# Nuclear PDFs at the LHC and beyond

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Universidade de Santiago de Compostela

Nuclei at the FHC
CERN - December - 2013

@CASSalgado @HotLHC

European Research Council
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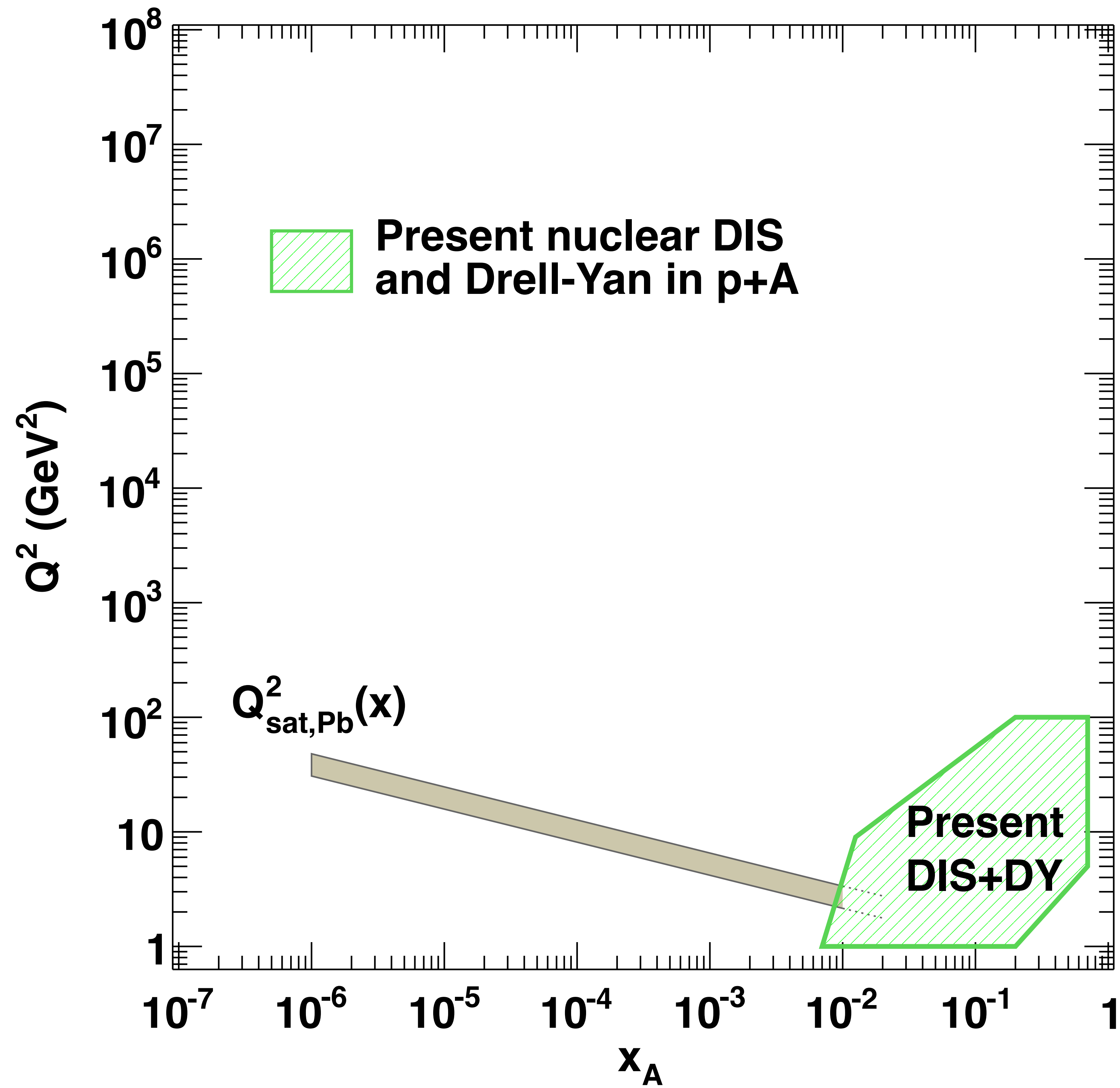
## Disclaimer

*Very little time to prepare this talk: Slides mostly taken from other (older) talks and/or stolen from other people [especially Pia Zurita and Hannu Paukkunen - they've agreed, so thanks :)]*

*[I hope this is good enough for this first informal meeting]*

# Kinematical reach in nuclear collisions



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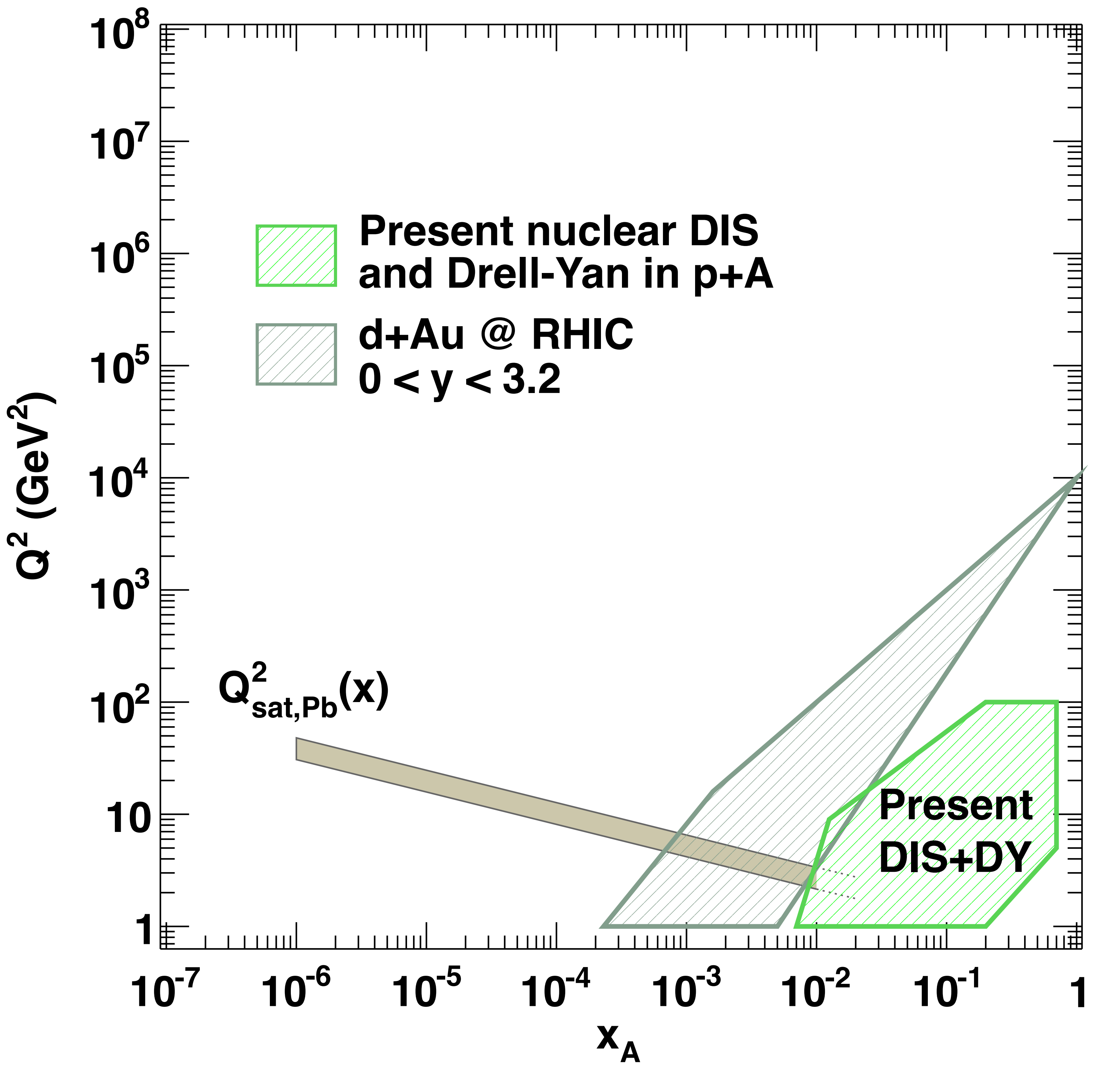

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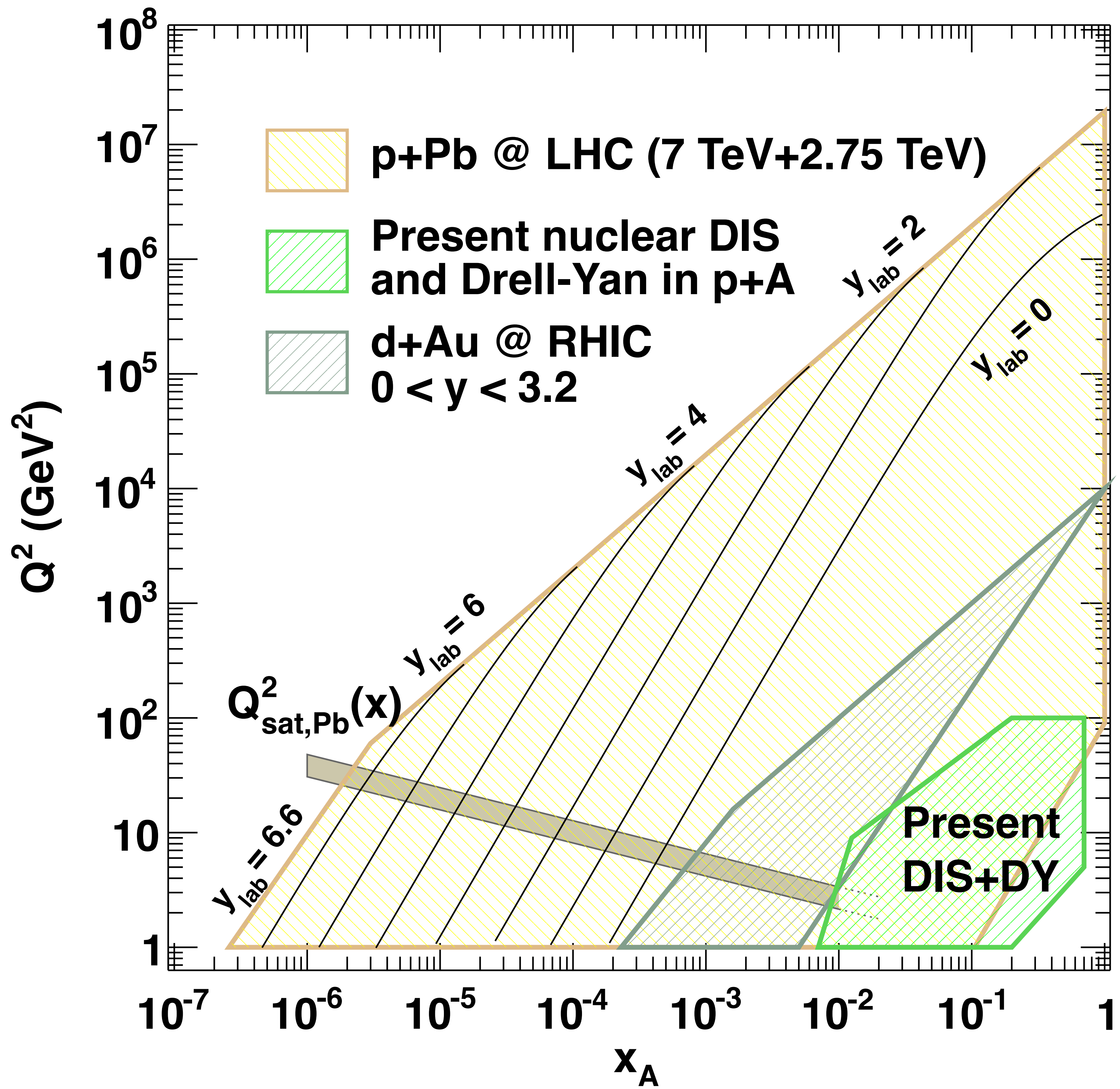

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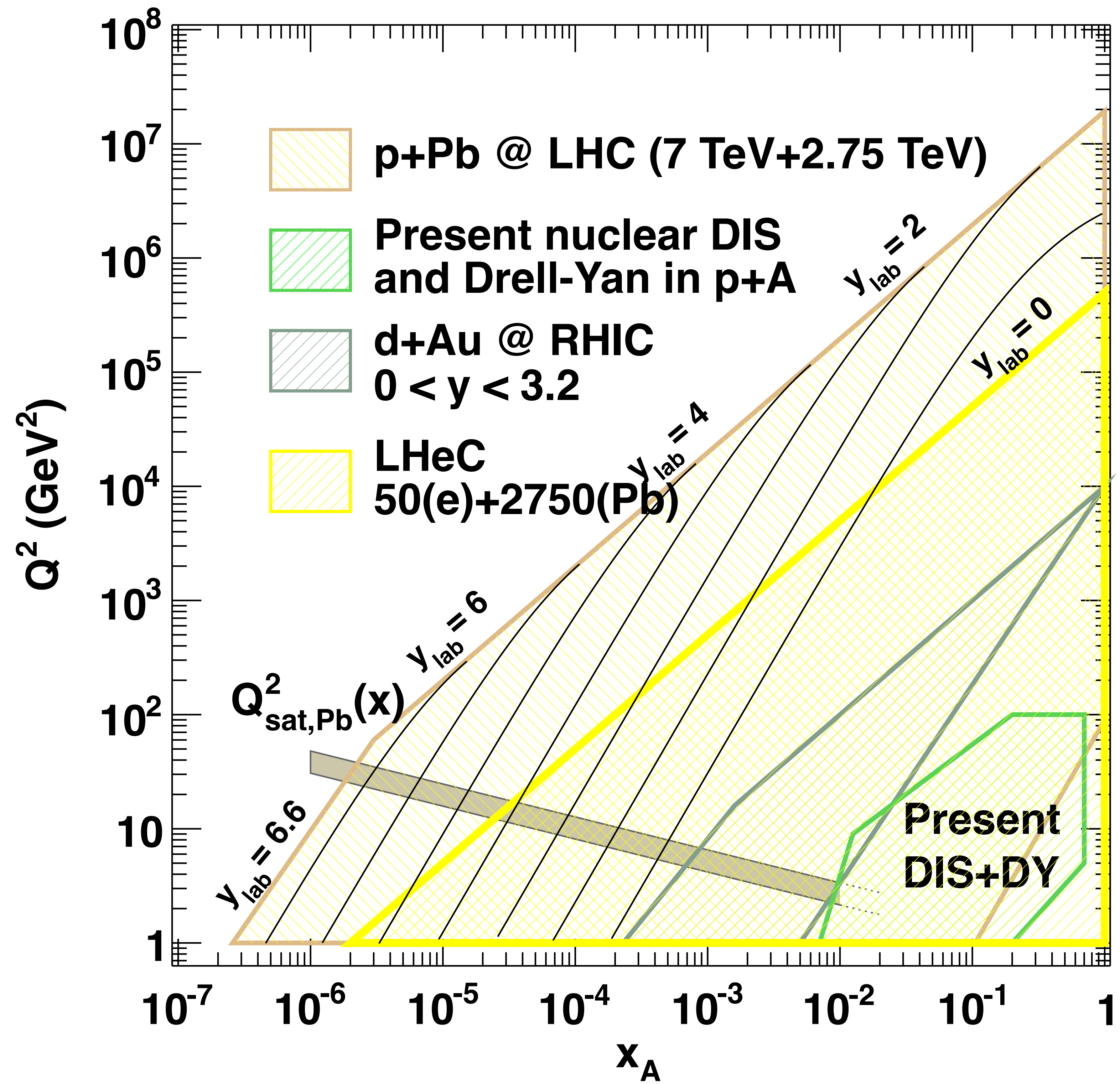

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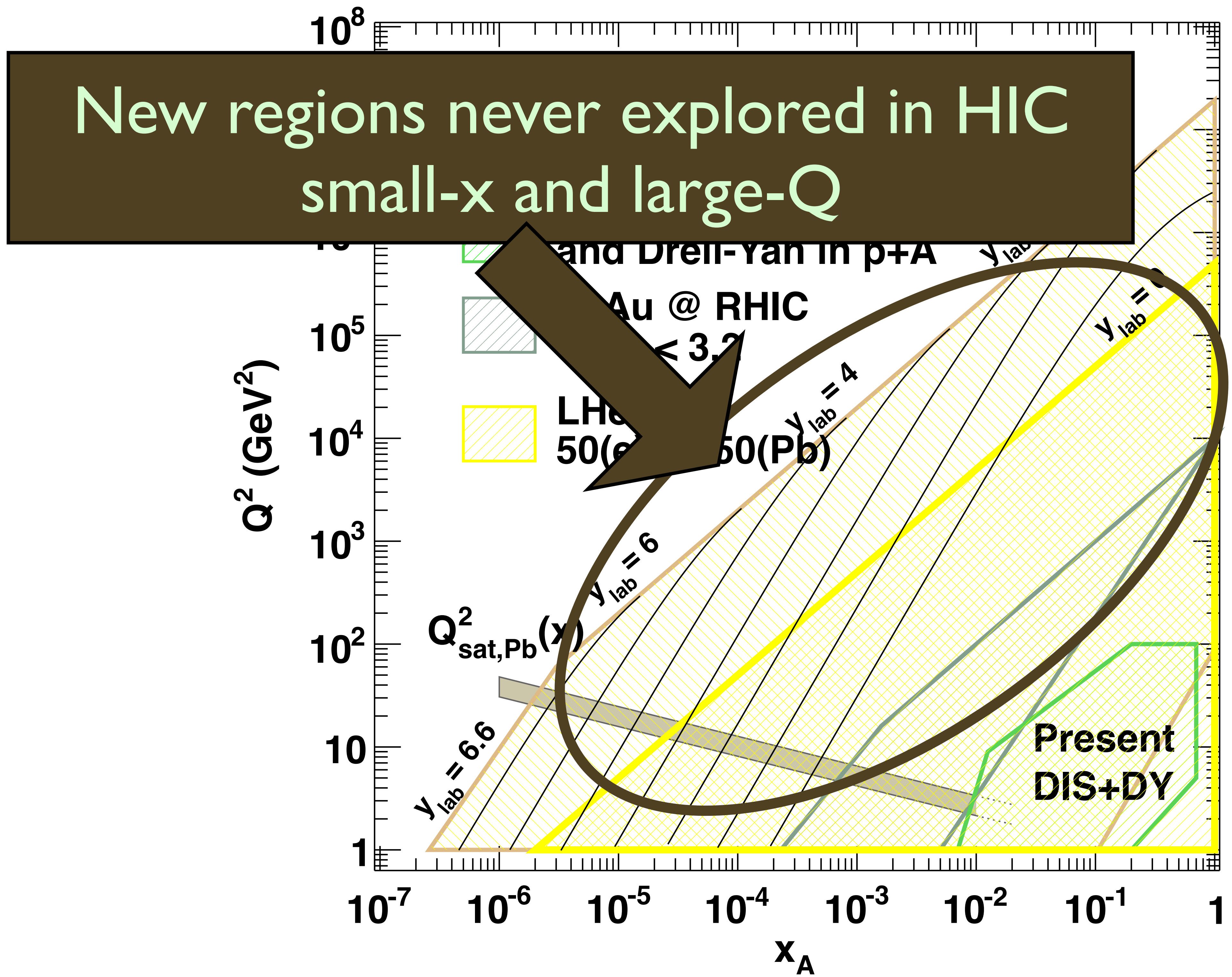

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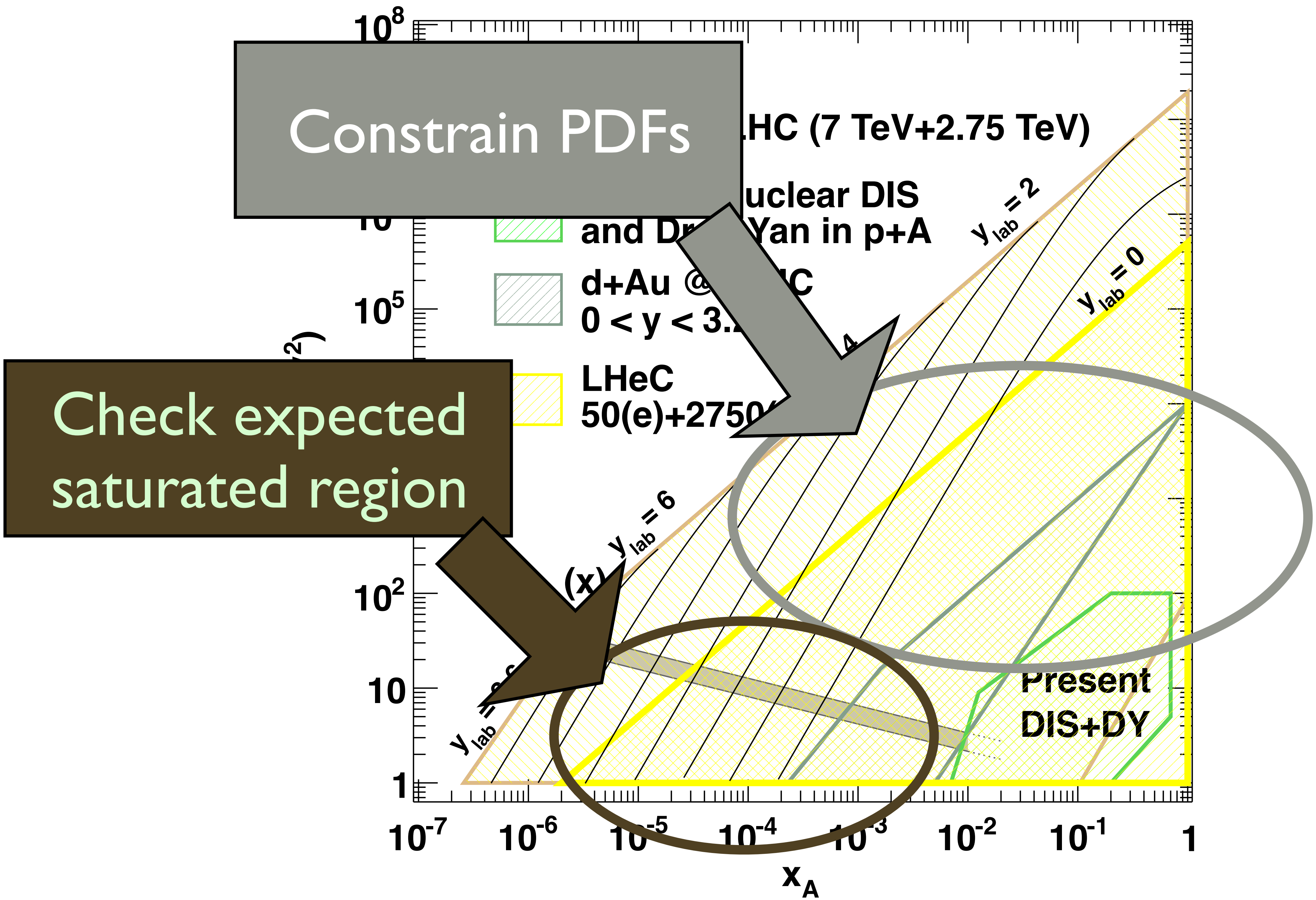

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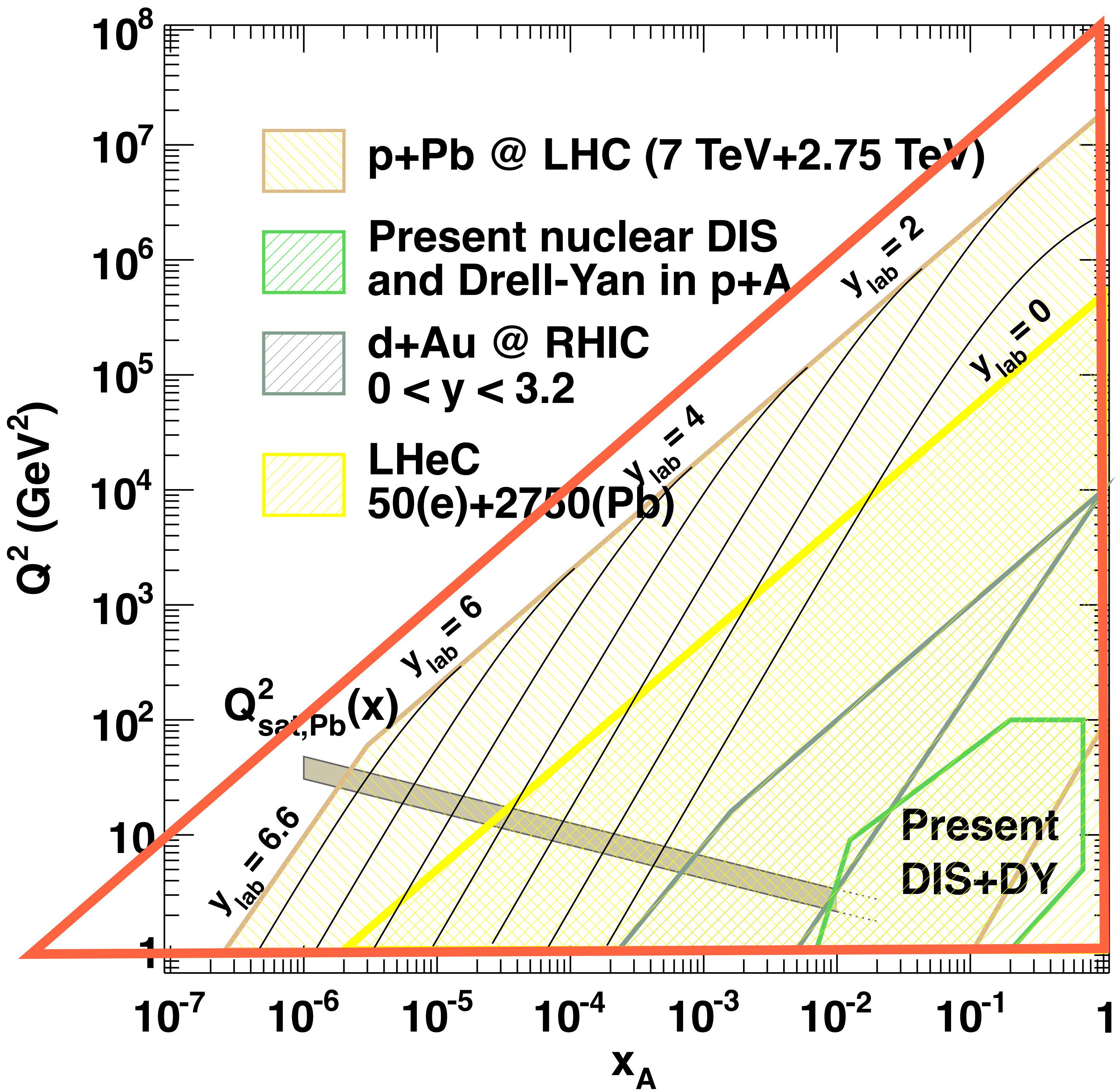
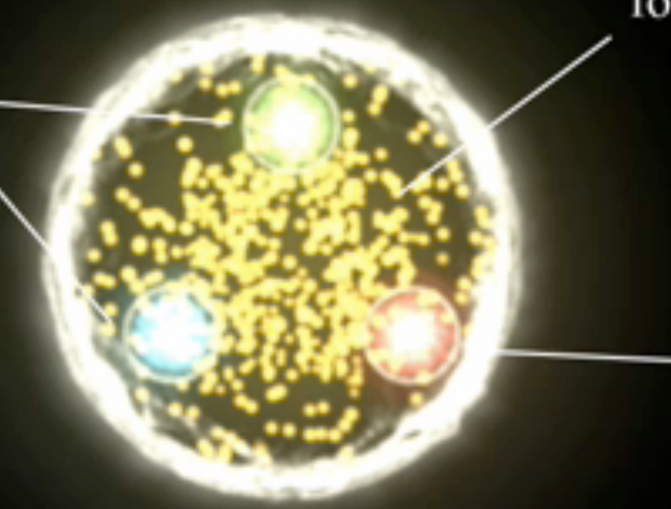



**Assuming 50+20 FHC**

$x_{\rm FCC} \sim x_{\rm LHC}\, e^{-2}$

# *Why proton-nucleus?*

*[To study the structure of a large object make collisions with smaller objects (Rutherford experiment...)]*




**The proton structure is constrained by DIS + other data**

— *HERA data of utmost importance*

***Need pA to study the high-energy nuclear structure***

— *DIS data is old (90's) short number and with limited range*

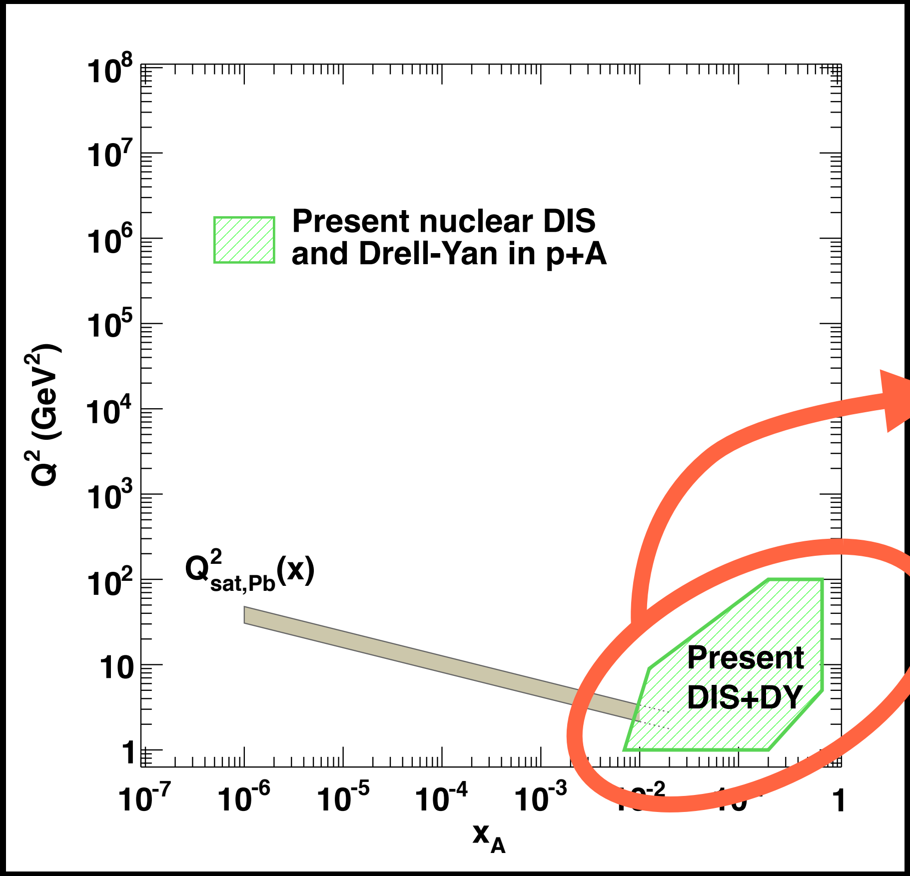
— *pA@LHC is the only experimental condition available before an eventual lepton-A collider (LHeC, eRHIC?)*

— *Needed as benchmark for the AA program*

— *High-density effects (saturation) enhanced in nuclei*

# nPDFs: global analyses. Status

- Main goals
  - Check the factorization of nPDFs for hard processes
  - Fix the benchmark for HI hot matter or saturation




EKS98 [Eskola, Kolhinen, Ruuskanen, Salgado 1998]

HKM [Hirai, Kumano, Miyama, 2001]

nDS [de Florian, Sassot, 2003]

HKN [Hirai, Kumano, Nagai, 2004; 2007]

EPS08, EPS09 [Eskola, Paukkunen, Salgado, 2008; 2009]

Also FGS [2004-2010]; Kovarik *et al.* [2011]

# The contemporary NLO nPDF fits

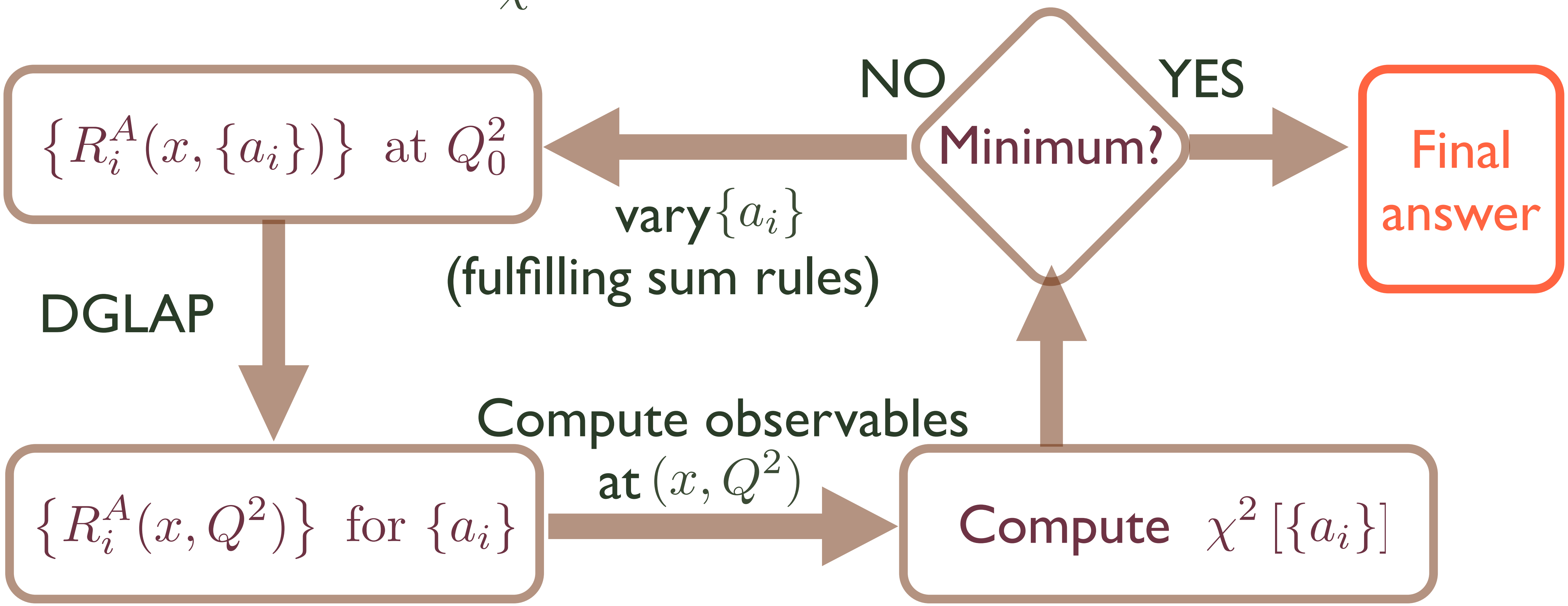
$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

| | HKN07 | EPS09 | DSSZ | nCTEQ prelim. |
|---|---|---|---|---|
| Ref. | Phys. Rev. C76 (2007) 065207 | JHEP 0904 (2009) 065 | Phys.Rev. D85 (2012) 074028 | arXiv:1307.3454 |
| Order | LO & NLO | LO & NLO | NLO | NLO |
| Neutral current e+A / e+d DIS | √ | √ | √ | √ |
| Drell-Yan dileptons in p+A / p+d | √ | √ | √ | √ |
| RHIC pions in d+Au / p+p | | √ | √ | |
| Neutrino-nucleus DIS | | | √ | |
| $Q^2$ cut in DIS | 1GeV | 1.3GeV | 1GeV | 2GeV |
| # of data points | 1241 | 929 | 1579 | 708 |
| Free parameters | 12 | 15 | 25 | 17 |
| Error sets available | | √ | √ | √ |
| Error tolerance $\Delta\chi^2$ | 13.7 | 50 | 30 | 35 |
| Baseline | MRST98 | CTEQ6.1 | MSTW2008 | CTEQ6M |
| Heavy quark treatment | ZM_VFNS | ZM_VFNS | GM_VFNS | GM_VFNS |

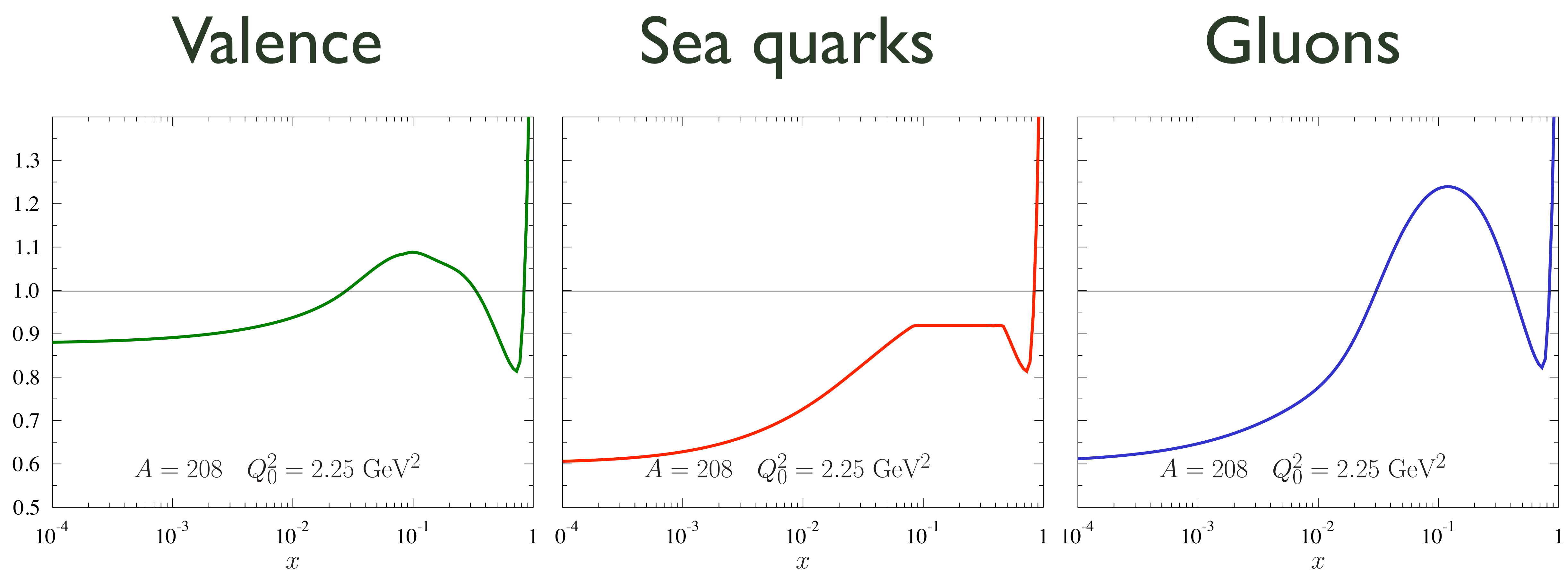
Stolen from Hannu Paukkunen at JLab Oct 2013

# How?: follow free proton approach

- Cross sections computed in collinear factorization
- Define $$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$
- Using a known set for free protons (CTEQ, MRST....)
- and DGLAP evolution of the nuclear and free proton PDFs
- Find the minimum of $\chi^2$

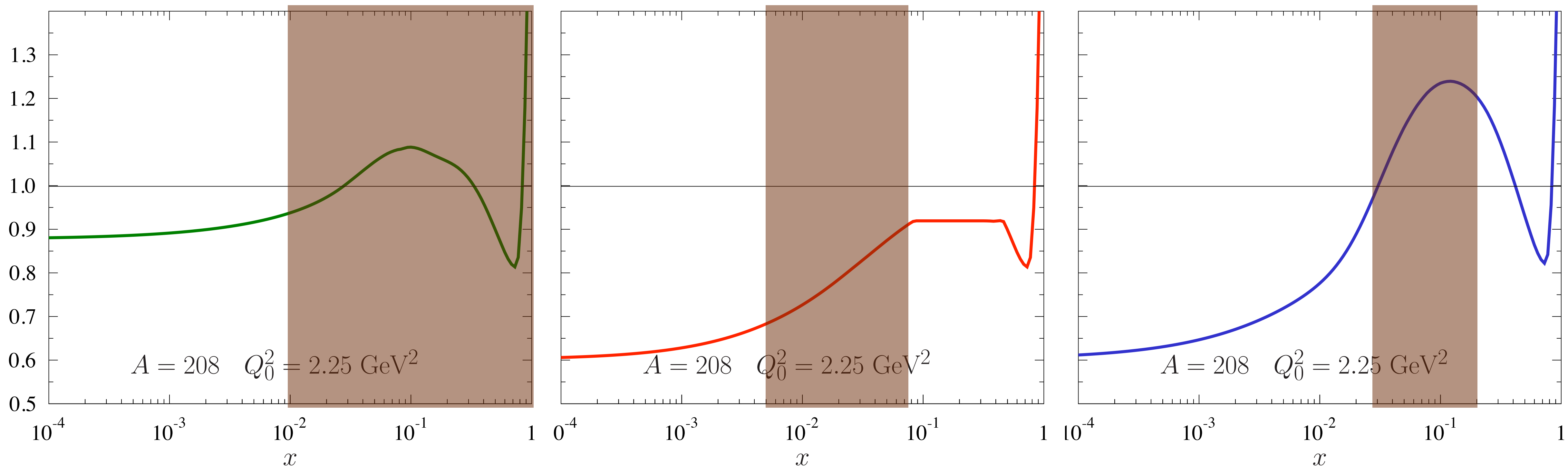


# Approximate ranges and constrains in EPS09



# Approximate ranges and constrains in EPS09

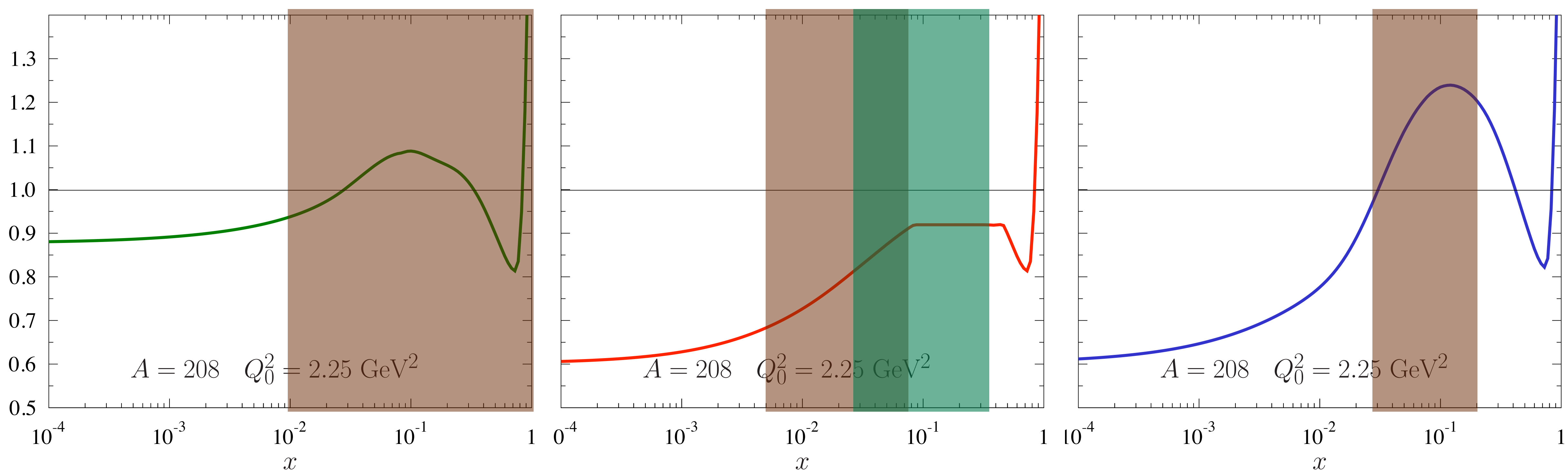
Valence    Sea quarks    Gluons




Constrained by DIS

# Approximate ranges and constrains in EPS09

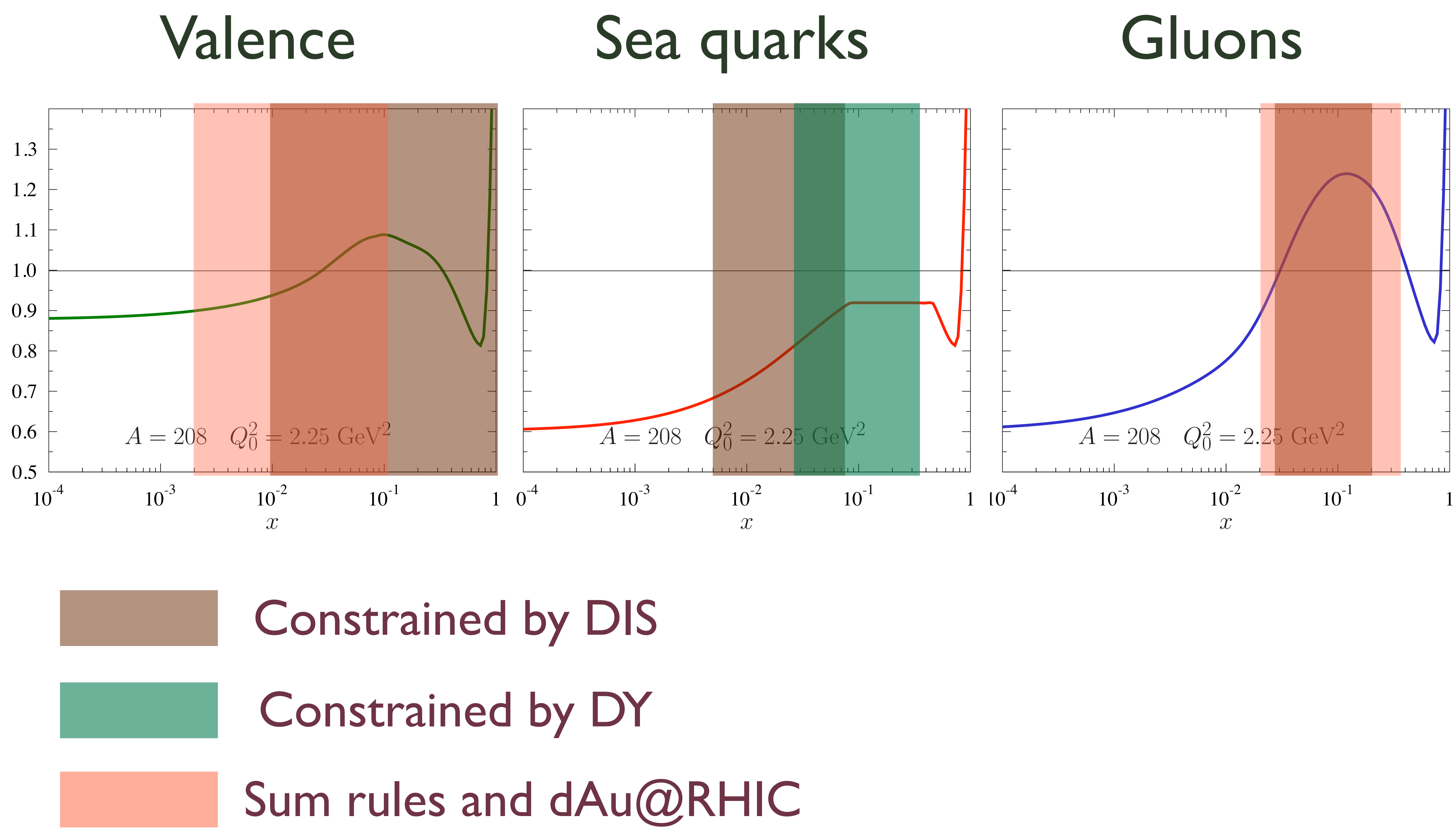
Valence | Sea quarks | Gluons




Constrained by DIS

Constrained by DY

# Approximate ranges and constrains in EPS09



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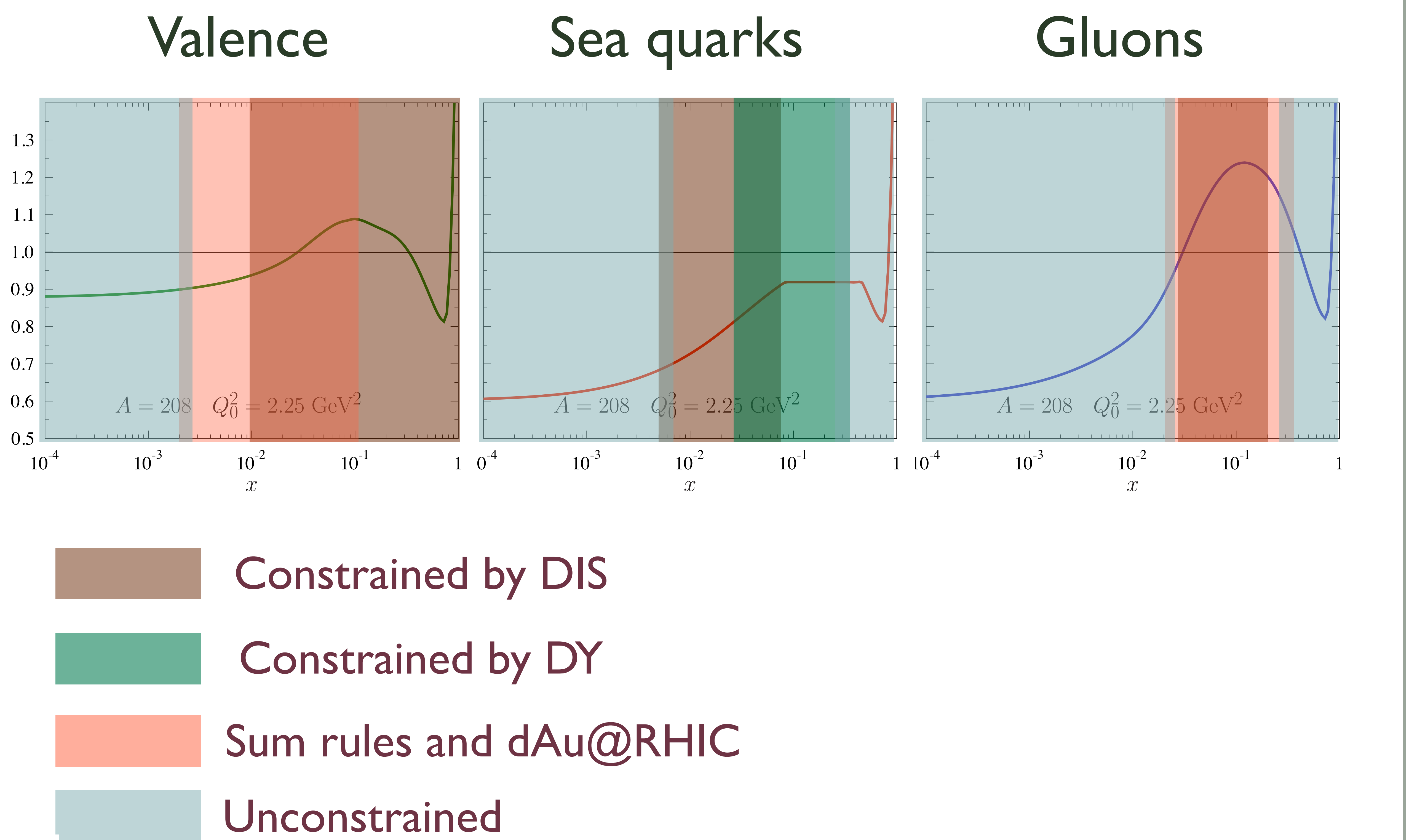

# Approximate ranges and constrains in EPS09

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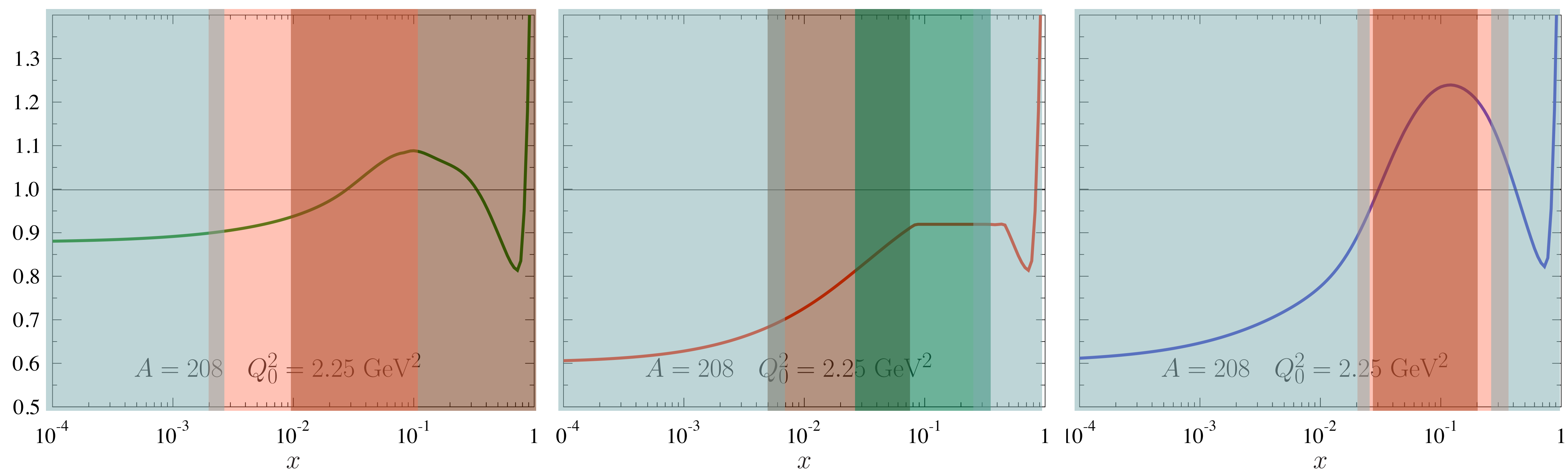



Constrained by DIS

Constrained by DY

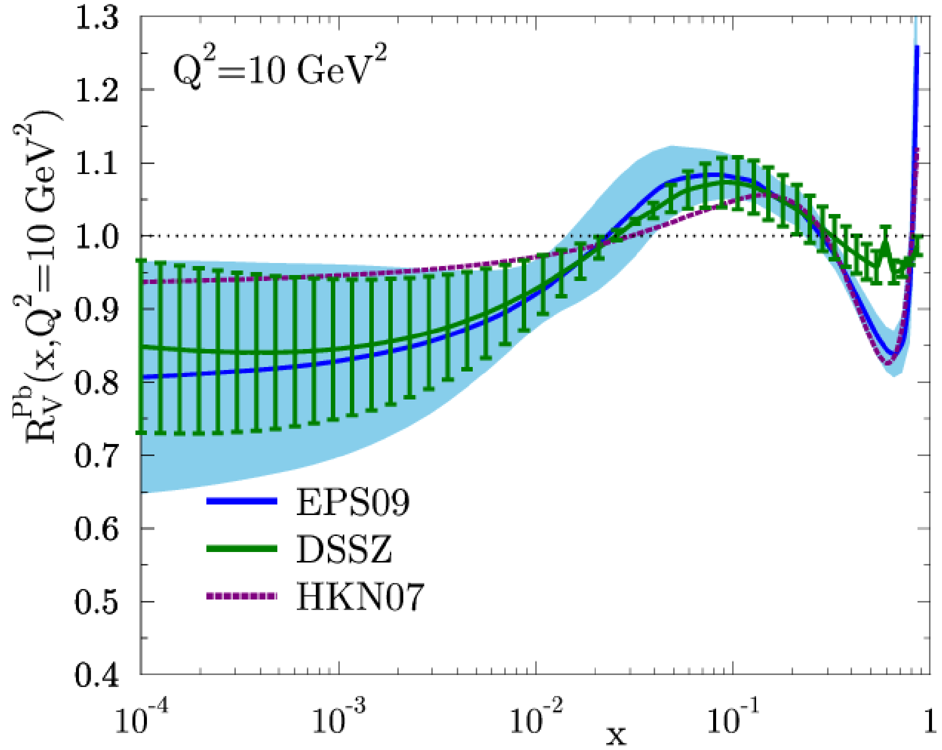
Sum rules and dAu@RHIC

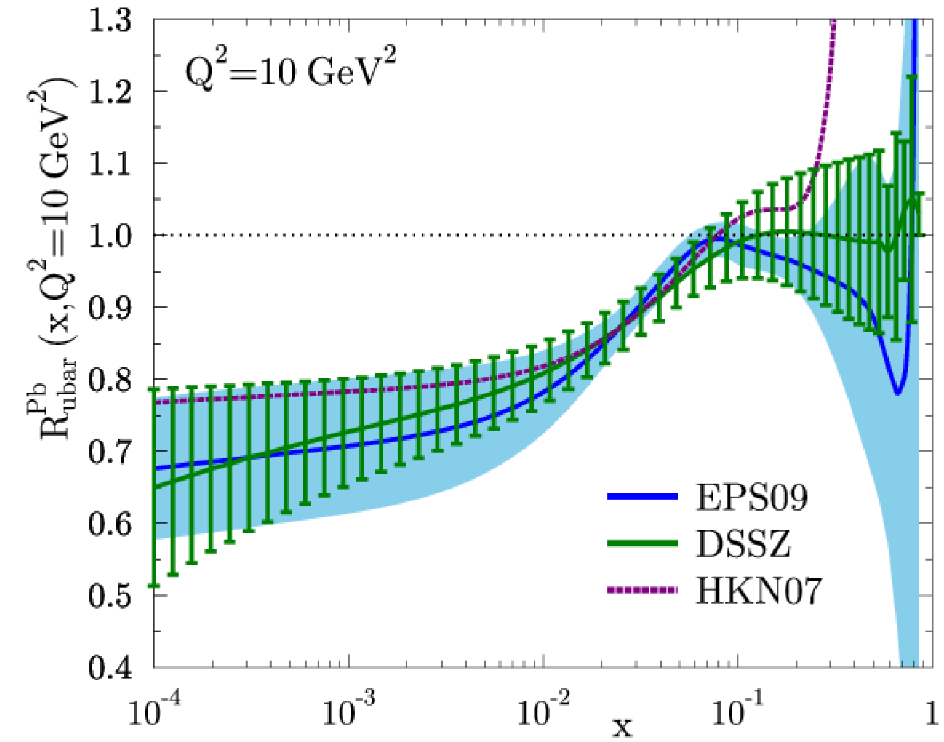
Unconstrained

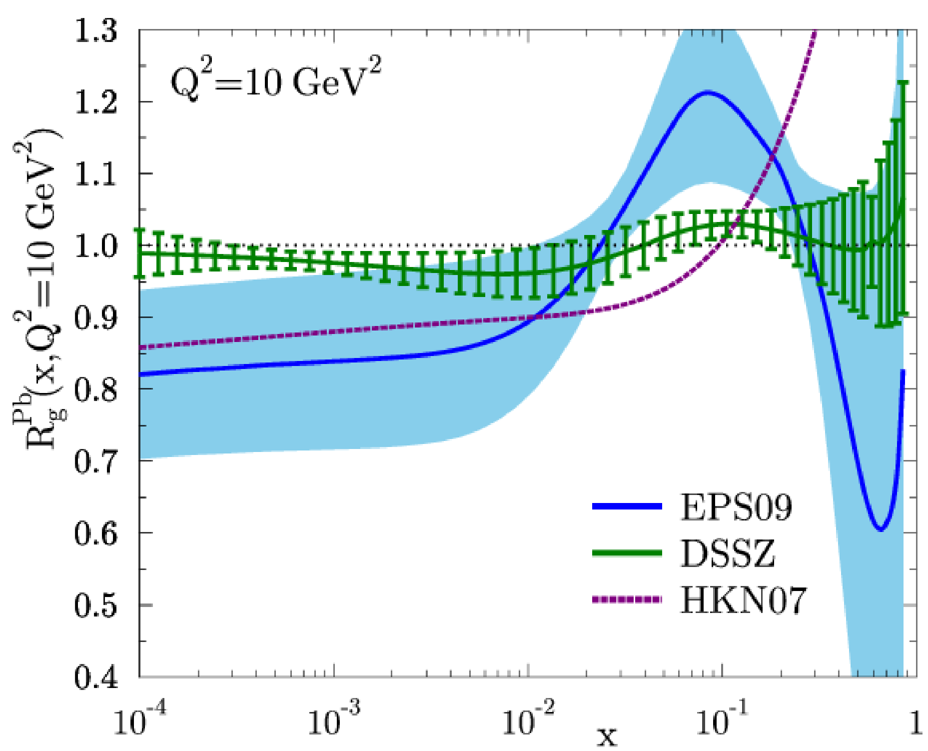
[these ranges are very approximative...
but valid in general for other analyses]

# Comparison

Plots Stolen from Hannu

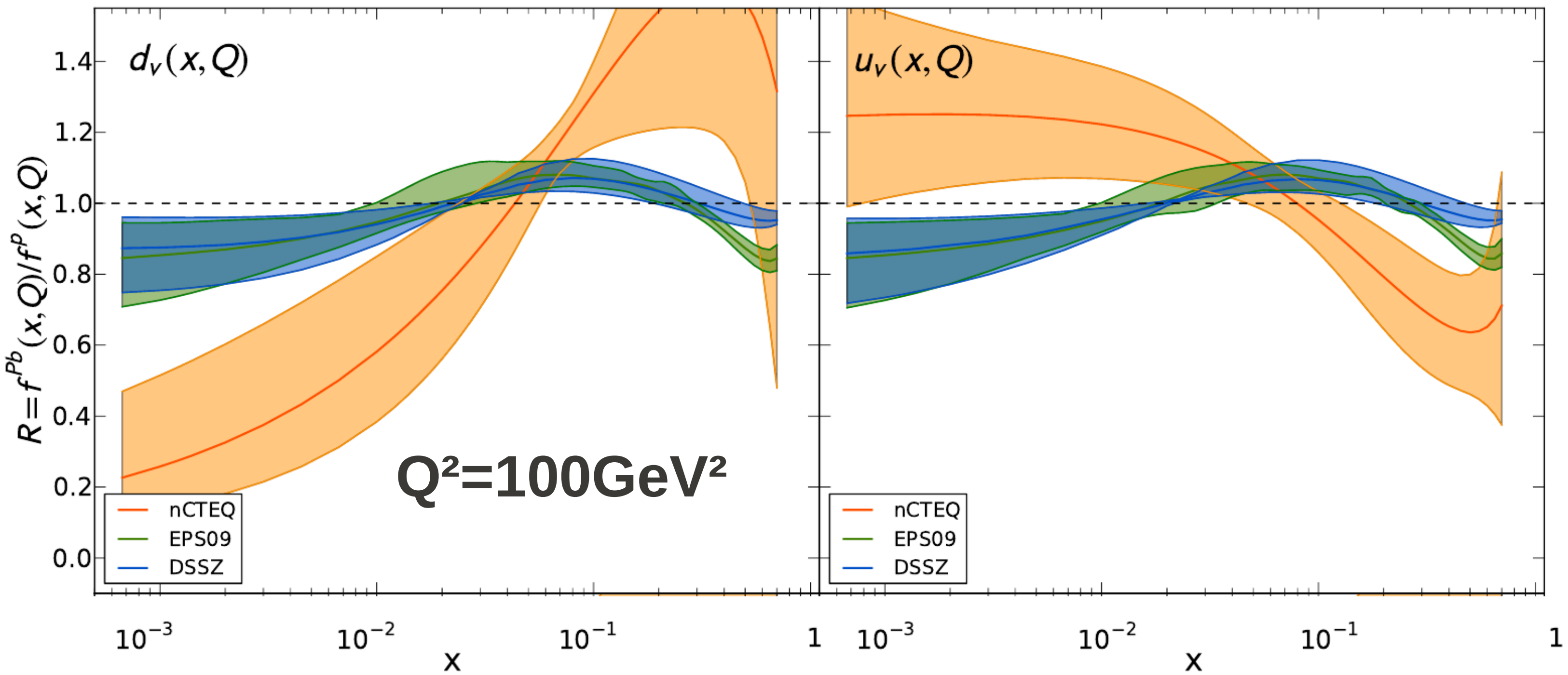


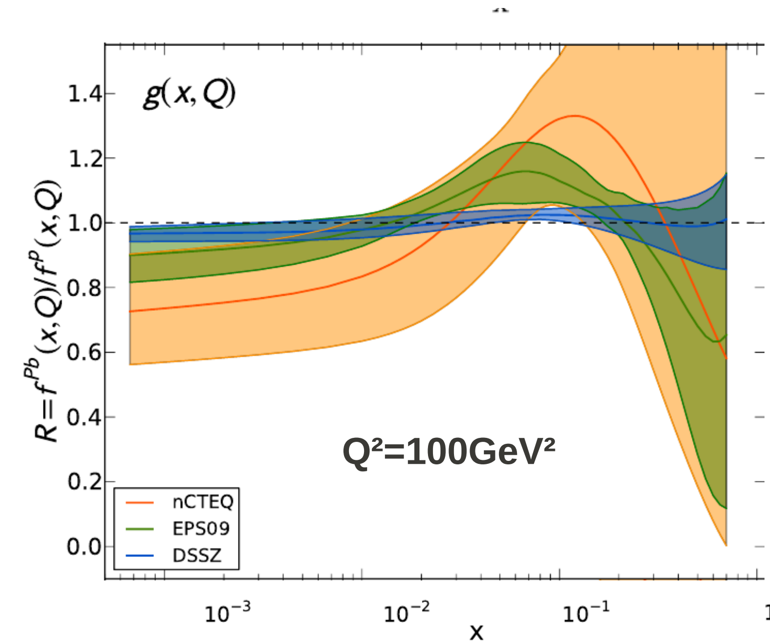



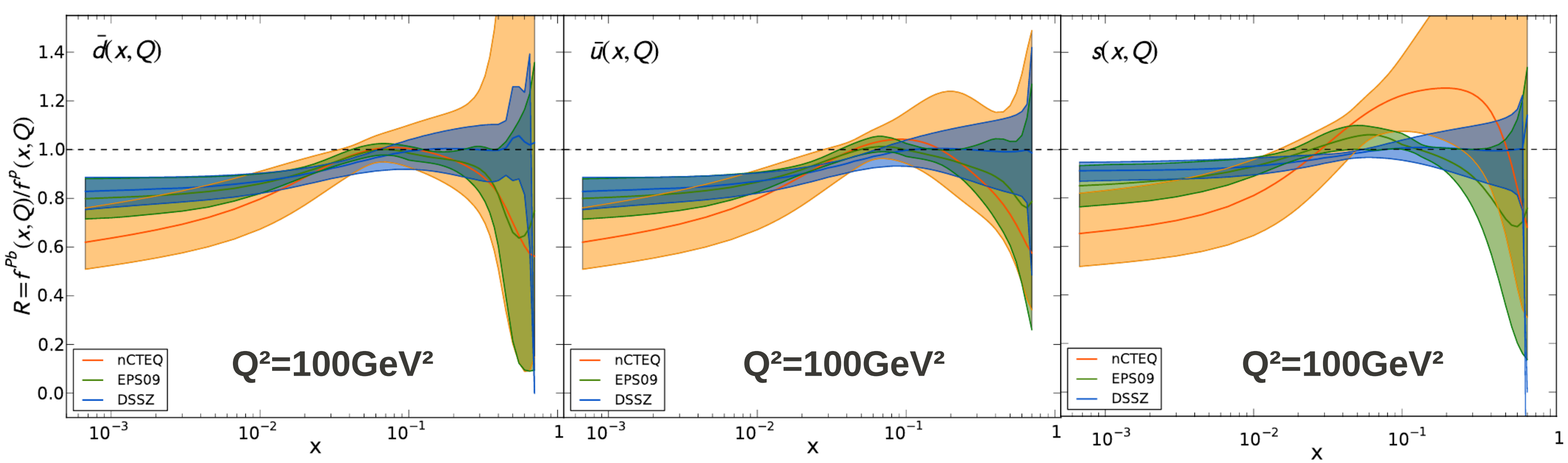

- *Sea and valence quarks are similar (except at large-x)*
- *Gluons different -- unconstrained + different assumptions and sets of data*

# nCTEQ is special




Plots Stolen from Hannu




**But these results are preliminary, only shown in conferences, not published**

# Neutrinos: Paukkunen & Salgado

*Phys.Rev.Lett. 110 (2013) 212301*

- An excellent agreement with e.g. CTEQ6.6+EPS09 nuclear PDFs

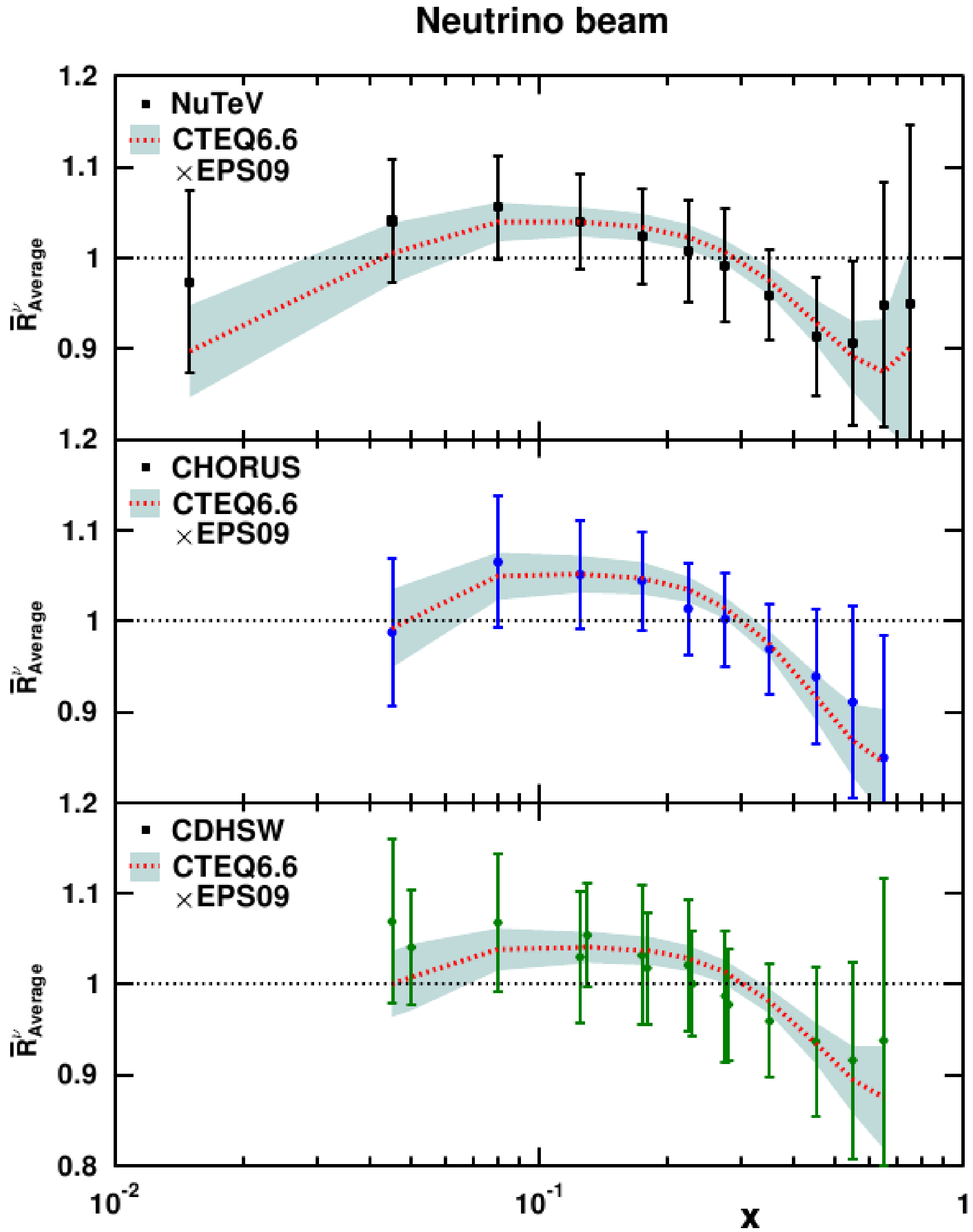
- A novel PDF re-weighting (not the NNPDF one) method was devised to reinforce the compatibilty

  With the normalization, OK

  Without the normalization the result of nCTEQ was “recovered” (for the NuTeV data).

- No reason to believe that the factorization would be violated.

- Points to an underestimation of the experimental errors (NuTeV)




Stolen from Hannu

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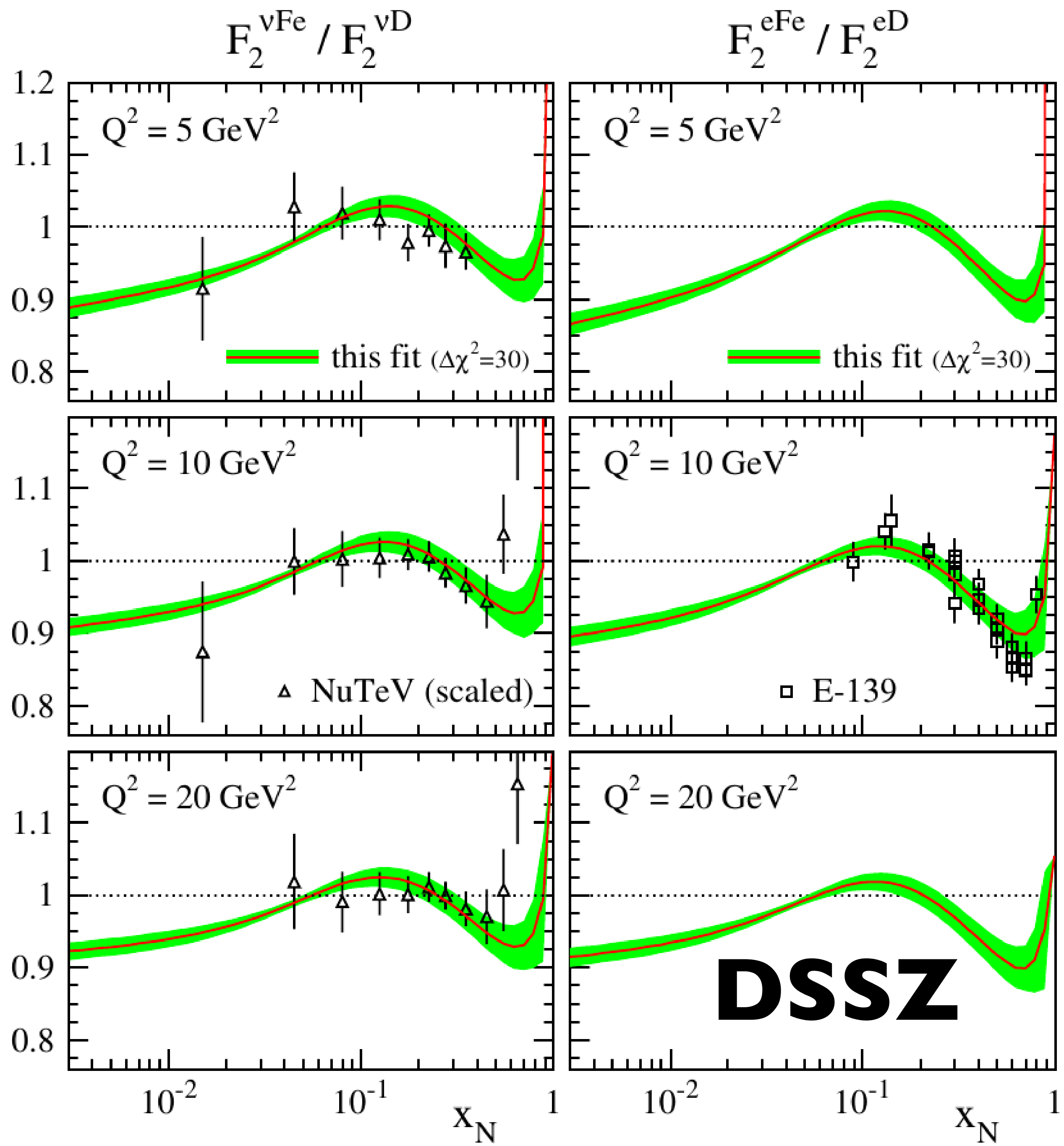
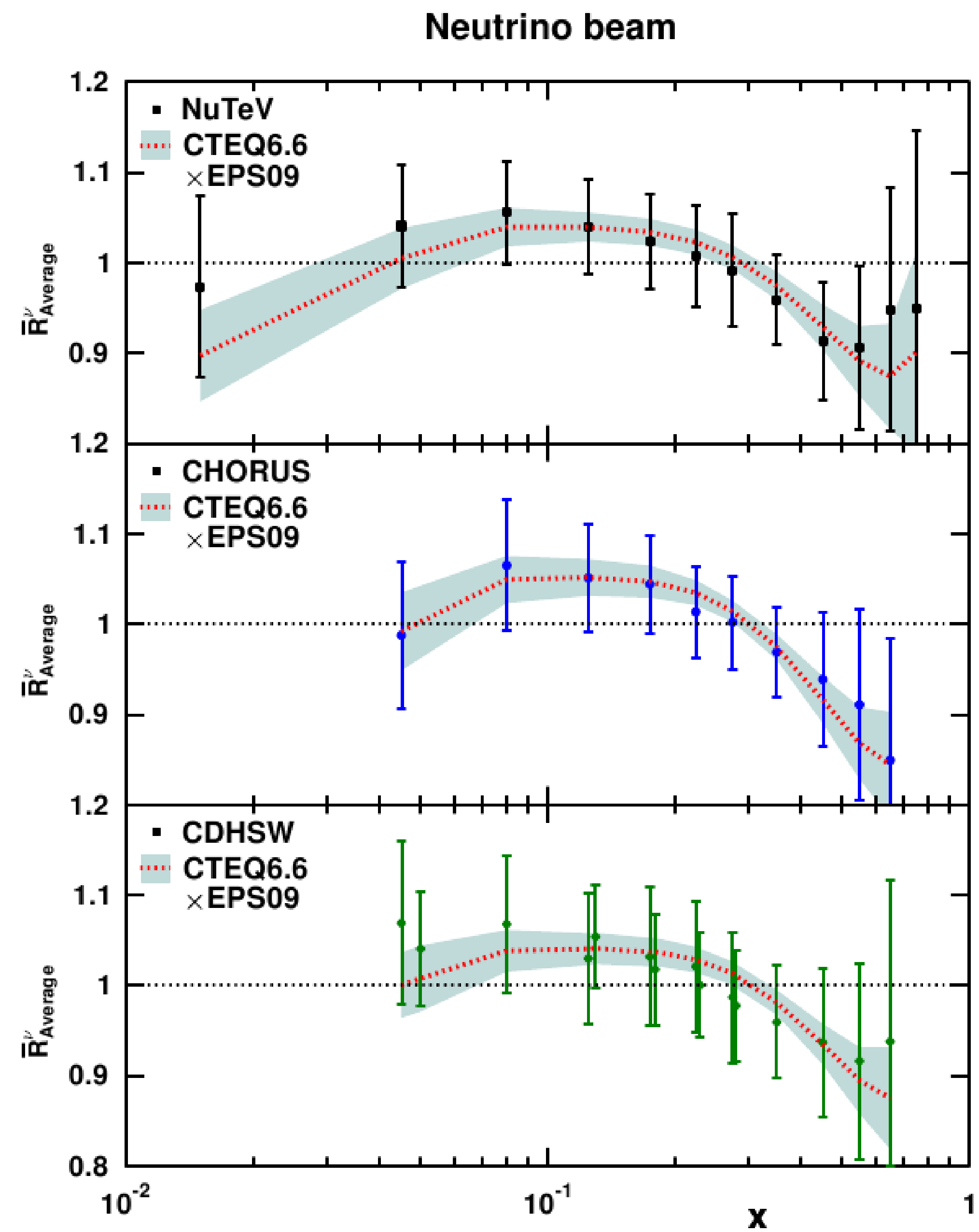
*Phys.Rev.Lett. 110 (2013) 212301*

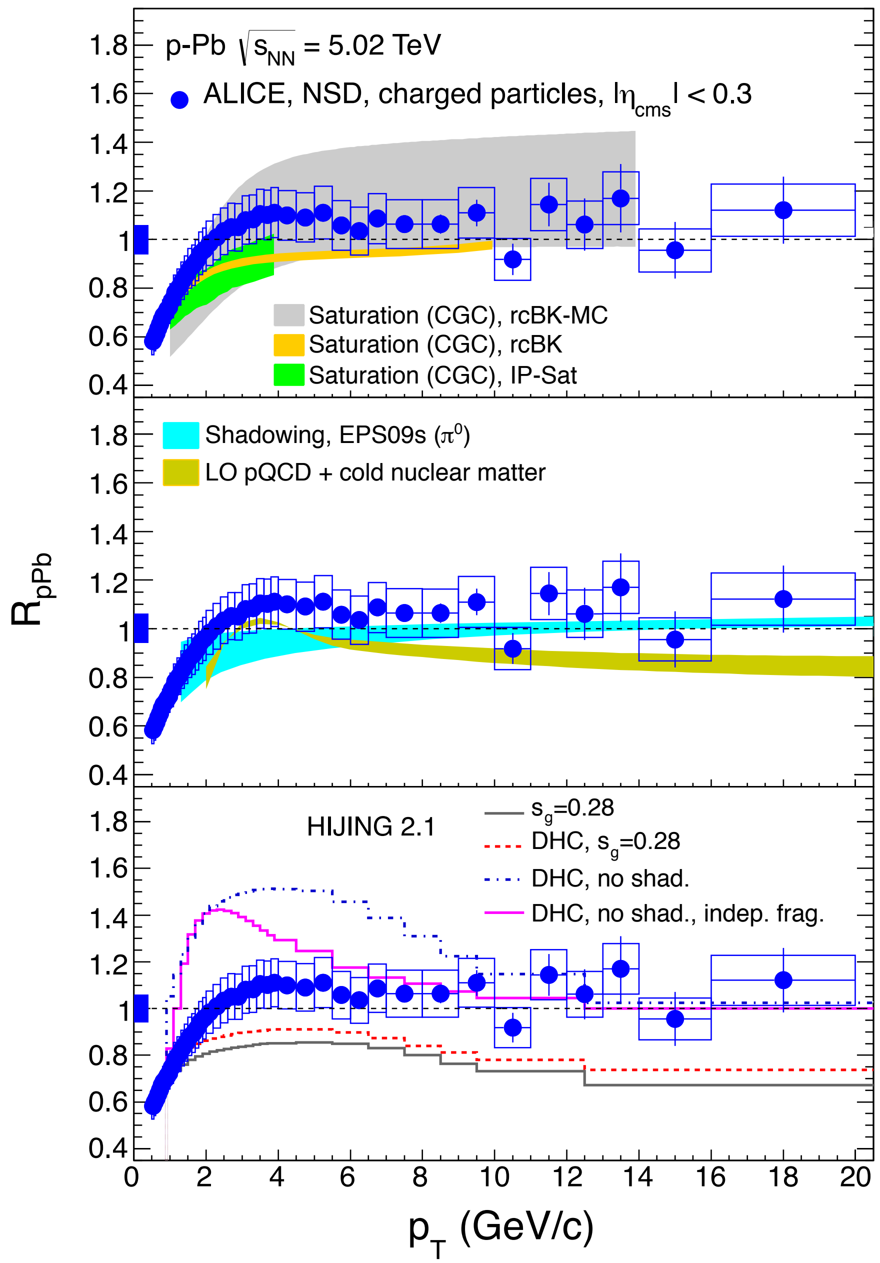


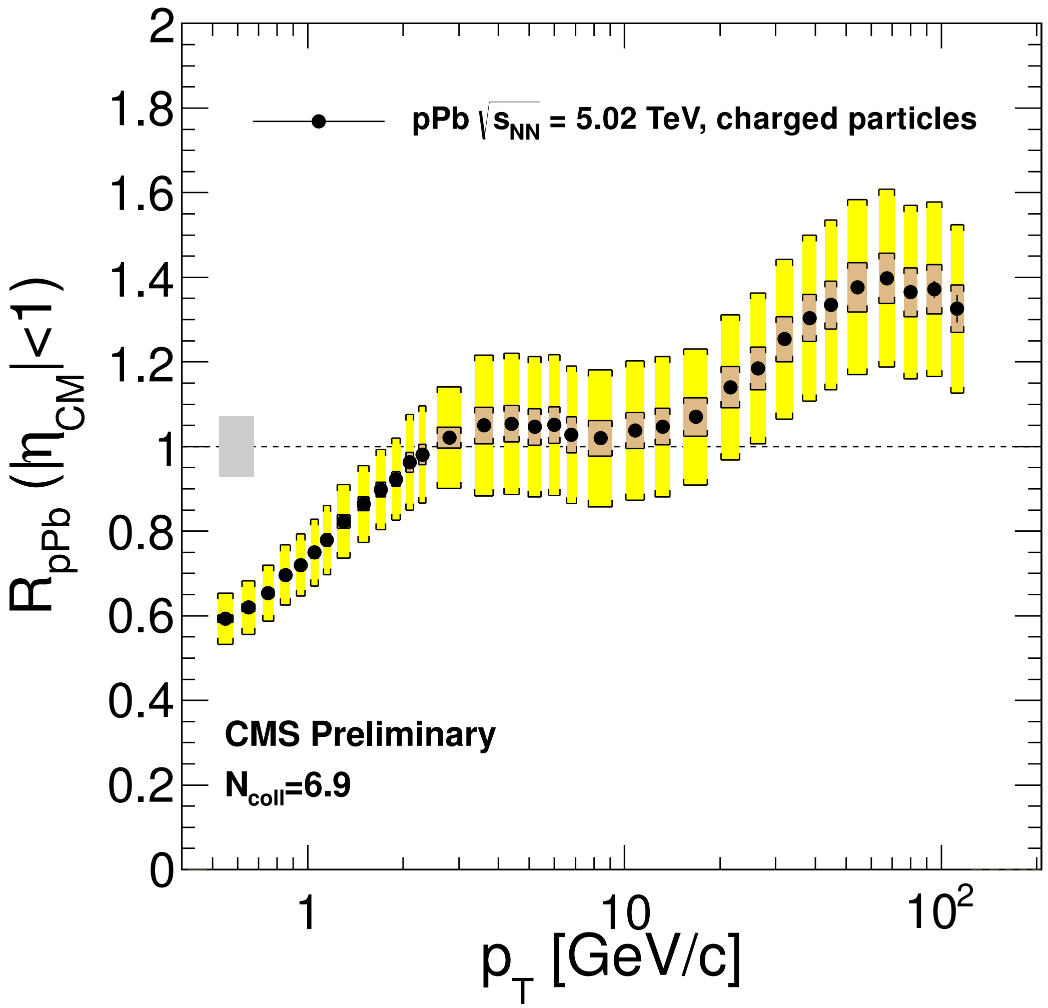

**+EPS09 nuclear PDFs**




Hannu

# Inclusive particle at high-pt

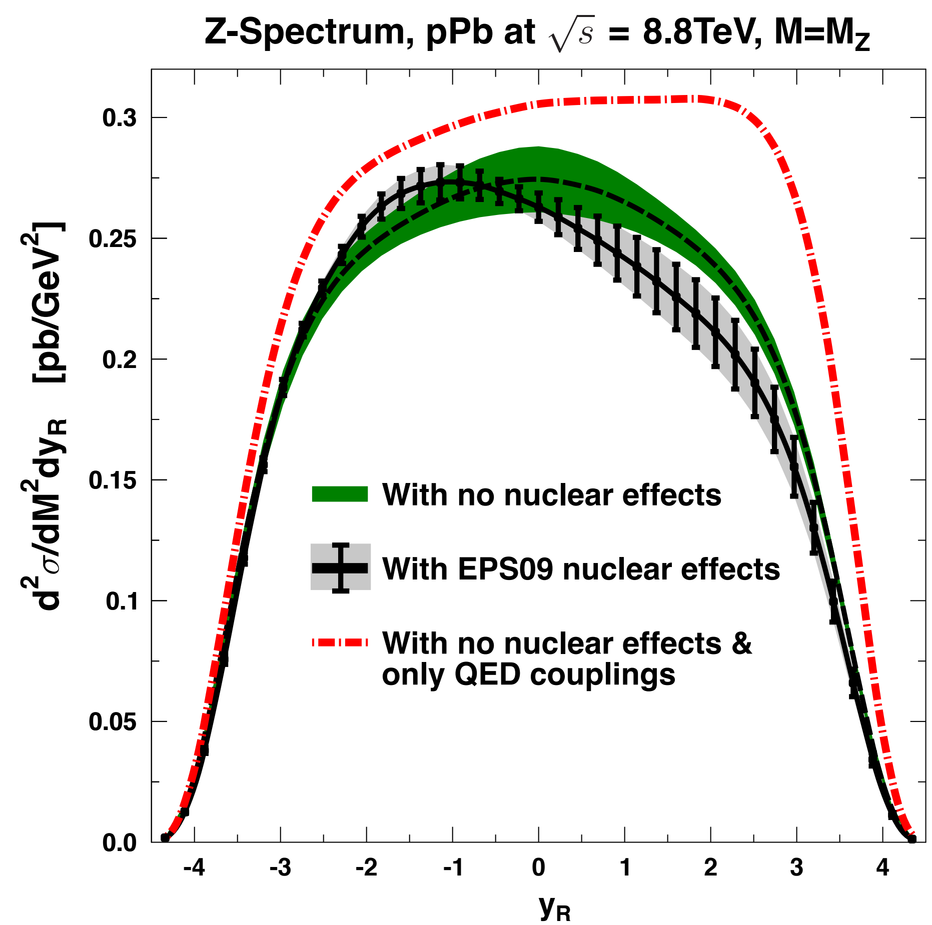


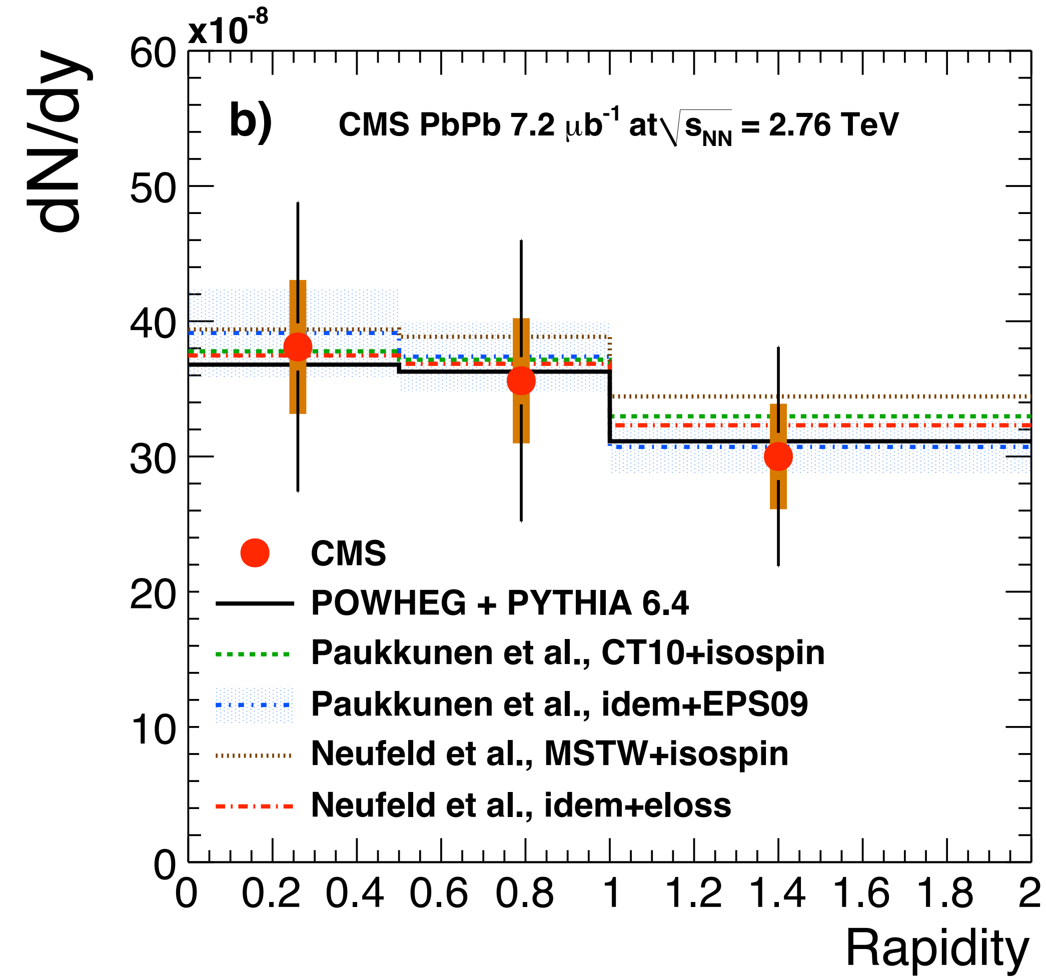



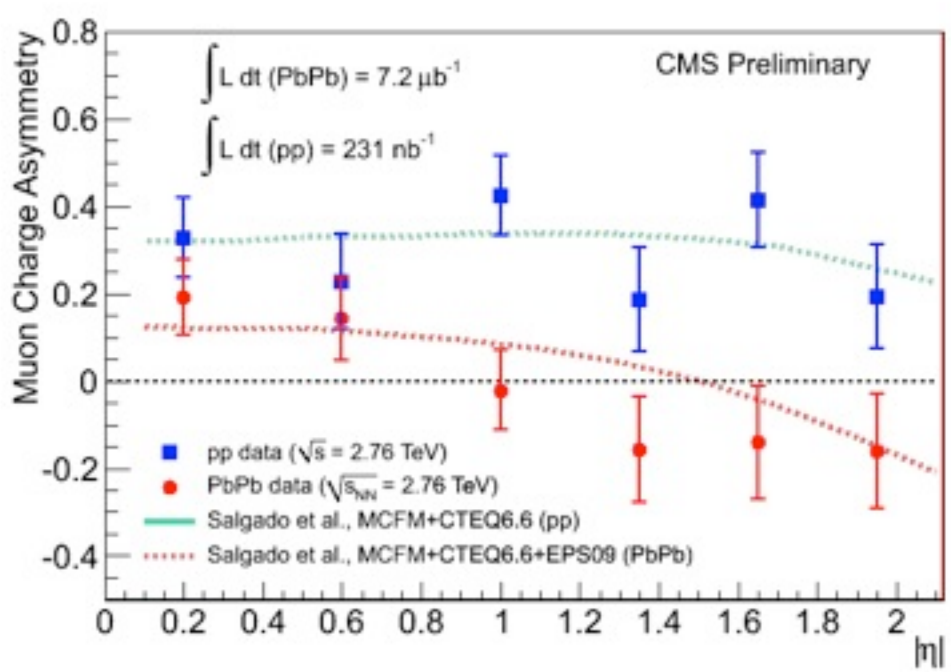

**Reasonable description, but baryons are not well described by FF**

- *Mesons needed - notice disagreement in proton-proton data*
- *CMS data needs to be understood - enhancement not possible within nPDFs*

# W/Z bosons in pA: a very promising tool




- *Comparison with present (PbPb) data good, but not very much sensitivity*
- *New data from the pPb run should provide more constraints*

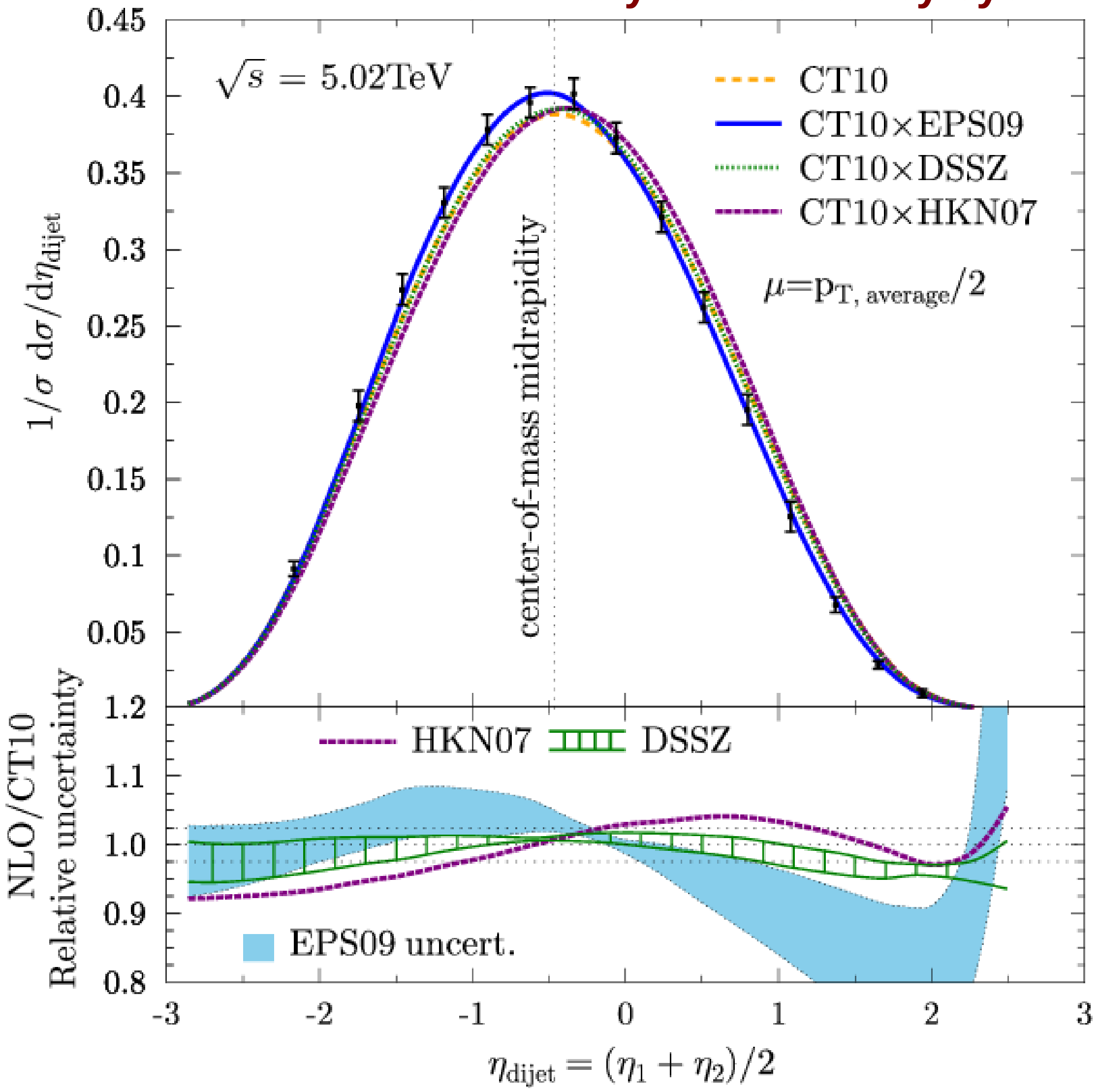
# The CMS dijets in p+Pb

*Eskola, Paukkunen, Salgado, arXiv:1308.6733*

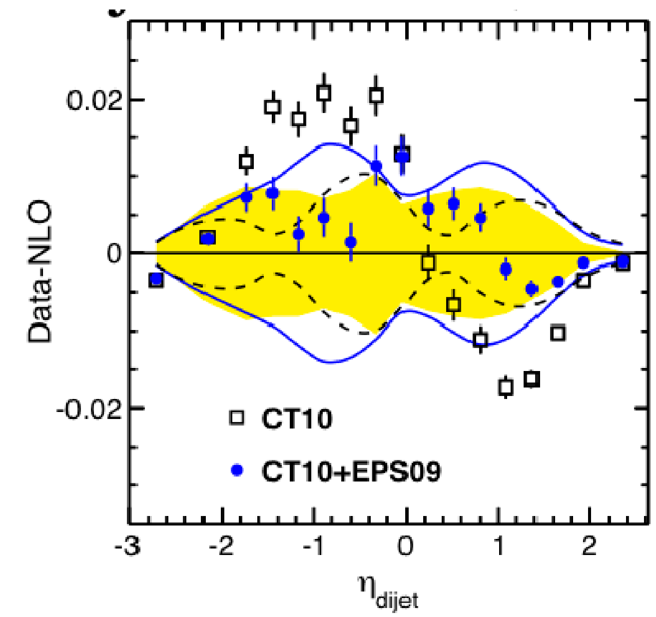
- **Comparison to the NLO calculations – the gluon PDFs make a difference!**

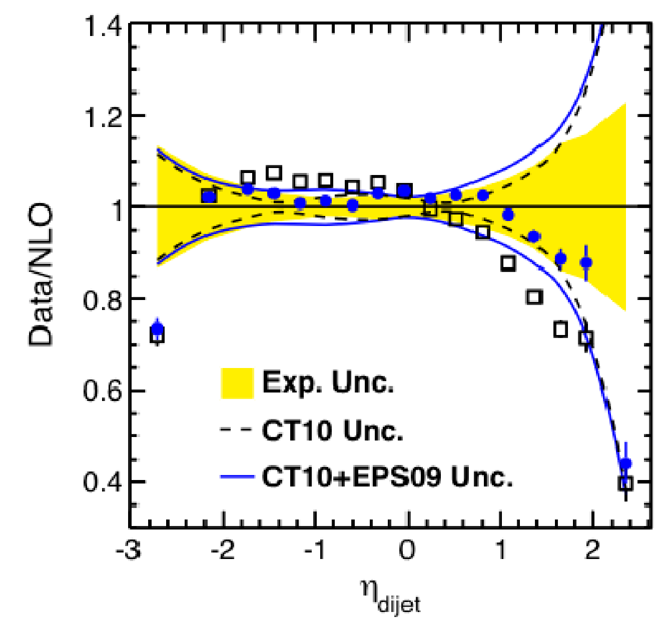
Stolen from Hannu

**Preliminary CMS data "by eye"**




Doga Gulhan, IS2013, Spain

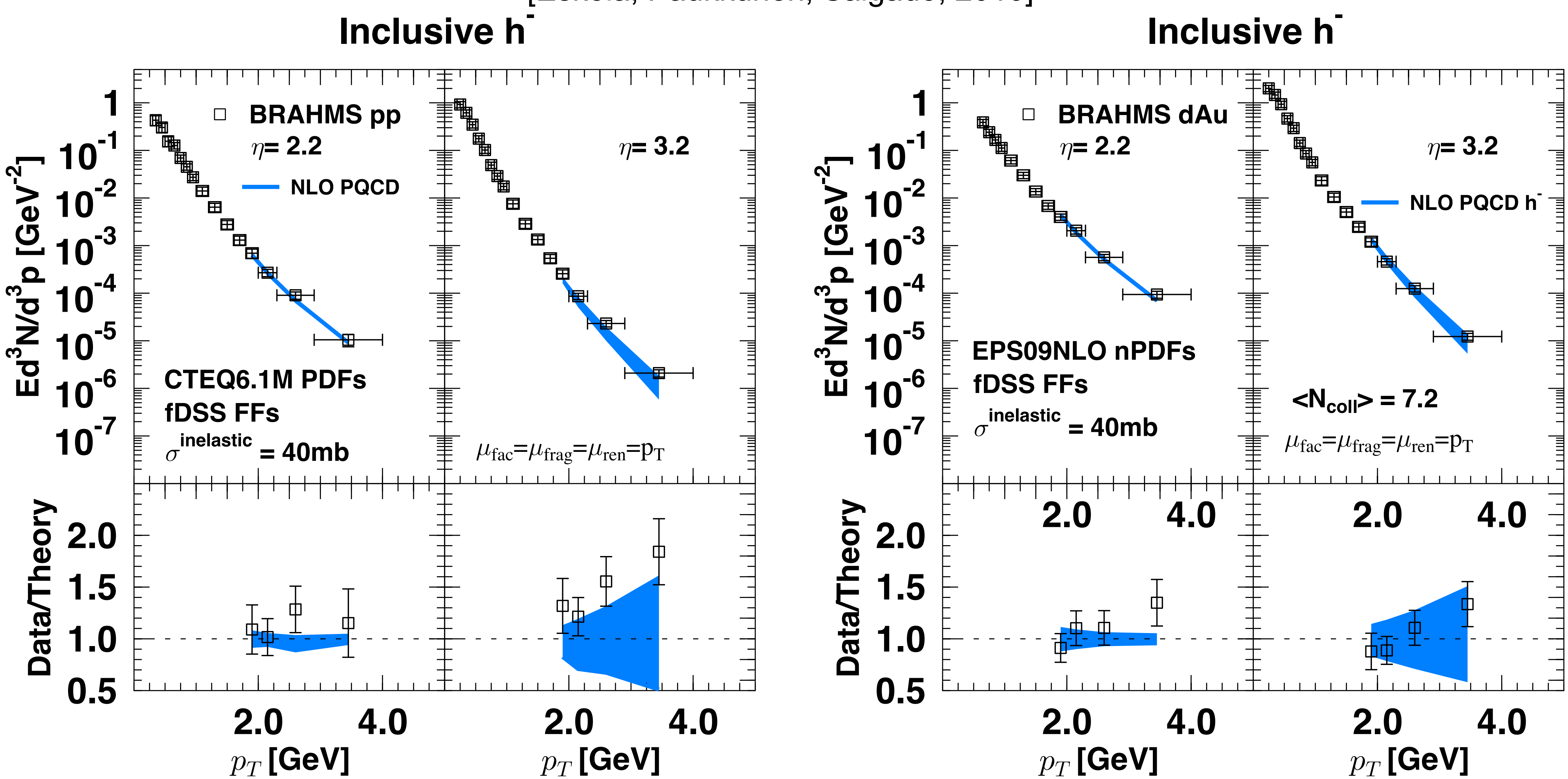



- **A striking agreement with CT10+EPS09!**

# Checks of factorization: forward@RHIC

[Eskola, Paukkunen, Salgado, 2010]

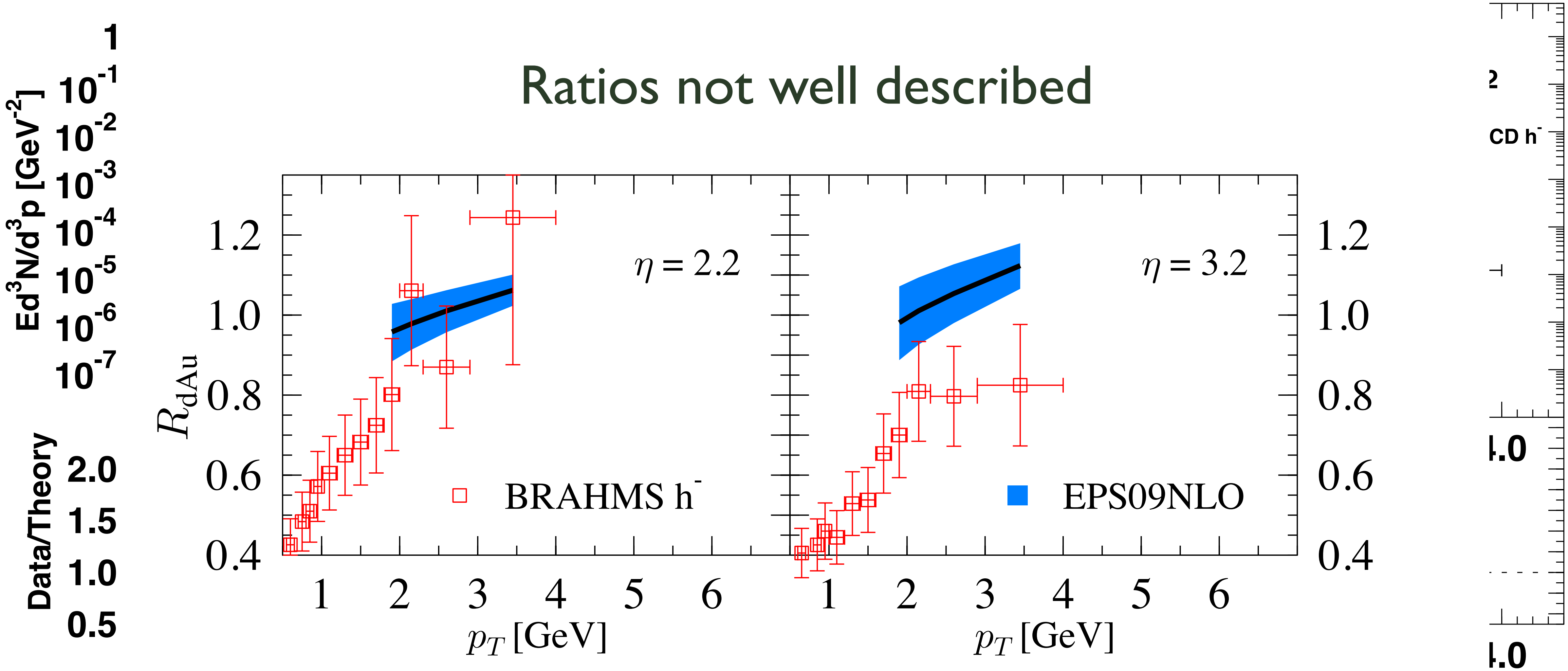



- ⇛ Good description except for pp @ y=3.2
- ⇛ Notice that only yields are provided: need to use Glauber

# Checks of factorization: forward@RHIC

[Eskola, Paukkunen, Salgado, 2010]

Ratios not well described




- ⇒ Good description except for pp @ y=3.2
- ⇒ Notice that only yields are provided: need to use Glauber

## Summary of comparison with LHC

— *Good compatibility so far with limited sensitivity (except, perhaps CMS dijets)*

— *Still waiting for final pPb results...*

# Bayesian re-weighting

# & the LHC

Idea: Study compatibility without a new global fit

This part stolen from Pia Zurita - Nantes Dec 2013

N. Armesto, J. Rojo, C. A. Salgado, P.Z., JHEP 1311 (2013) 015

# The method

## Developed:

W. T. Giele and S. Keller, Phys. Rev. D58 (1998) 094923.

R. D. Ball et al. [NNPDF Collaboration], Nucl. Phys. B 849 (2011) 112 [Erratum-ibid. B 854 (2012) 926] [Erratum-ibid. B 855 (2012) 927].

R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland and J. I. Latorre et al. [NNPDF Collaboration], Nucl. Phys. B 855 (2012) 608.

## Extended:

G. Watt and R. S. Thorne, JHEP (2012) 052.

## Other:

H. Paukkunen and C. A. Salgado, Phys. Rev. Lett.110, 212301 (2013).

For any observable

$$\langle \mathcal{O} \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} \mathcal{O}[f_k]$$

n new points ⇒

$$\mathcal{P}_{new}(f) = \mathcal{N}_\chi \mathcal{P}(\chi|f)\mathcal{P}_{old}(f)$$

each replica has a different importance

$$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}}{\frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}}$$

After the re-weighting

$$\langle \mathcal{O} \rangle_{\text{new}} = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} w_k \mathcal{O}[f_k]$$

For any

$$\langle \mathcal{O} \rangle = \frac{1}{\dots} \sum^{N_{\rm rep}} \mathcal{O}[f_k]$$

RE-Weighting ≠ NEW FIT

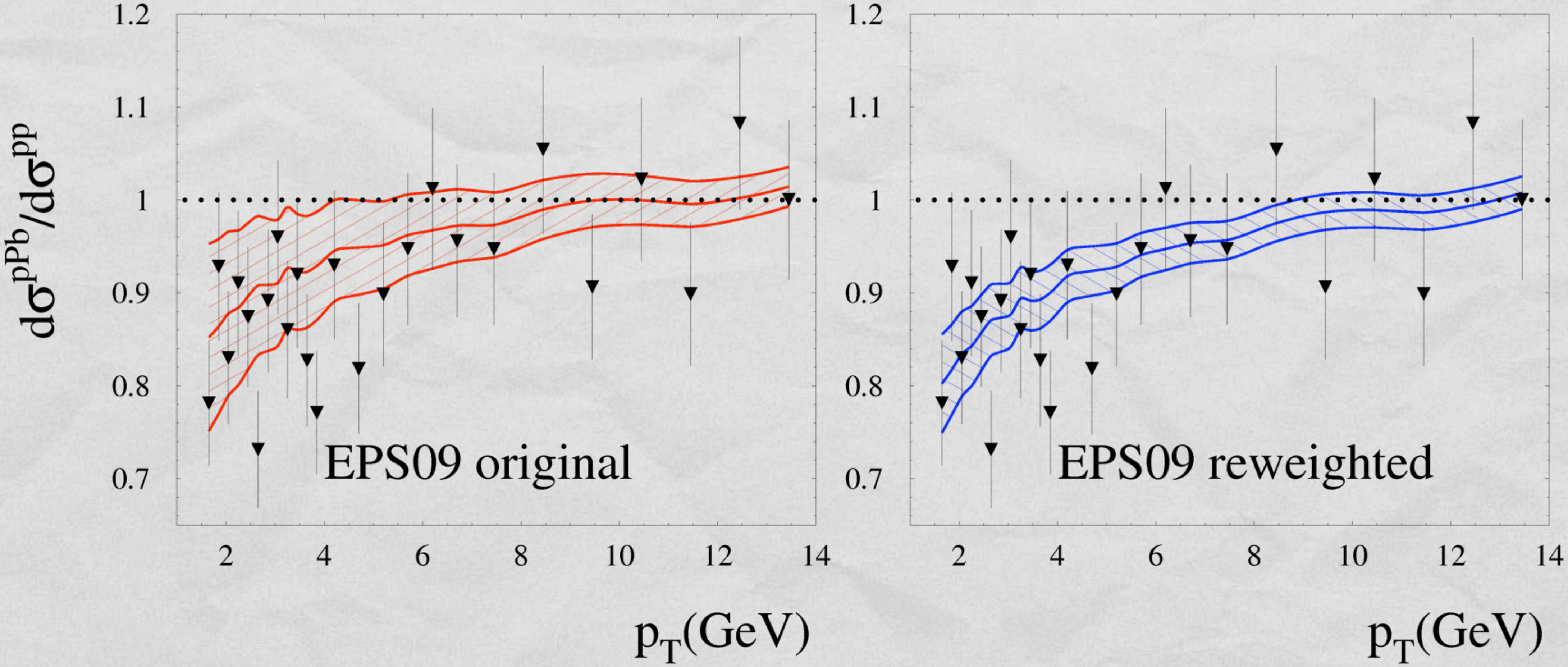
To quantify the accuracy

$$N_{\rm eff} \equiv \exp\left\{ \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \log(N_{\rm rep}/w_k) \right\}$$

re-weighting

$$\langle \mathcal{O} \rangle_{\rm new} \dots \frac{\dots}{N_{\rm rep}} \sum_{k=1} w_k \mathcal{O}[f_k]$$

# DGLAP for η=0

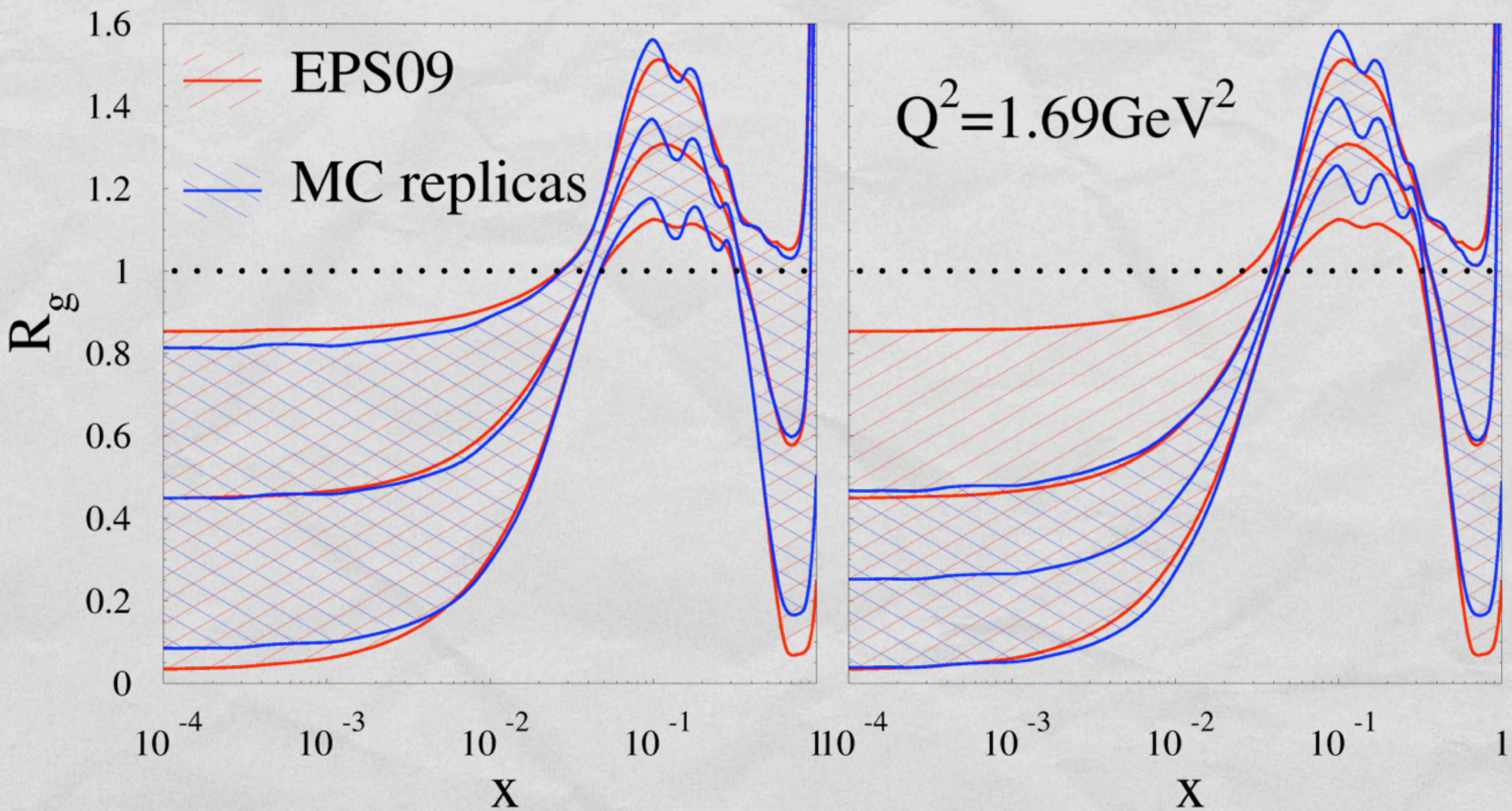



| N=25 | χ² / N | < χ² > / N | Neff |
|---|---|---|---|
| Before | 1.11 | 1.75 | - |
| After | 0.84 | 1.02 | 624 |

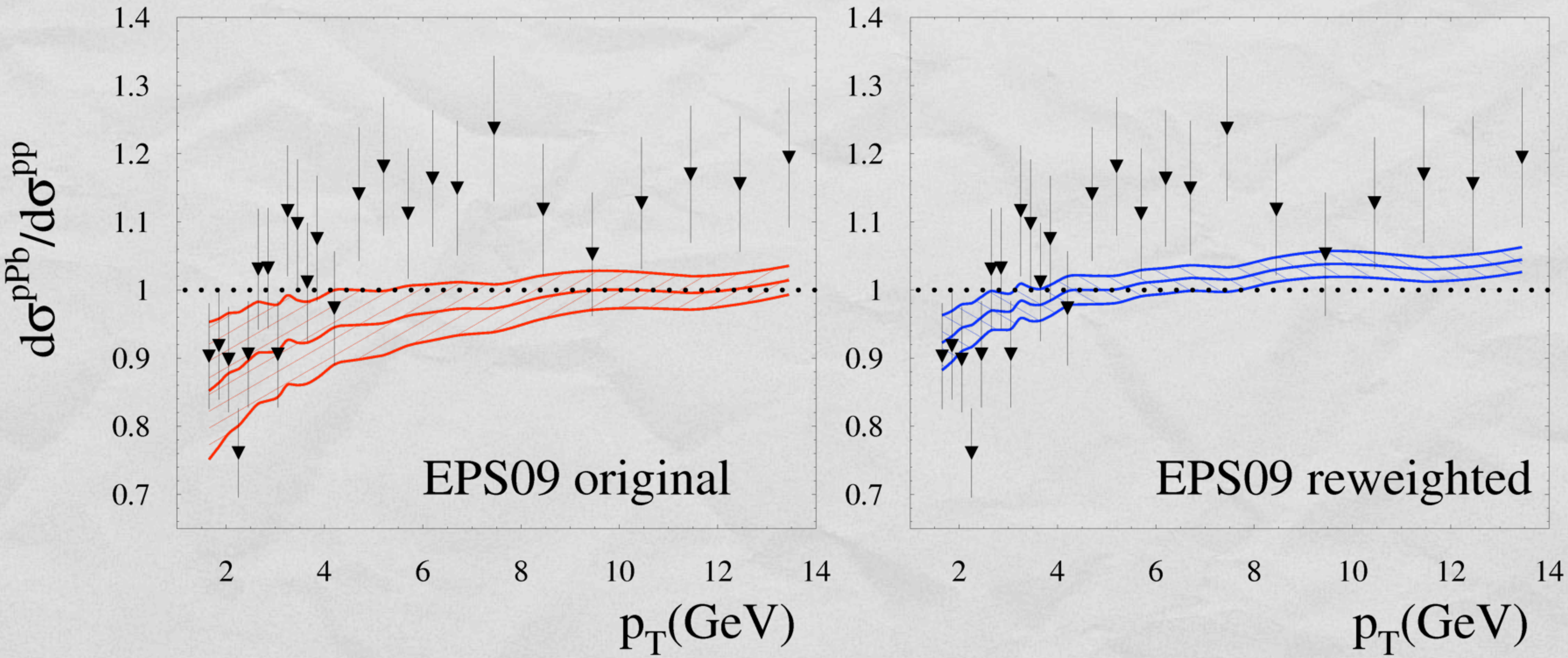
# η = 0 DGLAP

**No** change in the valence

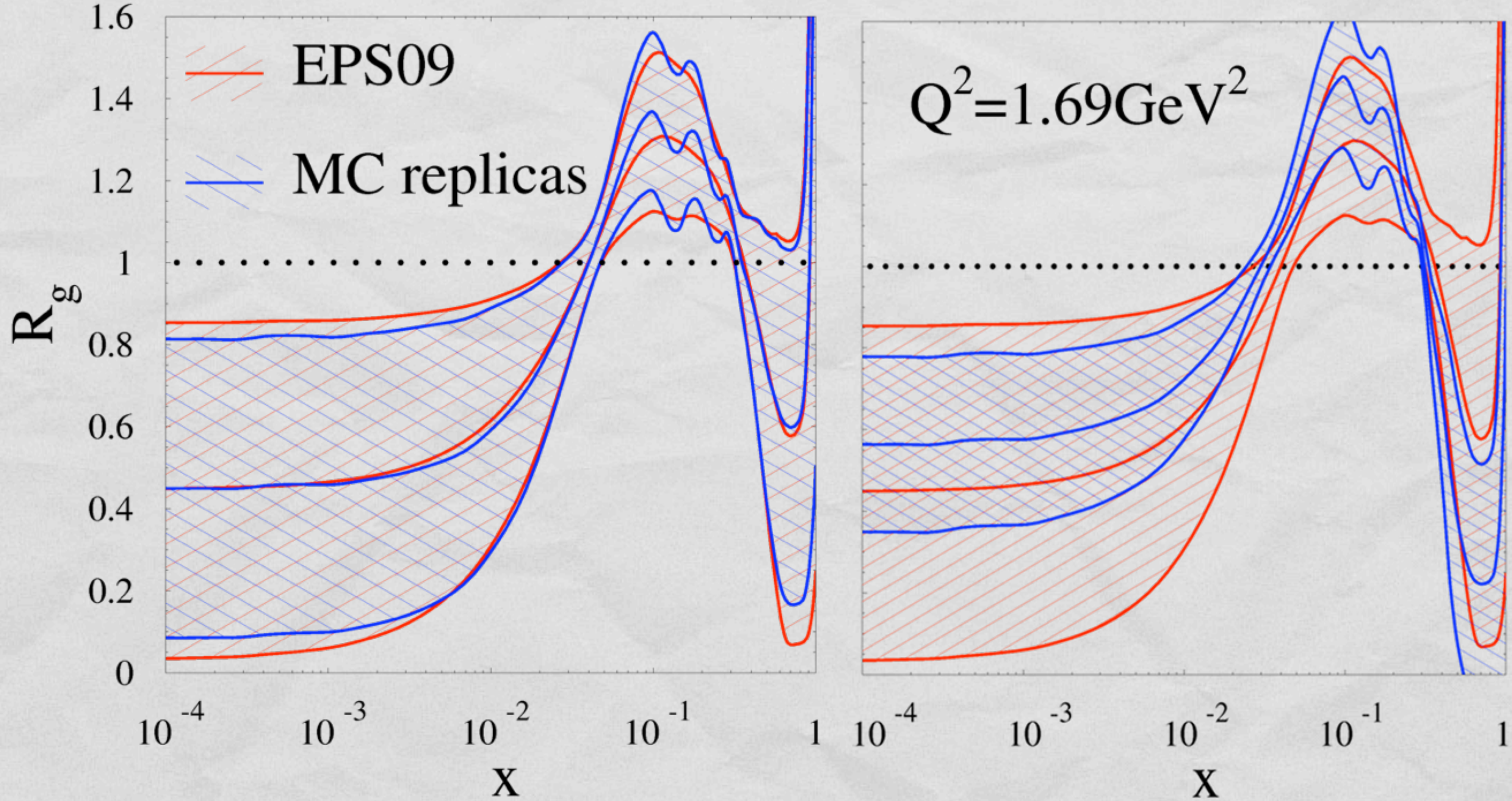
change in the sea



# CGC for η=0




| N=25 | $\chi^2$ / N | < $\chi^2$ > / N | $N_{EFF}$ |
|---|---|---|---|
| Before | 2.25 | 2.76 | - |
| After | 1.50 | 1.58 | 229 |



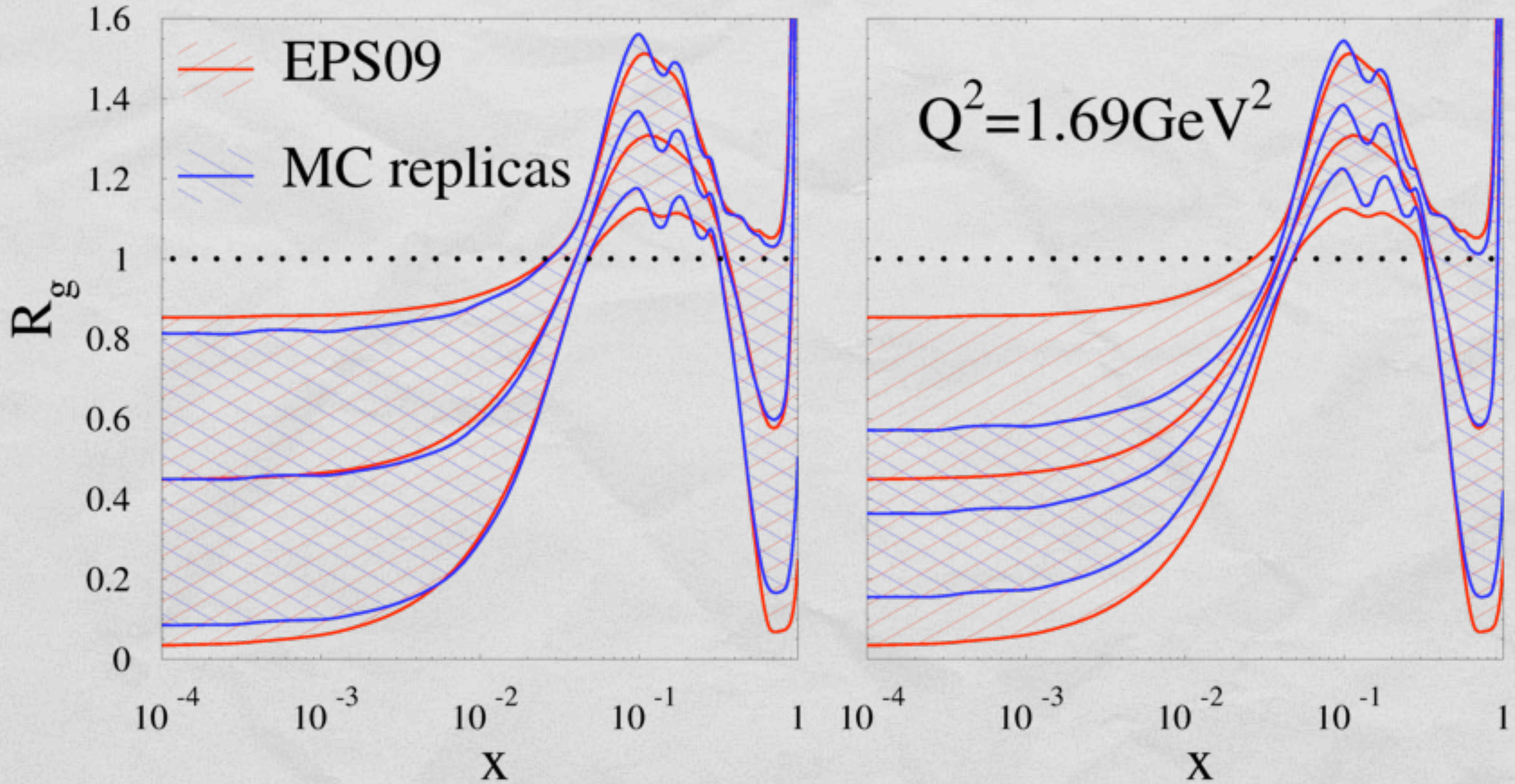

CHANGE IN THE VALENCE

NO CHANGE IN THE SEA

CGC

$\eta = 0$

# DGLAP for η=2

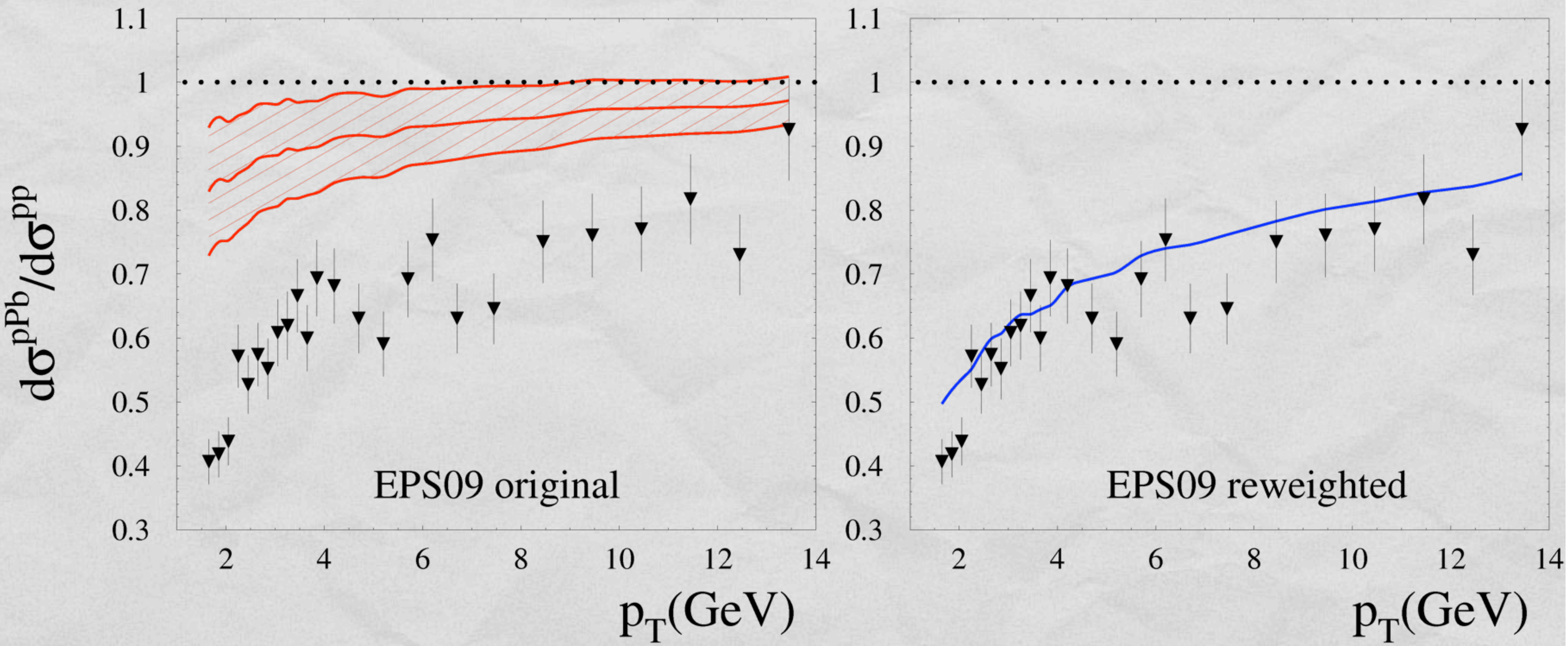



No change in the valence

Slight modification for the sea

**GLUON!**

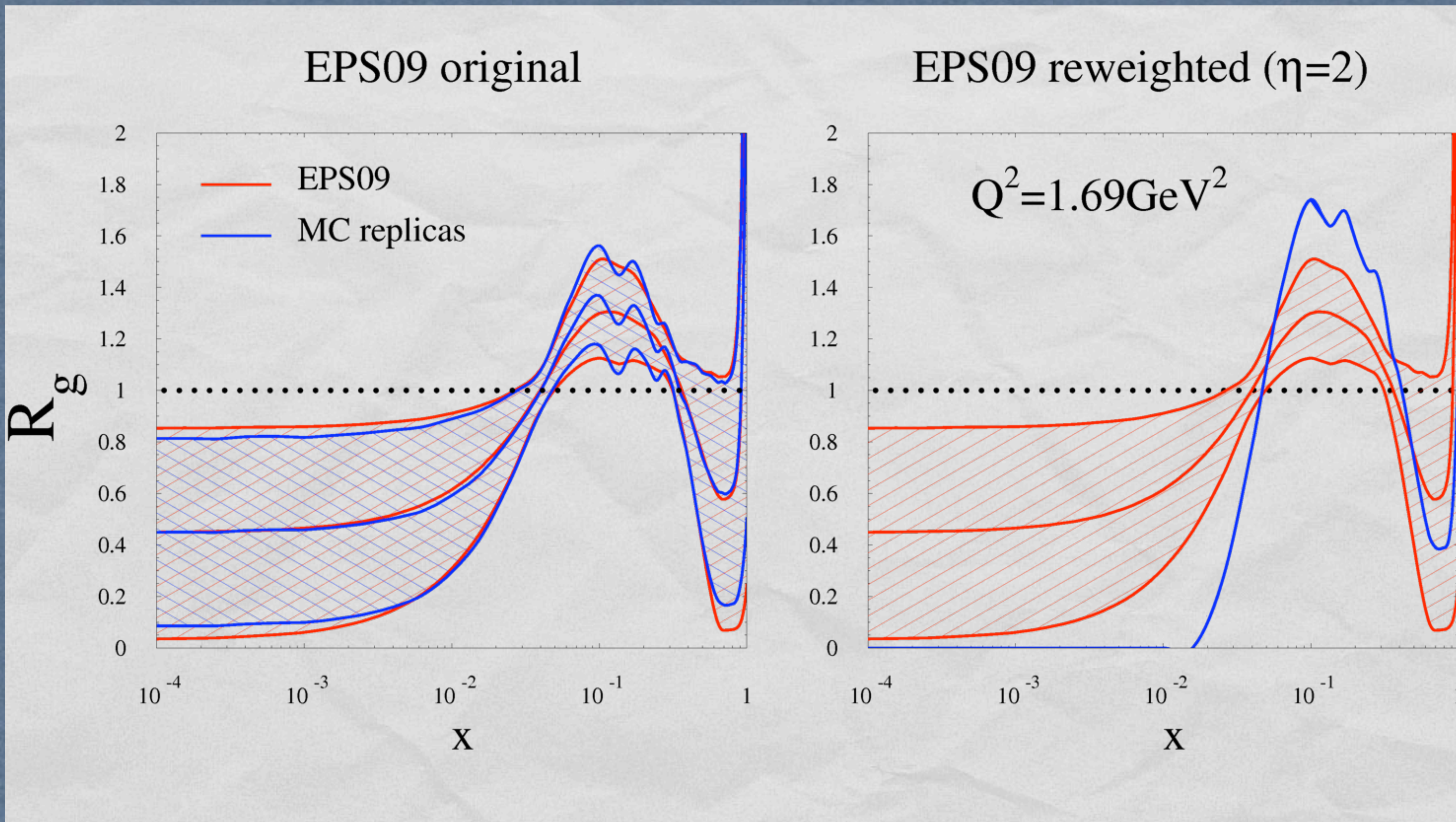
# CGC for $\eta$=2




| N=25 | $\chi^2$ / N | < $\chi^2$ > / N | $N_{EFF}$ |
|---|---|---|---|
| Before | 36.43 | 38.62 | - |
| After | 1.85 | 1.85 | **1** |

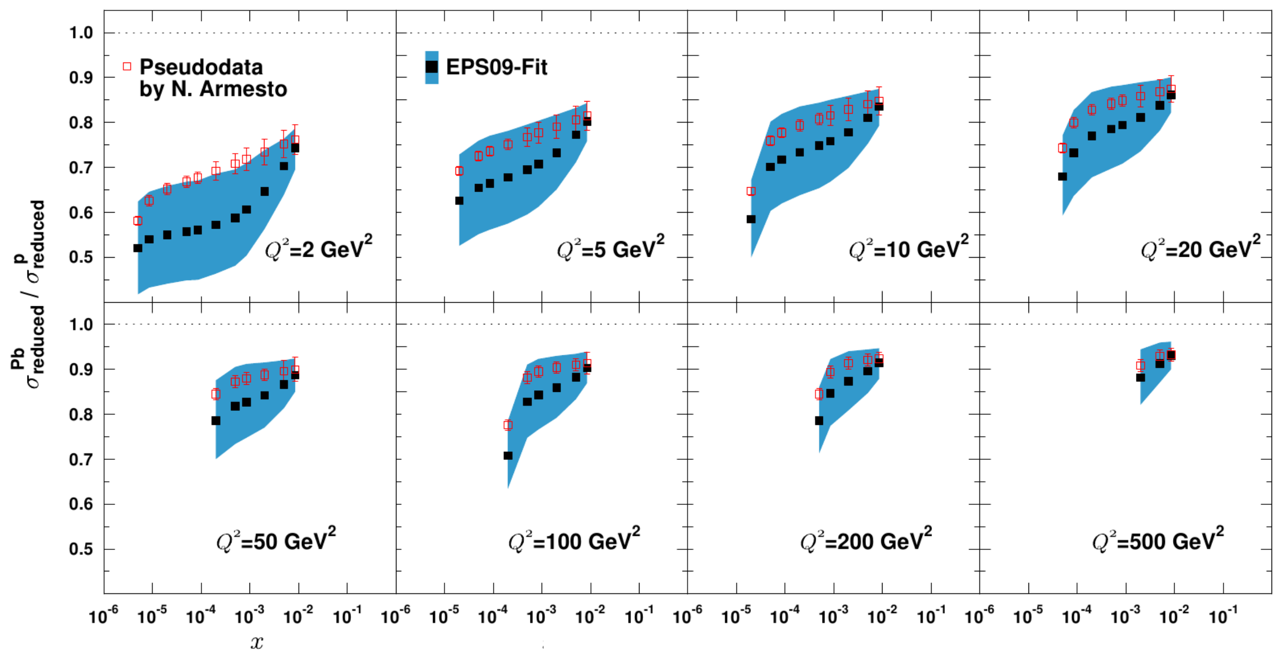
THE RE-WEIGHTING METHOD IS **INVALIDATED**

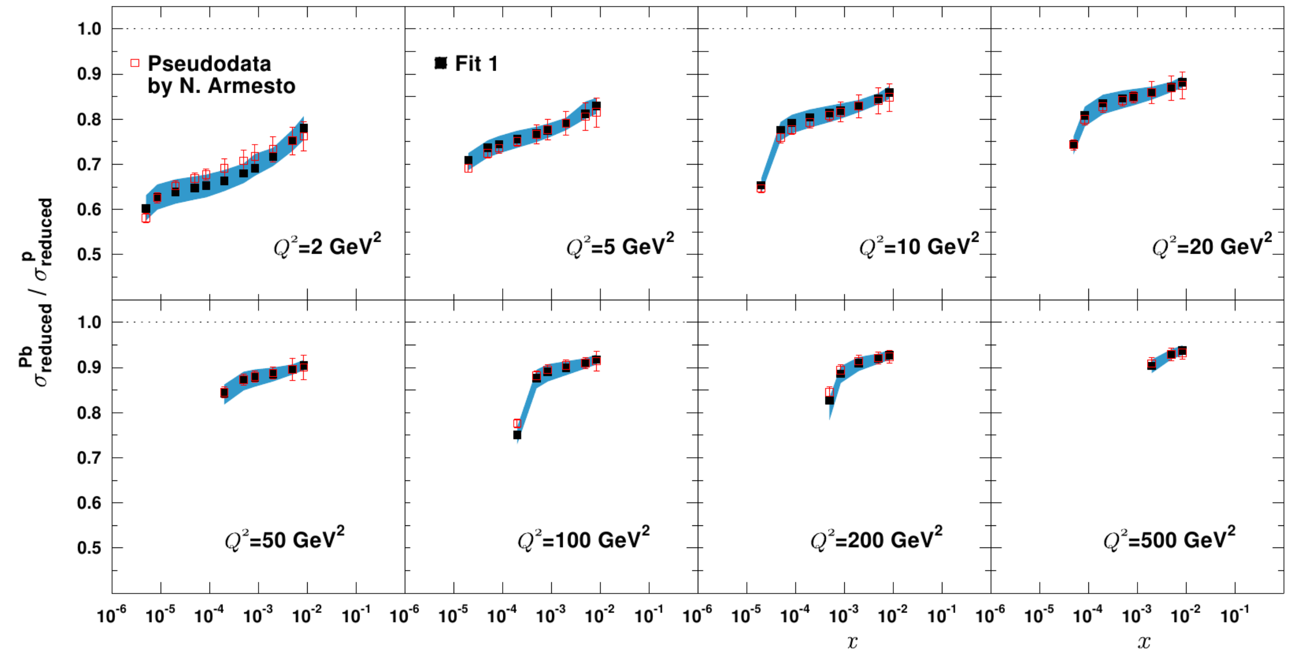
# CGC for η=2



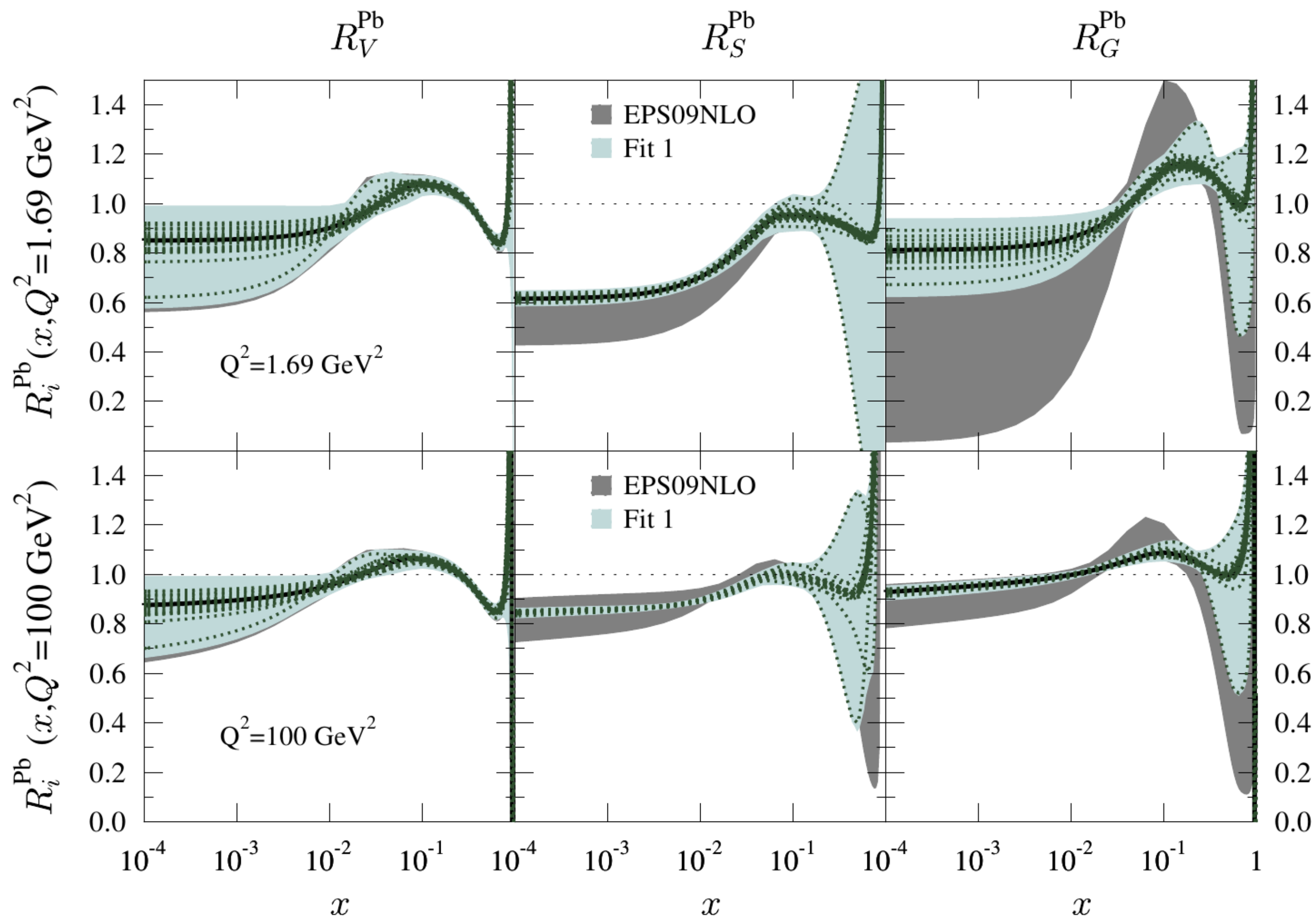

| | | | |
|---|---|---|---|
| After | 1.85 | 1.85 | 1 |

the re-weighting method is INVALIDATED


Pseudodata
by N. Armesto
EPS09-Fit
$Q^2$=2 GeV$^2$
$Q^2$=5 GeV$^2$
$Q^2$=10 GeV$^2$
$Q^2$=20 GeV$^2$
$Q^2$=50 GeV$^2$
$Q^2$=100 GeV$^2$
$Q^2$=200 GeV$^2$
$Q^2$=500 GeV$^2$
$\sigma^{Pb}_{reduced} / \sigma^{p}_{reduced}$
$x$


Pseudodata
by N. Armesto
Fit 1
$Q^2$=2 GeV$^2$
$Q^2$=5 GeV$^2$
$Q^2$=10 GeV$^2$
$Q^2$=20 GeV$^2$
$Q^2$=50 GeV$^2$
$Q^2$=100 GeV$^2$
$Q^2$=200 GeV$^2$
$Q^2$=500 GeV$^2$
$\sigma^{Pb}_{reduced} / \sigma^{p}_{reduced}$
$x$

# LHeC


$R_V^{Pb}$
$R_S^{Pb}$
$R_G^{Pb}$
EPS09NLO
Fit 1
$R_i^{Pb}(x,Q^2=1.69\ GeV^2)$
$R_i^{Pb}(x,Q^2=100\ GeV^2)$
$Q^2$=1.69 GeV$^2$
$Q^2$=100 GeV$^2$
$x$

# *Summary*

**Nuclear PDF analyses still taking off at the LHC**

- *Present fits are ok*
- *New constraints possible, but eventually smaller error bars needed*

**PDF analyses are precision...**

# *Do we need to go to higher energies?*

*[first thoughts...]*

**We gain a factor of 7 in CM energy - 2 units of rapidity**

**Questions in the last couple of years [my bias...]**

- *Jets in QCD matter - role of coherence (color matters, e.g. singlet)*
- *Initial stages and thermalization - CQC (factor 1.8 in Qsat)*

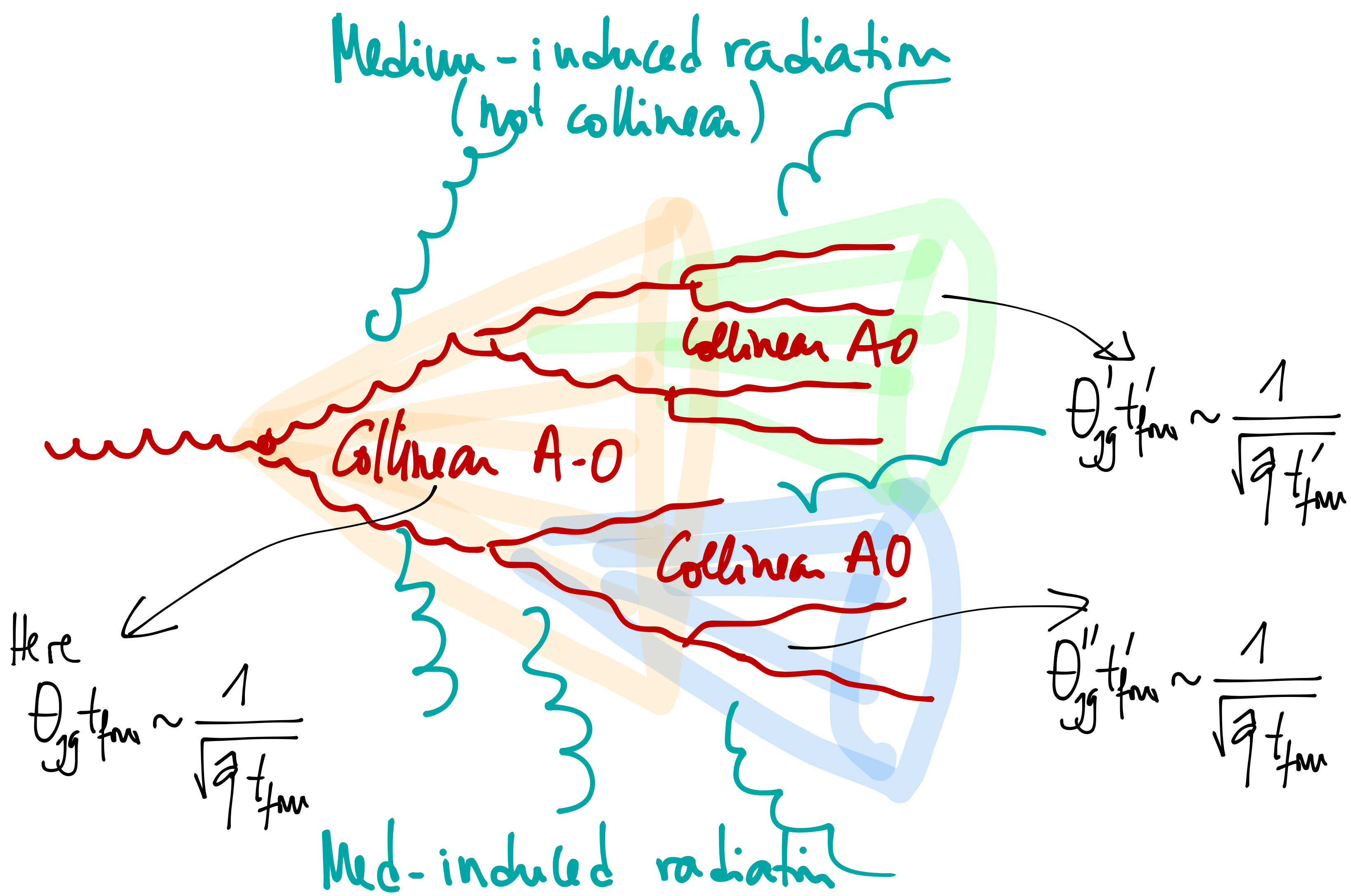
**More precision needed - explore smaller times!**

- *higher luminosity + higher energy (new observables)*
- *small systems - proton-nucleus*
- *Explore also new observables: tiny coupling of EW with medium?*

# A new picture of jet quenching

The parton shower is composed of **un-modified subjets** (vacuum-like)

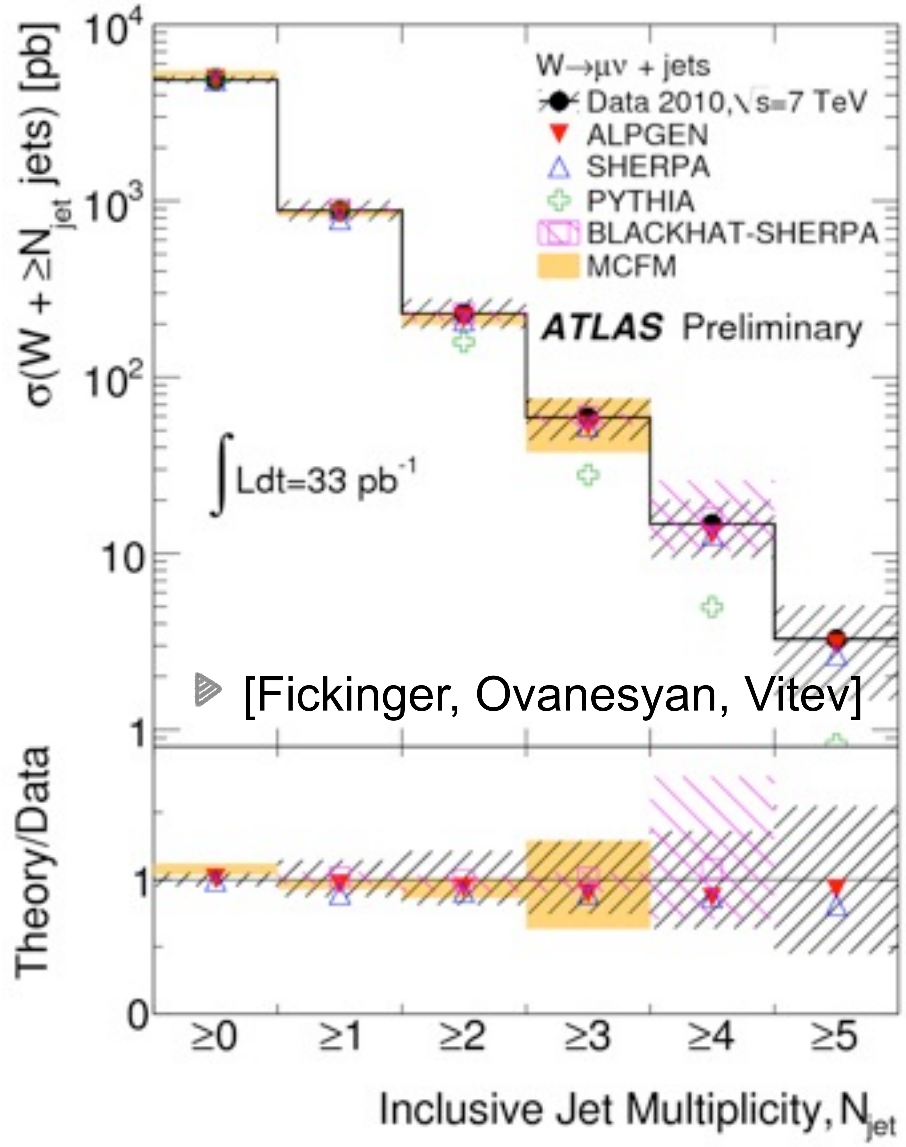
- **With a typical radius given by the medium scale**
- For medium-induced radiation **each subject is one single emitter**




Also, 1st calculation of 1->3 splitting performed in SCET and 1st order in opacity expansion

- [Fickinger, Ovanesyan, Vitev]

# More precise observables




[Fickinger, Ovanesyan, Vitev]

**Requires more luminosity and/or more energy**

- *Typical luminosity of pPb run ~ 0.1 $pb^{-1}$*
- *~10 times more at FHC - others, as Higgs (x20) or top (x50), have even larger enhancements*

[Estimates made in the plane with MCFM - need to be checked...]