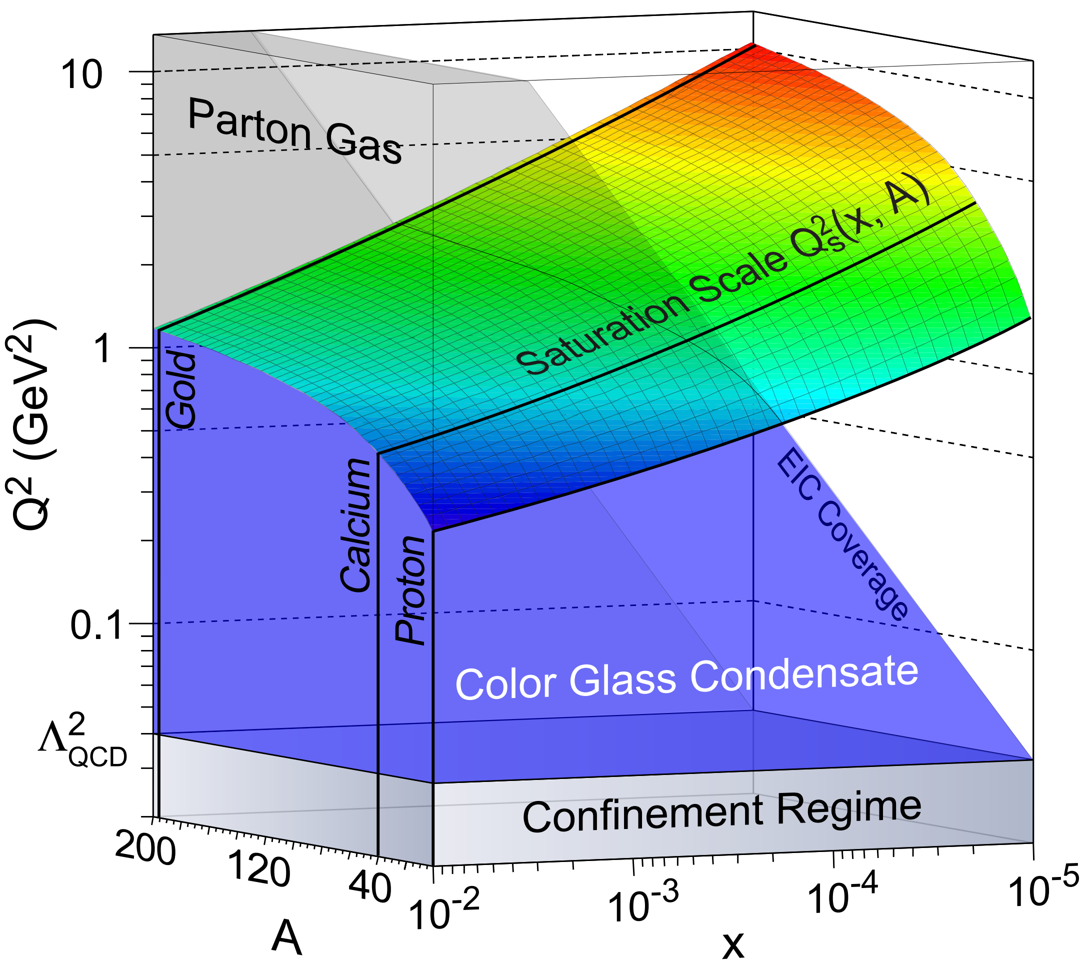
e+A Experiments at an Electron Ion Collider



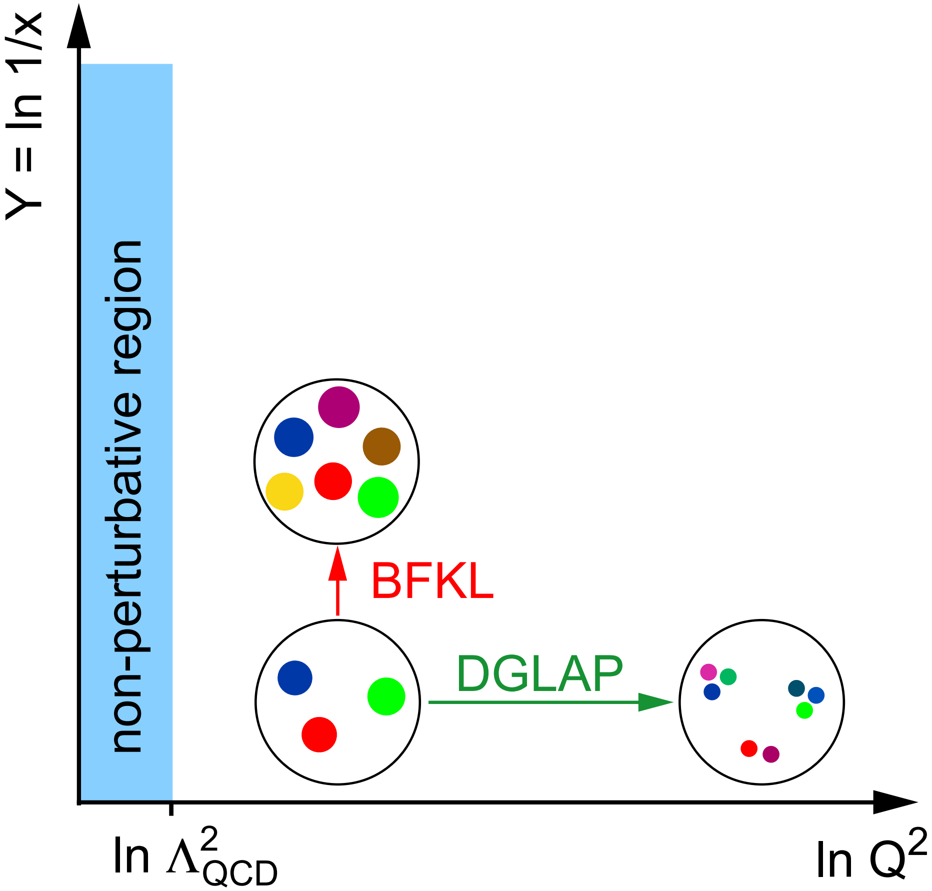
Thomas Ullrich
RIKEN/RBRC

Workshop on
Future Directions in High Energy QCD

October 22, 2011

RIKEN NISHINA CENTER
Office of Science
U.S. Department of Energy
BROOKHAVEN NATIONAL LABORATORY

New Regime of Hadronic Wave Function



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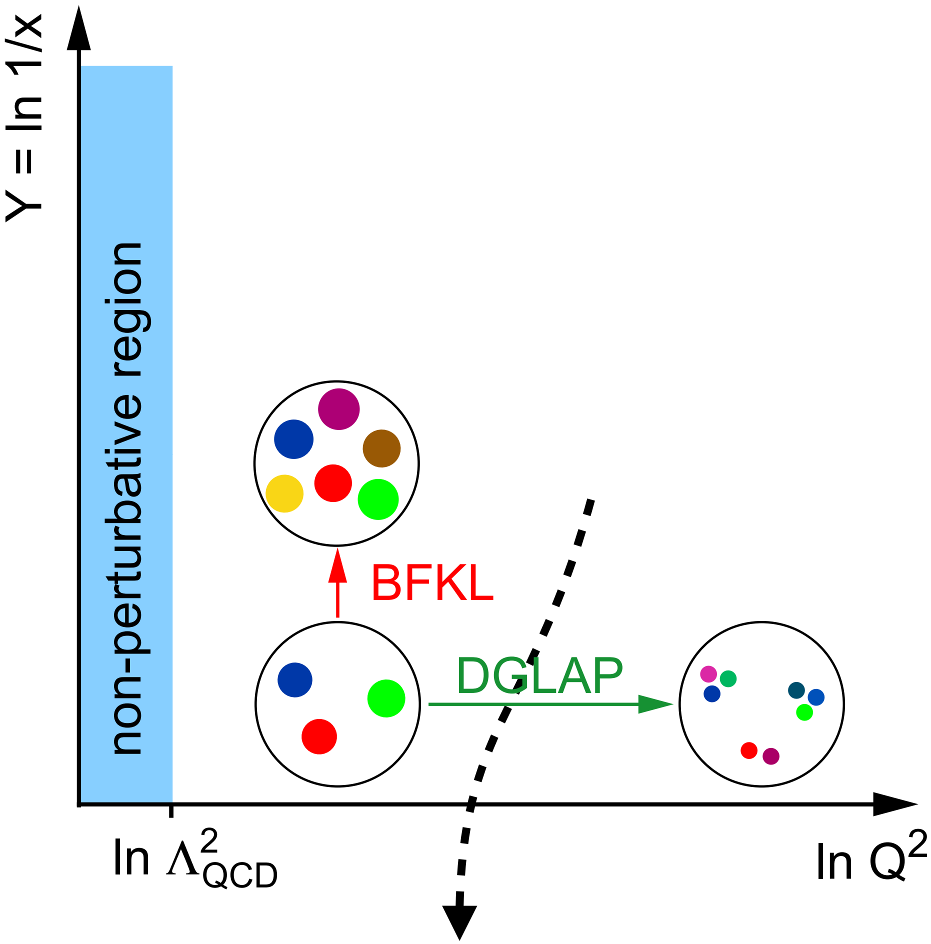

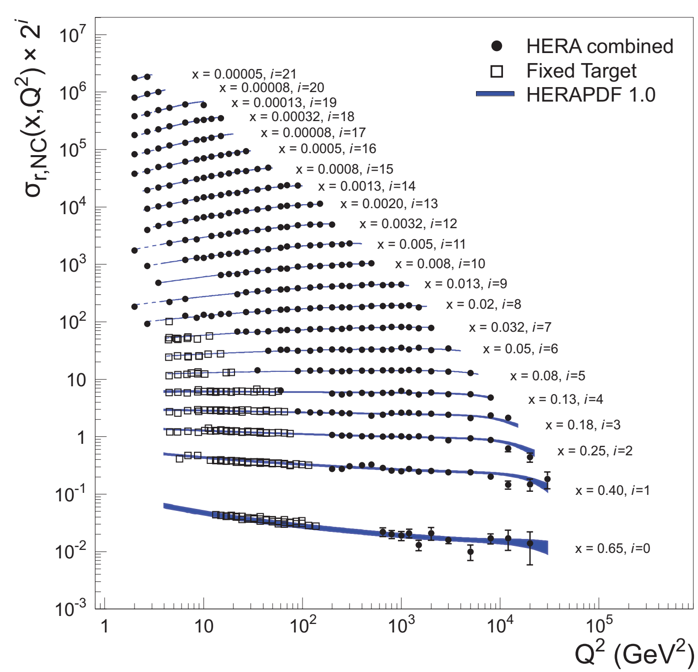

pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA)

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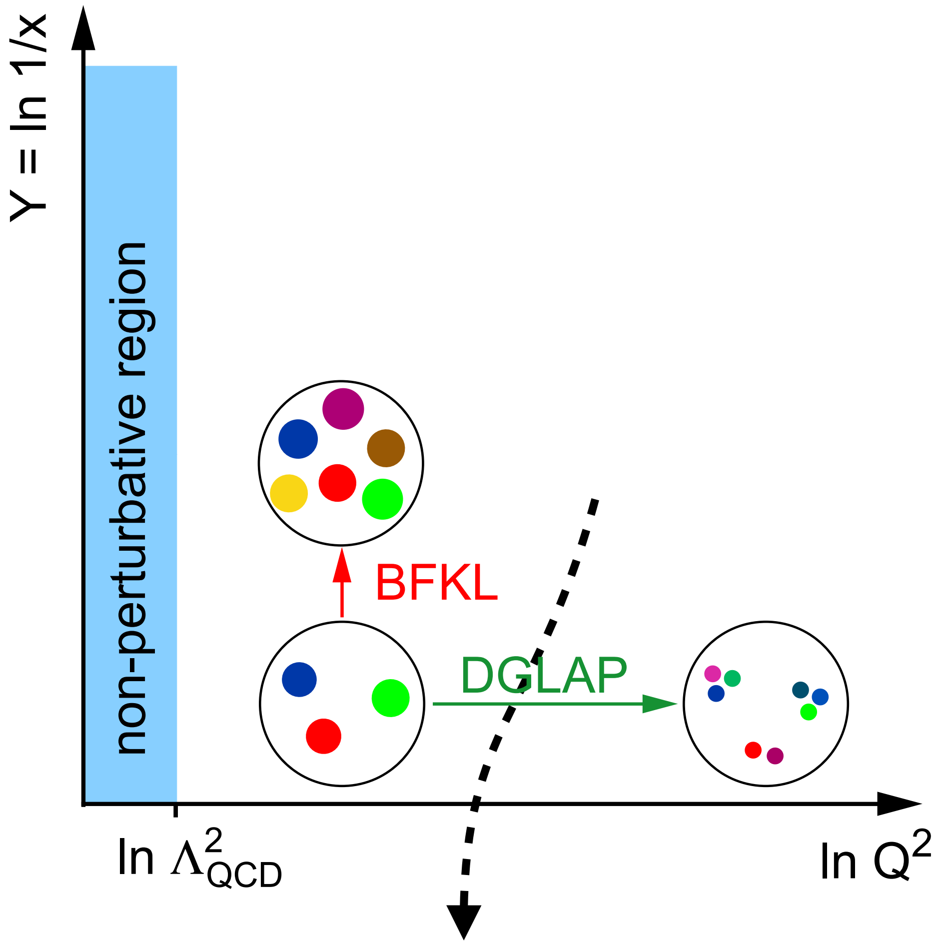
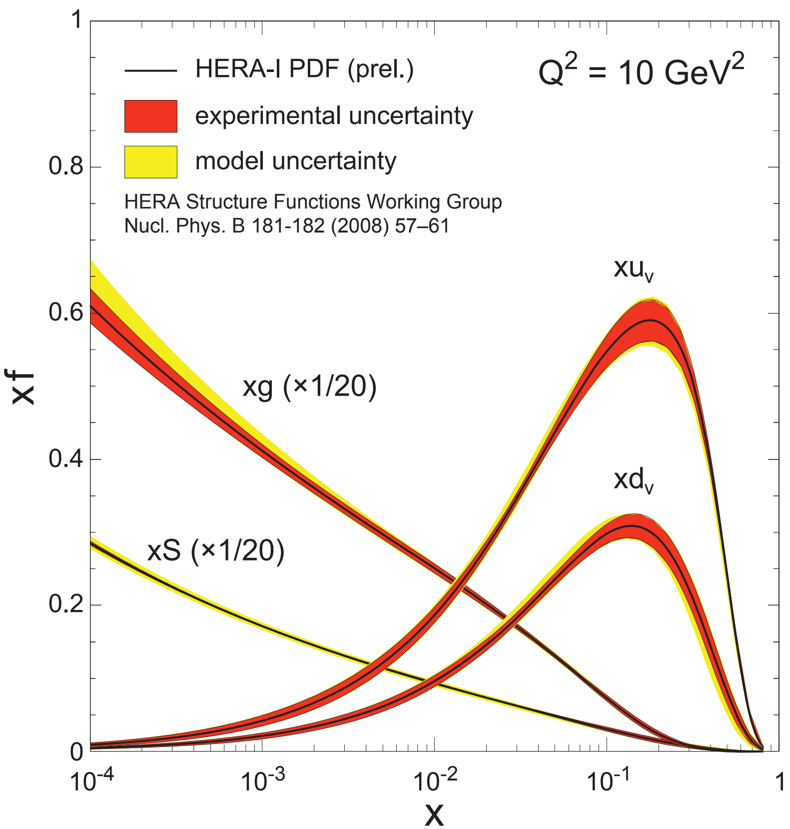


pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA)

HERA taught us that glue dominates for x < 0.1



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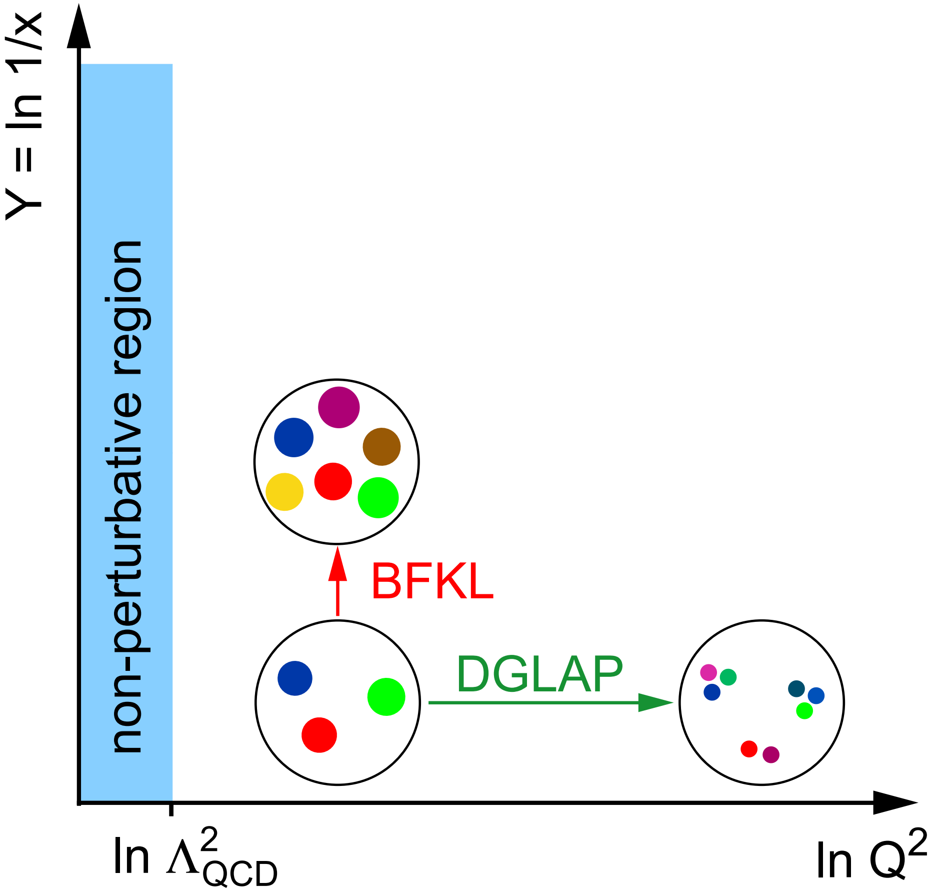

However DGLAP & BFKL evolution have their limits

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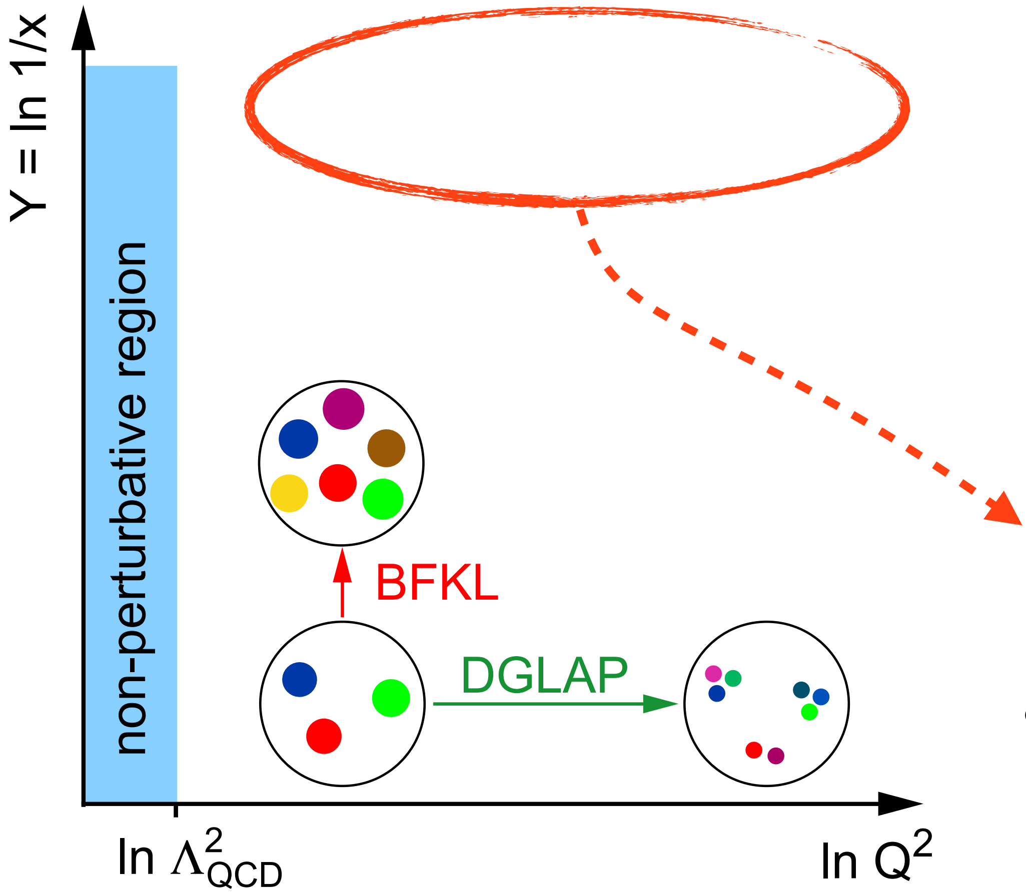
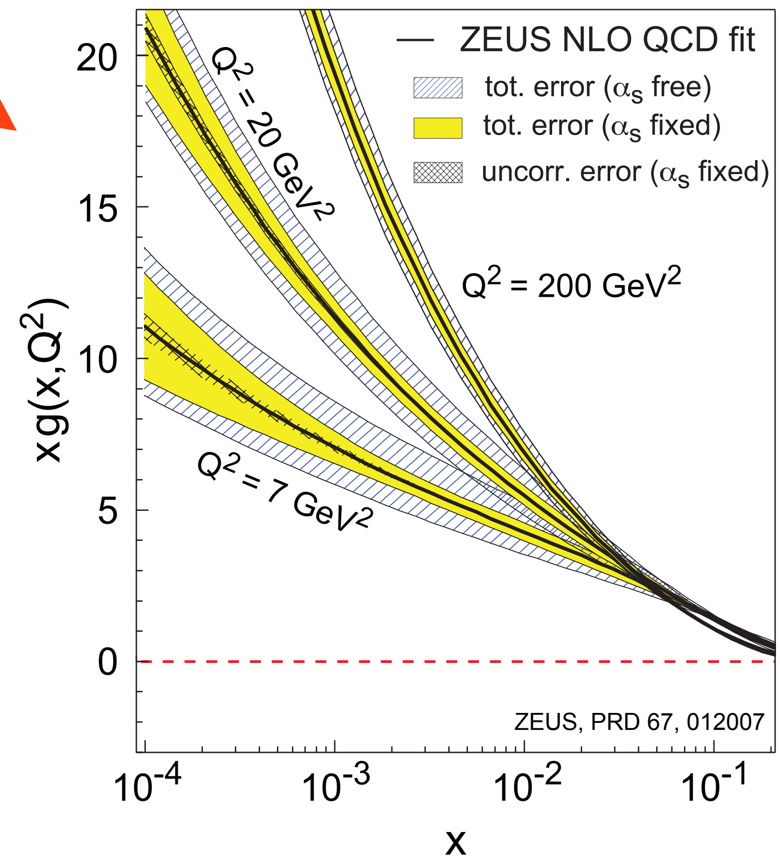


However DGLAP & BFKL evolution have their limits

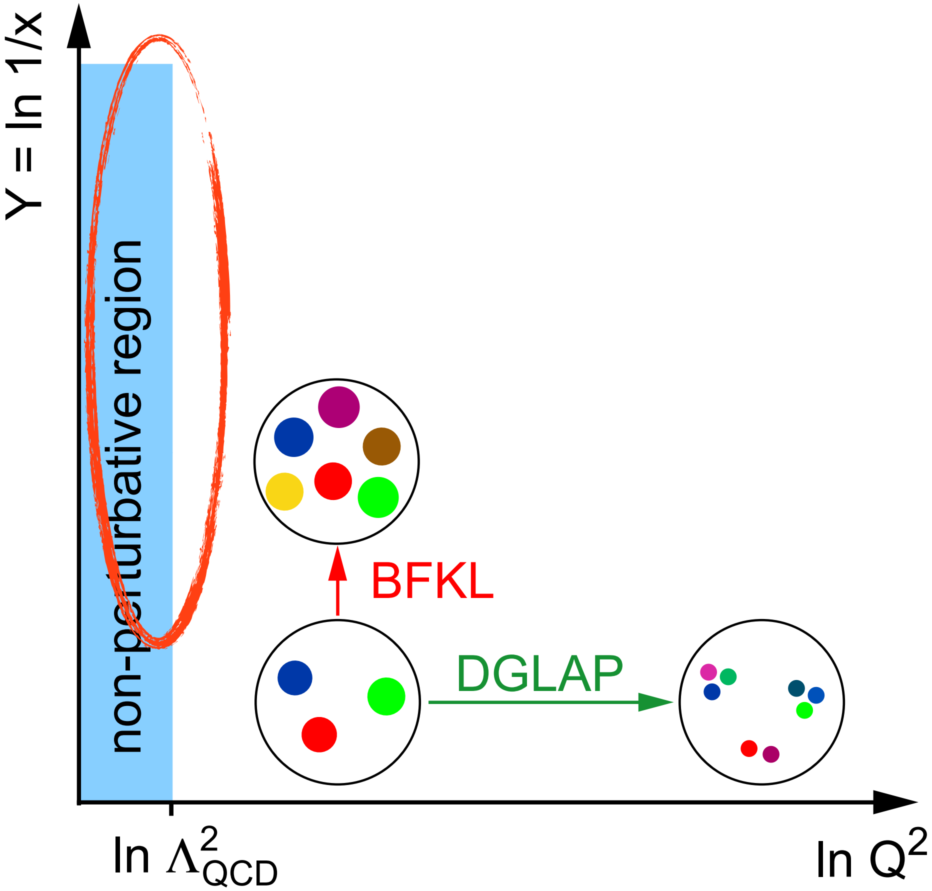
Gluon self-interaction has dramatic consequences at small x:



- built in high energy "catastrophe"
- xG rapid rise violates unitary bound

⇒ Need to tame/saturate evolution

New Regime of Hadronic Wave Function



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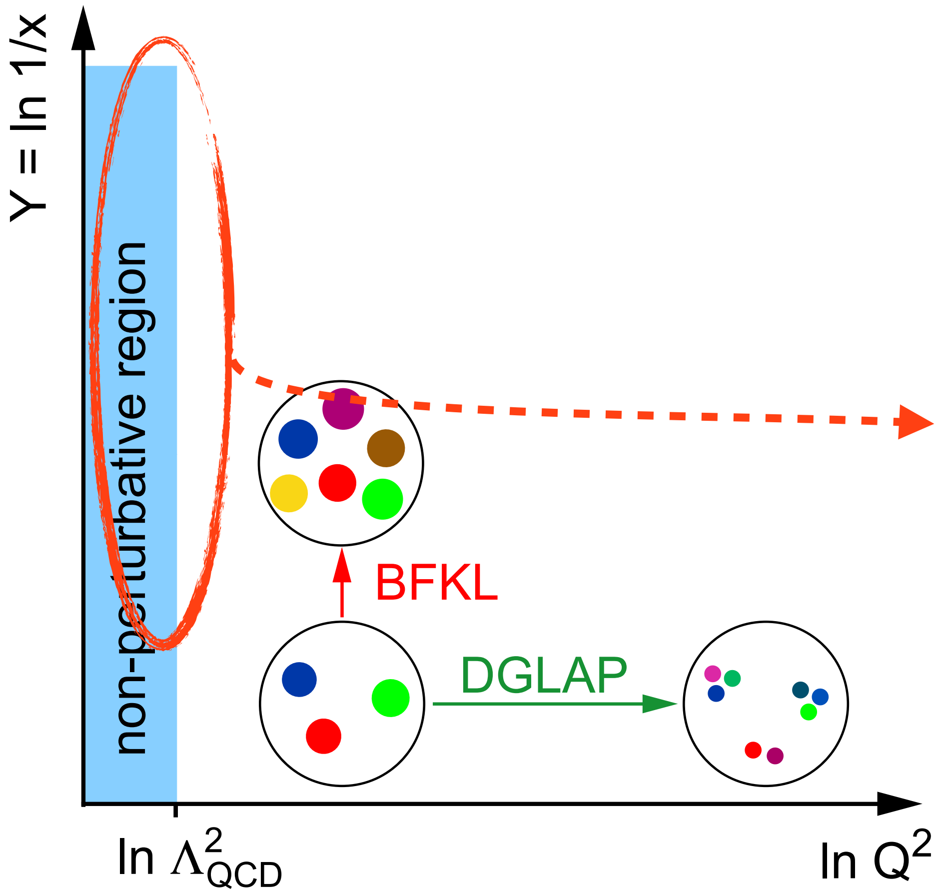

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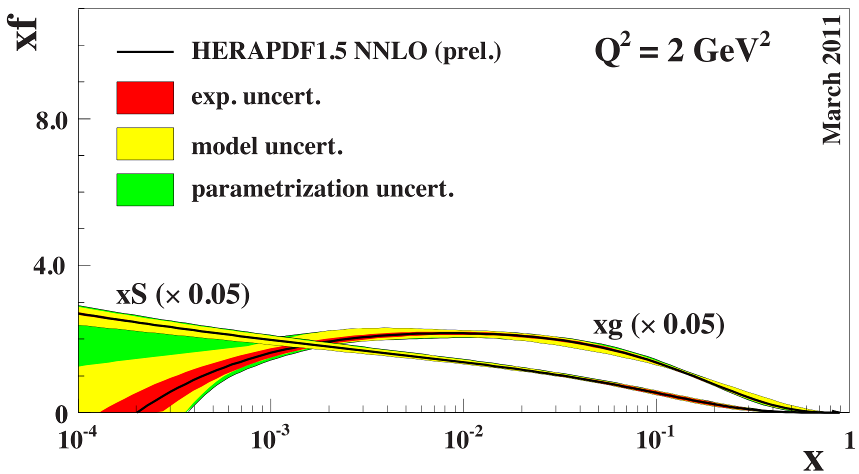
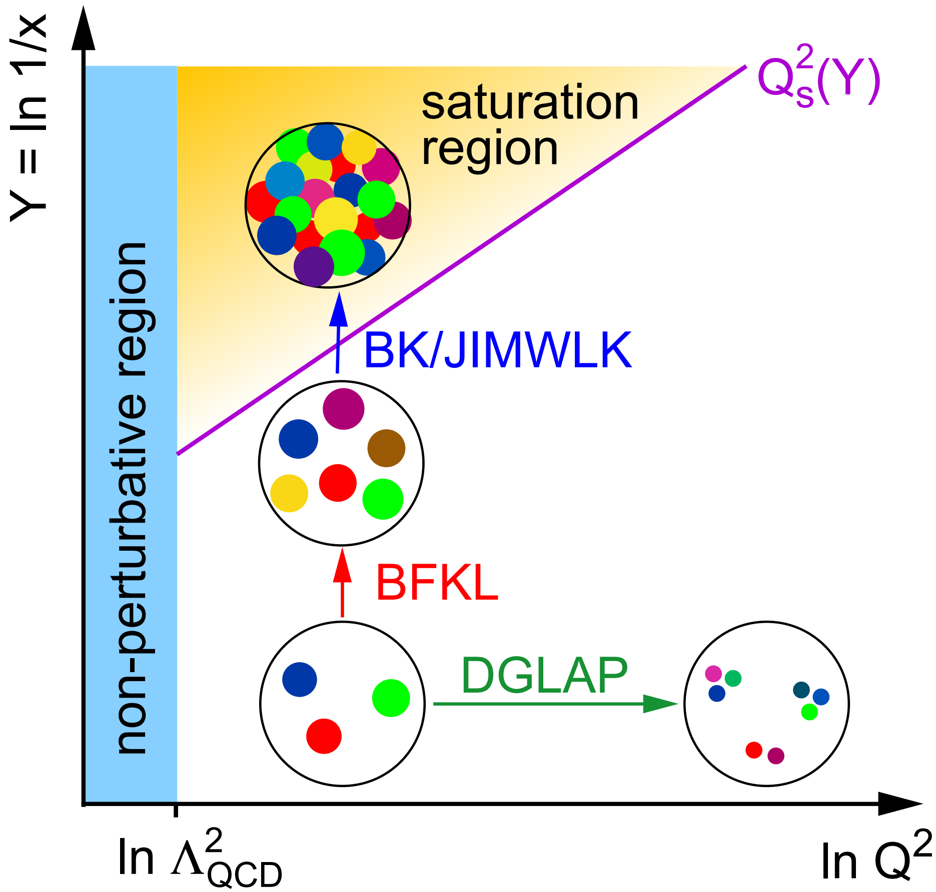


Hints at low-Q^2 that things are not in order

- $xG(x,Q^2) < 0$ (OK in NLO)
- $xG(x,Q^2) < xQ_{sea}(x,Q^2)$?

Issue: To what Q^2 is pQCD applicable?

New Regime of Hadronic Wave Function



New Approach: Non-Linear Evolution

- McLerran-Venugopalan Model:
  - Weak coupling description of wave function
  - Gluon field $A_\mu \sim 1/g \Rightarrow$ gluon fields are strong classical fields!
- BK/JIMWLK: non-linear effects $\Rightarrow$ saturation characterized by $Q_s(x)$
- Wave function is Color Glass Condensate in IMF description

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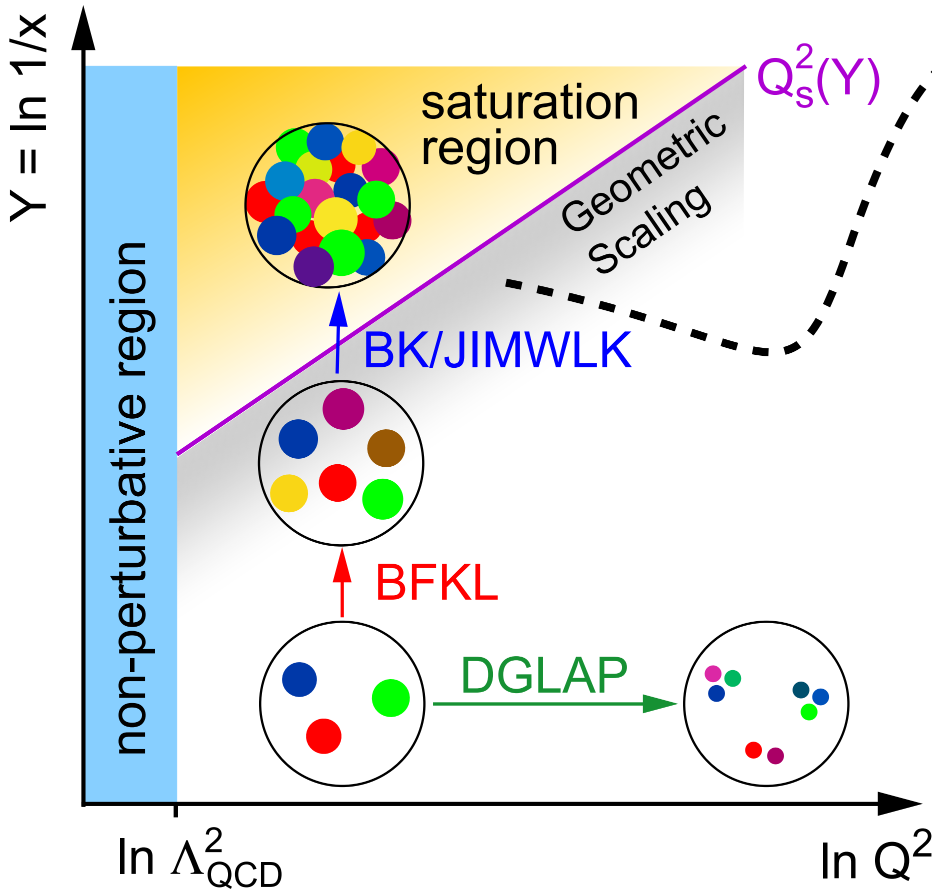
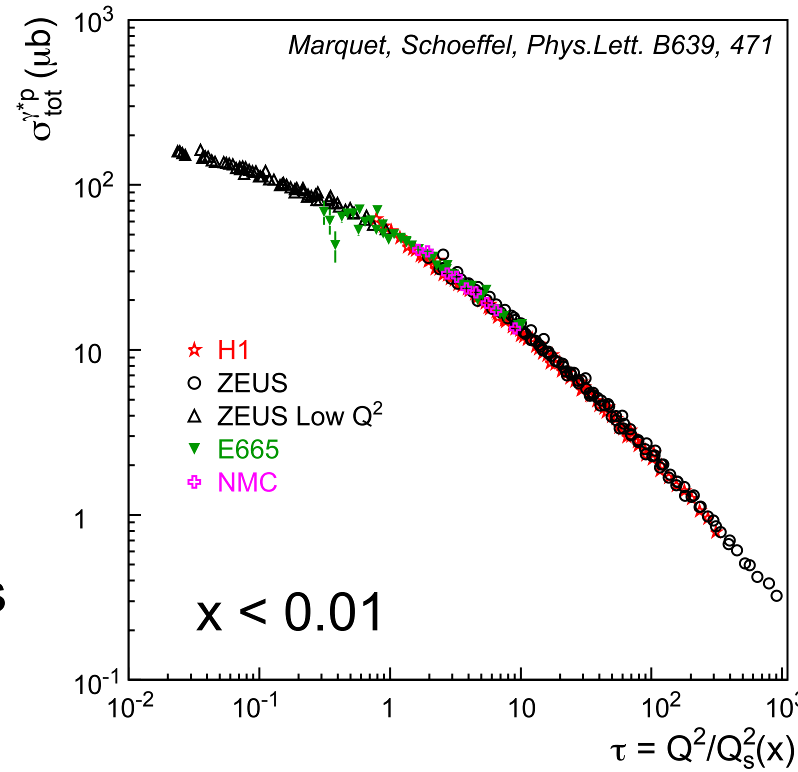


Appearance of Qs at HERA:

- DIS cross section for x < 0.01 only function of one variable (Stasto, Golec-Biernat, Kwiecinski, '01)

$$\sigma_{DIS}\,(x, Q^2) = \sigma_{DIS}\,(Q^2 / Q_S^2(x))$$

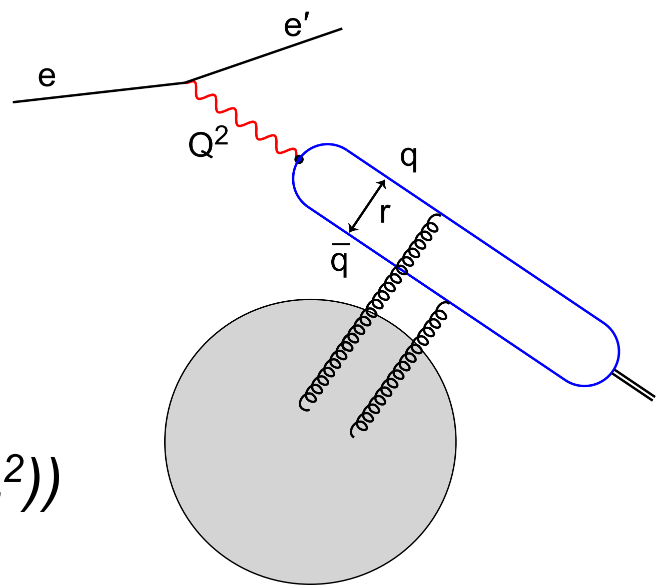


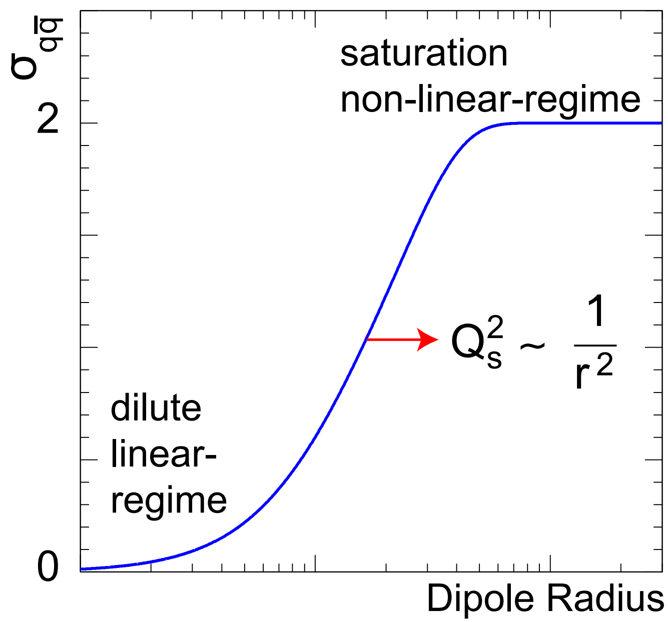
Geometric scaling predicted by non-linear JIMWLK/BK evolution equations (Iancu, Itakura, McLerran '02)

Q_S: Matter of Definition and Frame (I)

Rest frame of hadron:

- $\bar{q}q$ dipole (Mueller dipole)
- DGLAP: $\sigma_{qq} \propto r^2\, \alpha_s(\mu^2)\, xG(x,\mu^2)$
  - explodes with r^2
  - violates unitarity
- Saturation: $\sigma_{qq} \propto 1\text{-}\exp(-r^2\, \alpha_s(\mu^2)\, xG(x,\mu^2))$





Common definition: $\dfrac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\mathcal{N}$

$$\mathcal{N}(x_\perp = 1/Q_S, Y) = 1 - e^{-1/4}$$

$$\mathcal{N}(x_\perp = 1/Q_S, Y) = 1 - e^{-1/2}$$

$$\mathcal{N}(x_\perp = 1/Q_S, Y) = 1/2$$

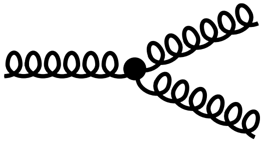
Important: universality of $\lambda = \mathrm{d}\ln Q_S/\mathrm{d}Y$

$Y = \ln 1/x$

Q_S: Matter of Definition and Frame (II)

Infinite Momentum Frame:

- BFKL (linear QCD): splitting functions ⇒ gluon density grows

BFKL: 

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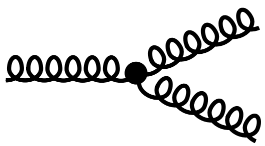
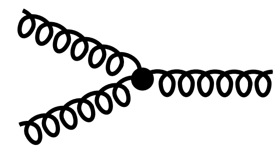
BFKL: 

BK adds: 

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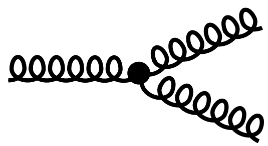
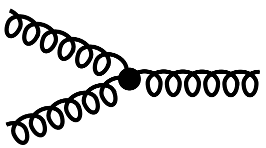
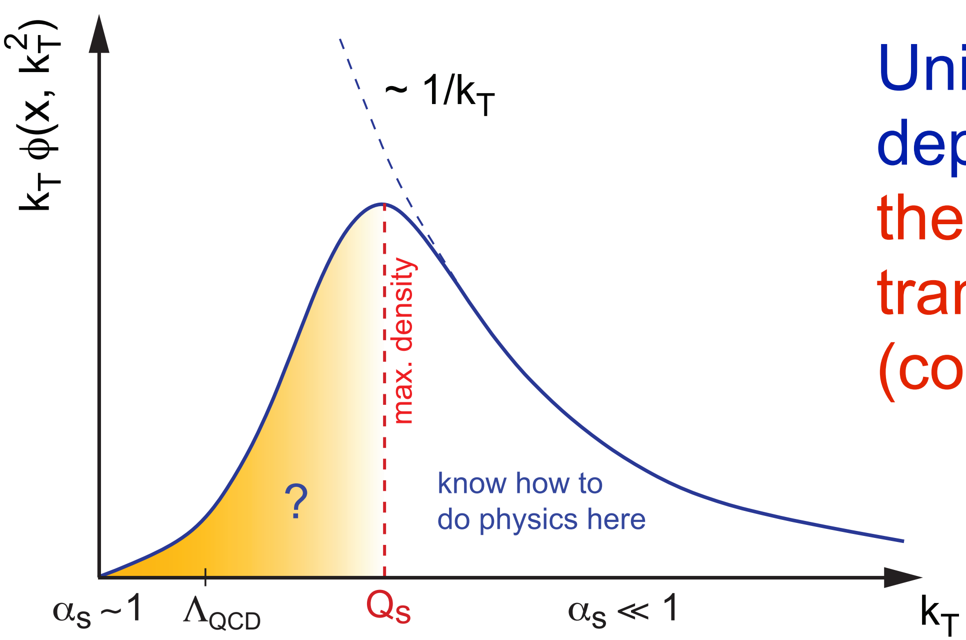
BFKL: 

BK adds: 

- At Q_S: gluon emission balanced by recombination



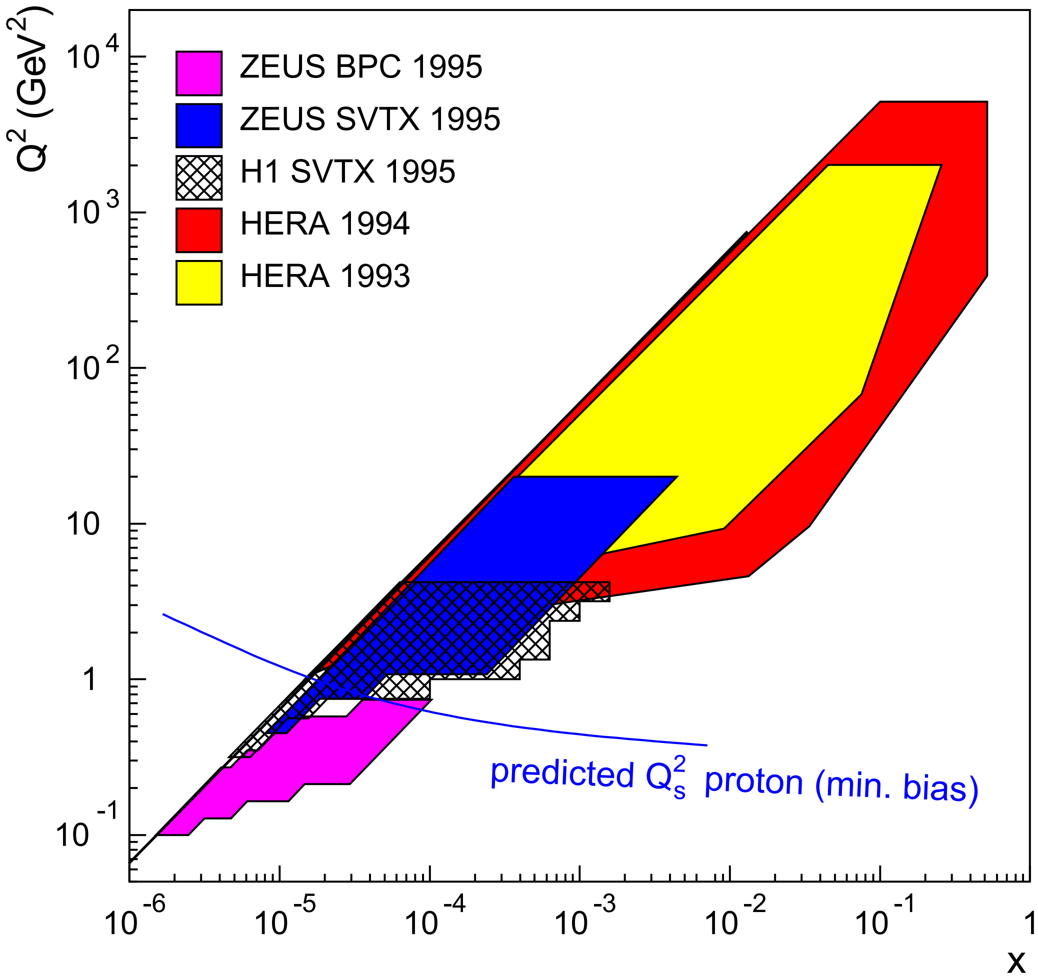
Unintegrated gluon distribution depends on k_T and x:
the majority of gluons have transverse momentum $k_T \sim Q_S$ (common definition)

Reaching the Saturation Region

HERA (ep):

Despite high energy range:

- F_2, $G_p(x, Q^2)$ outside the saturation regime
- Need also Q^2 lever arm!
- Only way in ep is to increase √s
- Would require an ep collider at √s ~ 1-2 TeV



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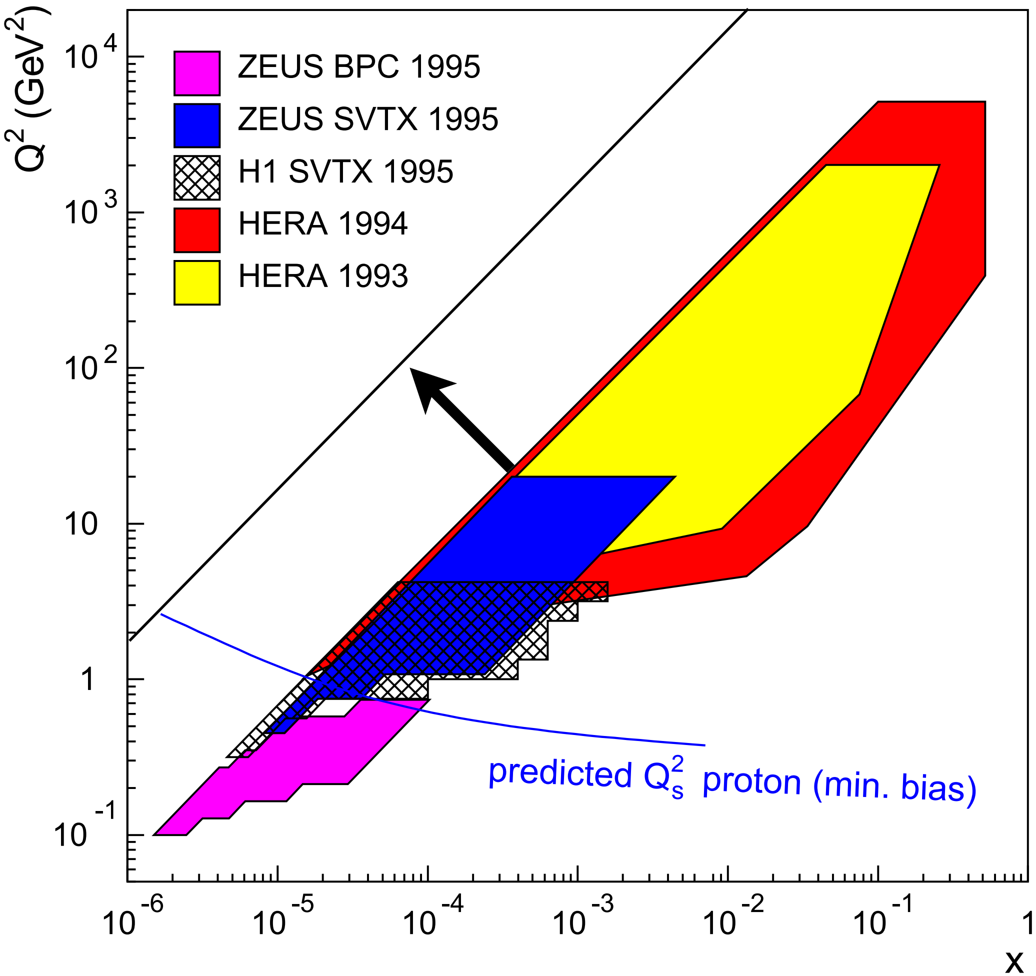

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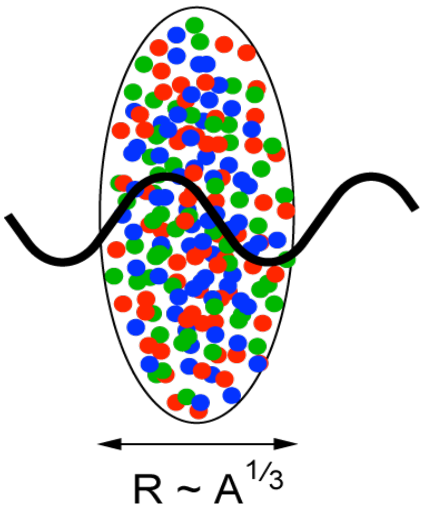
Different approach (eA):

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$



$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

Probe interacts ***coherently*** with all nucleons

Reaching the Saturation Region

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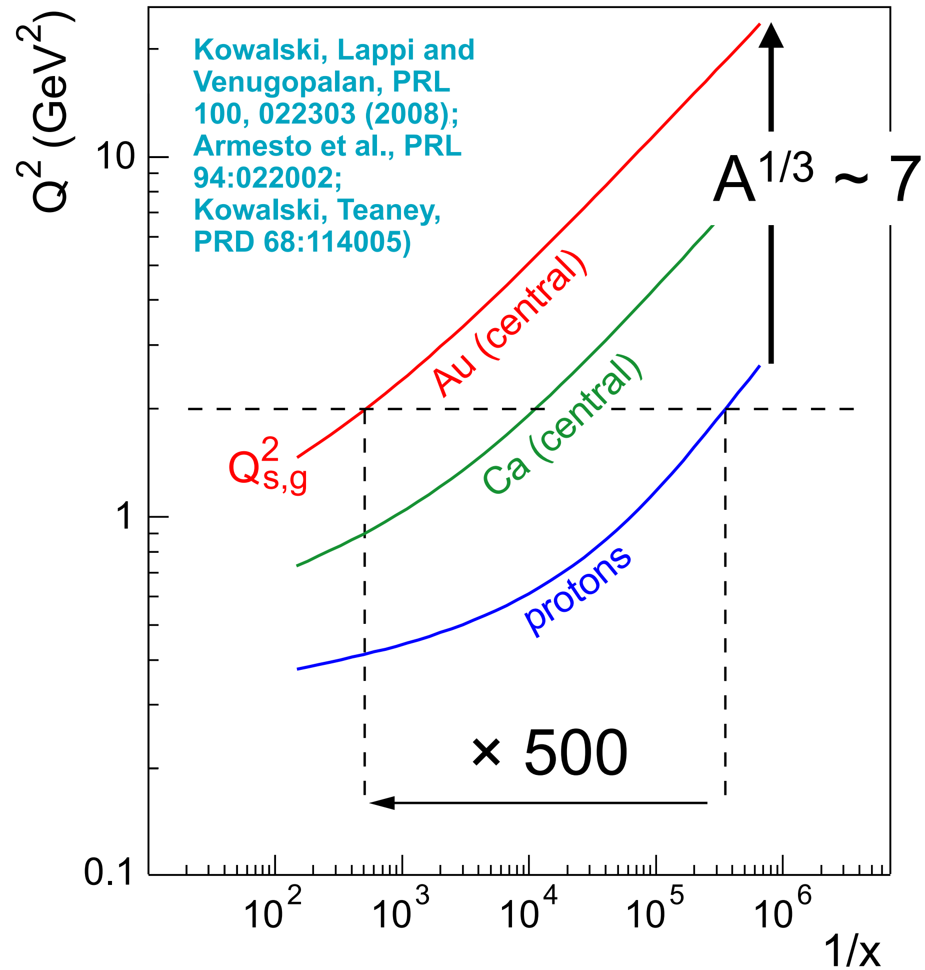

Enhancement of Q_S with A ⇒ saturation regime reached at significantly lower energy in nuclei

EIC: The e+A Physics Program

Investigate with precision the universal dynamics of gluons

Central Topics:

- Study the Physics of Strong Color Fields
  - Establish the existence of the saturation regime
  - Investigate the *dynamics* of this regime
- How do fast probes interact with the gluonic medium?
  - Energy loss, Fragmentation processes
- Study the nature of color singlet excitations (Pomerons)
- What's the role in gluons in the nuclear structure?

see talks by Abhay & Jianwei

e+A Physics Program: Science Matrix

Result of INT workshop in Seattle in fall ’10 (arXiv: 1108.1713)

Deliverables	Observables	What we learn	Phase-I	Phase-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavors and charm; jets	rare probes and bottom; large-x gluons

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transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavors and charm; jets	rare probes and bottom; large-x gluons
b dependence of gluon distribution and correlations	Diffractive VM production and DVCS, coherent and incoherent parts	Interplay between small-x evolution and confinement	Moderate x with light and heavy nuclei	Extend to low-x range (saturation region)

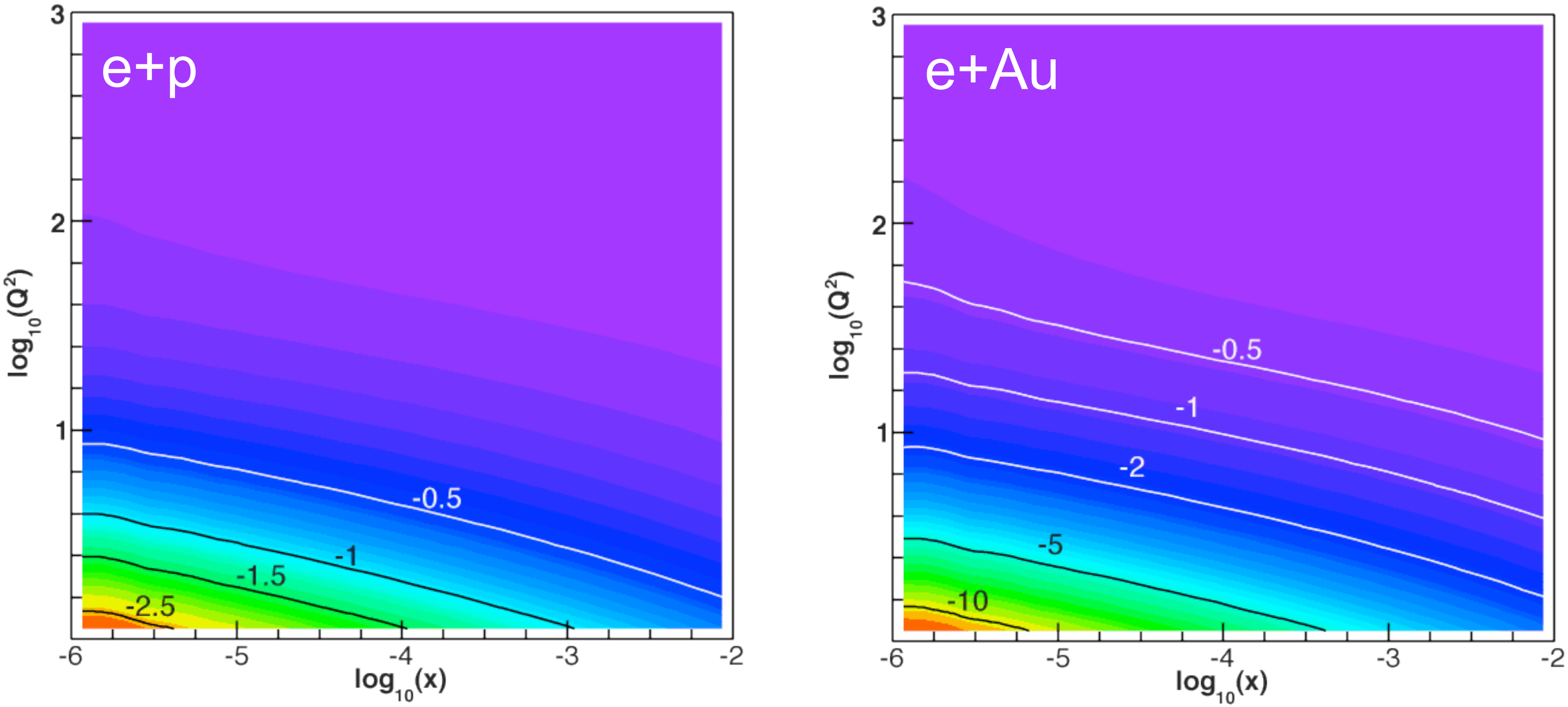
Example 1:
F_L Structure Function

Why is F_L Important?

$$F_L(x,Q^2) \sim xG(x,Q^2)$$

Momentum distribution of glue

$$\text{ratio} = \frac{F_L^{\text{total}} - F_L^{\text{leading twist}}}{F_L^{\text{total}}}$$



J. Bartels, K. Golec-Biernat and L. Motyka, '11 (based on IPSat Model)

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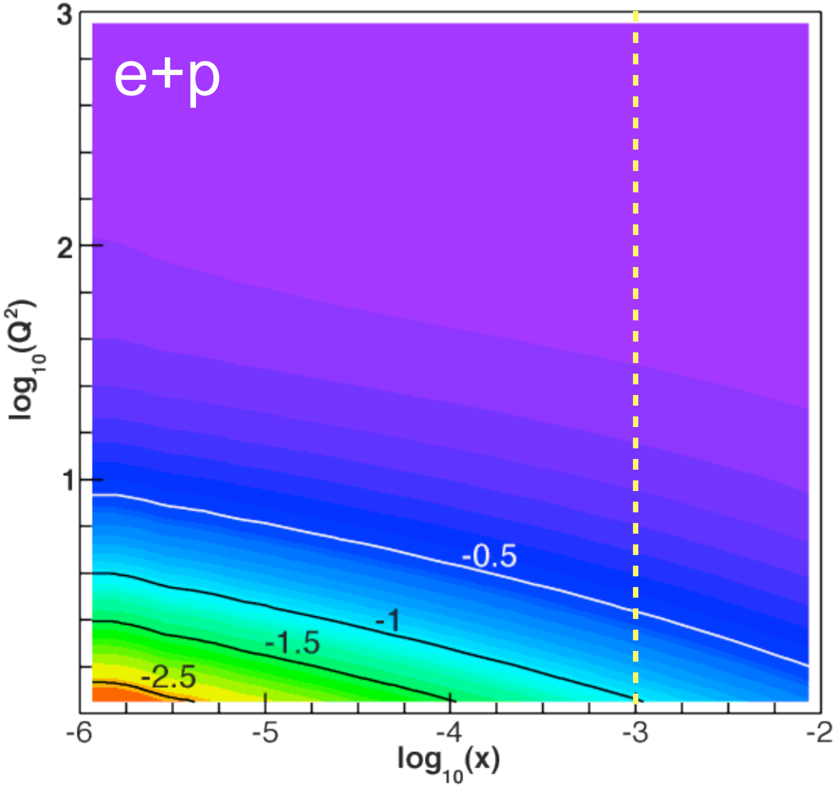

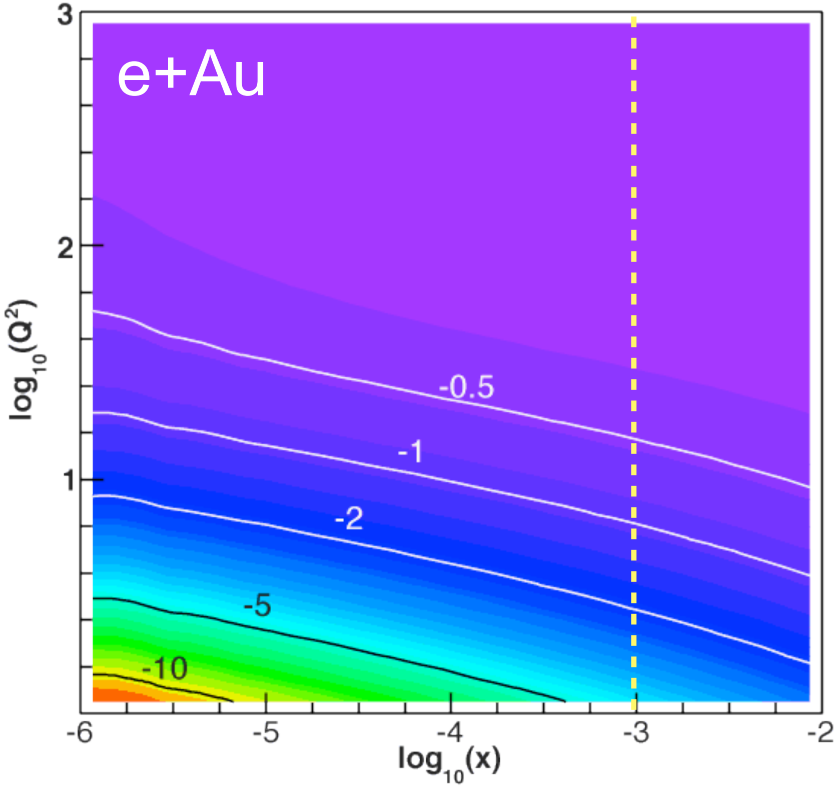

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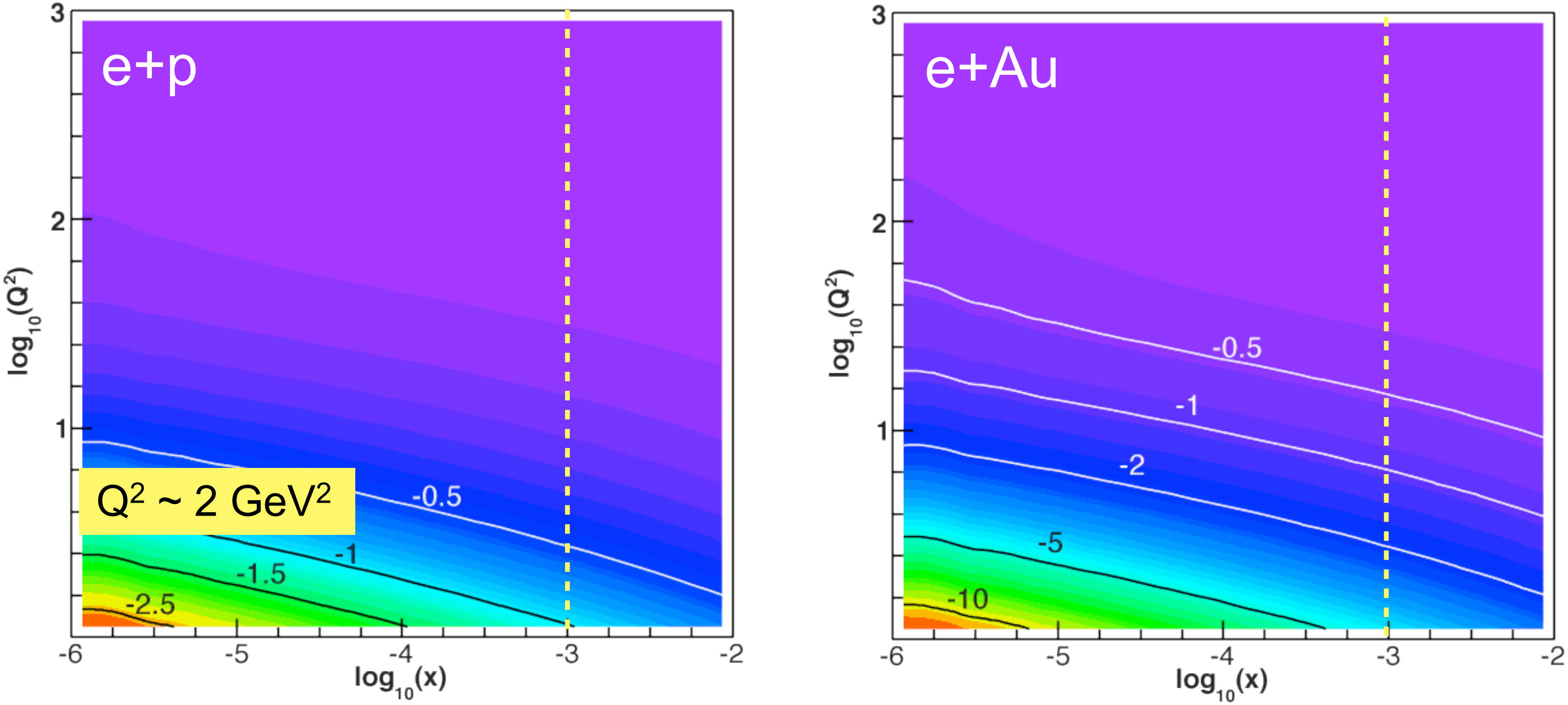

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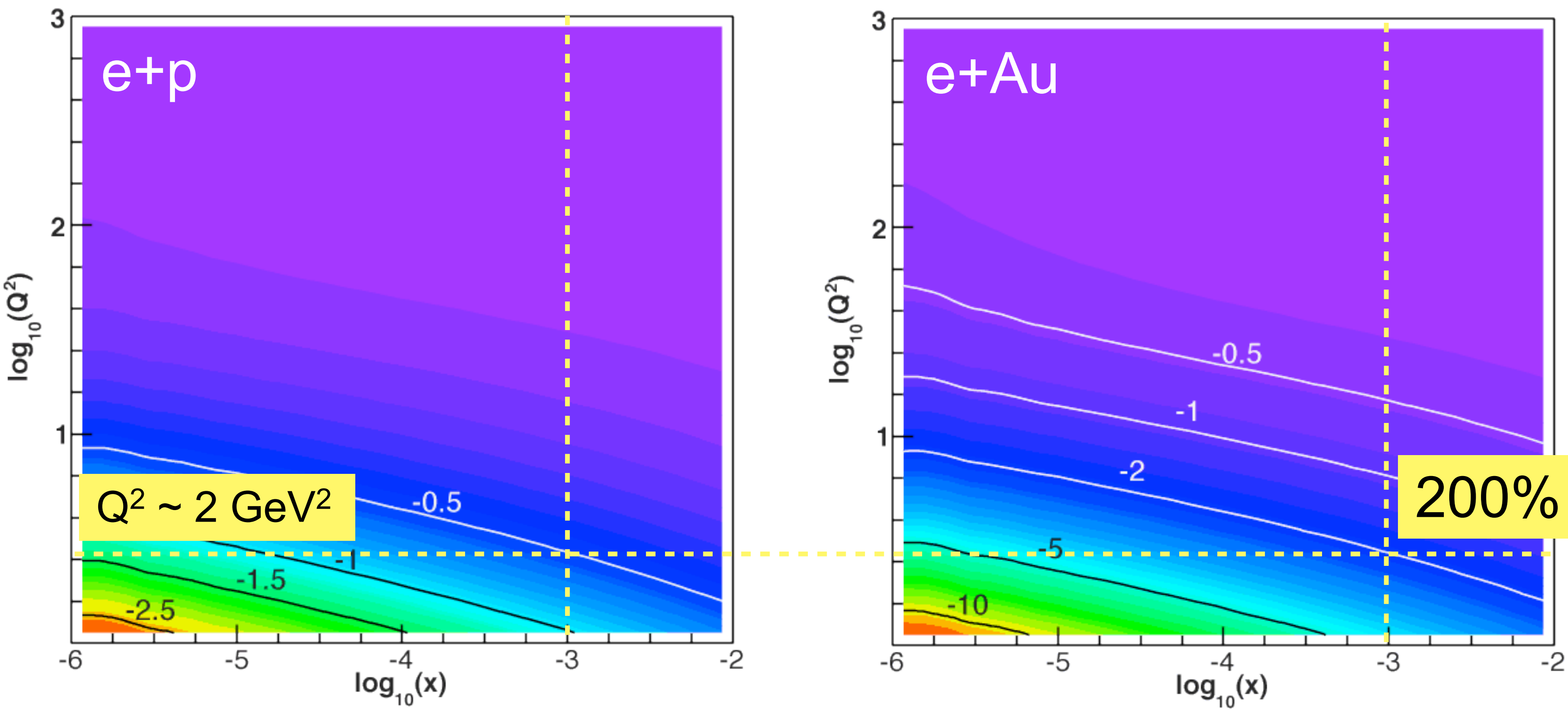

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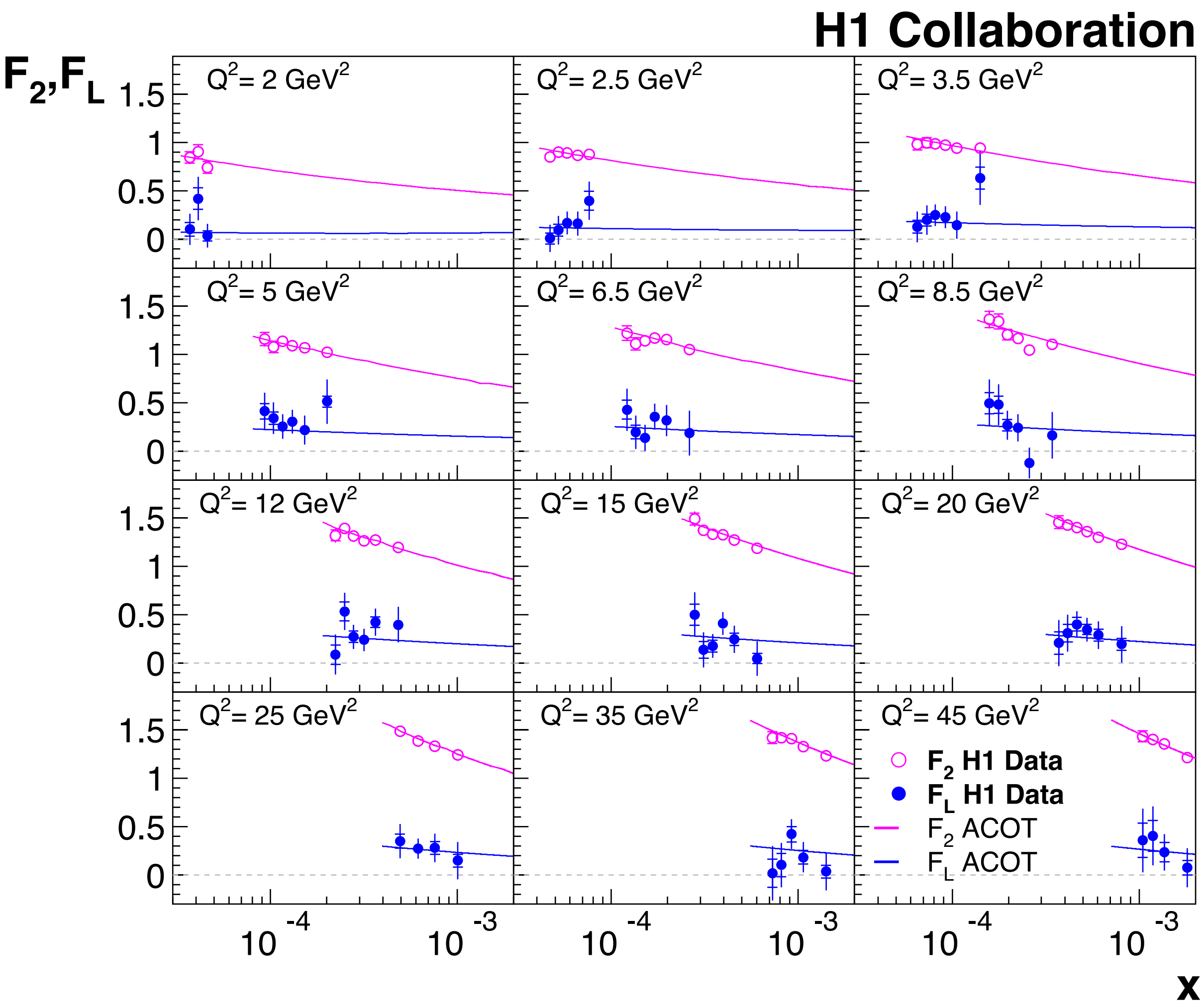
pQCD: higher twist $O(1/Q^2)$

Very different in saturation models!

First (Last) F_L Measurement at HERA

HERA in 2007 (last run) run at different energies enabling the first solid measurement of F_L in ep

- E_p = 920, 575, 460 GeV



Here H1:

$1.5 < Q^2/\text{GeV} < 120$

$2.9 \cdot 10^{-5} < x < 0.01$

Aaron et al.,
Eur. Phys. J.C71 1579

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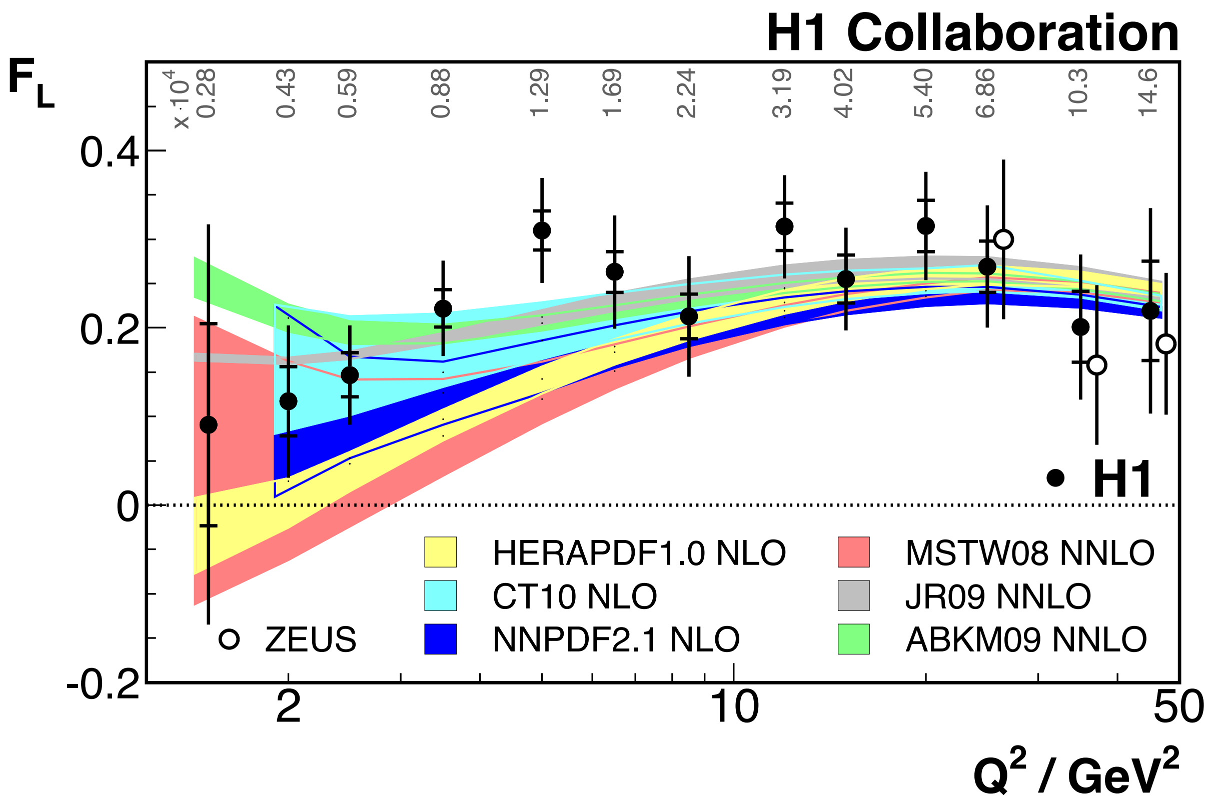

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Uncertainties (sys and stat) too large to distinguish unambiguously between models

Measuring F_L with the EIC (I)

$$\frac{d^2\sigma^{ep\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions (F_2)

gluon momentum distribution (F_L)

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quark+anti-quark momentum distributions

gluon momentum distribution

In practice use reduced cross-section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

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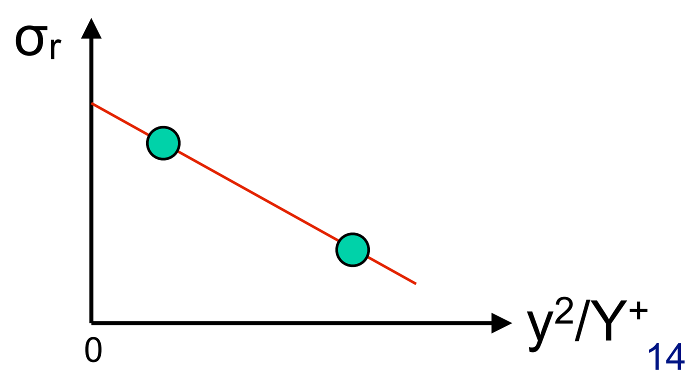
$$= F_2(x,Q^2) - \frac{y^2}{Y^+}F_L(x,Q^2)$$

How to extract F_L

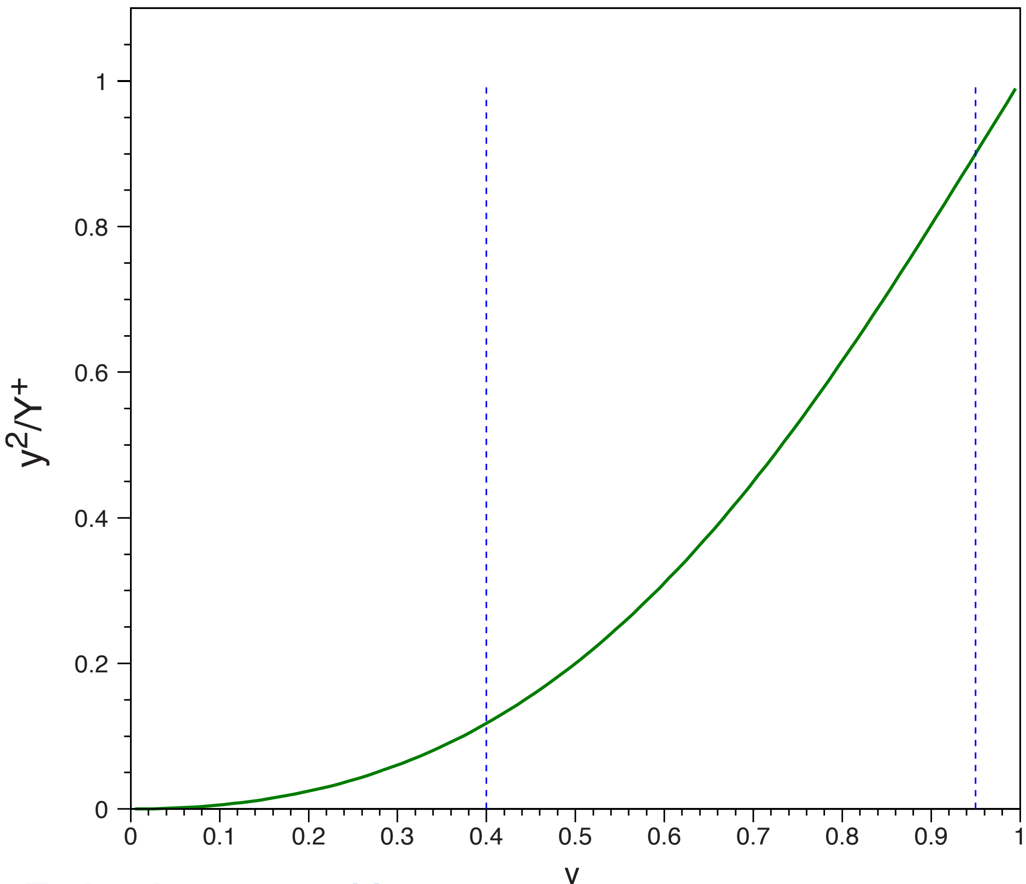
- Need different values of y^2/Y^+
- F_L slope of σ_r vs y^2/Y^+
- F_2 intercept of σ_r vs y^2/Y^+ with y-axis



Measuring F_L with the EIC (II)

In order to extract F_L one needs at least two measurements of the inclusive cross section with "wide" span in inelasticity parameter **y** ($Q^2 = sxy$)

F_L runs at various $\sqrt{s} \Rightarrow$ longer program



Need sufficient lever arm in y^2/Y^+

Limits on y^2/Y^+:

At small y:

detector resolution for e'

At large y:

radiative corrections and charge symmetric background

E. Aschenauer '11

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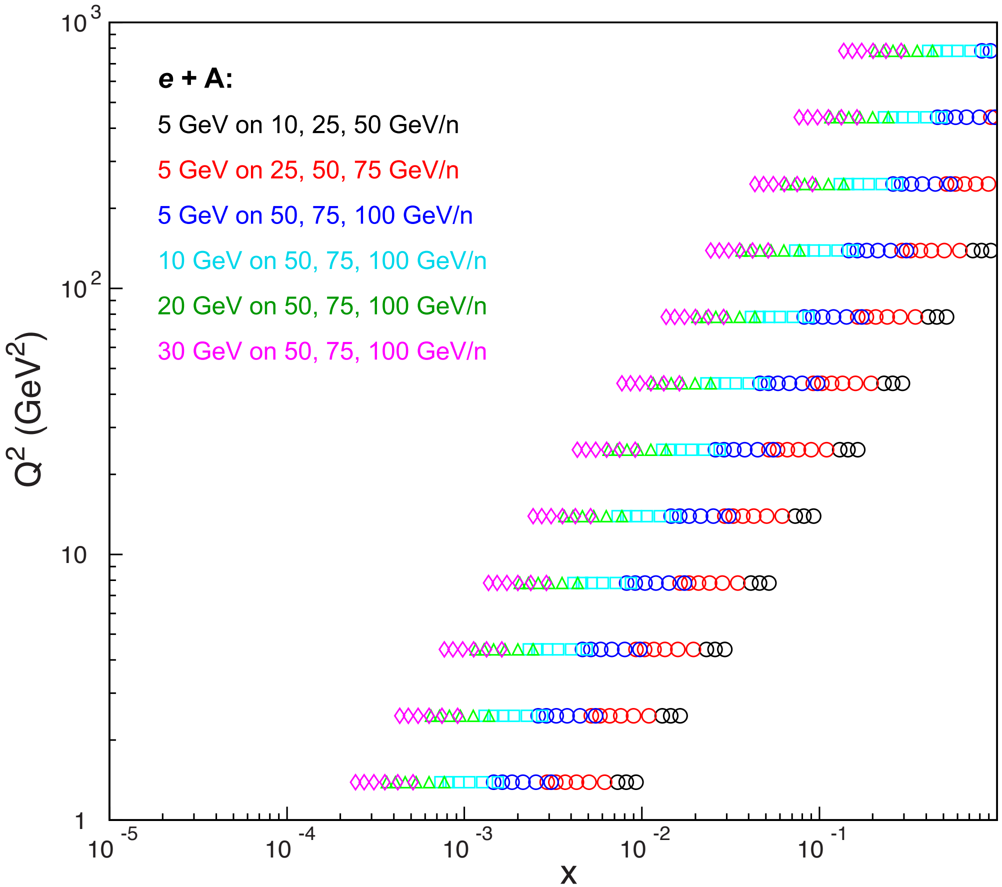

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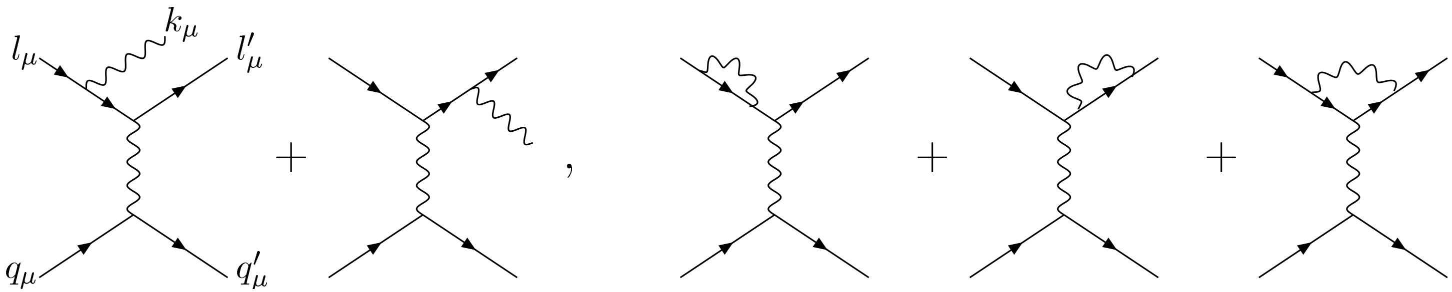
E. Aschenauer '11

Issue for e+A: Radiative corrections

Emission of real photons

- experimentally often not distinguished from non-radiative processes: soft photons, collinear photons



"Ideal" case: $Q^2 = -(l-l')^2, \quad x_B = \dfrac{Q^2}{2P\cdot(l-l')}$

True case: $\tilde{Q}^2 = -(l-l'-k)^2, \quad \tilde{x}_B = \dfrac{\tilde{Q}^2}{2P\cdot(l-l'-k)}$

Distortion of observed structure function:

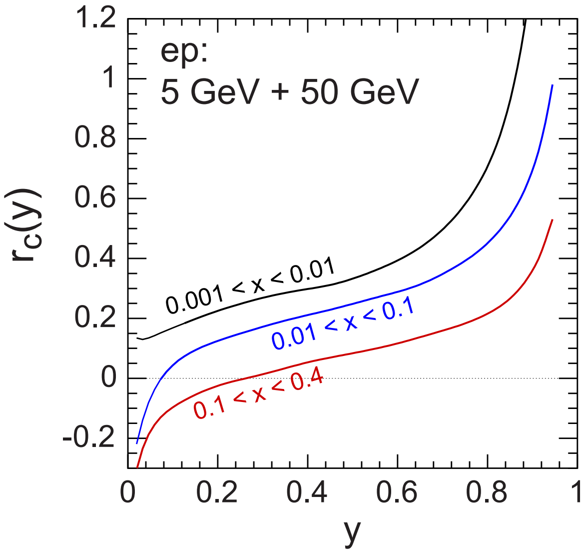
$$F_i^{\rm obs}(x_B,Q^2) = \int \mathrm{d}\tilde{x}_B \mathrm{d}\tilde{Q}^2\, R_i(x_B,Q^2,\tilde{x}_B,\tilde{Q}^2) F_i^{\rm true}(\tilde{x}_B,\tilde{Q}^2)$$

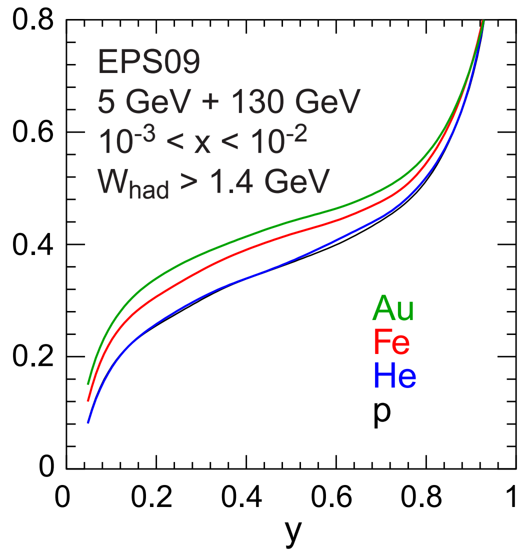
Radiator functions $R_i(l, l', k)$

Effect of radiative corrections

Correction function is fct. of y:

$$r_c(y) = \frac{\mathrm{d}\sigma/\mathrm{d}y|_{O(\alpha)}}{\mathrm{d}\sigma/\mathrm{d}y|_{Born}} - 1$$



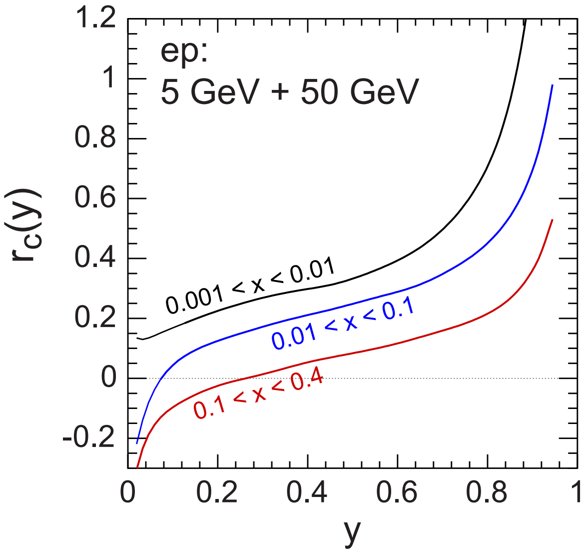


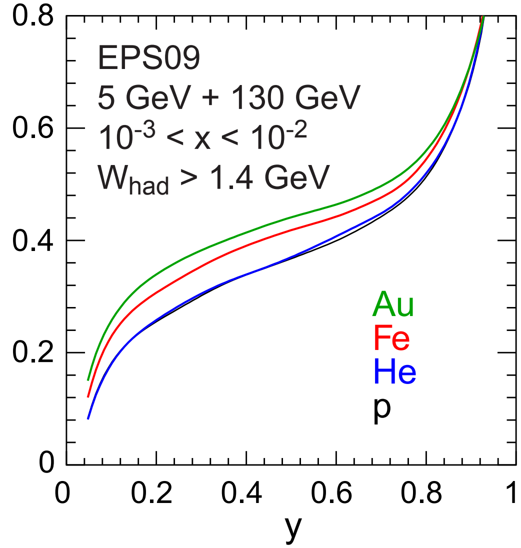
H. Spiesberger ’11

Effect of radiative corrections

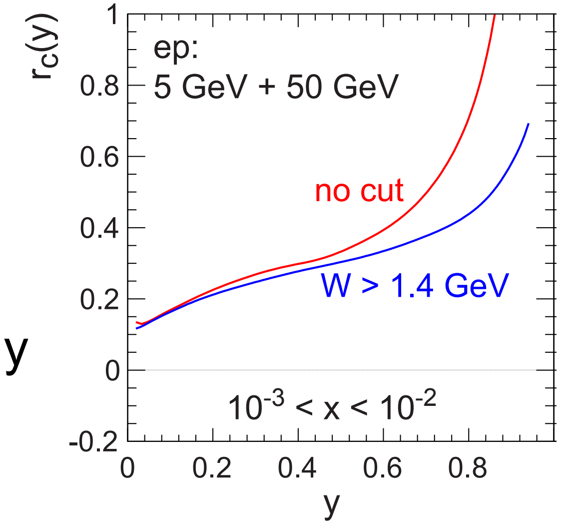
Correction function is fct. of y:

$$r_c(y) = \frac{d\sigma/dy|_{O(\alpha)}}{d\sigma/dy|_{Born}} - 1$$





H. Spiesberger '11



How to deal with it?

- Method 1
  - simple kinematic cuts in W reduce corrections slightly
    - not very effective
- Method 2
  - reconstruct x, Q^2 via hadronic final state (Jacquet-Blondel)
  - Problem in e+A: parton/hadron energy-loss, secondary particle production (typical at low-p_T)

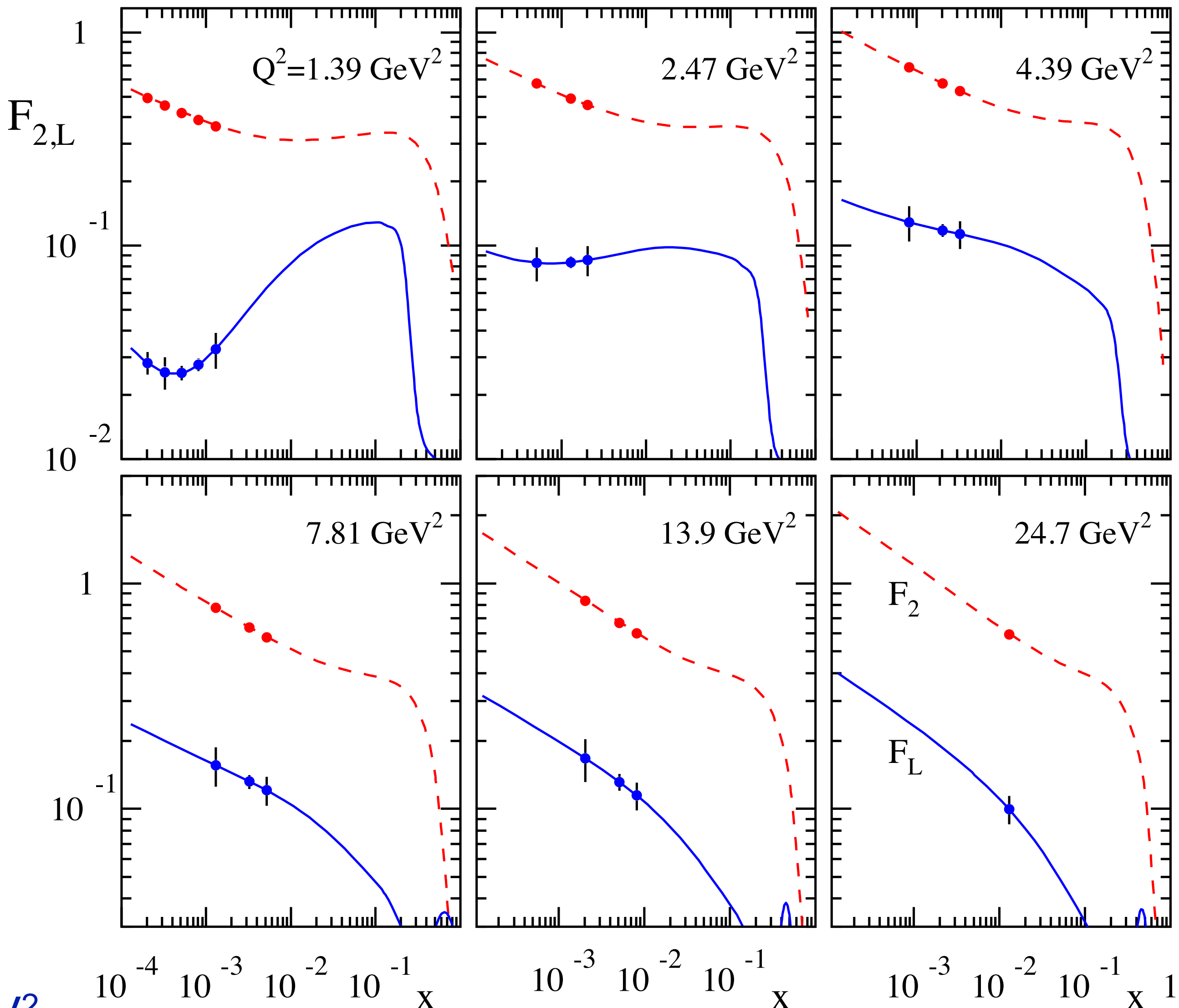
First Studies: Extraction of F_2 and F_L

$F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 EIC (eRHIC) energies (here ep)

- 5+100 GeV
- 5+250 GeV
- 5+325 GeV

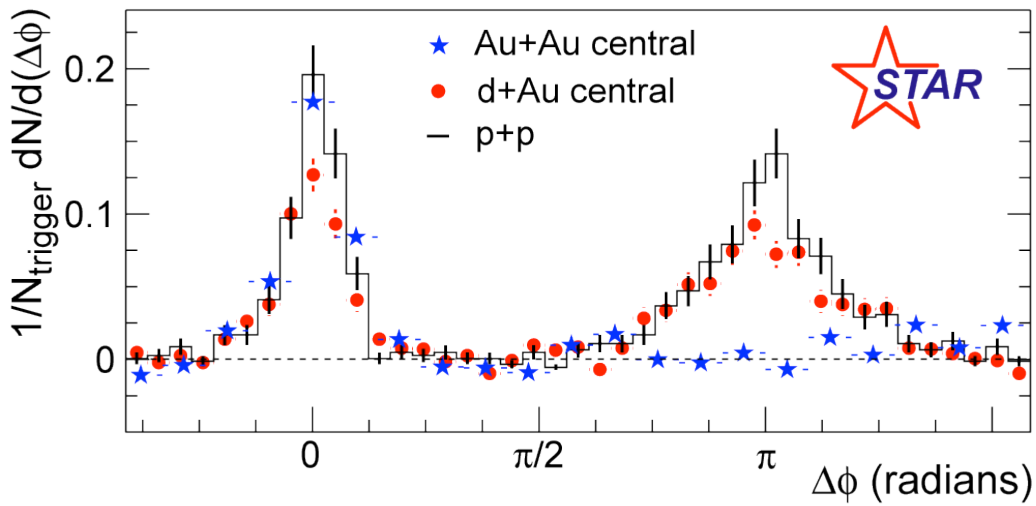
Data points added to theoretical expectations from ABKM09 PDF set to indicate stat. errors

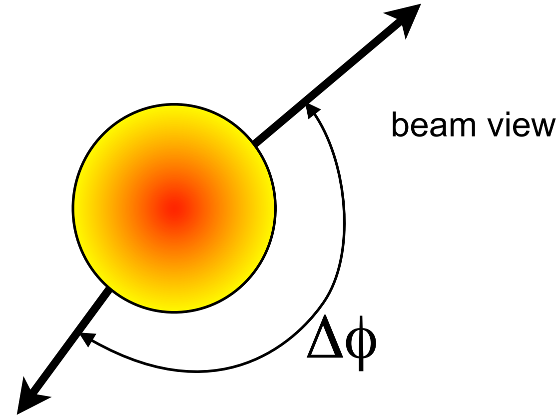
- valid for $Q^2 > 2.5$ GeV^2



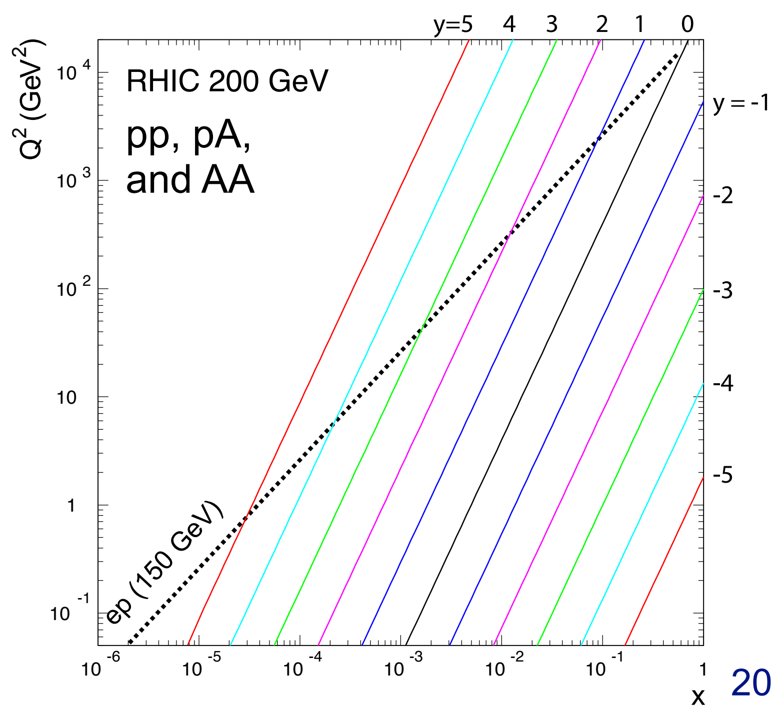
Example 2:
Dihadron Correlations

h-h Mid-Rapidity Correlation in pA at RHIC



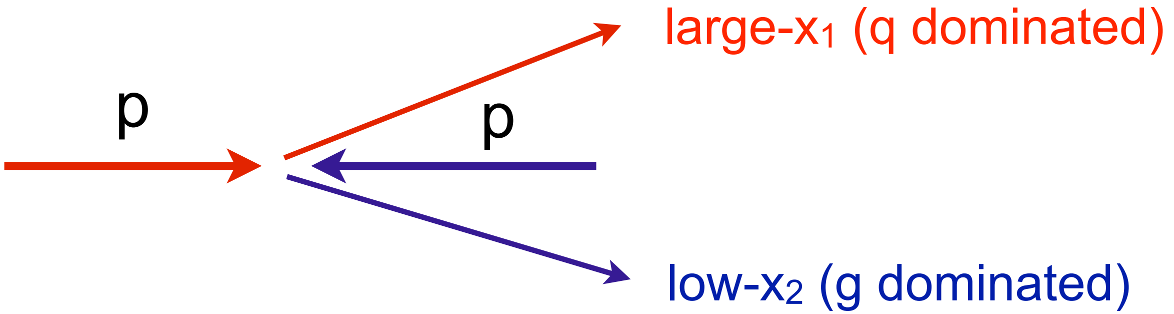


- d+Au h-h correlations: near and away side are p+p like
- helped to establish that away side suppression in Au+Au is a final state effect
- What happens at forward rapidities?
  - $x_{1,2} \approx m_T/\sqrt{s}\ \exp(\pm\eta)$

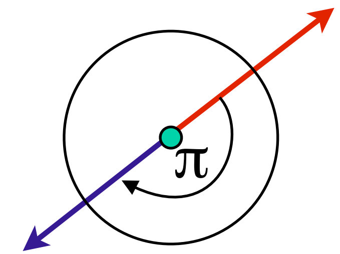


h-h Forward Correlation in pA at RHIC

side-view



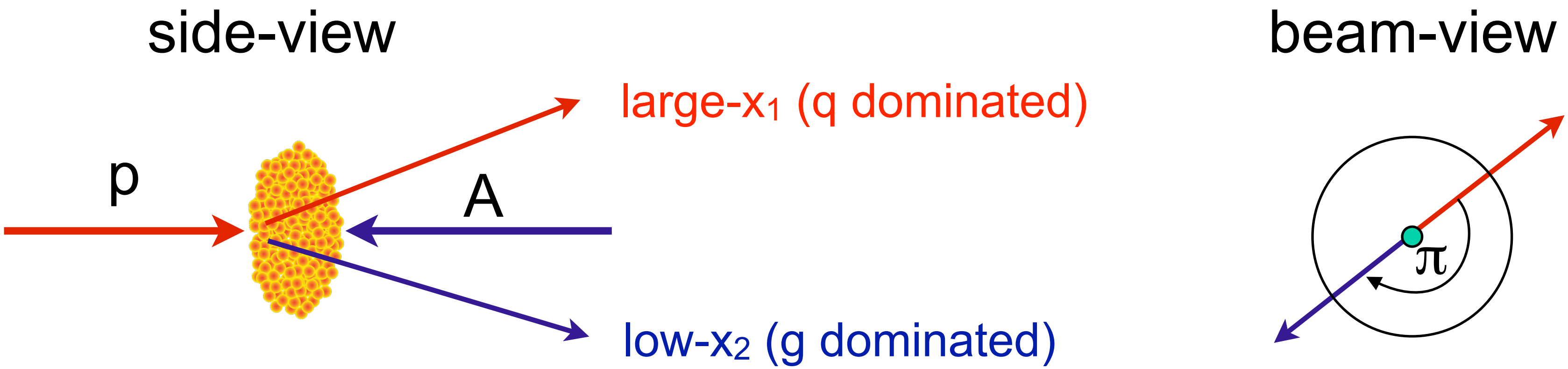
beam-view



Low gluon density (pp):

pQCD predicts 2→2 process
⇒ back-to-back di-jet

h-h Forward Correlation in pA at RHIC



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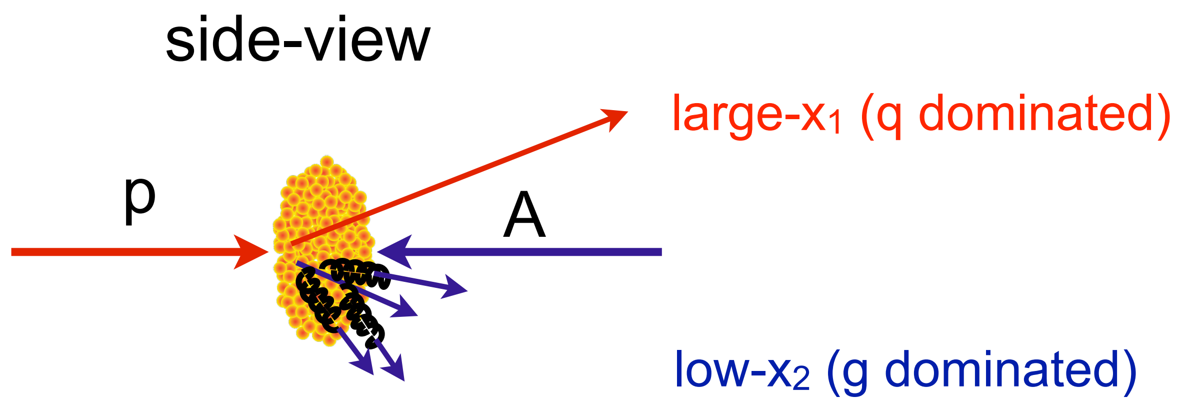
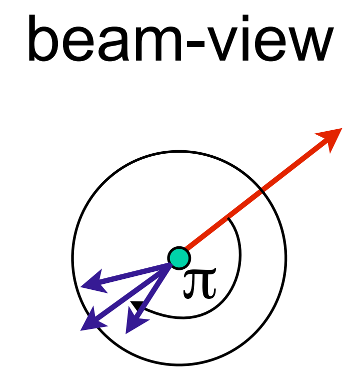




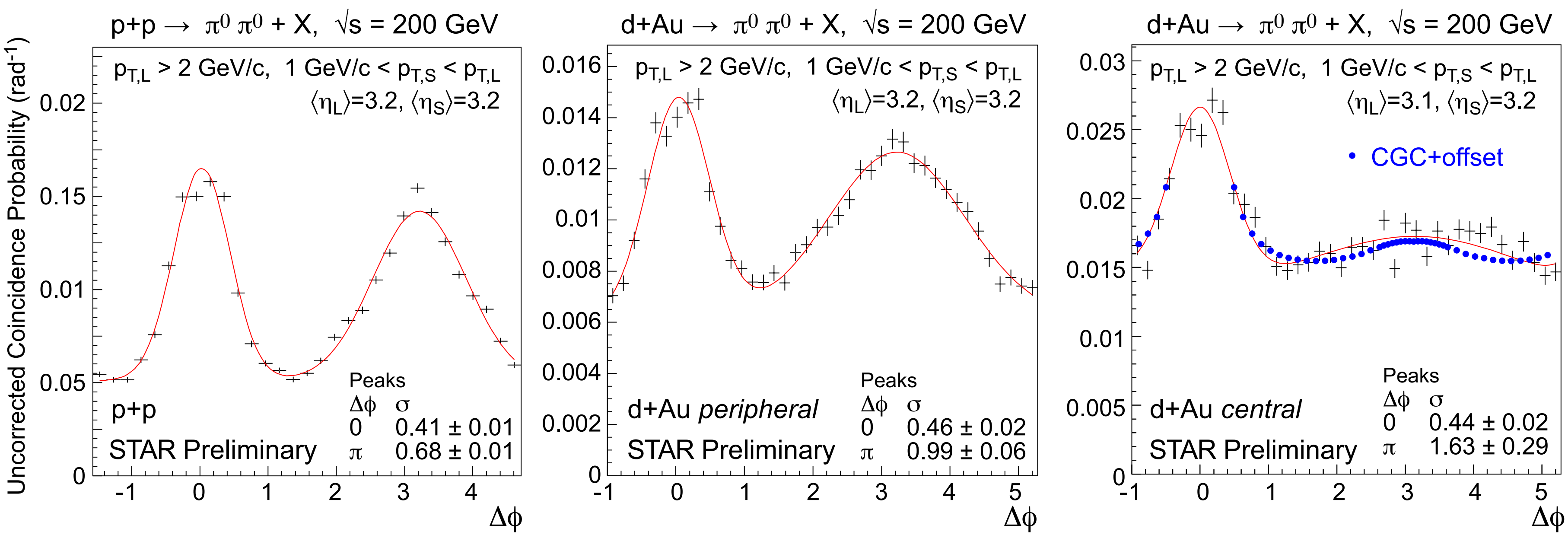
Low gluon density (pp):
pQCD predicts 2→2 process
⇒ back-to-back di-jet

High gluon density (pA):
2→many process
⇒ expect broadening of away-side

- Small-x evolution ↔ multiple emissions
- Multiple emissions → broadening
- Back-to-back jets (here leading hadrons) may get broadening in p_T with a spread of the order of Q_S

First prediction by: C. Marquet ('07)
Latest review: Stasto, Xiao, Yuan arXiv:1109.1817 (Sep. '11)

$\pi^0-\pi^0$ Forward Correlation in pA at RHIC

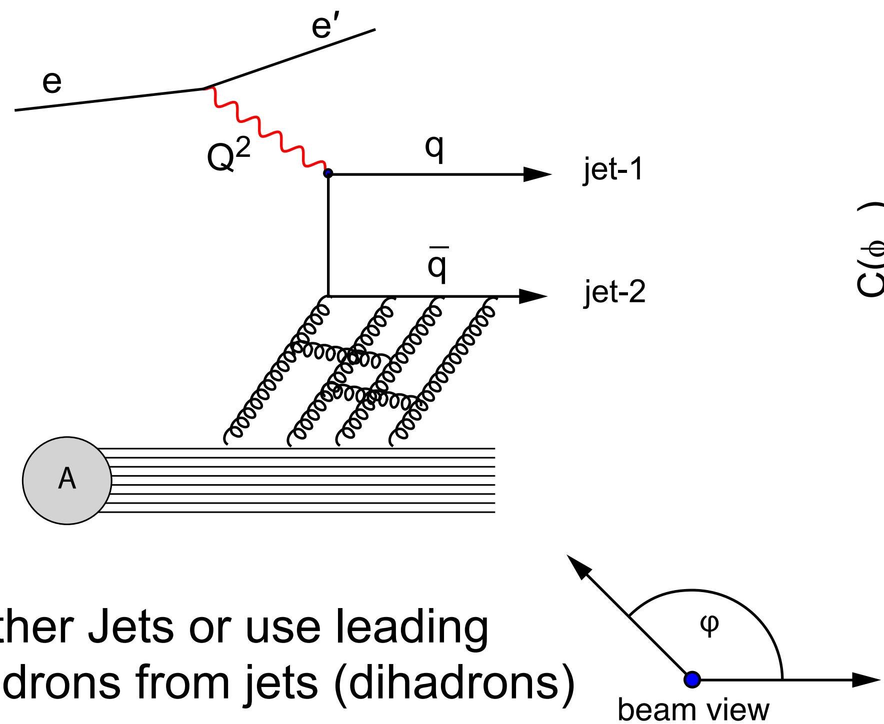


arXiv:1008.3989v1

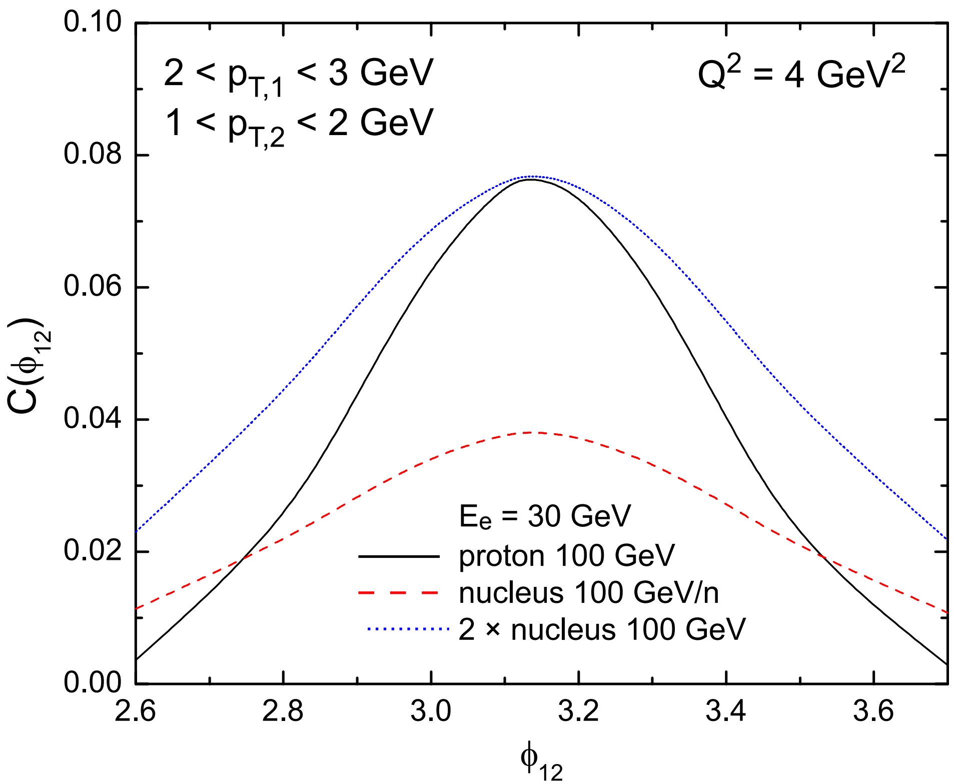
- Striking broadening in central dAu of away-side compared to pp and peripheral dAu
- Robust CGC result - difficult to reproduce in DGLAP
- x range: $x \sim 10^{-3}$

Dihadron Correlations: a Theorist's View

Excellent saturation signature:



Either Jets or use leading hadrons from jets (dihadrons)



Dominguez, Xiao, Yuan '11

- Prediction: factor ~2 suppression at EIC energies
- At small x, multi-gluon distributions are as important as single-gluon distributions
- Test of universality: p+A and e+A are sensitive to "dipole" and "quadrupole" operators which (same for both processes)

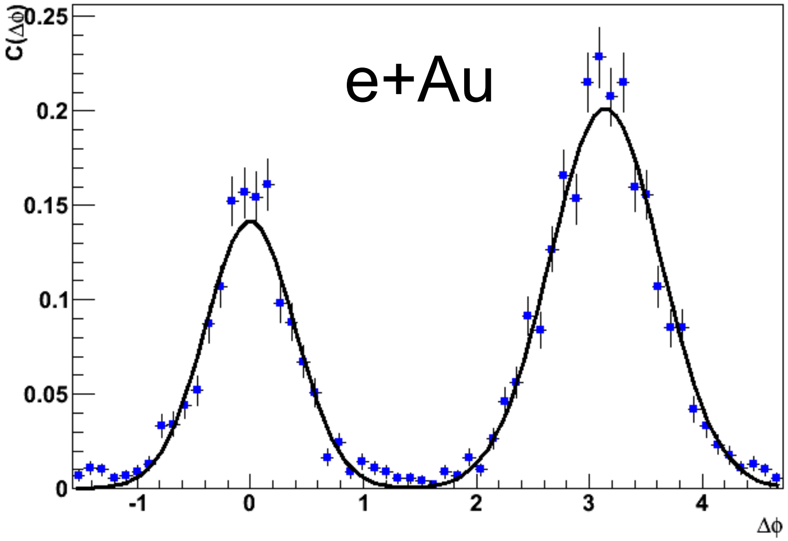
Dihadron Correlations: an Experimentalist's View

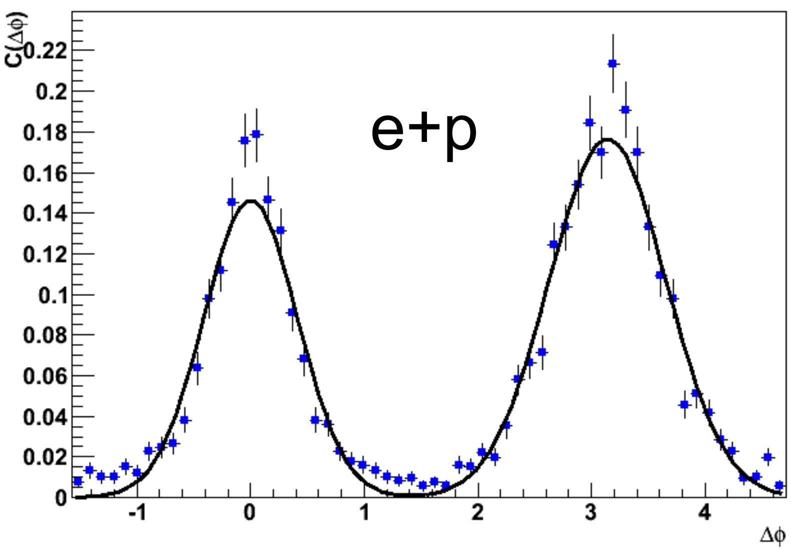
Simulations using DPMJet-III generator:

no suppression but leading twist shadowing

E_e=30 GeV
E_{Au}=100 GeV/n
Statistics
≈7 EIC min

Liang Zheng (Wuhan/BNL)





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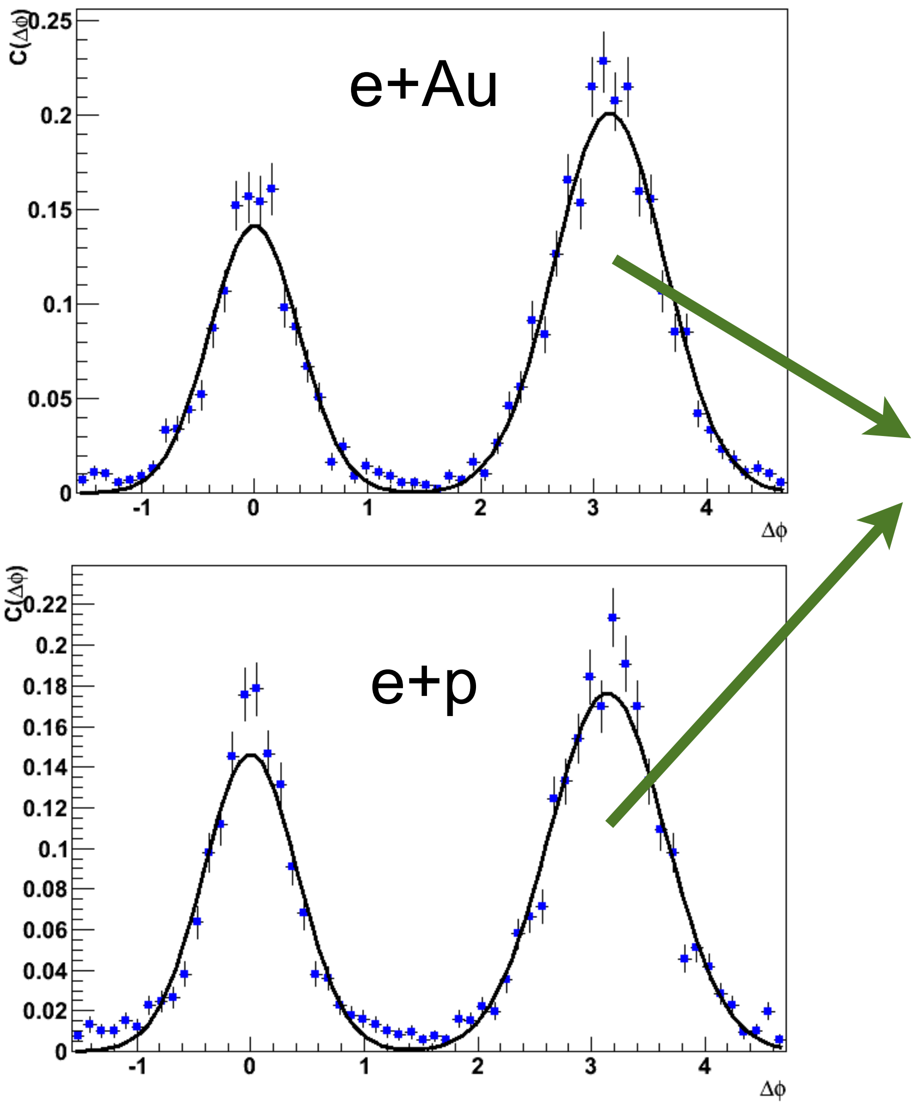

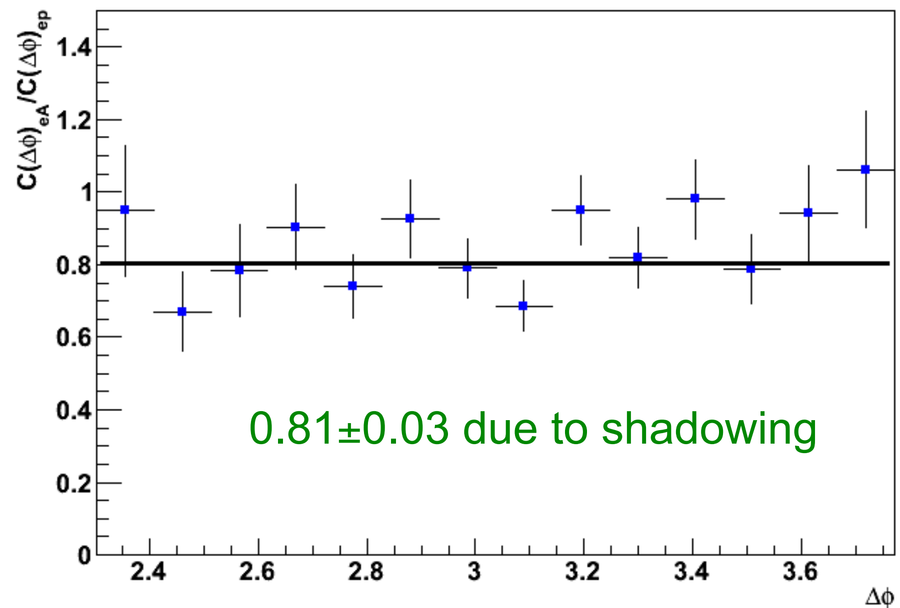

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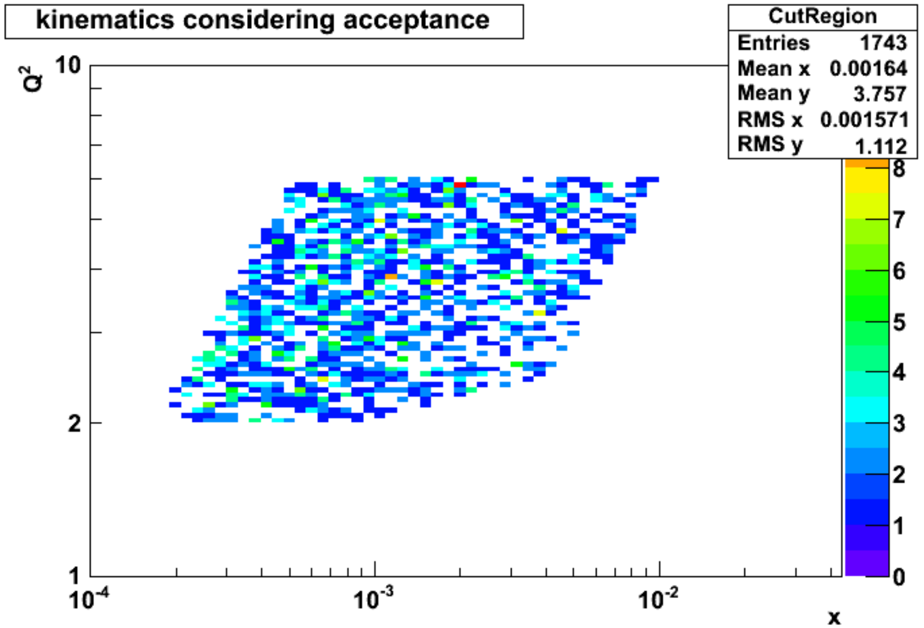

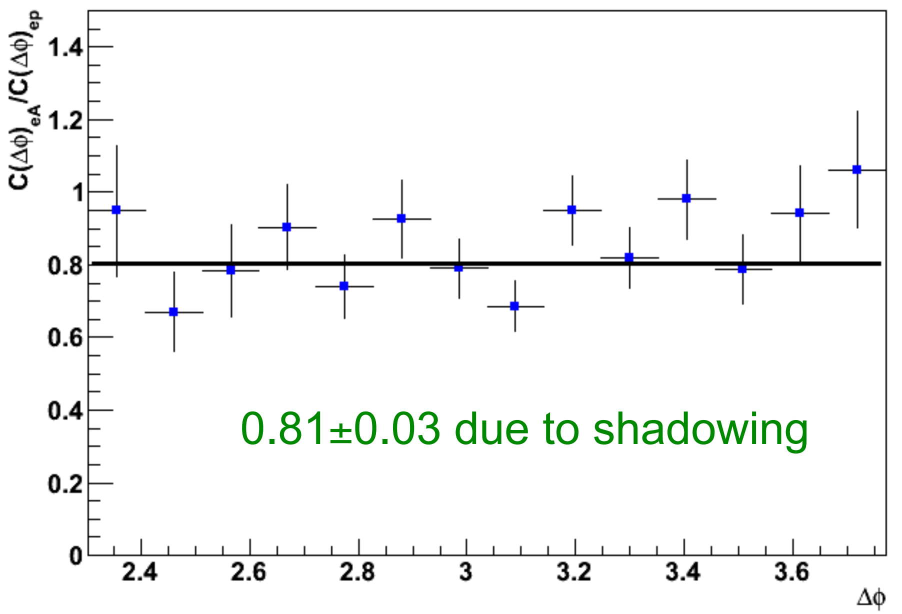

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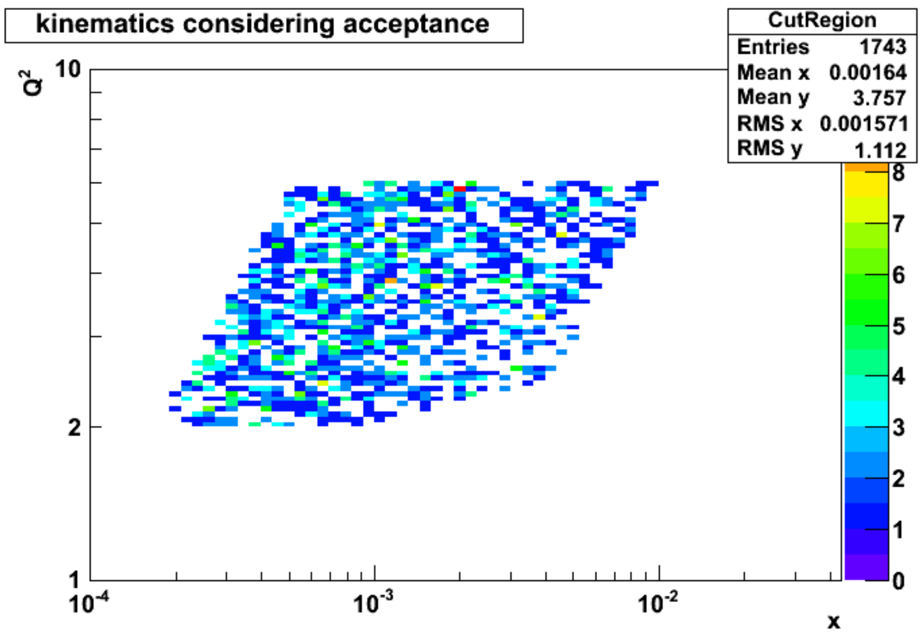
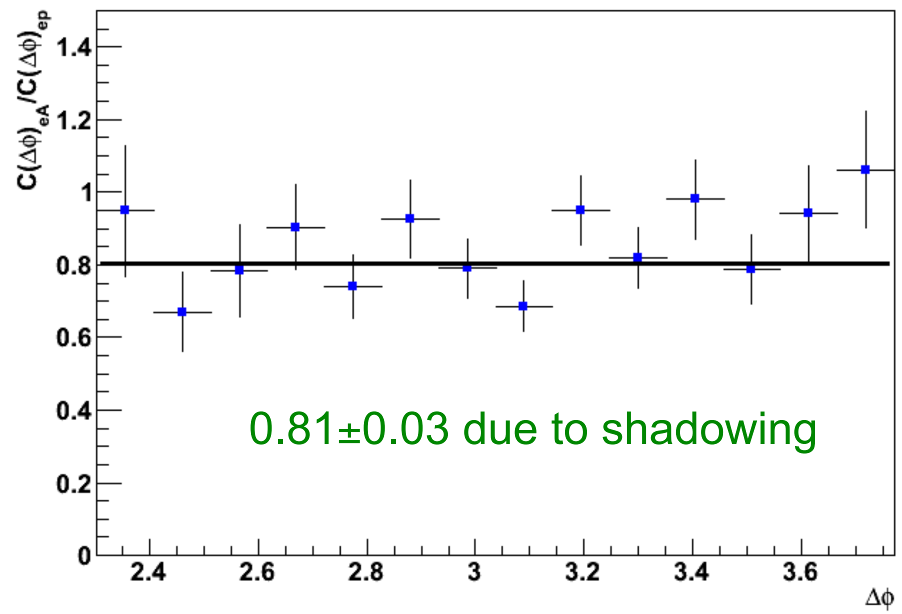
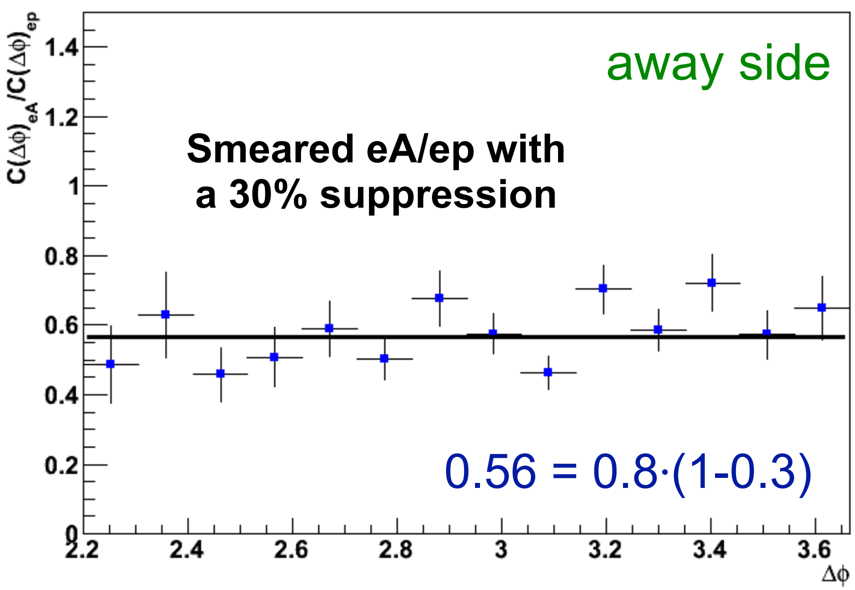


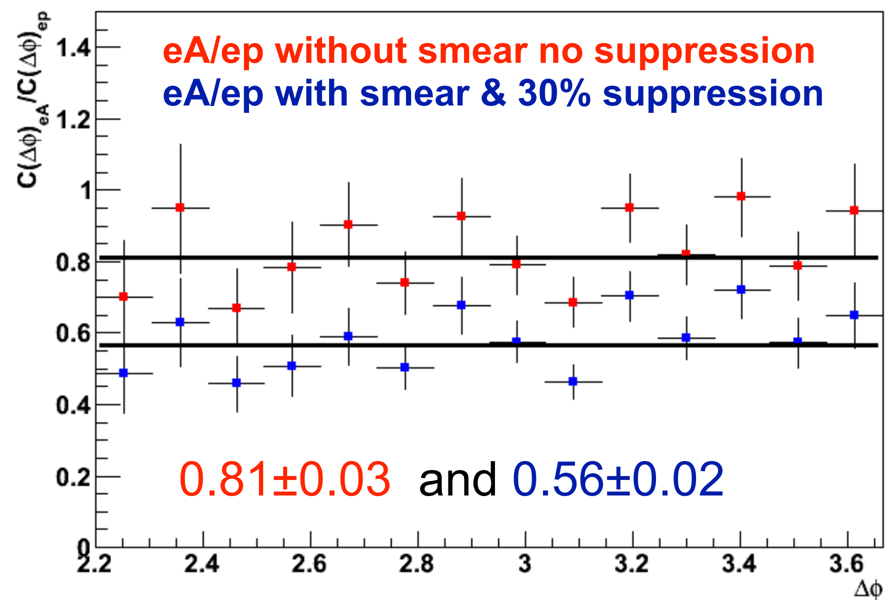


What if suppression is small? How sensitive are we?

Dihadron Correlations: an Experimentalist's View

- Use realistic detector simulations
- Assume 30% suppression only
- Based on statistics equivalent to 7 min EIC running



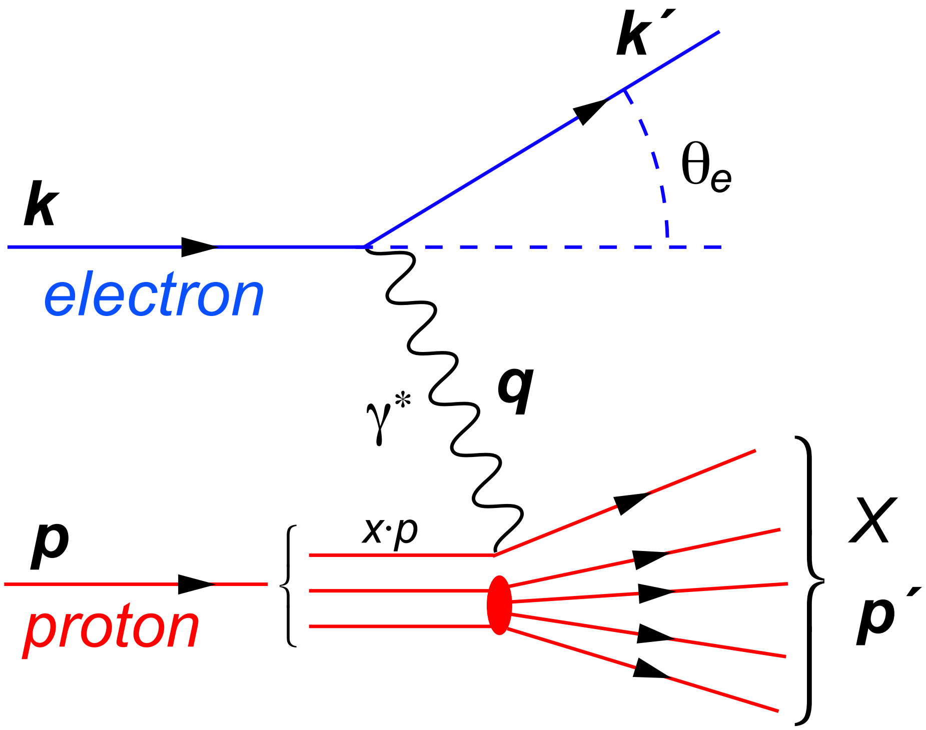


- Even with small statistics: straight forward measurement that is sensitive to at least 30% suppression
- True "golden" measurement

Example 3:
Diffractive Physics

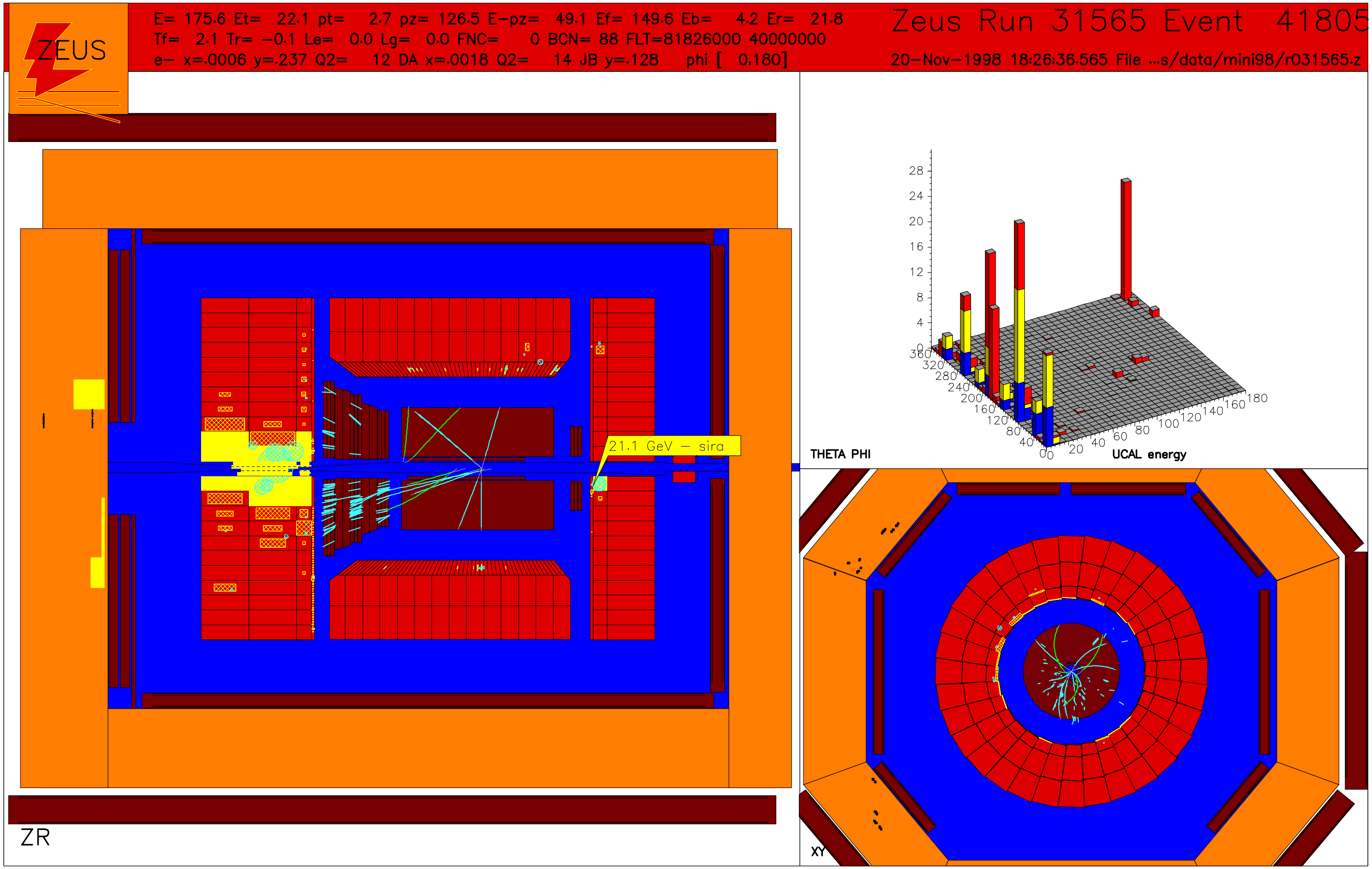
“Seeing” Diffraction

A DIS event (theoretical view)



“Seeing” Diffraction

A DIS event (experimental view)



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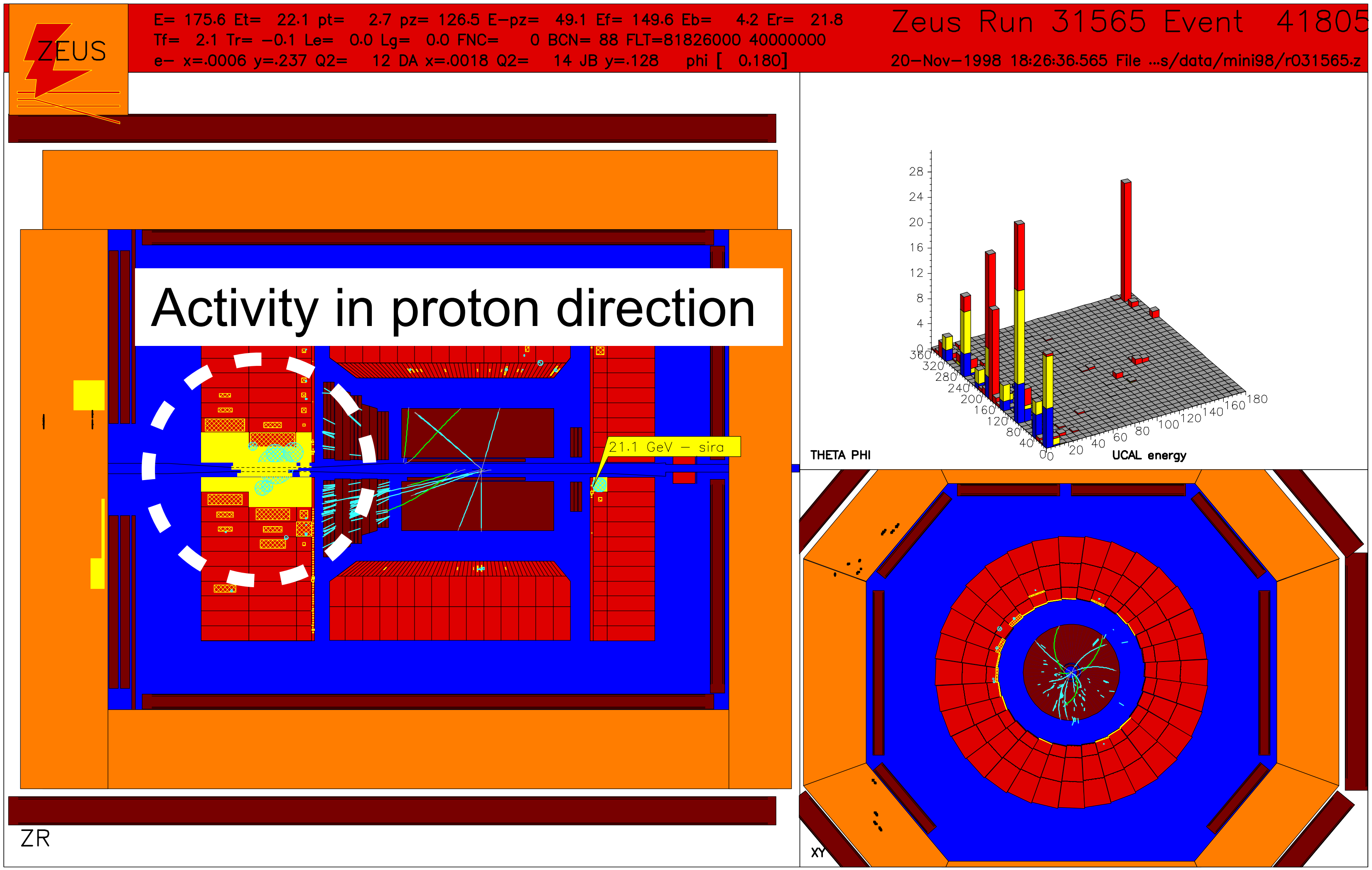

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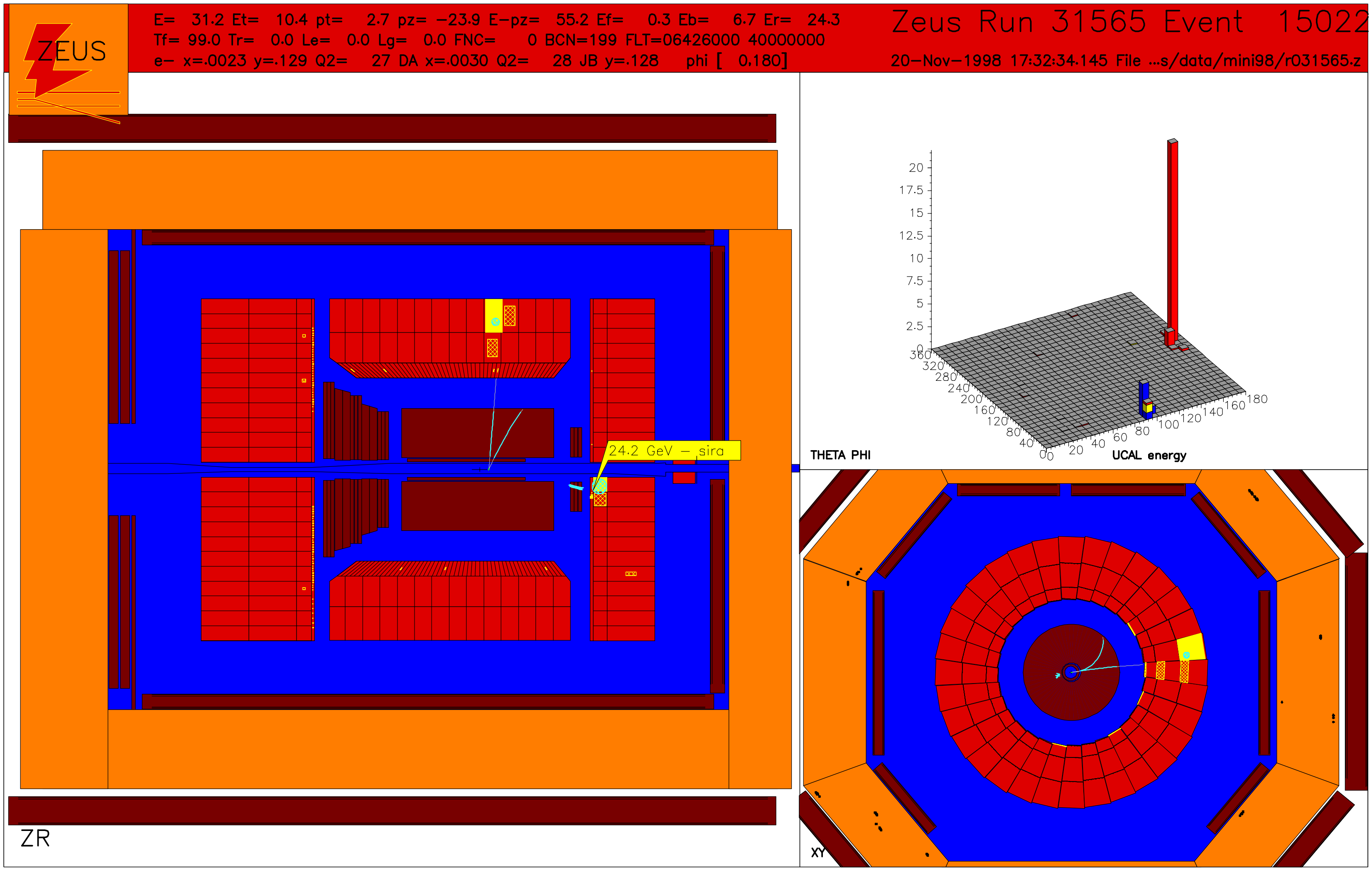

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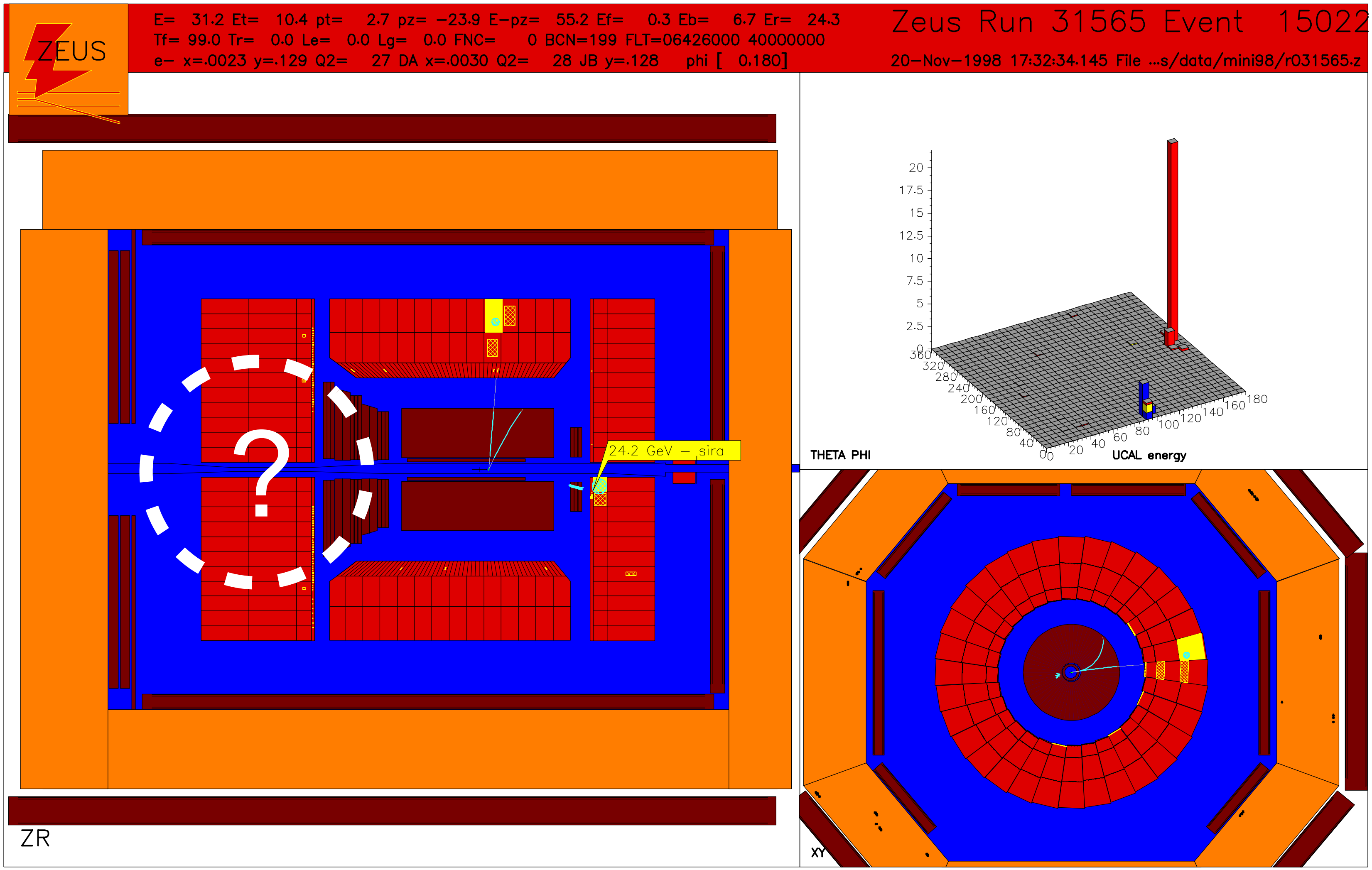

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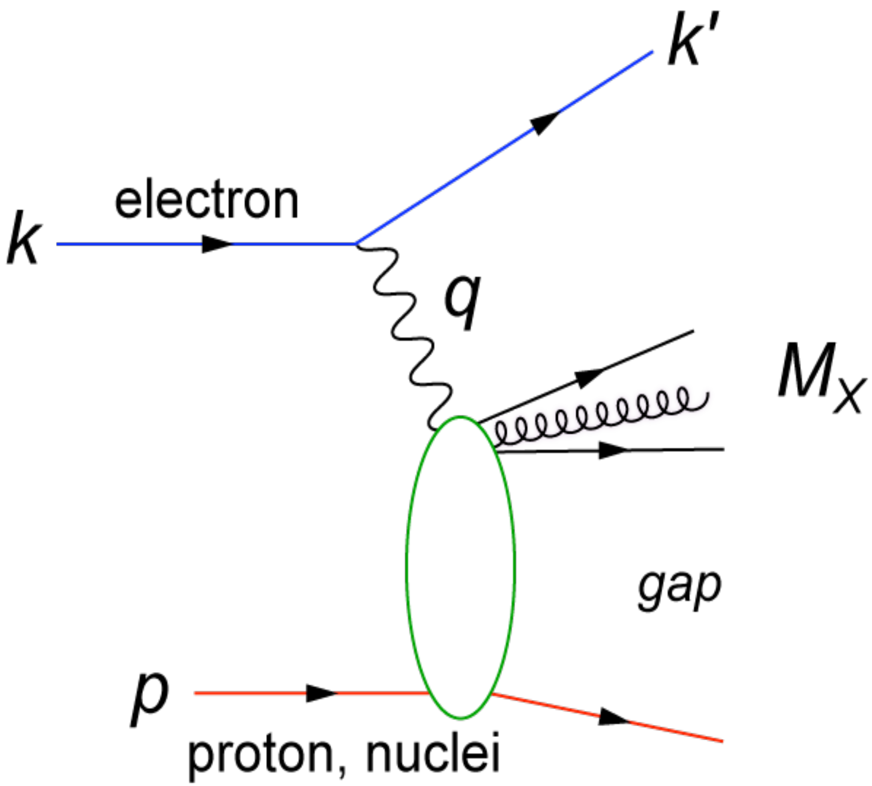
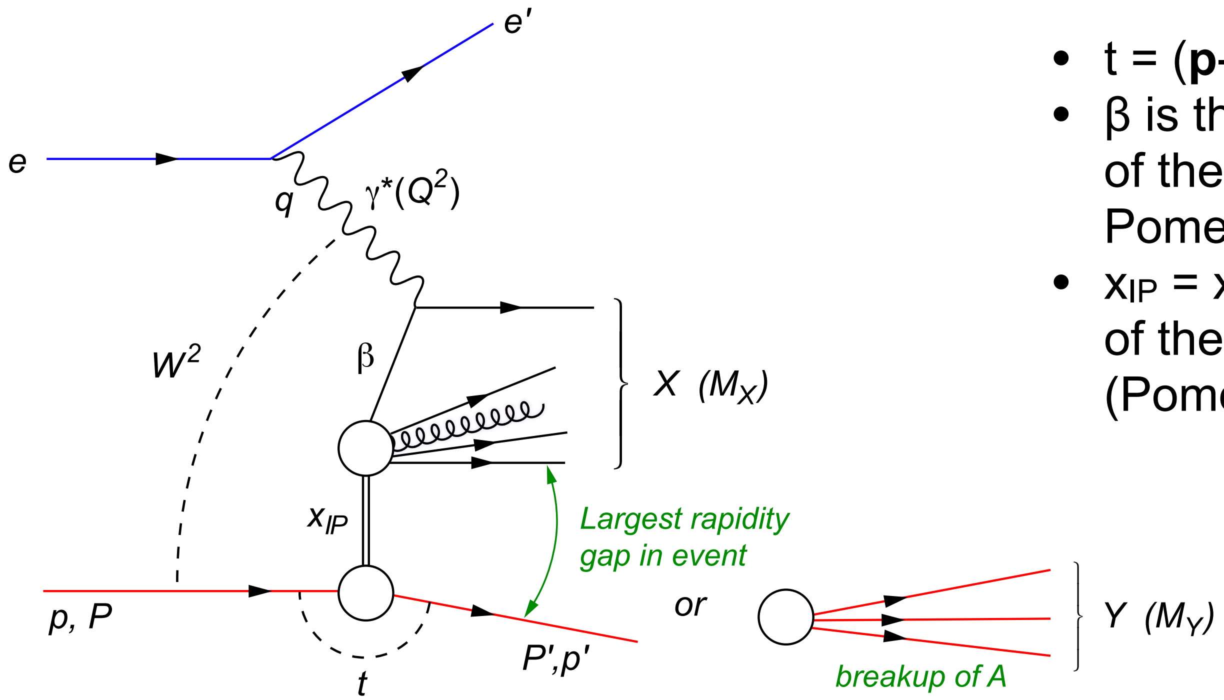


Hard Diffraction in DIS at Small *x*

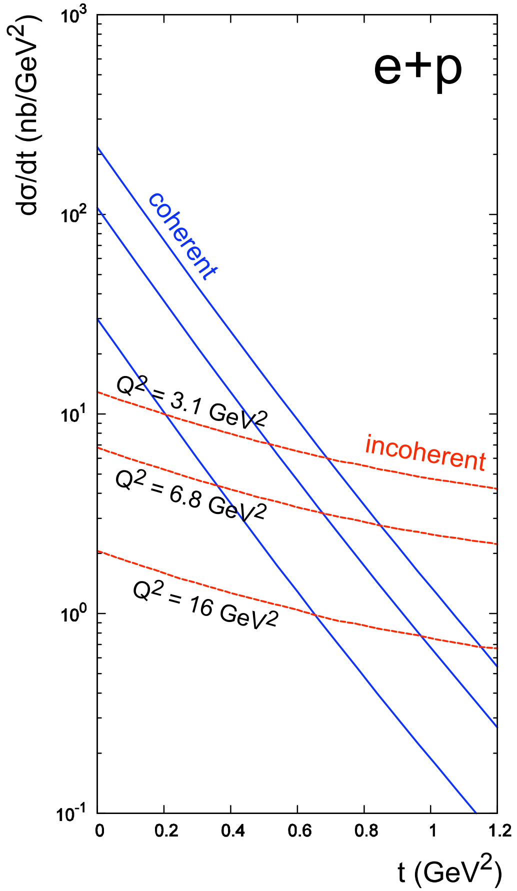


- t = (**p**-**p**')^2
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- x_{IP} = x/β: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\frac{d^4\sigma^{eh\to eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D,4}(x,Q^2,\beta,t)-\frac{y^2}{2}F_L^{D,4}(x,Q^2,\beta,t)\right]$$

- **Diffraction in e+p:**
  - coherent ⇔ p intact
  - incoherent ⇔ breakup of p
  - HERA: 15% of all events are hard diffractive
- **Diffraction in e+A:**
  - coherent diffraction (nuclei intact)
  - breakup into nucleons (nucleons intact)
  - incoherent diffraction
  - Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

Hard Diffraction in DIS at Small *x*



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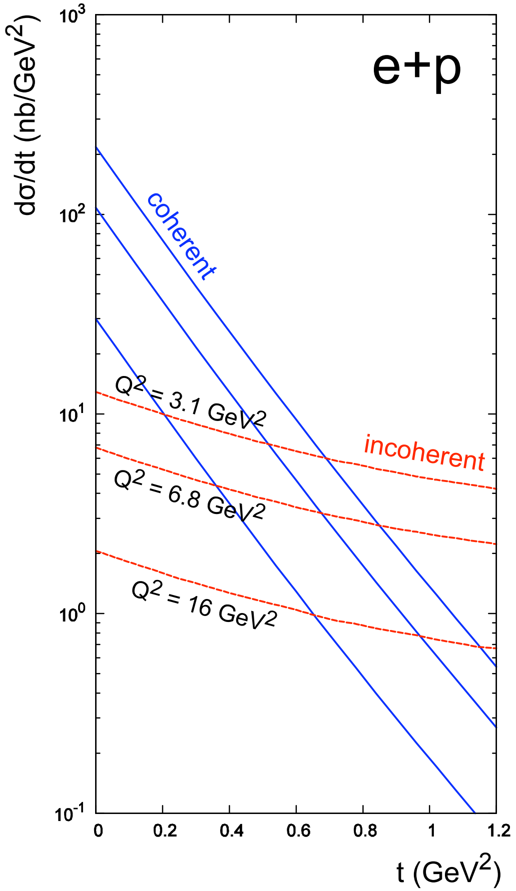

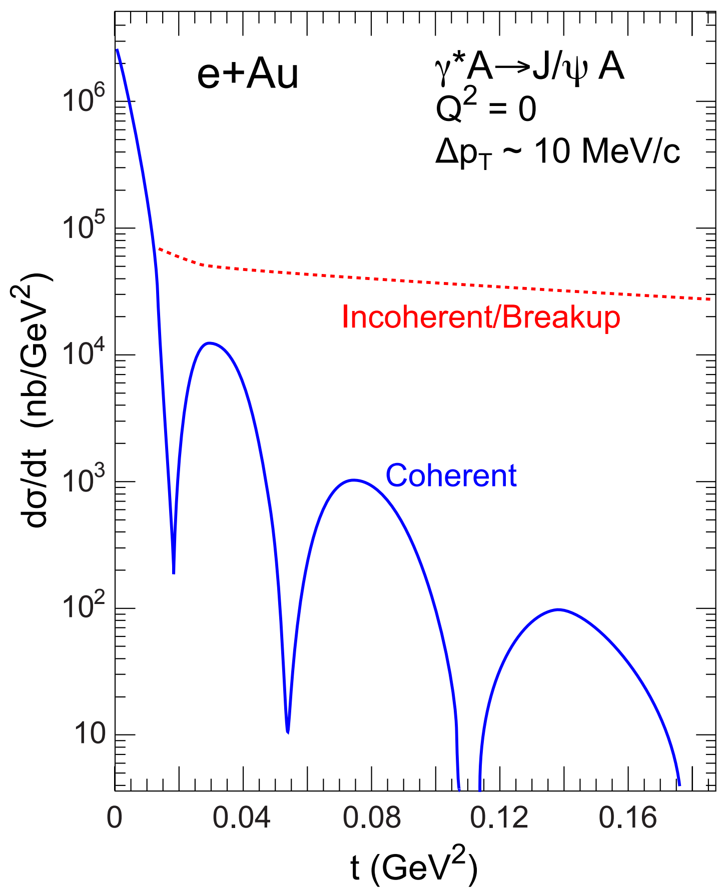

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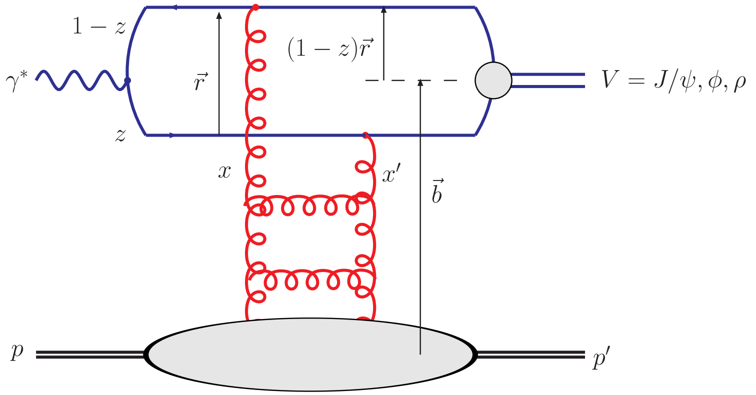
Why Is Diffraction So Important?

- Sensitive to gluon momentum distribution

$$\frac{d\sigma^{\gamma^* p \to pV}}{dt} \sim \left| \int \Psi_V^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \Psi e^{-ib\Delta} \right|^2$$

$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} \sim r^2 \alpha_s x g(x,\mu^2) T(b)$$

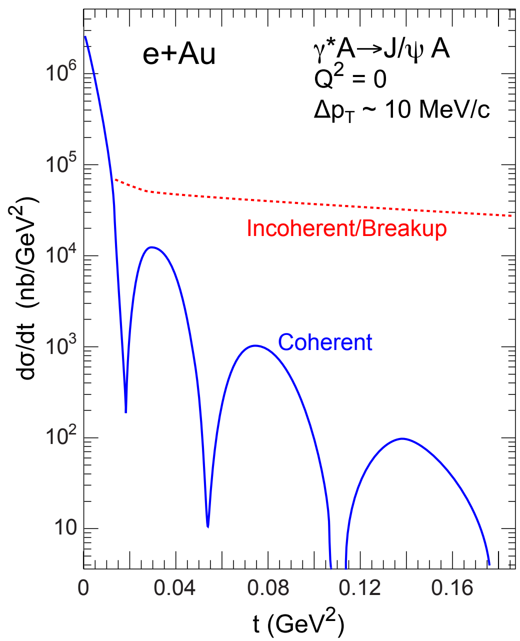


  - $\sigma \propto g(x,Q^2)^2$

- Sensitive to spatial gluon distribution

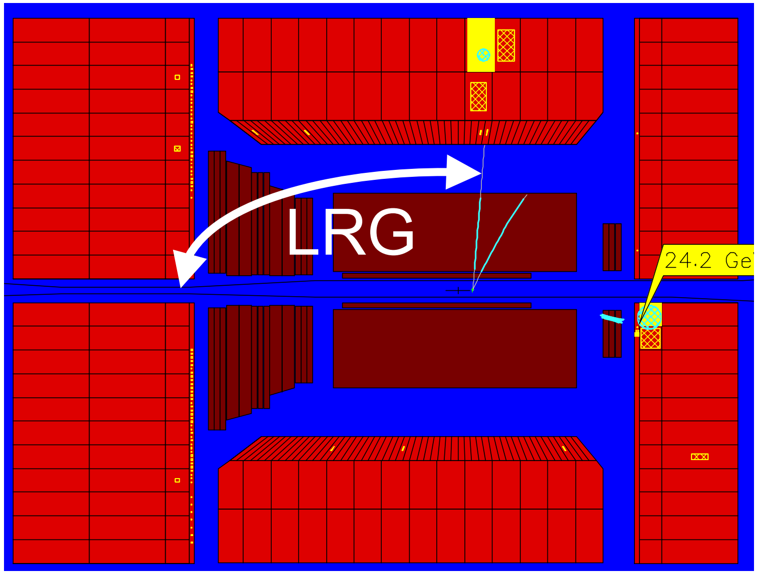
$$\frac{d\sigma}{dt}$$ ≡ Fourier Transformation of Source Density $\rho_g(b)$

  - Hot topic:
    - Gluonic form factor
    - just Wood-Saxon + nucleon g(b)
  - Incoherent case: measure of fluctuation/ lumpiness in $G_A(b)$



Why Is Diffraction So Difficult?

- Key in identifying diffraction is rapidity gap
  - requires hermetic detector
  - does not allow separation of coherent from incoherent
- Measuring the scattered nucleus with Forward Spectrometer (Roman Pots)
  - coherent ⇒ cannot separate from beam
  - incoherent ⇒ cannot reconstruct all fragments to get p'



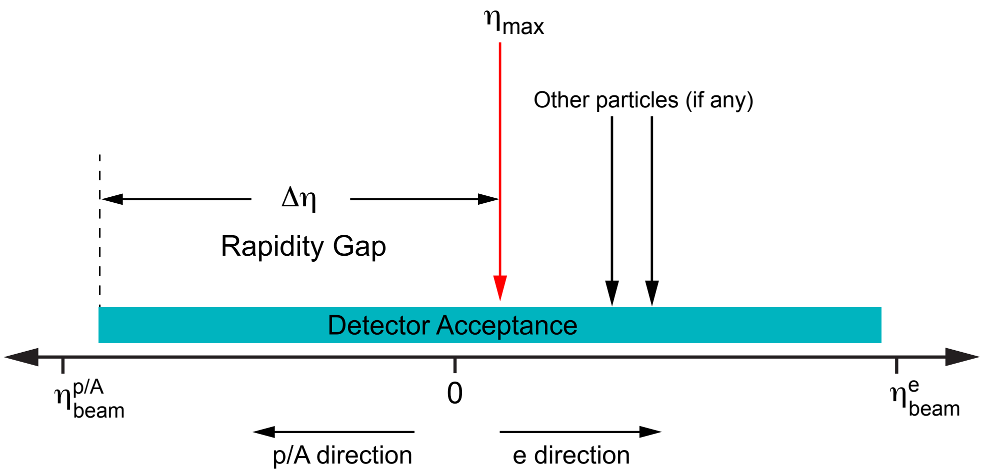
- Cannot measure *t* in eA except in exclusive vector meson production, e.g.:

$$e + A \to e' + J/\psi + A'$$

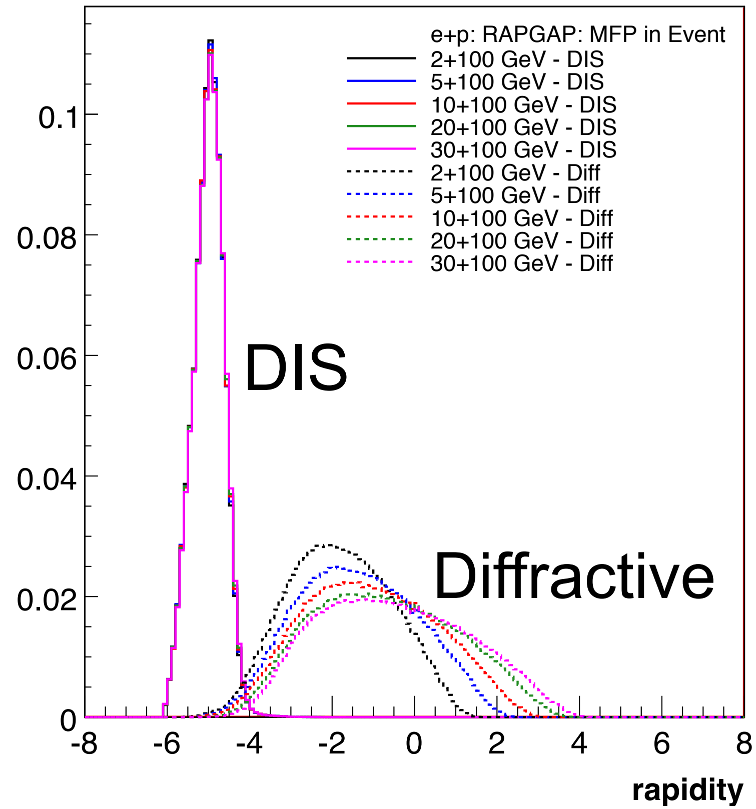
- Lack of t not a big issue for measurements of F_2^D, F_L^D and hence $G(x,Q^2)$

Large Rapidity Gap Method (LRG)

- Identify Most Forward Going Particle (MFP)
  - Works at HERA but at higher $\sqrt{s}$
  - EIC smaller beam rapidities



Diffractive ρ^0 production at EIC: η of MFP

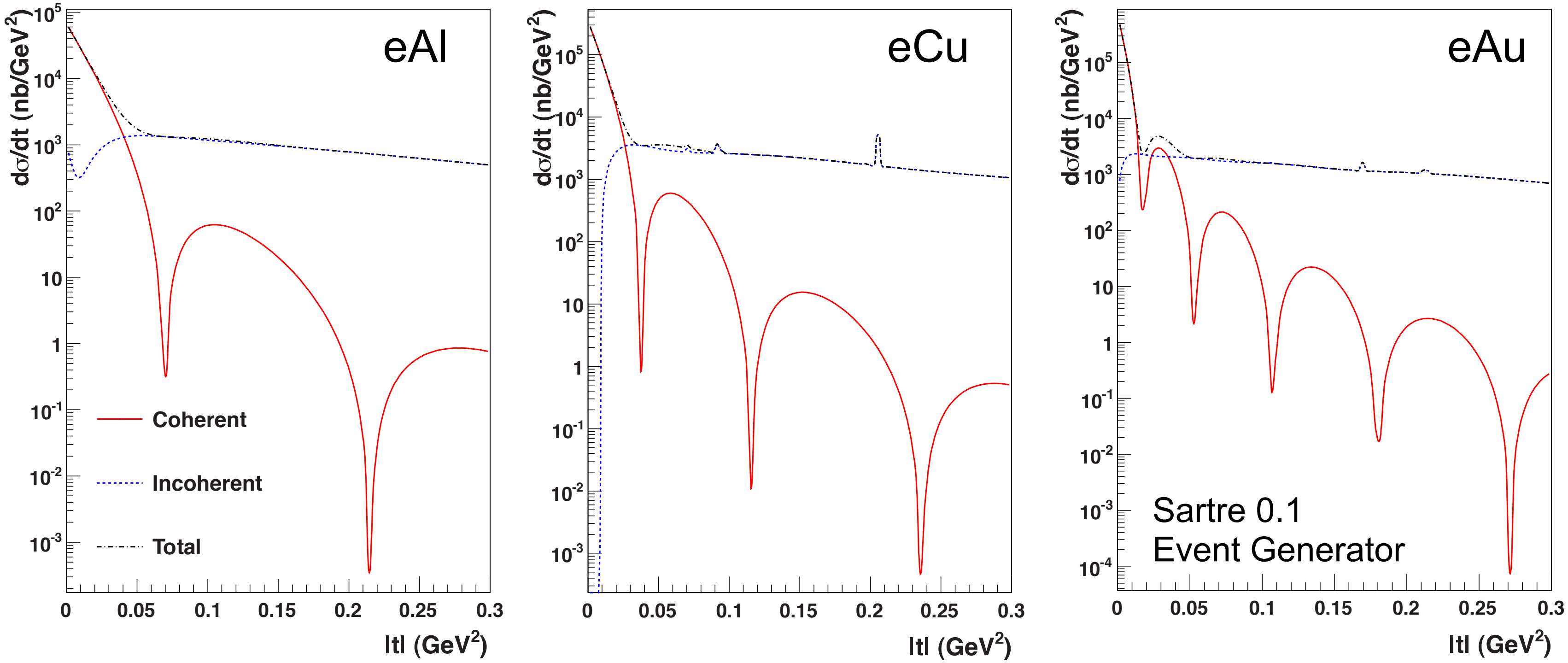


M. Lamont '10

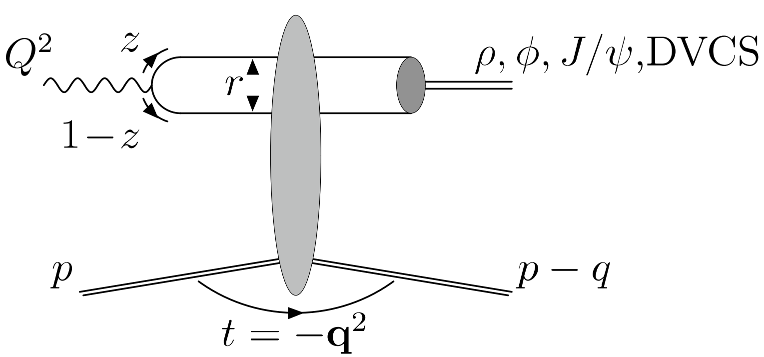
Hermeticity requirement:

- needs just to detector presence
- does not need momentum or PID
- simulations: $\sqrt{s}$ not a show stopper for EIC (can achieve 1% contamination, 80% efficiency)

Exclusive Vector Meson Production



- Golden channel: e + A → e' + A' + VM
  - $t = (P_A - P_{A'})^2 = (P_{VM} + P_{e'} - P_e)^2$
  - photoproduction ($Q^2 \approx 0$): $t \approx p^2_{T,VM}$
  - moderate Q^2: need p_T of e'
  - Issues:
    - transverse spread of the beam (distorts small t) ⇒ requires beam cooling
    - detect incoherent events ⇒ detect nuclear breakup



Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on n emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR
- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

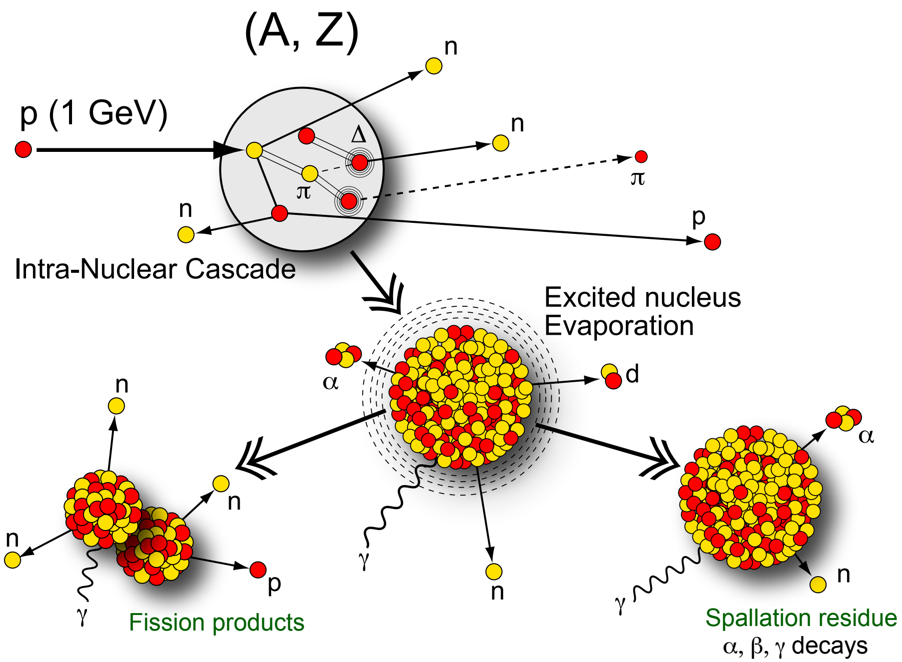
Traditional modeling done in pA:

Intra-Nuclear Cascade

- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

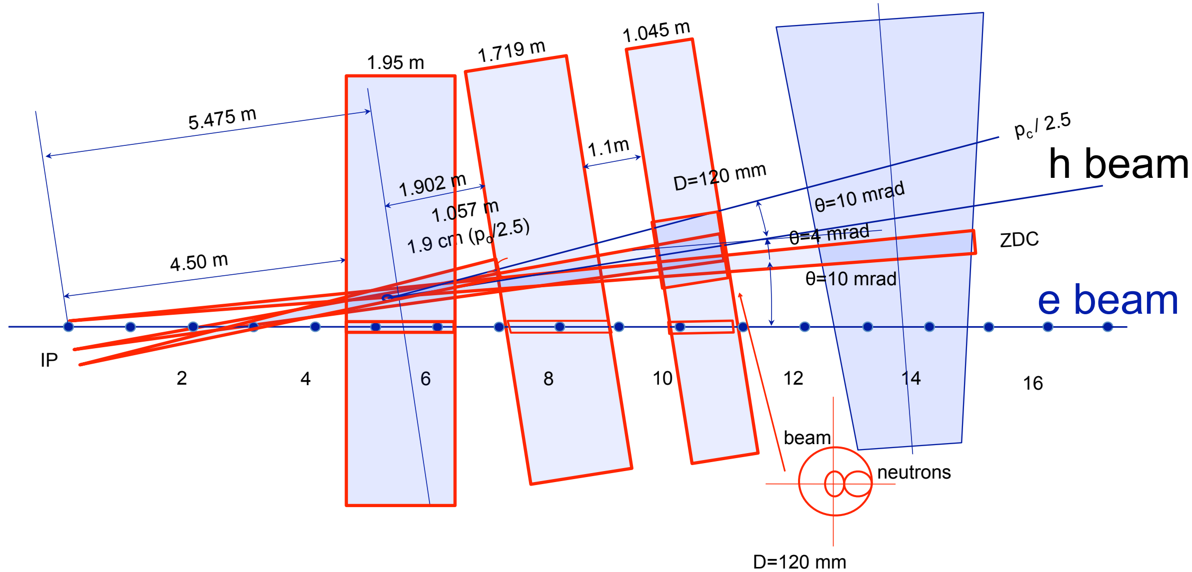
De-Excitation

- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



Experimental Reality

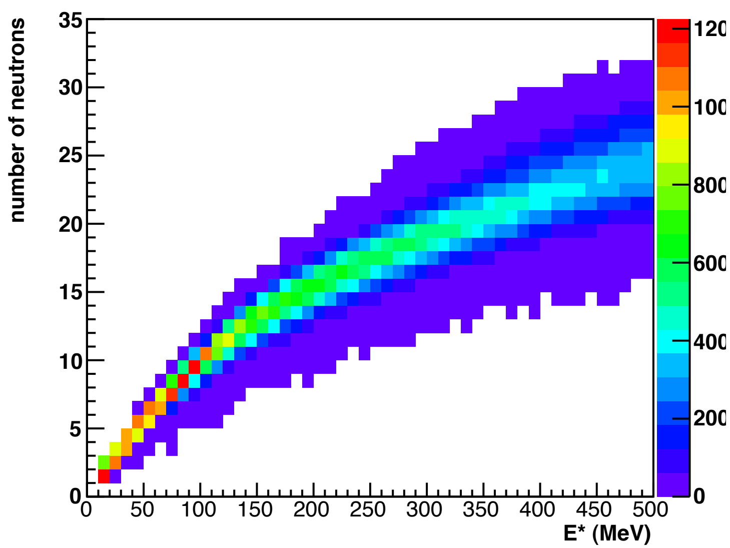
Here eRHIC IR layout:

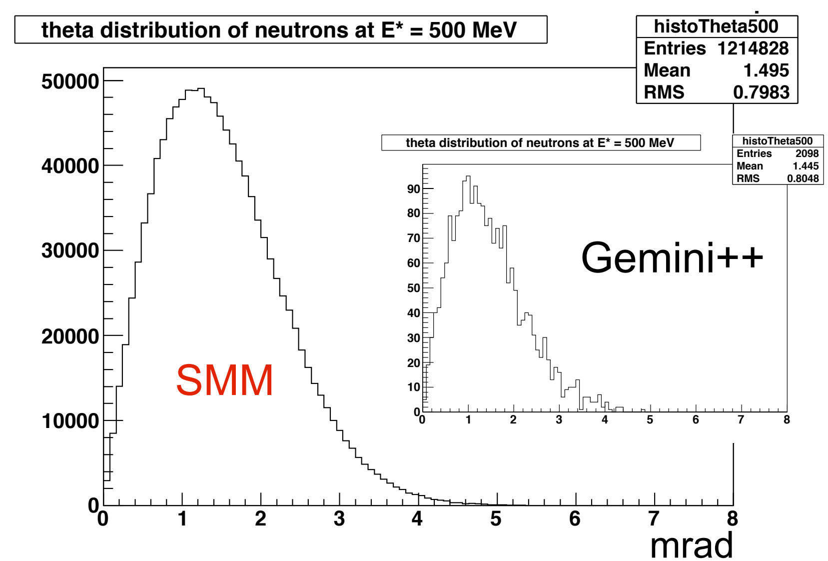


Need ±X mrad opening through triplet for *n* and room for ZDC

Big questions:

- Excitation energy E*?
- ep: $d\sigma/M_Y \sim 1/M_Y^2$
- eA? Assume ep and use $E^* = M_Y - m_p$ as lower limit





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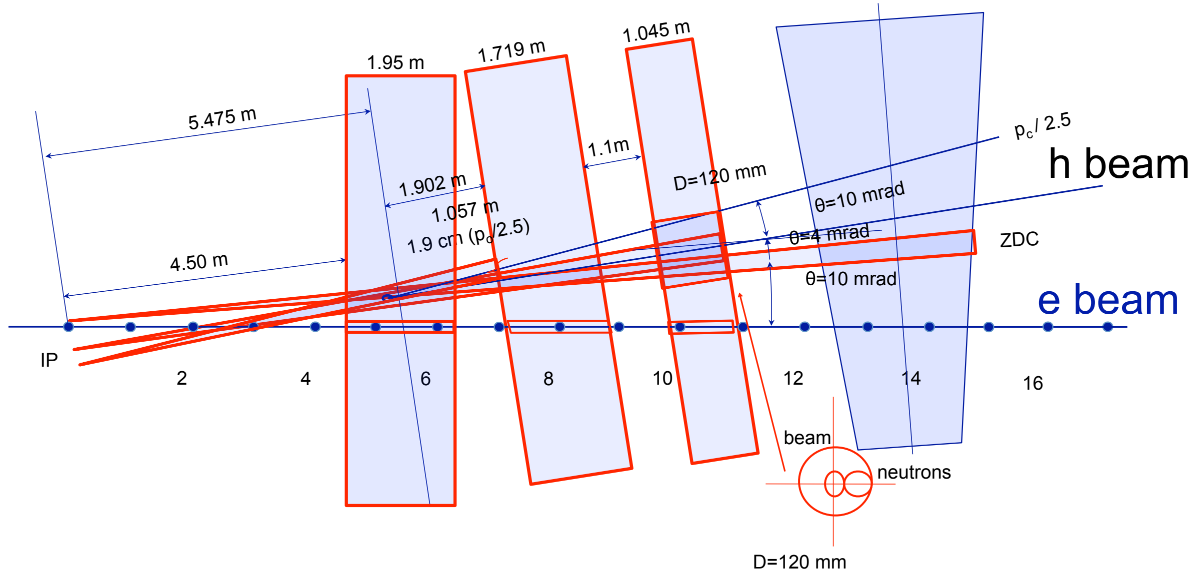

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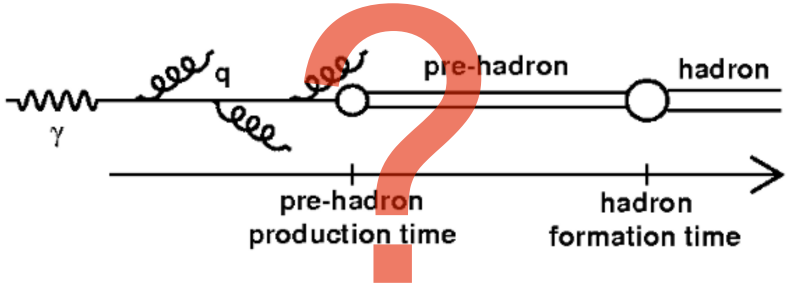
Simulations using Gemini++ & SMM show it works:

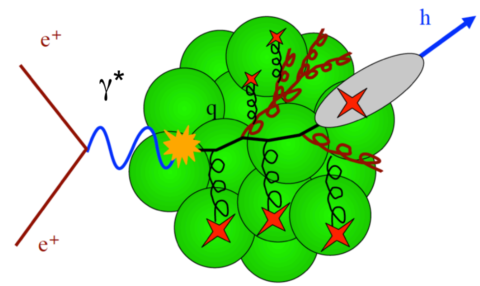
- For $E^*_{tot} \geq 10$ MeV and 2.5 mrad *n* acceptance we have rejection power of at least 10^5.
- Separating incoherent from coherent diffractive events is possible at a collider with *n*-detection via ZDCs alone

Example 4: Properties of Cold Nuclear Matter

Parton Propagation and Fragmentation



Hadronization not well understood non-perturbative process



- Nuclei as space-time analyzer
- EIC can measure:
  - fragmentation time scales to understand dynamic
  - in medium energy loss to characterize medium
- Observables
  - p_T distribution broadening $\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$
  - attenuation of hadrons

$$R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T) / N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T) / N_D^e(Q^2, x_{Bj})}$$

see talk by Jianwei Qiu

Hadron Attenuation in nDIS

Energy loss:

- gluon bremstrahlung?
  - hadronization outside media
- prehadron absorption?
  - color neutralization inside the medium

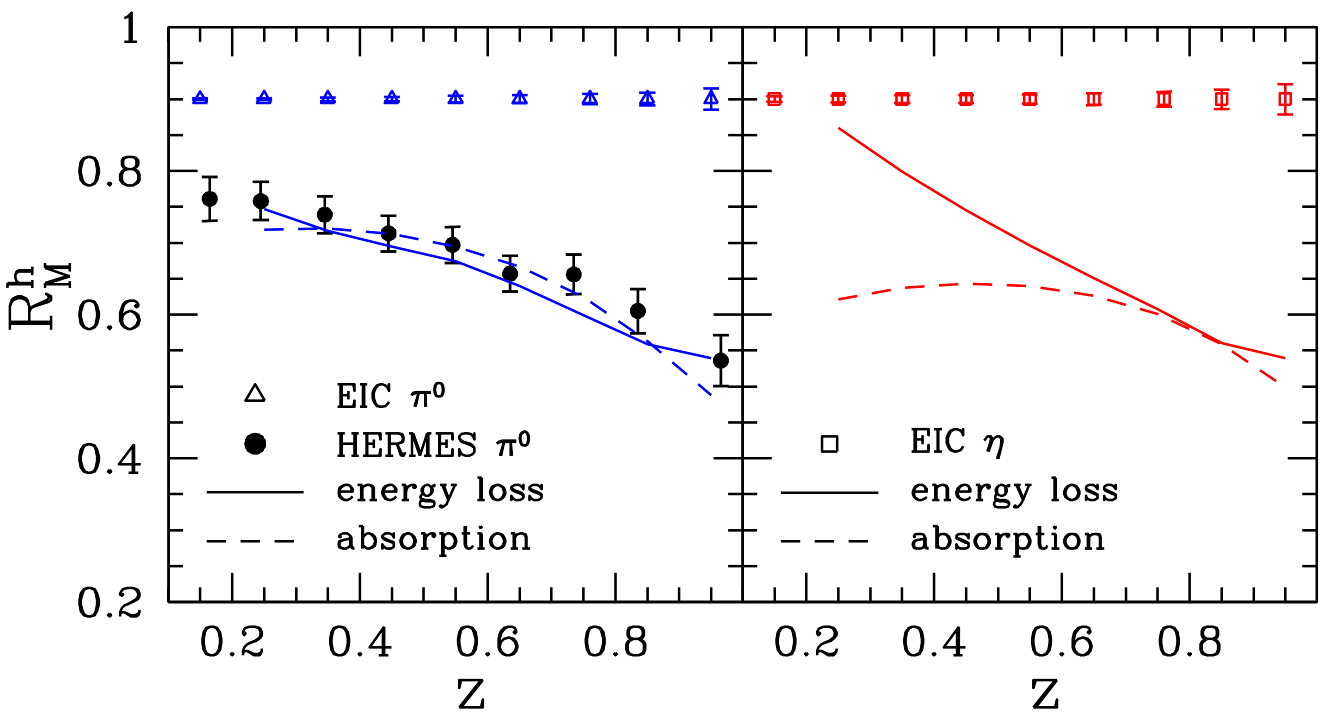
Energy transfer in lab rest frame

HERMES: ν = 2-25 GeV

EIC: 10 < ν < 1600 GeV

(LHC range)

EIC: *heavy flavor*!



Accardi, Dupre ’11

EIC Statistics for L = 200 fb^{-1}

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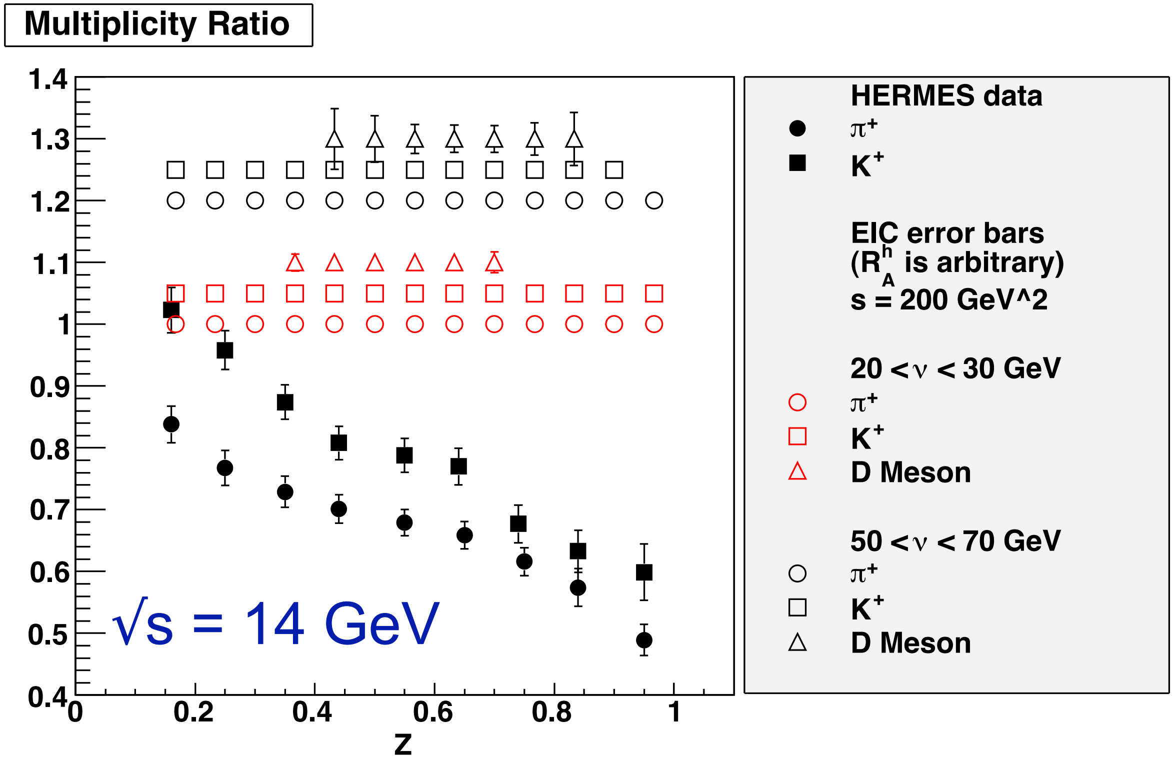
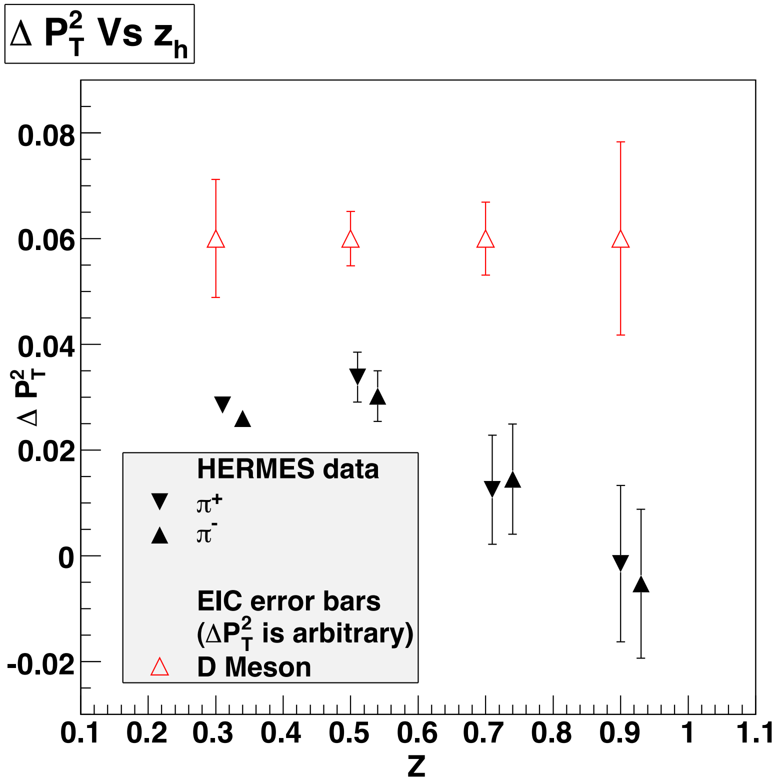


Accardi, Dupre '11

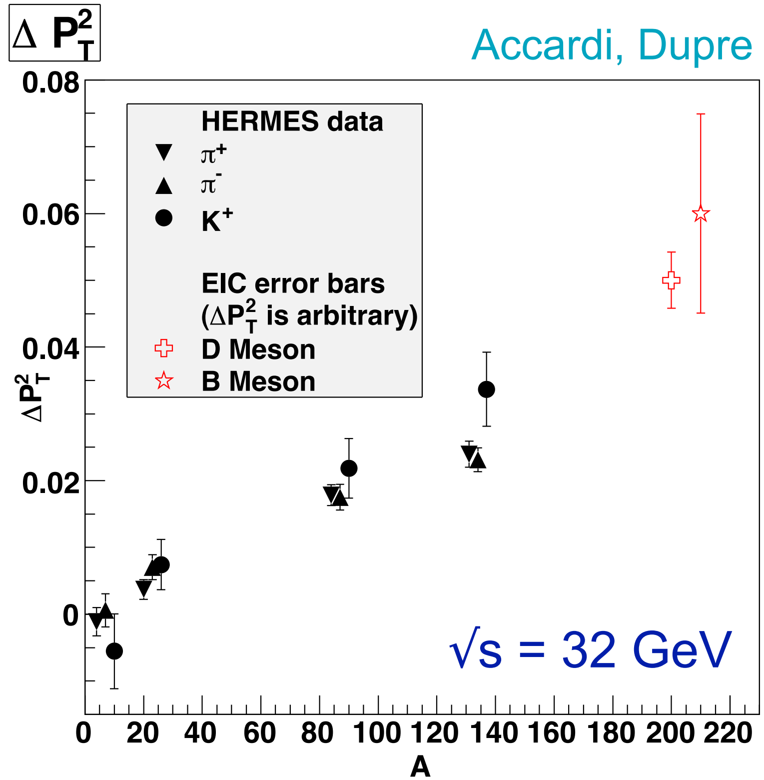
EIC Statistics for
L = 200 fb^{-1}

p_T Broadening in nDIS

- Δp_T^2 directly linked to saturation scale **e.g. BDMPS, Kopeliovich '10**
- Δp_T^2 of jets as direct measurement of $\hat{q}$
  - z, ν dependence to be taken into account



Accardi, Dupre '11



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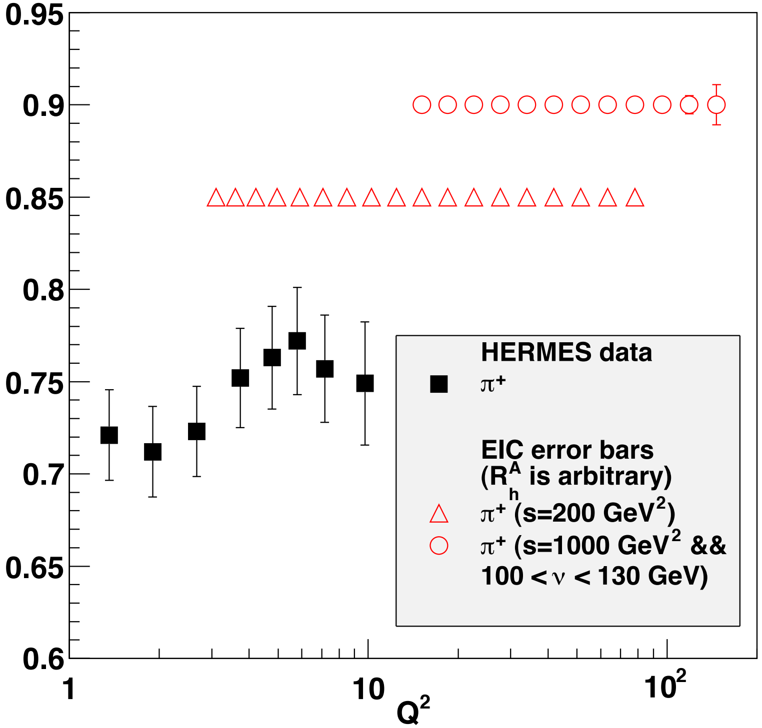
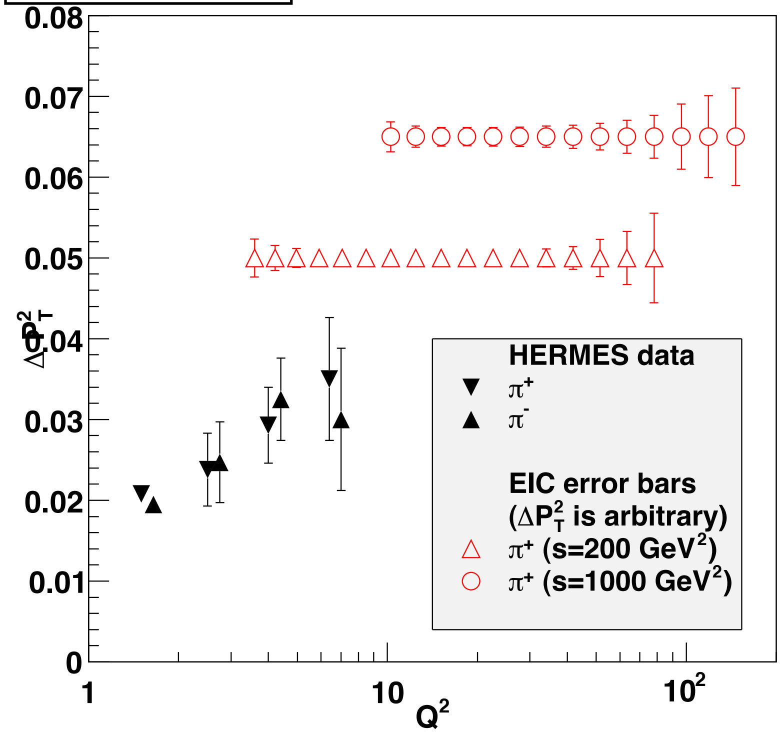
Multiplicity Ratio vs Q^2



Δp_T^2 vs Q^2 Accardi, Dupre '11



EIC: large Q^2 coverage to detect modifications in DGLAP evolution

Summary

The e+A program at an EIC is unprecedented, allowing the study of matter in a new regime where physics is not described by "ordinary" QCD

- set of key (aka golden or killer) measurements identified
- studies underway to establish their feasibility with realistic detectors and machine parameters.

The e+A program is also a challenge experimentally

- new difficulties compared to e+p
- measurements never conducted in a collider
- so far found no show-stopper for key measurements
- most key measurements are energy ($\sqrt{s}$) hungry ...
- ... but less luminosity demanding