The low-x programme at an Electron-Ion Collider

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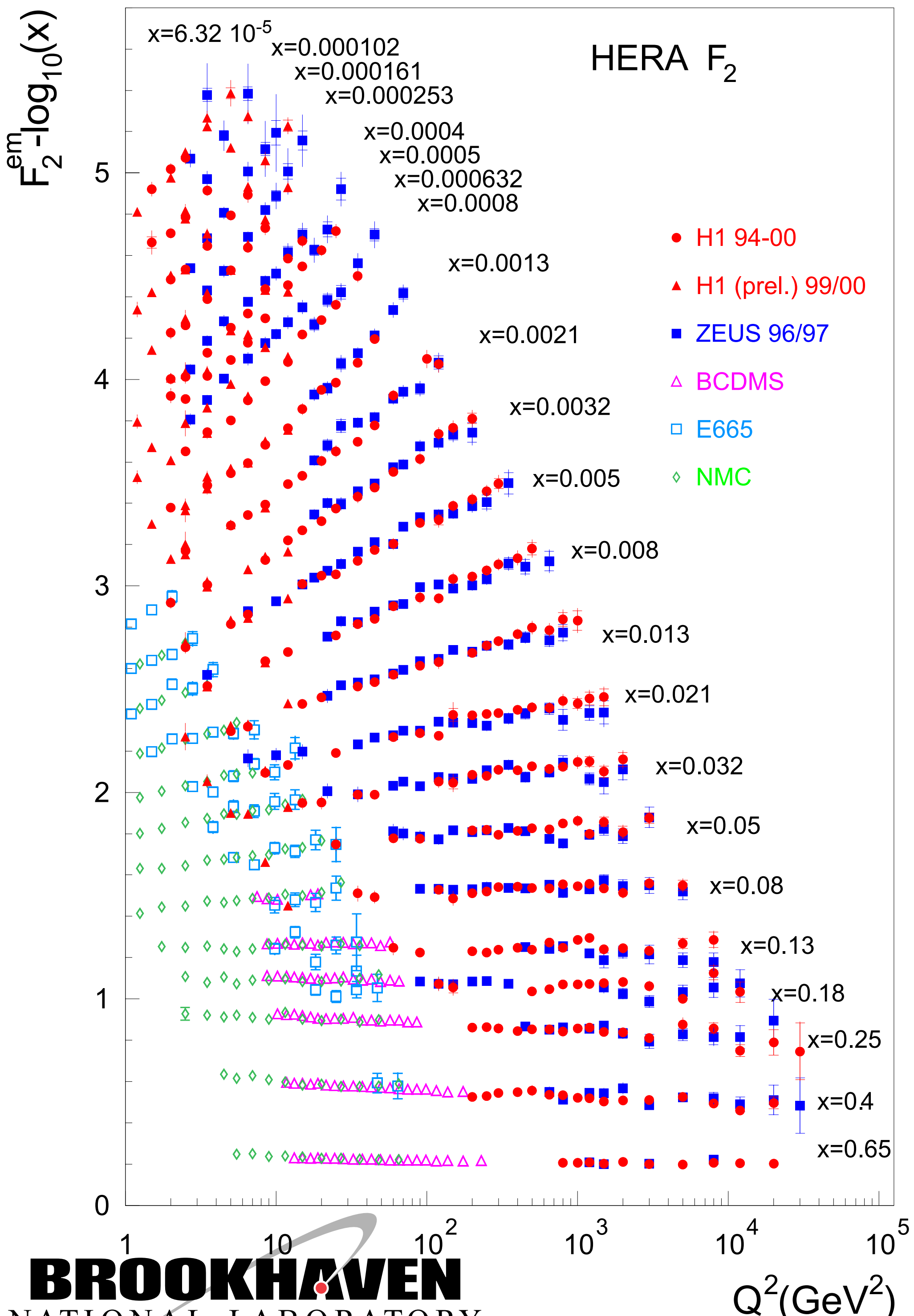
Measuring the gluon distribution in a nucleon

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

quark+anti-quark momentum distributions (F_2)

gluon momentum distribution (F_L)



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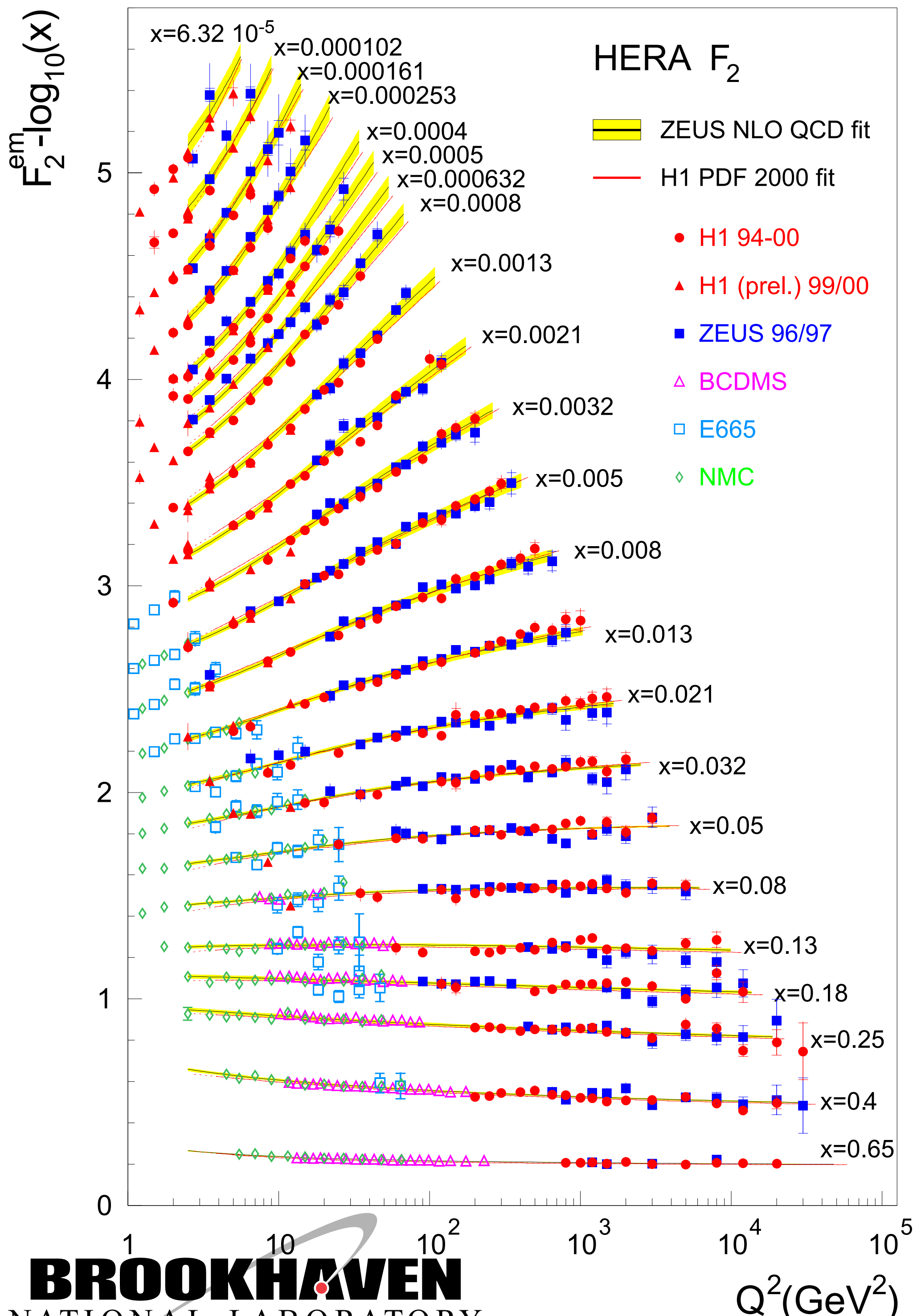

Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

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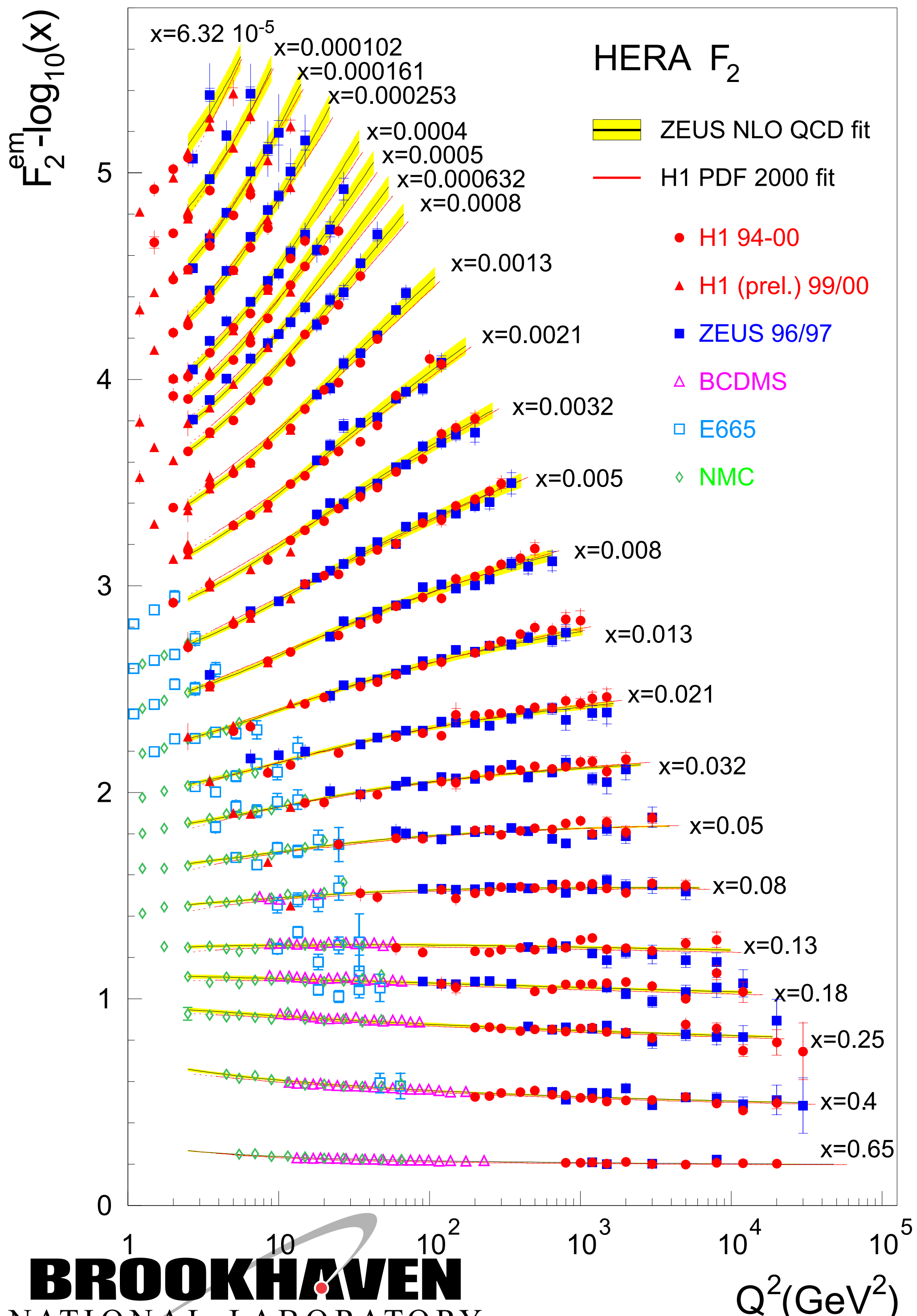

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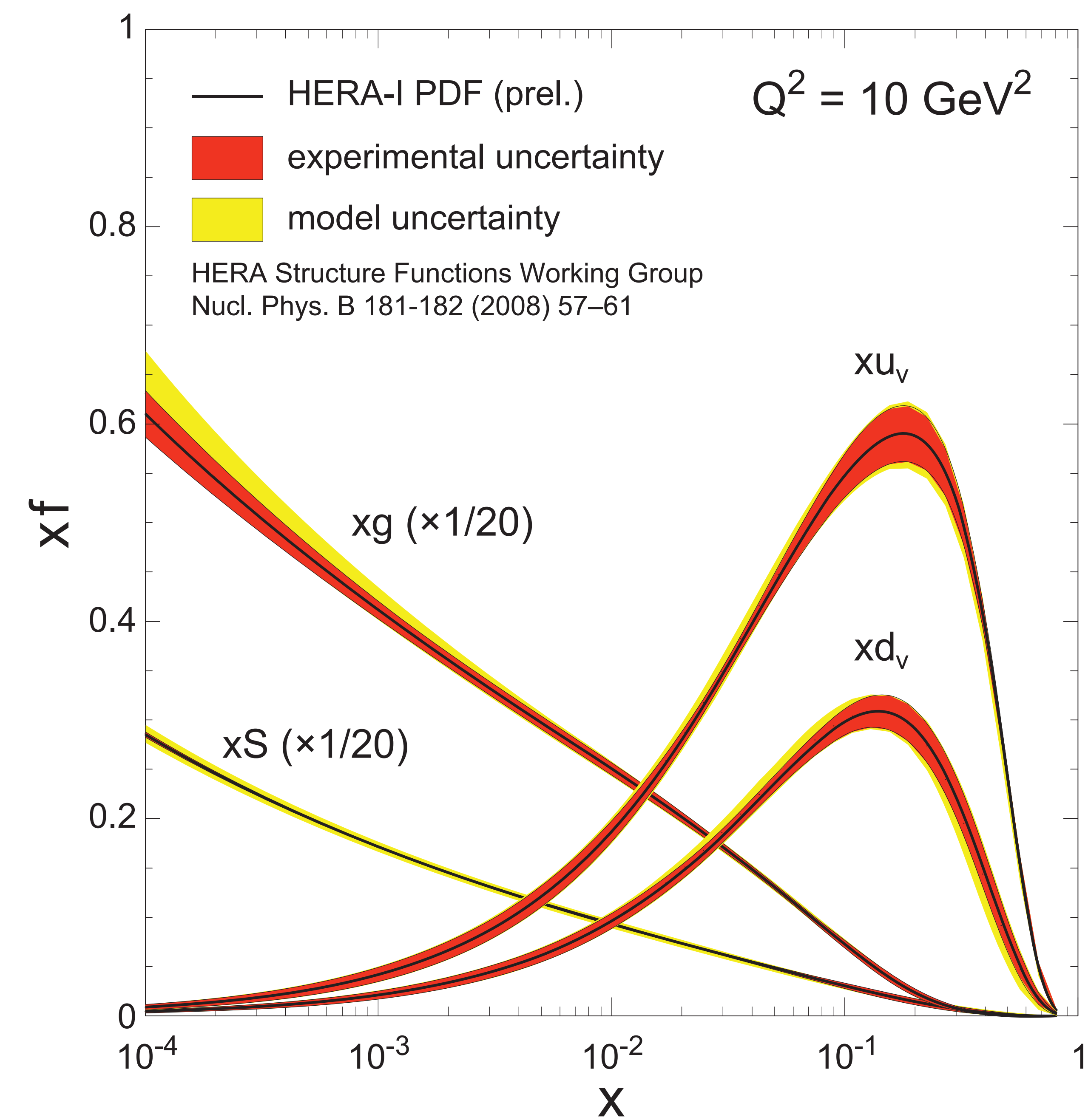
Evolution ⇒ $G(x,Q^2)$



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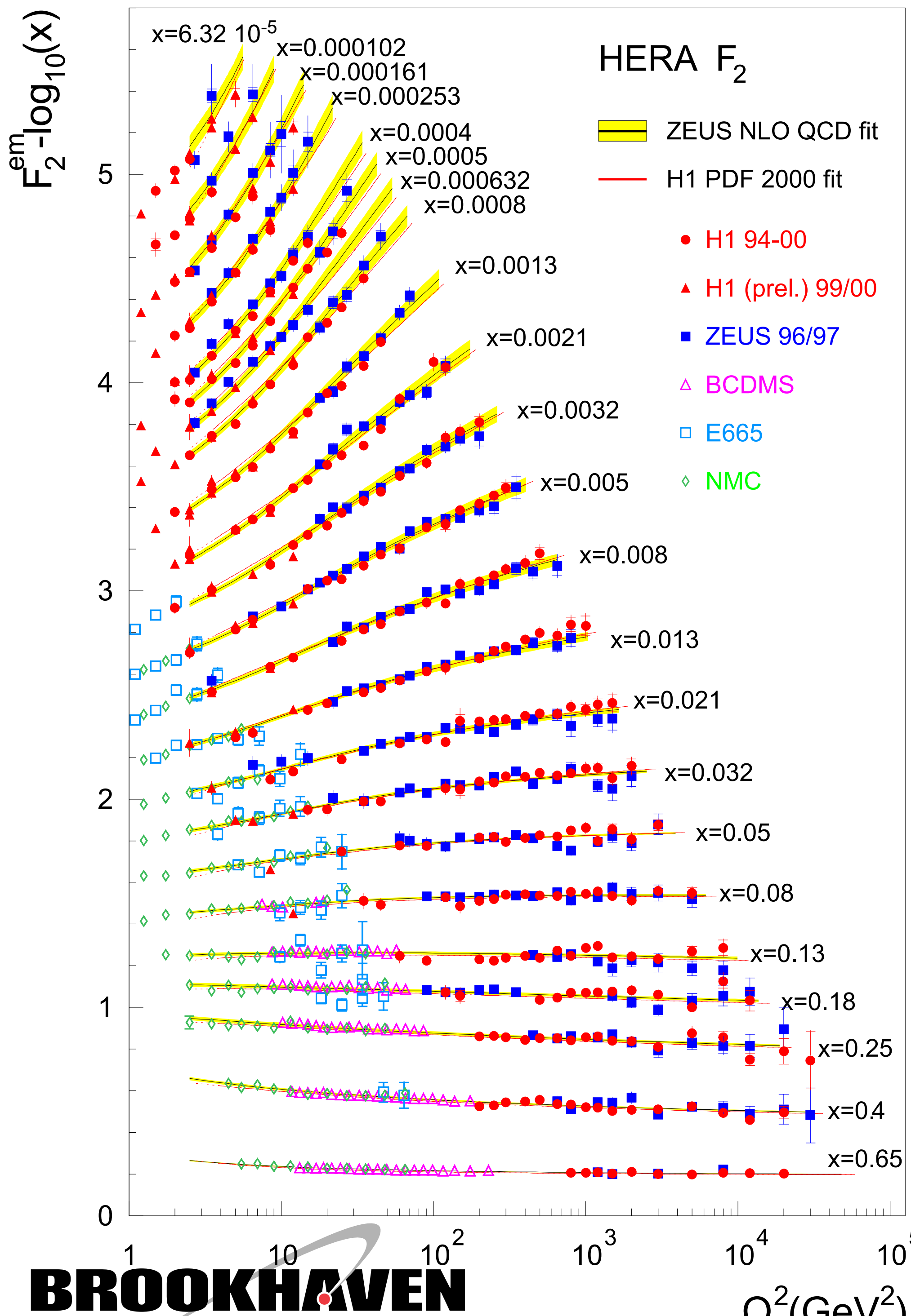

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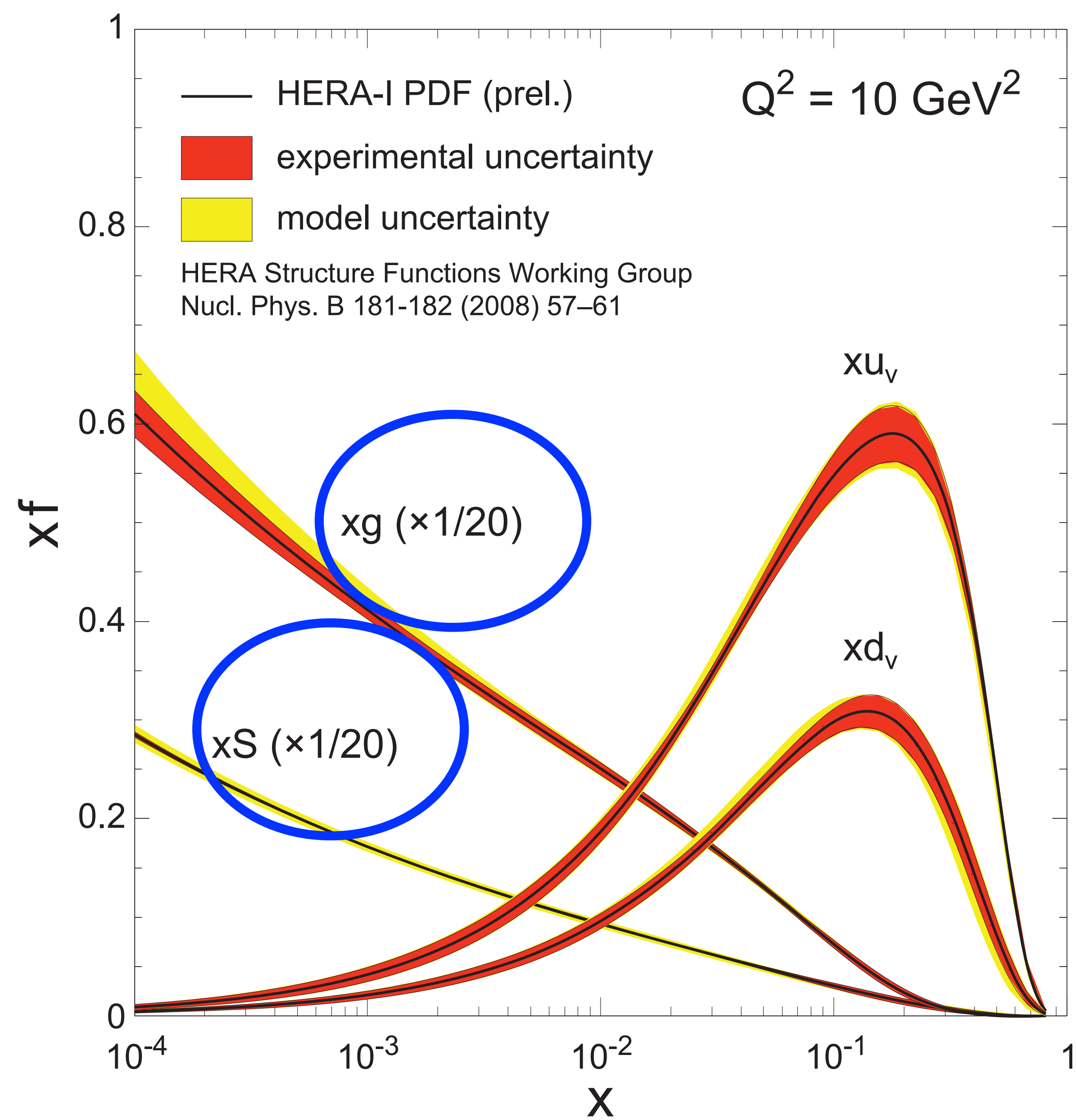

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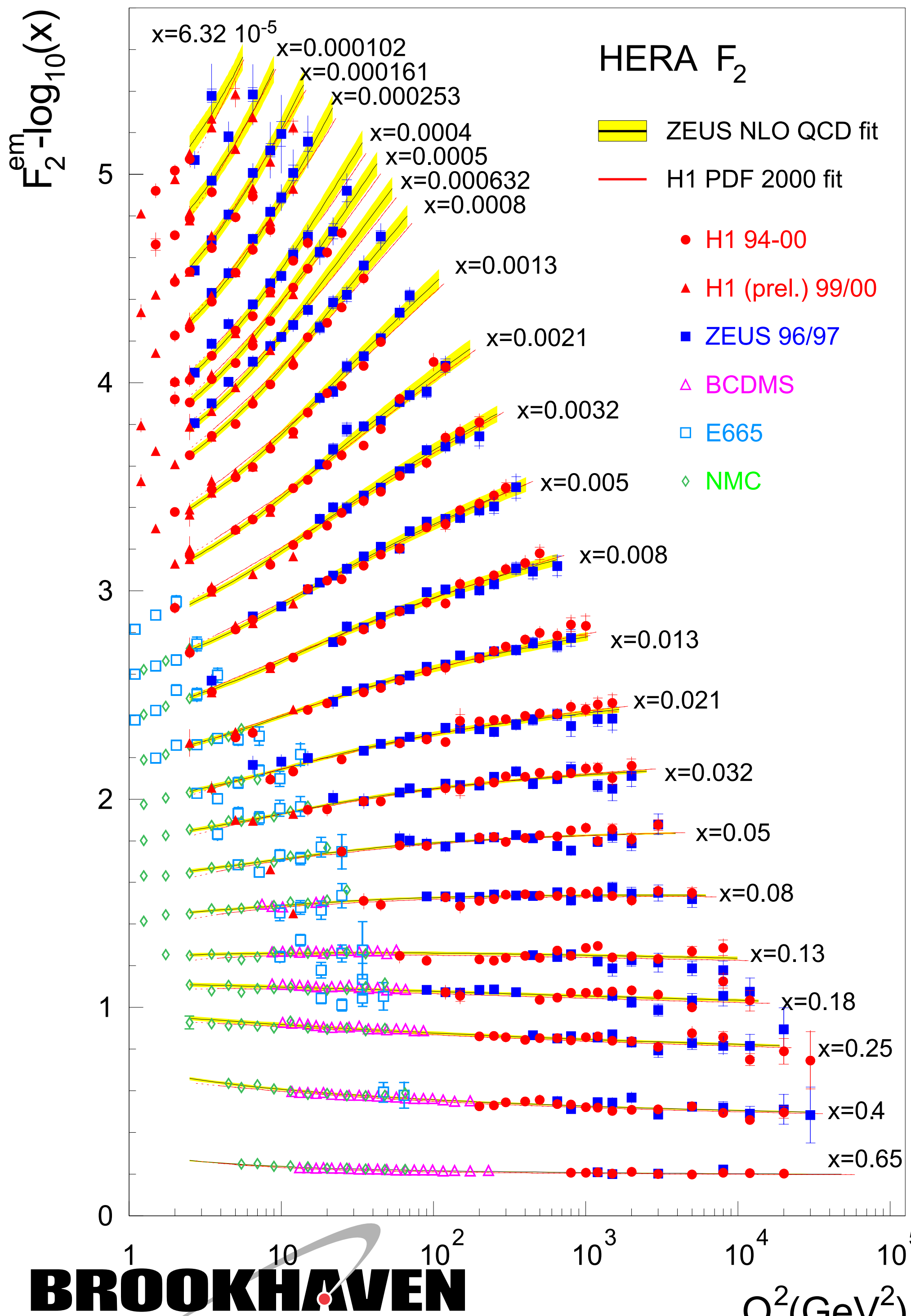

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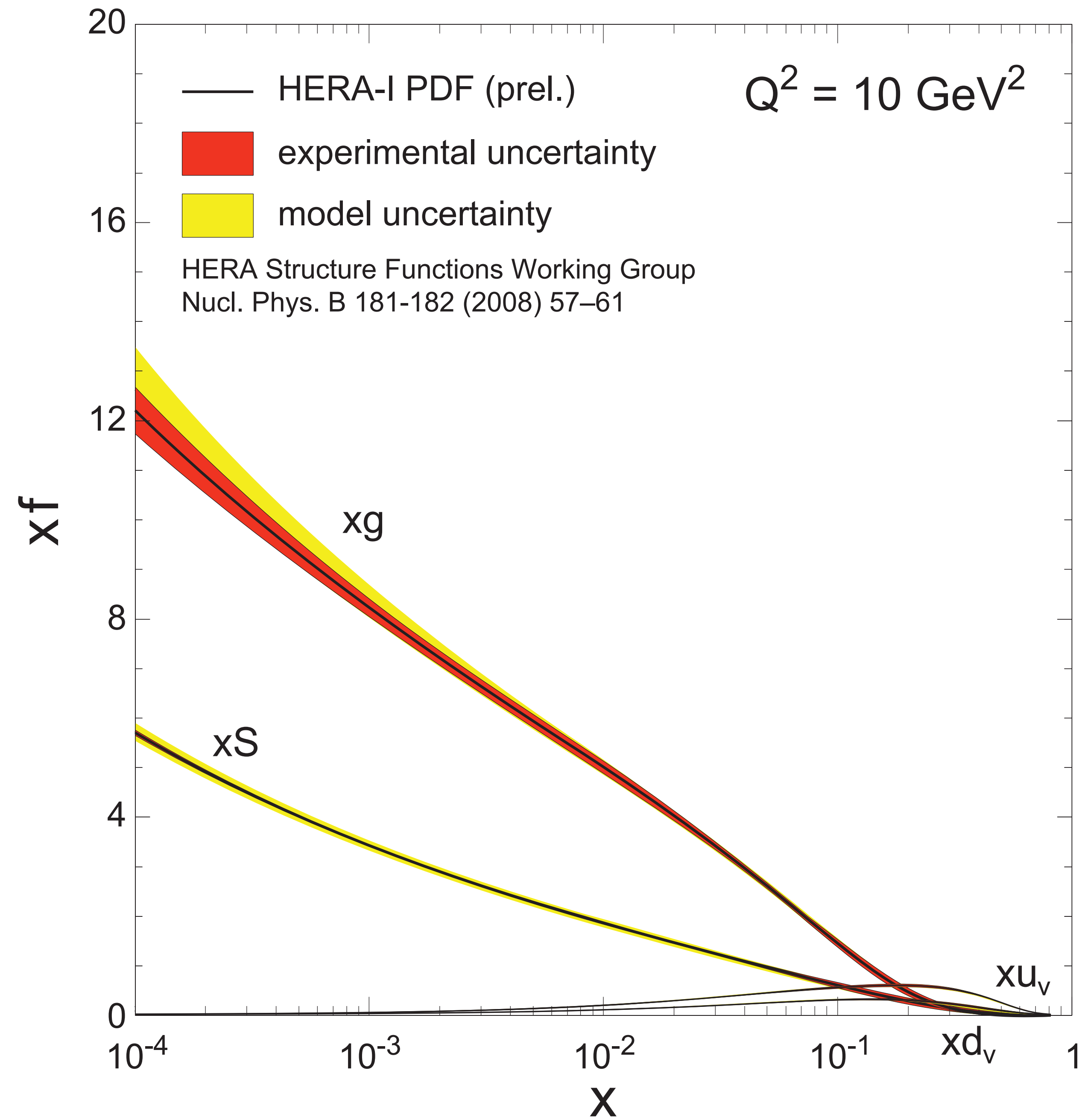

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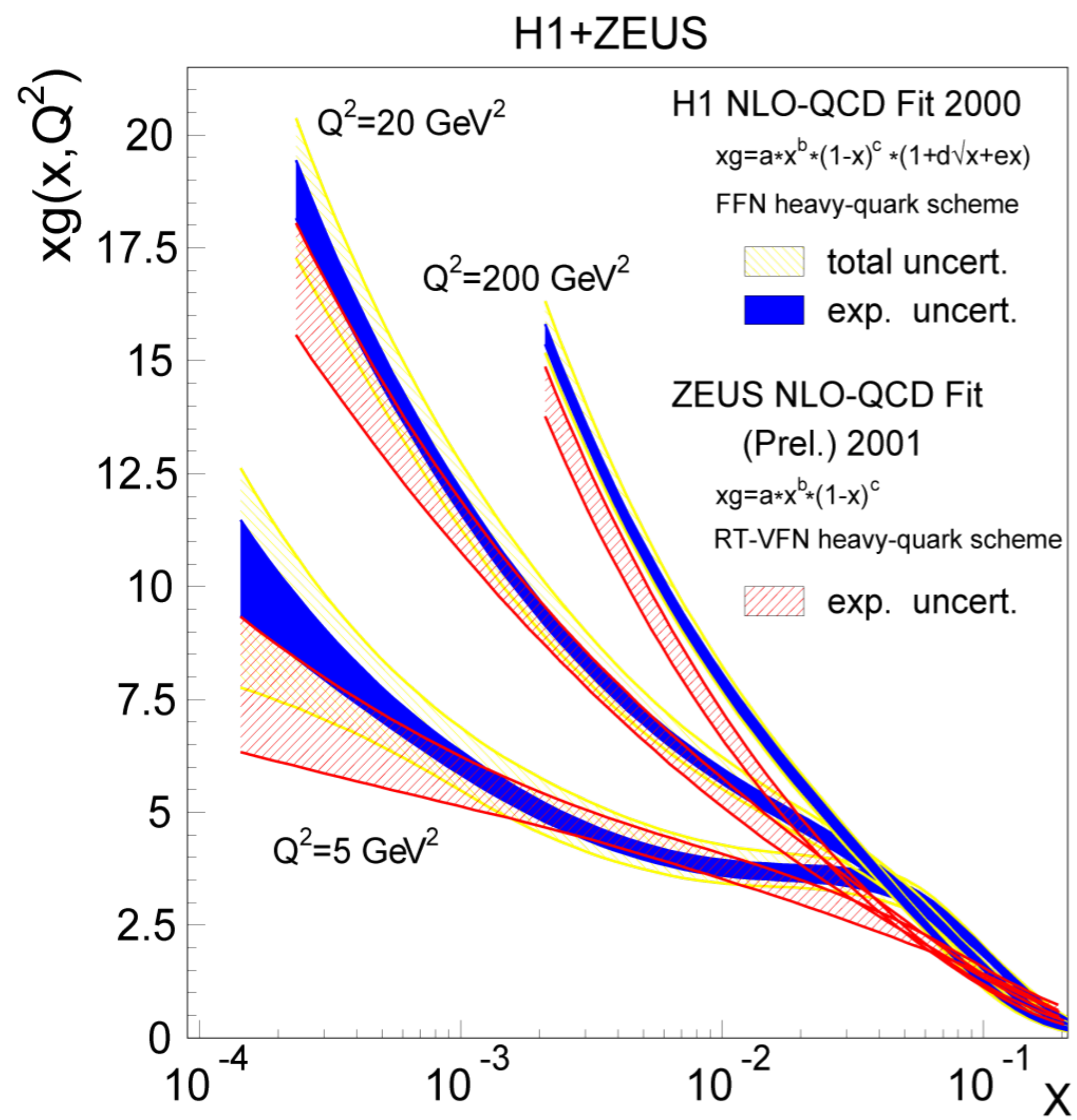
The problem with our current understanding

- Using the Linear DGLAP evolution model:
  - Linear evolution has a built-in high-energy "catastrophe"
  - *xG* has rapid rise with decreasing *x* (and increasing Q^2) ⇒ violation of Froissart unitarity bound

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln\ s)^2$$

- Must have saturation to tame the growth



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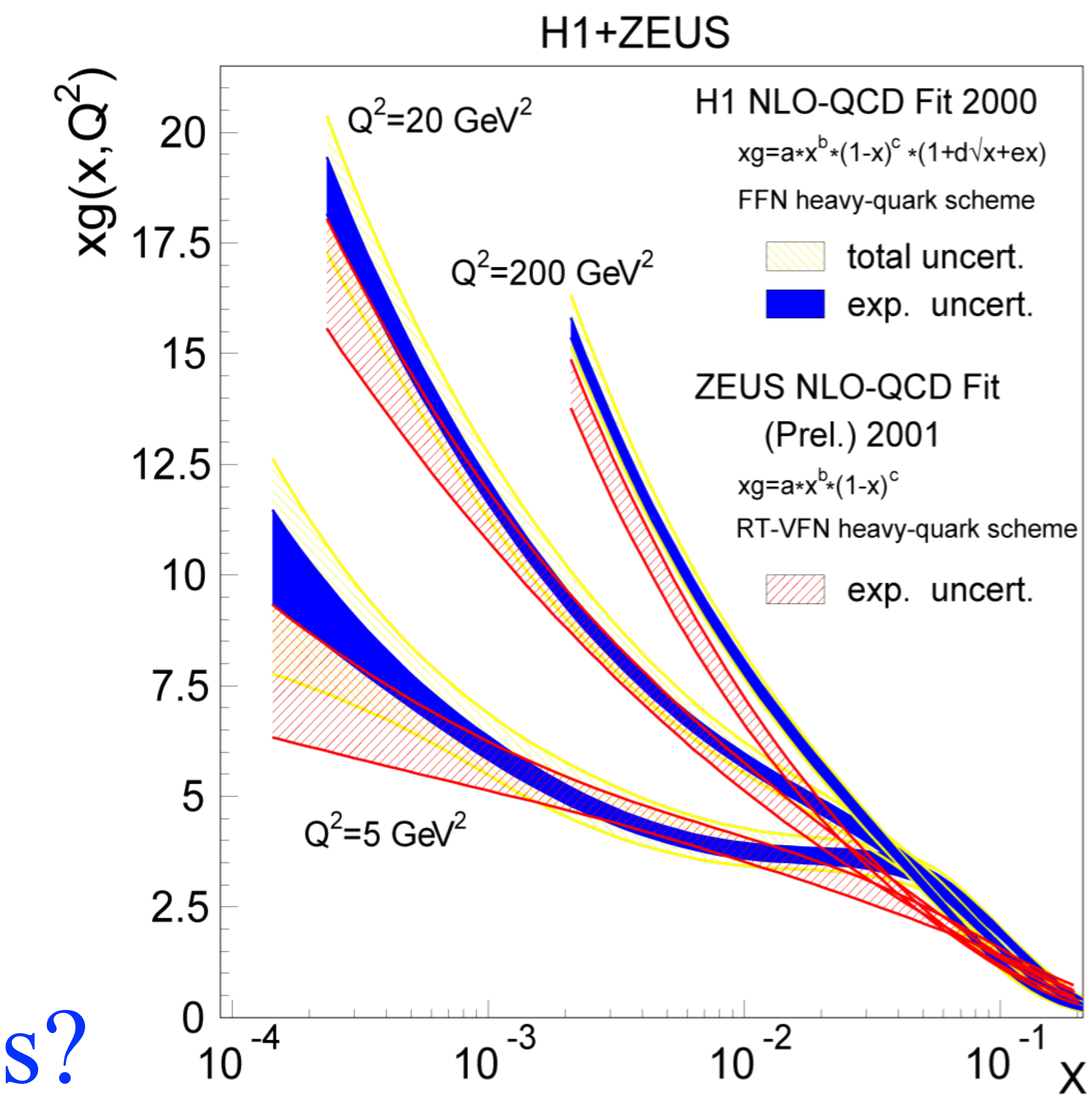

What’s the underlying dynamics?

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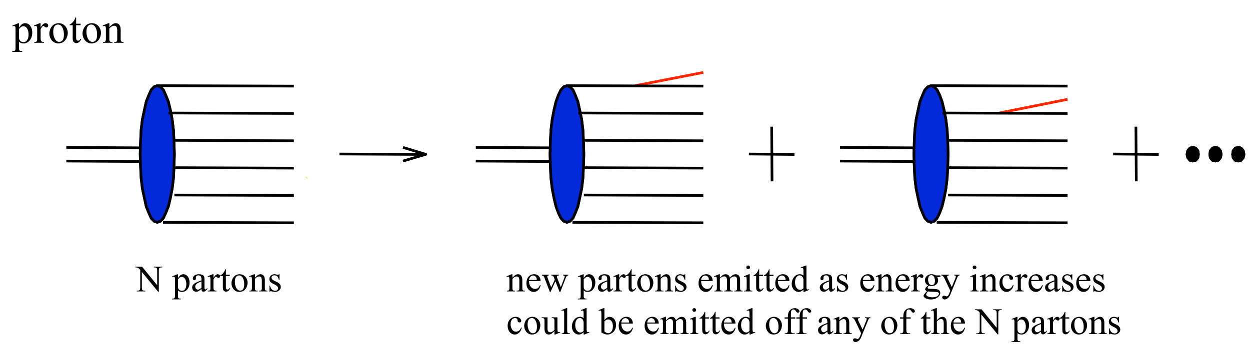
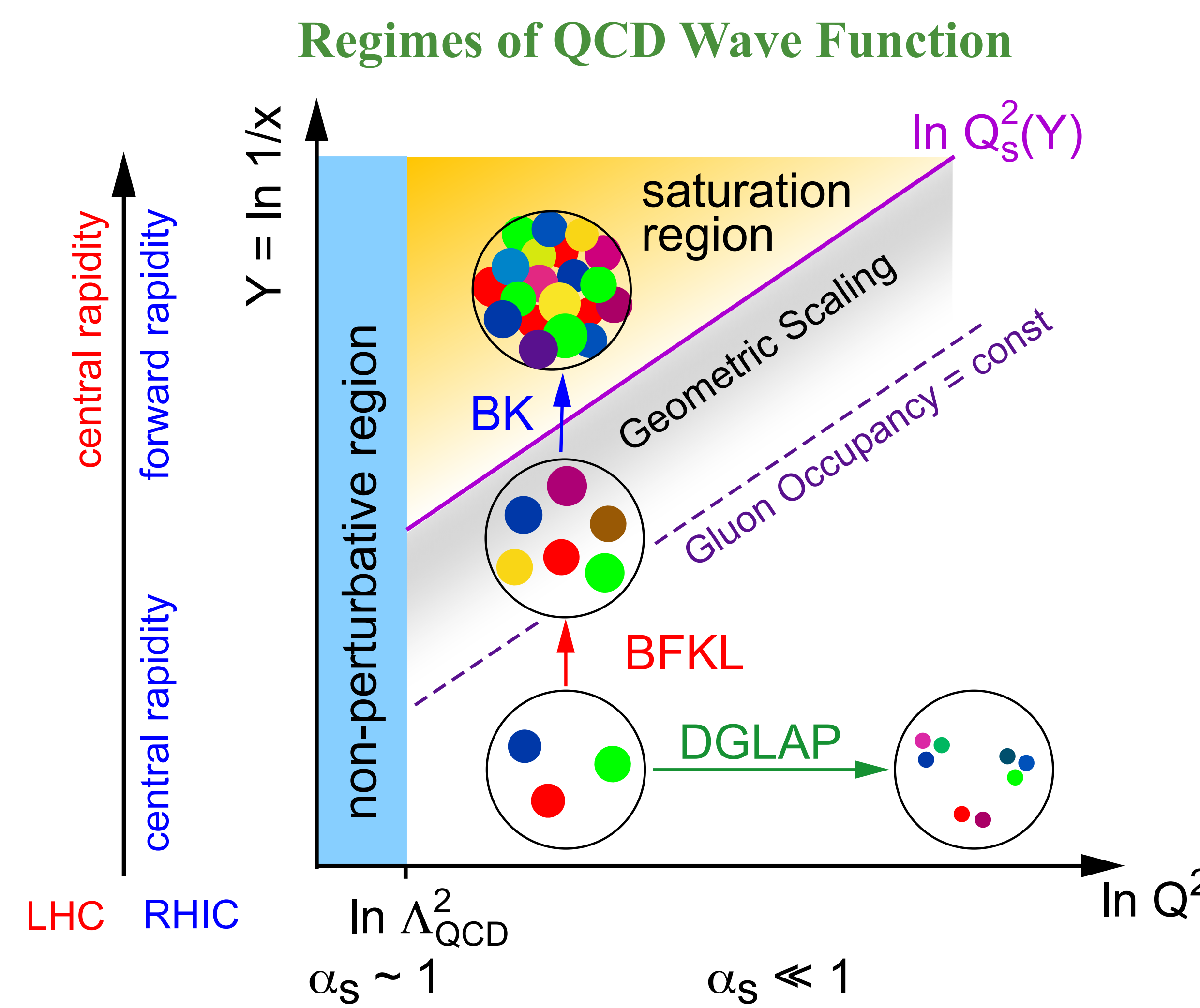
Non-linear QCD - saturation





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Non-linear QCD - saturation

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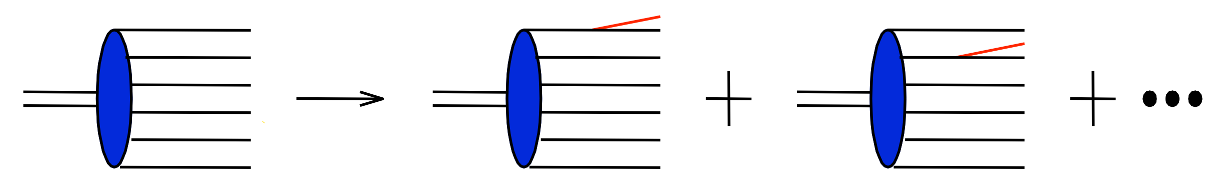
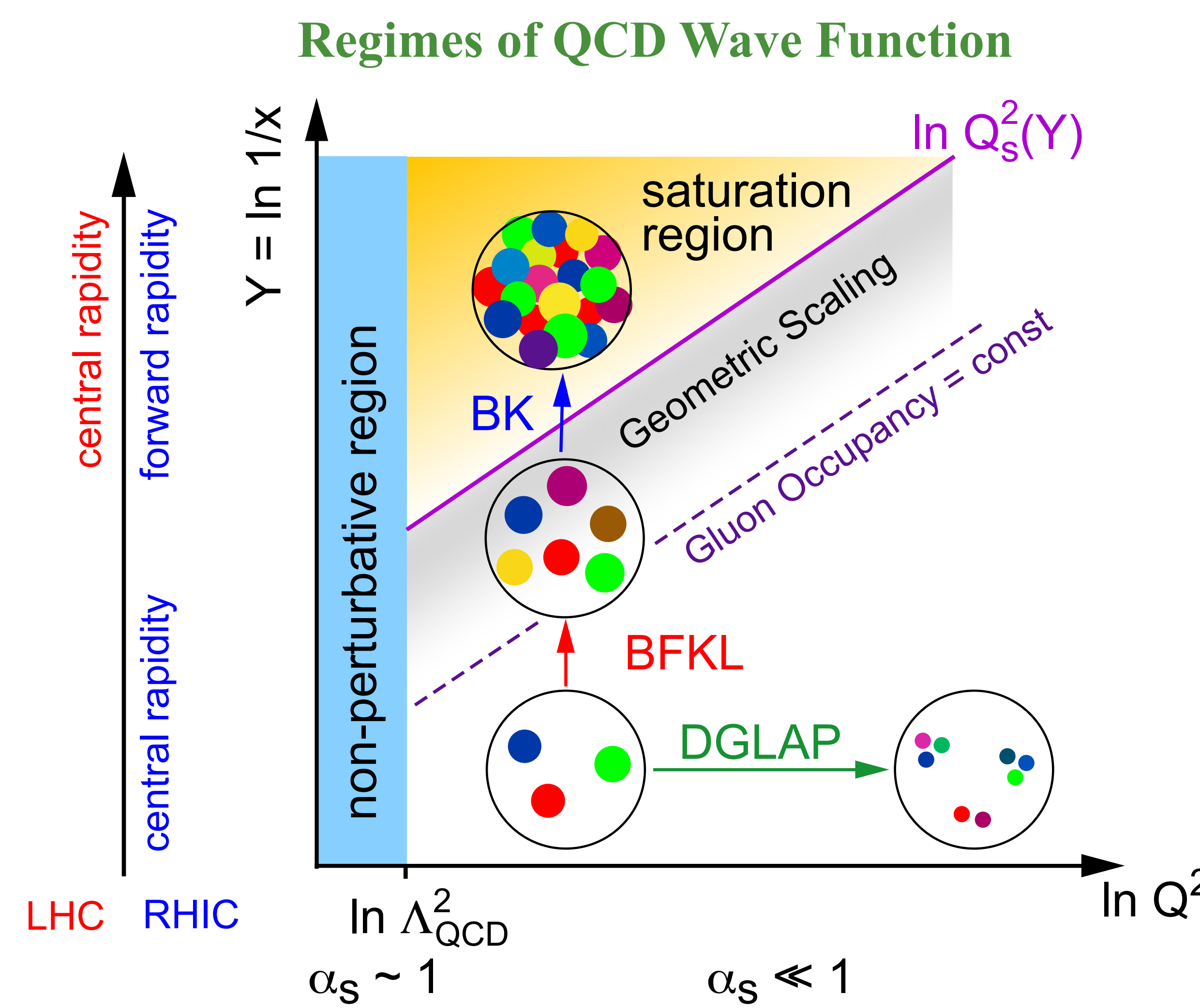
  - linear
    - explysion in colour field at low-x





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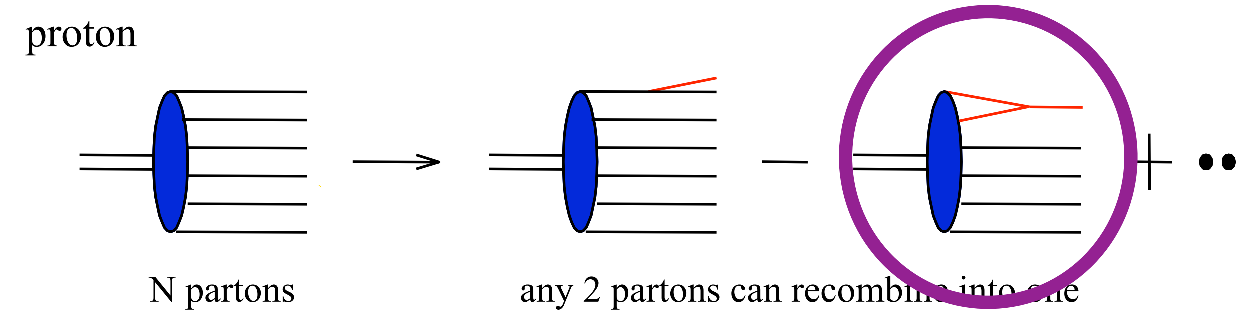
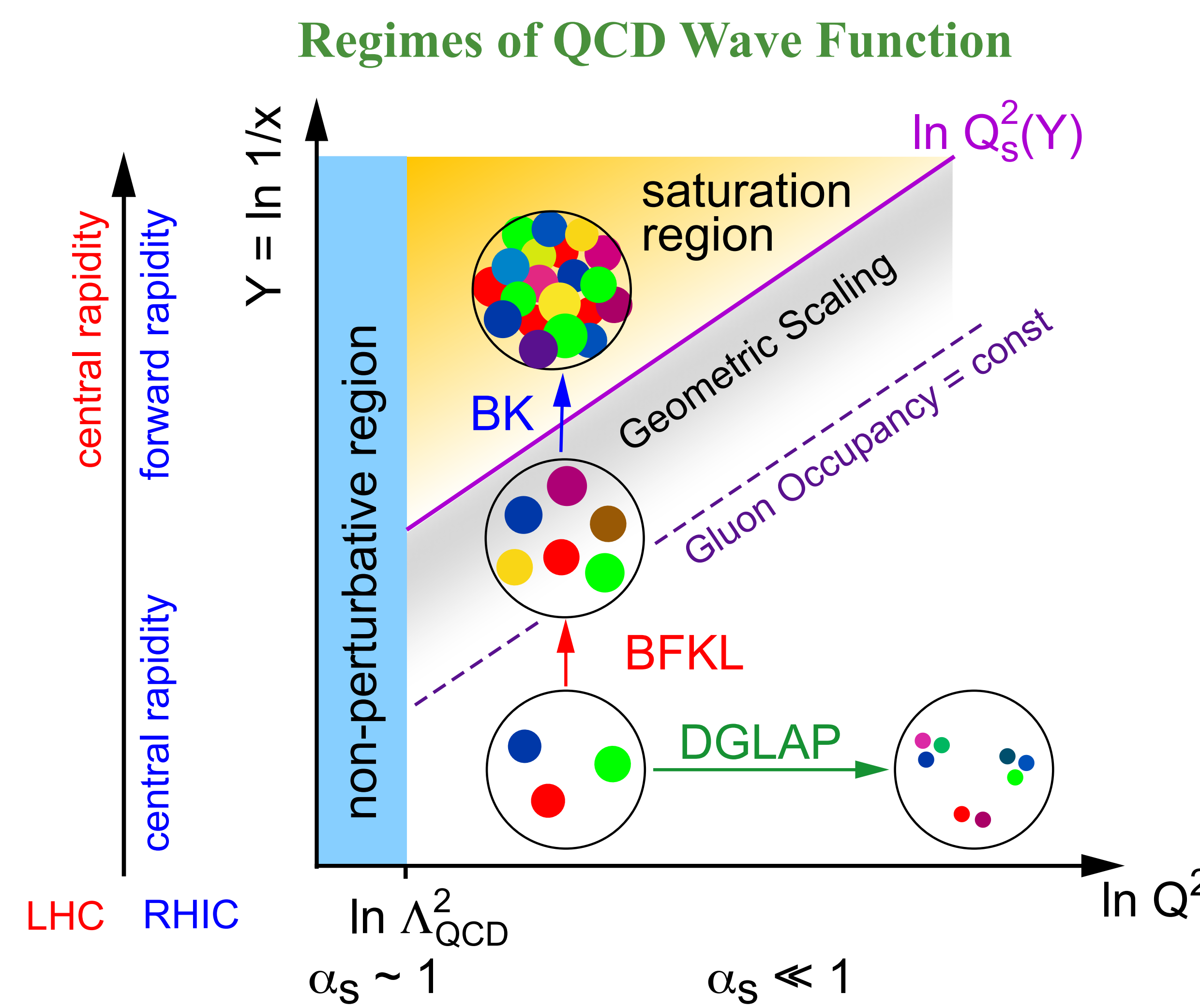
Non-linear QCD - saturation

- BFKL: evolution in x
  - linear
    - explosion in colour field at low-x
- Non-linear BK/JIMWLK equations
  - non-linearity ⇒ saturation
    - Allows for the recombination of gluons in a dense gluonic medium
  - characterised by the saturation scale, $Q_S(x,A)$





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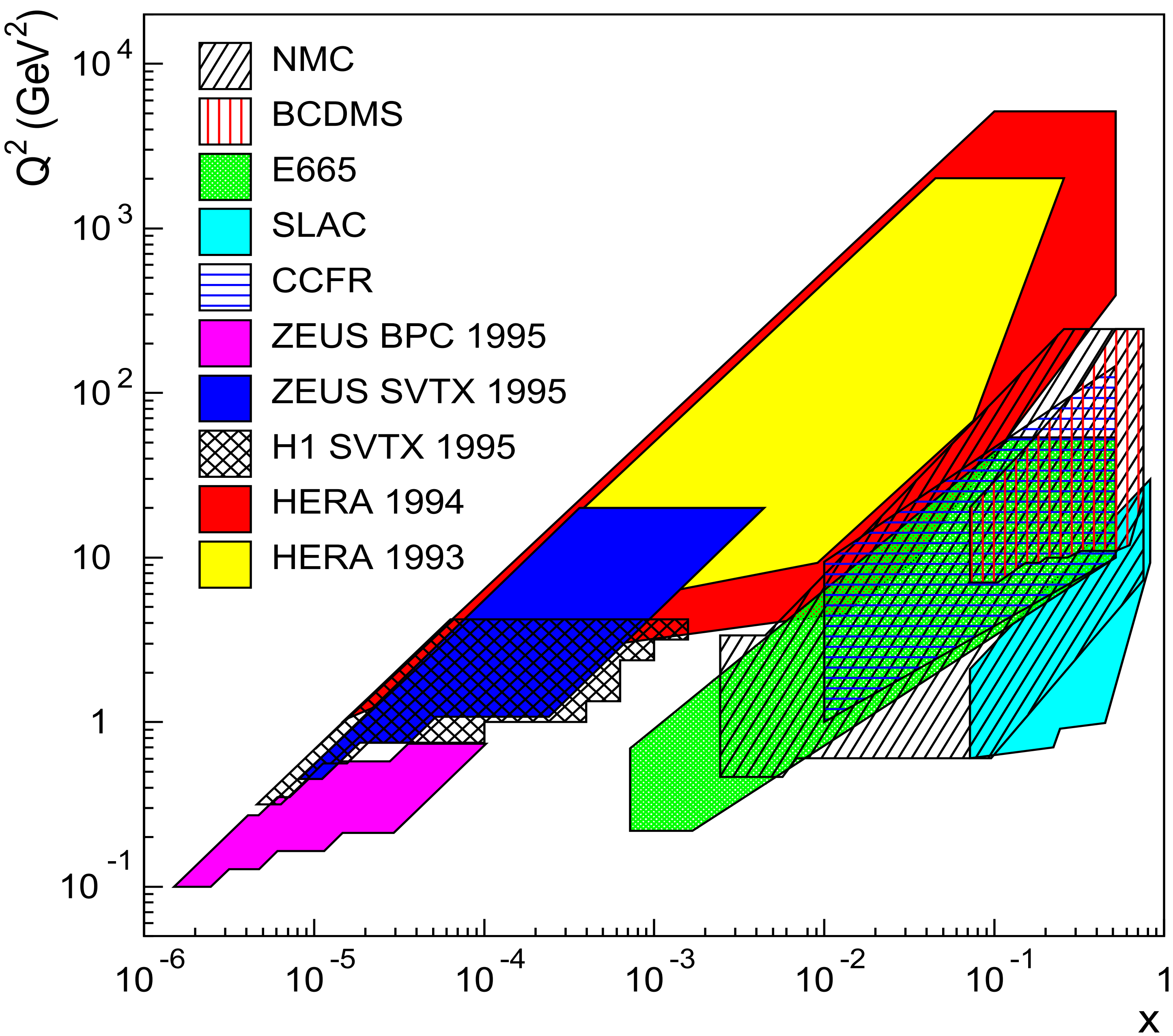
Phase-space coverage of an e+p/h experiments



- Large coverage in x-Q^2 phase space
  - Results from both collider and fixed-target experiments complement each other
- Onset of saturation possibly observed in collisions at HERA at very low-x
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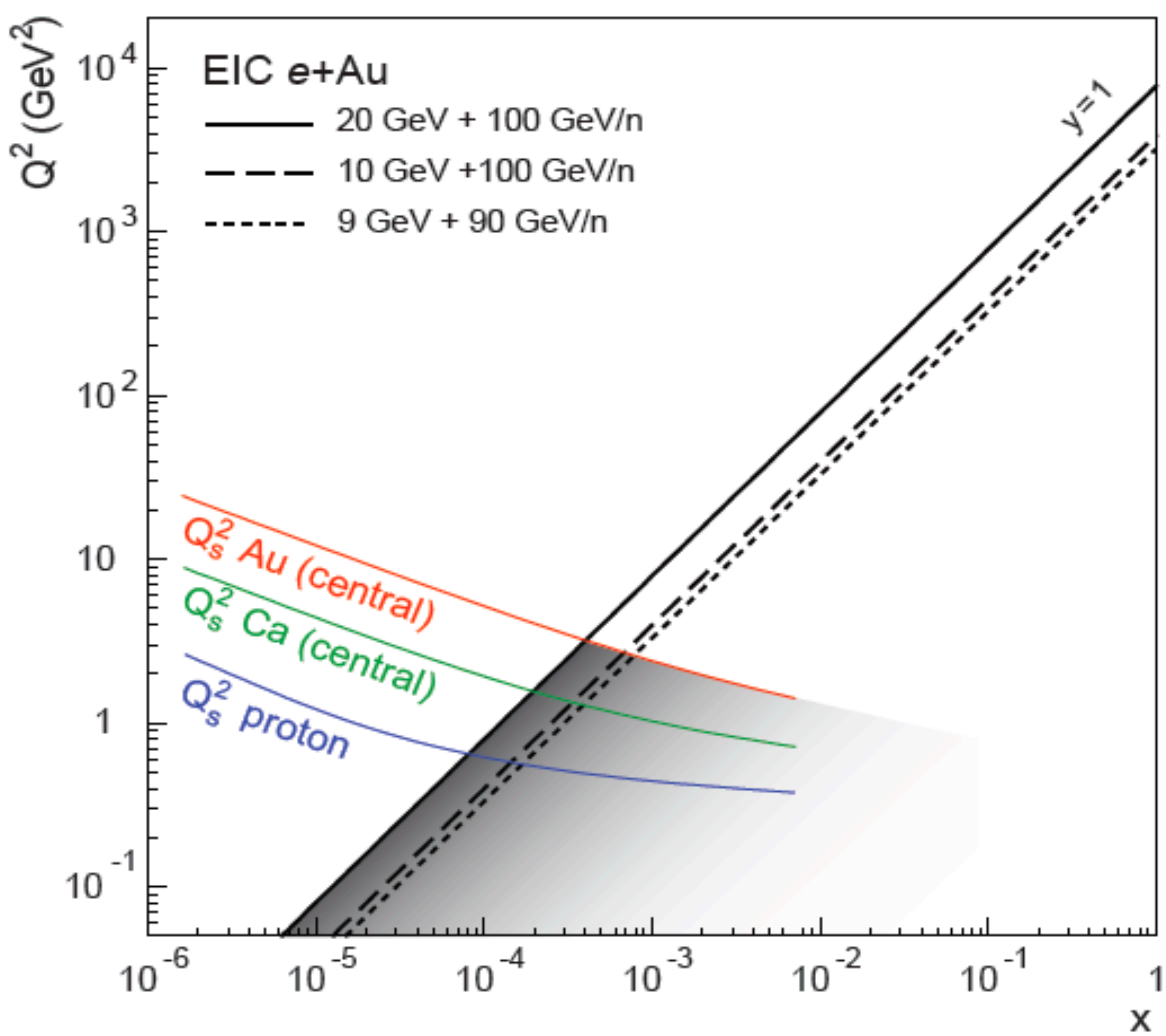

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Electron Ion Collider:

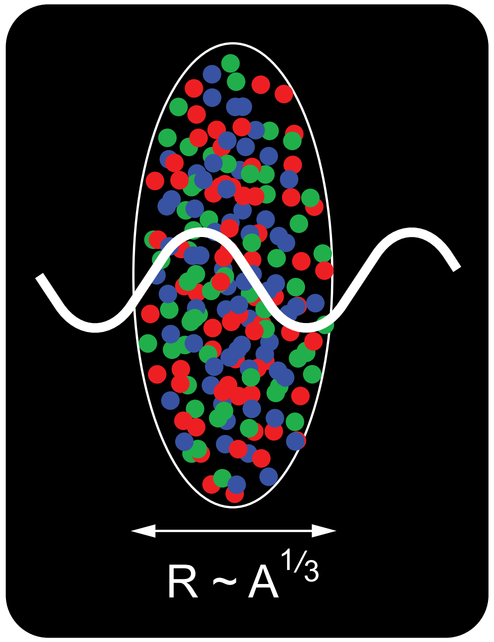
- $\mathcal{L}$(EIC) > 100 × $\mathcal{L}$(HERA)
- Electrons
  - E_e = 3 - 20 GeV
  - polarised
- Polarised *p*

EIC appears to be worse than HERA in looking for saturation effects - can saturation be observed?

5

The Nuclear "Oomph Factor"

- Enhancing Saturation effects:
  - Probes interact over distances $L \sim (2m_n x)^{-1}$
  - For probes where $L > 2R_A$ ($\sim A^{1/3}$) cannot distinguish between nucleons in front or back of the nucleus. Probe acts coherently with all nucleons!!



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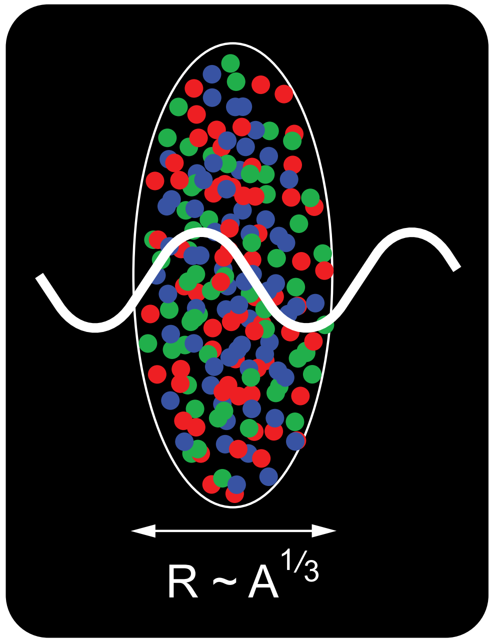

Simple geometric considerations lead to:

Nuclear "Oomph" Factor:

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

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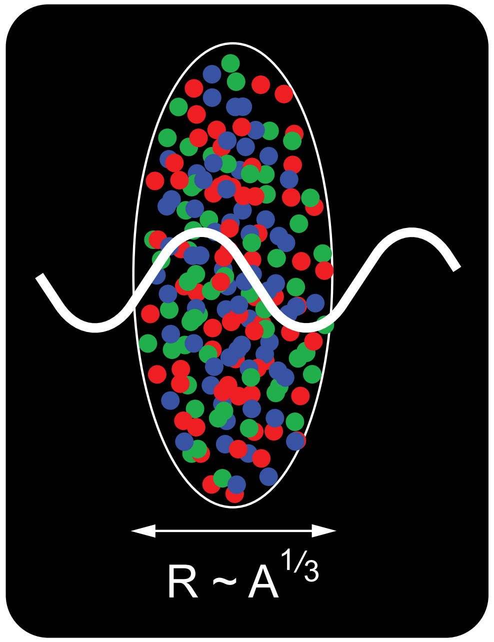

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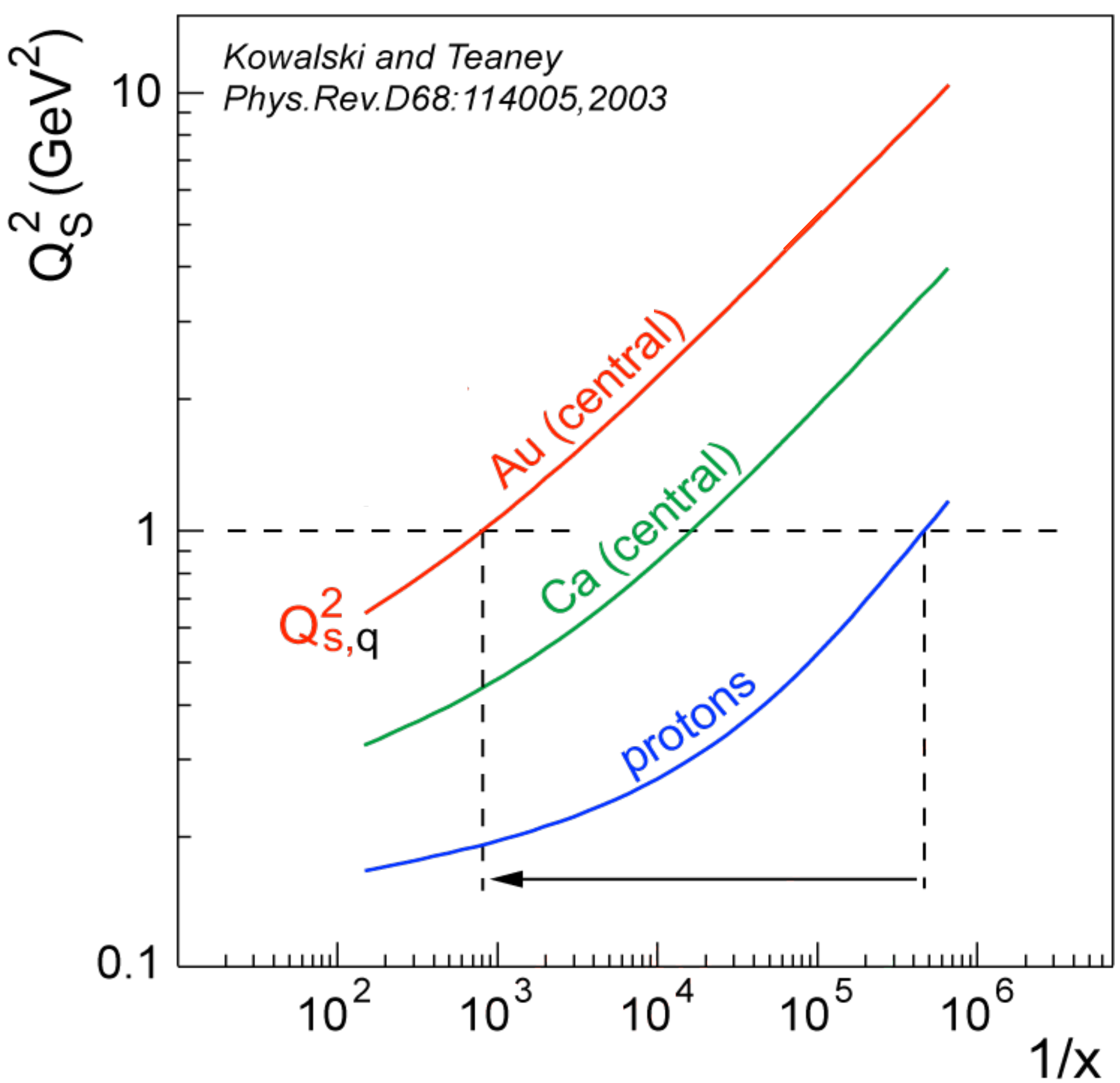

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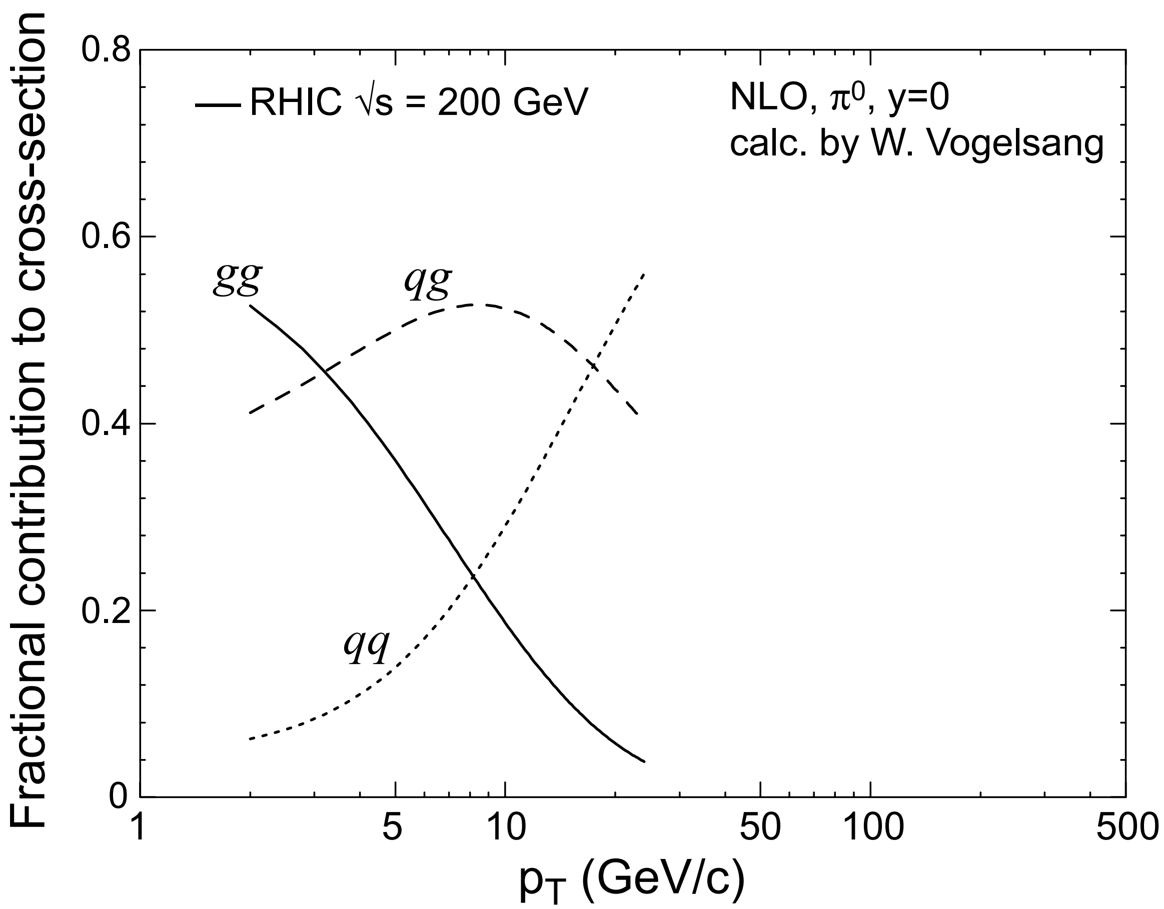
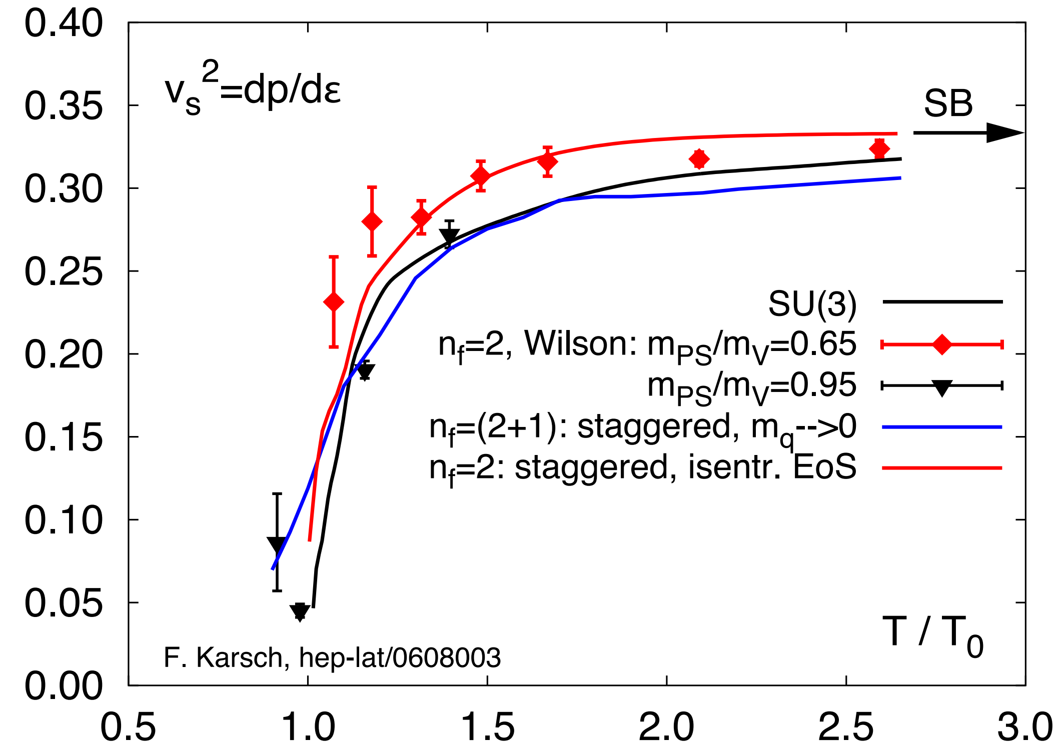
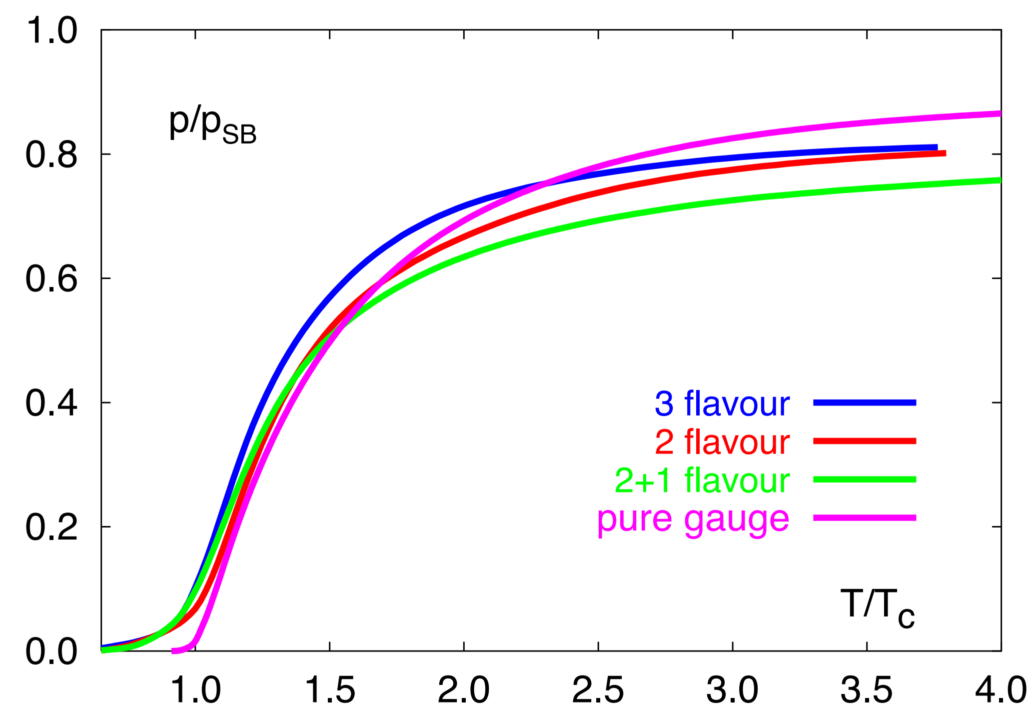
The role of Glue at RHIC and the LHC

Jets (π^0 production)

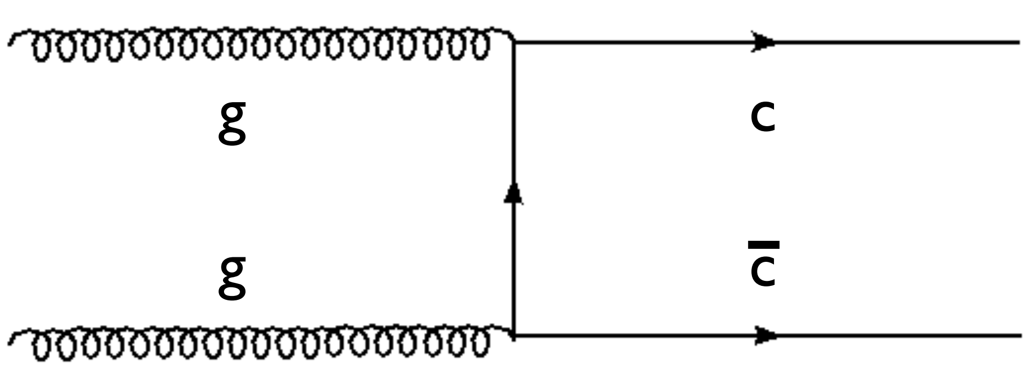


Lattice Gauge Theory:





Heavy Flavour Production



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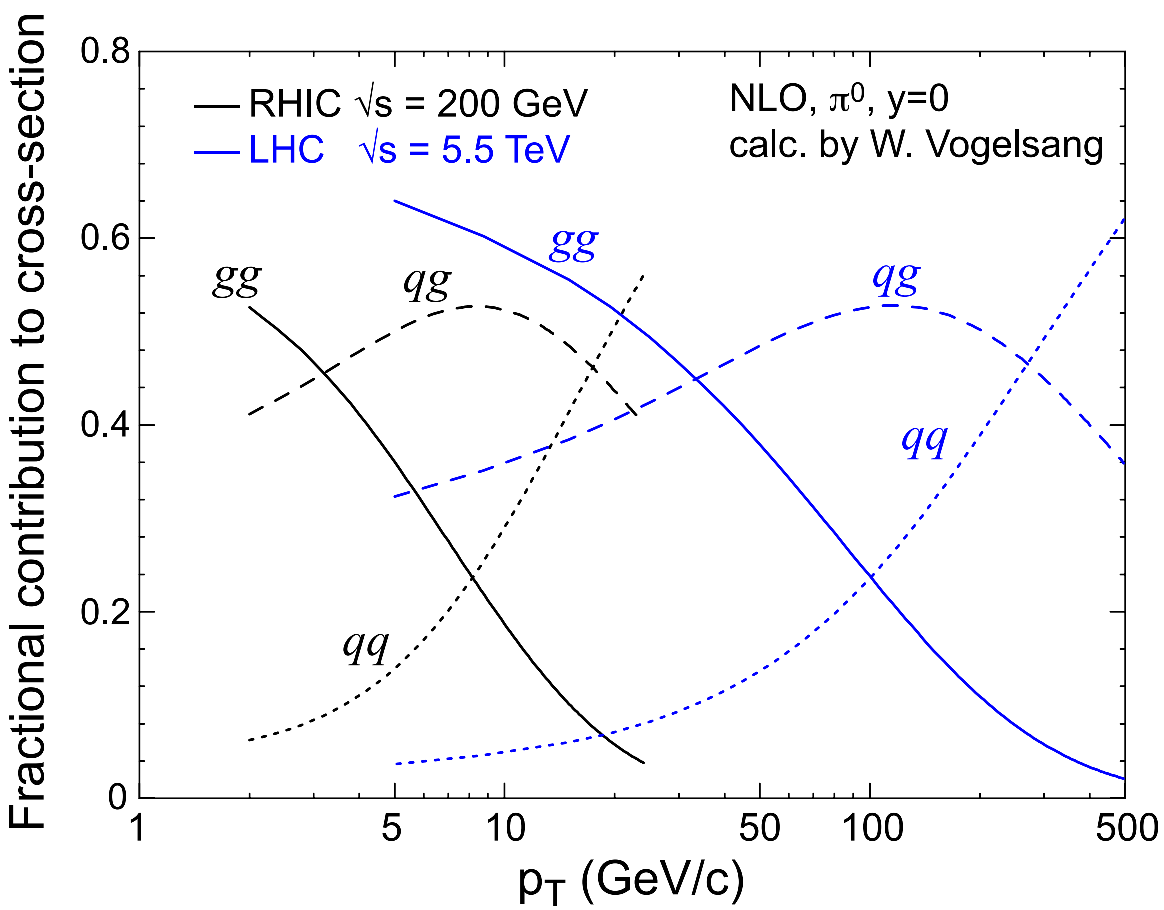

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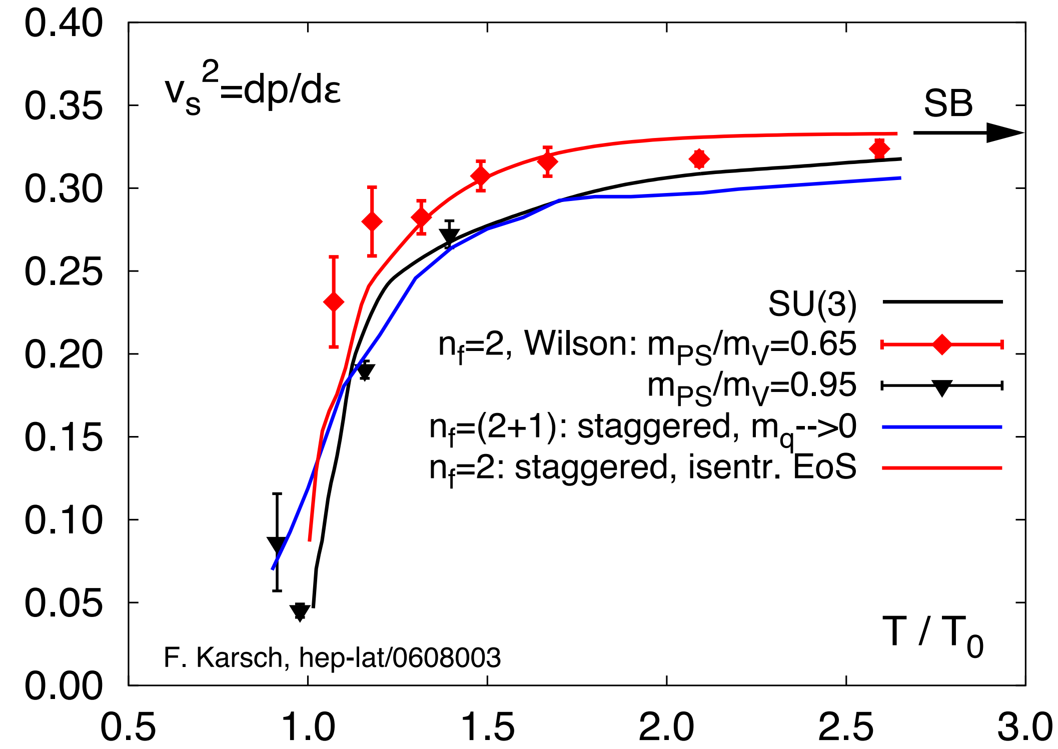

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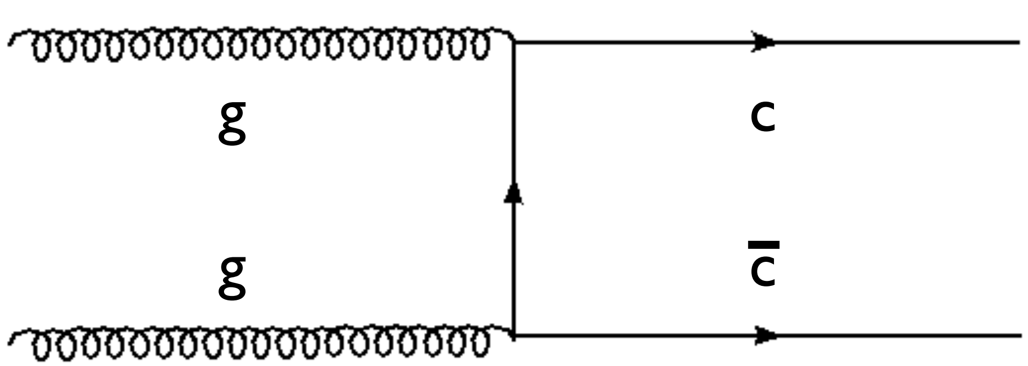

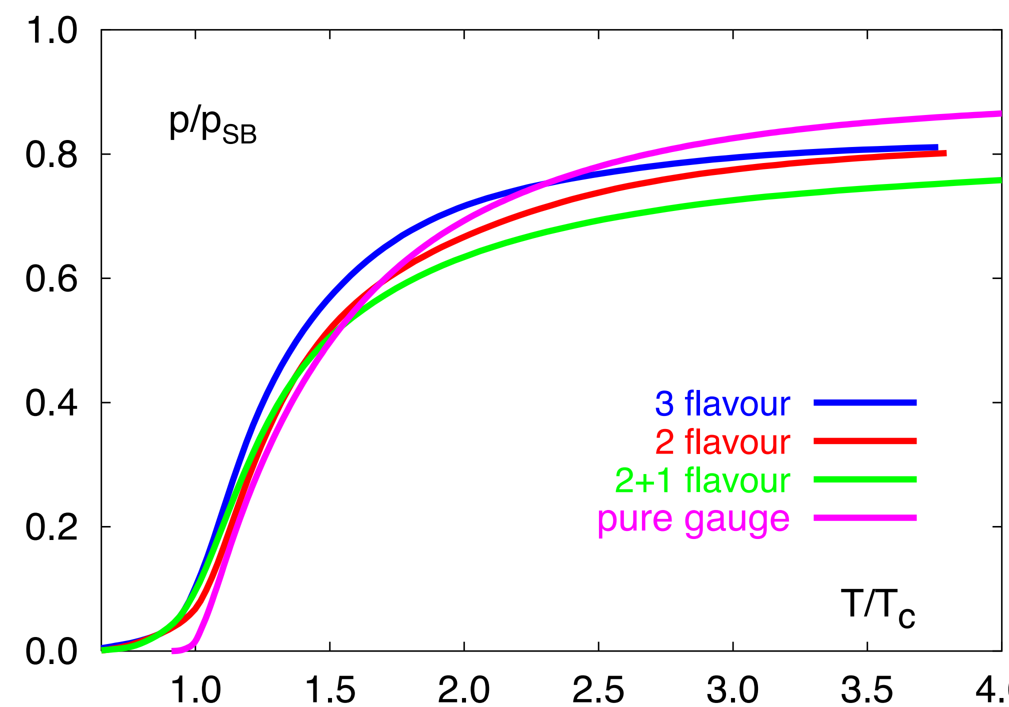

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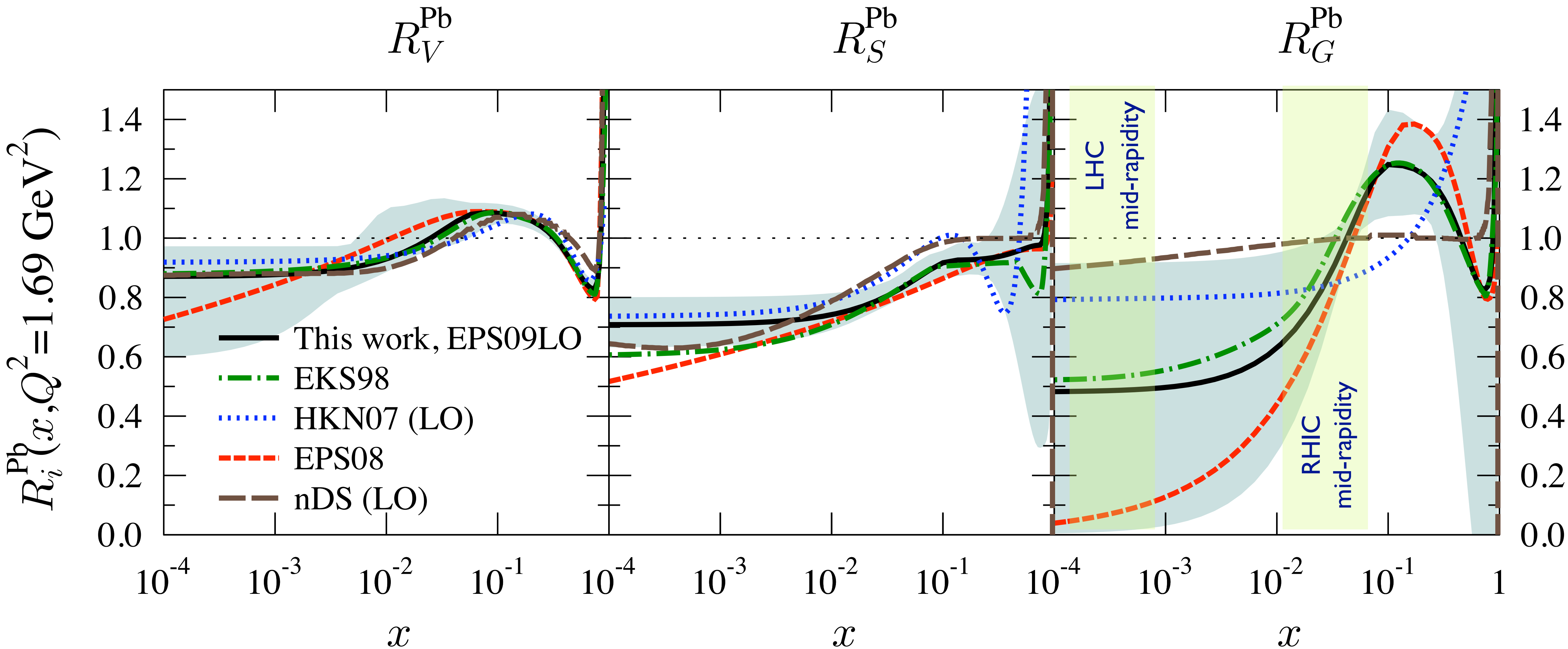
How well are gluons understood in nuclei?



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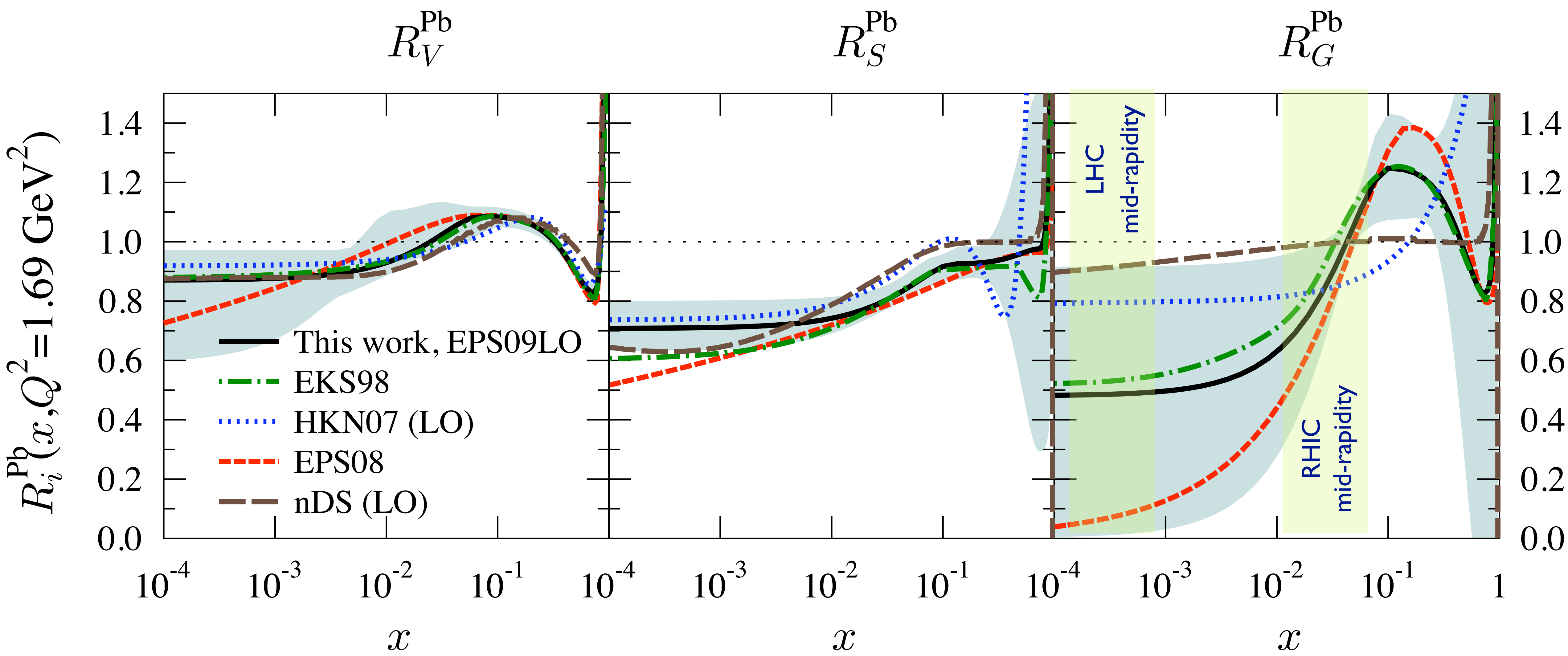

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

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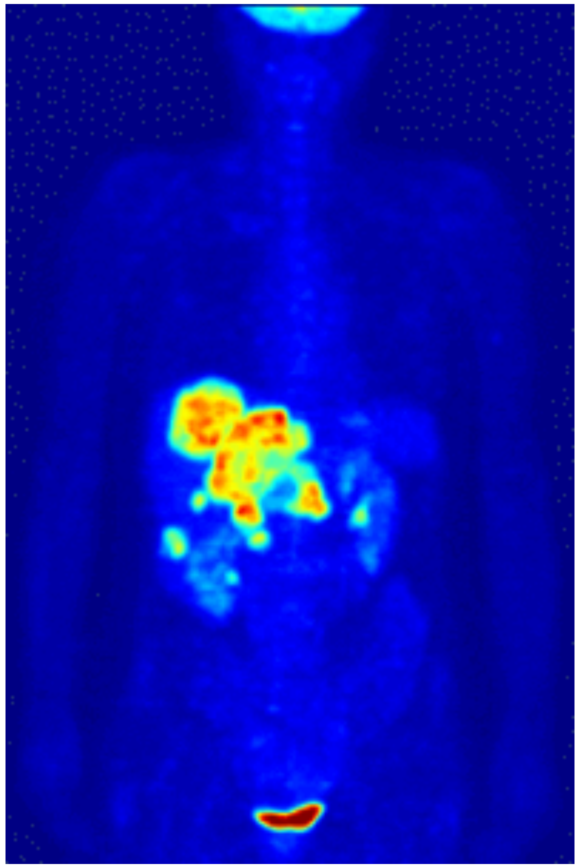
Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)



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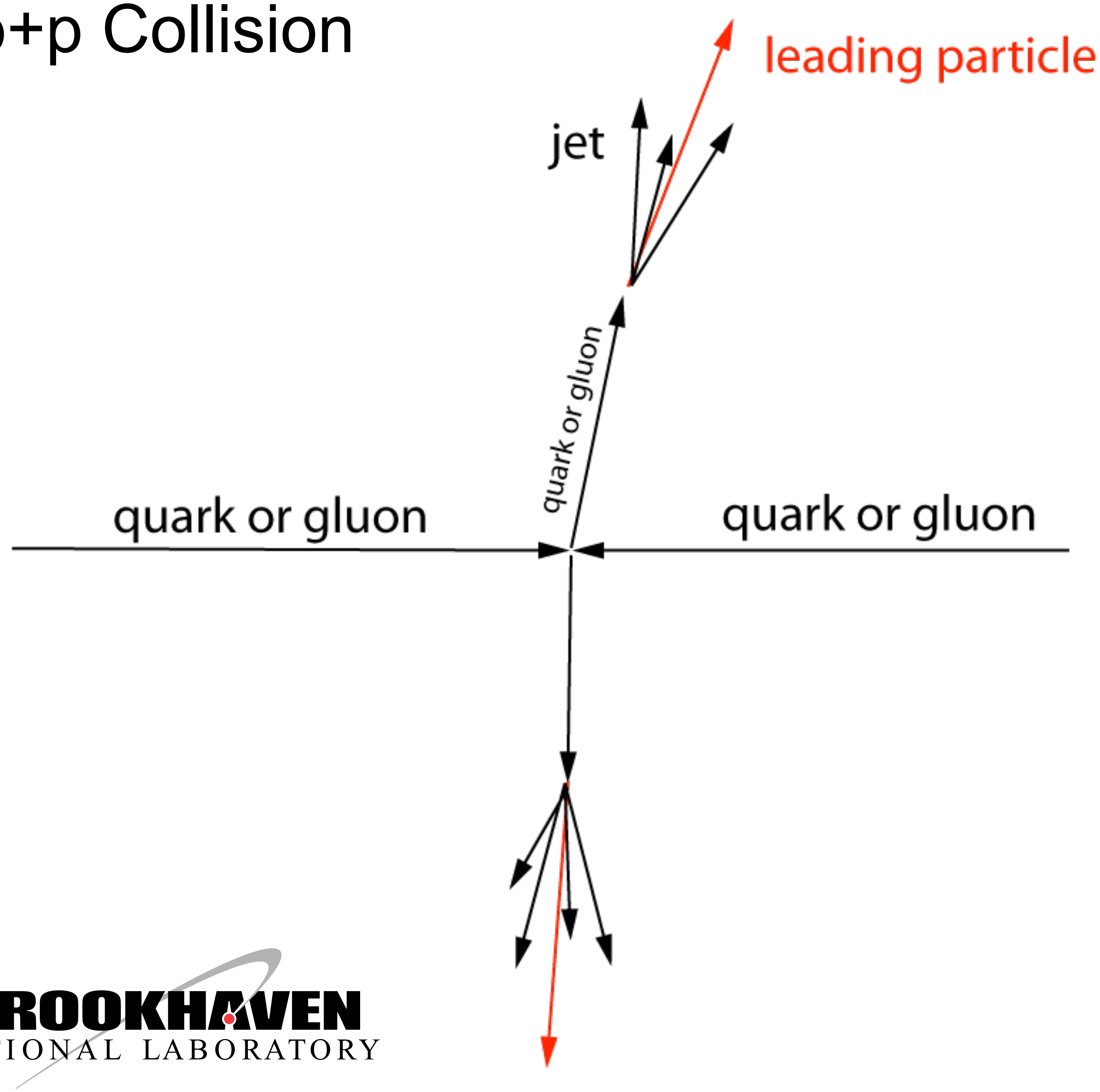
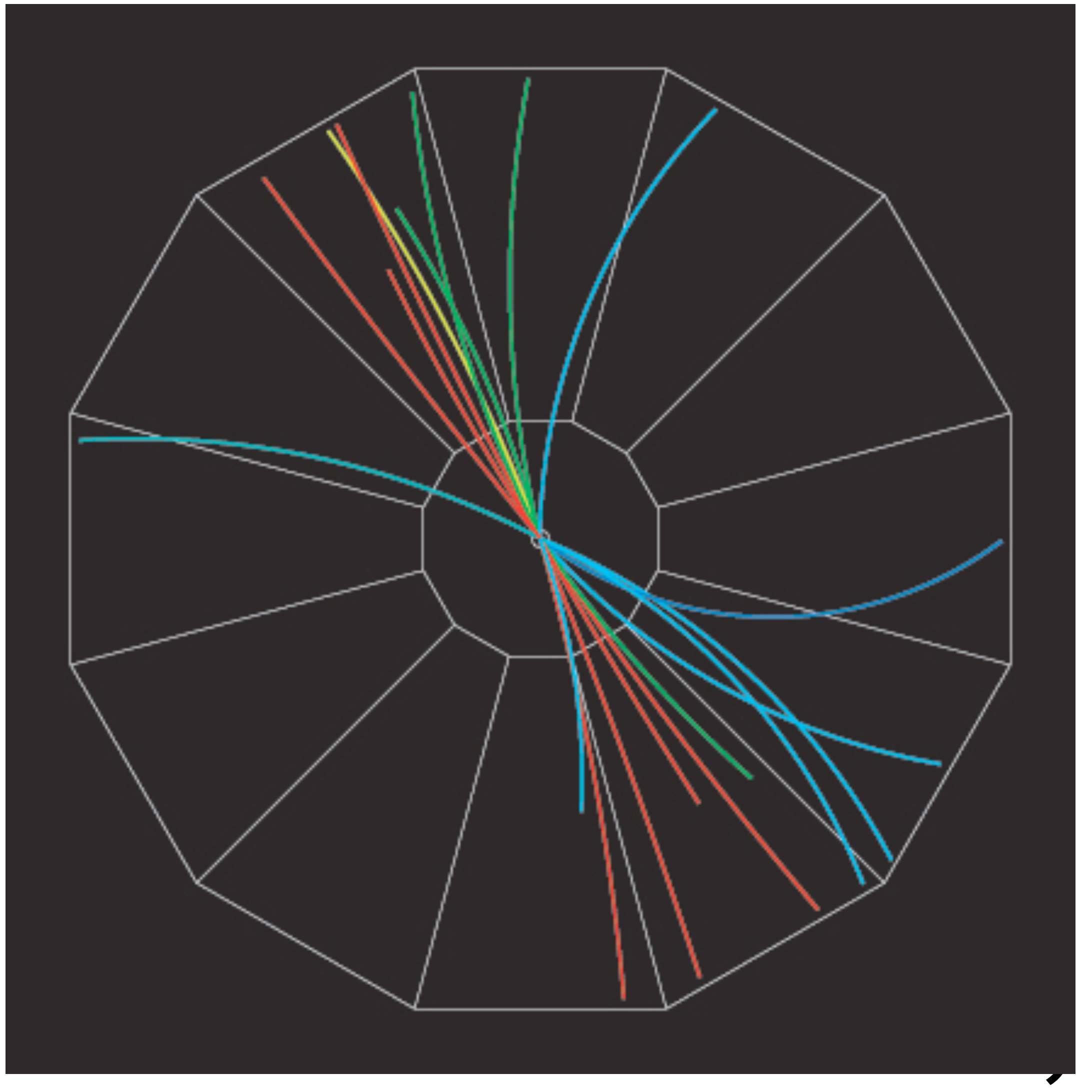
p+p Collision



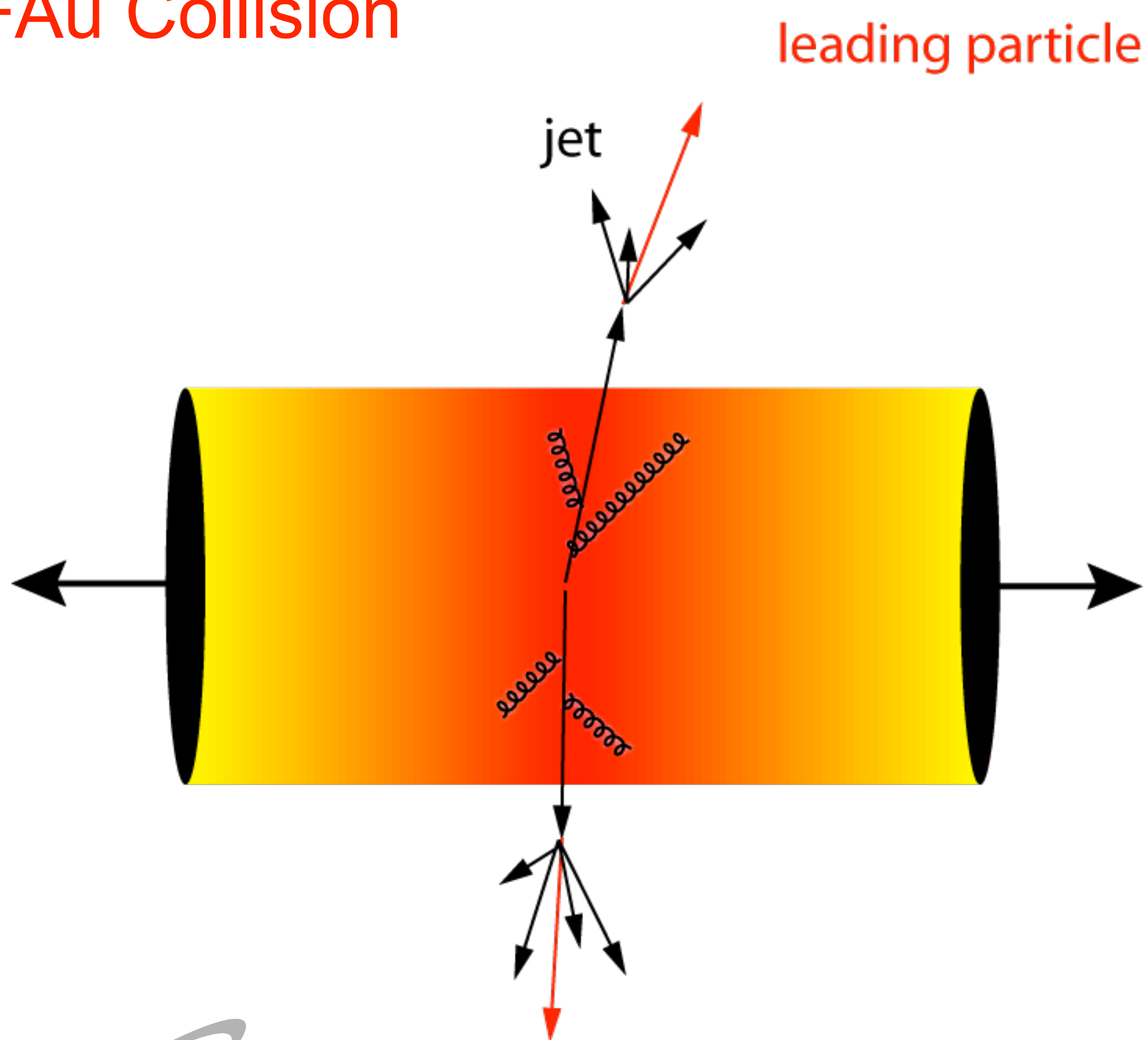


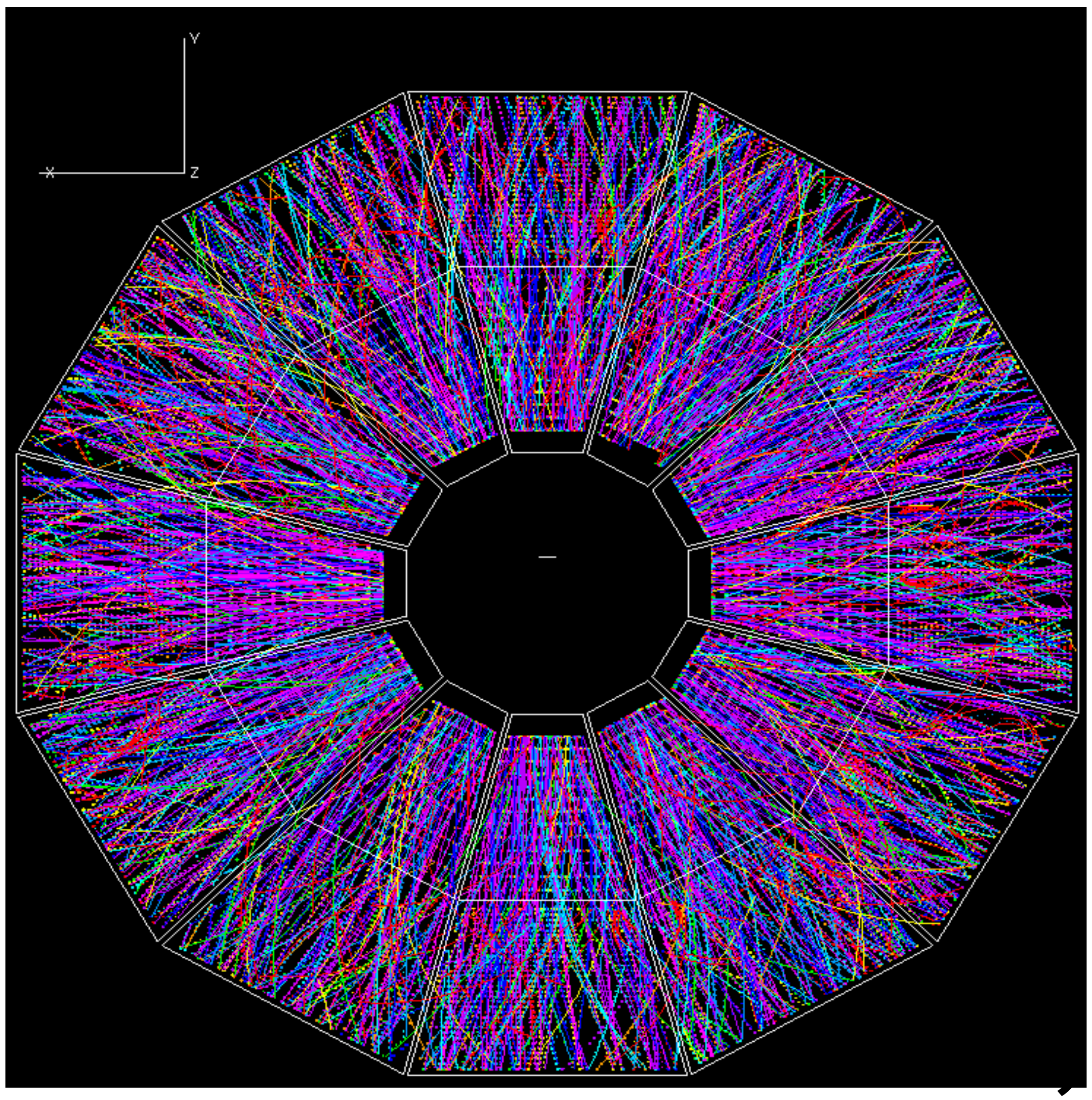
Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)
- Calibrated interaction (beam of known energy and direction)
- Suppression pattern tells about density profile

Au+Au Collision





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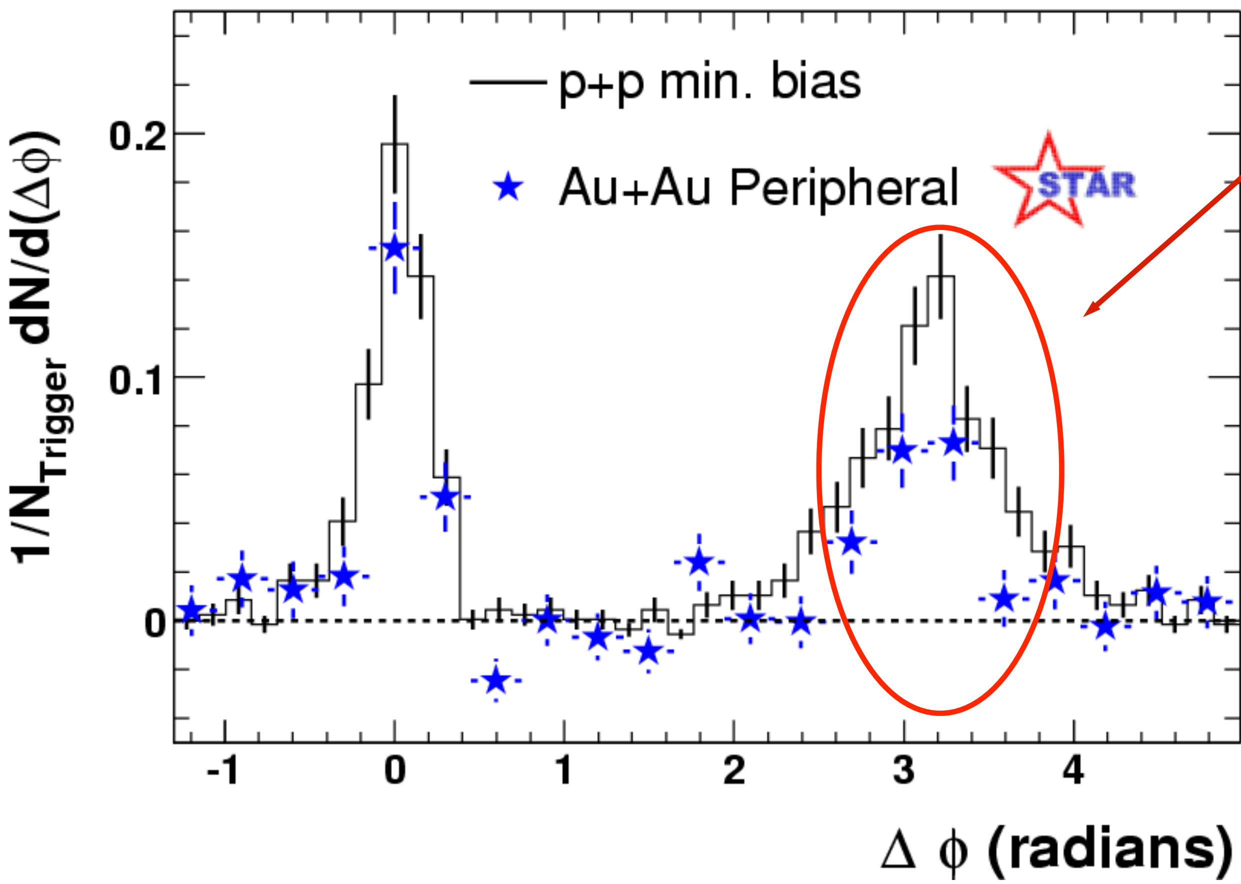
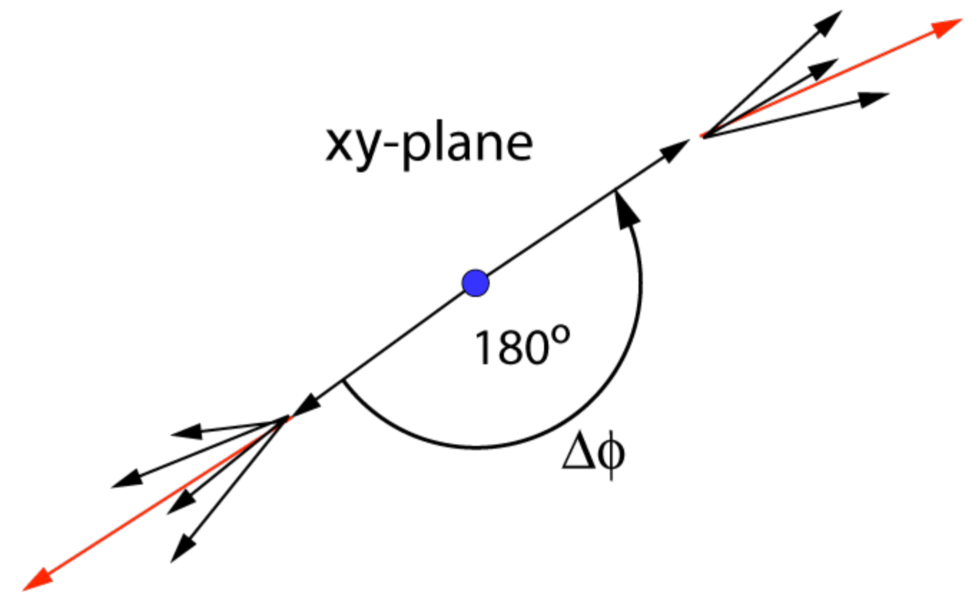
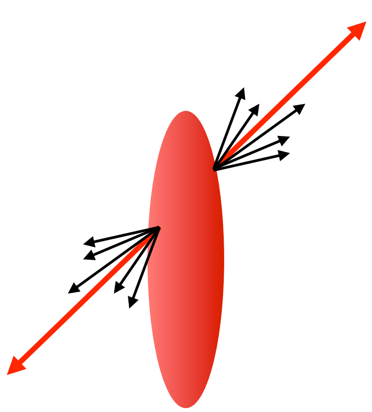
Disappearance of back-to-back jets



Back-to-back high-p_T hadrons are clearly seen in peripheral collisions.



Peripheral



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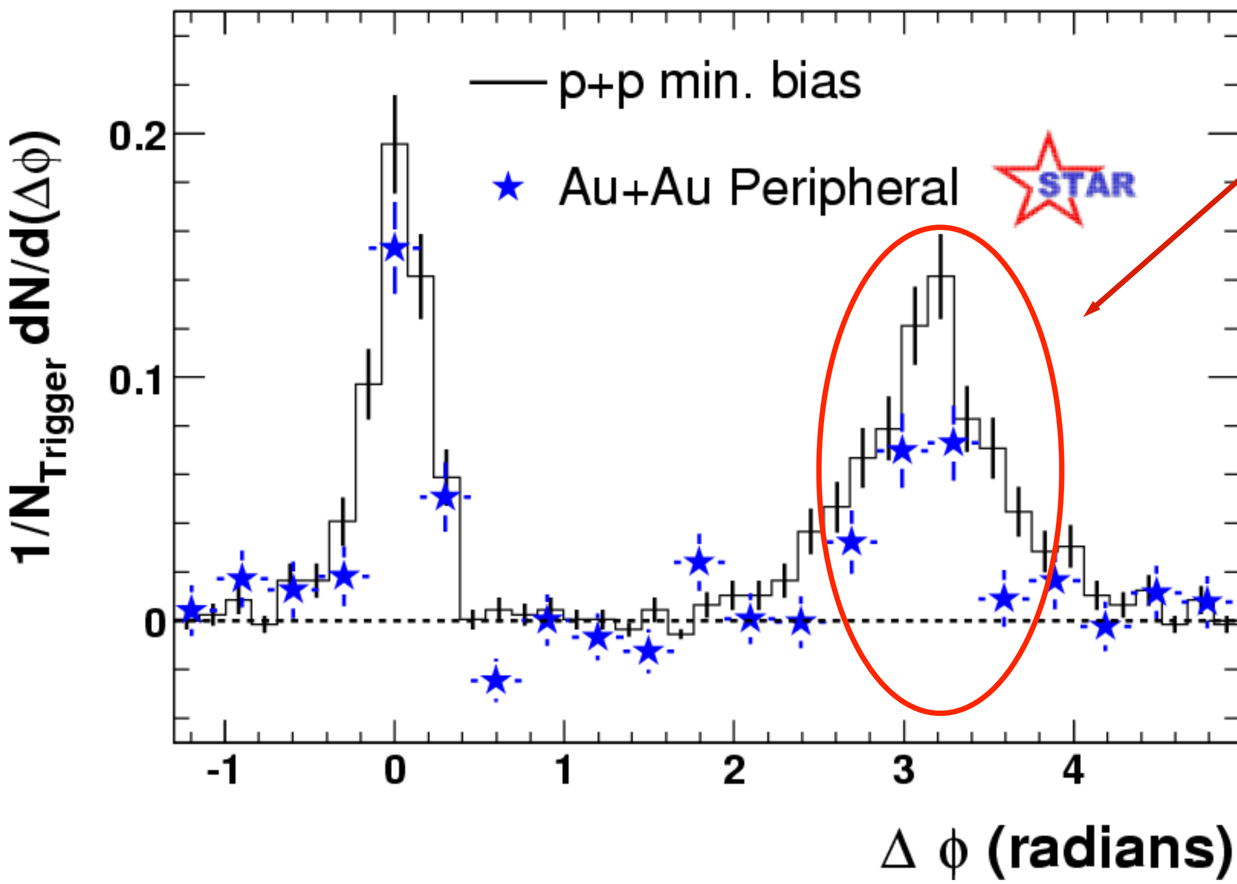
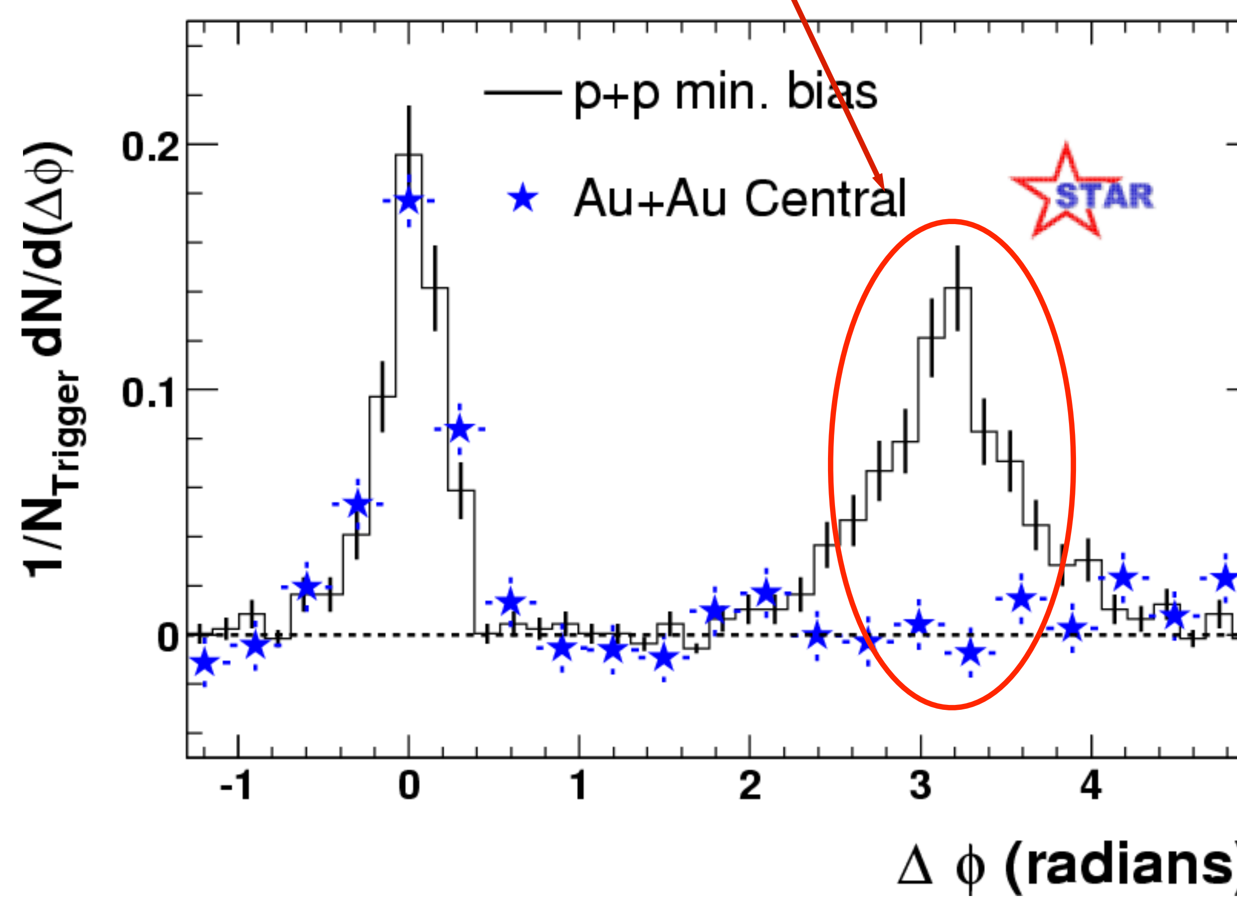
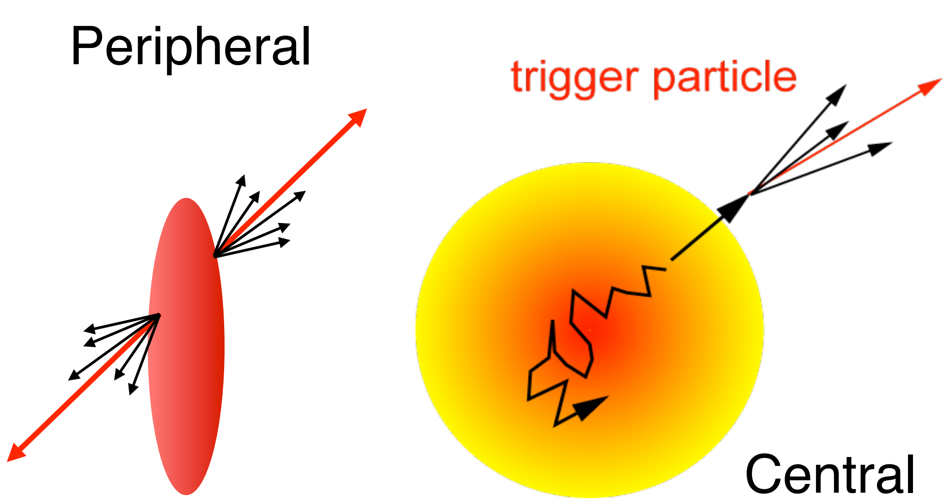
Disappearance of back-to-back jets

Back-to-back high-p_T hadrons are clearly seen in peripheral collisions.

Find an absence of back-to-back hadrons in central collisions







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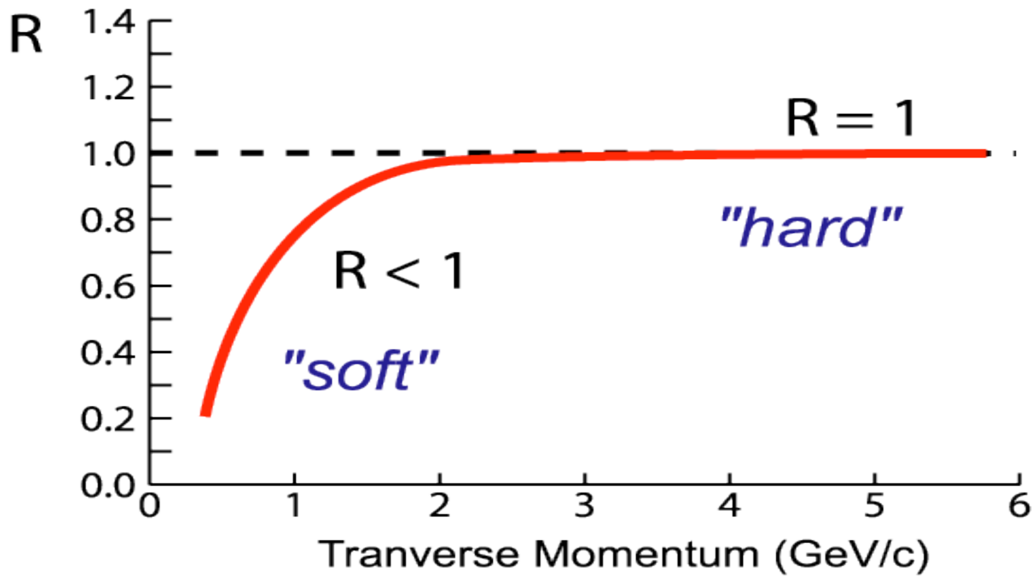
Suppression of inclusive hadron yield at high p_T



$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

N-N cross section

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$

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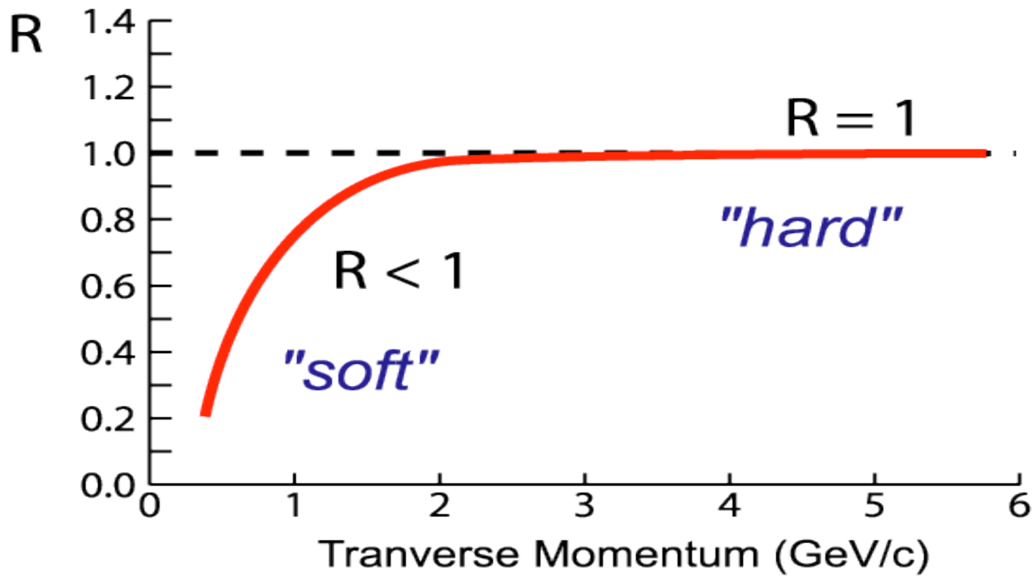

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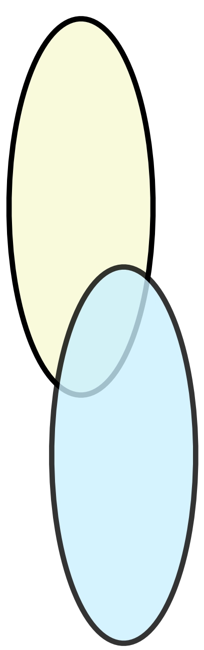
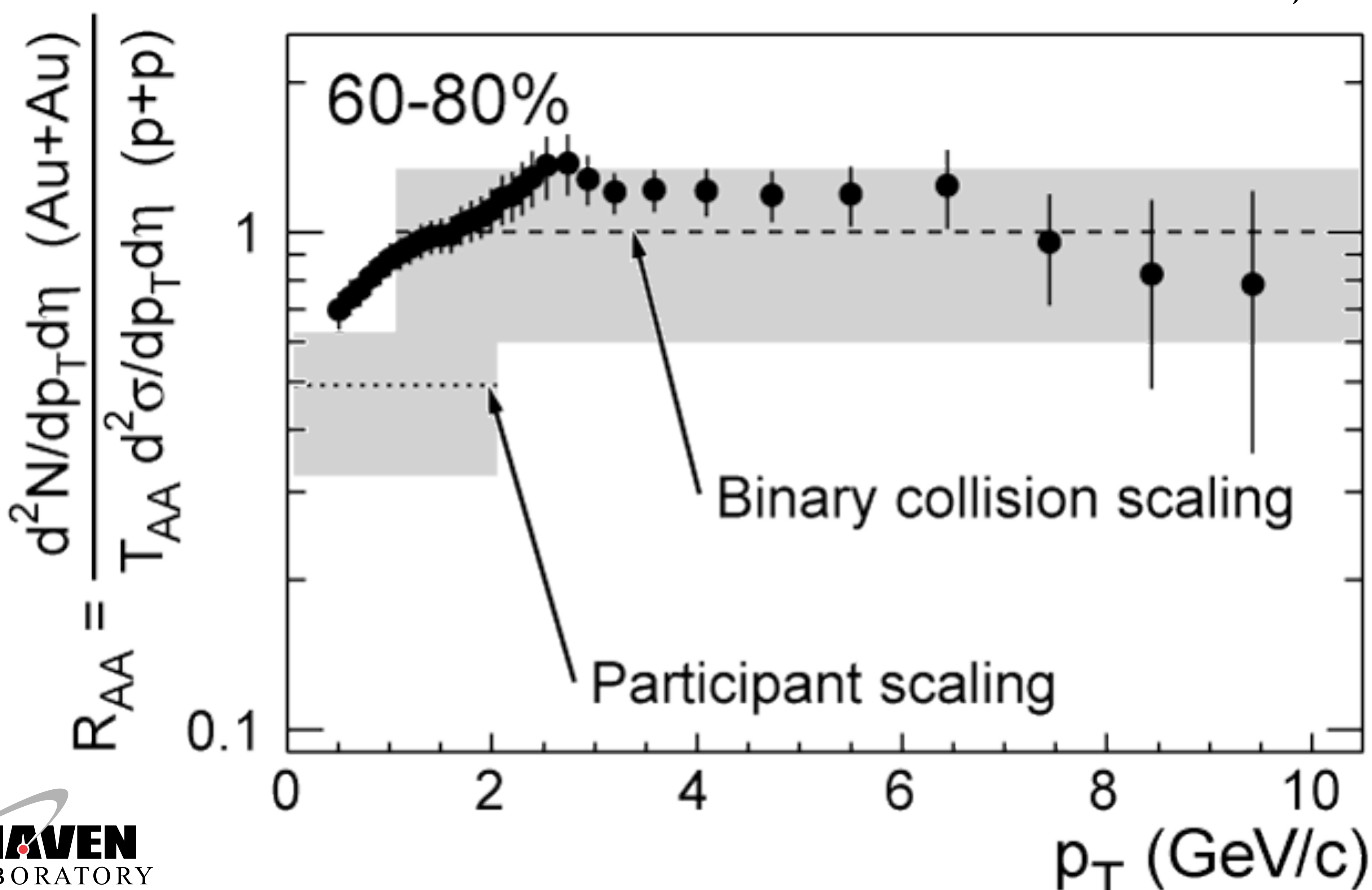
STAR, nucl-ex/0305015





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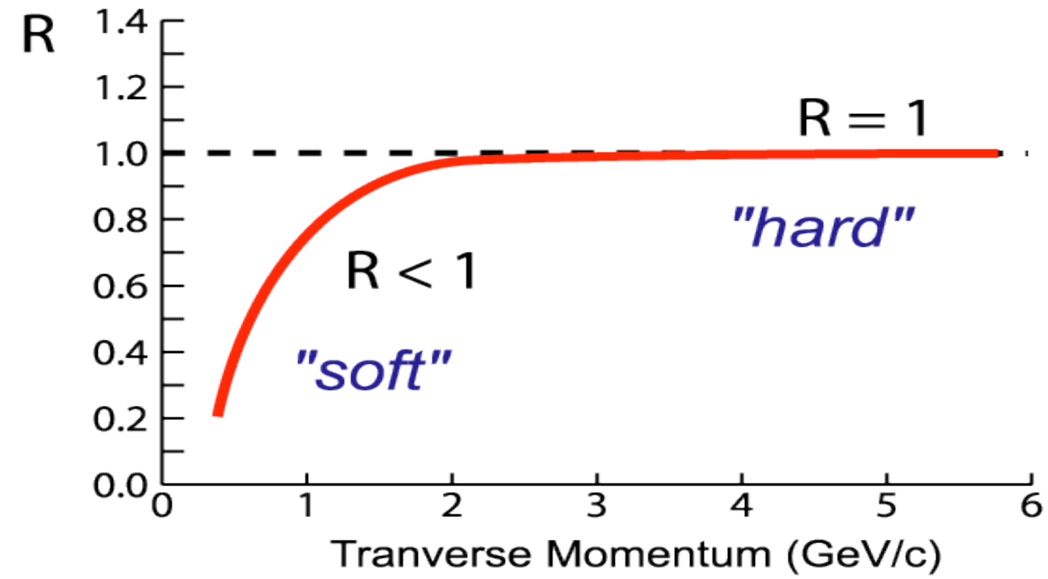

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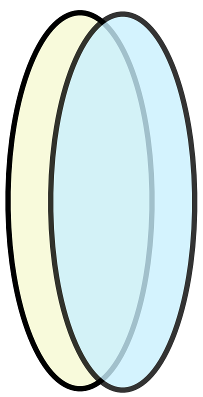

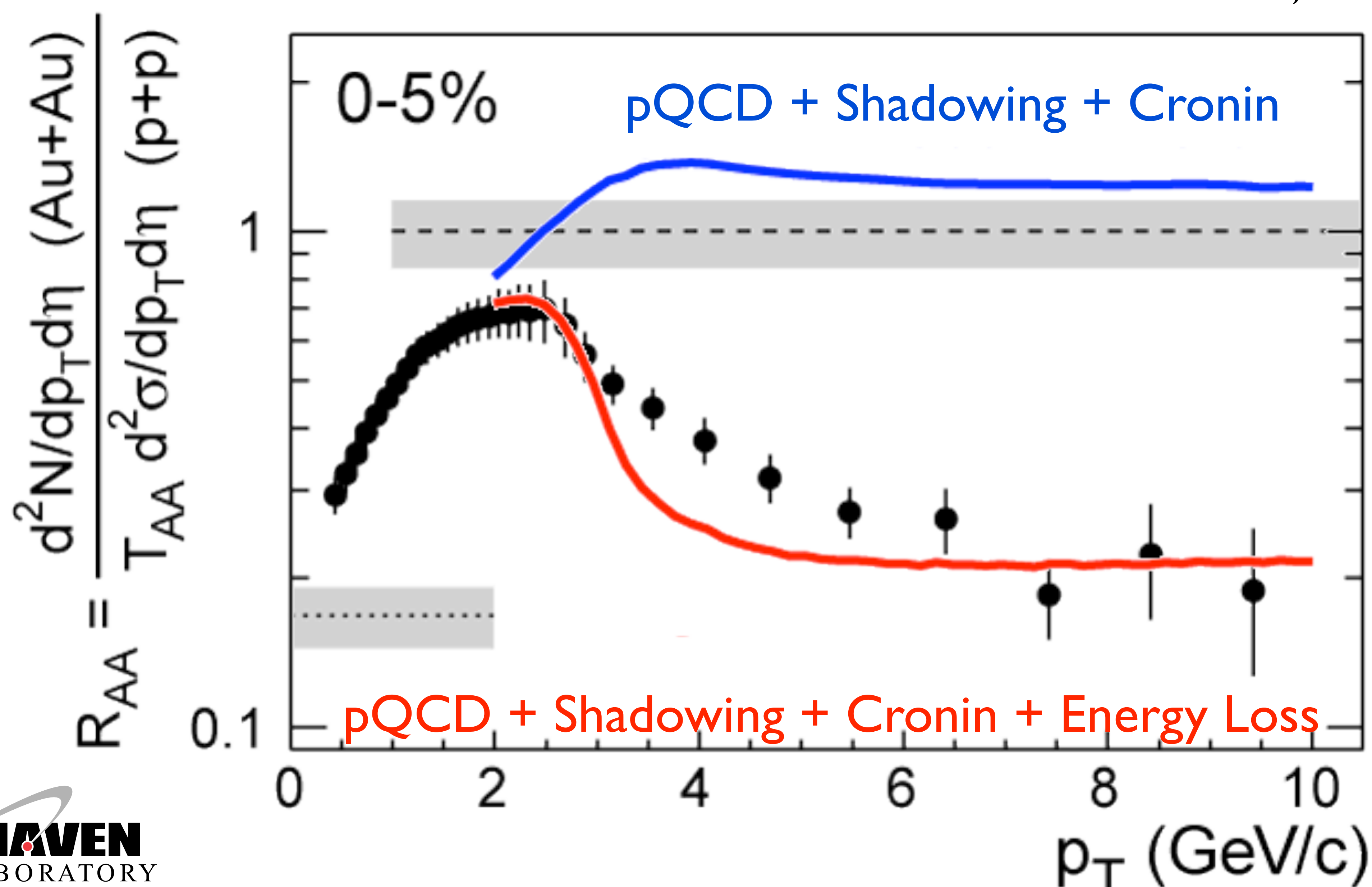

energy loss

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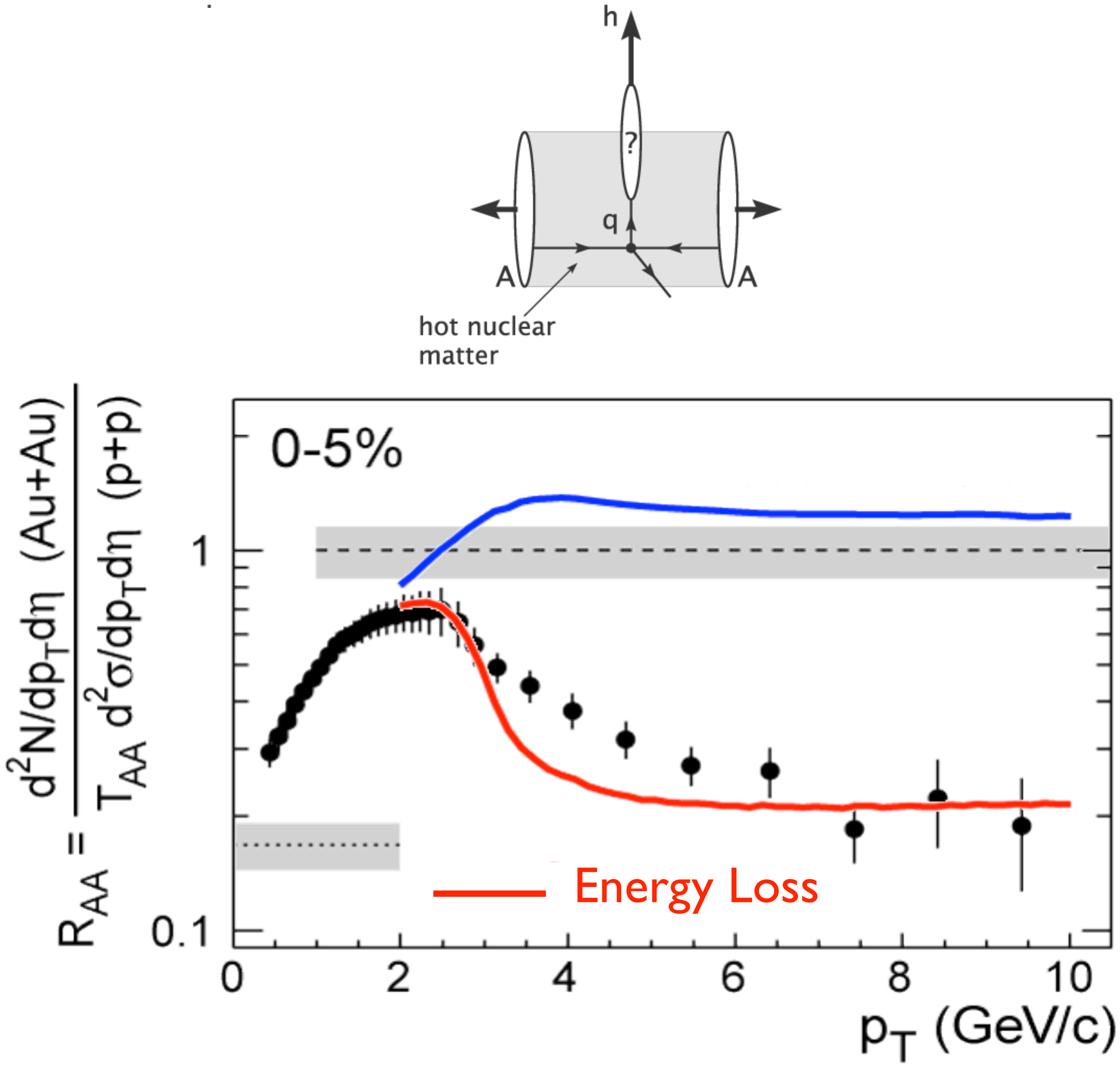
Jet suppression: “hot” vs “cold” nuclear matter



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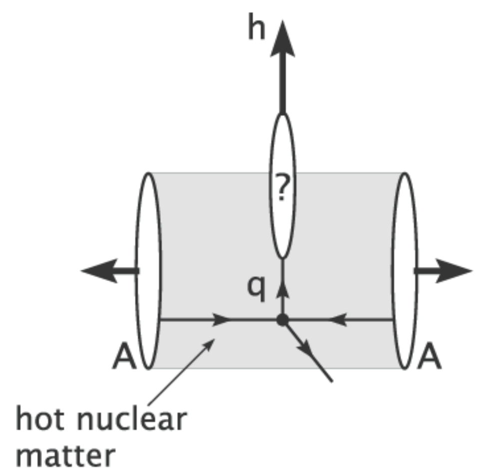
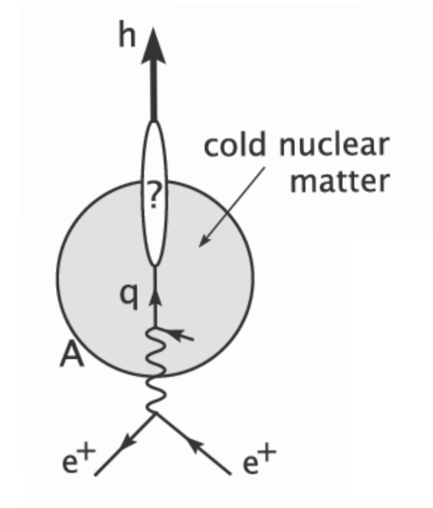
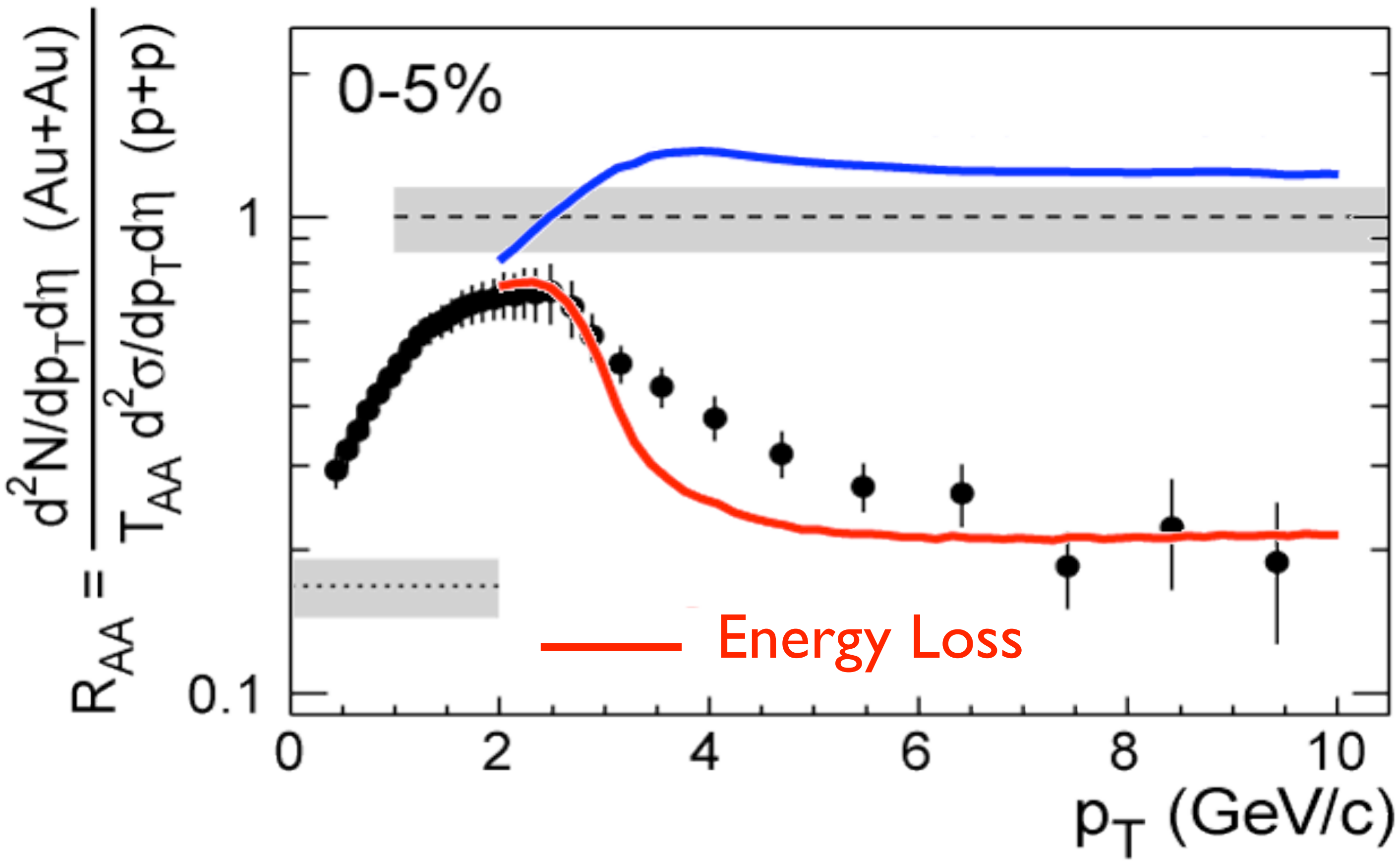
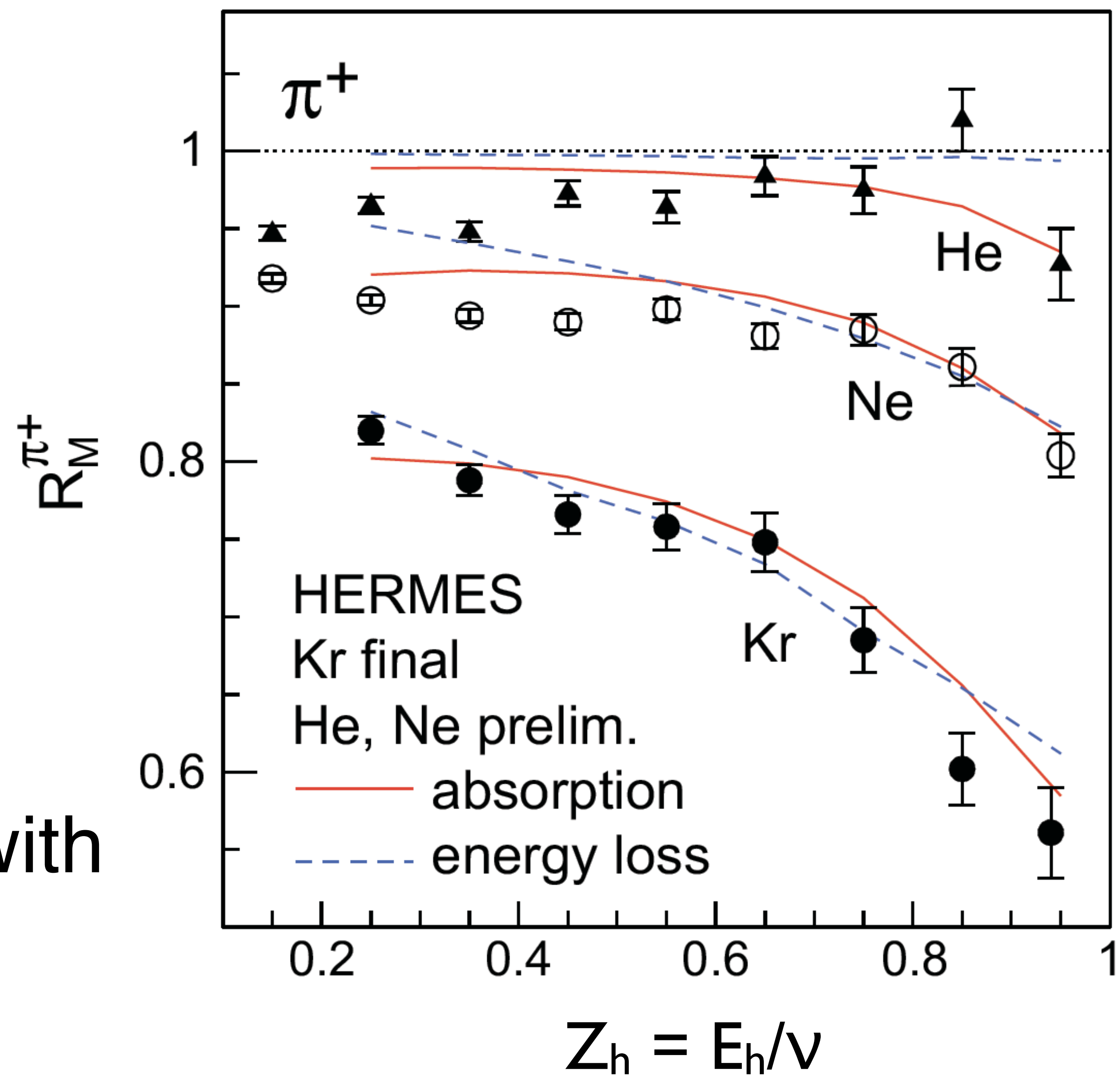
Jet suppression: “hot” vs “cold” nuclear matter









- Energy loss not just associated with jet travelling through hot nuclear matter!!

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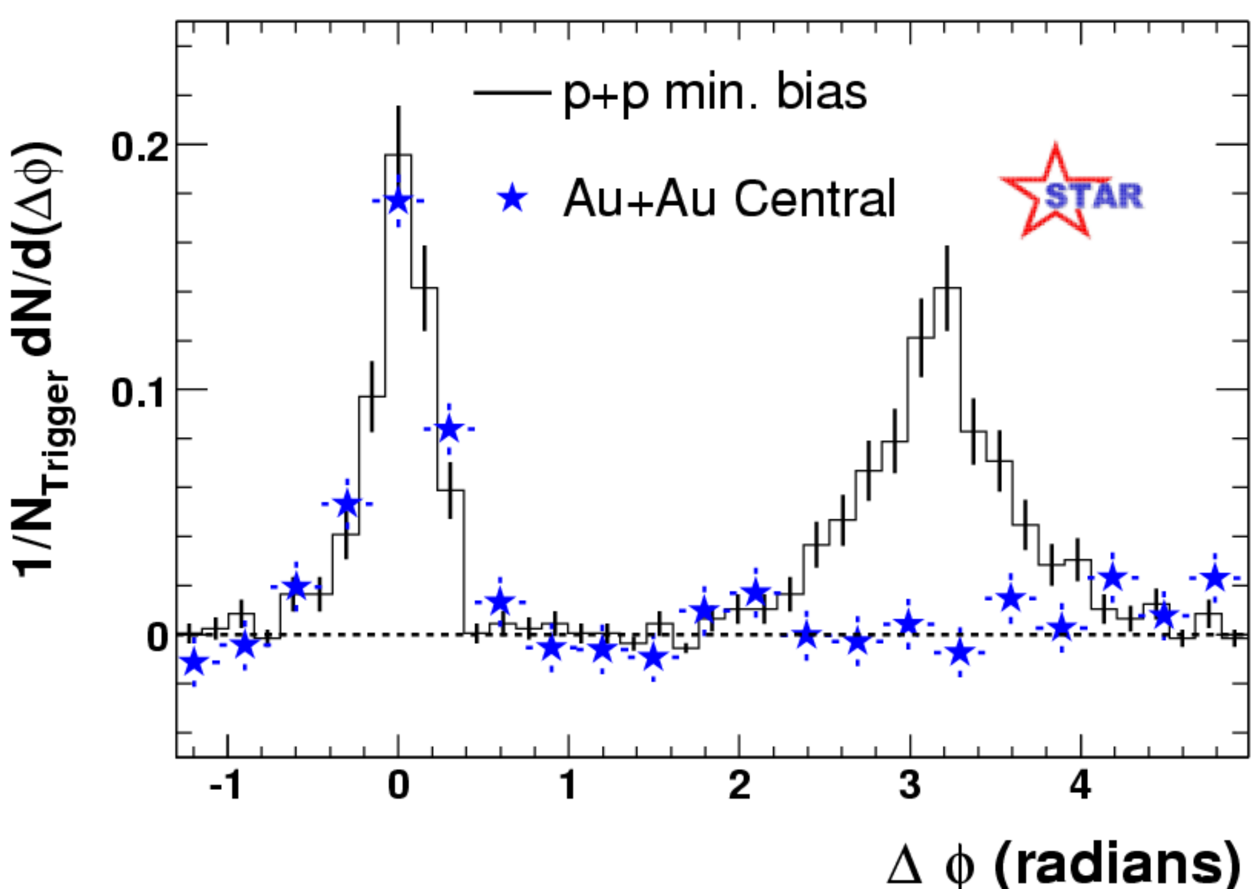
Jet suppression: final or initial state effect?



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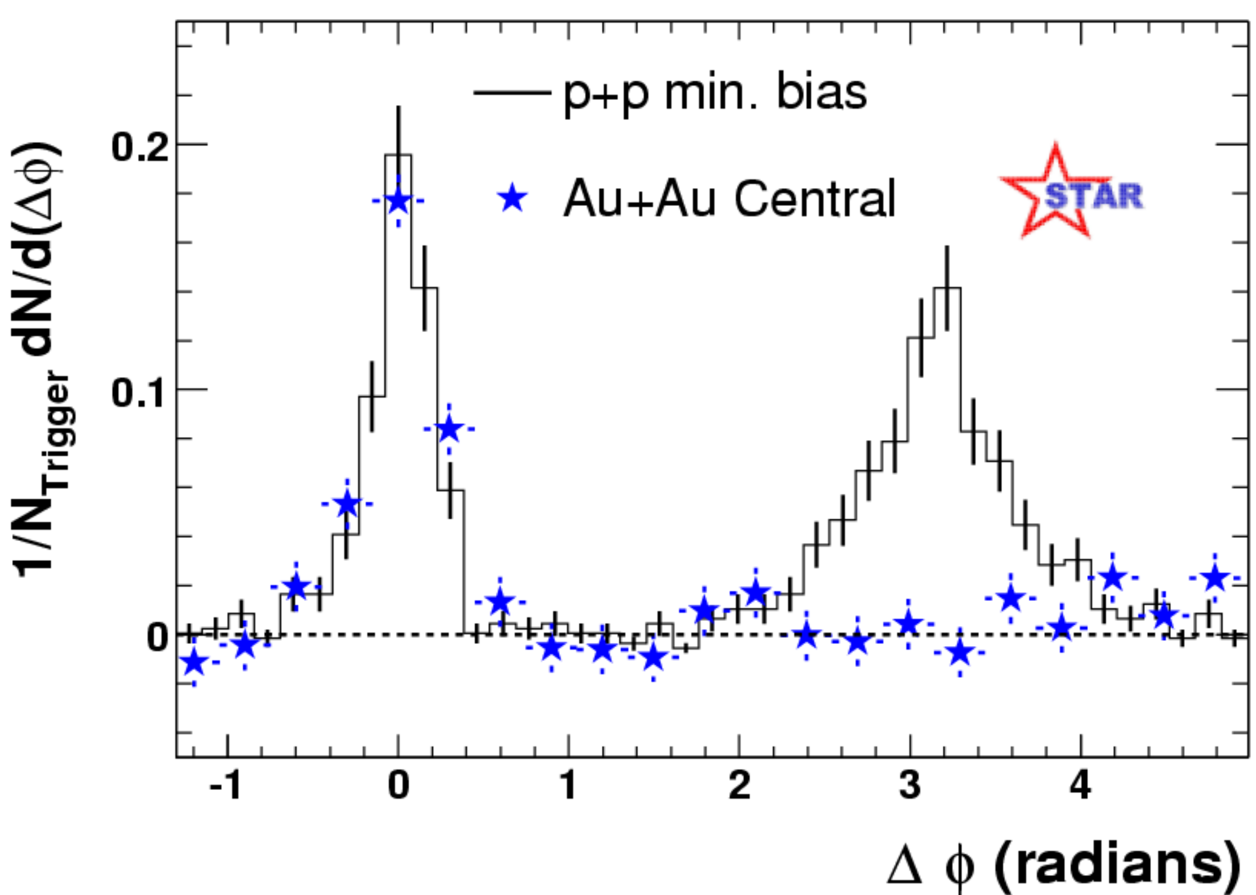
Jet suppression: final or initial state effect?

- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect



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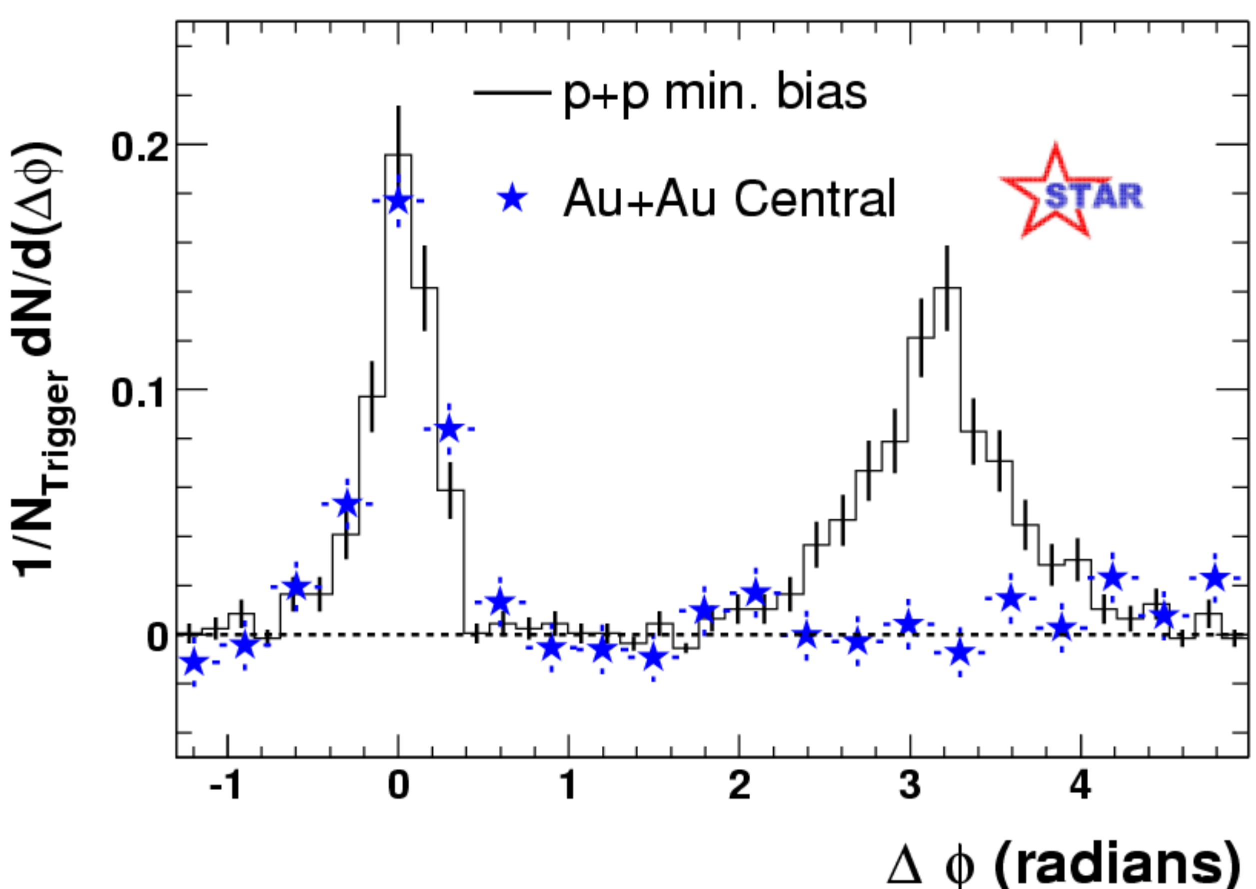
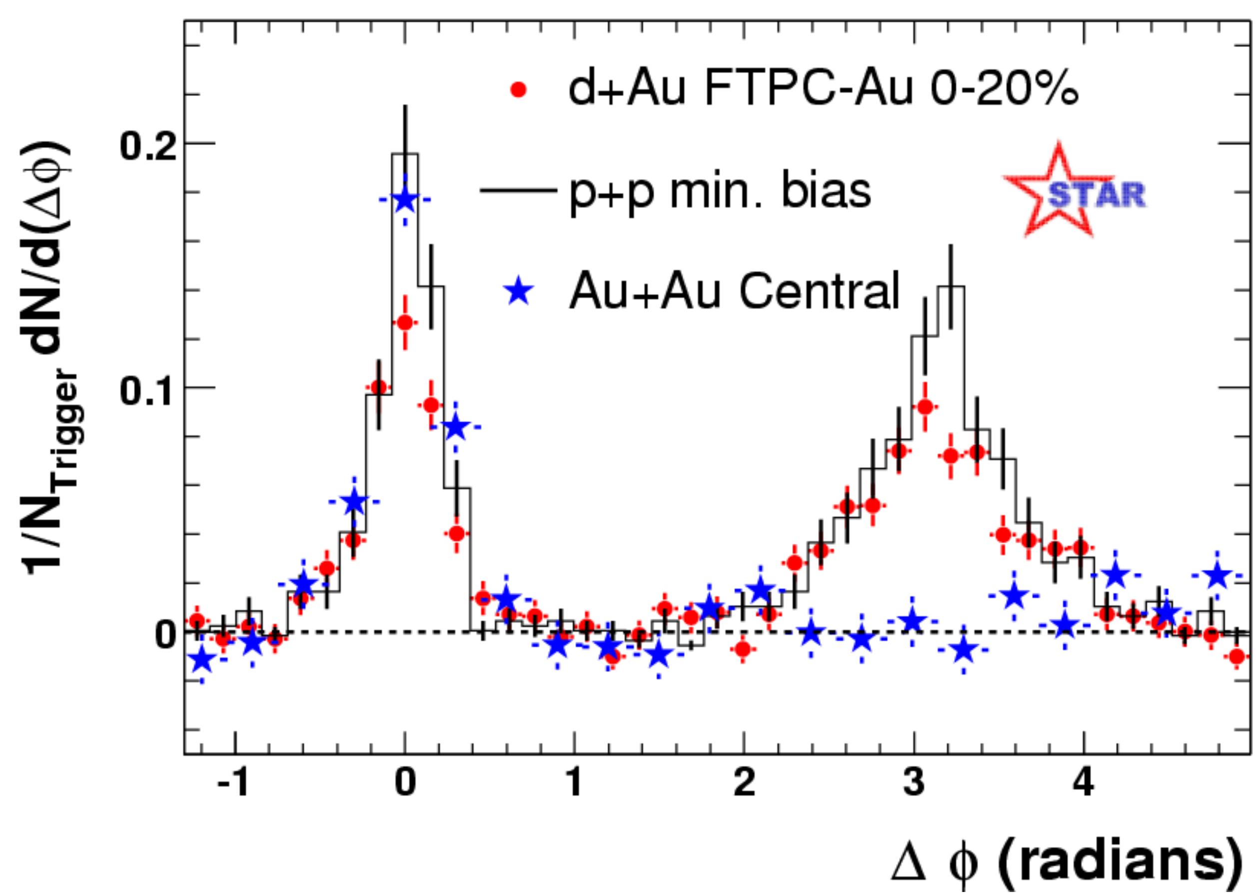
Jet suppression: final or initial state effect?

- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect
- No suppression is observed in d+Au collisions at **mid-rapidity** at RHIC
  - Jet suppression a final state effect?





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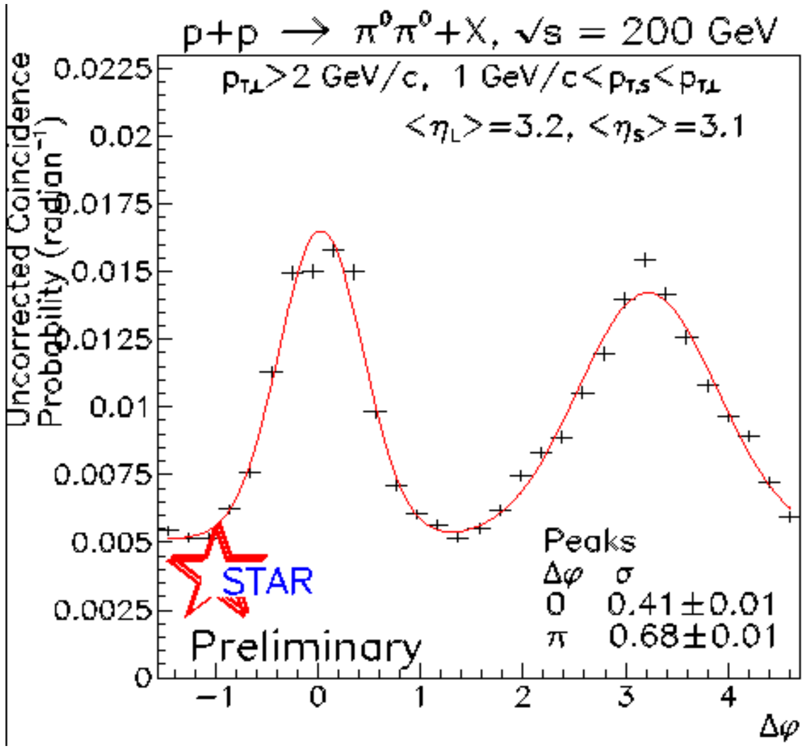
Correlations at forward rapidities

p+p



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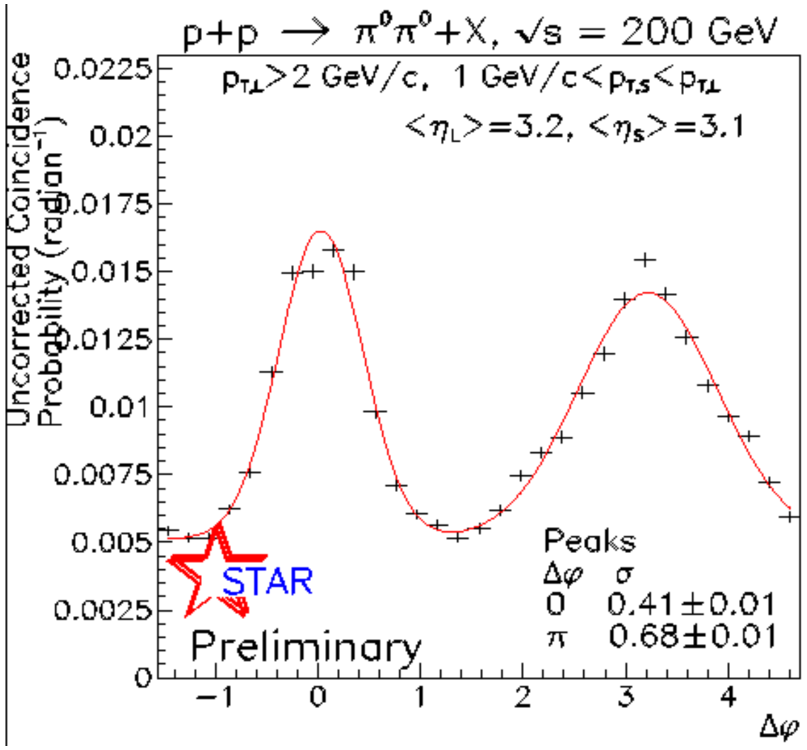
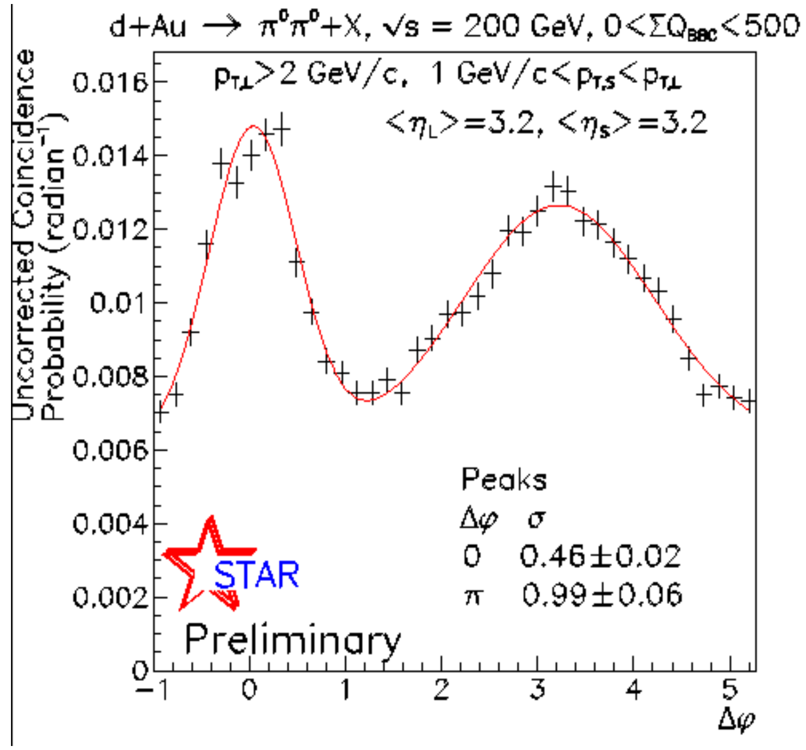
Correlations at forward rapidities

p+p



d+Au peripheral



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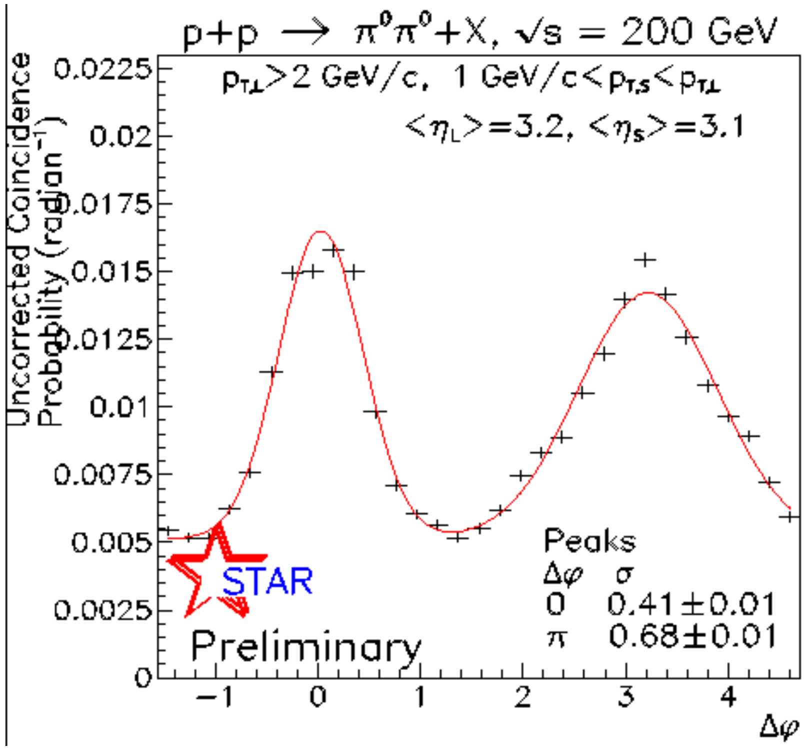
Correlations at forward rapidities

p+p



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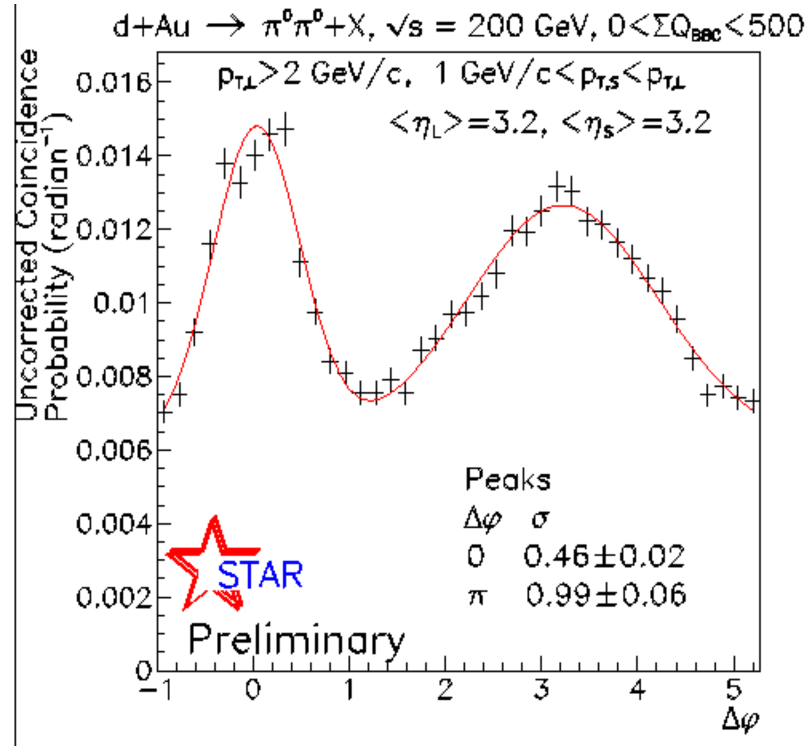
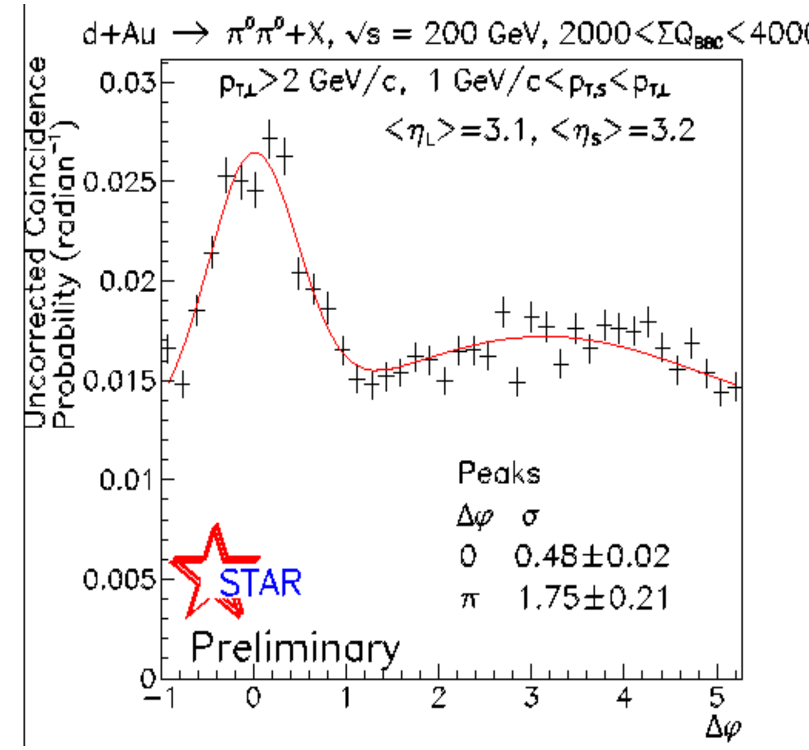


d+Au central



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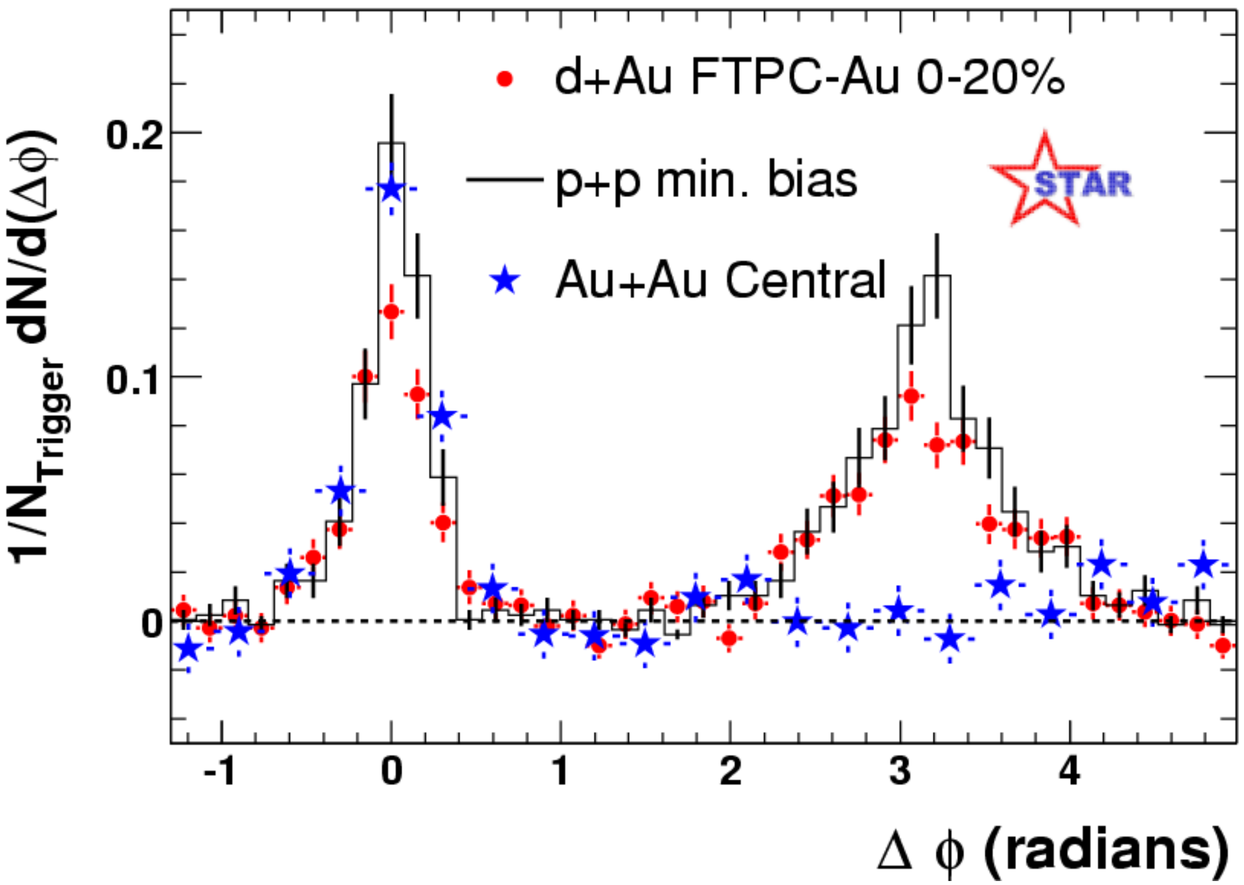
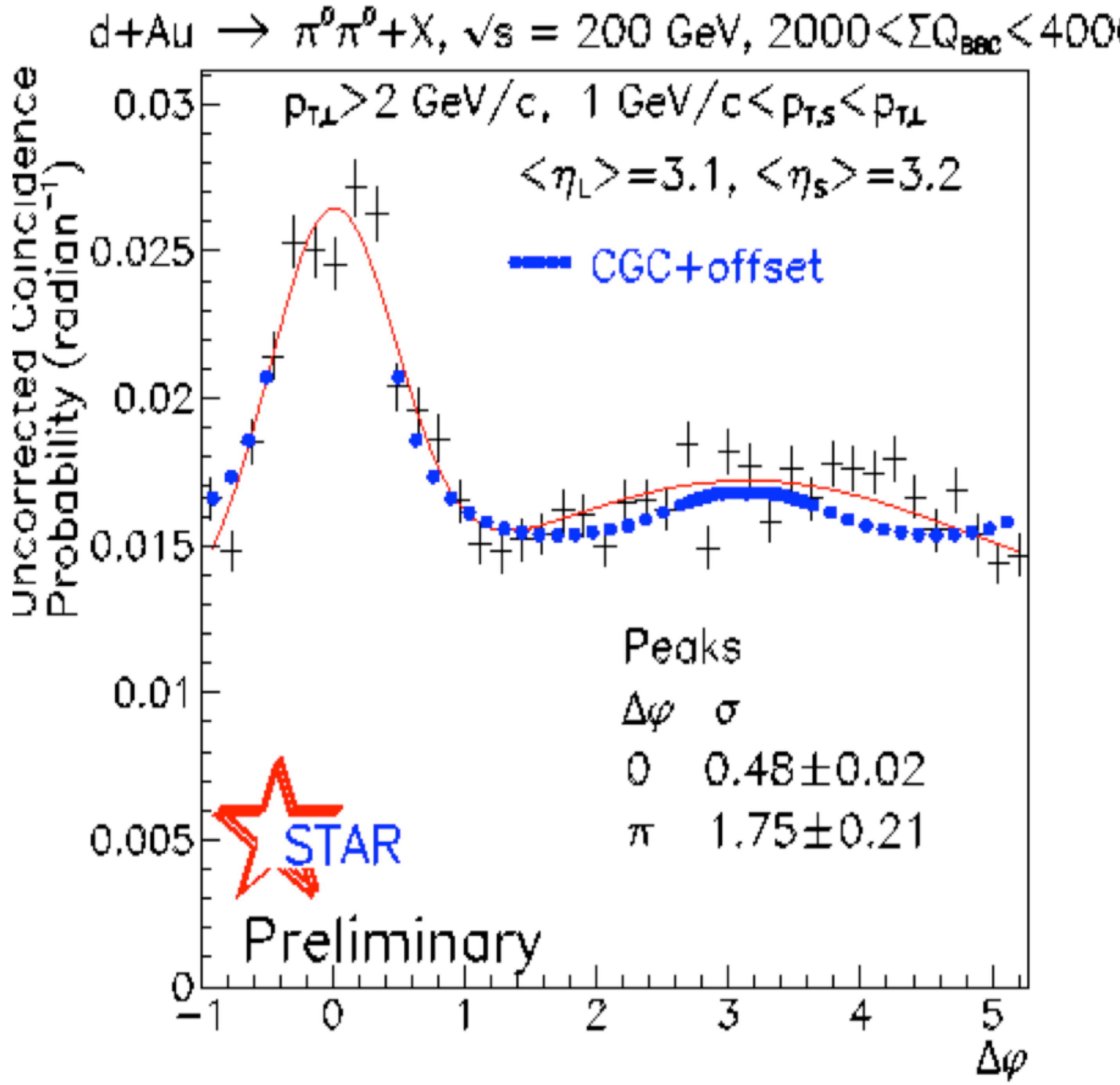
Correlations at forward rapidities

mid-rapidity



d+Au central



Model: Nucl.Phys.A796:41-60,2007

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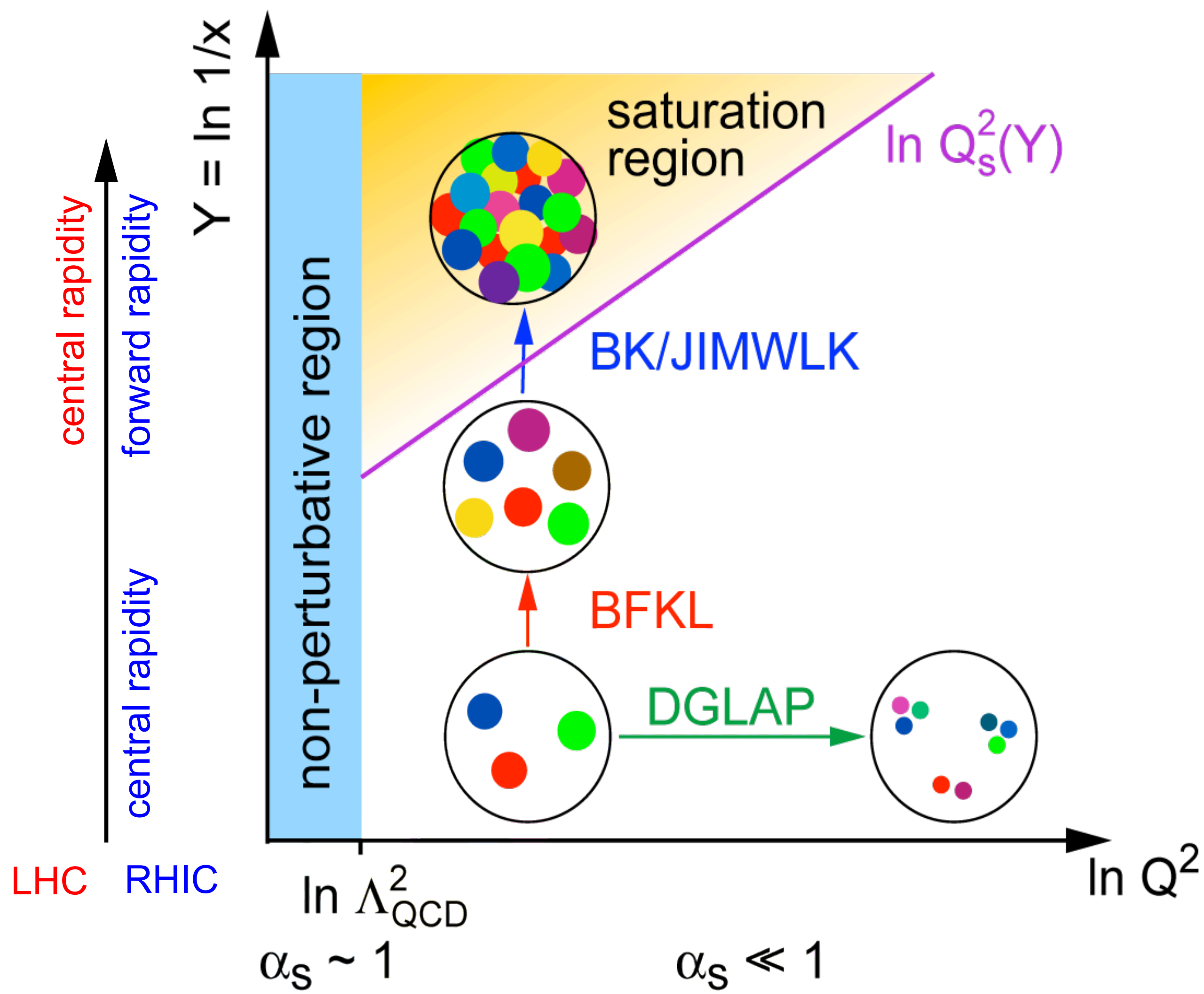
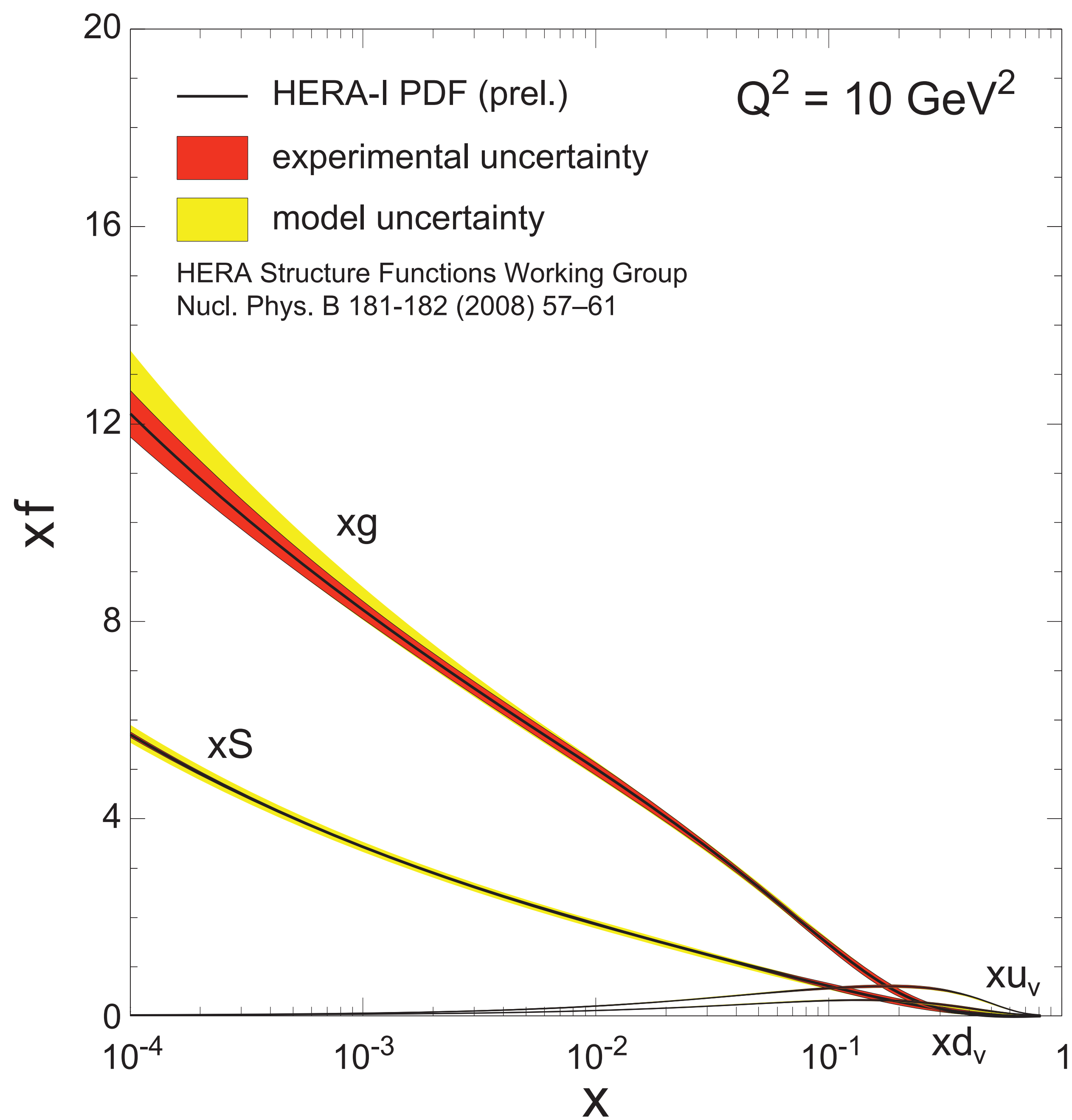
What's different between mid- and forward rapidity?



$$x = \frac{2p_T}{\sqrt{(s)}} e^{-\eta}$$



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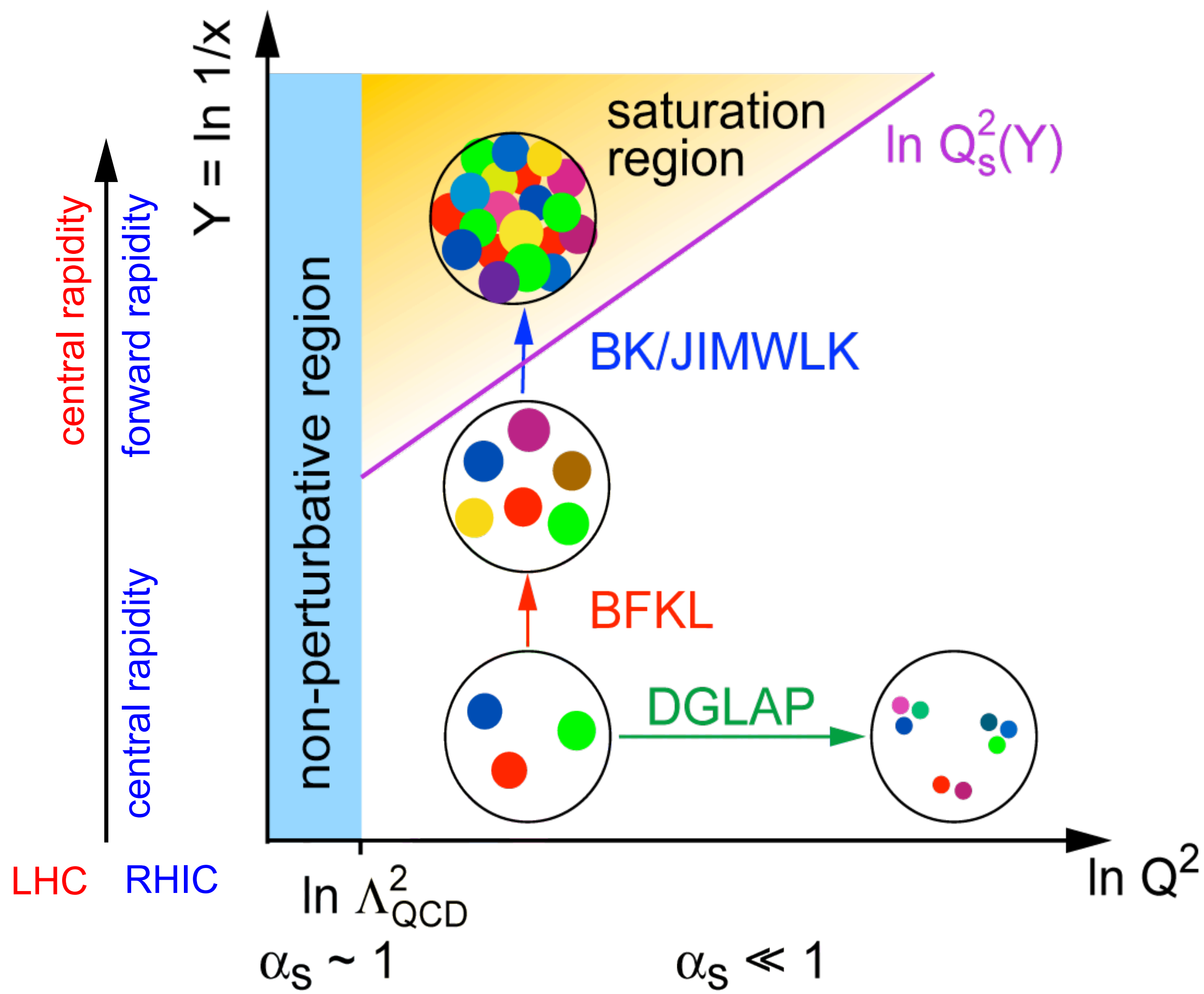

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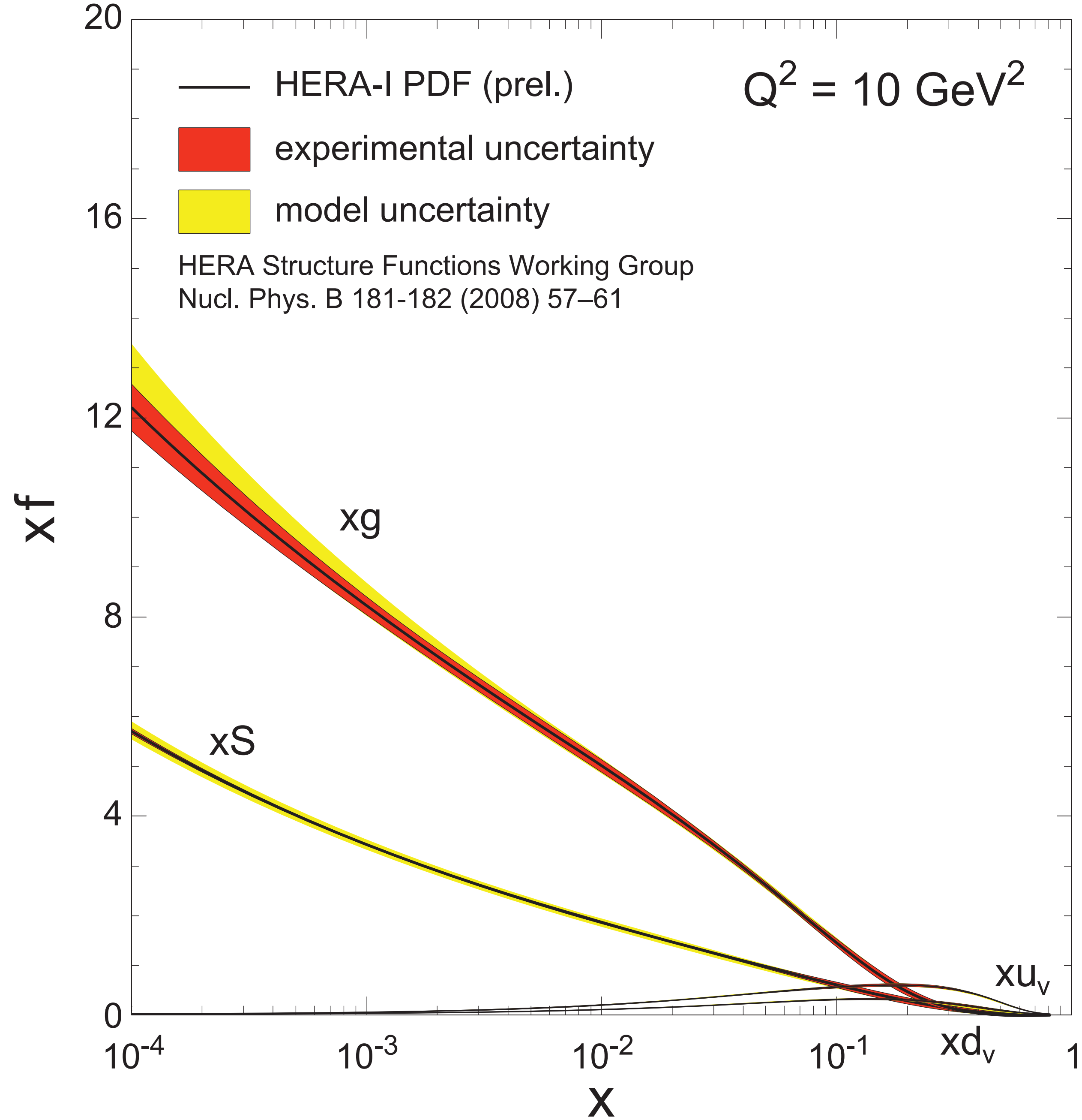

$\eta = 0.0 \Rightarrow x = 2\text{x}10^{-2}$: $\eta = 3.1 \Rightarrow x = 9\text{x}10^{-4}$

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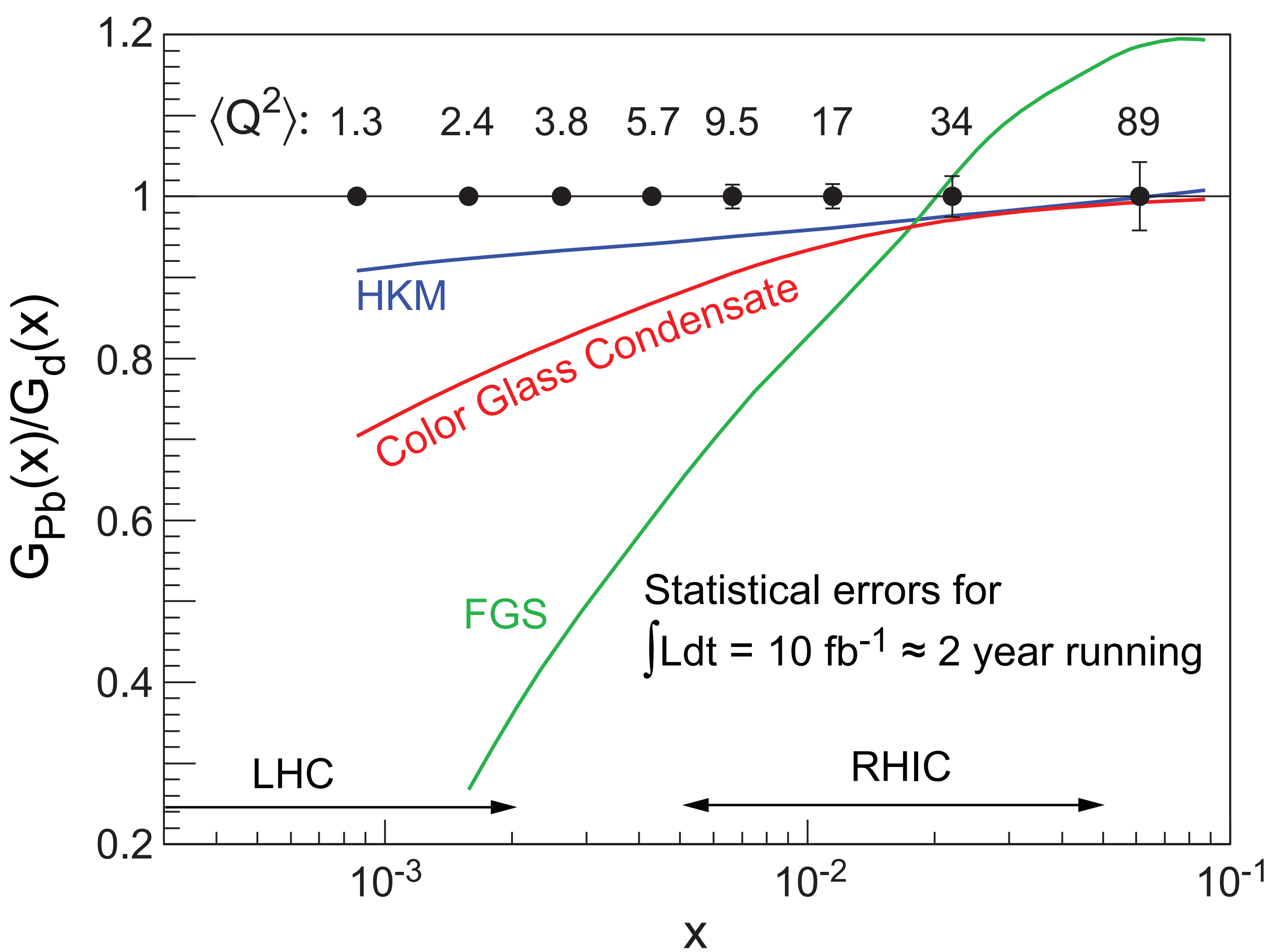
Example of Key Measurements: F_L

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



HKM and FGS are "standard" shadowing parameterizations that are evolved with DGLAP

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

requires $\sqrt{s}$ scan, $Q^2/xs = y$

Here:

$\int L dt$ = 4/A fb^{-1} (10+100) GeV

= 4/A fb^{-1} (10+50) GeV

= 2/A fb^{-1} (5+50) GeV

statistical error only

Syst. studies of $F_L(A,x,Q^2)$:

- $xG(x,Q^2)$ with great precision
- Distinguish between models

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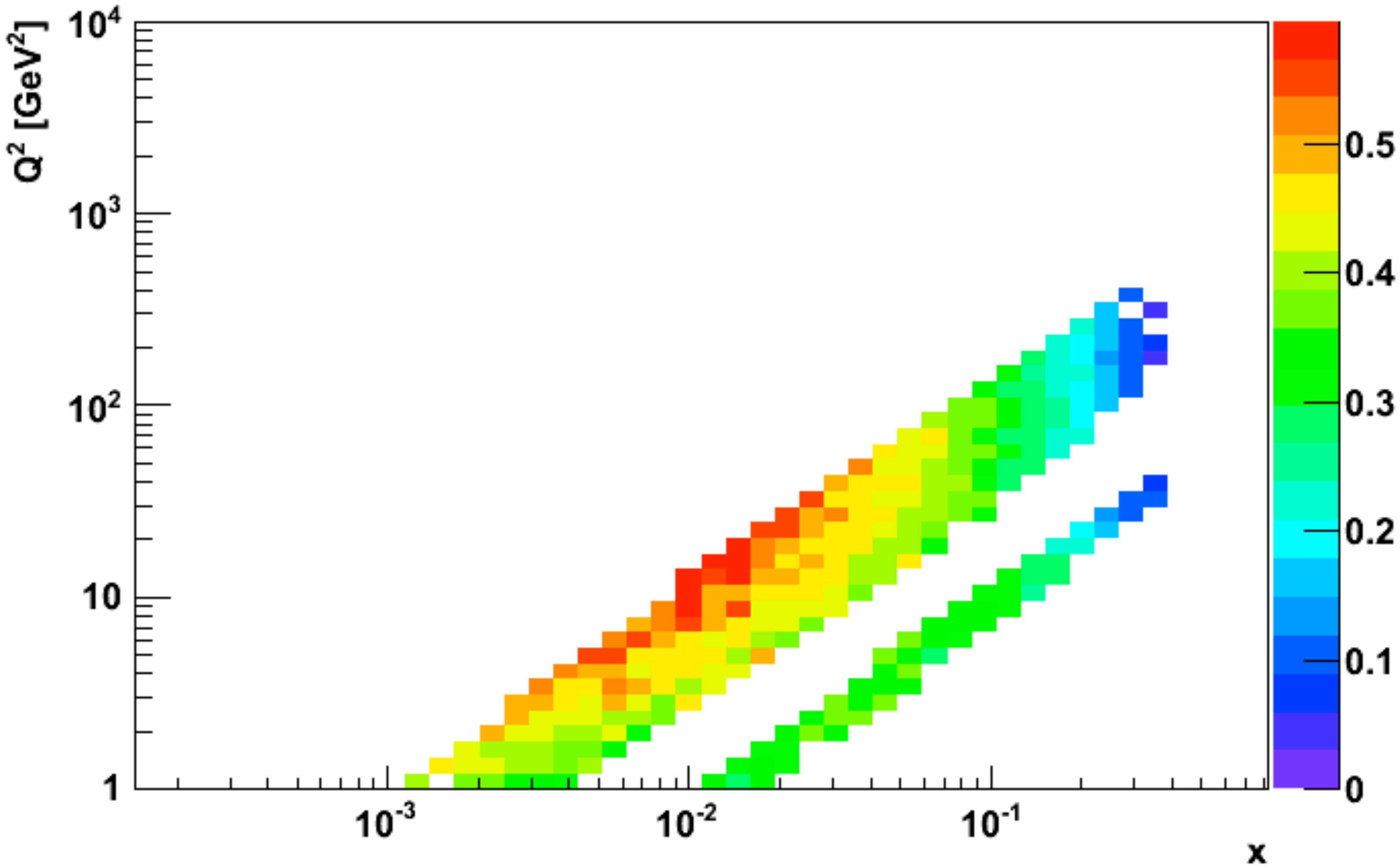
Further F_L studies for MeRHIC (4 GeV e^-)

- Fixed electron energy (4 GeV); proton energies: 10, 40, 50, 70, 100, 250 GeV
  - Luminosity: 4 fb^{-1} for each energy



Further F_L studies for MeRHIC (4 GeV e^-)

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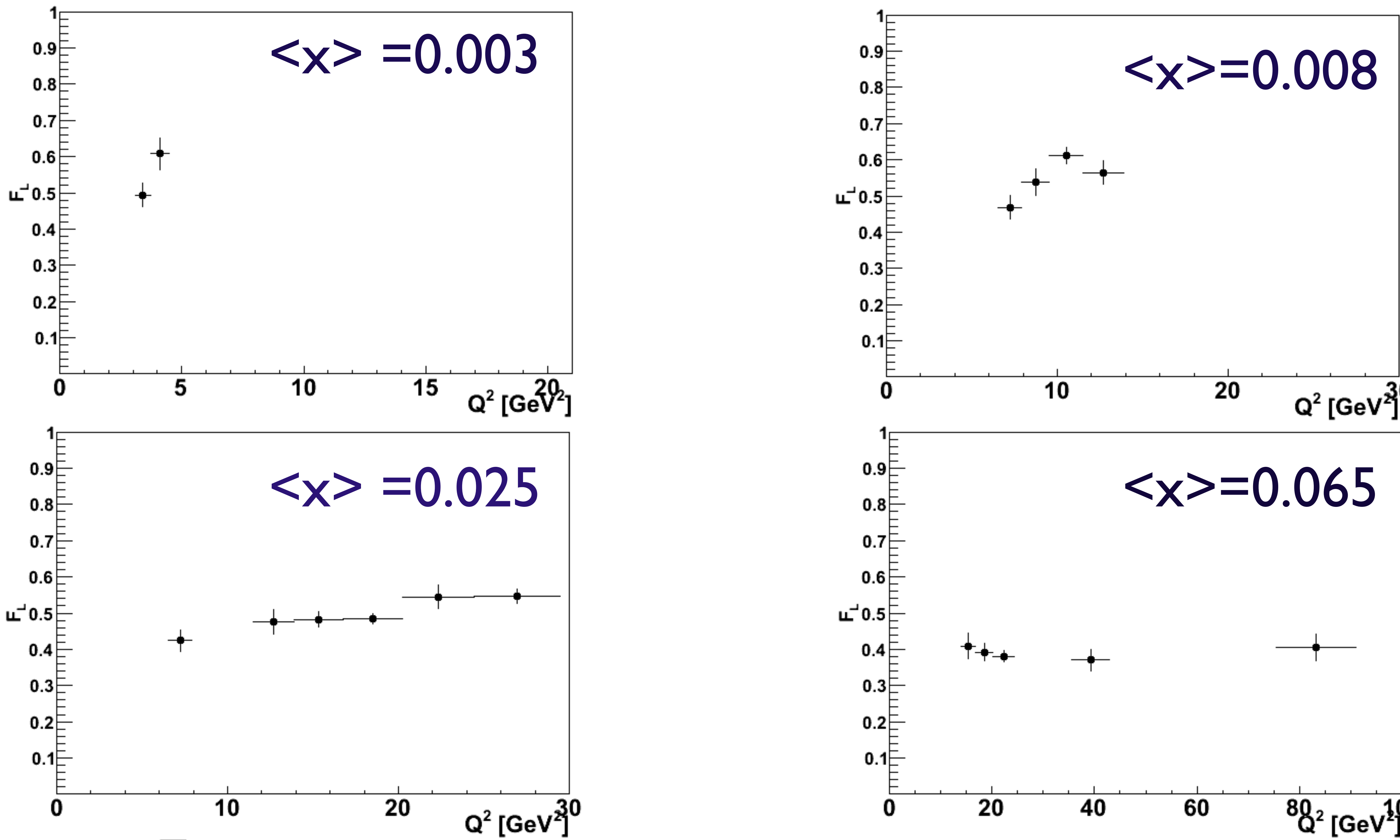


MC Tools for e+A collisions

- Diffractive vector meson production
  - Naively: $\sigma \sim G(x,Q^2)^2$
  - Can look at exclusive VM production in both Pythia and RAPGAP
    - Only available in e+p collisions
  - Solution for e+A collisions?
    - Modify RAPGAP/PYTHIA or write our own
      - ★ xDVMP (exclusive Diffractive Vector Meson Production) -T. Ullrich
      - ★ implement the b-SAT/b-CGC model for e+p and e+A collisions
      - ★ Allows study of:
        - ✓ detector requirements
        - ✓ sensitivity to saturation effects

Dipole Model (I)

Cross-section for production of final state VM:

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p\rightarrow Ep}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\rightarrow Ep}\right|^2 = \frac{1}{16\pi}\left|\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\right|^2$$

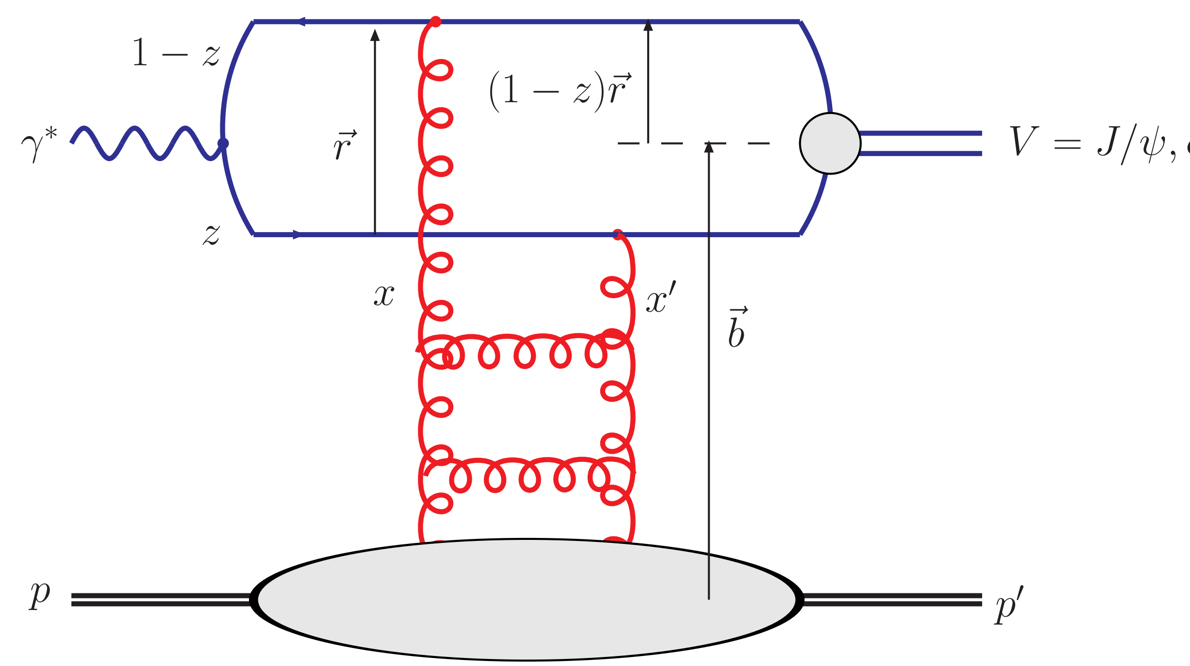
Amplitude

Overlap between photon and VM wave function

Dipole Cross-Section

Many dipole models on the market:

- Use : H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016
  - Describes Hera data well
  - Has b-dependence
  - We have experience with it
  - Henri is around to ask
  - Can be "easily" modified to do eA (via b-dependence)



Dipole Model (II)

Cross-section for production of final state VM:

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Ep}_{T,L}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}^{\gamma^* p\to Ep}_{T,L}\right|^2 = \frac{1}{16\pi}\left|\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\right|^2$$

Overlap between photon and VM wave function

Dipole Cross-Section

Wave function:

- Boosted Gaussian
  - Forshaw, Sandapen, Shaw
- GausLC
  - Dosch, Gousset, Kulzinger, Pirner, Teaney, Kowalski
- Parameters tuned for HERA are available
- Any improved wave function can be easily plugged in

Dipole Cross-Section:

- b-Sat
  - uses DGLAP evolution from initial G (x,Q)
  - can be adapted for A (b-dependence)
- b-CGC
- Parameters tuned for HERA are available

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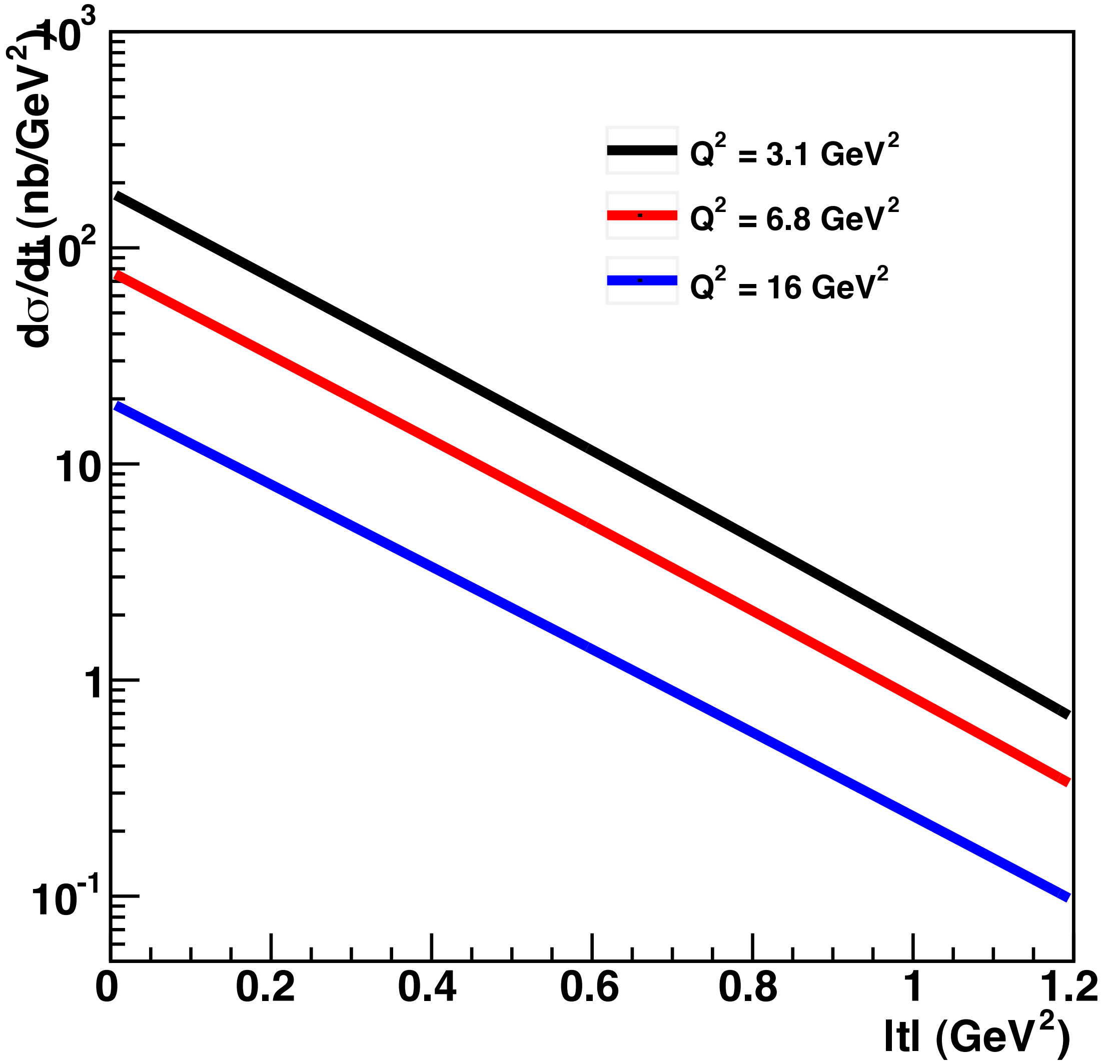
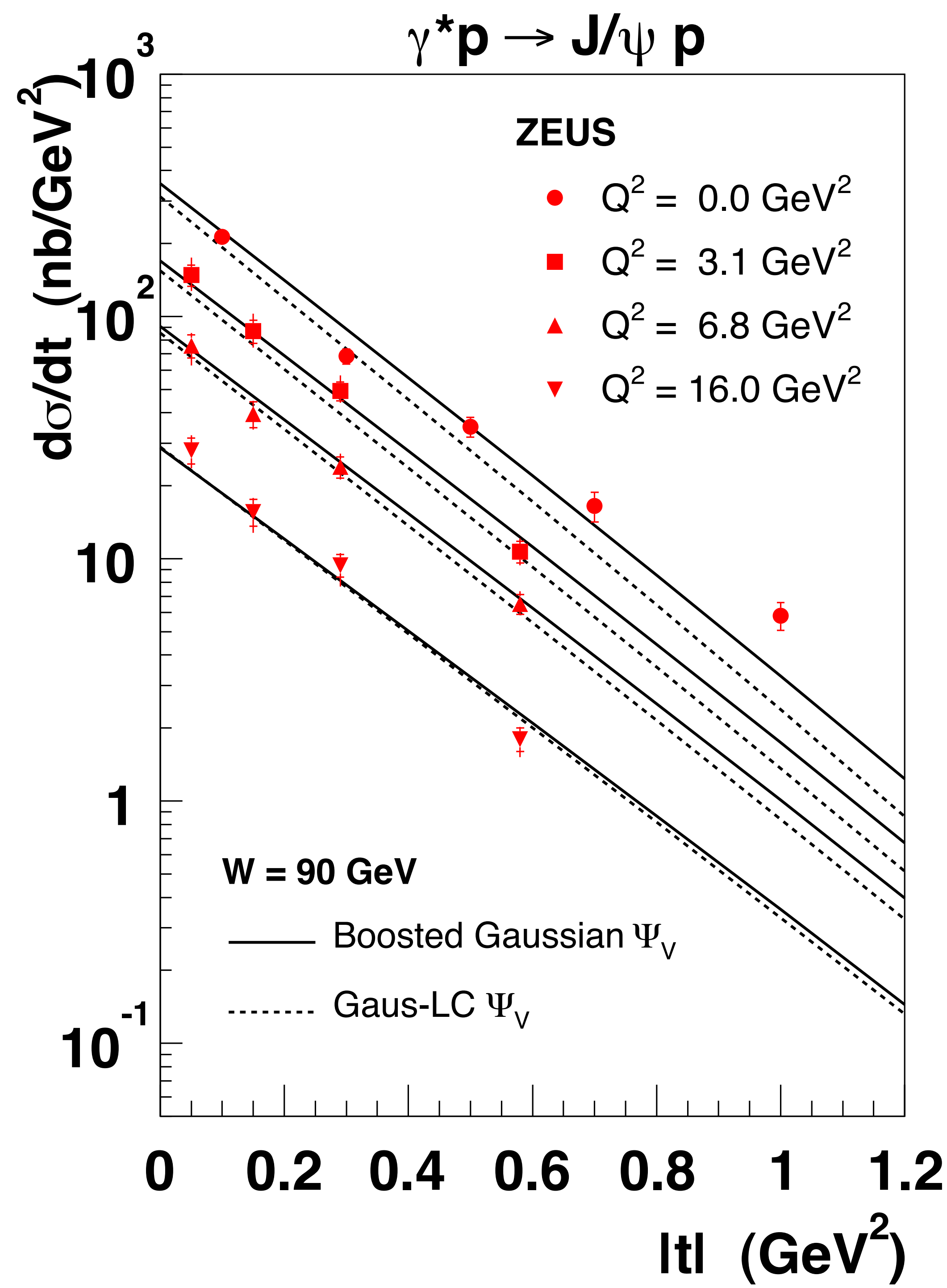
Status of xDVMP

- What xDVMP can do:
  - ep → e'p'V   where V = J/ψ, ϕ, ρ
  - choice between b-Sat and b-CGC model
  - choice between Boosted Gaussian and Gaus-LC wave functions
- What remains to be done?
  - DVCS (ep → e'p'γ)
    - know how to implement it but it requires some programming
  - Correction for real part of amplitude
    - know the idea but have to implement it w/o too much CPU burned
  - eA
    - ideas on how to do it but very CPU intensive

Dipole Model Test





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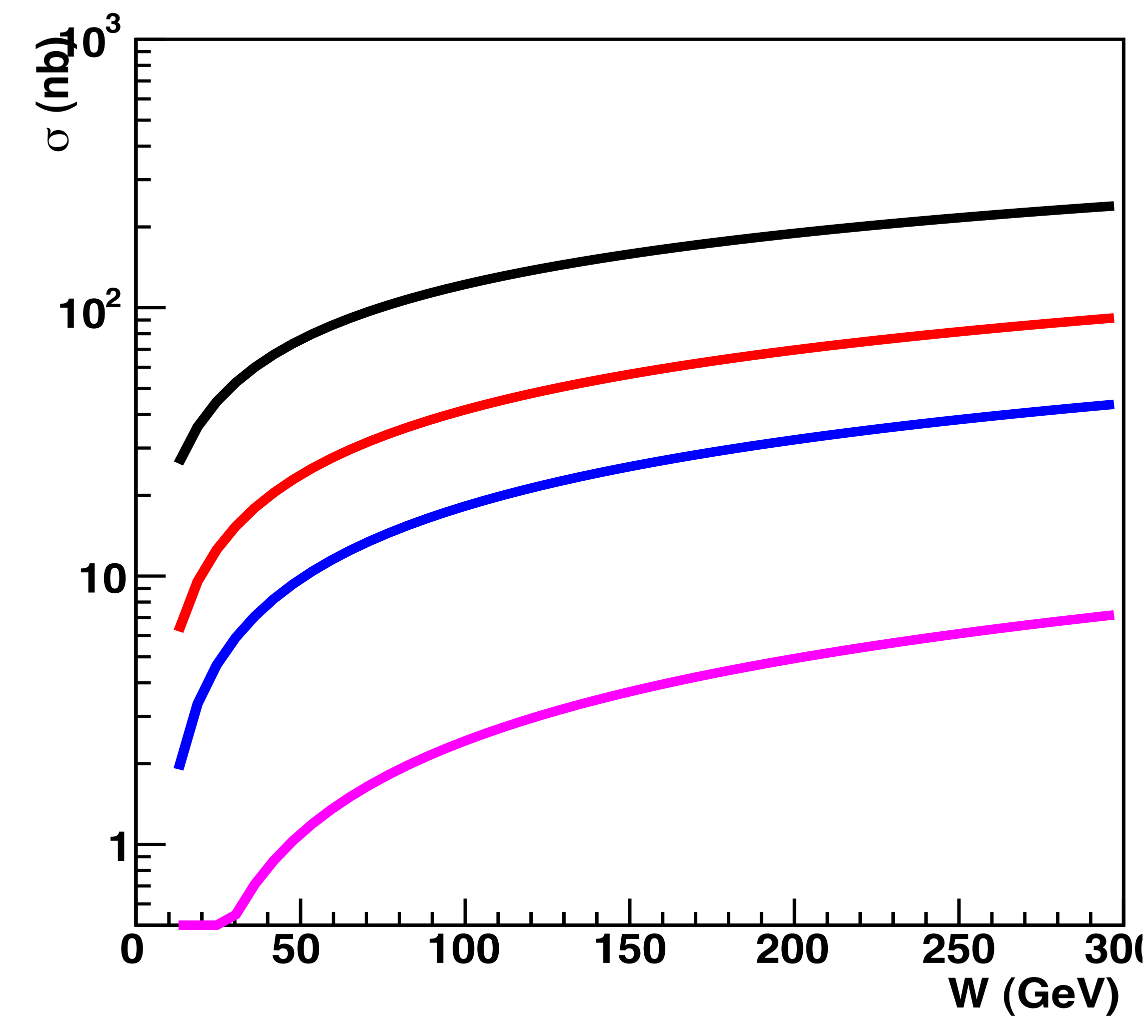
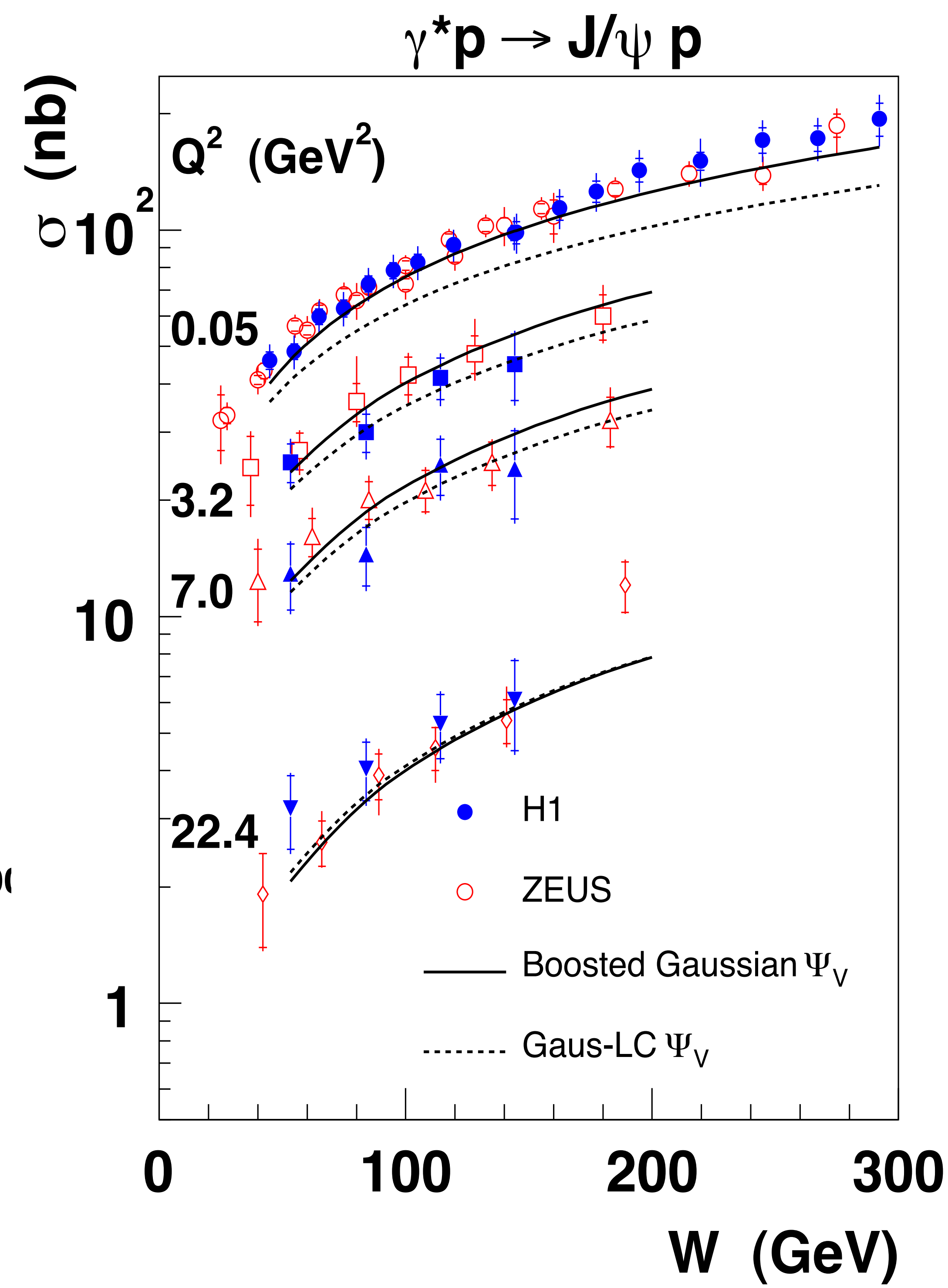
Dipole Model Test





Q2 = 0.5, 3.2, 7.0, 22.4 GeV2

Summary

- Low-x physics is an integral part of the EIC programme
  - Important to understand the gluon distributions in nucleons and nuclei
    - Has relevance for understanding heavy-ion collisions at both RHIC and the LHC
- The saturation of gluons is predicted to tame the explosive growth at low-x indicated by HERA data
  - Indications of saturation effects already observed at low-x in data
  - The saturation scale, Q_S, is enhanced in nuclei allowing the study of saturation at an EIC
- Simulation steps are underway
  - Studying the kinematic range of an FL measurement at a medium energy EIC
  - Writing a generator for exclusive diffractive vector meson production
  - Understanding jet reconstruction at an EIC
    - Work by G. Soyez

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