# The future of RHIC - an electron-ion collider (eRHIC)

Matthew A. C. Lamont
BNL

# Lots of work recently on the physics of e+A collisions

The EIC Science case:
a report on the joint
BNL/INT/JLab program

Gluons and the quark sea at high energies: distributions, polarization, tomography

Institute for Nuclear Theory • University of Washington, USA
September 13 to November 19, 2010

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**arXiv:1108.1713**

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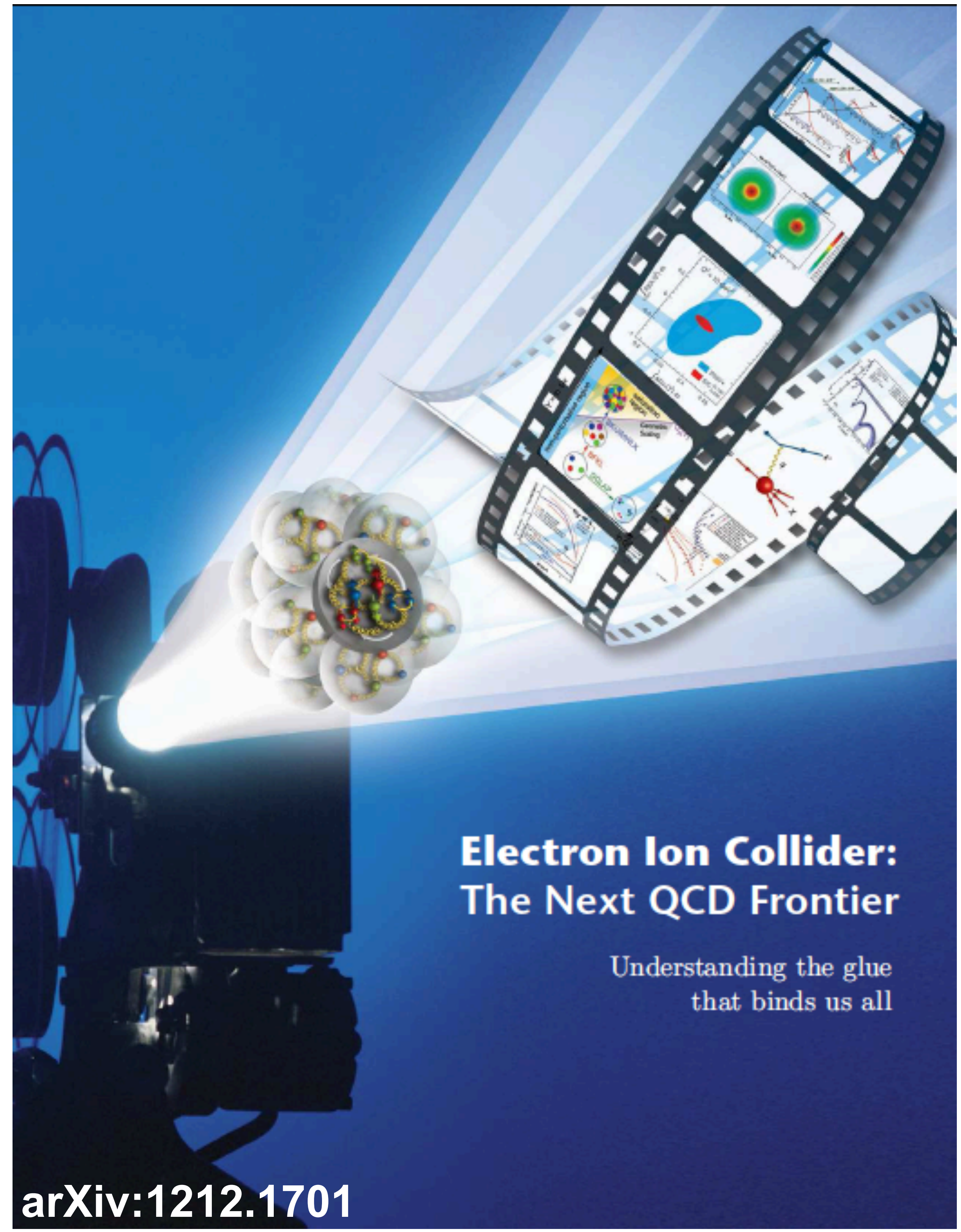
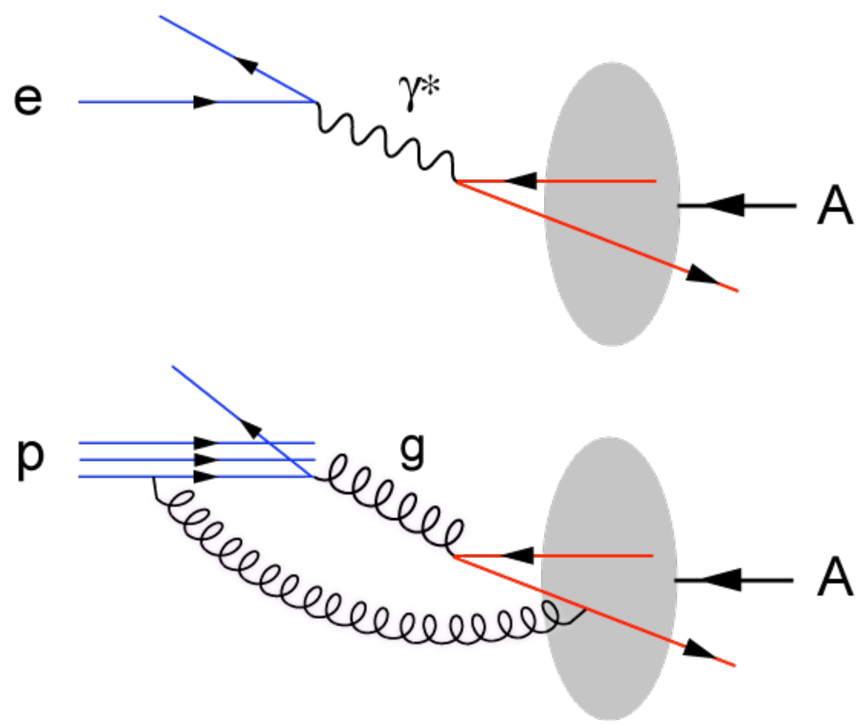


# Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
- Issues:
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to x, $Q^2$



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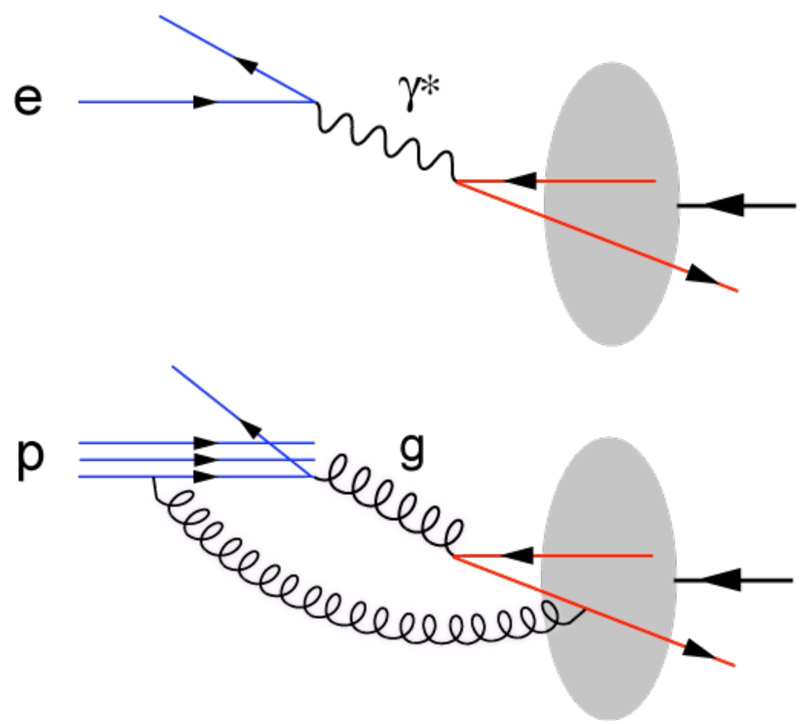


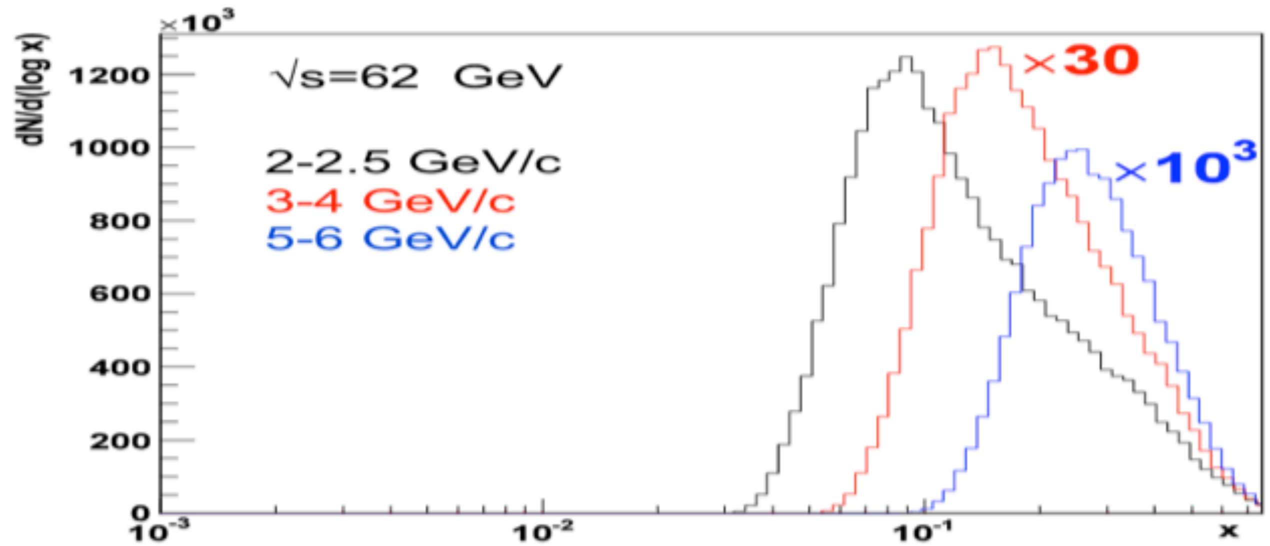


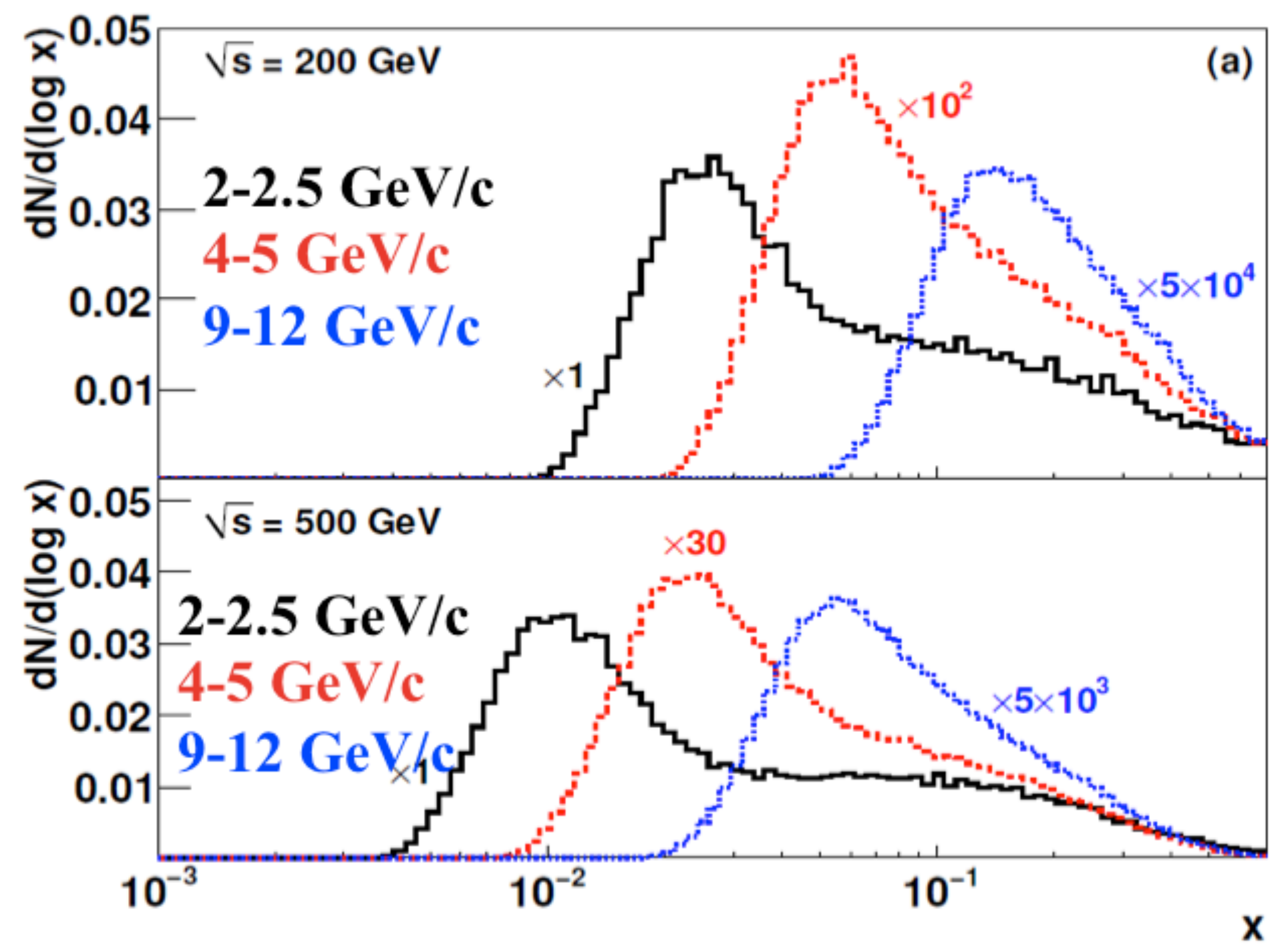


$p_T$ - x correlation in p+p

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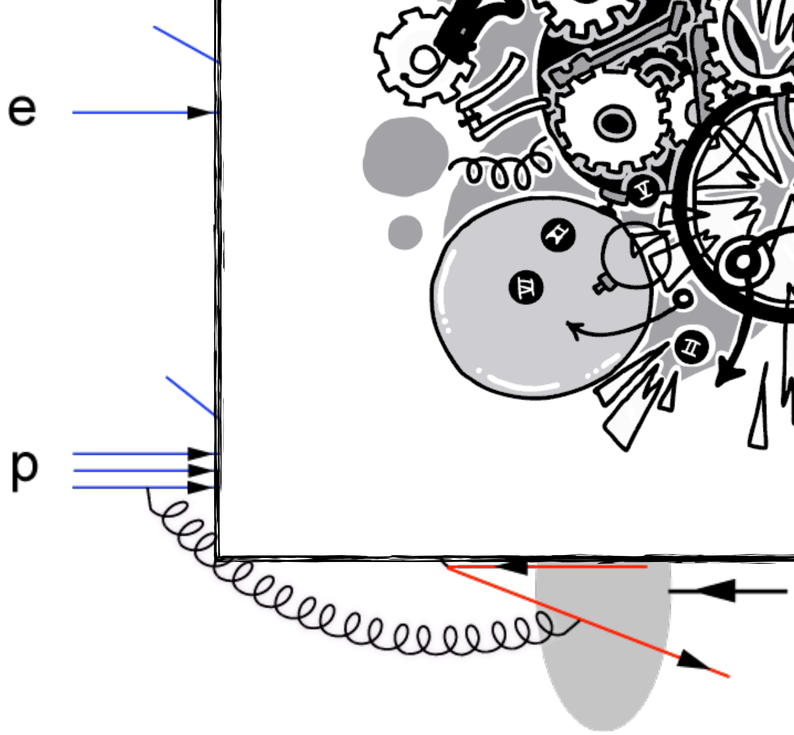
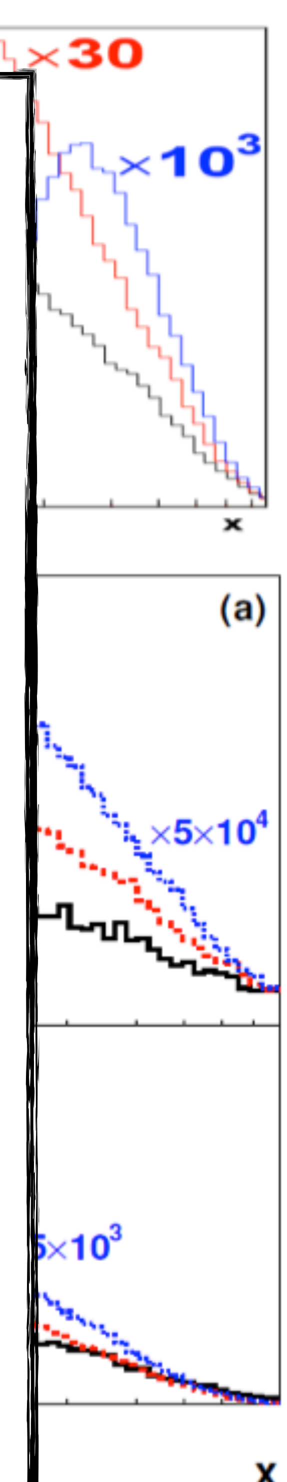
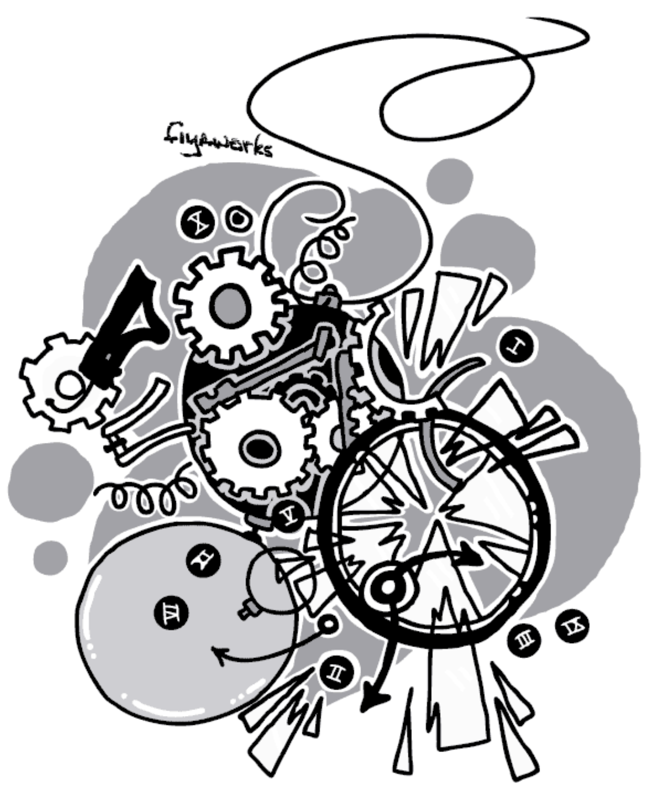



*Scattering of protons on protons*
*is like colliding Swiss watches to find out how they are built.*



R. Feynman

$p_T$ - x correlation in p+p

# What is eRHIC?

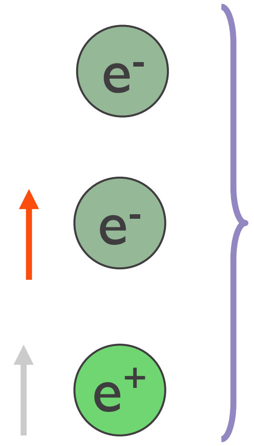
## Electron accelerator

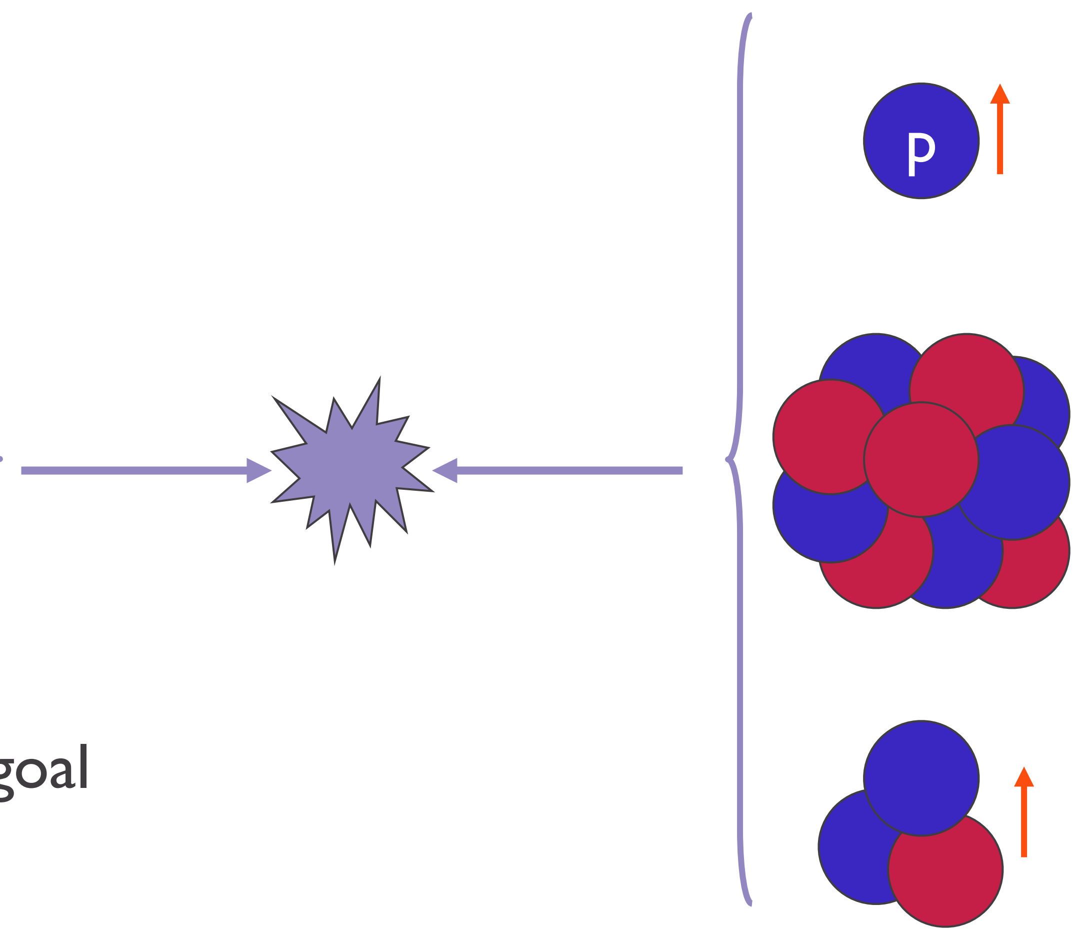
(to be built)

## RHIC

Existing = $2B

Unpolarized and polarized leptons
5-20 (30) GeV




Polarized protons
50-250 GeV

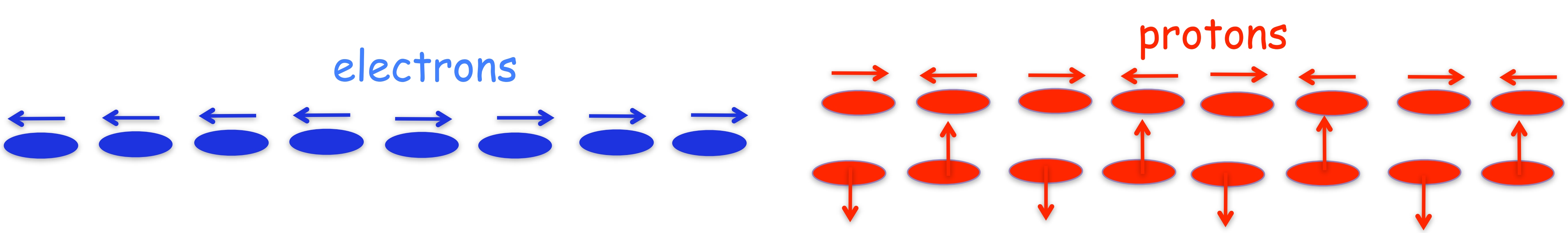
Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

Polarized light ions $He^3$
166 GeV/u

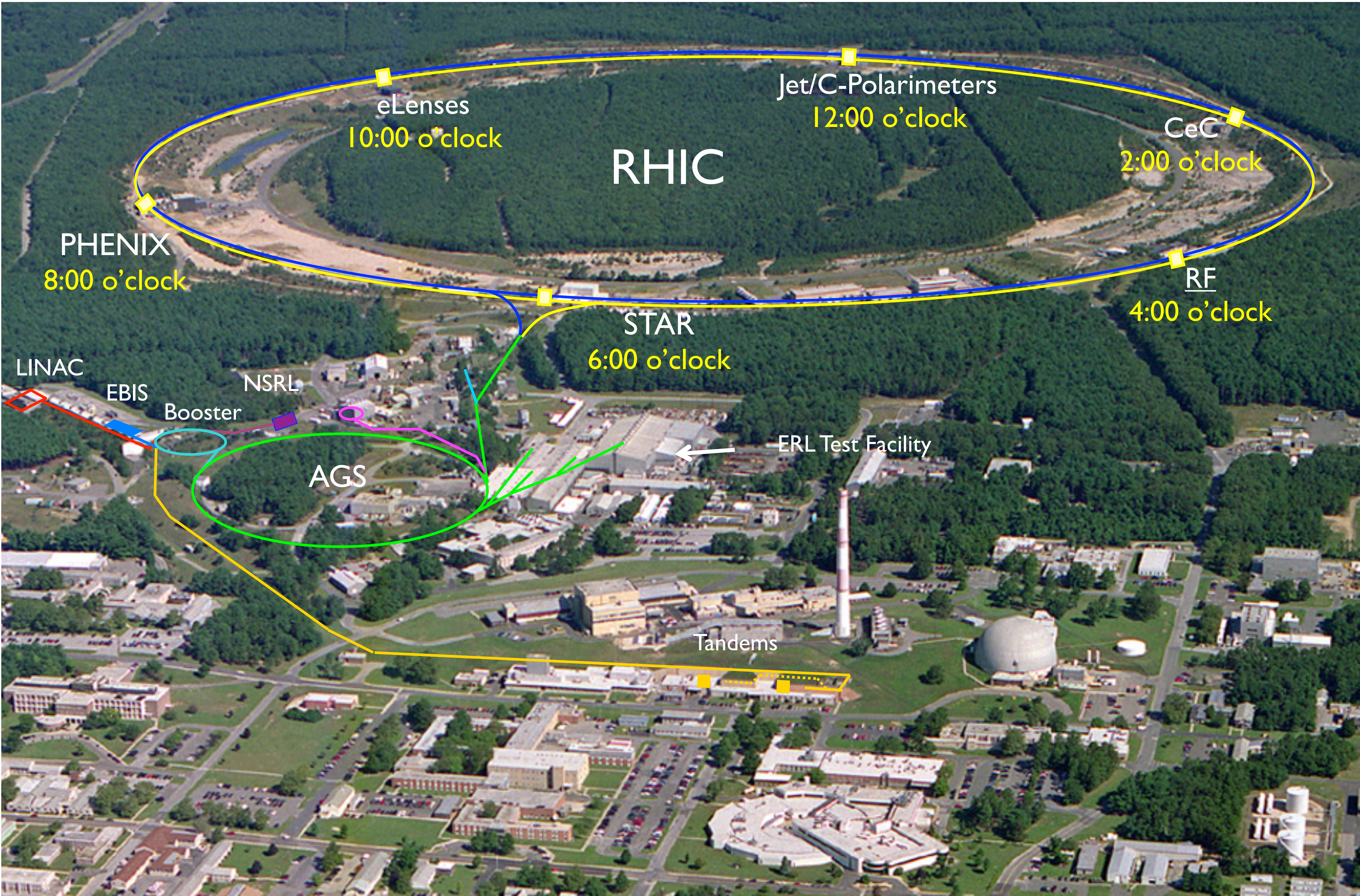
70% $e^-$ beam polarization goal

polarized positrons?

Center mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/$He^3$ possible



# From RHIC to eRHIC



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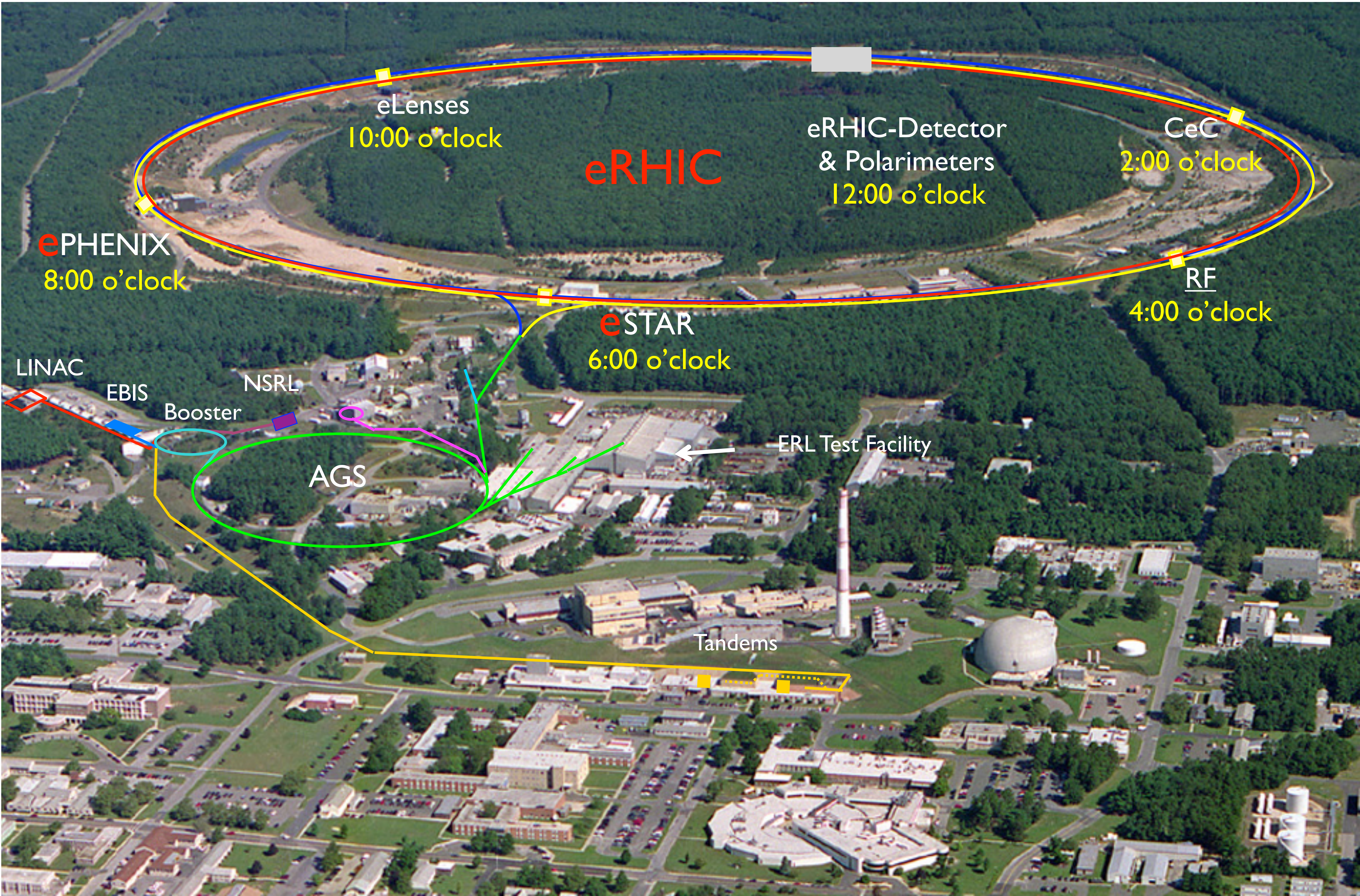
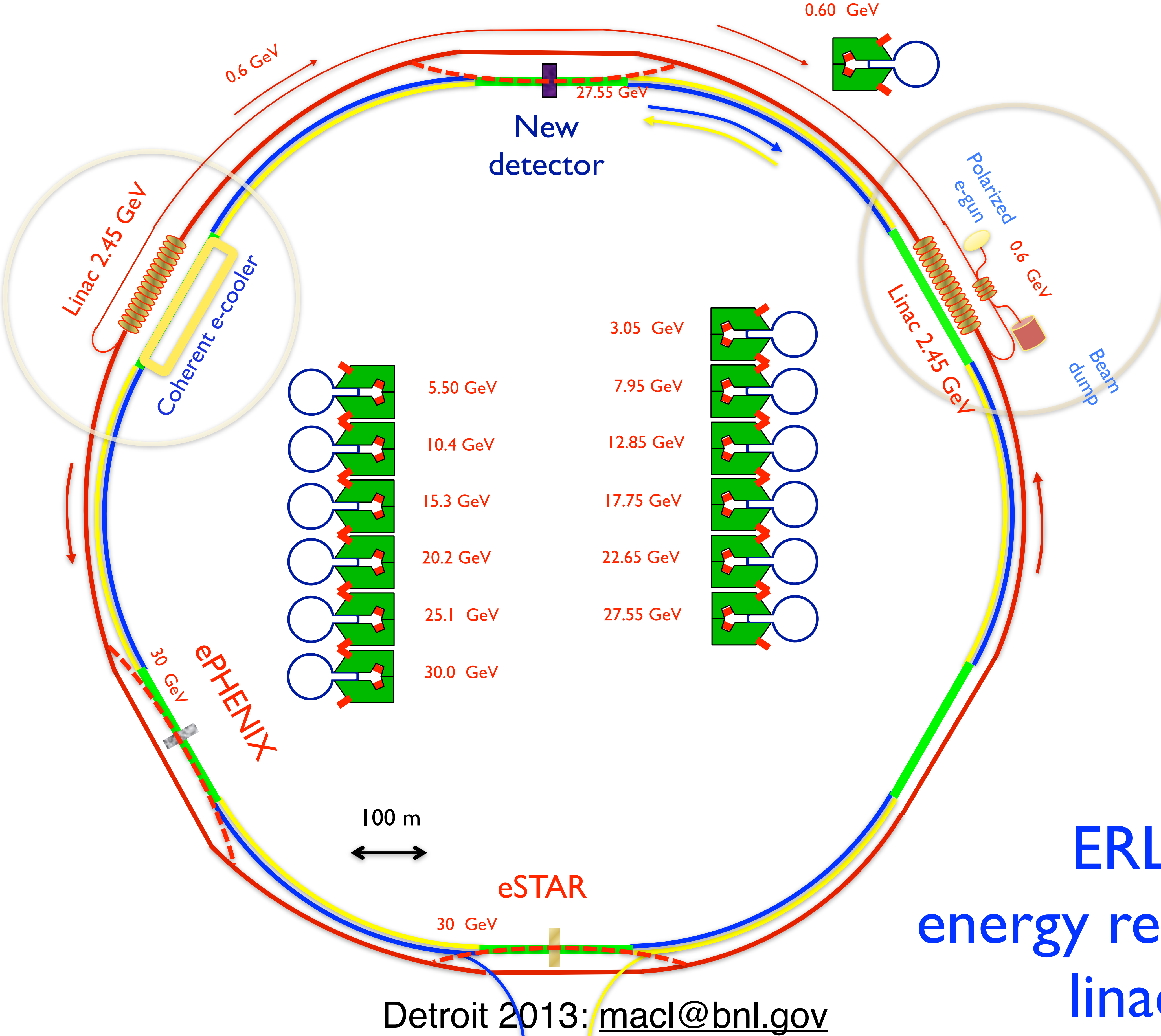


# Electron beam evolution in eRHIC's ERL




**ERL:**
**energy recovery linac**

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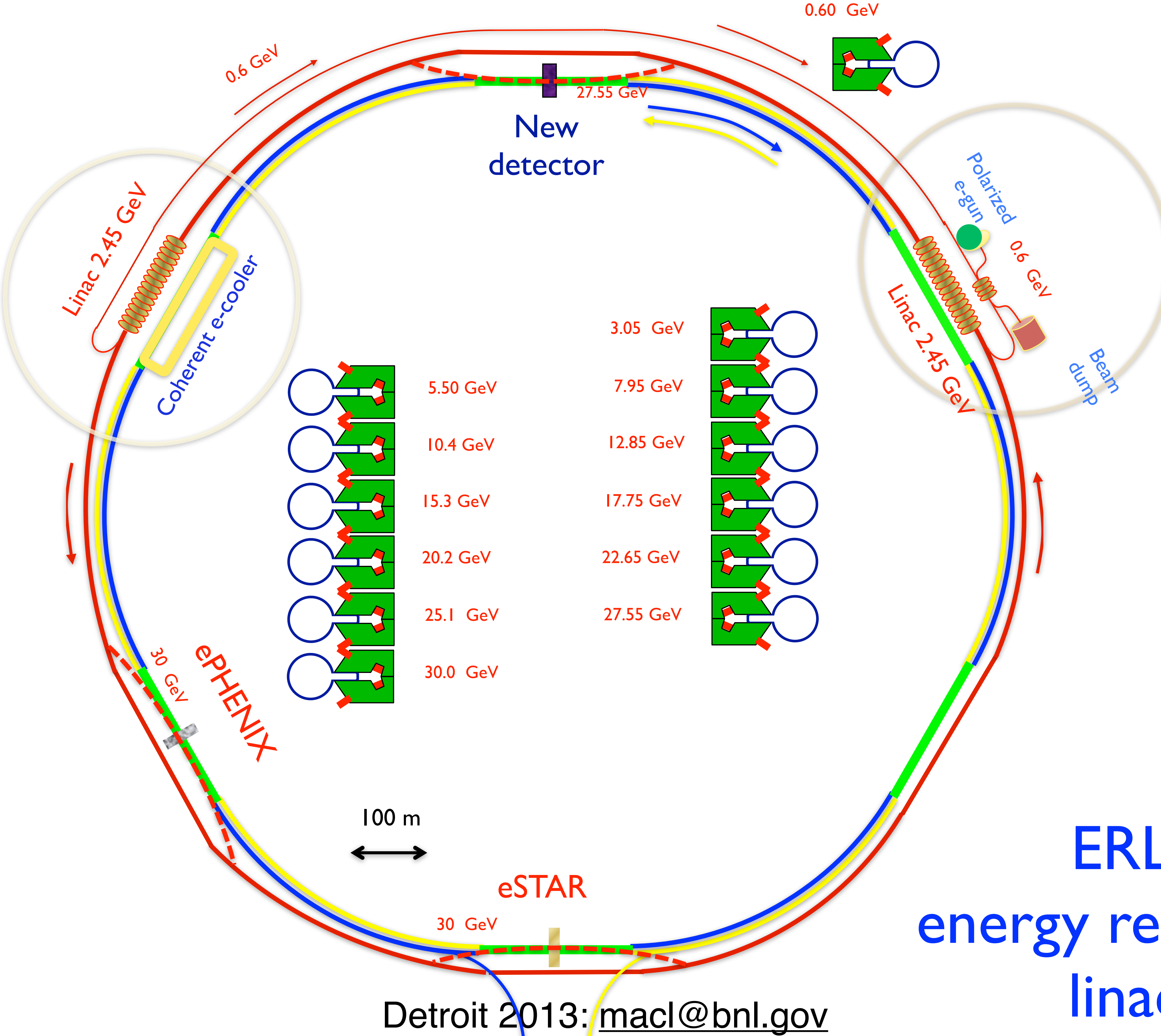


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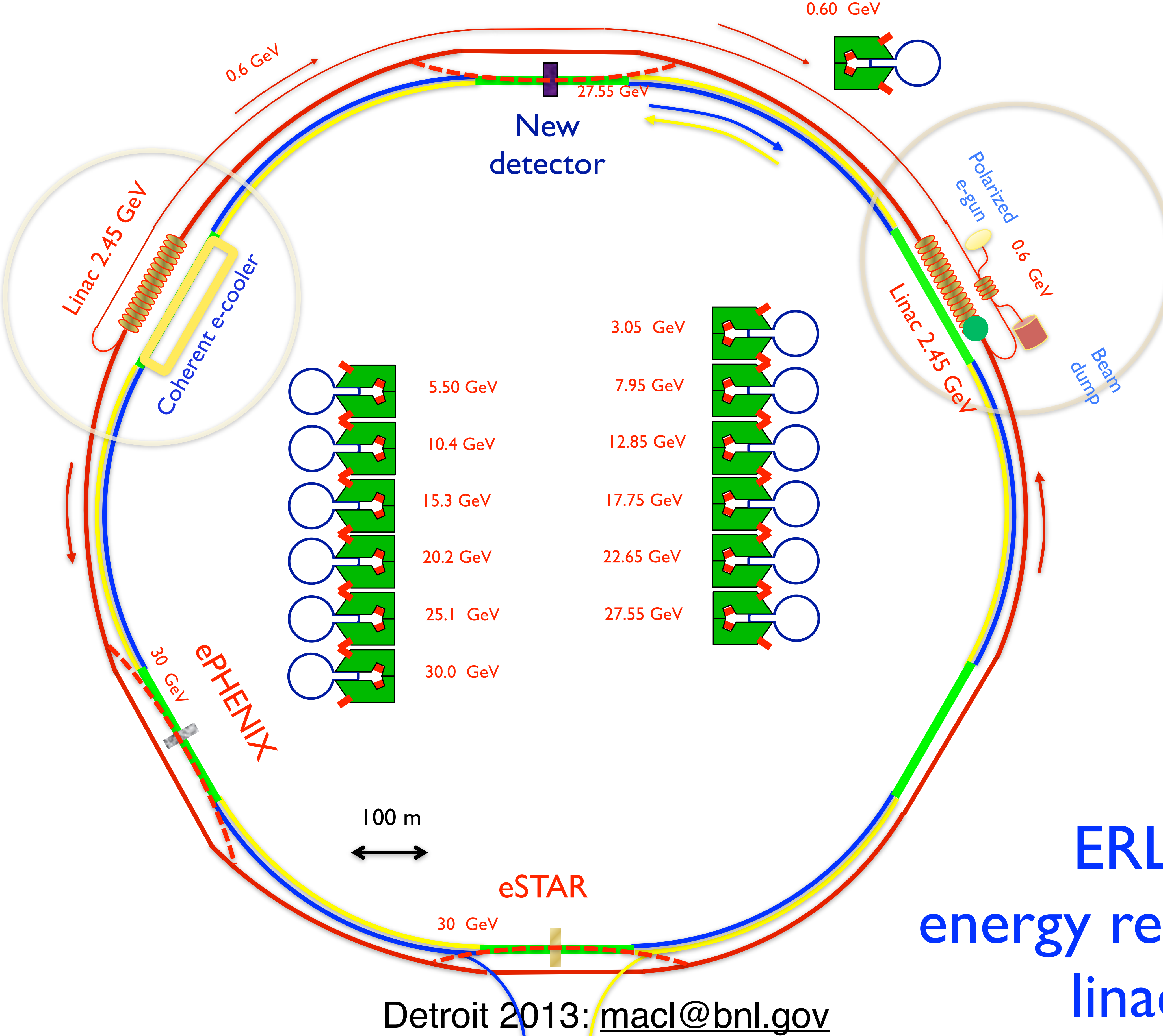


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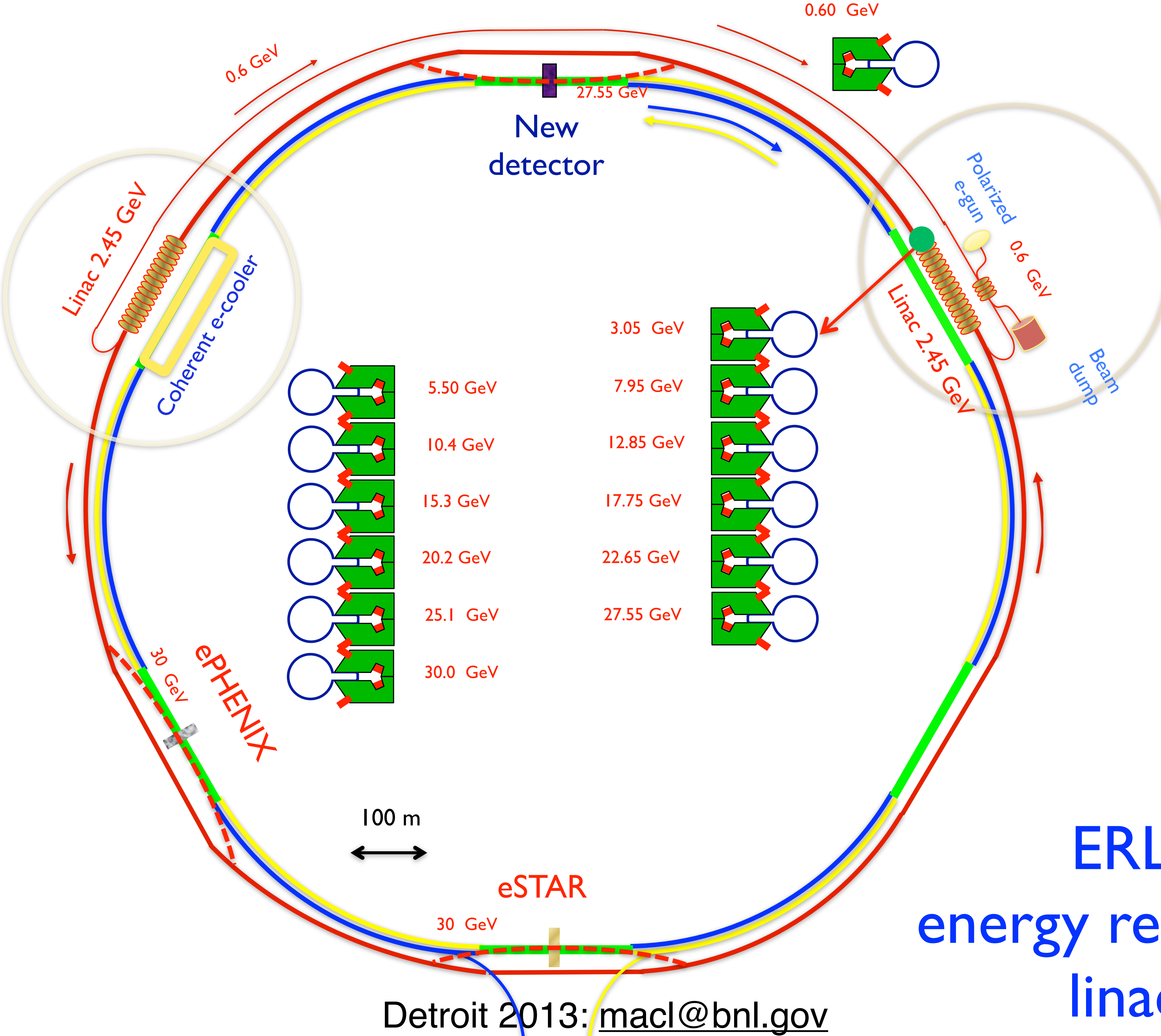


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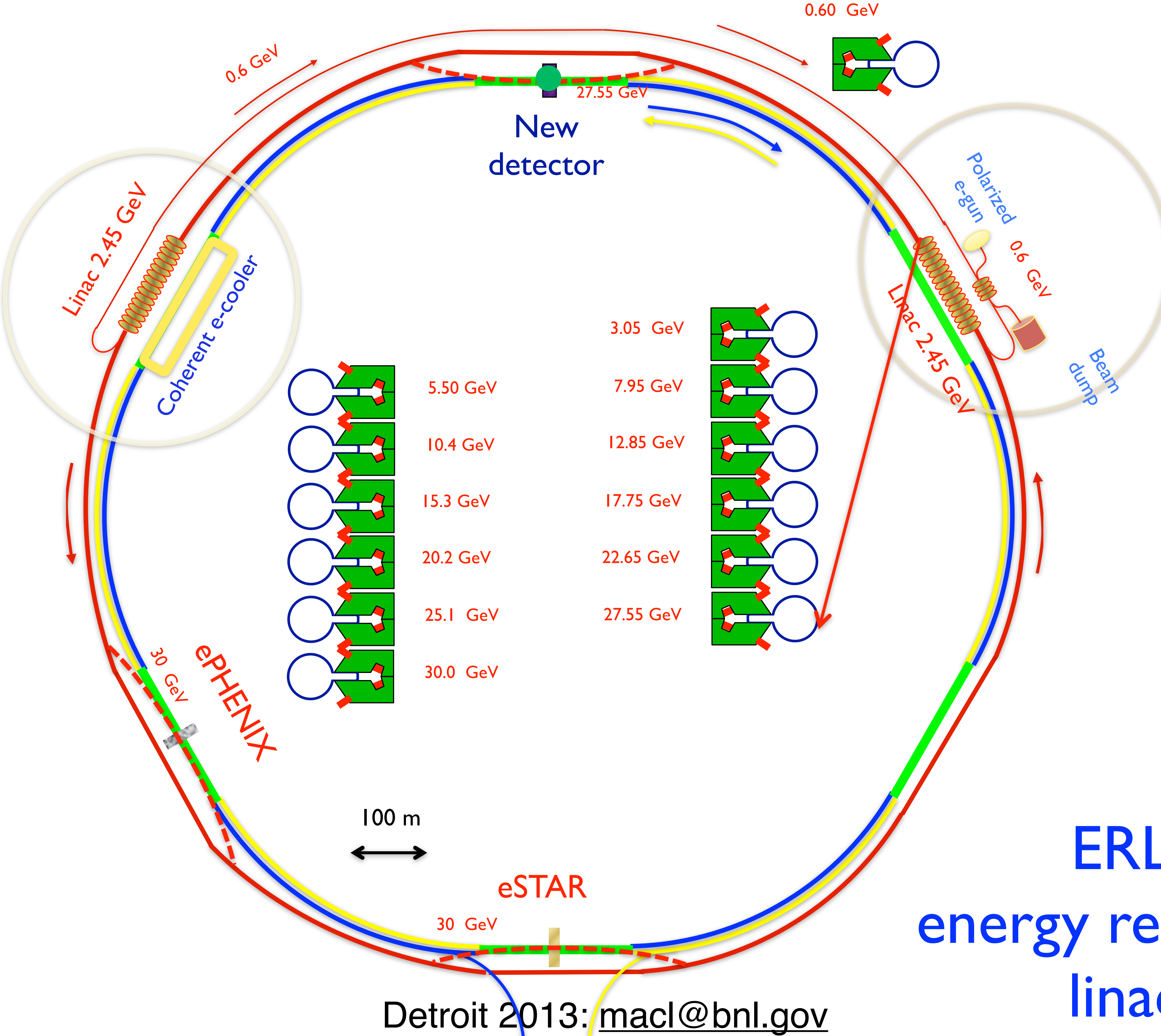


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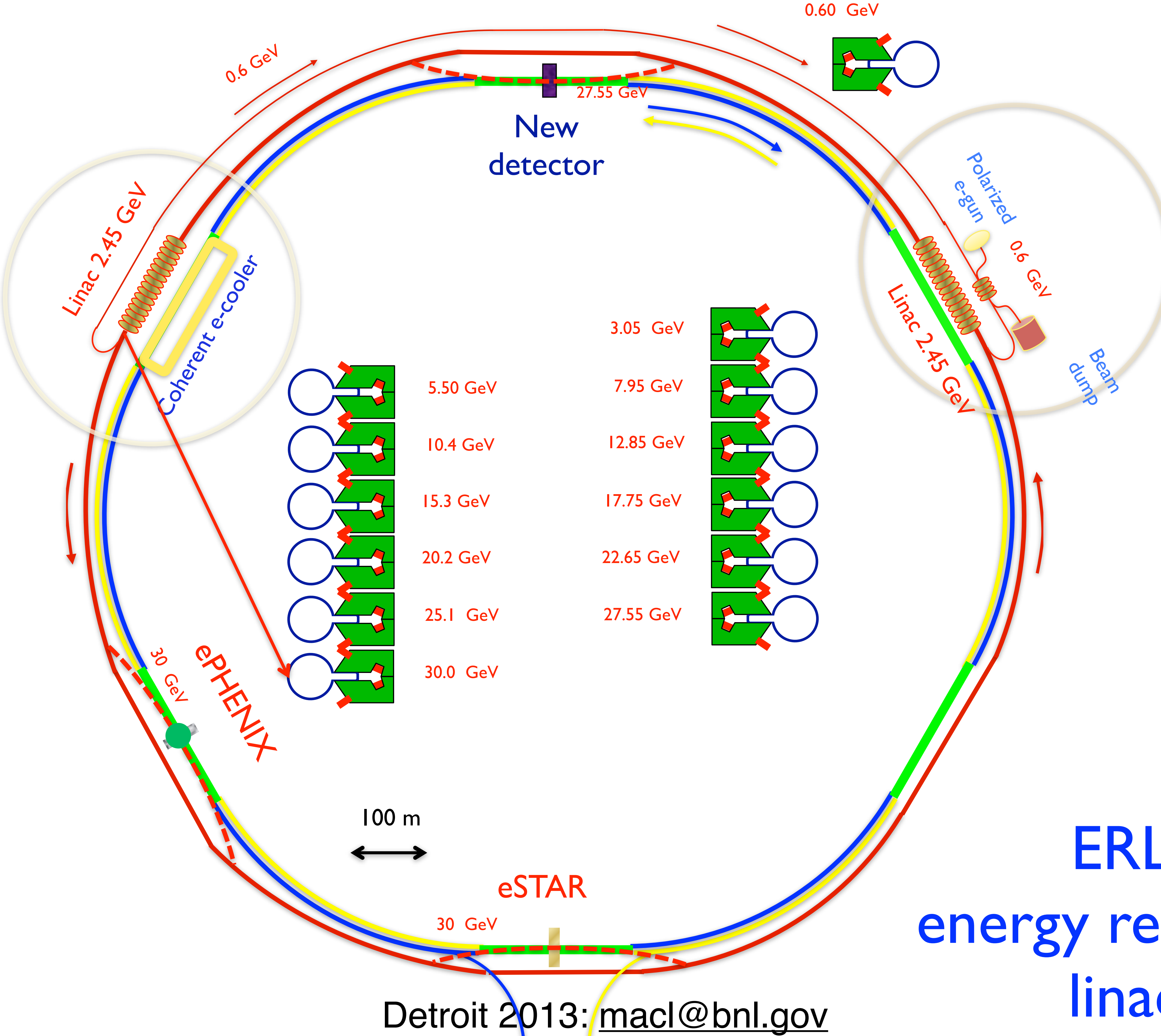


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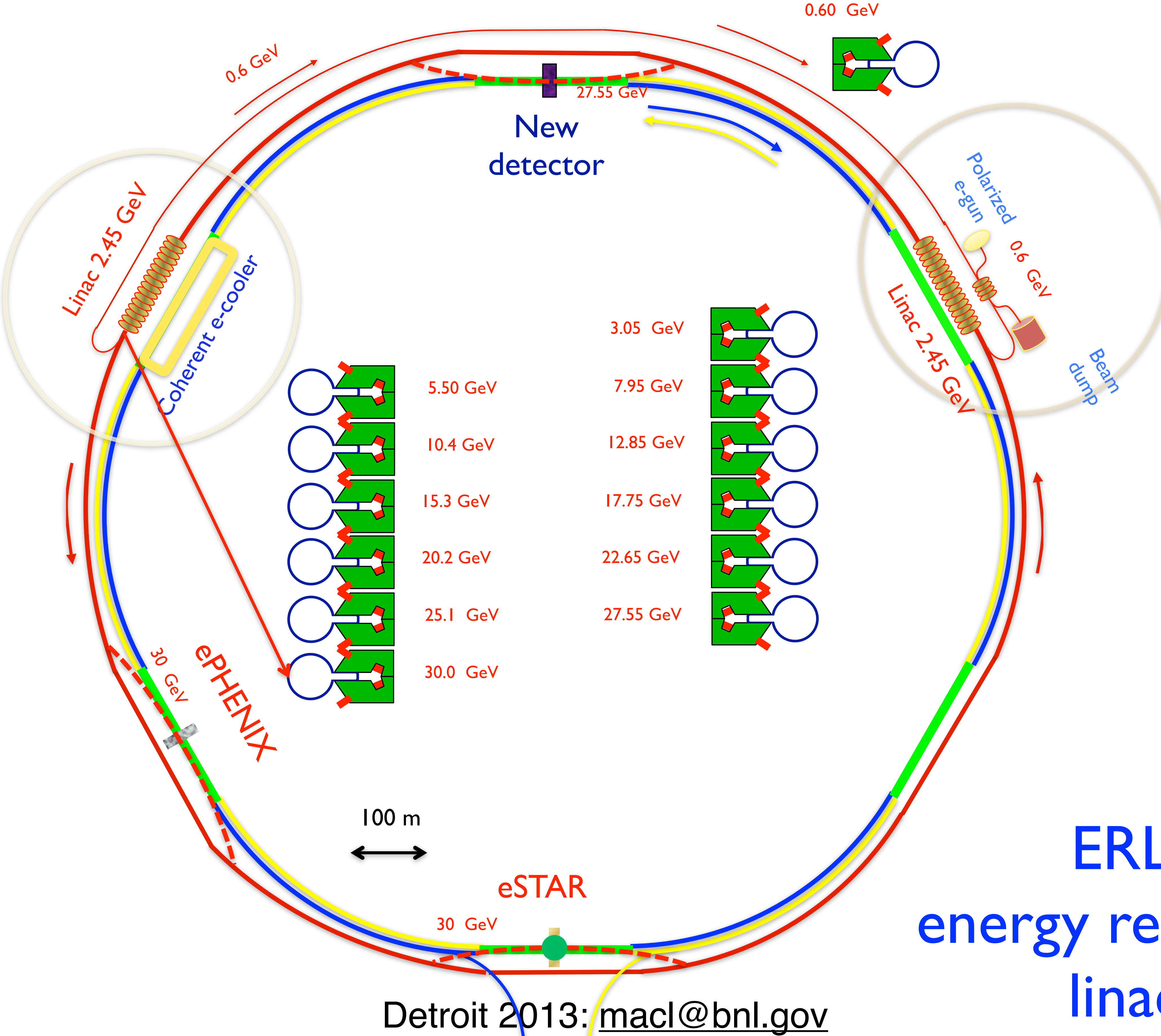


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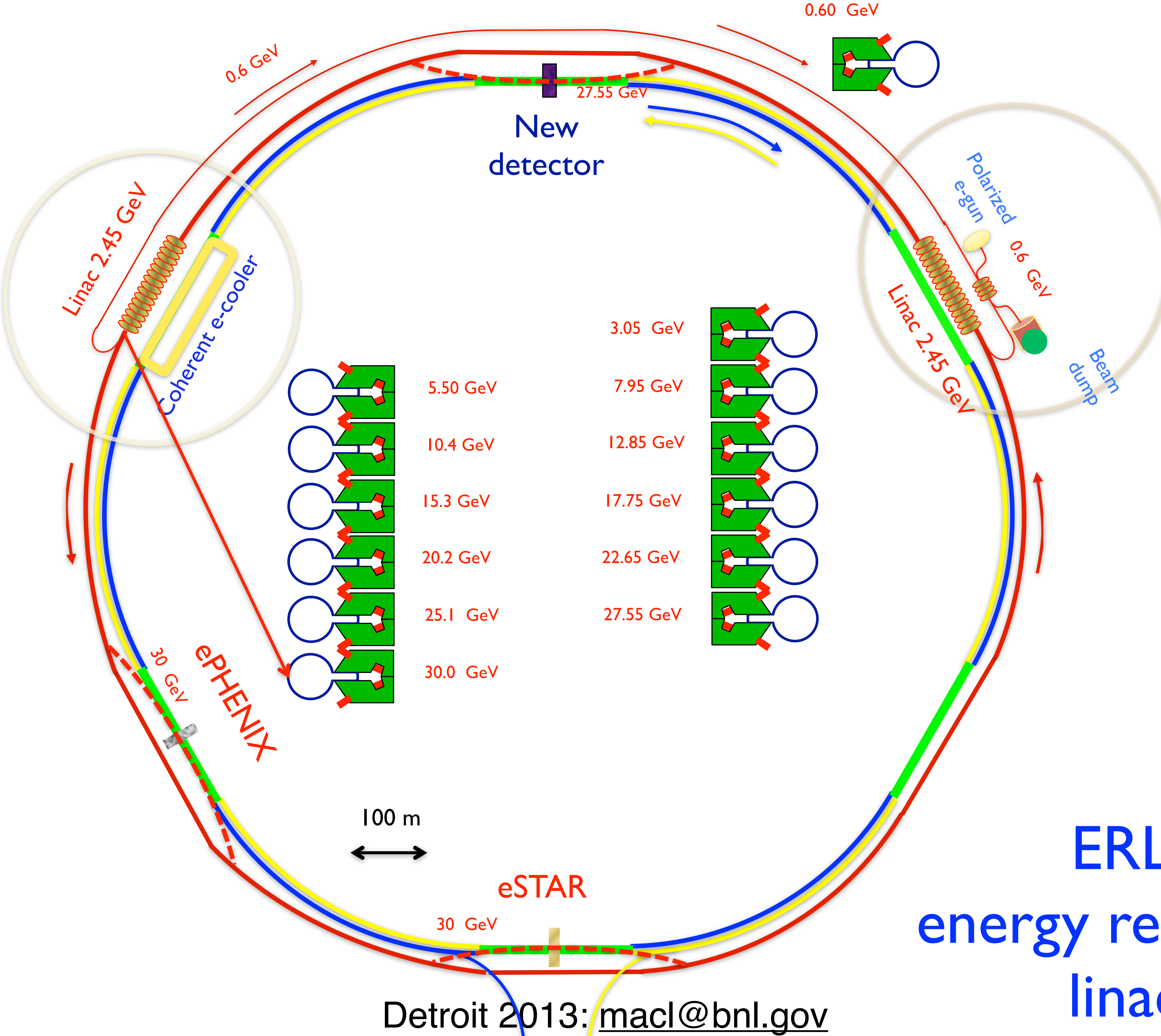


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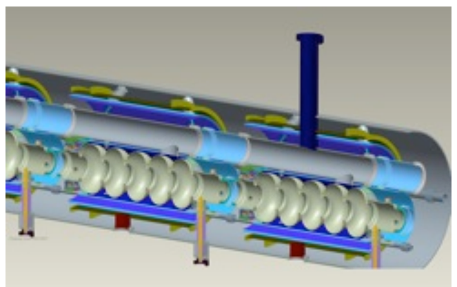
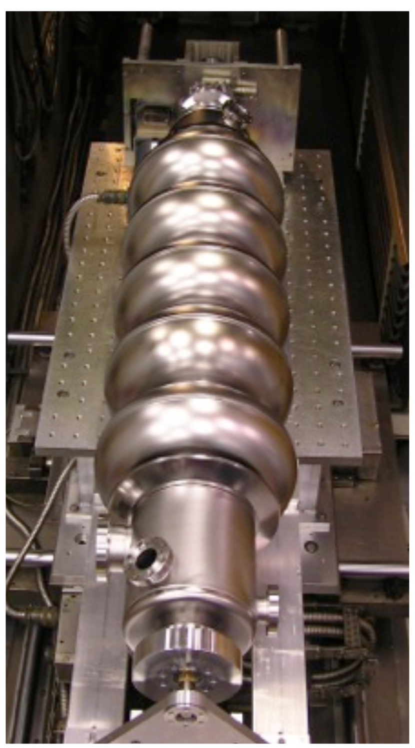
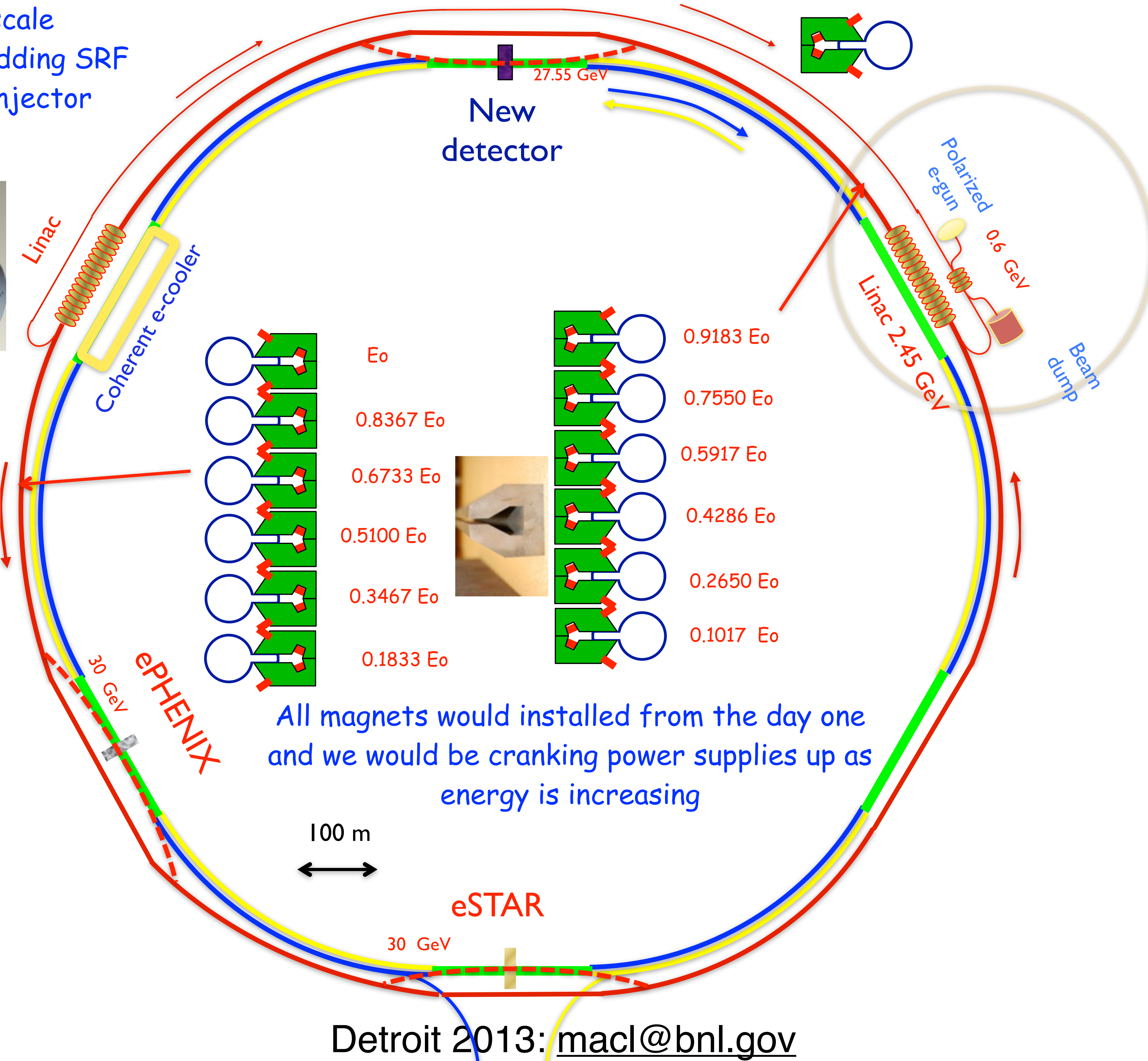
# Staging of eRHIC: $E_e$: 5 to 30 GeV

All energies scale proportionally by adding SRF cavities to the injector



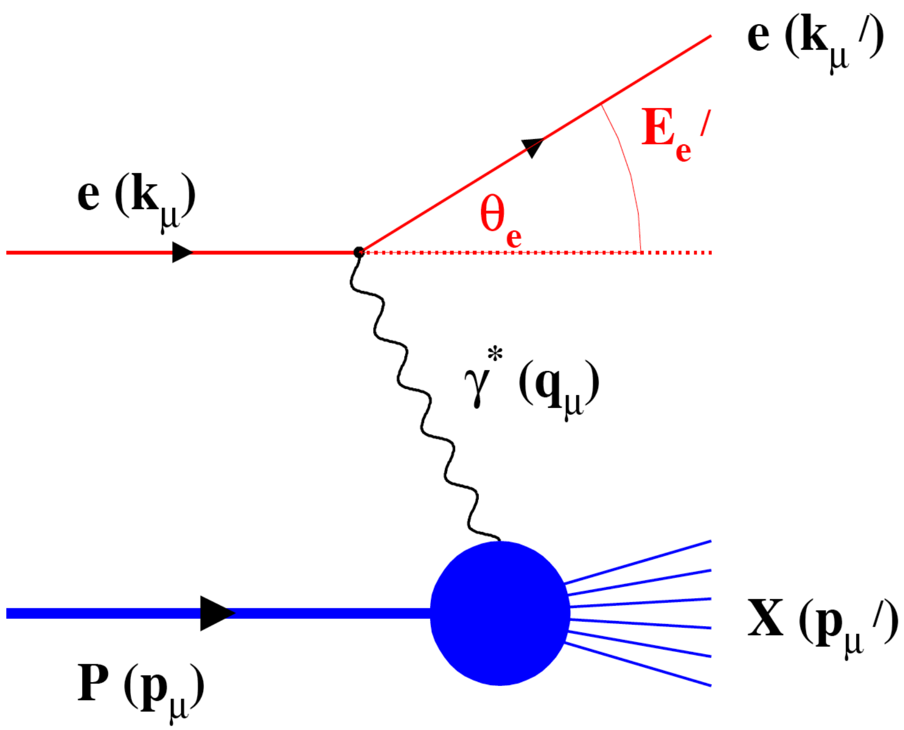





| E/Eo |
|---|
| 0.0200 |
| 0.1017 |
| 0.1833 |
| 0.2650 |
| 0.3467 |
| 0.4283 |
| 0.5100 |
| 0.5917 |
| 0.6733 |
| 0.7550 |
| 0.8367 |
| 0.9183 |
| 1.0000 |

# DIS Kinematics

e(k) + p(p) → e(k') +X(px)




$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e sin^2(\frac{\theta'_e}{2})$$

Measure of resolution power or “Virtuality”

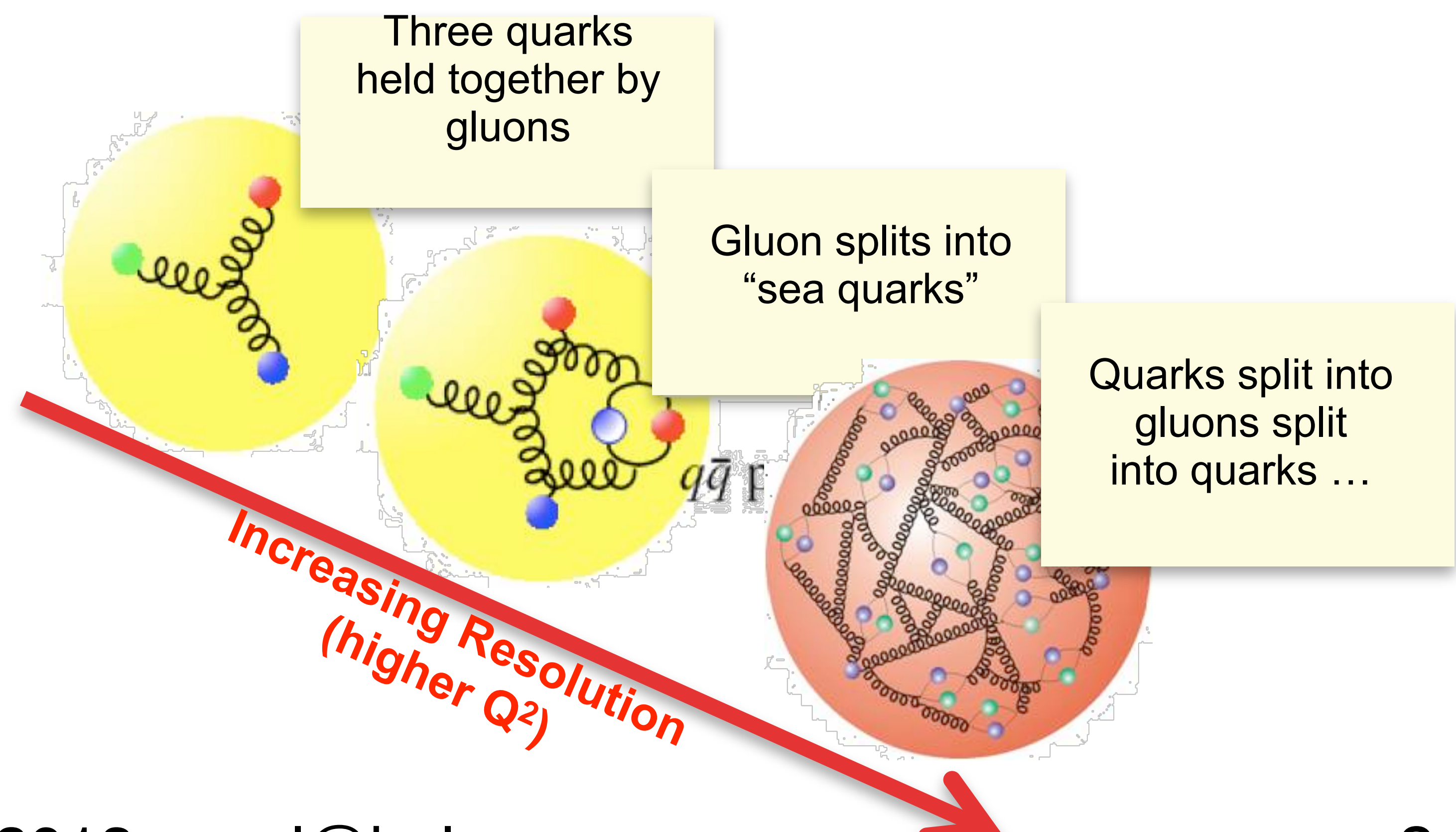
$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} cos^2(\frac{\theta'_e}{2})$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

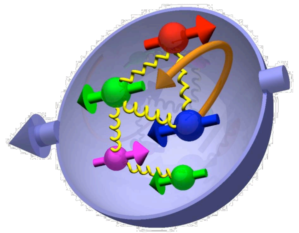
Measure of momentum fraction of struck quark

Important to note that in order to have different y for the same x and $Q^2$, need to change the beam energies



# Most compelling physics questions

Spin physics



- What is the polarisation of gluons at small x where they dominate?
- What is the x-dependence and flavour decomposition of the polarised sea?

Determine quark and gluon contributions to the proton spin at last!!

: macl@bnl.gov

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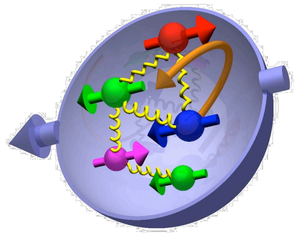

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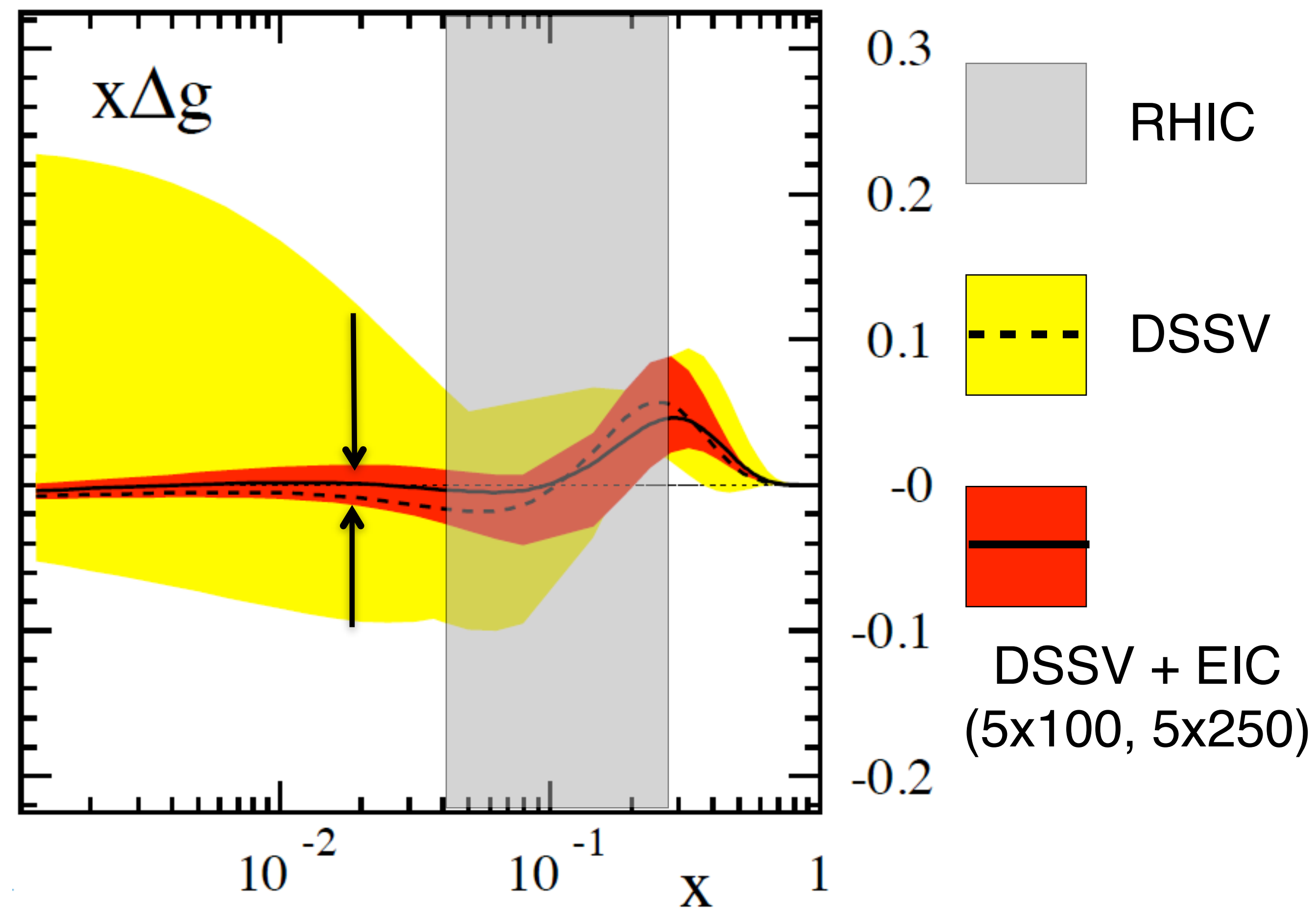

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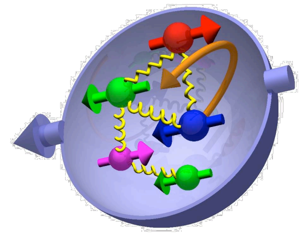

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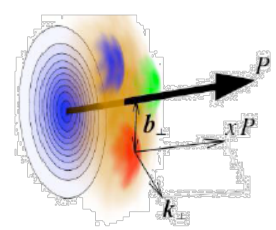
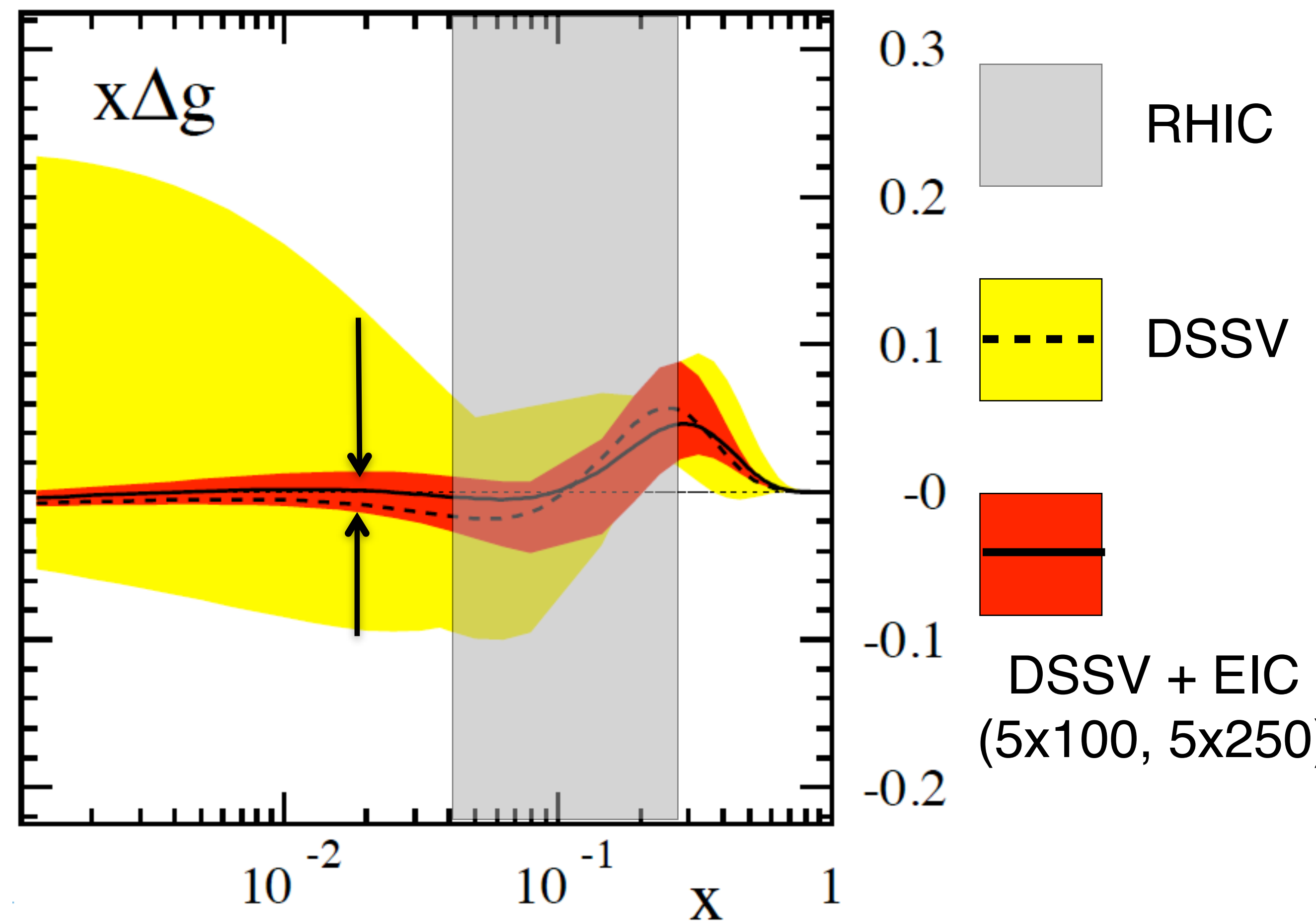
## Imaging




- What is the spatial distribution of quarks/ gluons in nucleons AND nuclei?
- Understand deep aspects of gauge theories revealed by $k_T$ dependent distributions

Possible window to orbital angular momentum



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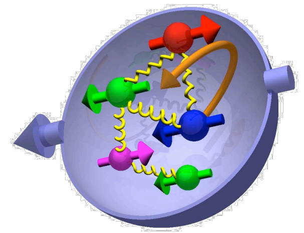

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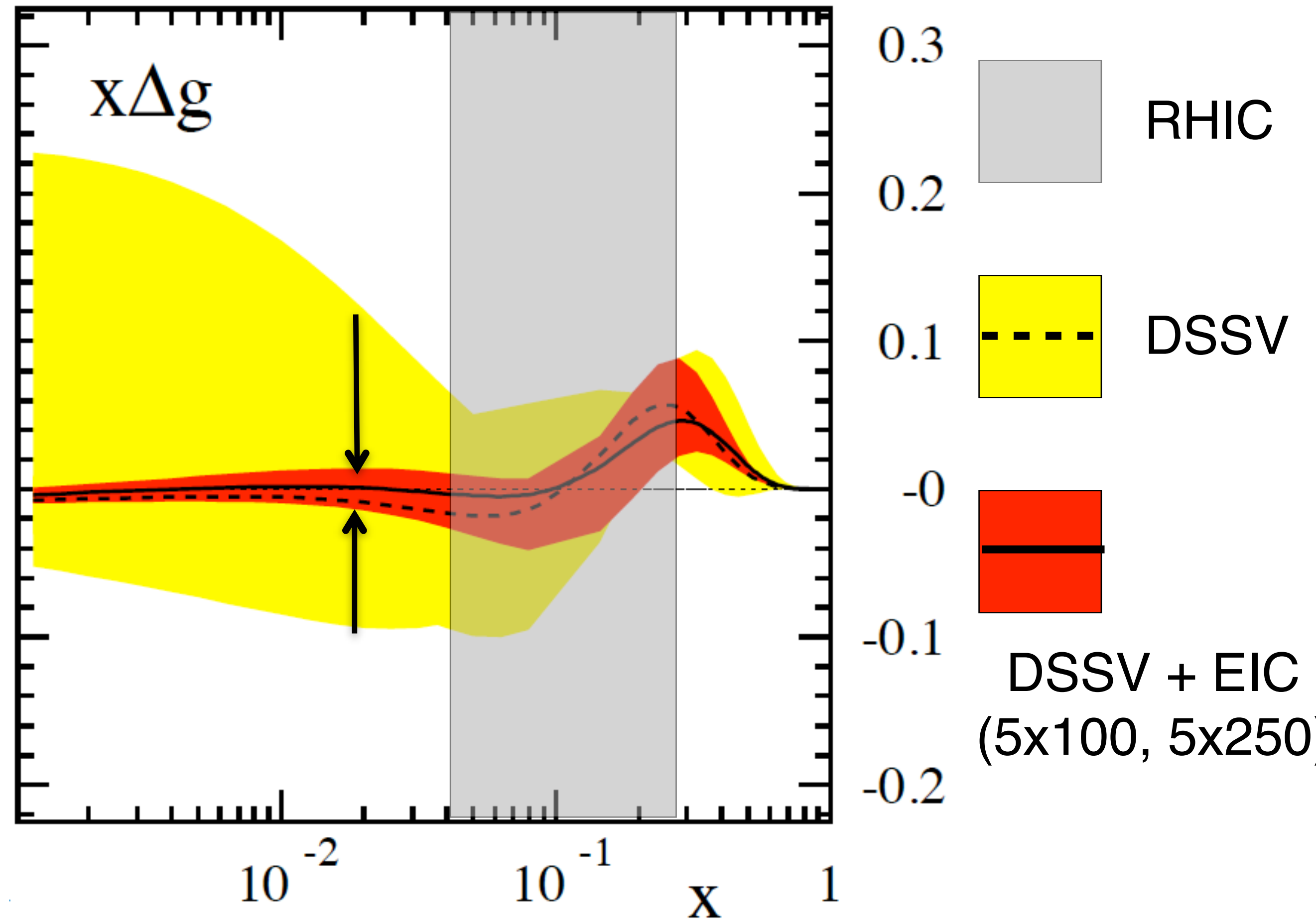


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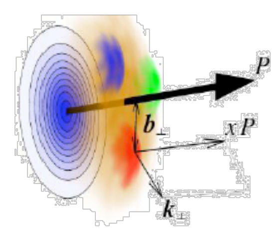

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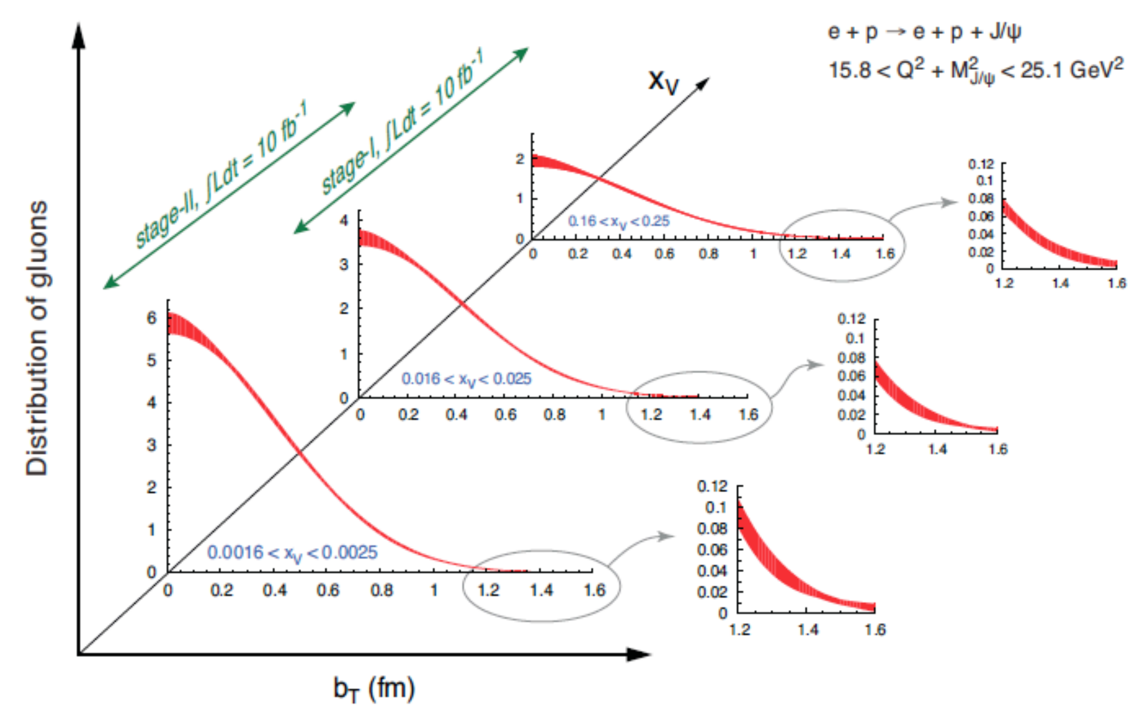
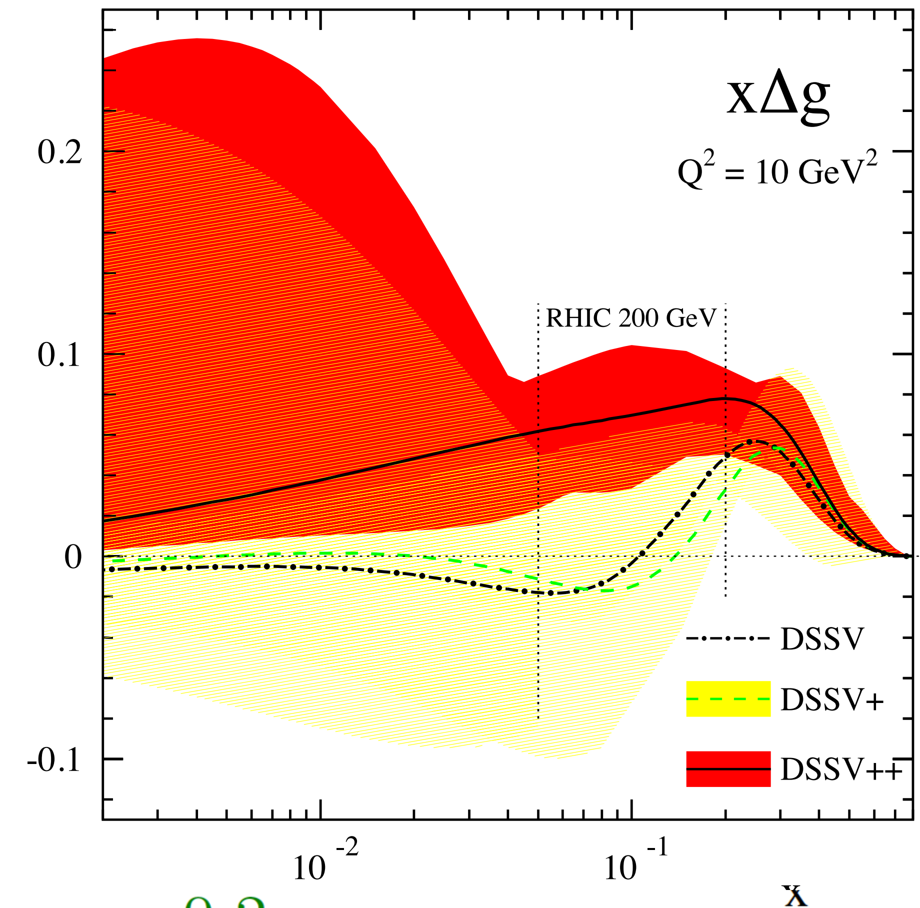


# Constraining Δg(x) at RHIC, EIC




$$\int_{0.05}^{0.2} \Delta g(x) = 0.1 \pm^{0.06}_{0.07}$$

- RHIC data can constrain Δg(x) down to a few x $10^{-2}$
  - ➡ Latest RHIC data show non-zero Δg(x) in measured range
  - ➡ Large unmeasured region still exists

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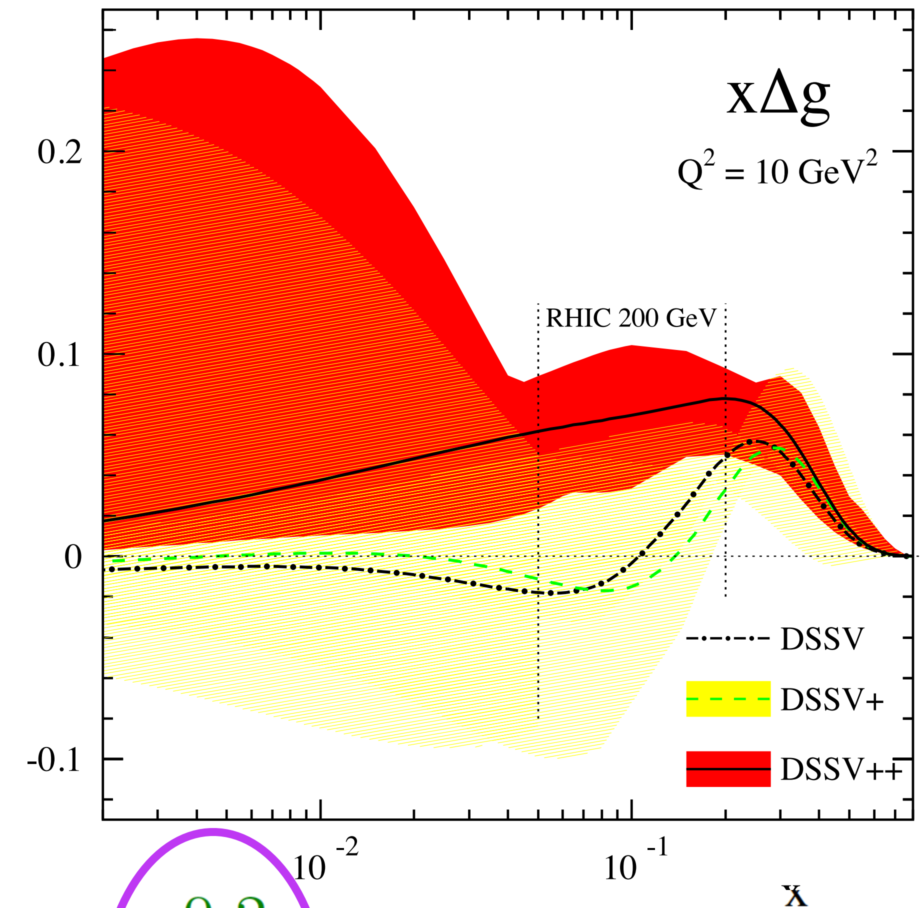


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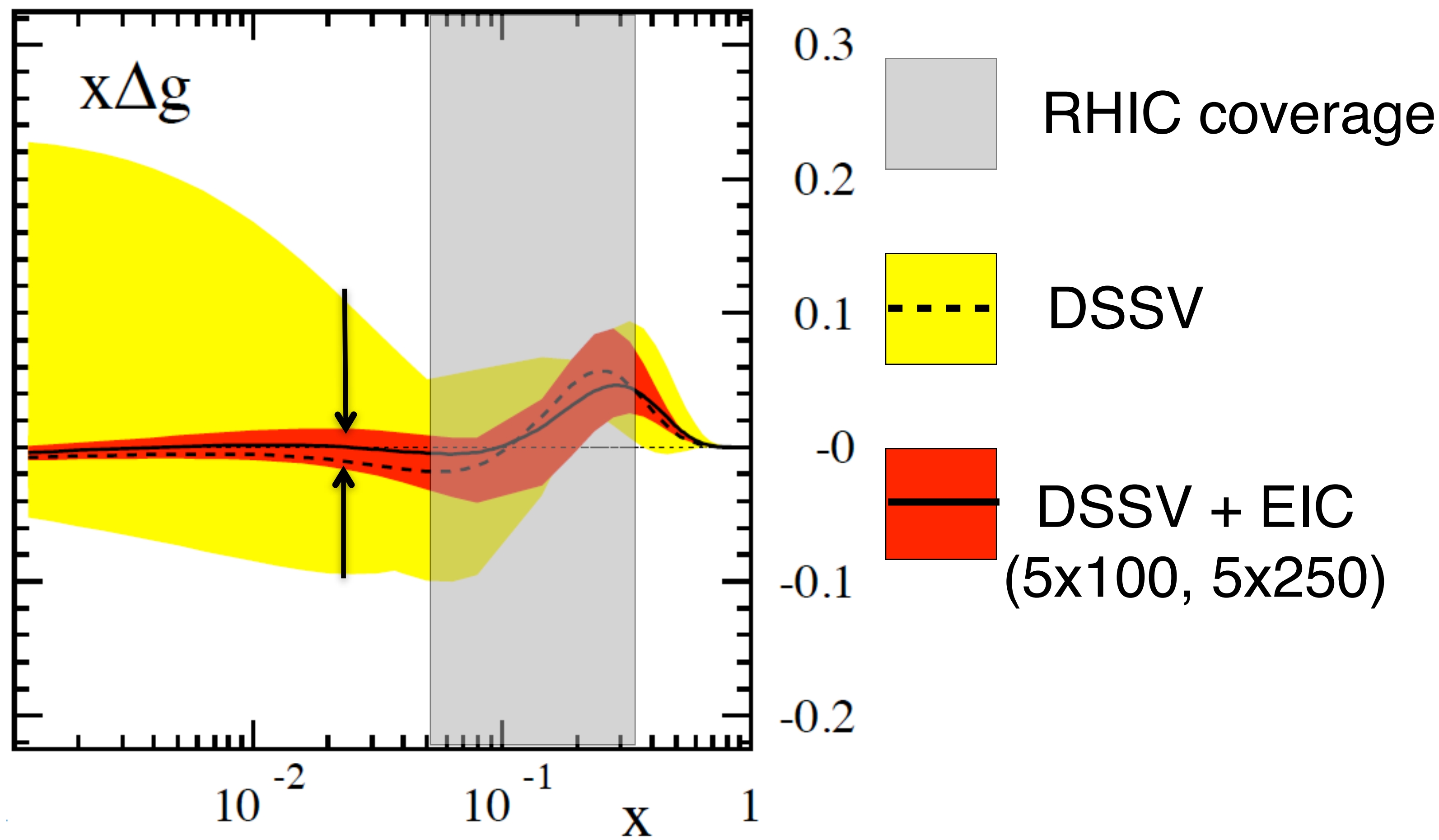


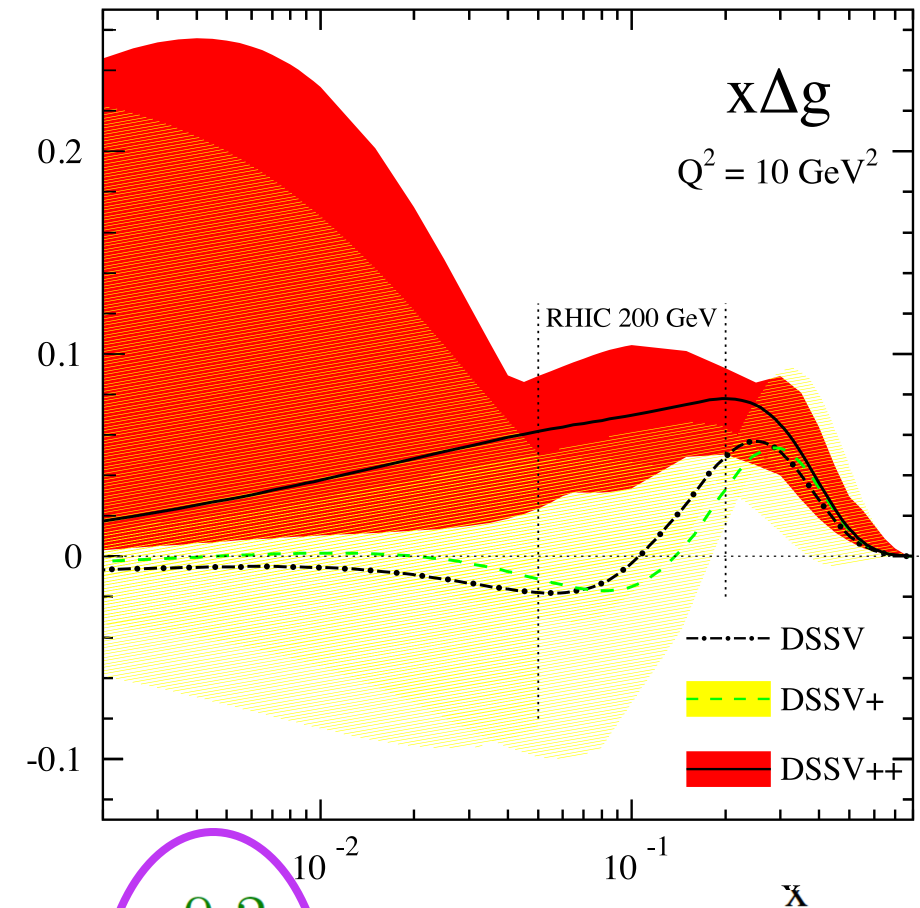


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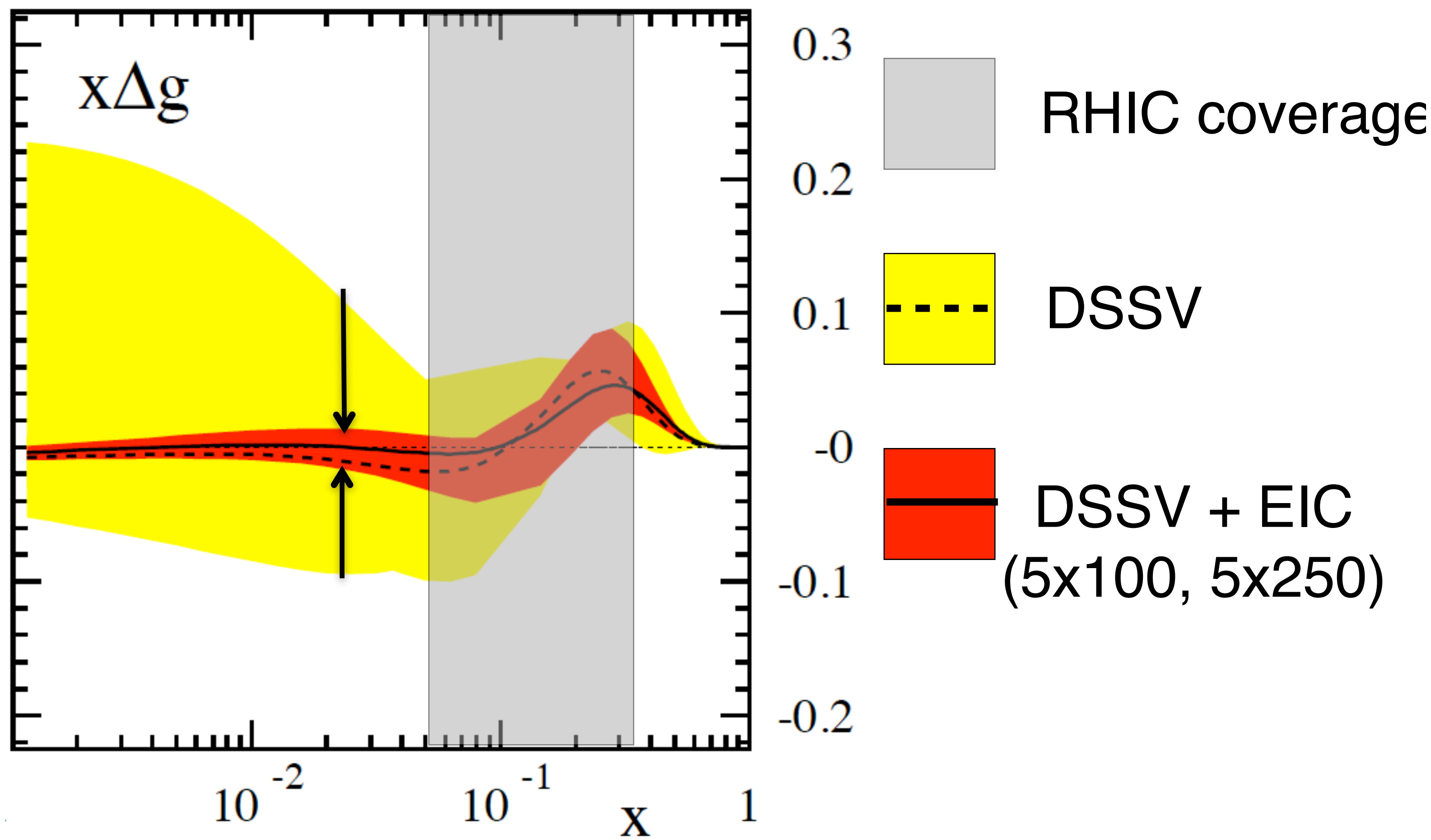


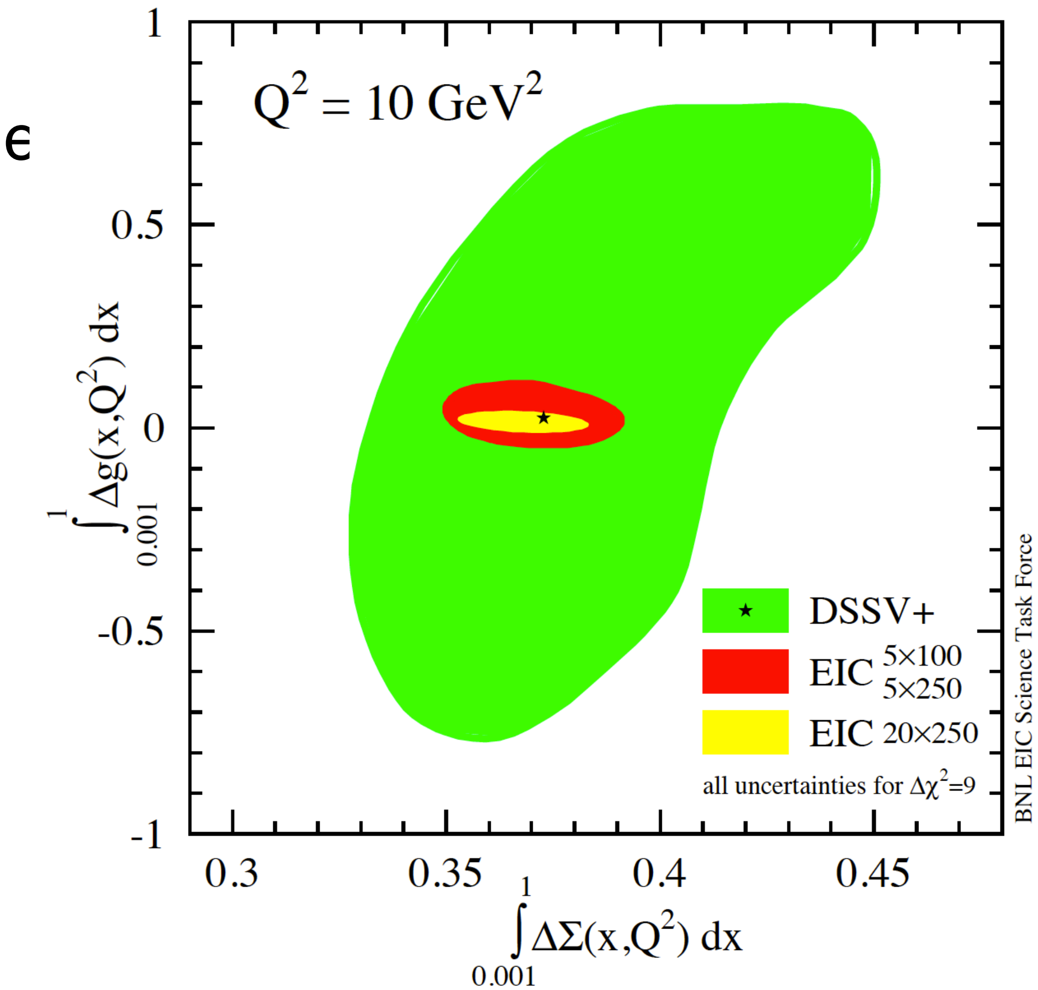


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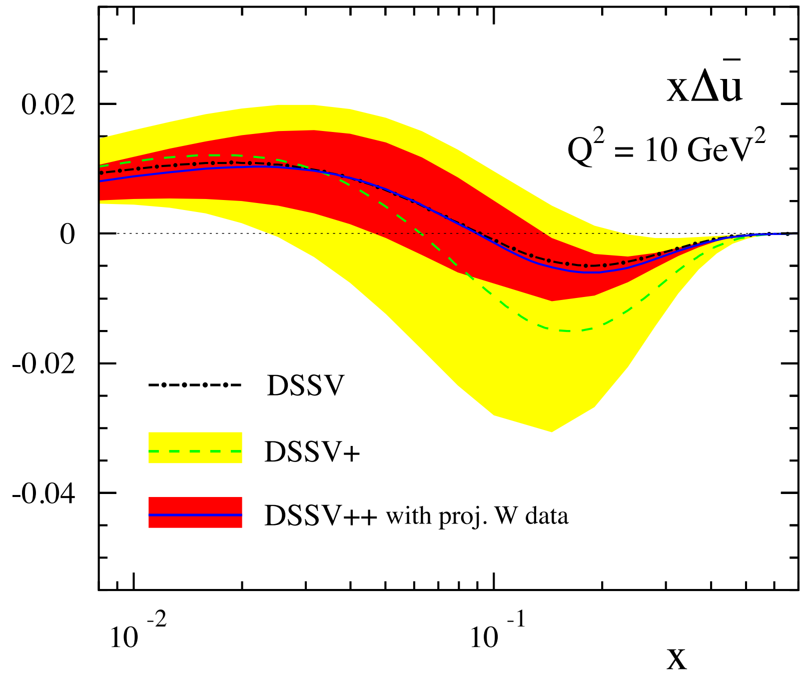
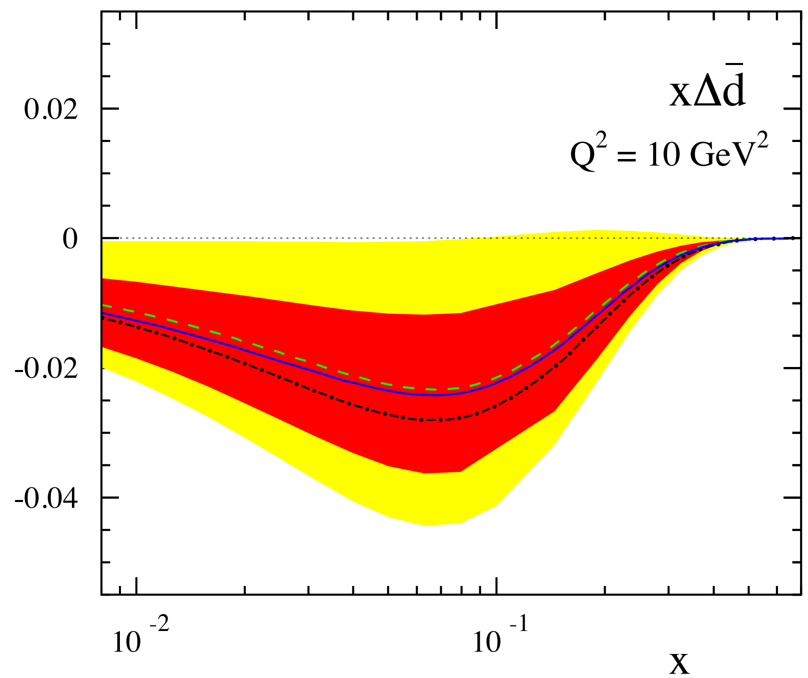
# SIDIS in e+p → flavour-separated helicity PDFs

- SIDIS measurements with identified π, k lead to much reduced uncertainties in the flavour-separated helicity PDFs as in Δg(x)



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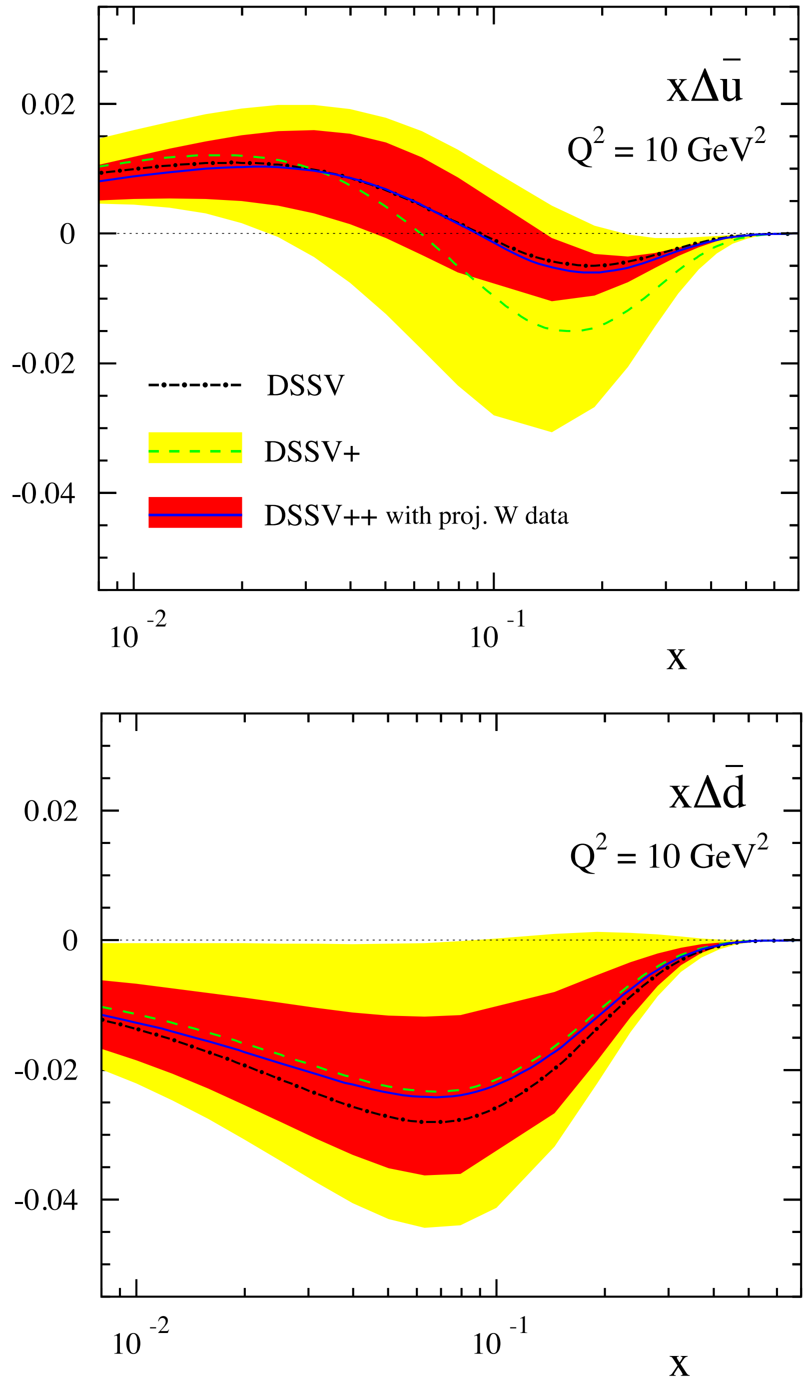
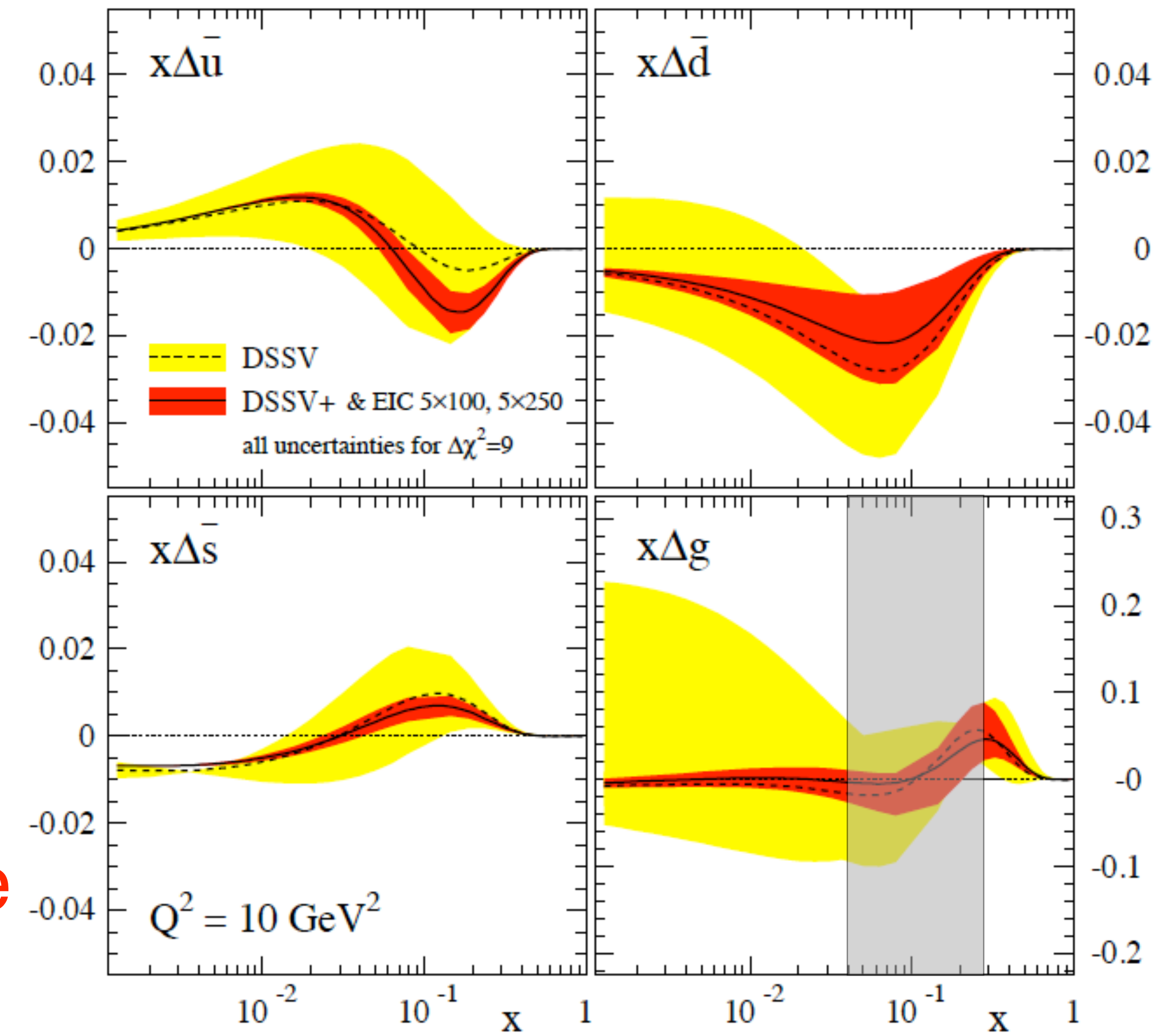



RHIC to eRHIC

smaller x; need integral from 0 to 1 for spin sum rule

Δs(s̄) cannot be accessed at existing facilities

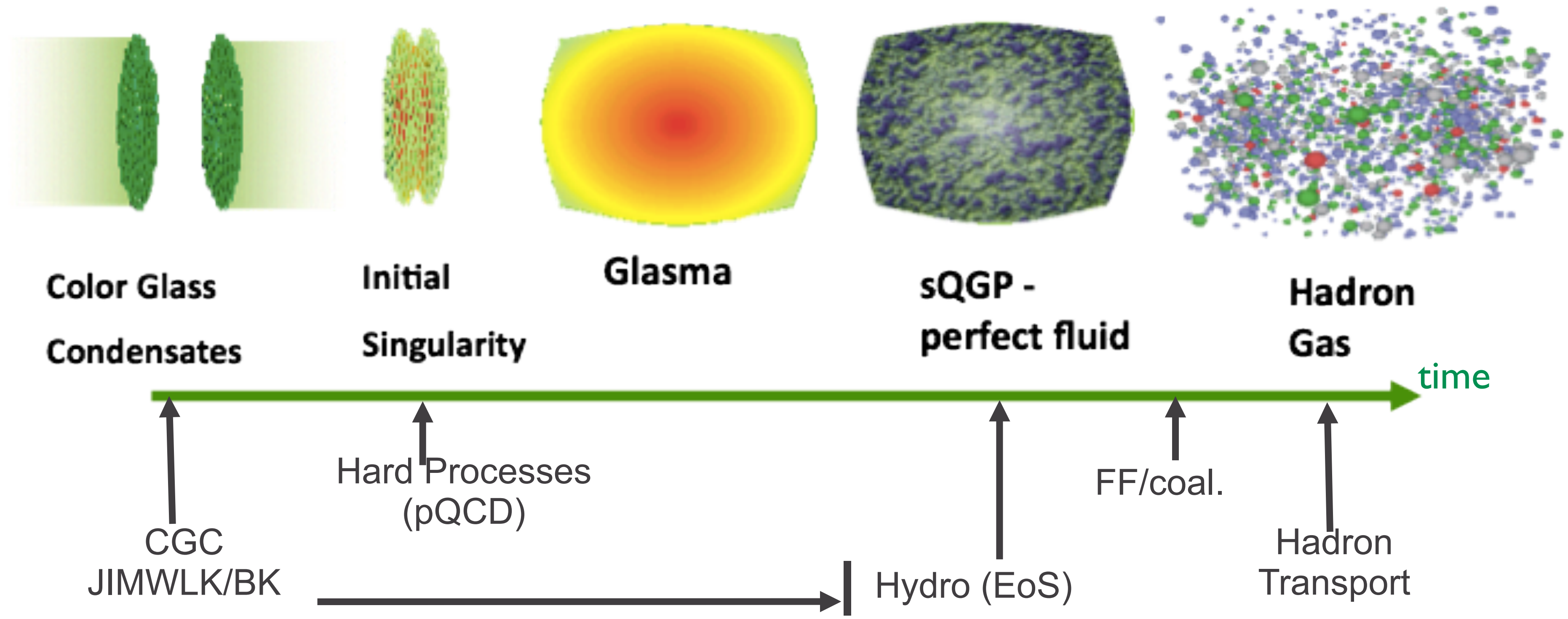


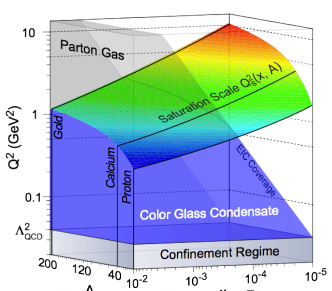

DSSV

DSSV + EIC (5x100, 5x250)

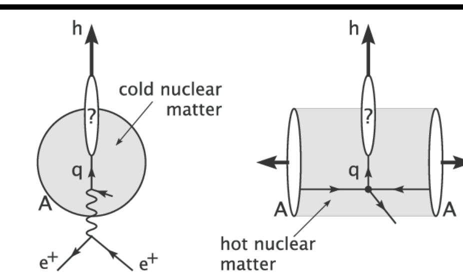
RHIC coverage

# Most compelling physics questions




## Strong Colour Fields and Hadronisation

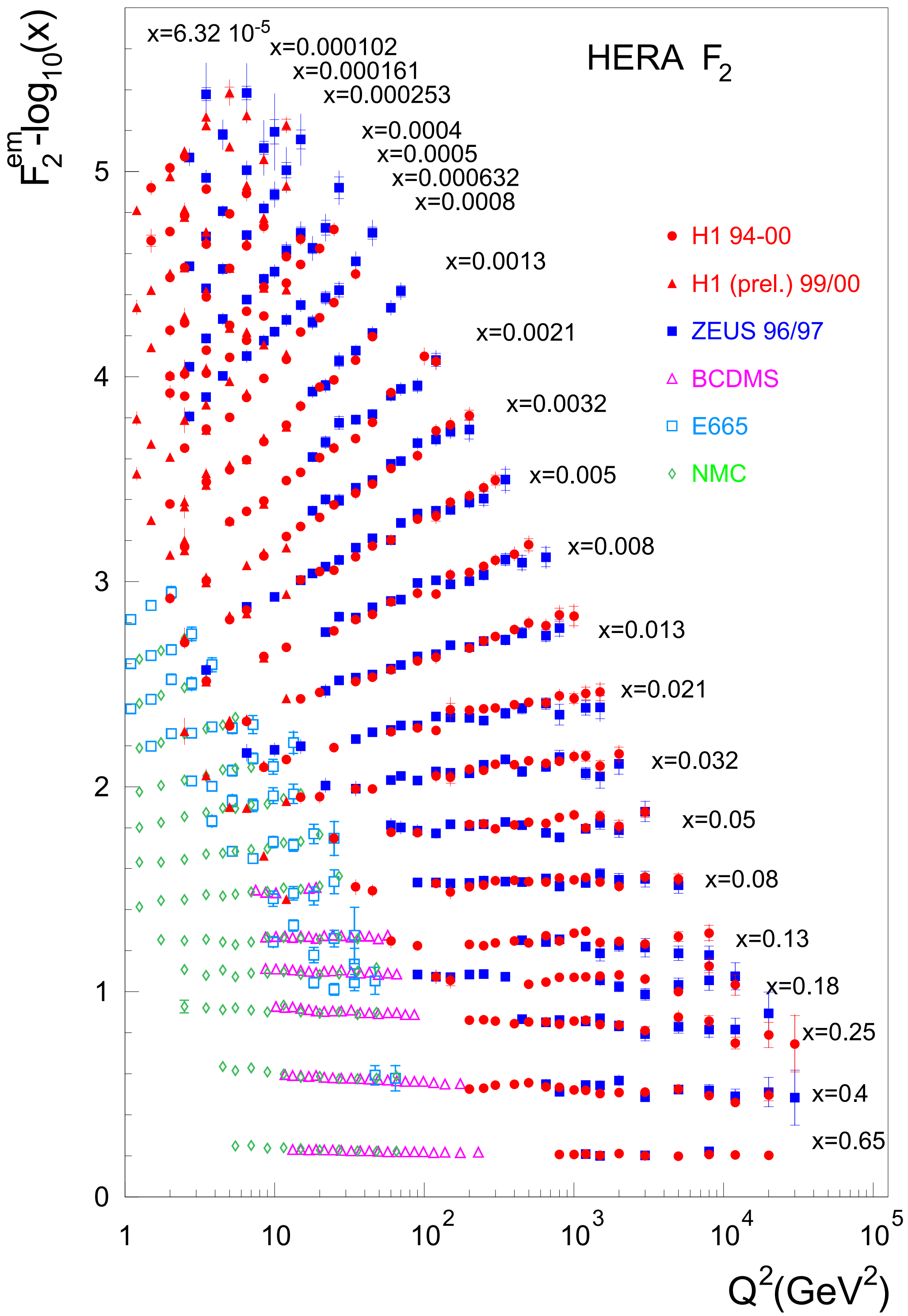



- Quantitatively probe the universality of strong colour fields in A+A, p+A and e+A
- Understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- What is the spatial distribution of quarks and gluons in nucleu and how much does it fluctuate?
- How do hard probes in e+A interact with the medium?

Currently have no experimental knowledge of gluons in nuclei at small x!!

# What did we learn from e+p collisions at HERA?

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




**quark+anti-quark momentum distributions**

**gluon momentum distribution**

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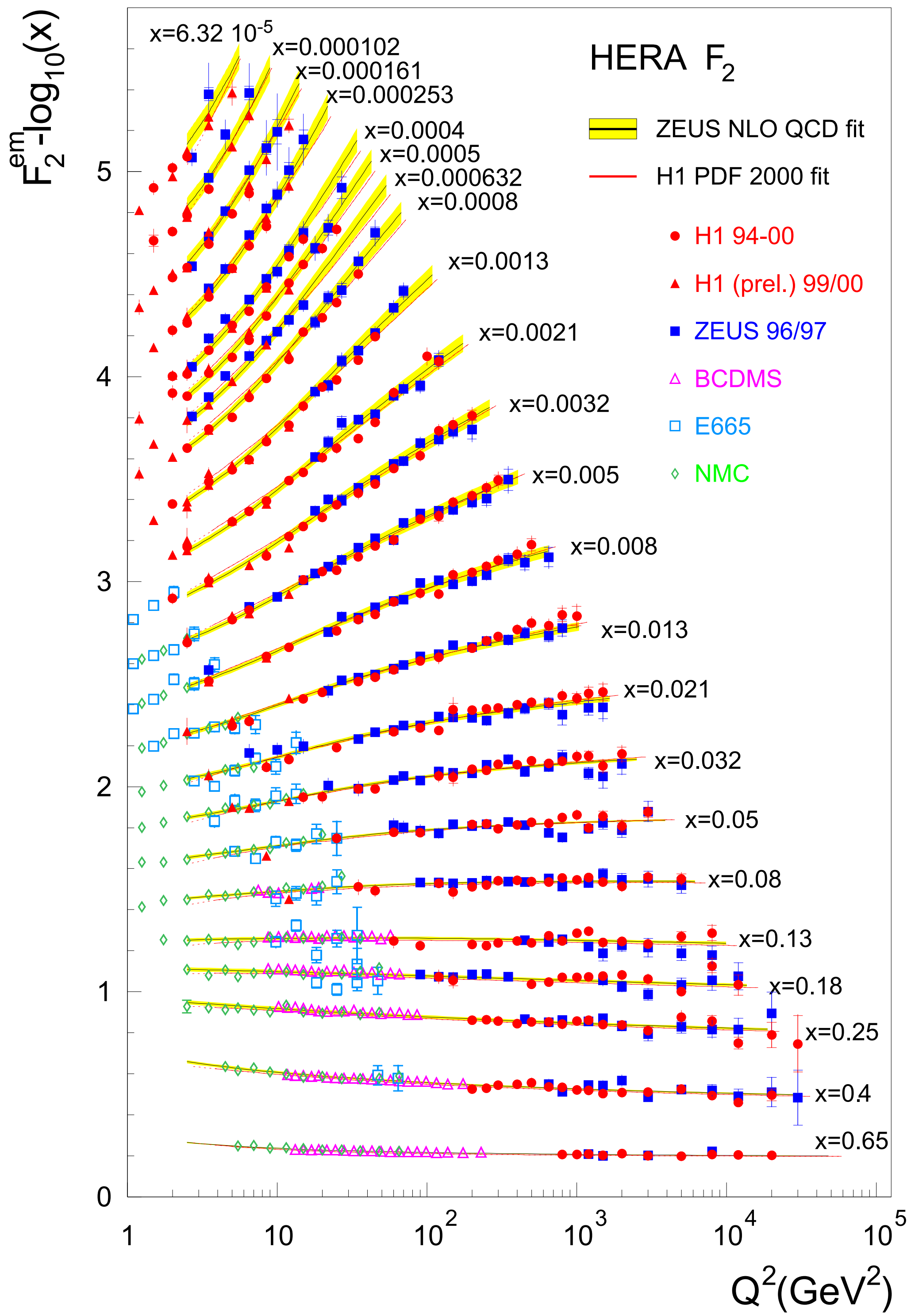


Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

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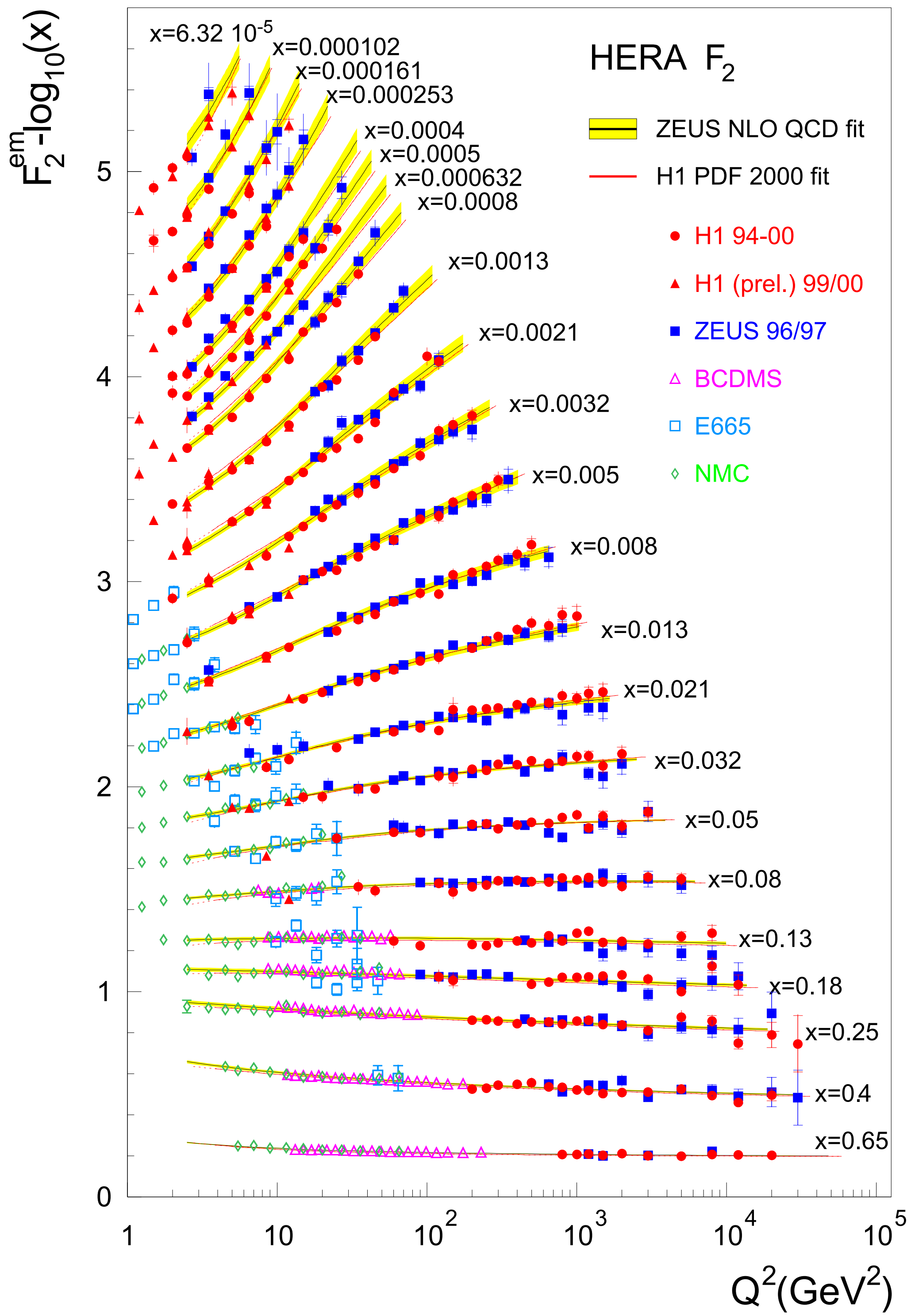
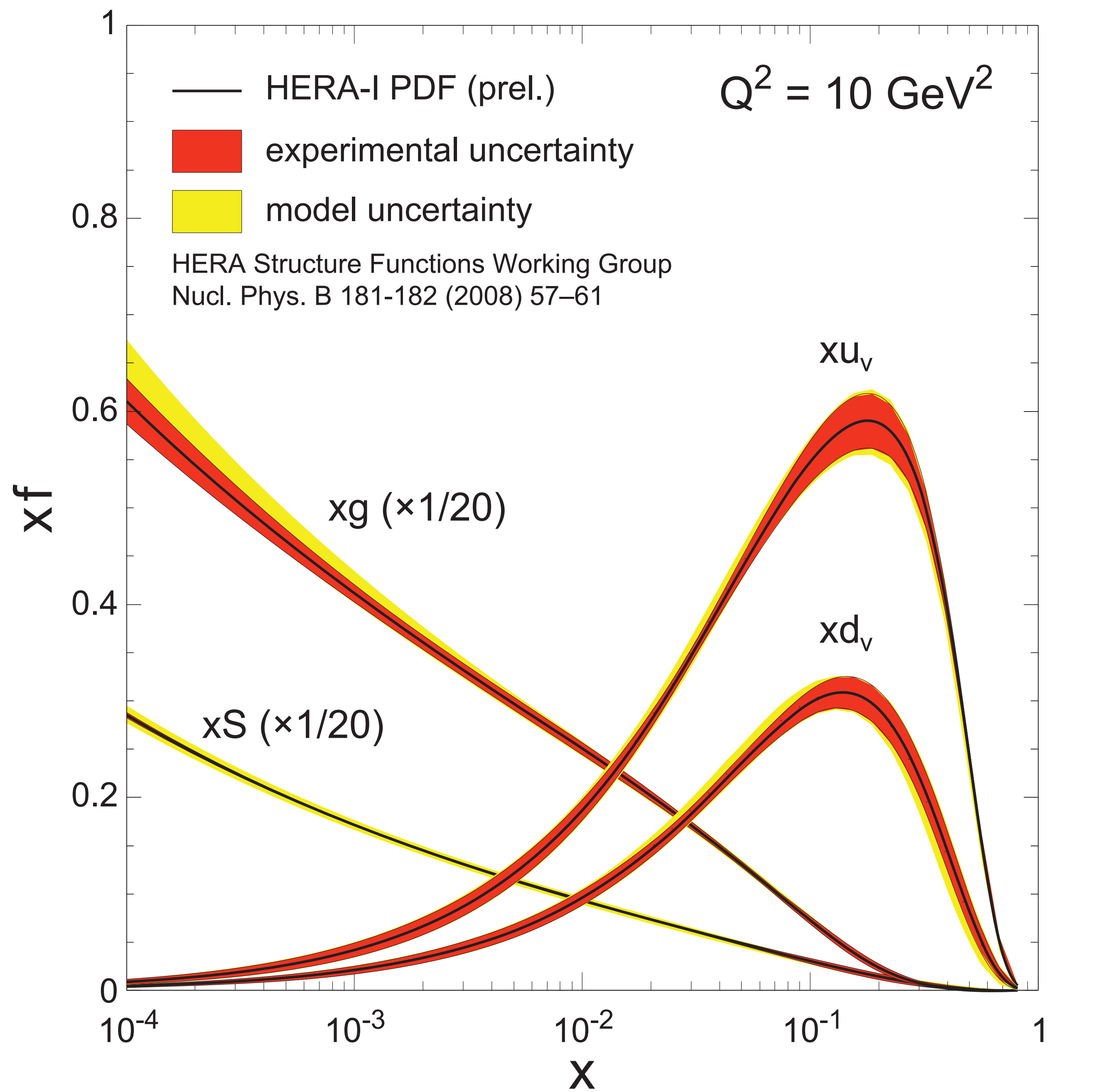



Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$



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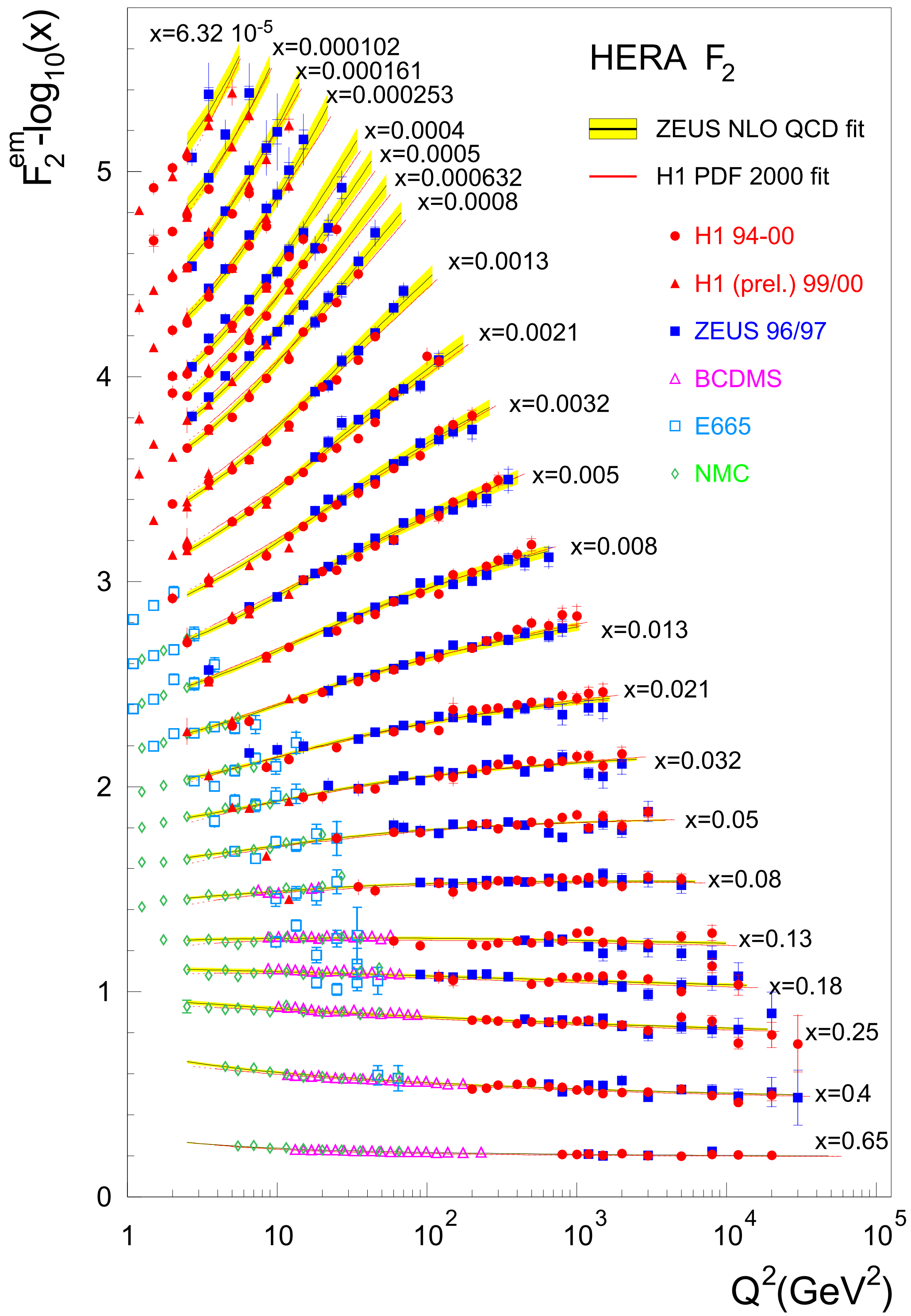


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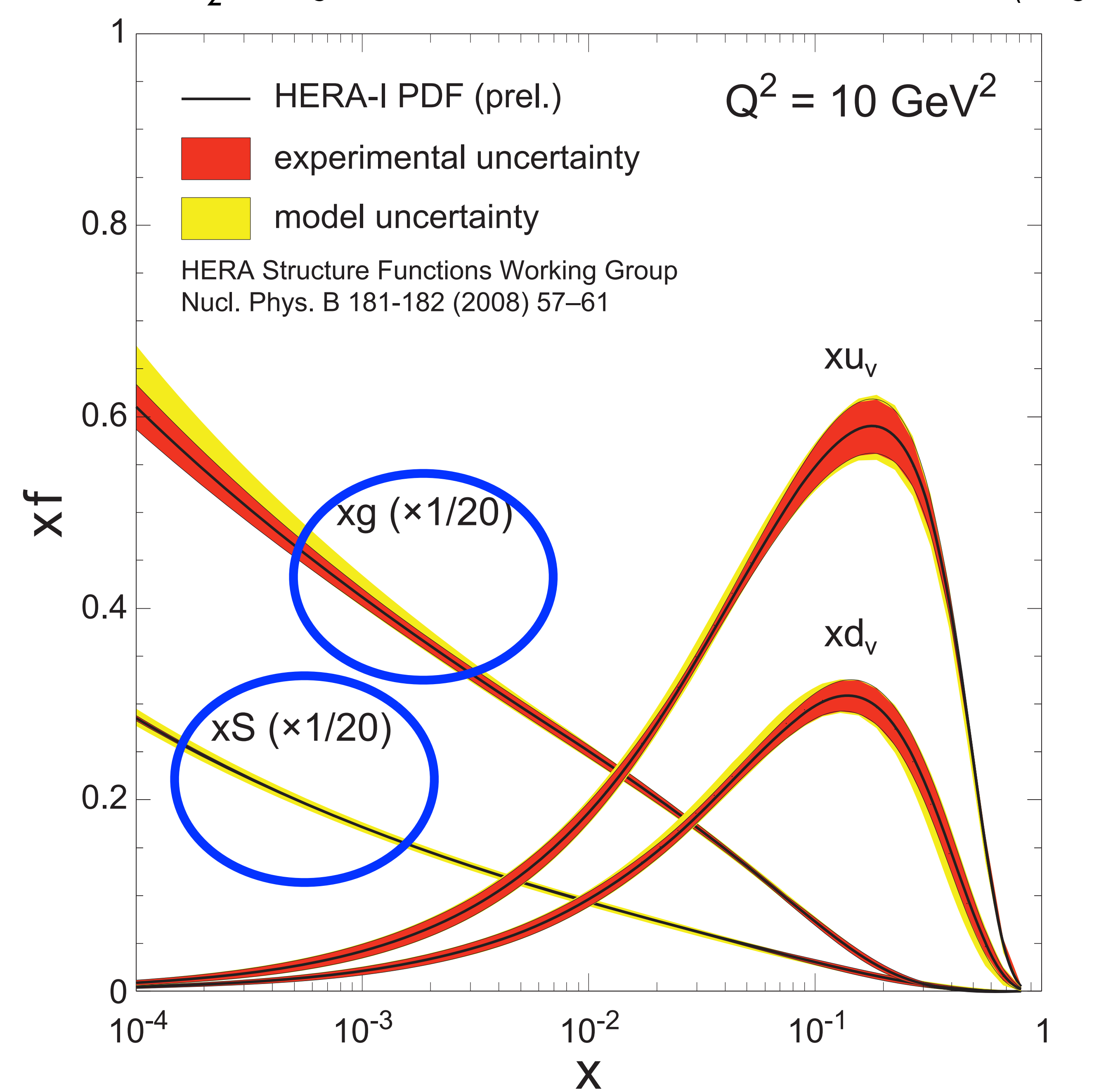

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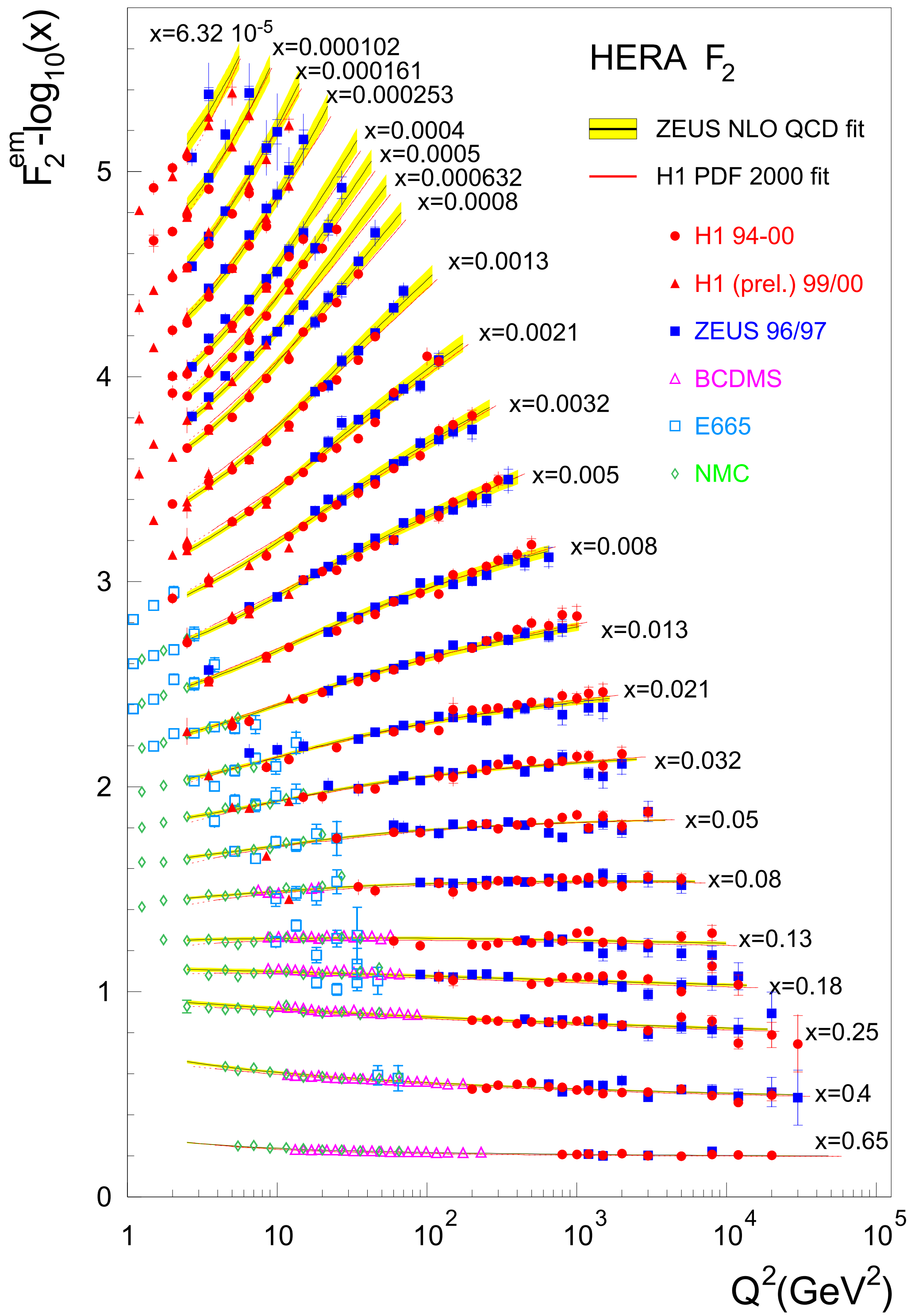


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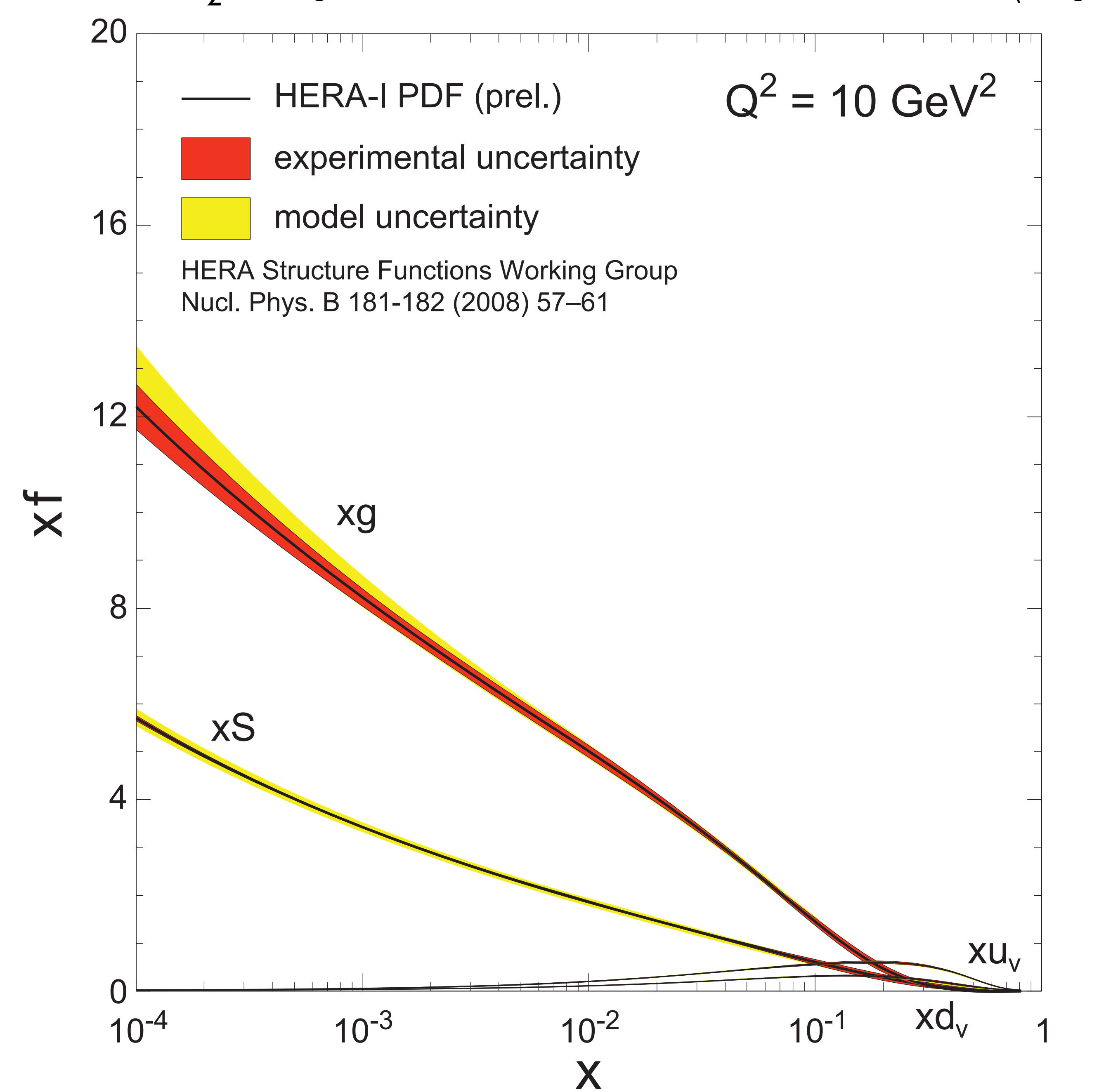
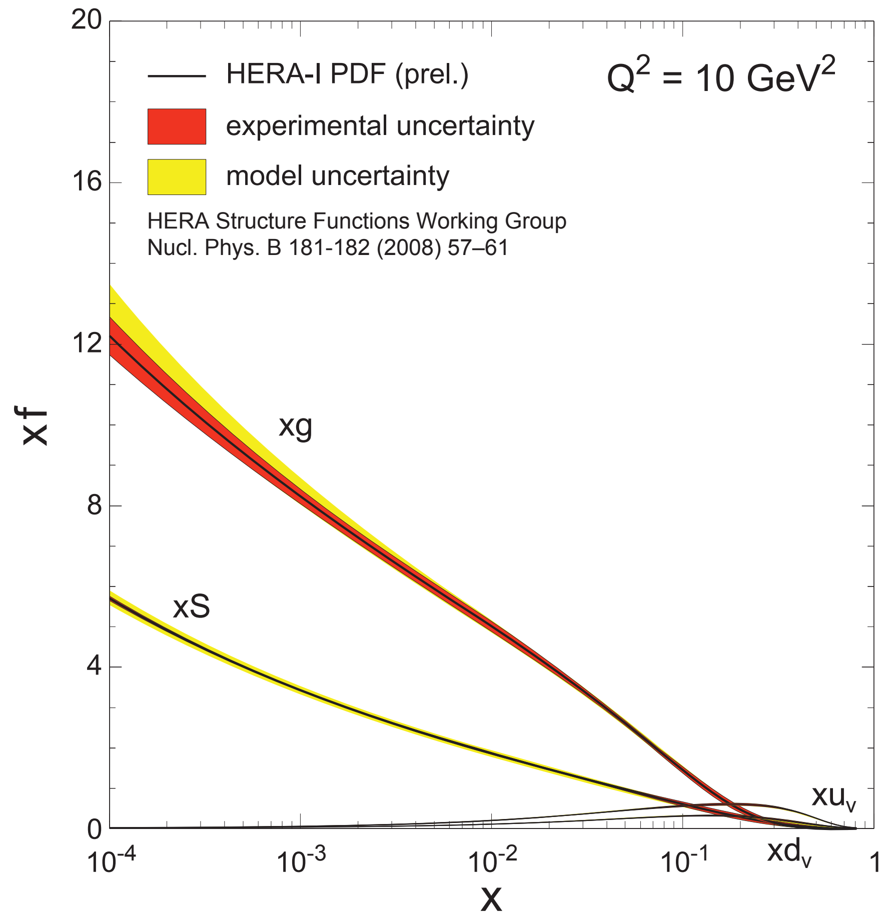
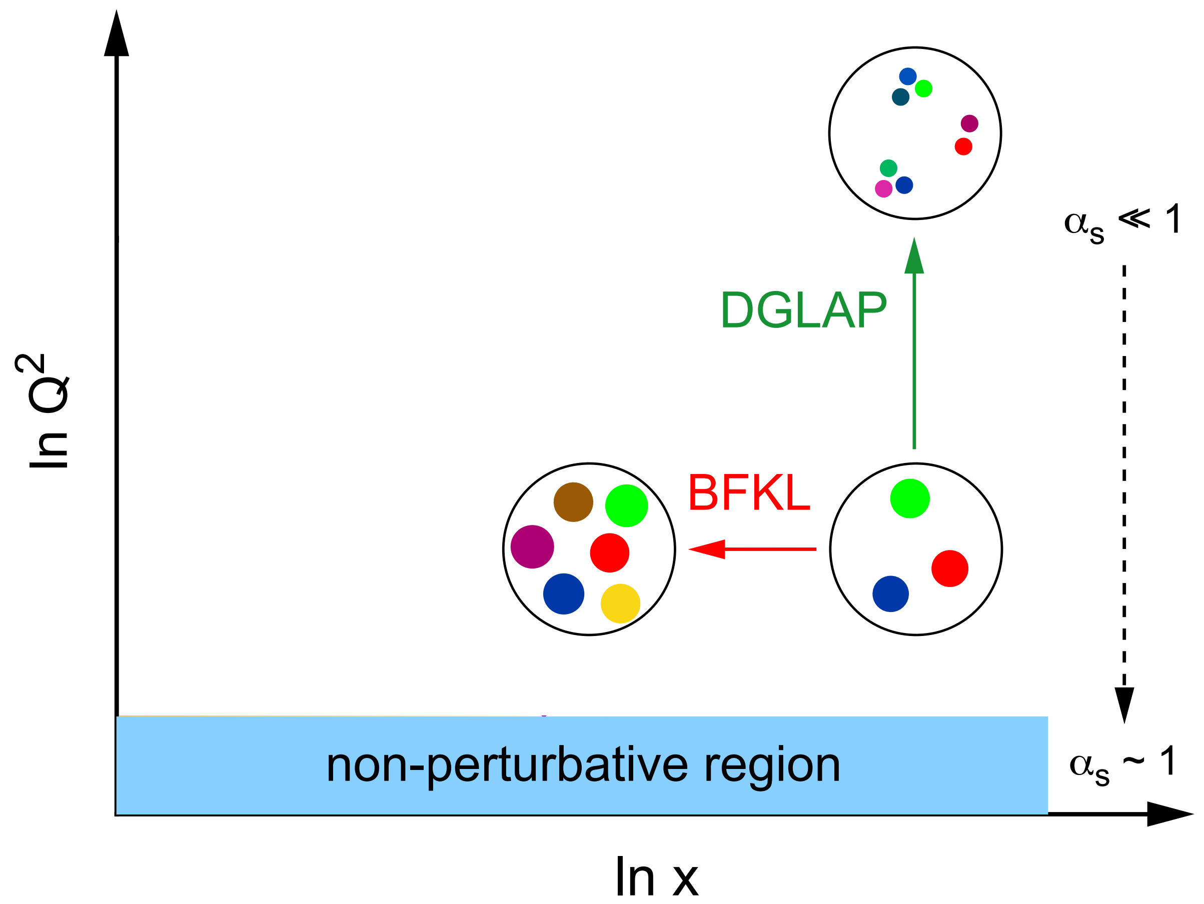


# The structure of matter at small-x




- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
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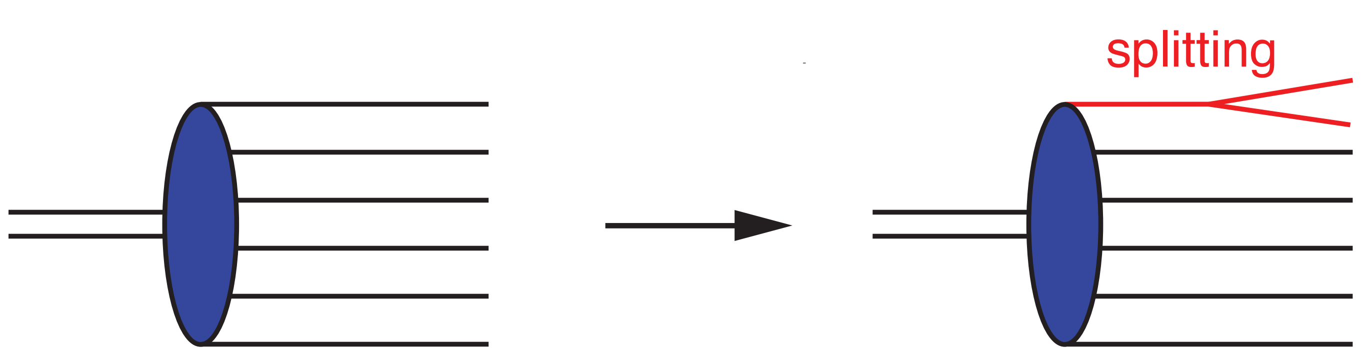

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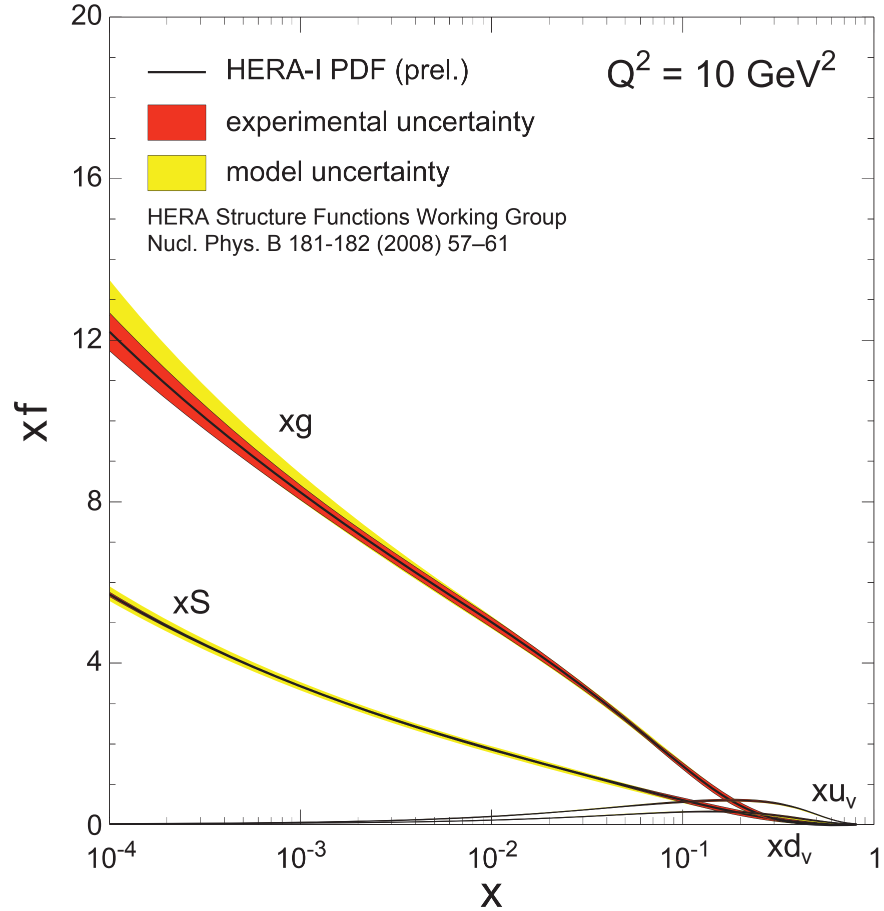


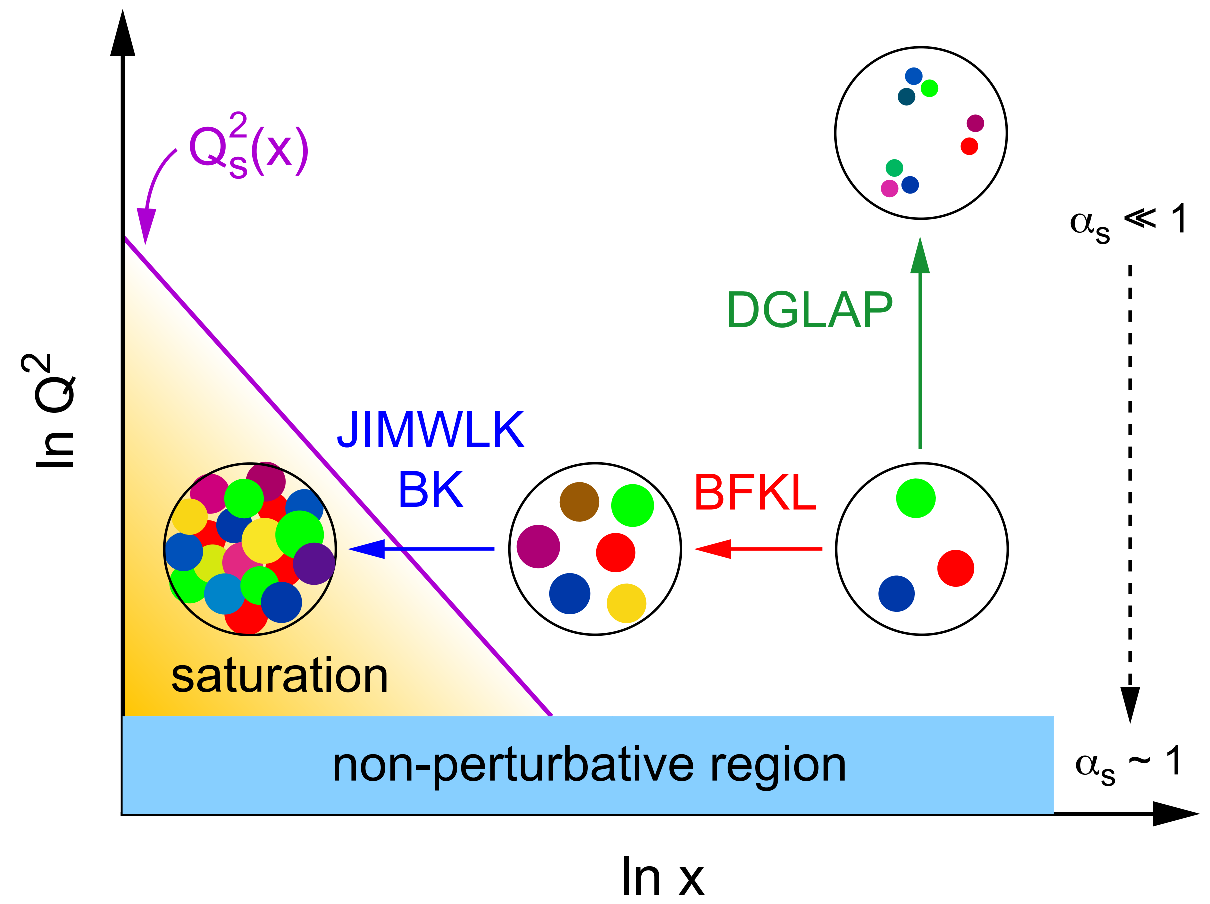


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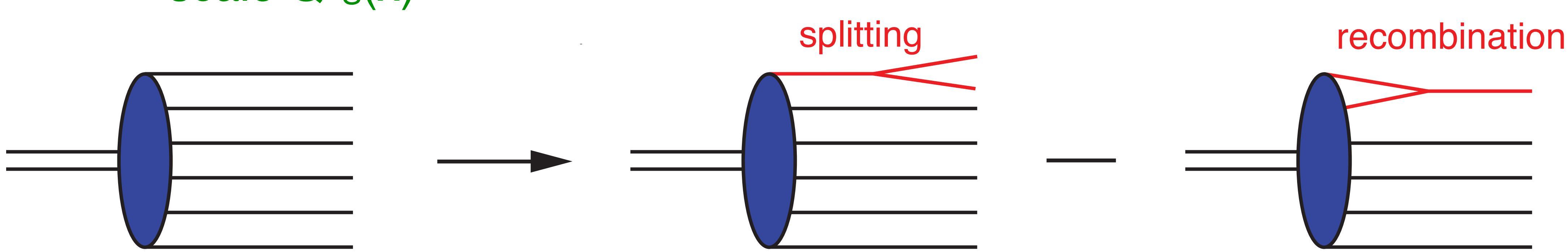
  - ➡ This rise cannot increase forever - limits on the cross-section
    - ▸ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_S(x)$



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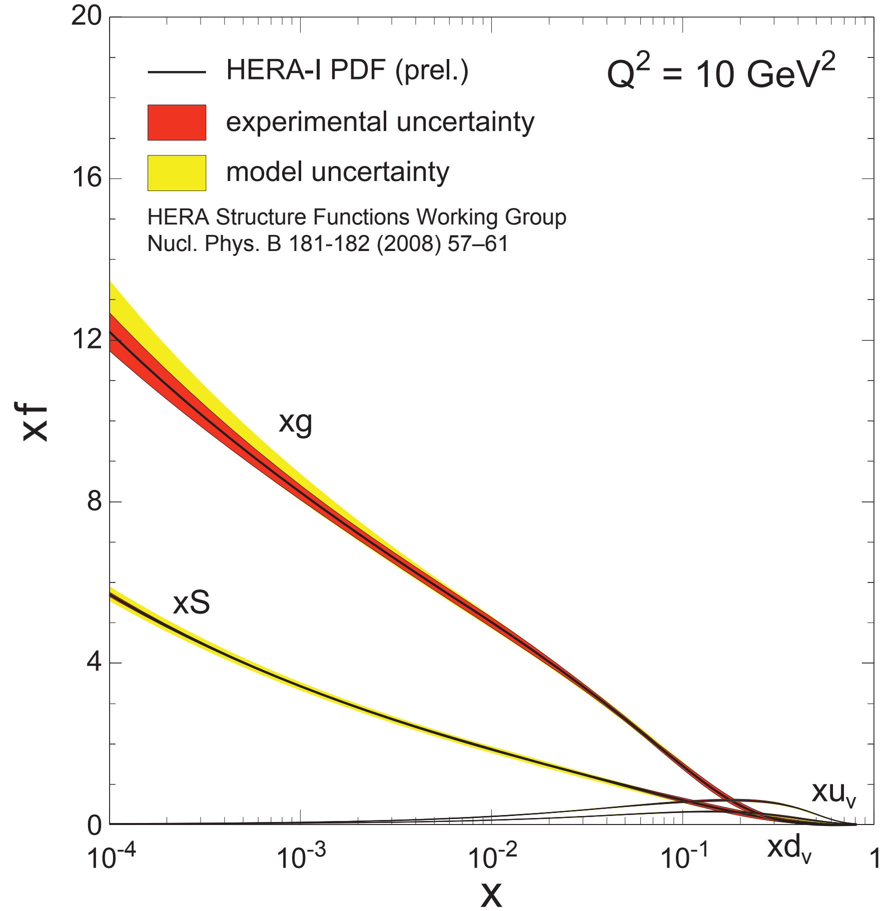


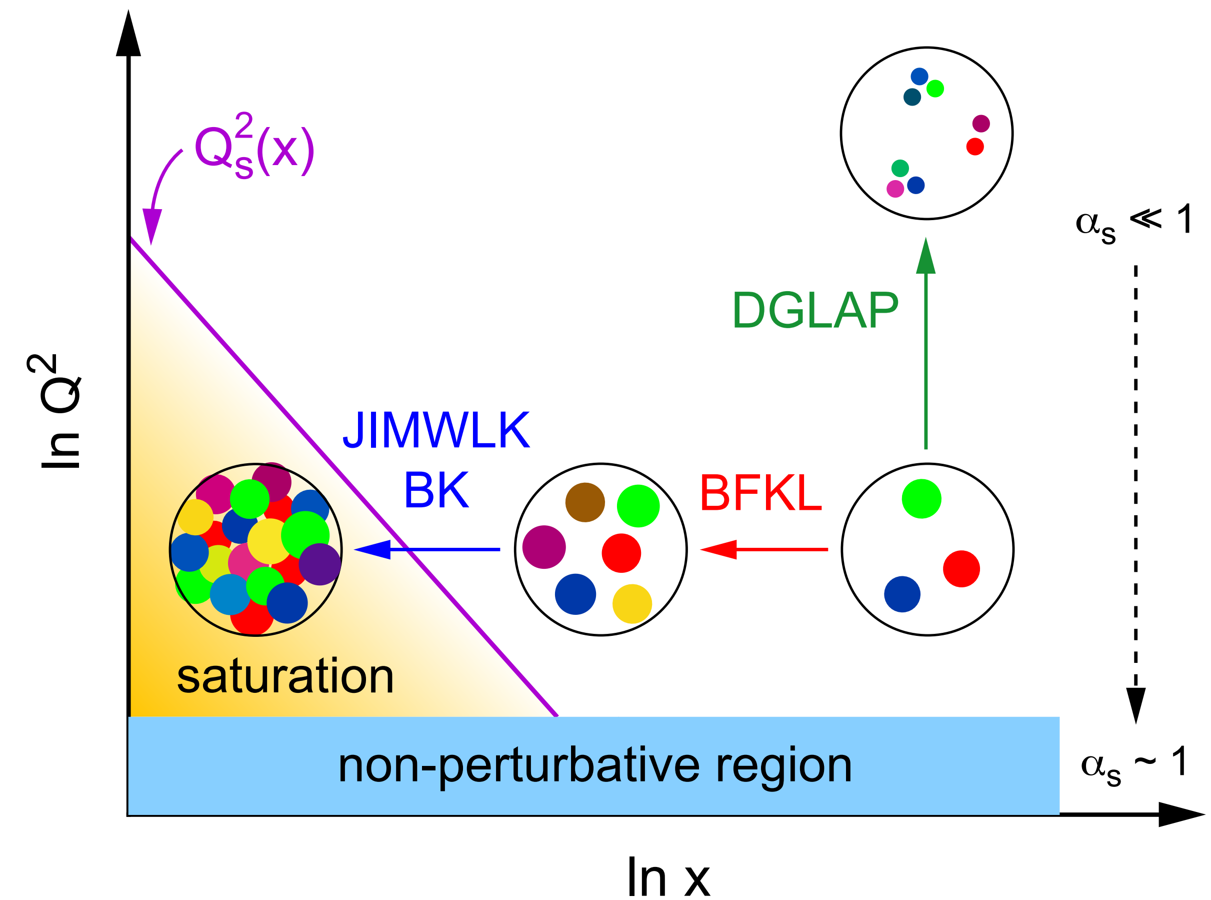


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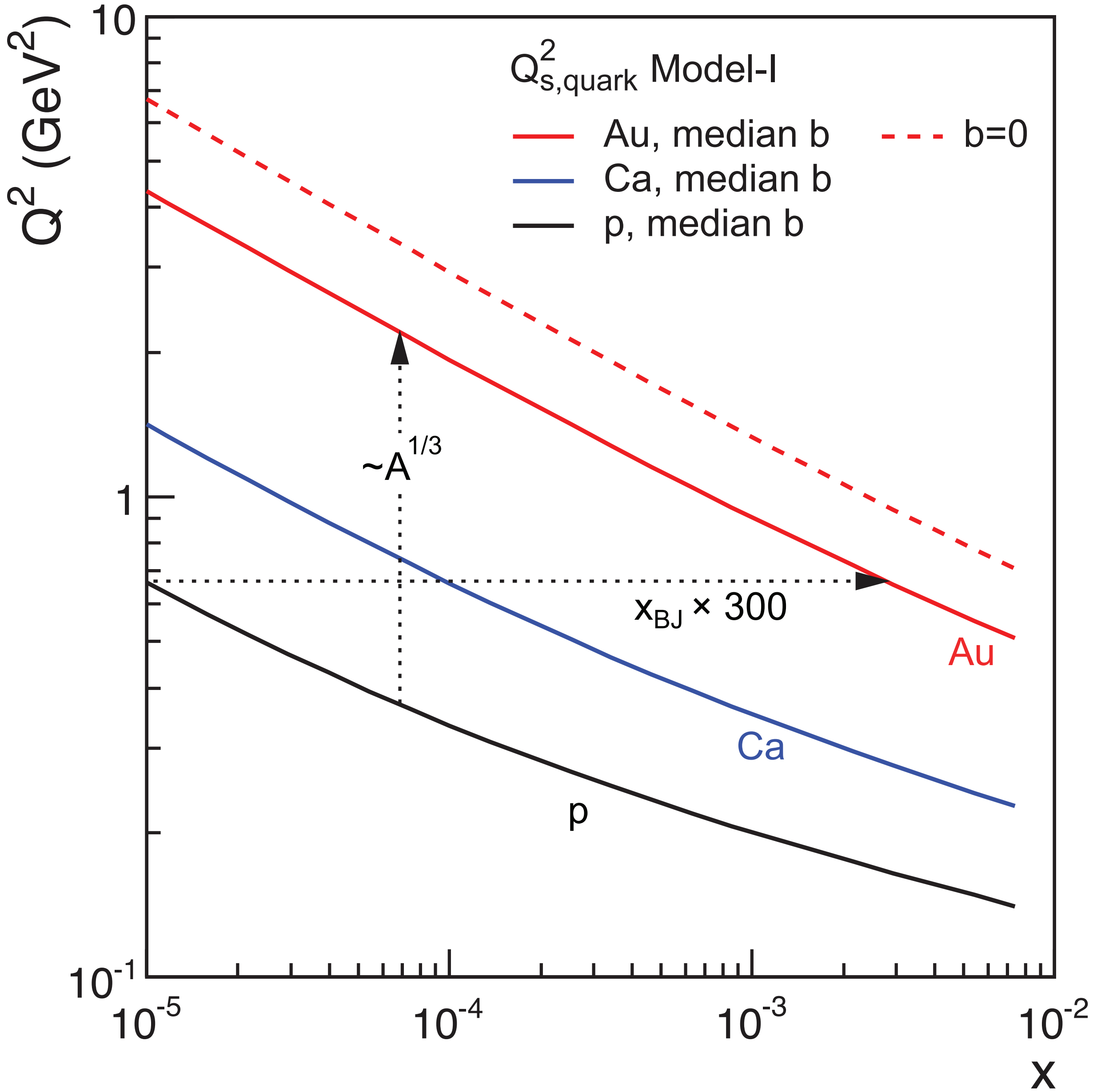
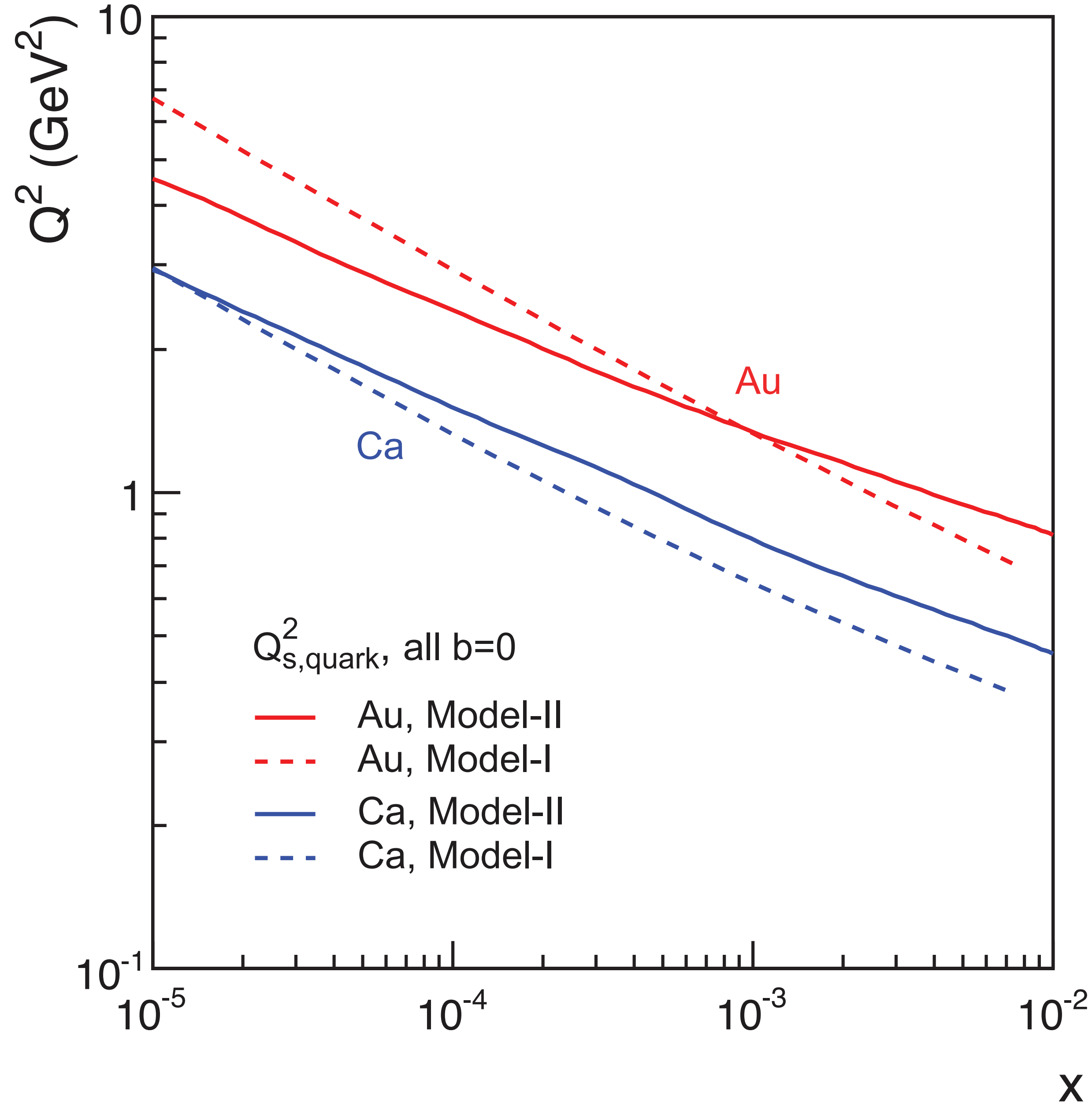
**however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x**

**How can this be observed at eRHIC?**

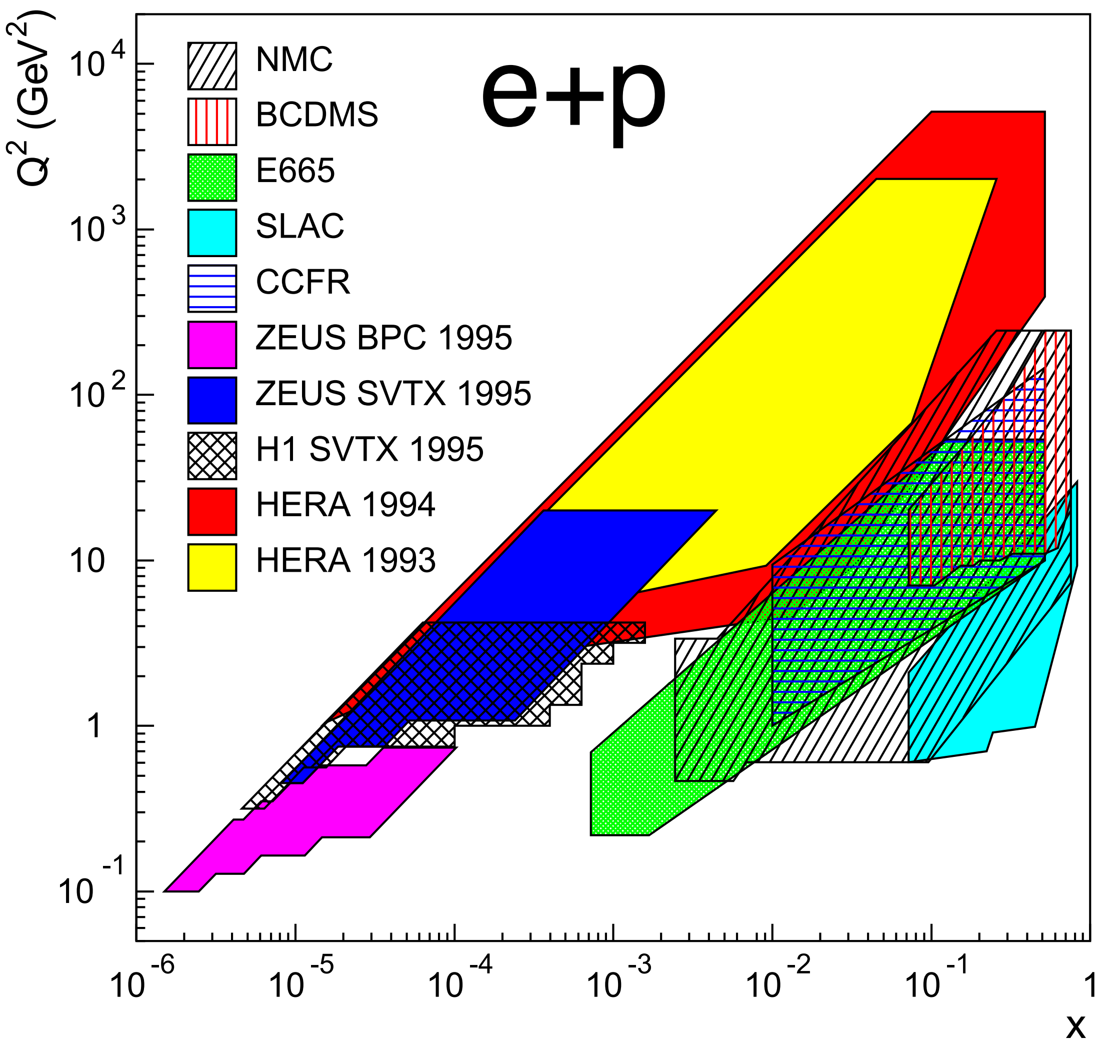
# Nuclear "oomph" effect

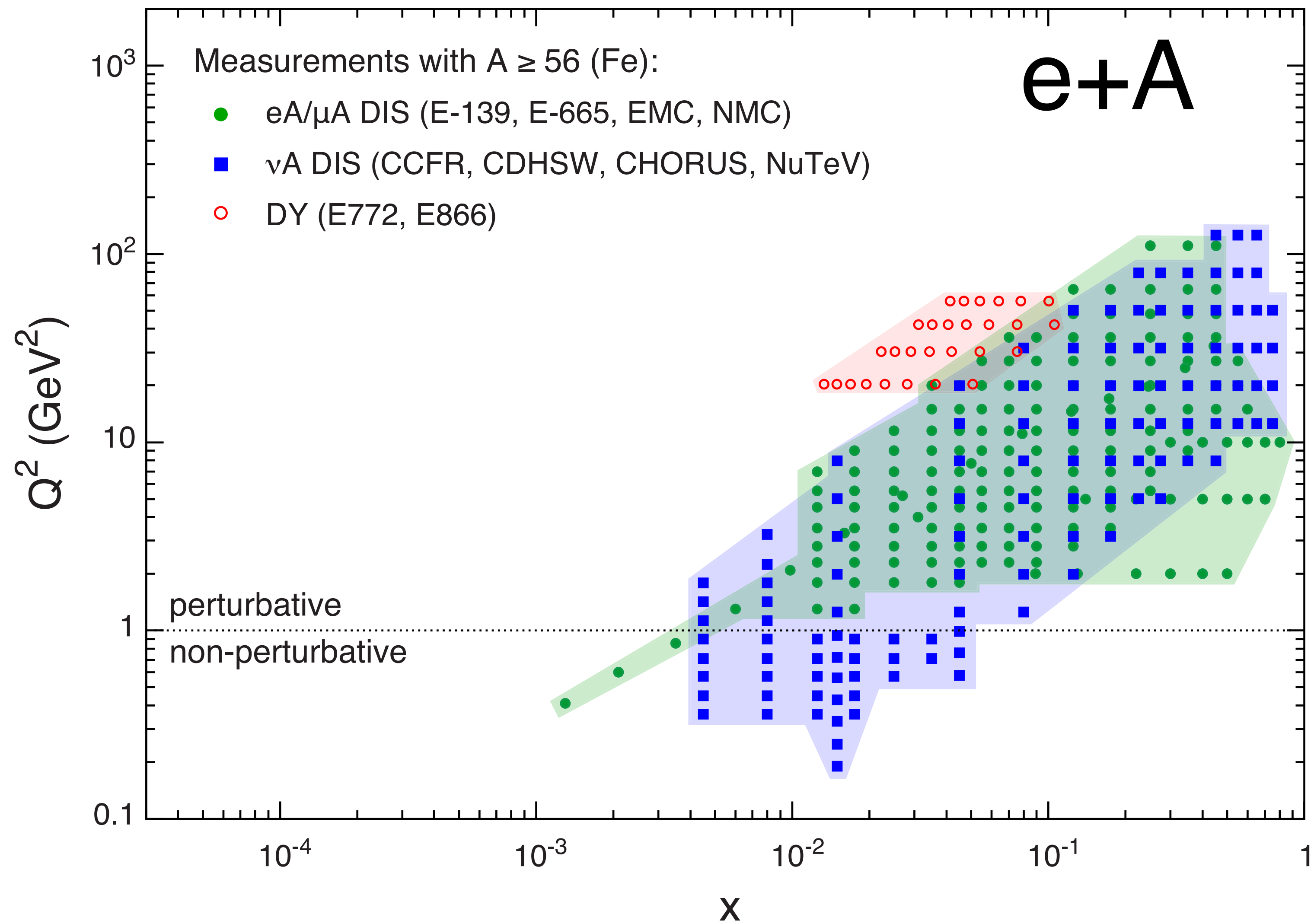
Pocket formula: $Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$



# What do we know about the structure of nuclei?




- e+p data covers large part of phase space
  - ➡ low x and large $Q^2$
- e+A data only a small fraction of this (e+A was a fixed target programme at HERA)
  - ➡ high-medium x and low $Q^2$

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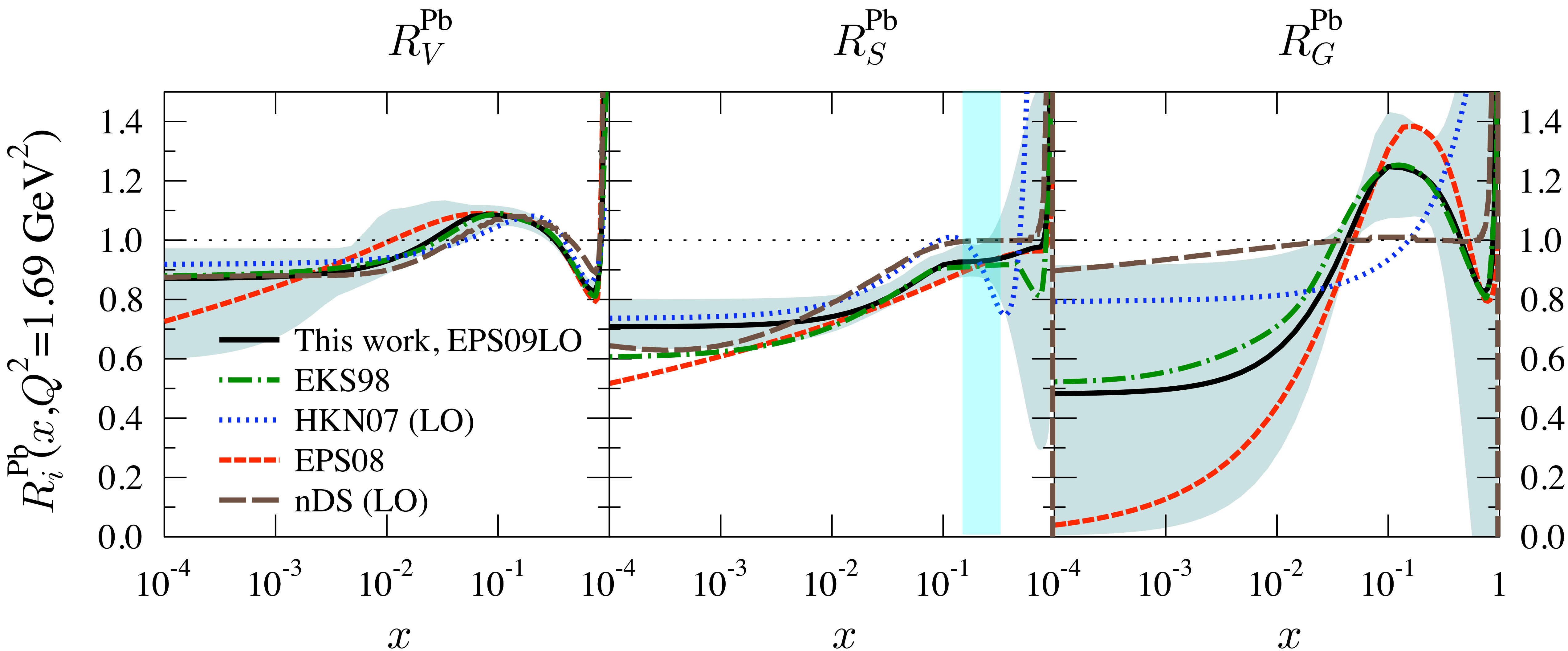


The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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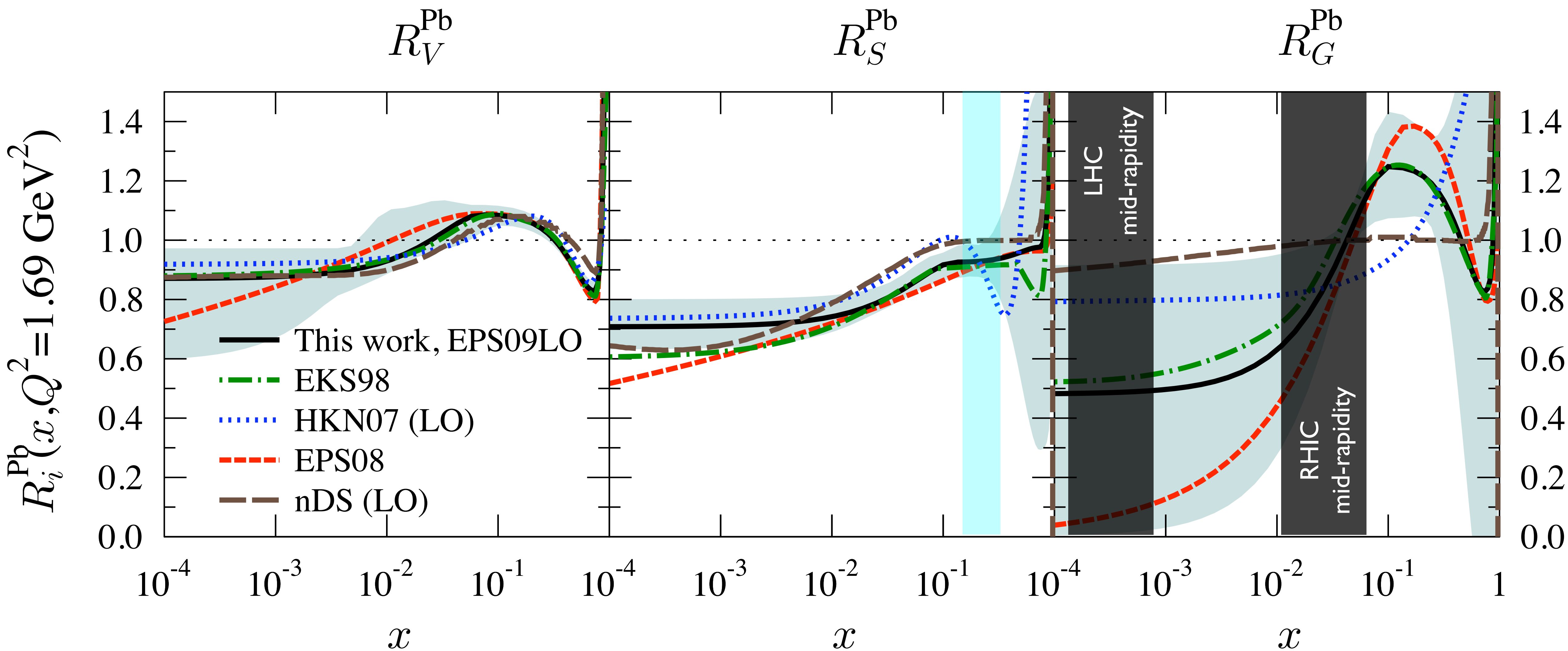


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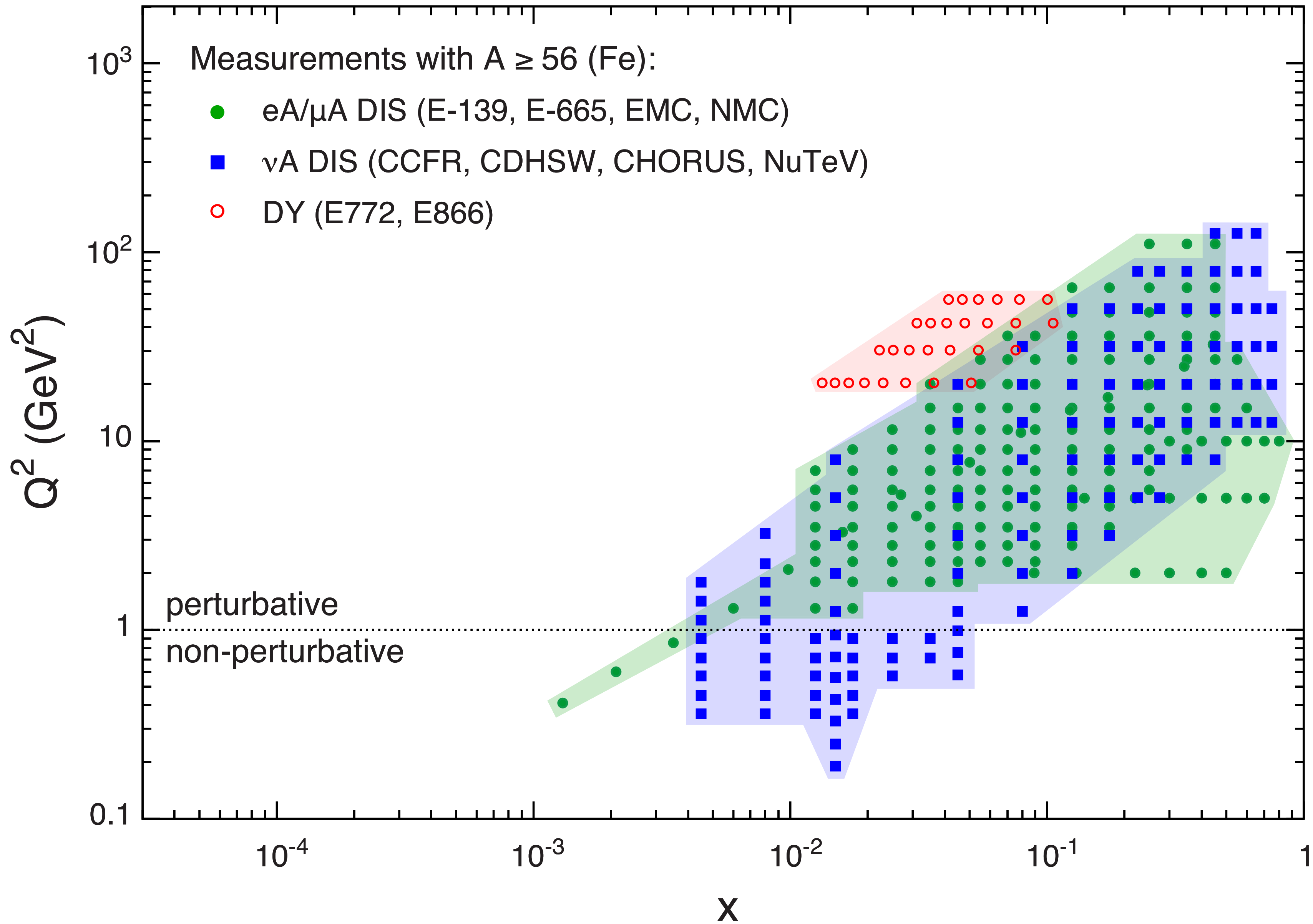
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

# Phase-space coverage of e+A collisions for an EIC

- Existing data:
  - ➡ Low energy (fixed target)
  - ➡ Low statistics
  - ➡ Mainly light A
- EIC coverage:
  - ➡ Both “low energy” and “high energy” options extend the reach in x-$Q^2$ beyond current data
  - ➡ A coverage extended up to U
  - ➡ Saturation scale at moderate $Q^2$ can be investigated at the lowest x



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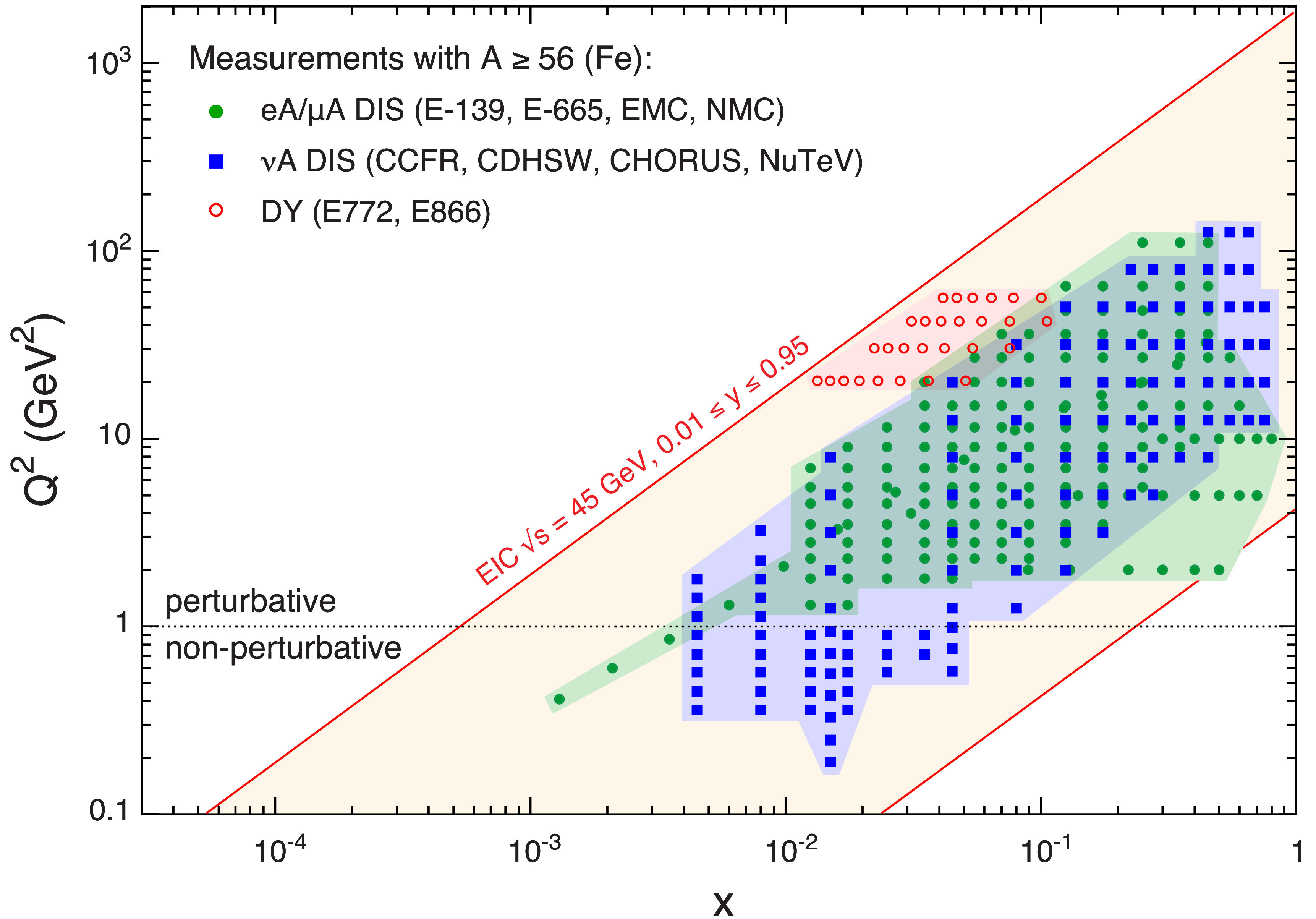

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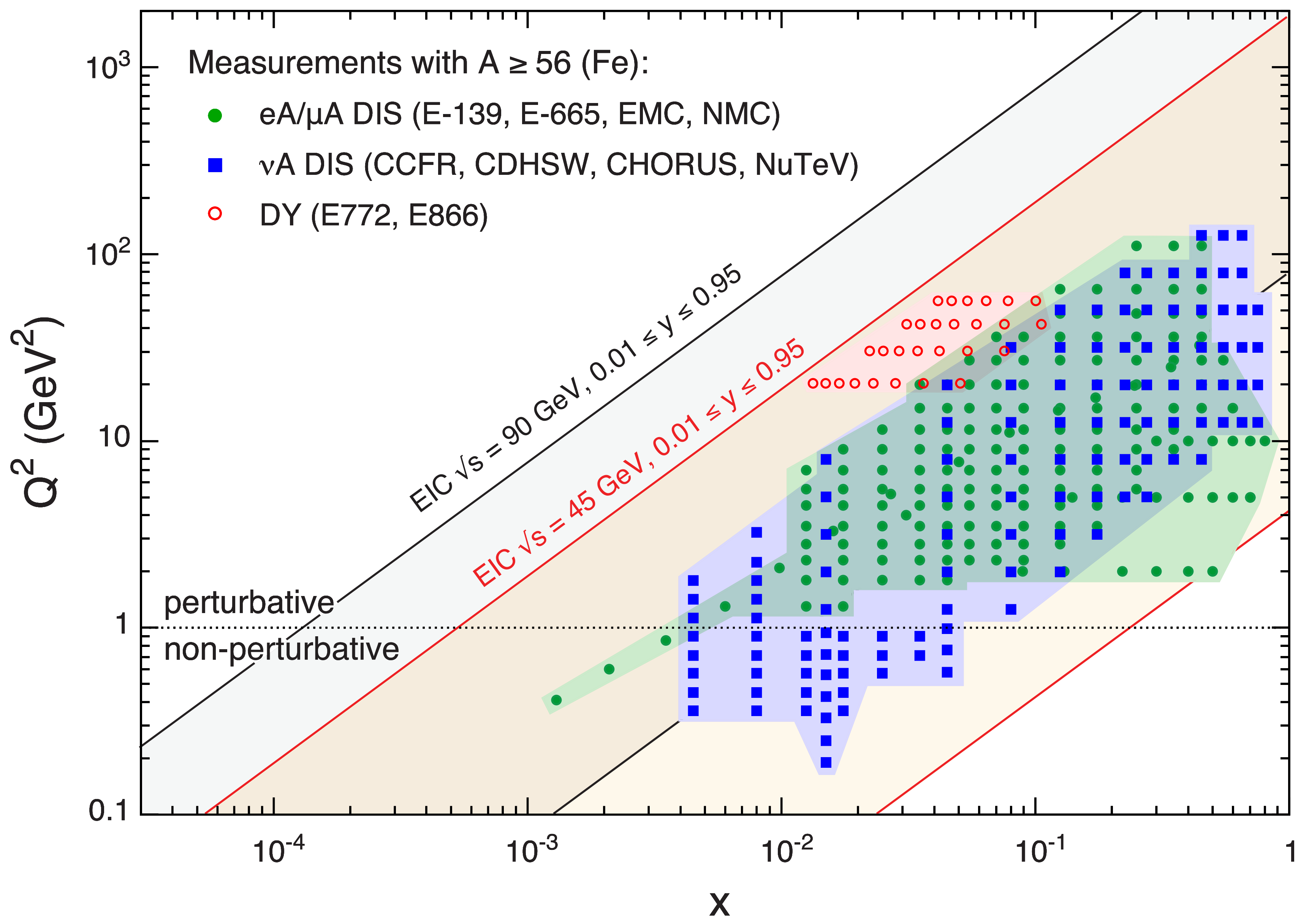

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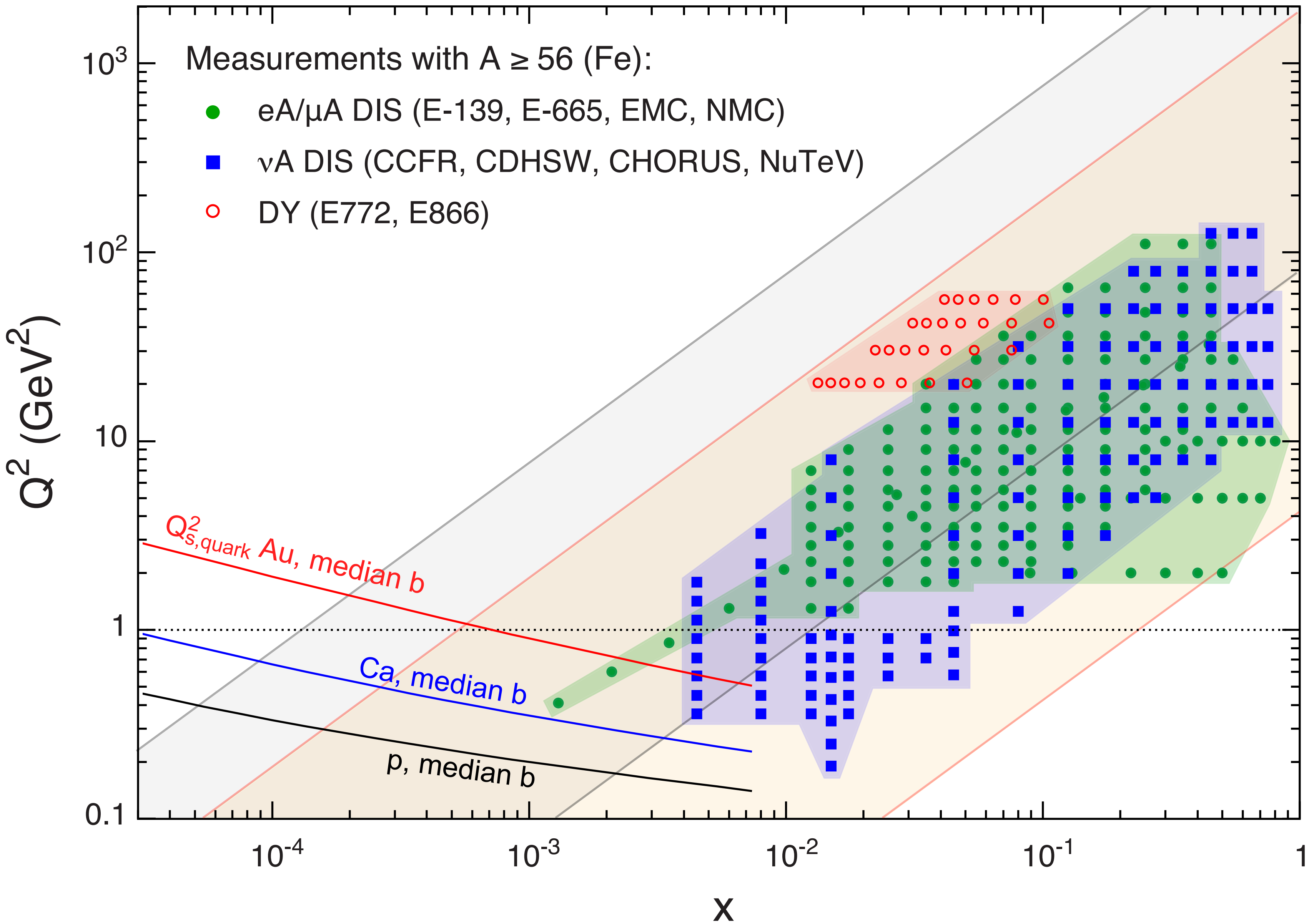
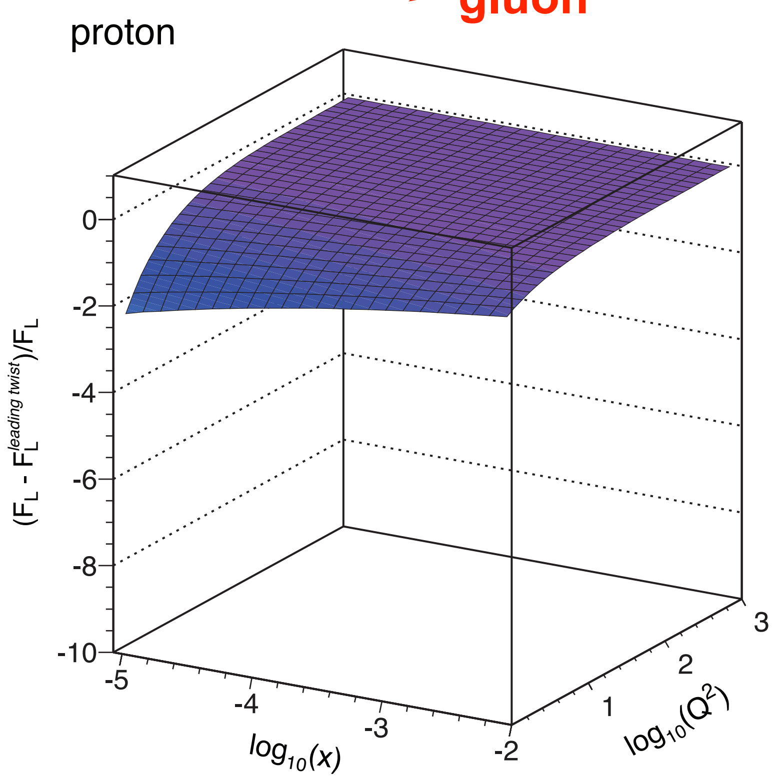


# Saturation effects in the proton and nucleus

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

**quark+anti-quark** **gluon**

Measure of non-linear effects in the $F_L$ structure function




Dipole model (J. Bartels *et al.*)

- Plotting this distribution coming out of saturation inspired GBW model
  - ➡ p: small effect only starting to come in at small-x and small $Q^2$

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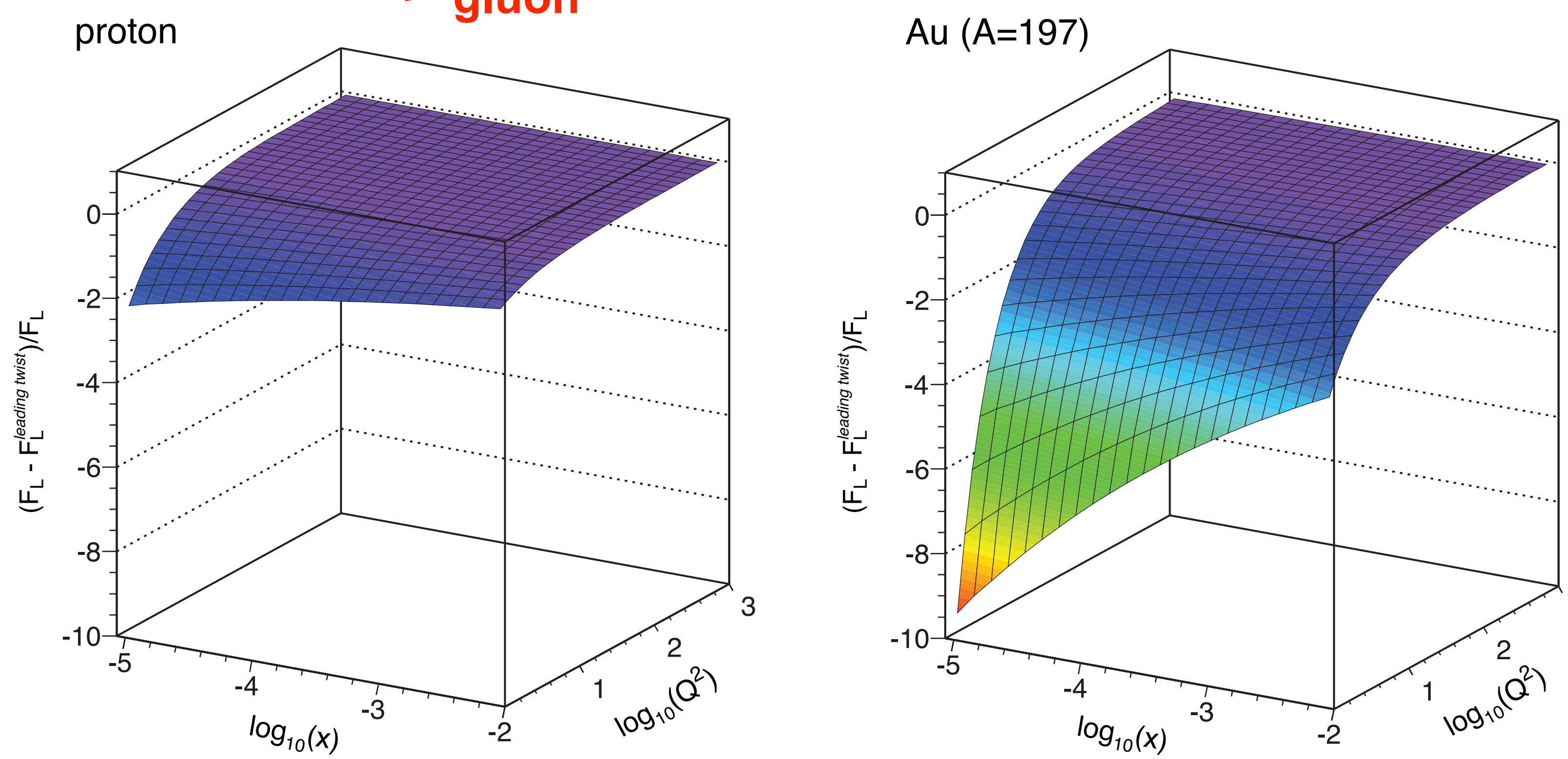


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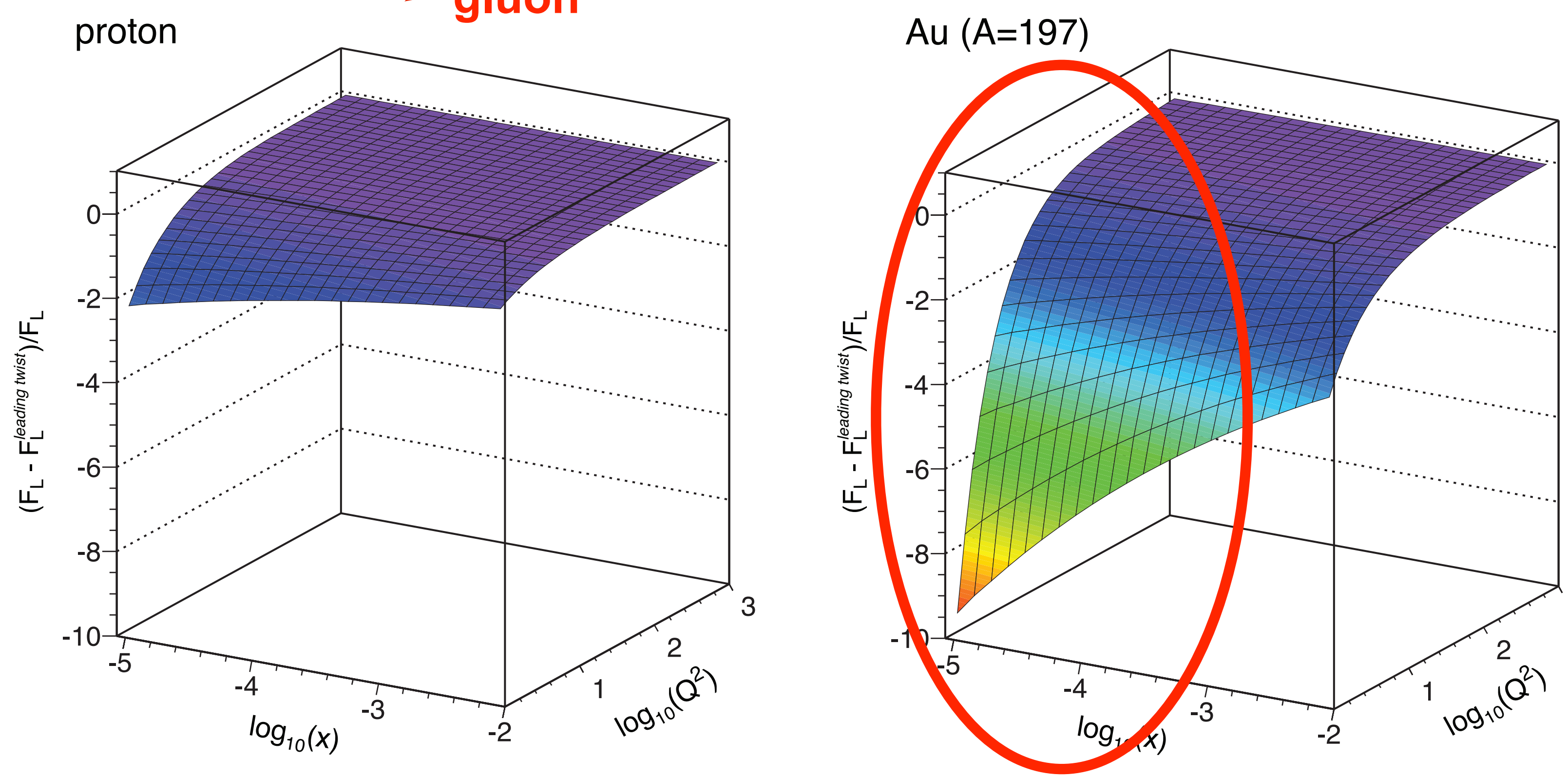


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Strategies:

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e+Au:

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20x75 - A∫Ldt = 4 $fb^{-1}$

20x100 - A∫Ldt = 4 $fb^{-1}$

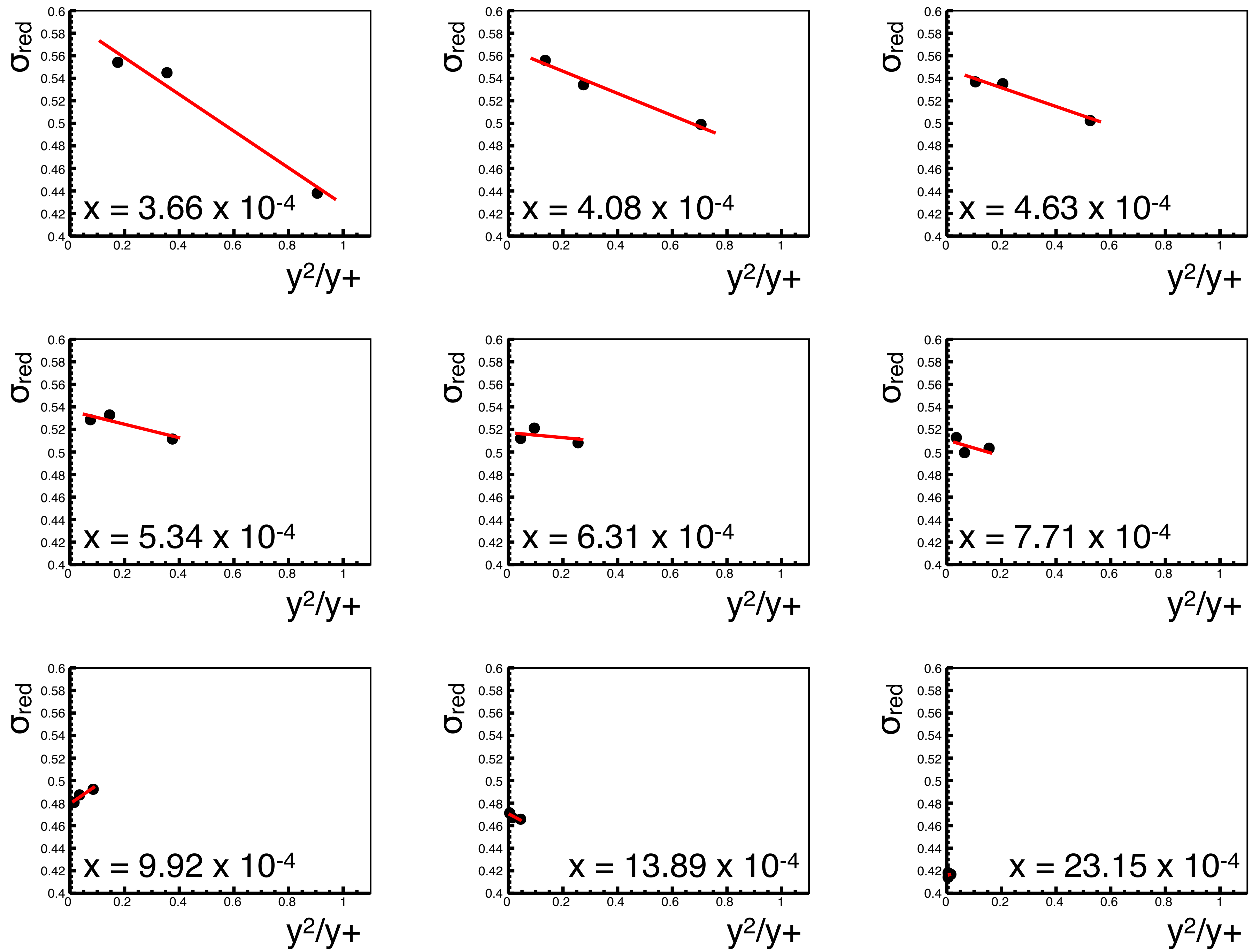
running combined

~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

Will be dominated by systematics, but would need a full detector simulation in order to estimate them

$Q^2 = 1.389\ GeV^2$



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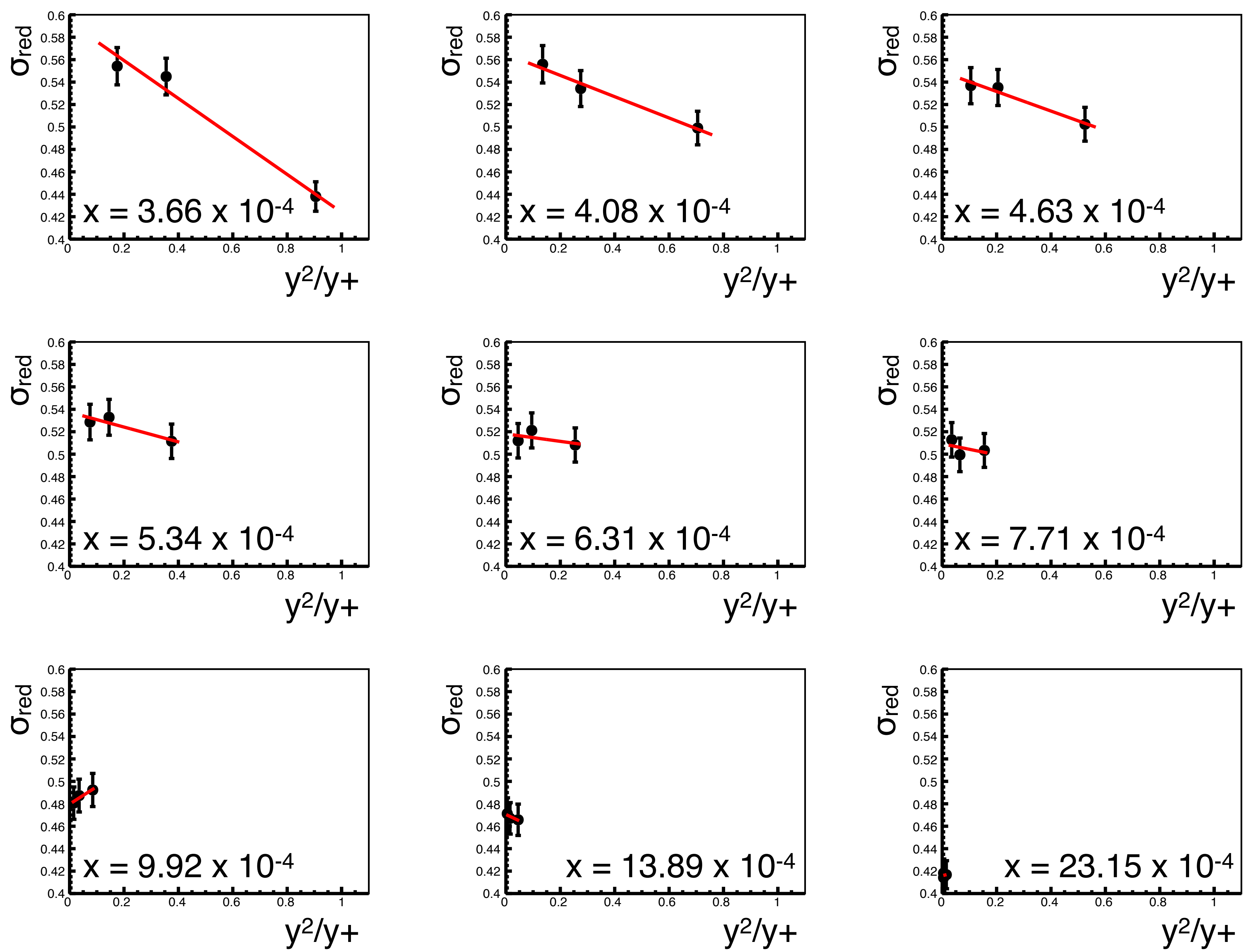


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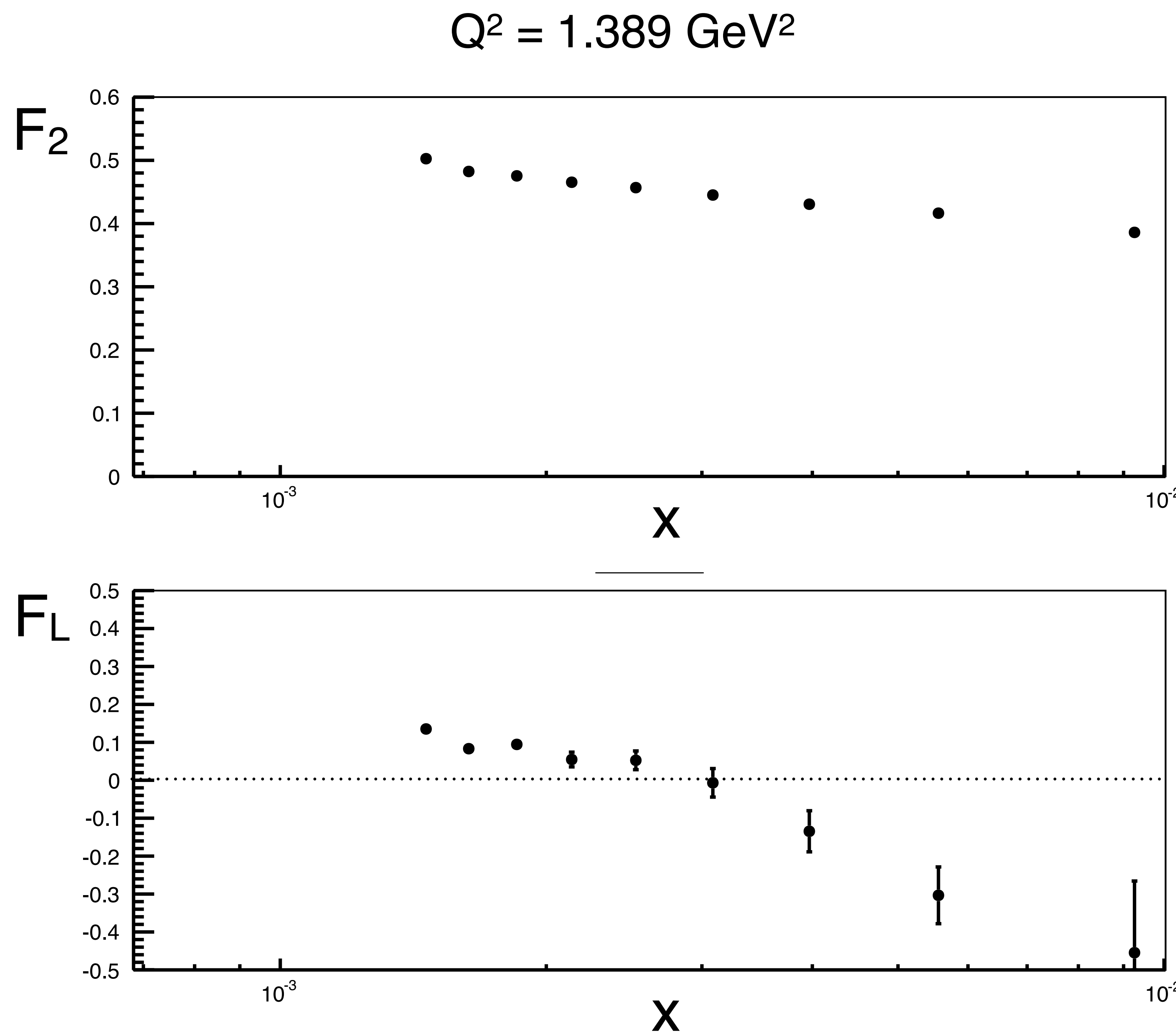

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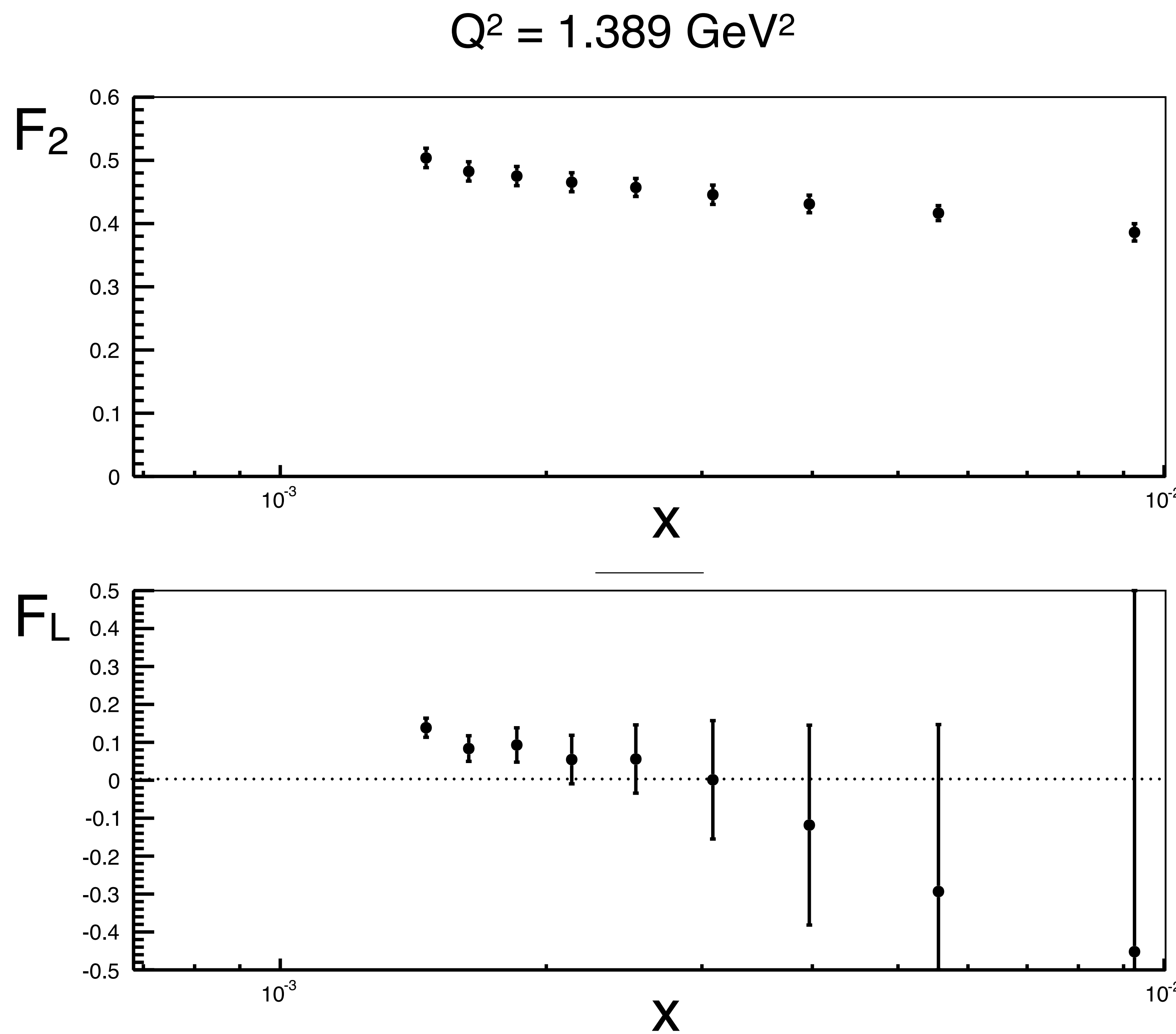

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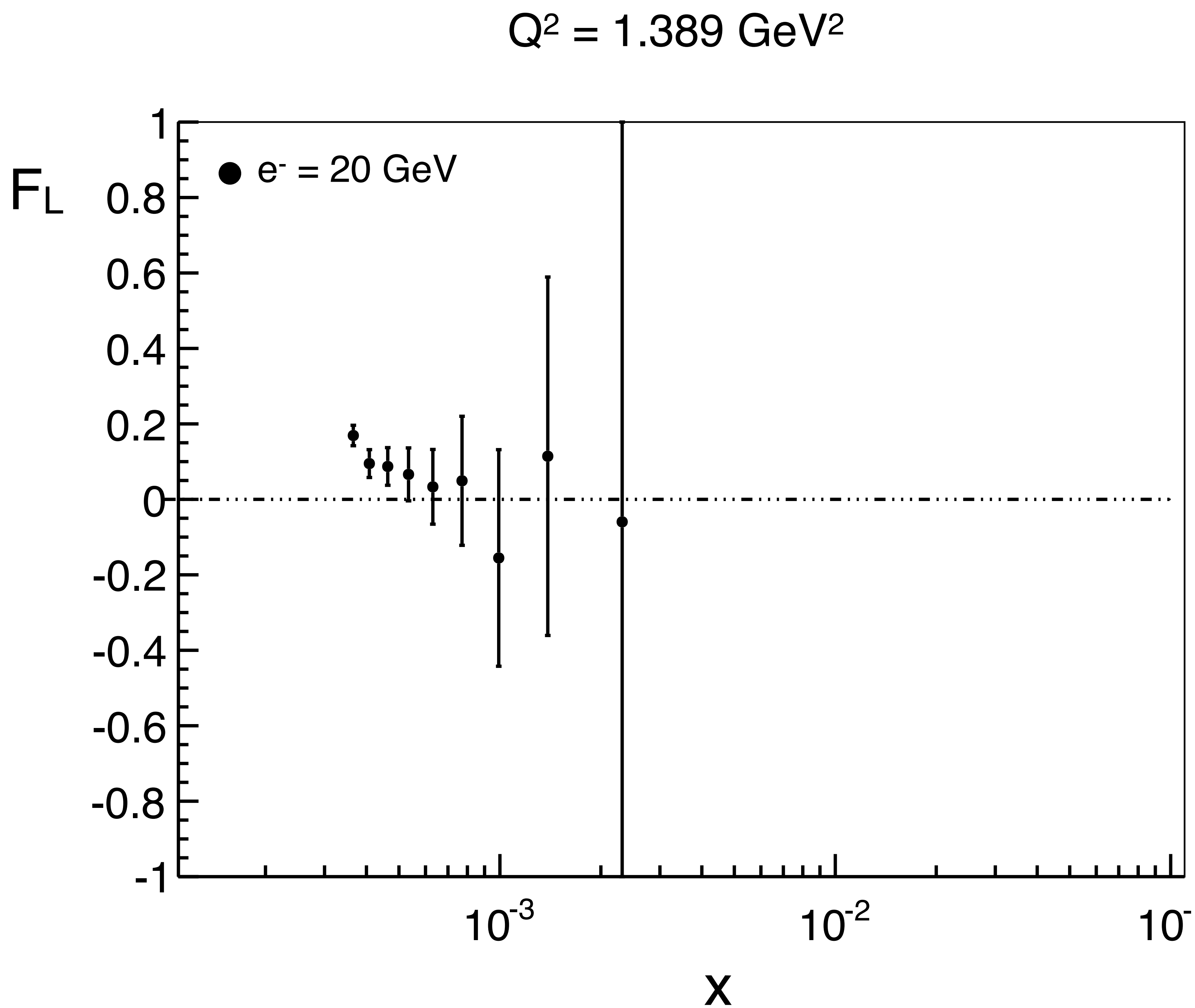

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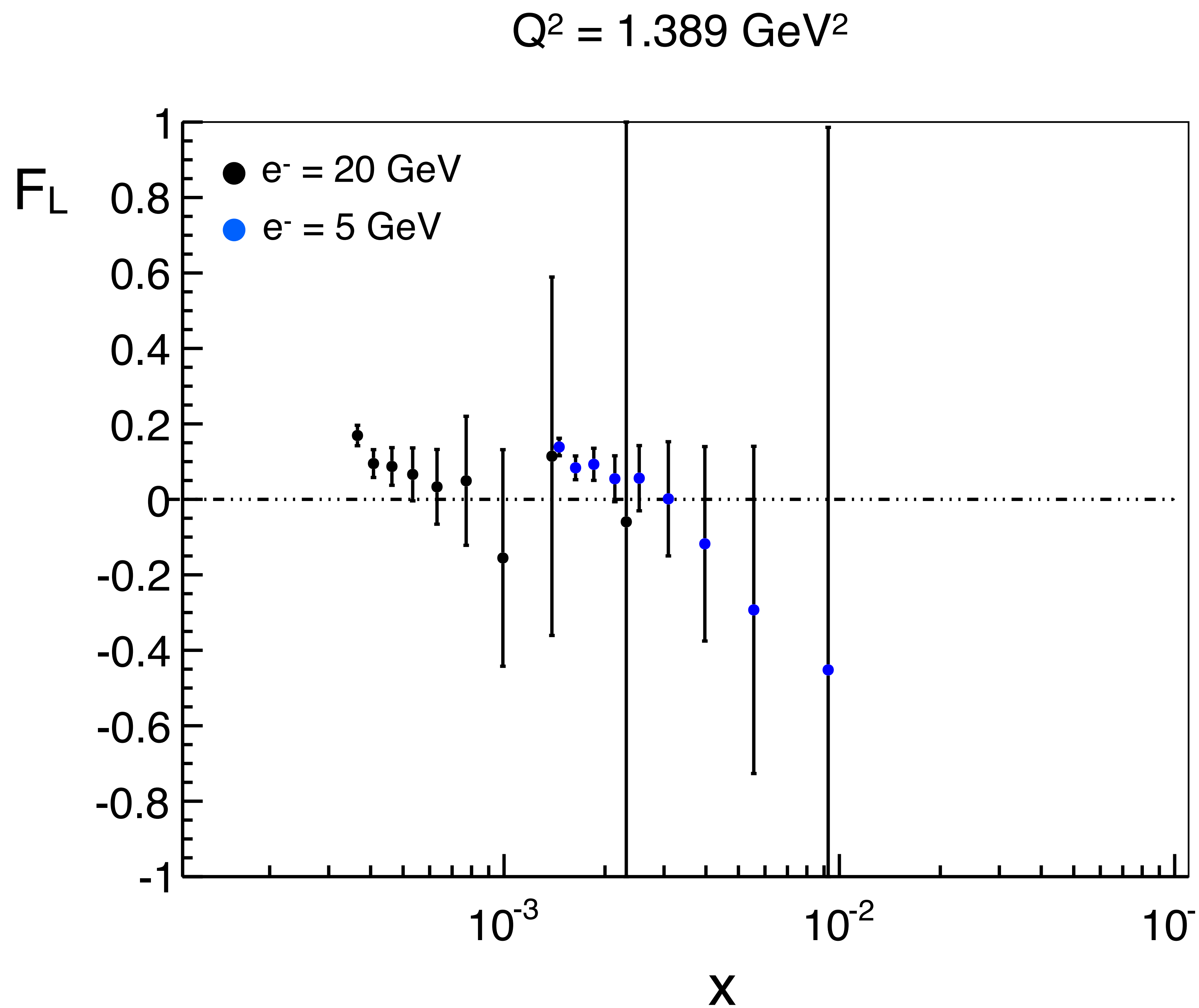

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e+Au: 1st stage
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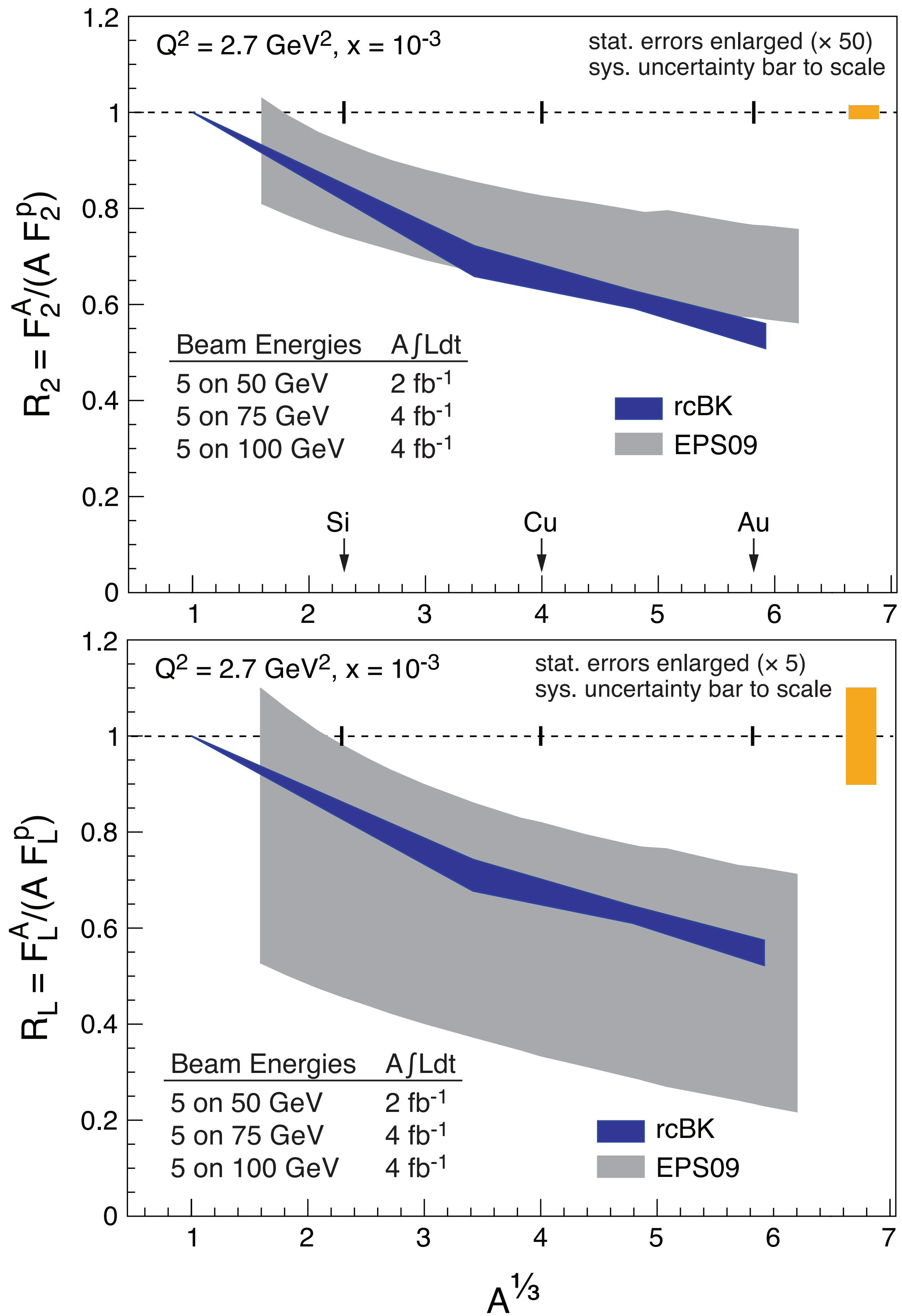

# Work in progress… (H. Paukkunen)

- Take the generated Pseudo-data and include it in a global fit
  - ➡ Only 20x100 and 5x100 included in these plots
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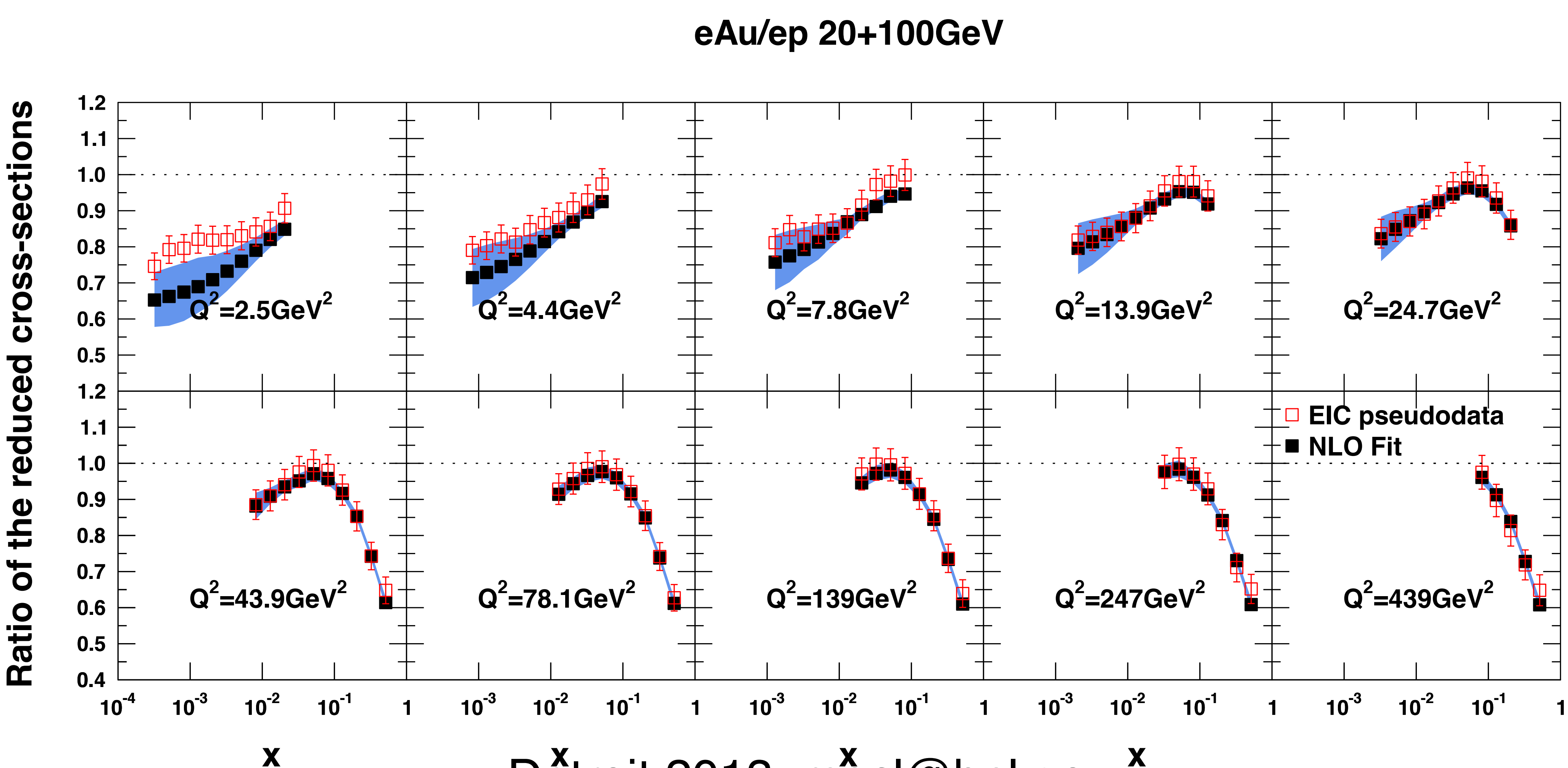

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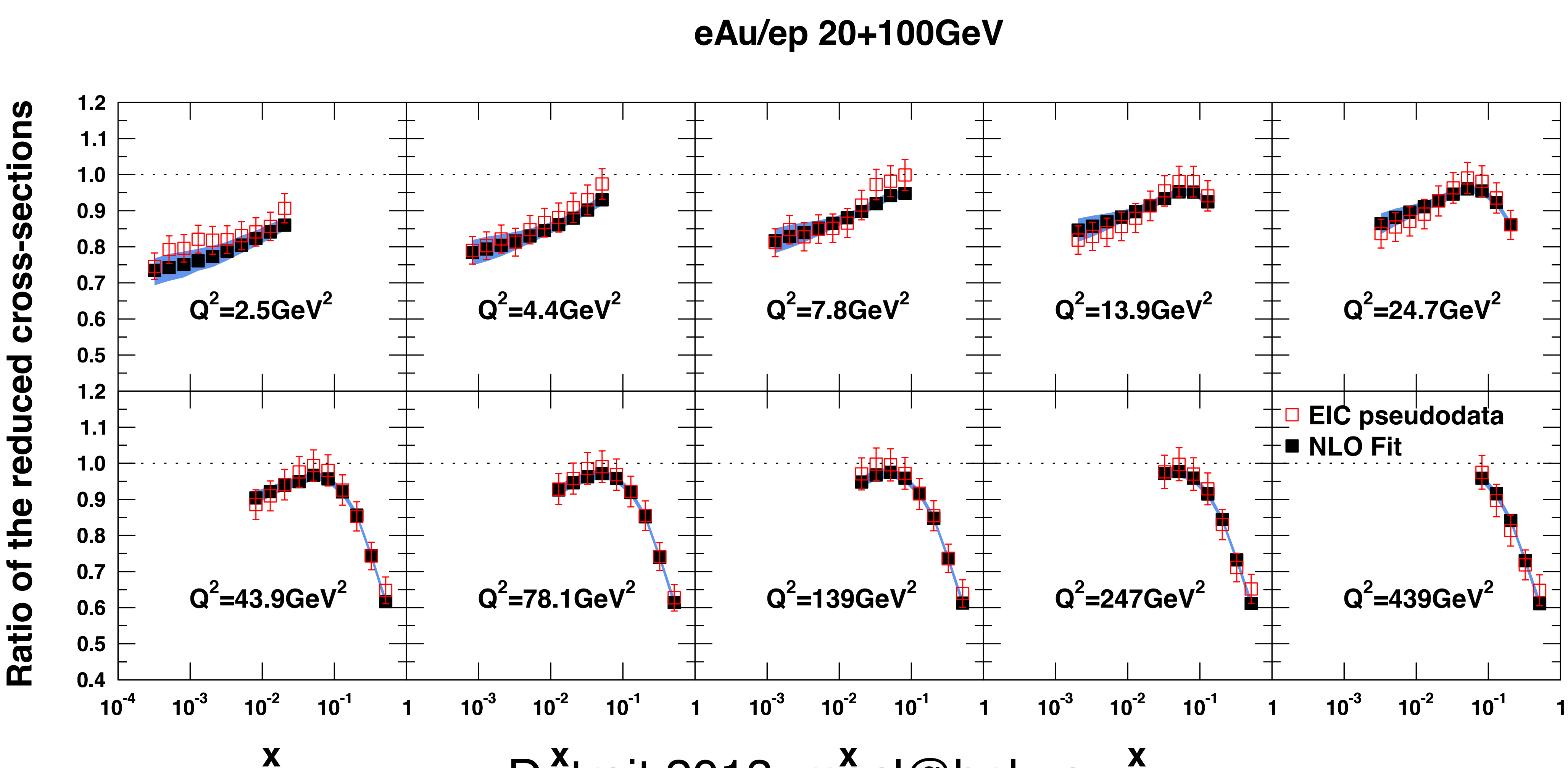

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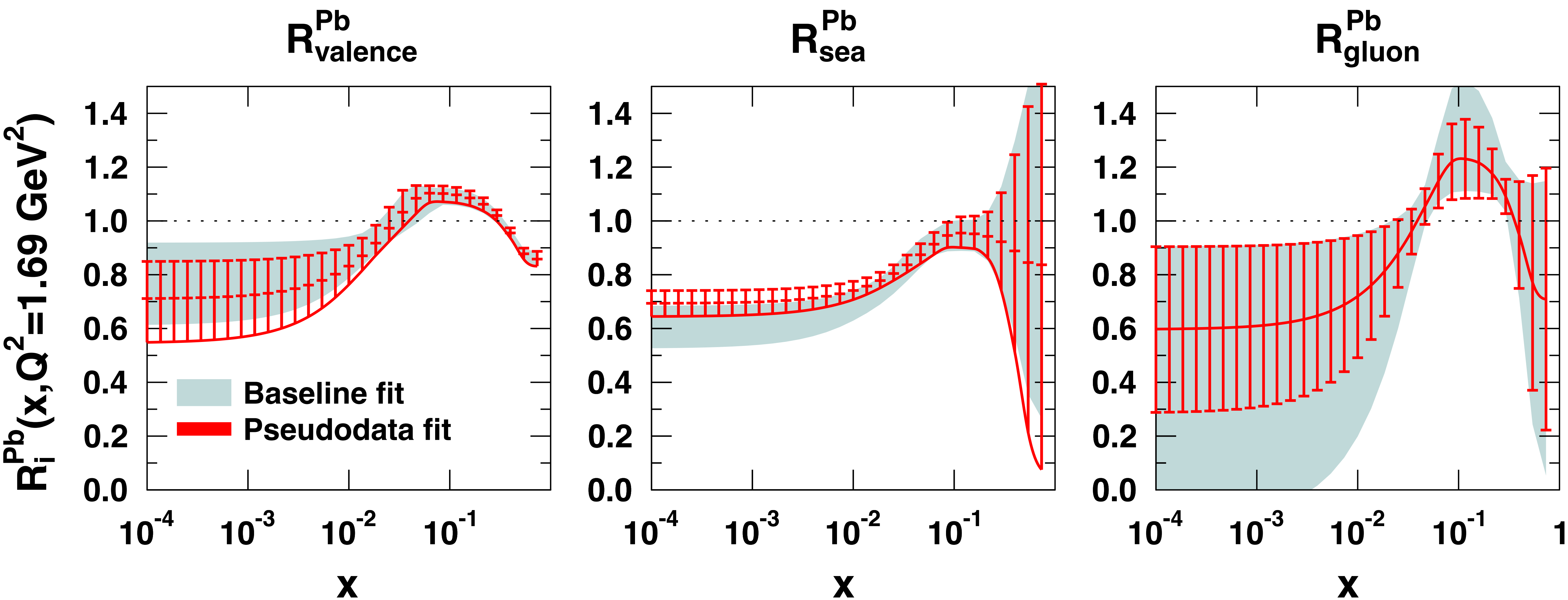
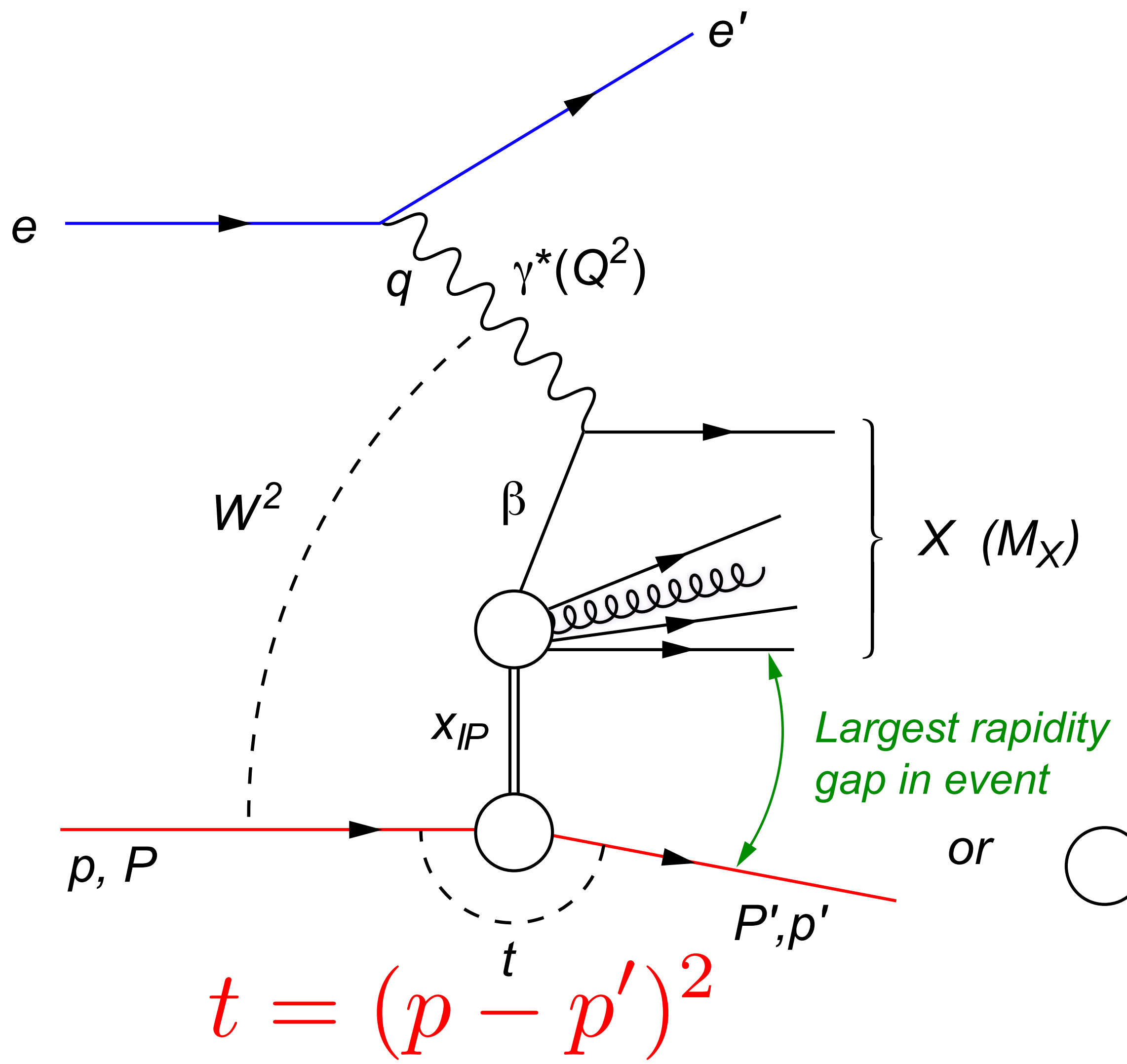
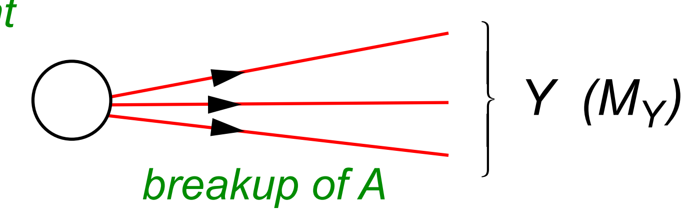


# Exclusive processes in e+A - diffraction




- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- **Diffraction in e+p:**
  - ➡ HERA: 15% of all events are diffractive

- **Diffraction in e+A:**
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

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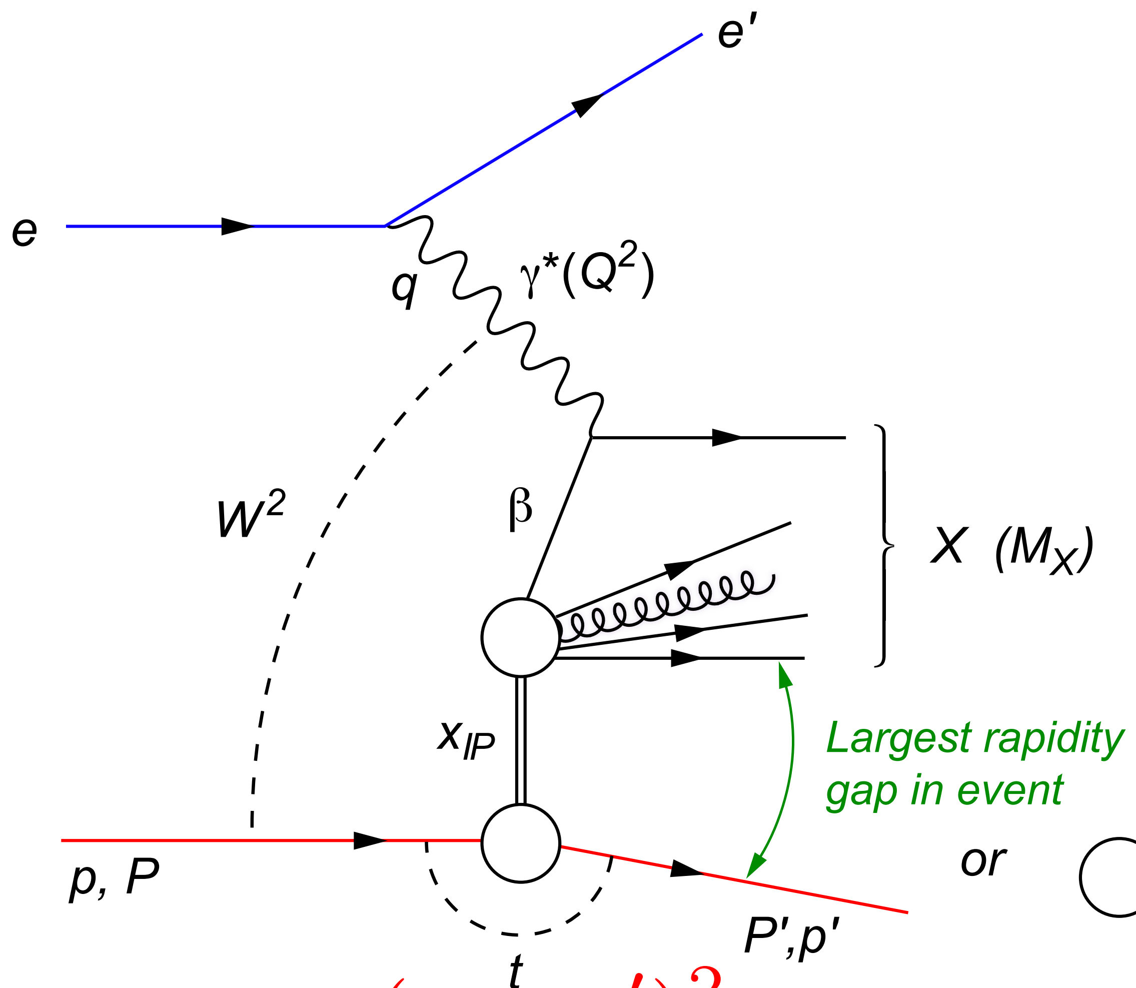
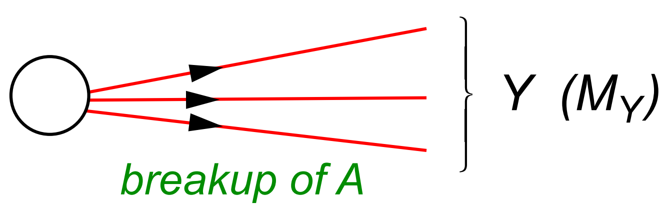


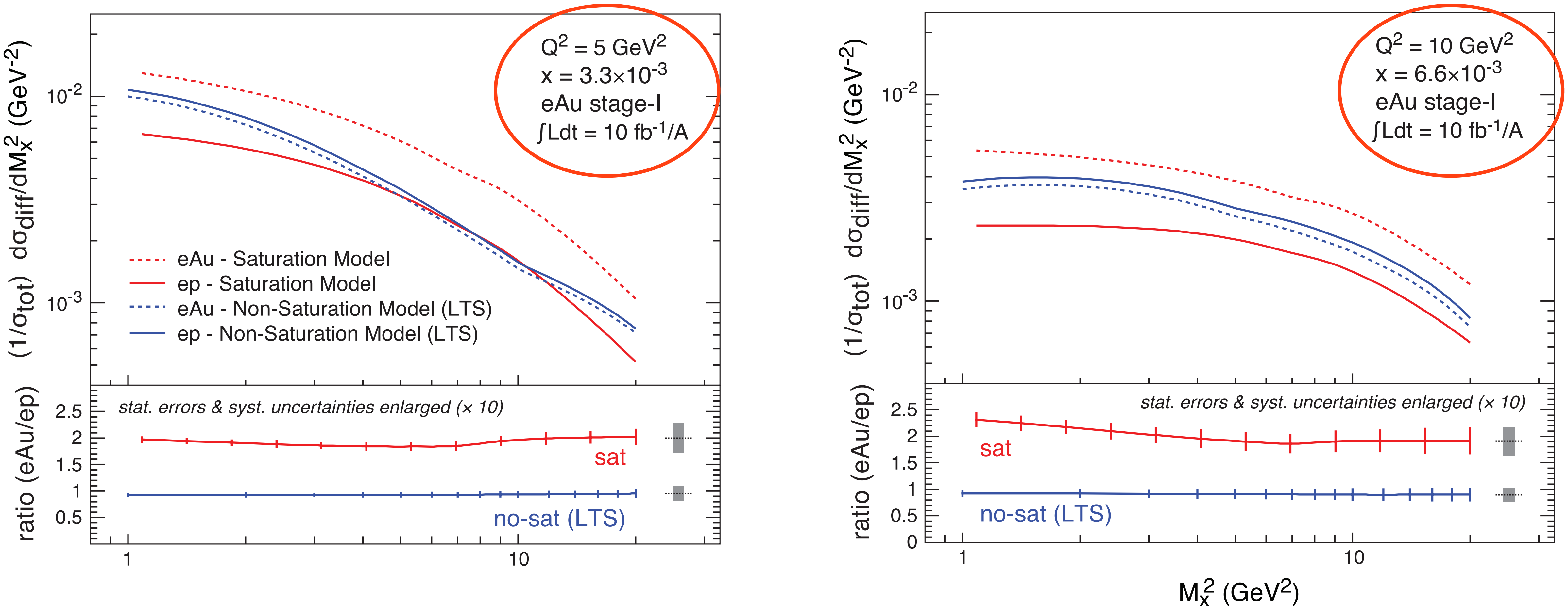

$$t = (p - p')^2$$

- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

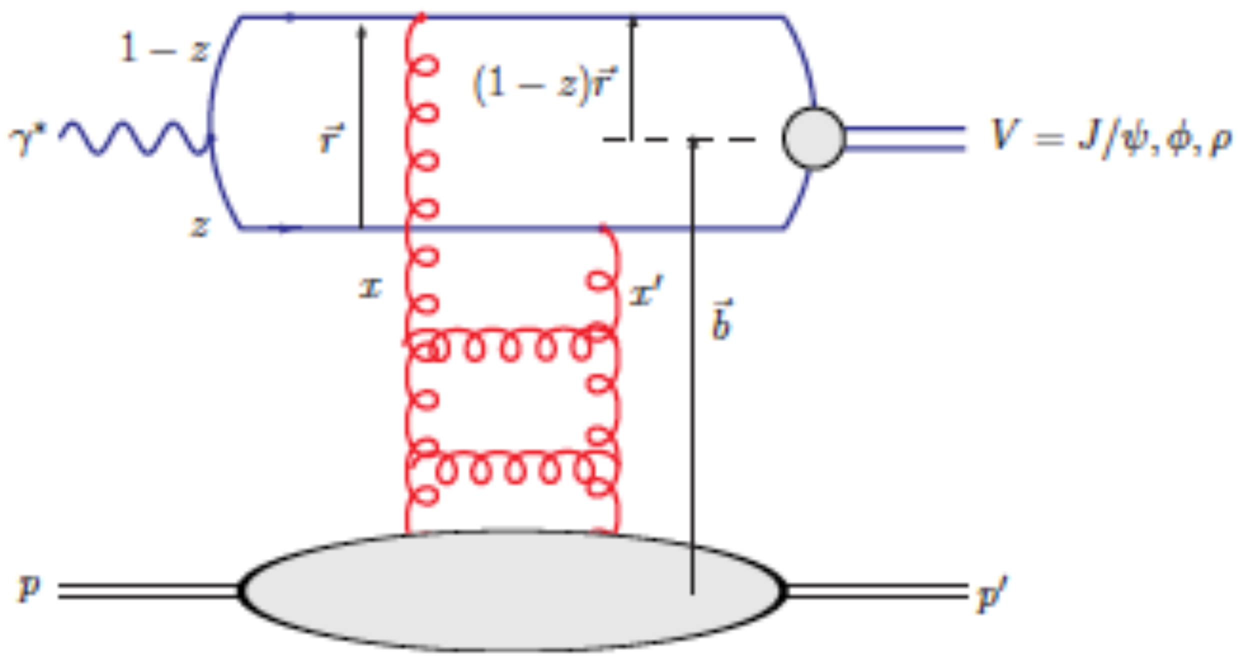
- **Diffraction in e+p:**
  - ➡ HERA: 15% of all events are diffractive
- **Diffraction in e+A:**
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

# Day 1: Diffractive Cross-sections

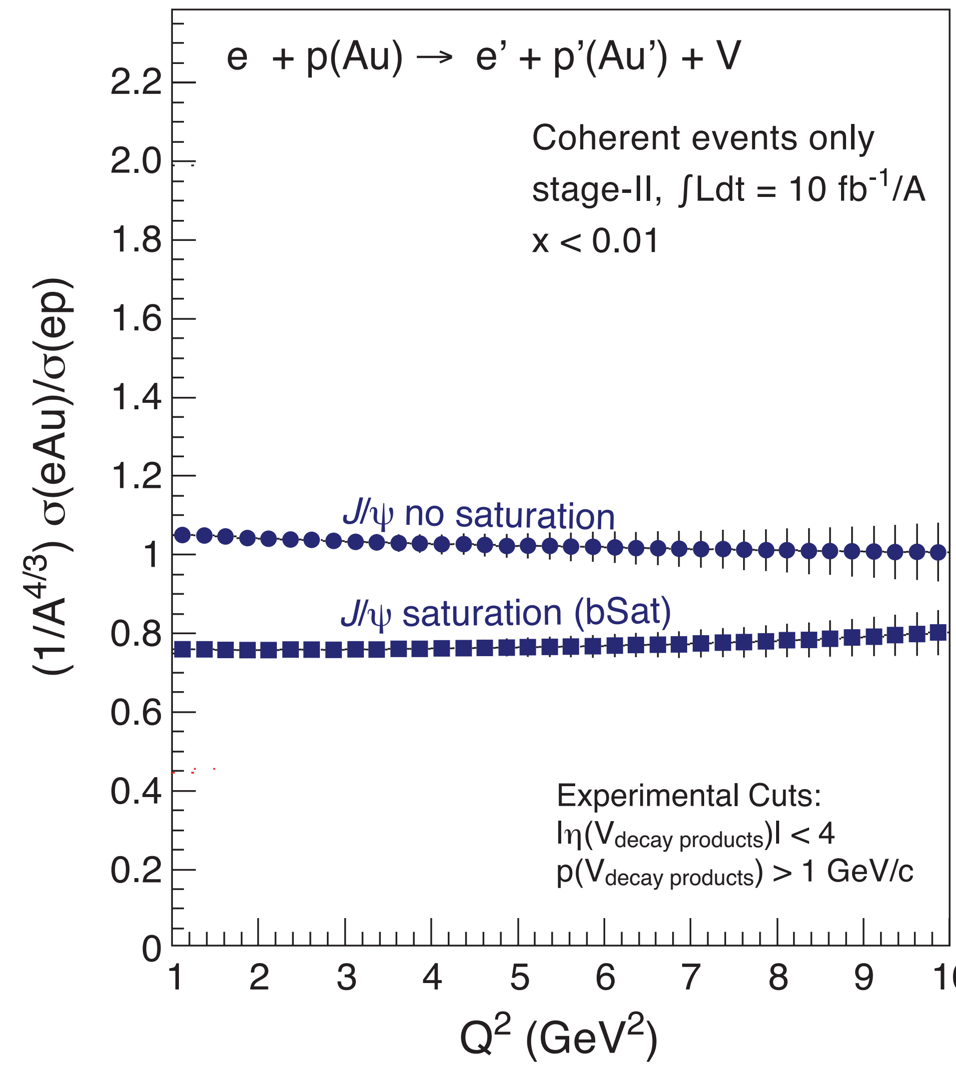



- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 $fb^{-1}$ of data for a low-energy eRHIC) can distinguish between the two scenarios

# Exclusive vector meson production




$$d\sigma \propto g(x)^2$$




- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation

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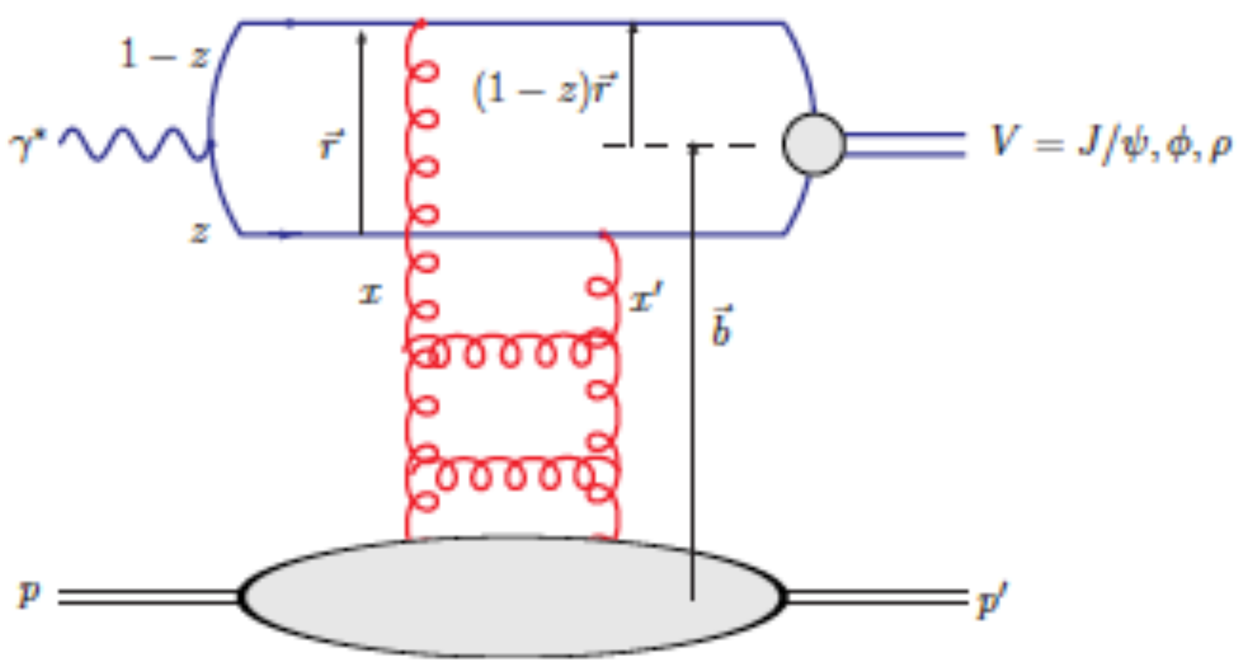


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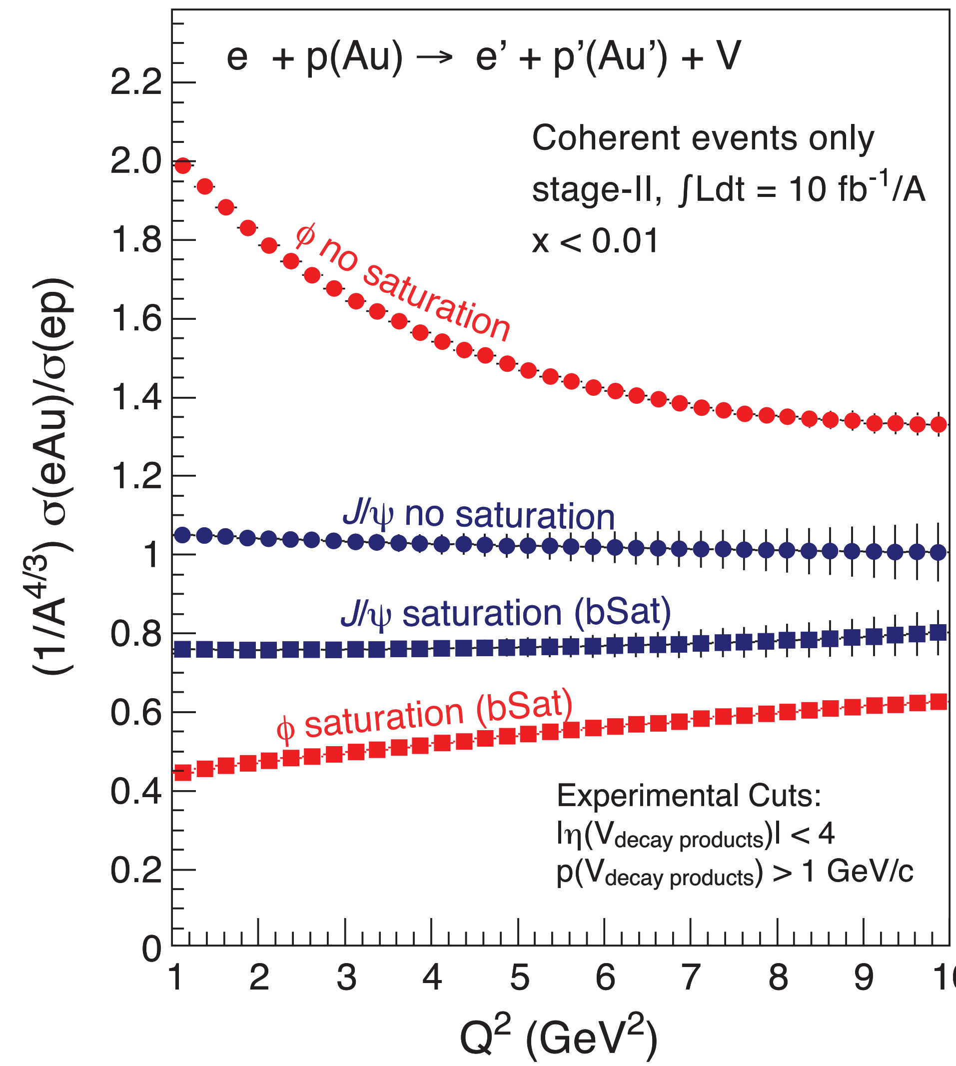
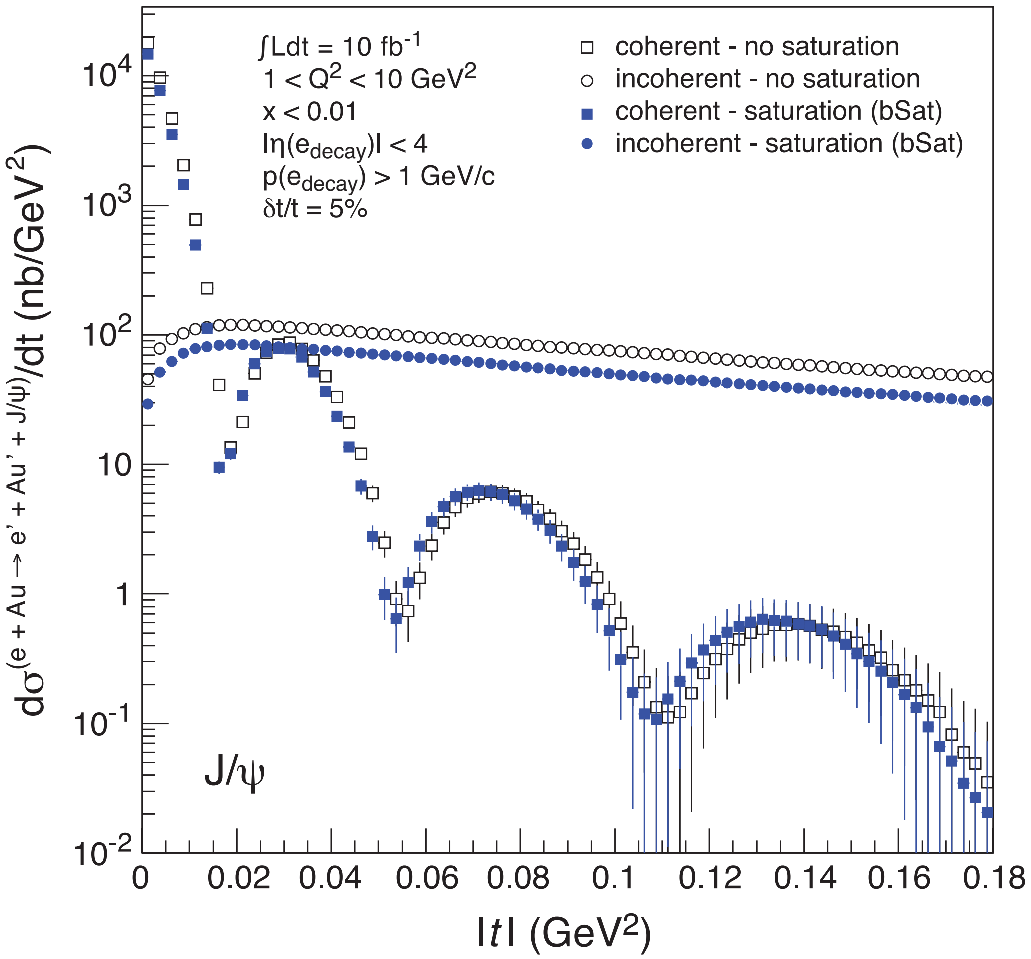
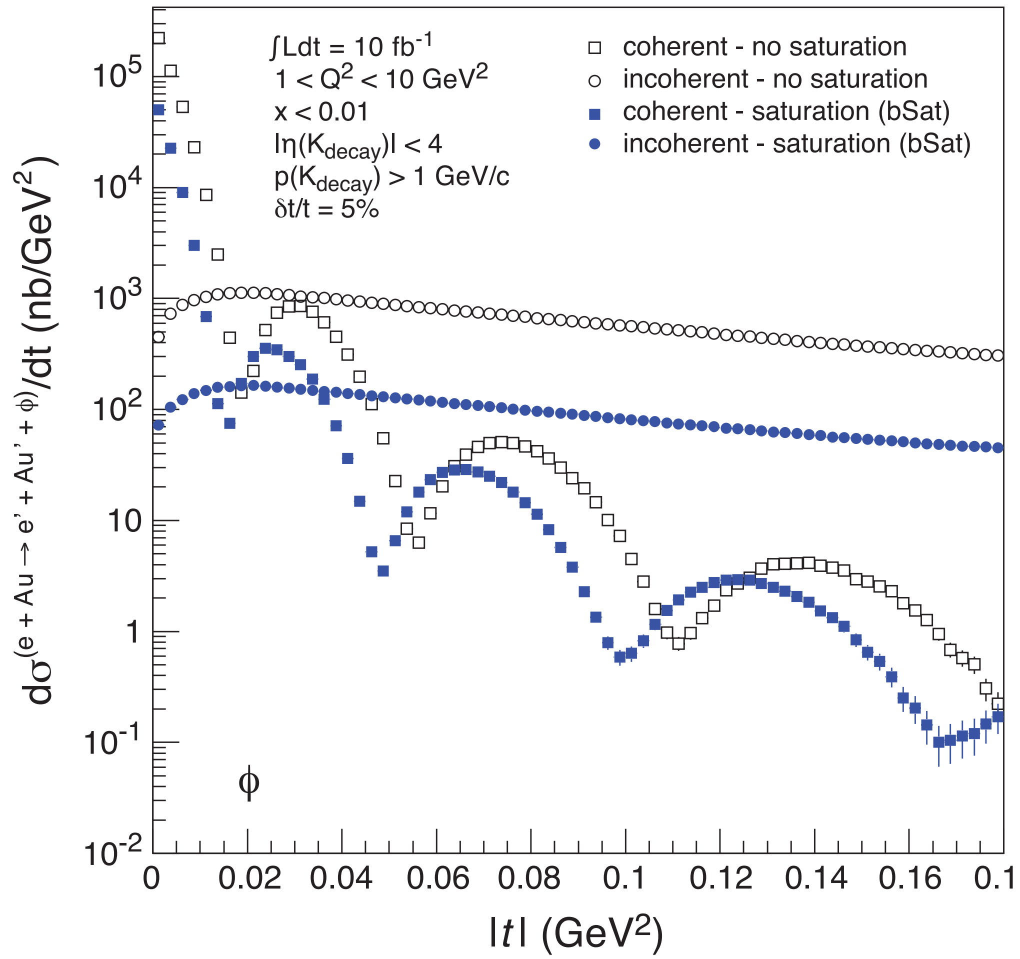



- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

# Exclusive Vector Meson Production in e+A




- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡ Need good breakup detection efficiency to discriminate between the two scenarios

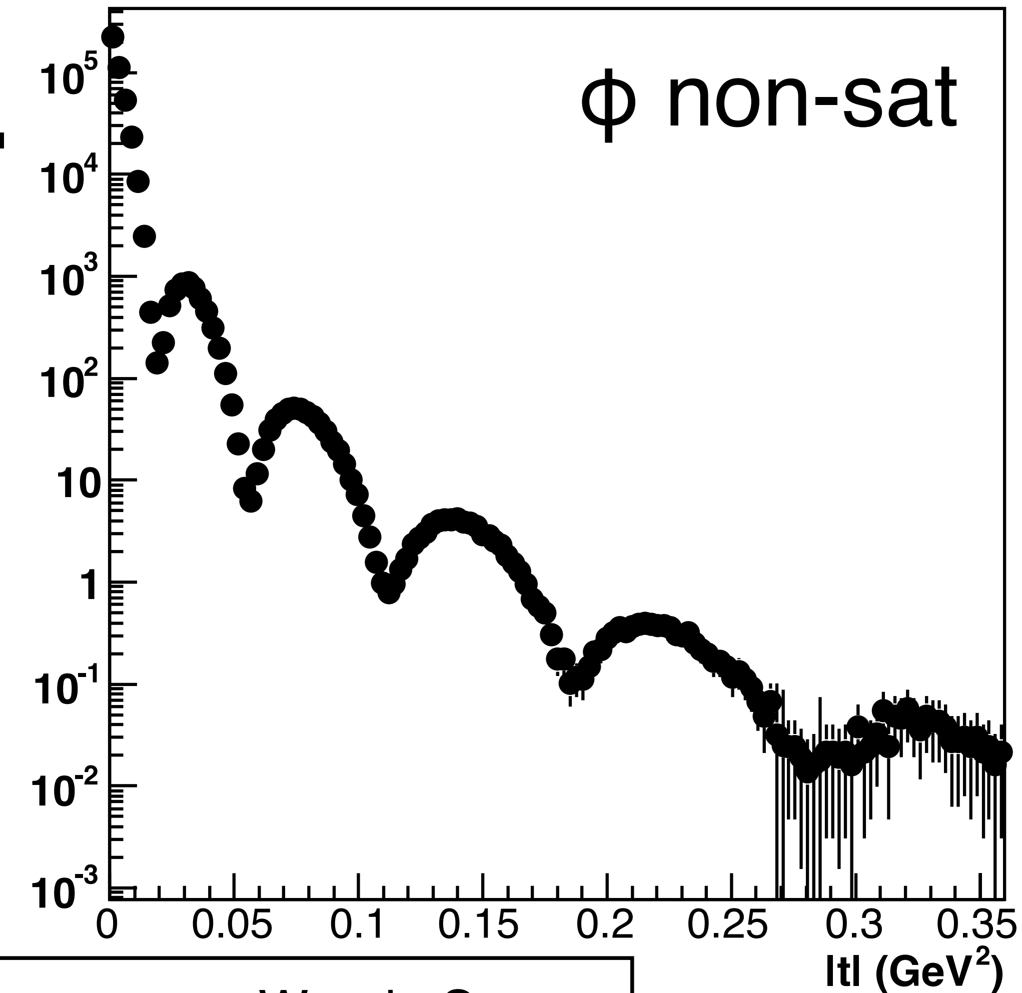
- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

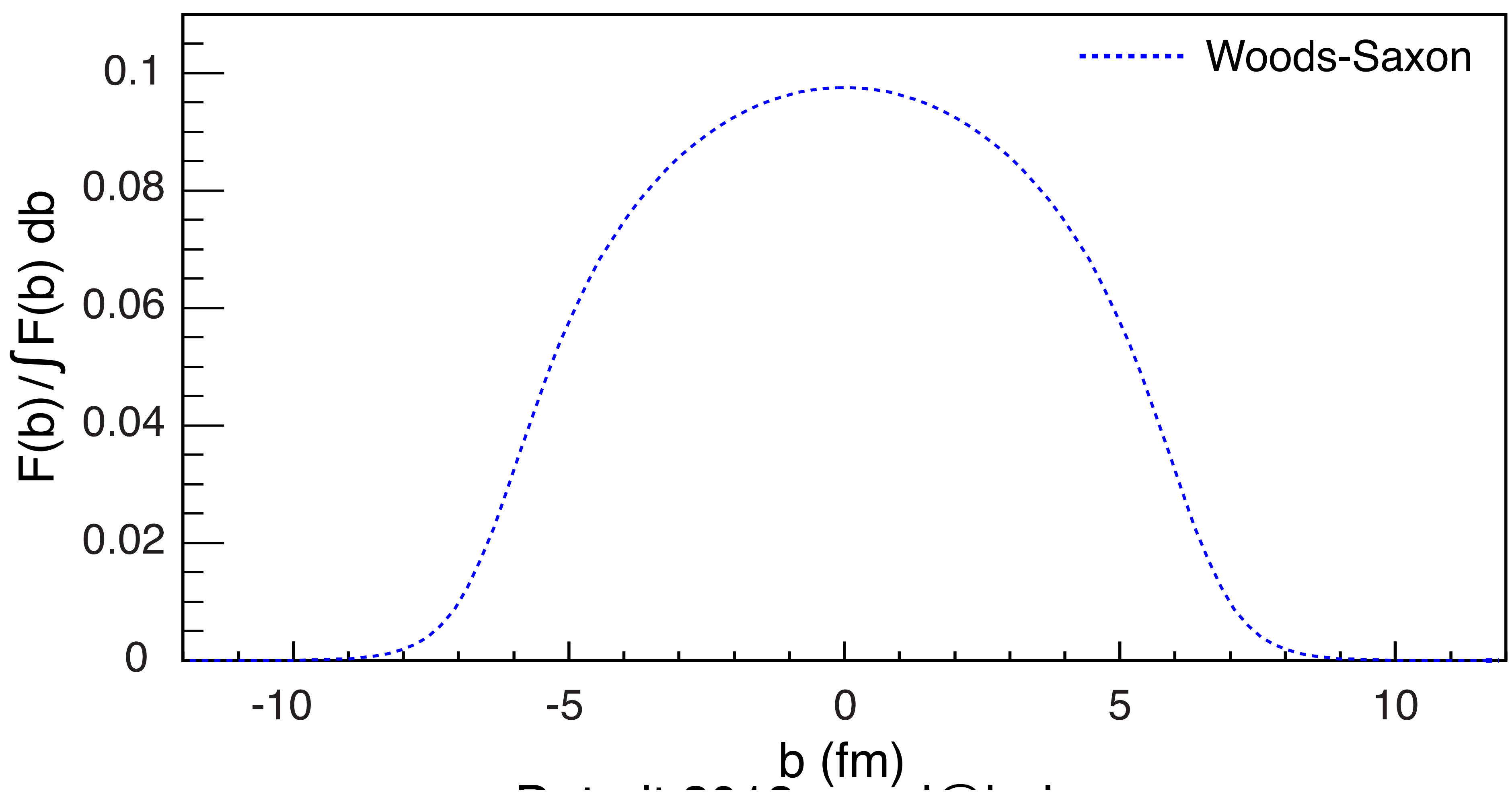
# Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)



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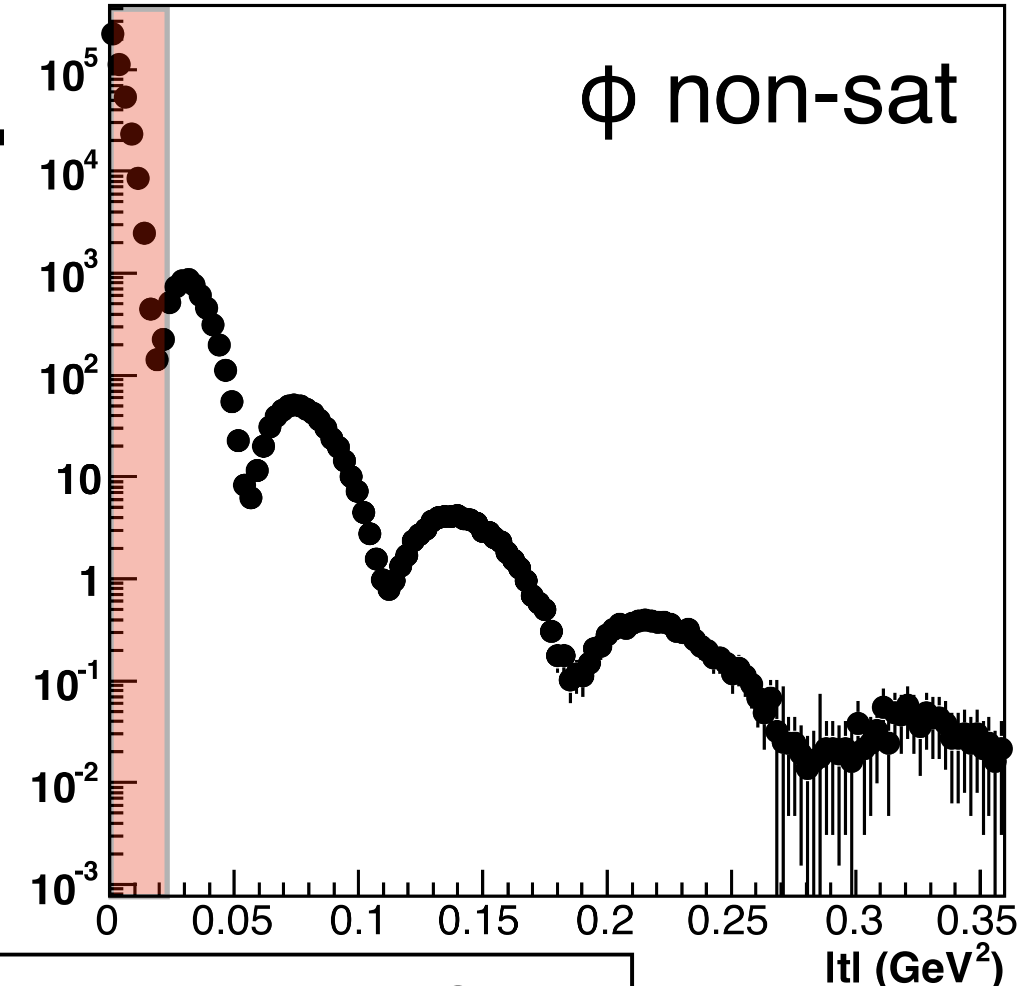


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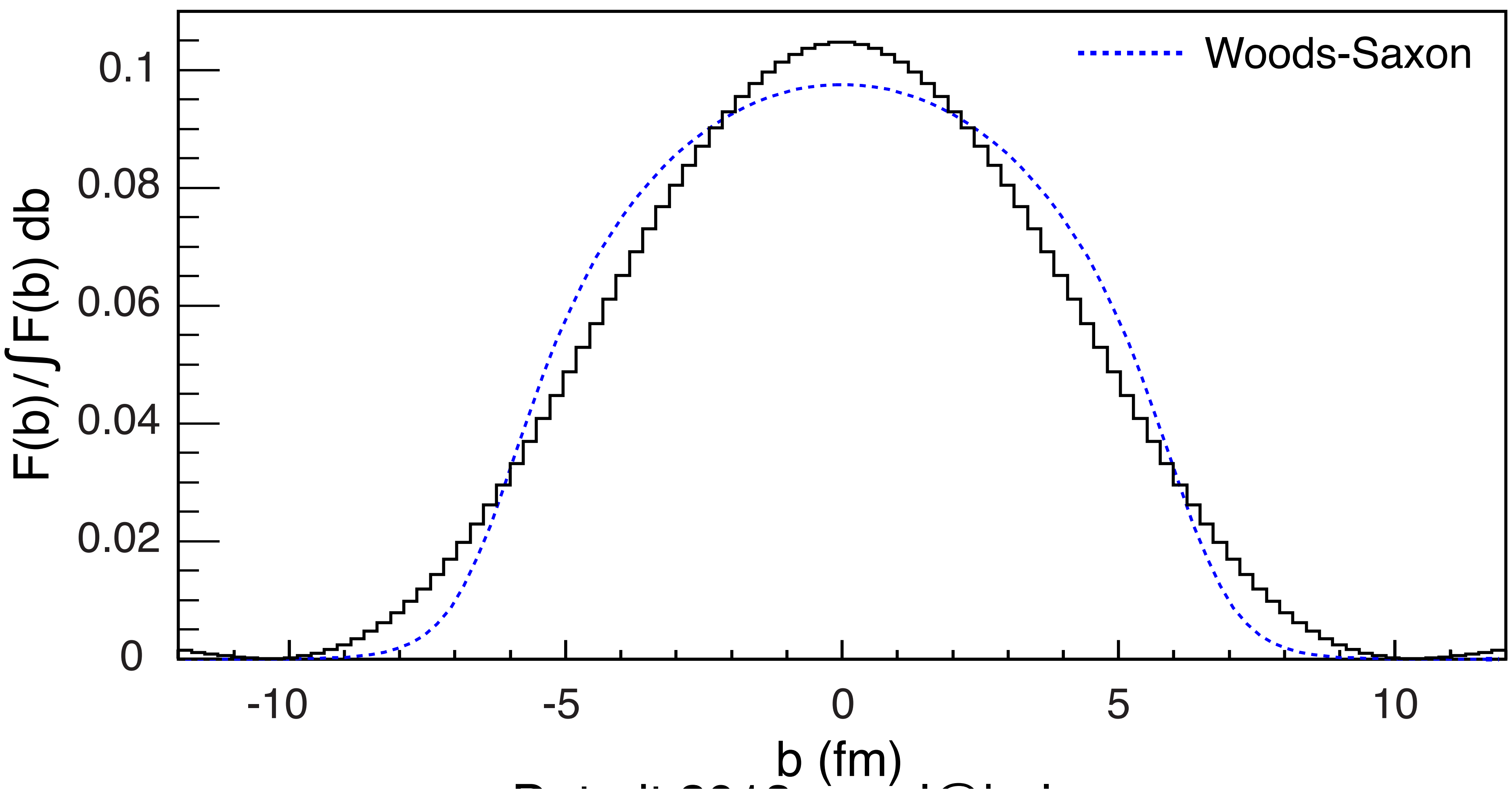

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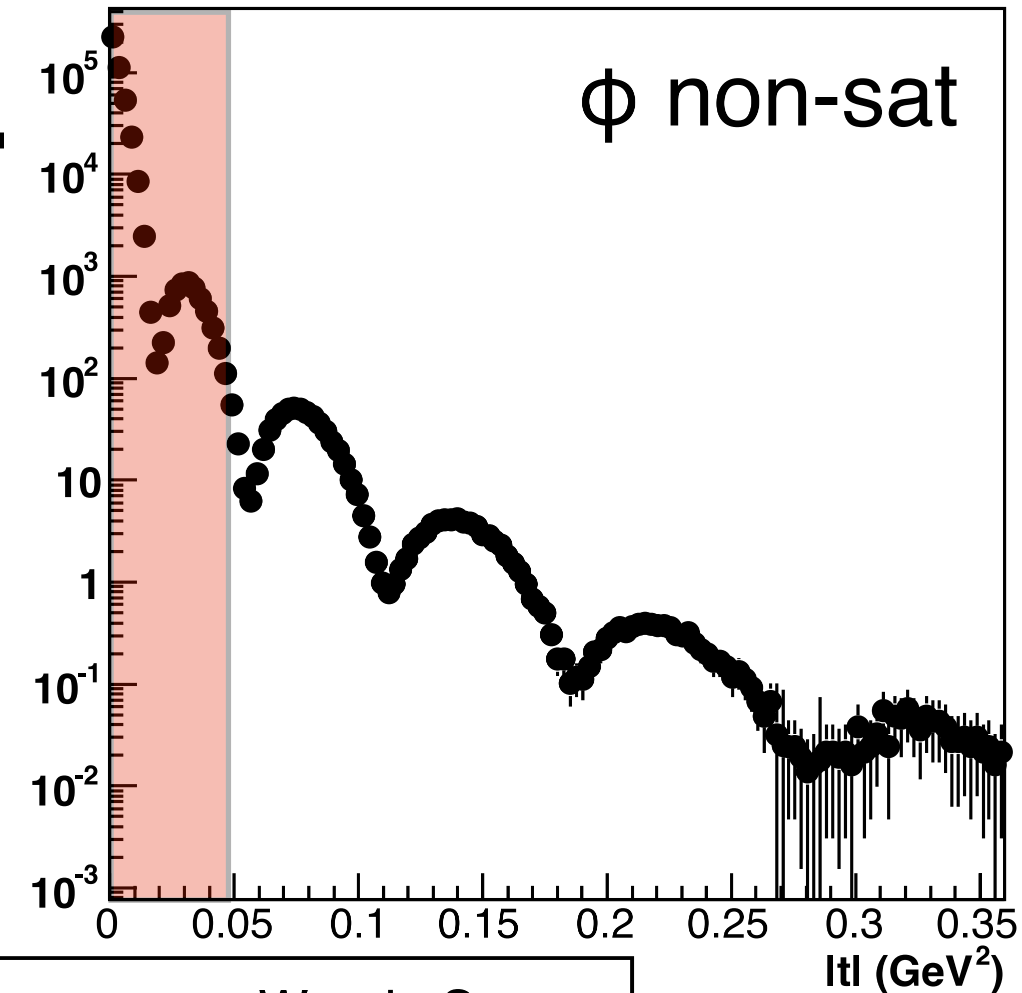


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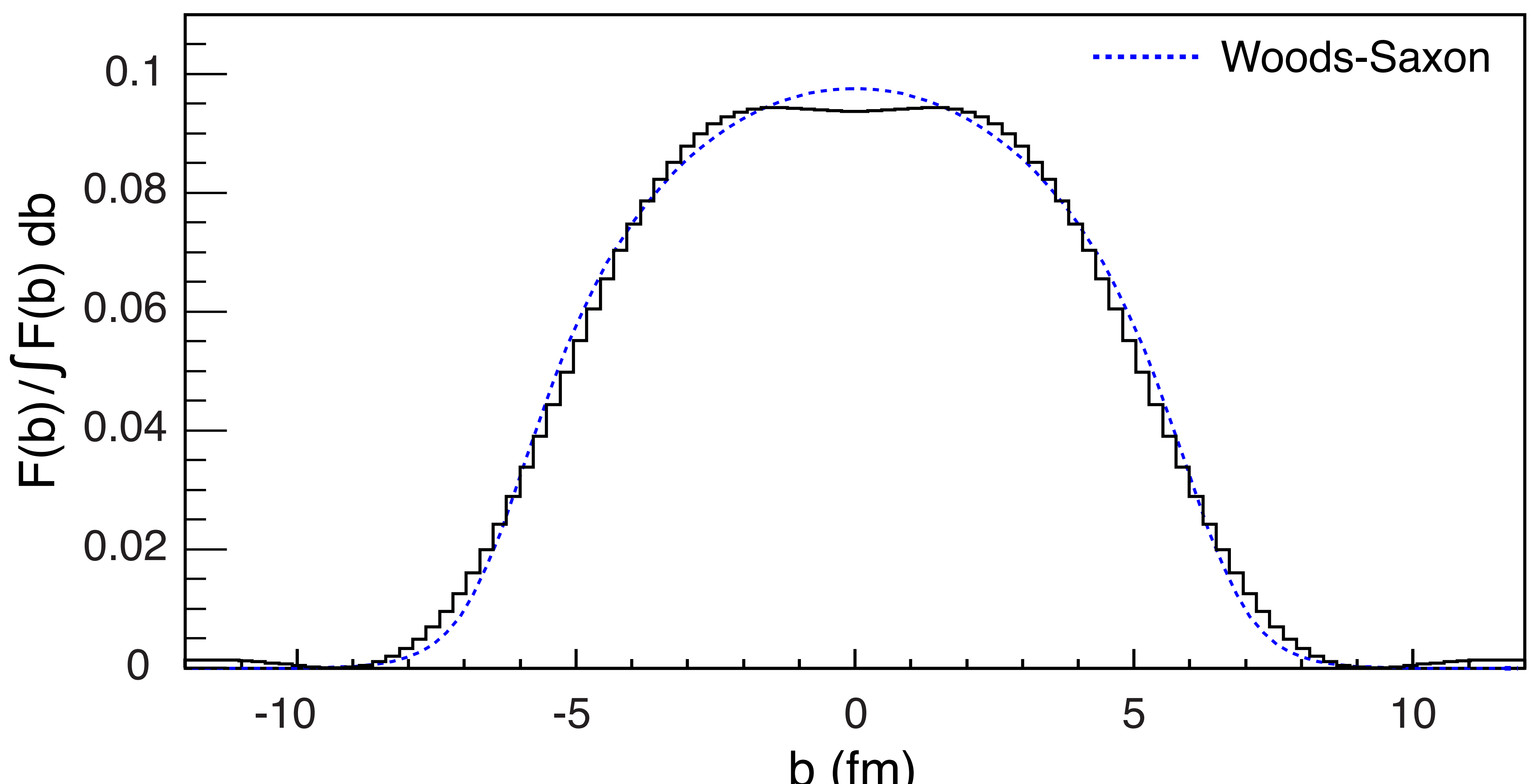

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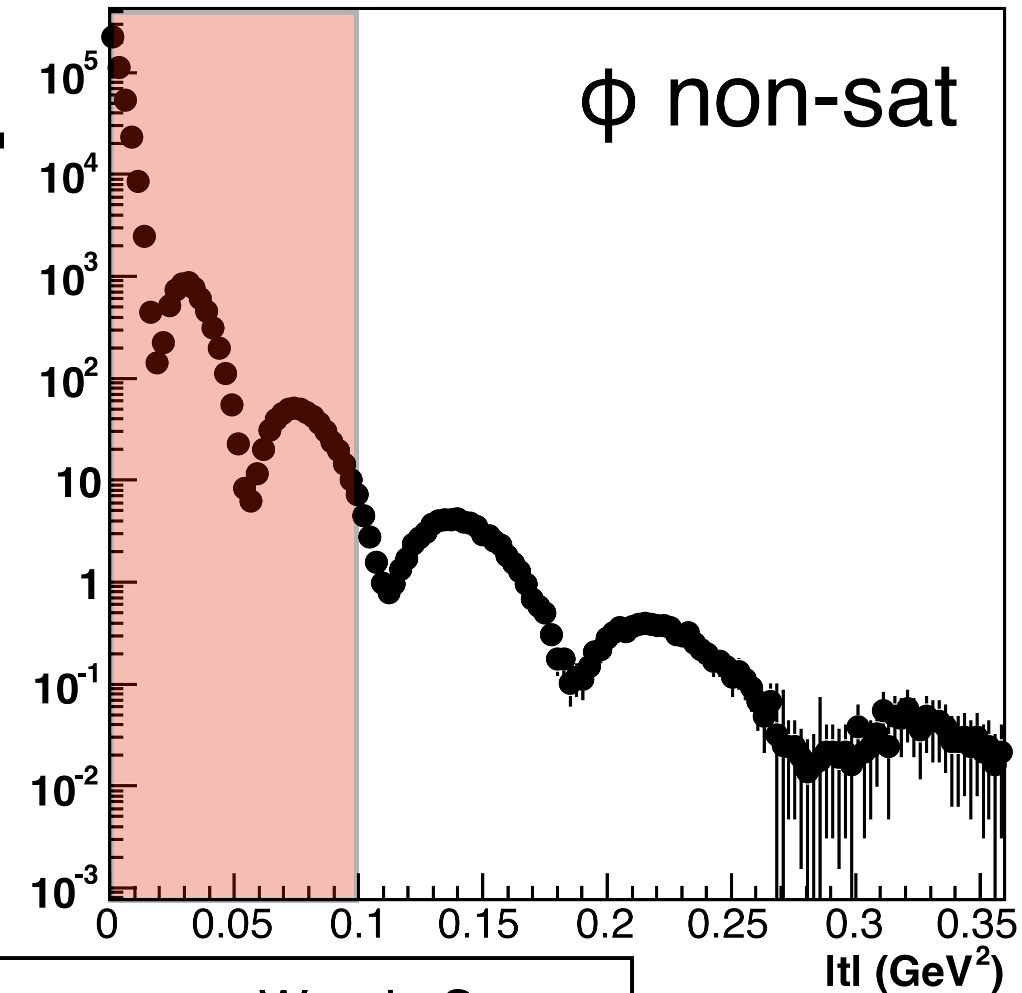


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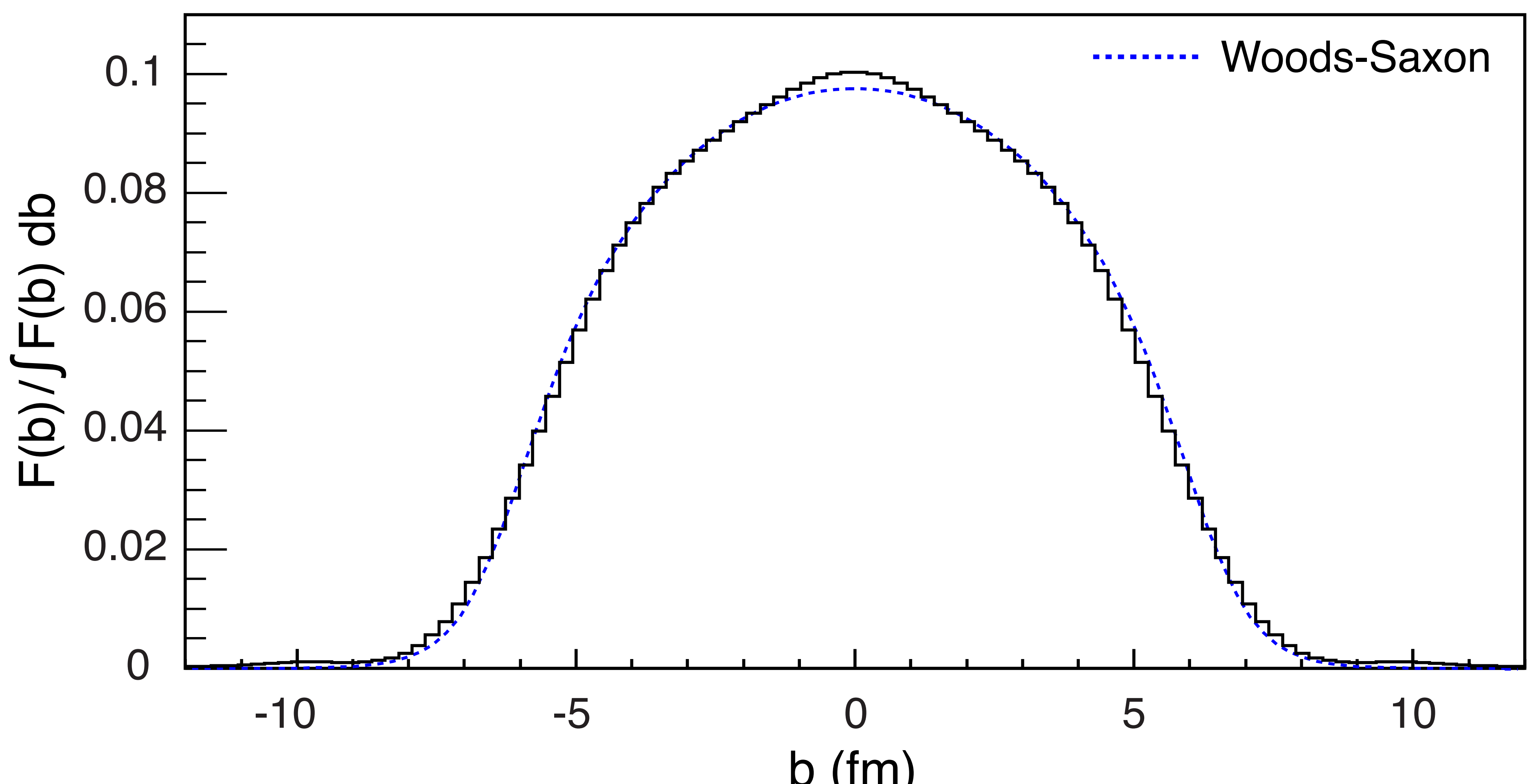

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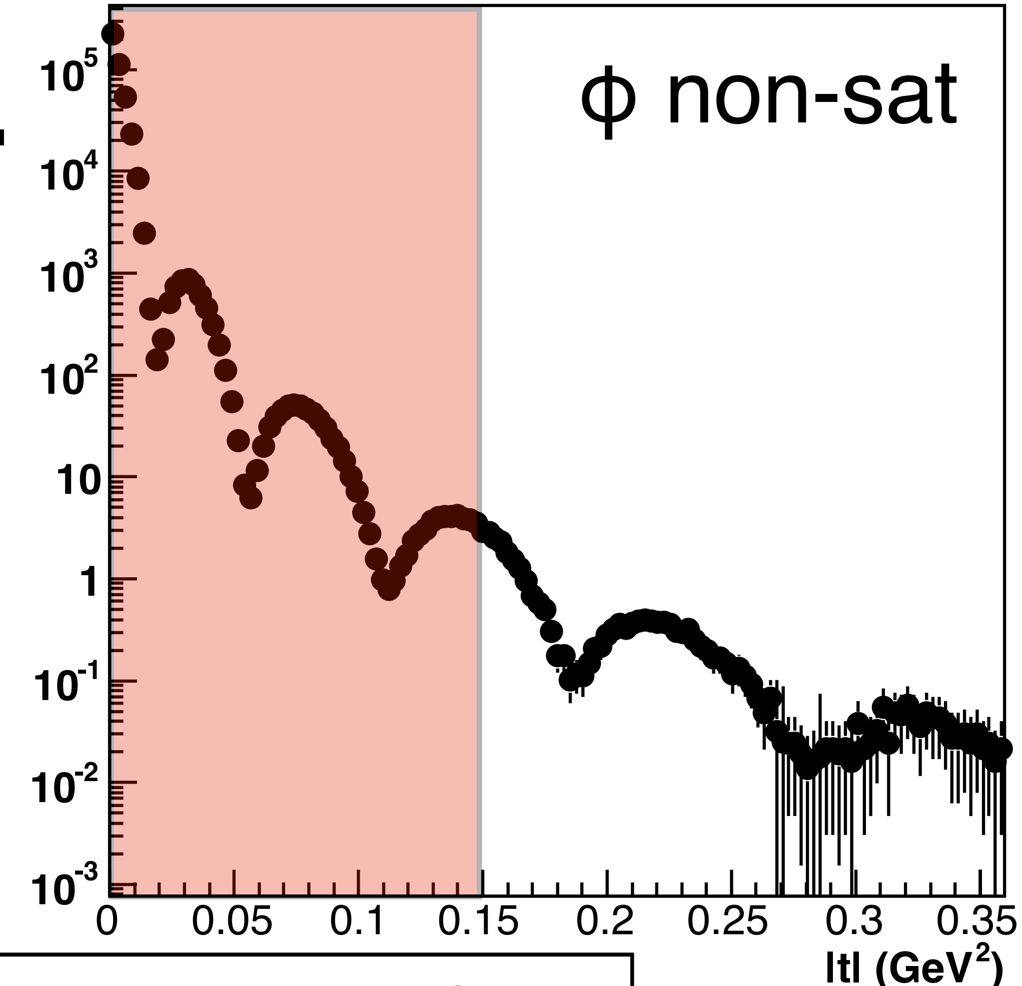


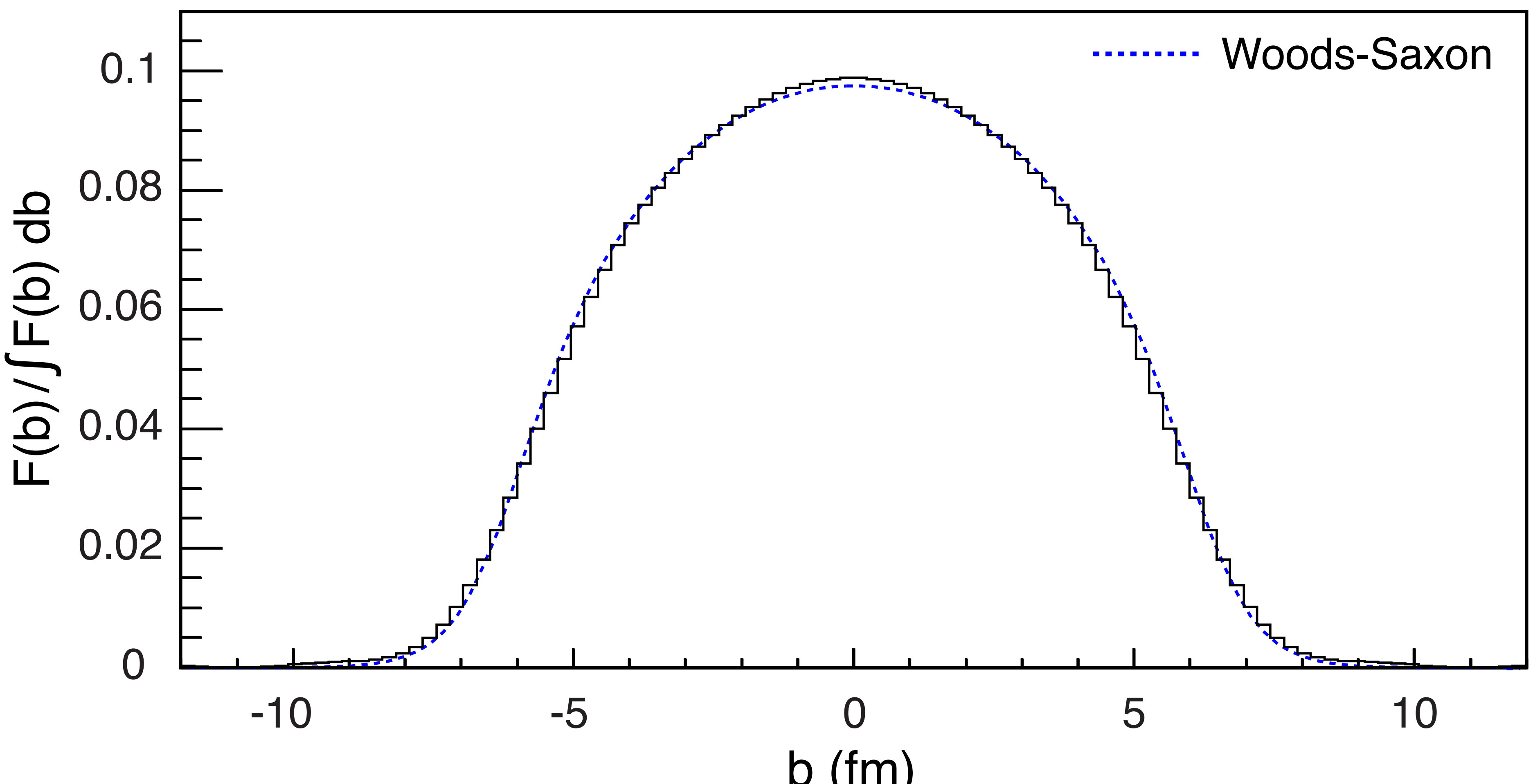

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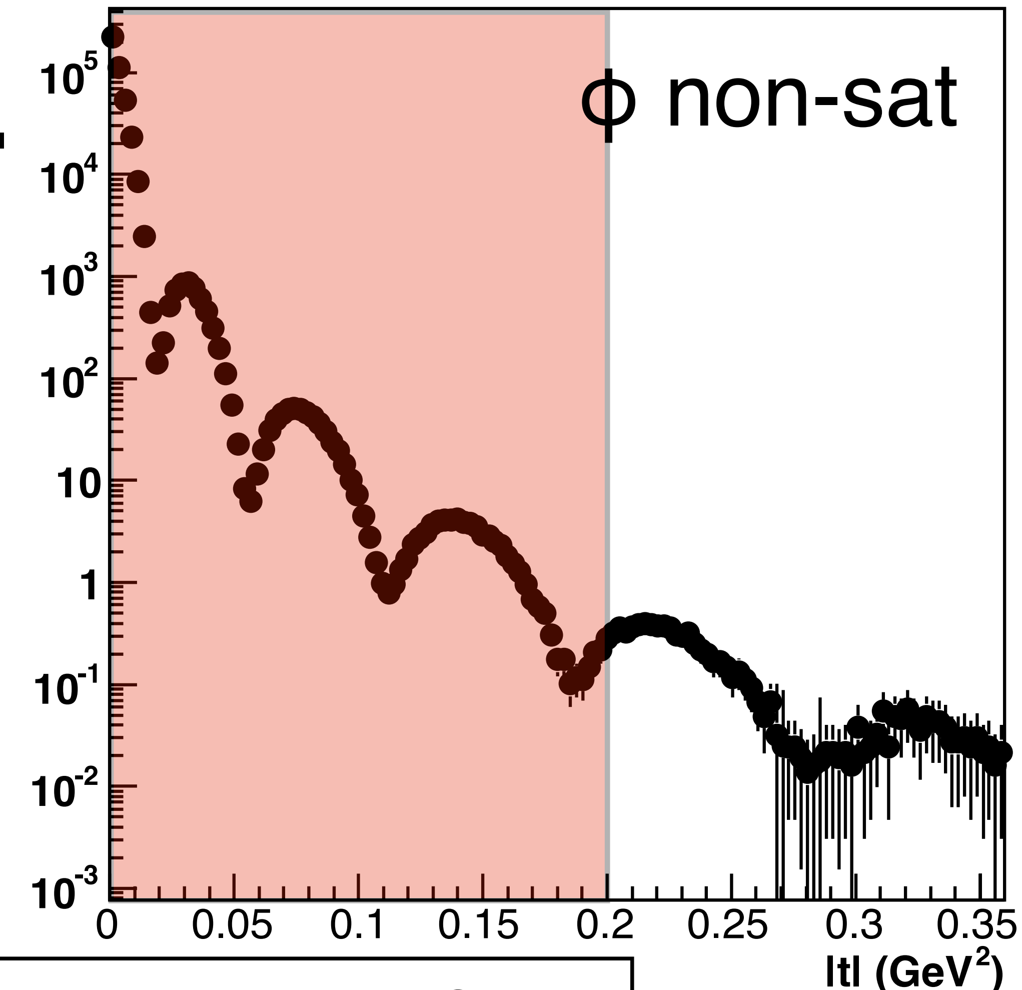


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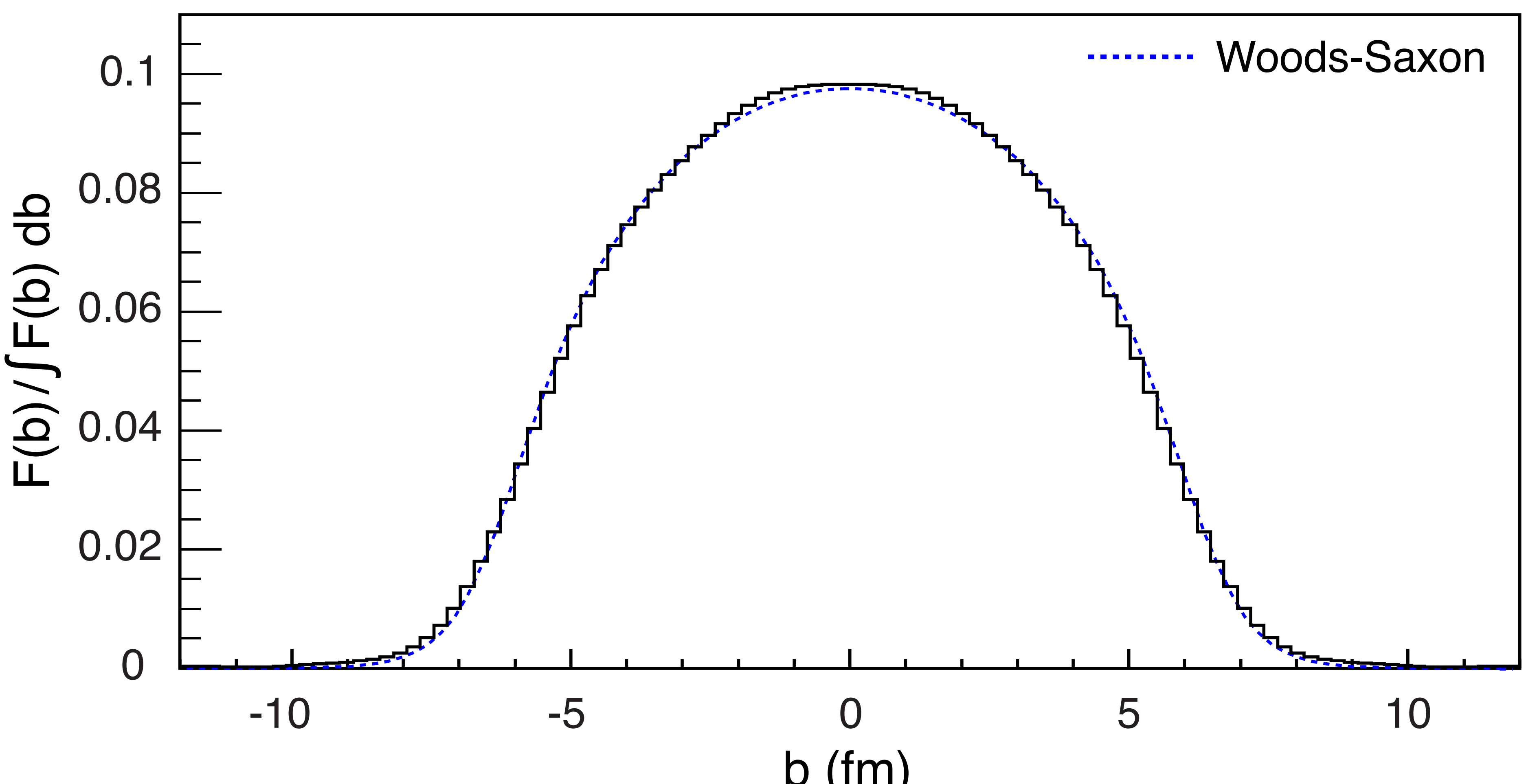

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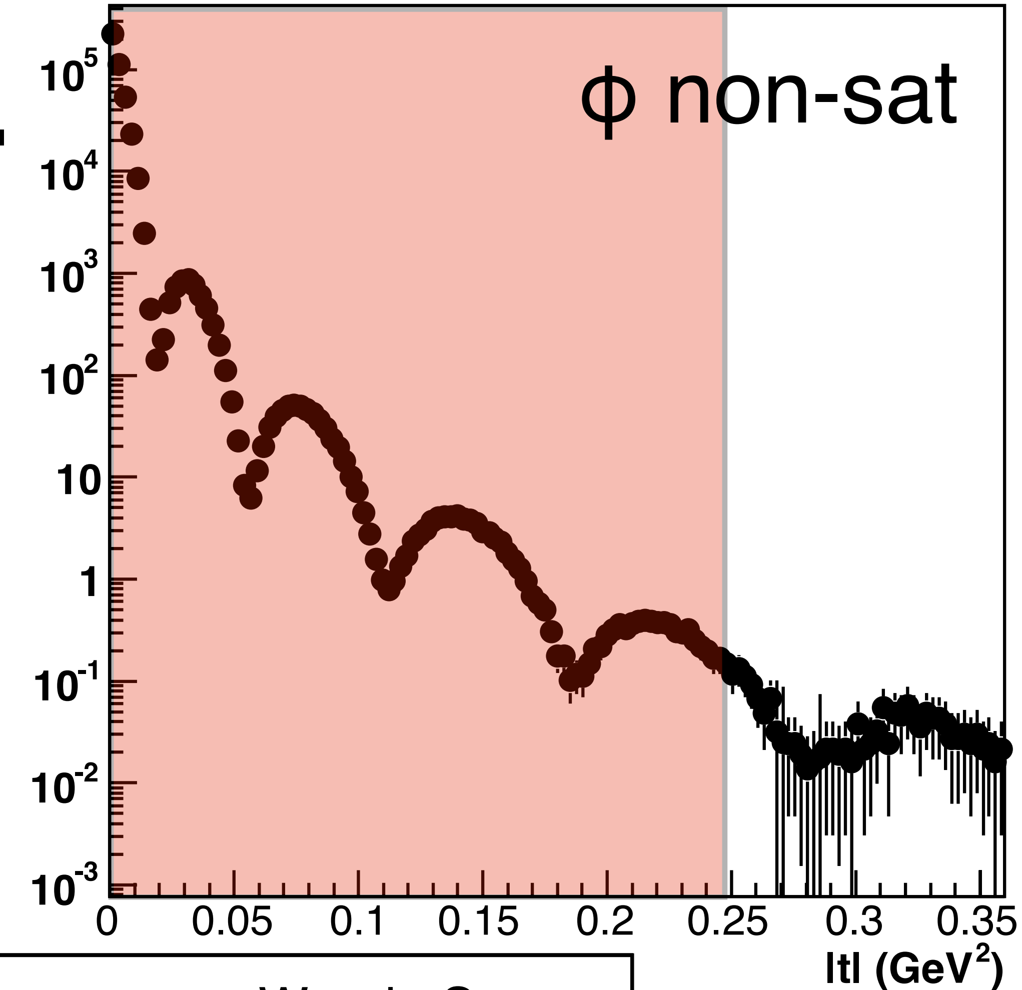


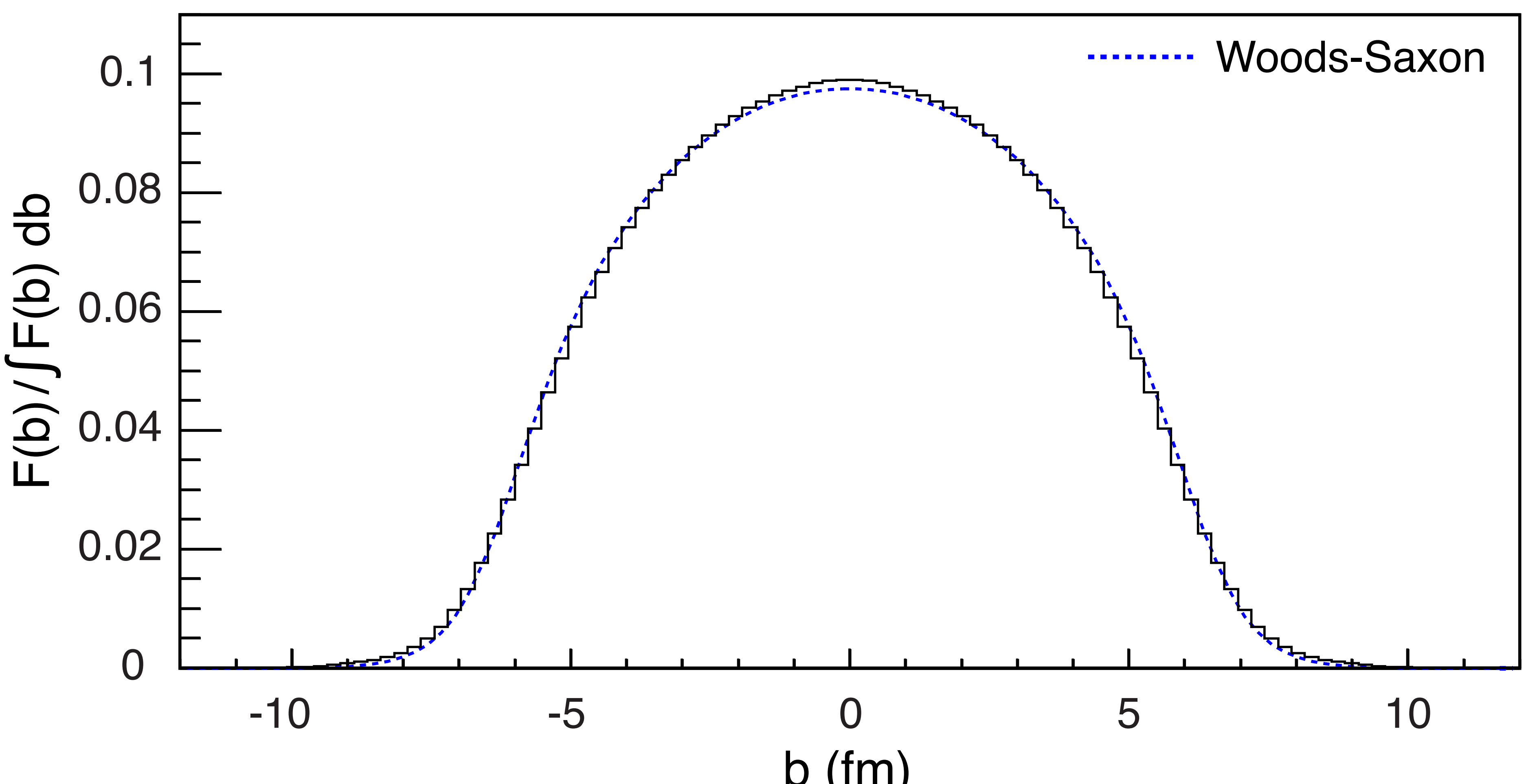

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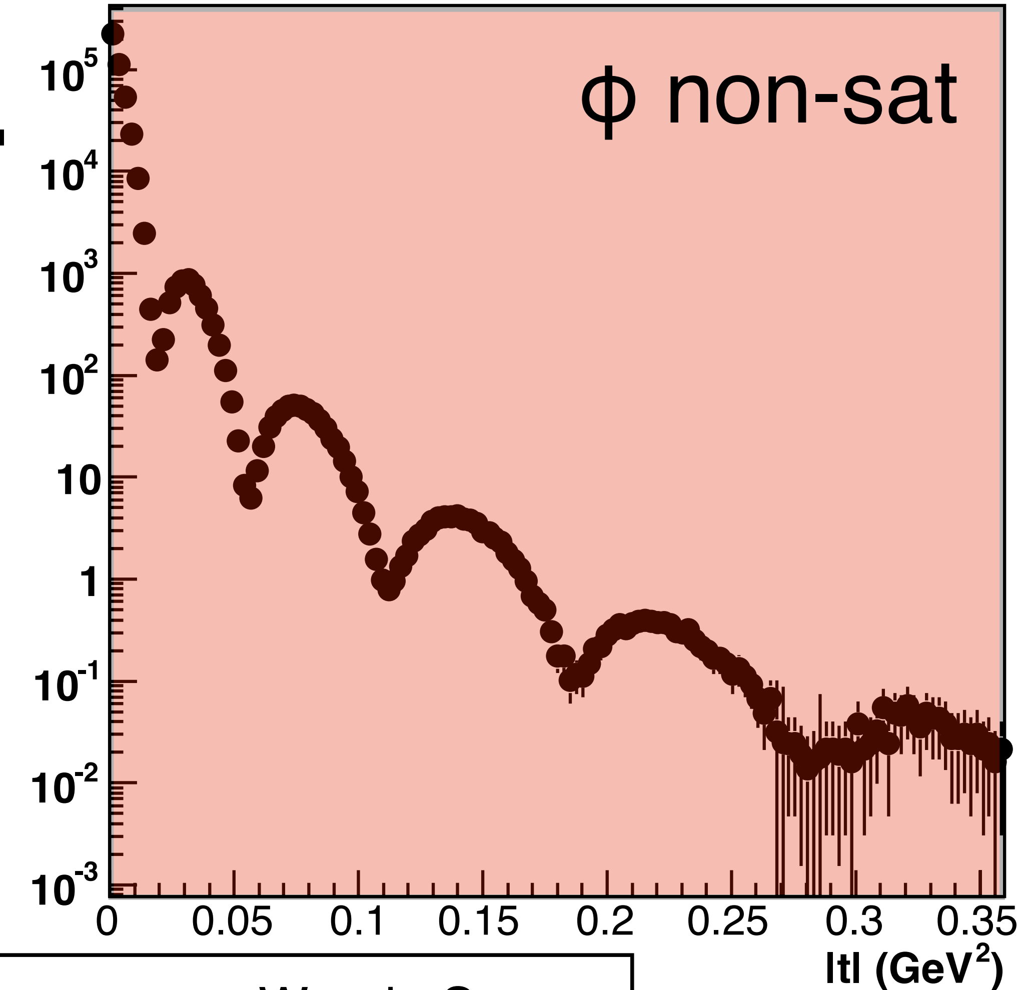


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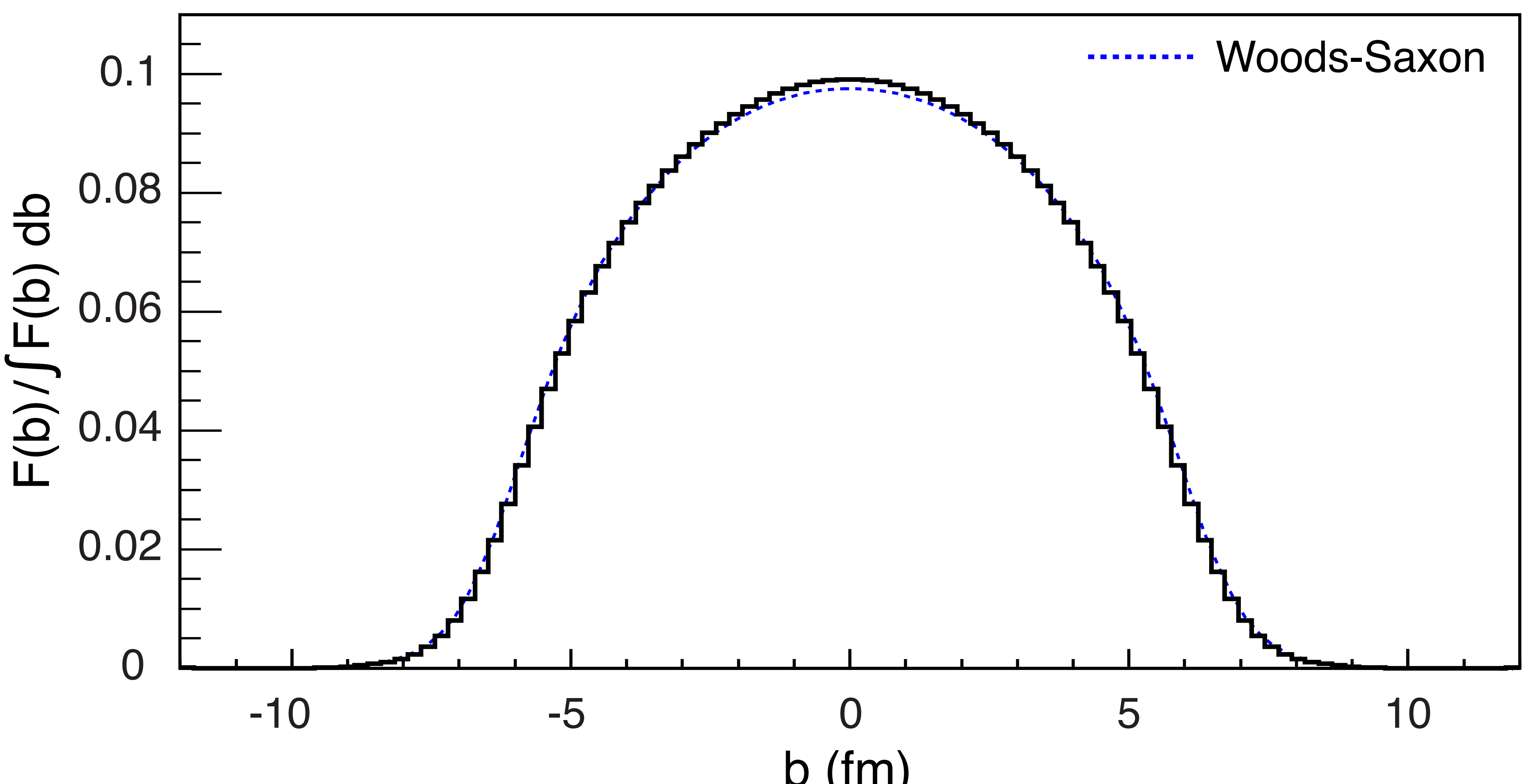
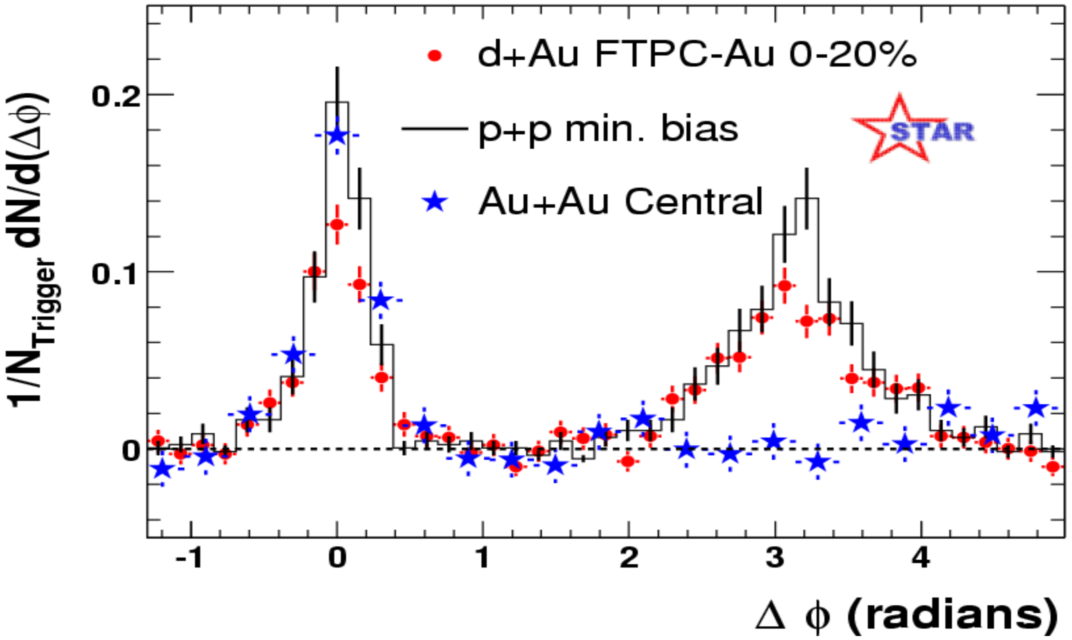
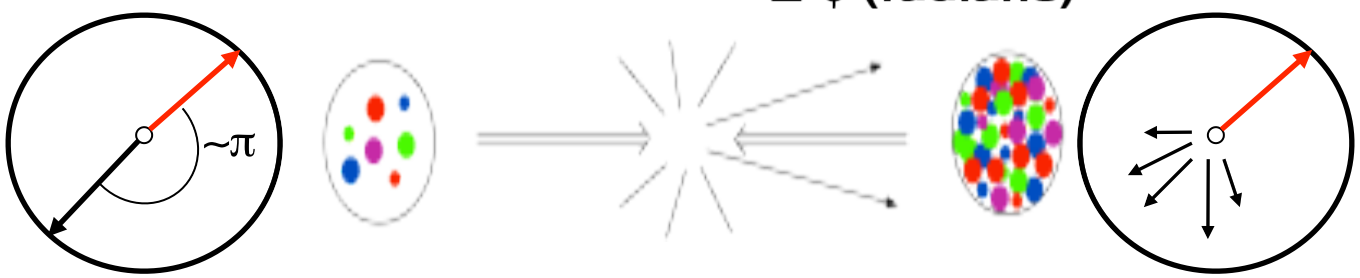


# di-hadron correlations in d+A

comparisons between d+Au → $h_1$ $h_2$ X (or p +Au → $h_1$ $h_2$ X ) and p+p → $h_1$ $h_2$ X




- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A

➡ x ~ $10^{-2}$

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$

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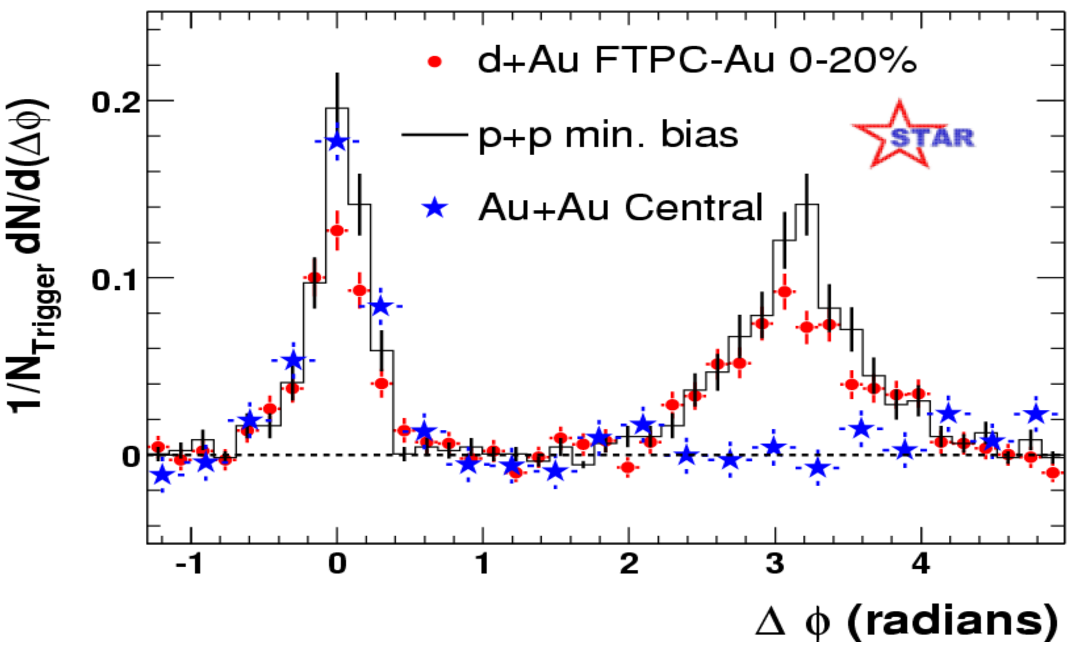


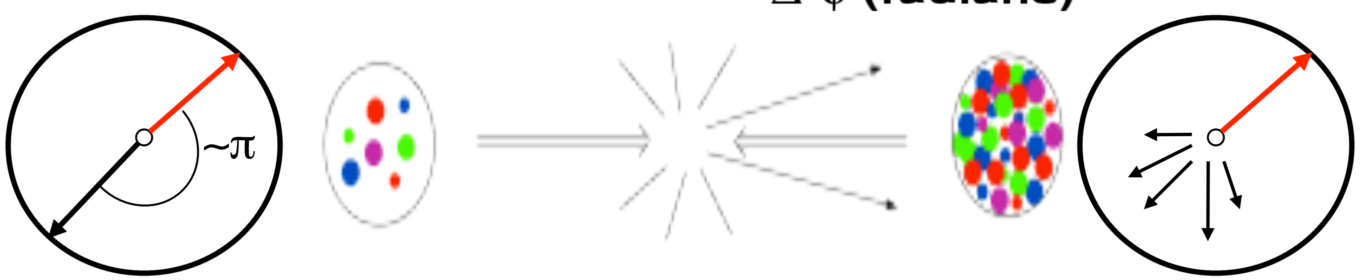


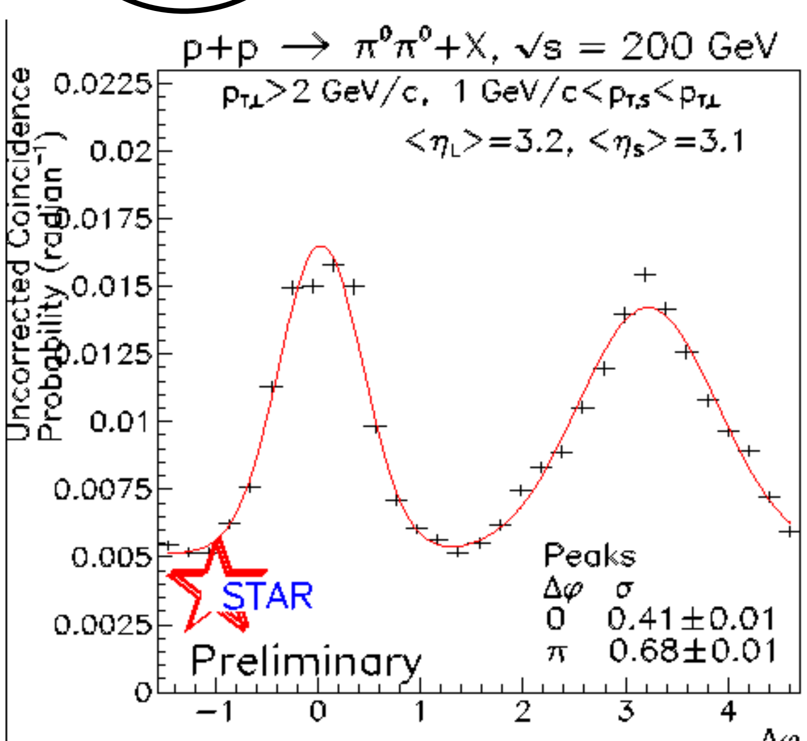


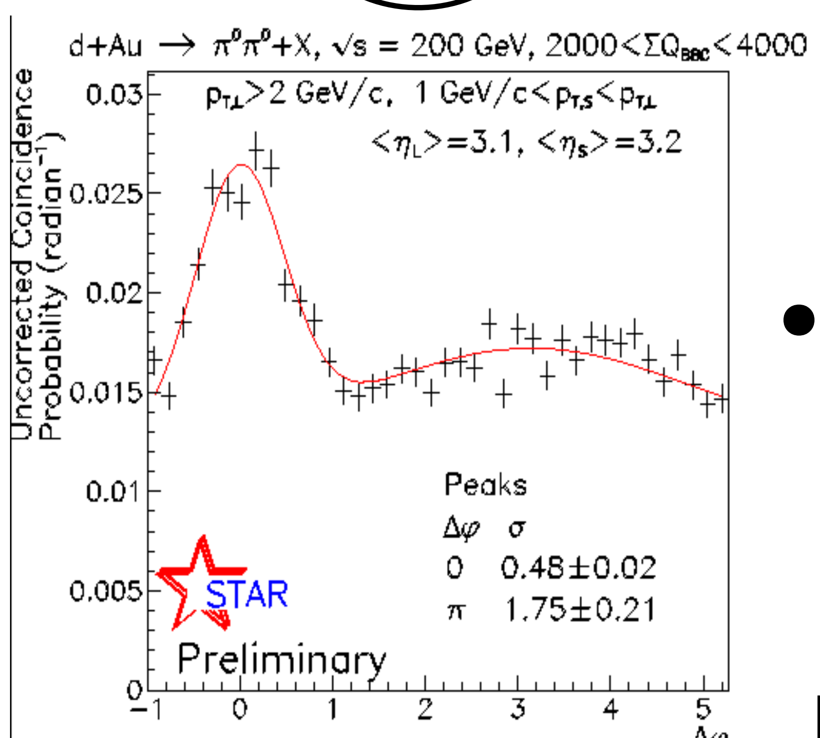


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$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$

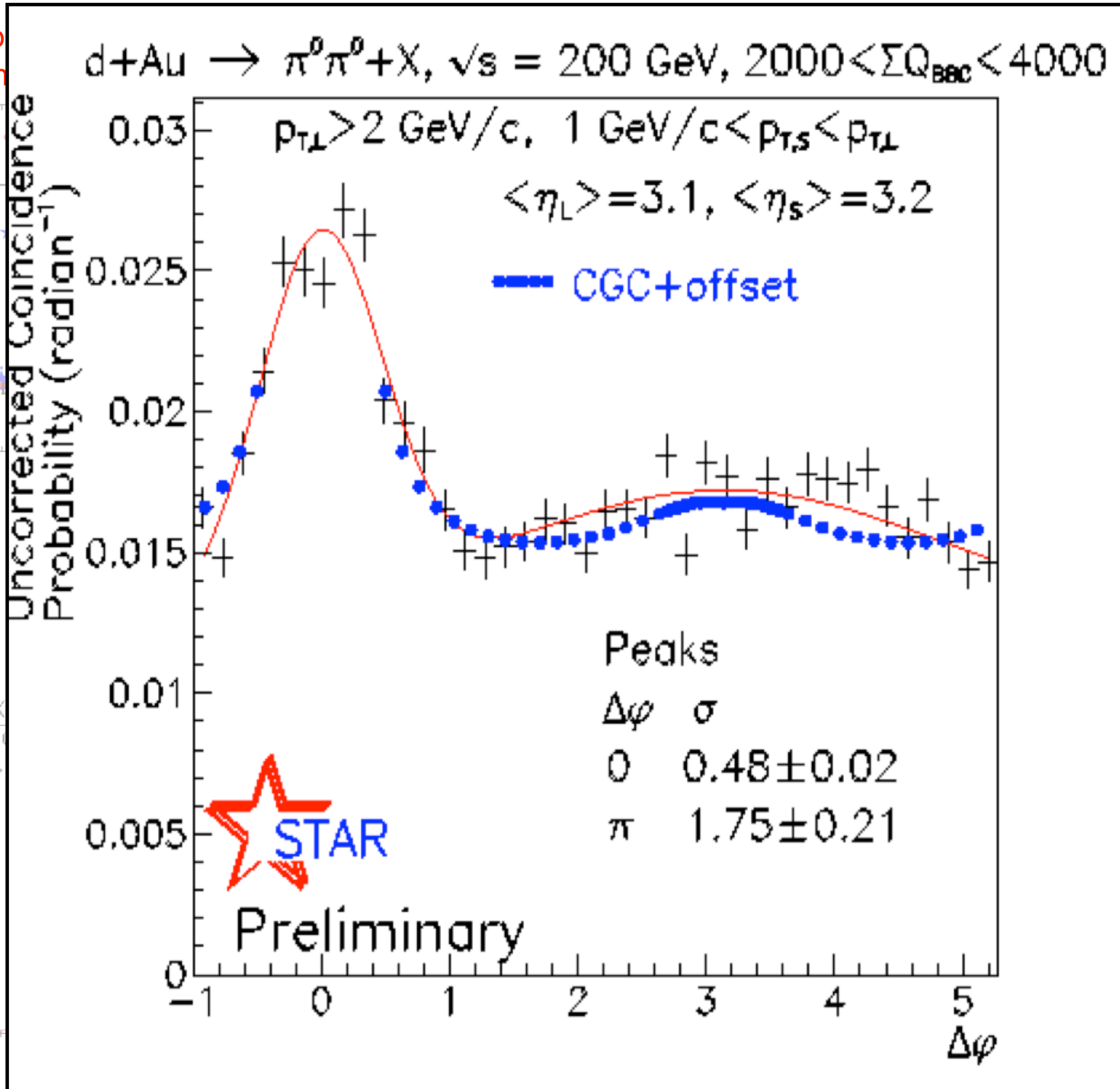
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

➡ $x \sim 10^{-3}$

l.gov

# di-hadron correlations in d+A

comparisons b
+Au → $h_1$ h

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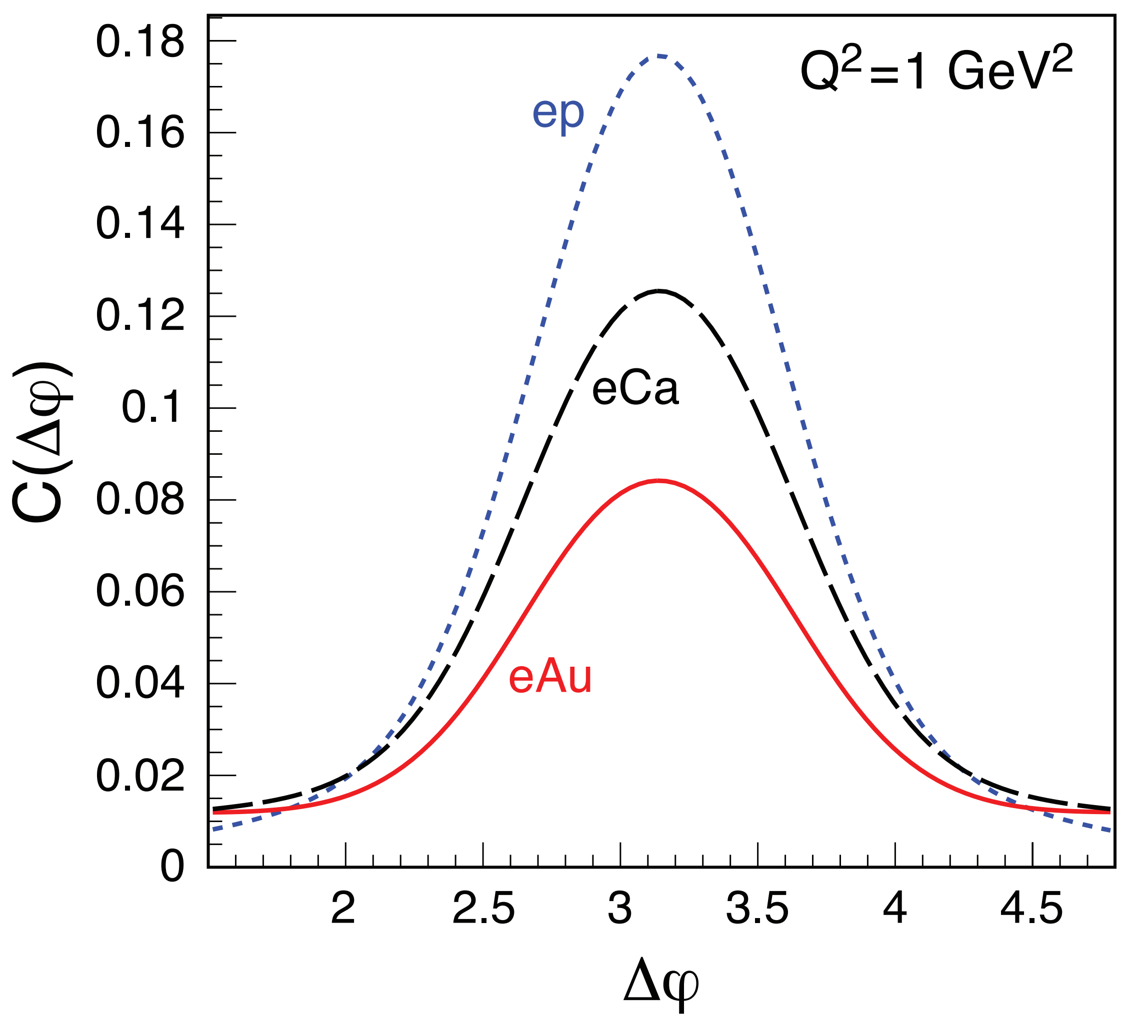
# di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A




Dominguez, Xiao and Yuan (2012)

- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
  - ➡ The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is equally important that we understand it
- The d+Au RHIC data is therefore subject to many uncertainties
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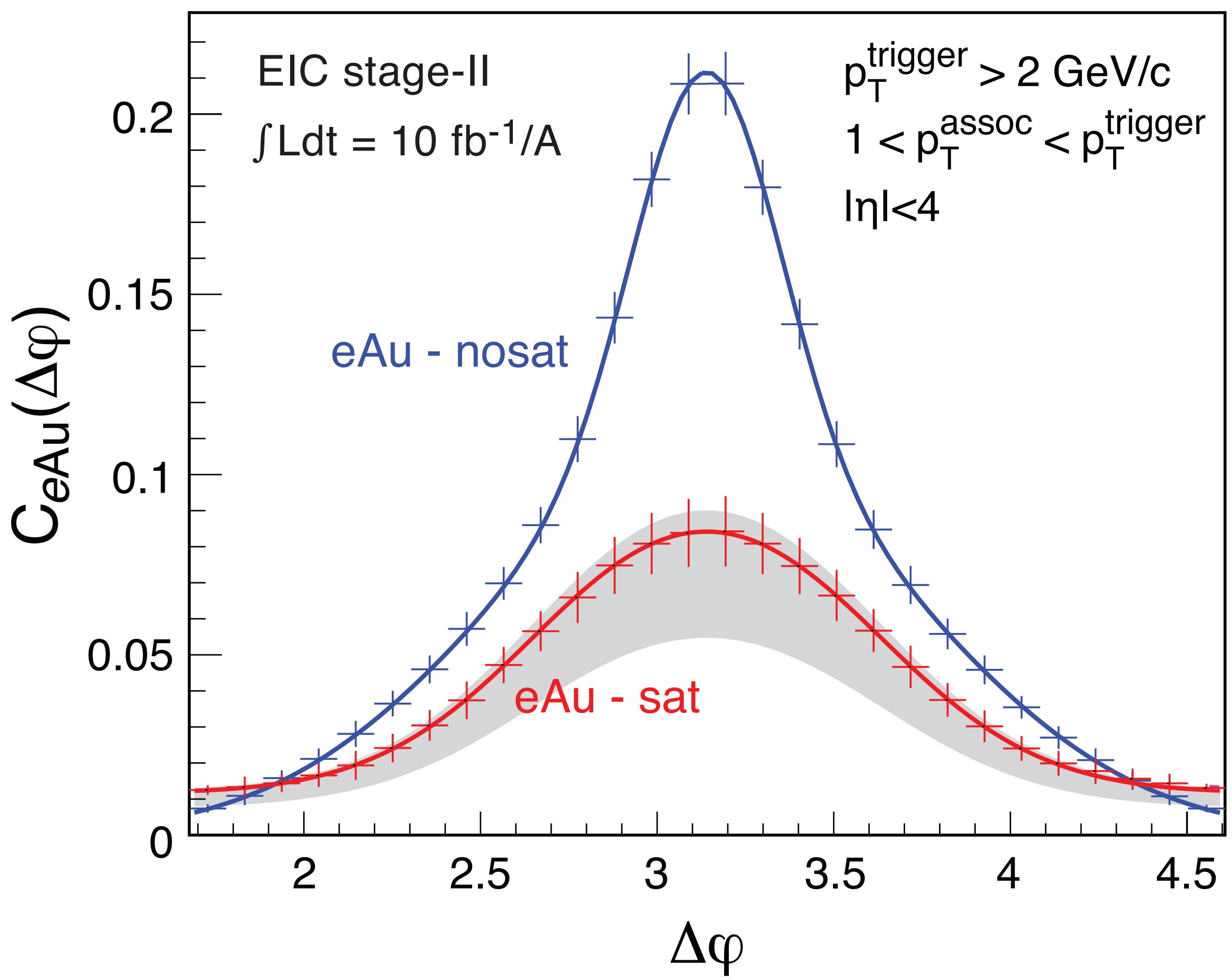


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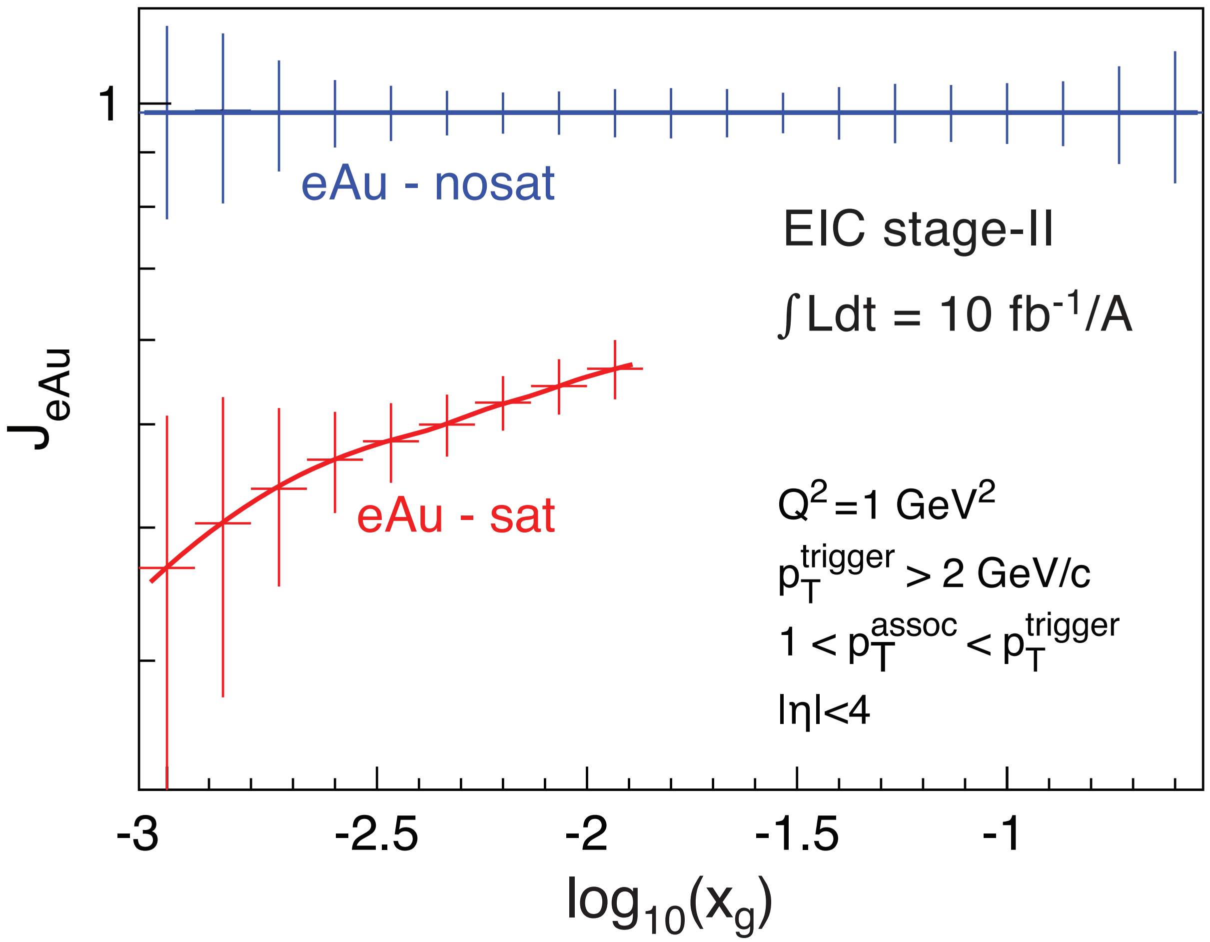
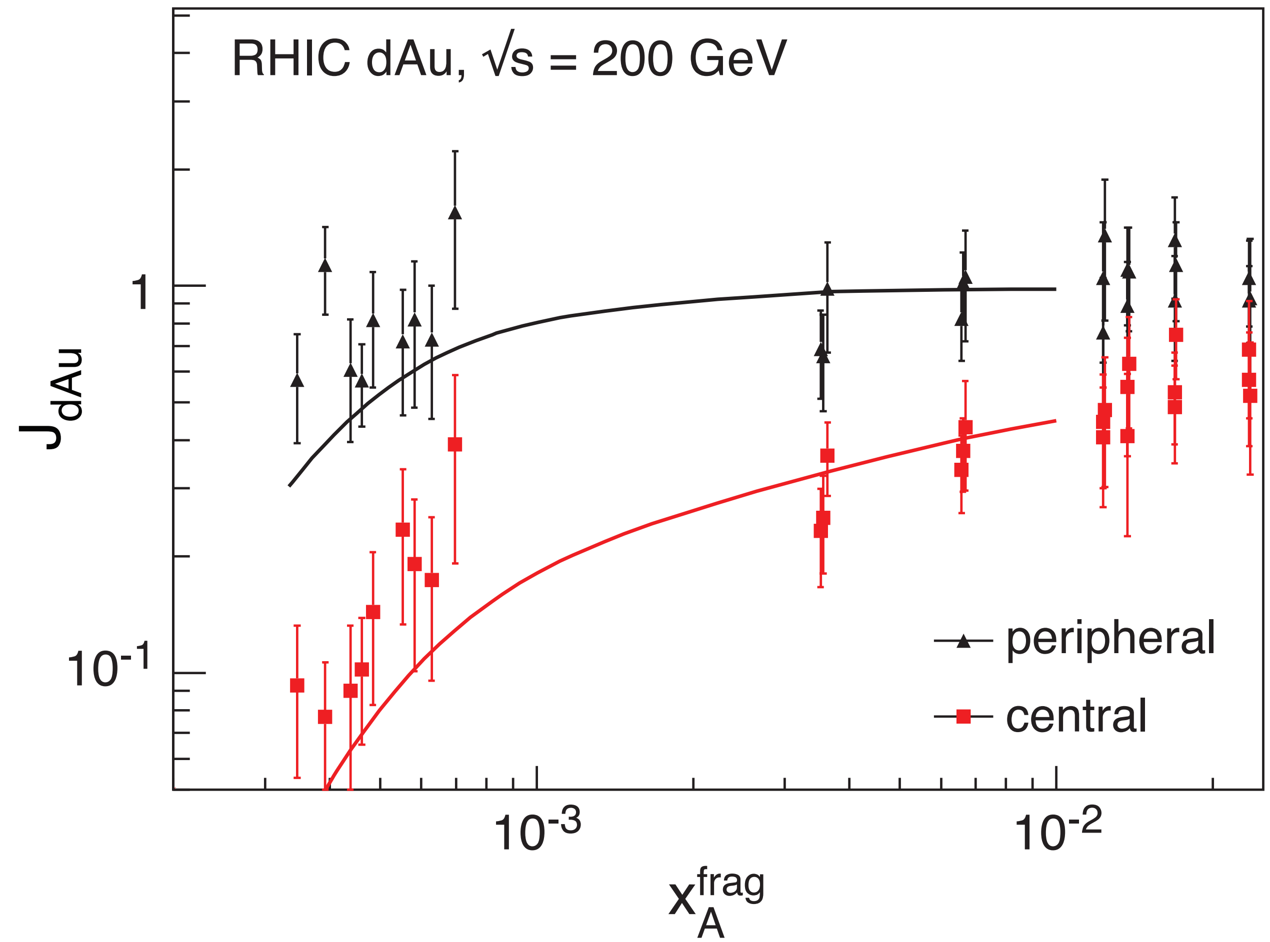
# di-hadron Correlations - relative yields

- PHENIX measured $J_{dAu}$ - relative yield of di-hadrons produced in d+Au compared to p+p collisions
  - ➡ Suppression in central events compared to peripheral as a function of $x_A^{frag}$
    - Curves come from saturation model
- Can perform the same measurement in e+A collisions

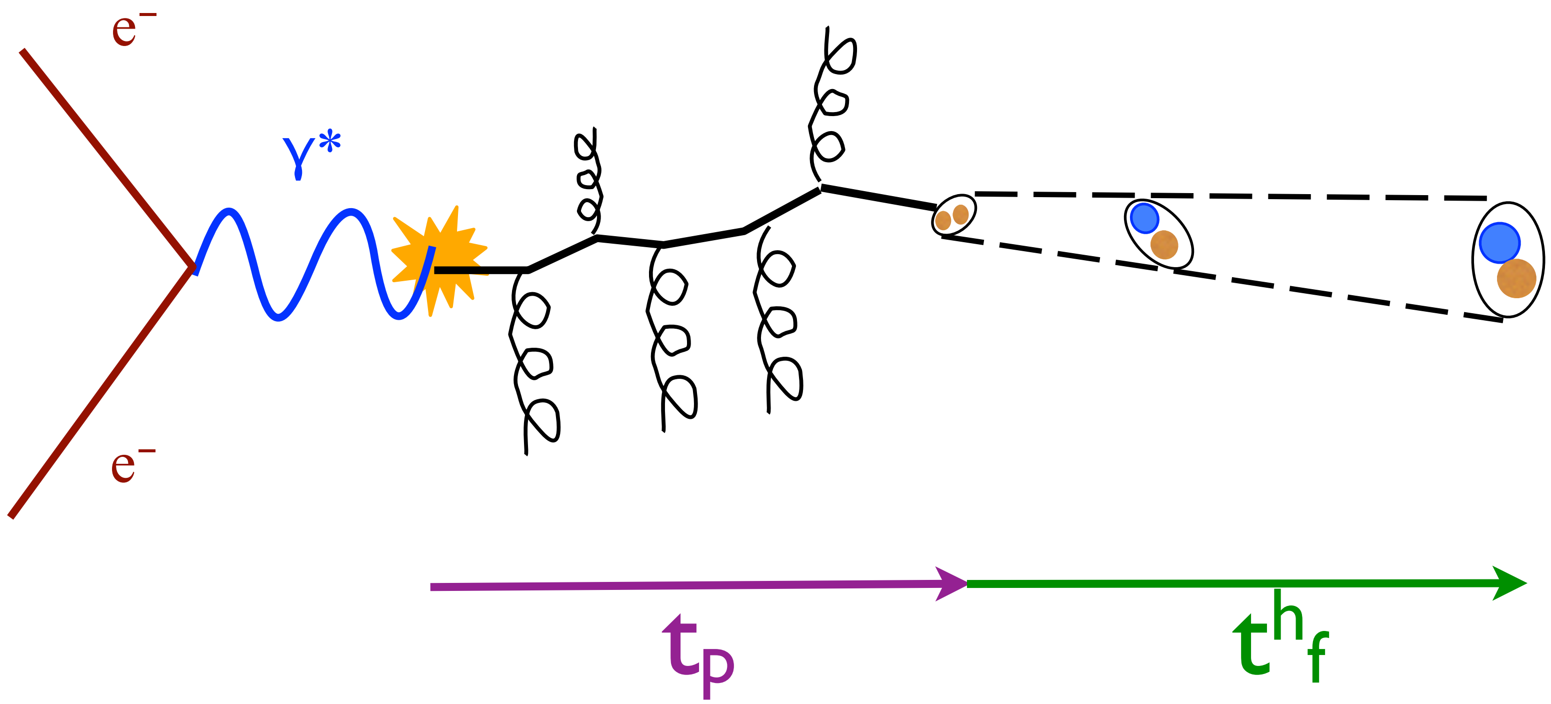



forward-forward mid-forward




A. Adare et al., Phys. Rev. Lett. 107, 172301 (2011)

# Jets and hadronization




- $t_p$ - production time of propagating quark
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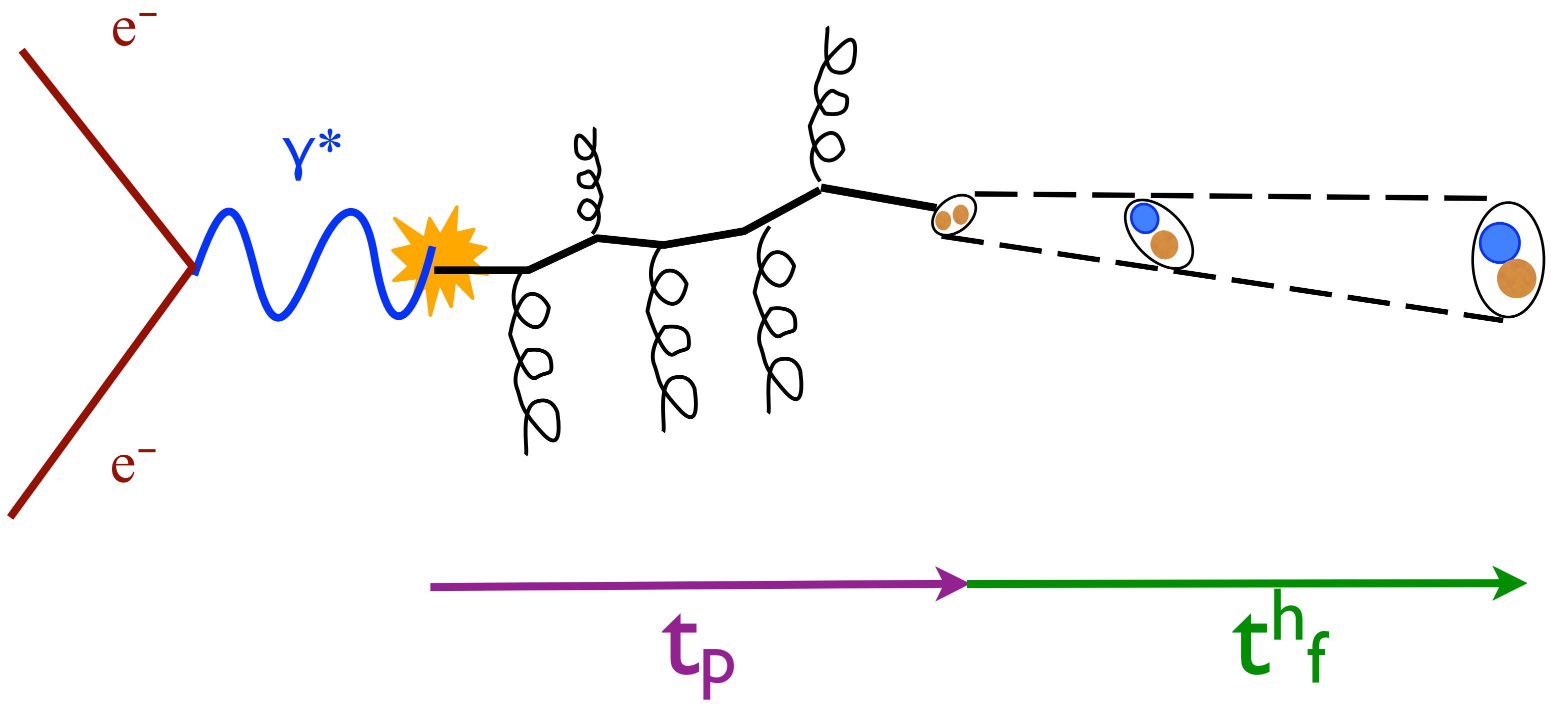


What happens if we add a nuclear medium?

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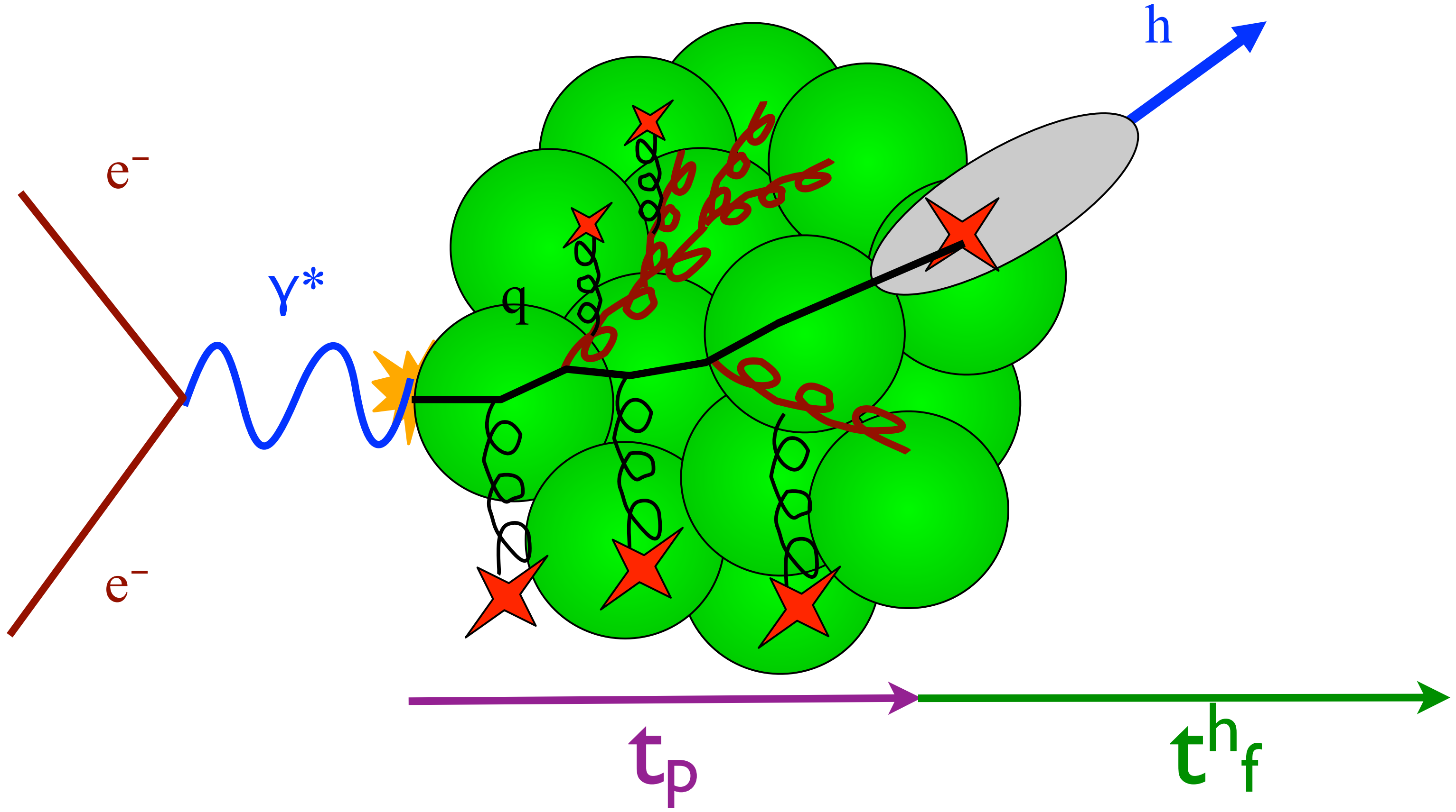


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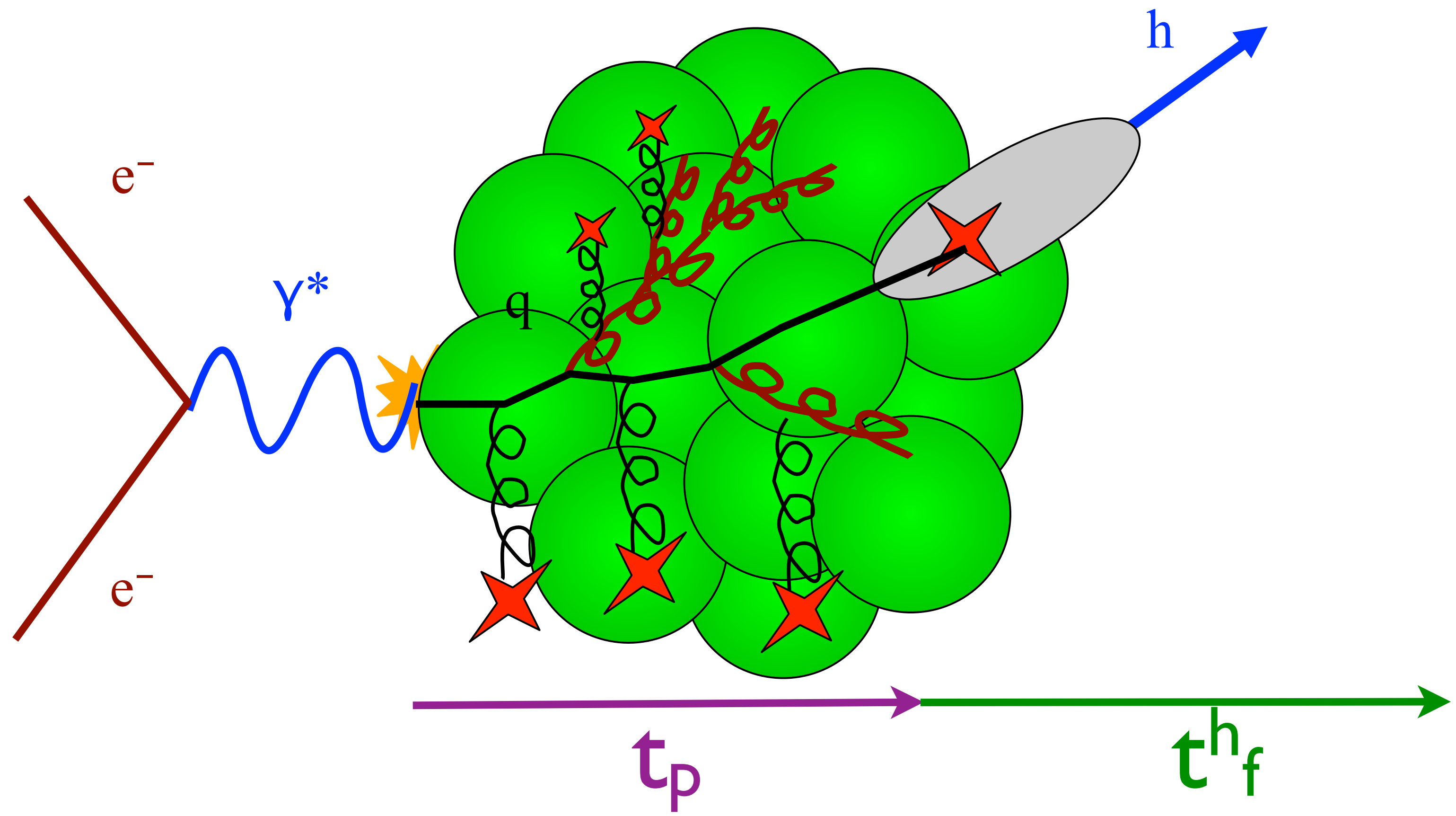


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## Observables:

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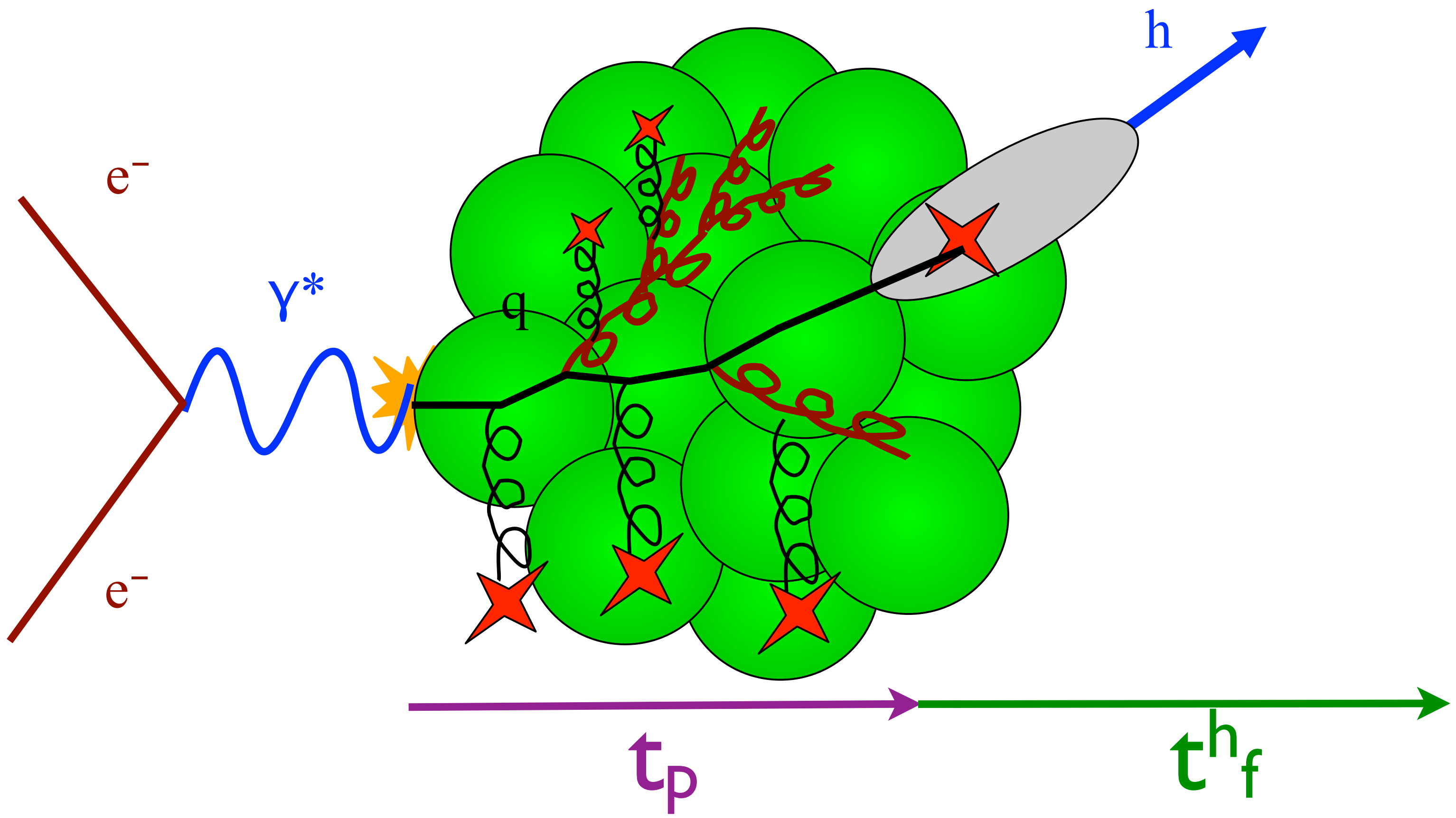


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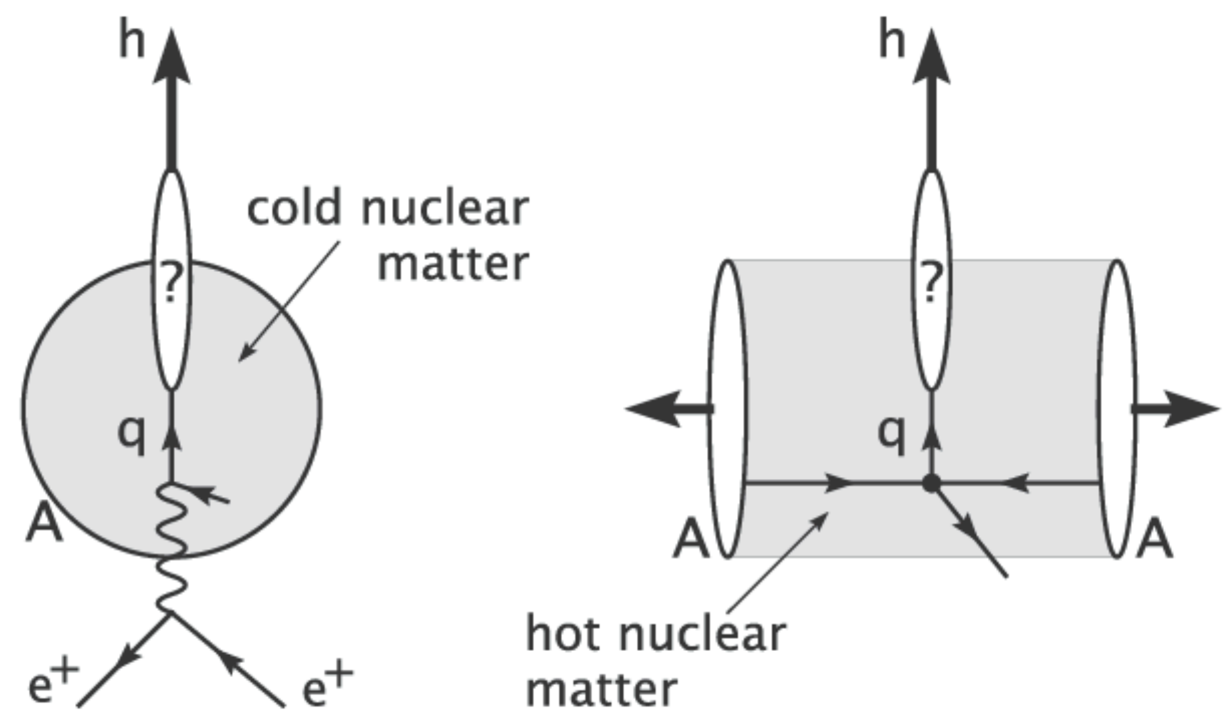


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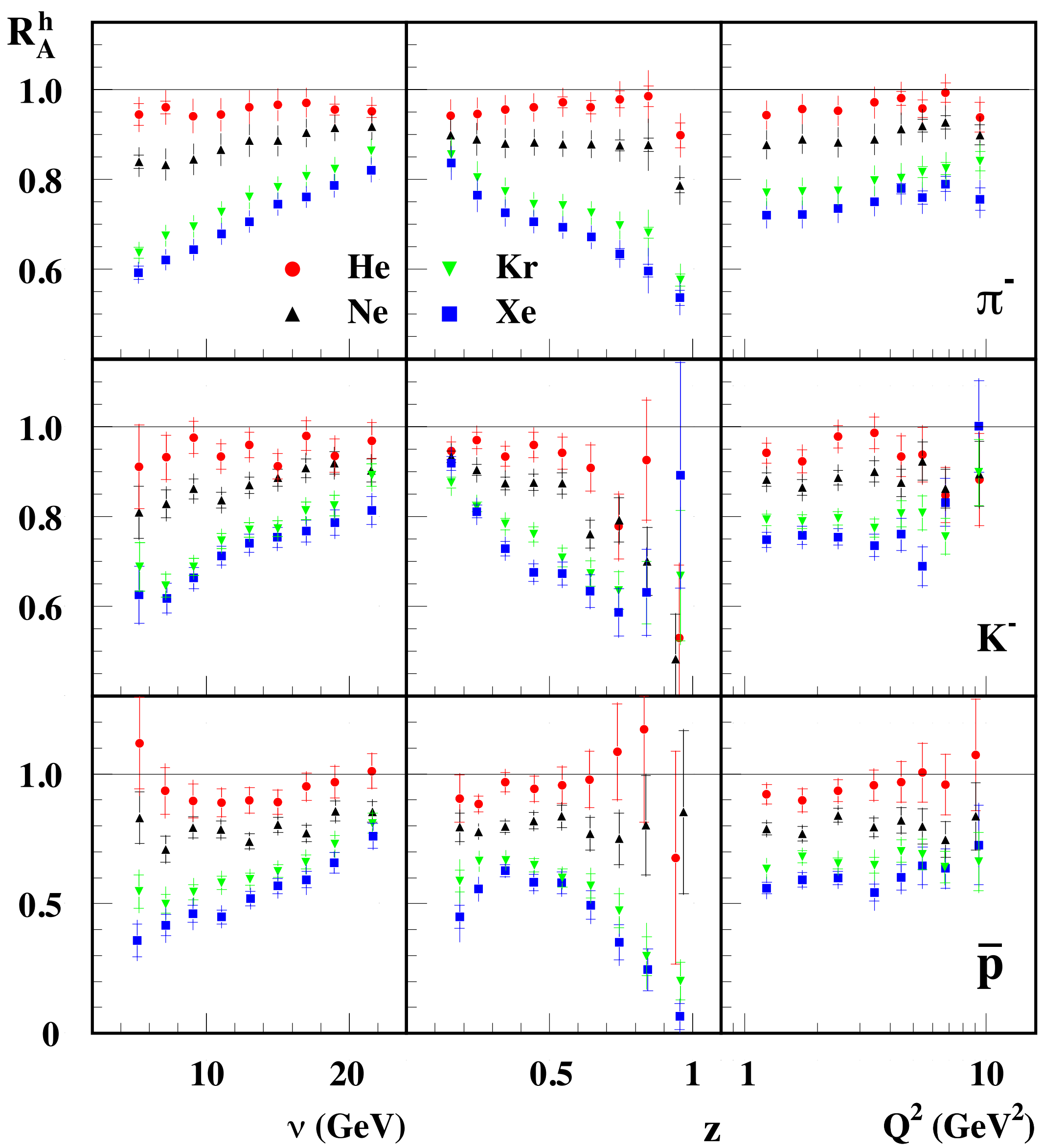
# How can the EIC contribute?

HERMES:

$E_e$ = 27 GeV → $\sqrt{s}$ = 7.2 GeV

$E_h$ = 2-15 GeV

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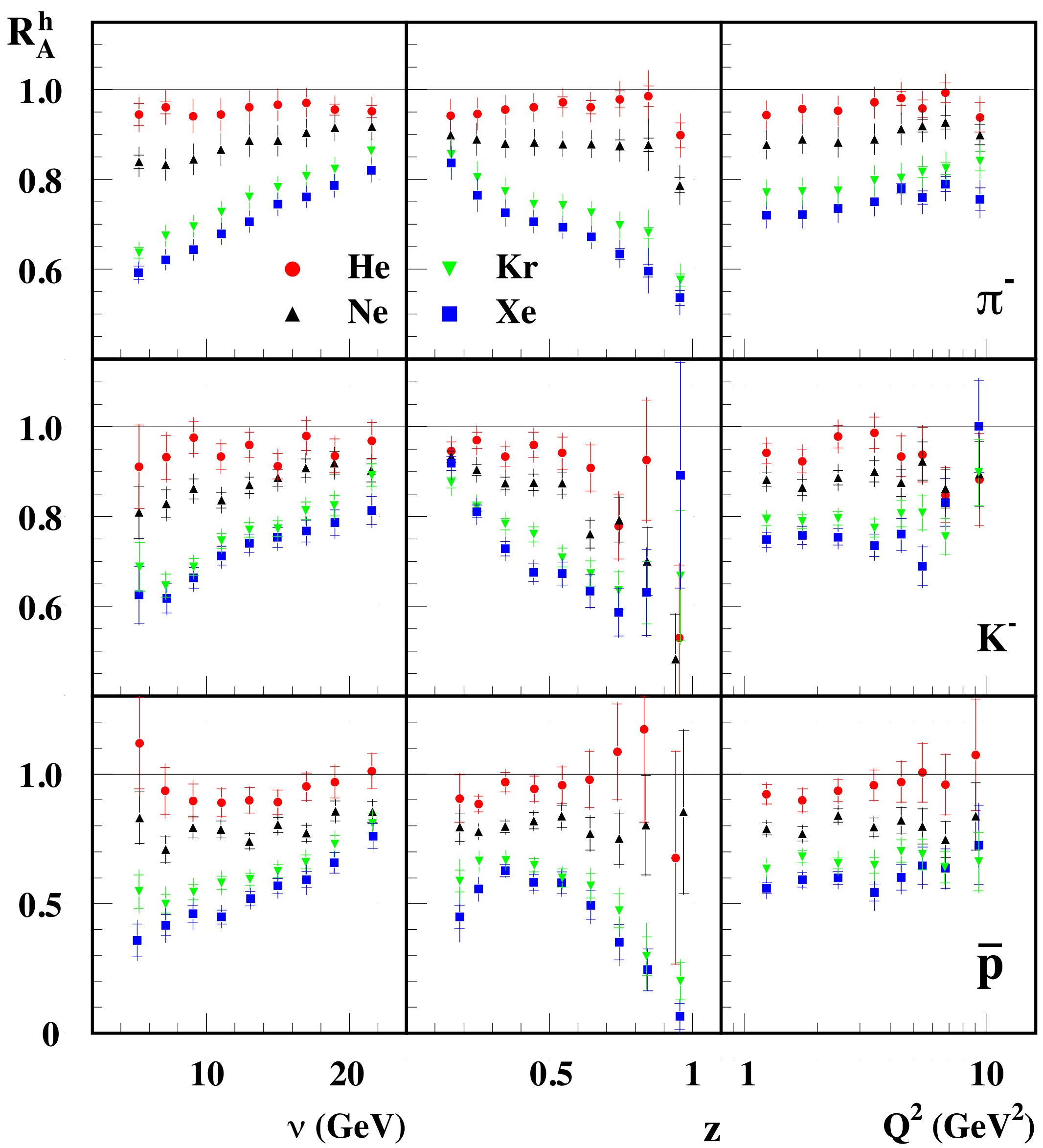


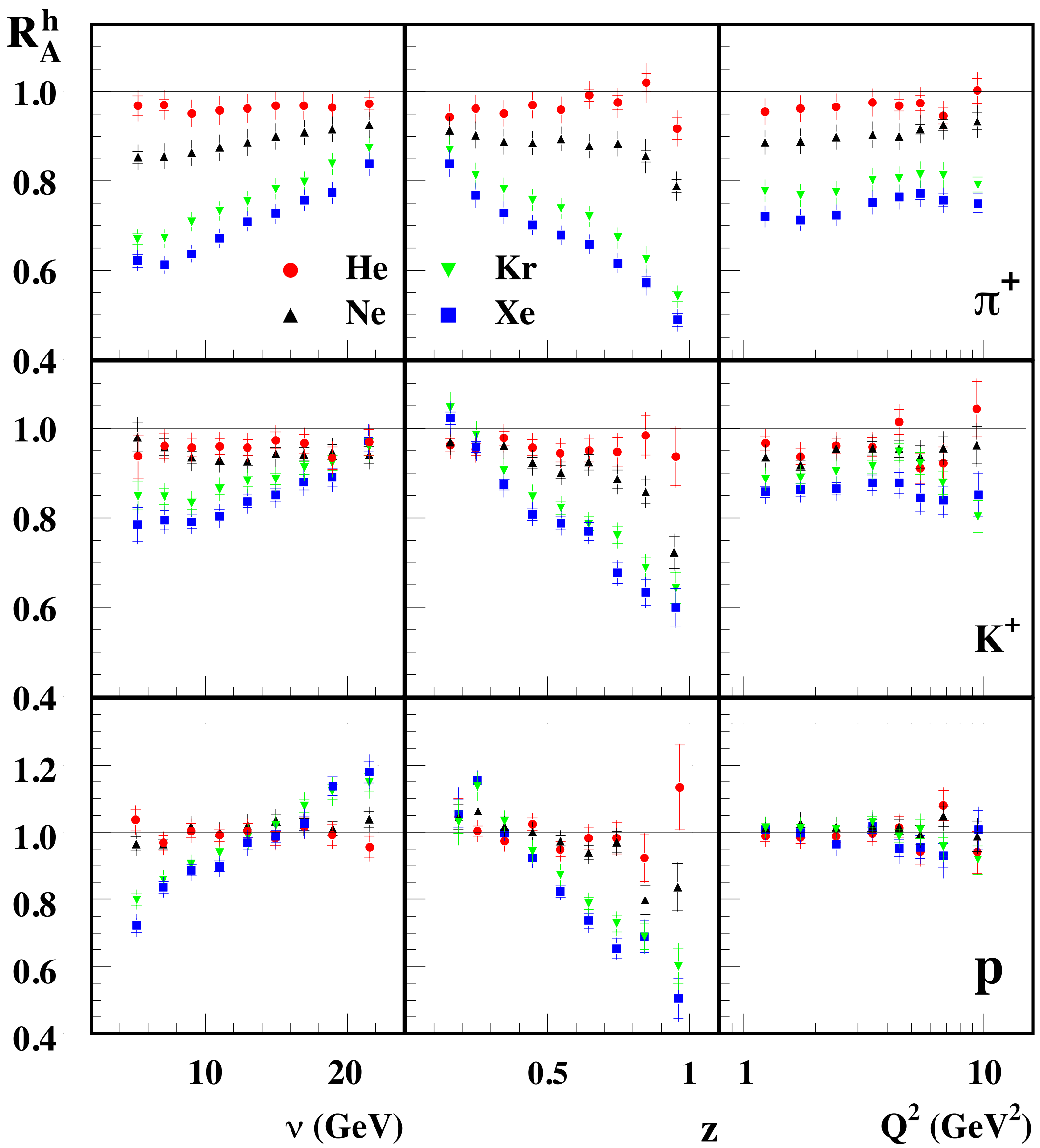


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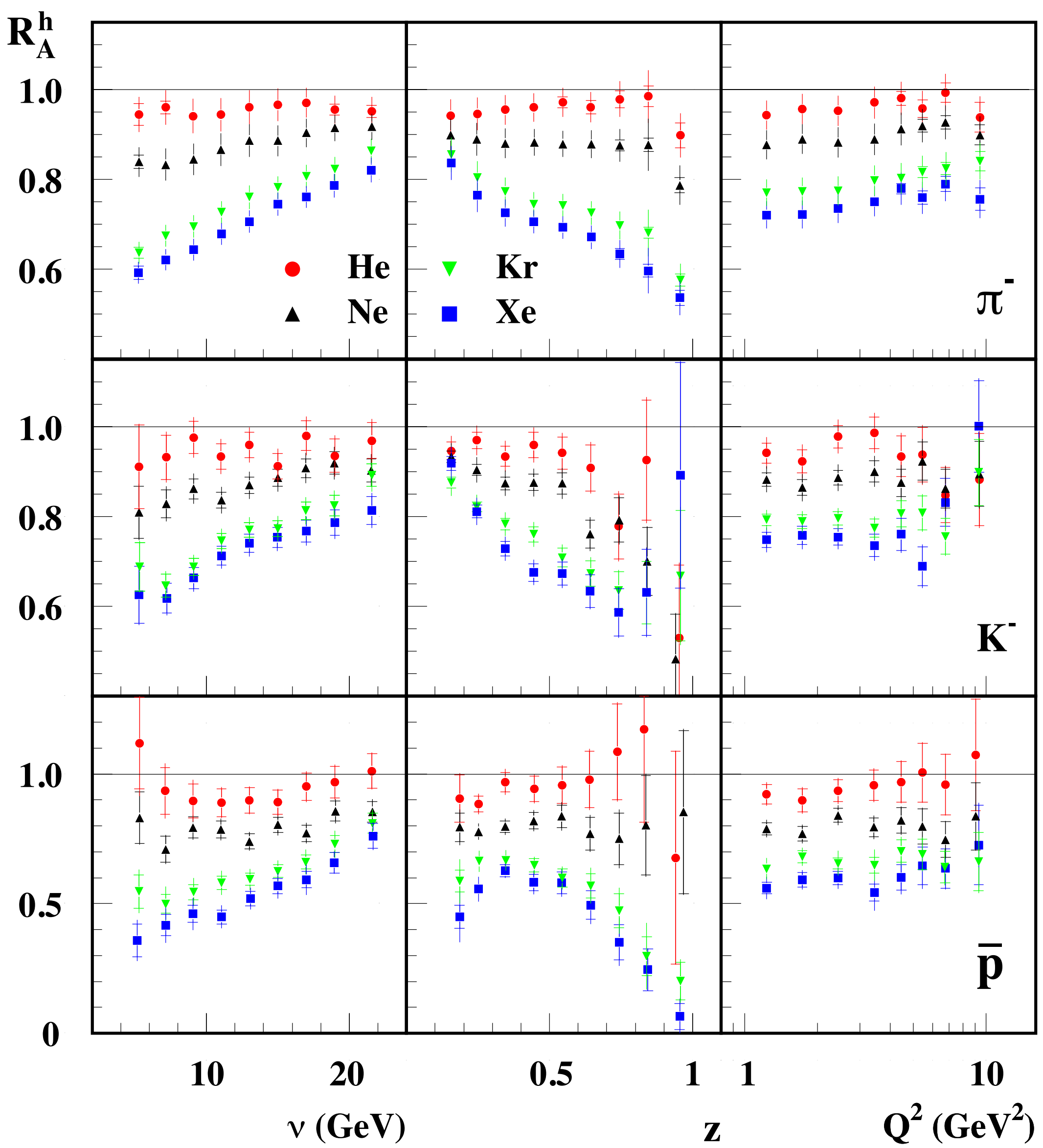


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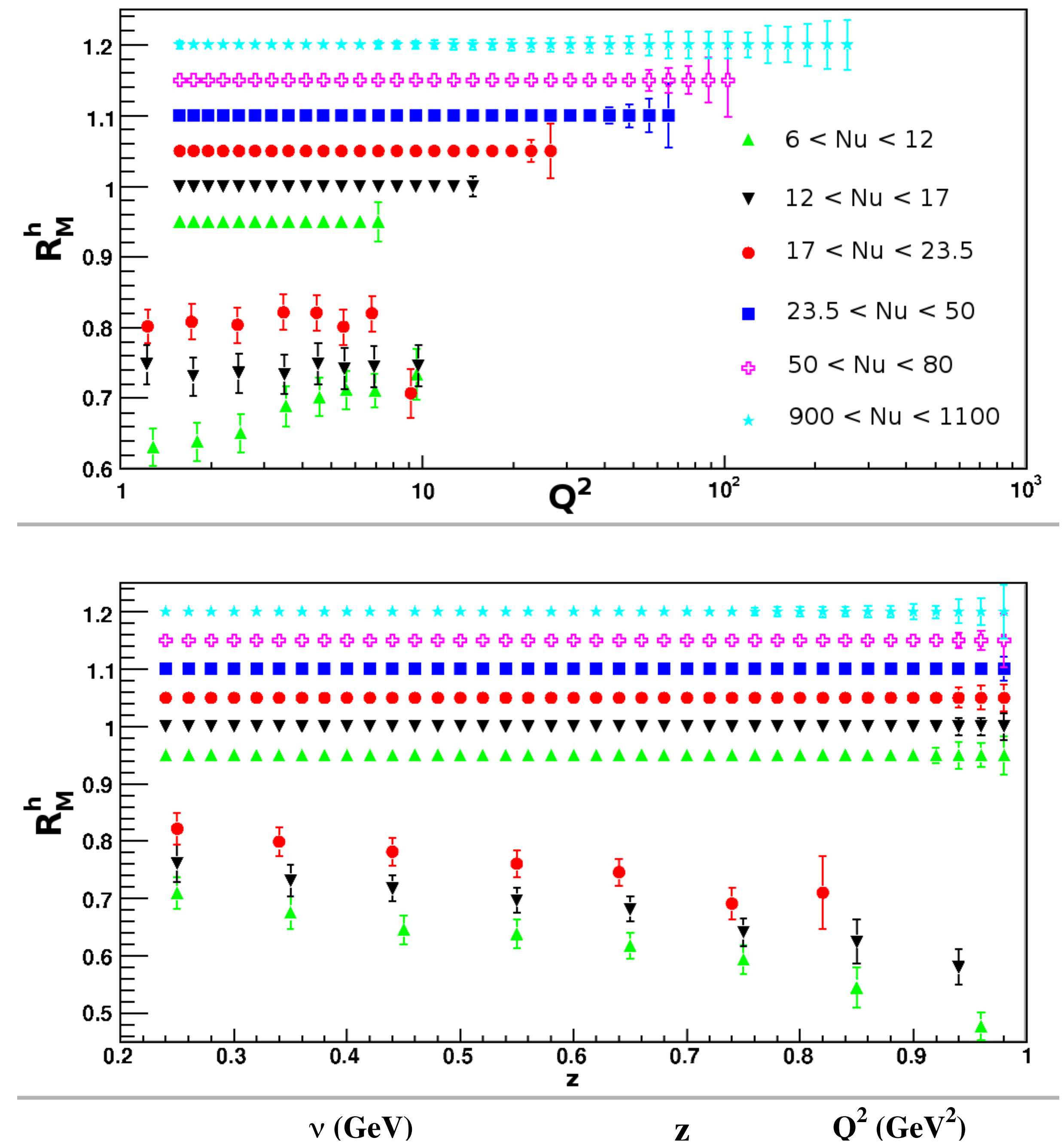
light hadrons:




large ν range → boost

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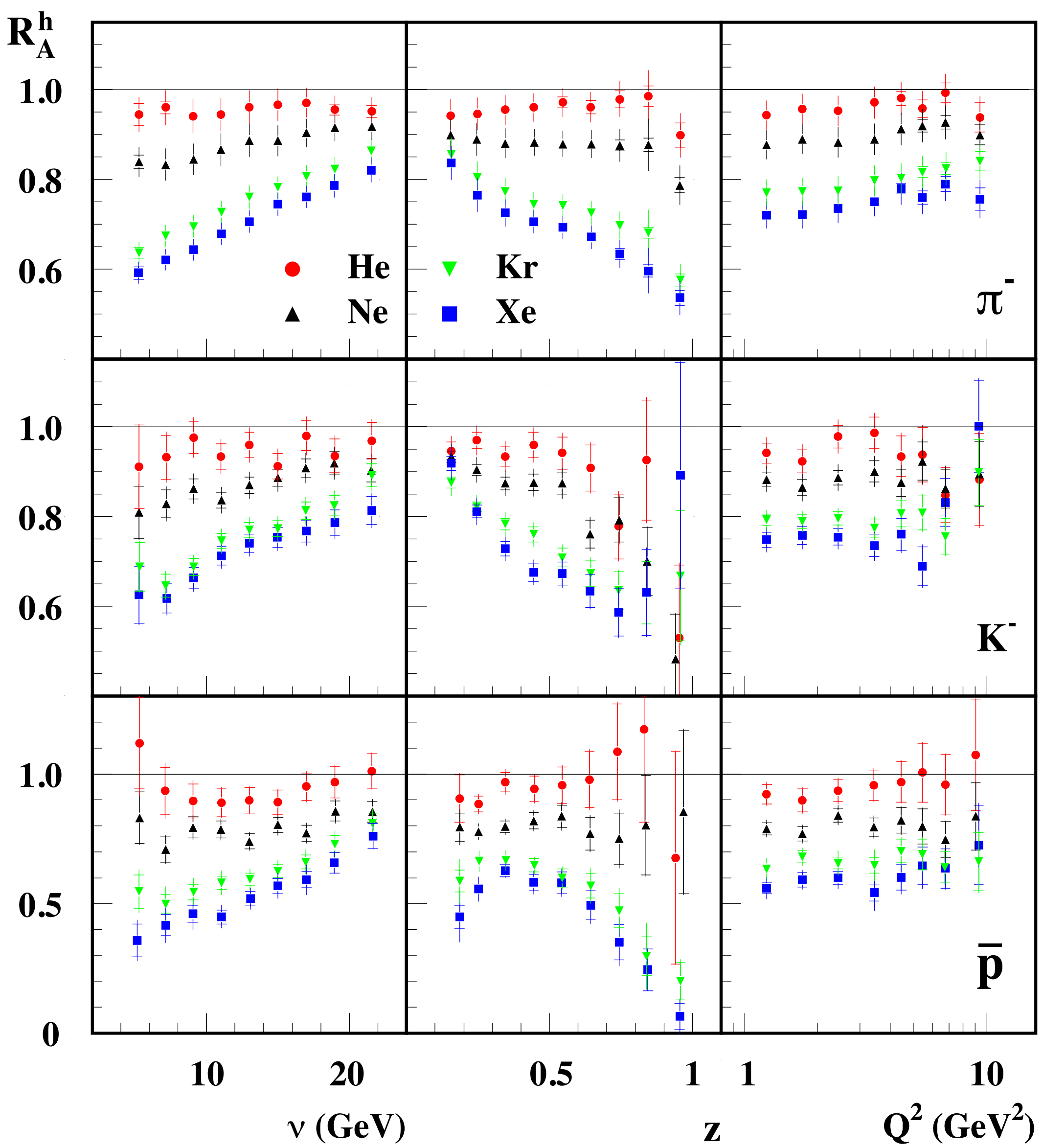


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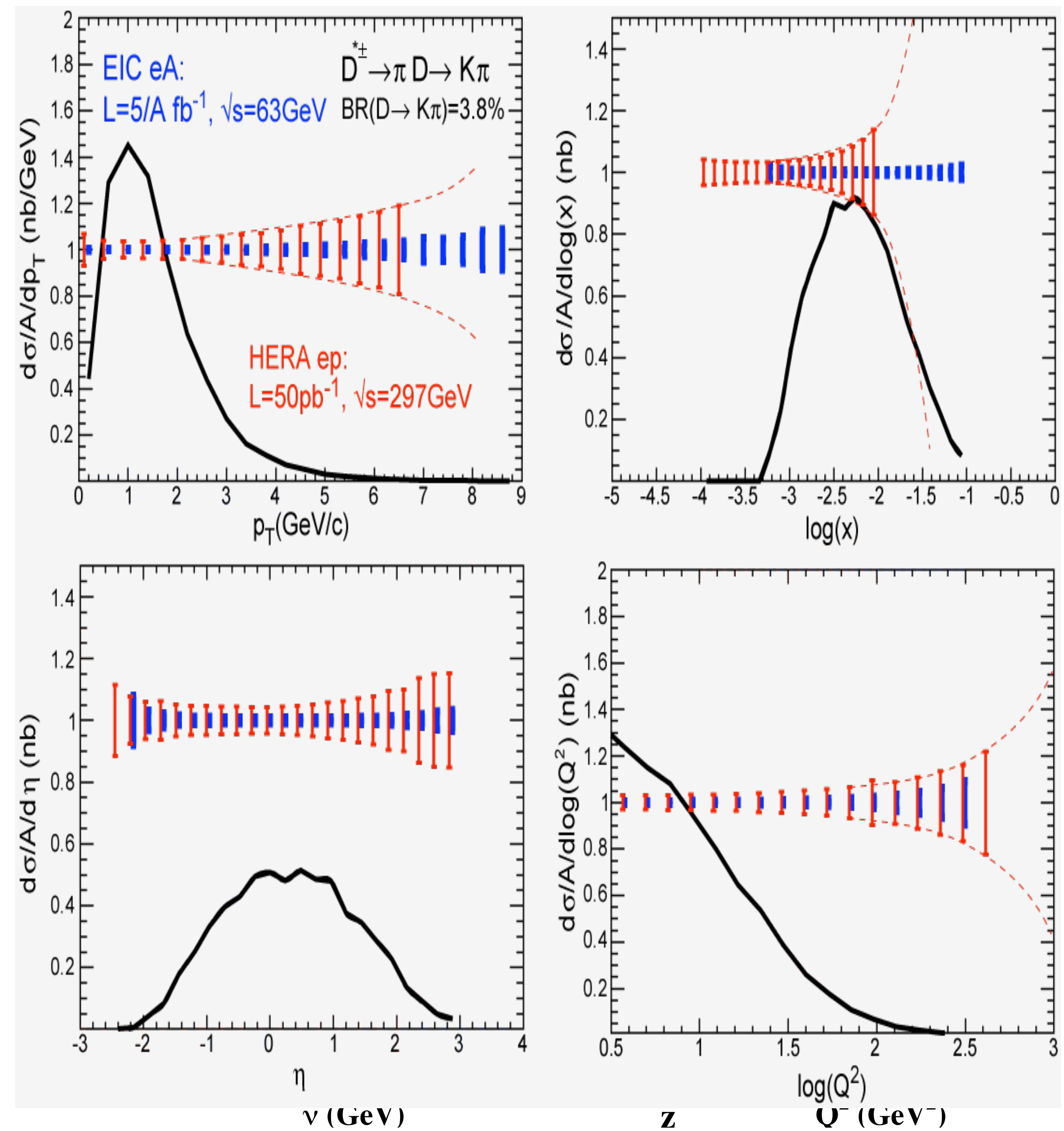
charm hadrons:

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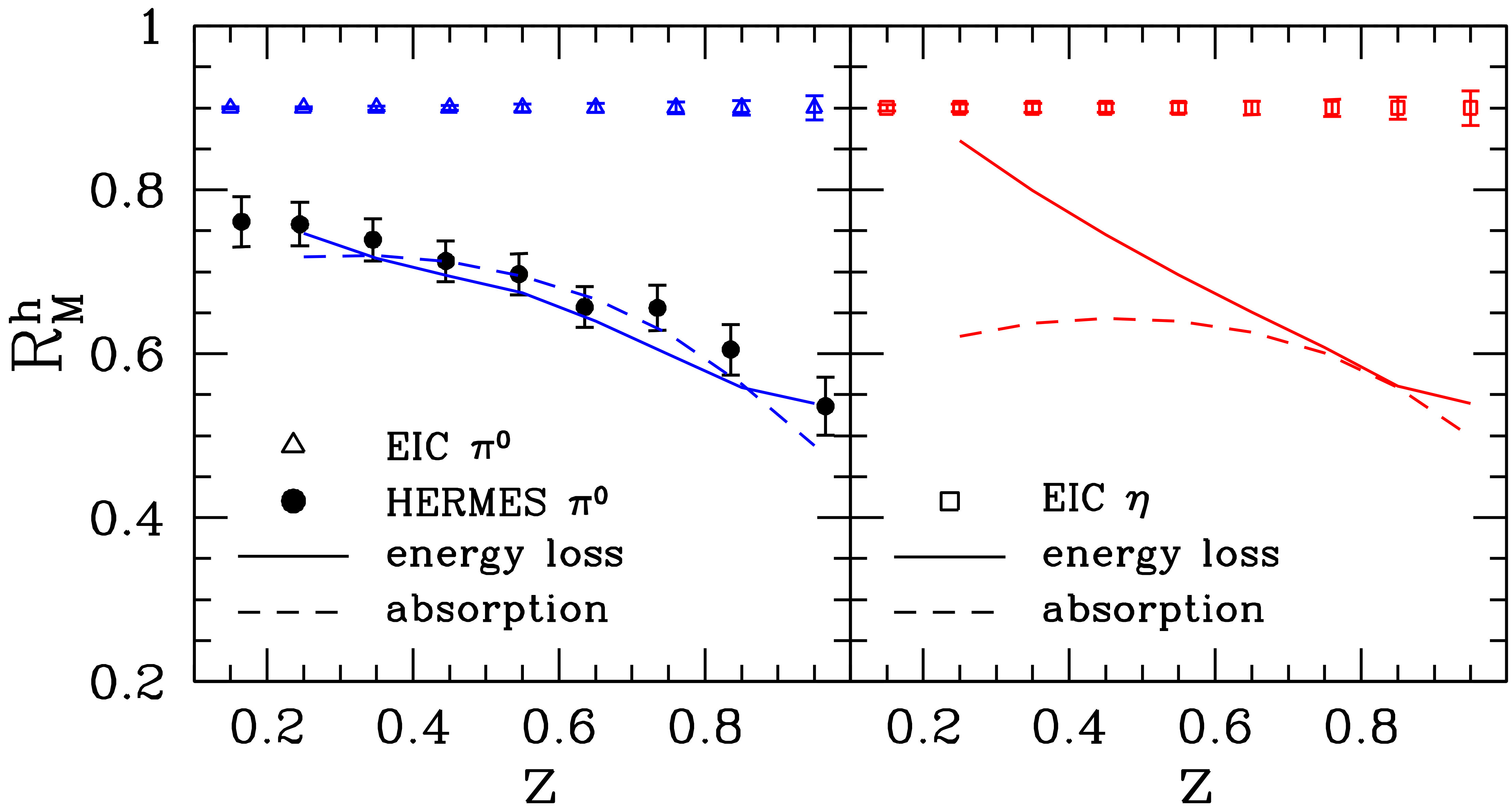
$E_h$ = 2-15 GeV

EIC:




$\nu$ = virtual photon energy

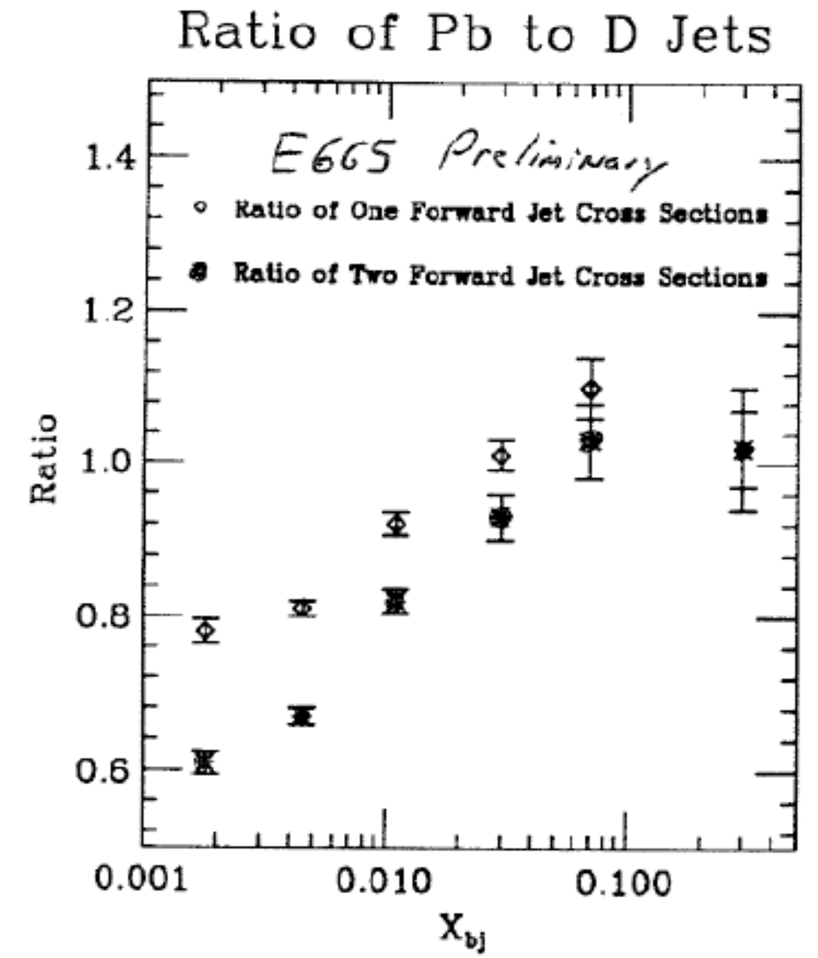
$Z_h = E_h/\nu$

large $\nu$ range → boost

hadronization in and out of nucleus

# Jets at an EIC

- E665 at FNAL have measured jets in μ+A at $\sqrt{s} \sim 30$ GeV
  - ➡ Feasible to start a jet programme in phase 1
  - ➡ caveat that collider kinematics are different to fixed target



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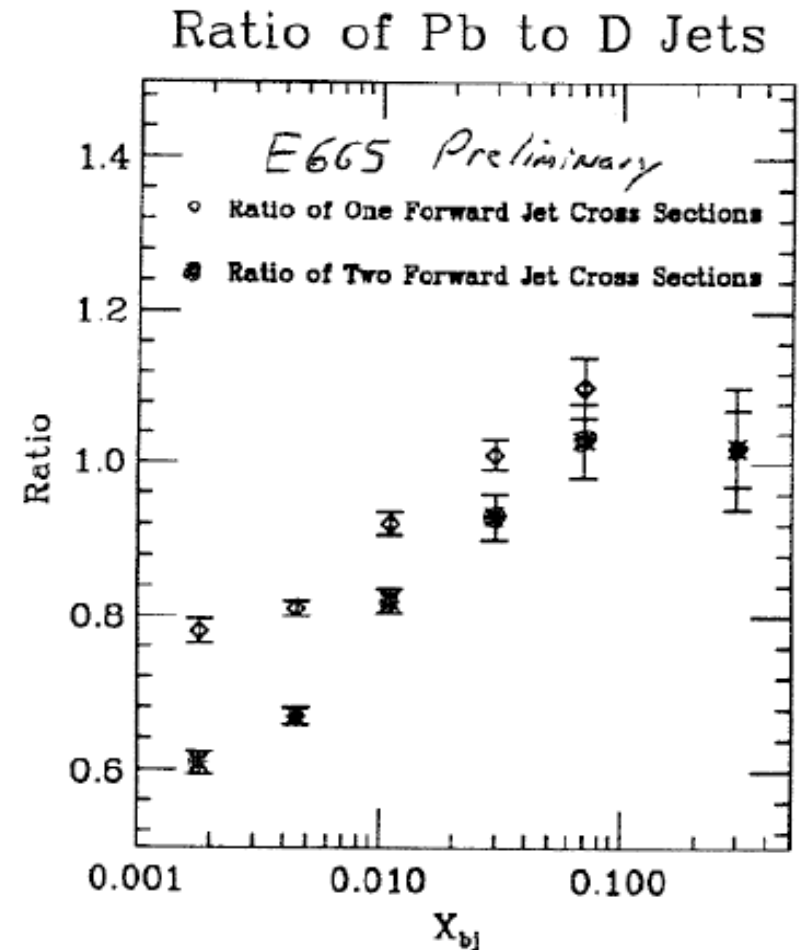


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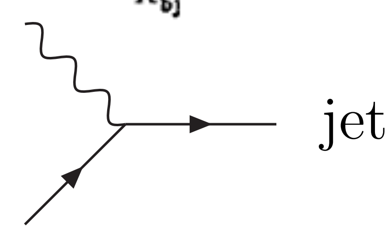
1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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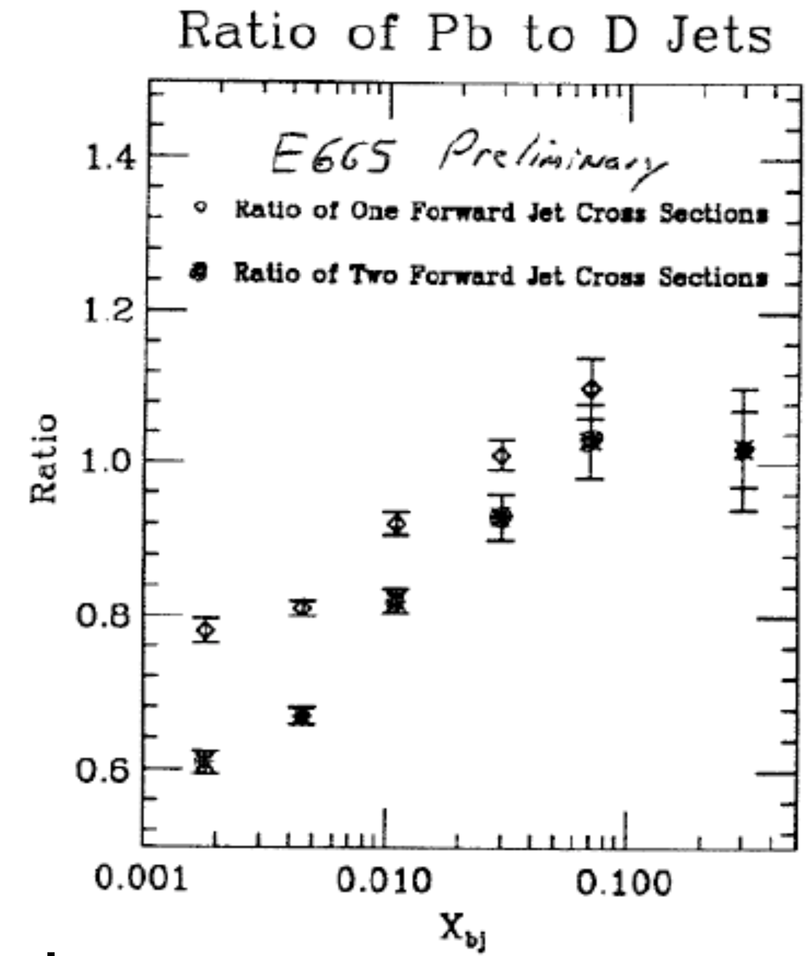


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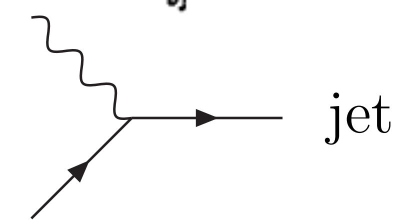
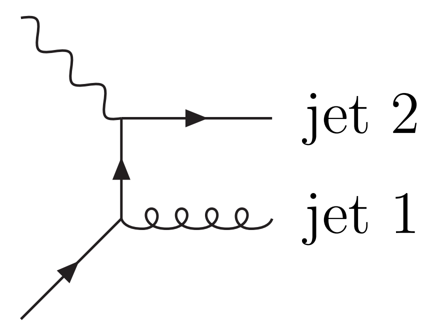
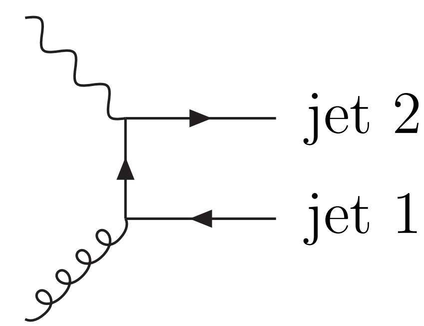



$$\frac{d^2\sigma_{2+1}}{dxdQ^2} = A_q(x,Q^2)q^A(x,Q^2) + A_g(x,Q^2)g_A(x,Q^2)$$

2+1 jets→ sensitive to nuclear gluons

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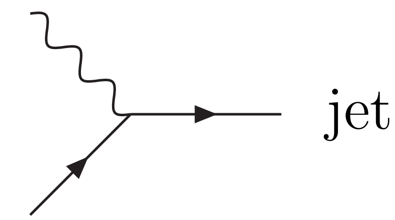


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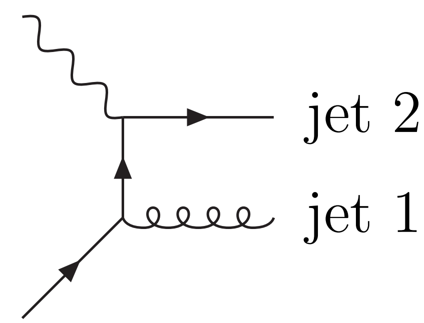


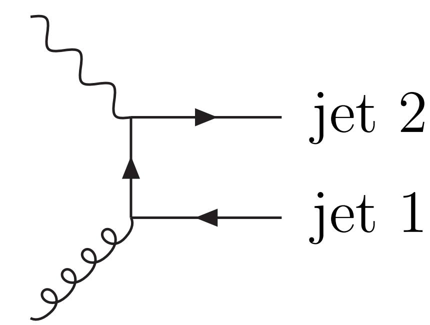


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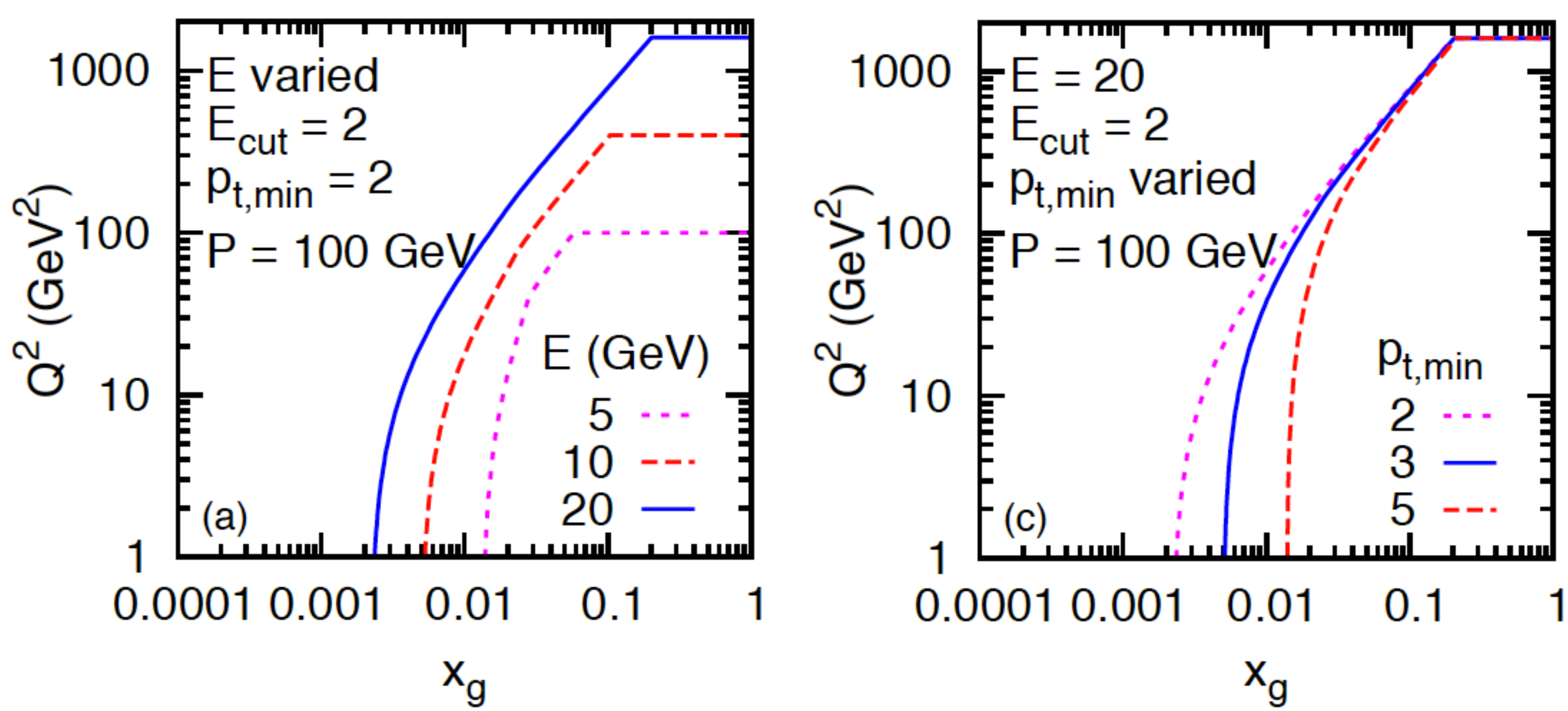

# Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
  - ➡ Low-x: Measure the properties of gluons where saturation is the dominant governing phenomena
  - ➡ Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization
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**entire science programme is uniquely tied to a**
**future high-energy electron-ion collider**
**never been measured before & never without**

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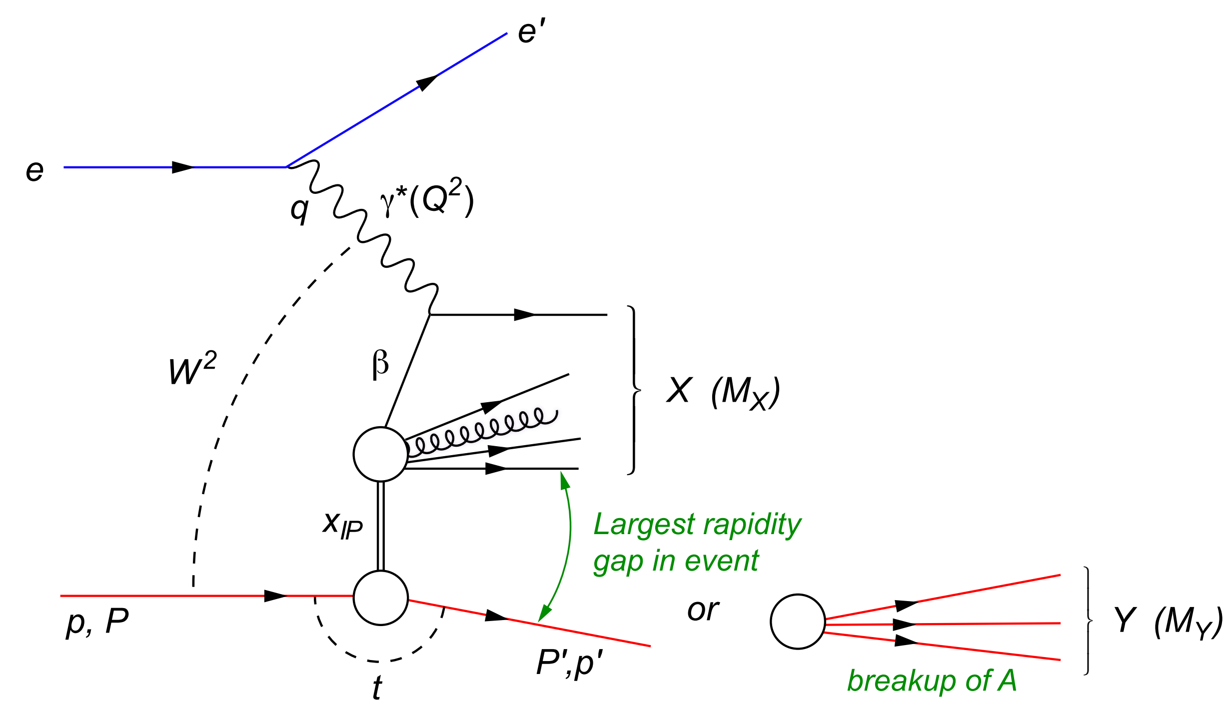
# BACKUP

# Diffractive Events: Experimental Side

- **How to identify**
- **diffractive events?**




➡ Rapidity Gap

- ‣ requires hermetic (large acceptance) detector

➡ Separating coherent from incoherent diffraction

- ‣ detector and IR needs to be carefully designed to detect nuclear breakup

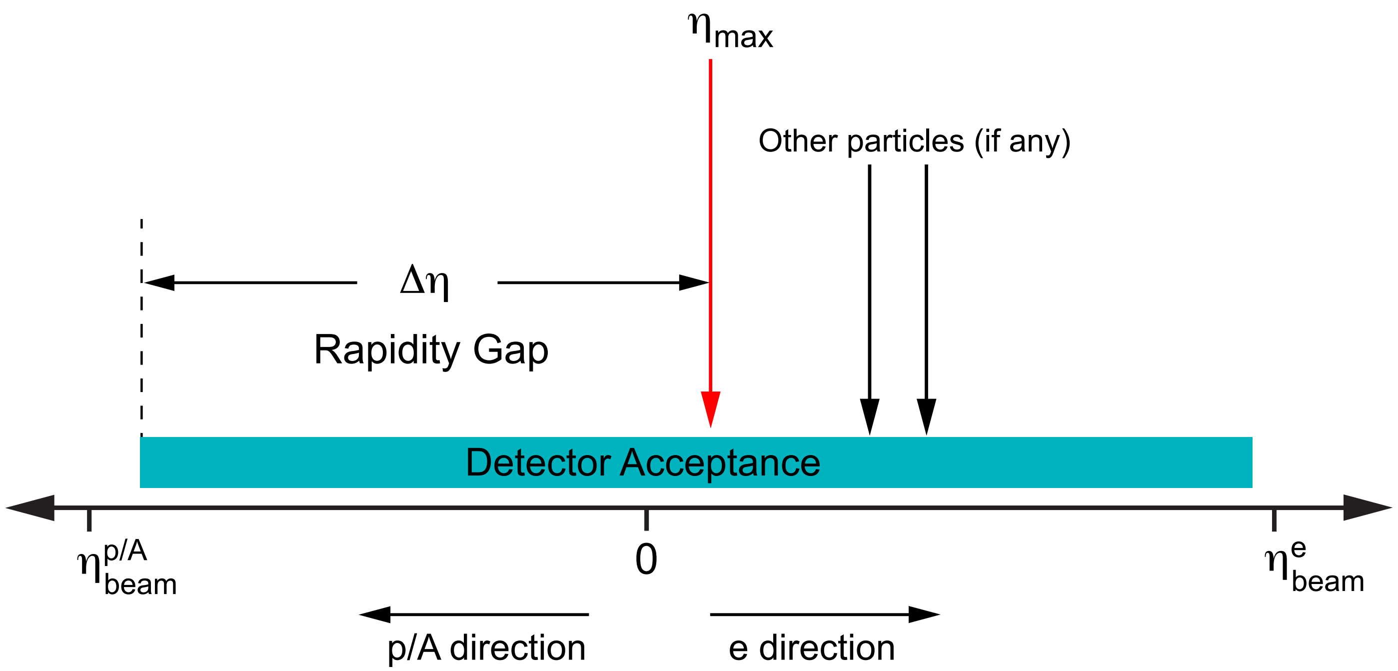
➡ Limitation at a collider

- ‣ Coherent: scattered ion cannot be measured, *t* not directly measurable (may be in very light ions)
- ‣ Breakup can be detected using emitted *n* and γ, some charged fragments can be measured in Roman Pots

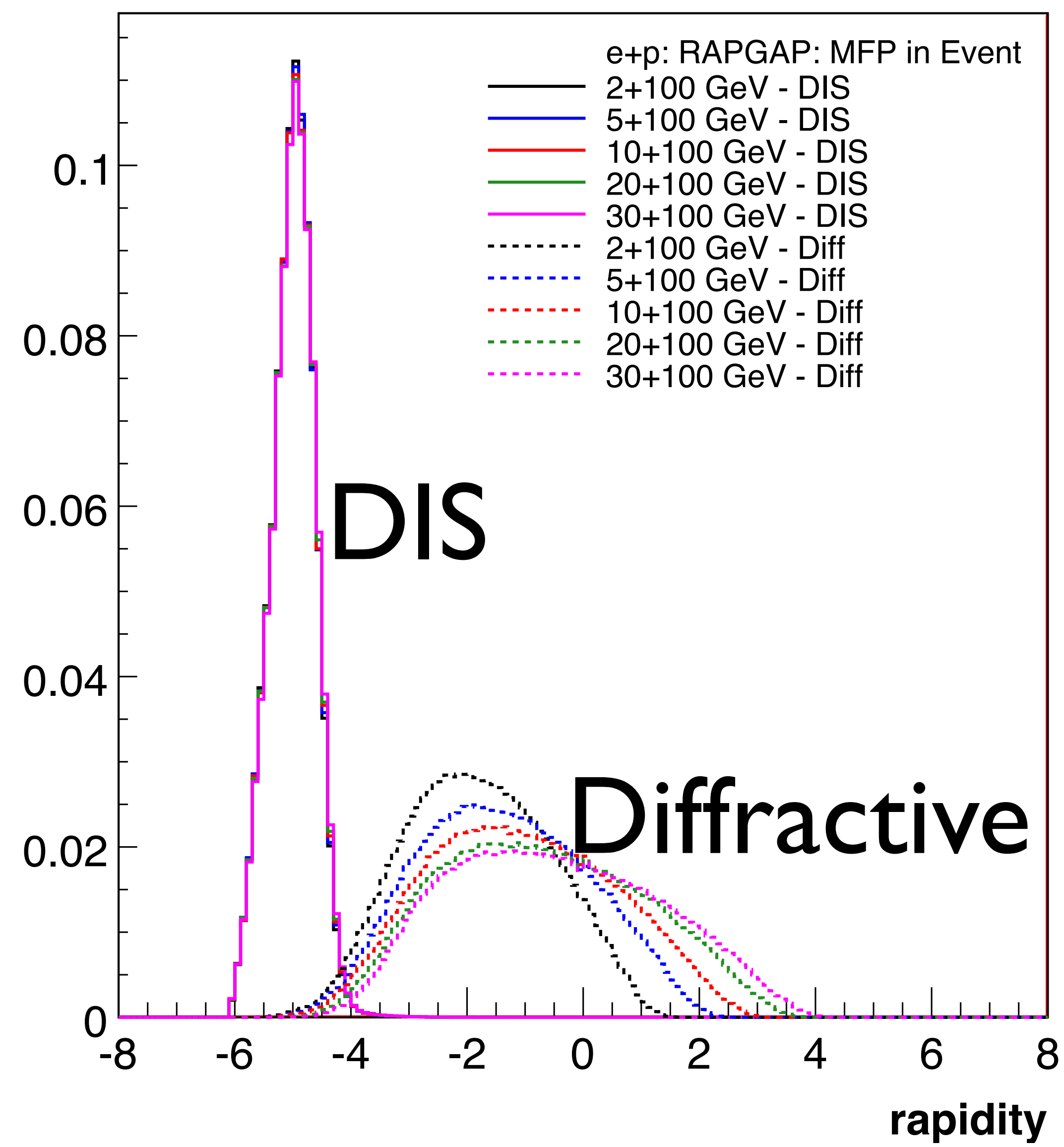
# Large Rapidity Gap Method (LRG)

➡ Identify Most Forward Going Particle (MFP)

- Works at HERA but higher $\sqrt{s}$
- EIC smaller beam rapidities




Diffractive $\rho^0$ production at EIC:
$\eta$ of MFP




## 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)

# 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
  - $\gamma$ via EMC

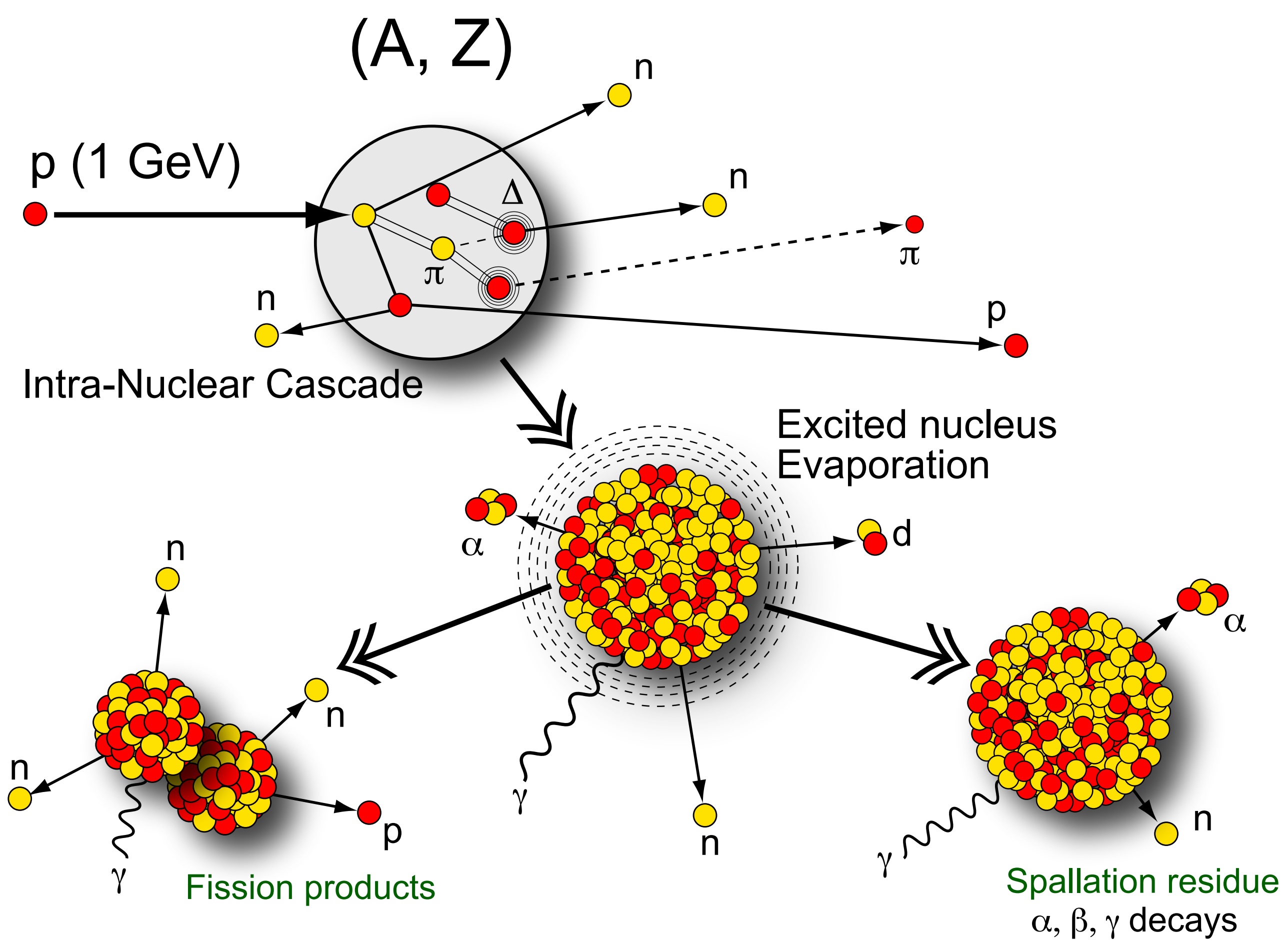
## Traditional modelling done in pA:

### Intra-Nuclear Cascade

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

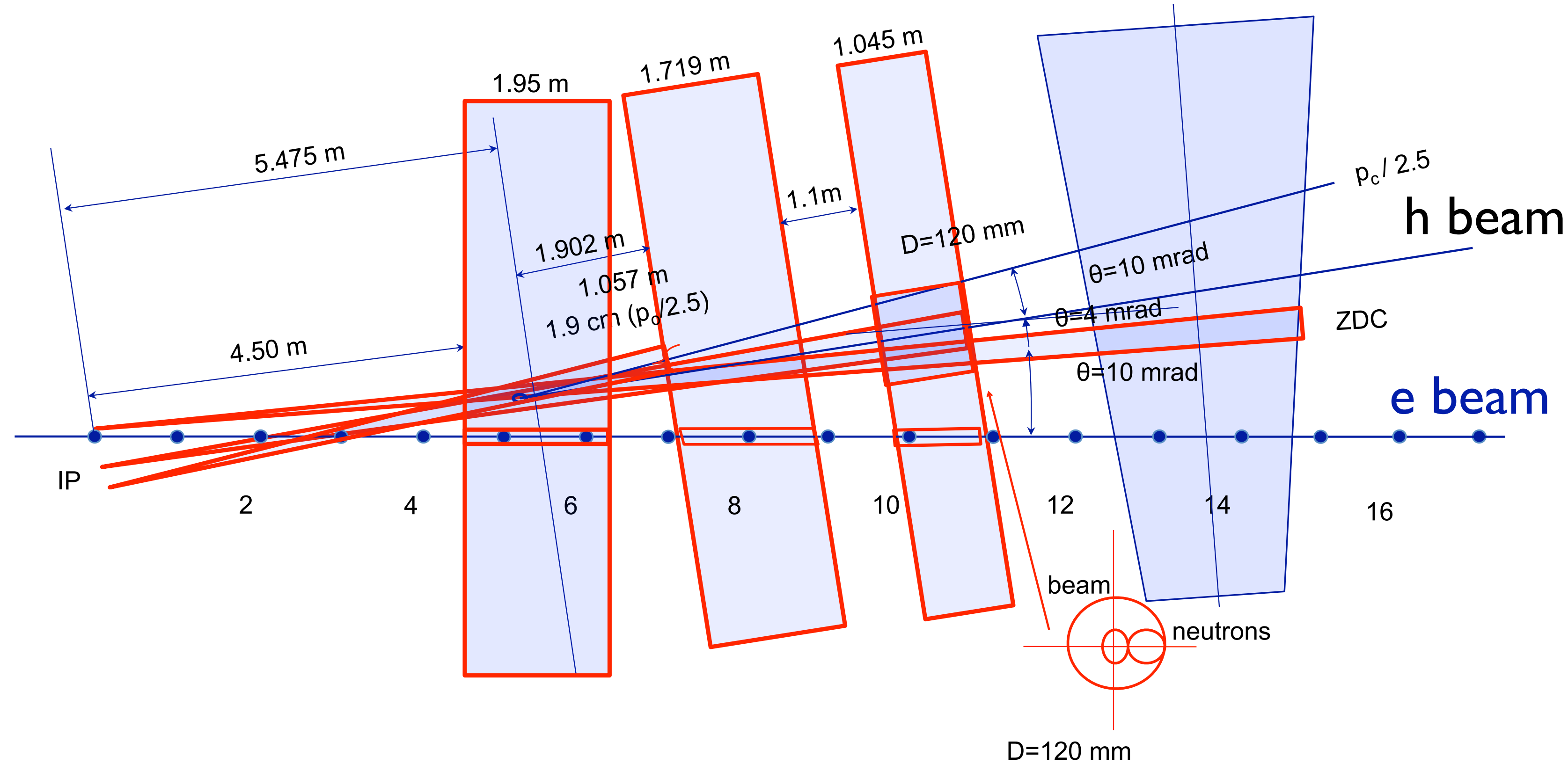
### De-Excitation

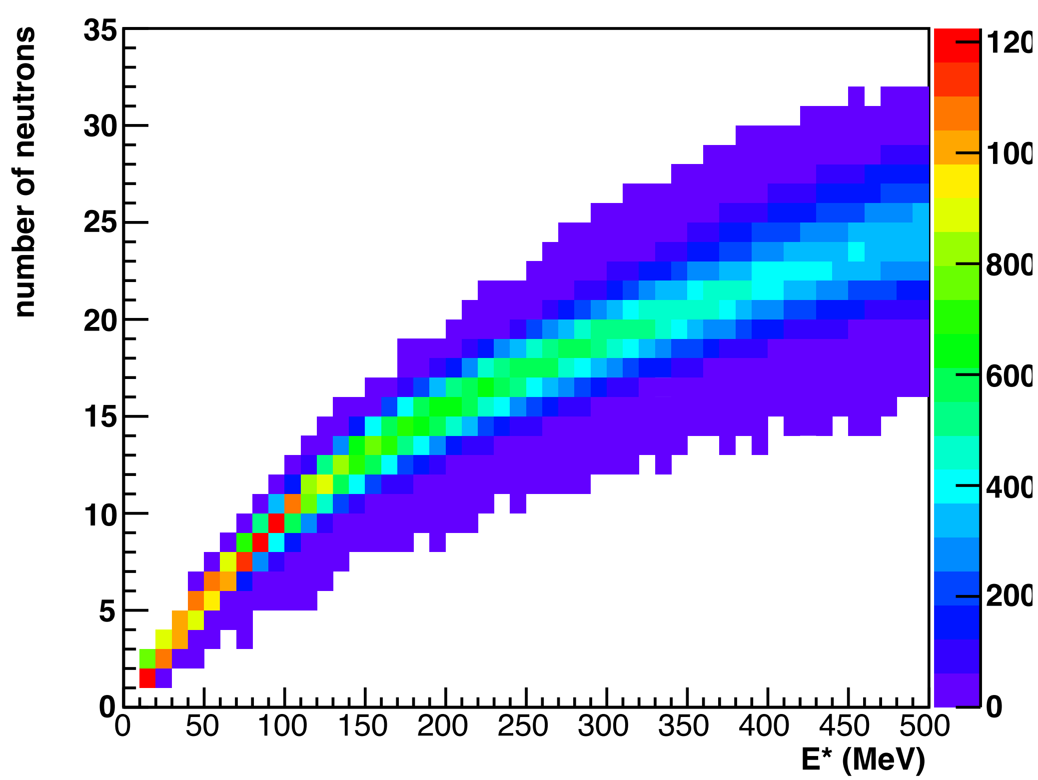
- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no $\gamma$)

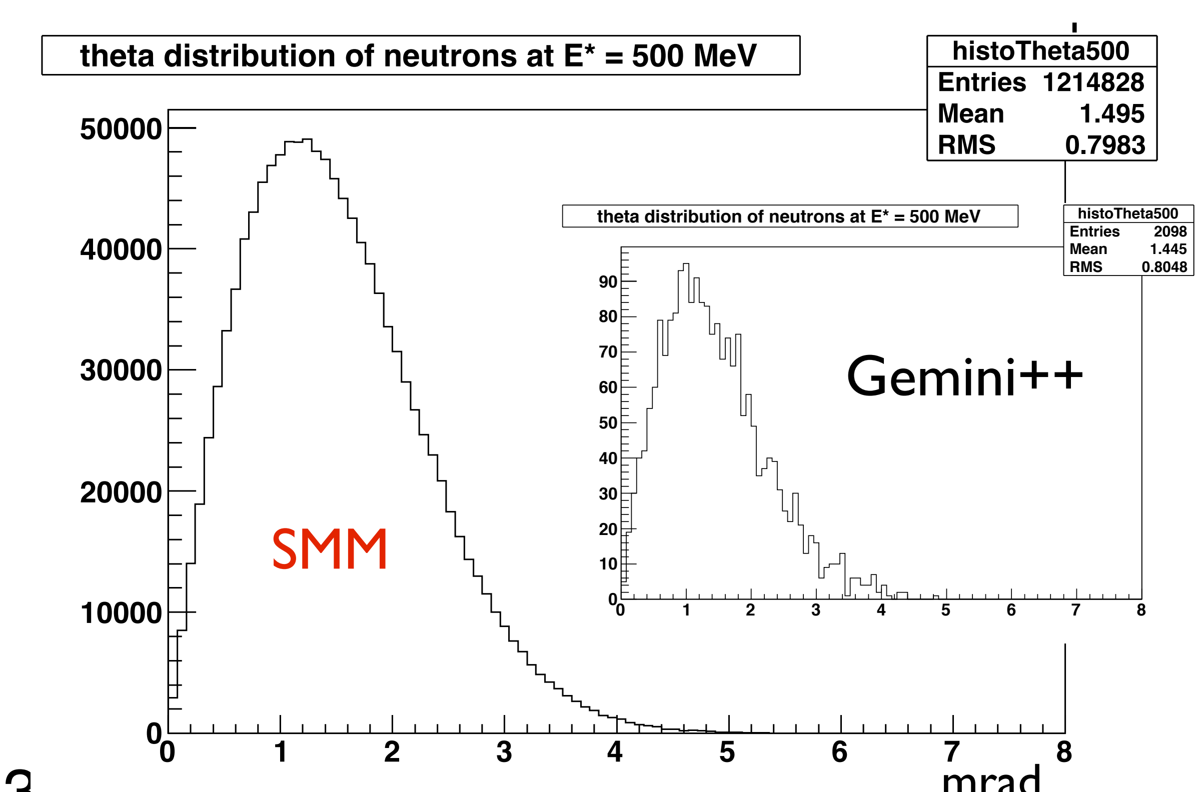


# Experimental Reality

- 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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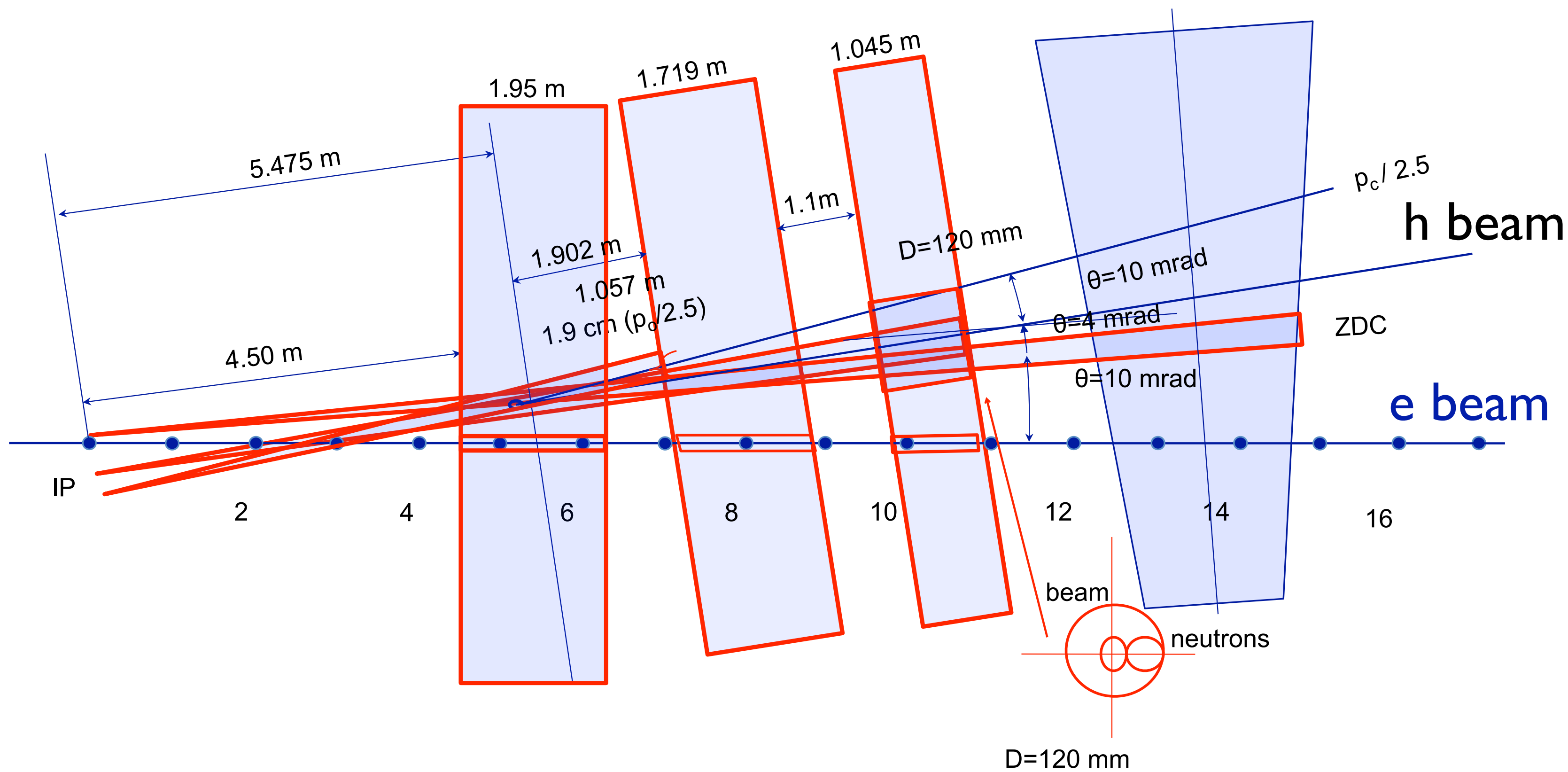


## Simulations using Gemini++ & SMM show it works:

- 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