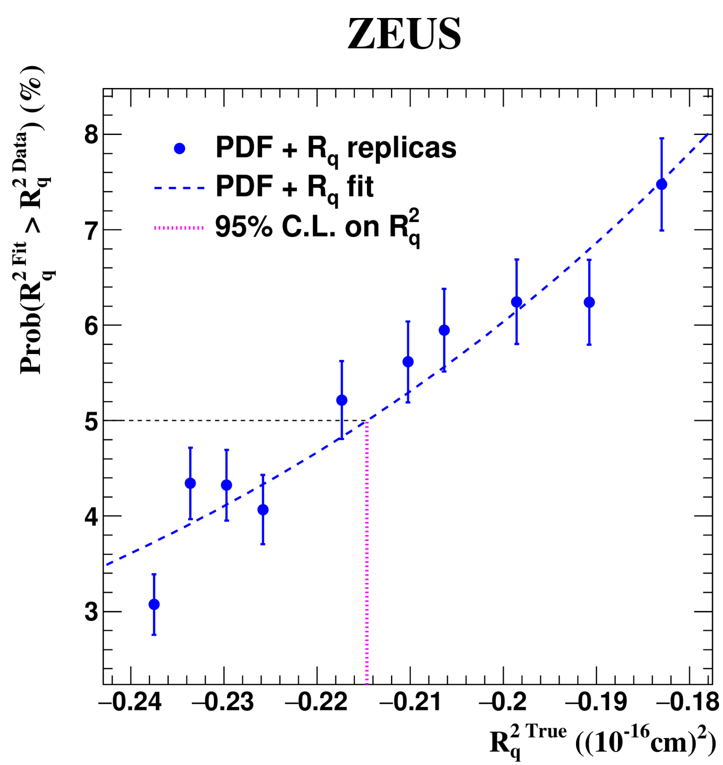
$$R_q^{Limit} = 0.425 \pm 0.003 \cdot 10^{-16}\ \mathrm{cm}$$

Negative R^2_q limit for central variant:



Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



$$R^{2\,Limit}_q = -[0.463 \pm 0.004 \cdot 10^{-16}\ \text{cm}]^2$$

χ^2 method of limits setting

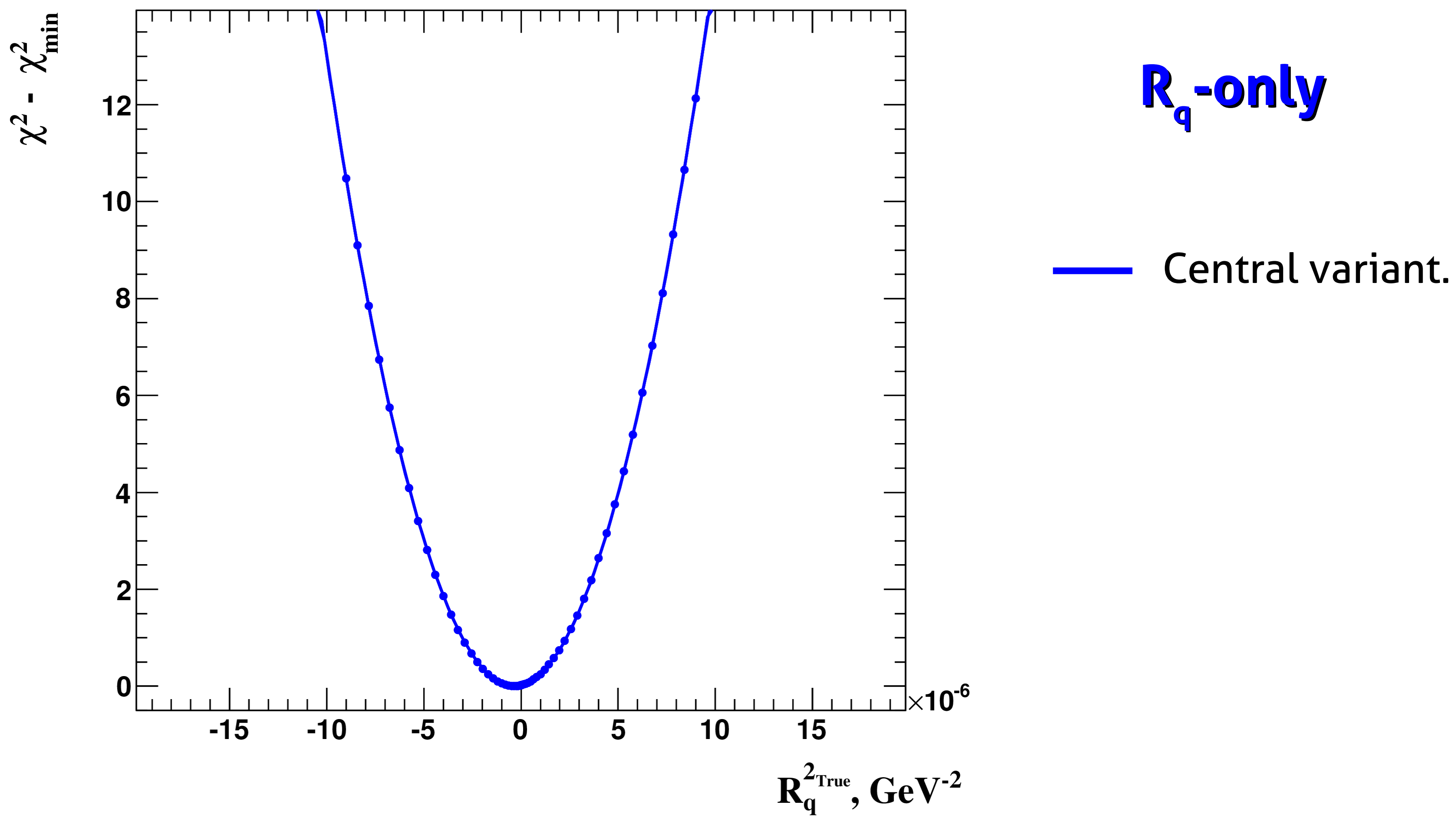
χ^2 method of limits setting for two procedures:

R_q-only R_q fixed to R_q^{True} and PDFs fixed to SM PDFs.
χ^2 estimated for one iteration fit on Data.

QCD+R_q R_q fixed to R_q^{True} and PDFs are fitted, final χ^2 estimated.

This method is used as a cross check for the probability method.

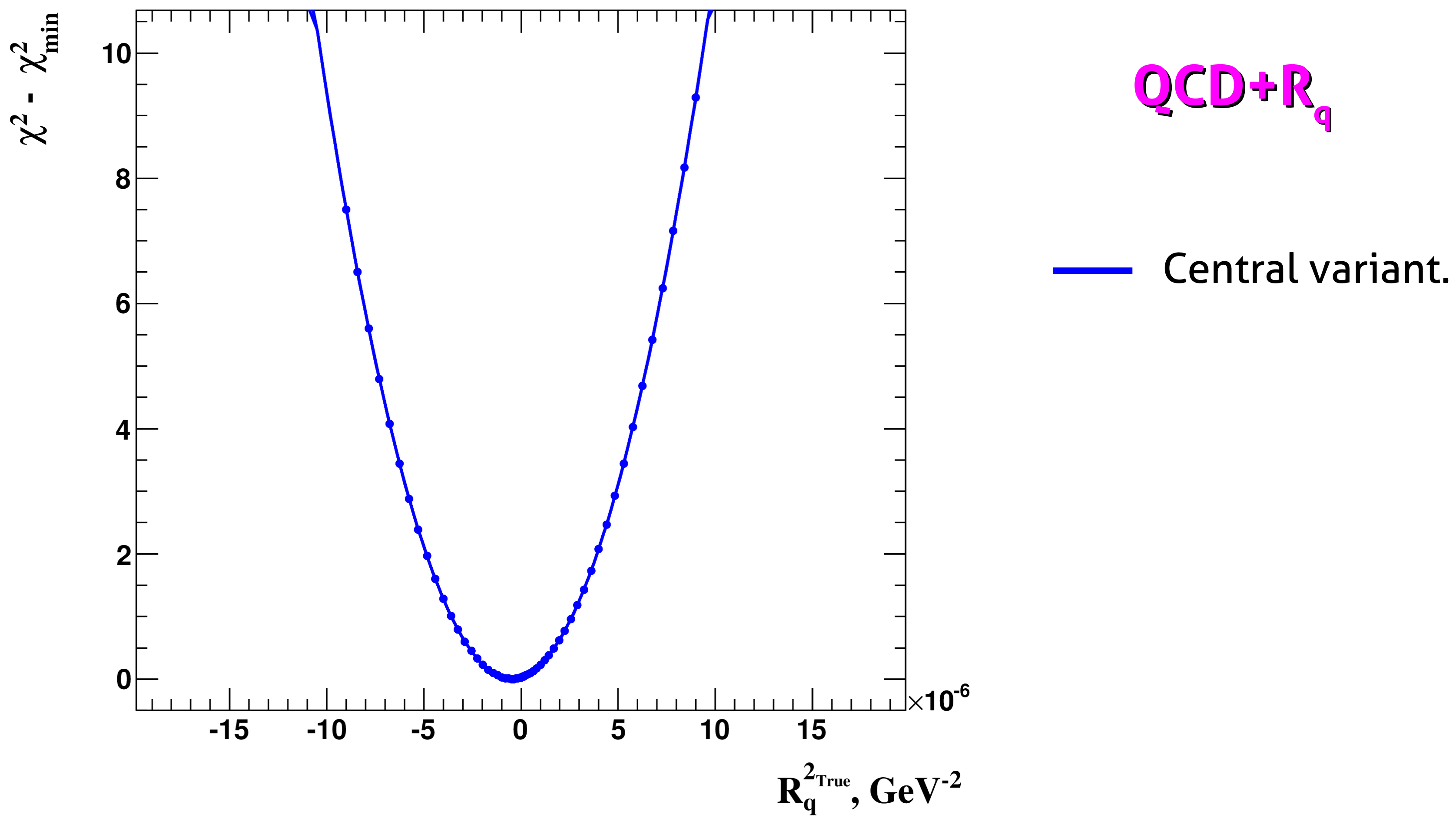
χ^2 full scan



Limit estimated for $\Delta\chi^2 = (1.64)^2$, which corresponds to 95% CL assuming Gaussian distribution:

$$-[0.429 \cdot 10^{-16}\ \text{cm}]^2 < R^2_q < [0.397 \cdot 10^{-16}\ \text{cm}]^2$$

χ^2 full scan



Limit estimated for $\Delta\chi^2 = (1.64)^2$, which corresponds to 95% CL assuming Gaussian distribution:

$$-[0.466 \cdot 10^{-16}\ \text{cm}]^2 < R^2_q < [0.424 \cdot 10^{-16}\ \text{cm}]^2$$

Estimated R_q limits

Limits for probability method:

R_q-only : $-[0.424 \cdot 10^{-16}\ \mathrm{cm}]^2 < R^2_q < [0.397 \cdot 10^{-16}\ \mathrm{cm}]^2$

