Limits on the Effective Quark Charge Radius

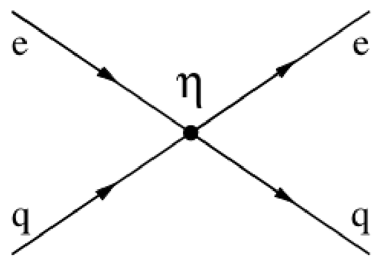
O. Turkot, K. Wichmann, A.F. Żarnecki

Group 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

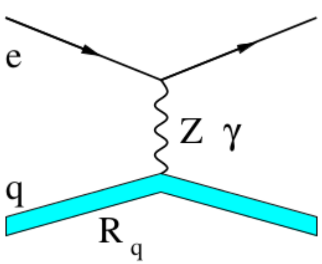
Introduction to contact interactions

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:

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

Cause for new limits estimation procedures

- 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 .

See ZEUS note by A. F. Żarnecki
“CI analysis with proper treatment of PDF uncertainties”

Probability method of limits setting

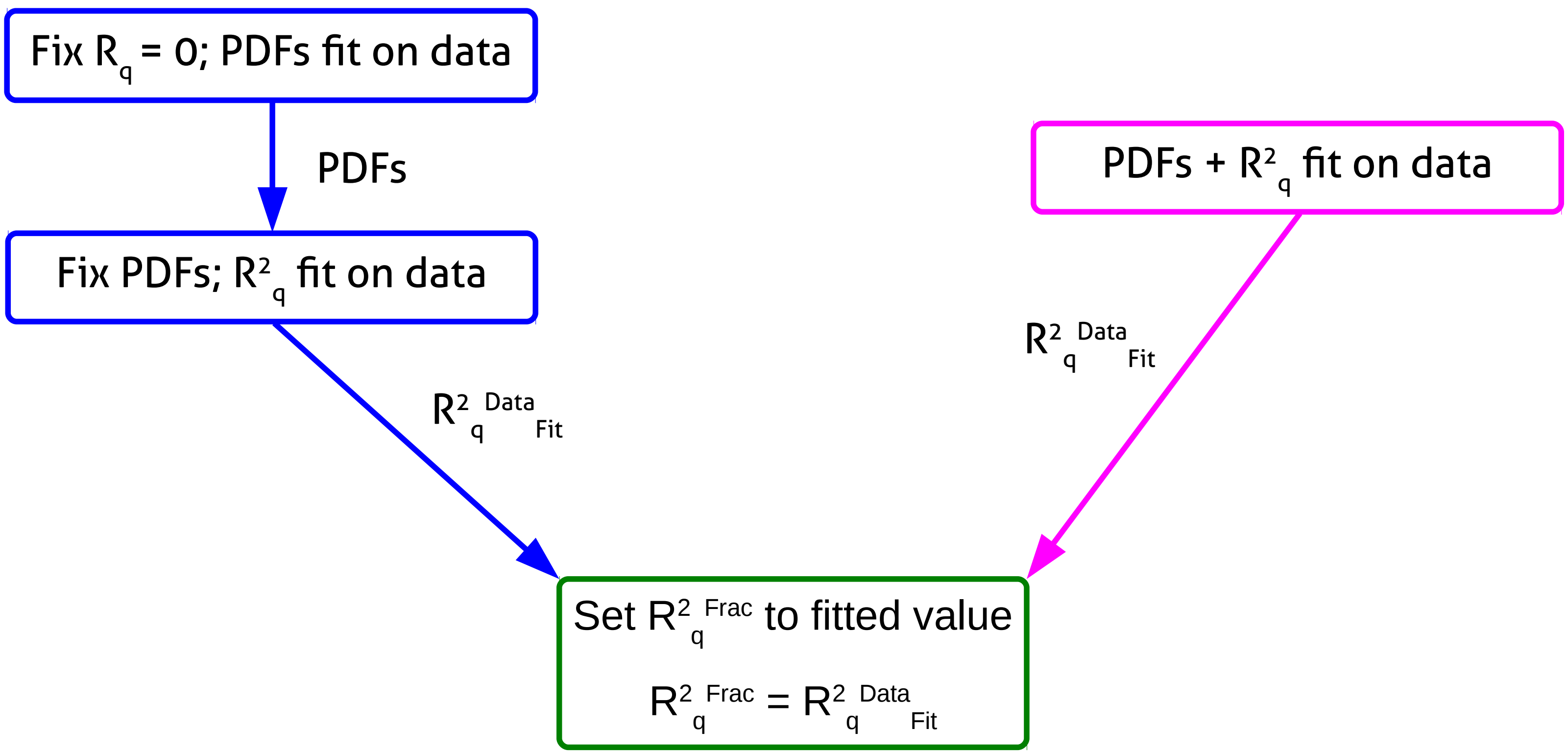
Probability method of limits setting for two procedures:

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 **QCD+R_q**



Full H1-ZEUS HERA I+II combined inclusive NC and CC data used.

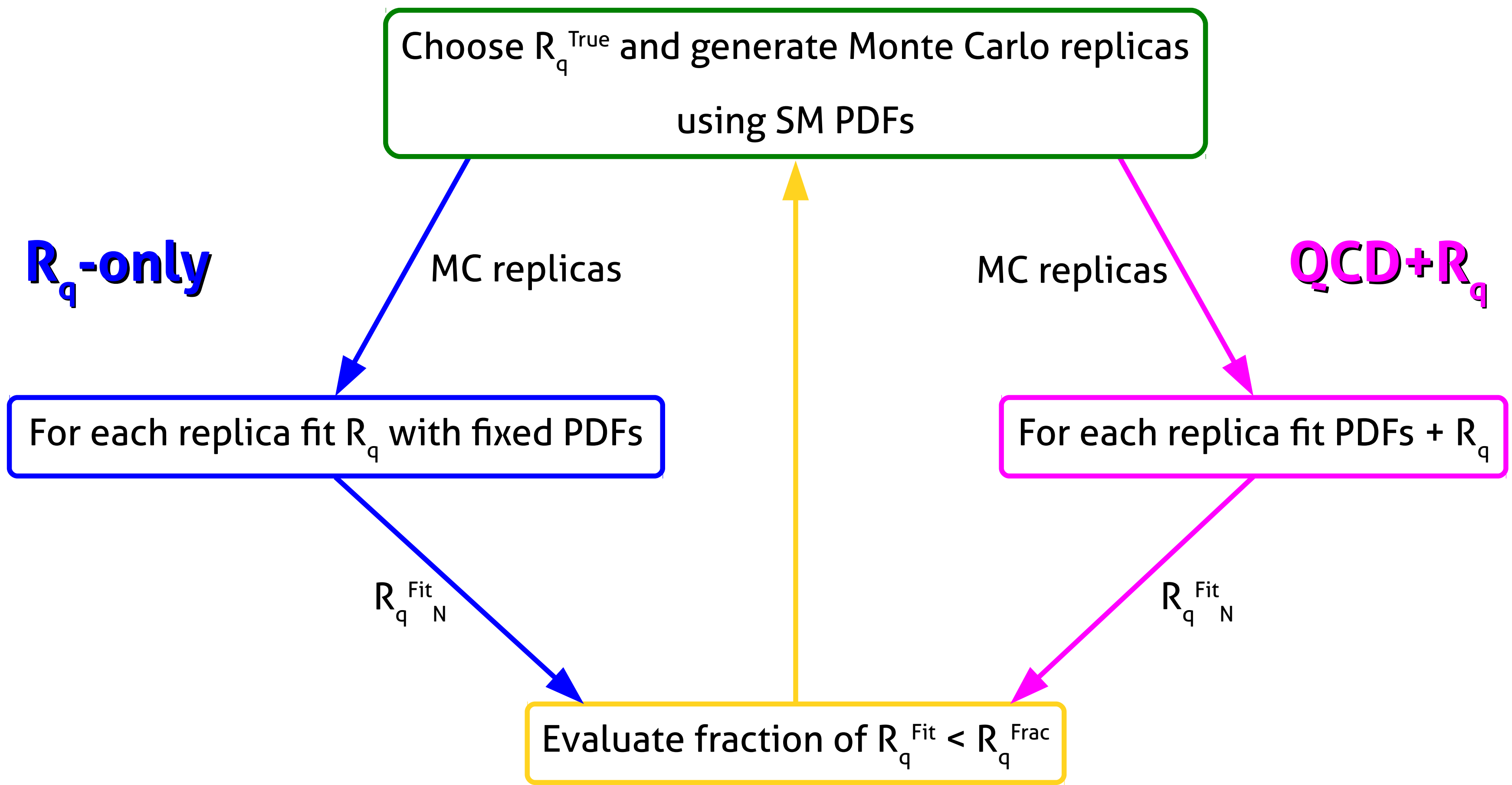
Q^2_{min} = 3.5 GeV^2

$$\chi^2_{exp}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i + \sum_j \gamma^j_i b_j m^i - \mu^i\right]^2}{\delta^2_{i,tot.uncor.} D^2_i} + \sum_j b^2_j$$

R_q fit on data provided next results:

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

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

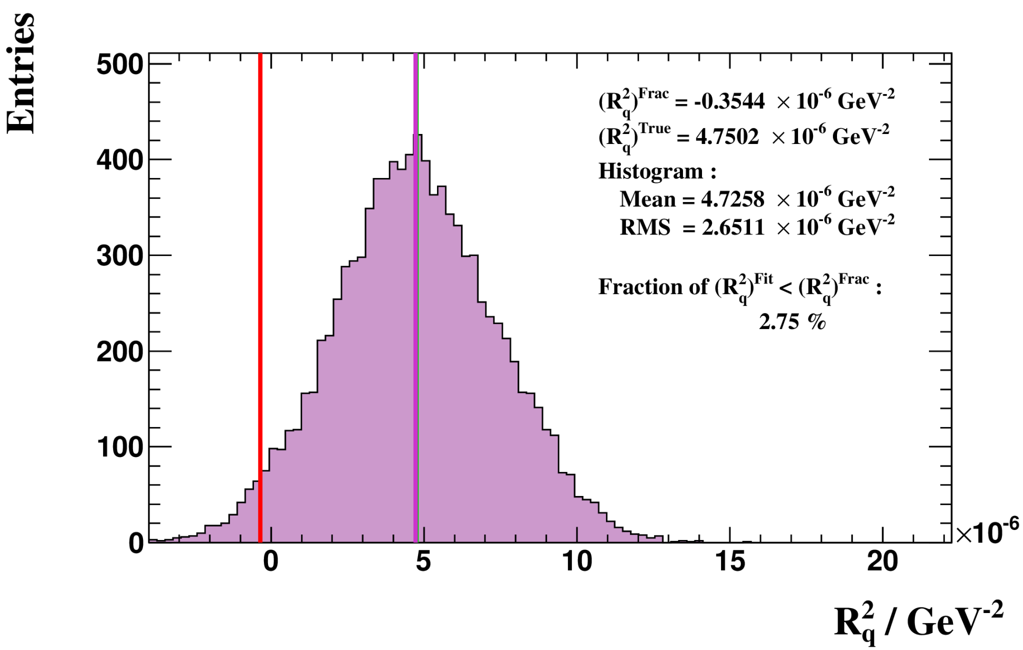

Choose R_q^{True} and generate Monte Carlo replicas using SM PDFs
R_q-only
MC replicas
MC replicas
QCD+R_q
For each replica fit R_q with fixed PDFs
For each replica fit PDFs + R_q
$R_q^{Fit}{}_N$
$R_q^{Fit}{}_N$
Evaluate fraction of $R_q^{Fit} < R_q^{Frac}$

Monte Carlo replicas of cross sections calculated as:

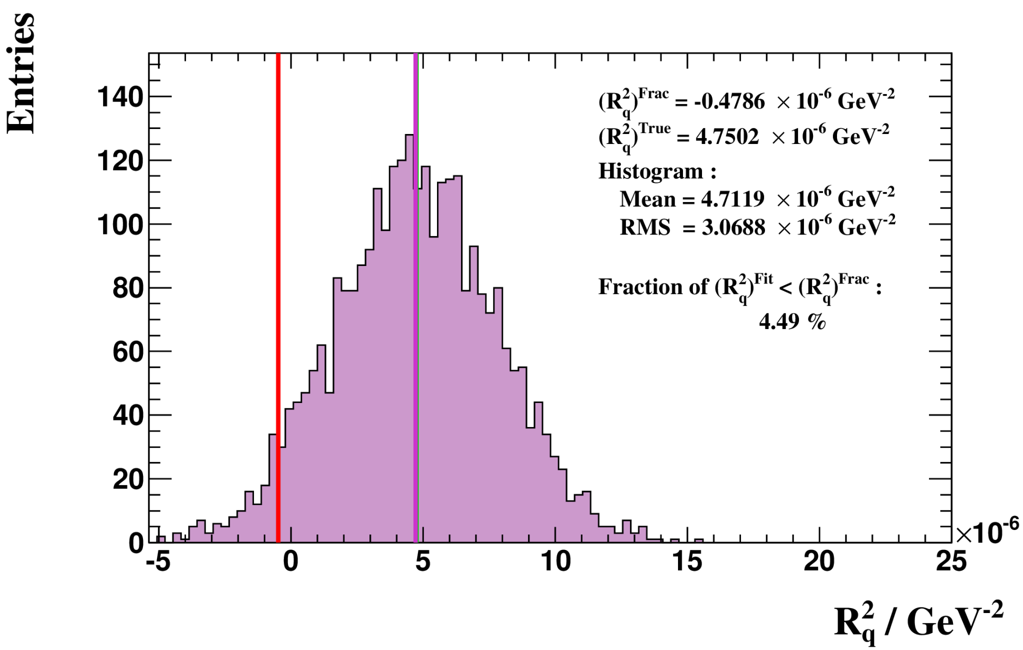
$$\mu^i = [M^i + \delta^i_{tot.uncor.} \cdot R^i_{tot.uncor.} \cdot D^i] \cdot (1 + \sum_j \gamma^j \cdot R^j_{sys.sh.})$$

