non-linear QCD meets data

:: from proton to nuclei ::

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[AAM(Q)S]

PRD 80:034031, 2009
DIS2009 Proceedings

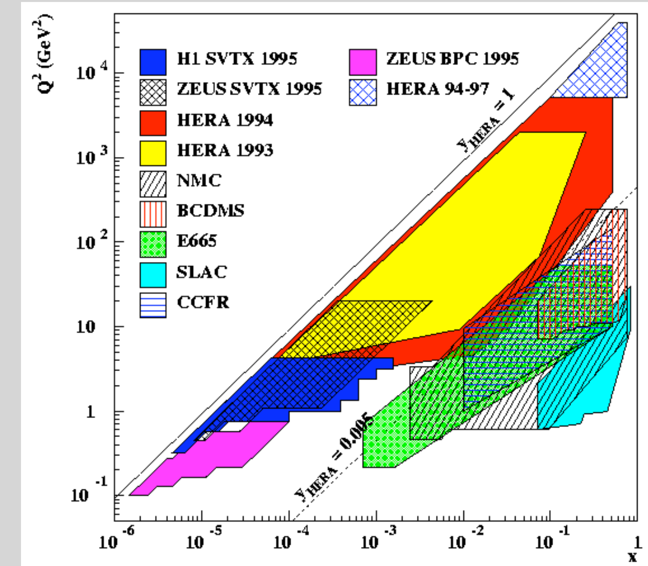
Workshop on Nuclear Parton Distribution Functions
– 22 Feb 2010 –

parton distribution functions [DGLAP]

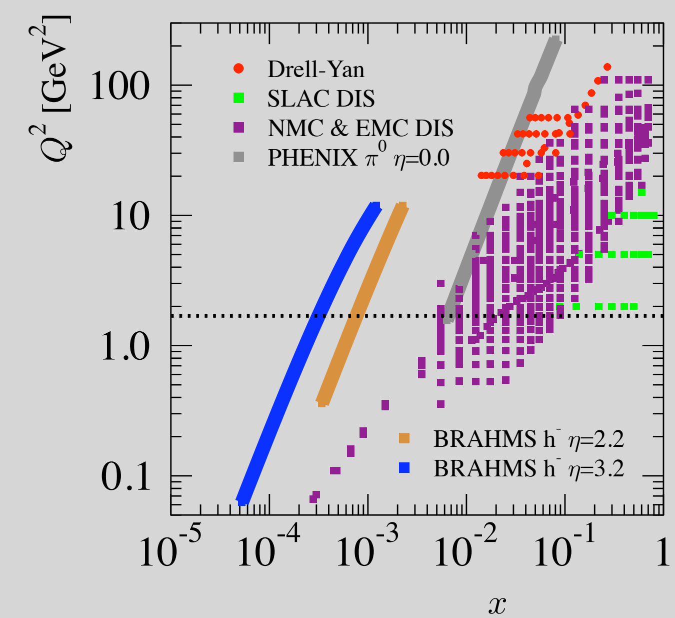
- 'standard' approach
  - *collinear* factorization allows for identification of universal [process independent] pdfs
  - pdfs extracted via global fits to data
    ↪ parameterized non-perturbative initial condition
  - systematically improvable in perturbation theory [NLO, NNLO,...]

proton vs. nuclear pdfs

- *proton case*
  - collinear factorizability proven
  - wealth of data (DIS, DY, jets)
    - ↪ very reliable pdfs in ‘data covered’ kinematical range



- *nuclear case*
  - collinear factorizability is a working assumption
    - ↪ for testability, see Paloma’s talk
  - relatively scarce data
  - standardly encoded as nuclear modification of proton pdfs [inherits proton pdf uncertainties]



$$f_{i/A}(x,Q^2) = R_i^A(x,Q^2)\, f_{i/p}(x,Q^2)$$

pdf of parton in nucleon inside nucleus

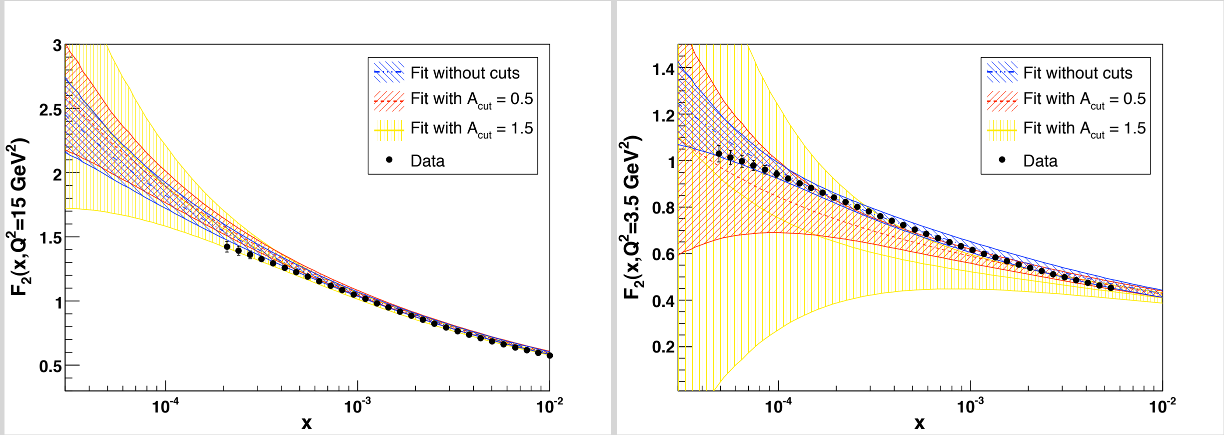
nuclear modification

pdf of parton in free nucleon

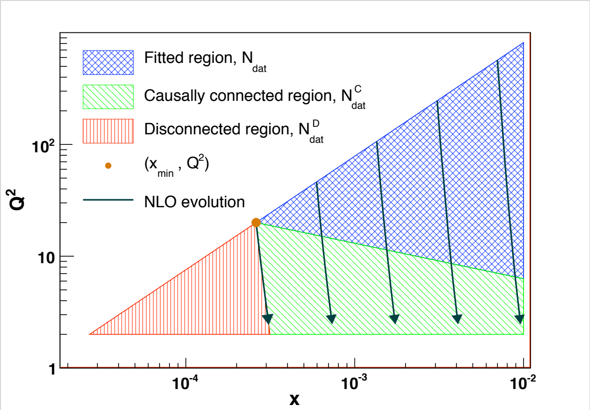
small-x and DGLAP

- at small-x *novel* [non-linear parton density induced] effects come into play

- deviations from NLO-DGLAP identified in [of all places…] HERA data for F_2 *Caola, Forte, Rojo 0910.3143 [hep-ph]*



:: not NLLO, not only heavy quark, … ::



:: initial condition independent statement ::

- BFKL resumed DGLAP
  - accounts for small-x evolution linearly
    - an interim fix…
- ***DGLAP is not a predictive tool at small-x***

- nuclei probe smaller x at lower energy [as compared to proton]

non-linear QCD approach

- k_t factorization + dipole formulation of high energy QCD
  - limited by k_t factorizability and its compatibility with dipole formulation
    - ↪ no access to 'standard' pdfs
      - rather, unintegrated gluon distribution is the relevant object
  - recall François' talk for nuclear case

- first principle QCD calculation of x-evolution of dipole scattering amplitude
  - running coupling BK
    - ↪ best, numerically implementable, incarnation of non-linear QCD
    - ↪ unlike most [phenomenological] 'dipole models'
    - ↪ first proton then nuclei

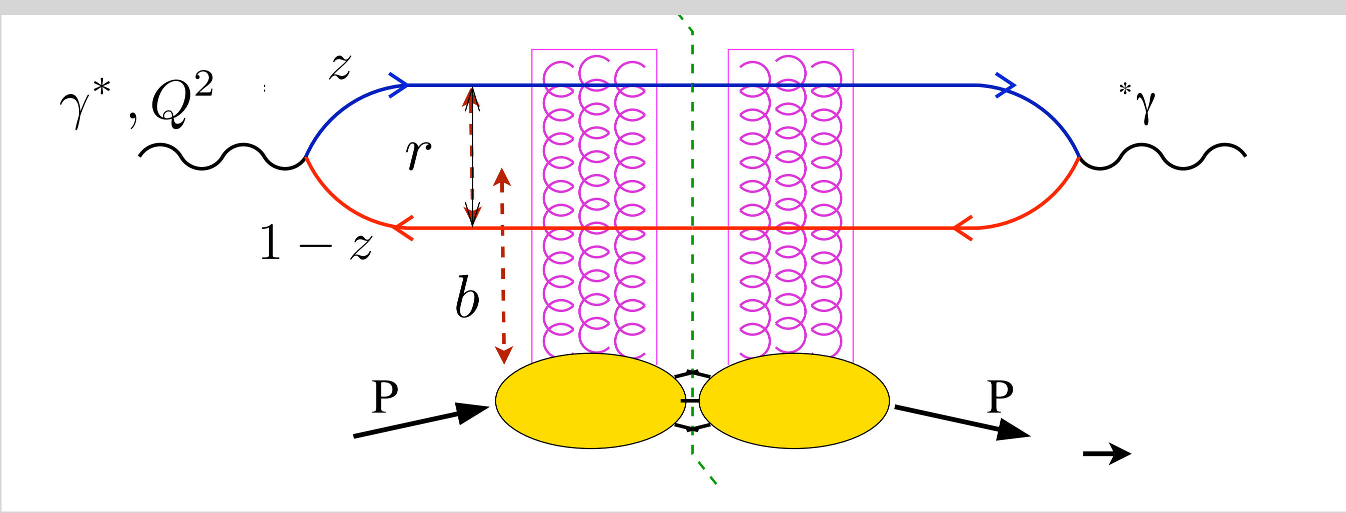
dipole QCD [in DIS]

- at high energy [x << 1] the coherence length of the virtual photon fluctuation

$$l_c \sim (2m_N x)^{-1} \simeq 0.1/x \text{ fm} \gg R_N$$

- total virtual photon-proton cross section can be factorized as

$$\sigma_{T,L}(x,Q^2) = \int_0^1 dz \int d\mathbf{b}\, d\mathbf{r}\, |\Psi_{T,L}(z,Q^2,\mathbf{r})|^2\, \mathcal{N}(\mathbf{b},\mathbf{r},x)$$



QED calculation

[imaginary part of]
dipole-target scattering amplitude
:: all QCD information
:: all x dependence
:: non-perturbative, but x-evolution computable from first principles

impact parameter dependence

- b-dependence governed by long-distance non-perturbative physics
- AAMS 1.0 resorts to translational invariance approximation
  - proton homogeneous in transverse plane

$$\sigma_{T,L}(x,Q^2) = \int_0^1 dz \int d\mathbf{b}\, d\mathbf{r}\, |\Psi_{T,L}(z,Q^2,\mathbf{r})|^2\, \mathcal{N}(\mathbf{b},\mathbf{r},x)$$

$$\sigma_{T,L}(x,Q^2) = \sigma_0 \int_0^1 dz \int d\mathbf{r}\, |\Psi_{T,L}(z,Q^2,\mathbf{r})|^2\, \mathcal{N}(r,Y)$$

'b-integration'
fit parameter
:: if factorized structure [of x, r and b dependence]
unchanged by evolution, then related to
t-dependence in diffractive events

  - exclusive observables require more sophisticated treatment of b-dependence

⥁ from A to B

- want the best possible, numerically tractable, incarnation of non-linear evolution
  - with Dense-Dense effects and NLO
    - ↪ RFT-QCD contains all Dense-Dense effects
      - no known strategy for numerical implementation
      - NLO [running coupling] should trump Dense-Dense [toy model]

[Dumitru, Iancu, Portugal, Soyez and Triantafyllopoulos, JHEP 0708:062, 2007]

- 'safely' neglect Dense-Dense if NLO formulation available
  - B-JIMWLK
    - ↪ no Dense-Dense, no NLO, numerically challenging ...
    - ↪ but BK [large N, mean field] solutions deviate only 0.1% from full B-JIMWLK

[Kovchegov, Kuokannen, Rummukainen, Weigert, NPA 823, 47 (2009)]

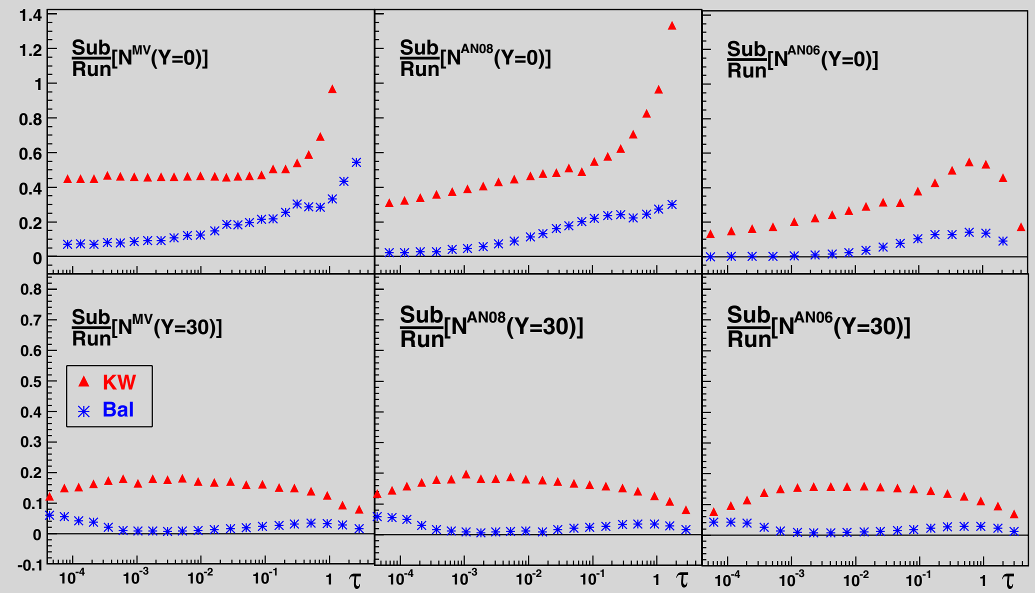
- 'safely' replace full B-JIMWLK by BK
  - LO-BK not consistent with data [unless coupling very small]
  - NLO-BK computed *[Balitsky, Chirilli, Kovchegov, Weigert]*
  - running coupling part numerically tractable

⥁ on why B is B’

- NLO-BK = all orders in $\alpha_s N_f$ + other
  - all orders in $\alpha_s N_f$ = rc + subtraction

$$\frac{\partial \mathcal{N}(r,Y)}{\partial Y} = \mathcal{R}[\mathcal{N}] - \mathcal{S}[\mathcal{N}]$$

  - subtraction piece numerically demanding
    - ↪ running coupling contribution dominant over conformal piece in $\alpha_s N_f$ piece



[Albacete, Kovchegov]

- scheme dependent definition of ‘subtraction’ piece
  - Balitsky’s (Bal) scheme minimizes ‘subtraction’ contribution

- [other] yet to be numerically computed :: challenging ::

BK evolution with running coupling [Bal scheme]

$$\frac{\partial \mathcal{N}(r,Y)}{\partial Y} = \int d\mathbf{r_1}\, K^{\rm Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) \;\; [\mathcal{N}(r_1,Y) + \mathcal{N}(r_2,Y) - \mathcal{N}(r,Y) - \mathcal{N}(r_1,Y)\mathcal{N}(r_2,Y)]$$

same structure as LO-BK

modified kernel

$$K^{\rm Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

$$\Lambda_{QCD} = 0.241 \text{ GeV}$$

$$\alpha_s(M_Z) = 0.1176$$

- $r < r_{fr}, \quad \alpha_s(r^2) = \dfrac{12\pi}{(11N_c - 2N_f)\,\ln\left(\frac{4\,C^2}{r^2\Lambda_{QCD}^2}\right)}$
- $r > r_{fr}, \quad \alpha_s(r_{fr}^2) \equiv \alpha_{fr} = 0.7$

regulated IR behaviour

C^2 — uncertainty in FT from momentum to coordinate space
:: fit parameter

initial condition[s]

- 2 families of initial conditions
  - generalized with anomalous dimension GBW and MV forms

$$\mathcal{N}^{GBW}(r, Y=0) = 1 - \exp\left[-\left(\frac{r^2\, Q_{s\,0}^2}{4}\right)^{\gamma}\right]$$

$$\mathcal{N}^{MV}(r, Y=0) = 1 - \exp\left[-\left(\frac{r^2 Q_{s\,0}^2}{4}\right)^{\gamma} \ln\left(\frac{1}{r\,\Lambda_{QCD}} + e\right)\right]$$

  - differ in UV behaviour
  - fit parameters
    - ↪ initial saturation scale $Q_{s\,0}^2$
    - ↪ anomalous dimension γ
  - anomalous dimension in GBW form set to one after initial tests

data

- all available $F_2(x,Q^2)$ data [before 'new' combined H1/ZEUS data]
  - with :: $x \leq 10^{-2}$
  - no cut on Q^2 :: $0.045\ \mathrm{GeV}^2 \leq Q^2 \leq 800\ \mathrm{GeV}^2$
- no F_L data included, but shown to be consistent with fit results

- 847 data points
  - statistical and systematic uncertainties added in quadrature
  - normalization uncertainties not considered

- redefinition of Bjorken x as to go smoothly to photoproduction

$$\tilde{x} = x\left(1 + \frac{4m_f^2}{Q^2}\right)$$ with $m_f = 0.14\ \mathrm{GeV}$, only light quarks

summary [for fit]

- F_2 calculated from

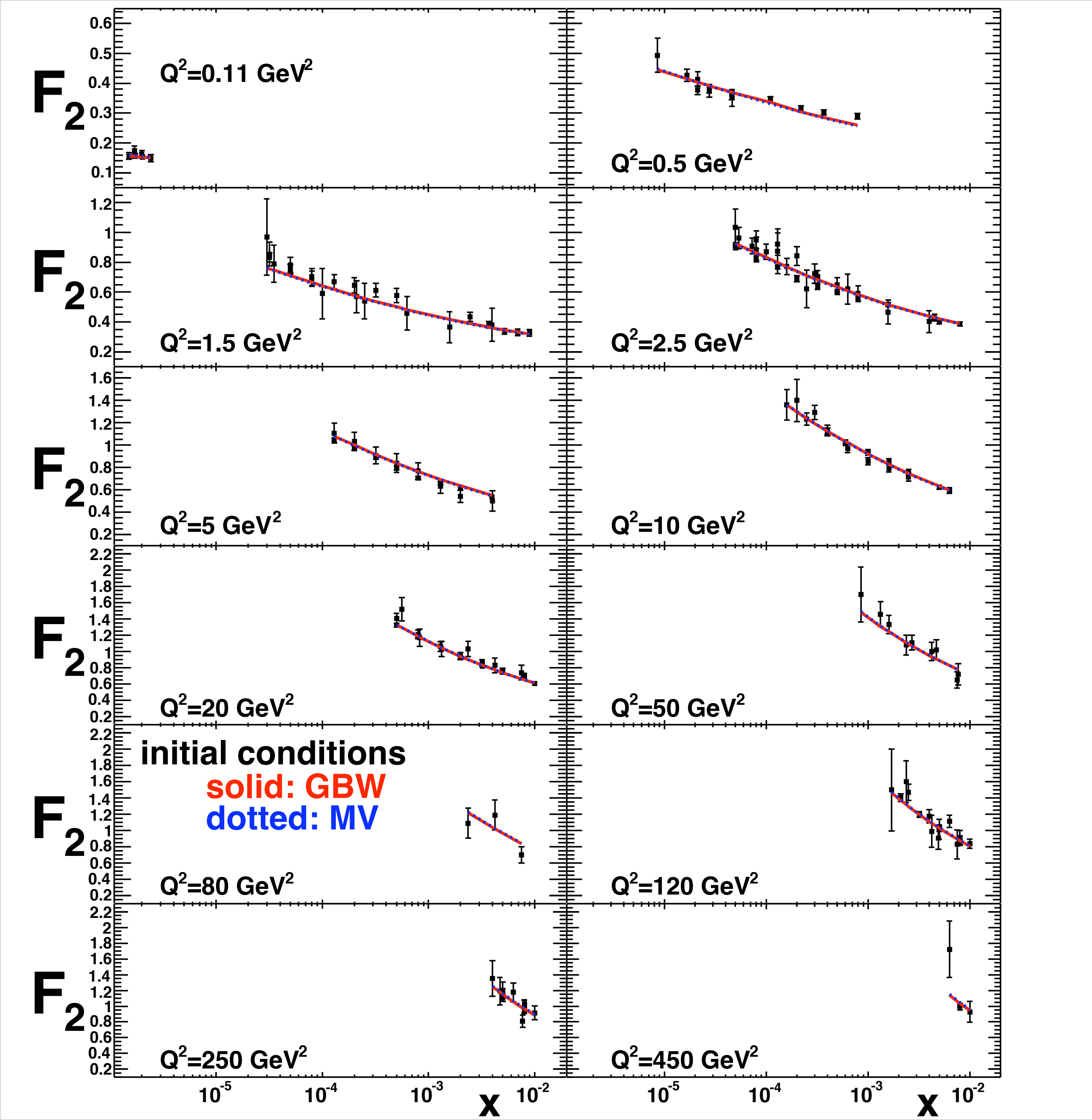
$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,(\sigma_T + \sigma_L)$$

$$\sigma_{T,L}(x,Q^2) = \sigma_0 \int_0^1 dz \int d\mathbf{r}\,|\Psi_{T,L}(z,Q^2,\mathbf{r})|^2\,\mathcal{N}(r,Y)$$

- 4 fit parameters [3 for GBW ic]

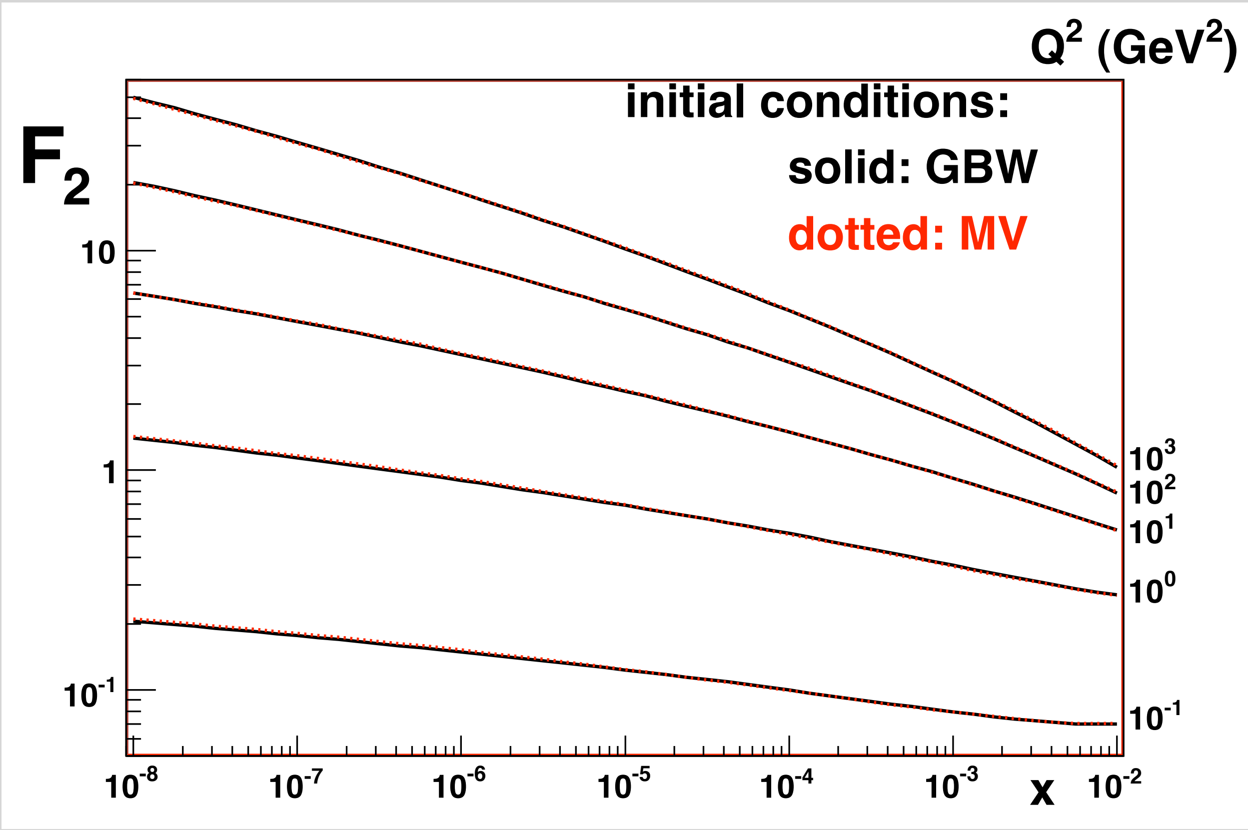
  - total normalization of cross section [b-integration]
  - IR uncertainty in running coupling [from FT]
  - initial saturation scale [in ic]
  - anomalous dimension [in ic] :: MV only

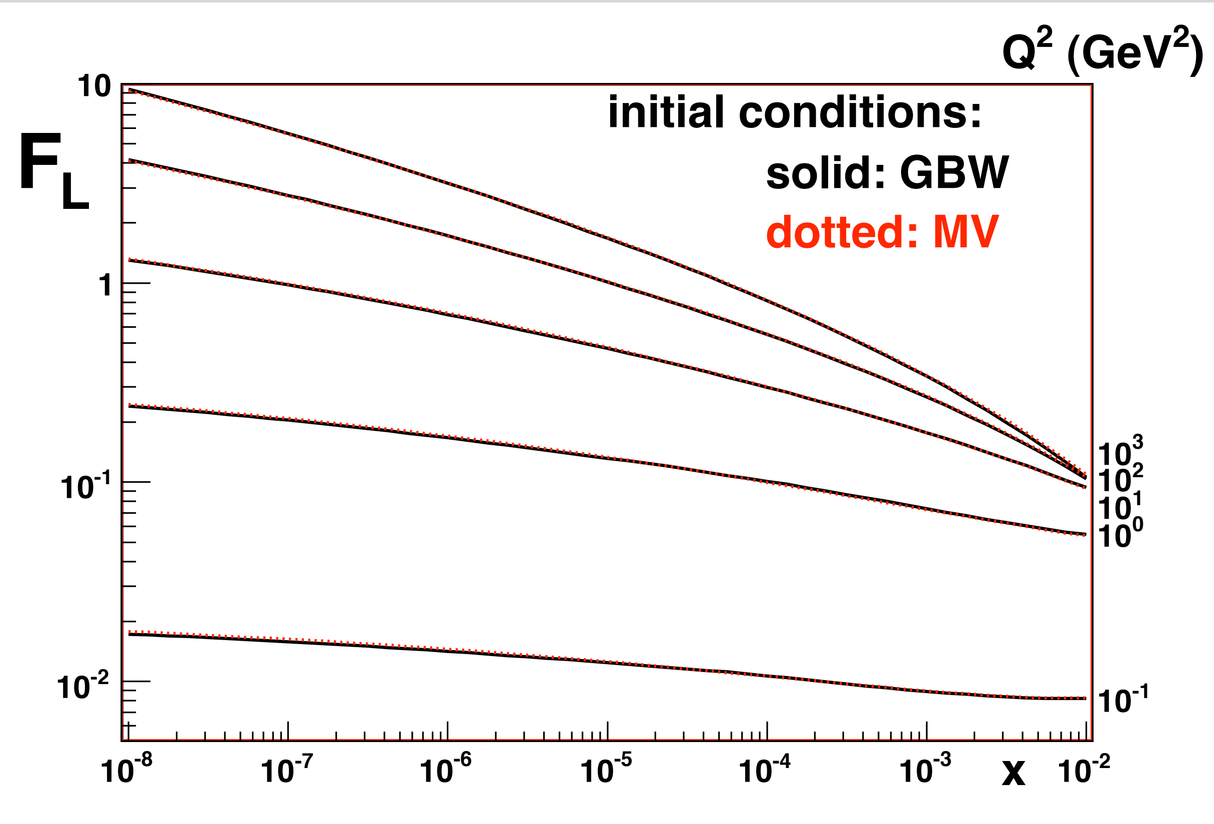
fit results



Initial condition	σ_0 (mb)	Q^2_{s0} (GeV^2)	C^2	γ	χ^2/d.o.f.
GBW	31.59	0.24	5.3	1 (fixed)	916.3/844=1.086
MV	32.77	0.15	6.5	1.13	906.0/843=1.075

predictions

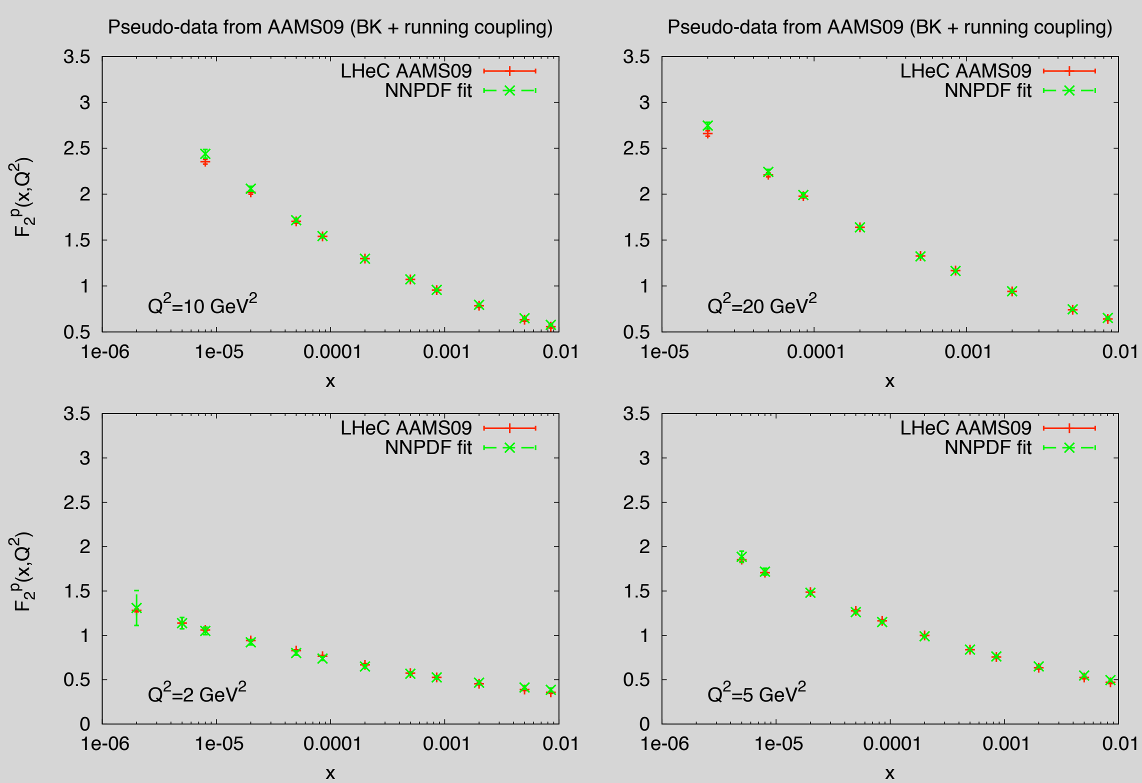


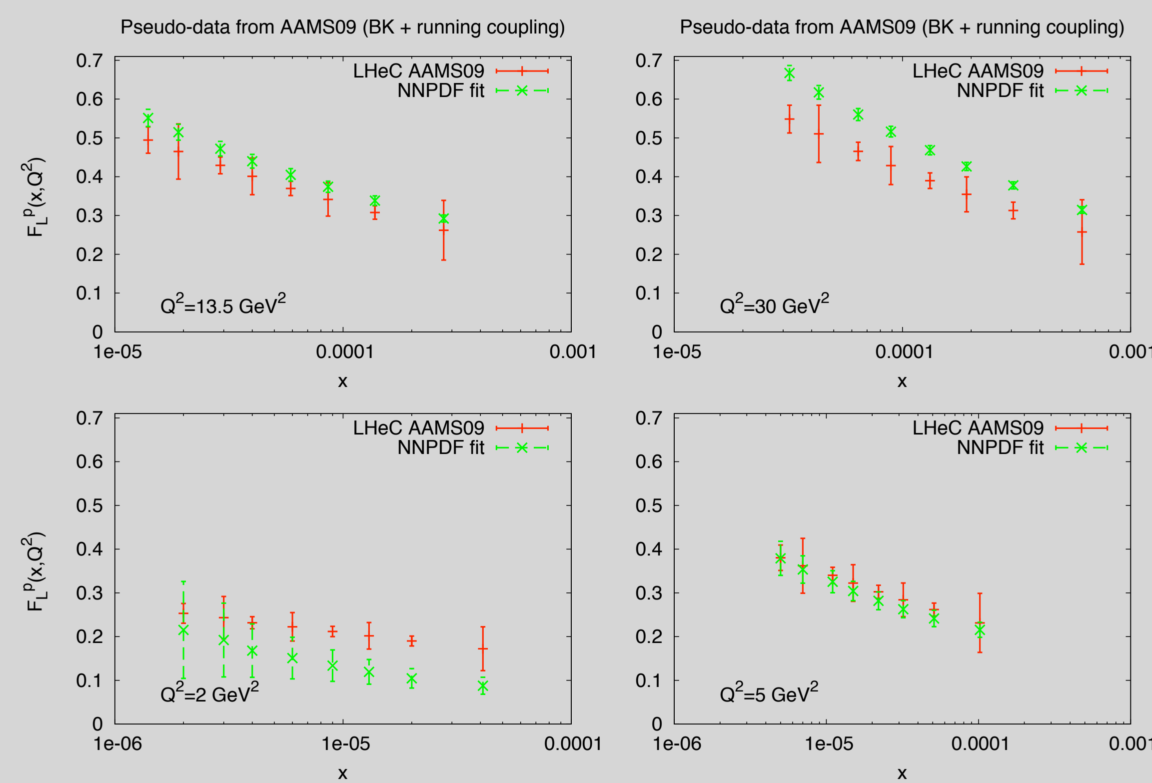


- F_2 and F_L extrapolated to LHeC and UHECR kinematical conditions
  - near independence on [tested] initial conditions
  - first principle approach allows for credible extrapolation
    - ↪ 'all' relevant physics included

vs. DGLAP

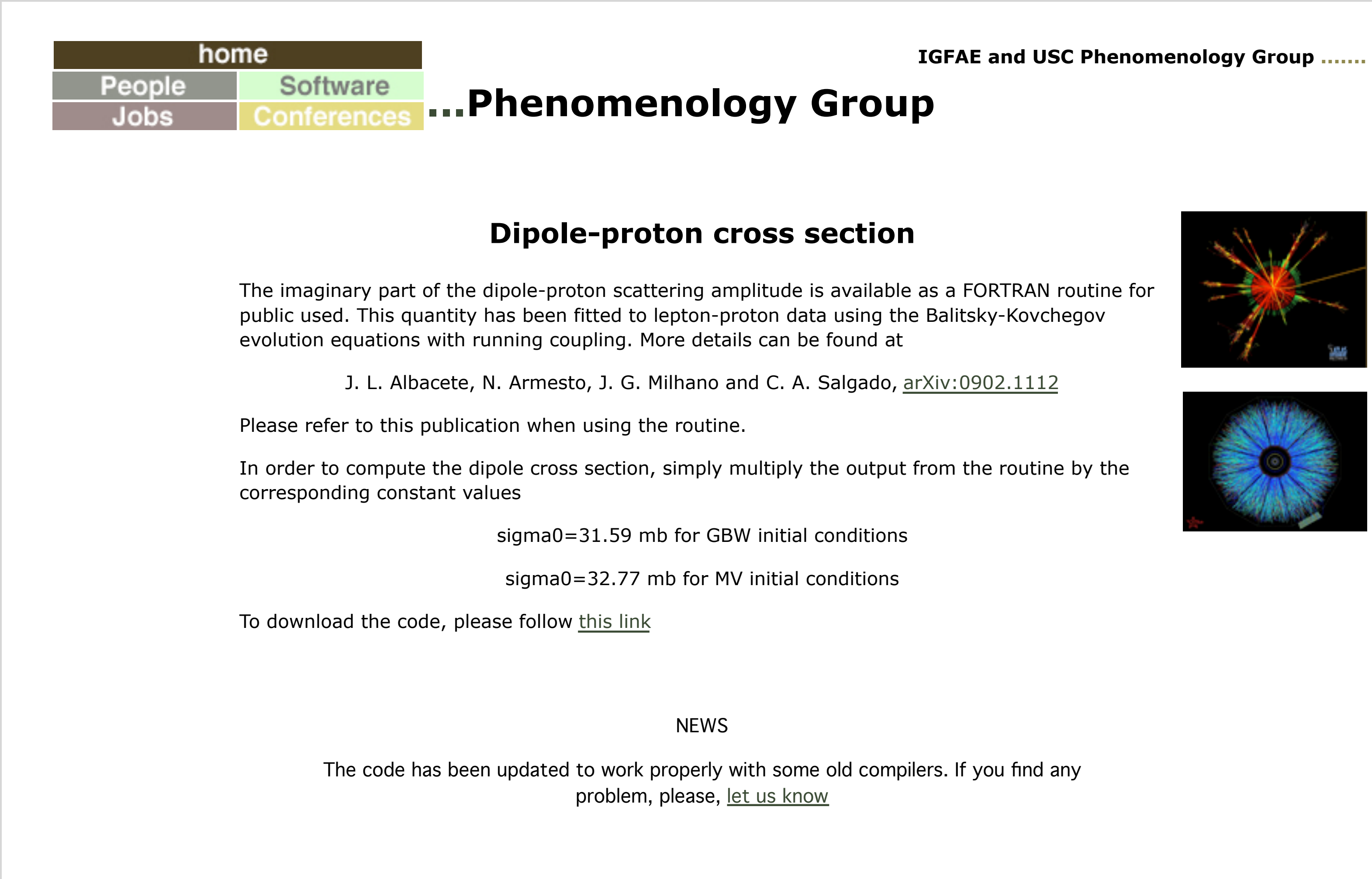
- AAMS F_2 and F_L cannot be fitted by NLO-DGLAP





- i.e., pseudo-data (for LHeC) generated from AAMS is inconsistent with NLO-DGLAP
- differences cannot be absorbed into initial condition

current release :: AAMS 1.0 ::



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Dipole-proton cross section

The imaginary part of the dipole-proton scattering amplitude is available as a FORTRAN routine for public used. This quantity has been fitted to lepton-proton data using the Balitsky-Kovchegov evolution equations with running coupling. More details can be found at

J. L. Albacete, N. Armesto, J. G. Milhano and C. A. Salgado, arXiv:0902.1112

Please refer to this publication when using the routine.

In order to compute the dipole cross section, simply multiply the output from the routine by the corresponding constant values

sigma0=31.59 mb for GBW initial conditions

sigma0=32.77 mb for MV initial conditions

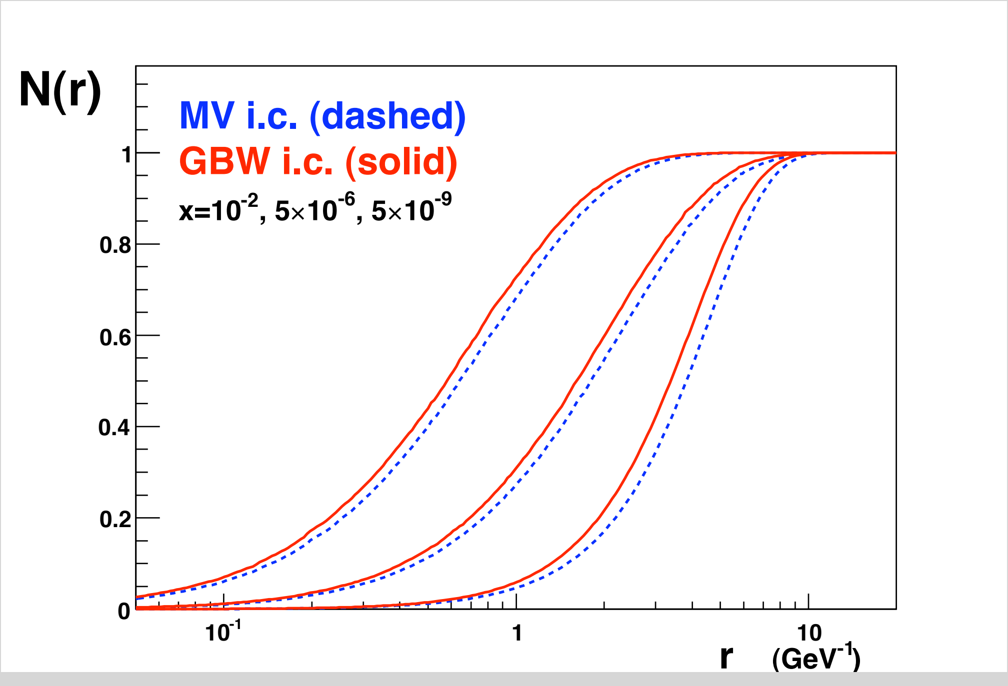
To download the code, please follow this link

NEWS

The code has been updated to work properly with some old compilers. If you find any problem, please, let us know

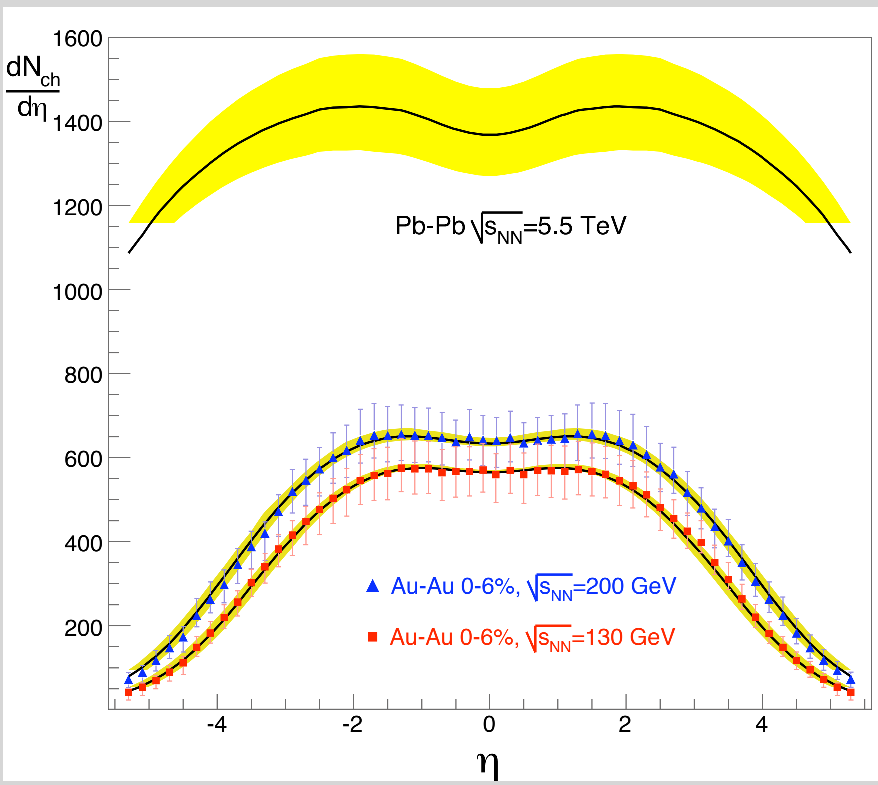
http://www-fp.usc.es/phenom/rcbk/

$$10^{-12} \leq x \leq 10^{-2}$$



also used in ...

- mid-rapidity multiplicities in AA *[Albacete PRL 99, 262301]*
  - preceded present work



$$\frac{dN_{ch}}{dy\,d^2b} = C\frac{4\pi N_c}{N_c^2-1}\int\frac{d^2p_t}{p_t^2}\int^{p_t} d^2k_t\,\alpha_s(Q)\;\varphi\left(x_1,\frac{|\underline{k_t}+\underline{p_t}|}{2}\right)\varphi\left(x_2,\frac{|\underline{k_t}-\underline{p_t}|}{2}\right)$$

$$\varphi(Y,k) = \int\frac{d^2r}{2\pi\,r^2}\exp\{i\,\underline{r}\cdot\underline{k}\}\,\mathcal{N}(Y,r)$$

- diffractive and forward hadron production in pp *[Betemps, Gonçalves and Santana Amaral]*
- hadron and direct photon production in ep and pA *[Rezaeian and Schafer]*
- long range 2-particle rapidity correlation in AA *[Dusling, Gelis, Lappi and Venugopalan]*
- single inclusive hadron production in pp, pA and AA *[Albacete and Marquet]*

⟳ new release [AAMQS] :: very soon

- proton
  - include H1/ZEUS combined data
    - ↪ fit reduced cross-section directly [much better, extraction indep.]
  - include F_2^{charm} and F_2^{beauty} data
  - include heavy quarks in calculation
  - improved treatment of running coupling
    - ↪ matched over mass thresholds
  - NO EXTRA PARAMETERS

- nuclei
  - direct fit of nuclear DIS data with proton parameters [2 nuclear params]

$$Q^2_{s,A} = c\, A^{\delta}\, Q^2_{s,p}$$

harder...

- impact parameter dependence [for both nuclei and proton]
  - access to diffractive and non-inclusive observables
  - centrality dependence for AA

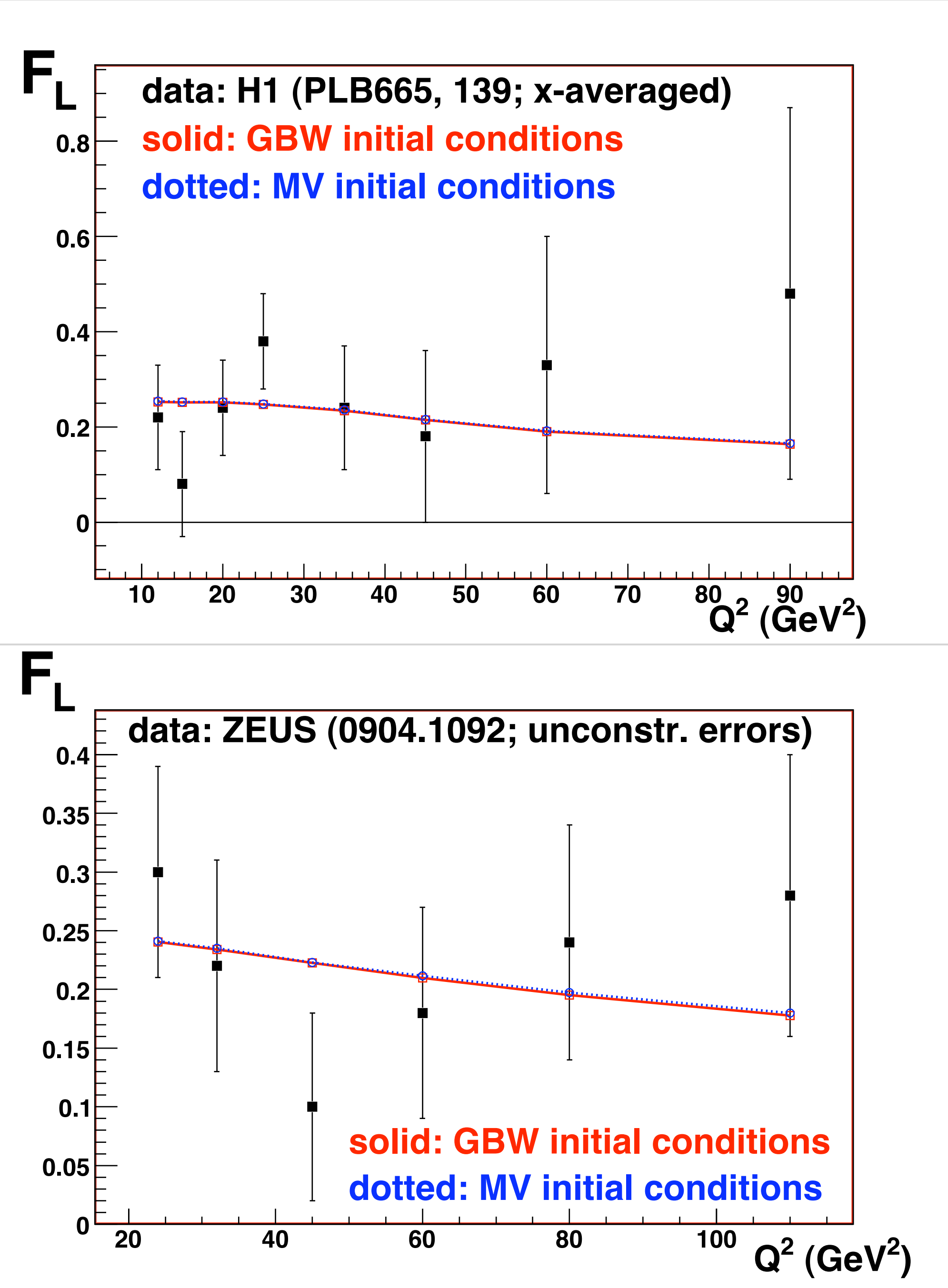
- speculative...
  - extract integrated [standard] gluon distribution
    - $\hookrightarrow$ no unique meaningful procedure

abstract

- small-x effects cannot be neglected at the LHC [and more so for nuclei]
- DGLAP is not an appropriate tool to address small-x physics
- useful, phenomenologically usable, parametrizations can be obtained within k_t factorized approach
- they are easy to use...

backups

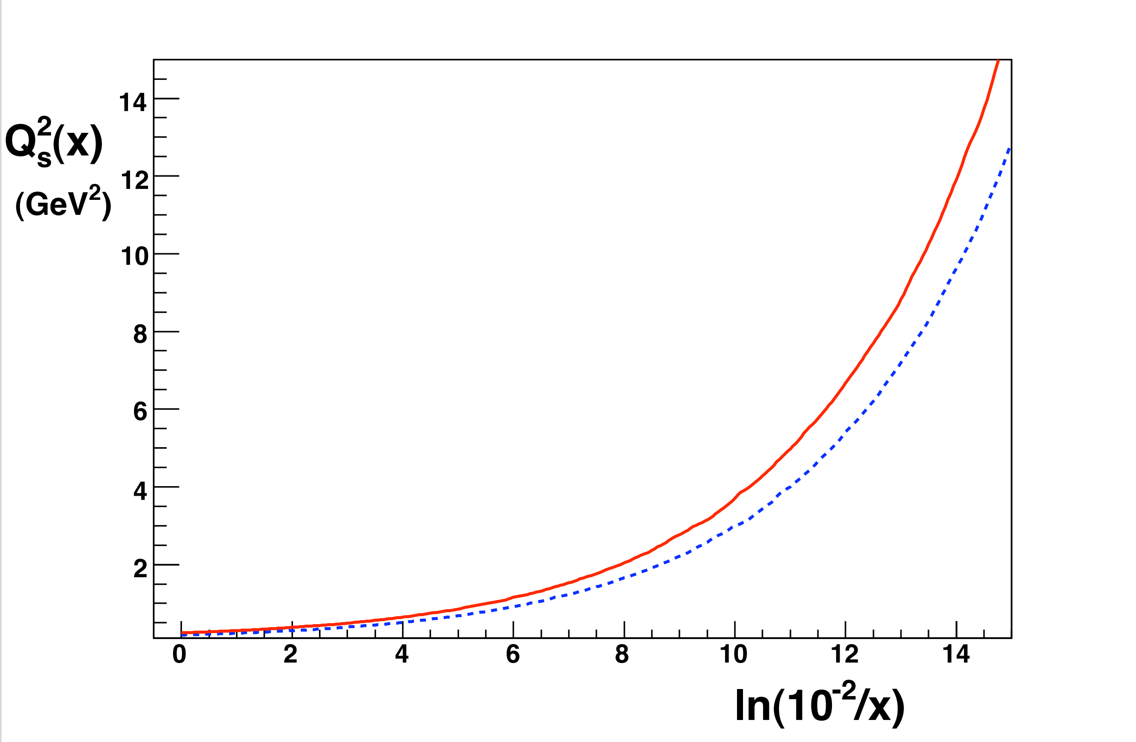
F_L



$$F_L(x, Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,\sigma_L$$

- F_L data not included in the fit
  - consistently described [error bars too large for meaningful statement]

saturation momentum, geometric scaling



$$\mathcal{N}(r = 1/Q_s(x), x) = 1 - \exp\left[-1/4\right]$$

- large [perturbative] saturation scale for forward region in pp at the LHC

$$x = (2\,M/\sqrt{s})e^{-y} \qquad Q_s^2 \simeq 3 \div 4\ \mathrm{GeV}^2 \qquad y = 6$$

- geometric scaling in DGLAP ?? [no scale]