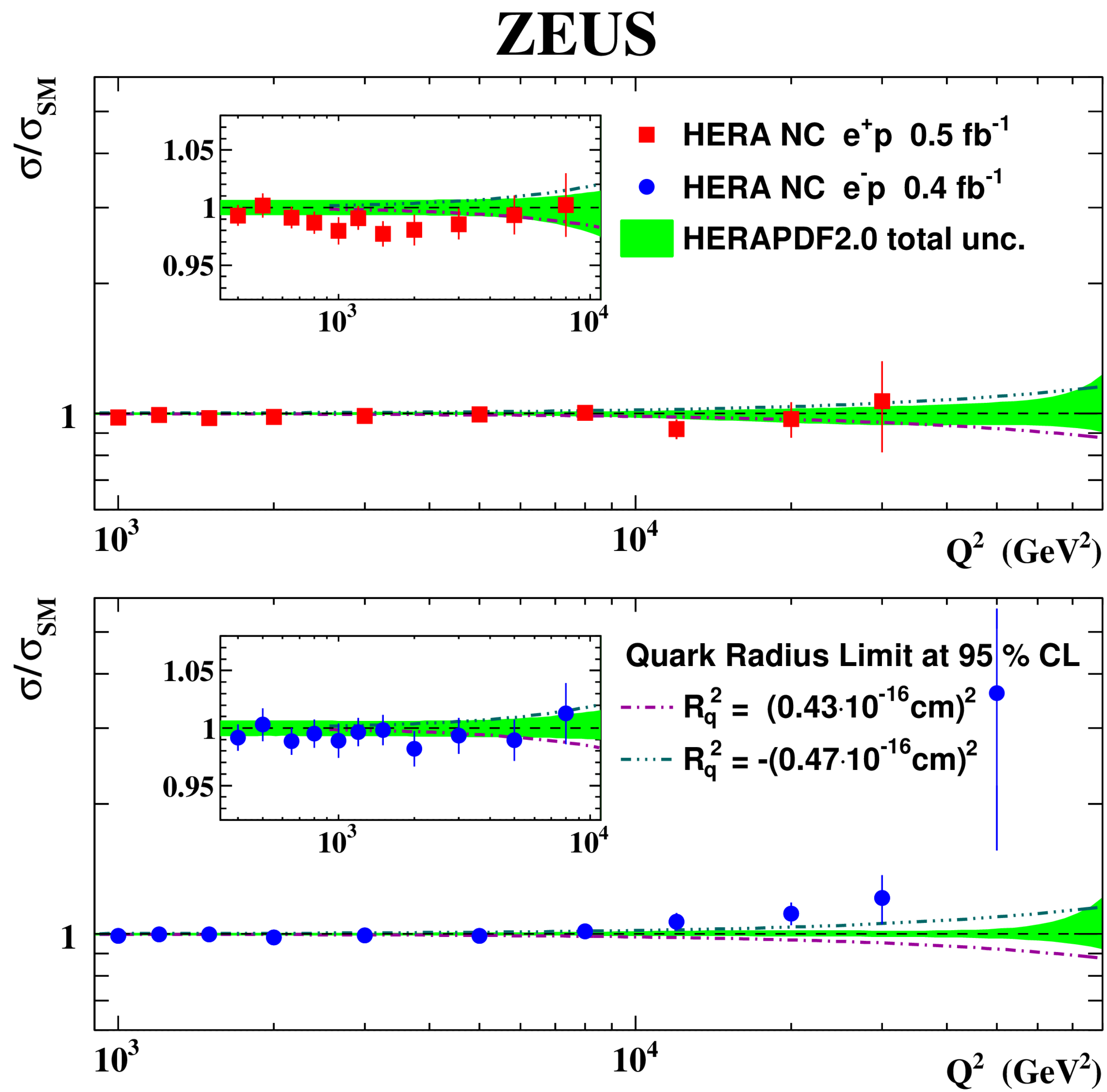
QCD+R_q : $-[0.463 \cdot 10^{-16}\ \mathrm{cm}]^2 < R^2_q < [0.425 \cdot 10^{-16}\ \mathrm{cm}]^2$

Limits for χ^2 method:

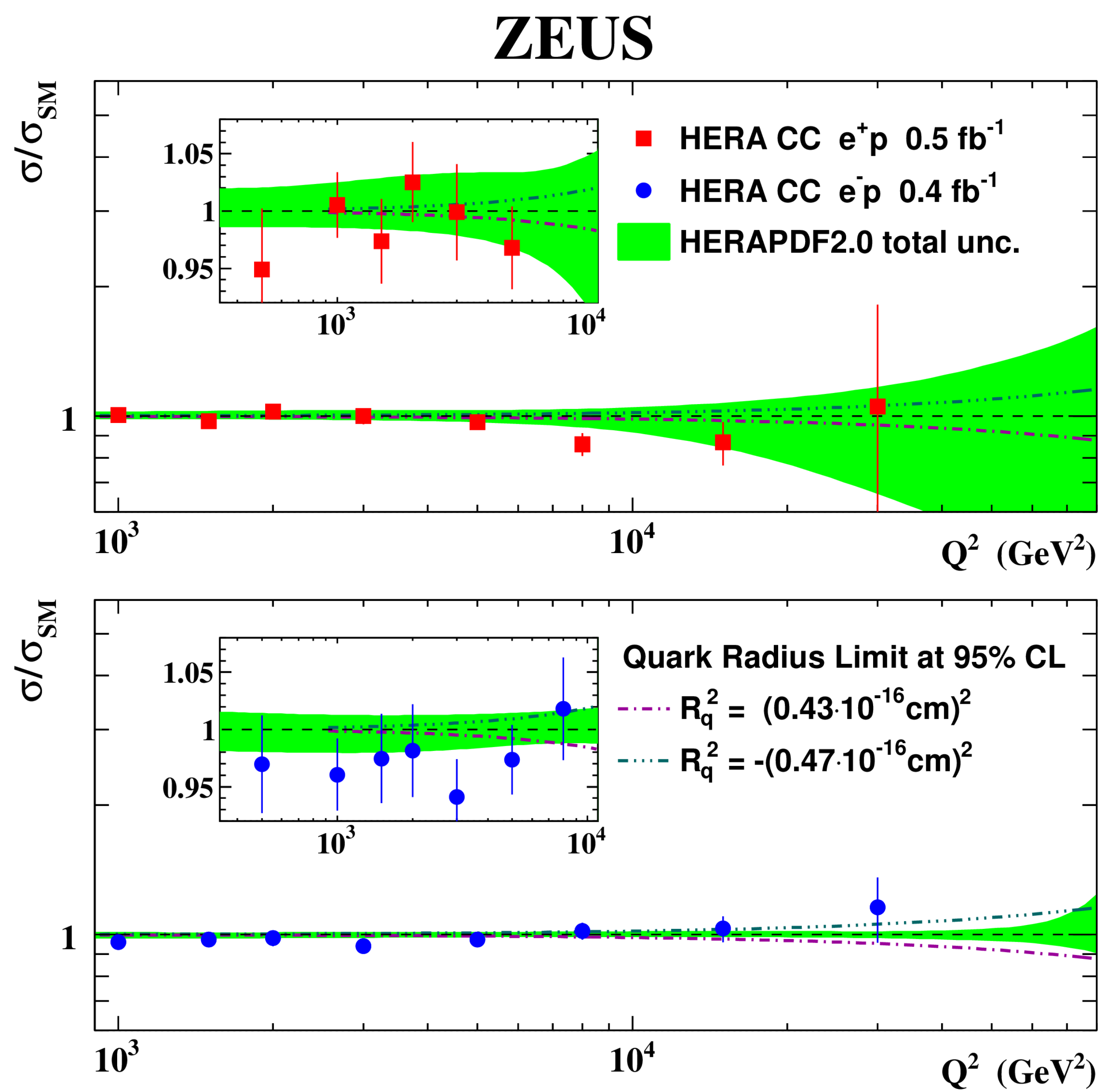
R_q-only : $-[0.429 \cdot 10^{-16}\ \mathrm{cm}]^2 < R^2_q < [0.397 \cdot 10^{-16}\ \mathrm{cm}]^2$

QCD+R_q : $-[0.466 \cdot 10^{-16}\ \mathrm{cm}]^2 < R^2_q < [0.424 \cdot 10^{-16}\ \mathrm{cm}]^2$

- Both methods provide consistent limits.
- Difference between QCD+R_q and R_q-only procedures ~ 6-8%



Comparison of R_q^{Limit} model to NC ep HERA Data.



Comparison of R_q^{Limit} model to CC ep HERA Data.

Model and parameterisation variations

Variations for Model uncertainty :

Variation	Standard value	Lower limit	Upper limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
m_c [GeV]	1.47	1.41	1.53
m_b [GeV]	4.50	4.25	4.75
f_s	0.4	0.3	0.5
$f_{sHERMES}$	-	0.3	0.5
α_s	0.1180	0.1220	0.1146

Variations for Parameterisation uncertainty :

Variation	Standard value	Lower limit	Upper limit
Q^2_0 [GeV^2]	1.9	1.6	2.2 (m_c = 1.53 GeV)
D_{u_v}	-		+

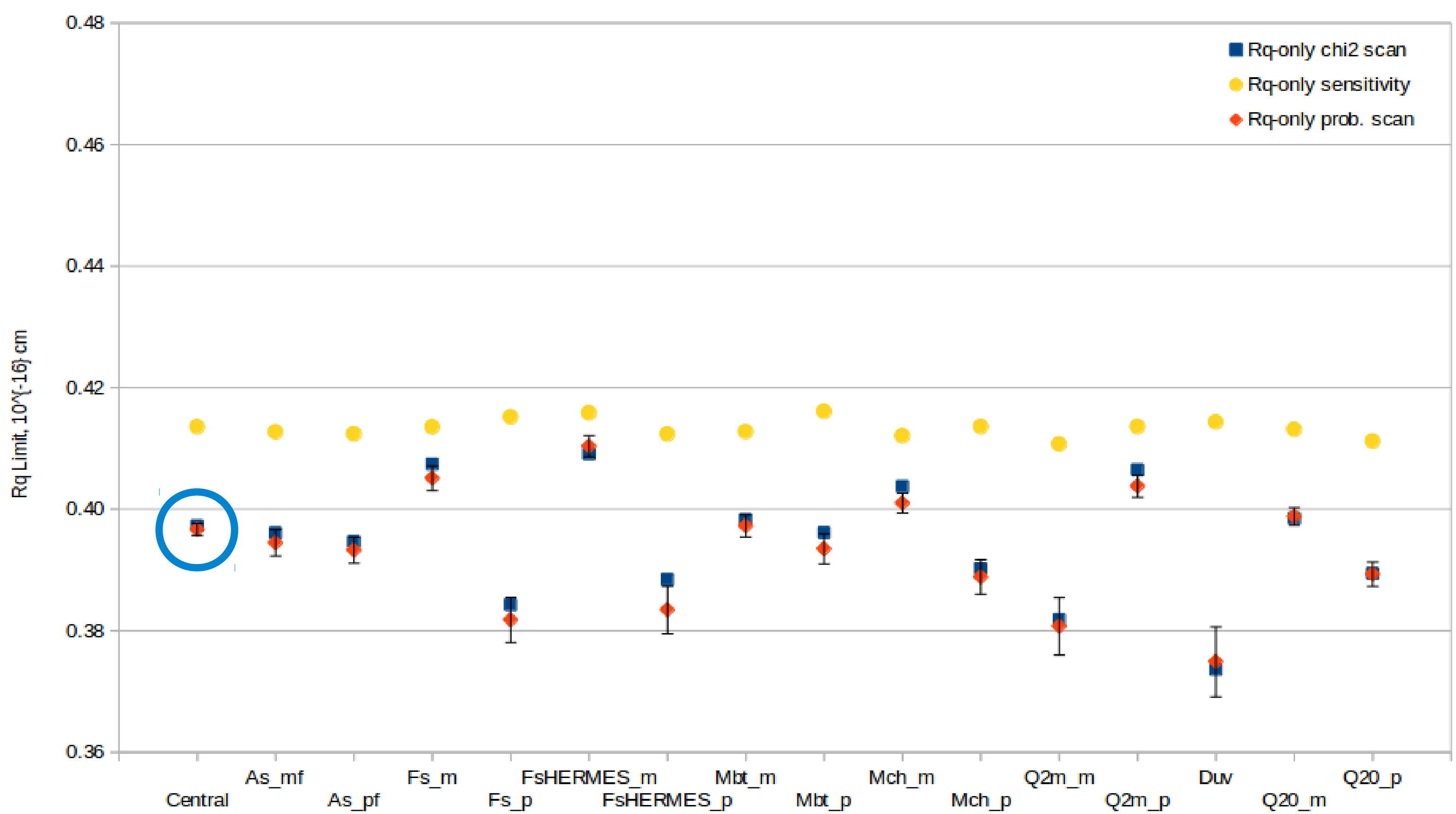
Variations used correspond to HERAPDF2.0 paper.

Probability method vs χ^2 scan

Same procedure used for model and parameterization variations:

Sensitivity defined as median of the limit distribution for MC replicas.

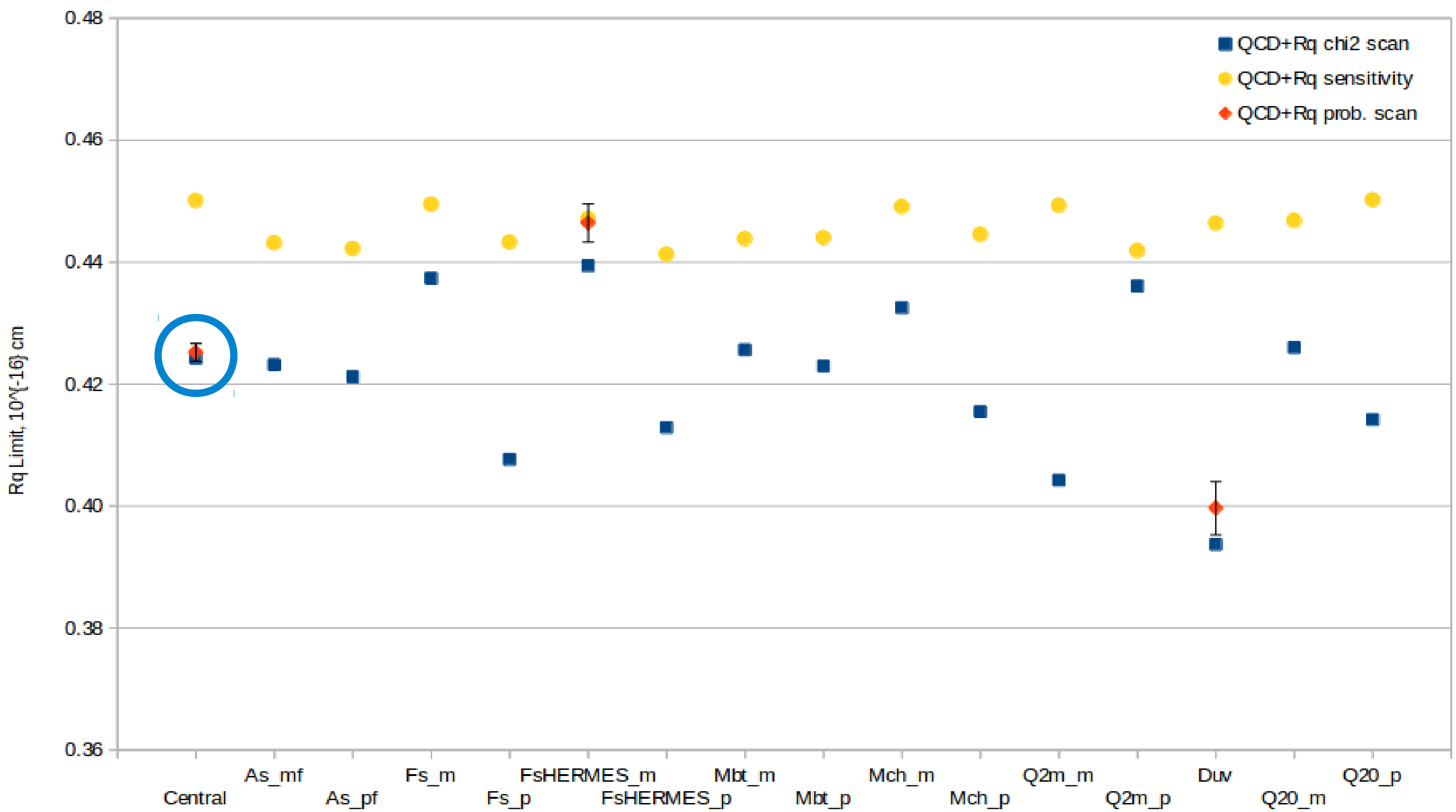
R_q-only



Same procedure used for model and parameterization variations:

Sensitivity defined as median of the limit distribution for MC replicas.

QCD+R_q

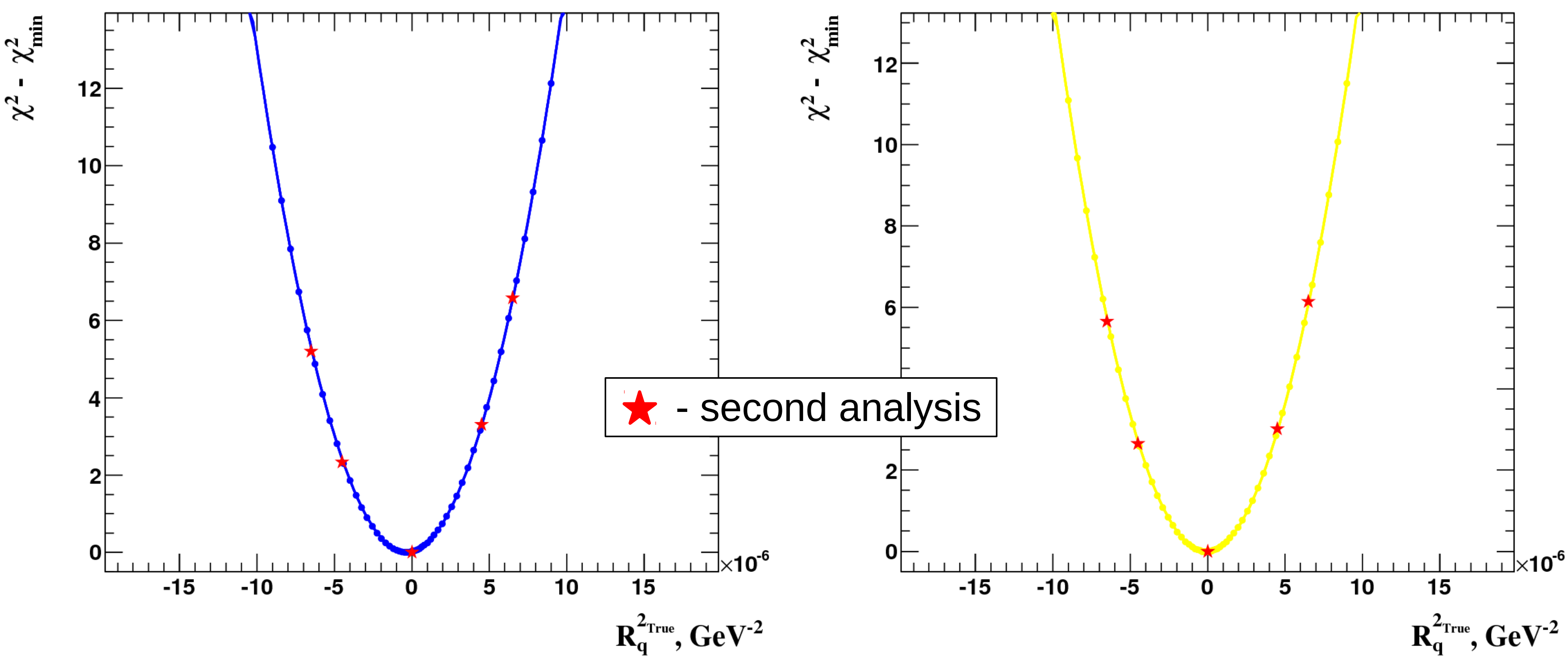


Variations of R_q^{Limit} values are of the order of 2-3%, we quote central limit as the result.

Second analysis

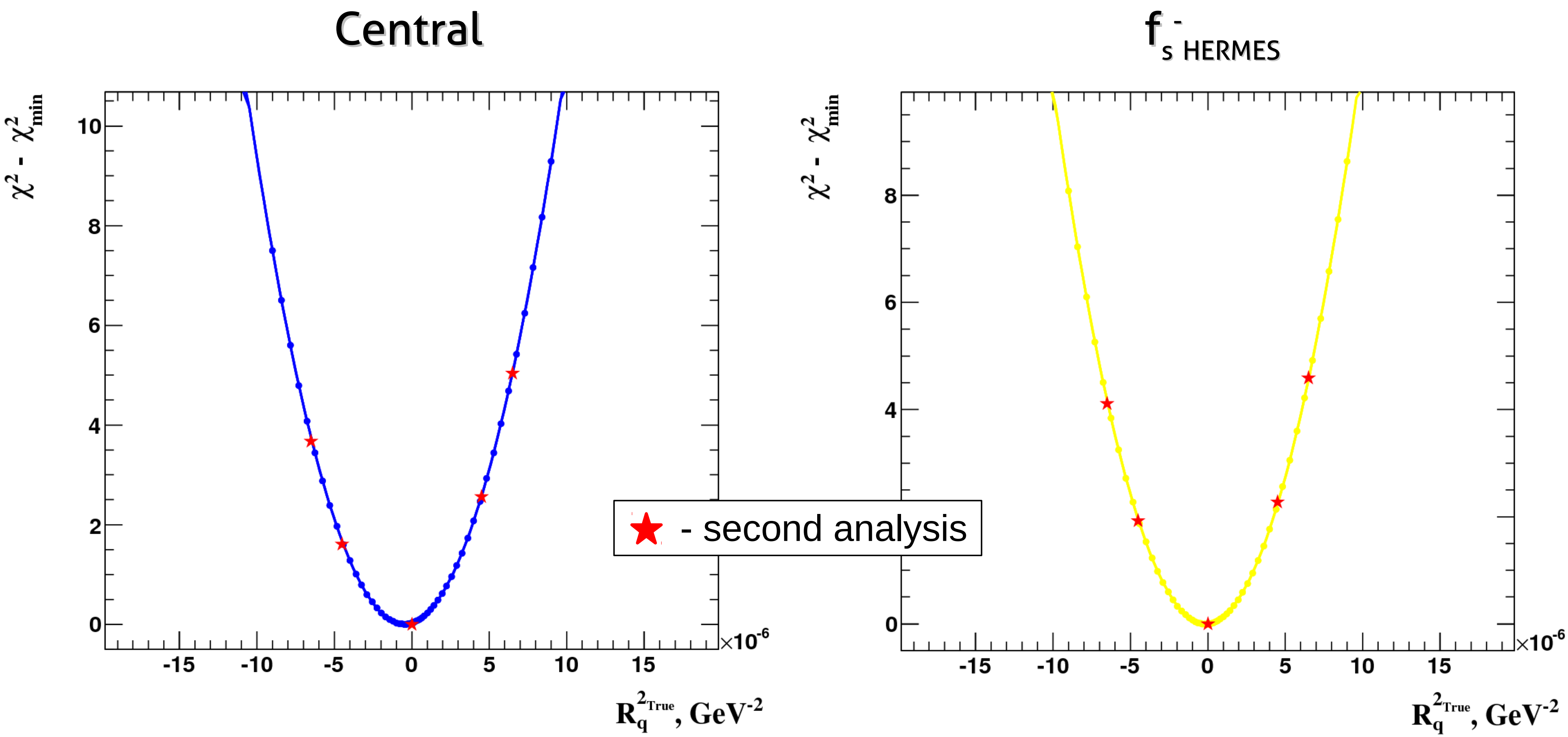
- χ^2 limits setting procedure was a first cross check for the probability limits and it agrees within few percents.
- For second analysis Katarzyna Wichmann has repeated the χ^2 limit estimation method for the central and weakest limit variants:

R_q-only : Central $f_{\bar{s}}$ HERMES



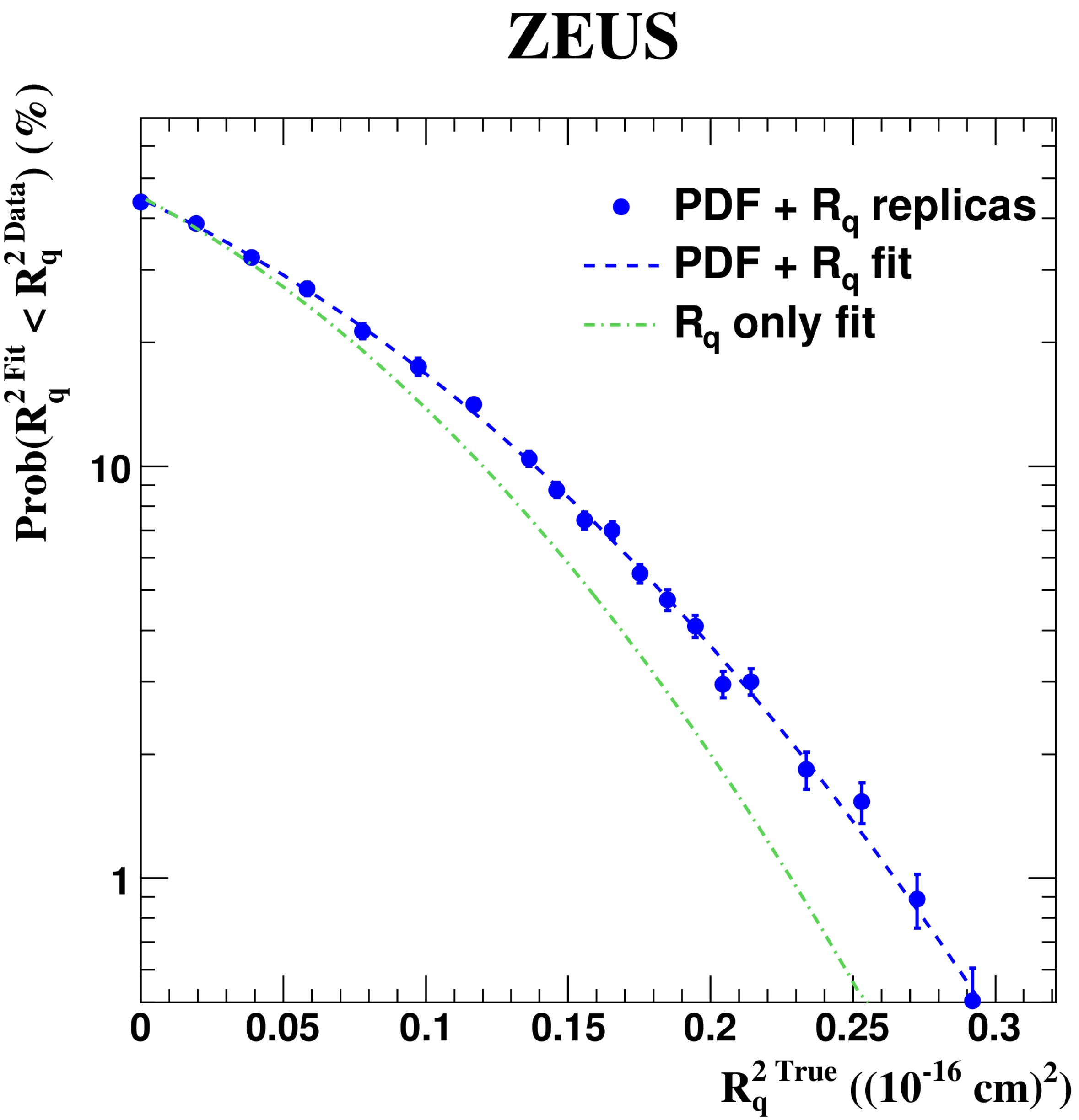
Results perfectly agree with main analysis.

$QCD+R_q$:

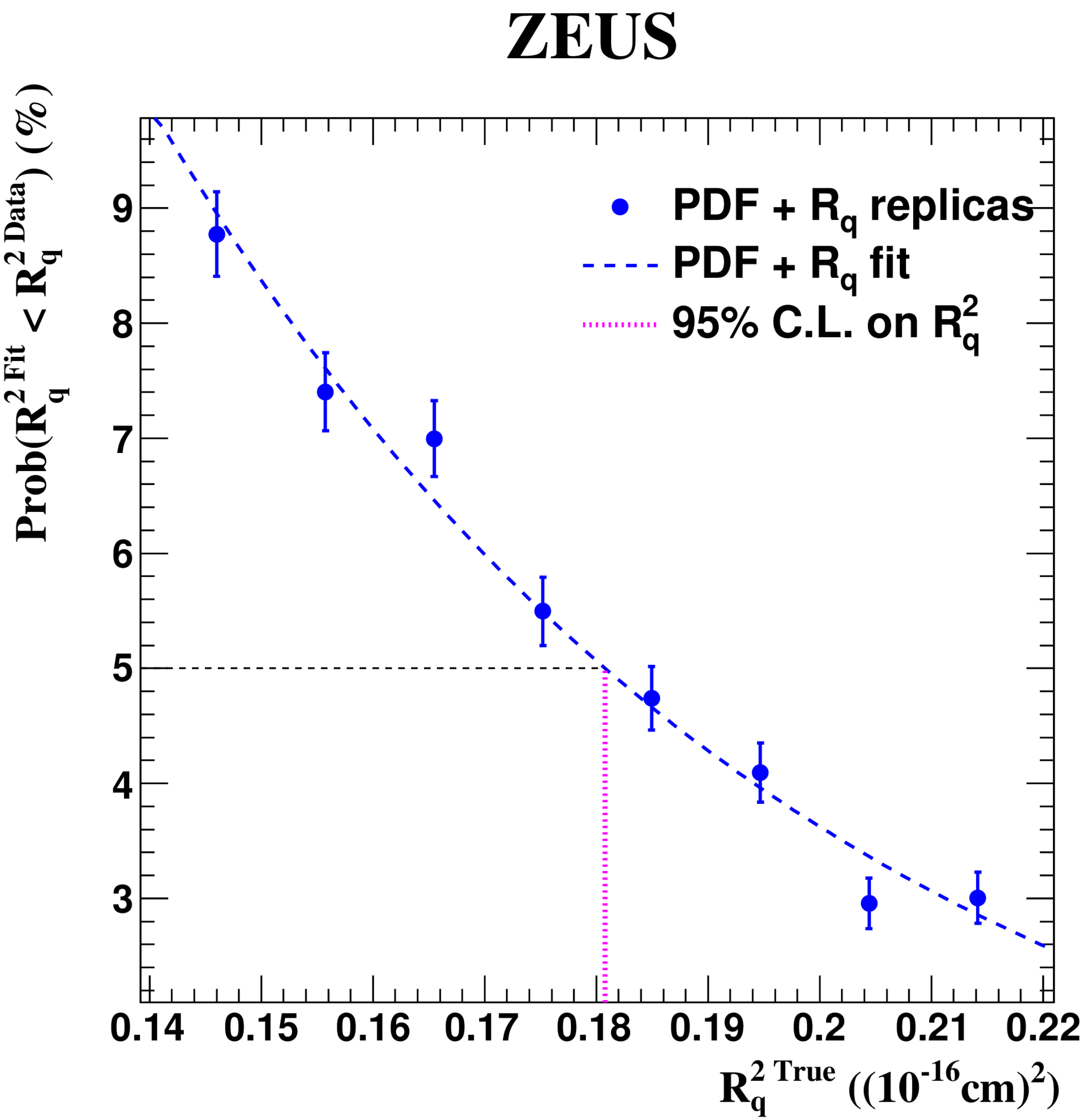


Results perfectly agree with main analysis.

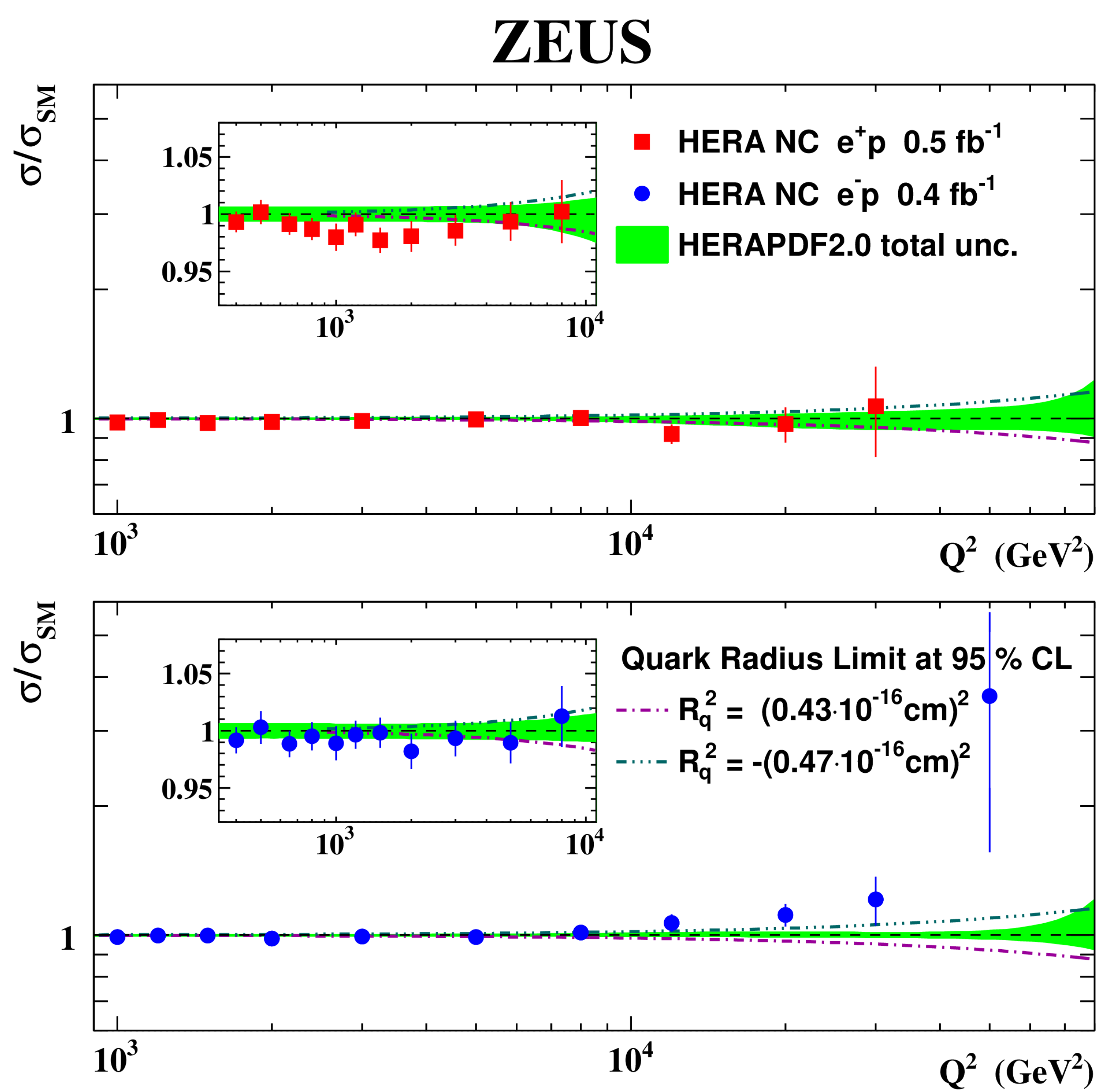
Results for publication



Probability distributions for two procedures.



Limit evaluation for central variant of QCD+R_q.



Comparison of R_q^{Limit} model to NC ep HERA Data.

Summary

- We have evaluated limits on quark form factor:

$$-[0.47 \cdot 10^{-16}\ \mathrm{cm}]^2 < R^2_q < [0.43 \cdot 10^{-16}\ \mathrm{cm}]^2$$

- And sensitivity:

$$R_q^{sens} = 0.45 \cdot 10^{-16}\ \mathrm{cm}$$

- Cross check with χ^2 method provides consistent limits to probability method.

- Second analysis perfectly agree with main result.

Changes to analysis compared to EPS'2015 results
(after EBO and group presentation)

- Use nominal ("cental") fit model for limit calculation
- Include the result on negative R^2_q
- Use of negative $R^{2\ \mathrm{Data}}_q$ in limit setting
- Include estimate of experimental sensitivity
- Do not make a dedicated PDF fit for each R_q^{True} for replica generation
- Use cm scale in the plots

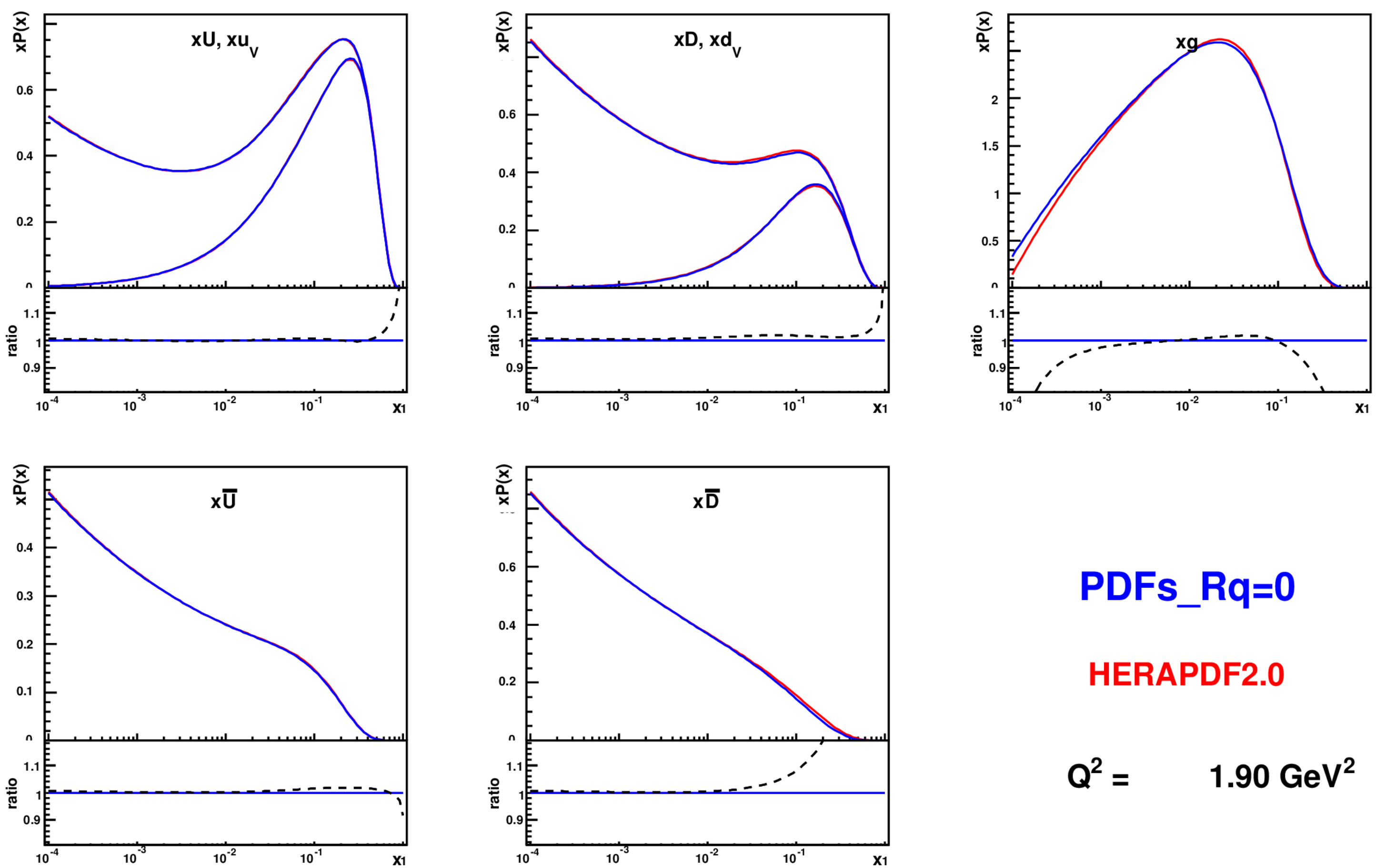
Additional checks performed after EPS'2015

➔ PDF change due to χ^2 modification negligible — results consistent with nominal HERAPDF2.0

➔ Using Gaussian distribution for modeling of statistical fluctuations of high-Q^2 cross-section points does not result in any visible change in limit values when compared to the "full" Poisson approach.

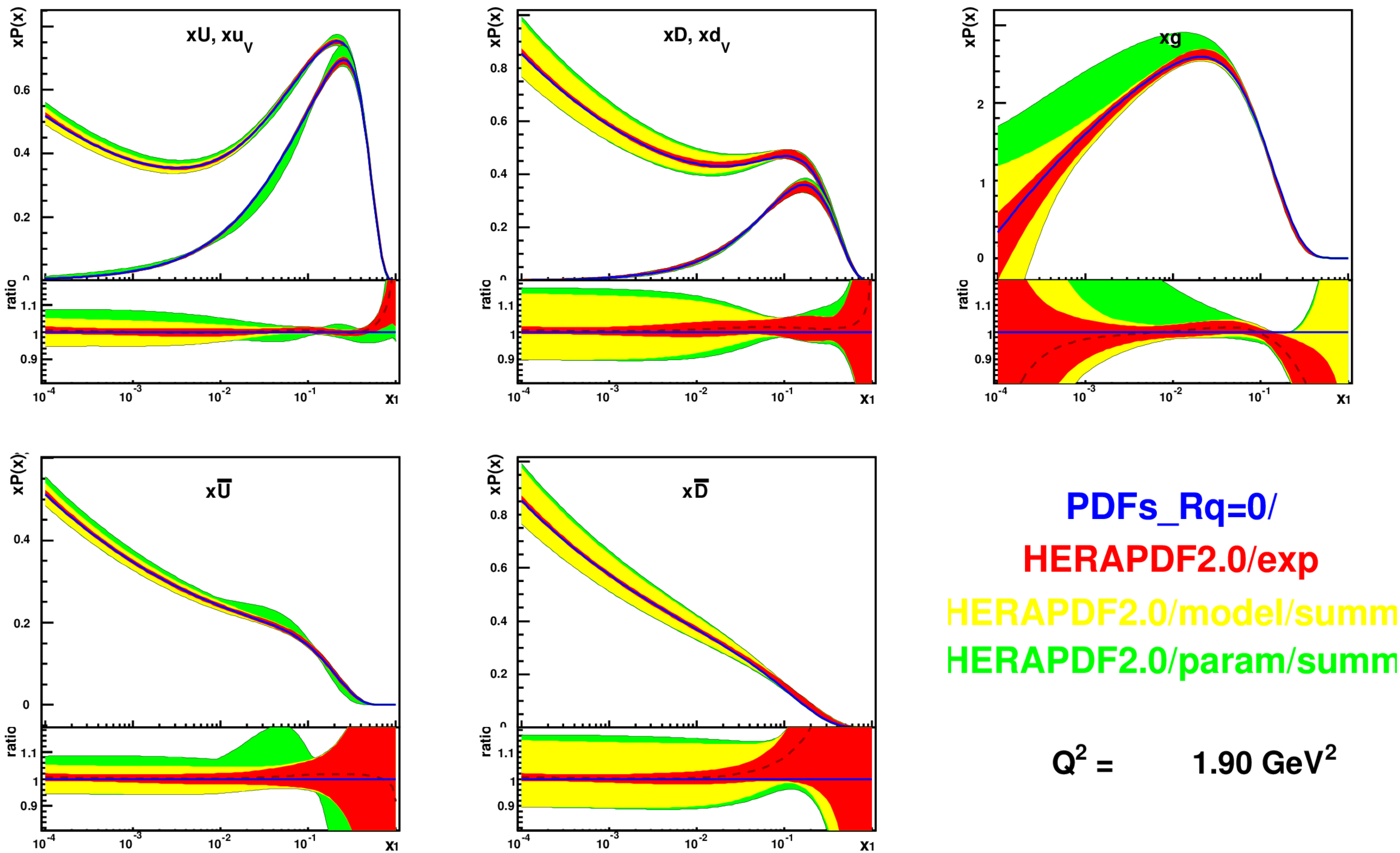
Backup
Comparison to HERAPDF2.0

Compare our PDF fit on Data for $R_q^{True} = 0$ with HERAPDF 2.0 :



Only small difference in gluon.

Compare our PDF fit on Data for $R_q^{True} = 0$ with HERAPDF 2.0, full uncertainty :



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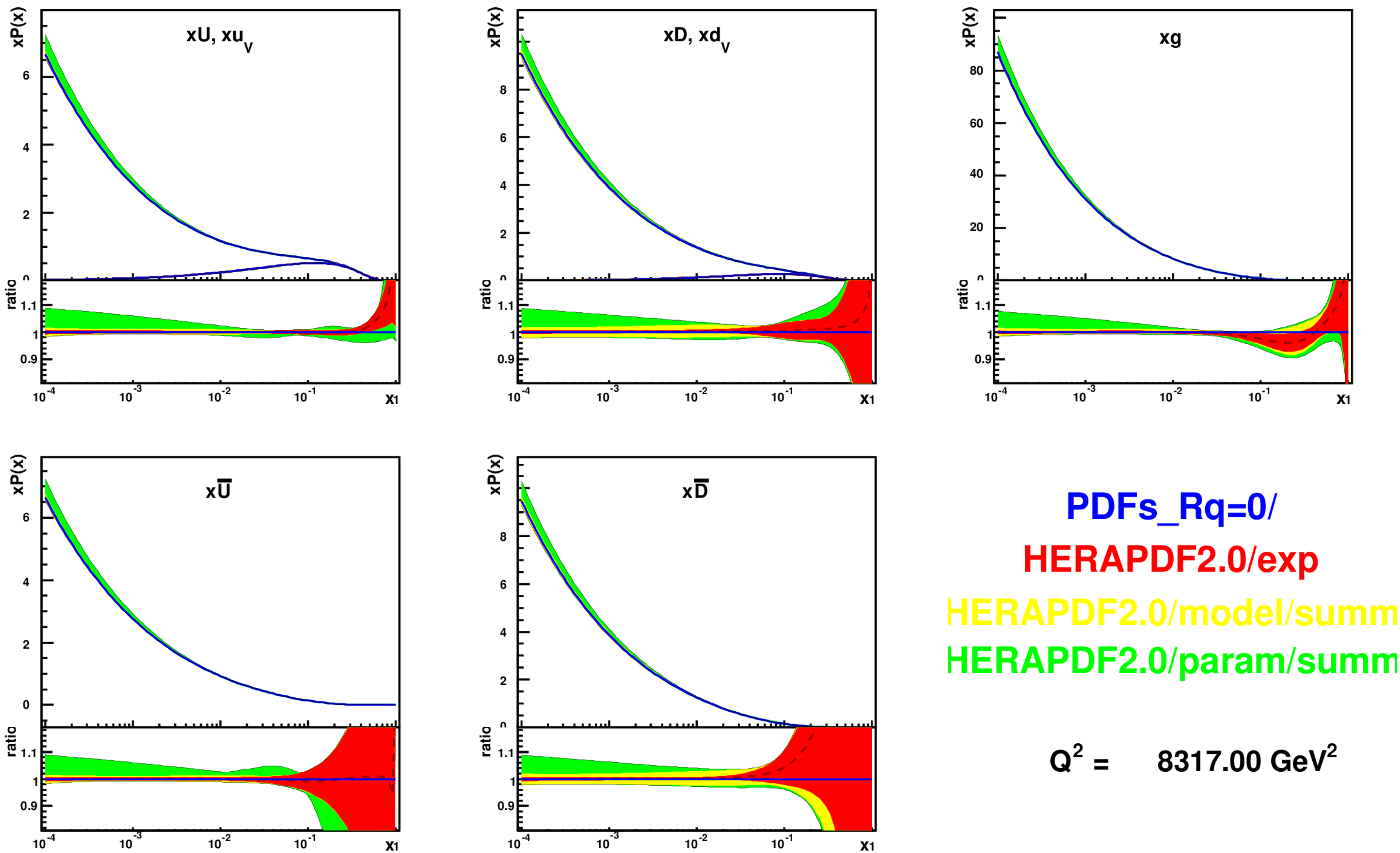


Gaussian vs Poisson

- Inclusive HERA cross sections from H1 and ZEUS combination are published with Gausian uncertainties.
  - We know that event statistics in some high-Q^2 bins is very low. Does it influence our limits?
- When using the frequentist approach to R_q limit setting, based on generation of multiple pseudo-data sets, **replicas**:
  - we can use Gaussian approximation in χ^2 minimization, as long as data and replicas are treated in the same way. Limits remain valid.
  - what is crucial is the way replicas are generated. We need to confirm that Gaussian approximation in replica generation does not affect the limit setting procedure
- First comparison of Gaussian vs Poisson done before EB0.
  - **Weak point**: number of expected events (for generation of Poisson distribution) **estimated from the statistical error** of inclusive cross sections
  - We decided to make additional test, with more realistic modeling of event statistics, reflecting the data analysis better.

Gaussian vs Poisson

We do not change the way MC replicas are generated for points with high statistics ($Q^2 < 10000$ GeV^2 or stat. Unc. < 20%). The formula used is:

$$\mu^i = [M^i + \delta^i_{tot.uncor.} \cdot R^i_{tot.uncor.} \cdot D^i] \cdot (1 + \sum_j \gamma^j_i \cdot R^j_{sys.sh.})$$

Notation as in the paper draft, see backup slide

However, for 14 data points with $Q^2 > 10000$ GeV^2 and stat. unc. < 20%, we calculate expected event statistics based on the integrated cross section:

$$N_{\exp} = A \cdot L \cdot \sigma_{bin} = A \cdot L \cdot \int \left(\frac{d^2\sigma}{dQ^2 dx}\right) dQ^2 dx = \frac{M^i}{M^i_{SM}} \cdot A \cdot L \cdot \int \left(\frac{d^2\sigma_{SM}}{dQ^2 dx}\right) dQ^2 dx = M^i \cdot \epsilon$$

Gaussian approximation:

$$\Delta_{\exp} = \frac{1}{\sqrt{(N_{\exp})}} \qquad \mu^i_0 = M^i \cdot (1 + \sqrt{(\Delta^2_{\exp} + \Delta^2_{uncor})} \cdot R^i)$$

relative statistical uncertainty

Generation with "full" Poisson:

$$Poisson\,Rand(N_{\exp}, N_{obs}) \qquad \mu^i_0 = \left(\frac{N_{obs}}{\epsilon}\right) \cdot (1 + \Delta_{uncor} \cdot R^i)$$

Imposing correlated systematics (same for both):

$$\mu^i = \mu^i_0 \cdot (1 + \sum_j \gamma^j_i \cdot R^j_{sys.sh.}) \qquad \Delta_{\exp} = \sqrt{\left(\frac{\mu^i}{\epsilon}\right)}$$

Gaussian vs Poisson

Unfortunatly, we do not have all information needed (fot H1 and ZEUS) to obtain valid HERA limits with this approach => we only verify validity of approximation.

Assume average high-Q^2 acceptance (based on old ZEUS publications): $A=0.95$

Luminosities (H1+ZEUS): $L_{CCe-}=359.5\frac{1}{pb}$ $L_{CCe+}=523.4\frac{1}{pb}$

$L_{NCe-}=353.9\frac{1}{pb}$ $L_{NCe+,\sqrt{s}=300\,GeV}=65.6\frac{1}{pb}$ $L_{NCe+,\sqrt{s}=300\,GeV}=445.9\frac{1}{pb}$

We integrated double differential cross sections (theory predictions) using bin boundaries from ZEUS published analysis:

CC:

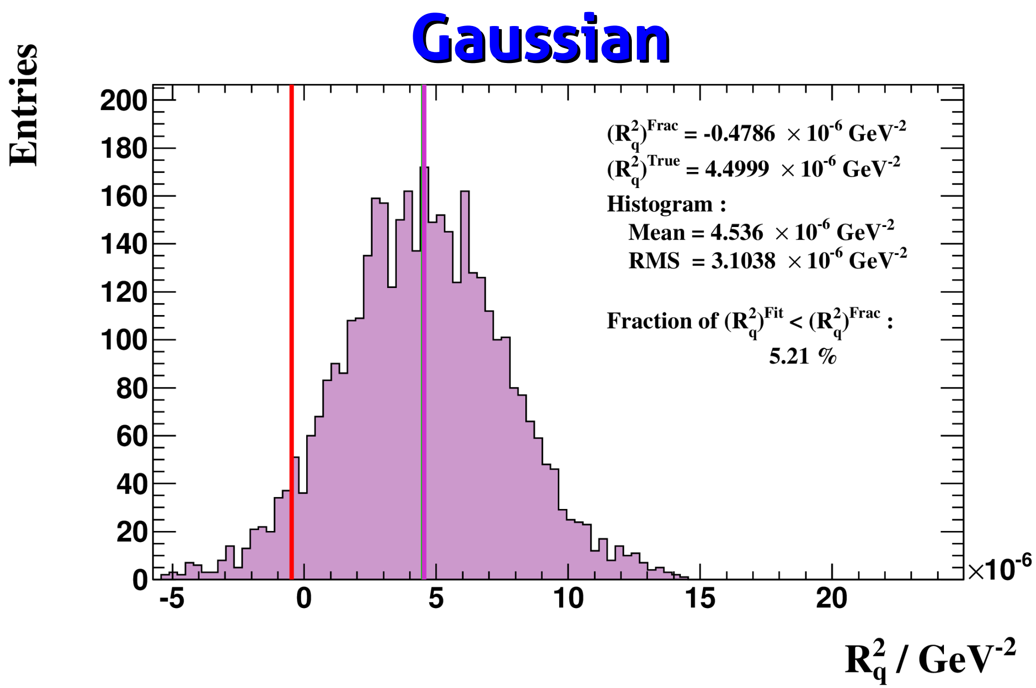
$$Q^2=[12600, 22500, 60000]\,GeV^2$$
$$x=[0.18, 0.32, 0.56, 1.00]$$

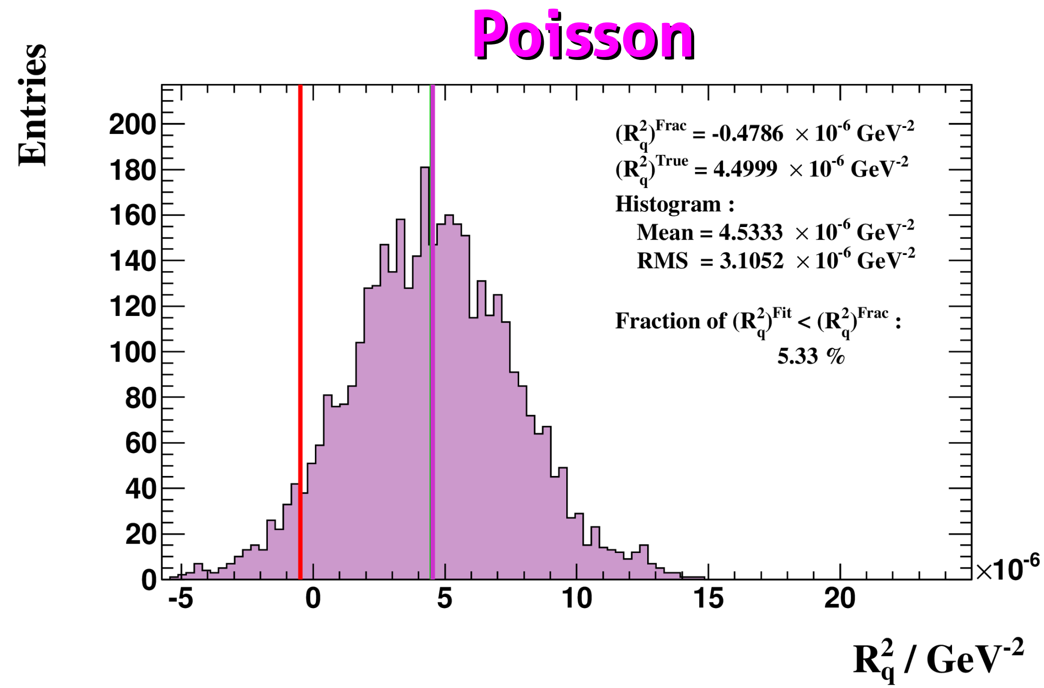
NC:

$$Q^2=[9000, 15000, 25000, 42000, 70000]\,GeV^2$$
$$x=[0.09, 0.15, 0.23, 0.35, 0.53, 0.75]$$

Gaussian vs Poisson

Distributions of fitted R_q^2 values for replicas generated with two different approaches, for $(R_q^2)^{True}$ corresponding to the expected 95% CL limit.





Distributions are consistent within expected statistical fluctuations:

Variable	Gaussian	Poisson	Stat. Unc.
Mean (x10^{-6})	4.536	4.5333	+/- 0.049
RMS (x10^{-6})	3.1038	3.1052	+/- 0.035
Prob($R_q^{2,Fit} < R_q^{2,Data}$) (%)	5.21	5.33	+/- 0.36

Gaussian vs Poisson
Conclusions

➔ New test confirms previous observations:

using Gaussian distribution for modeling of statistical fluctuations of high-Q^2 cross section points does not result in any visible bias when compared to the “full” Poisson method.

➔ we believe that we can safely continue to use Gaussian statistics in replica generation (and the rest of the analysis).

Quark charge radius results from other collaborations:

- L3 Collaboration, M. Acciarri et al., Phys. Lett. B 489, 81 (2000).

  $$R_{q,e} < 0.3 \cdot 10^{-16}\ \text{cm},$$

  but this is assuming that Rq = Re. If we assume R_e=0 (as we do) :

  $$R_q < 0.42 \cdot 10^{-16}\ \text{cm}.$$

  Erich Lohrmann: "there is a similar limit by the LEP experiments … it is complementary to ours, because the LEP value is in the time-like and ours is in the space-like domain"

- CDF Coll., F. Abe et al., Phys. Rev. Lett. 79, 2198 (1997).

  limit from Drell-Yan is

  $$R_{q,e} < 0.56 \cdot 10^{-16}\ \text{cm},$$

  but it is also assuming $R_q=R_l$

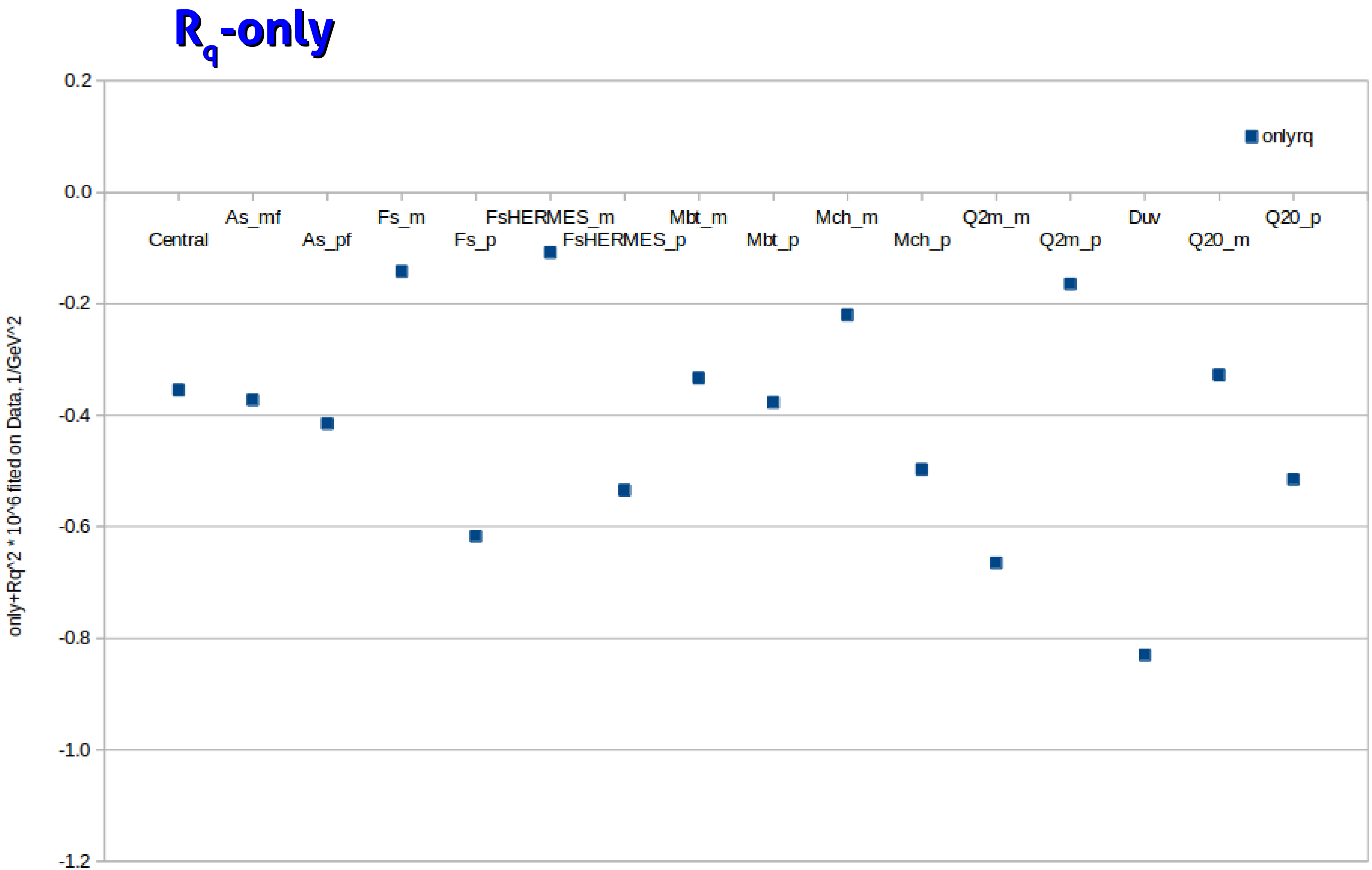
- H1 Collaboration, F.D. Aaron et al., Phys.Lett. B705 (2011) 52-58

  $$R_q < 0.65 \cdot 10^{-16}\ \text{cm}$$

- Previous ZEUS preliminary result (ZEUS-prel-09-013)

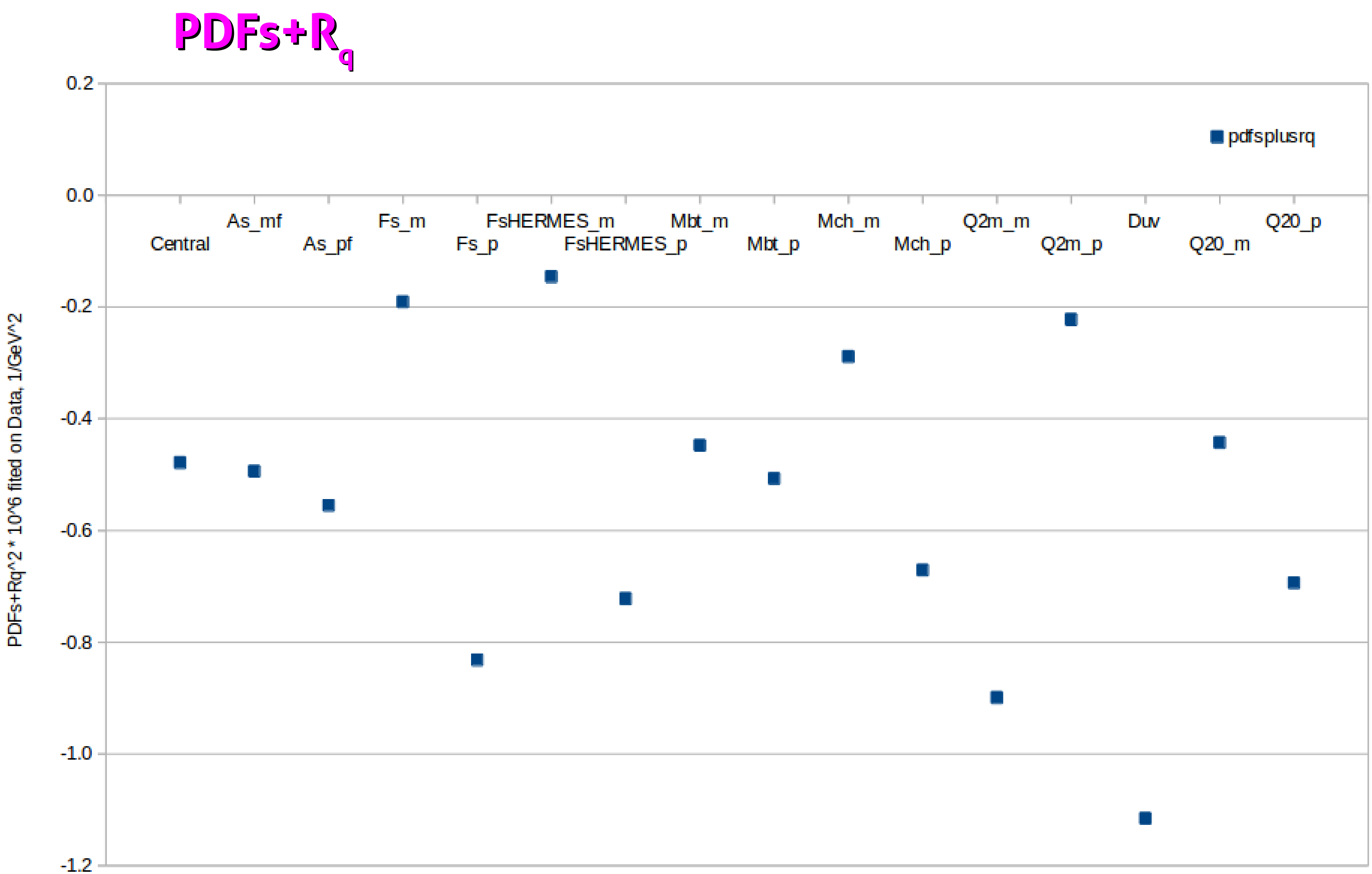
  $$R_q < 0.63 \cdot 10^{-16}\ \text{cm}$$

Best fit results: R_q-only



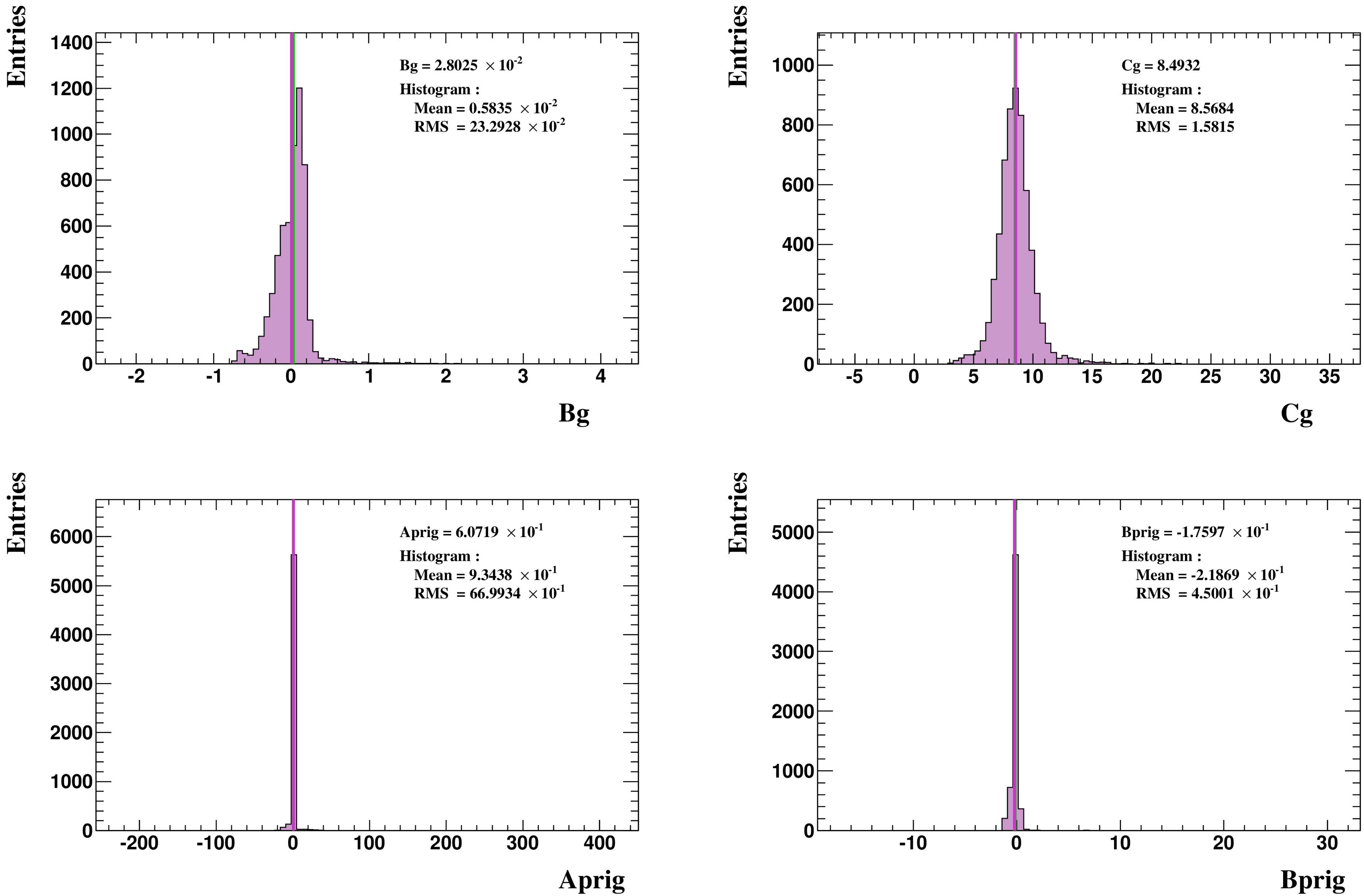
Largest value obtained for $f_{sHERMES}$ lower variation.

Best fit results: PDFs+R_q

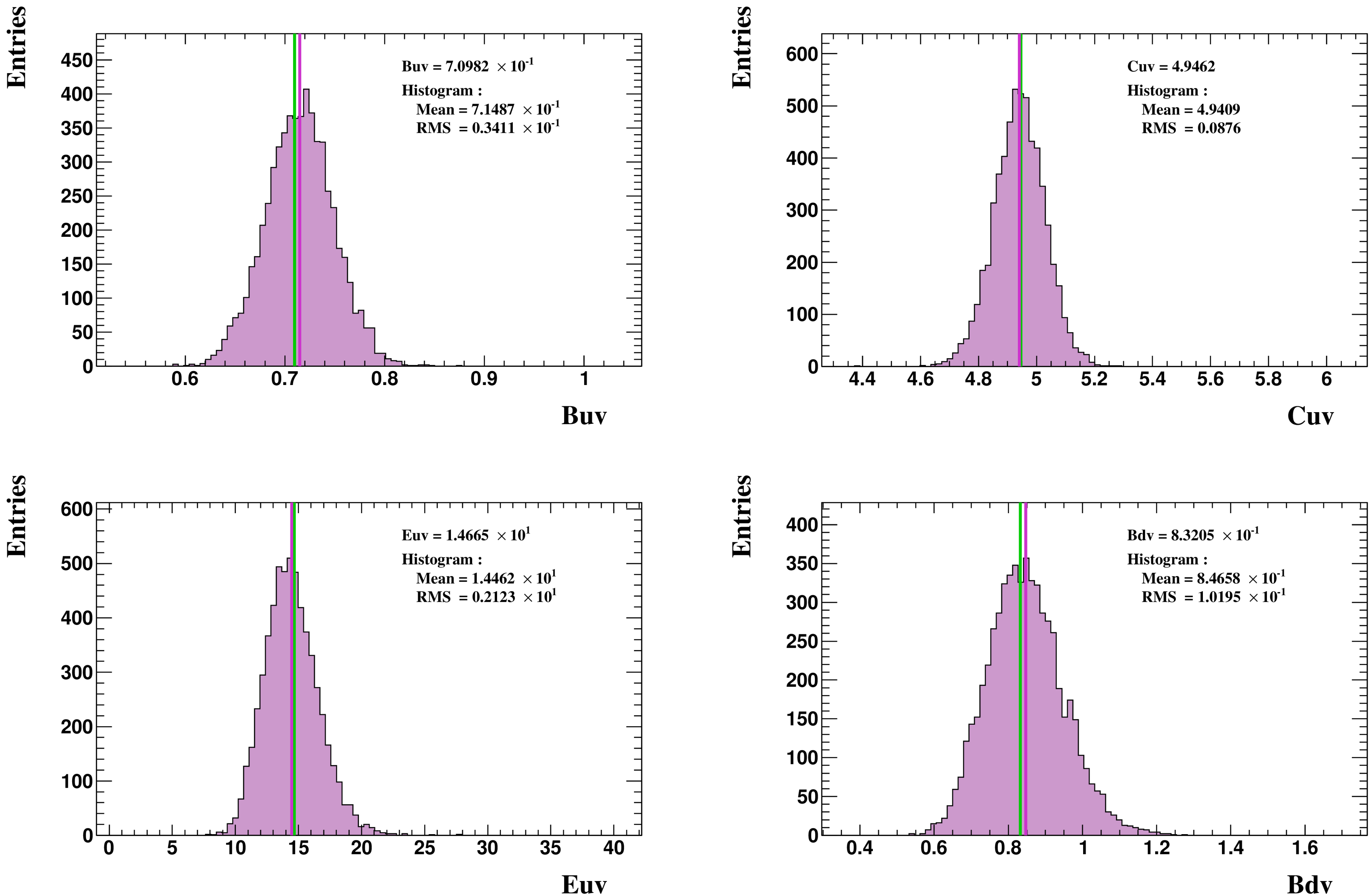


Largest value obtained for $f_{sHERMES}$ lower variation.

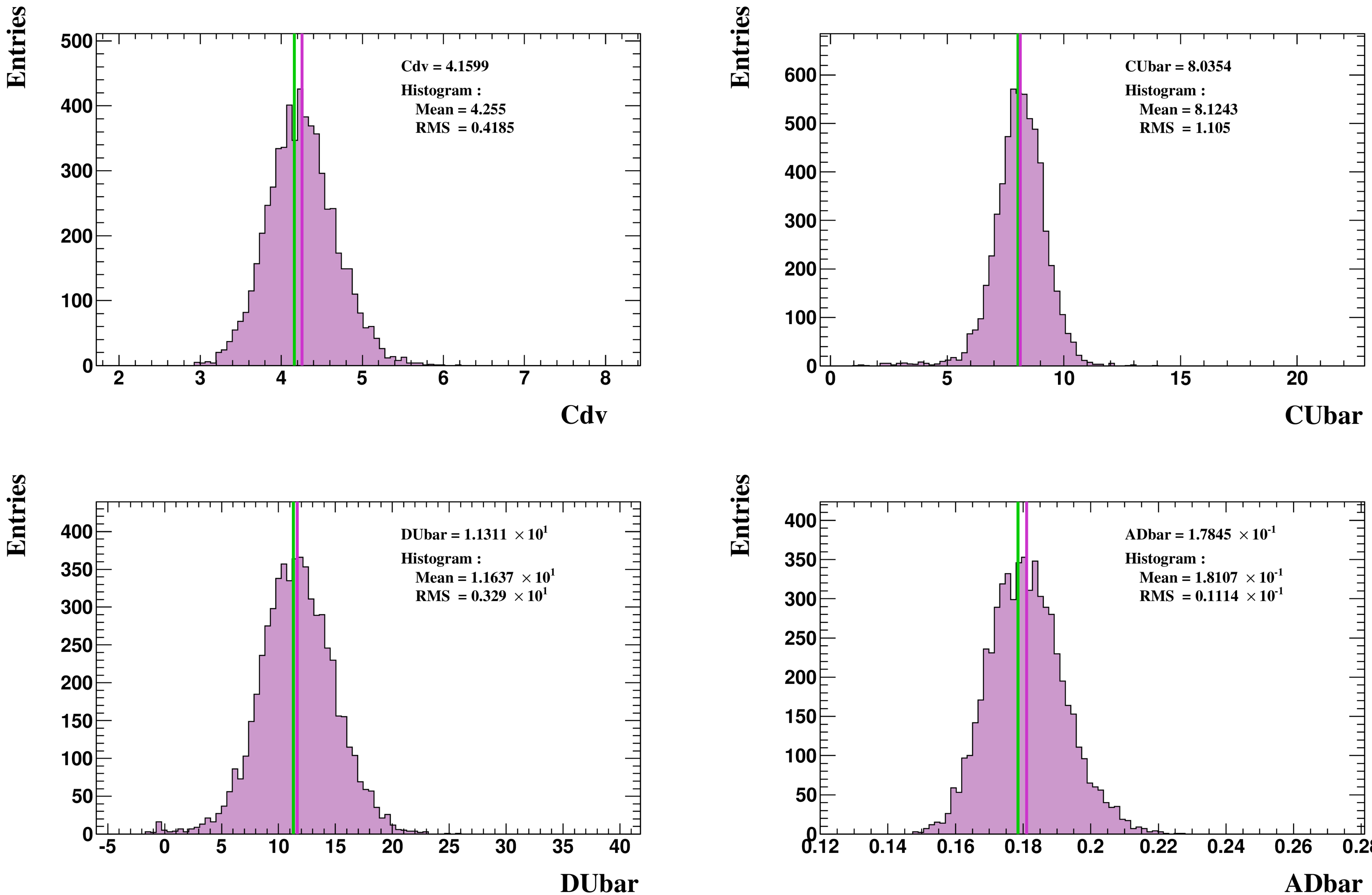
MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1795 \cdot 10^{-3}$ GeV^{-1}:



MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1795 \cdot 10^{-3}$ GeV^{-1}:



MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1795 \cdot 10^{-3}$ GeV^{-1}:



MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1795 \cdot 10^{-3}$ GeV^{-1}: