Deep inelastic scattering off nucleons and nuclei

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Work done in collaboration with:
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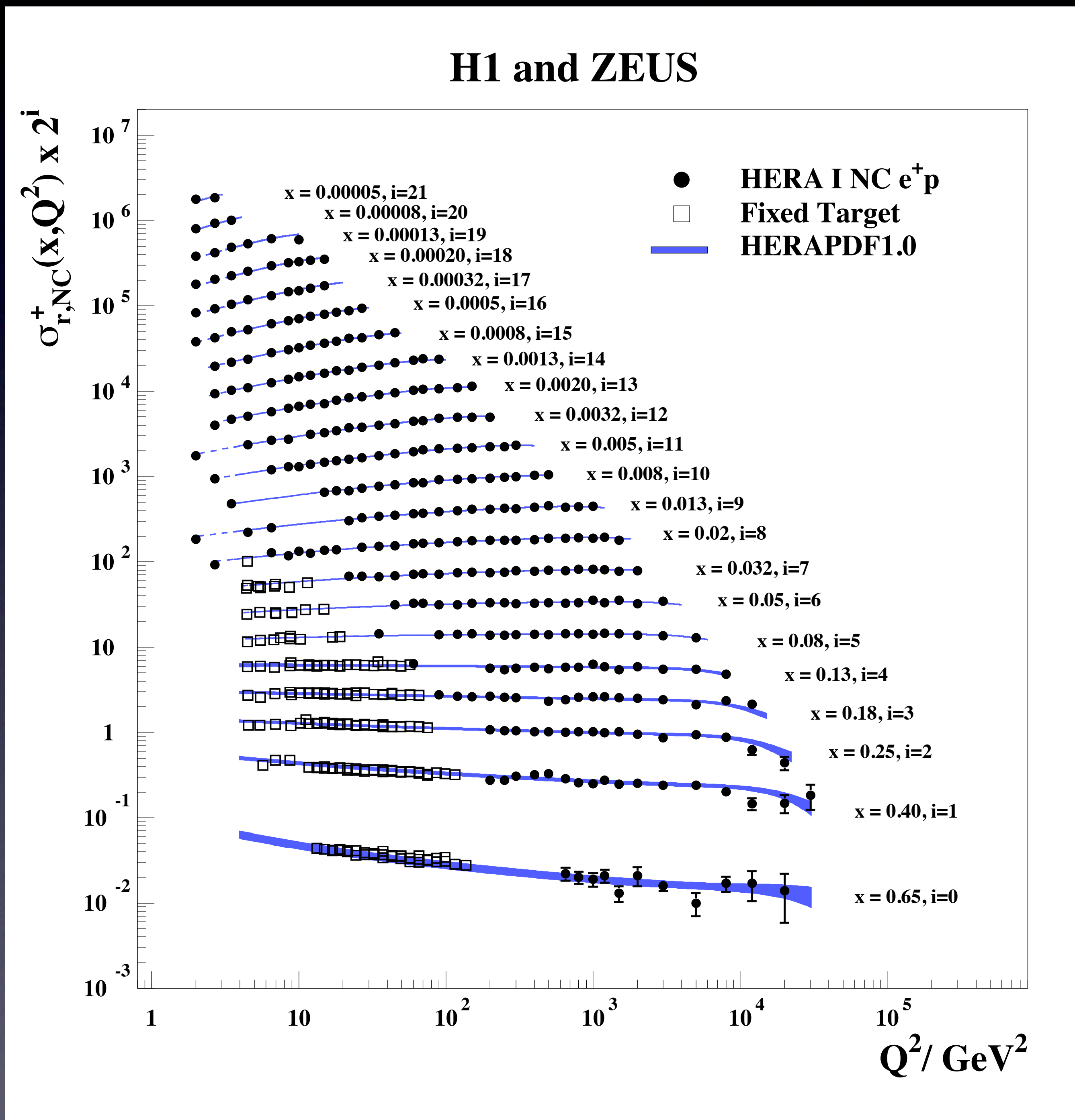
Outline

- ✓ a picture of strong interactions
- ✓ γp and γA interactions
- ✓ structure functions at low-x and high-Q^2
  - — total inclusive F_2
  - — longitudinal F_L
  - — diffractive $x_P F_{2D}^{(3)}$
- ✓ outlook

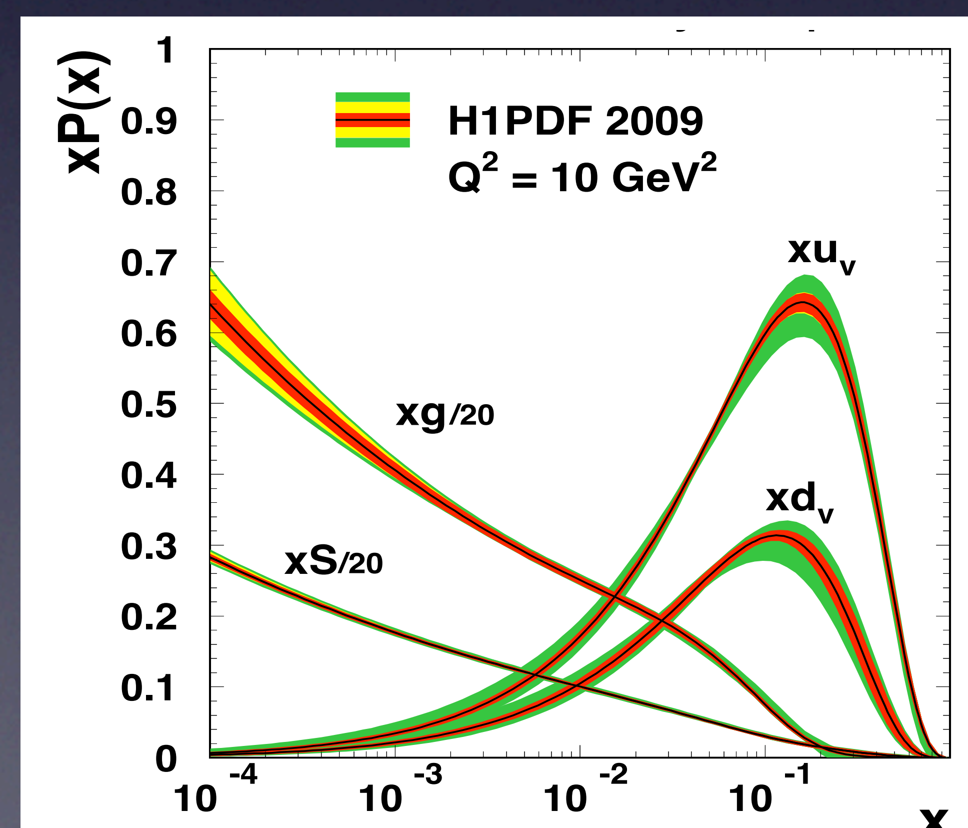
Q/A from DIS

- ✓ how does QCD behave at high energies?
  - what are the fundamental degrees of freedom?
- ✓ what is the hadronic wave function at small momentum fractions?
- ✓ how fast can cross sections grow?
- ✓ what are the initial conditions in heavy-ion collisions?

Experimental status



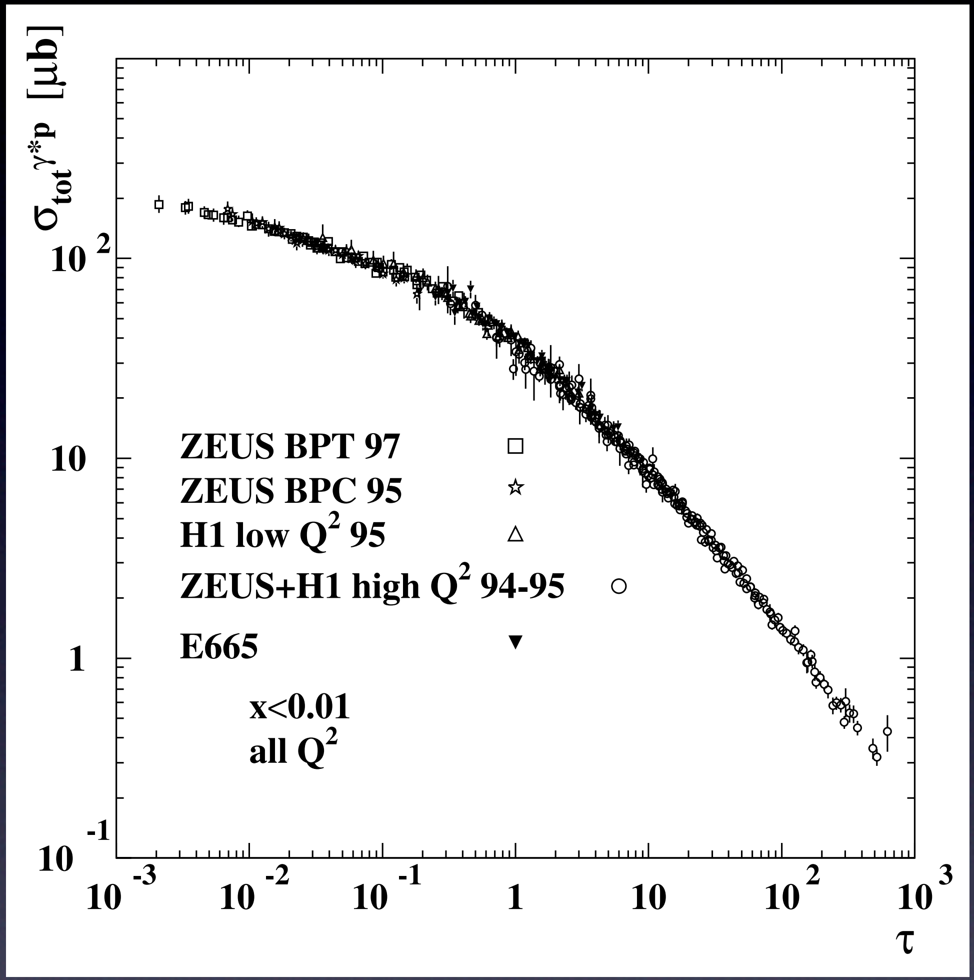
- ✓ at low scales
  - Bjorken scaling
- ✓ higher Q^2
  - QCD scaling violations
  - gluon dominated low-x



Signals of saturation?

- ✓ geometric scaling in γp collisions
  - λ ~ 0.25-0.3
  - similar scaling in γA!
  - breakdown of DGLAP equations at low Q^2?
  - no definite answers
  - yet!
- ✓ RHIC forward rapidity suppression, charm etc...

$$\boxed{x < 1/m_N R_N \sim 0.1}$$



$$\tau = \frac{Q^2}{Q_s^2(x)} \qquad Q_s^2(x) = \left(\frac{x_0}{x}\right)^\lambda$$

Stasto, Golec-Biernat, Kwiecinski PRL 86 (2001) 596
Freund, Rummukainen, Weigert, Schafer PRL 90 (2003)
Marquet, Schoeffel PLB 639 (2006) 471
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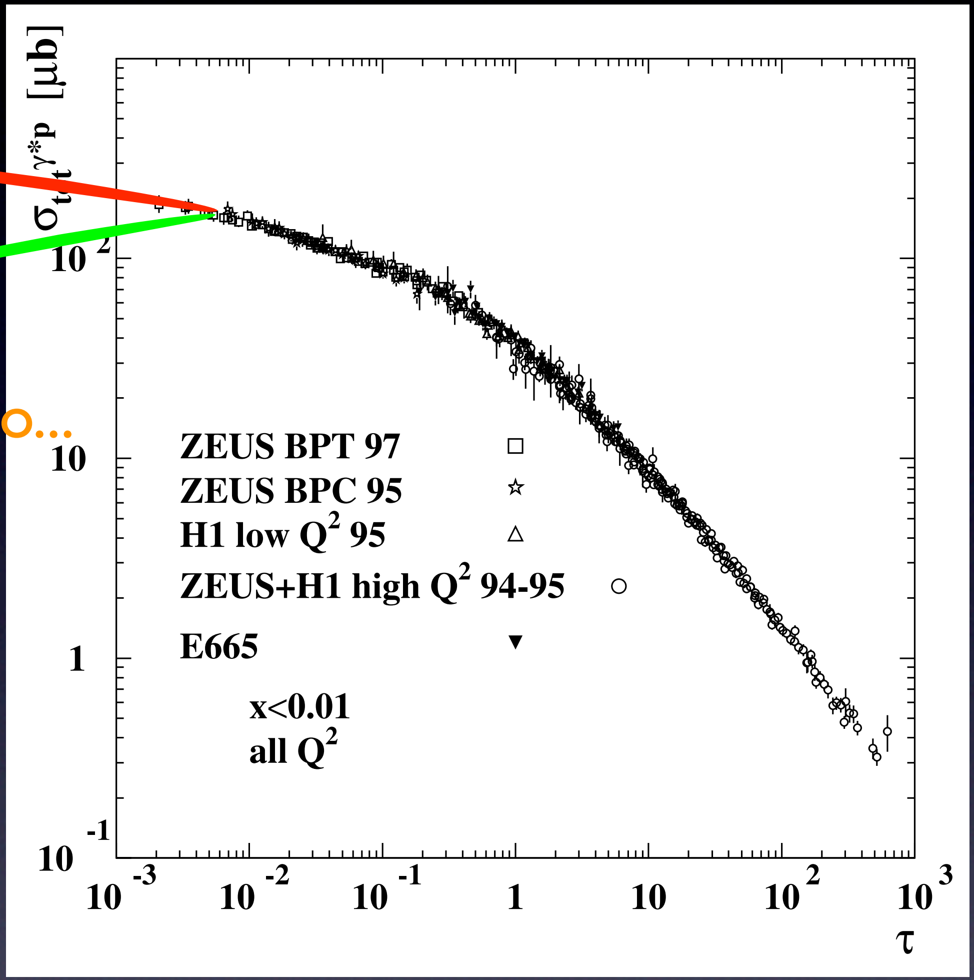
SAT

DGLAP

Forte, Caola, Rojo...



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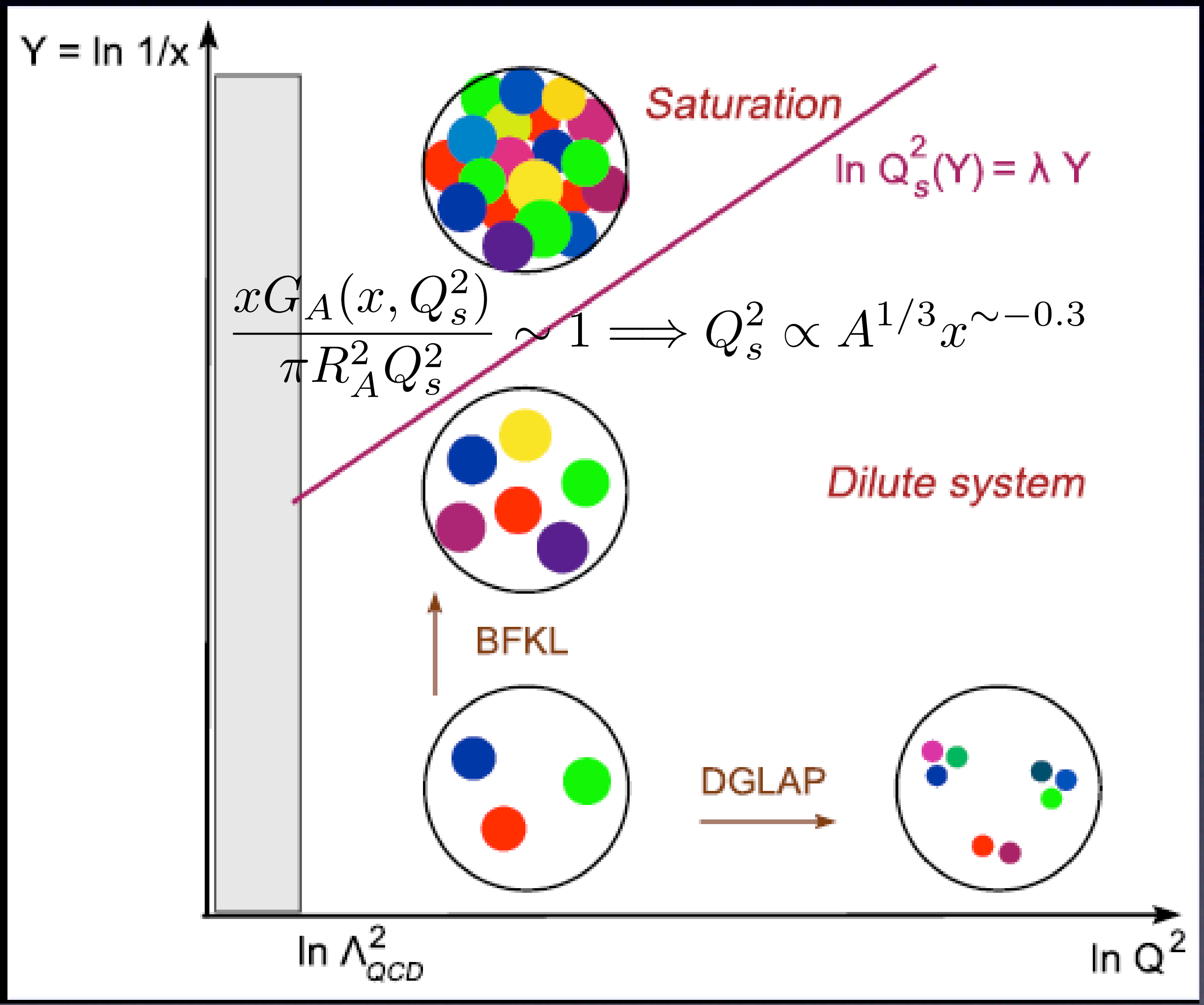
QCD "phase" diagram

- ✓ evolution equations govern the change along two directions
  - DGLAP in $\ln(Q^2)$
  - BFKL in $\ln(1/x)$
- ✓ at some density
  - linear terms ~ non-linear terms
  - recombination of gluons
  - saturation of parton density
- ✓ introduction of a new scale!
  - typical configurations of the probe still remain perturbative



Gribov, Levin, Ryskin PR 100 (1983) 1
Mueller, Qiu NPB 291 (1986) 427

Saturation physics

- ✓ semiclassical treatment of hadronic wave function
  - CGC
  - initial condition: MV, ...
- ✓ JIMWLK equation
  - dilute-dense solution → extension?
- ✓ equivalent to BK equation
  - neglecting higher-order correlators (1-2% effect)

- numerical trea[...] feasible
- scaling solution
- ✓ running coupling effects of higher order, but prove to be numerically important!
  - slowing down of evolution
- ✓ impact parameter dependence
- ✓ stronger effect in nuclear collisions, density ~ $A^{1/3}$

violation of Froissart bound not equal to violation of unitarity...

since the theory is massless it violates the Froissart!!!

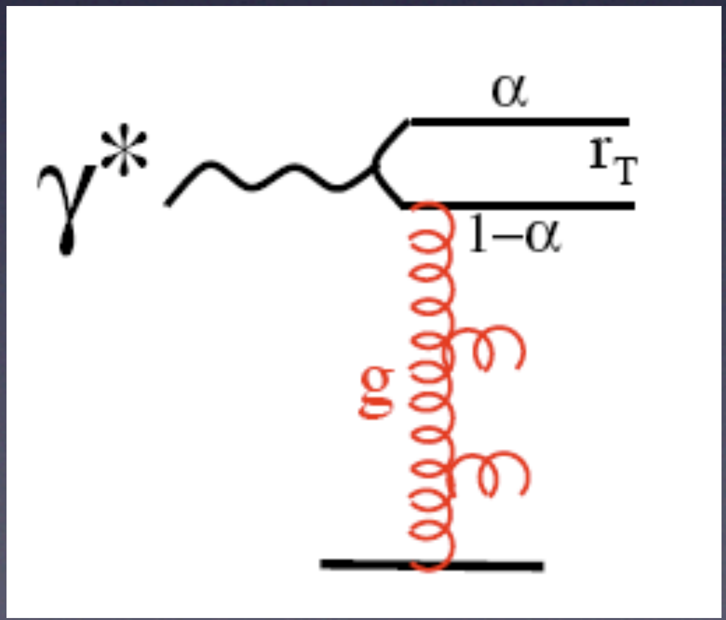
McLerran, Venugopalan, Jalilian-Marian, Iancu, Weigert, Leonidov, Kovner, Lublinsky, Wiedemann, Balitsky, Kovchegov, Mueller, Albacete, Armesto, Salgado, Ferreiro...

The color dipole model

$$\sigma^{(tot)}(s, Q^2) = \sum_{T,L} \int_0^{r_0} dr \int_0^1 dz \left|\psi^{T,L}(r,z)\right|^2 \sigma_S(r,s,Q^2)$$

$$\left|\psi^T(r,z)\right|^2 = \frac{6\alpha_{e.m.}}{4\pi^2} \sum_q e_q^2 \left[z^2 + (1-z)^2\epsilon^2 K_1^2(\epsilon r) + m_q^2 K_0^2(\epsilon r)\right]$$

$$\left|\psi^L(r,z)\right|^2 = \frac{6\alpha_{e.m.}}{4\pi^2} \sum_q e_q^2 \left[4Q^2 z^2 + (1-z)^2 K_0^2(\epsilon r)\right]$$



Mueller; Nikolaev, Zakharov...

- valid for high energies = small-x
- flexible framework
- QCD properties
  - Bjorken scaling & violations!
  - color transparency ($\sigma_{\gamma p} \sim r^2$)

Dipole-target cross section

Nikolaev, Zakharov Z

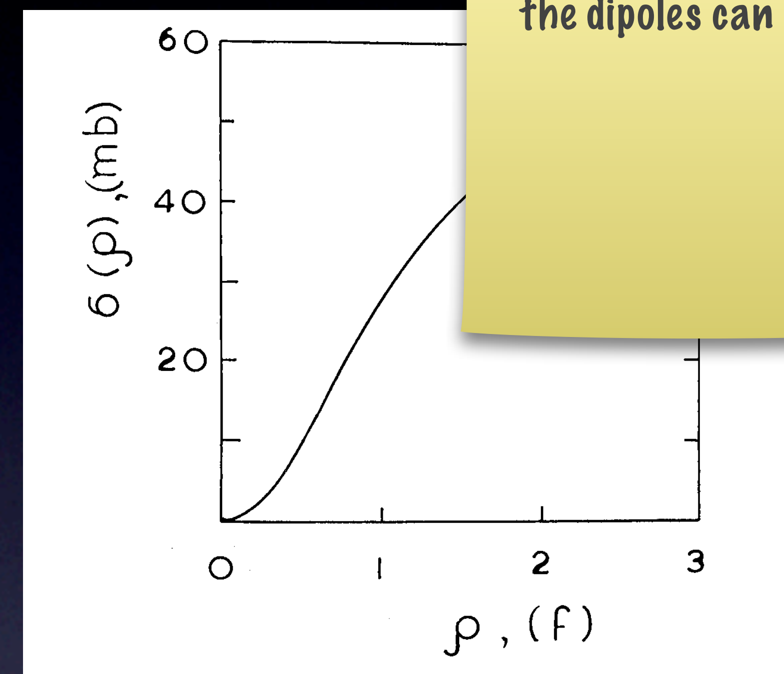
there is no cut-off on the size of dipoles in GBW.. the dipoles can be huge...

- ✓ simplest model: two-gluon exchange
  - gluon mass gives a cut-off in r
- ✓ damping dependent on x
  - GBW model

$$\sigma_S = \sigma_0 \left(1 - \exp\left[-r^2 Q_s^2(x)/4\right]\right)$$

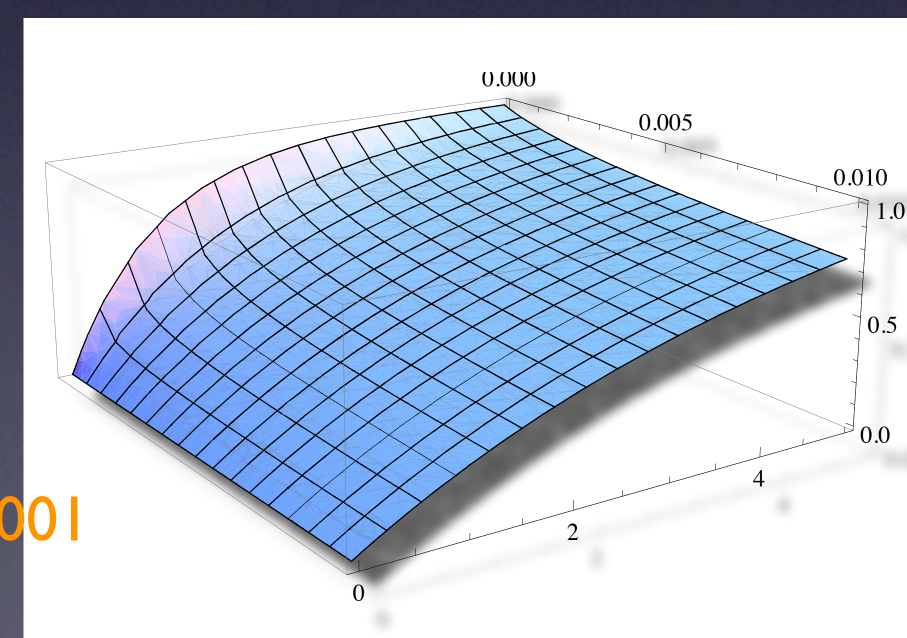
$$Q_S(x) = 1 \text{ GeV} \times \left(x/x_0\right)^{-\lambda/2}$$

Golec-Biernat, Wüsthoff PRD 59 (1998) 014017
Golec-Biernat, Wüsthoff PRD 60 (1999) 114023



- ✓ improvement I: QCD scaling included
- ✓ improvement II: b-dependence

Bartels, Golec-Biernat, Kowalski PRD 66 (2002) 014001
Kowalski, Teaney PRD 68 (2003) 114005
Kowalski, Motyka, Watt PRD 74 (2006) 074016



T	$\|\psi\|^2$	σ	$\langle\sigma\rangle$
hard	1	$1/Q^2$	$1/Q^2$
soft	m^2/Q^2	σ_h	$1/Q^2$

σ^{tot}

Bjorken, Kogut PRD 8 (1973) 1341
Nikolaev, Zakharov ZPC 49 (1991) 607

	T	$\lvert\psi\rvert^2$	σ	$\langle\sigma\rangle$	L	$\lvert\psi\rvert^2$	σ	$\langle\sigma\rangle$
σ^{tot}	hard	1	$1/Q^2$	$1/Q^2$	hard	1	$1/Q^2$	$1/Q^2$
	soft	m^2/Q^2	σ_h	$1/Q^2$	soft	m^4/Q^4	σ_h	$1/Q^4$

Bjorken, Kogut PRD 8 (1973) 1341
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σ^{tot}	T	$|\psi|^2$	σ	$\langle\sigma\rangle$	L	$|\psi|^2$	σ	$\langle\sigma\rangle$
	hard	1	$1/Q^2$	$1/Q^2$	hard	1	$1/Q^2$	$1/Q^2$
	soft	m^2/Q^2	σ_h	$1/Q^2$	soft	m^4/Q^4	σ_h	$1/Q^4$

σ^D	T	$|\psi|^2$	σ^2	$\langle\sigma^2\rangle$	L	$|\psi|^2$	σ^2	$\langle\sigma^2\rangle$
	hard	1	$1/Q^4$	$1/Q^4$	hard	1	$1/Q^4$	$1/Q^4$
	soft	m^2/Q^2	σ_h^2	$1/Q^2$	soft	m^4/Q^4	σ_h^2	$1/Q^4$

Bjorken, Kogut PRD 8 (1973) 1341
Nikolaev, Zakharov ZPC 49 (1991) 607

Motivation

diffraction involves non-forward BK equation... non-forward amplitudes are much harder to compute..

✓ saturation relevant @ HERA & RHIC...

— essential for extrapolation to LHC, EIC

✓ CGC/saturation provides 1st principle theoretical framework, but

— several observables are hard to calculate

— diffraction...

— non-perturbative effects (b-dependence)

Motivation

✓ factorization framework..?

— comparison between eRHIC & RHIC

— universal treatment of observables

> DIS: inclusive, longitudinal, diffractive (coherent & incoherent), inclusive spectra

> HI: initial condition, parton densities, UPC

✓ saturation ⇔ multiple scattering

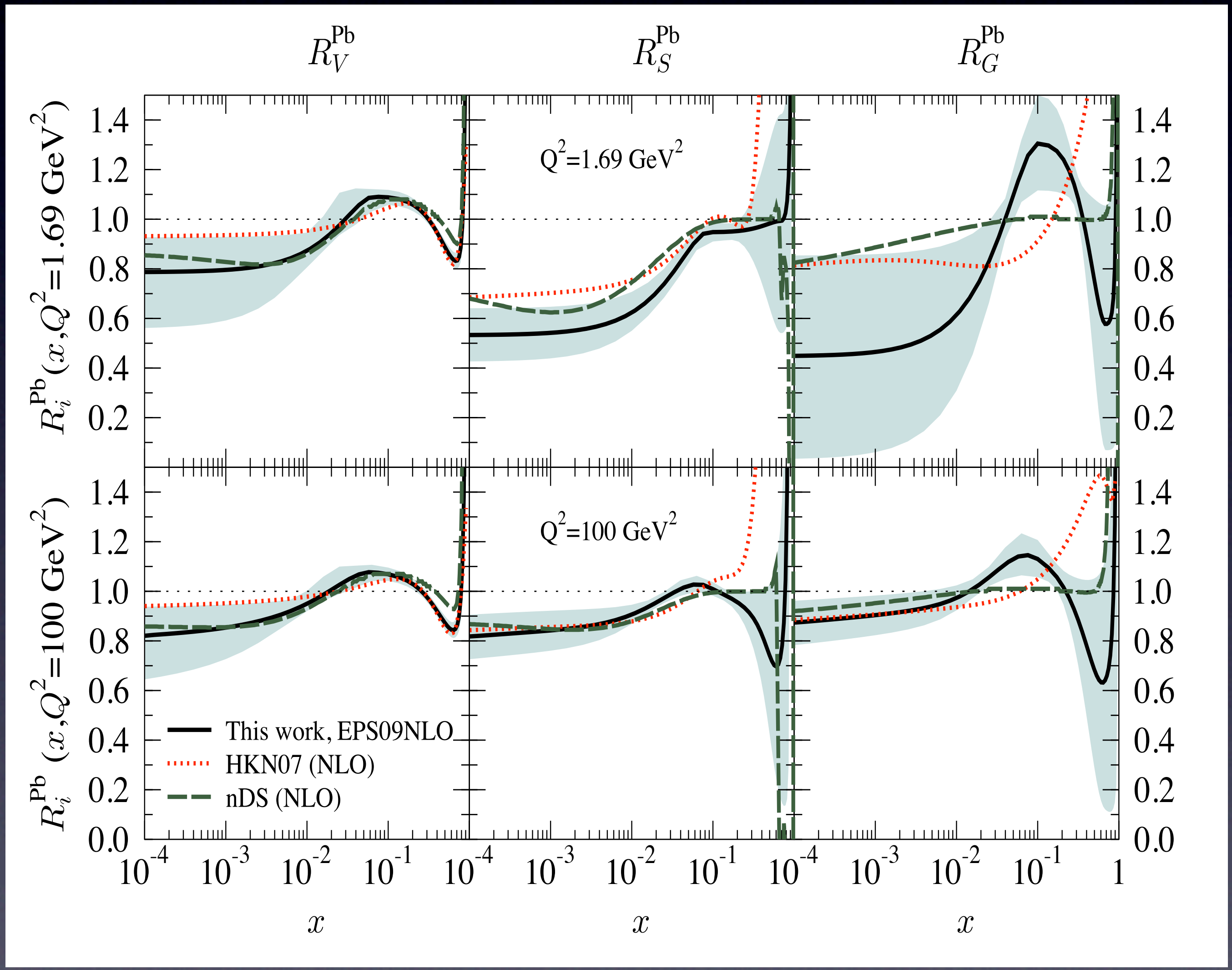
— simpler treatment extensively tested

— prescription: AGK cutting rules

Motivation

also tested in MC codes!
- QGSM
- DPM
- DPMJET
- etc..

NLO analysis for hA



Eskola, Paukkunen, Salgado JHEP 0904:065 (2009)
de Florian, Sassot, Hirai, Kumano, Nagai....

- ✓ Reggeon calculus and Glauber-Gribov theory a controllable framework!
  - connection between Gribov ideas ('60) and pQCD
- ✓ simple to calculate
- ✓ b-dependence
- ✓ give good estimates

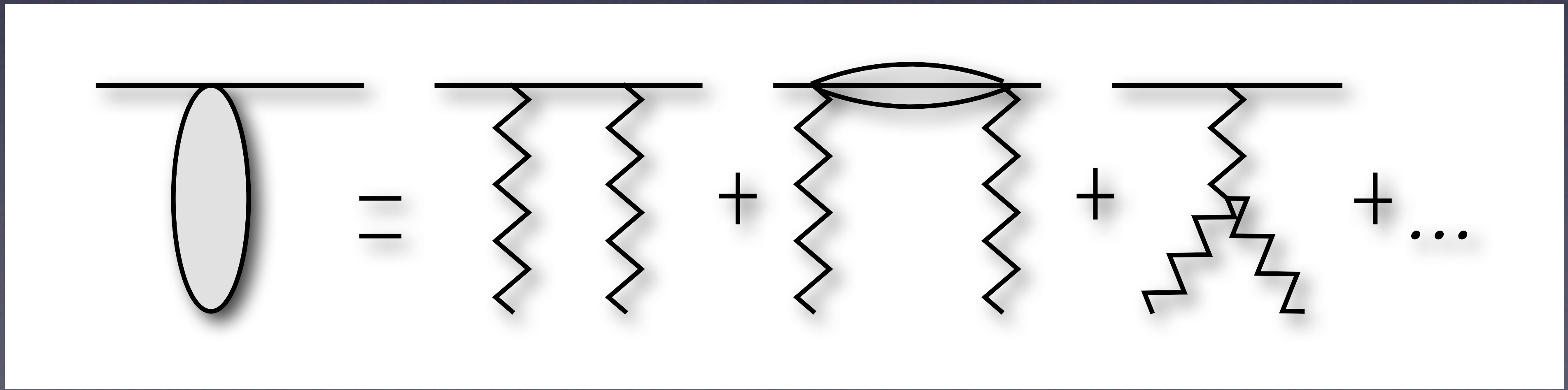
Model for γp interacti

Capella, Ferreiro, Kaidalov, Salgado NPB 593 (2001) 336, PRD 6
Armesto, Kaidalov, Salgado, Tywoniuk (in preparation...)

size of diffraction gives amount of rescattering/ saturation

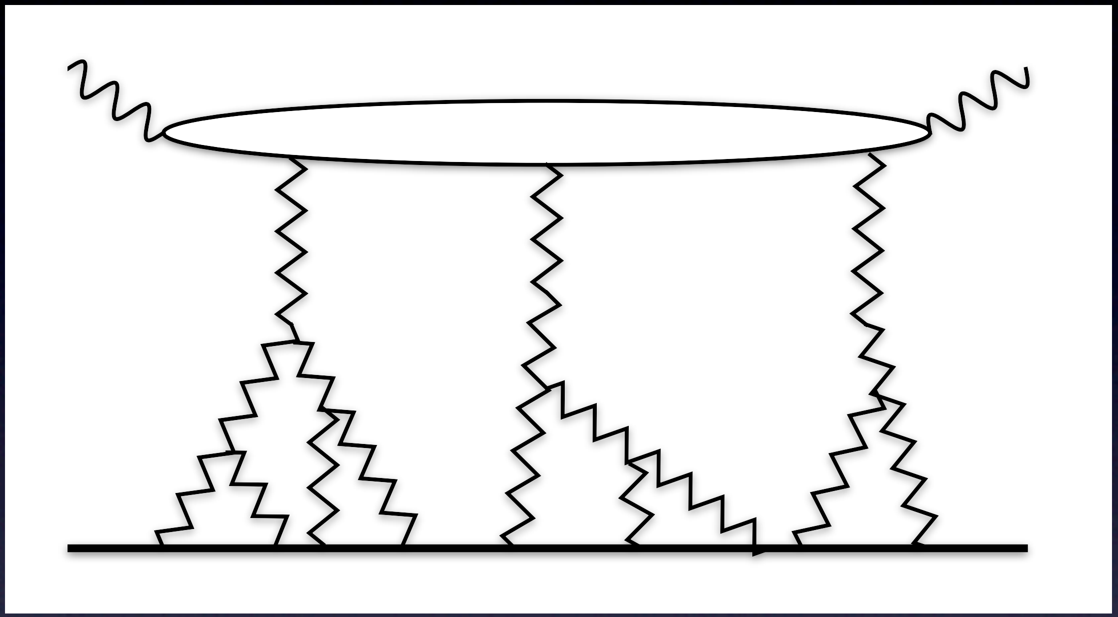
3P couple to L and S component

- ✓ Multi-reggeon interactions → unitarity
- ✓ two-components: large (non-perturbative) & small (dipole)
- ✓ describes simultaneously inclusive and diffractive DIS
  - — saturation linked to diffraction through unitarity
- ✓ valid for $x < 0.01$ and $0 < Q^2 < 10$ GeV^2



Multi-reggeon exchanges

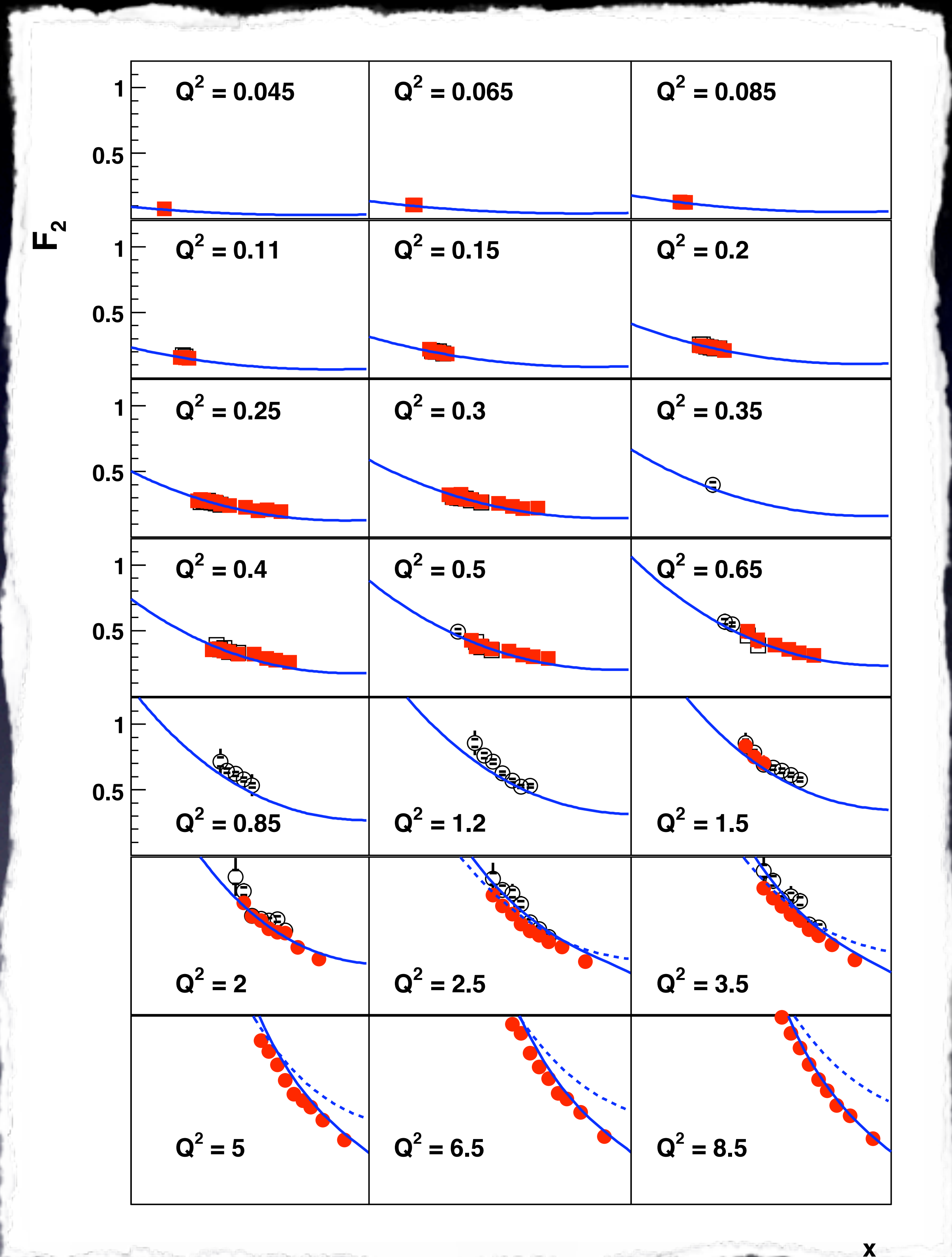
- ✓ exchanged objects are
  - — reggeon
  - — pomeron
- ✓ fixed parameters taken from hadronic analysis
- ✓ pQCD effect taken into account in S residue
- ✓ model valid for photoproduction Q^2=0
- ✓ cut-off on large dipoles is 0.2-0.25 fm

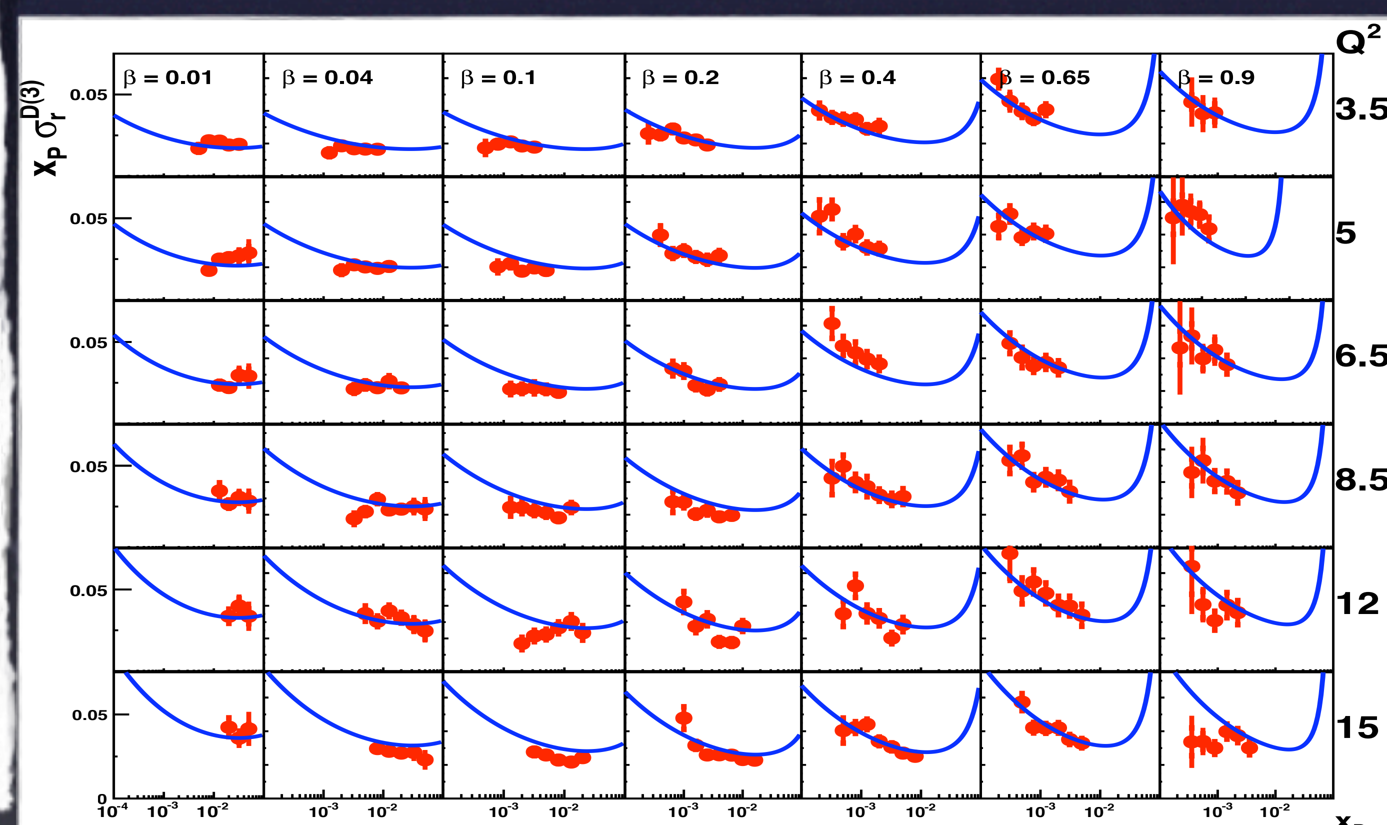


$$\chi^P_{i0}(b,\xi) = \frac{C_i^P\, f(r)}{\lambda^i_{0P}(\xi)} \exp\left(\Delta_P \xi - \frac{b^2}{4\lambda^i_{0P}(\xi)}\right)$$

$$f(r) = \begin{cases} 1 & \text{i=L} \\ r^2 & \text{i=S} \end{cases}$$

$$\xi = \ln\left[\frac{s+Q^2}{s_0+Q^2}\right]$$





in the left plot, the dotted curve is the original CFSK model for high-Q2 bins!!!!

✓9 parameters fixed ... low-Q^2 data

✓Agreement with data < 4 GeV^2 good!

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Partonic decomposition of CFSK

- ✓ identify different reggeon exchanges as contribution to initial valence and sea quark PDFs
- ✓ need also extension to high-x — Capella, Kaidalov, Merino, Tran...

$$xu_V(x,Q_0^2) \;=\; 2F_{2\,R}^{low-x}(x,Q_0^2)\;(1-x)^{n(Q_0^2)}$$

$$xd_V(x,Q_0^2) \;=\; F_{2\,R}^{low-x}(x,Q_0^2)\;(1-x)^{n(Q_0^2)+1}$$

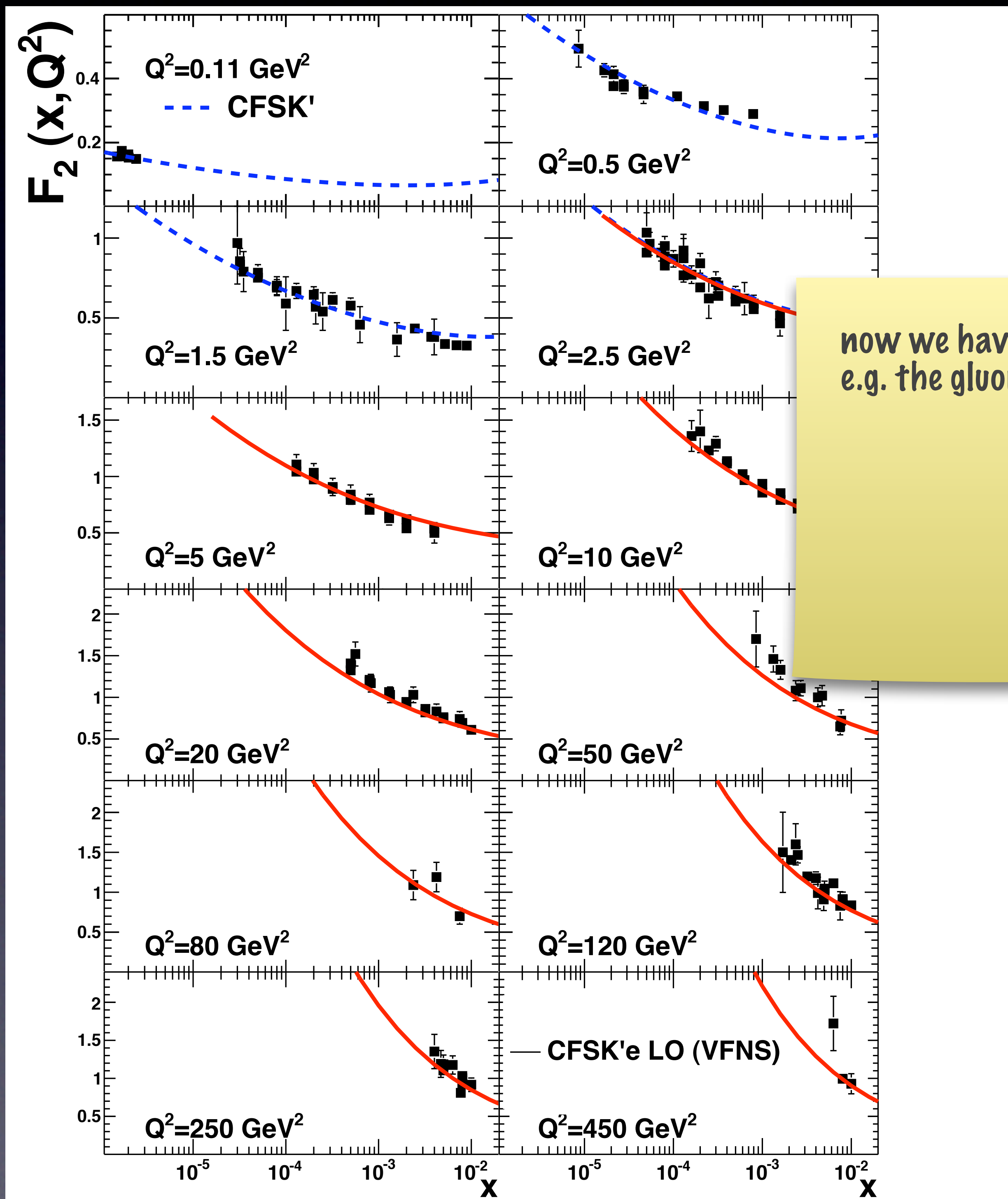
$$xS(x,Q_0^2) \propto F_{2\,tot}^{low-x}\Big|_{R=0}\;(1-x)^{n(Q_0^2)+4}$$

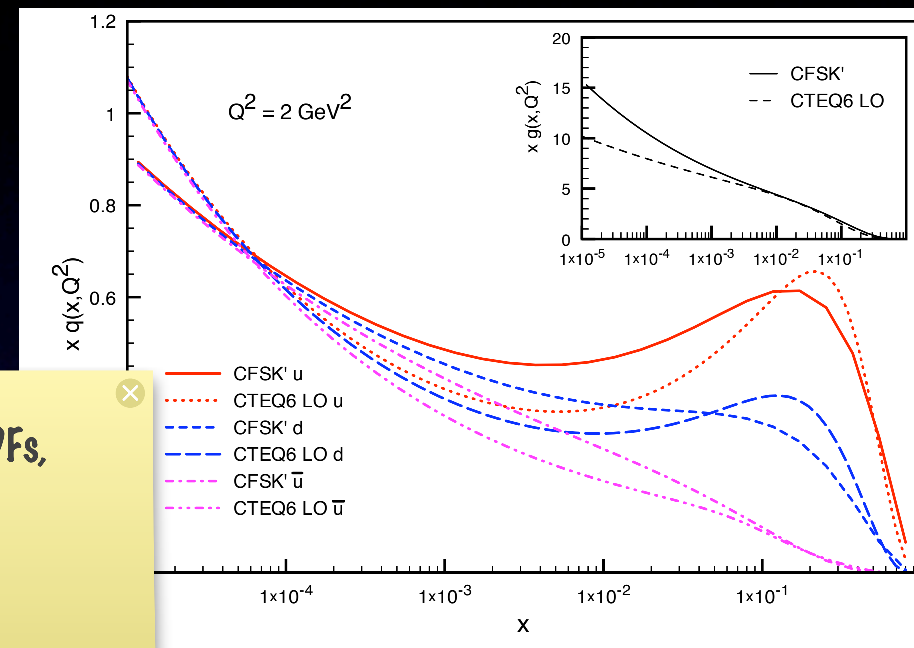
- ✓ the relevant two-gluon form factor of the proton related to the inclusive gluon distribution @ LLA

$$\sigma_S(r,s,Q^2) \;=\; r^2\frac{\pi^2}{3}\alpha_S(Q^2)\,xg(x,Q^2)$$

Ryskin ZPC 57 (1993) 89; Frankfurt, Miller, Strikman PLB 304 (1993) 1

CFSKe F_2 results



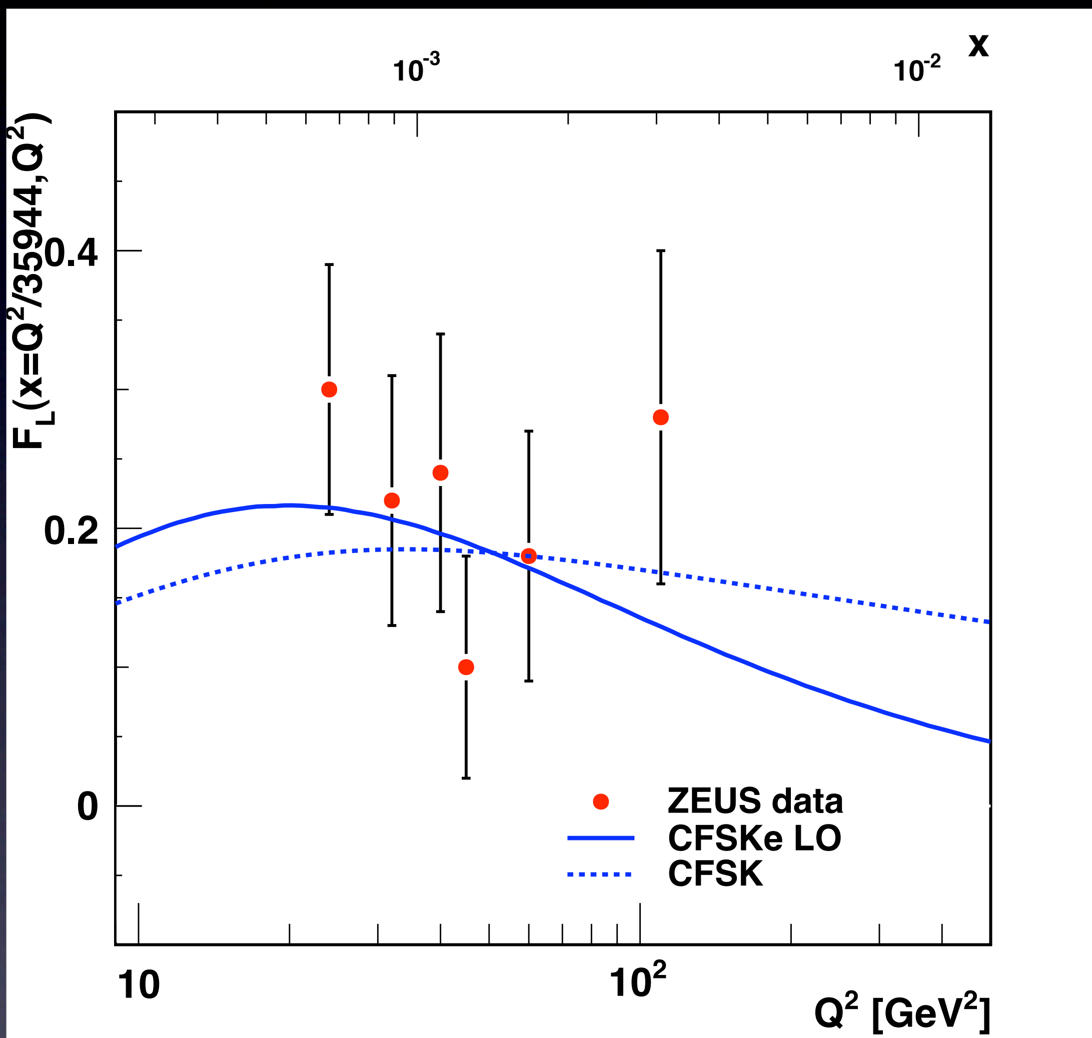


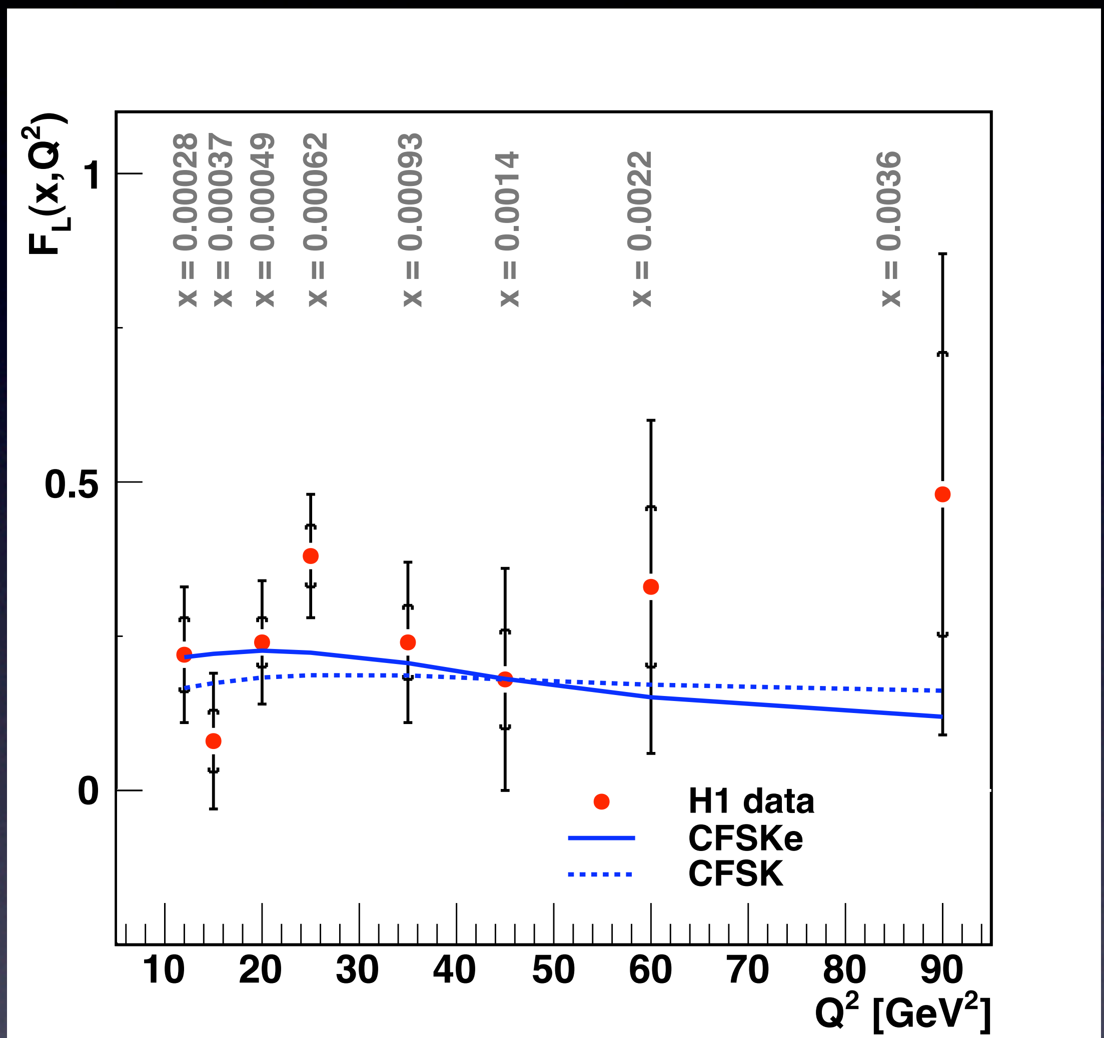
now we have the PDFs, e.g. the gluon!

with no extra parameters

- ✓ sum rules ~10%
- ✓ LO DGLAP evolution
- ✓ VFNS for heavy quarks
- ✓ good agreement
- ✓ what about unitarity?

Results on F_L

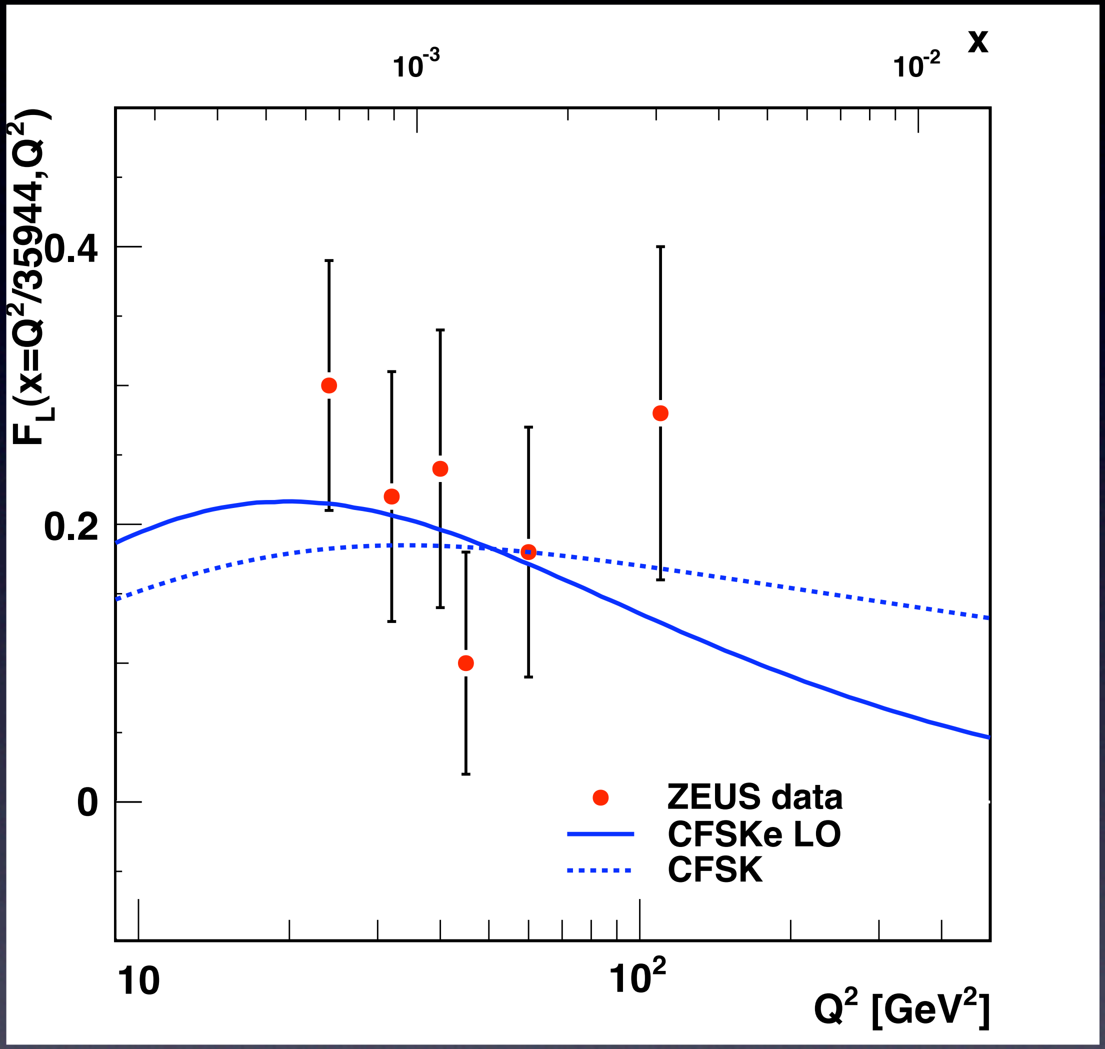


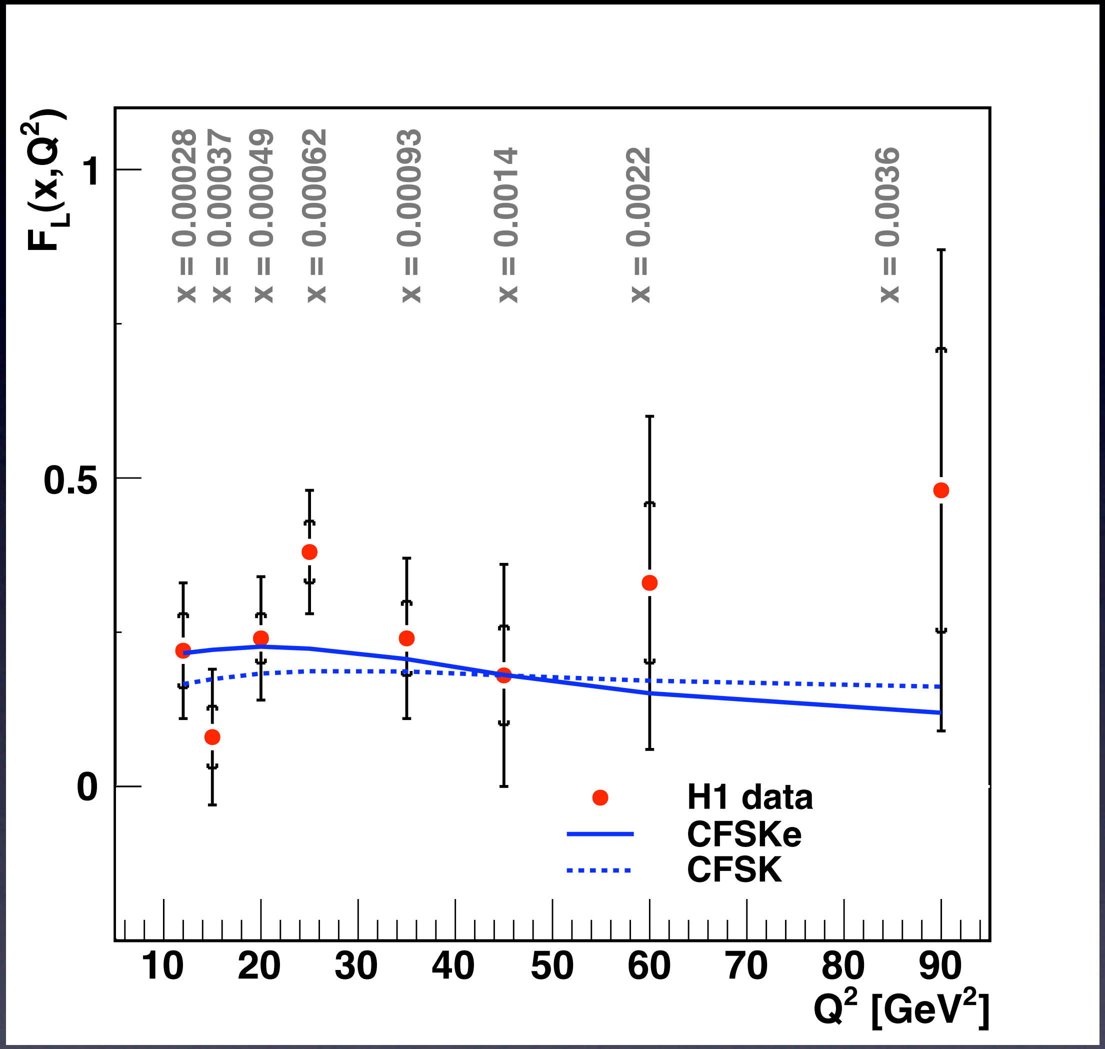


Dipole model calculation + matching with non-pert model....

$$\sigma_S(r,x,Q^2) = 4\int d^2b\,\frac{1}{2C}\left[1-\exp\left\{-C\,\frac{\pi^2\alpha_S(Q^2)}{6}\,\frac{\exp\left\{-b^2\Big/4\lambda^S_{0P}(\xi)\right\}}{4\pi\lambda^S_{0P}(\xi)}\,xg(x,Q^2)\,r^2\right\}\right]$$

Results on F_L





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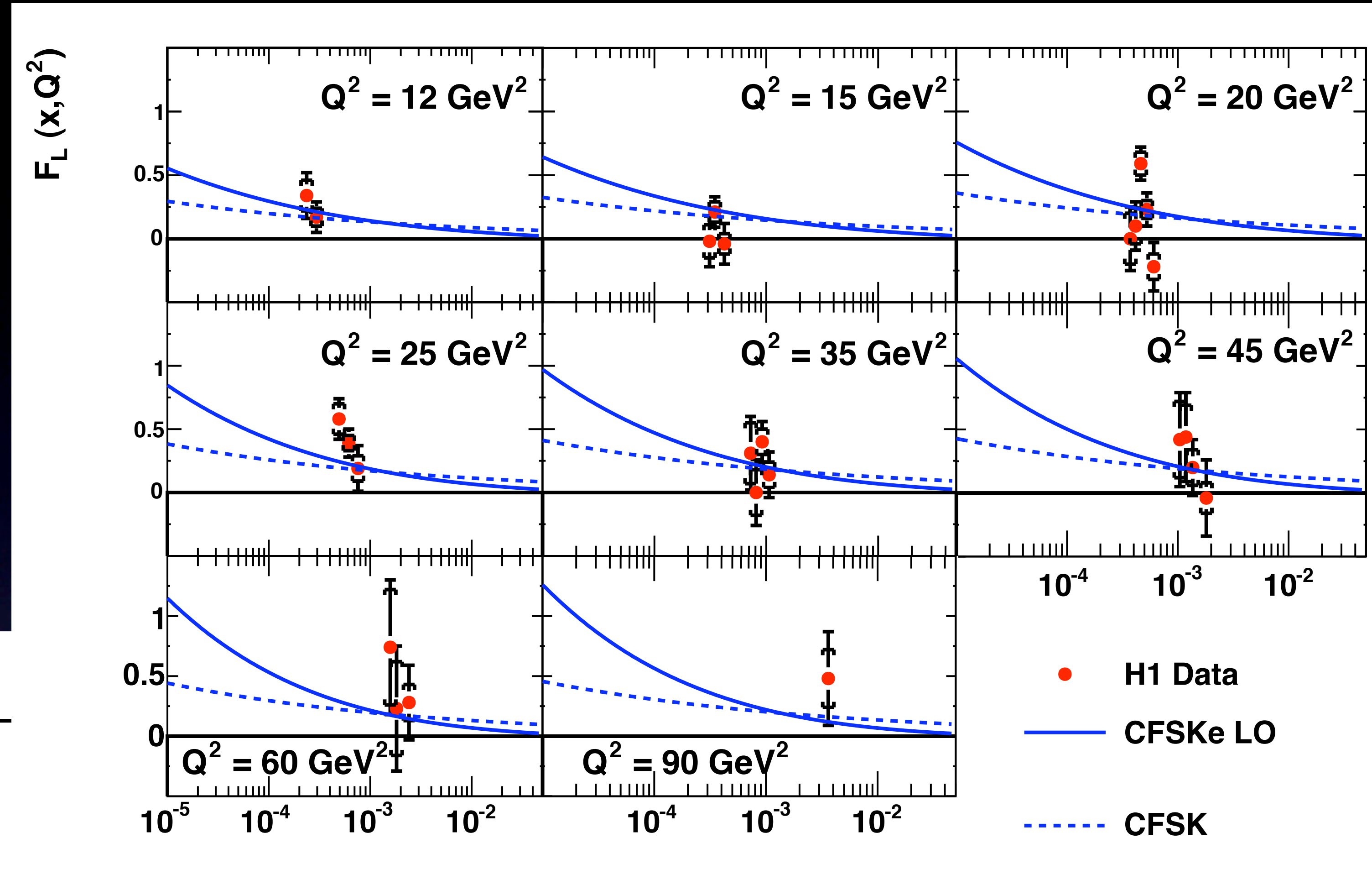
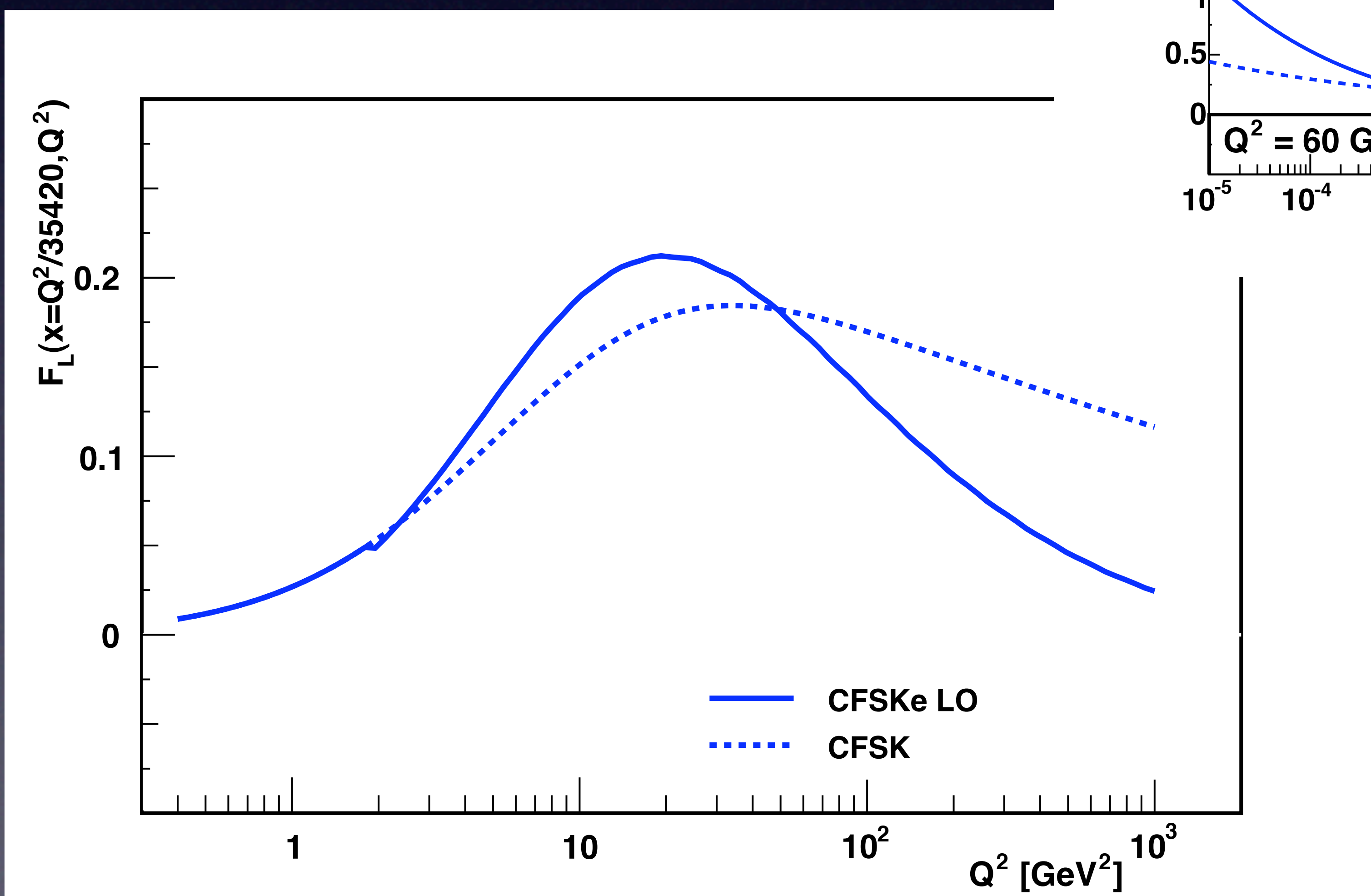
Predictions for
- low-x
- low and high-Q^2



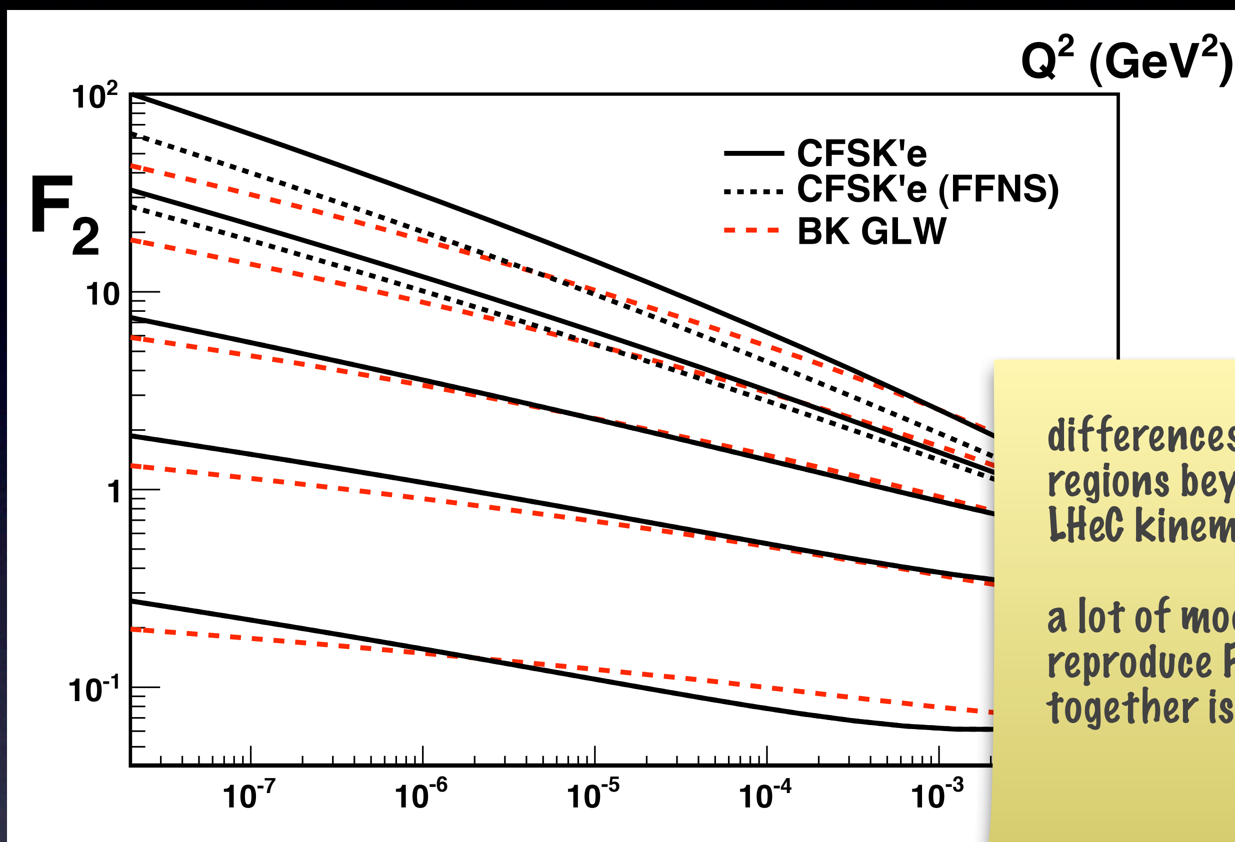


At low-Q^2 CFSK model probes transition to Regge-regime.

✓ interesting check!

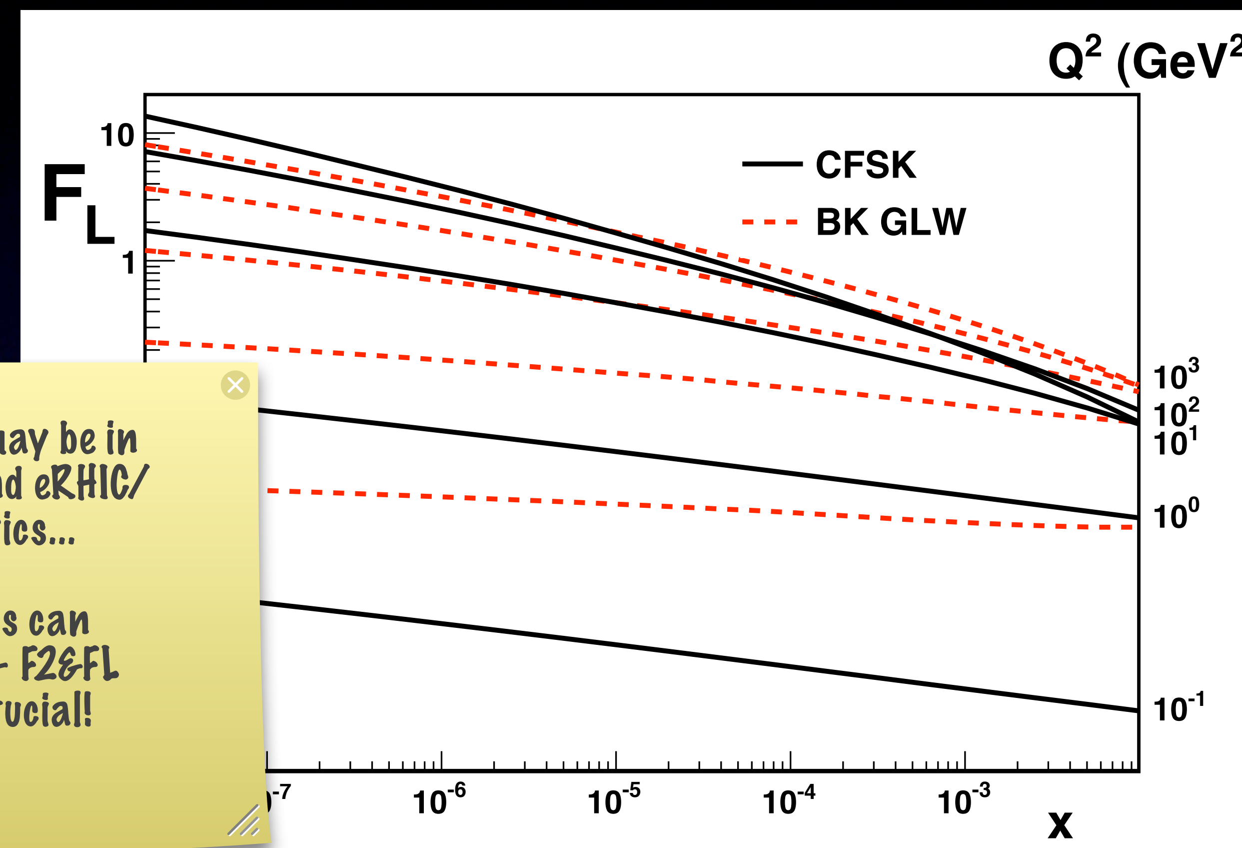
Comparison to RC BK

Albacete, Armesto, Milhano, Salgado PRD 80 (2009) 034031



differences may be in regions beyond eRHIC/LHeC kinematics...

a lot of models can reproduce F2 - F2&FL together is crucial!



- ✓ significant difference at low-x and high-Q2
- ✓ partly because of heavy quarks?
- ✓ break-down of DGLAP evolution?

- ✓ large differences, especially at low-Q2
- ✓ break-down of perturbative QCD
- ✓ differentiate between real QCD and models

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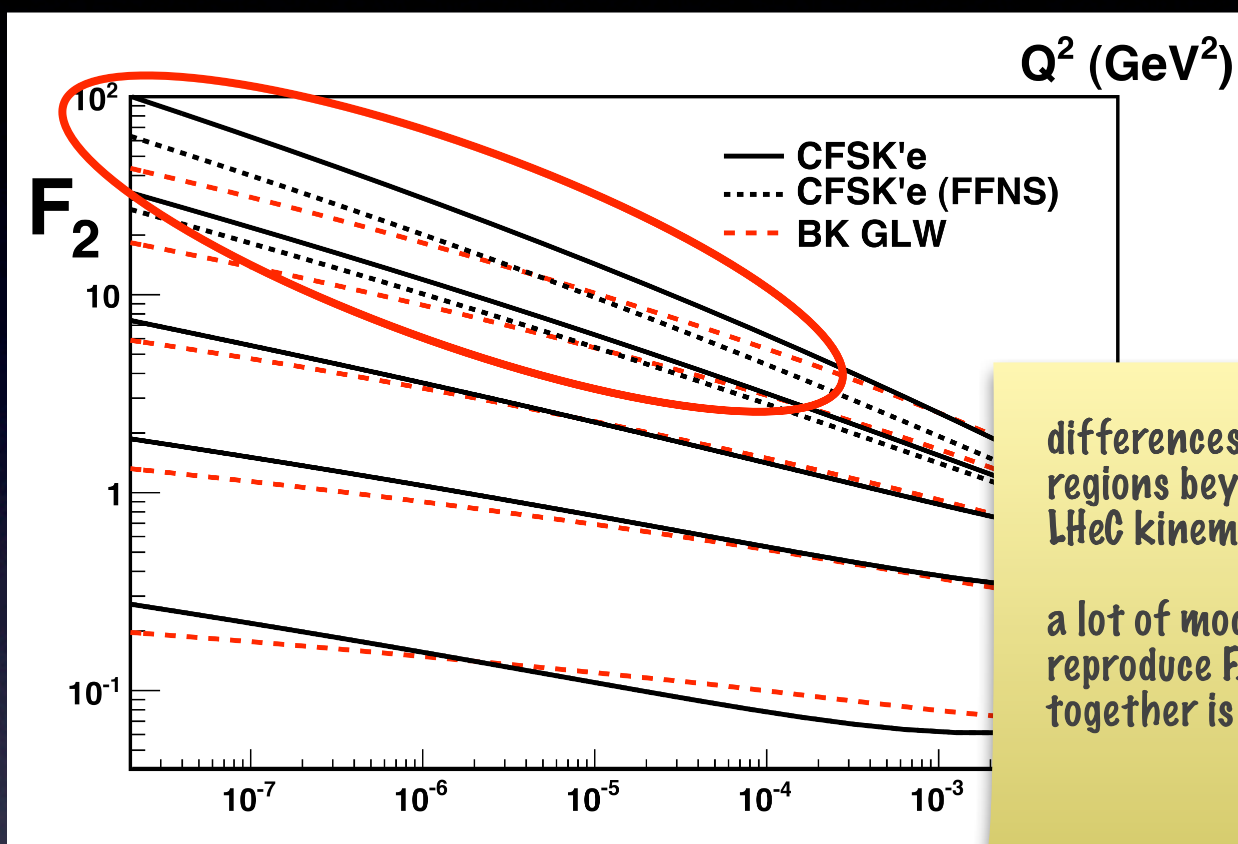

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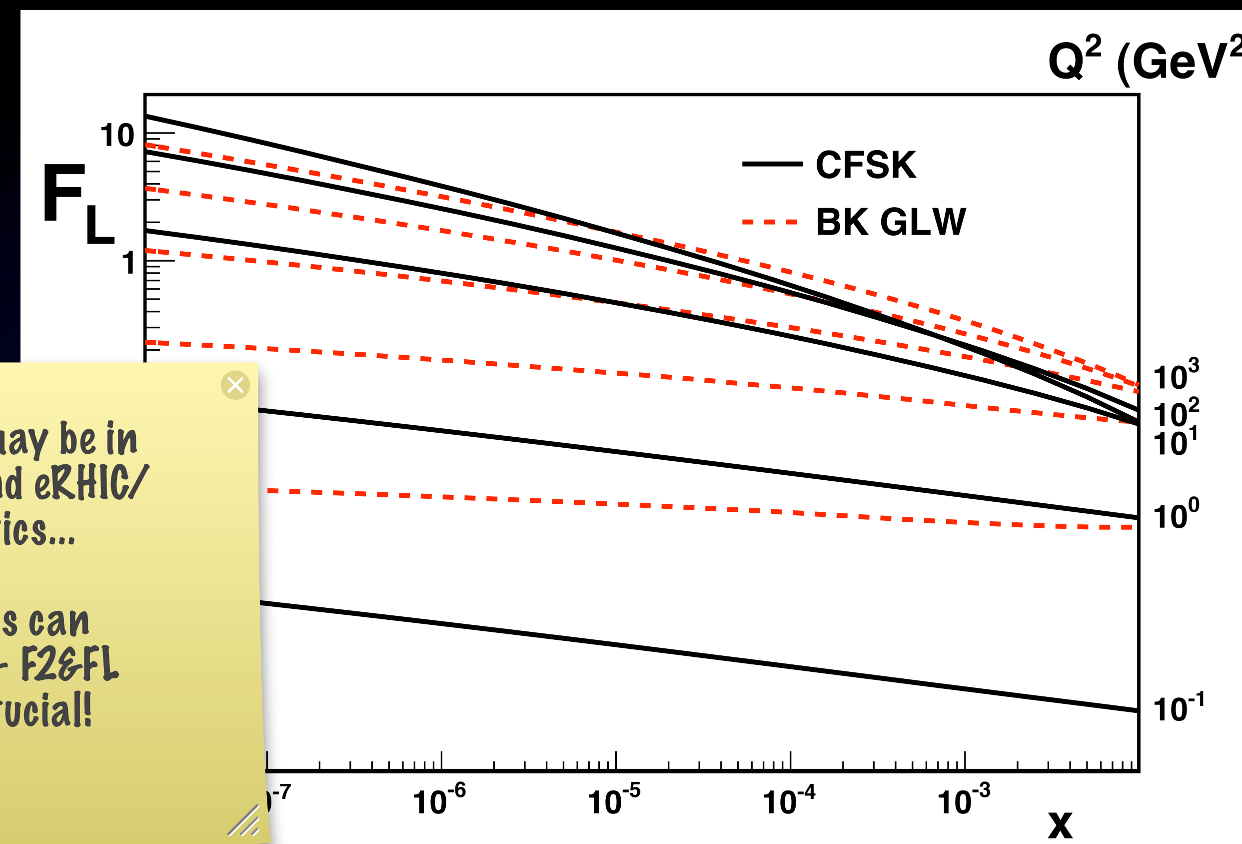

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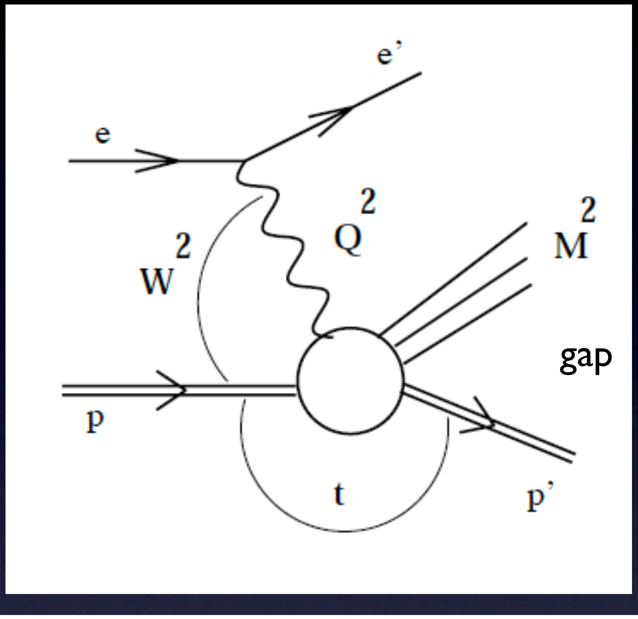
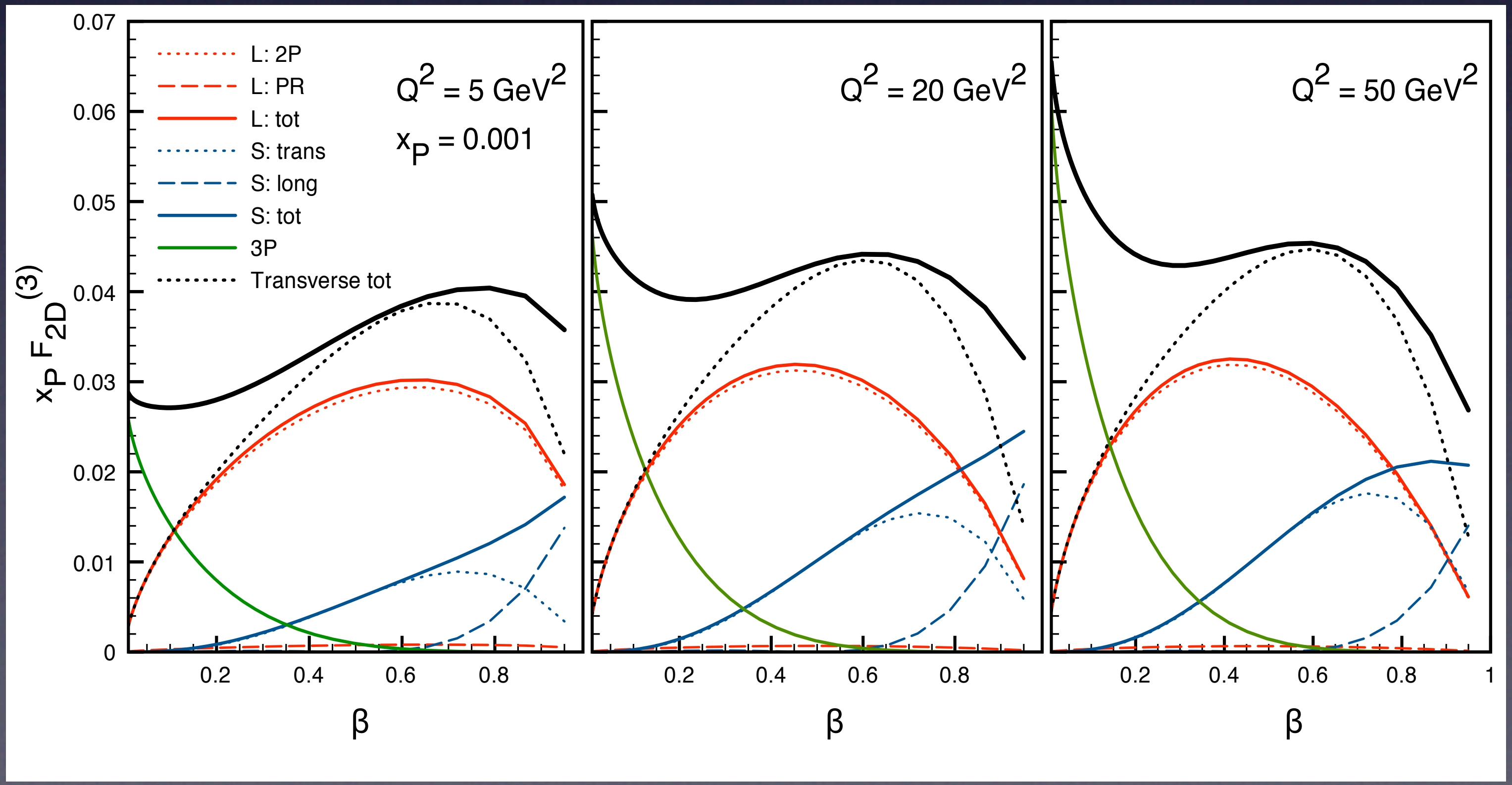
Diffraction in CFSK



$$F_{2\mathcal{D}}^{(3)} = F_{2\mathcal{D}\,S}^{(3)} + F_{2\mathcal{D}\,L}^{(3)} + F_{2\mathcal{D}\,3P}^{(3)}$$

- ✓ diffraction probes larger partonic configurations
- ✓ works to higher Q^2
- ✓ high-mass diffraction through 3**P**-contribution
- ✓ β-behavior is taken from non-perturbative models and pQCD
- ✓ proton-vertex factorization
- ✓ fit the gluon dPDF



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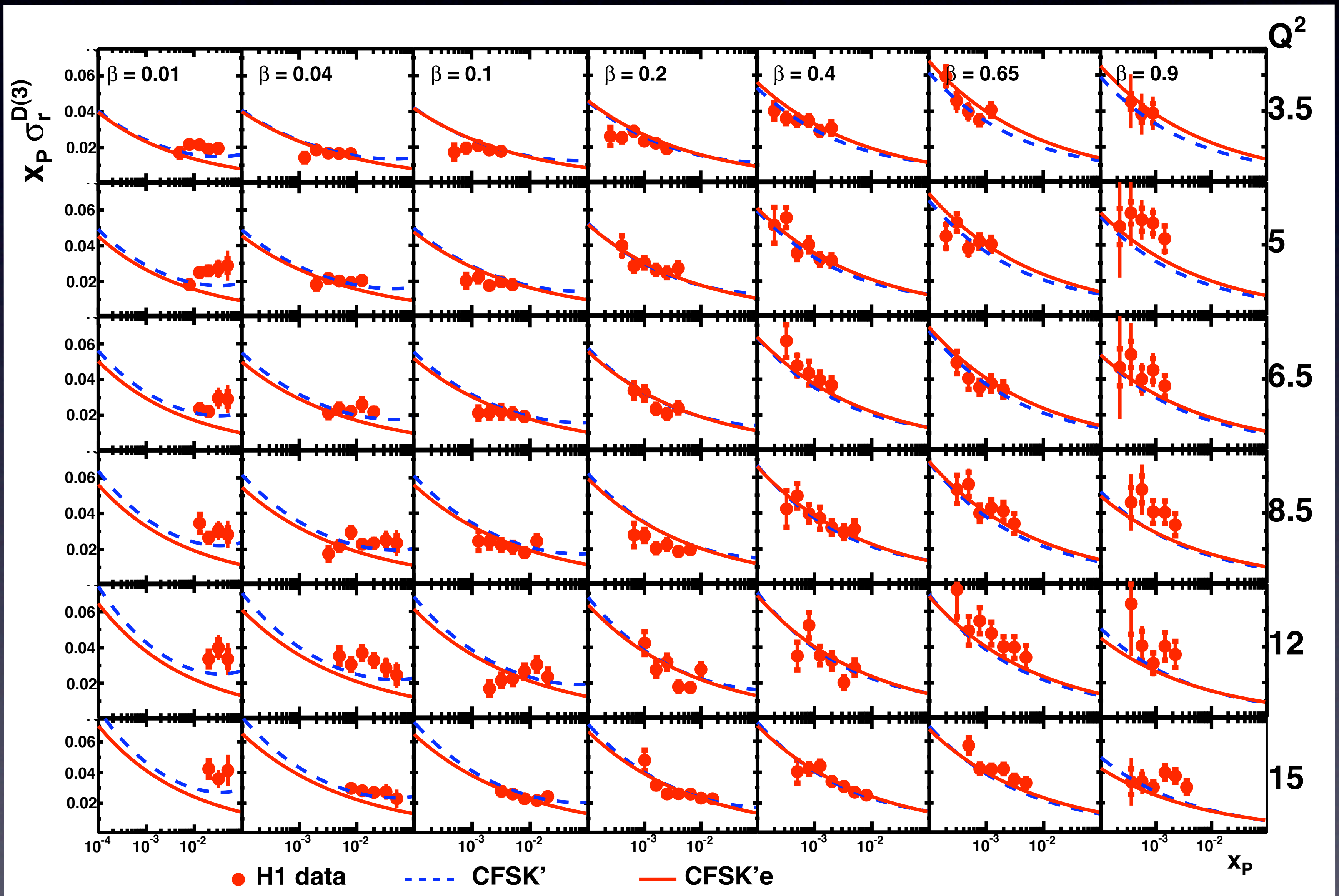
CFSK diffractive results



- ✓ model proves to work well
- ✓ χ^2 analysis shows slight improvement
- ✓ systematics between ZEUS and H1 data
- ✓ multi-reggeon features partly lost
- ✓ drop factorization?

γA coherence effects

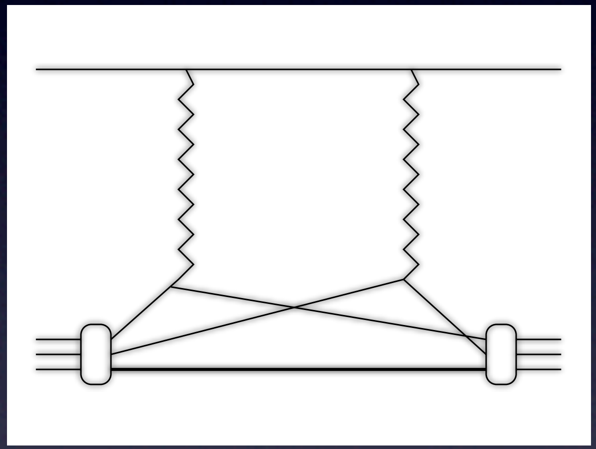
$$\sigma_{\gamma^* A} = A\sigma_{\gamma^* p} + \sigma^{(2)}_{\gamma^* A} + \ldots$$

$$\boxed{x < 1/m_N R_A \sim 0.1 A^{-1/3}}$$

The driving term in the multiple scattering series:

$$\sigma^{(2)}_{\gamma^* A} = -\frac{1}{2}\int d^2b\,\left(T_A(b)\sigma^{tot}_{\gamma^* p}\right)^2$$

→ elastic shadowing!



Glauber 1959

Eikonalization: $\sigma_{\gamma^* A} = 2\int d^2b\,\left(1 - \exp\left[-\sigma^{tot}_{\gamma^* p} T_A(b)/2\right]\right)$

✓ projectile remains intact during scattering

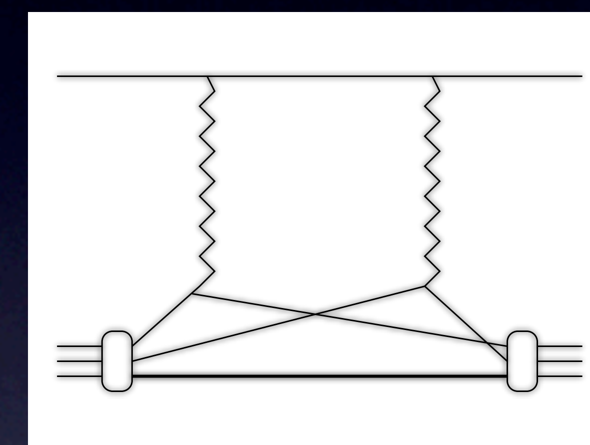
✓ usually limited to the lowest Fock state

✓ many models of shadowing use only this..?

γA coherence effects

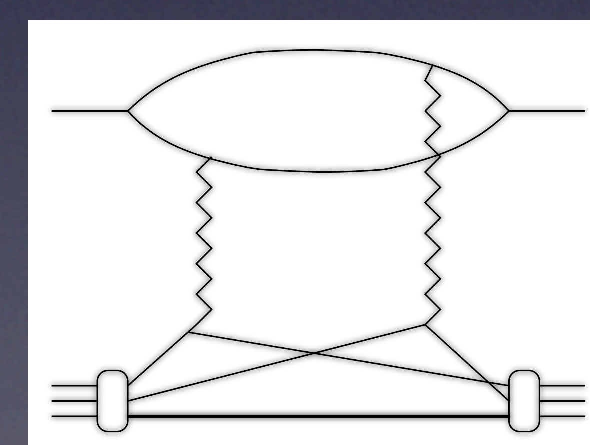
AGK:

- diffractive cut = 0 in incoherent regime
- diffractive cut ≠0 in coherent
- new type of diagrams emerge → non-planar!



+ high-mass diffraction → inelastic shadowing!

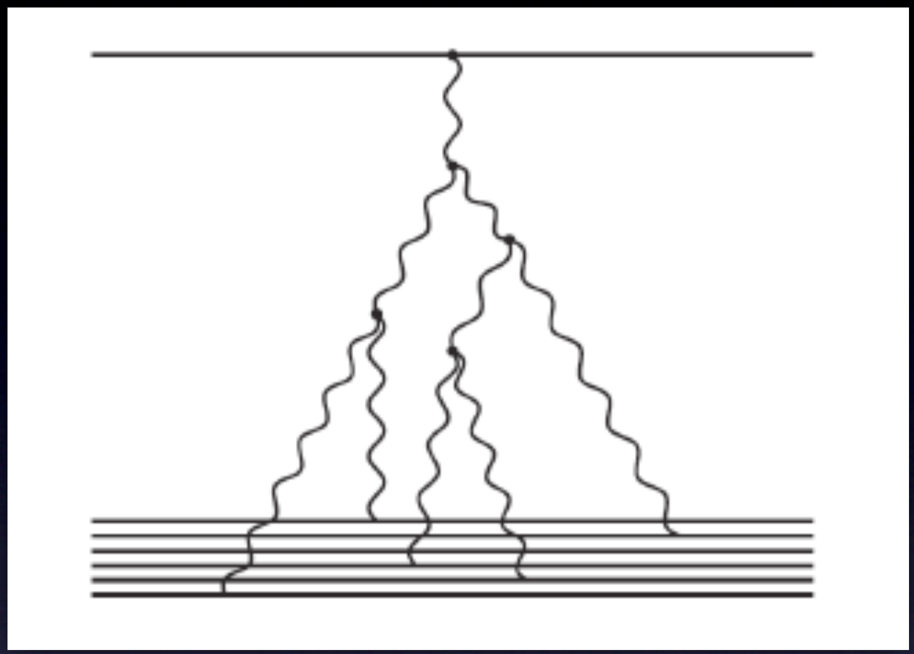
$$\sigma^{(2)}_{\gamma^* A} = -4\pi \int d^2b T_A^2(b) \int dM^2 \left.\frac{d\sigma^{\mathcal{D}}_{\gamma^* p}}{dM^2 dt}\right|_{t=0} F_A^2(t_{min})$$



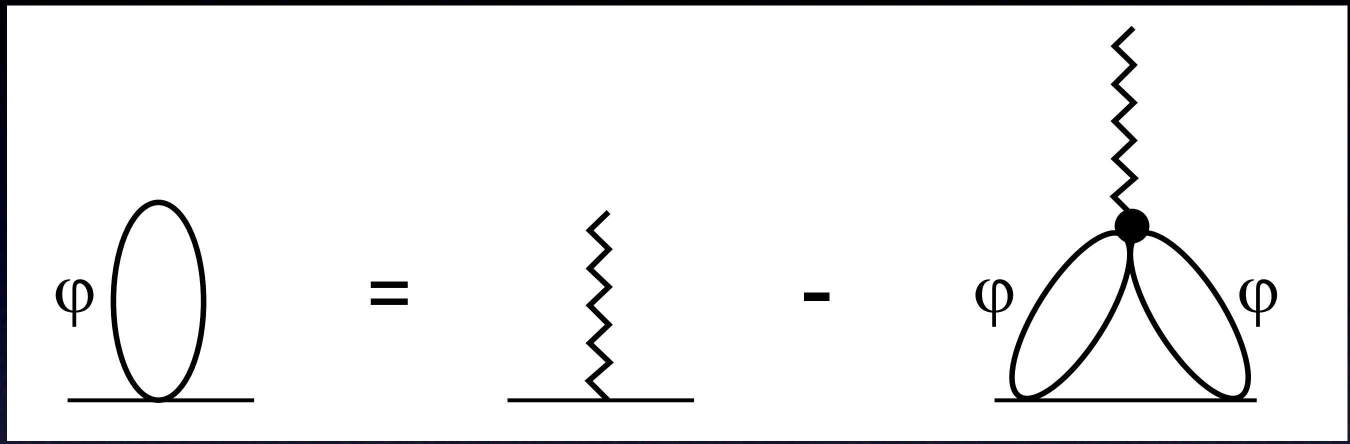
- gives the realistic rescattering cross section...

Gribov 1969-1970, Abramovsky, Kancheli

Shadowing from fan summations



$\Rightarrow$

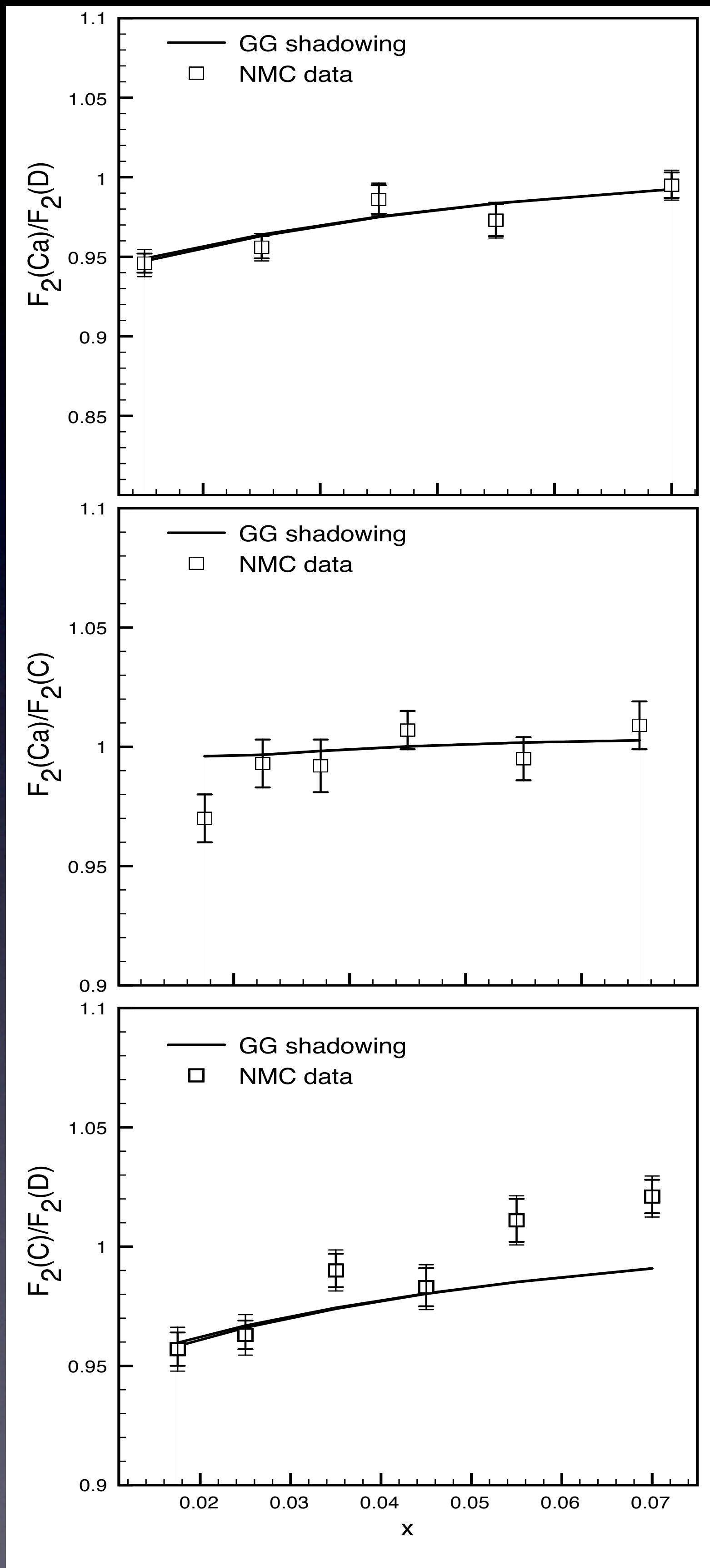


$$\sigma^{tot}_{\gamma * A}(Y, b) = \frac{A T_A(b) \sigma^{tot}_{\gamma * p}}{\kappa_A(Y, Y, b) + 1}$$

$$\kappa_A(Y, y_M, b) = \frac{4\pi A T_A(b)}{\sigma^{tot}_{\gamma * p}(Y)} \int_{M^2_{min}}^{M^2} dM'^2 \left. \frac{d\sigma^{\mathcal{D}}_{\gamma * p}}{dM'^2\, dt} \right|_{t=0} F^2_A(t_{min})$$

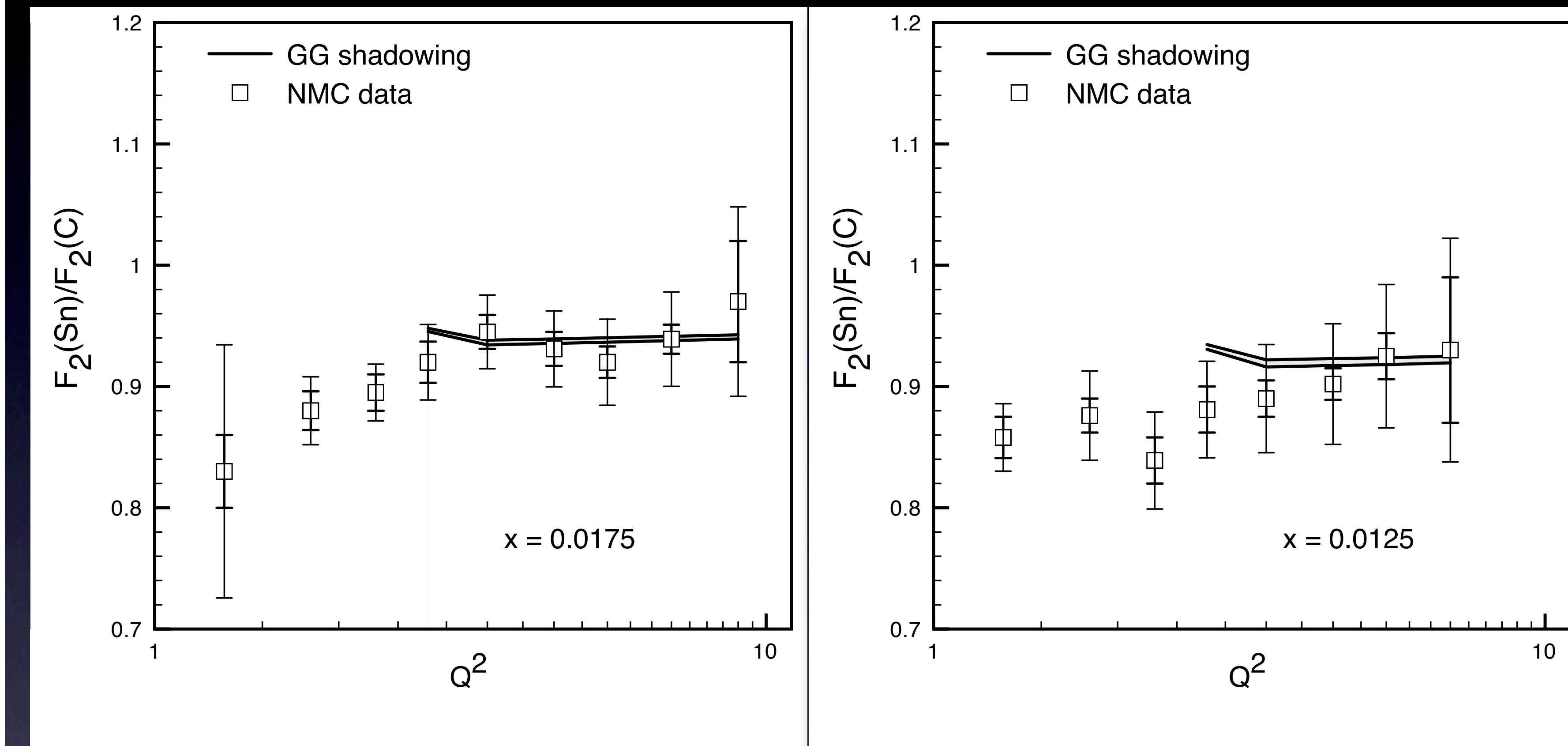
- ✓ effective re-scattering cross section κ_A
- ✓ valid for small projectile on extended target
- ✓ similar to BK equation
- ✓ valid for x < 0.01

Matinian, Kancheli SJNP 11 (1970) 726
Schwimmer NPB 94 (1975) 445
Boreskov, Kaidalov, Khoze, Martin, Ryskin EPJC 44 (2005) 523
Bondarenko, Gotsman, Levin, Maor NPA 683 (2001) 649



Low energy data

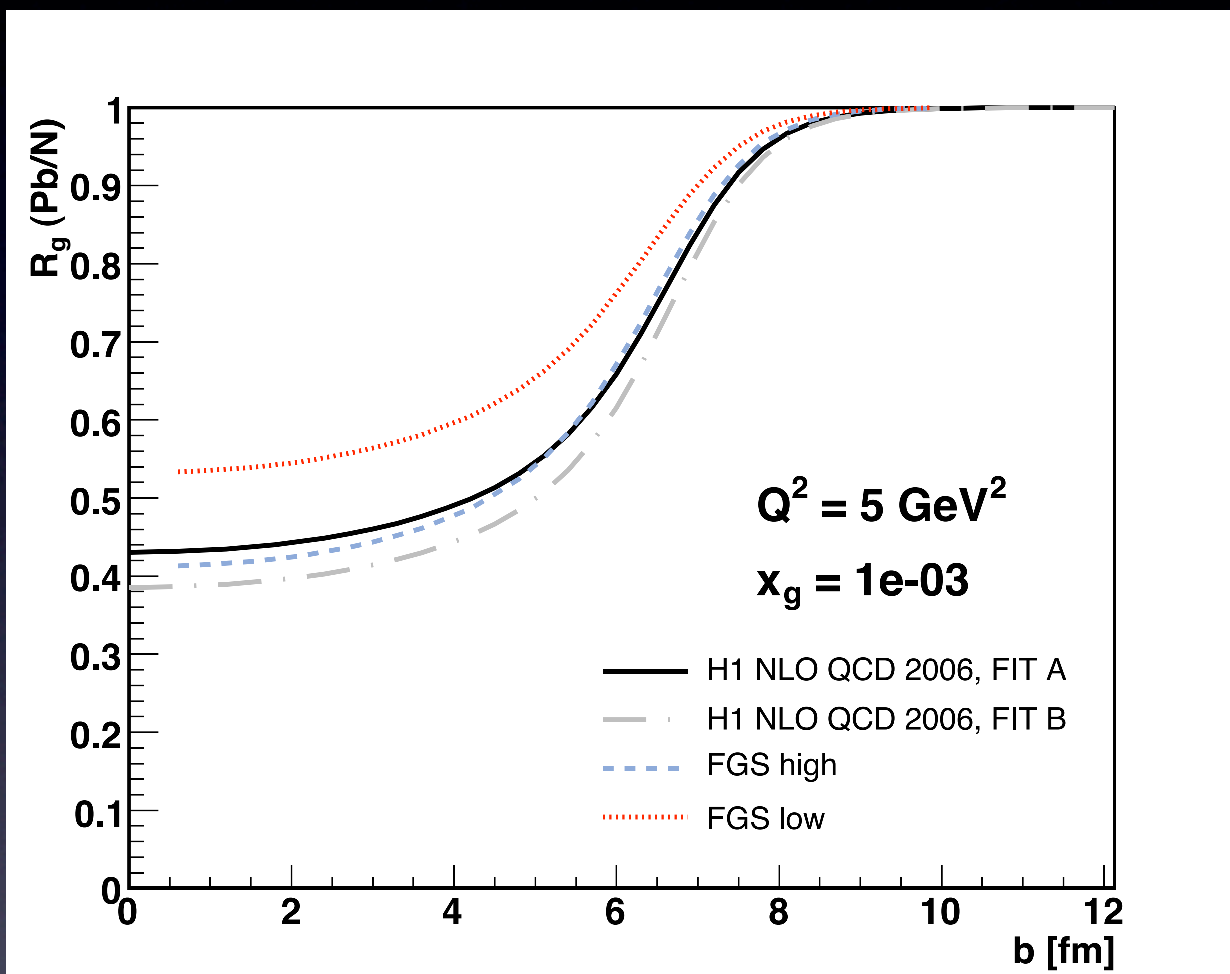
Armesto, Kaidalov, Salgado, Tywoniuk (in preparation...)

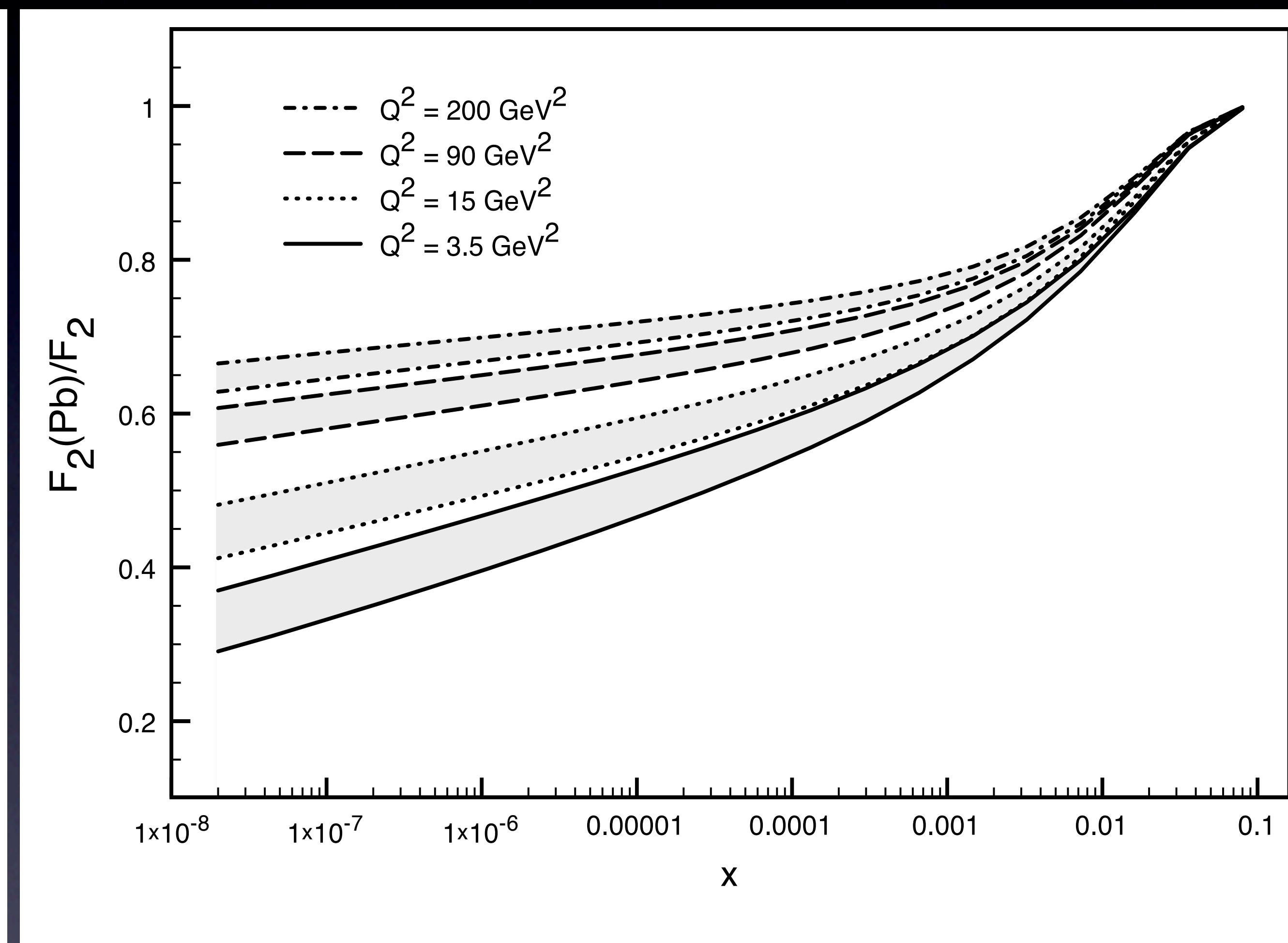


- ✓ agreement with low-energy data
- ✓ few data points within model applicability
- ✓ slow Q^2-behavior
- ✓ applicable x < 0.01
  - — do not include EMC, anti-shadowing

Predictions for low-x

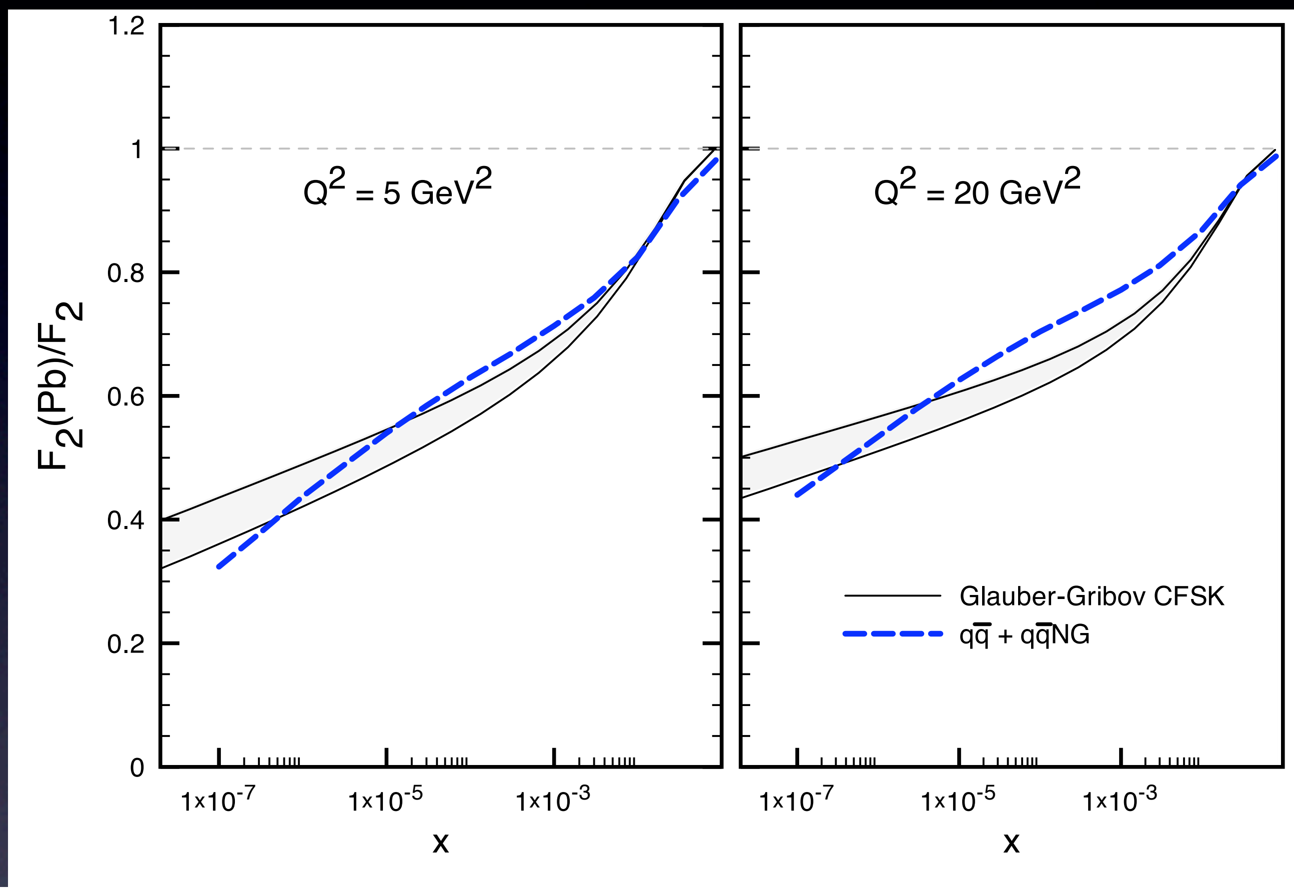
Arsene, Bravina, Kaidalov, Tywoniuk , Zabrodin PLB 657 (2007) 170





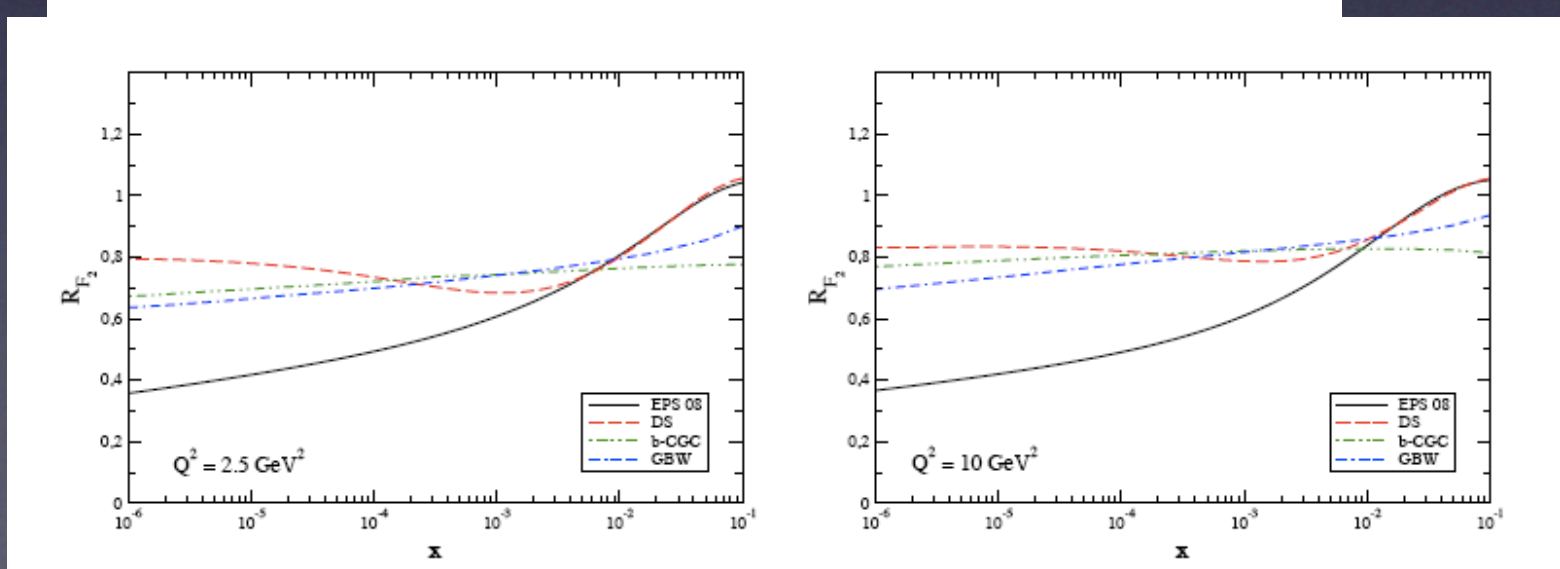
- ✓ large shadowing effects expected
- ✓ shadowing ~1/ln(Q^2)
- ✓ impact parameter dependence
- ✓ suppression of multiplicity, mini-jets, charm in heavy ions!

Comparison I



Kopeliovich, Nemchik, Potashnikova, Schmidt JPG (2008)

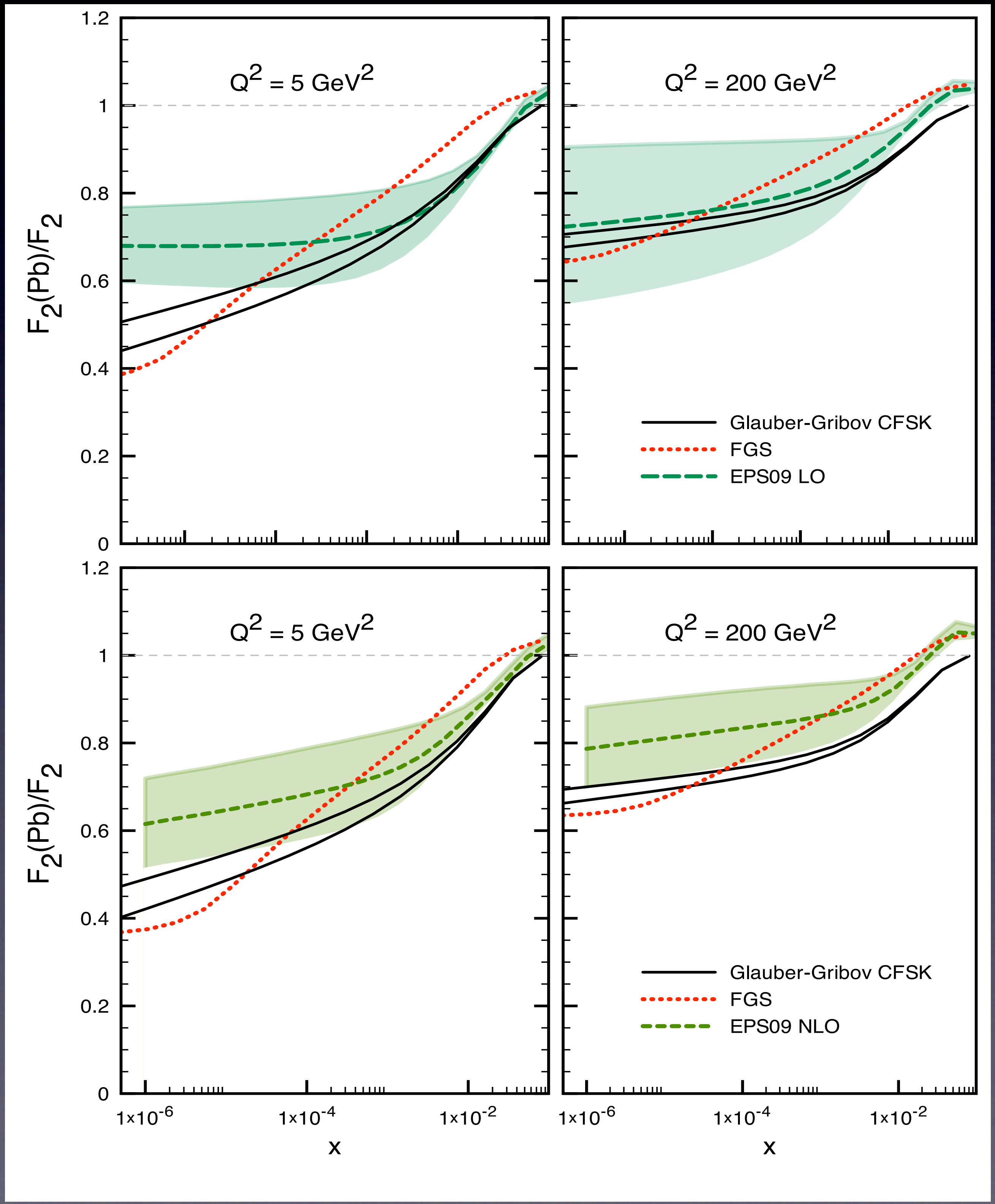
- ✓ Dipole model calculation
  - all $q\bar{q} + NG$ fluctuations are taken into account
  - small GG dipole 0.3 fm
  - LC Green function



- ✓ Shadowing in saturation models
  - only elastic shadowing!

Cazaroto, Carvalho, Gonçalves, Navarra PLB (2009)

Comparison II



- ✓ FGS parameterization
  - same framework
  - different DGLAP analysis

Frankfurt, Guzey, McDermott, Strikman JHEP 02 (2002) 027

- ✓ EPS09 @ LO and NLO
  - fit to nuclear data
  - error analysis included

Eskola, Paukkunen, Salgado JHEP 0904:065 (2009)

Diffraction off nuclei

Coherent diffraction

$$\sigma(\gamma^* A \to Xh + A) = \sum_n \int d^2b |a_{n\gamma^*}|^2 4\pi \left. \frac{\sigma^n(\gamma^* p \to h)}{dt} \right|_{t=0} T_A^2(b) e^{-\sigma_n^{tot} T_A(b)}$$

- small momentum transfer: t ~ R_A^2
- possible as long as $M^2/s \ll 1/m_p R_A$

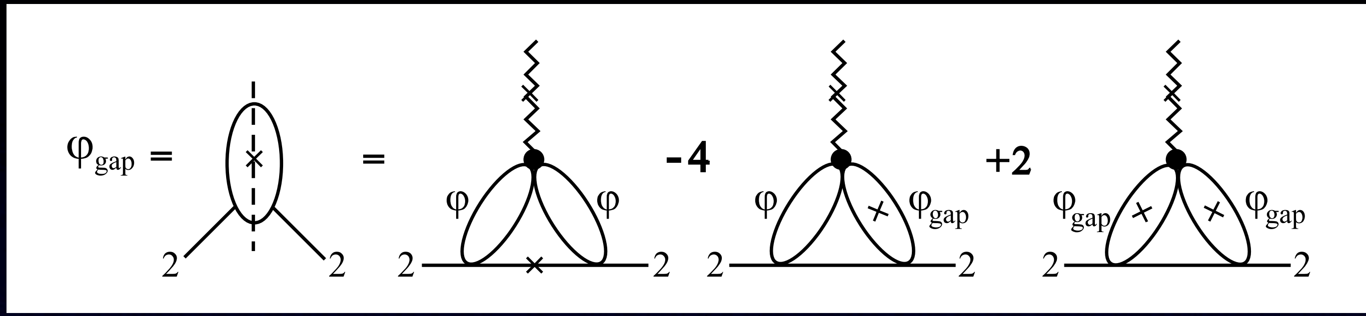
Incoherent diffraction

$$\sigma(\gamma^* A \to Xh + Y_A) = \sum_n \int d^2b |a_{n\gamma^*}|^2 \sigma^n(\gamma^* p \to h) T_A(b) e^{-\sigma_n^{abs} T_A(b)}$$

- large momentum transfer: t ~ R_N^2
- survival probability S
- nuclear transparency

Frankfurt, Miller, Strikman PRL 18 (1993) 2859
Kaidalov, Khoze, Martin, Ryskin APPB 34 (2003) 3163
Guzey, Strikman PRC 75 (2007) 045208
Kowalski, Lappi, Venugopalan PRL 100 (2008) 022303
Kowalski, Lappi, Marquet, Venugopalan PRC 78 (2008) 045201

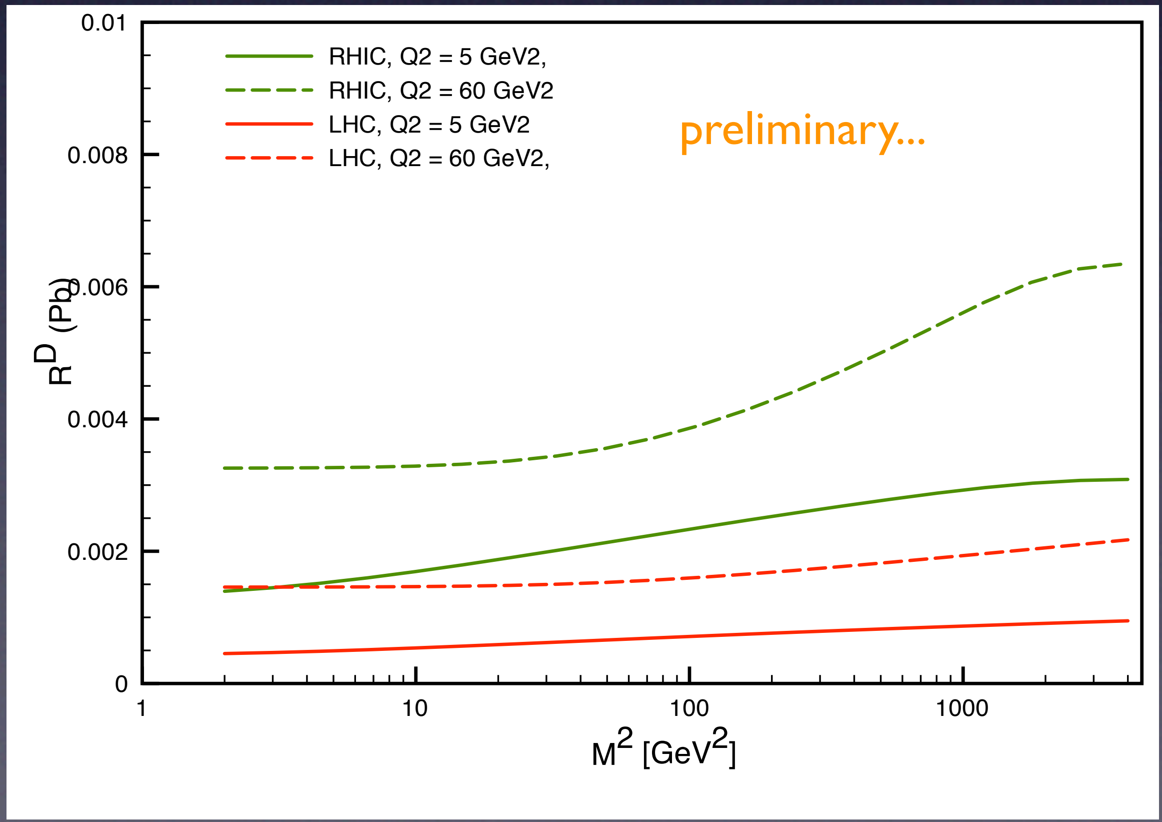
γA diffraction from fans



$$\frac{d\sigma^{\mathcal{D}}_{\gamma * A}}{dM^2} = 4\pi A^2 \left. \frac{d\sigma^{\mathcal{D}}_{\gamma * p}}{dM^2\, dt} \right|_{t=0} \int d^2 b \frac{T_A^2(b) e^{-\sigma^{tot}_{\gamma * p} T_A(b)}}{\left[2\kappa_A(Y,Y,b) - \kappa_A(Y,y_M,b) + 1\right]^2}$$

$$R^{\mathcal{D}}(s, M^2, Q^2) = \frac{d\sigma^{\mathcal{D}}_{\gamma^* A}}{dM^2} \Bigg/ A^2 \frac{d\sigma^{\mathcal{D}}_{\gamma^* p}}{dM^2}$$

- ✓ Regge-factorization explicitly broken!
- ✓ one-channel model
  - realistically should include at least two...
- ✓ can also calculate pA
  - $\sigma^{tot}_{\gamma p}(x,Q^2) \to \sigma^{tot}_{pp}(s)$



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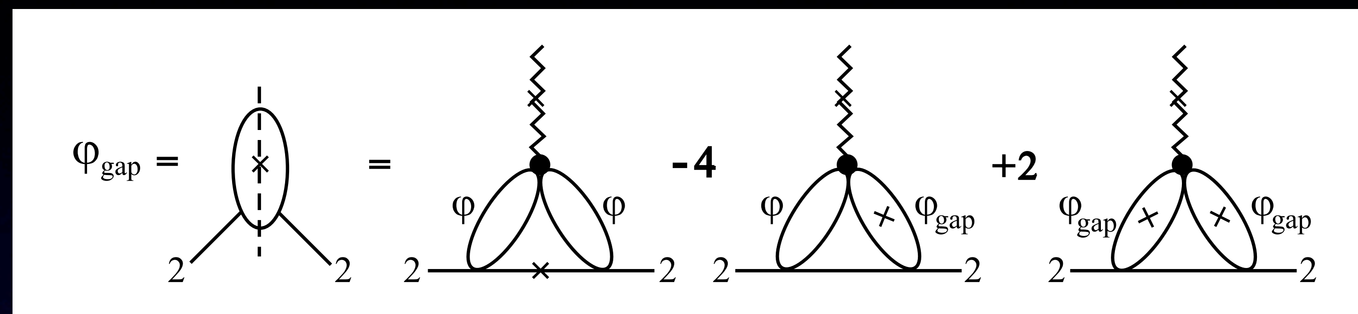
γA diffraction from fans



$$\frac{d\sigma^{\mathcal{D}}_{\gamma * A}}{dM^2} = 4\pi A^2 \left. \frac{d\sigma^{\mathcal{D}}_{\gamma * p}}{dM^2\, dt} \right|_{t=0} \int d^2 b \frac{T_A^2(b) e^{-\sigma^{tot}_{\gamma * p} T_A(b)}}{[2\kappa_A(Y,Y,b) - \kappa_A(Y,y_M,b) + 1]^2}$$

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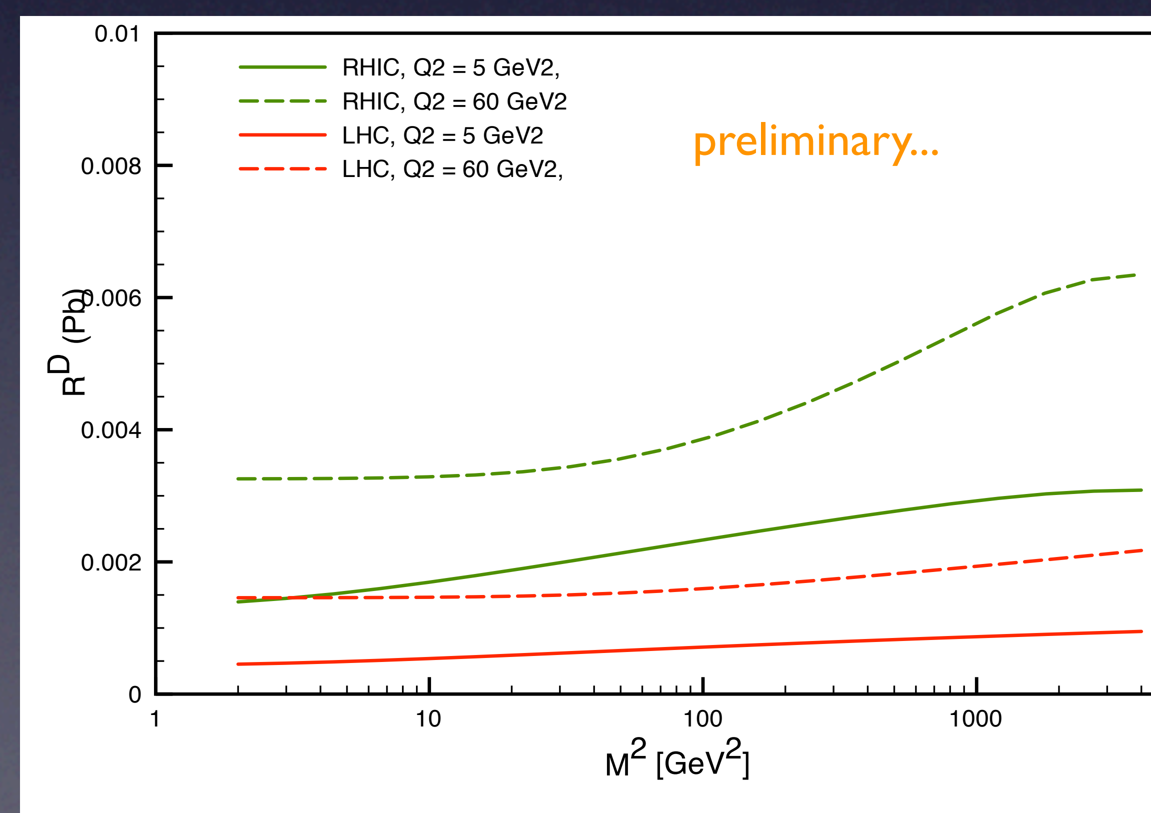
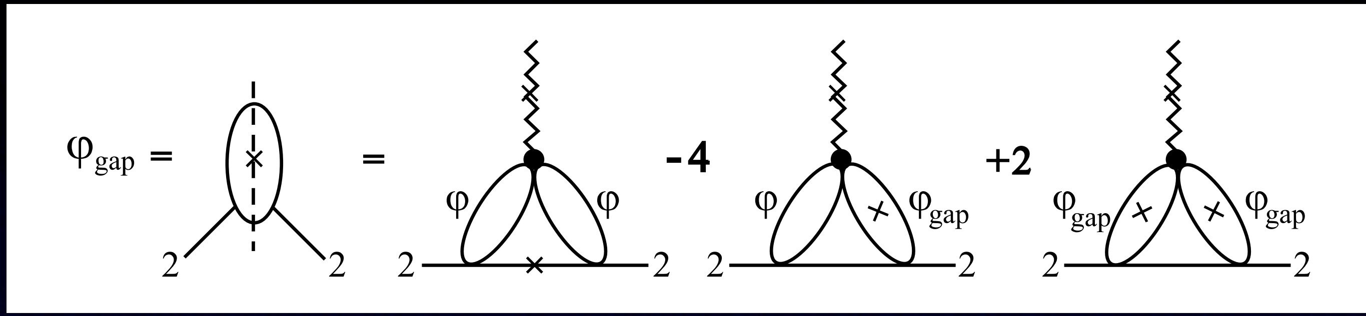


γA diffraction from fans



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$$R^{\mathcal{D}}(s,M^2,Q^2) = \frac{d\sigma^{\mathcal{D}}_{\gamma^*A}}{dM^2} \Bigg/ A^2\frac{d\sigma^{\mathcal{D}}_{\gamma^*p}}{dM^2}$$

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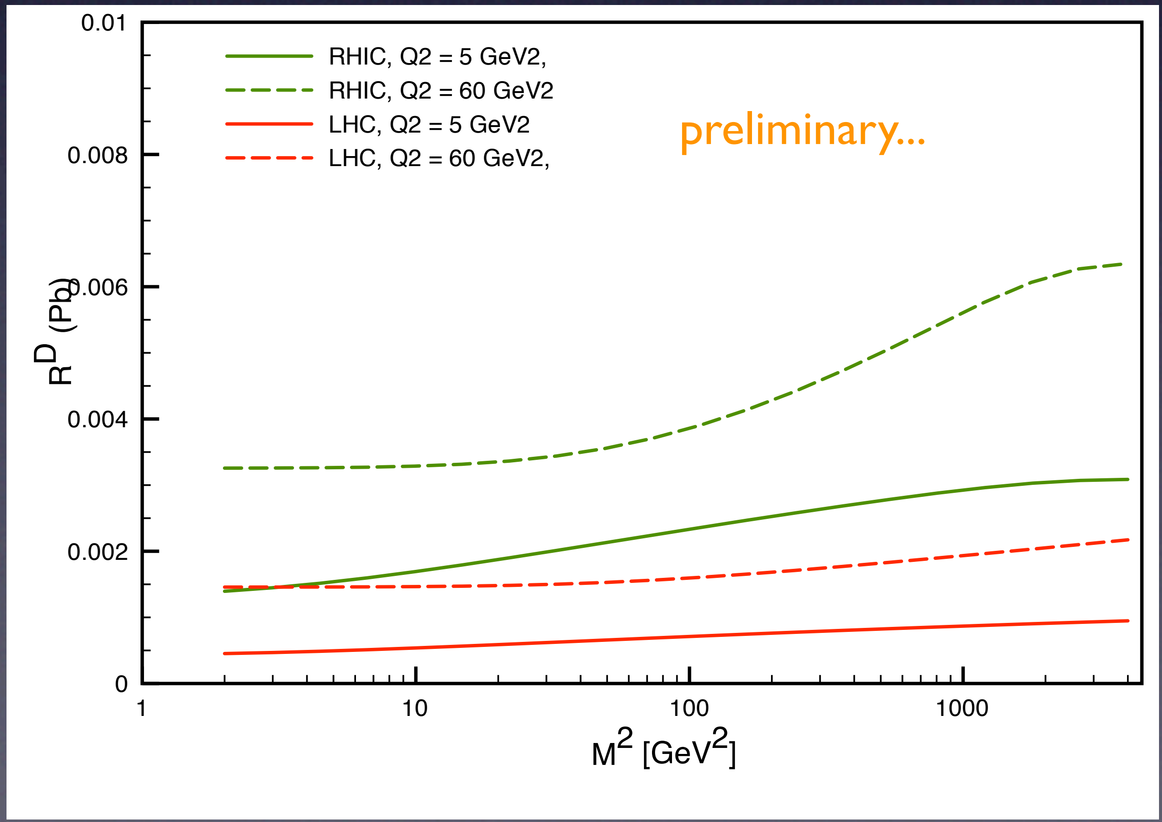
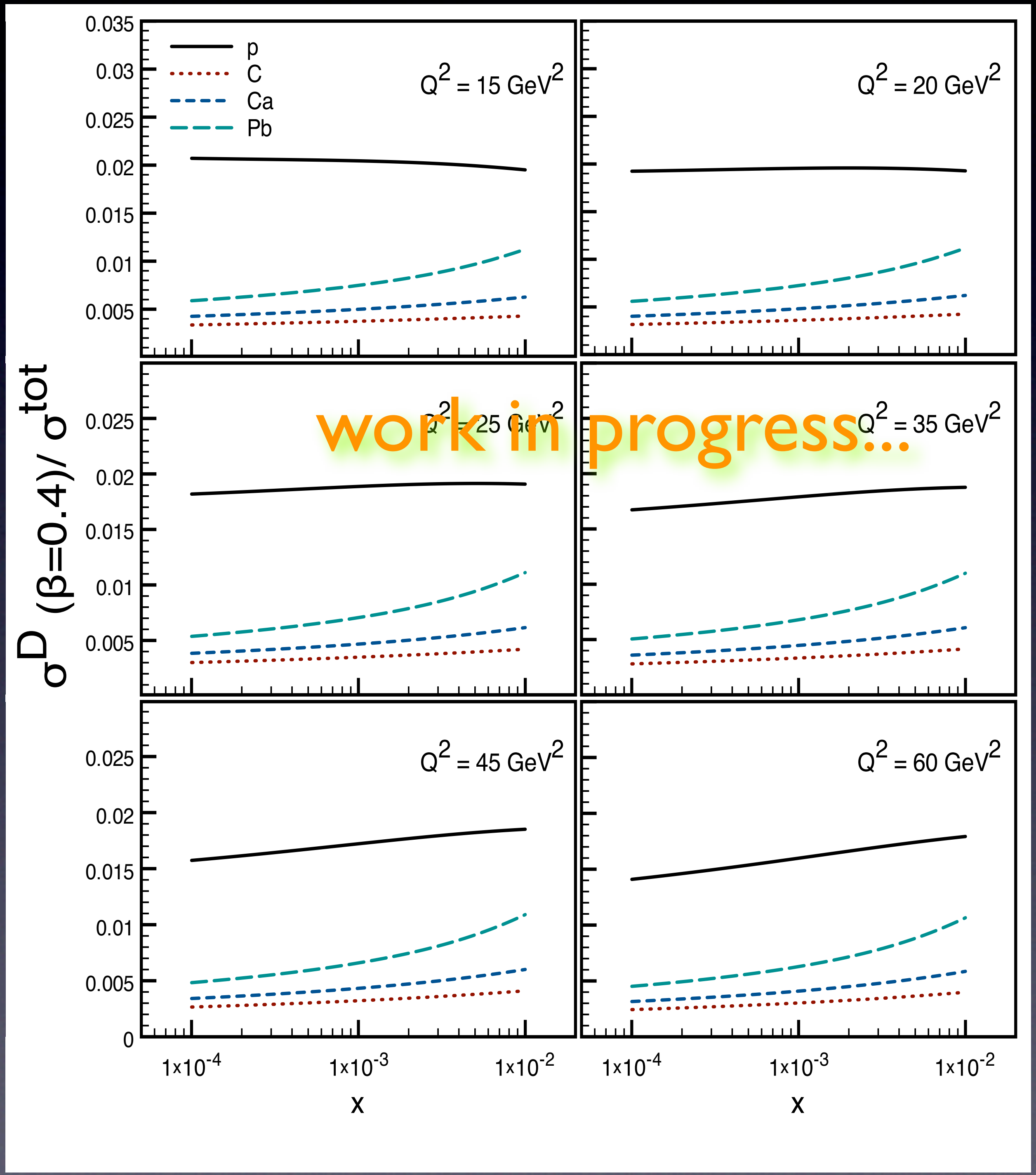
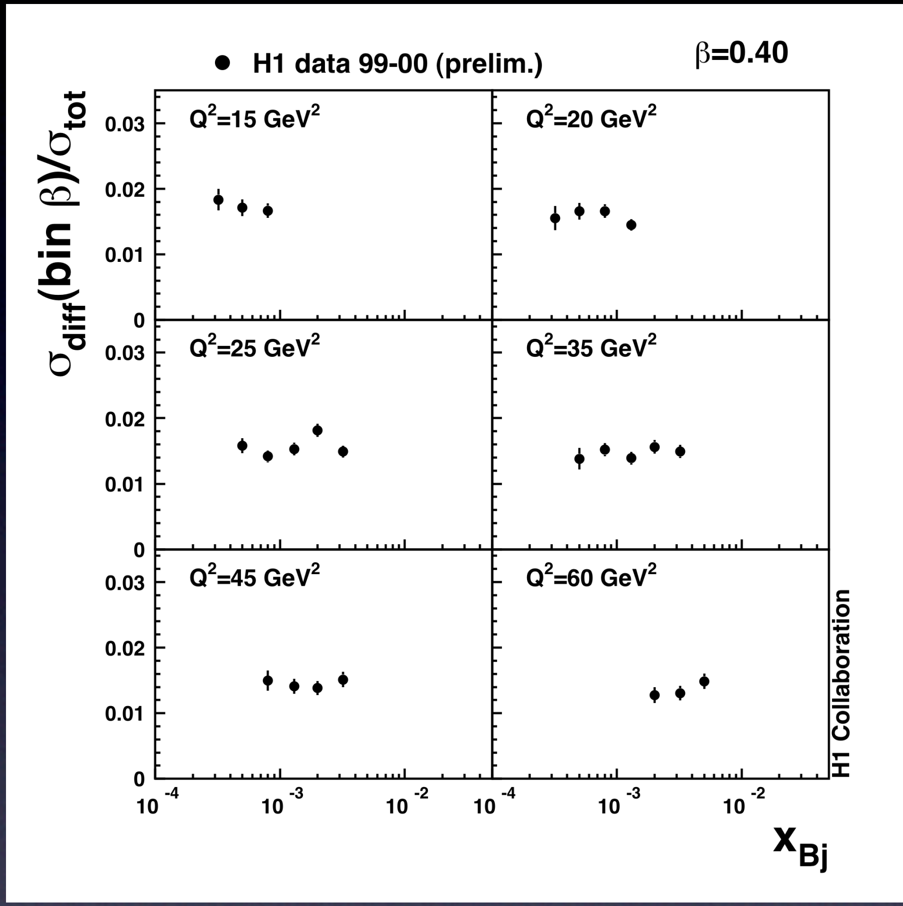
- ✓ can also calculate pA
  - $\sigma^{tot}_{\gamma p}(x,Q^2) \rightarrow \sigma^{tot}_{pp}(s)$



Diffractive over total cross section





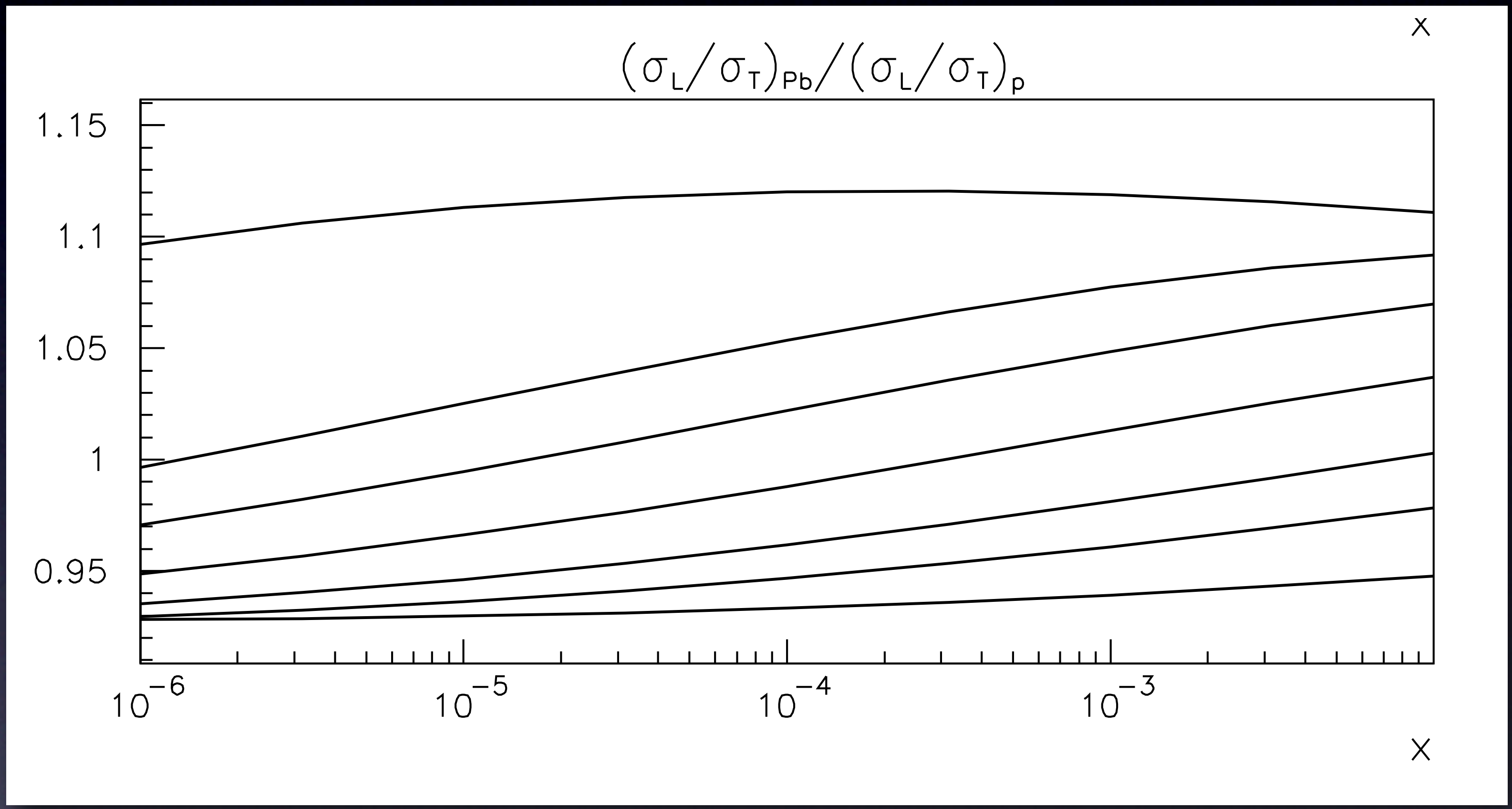
✓ a measure of

– multi-reggeon interaction

– saturation

– $\propto$ second rescattering

Nuclear dependence of R



$$R = \frac{\sigma_L}{\sigma_T}$$

Nikolaev, Zakharov ZPC 49, 607 (1991)
Armesto EPJC 26, 35 (2002)

- ✓ clear prediction from the dipole model
- ✓ small effect when shadowing is weak
  - — usually assumed to be 1 in fits to data
- ✓ if not, need to constrain both F_2 and F_L from the cross section

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The nuclear F_L

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4 x} Y_+ \left(\frac{1+\varepsilon R}{1+R}\right) F_2(x,Q^2)$$

$$Q^2 = xys$$

$$R = \frac{F_L(x,Q^2)}{F_2(x,Q^2) - F_L(x,Q^2)}$$

$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2}$$

$$Y_+ = 1 + (1-y)^2$$

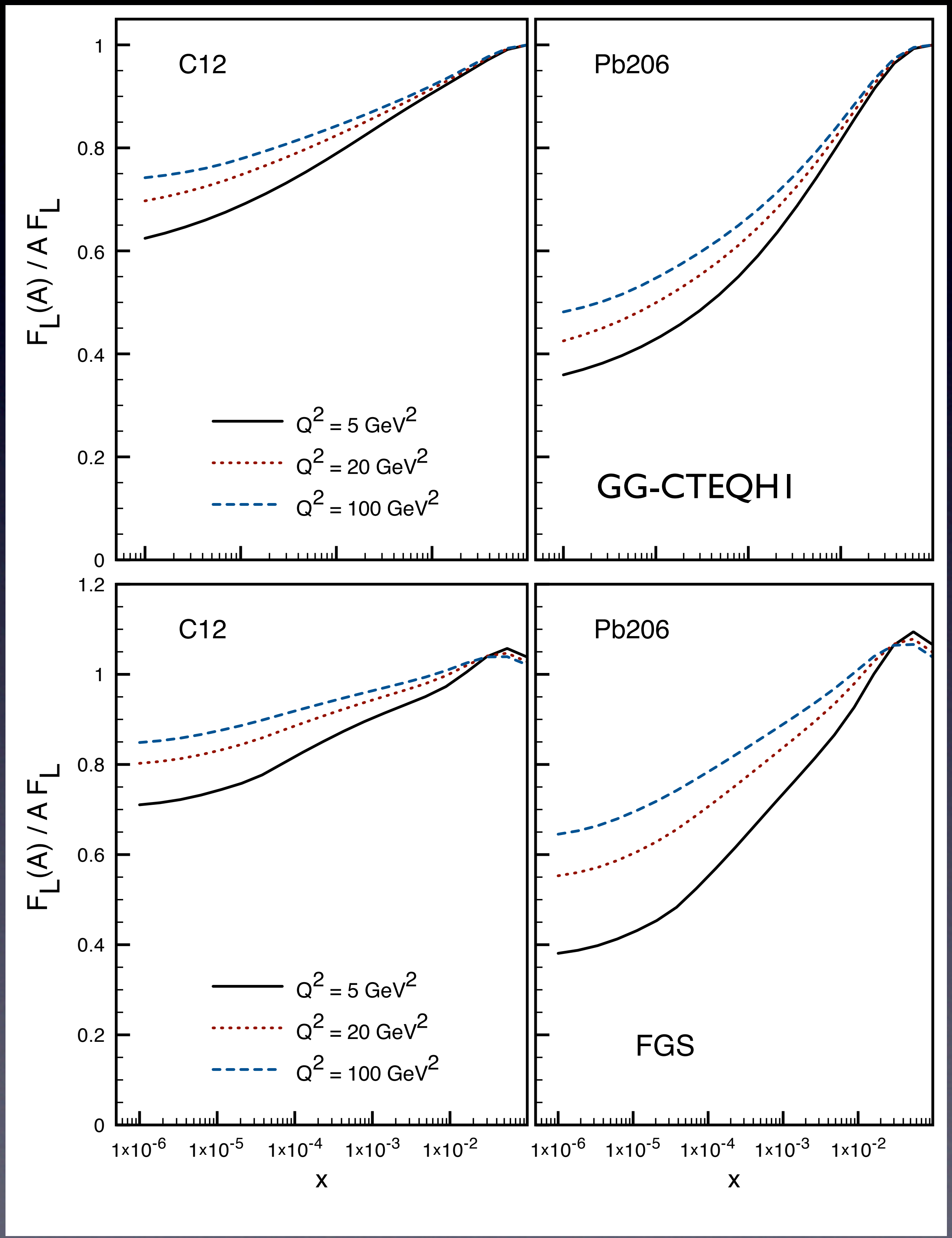
Usual assumption: R $\neq$ R(A)

- not true in dipole model!
- what about modification at low-x?

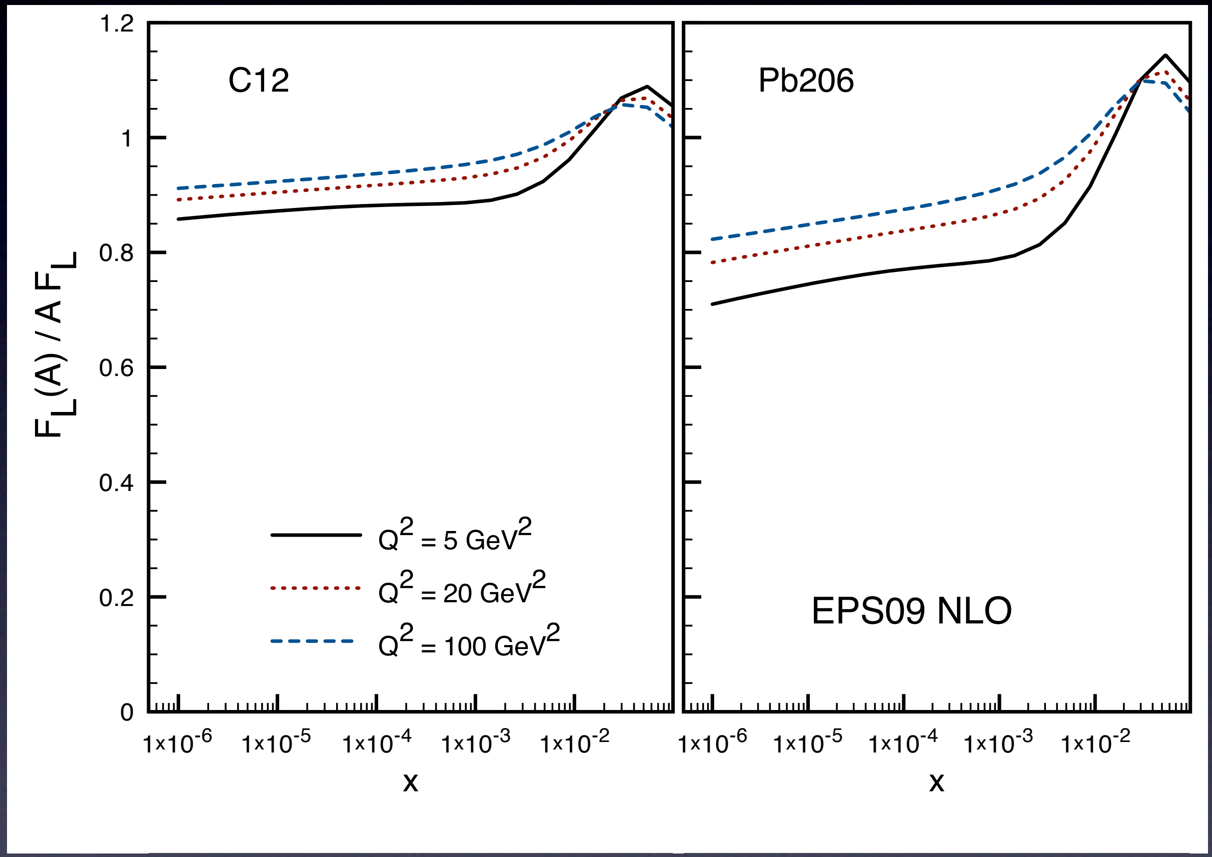
$$F_L^A(x,Q^2) = \frac{2\alpha_S(Q^2)}{\pi} \int_x^1 \frac{dz}{z} \left(\frac{x}{z}\right)^2 \left[\sum_{i=q,\bar{q}}^{N_f} e_i^2 \left(1-\frac{x}{z}\right) z g^A(z,Q^2) + \frac{2}{3} F_2^A(z,Q^2)\right]$$

Altarelli, Martinelli PLB 76, 89 (1978)

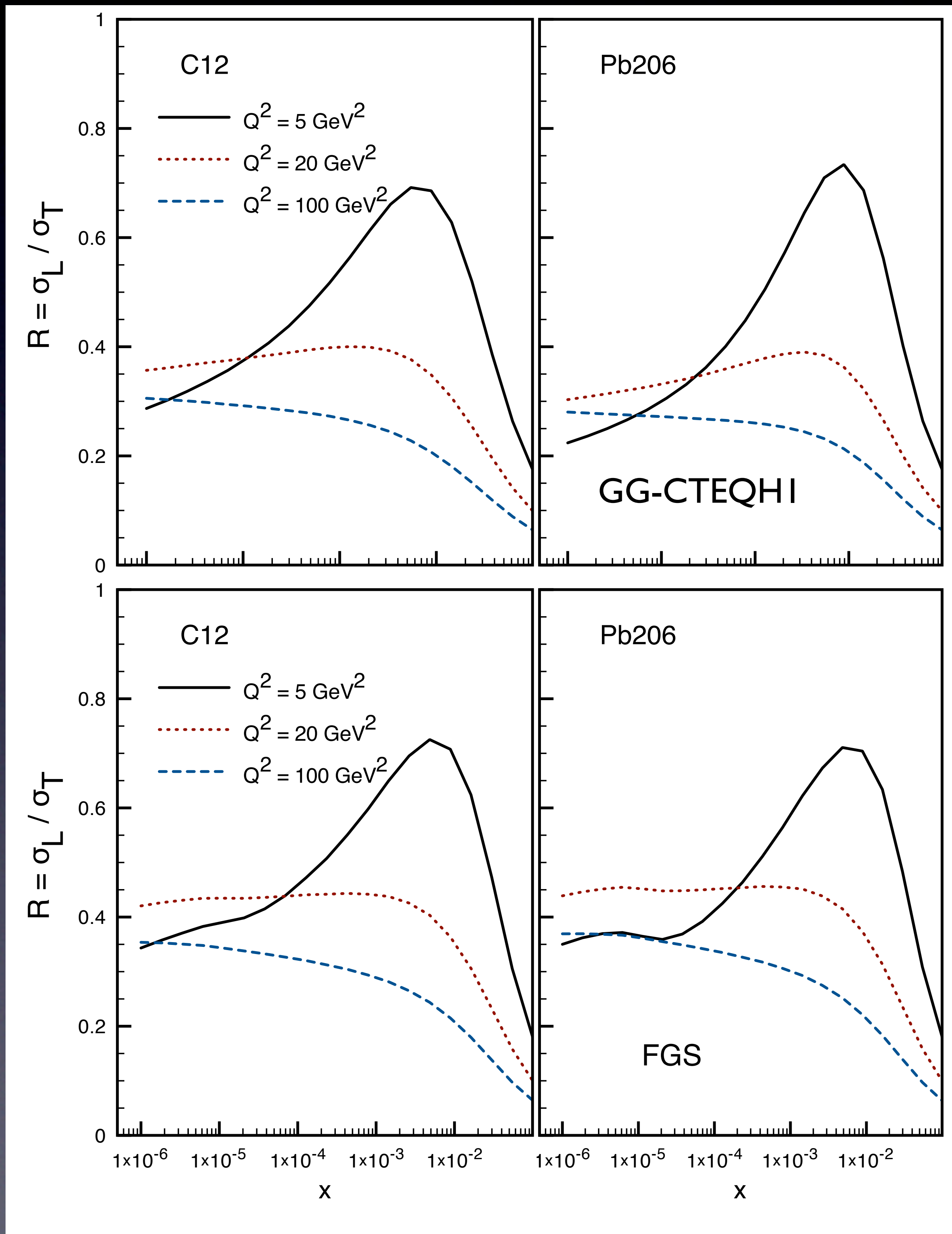
The nuclear F_L

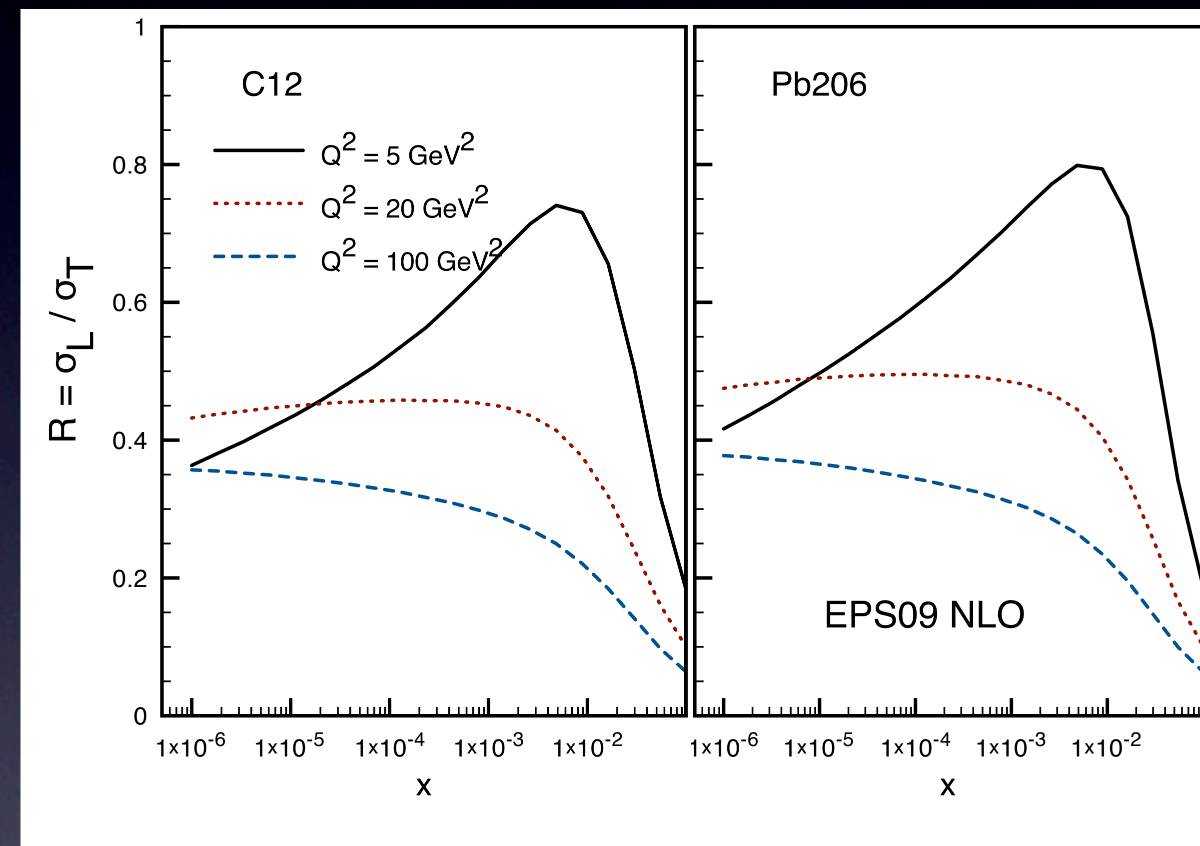


Armesto, Kaidalov, Paukkunen,
Salgado, Tywoniuk (in preparation...)



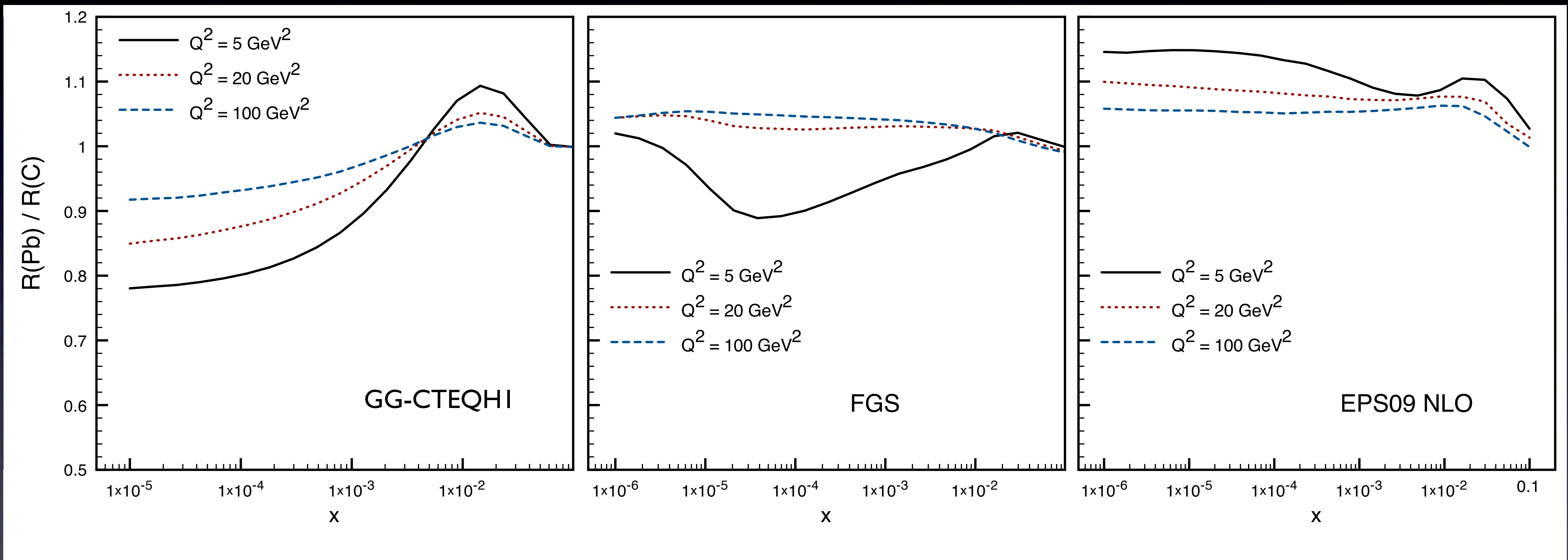
The nuclear F_L





Nuclear dependence of R

Armesto, Kaidalov, Paukkunen, Salgado, Tywoniuk (in preparation...)



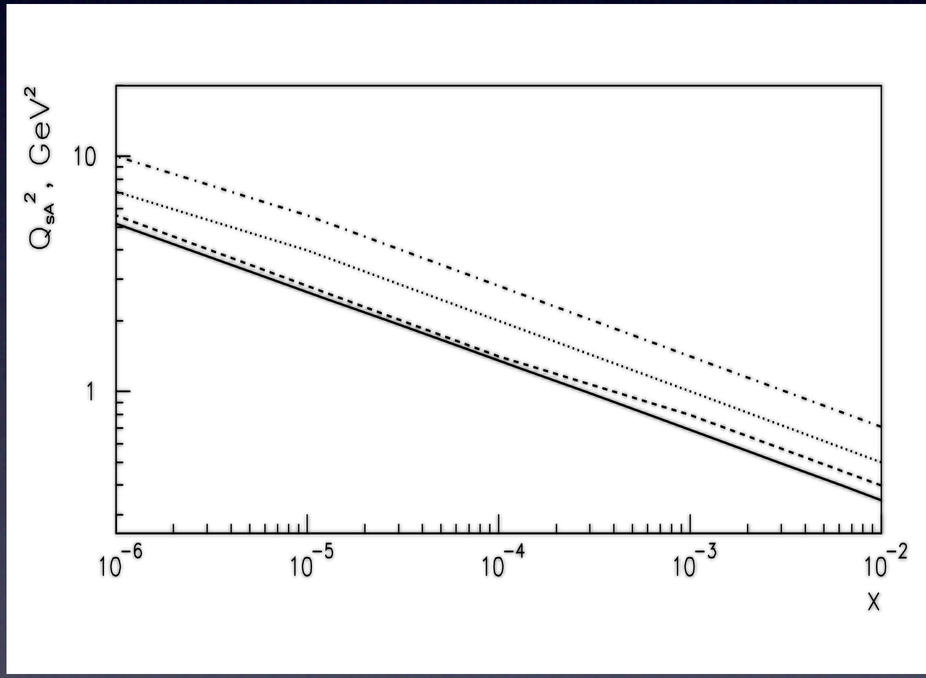
- Potentially a 20% effect for large nuclei and low x!
- The effect disappears rapidly with Q^2

How much will this affect @ eRHIC kinematics?. ... work in progress

Outlook

$$\phi_A(x,k,b) = -\frac{N_c}{4\pi^2\alpha_S}k^2\int\frac{d^2r}{2\pi}e^{ikr}\sigma_S(x,r,b)$$

Armesto, Braun EPJC 22 (2001) 351
Armesto EPJC 26 (2002) 35



- ✓ what is the nuclear saturation scale, Q_S, and the unintegrated gluon distribution from a model with inelastic shadowing?
- ✓ multiplicity distributions in DIS

$$\sigma^k_{\gamma^*p} = \frac{\sigma_P}{kZ}\left[1 - e^{-Z}\sum_{i=0}^{k-1}\frac{Z^i}{i!}\right] \qquad Z \approx 8\sigma^{\mathcal{D}}_{\gamma^*p}/\sigma^{tot}_{\gamma^*p}$$

Conclusions

Diffractive -> controls saturation
Longitudinal -> controls gluon

Saturation -> all observables interlinked, need for coherent description of all simultaneously!

MC with saturation ideas!

- ✓ CFSKe gives a good baseline to study
  - — low-x structure functions
  - — breakdown of DGLAP - resummation?
- ✓ nuclear effects calculated
  - — total, longitudinal and diffractive cross section + PDFs, nuclear effects on R
- ✓ a coherent picture of hadronic interactions at high energies needs a study of different observables
- ✓ upcoming facilities call for estimates on those
- ✓ a MC implementation is needed