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

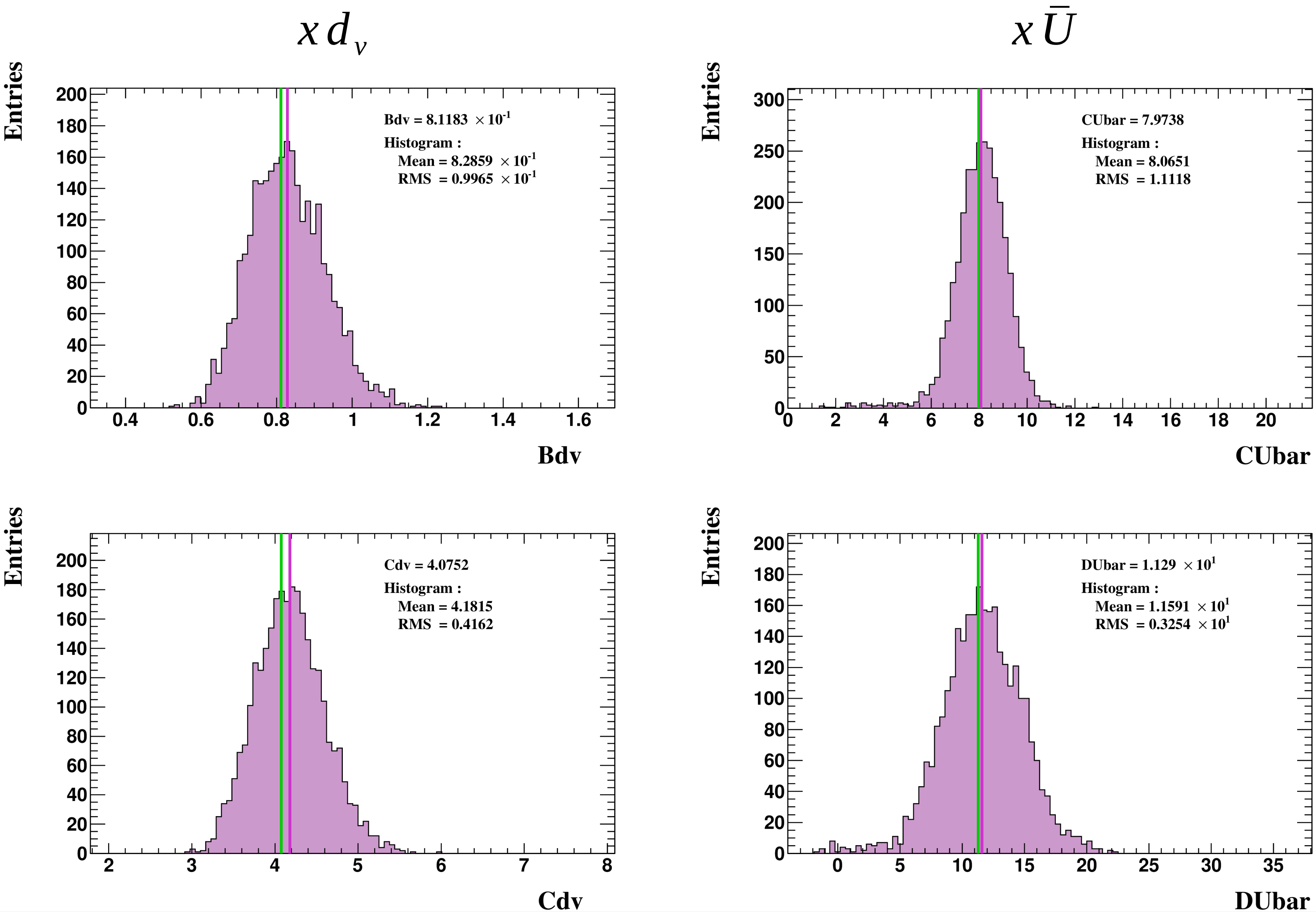
R_q-only



QCD+R_q



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



R_q-only and QCD+R_q

Plot Prob($R^2_q{}^{Fit} < R^2_q{}^{Frac}$) as a function of $R^2_q{}^{Data}$,

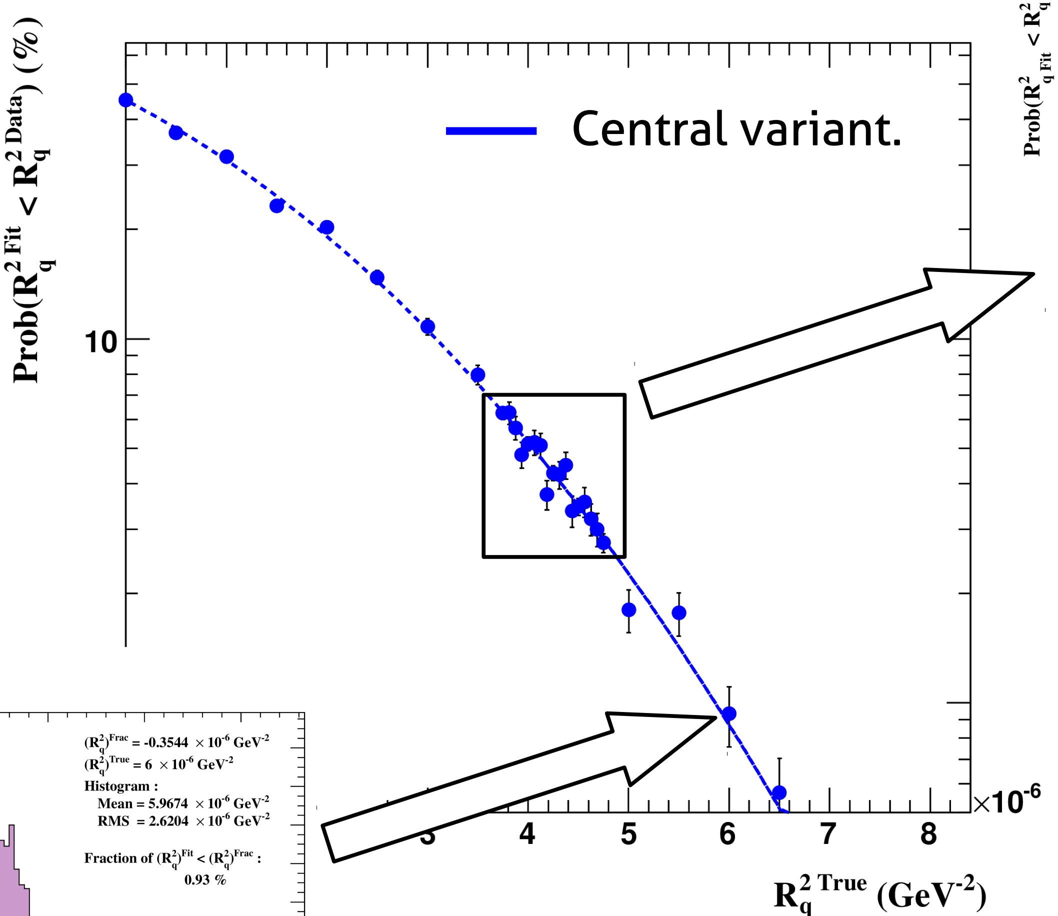
calculate $R^2_q{}^{Limit}_A$ for CL = 95 %

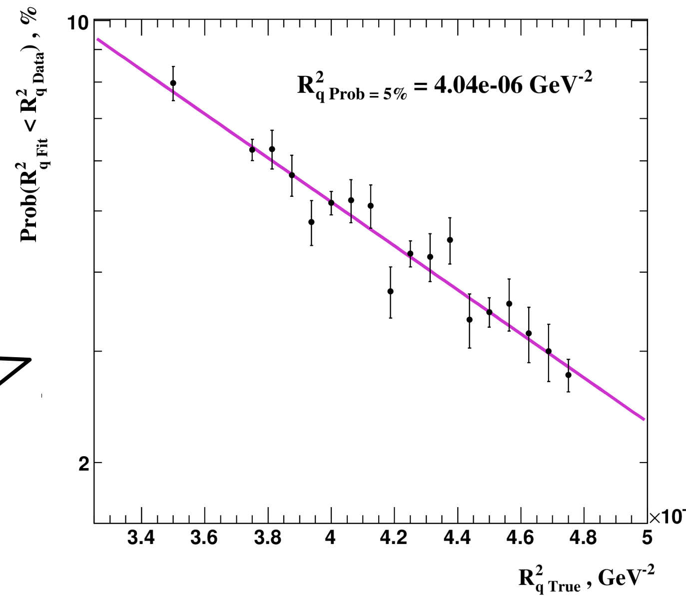
↓

Set $R_q{}^{Limit}_A$ as a final $\mathbf{R_q}^{\mathbf{Limit}}$

R_q-only

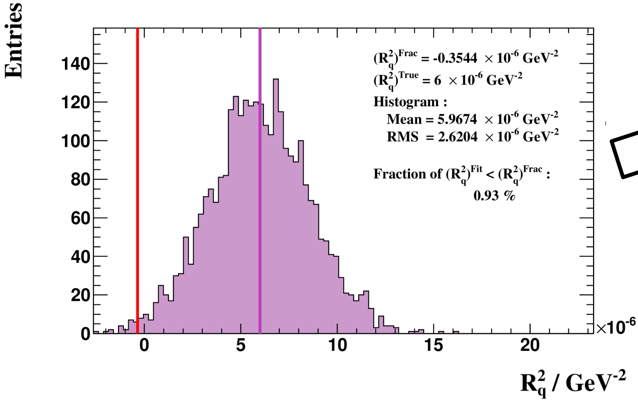
For central variant:





Fractions close to 5% fitted with:

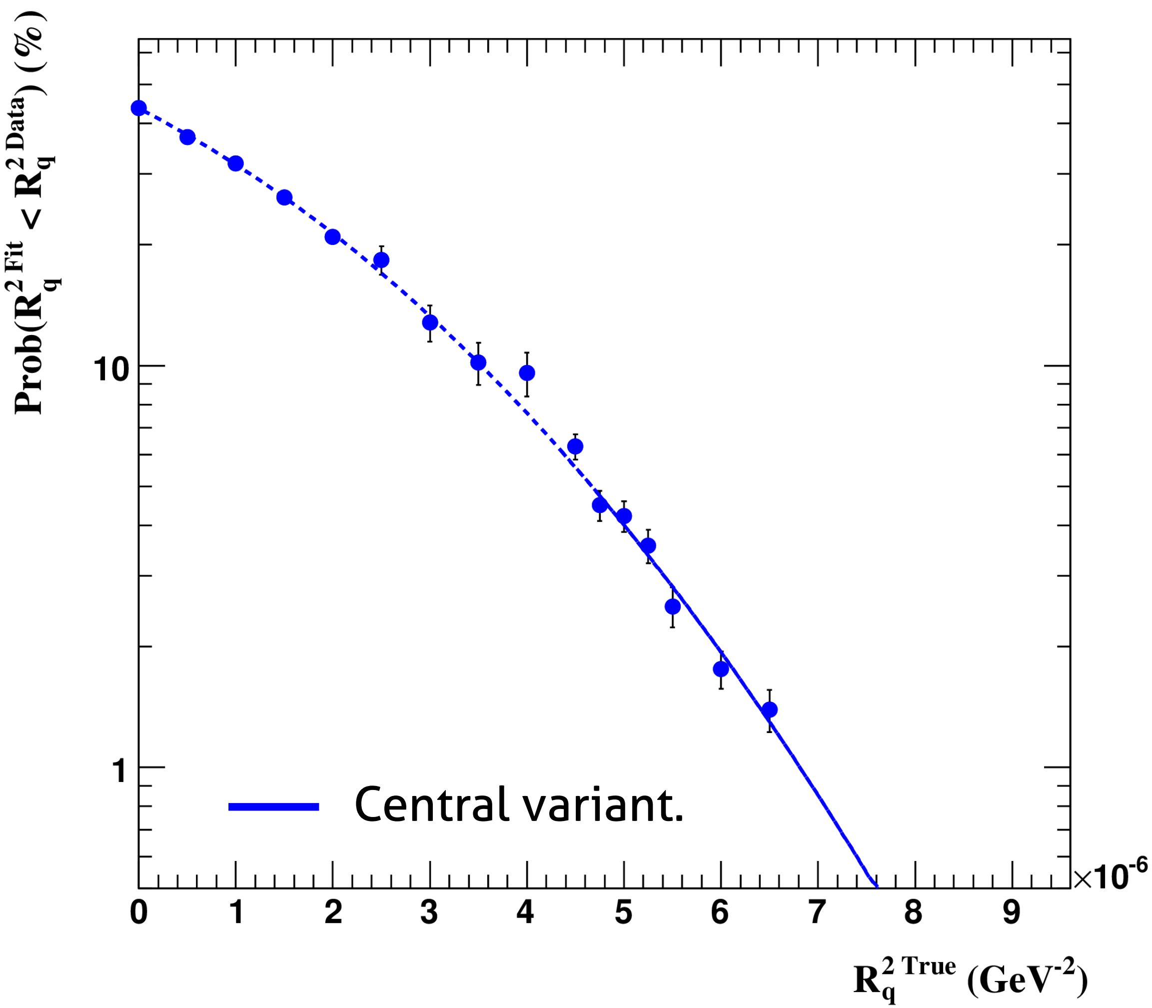
$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



$$R_q^{Limit} = 2.010 \pm 0.005 \cdot 10^{-3}\ GeV^{-1}$$

QCD+R_q

For central variant:



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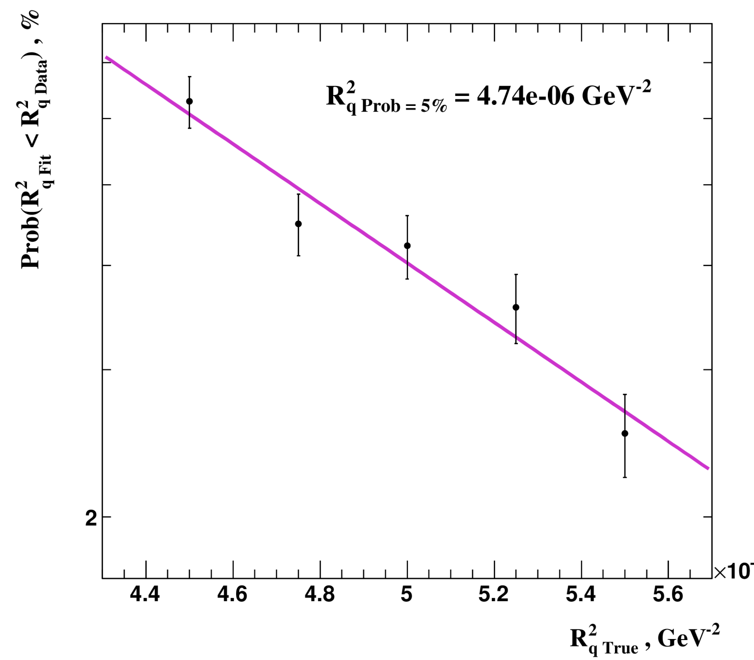


$$R_q^{Limit} = 2.176 \pm 0.012 \cdot 10^{-3}\ \text{GeV}^{-1}$$

Model and parameterisation variations

Variations for Model uncertainty :

Variation	Standard value	Lower limit	Upper limit
Q^2_{min} [GeV²]	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

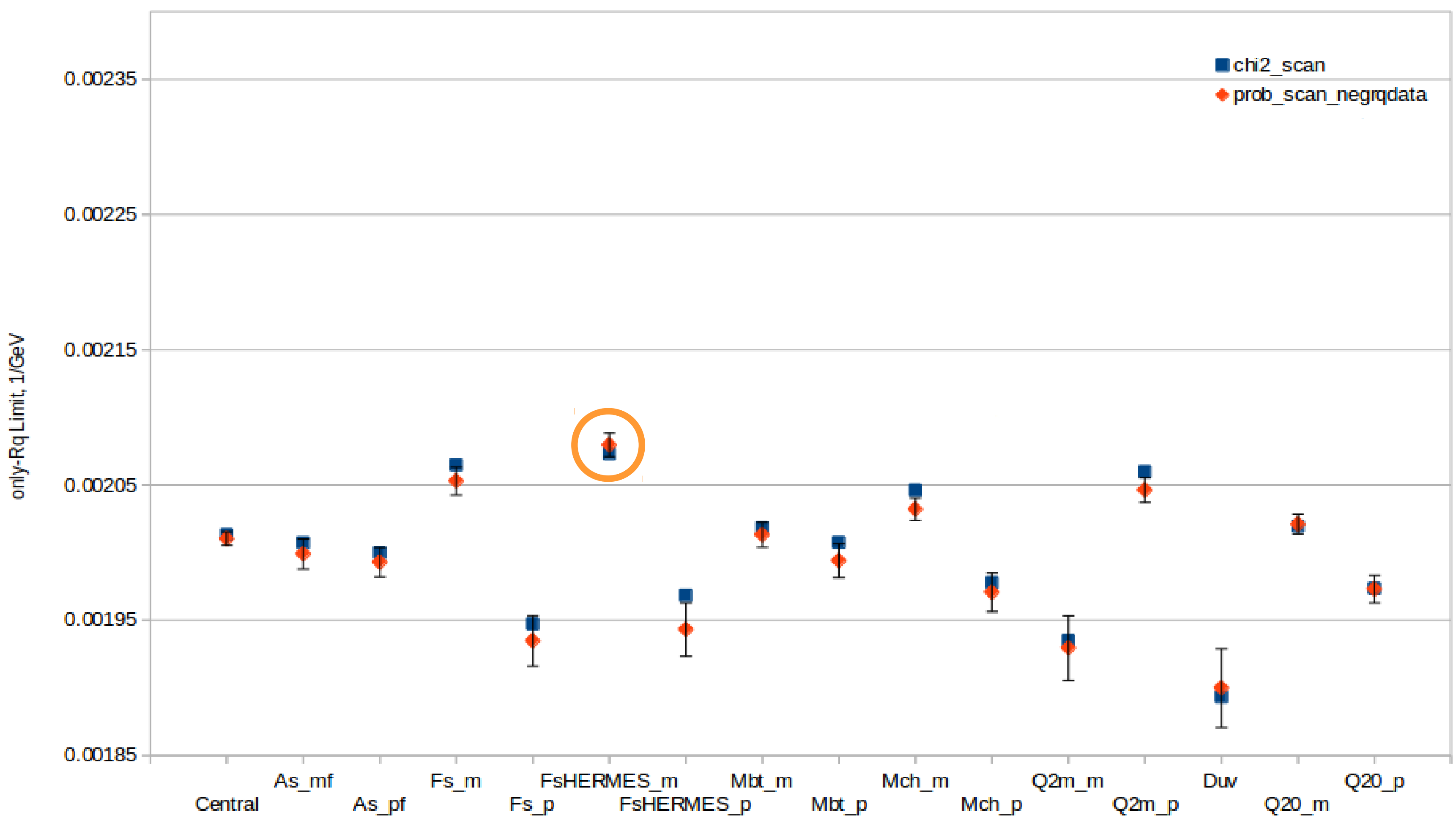
Variations for Parameterisation uncertainty :

Variation	Standard value	Lower limit	Upper limit
Q^2_0 [GeV²]	1.9	1.6	2.2 (m_c = 1.53 GeV)
Du_v	-		+

Probability method vs χ^2 scan

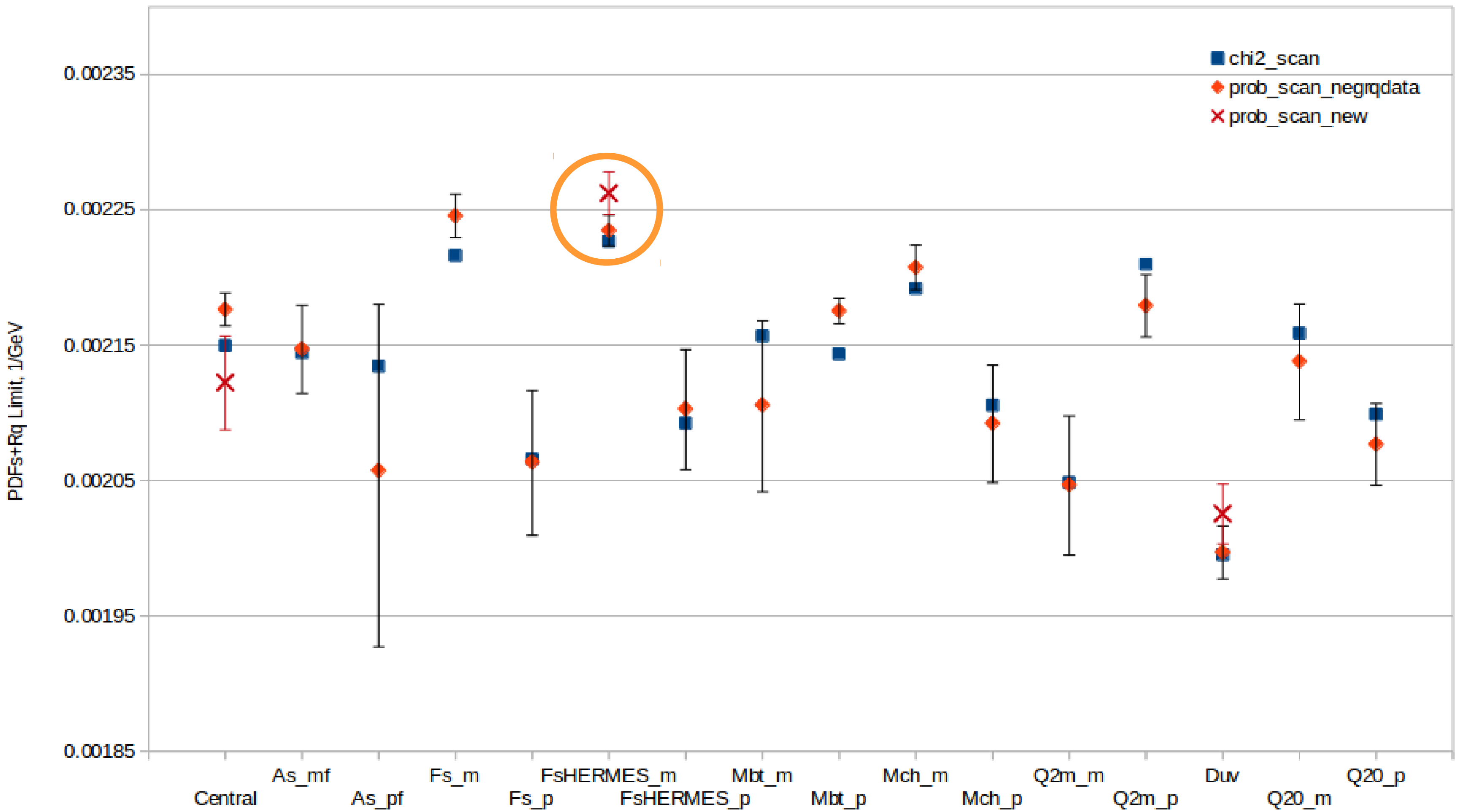
Same procedure used for model and parameterization variations to find the weakest limit:

R_q-only



Same procedure used for model and parameterization variations to find the weakest limit:

QCD+R_q



χ^2 method of limits setting

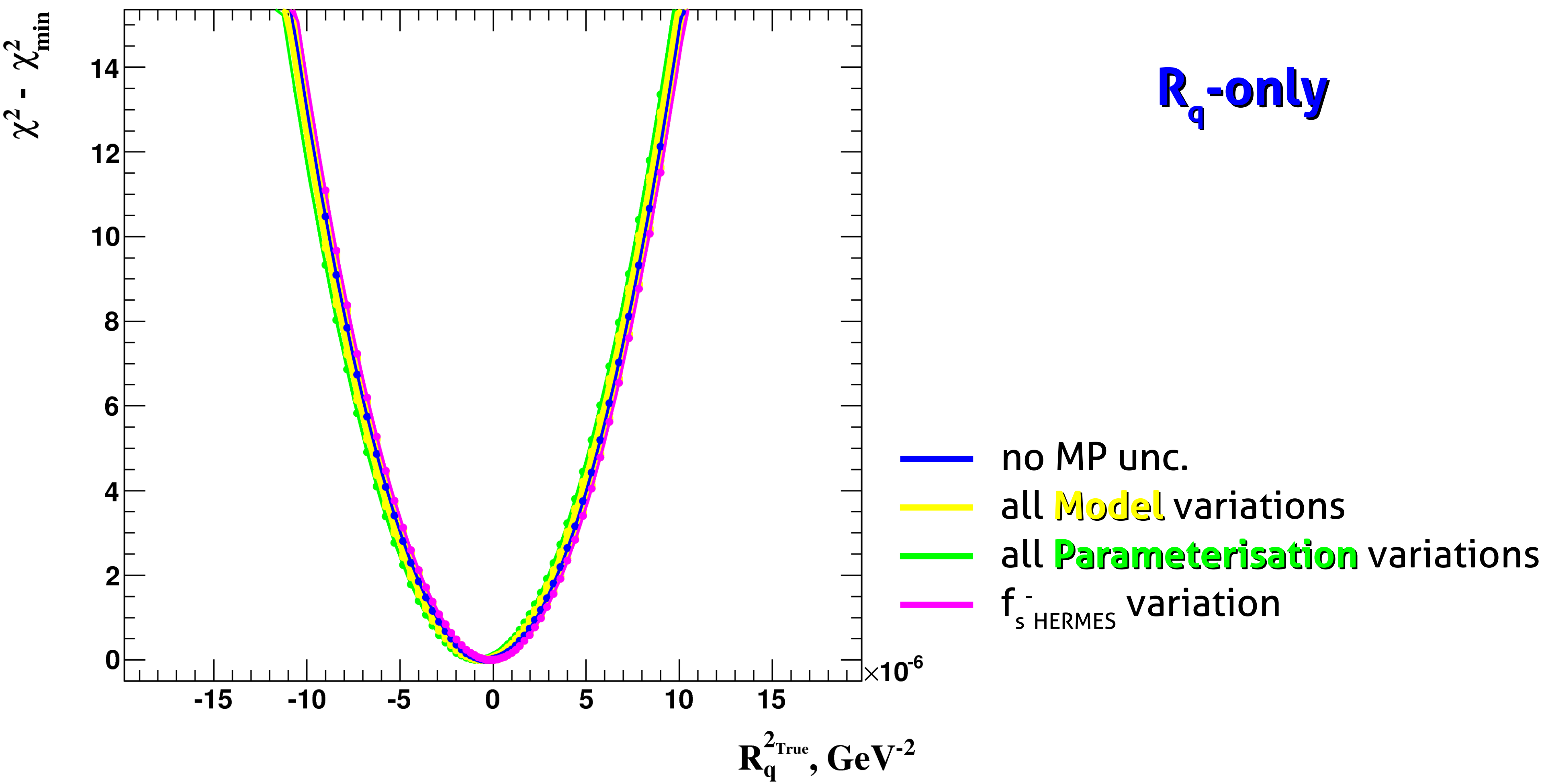
χ^2 method of limits setting for two procedures:

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.

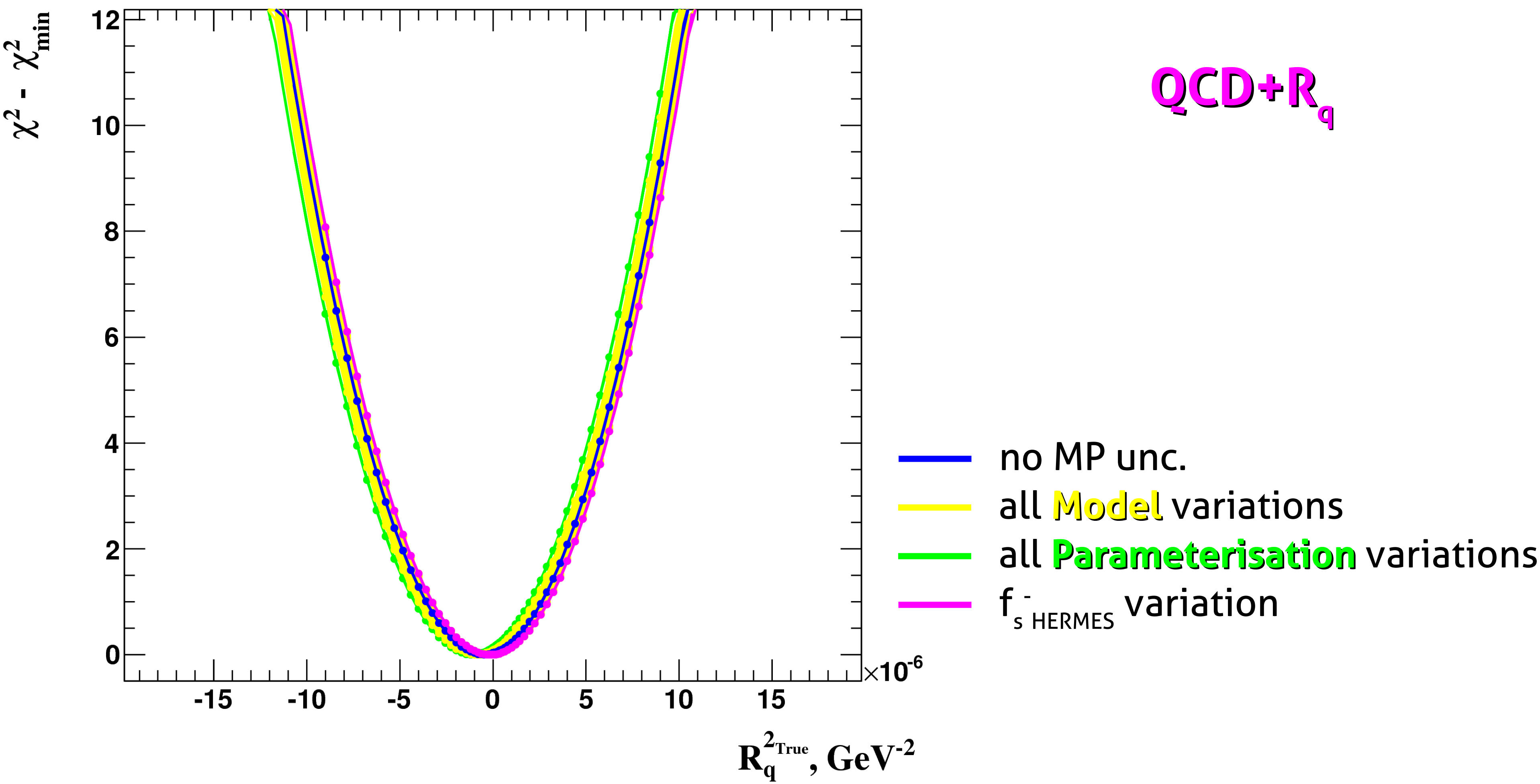
χ^2 full scan



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

$$R_q < 2.0731 \cdot 10^{-3}\ \text{GeV}^{-1}$$

χ^2 full scan



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

$$R_q < 2.2267 \cdot 10^{-3}\ \text{GeV}^{-1}$$

Estimated R_q limits

Limits for probability method:

R_q-only : $R_q < 0.4104 \cdot 10^{-16}$ cm

QCD+R_q : $R_q < 0.4464 \cdot 10^{-16}$ cm

Limits for χ^2 method:

R_q-only : $R_q < 0.4091 \cdot 10^{-16}$ cm

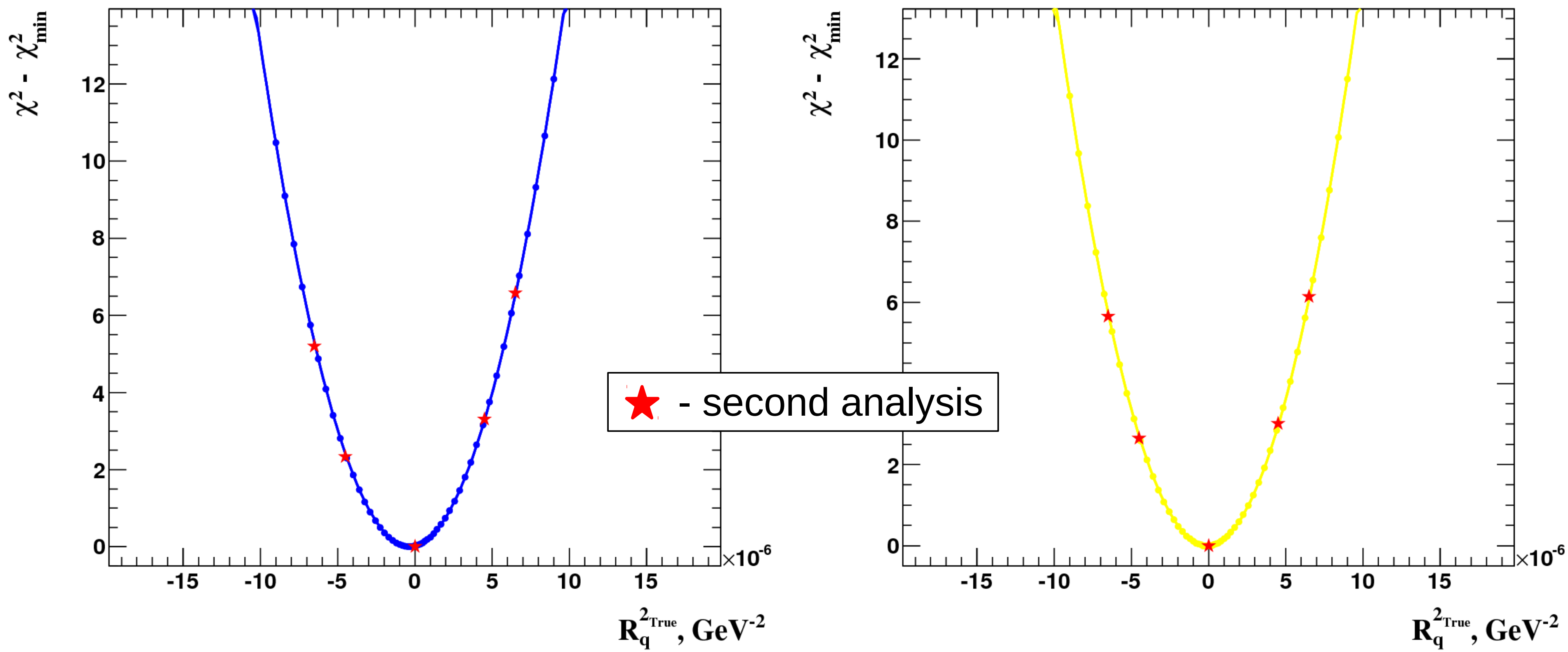
QCD+R_q : $R_q < 0.4394 \cdot 10^{-16}$ cm

- Both methods provide consistent limits.
- Difference between QCD+R_q and R_q-only procedures ~ 7-8%

Second analysis

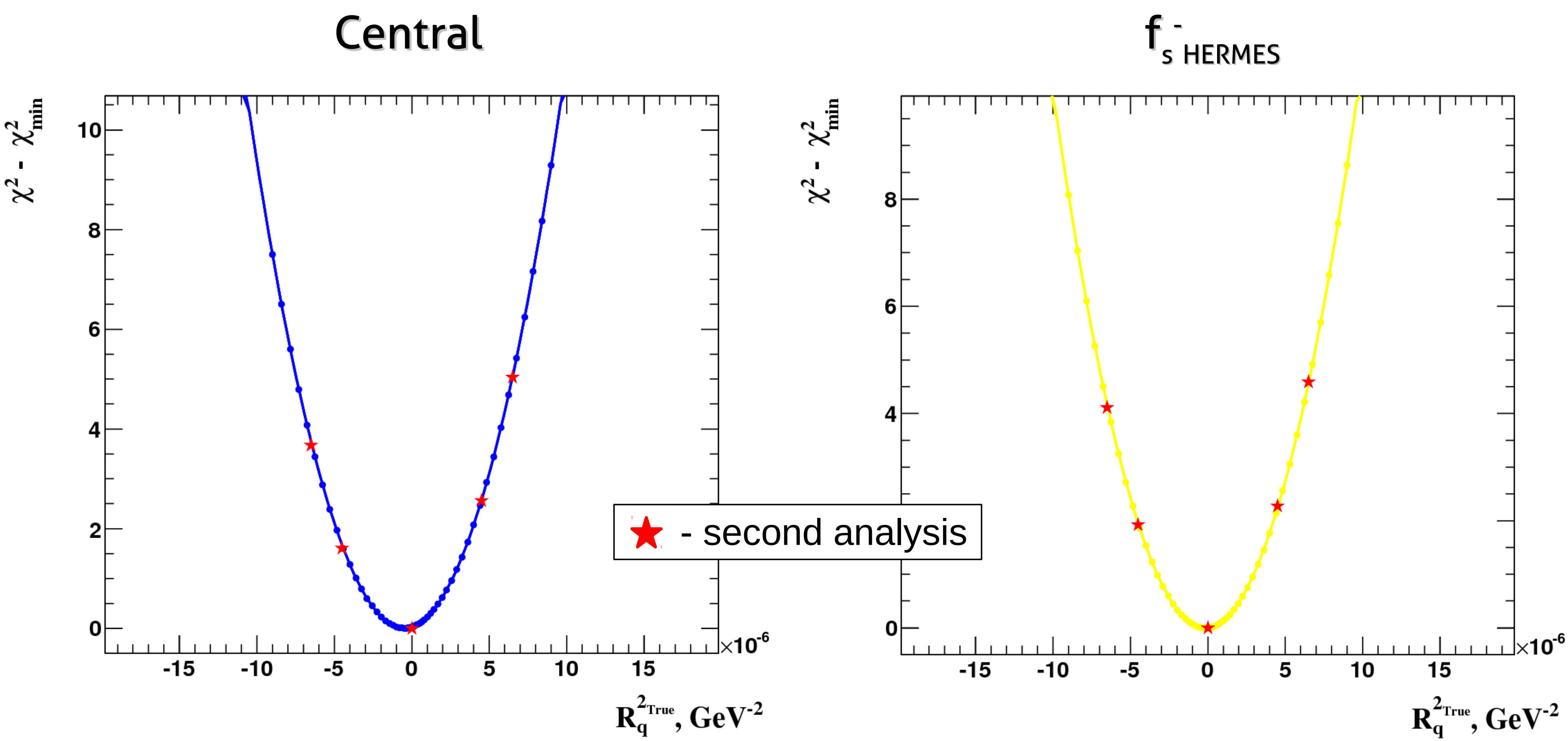
- χ^2 limits setting procedure was a first cross check for the probability limits and it agrees within few percents.
- For second analysis Katarzyna Wichmann has repeated the χ^2 limit estimation method for the central and weakest limit variants:

R_q-only : Central $f_{s\,\mathrm{HERMES}}^{-}$



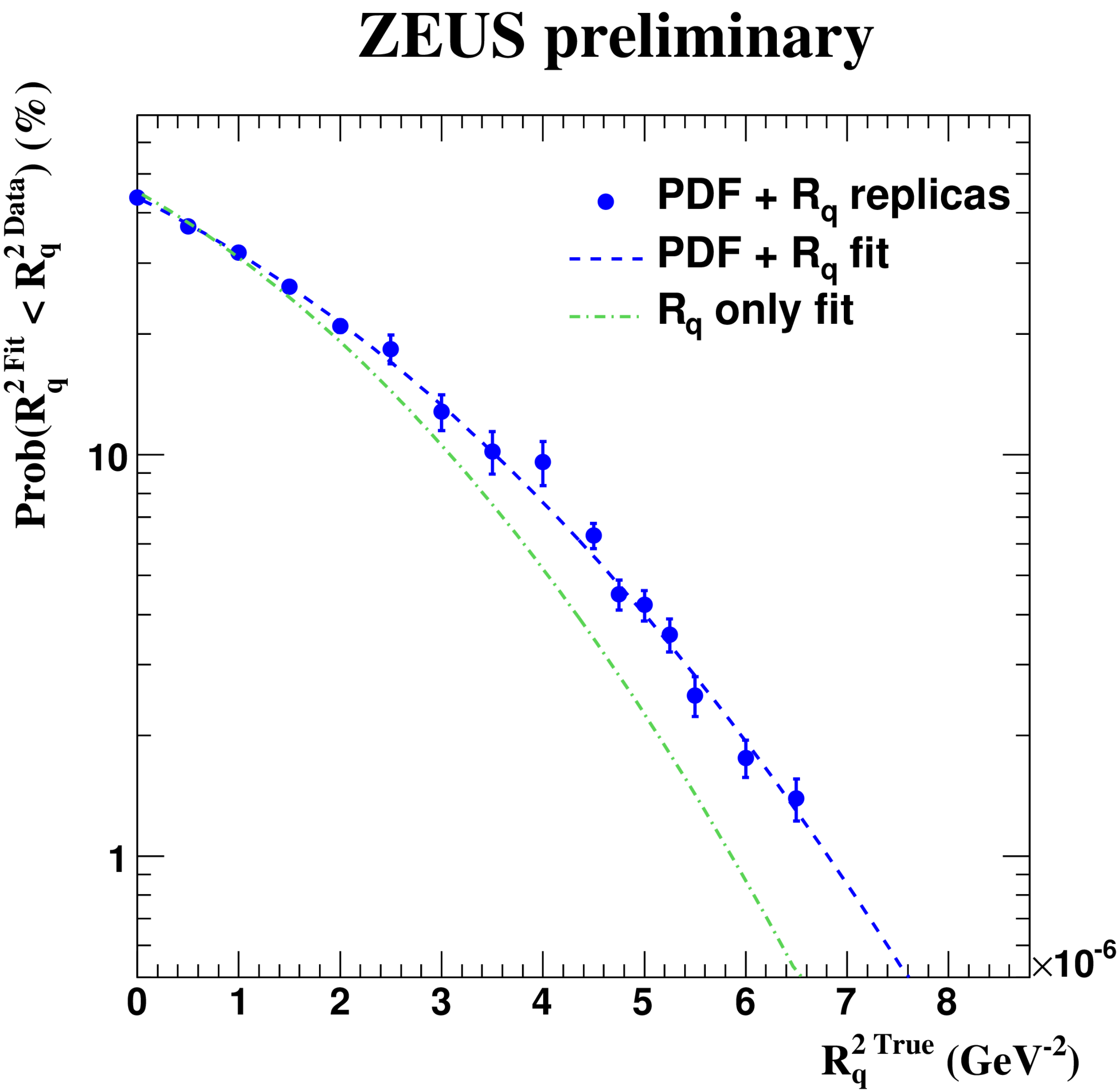
Results perfectly agree with main analysis.

QCD+R_q :

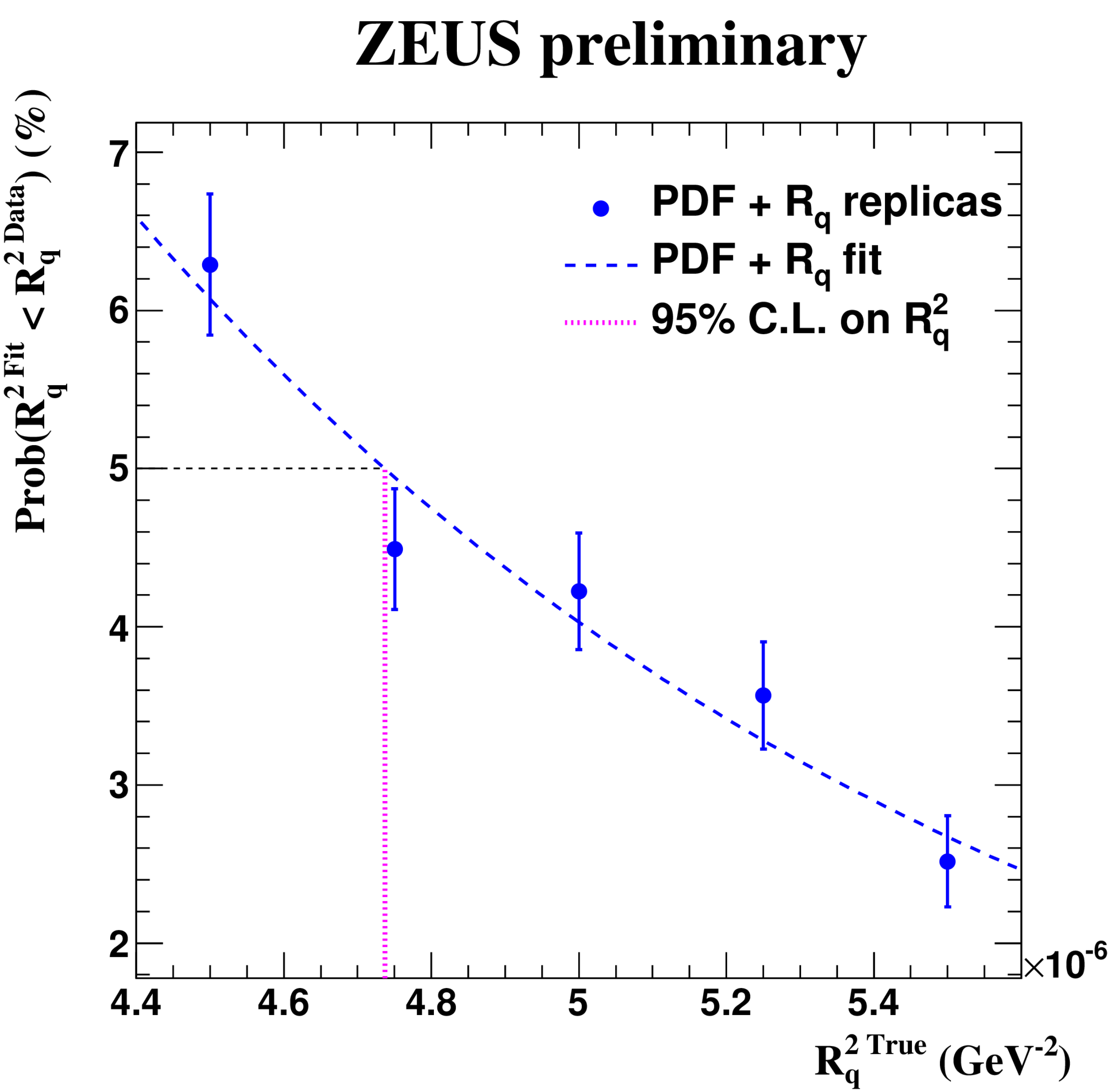


Results perfectly agree with main analysis.

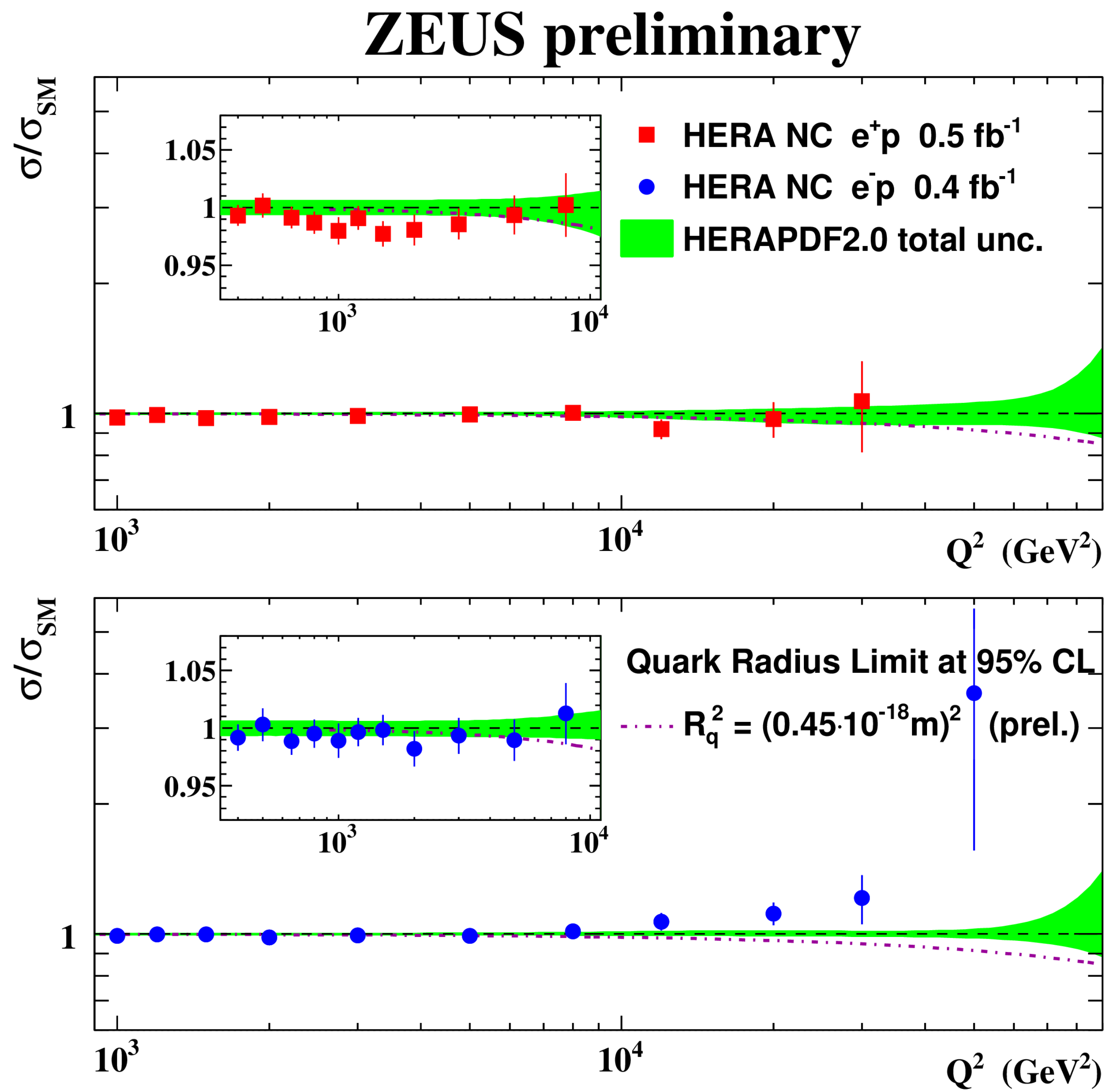
Results for publication



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 limit on quark form factor:

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

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

➔ Second analysis perfectly agree with main result.

➔ We have a paper draft which is being updated to include your comments.

Backup

Quark charge radius results from other collaborations:

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

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

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

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

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

  but it is also assuming R_q=R_l

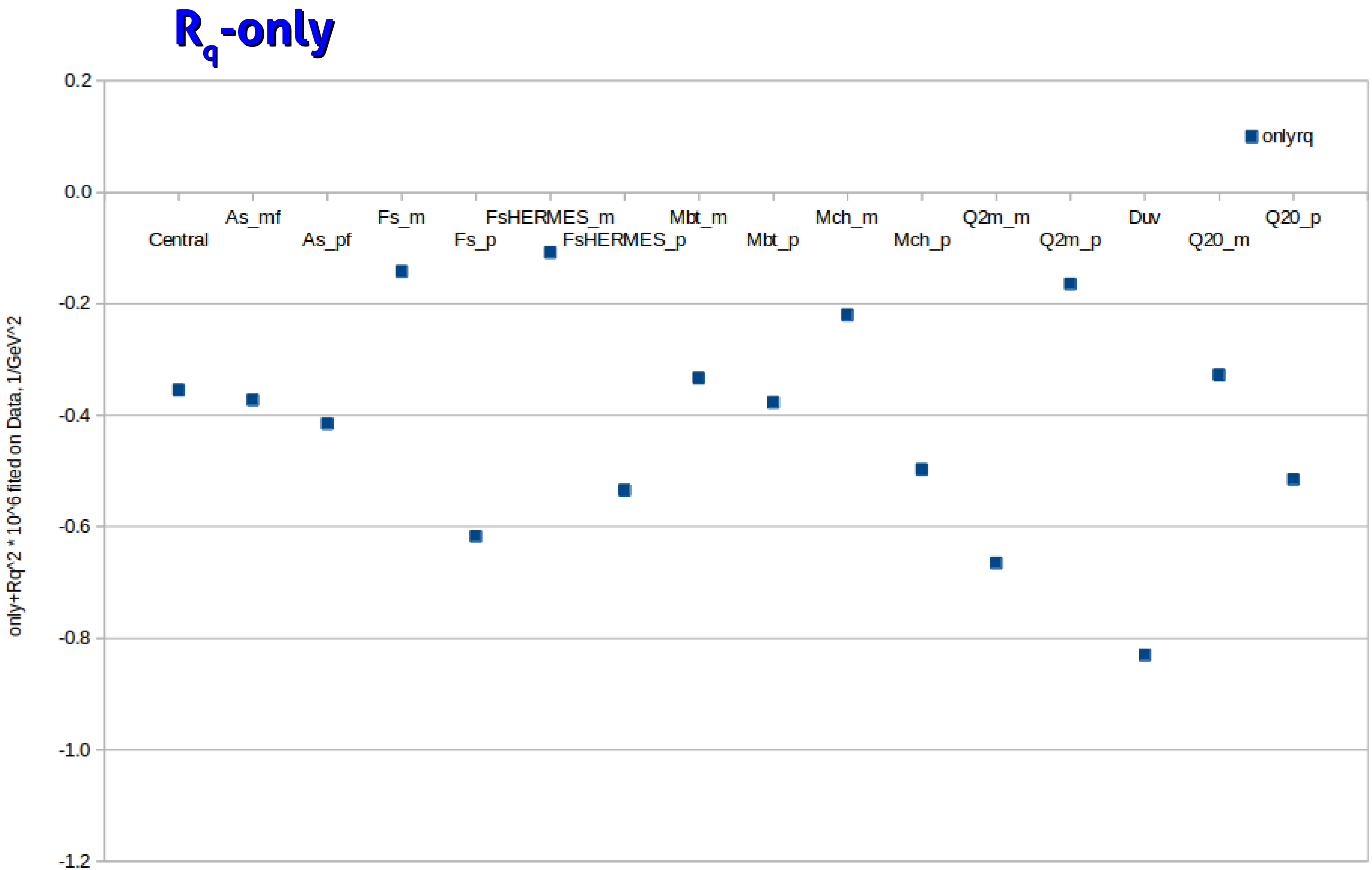
* H1 Collaboration, F.D. Aaron et al., Phys.Lett. B705 (2011) 52-58

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

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

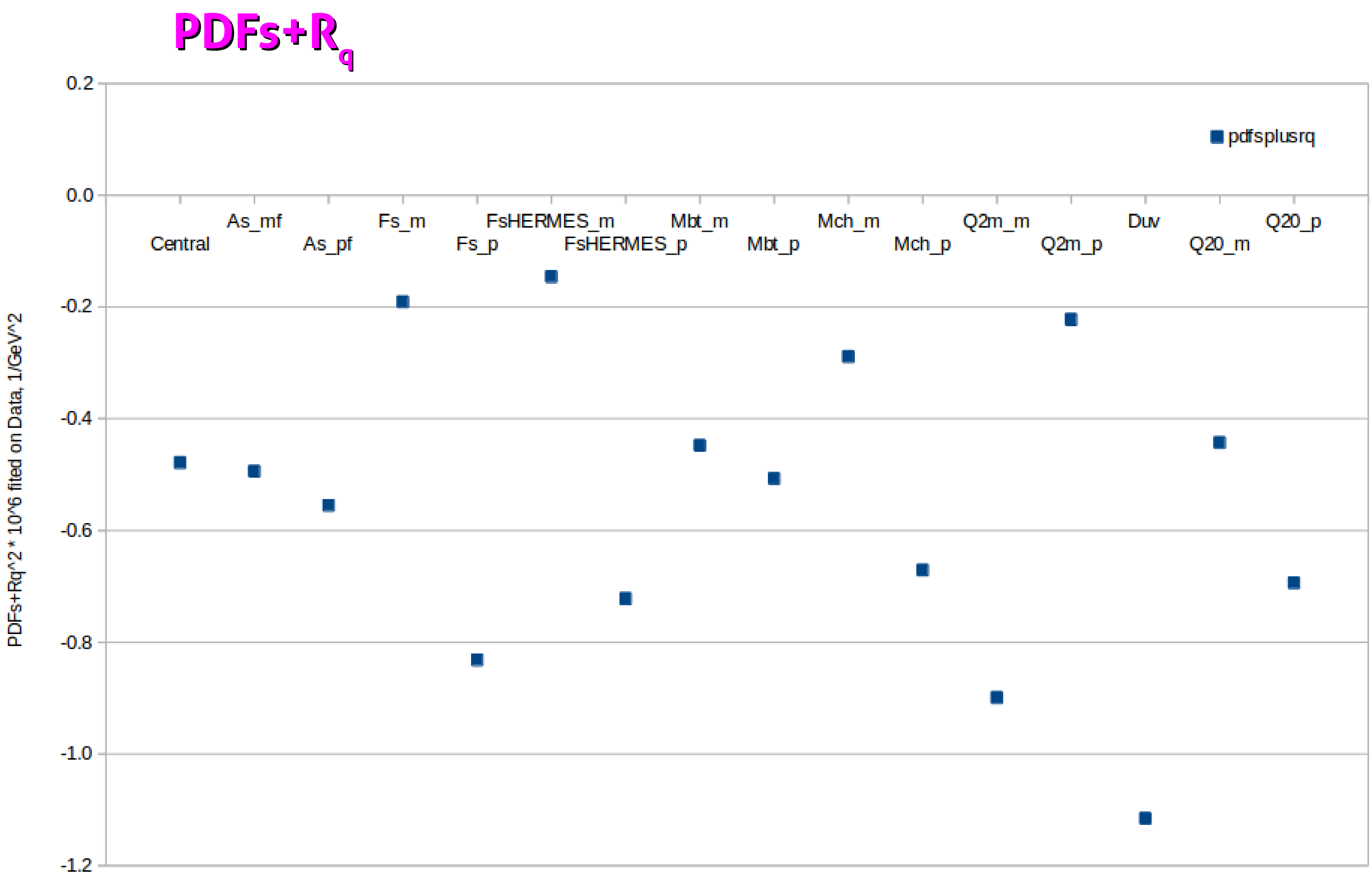
  $R_q < 0.63 \cdot 10^{-16}$ cm

Best fit results: R_q-only



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

Best fit results: PDFs+R_q

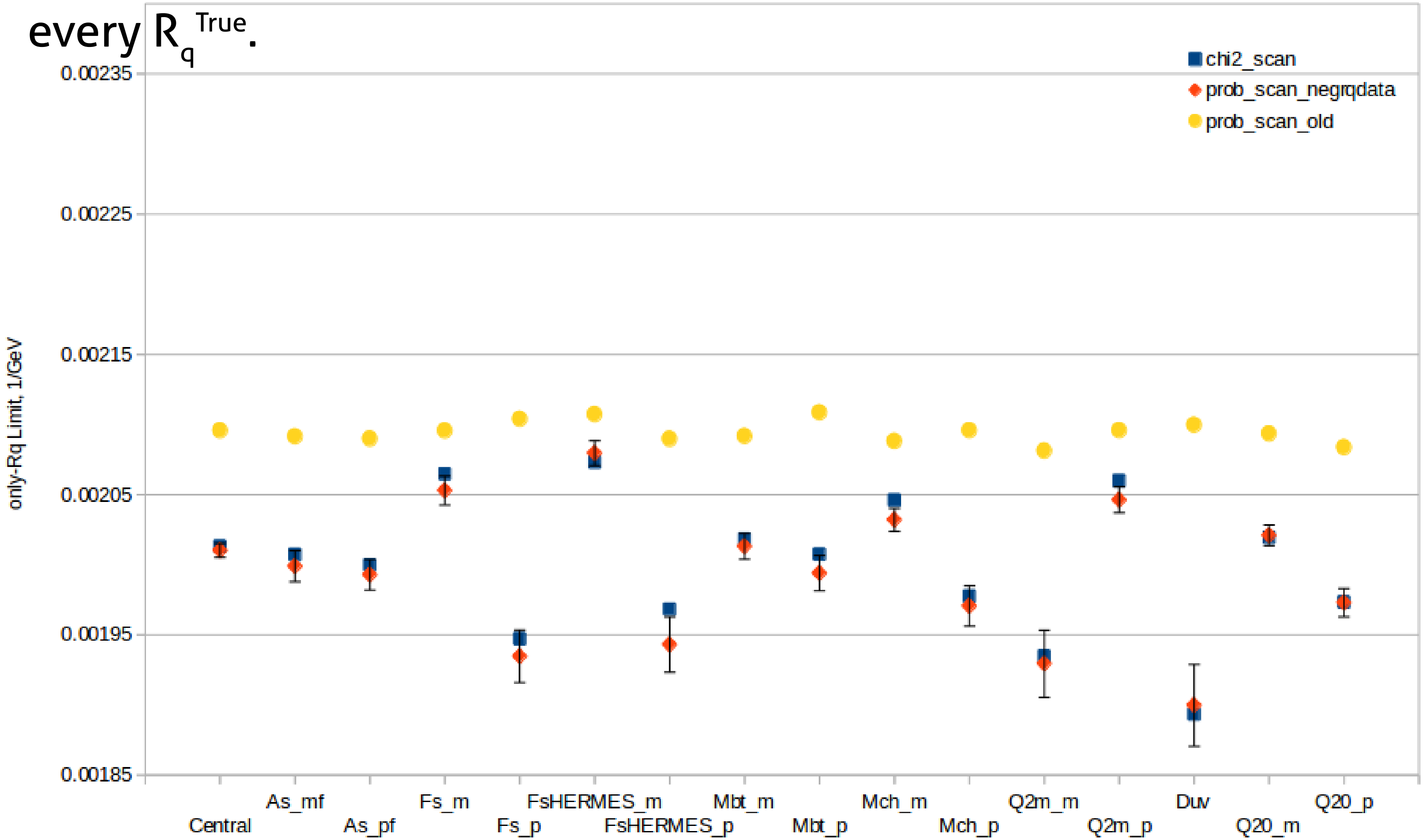


Largest value obtained for $f_{sHERMES}$ lower variation.

95% CL limits on R_q, from MC replicas: R_q-only

R_q-only

Limits estimated using negative $R_q^2{}_{Data}$, but yet with different PDFs for every R_q^{True}.

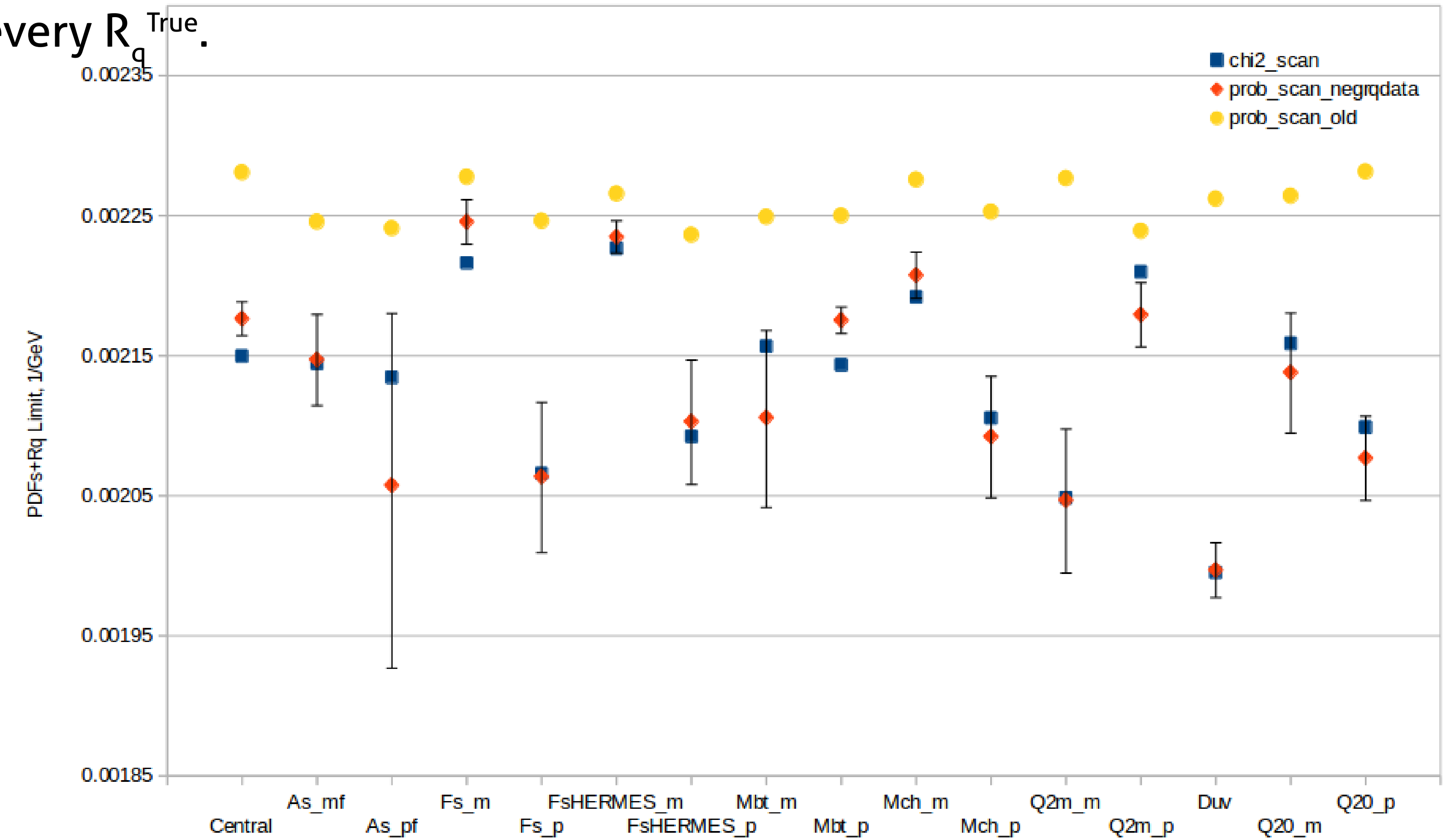


Using negative $R_q^2{}_{Data}$ results in limits improved by about 2 %.

95% CL limits on R_q, from MC replicas: PDFs+R_q

PDFs+R_q

Limits estimated using negative $R_q^{2}{}_{Data}$, but yet with different input PDFs for every R_q^{True}.

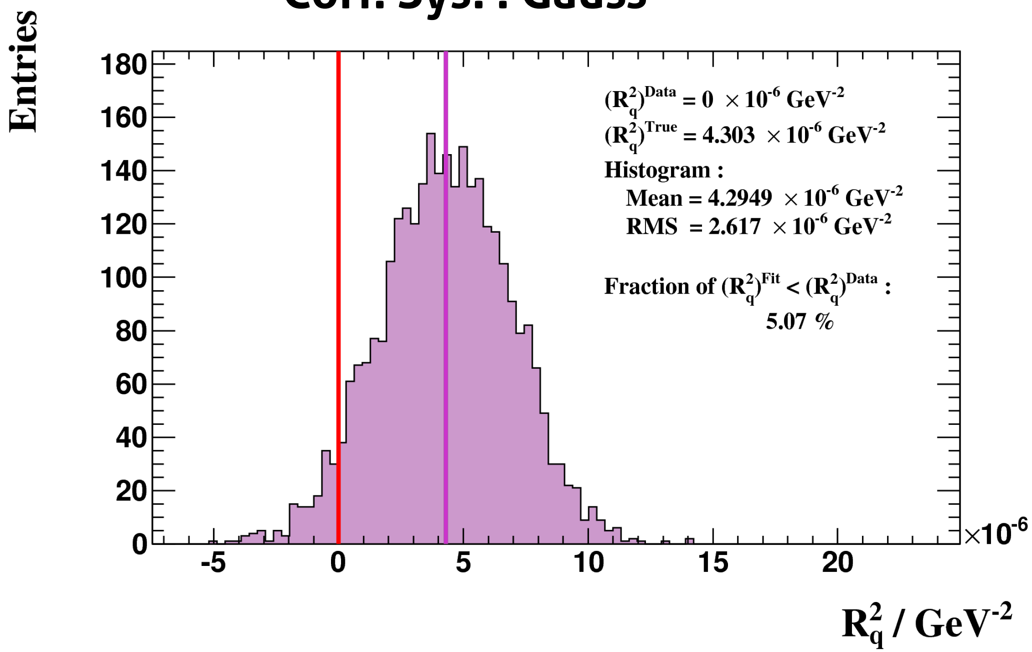


Using negative $R_q^{2}{}_{Data}$ results in limits improved by about 2 %.

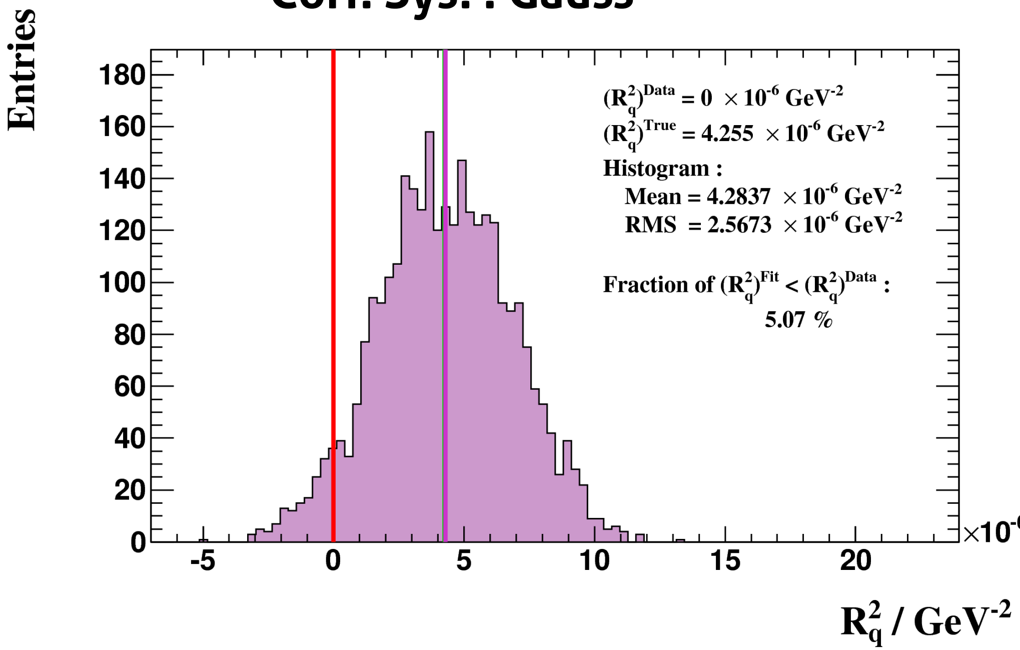
Statistical uncertainty : Poisson vs Gauss

We use normal distribution for smearing MC replica cross sections, but for statistical uncertainties Poisson distribution might be a better option. To compare the effect of both :

Stat. and Uncorr : Gauss
Corr. Sys. : Gauss



Stat. and Uncorr : Poisson
Corr. Sys. : Gauss

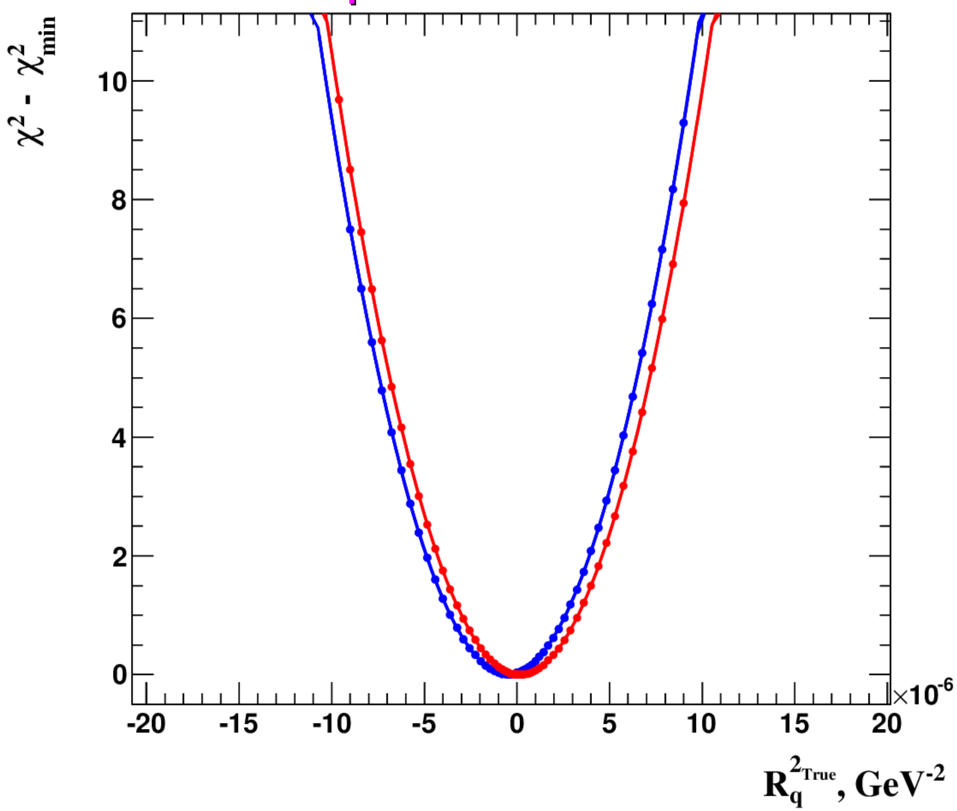


Difference is negligible for limits setting.

Influence of High-Q^2 bins with low statistics

All data points with $N_{obs} < 25$ and $Q^2 > 10000$ GeV^2 (total 14 points) are removed from the data sets and χ^2 scan with standart χ^2 deffinition prepared:

PDFs+R_q



- scan with $N_{obs} < 25$, $Q^2 > 10000$ GeV^2 data points removed.

  $R_q^{Limit} = 2.303 \cdot 10^{-3}$ GeV^{-1}

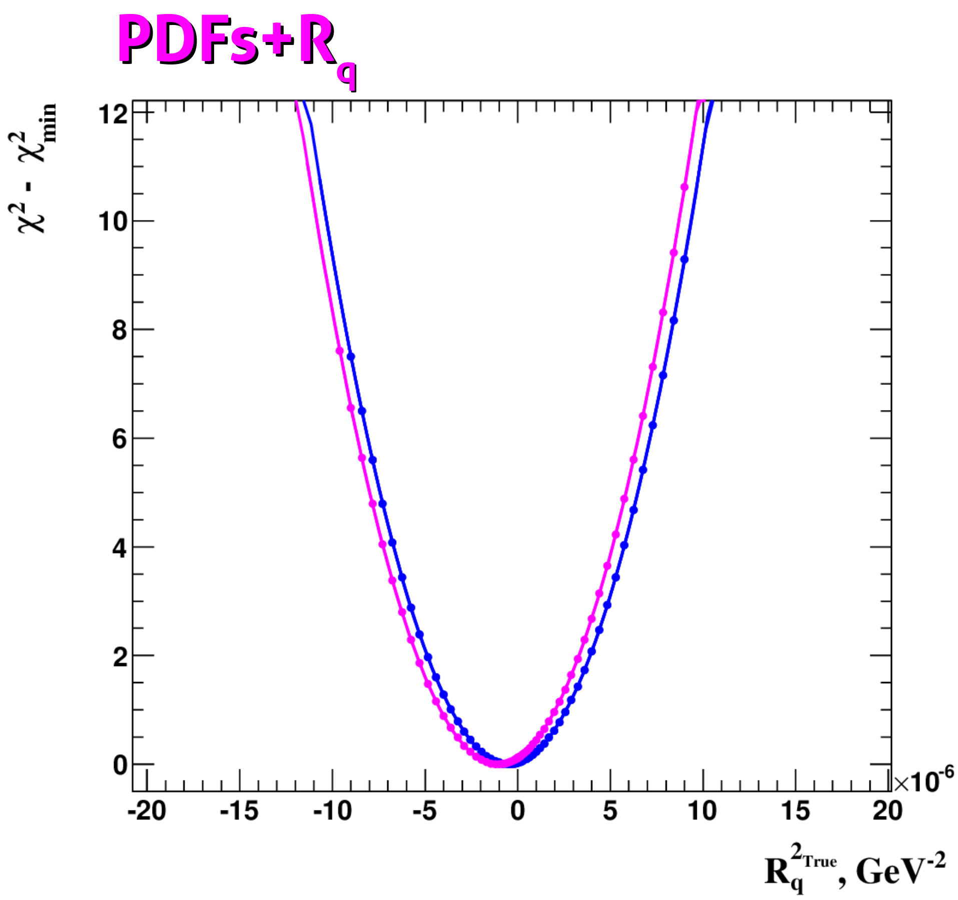
- original scan.

  $R_q^{Limit} = 2.150 \cdot 10^{-3}$ GeV^{-1}

High-Q^2 bins hardly influence the sensitivity (width of the parabola), but do influence the best fit position, and thus final limit.
Limits are sensitive to statistical fluctuations in low statistics bins.

Influence of High-Q^2 bins with low statistics

Data points with $N_{obs} < 25$ and $Q^2 > 10000$ GeV^2 are treated with Poisson statistics.



- scan with Poisson statistics for $N_{obs} < 25$, $Q^2 > 10000$ GeV^2 data points.

  $R_q^{Limit} = 1.999 \cdot 10^{-3}$ GeV^{-1}

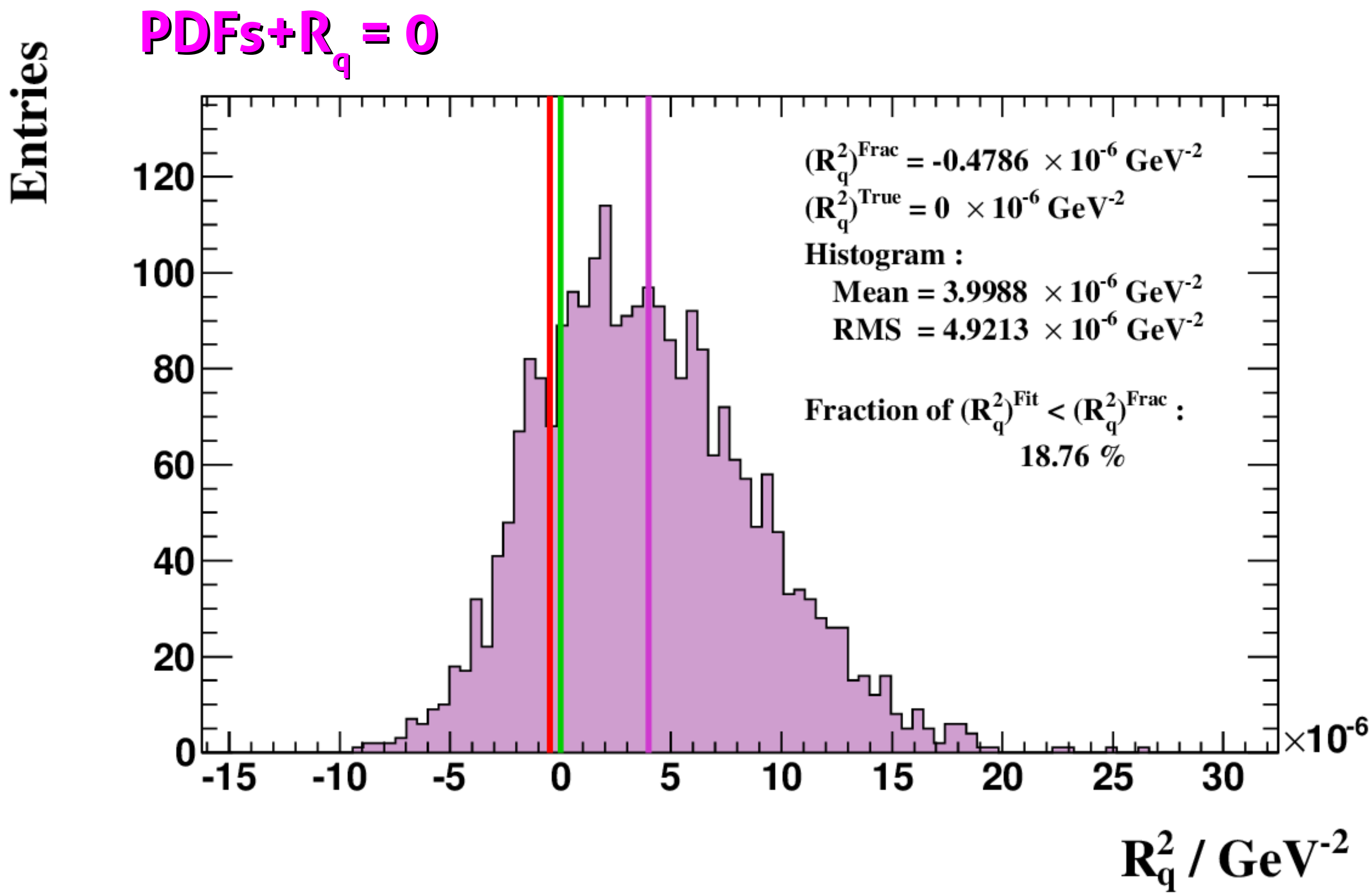
- original scan.

  $R_q^{Limit} = 2.150 \cdot 10^{-3}$ GeV^{-1}

Using Poisson statistics results in stronger limit estimates with χ^2 method.

Influence of High-Q^2 bins with low statistics

MC replicas for data points with N_{obs} < 25 and Q^2 > 10000 GeV^2 are generated with Poisson statistics and treated with Poisson χ^2 deffinition.

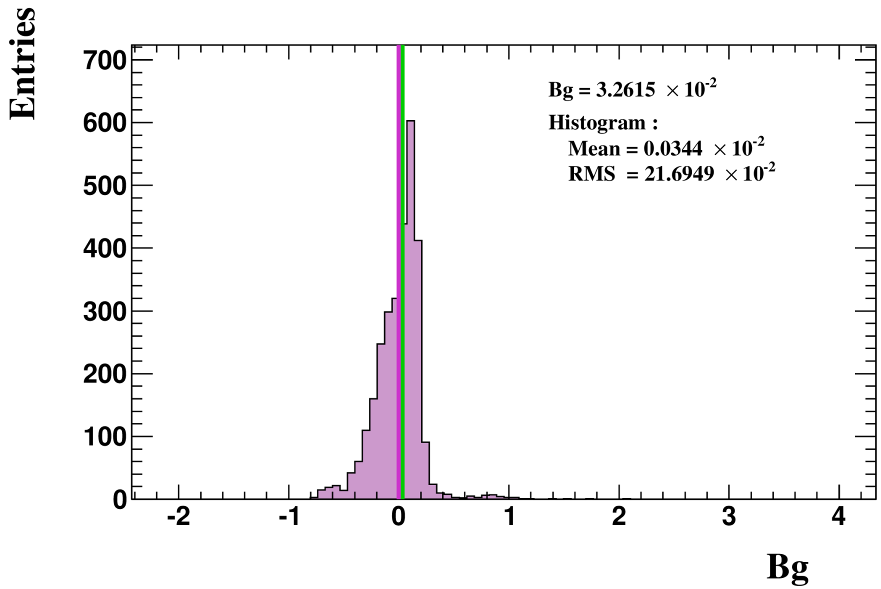


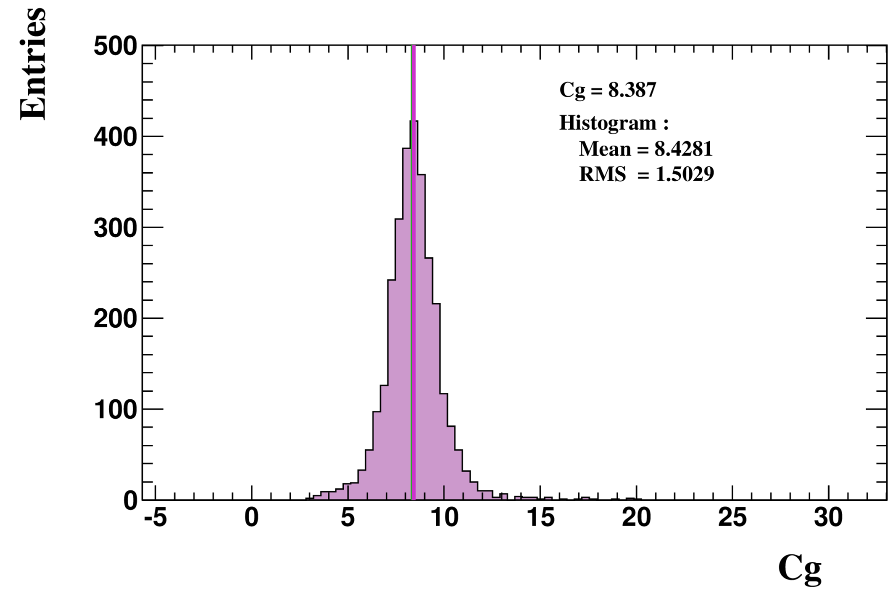
Unfortunately, using Poisson statistics results in significant biases in fit results.

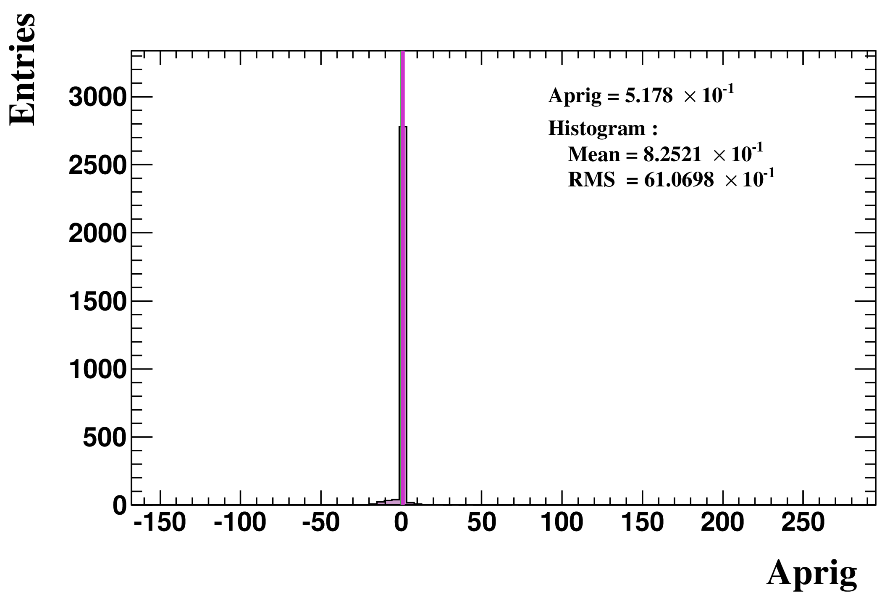
Comments for EBO

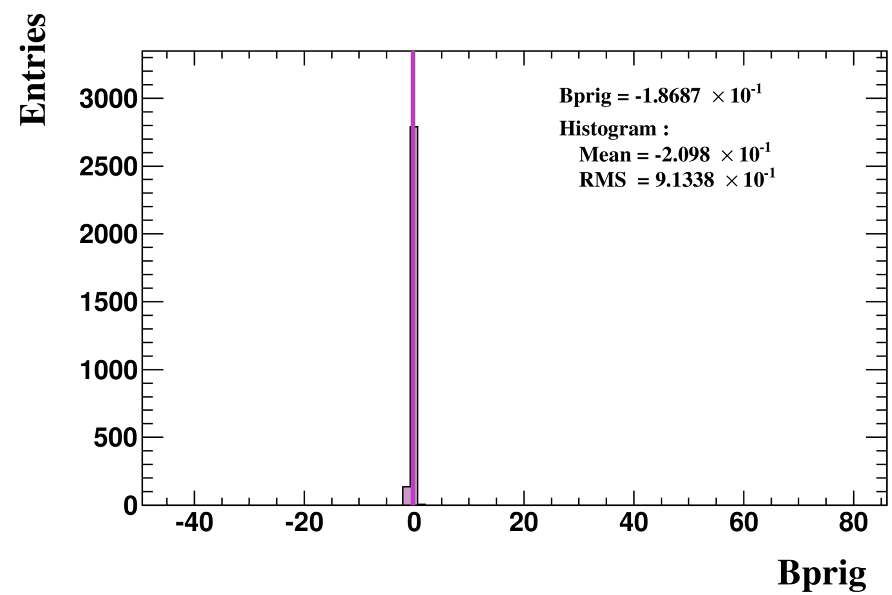
- ➔ Using negative $R_q^2{}_{Data}$ in limit setting improves the limits by 2 %.
- ➔ Changing the way replicas are generated has negligible effect on limits.
- ➔ Replicas generation for the selected model variations is being repeated with the new generation method, final results expected soon.
- ➔ Statistical treatment of high-Q^2 bins with low statistics does influence the obtained limits at the ~7% level.
- ➔ We propose using the standard χ^2 definition also for low statistics bins, as:
  - ► cross sections were combined assuming Gaussian errors;
  - ► we are not able to use actual event numbers, only estimates;
  - ► using Poisson probability results in significant biases in fit results.

MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1213 \cdot 10^{-3}$ GeV^{-1}:









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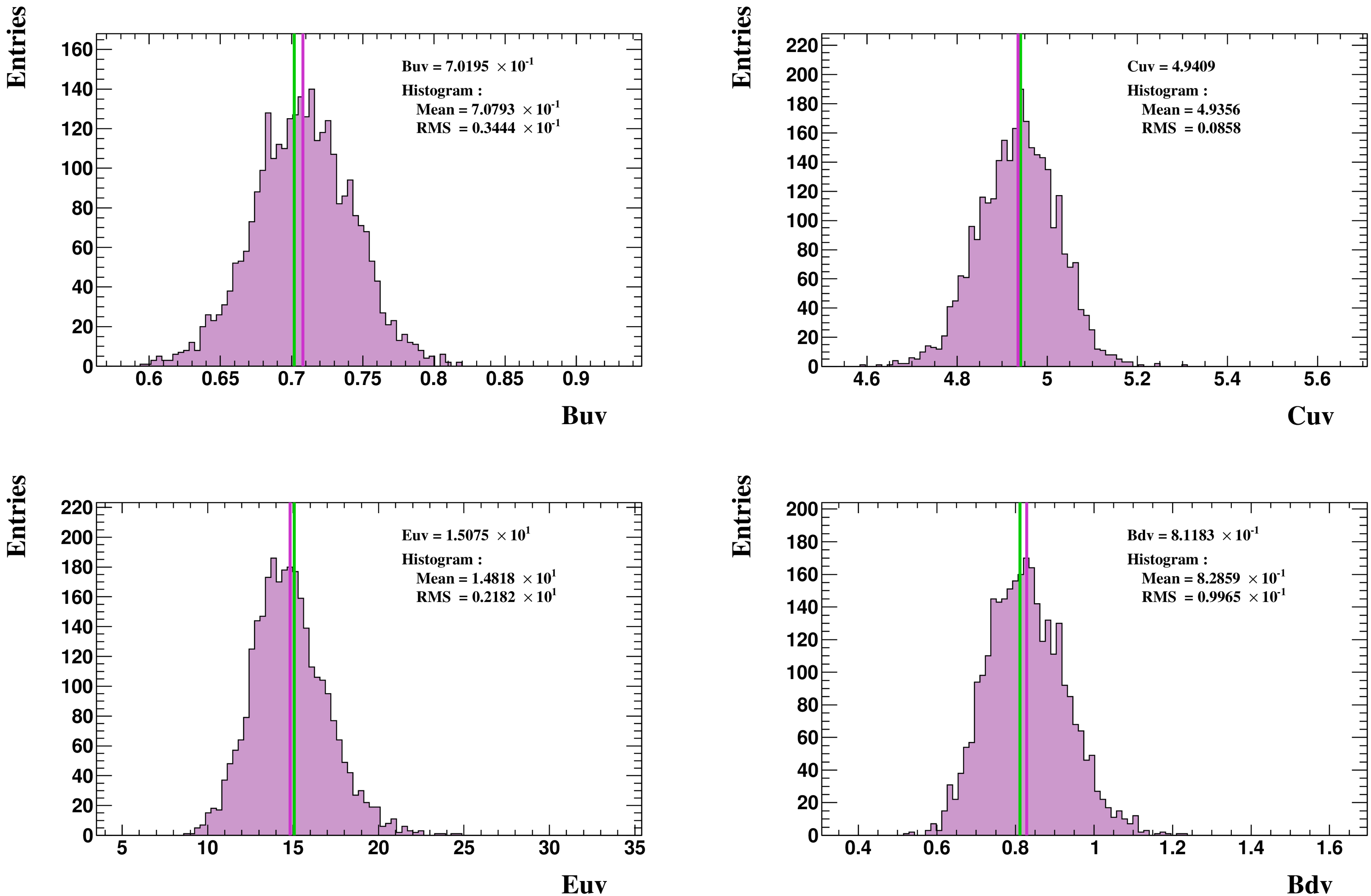

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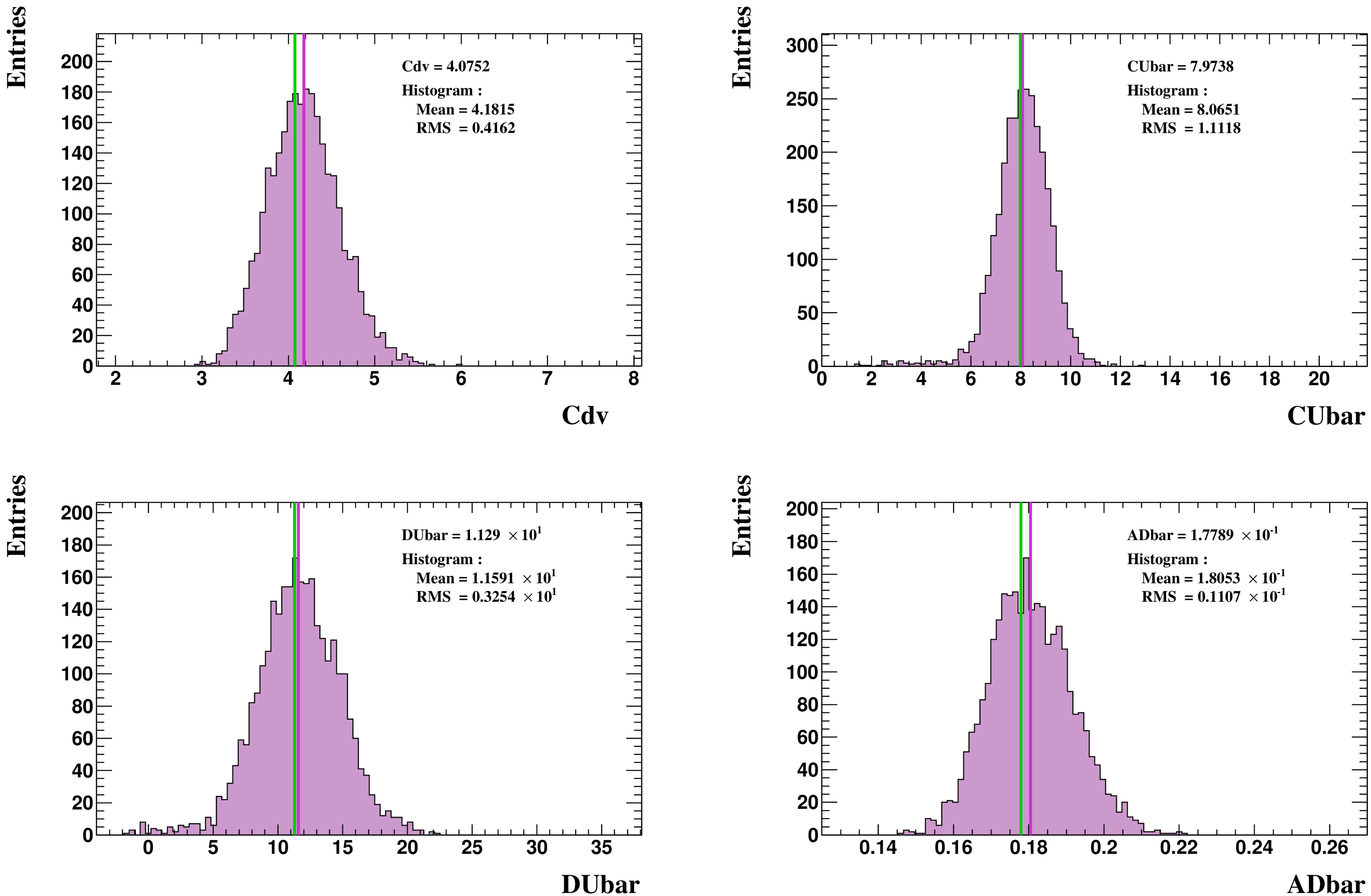

MC replicas PDFs distributions for central variant with $R_q^{True} = 2.1213 \cdot 10^{-3}$ GeV^{-1}: