La fisica a EIC: base-line e nuove prospettive

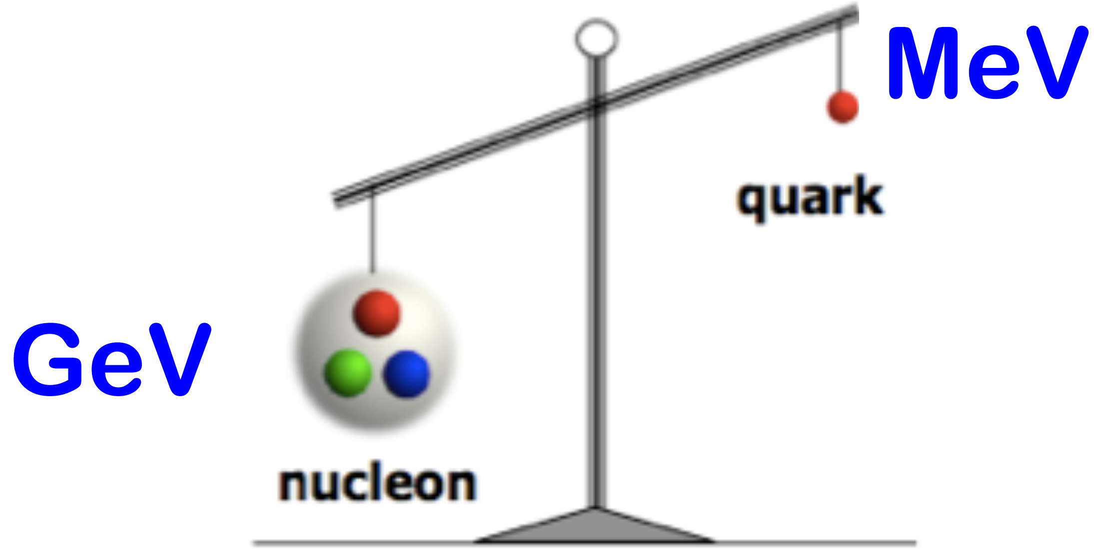
giuseppe bozzi
Uni Pavia & INFN Pavia

Motivation

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q \left(i\partial\!\!\!/ \; - g A\!\!\!/ \; + m \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

So, why the EIC?

Why #1 : the Nucleon mass



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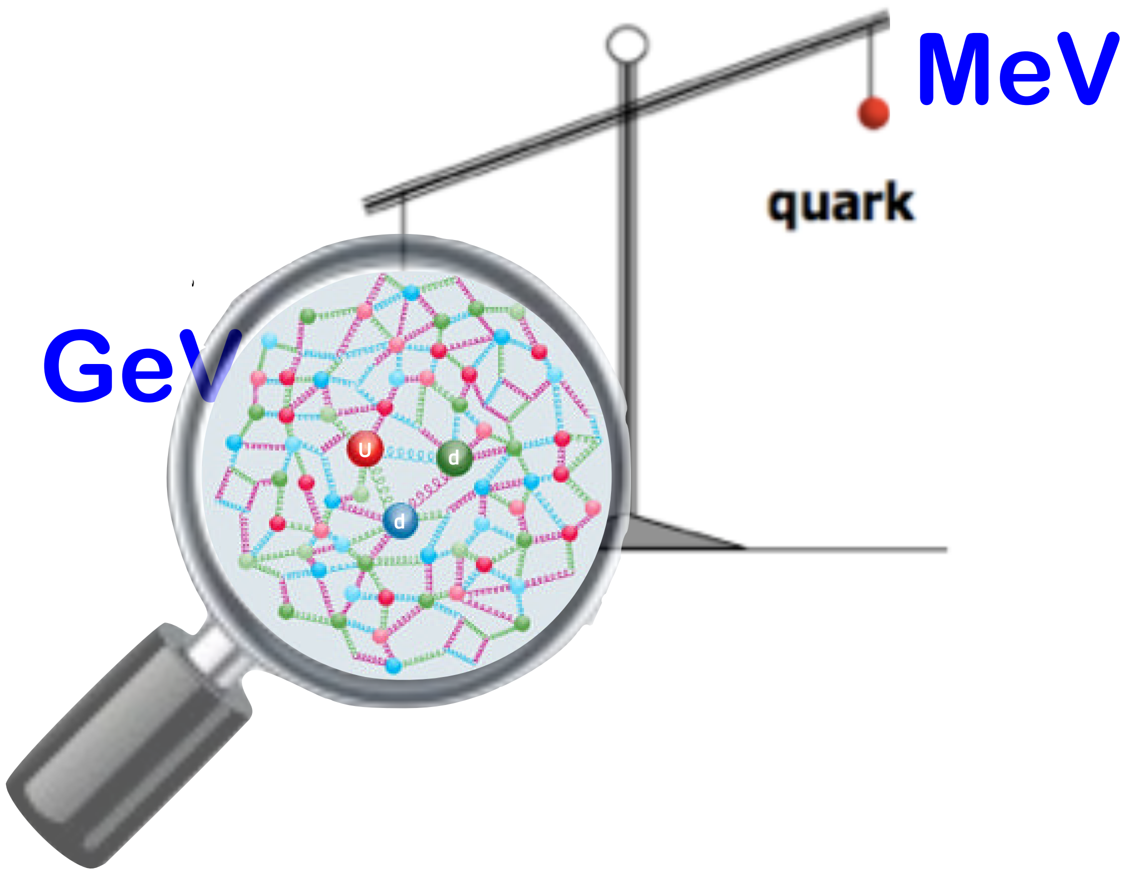
Why #1 : the Nucleon mass



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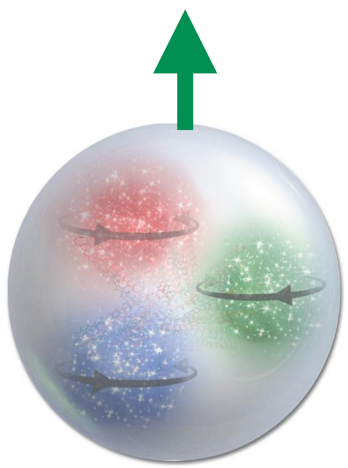
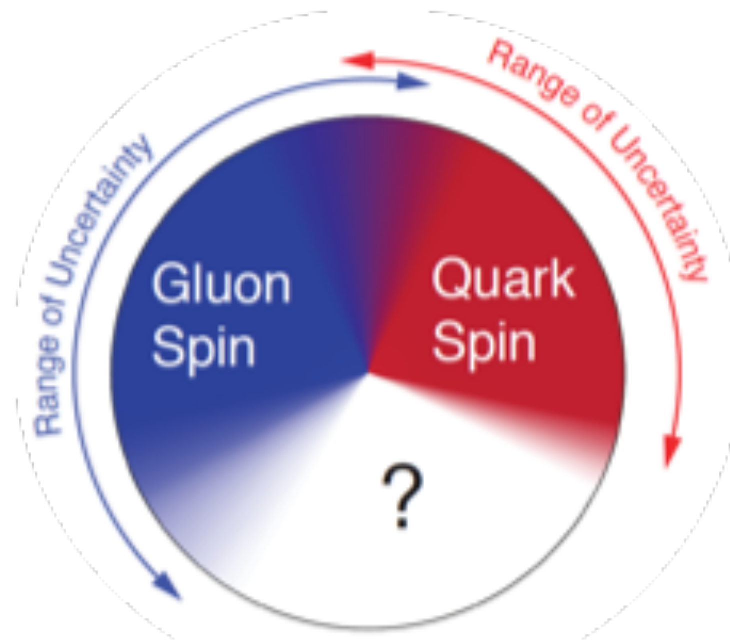
Why #2 : the Nucleon spin

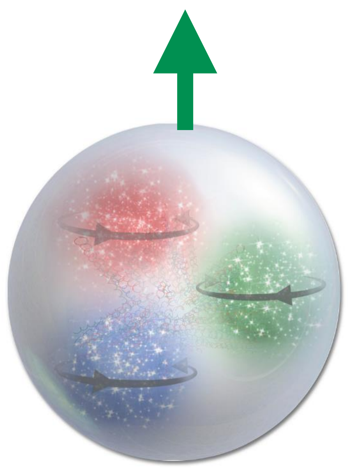


$$\frac{1}{2} =$$



(EMC, CERN 1987!)

Why #2 : the Nucleon spin



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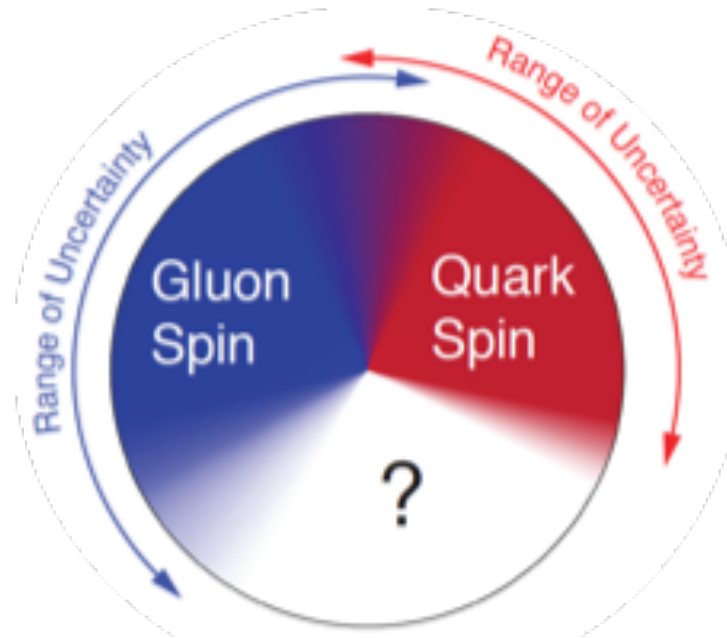

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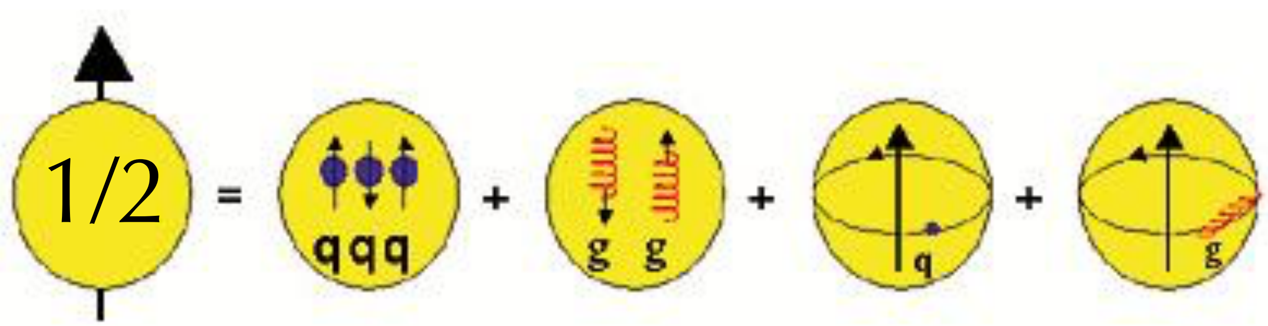
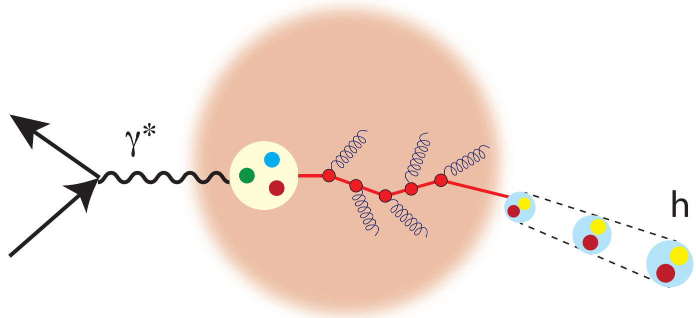
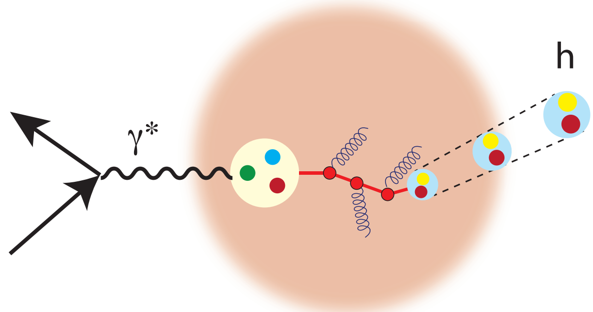


?? ?? ??

Why #3 : hadronization

confinement intimately connected with
fragmentation / hadronization





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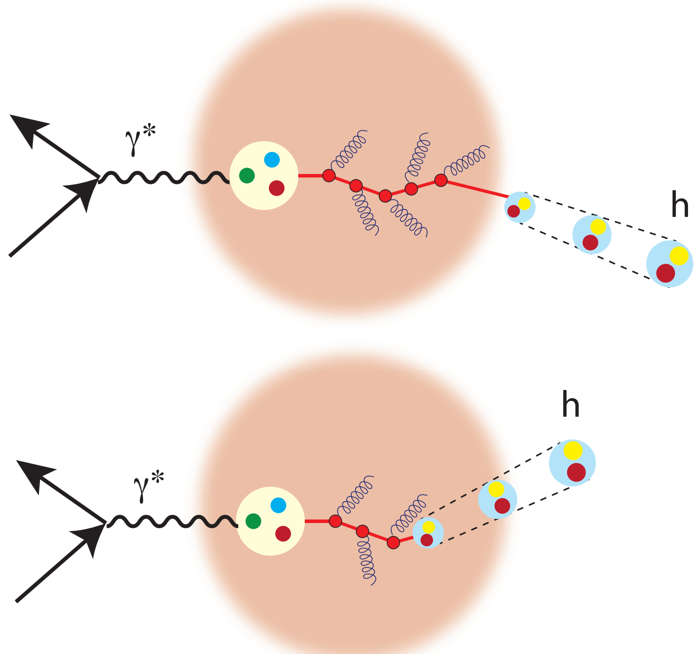
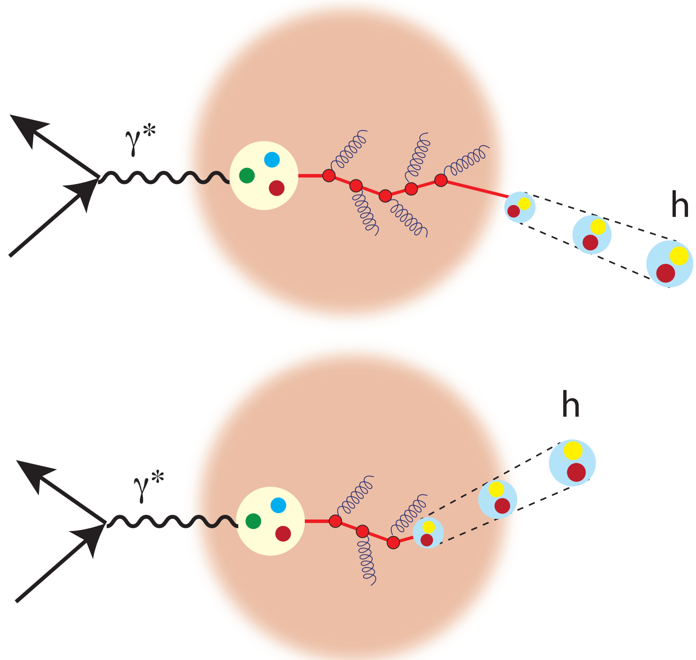


How do color charges propagate, shower, hadronize ?

Why #3 : hadronization

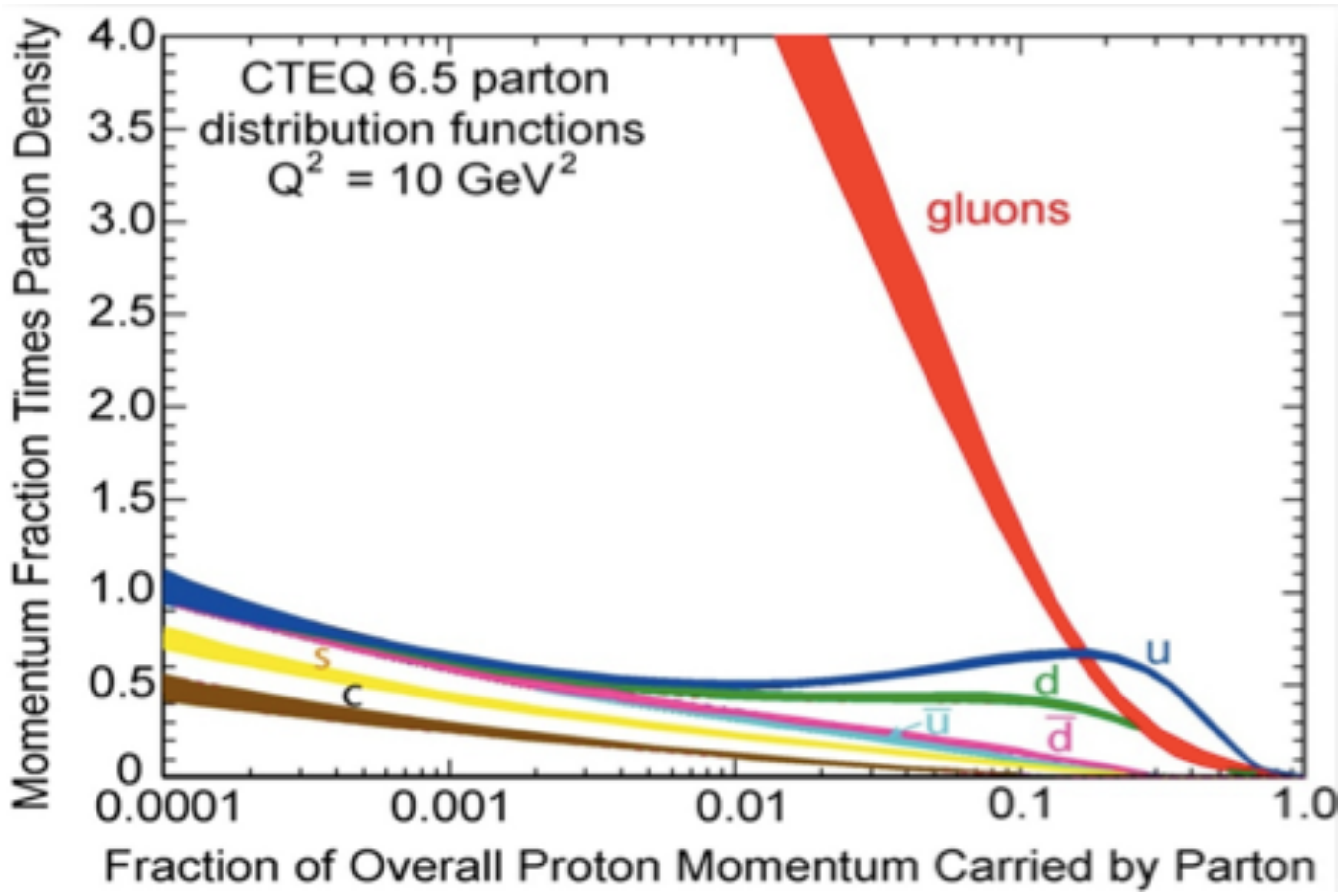
confinement intimately connected with
fragmentation / hadronization



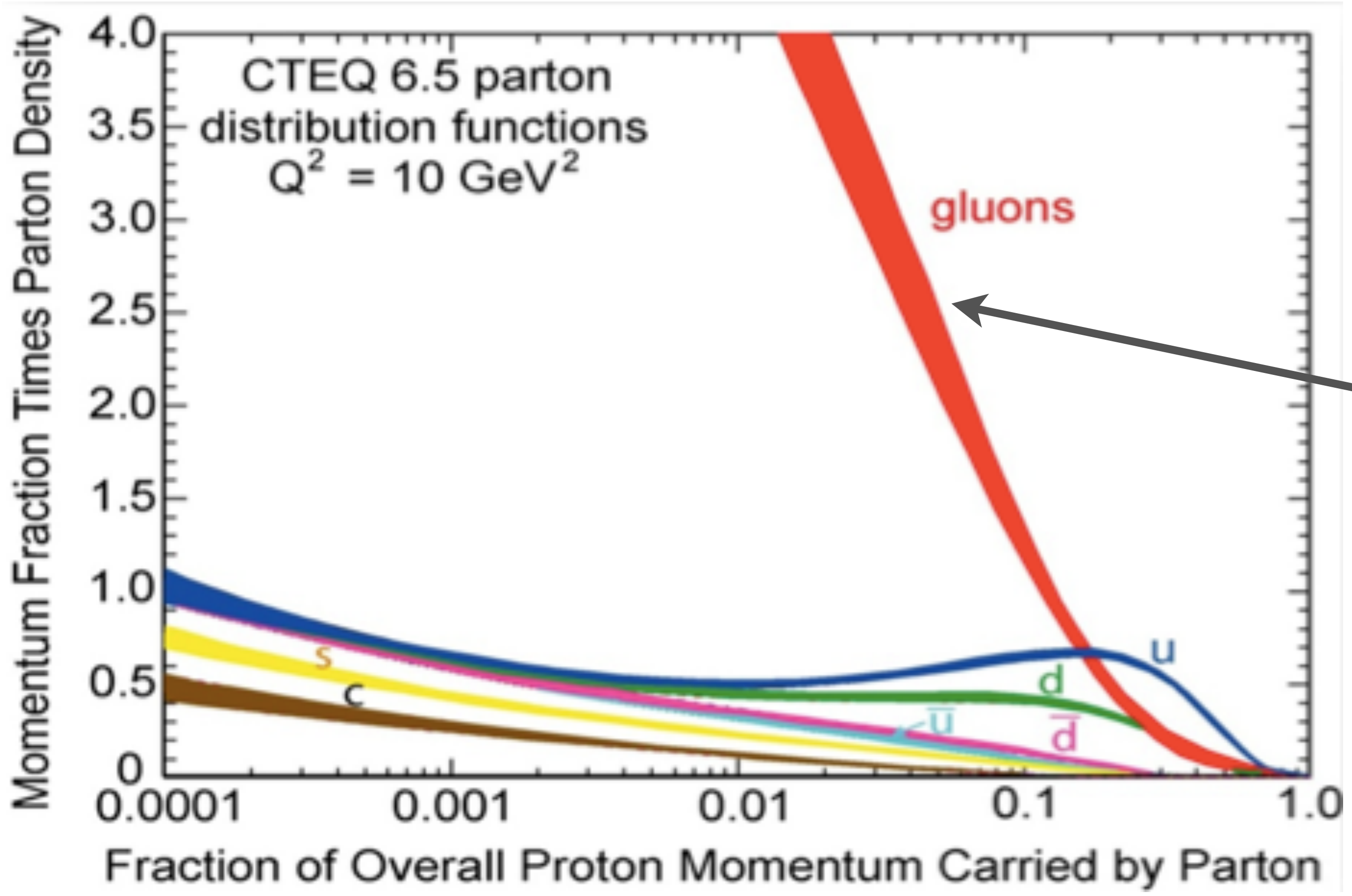
How do color charges
propagate, shower, hadronize ?

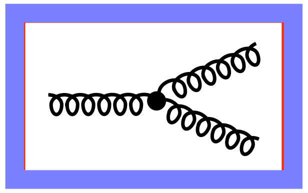
Nuclei as femto-detectors of parton showering and hadronization

Why #4 : gluon saturation

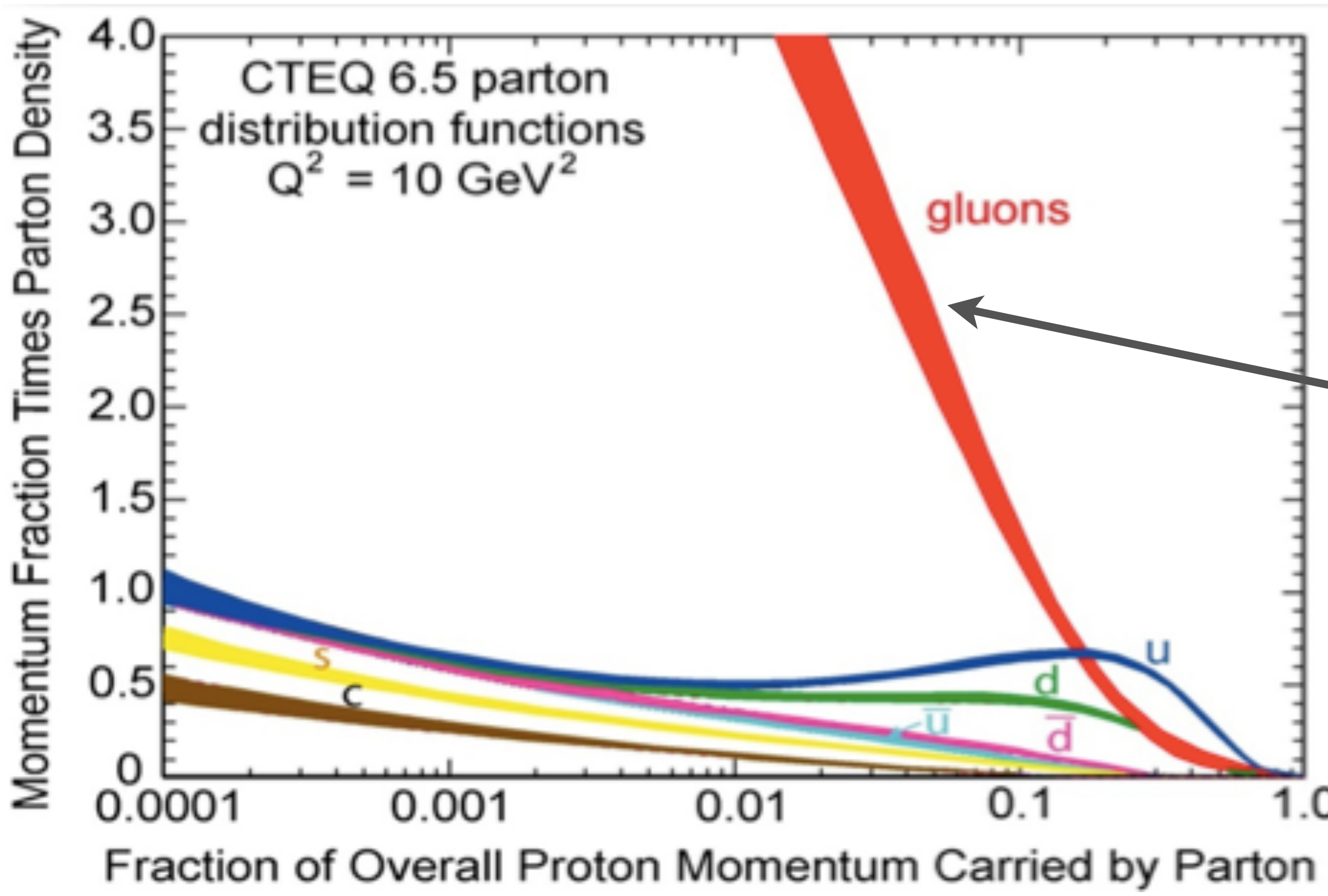


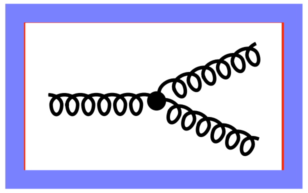
Why #4 : gluon saturation





Why #4 : gluon saturation





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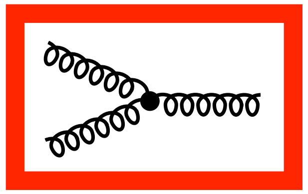
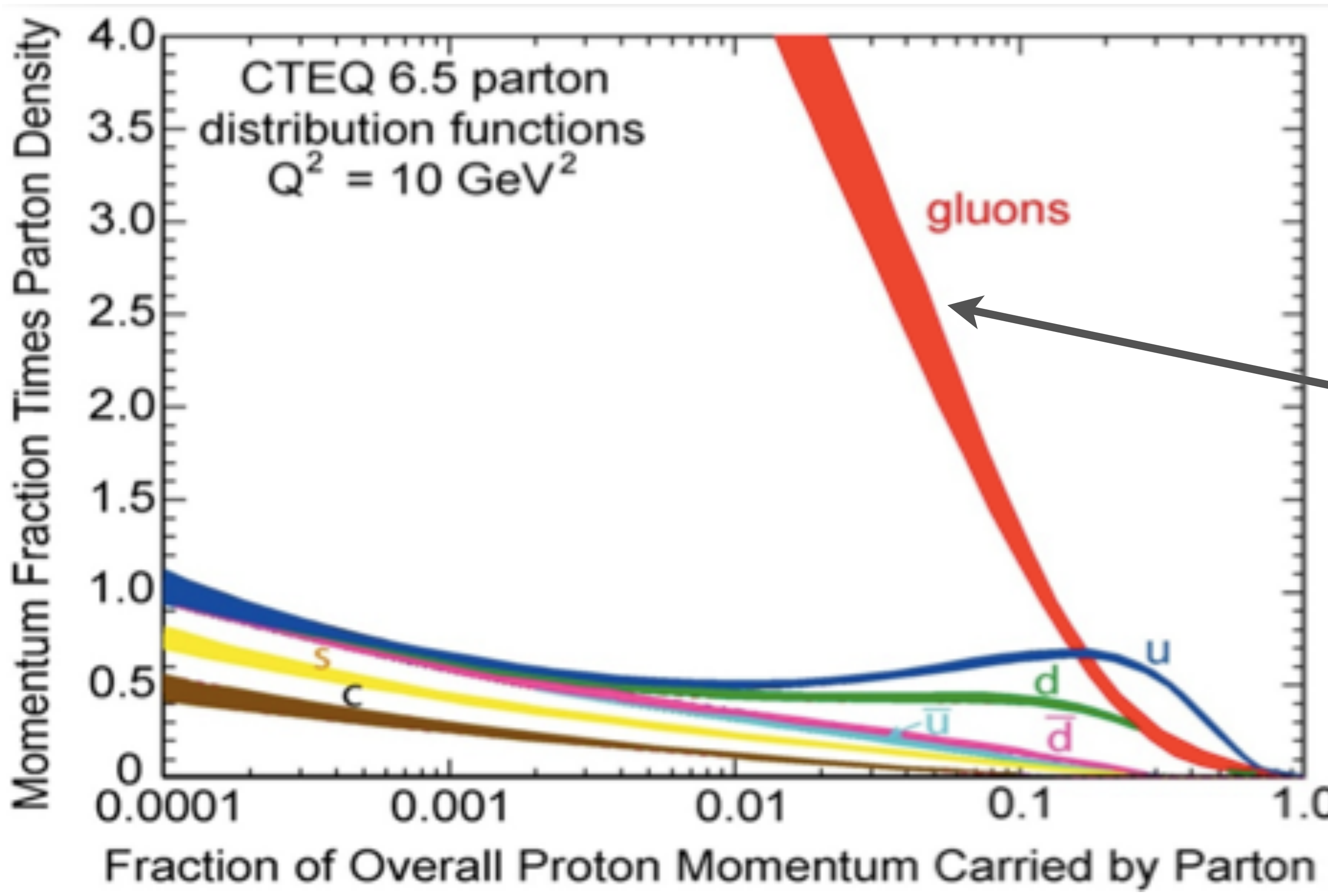
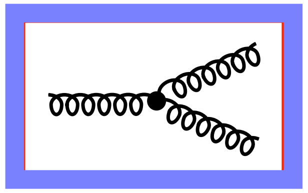


unitarity → gluons must recombine to
balance splitting (**saturation**)

Why #4 : gluon saturation





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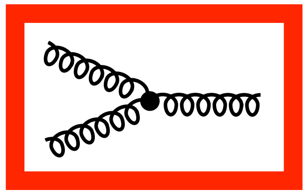


unitarity → gluons must recombine to balance splitting (**saturation**)

Where does saturation set in?
Is there a universal gluonic matter at high density?
How does nuclear matter affect quark & gluon interactions?

Processes

Deep-**I**nelastic **S**cattering (DIS)

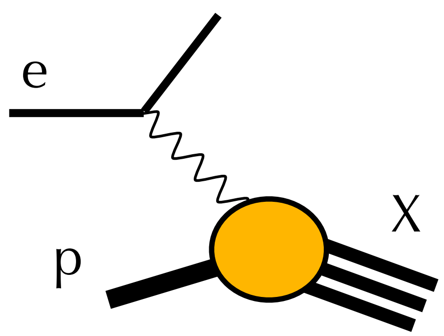
inclusive — $Q^2 = s\ x\ y$

semi-inclusive — very high luminosity

exclusive — very good detector PID

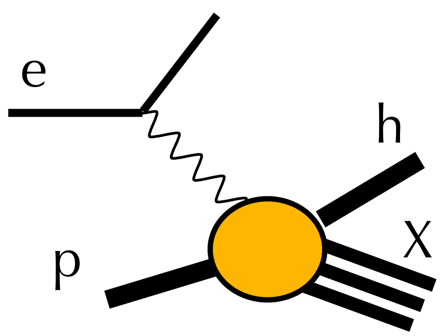
Processes

Deep-**I**nelastic **S**cattering (DIS)



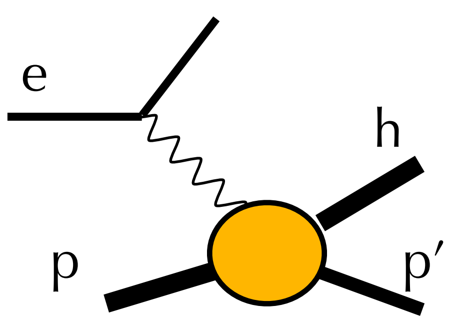
inclusive

$Q^2 = s\ x\ y$



semi-inclusive

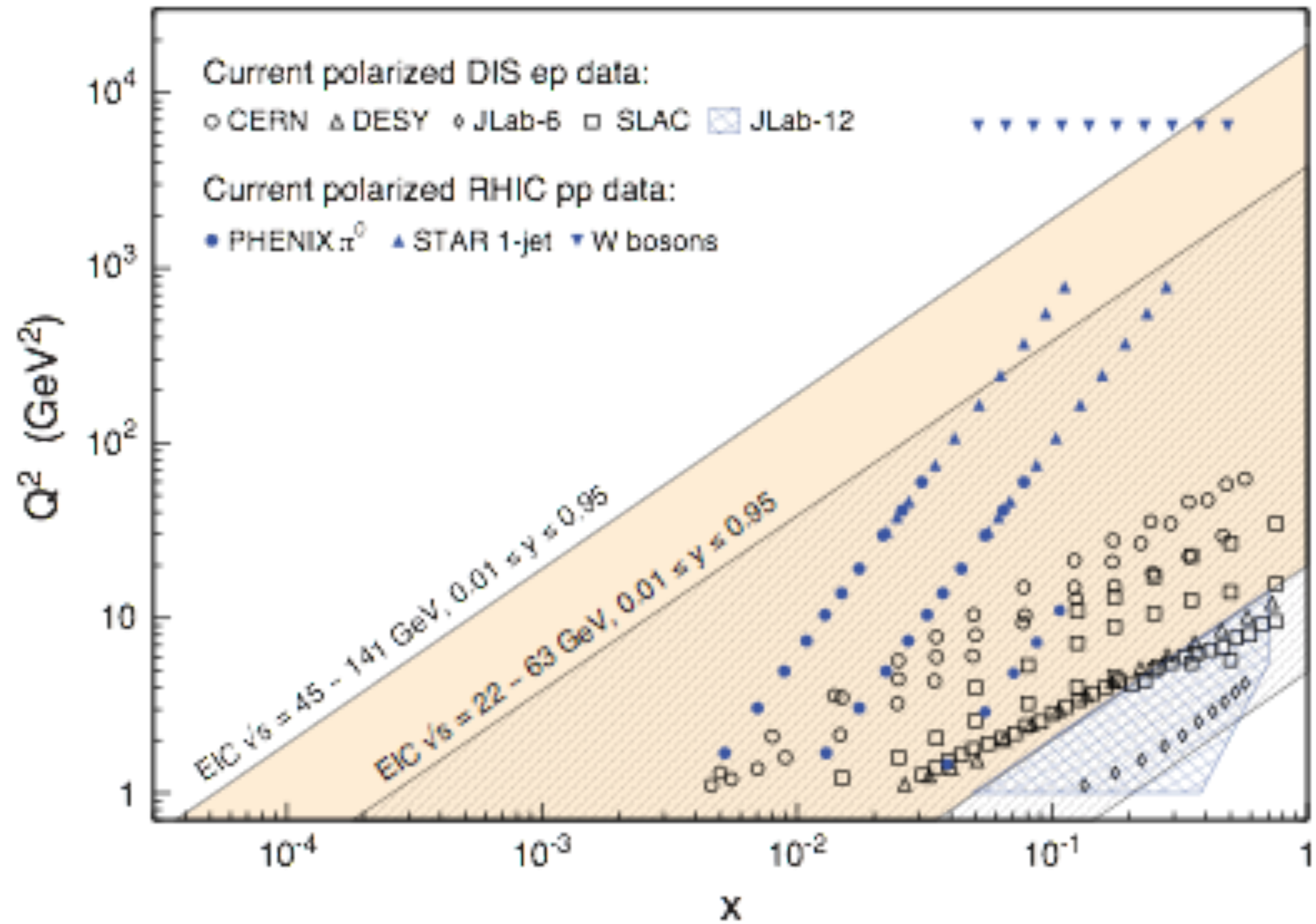
very high luminosity



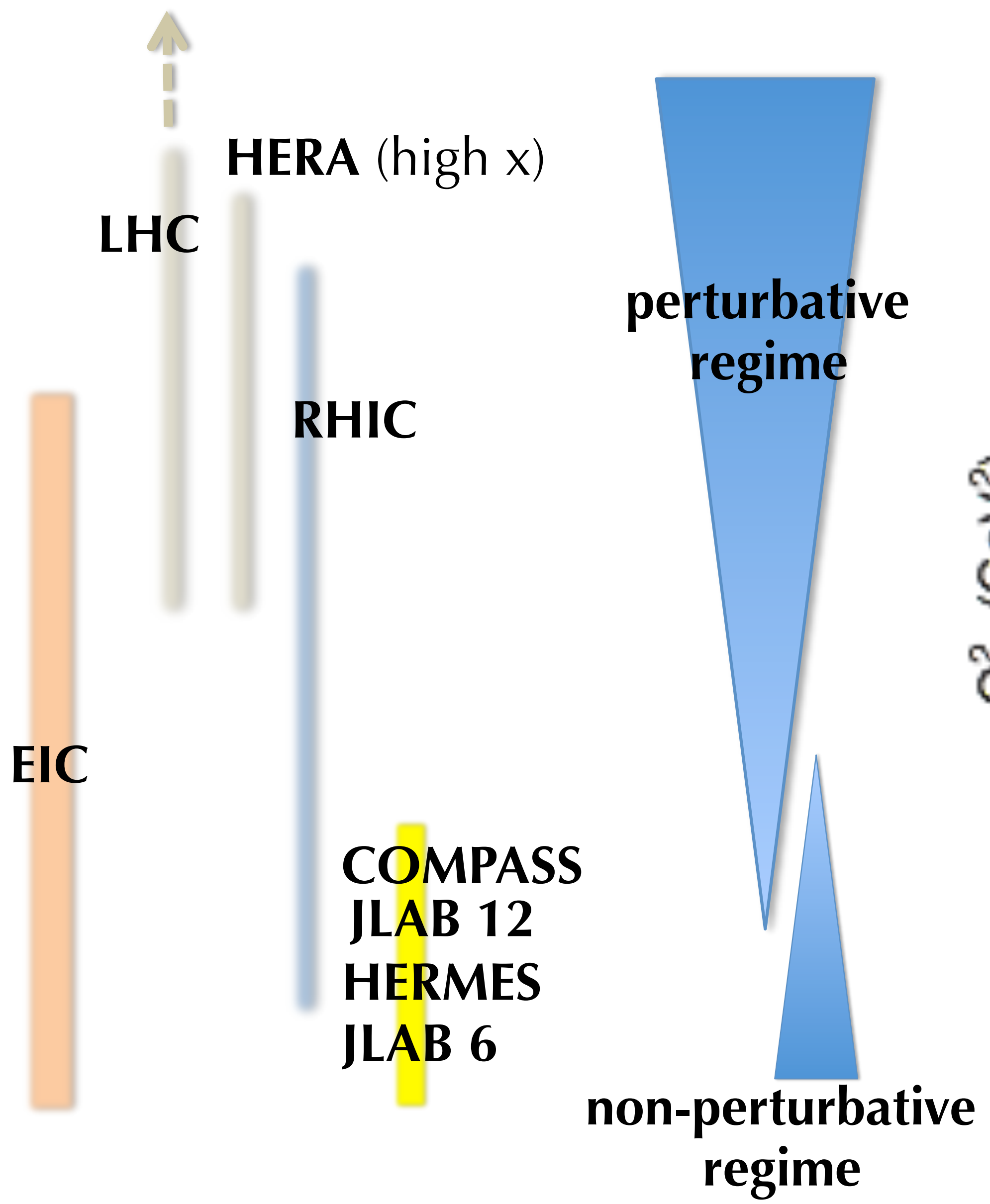
exclusive

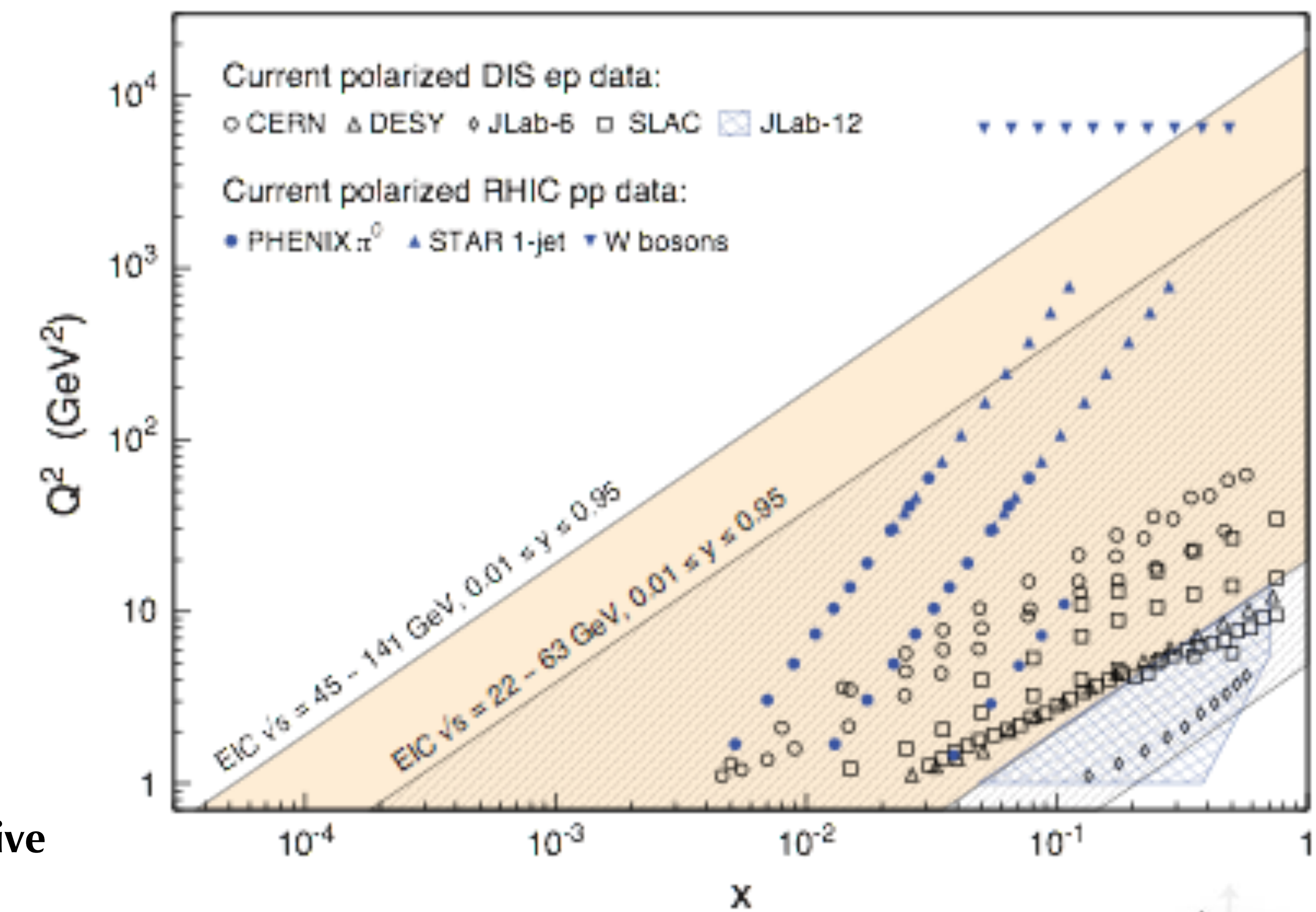
very good detector PID

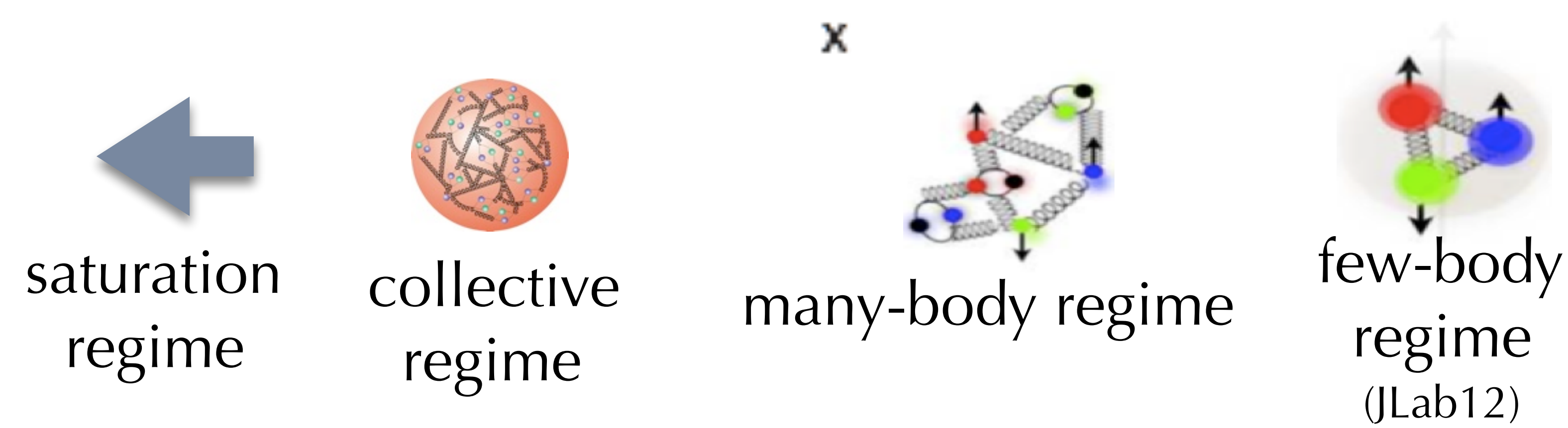
The Phase Space



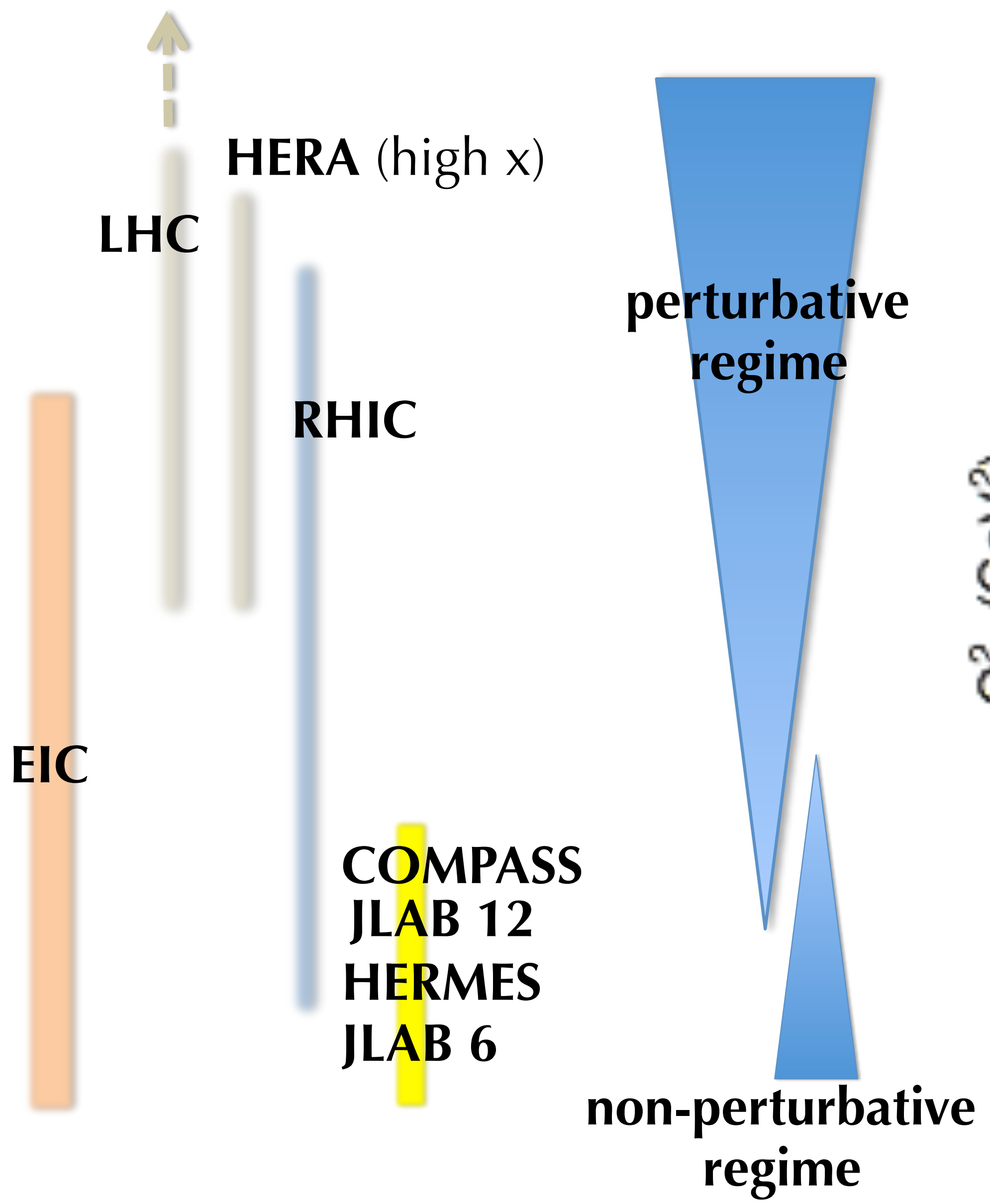
The Phase Space

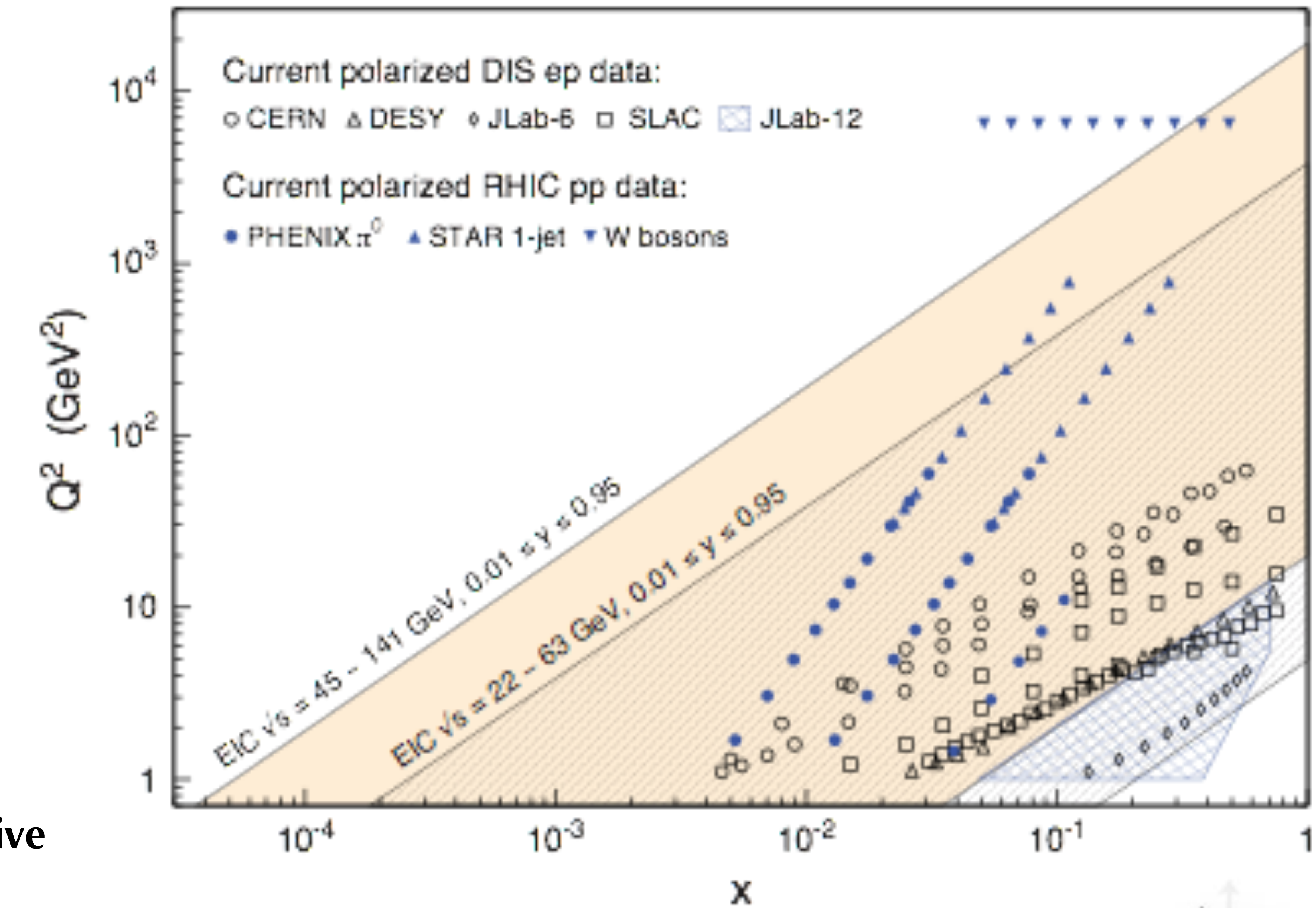


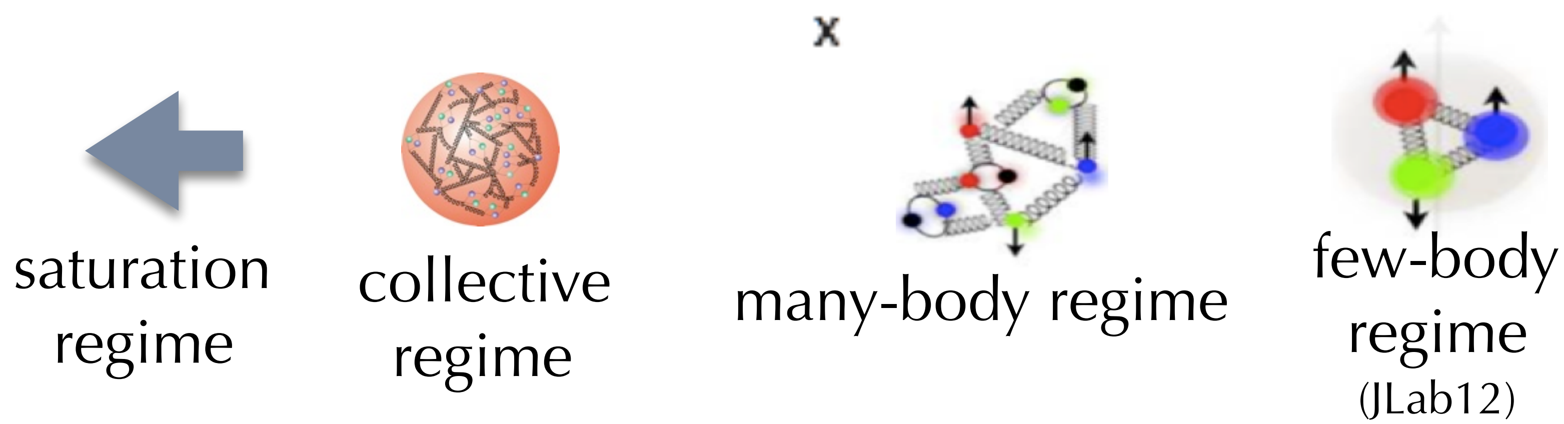




The Phase Space



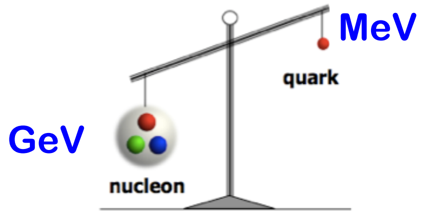




- large lever arm in Q^2 (evolution)
- disentangle change of regimes

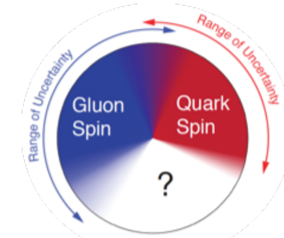
From Questions to Answers

Why #1

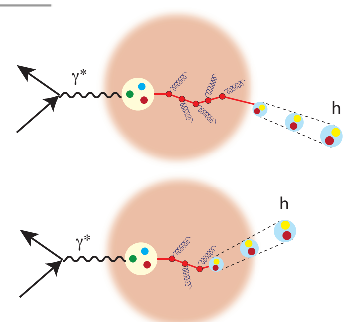


Why #2

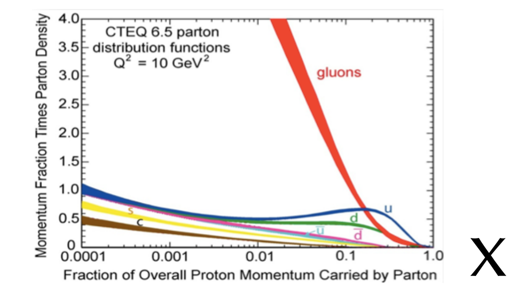
proton
spin 1/2

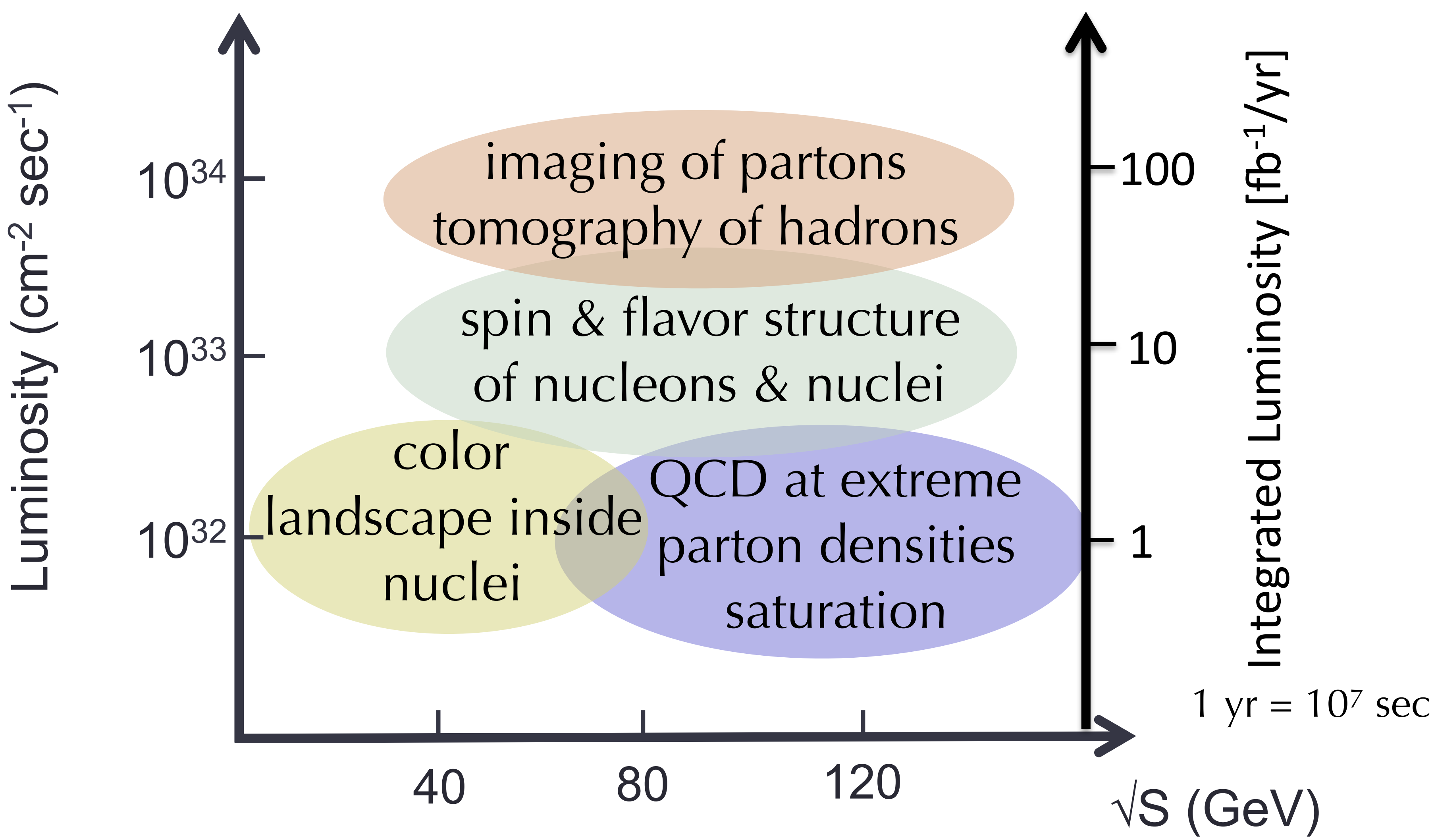


Why #3



Why #4

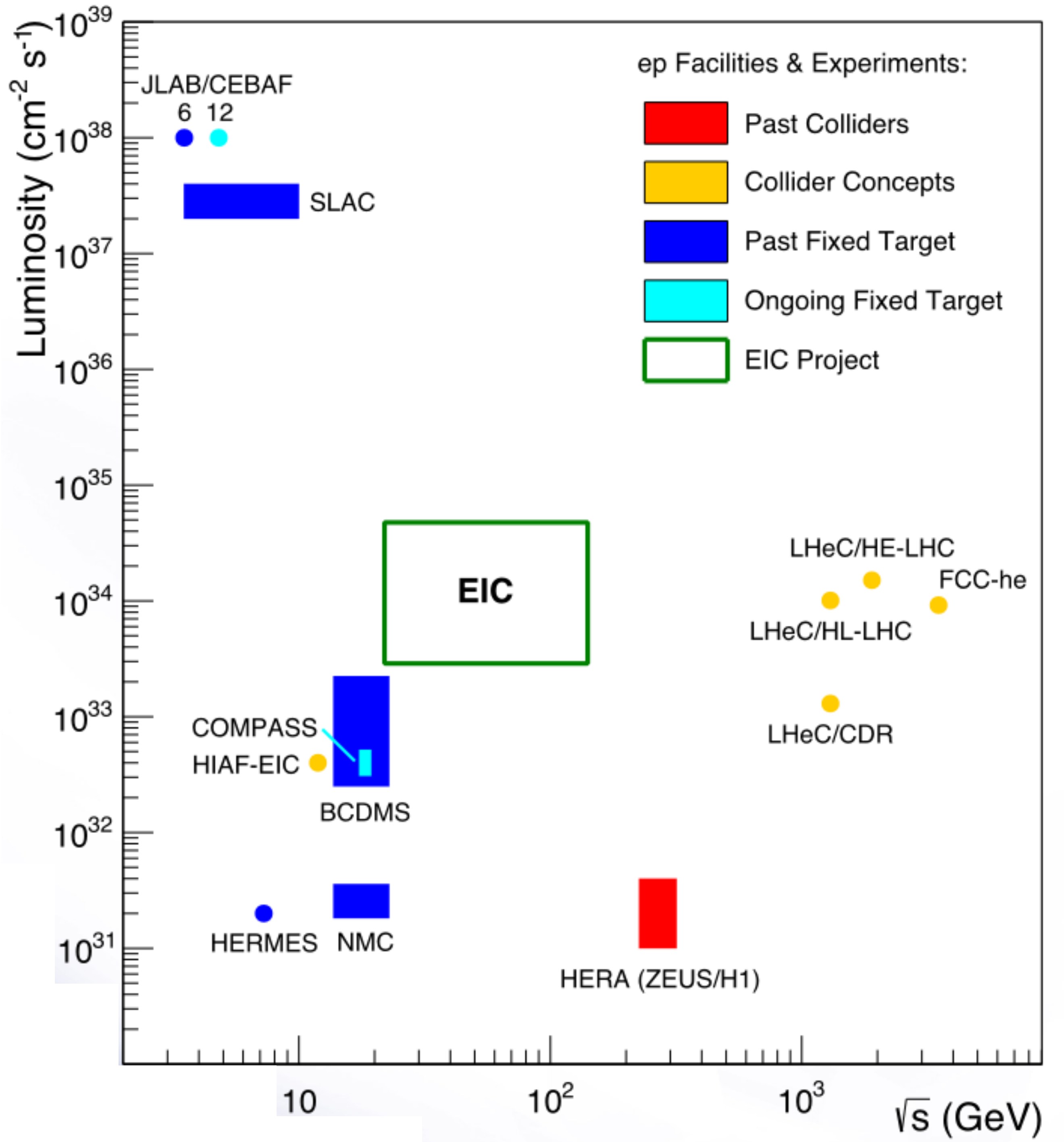




high luminosity
and polarization

wide range of
c.m. energies and
nuclear probes

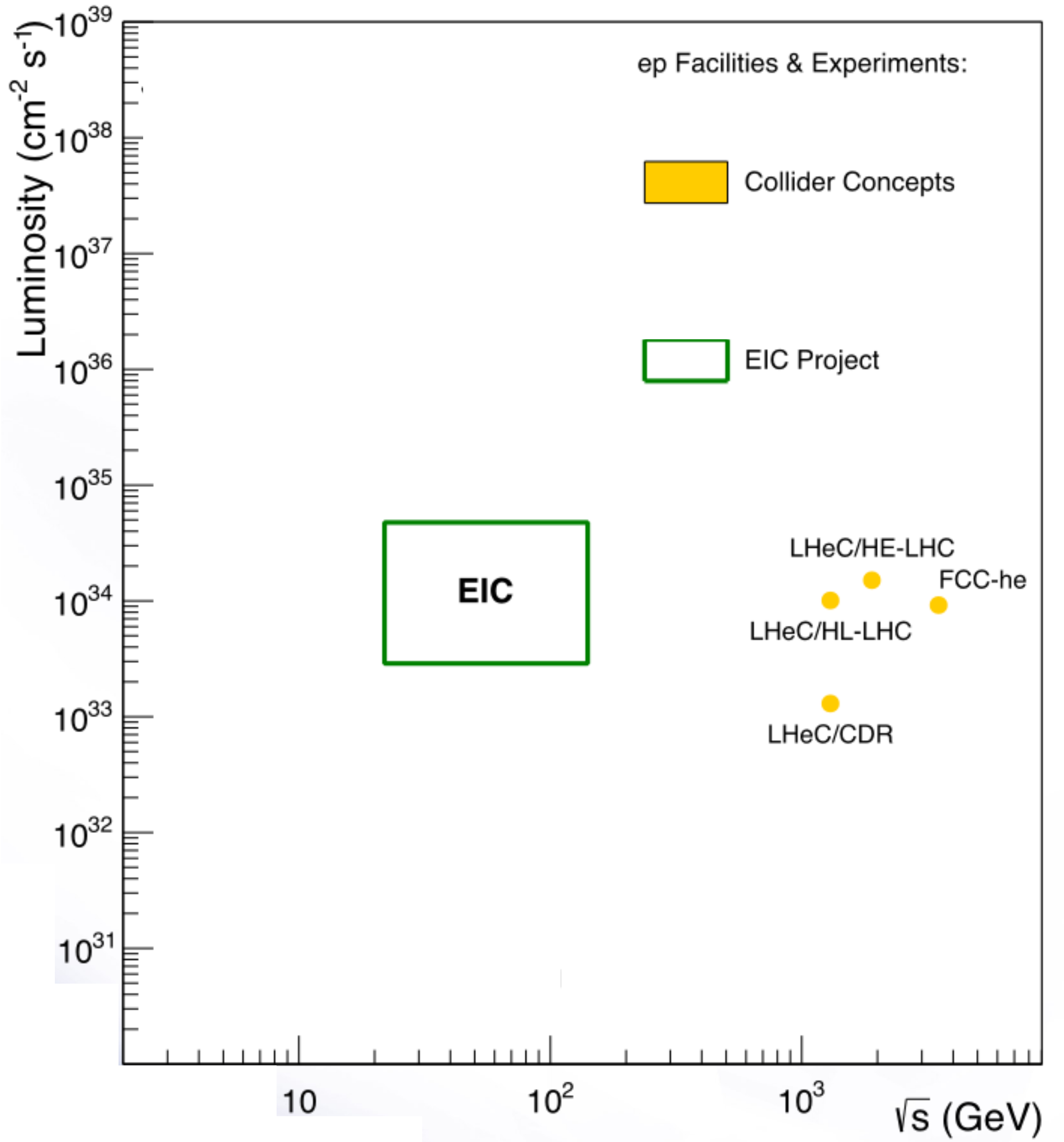
Uniqueness of EIC



All DIS facilities in the world

However, if we ask for…

Uniqueness of EIC

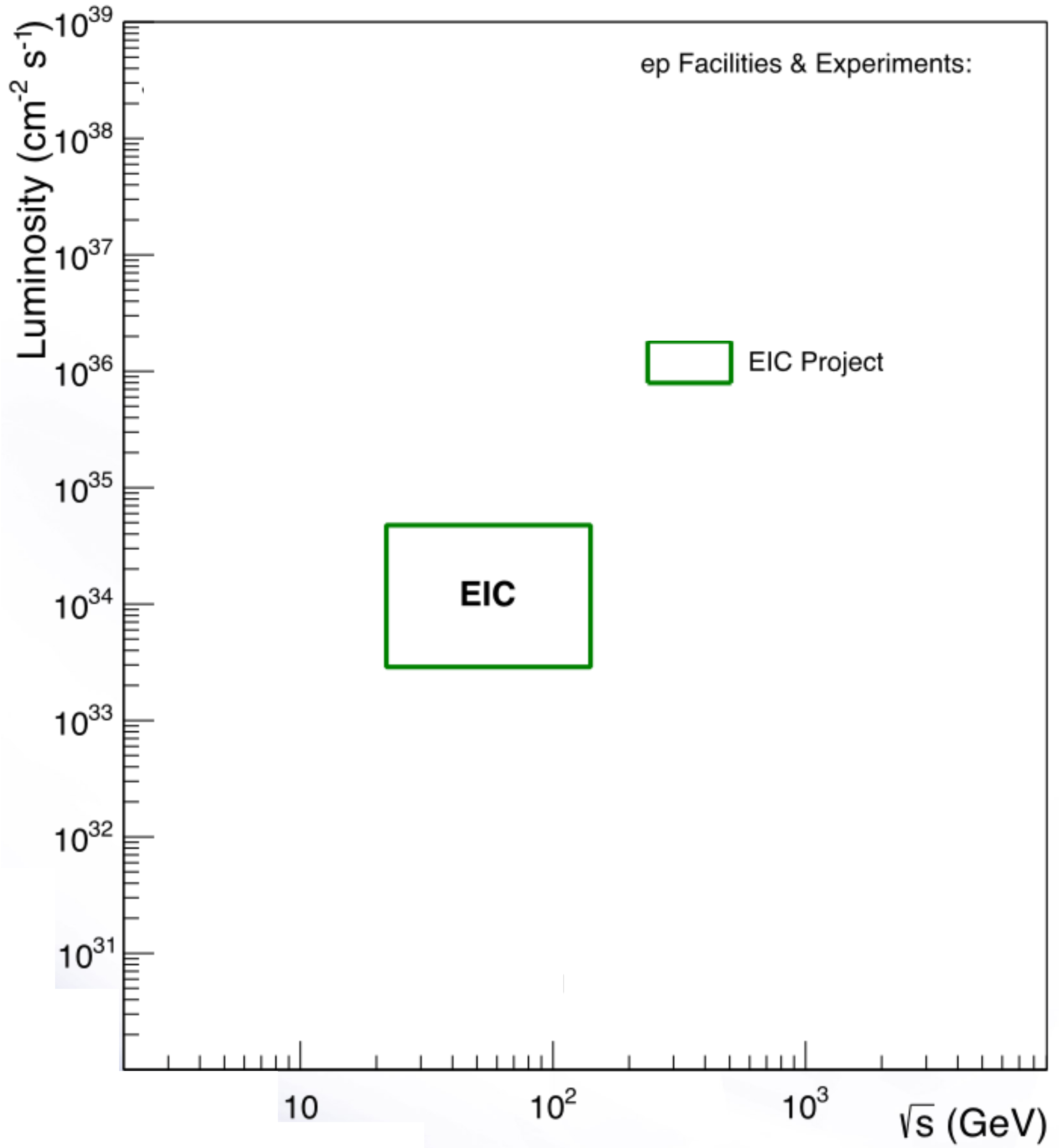


All DIS facilities in the world

However, if we ask for…

- high luminosity and wide reach in $\sqrt{s}$

Uniqueness of EIC



All DIS facilities in the world

However, if we ask for…

- high luminosity and wide reach in $\sqrt{s}$
- polarized lepton & hadron beams
- nuclear beams

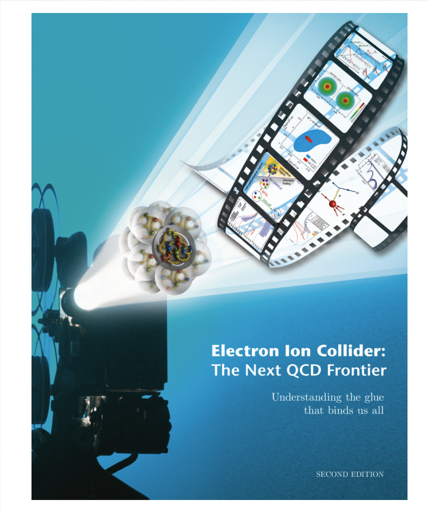
EIC stands out as unique facility

Potential of EIC

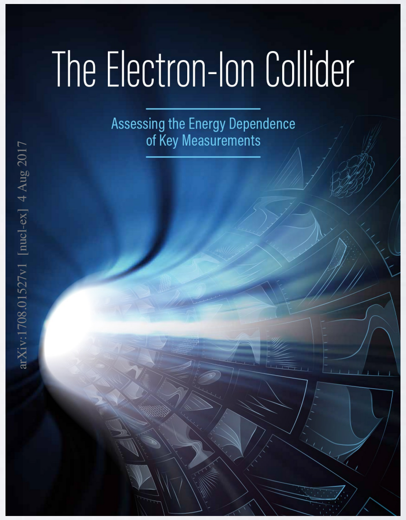
A glimpse of
the expected performance of EIC

see also

INT 2010
arXiv:1108.1713



White Paper
*EPJ **A52** (16) 268, arXiv:1212.1701*

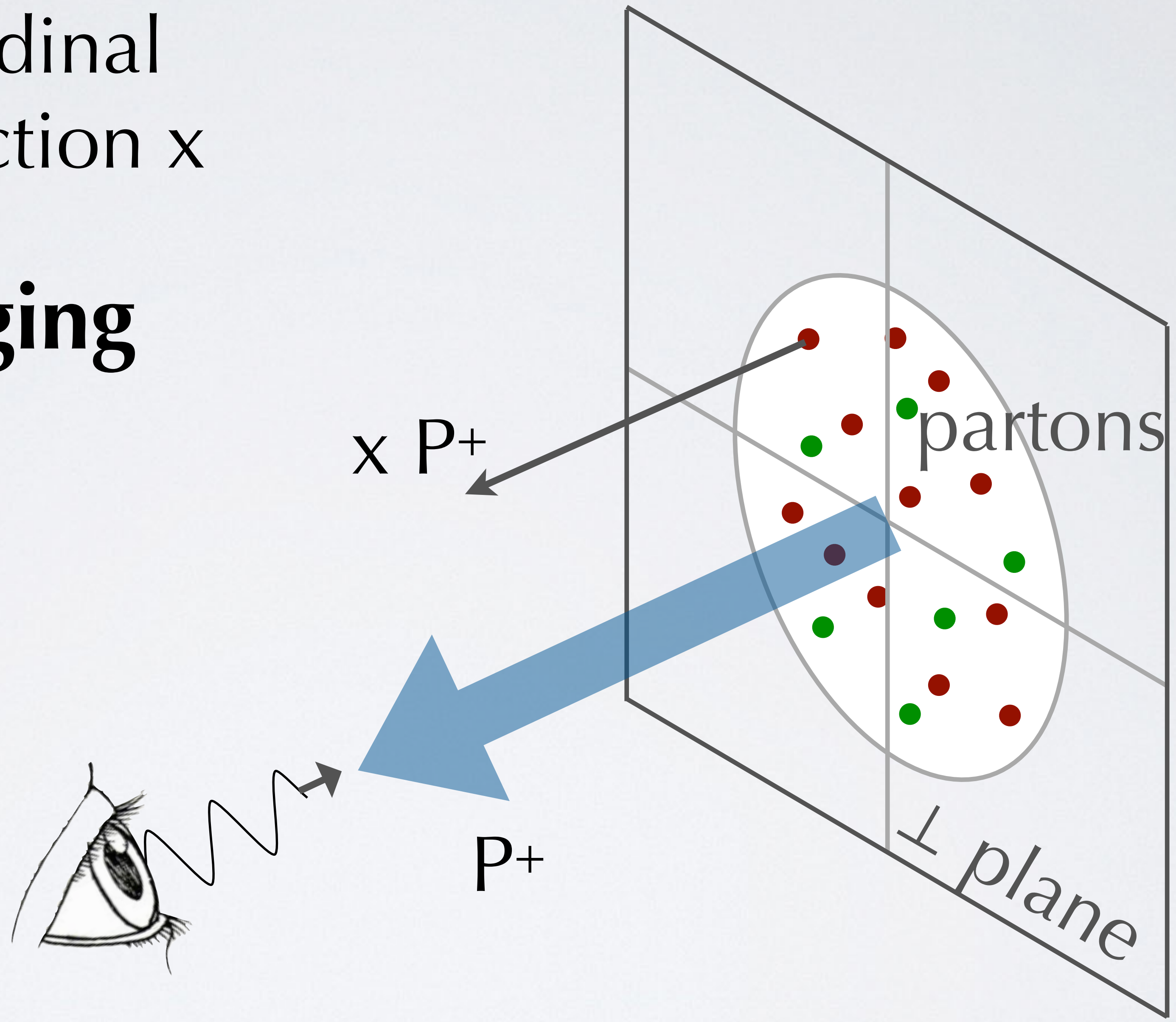


Aschenauer et al.,
arXiv:1708.01527

Collinear Parton Distribution Functions

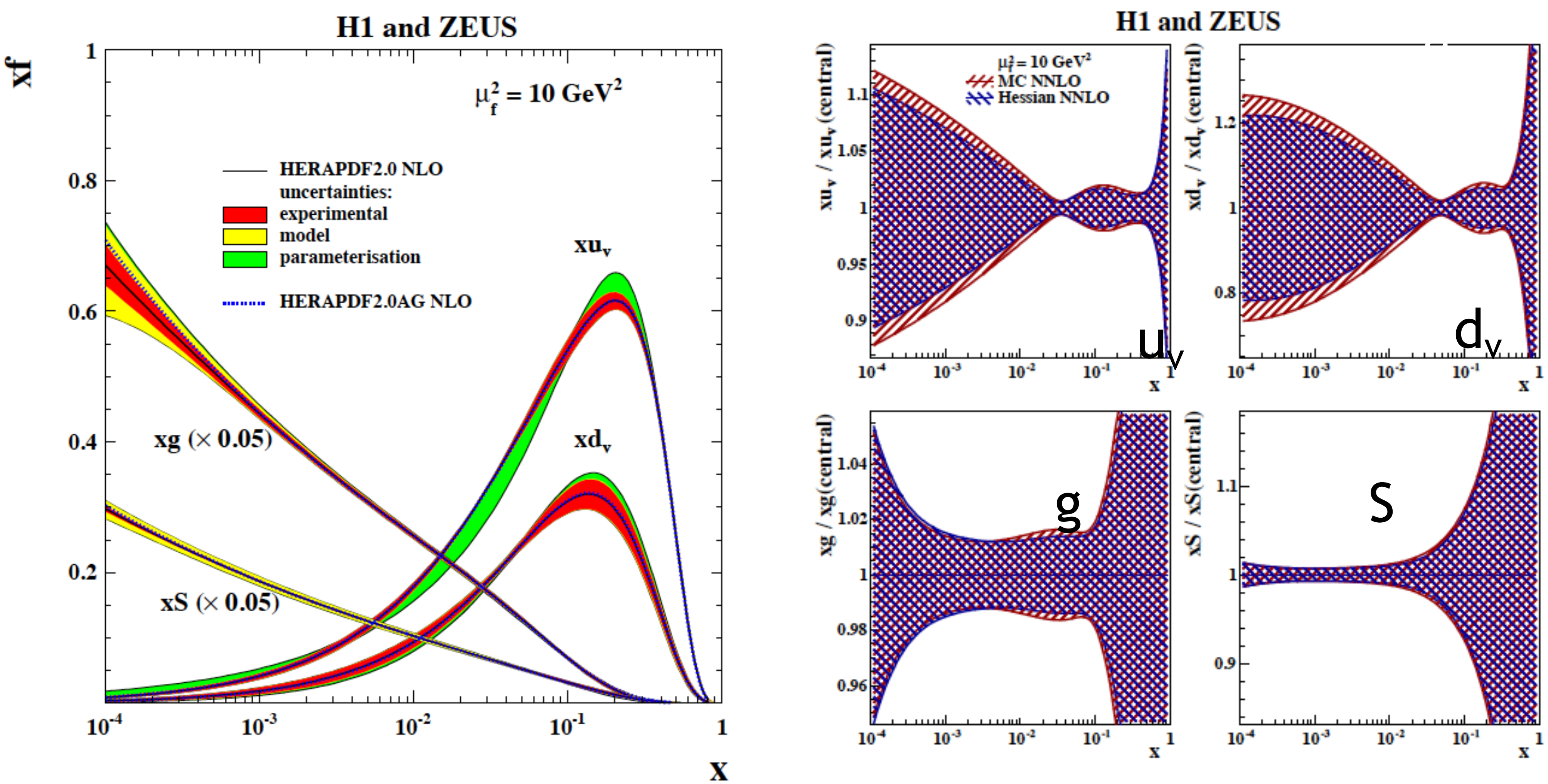
PDF (x) are functions only of parton longitudinal momentum fraction x

1-dim imaging



Collinear PDF now

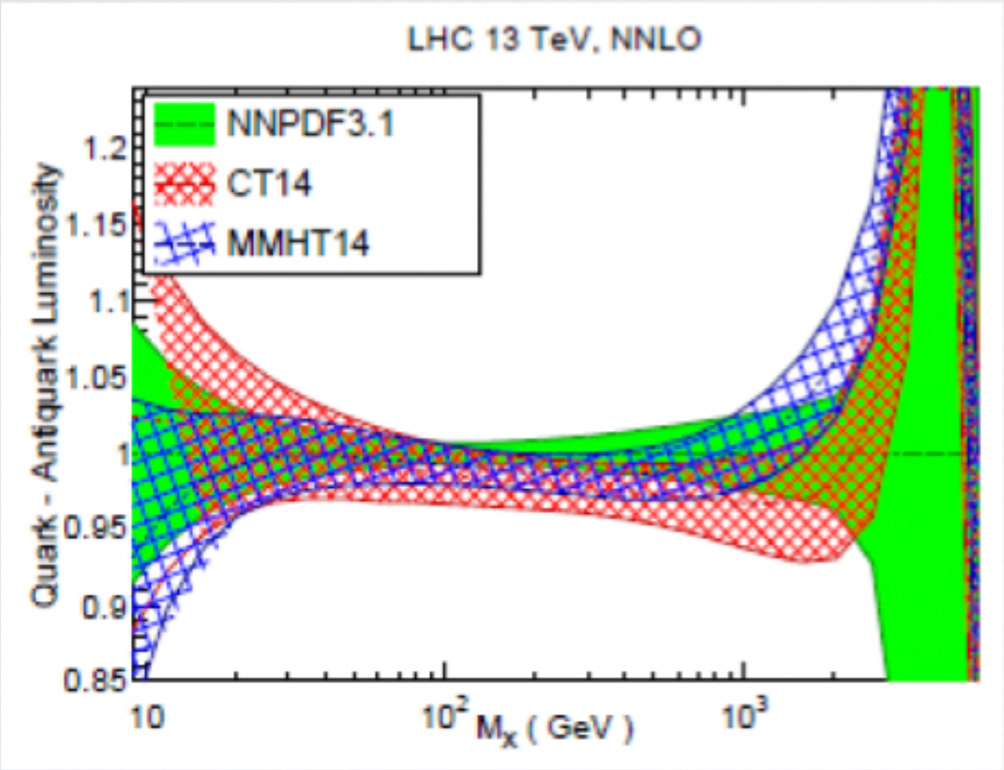
Final HERA Picture of Proton (HERAPDF2.0)

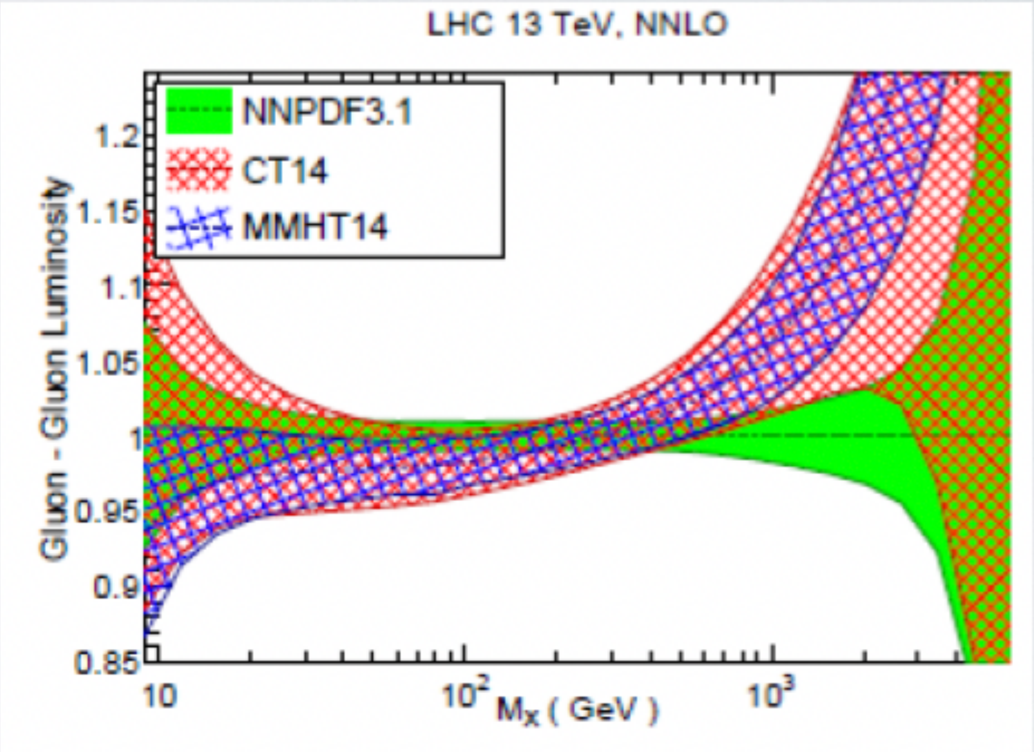


- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2}
- Uncertainty explodes above $x=10^{-1}$ and below $x=10^{-3}$
- Low x gluon rising in a non-sustainable way at large Q^2 …

  [Note 'Standard' presentation is at Q^2 = 10 GeV^2]

Precision matters!





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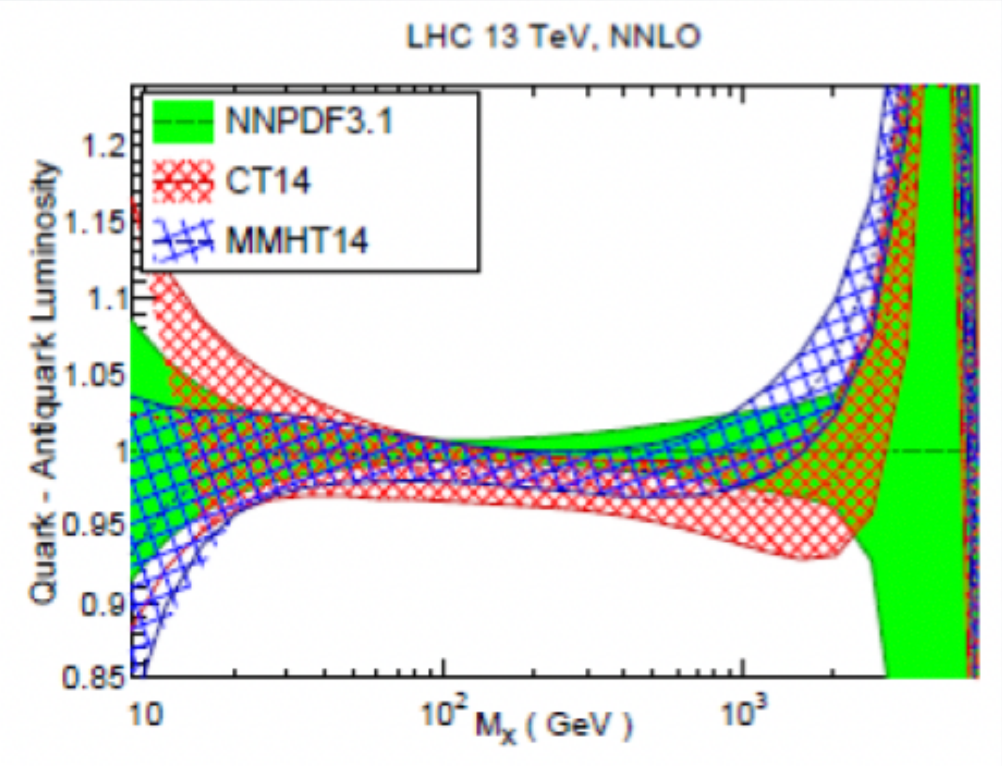
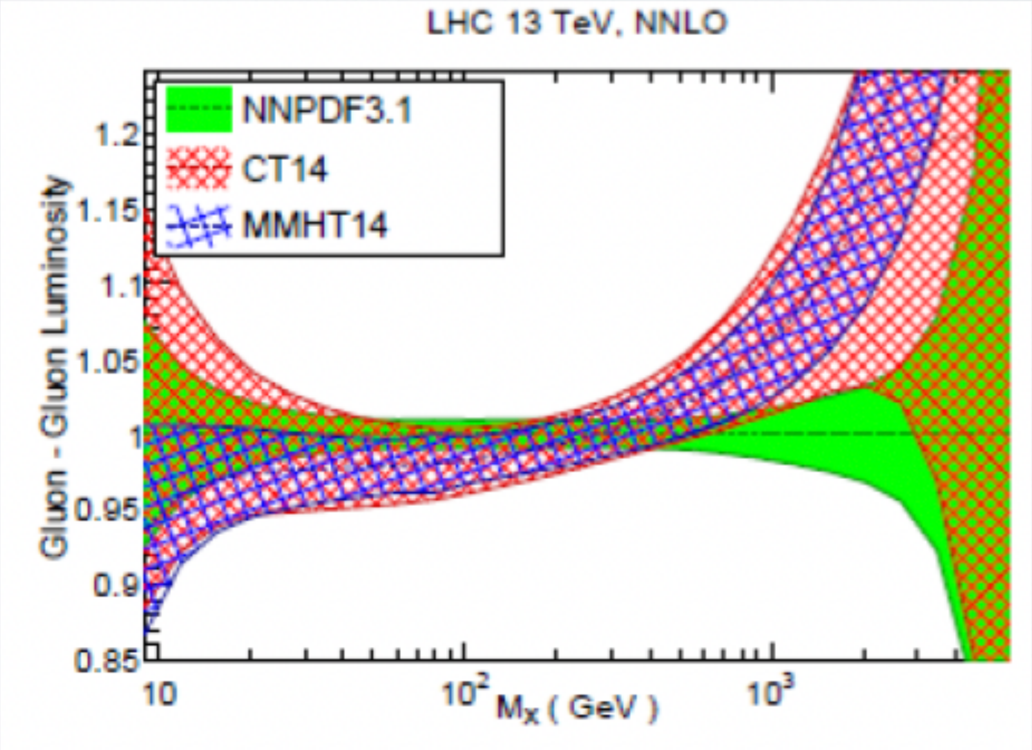
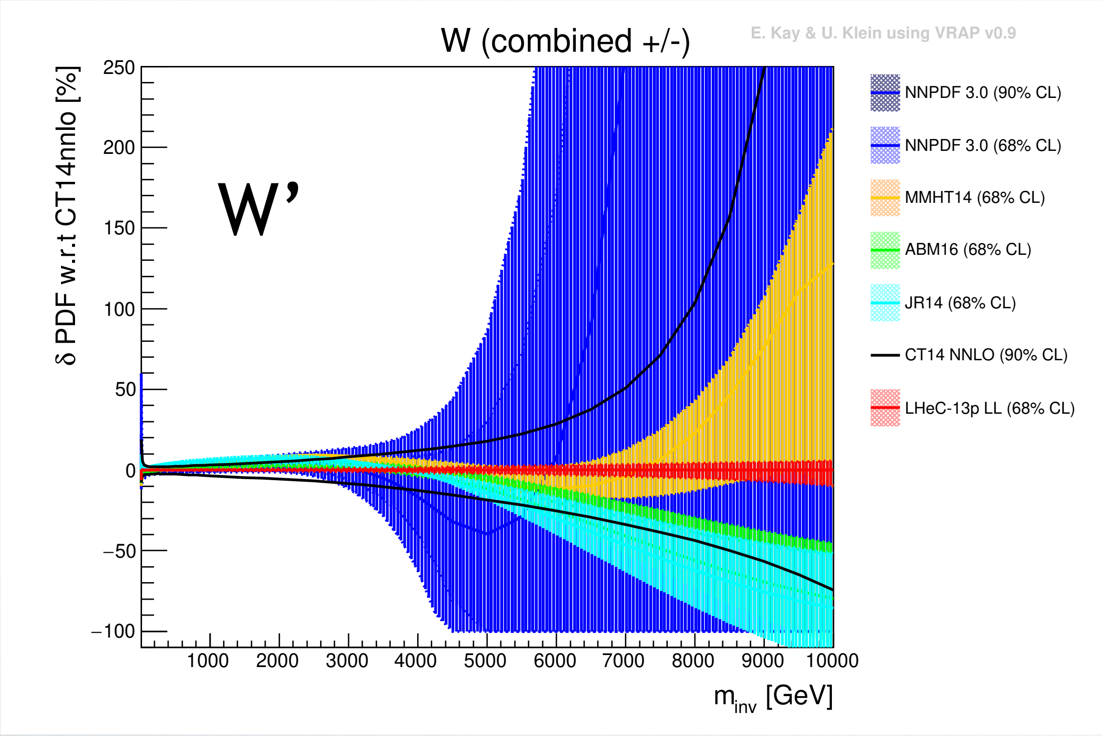
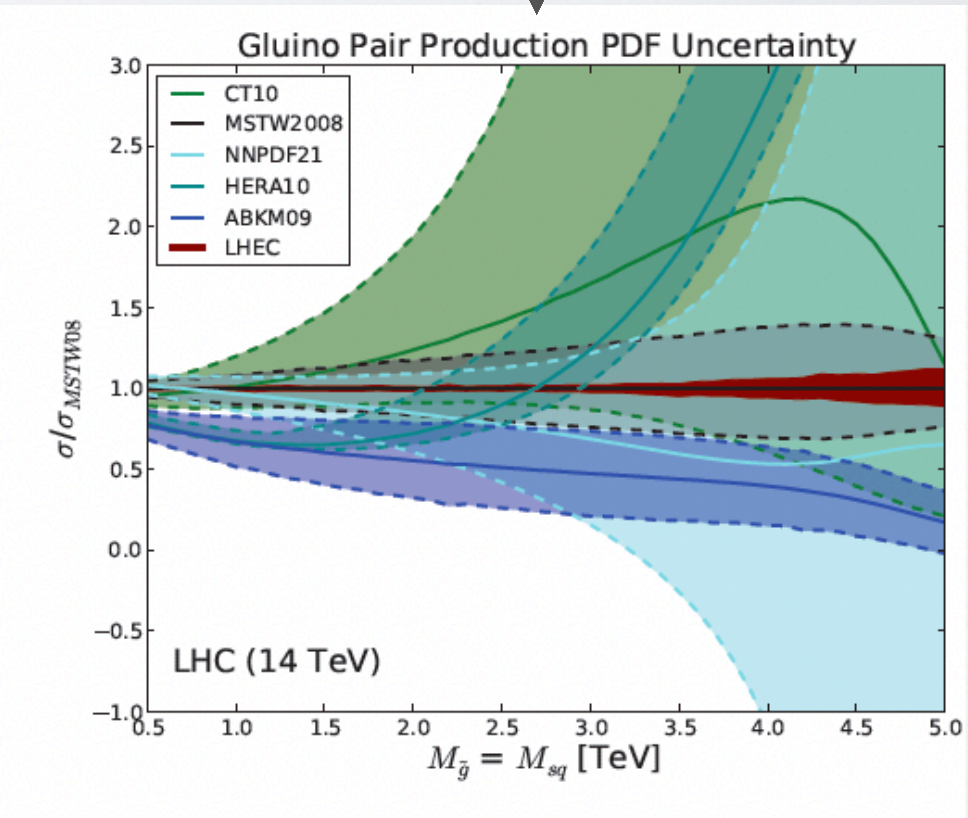
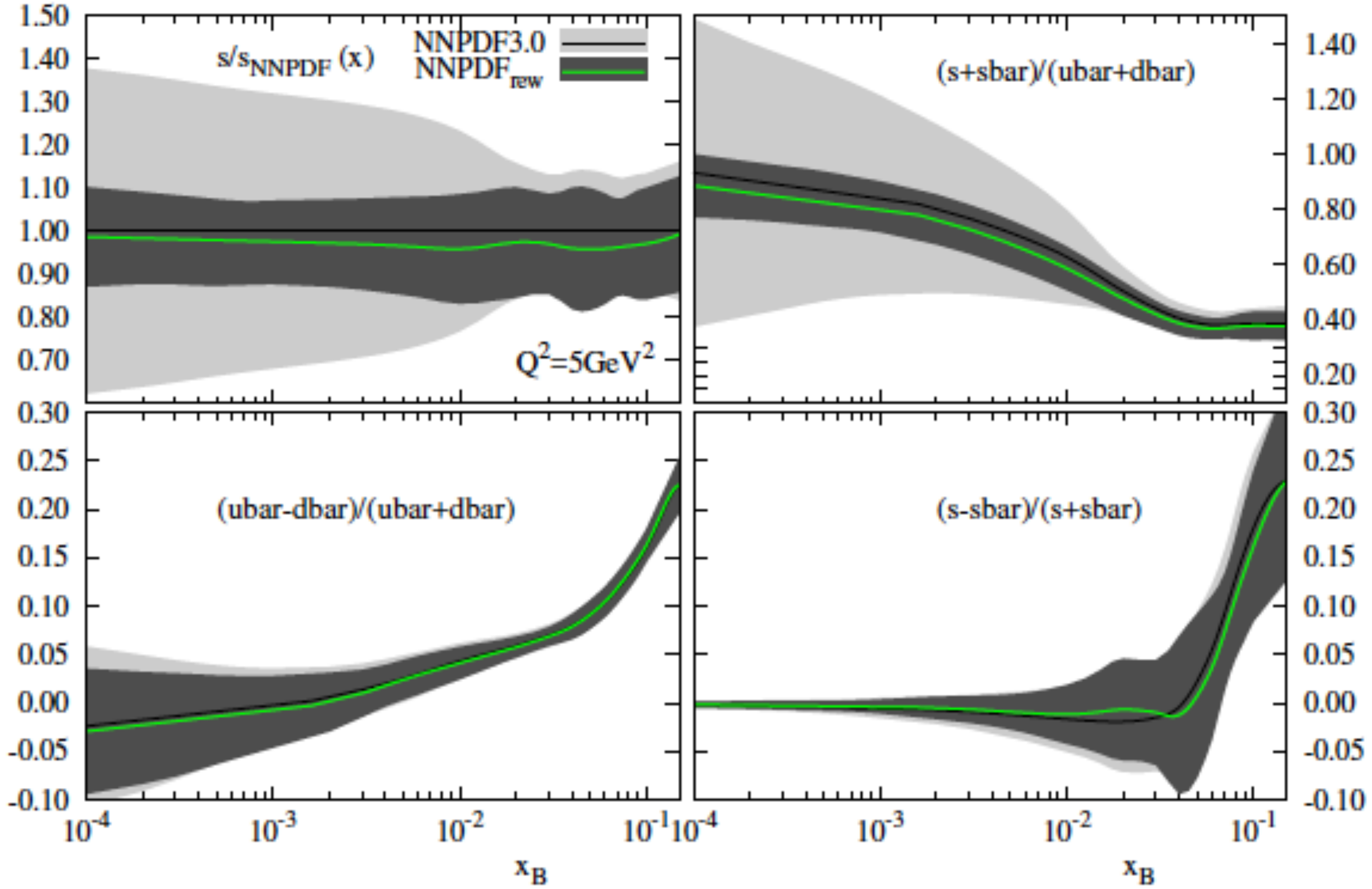








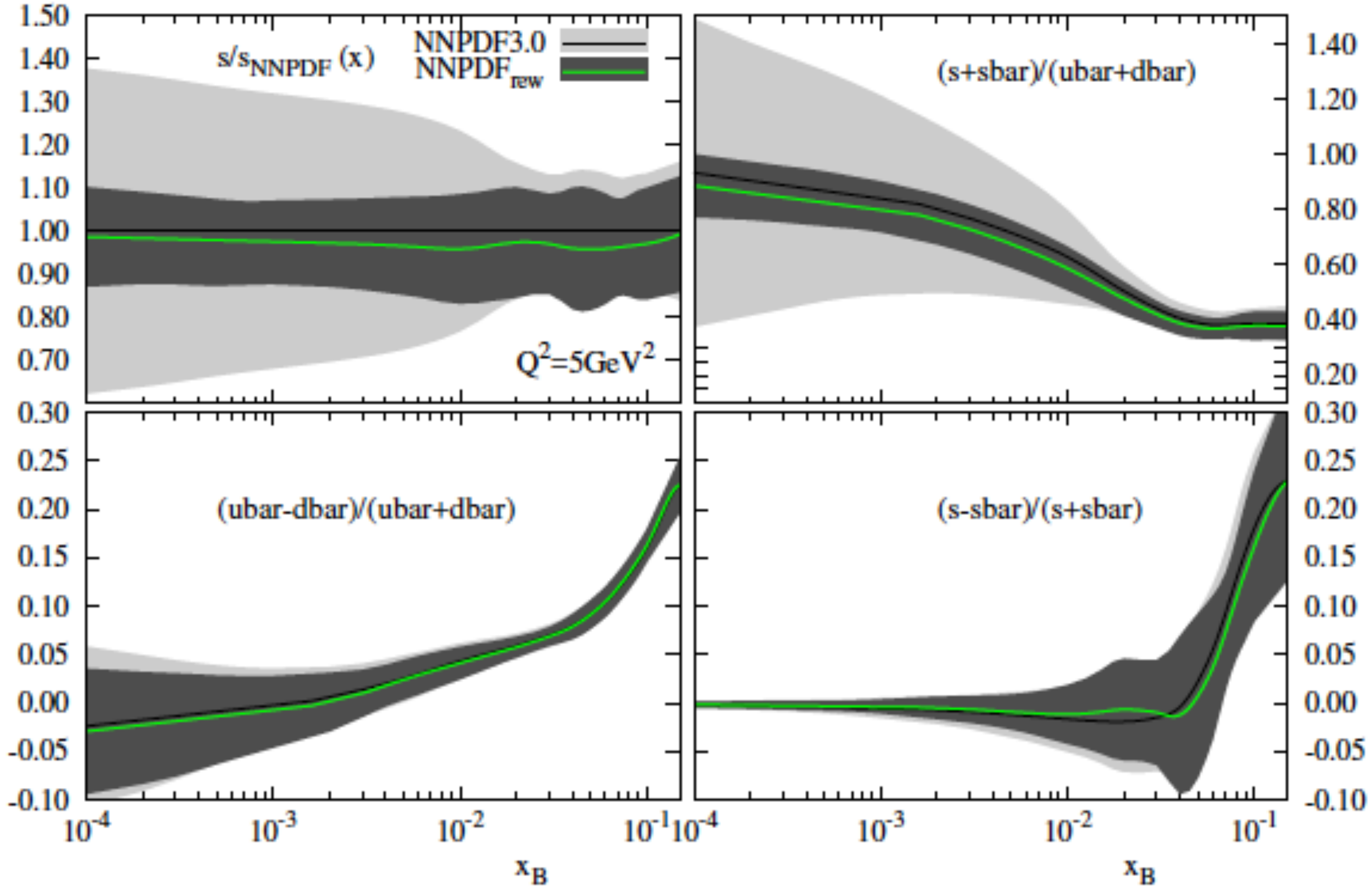
Collinear PDFs @ EIC



EIC at √s = 140 GeV

SIDIS e−p with $K^{\pm}, \pi^{\pm}$

Collinear PDFs @ EIC



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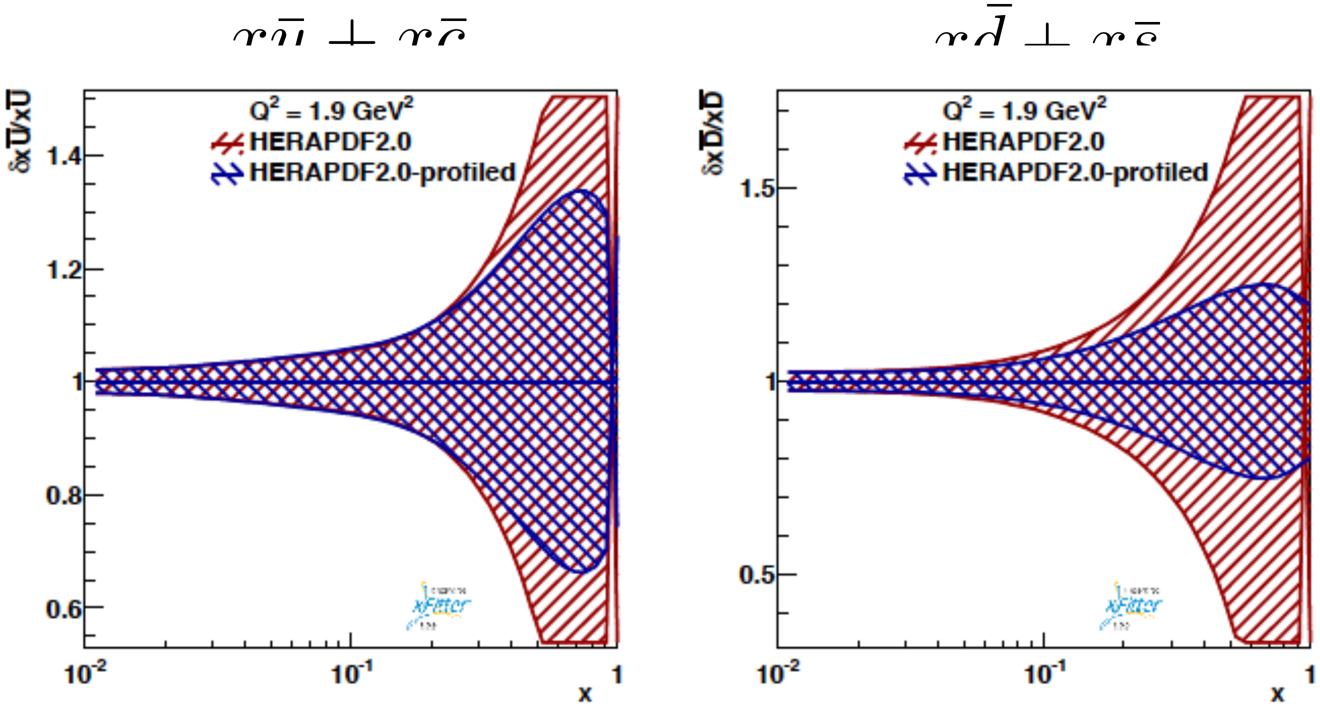
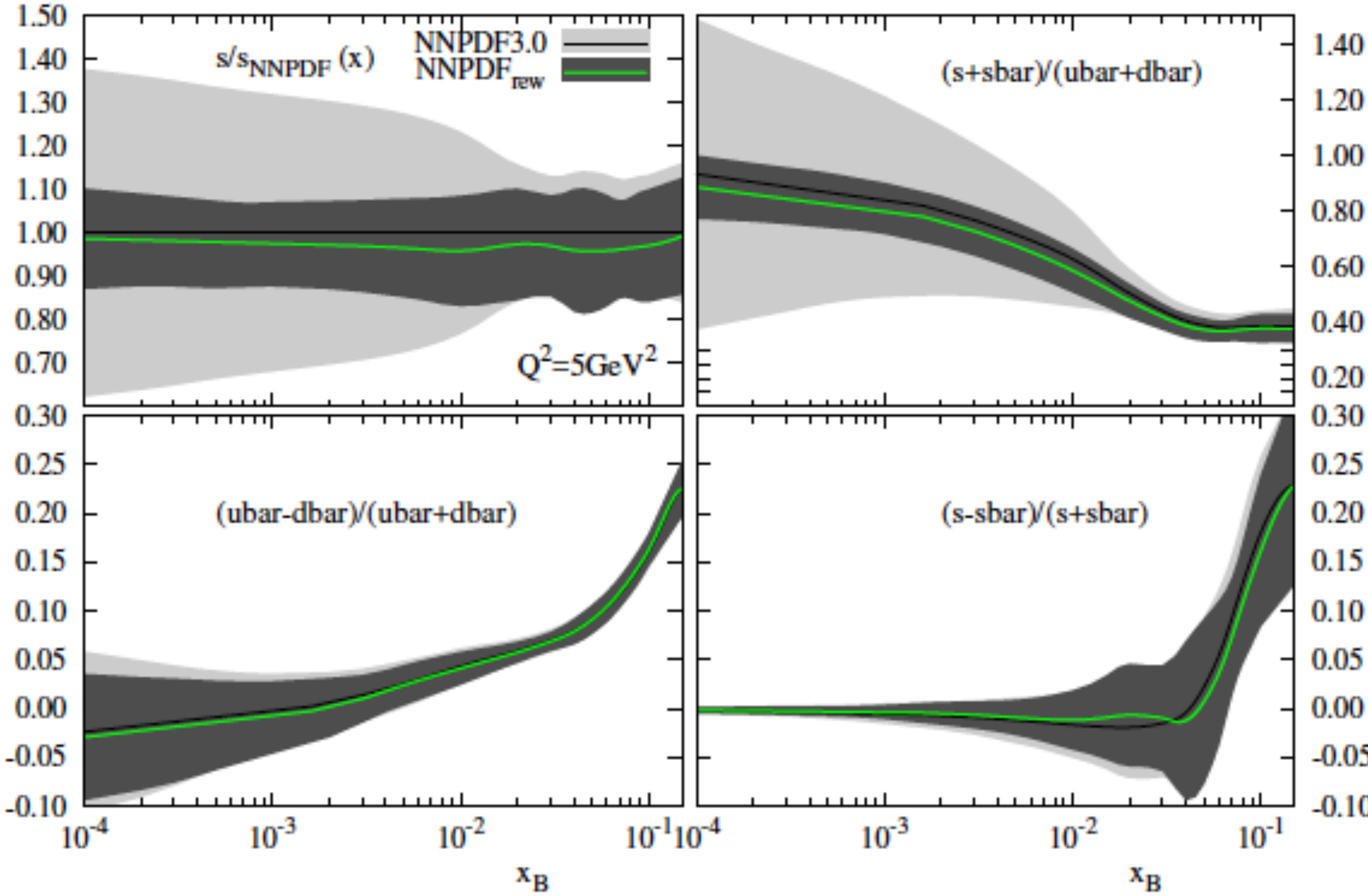


EIC at √s = 140 GeV
Charged-Current DIS

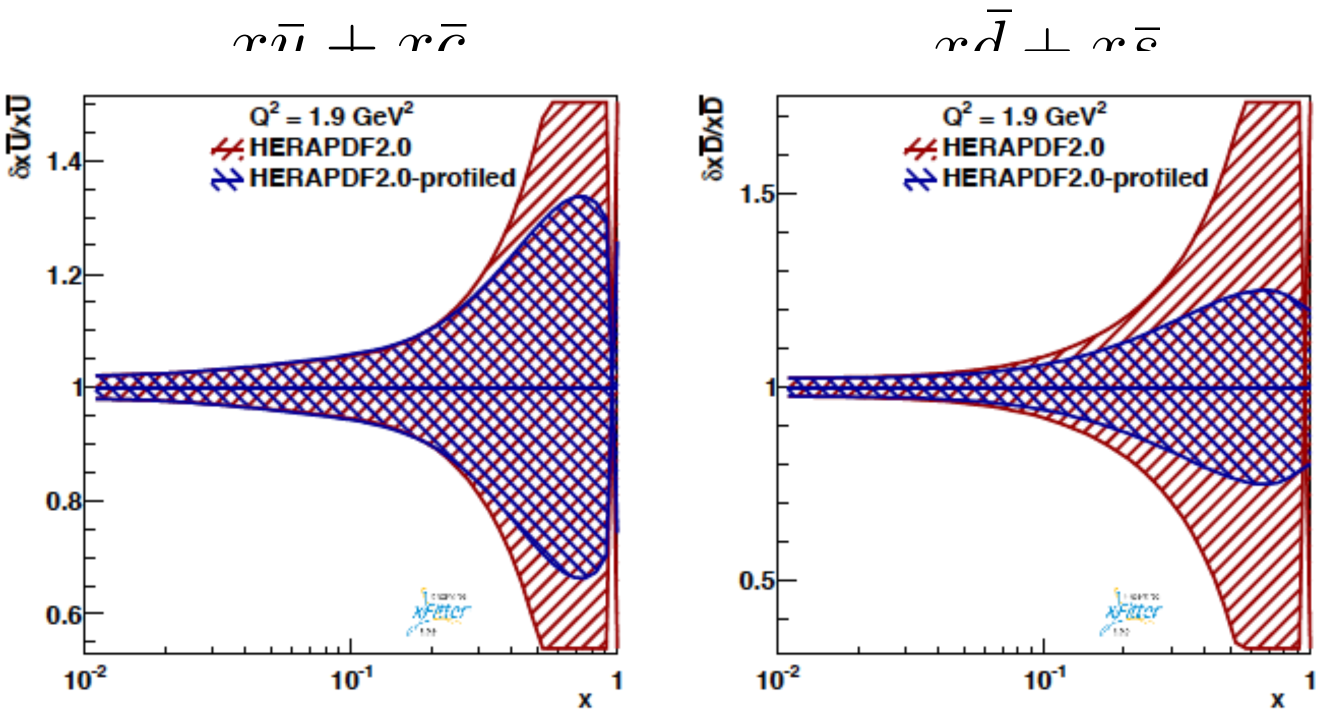
E. Aschenauer, talk at INT-1803

Collinear PDFs @ EIC



EIC at √s = 140 GeV
SIDIS e–p with $K^{\pm}, \pi^{\pm}$

important for Higgs & BSM physics
using "BSM-insensitive" PDFs



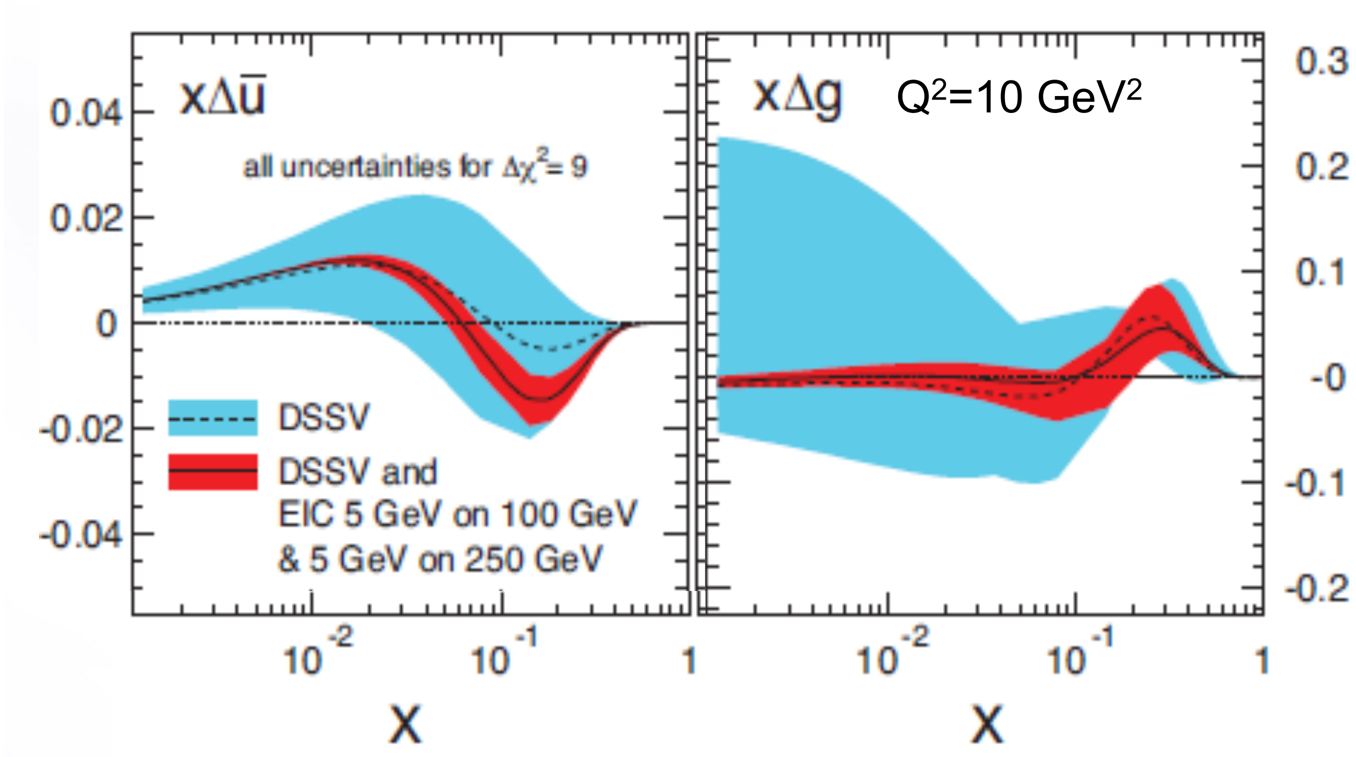
EIC at √s = 140 GeV
Charged-Current DIS

important for large-q_T W & Z
production and for BSM physics

E. Aschenauer, talk at INT-1803

The Nucleon Spin Puzzle

generate EIC pseudo-data and fit → g_1^q, g_1^q, g_1^g



The Nucleon Spin Puzzle

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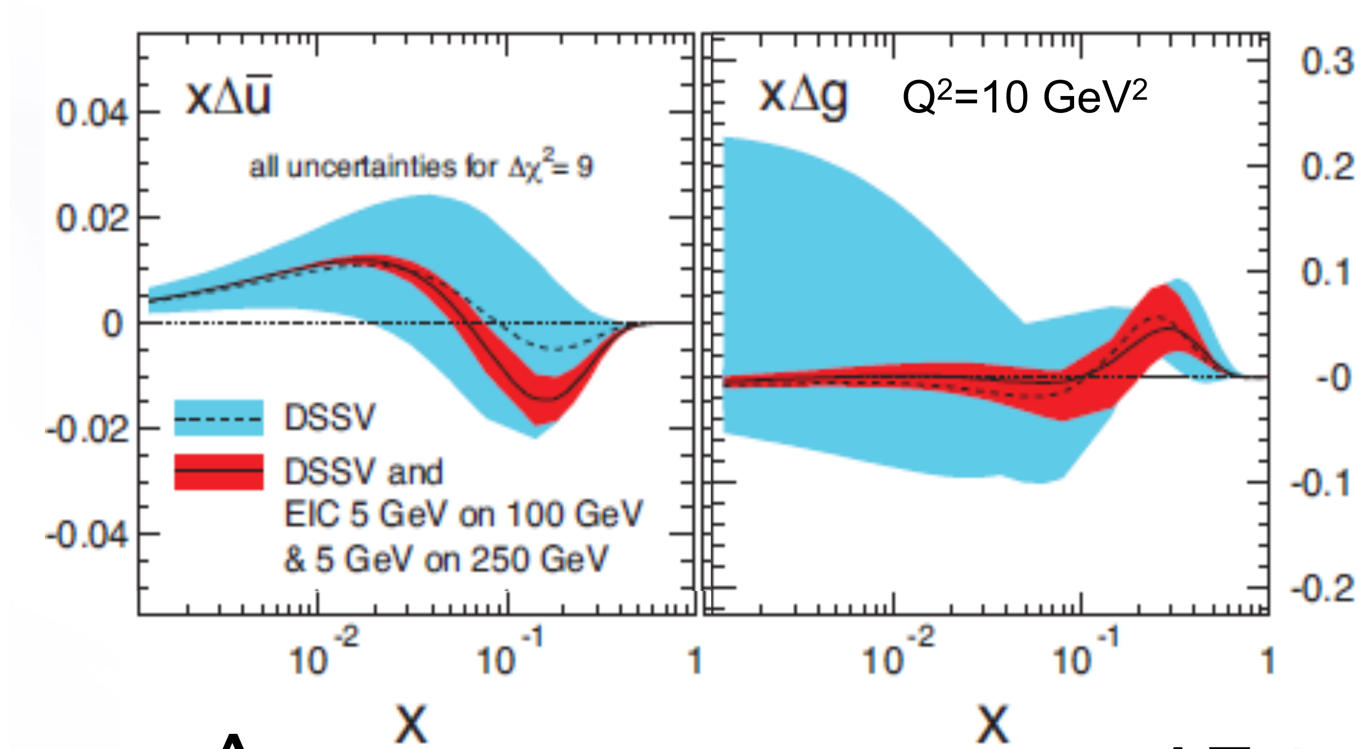
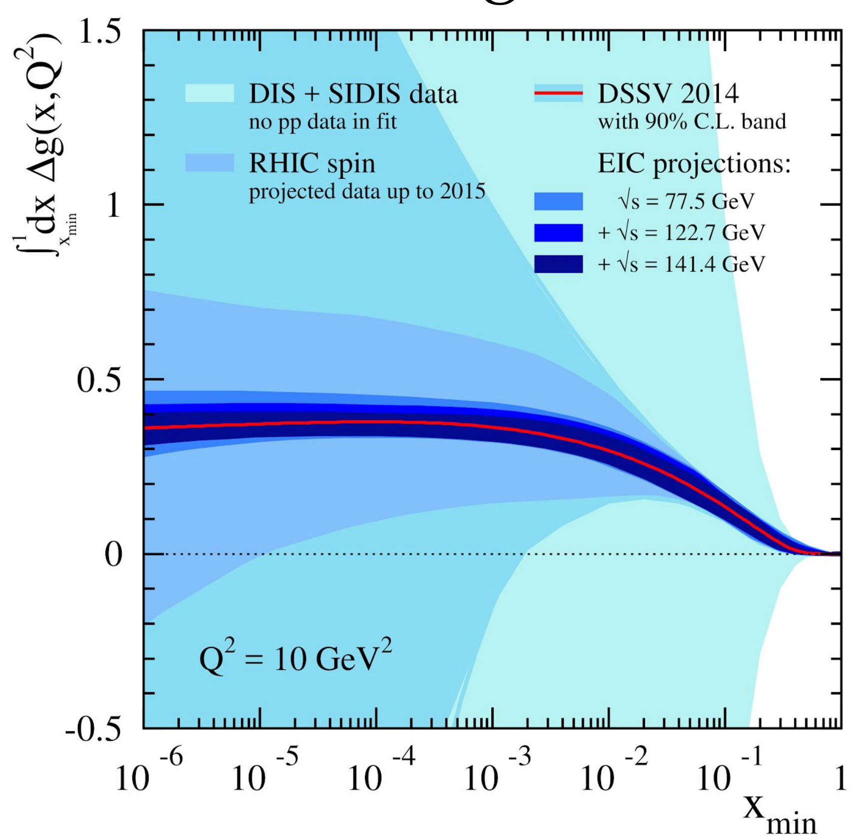
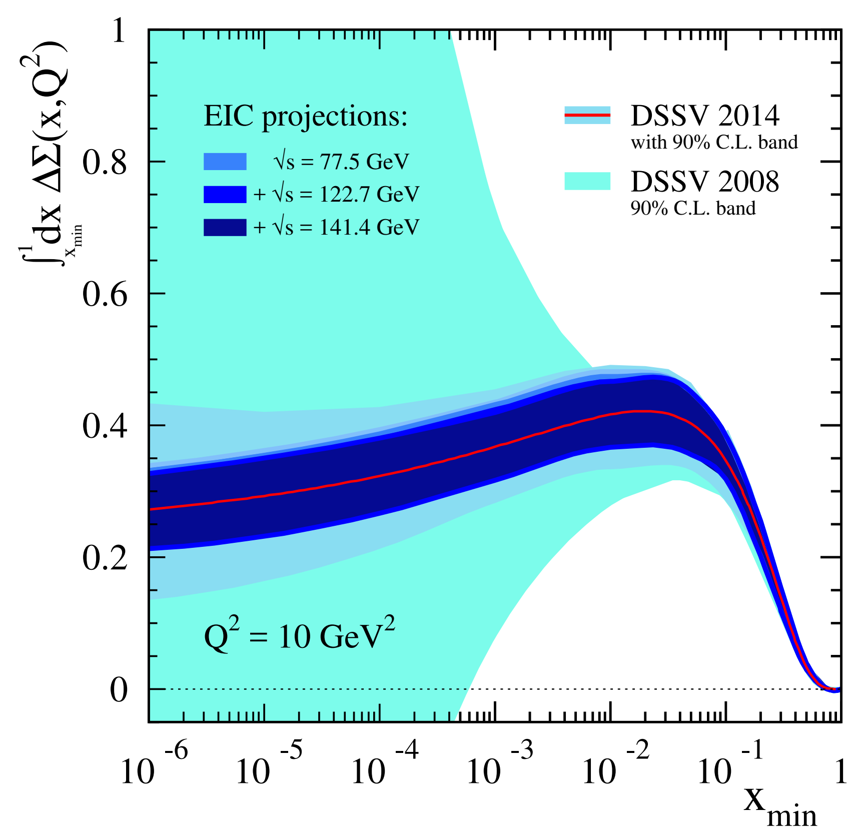


Δg



ΔΣ /2



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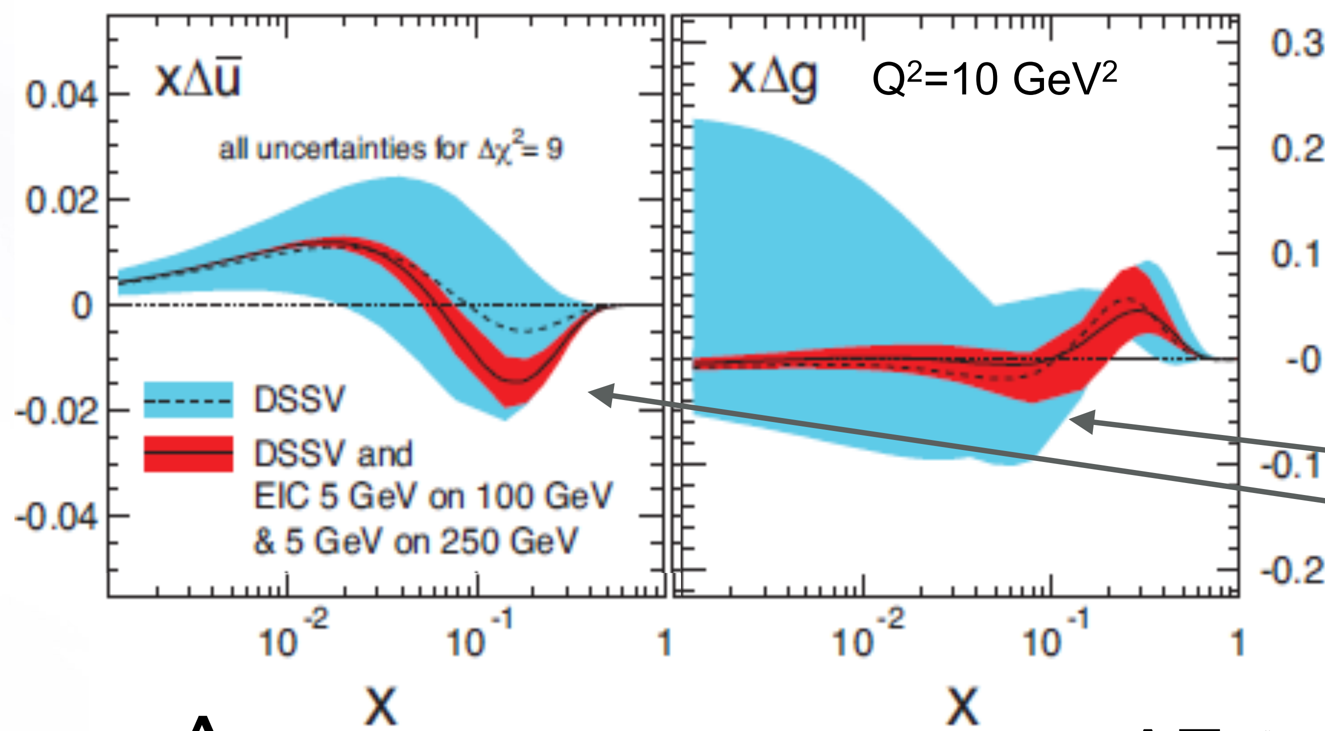
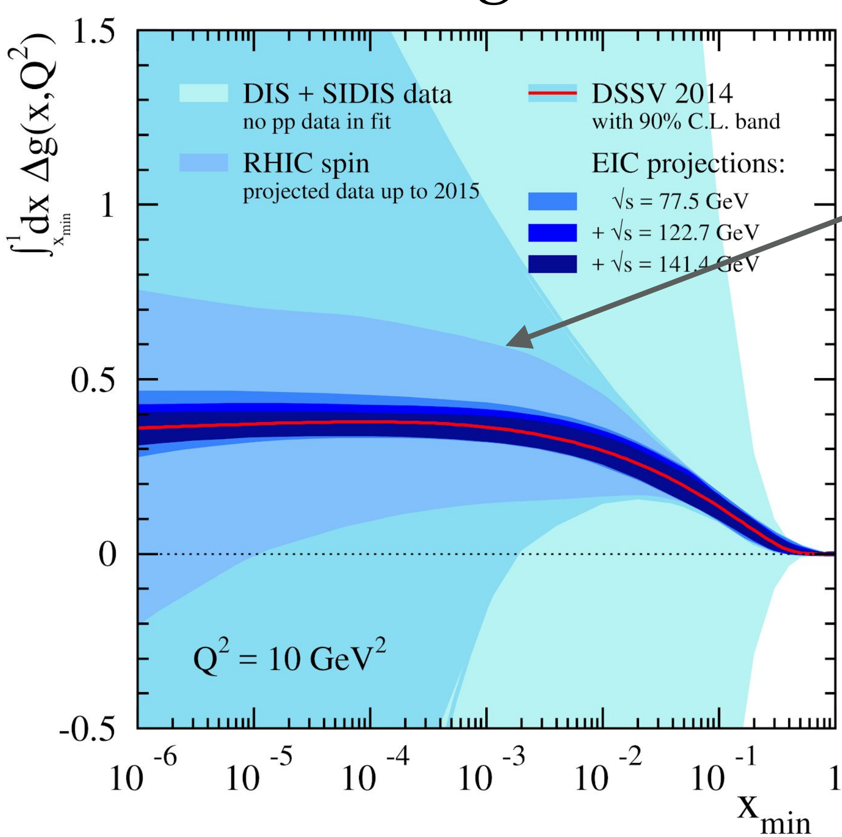
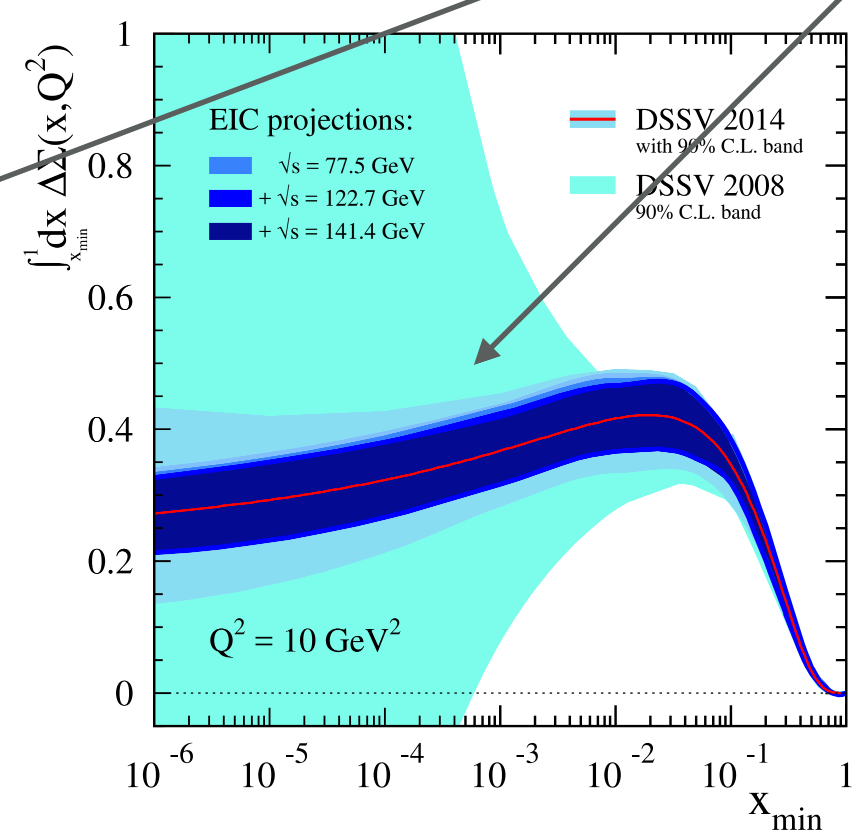


huge impact
from EIC !

Δg



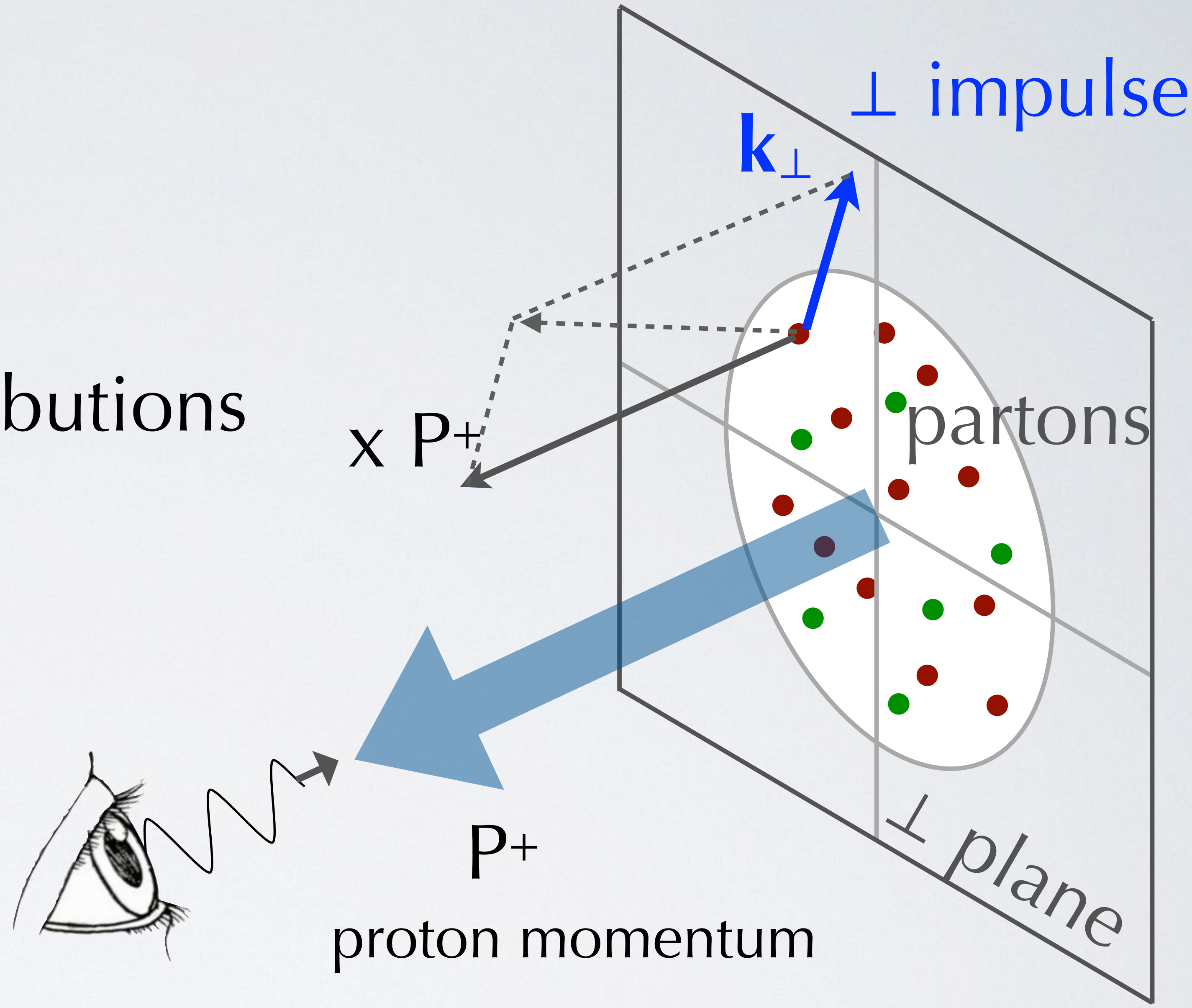
ΔΣ /2



Transverse–Momentum Distributions

Transverse-**M**omentum **D**istributions

TMD(x,$\mathbf{k}_\perp$) functions
of x and parton
transverse momentum $\mathbf{k}_\perp$



a new paradigm :
3D - imaging
in momentum space

The TMD "zoo"

at leading twist

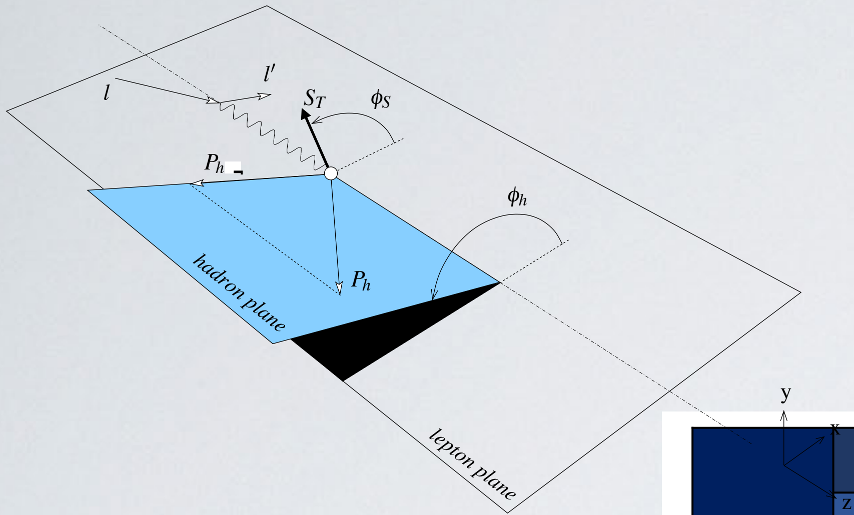
$\mathcal{O}\left(\frac{M}{Q}\right)^0$

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	*	$h_1^\perp =$ -
	L	*	$g_1 =$ -	$h_{1L}^\perp =$ -
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

* forbidden by Parity invariance

each TMD enters the cross section
with a specific dependence on (azimuthal) angles of kinematics
→ extract them with azimuthal (spin) asymmetries

The TMD "zoo"



at leading twist

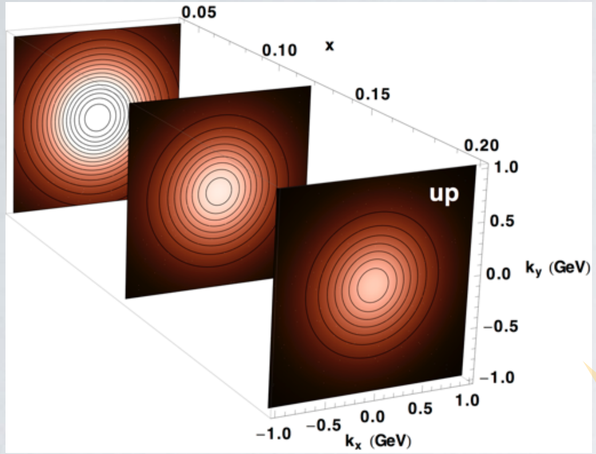
$\mathcal{O}\left(\frac{M}{Q}\right)^0$

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$	*	$h_1^\perp =$ -
L	*	$g_1 =$ -	$h_{1L}^\perp =$ -
T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

* forbidden by Parity invariance

each TMD enters the cross section
with a specific dependence on (azimuthal) angles of kinematics
→ extract them with azimuthal (spin) asymmetries

The TMD "zoo"



tomography
cylindrical symmetry

at leading twist

$$\mathcal{O}\left(\frac{M}{Q}\right)^0$$

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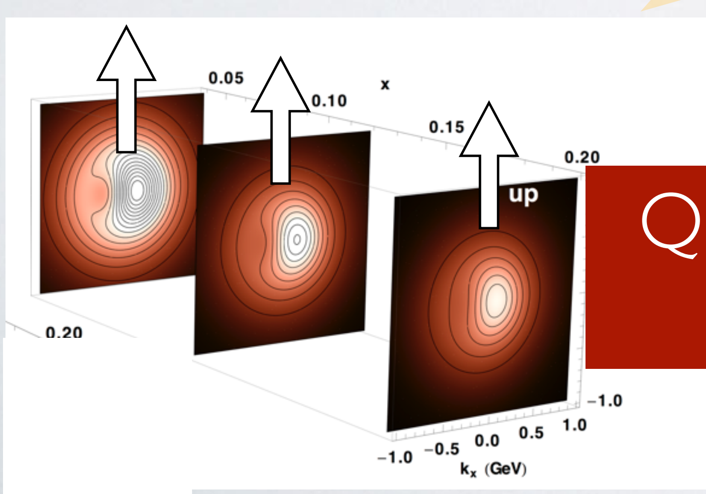
* forbidden by Parity invariance

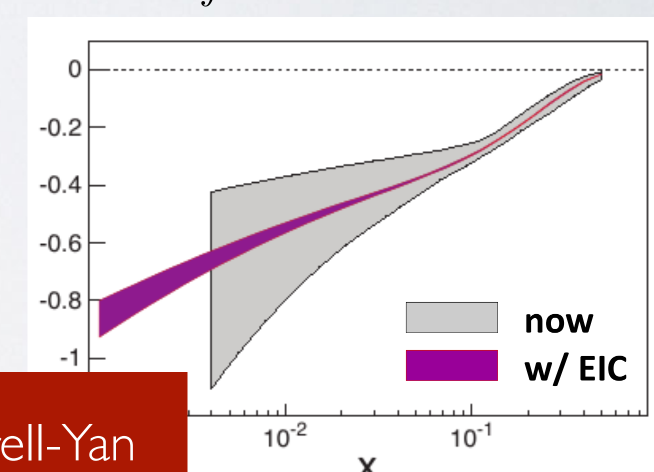
distortion of $k_\perp$-distribution

Sivers function

*Sivers, P.R. D **41** (90) 83*

$$\int dk_\perp^2 \frac{k_\perp^2}{2M^2} f_{1T}^{\perp\, u-\bar{u}}$$

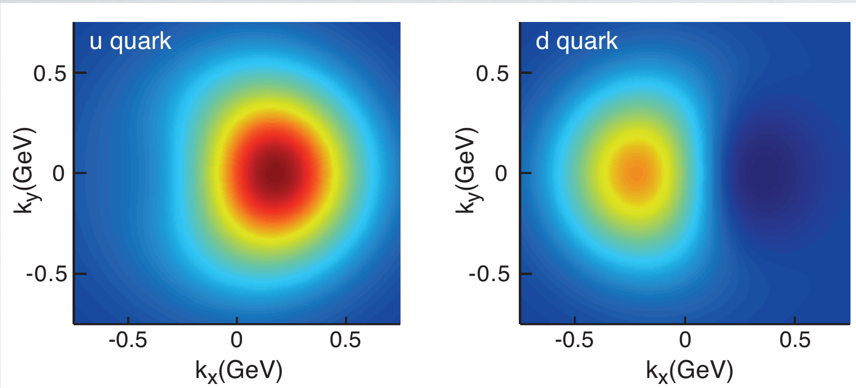




QCD prediction: Sivers $|_{\text{SIDIS}} = -$ Sivers $|_{\text{Drell-Yan}}$
test the time-reversal symmetry of QCD

*Collins, P.L. **B536** (02)*

The TMD "zoo"



at leading twist

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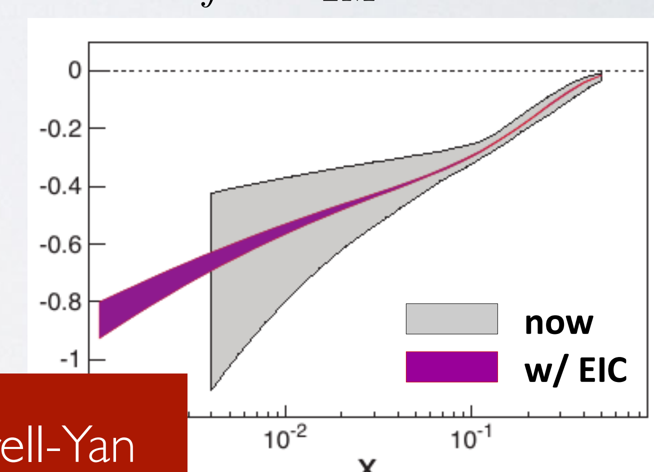

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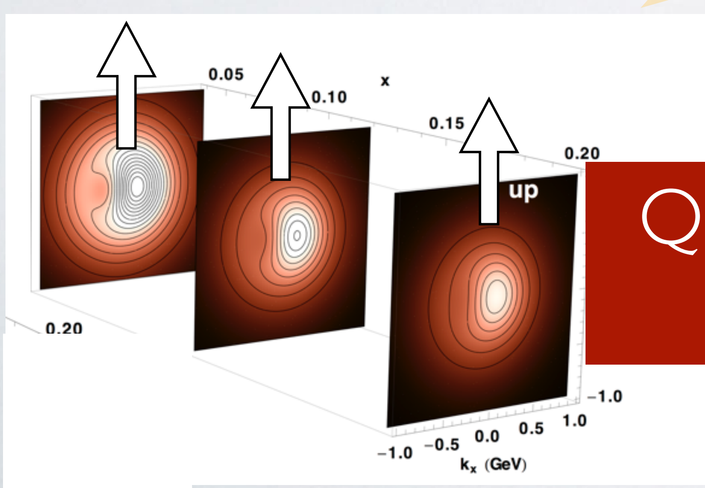
*Sivers, P.R. D **41** (90) 83*



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* forbidden by Parity invariance

transversity

3 independent PDFs

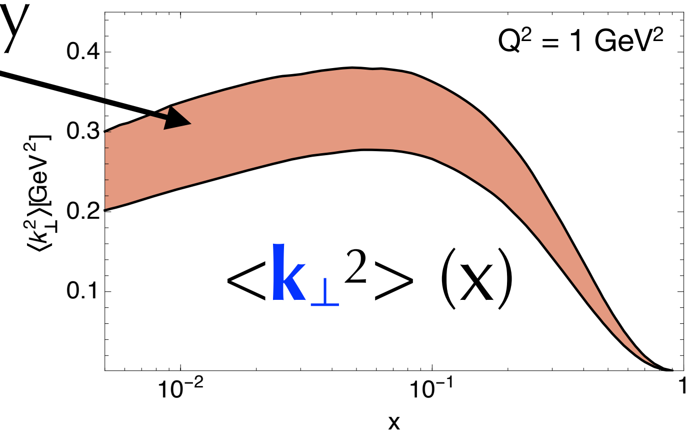
chiral odd (quark helicity flip)
connected to tensor operator $\bar{\psi}\sigma^{\mu\nu}\psi$

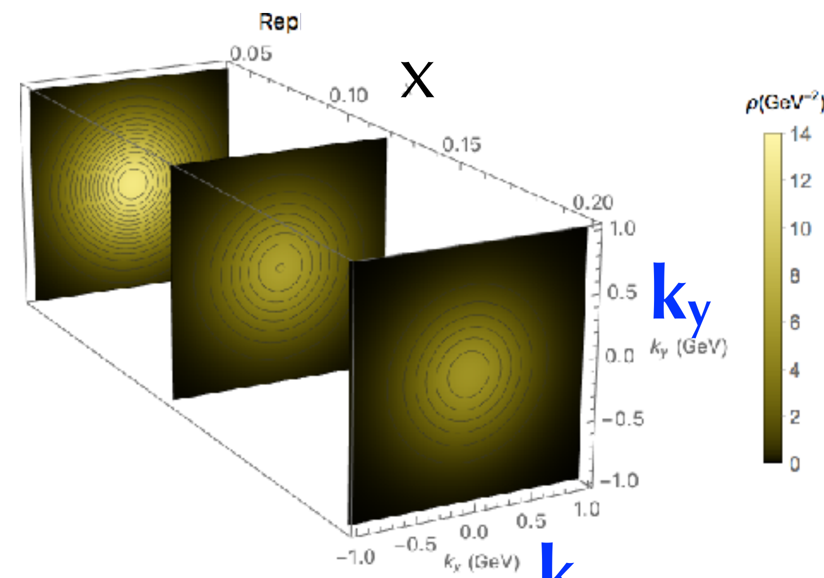
footprint of new physics at higher scale ?

femto-tomography in momentum space

$\mathbf{k}_\perp$-distribution of unpolarized quarks for each x

68% uncertainty band

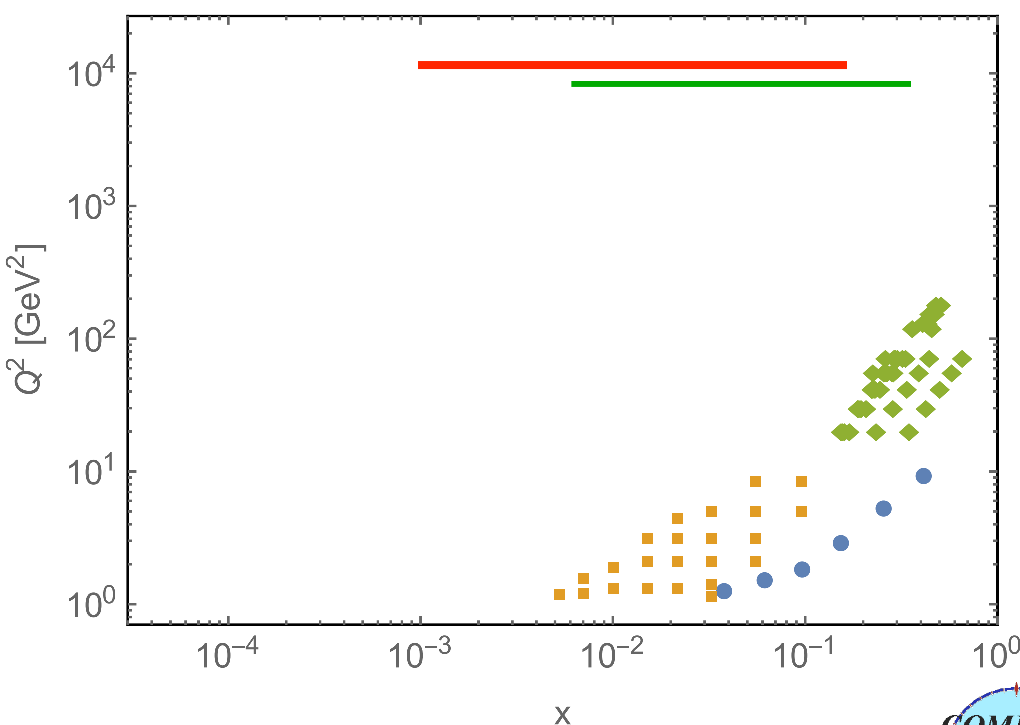




*Bacchetta et al., JHEP **1706** (17) 081*

first extraction from a **global fit** by Pavia team

(Several active groups: Pavia, Torino, Madrid,…)



Z production @Tevatron

Drell-Yan Fermilab

SIDIS @ DESY

SIDIS COMPASS @ CERN

femto-tomography in momentum space

$k_\perp$-distribution of unpolarized quarks for each x

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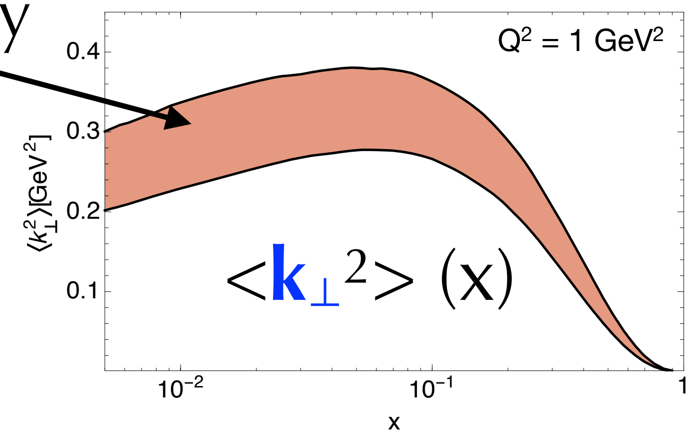

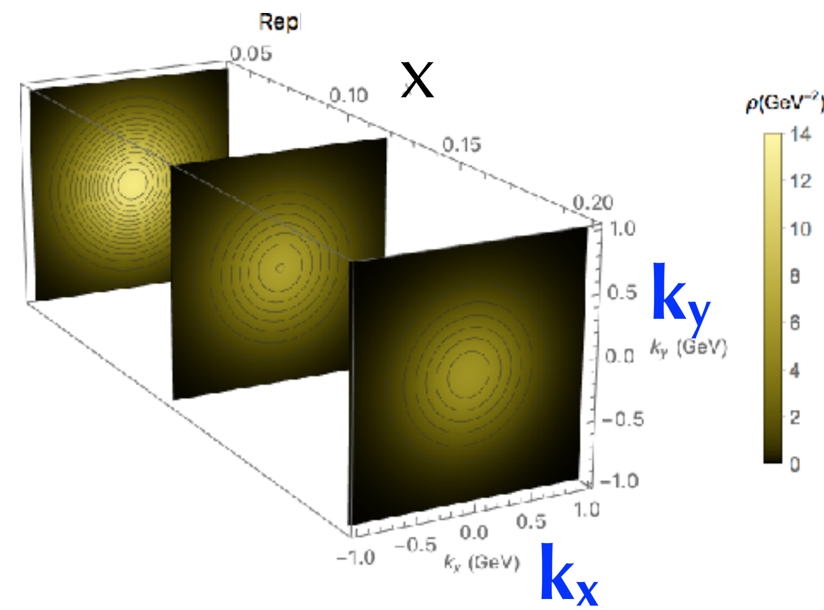

*Bacchetta et al., JHEP **1706** (17) 081*

first extraction from a **global fit** by Pavia team

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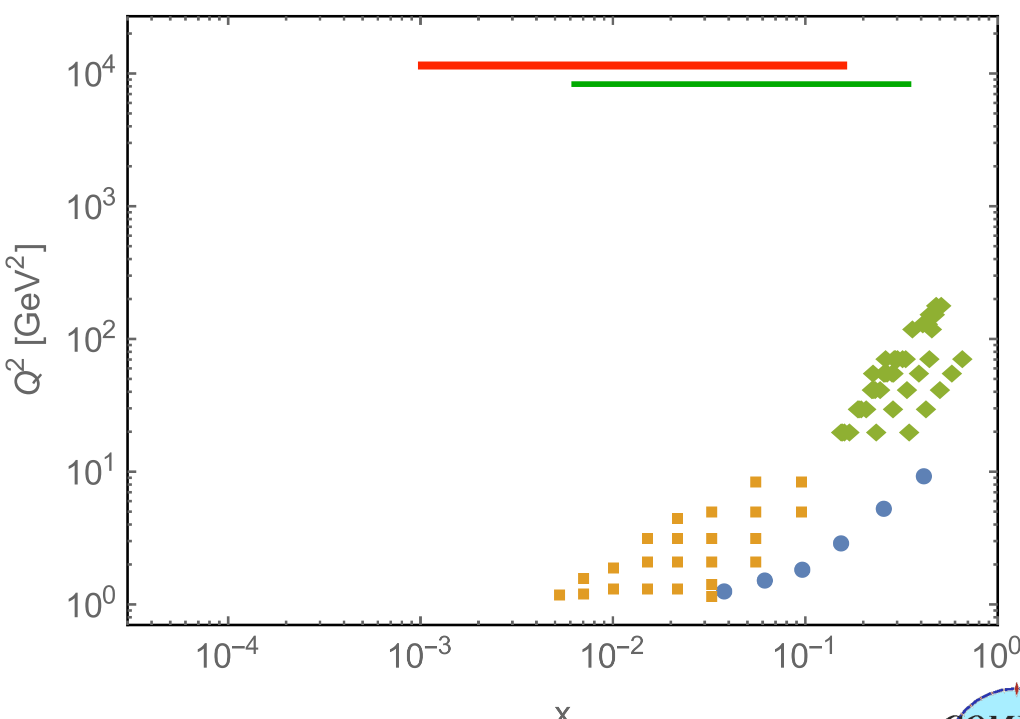
Z production @LHC



Z production @Tevatron

Drell-Yan Fermilab

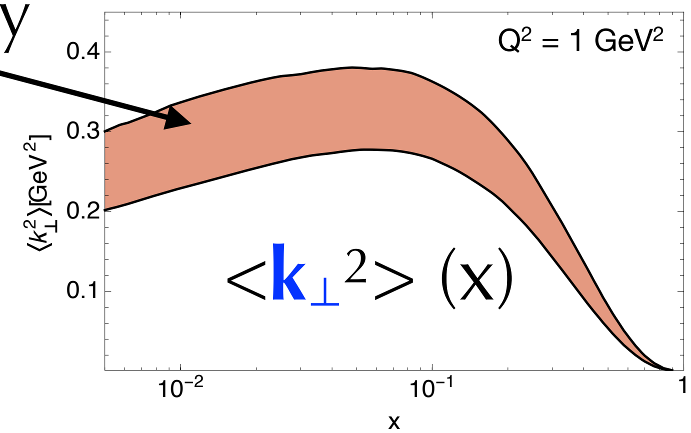
SIDIS hermes @ DESY

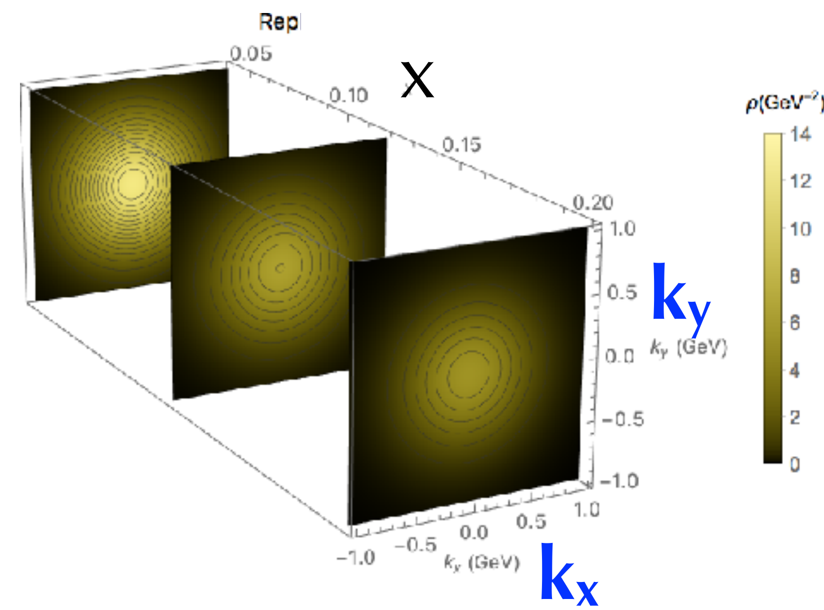
SIDIS COMPASS @ CERN

femto-tomography in momentum space

$\mathbf{k}_\perp$-distribution of unpolarized quarks for each x

68% uncertainty band





Bacchetta et al., JHEP ***1706*** *(17) 081*

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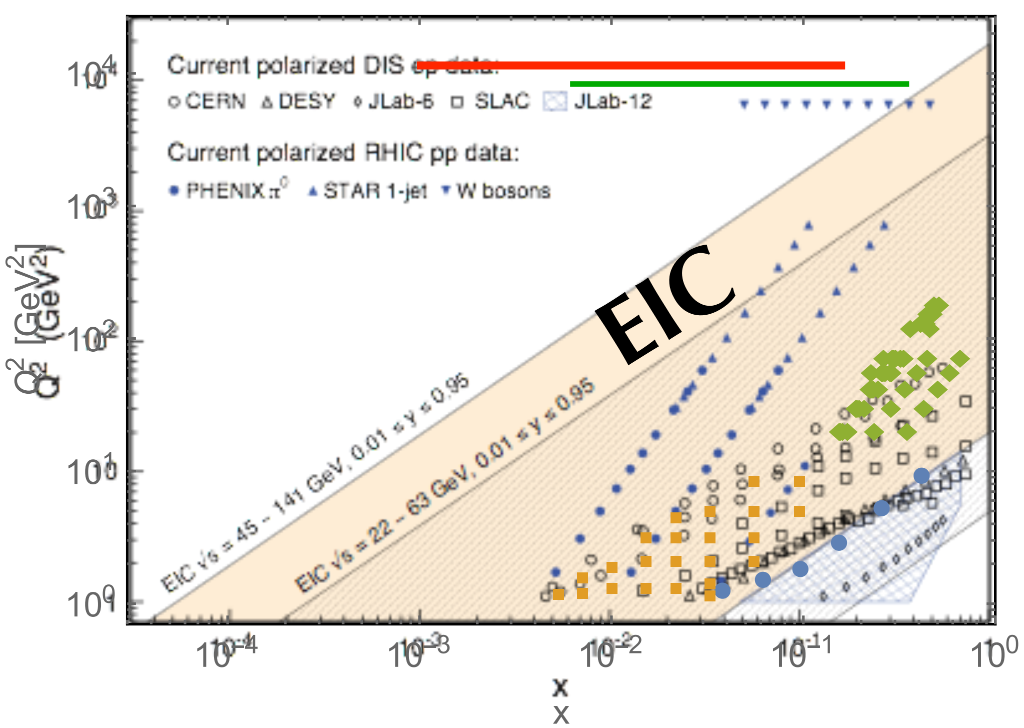
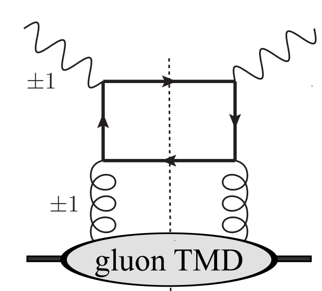


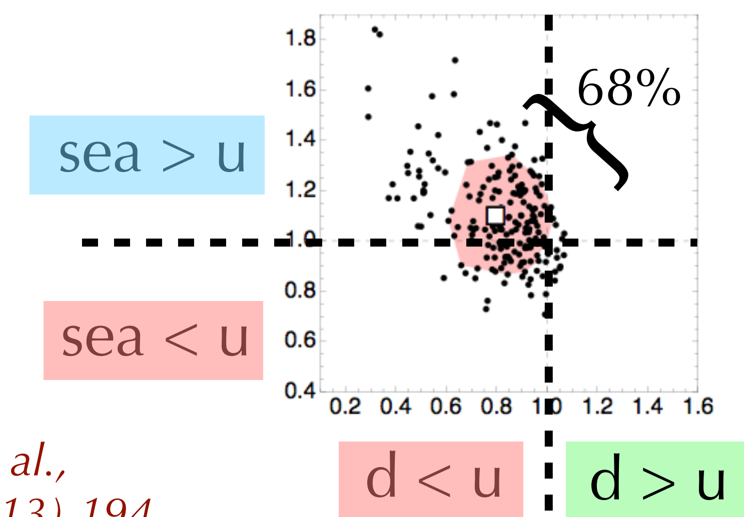
EIC explores larger phase space

- test universality
- test evolution of TMD with Q^2
- study matching with pQCD at $P_{hT}^2 \sim Q^2$
- test factorization e−p ↔ p−p
- gluon TMD from e p → jet jet X

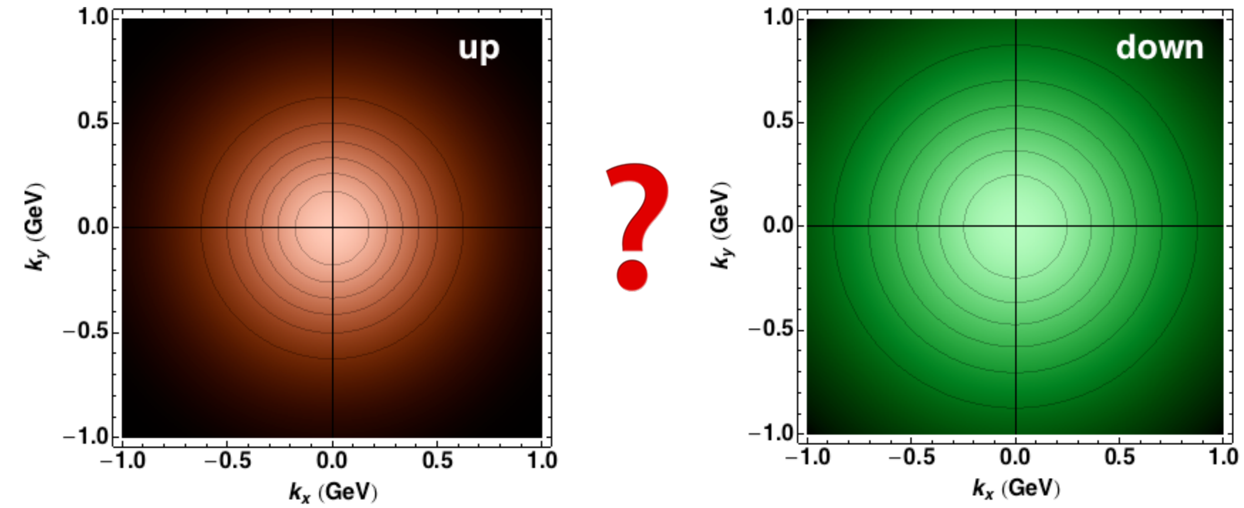


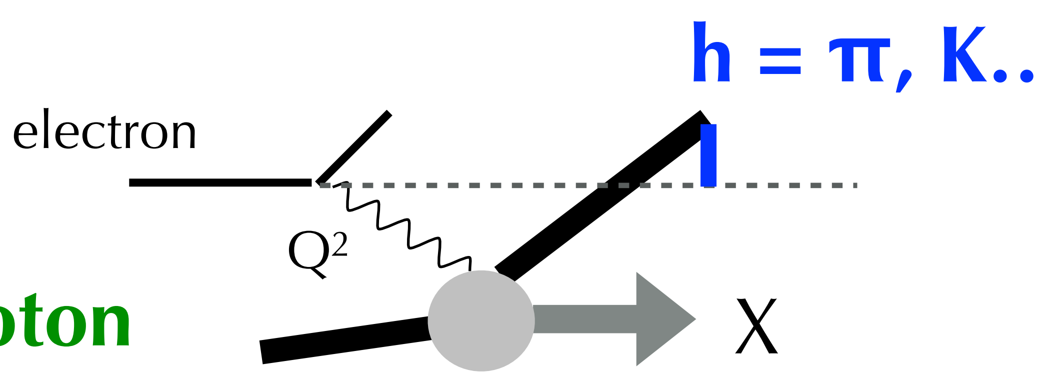
flavor dependence of $k_\perp$-distribution

hints of flavor dependence
from fit of HERMES data



Bacchetta et al.,
*JHEP **1311** (13) 194*





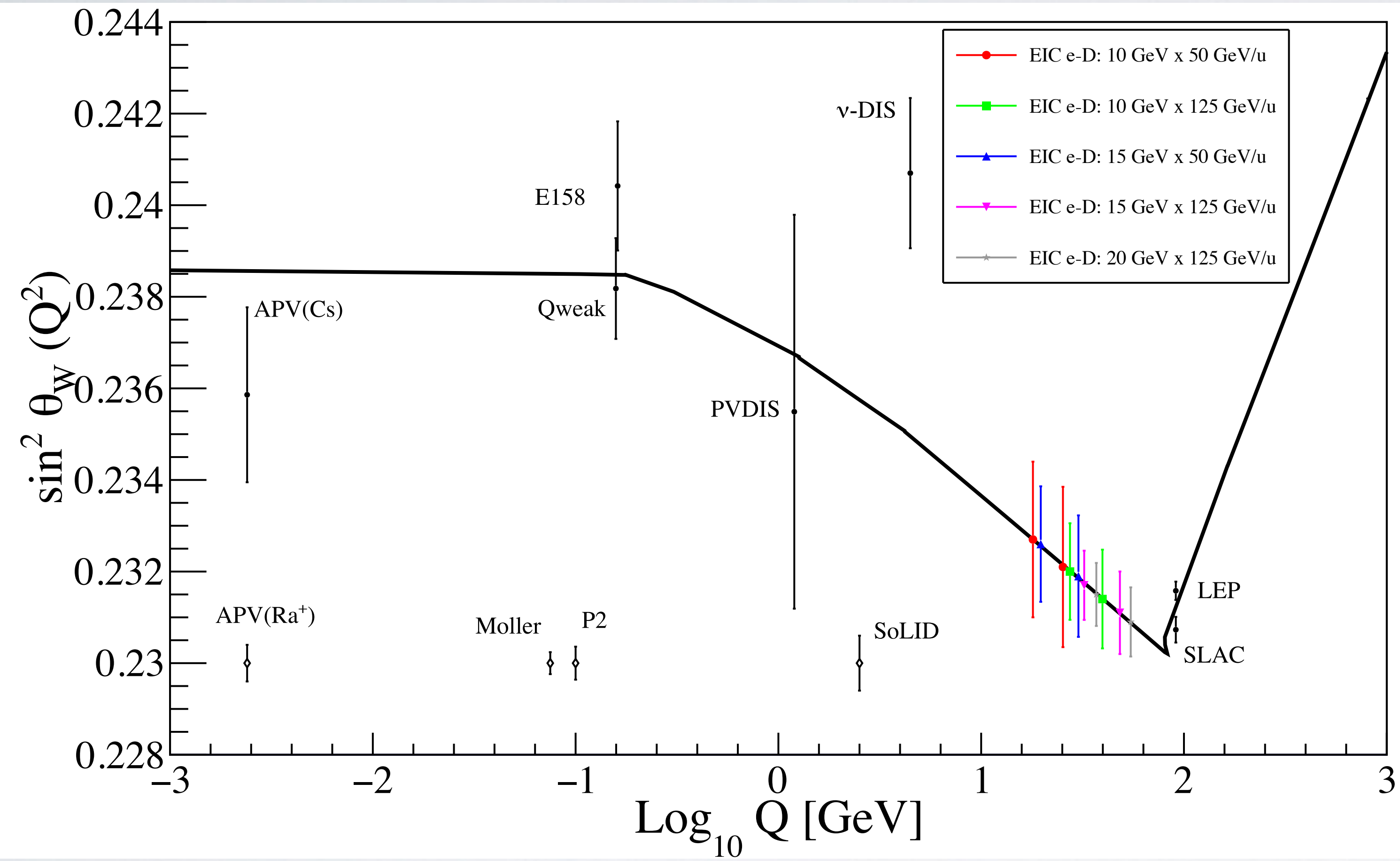
EIC disentangle flavors
with **different targets**
and **hadron species**

proton
deuteron
^{3}He…

can affect extraction of $\mathbf{m_W}$ from q_T distribution of W decay at LHC
if precision ≲ 10 MeV. Is it $W^+ \neq W^-$?

*Bacchetta et al., **PLB** 788 (18)*

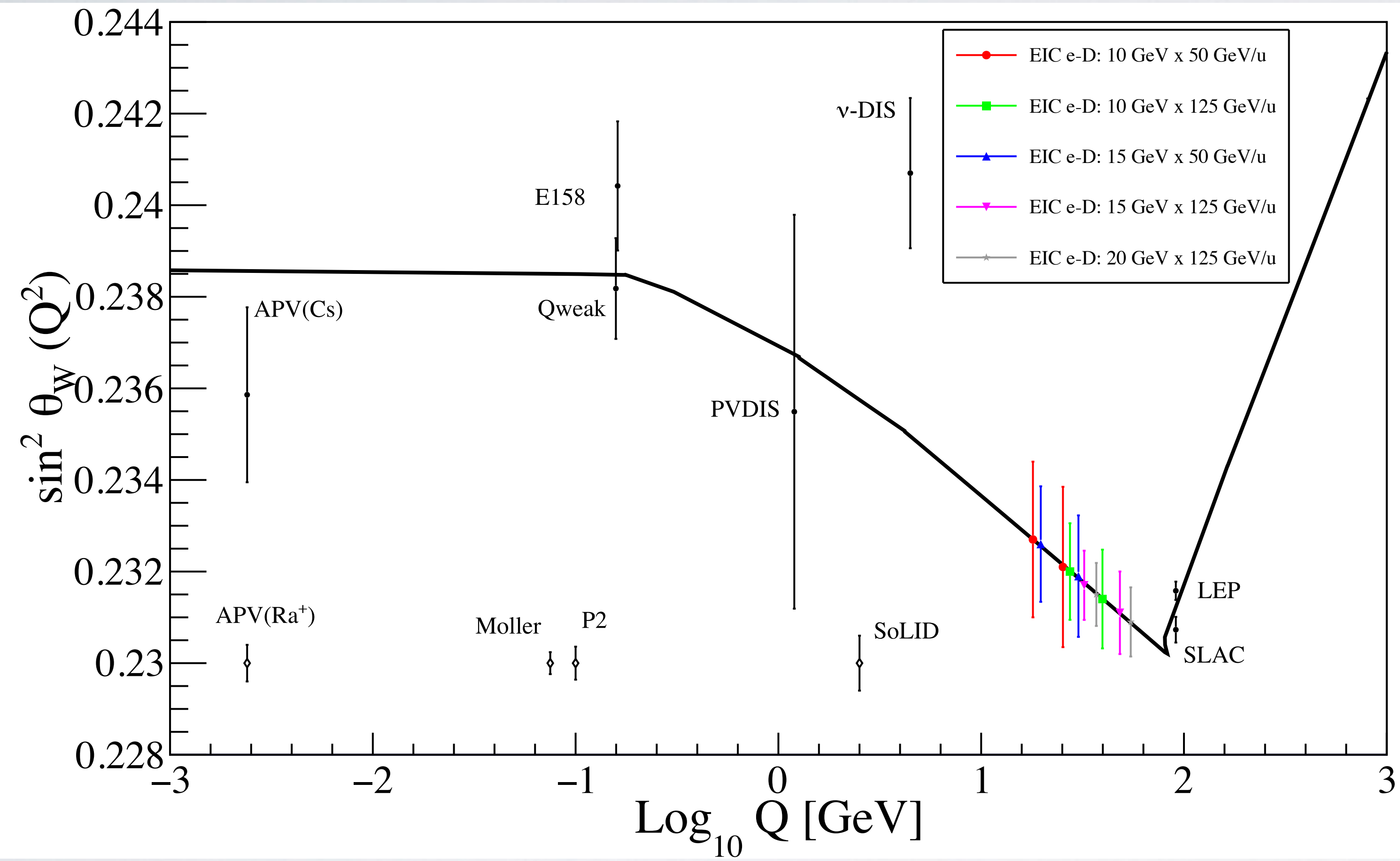
EIC for precision EW physics



weak mixing angle

(*Y.X. Zhao et al., Eur. Phys. J. A53 (2017) 55*)

EIC for precision EW physics

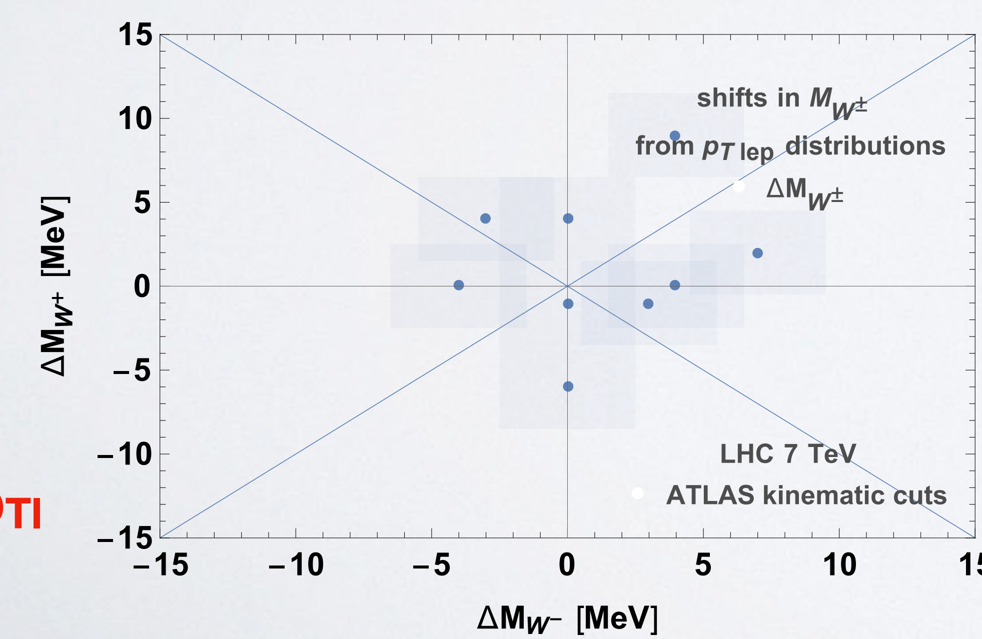


weak mixing angle

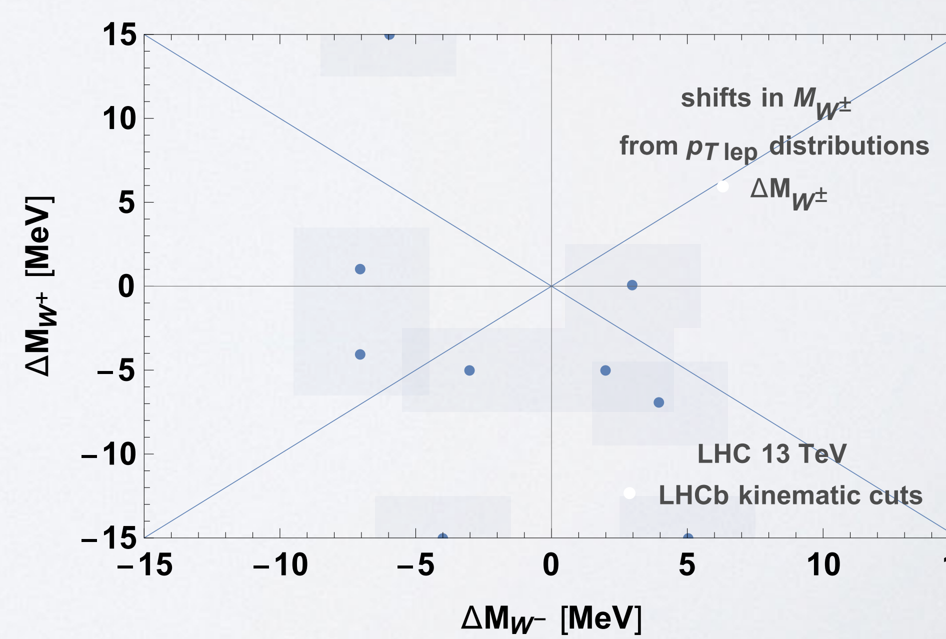
(*Y.X. Zhao et al., Eur. Phys. J. A53 (2017) 55*)

W mass

(Bacchetta *et al., Phys. Lett. B 788 (2018) 542*)



ATLAS p_{Tl}



LHCb p_{Tl}

Generalised Parton Distributions

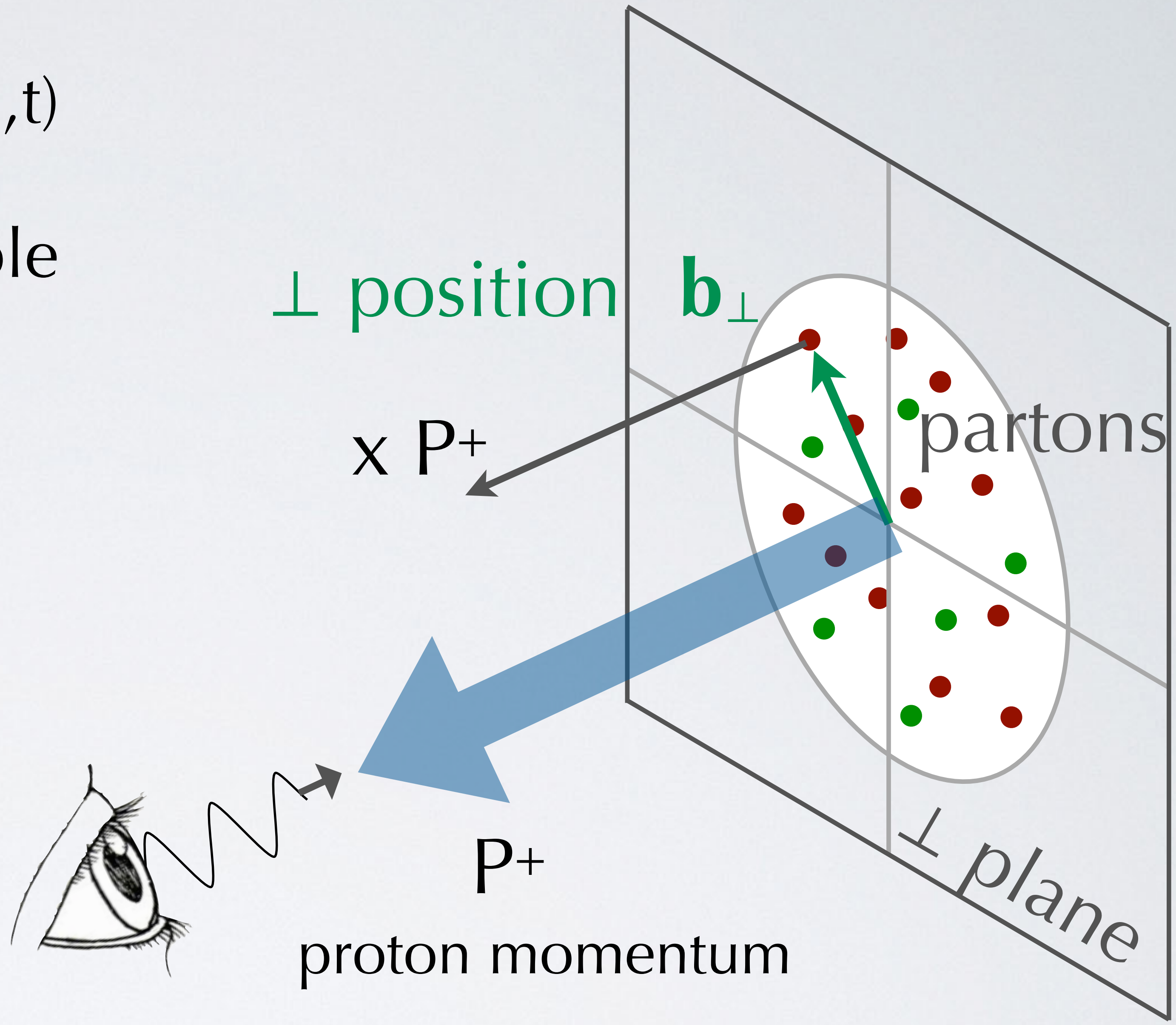
$\rho(x,\mathbf{b}_\perp) \xleftrightarrow[\text{Transf.}]{\text{Fourier}}$ **GPD** $(x,\xi=0,t)$

$(x,\mathbf{b}_\perp)$ dependence not accessible in cross section

$\boxed{\rho(x,\mathbf{b}_\perp)}$

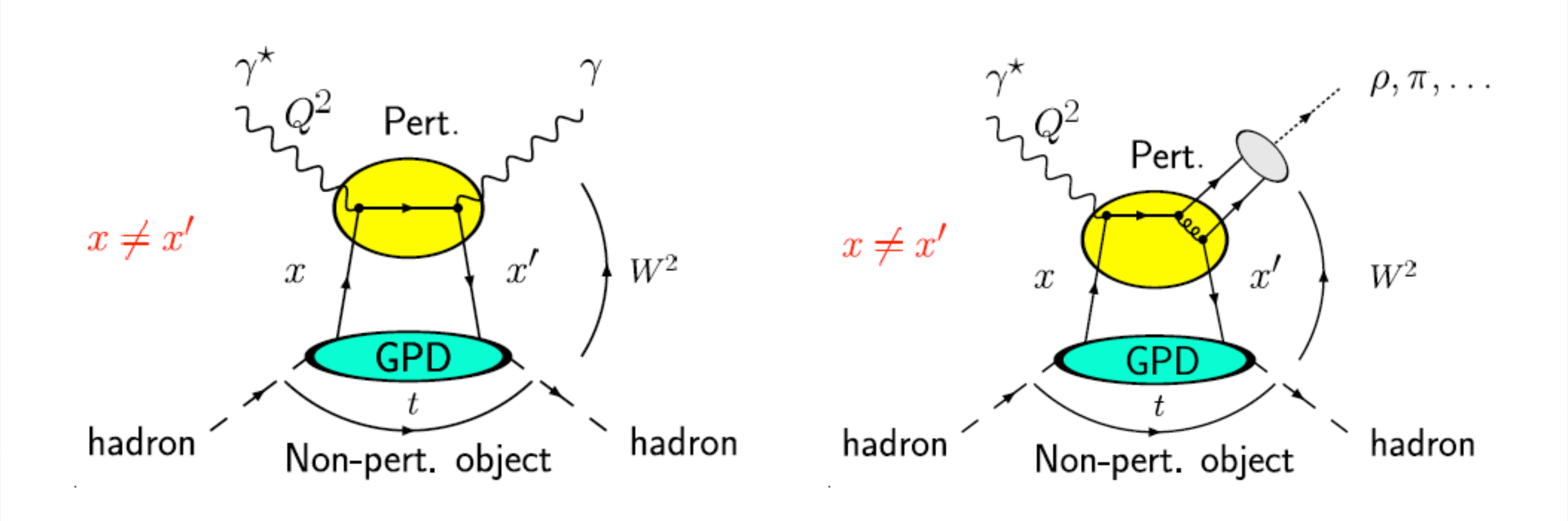
$\boxed{\mathbf{b}_\perp \not\leftrightarrow \mathbf{k}_\perp}$

ρ independent from TMD



localize partons inside hadron
baseline info to study correlations
GPD / ρ → MPI

How to measure GPDs



- accessible in exclusive reactions
- factorization for large Q^2, $|t| << Q^2$, W^2
- depend on 3 variables: x, ξ, t
- 8 independent GPDs:
  real functions depending on the parton and target polarization

Compton Form Factors

$$\mathrm{Im}\,\mathcal{H}(\xi, t) \stackrel{\mathrm{LO}}{=} H(\xi, \xi, t)$$

$$\mathrm{Re}\,\mathcal{H}(\xi, t) \stackrel{\mathrm{LO}}{=} \mathcal{P} \int_{-1}^{1} \mathrm{d}x\ \mathrm{H}(x, \xi, t) \frac{1}{x-\xi}$$

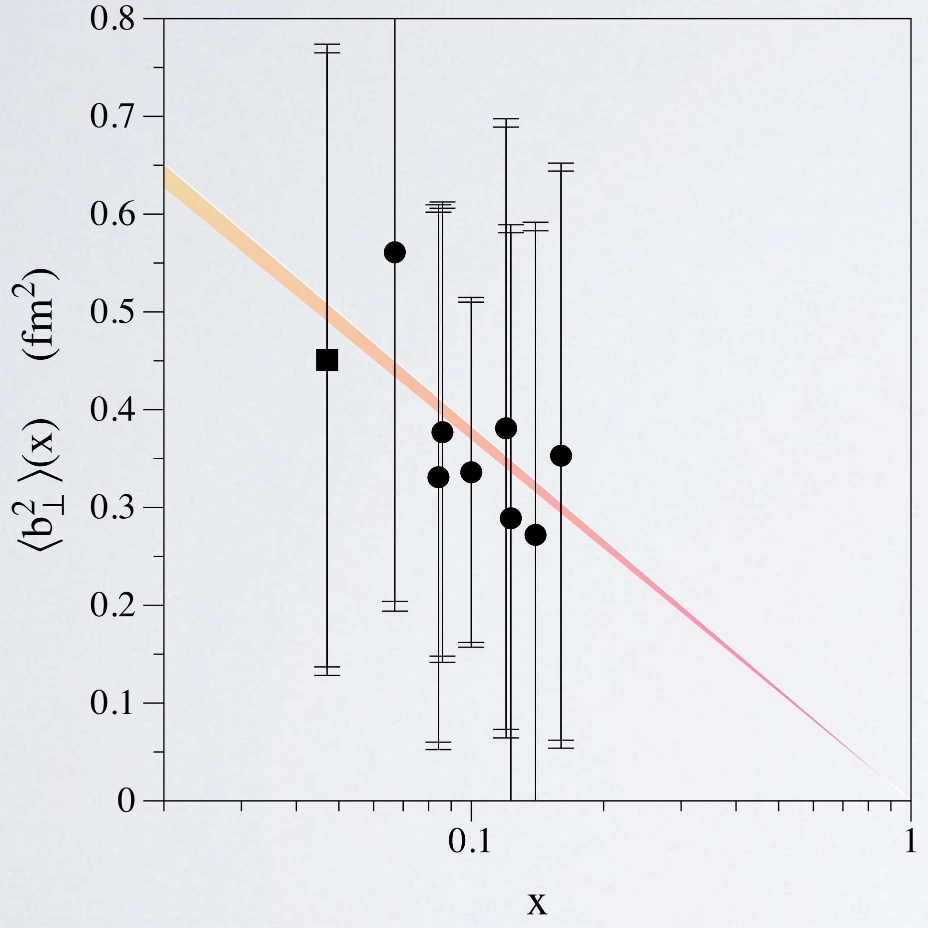
Transverse square radius

$$H(x,0,\vec{b}_\perp) = \int_{-\infty}^{+\infty} \mathrm{d}^2\vec{\Delta}_\perp\, H(x,0,t)\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \longrightarrow \langle \vec{b}_\perp^{\,2}(x)\rangle = \frac{\int \mathrm{d}^2\vec{b}_\perp\, \vec{b}_\perp^{\,2}\, H(x,0,b_\perp)}{\int \mathrm{d}^2\vec{b}_\perp H(x,0,b_\perp)}$$

$(t = -\vec{\Delta}_\perp^2)$ $\quad \xi = 0$ extrapolation from data

x-dependent transverse squared radius

DVCS data from CLAS and HERMES



The errors are large,
but slowly we are getting some 3D information

Dupré et al., PRD95(2017)011501

Transverse square radius

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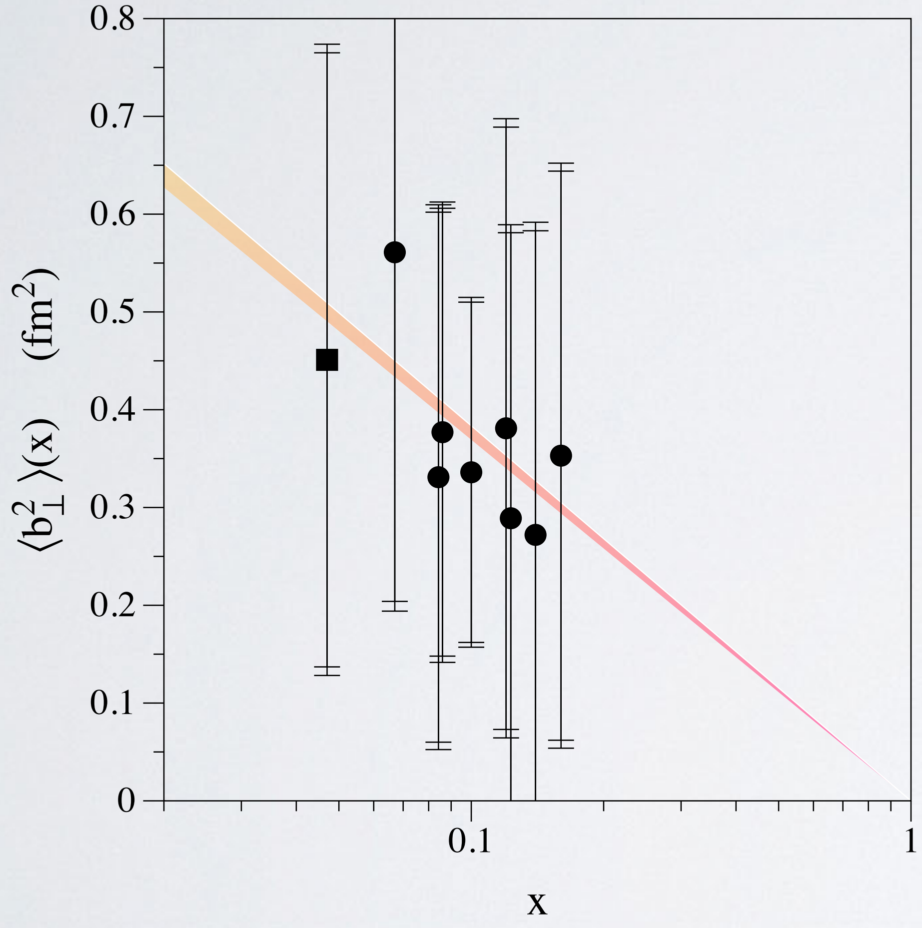
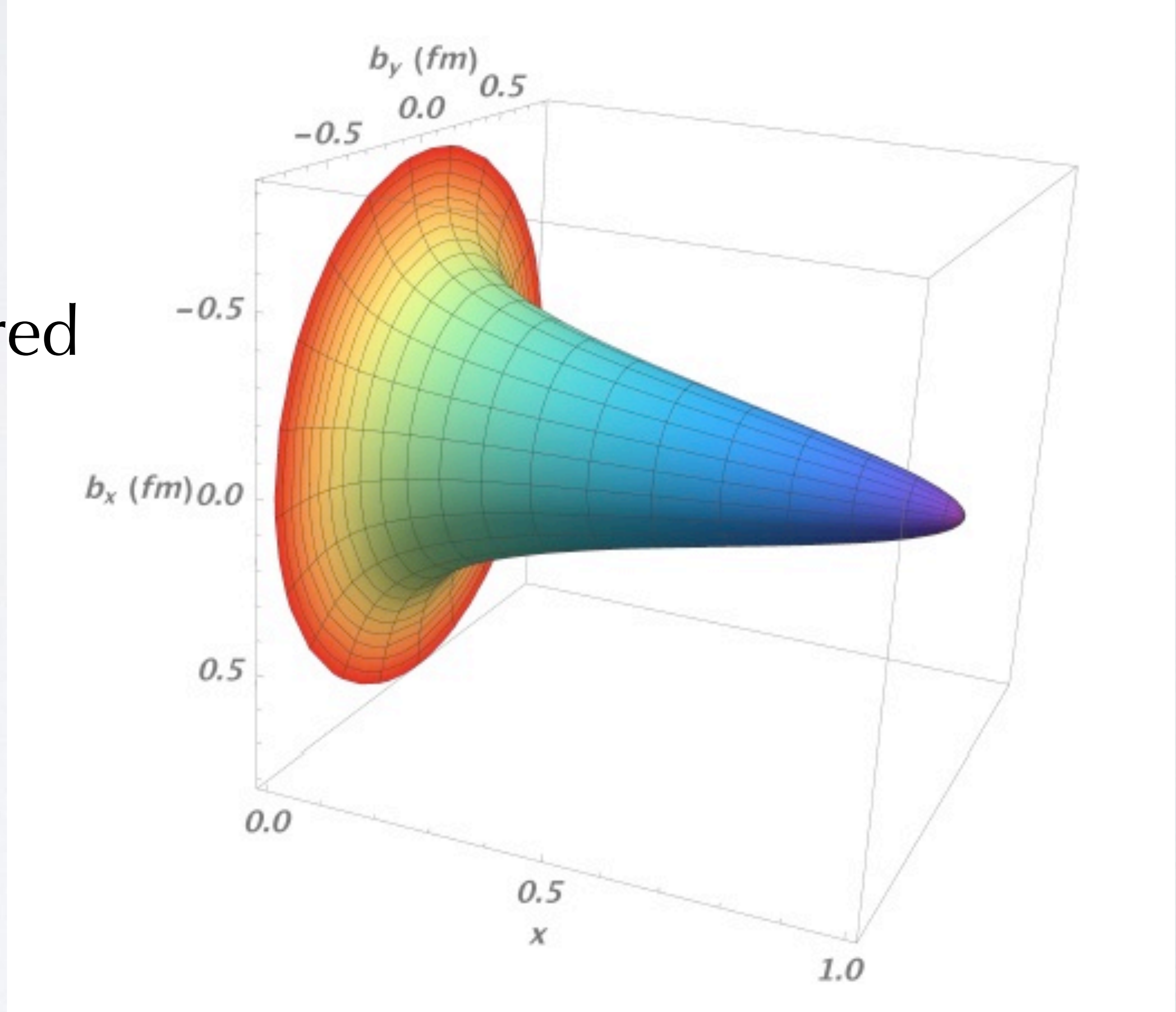


extrapolating
in the unmeasured
x-range



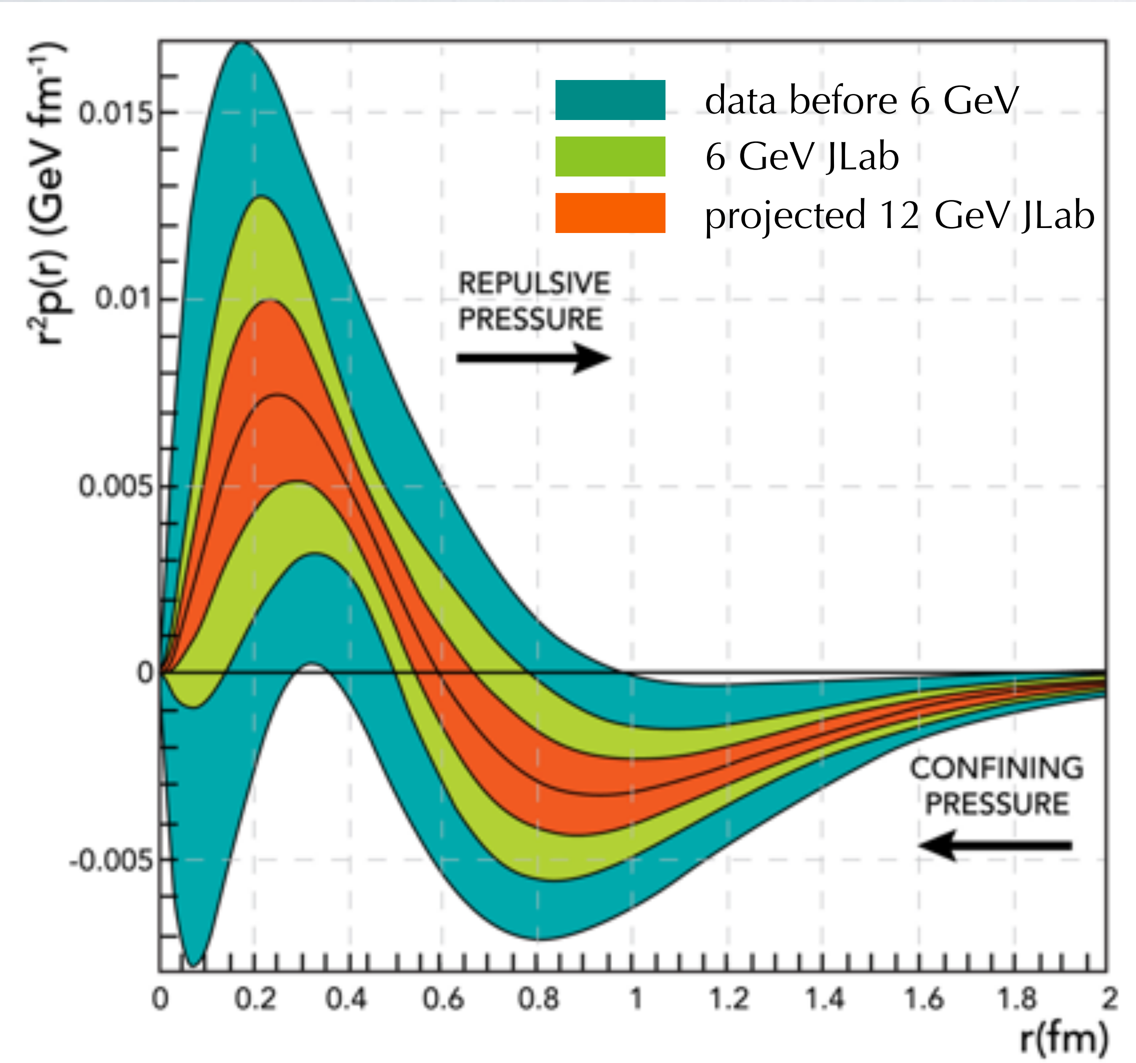
As x $\longrightarrow$ 1, the active parton carries all the momentum
and represents the centre of momentum

Dupré et al., PRD95(2017)011501

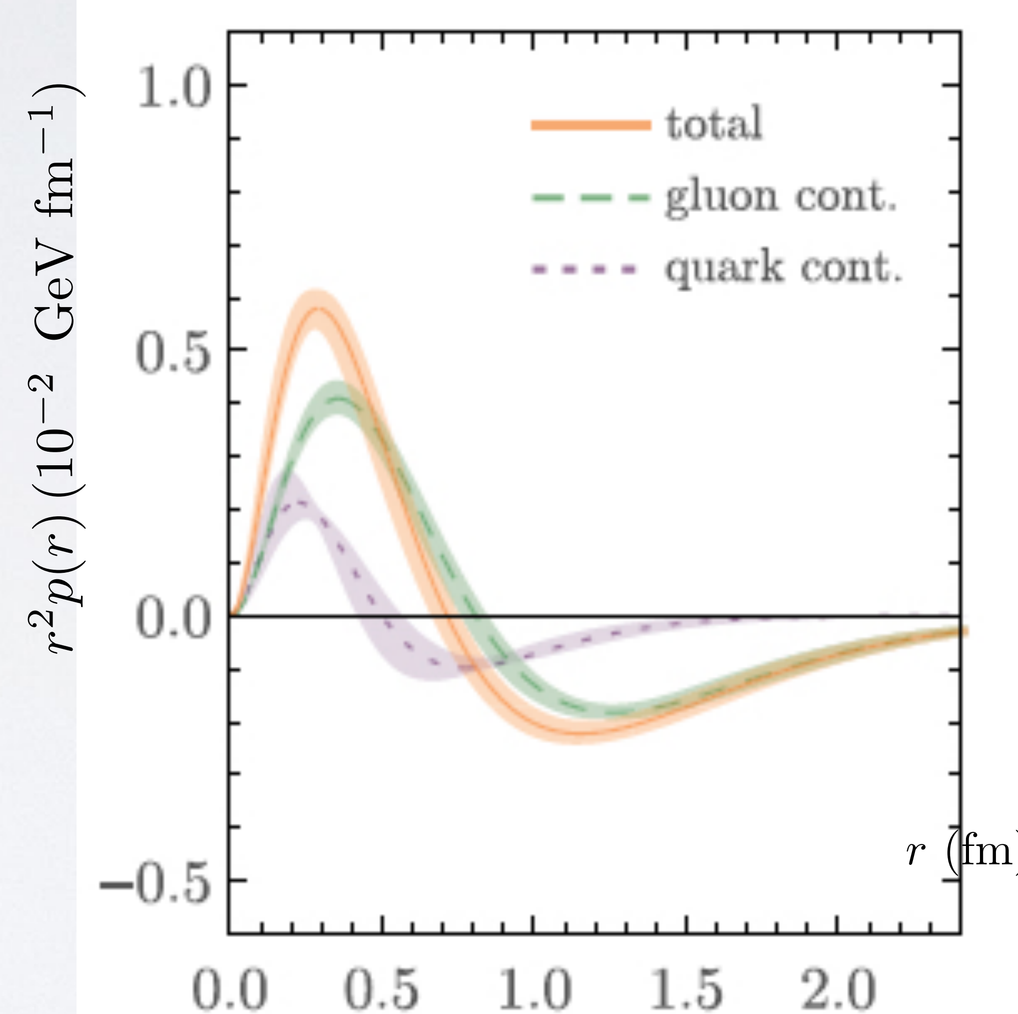
Radial pressure distribution

polynomiality of GPDs $$\int dx\, x\, H(x,\xi,t) = M_2(t) + \frac{4}{5} d_1(t)\, \xi^2$$

$$\tilde{D}(r) \xleftrightarrow{\text{FT}} D(t) \qquad r^2 p(r) = \frac{1}{3}\frac{d}{dr} r^2 \frac{d}{dr} \tilde{D}(r)$$



Girod, Elouadrhiri,Burkert, Nature 557 (2018) 7705



Shanahan, Detmold, PRL122 (2019) 072003

Necessary to verify model assumptions in the exp extraction with more data coming from JLab, COMPASS and EIC

Kumericki, Nature 570 (2019) 7759

Orbital angular momentum from GPDs

Ji's sum rule $$\frac{1}{2}\int dx\, x\left[H(x,0,0)+E(x,0,0)\right]=J$$

X. Ji, P.R.L. ***78*** *(97)*

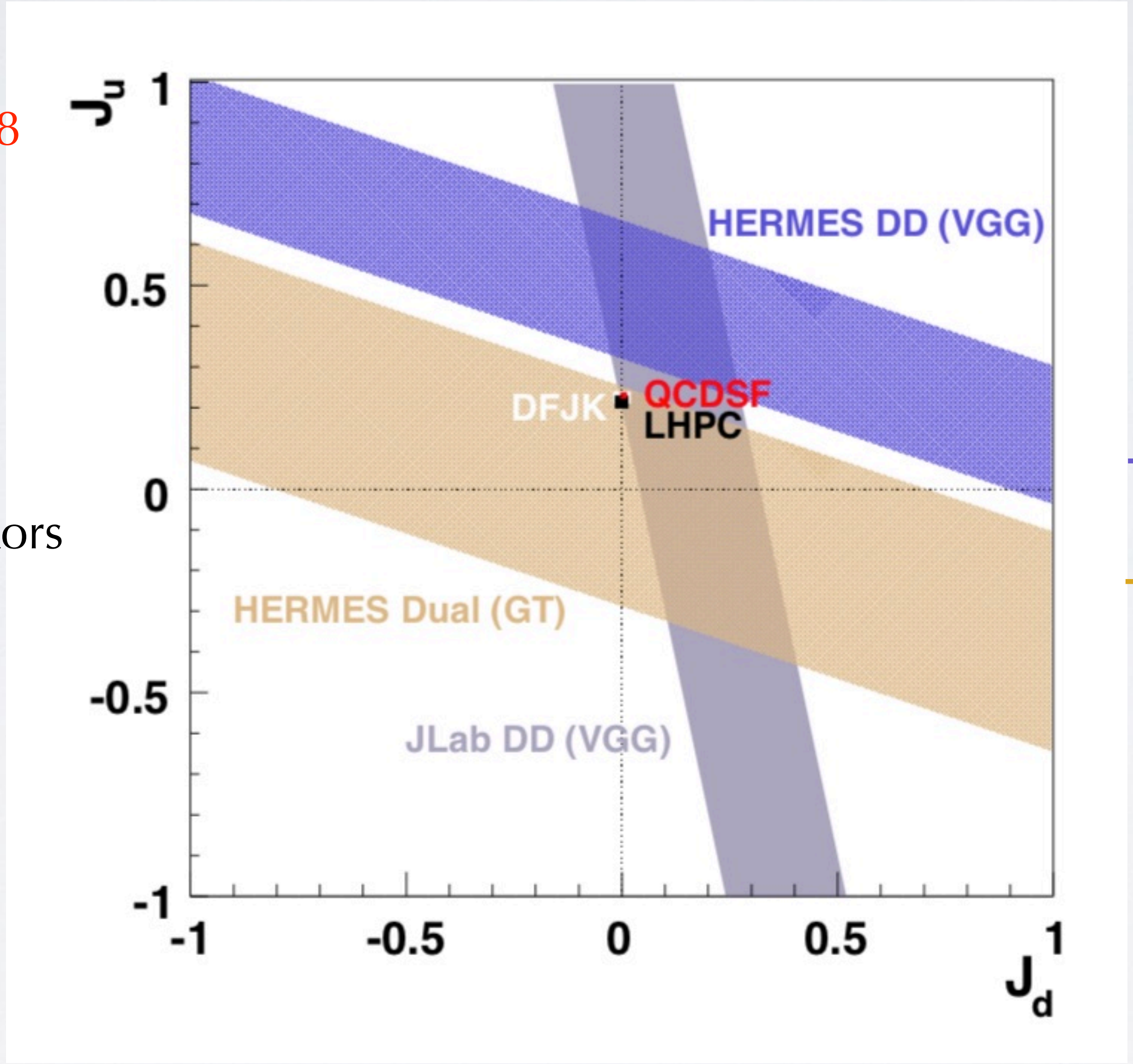
Lattice results

QCDSF: PoS (Lattice 2007) 158

LHPC: PRD77 (2008) 094502

GPDs extracted from form factors

DFJK, EPJC39 (2005) 1



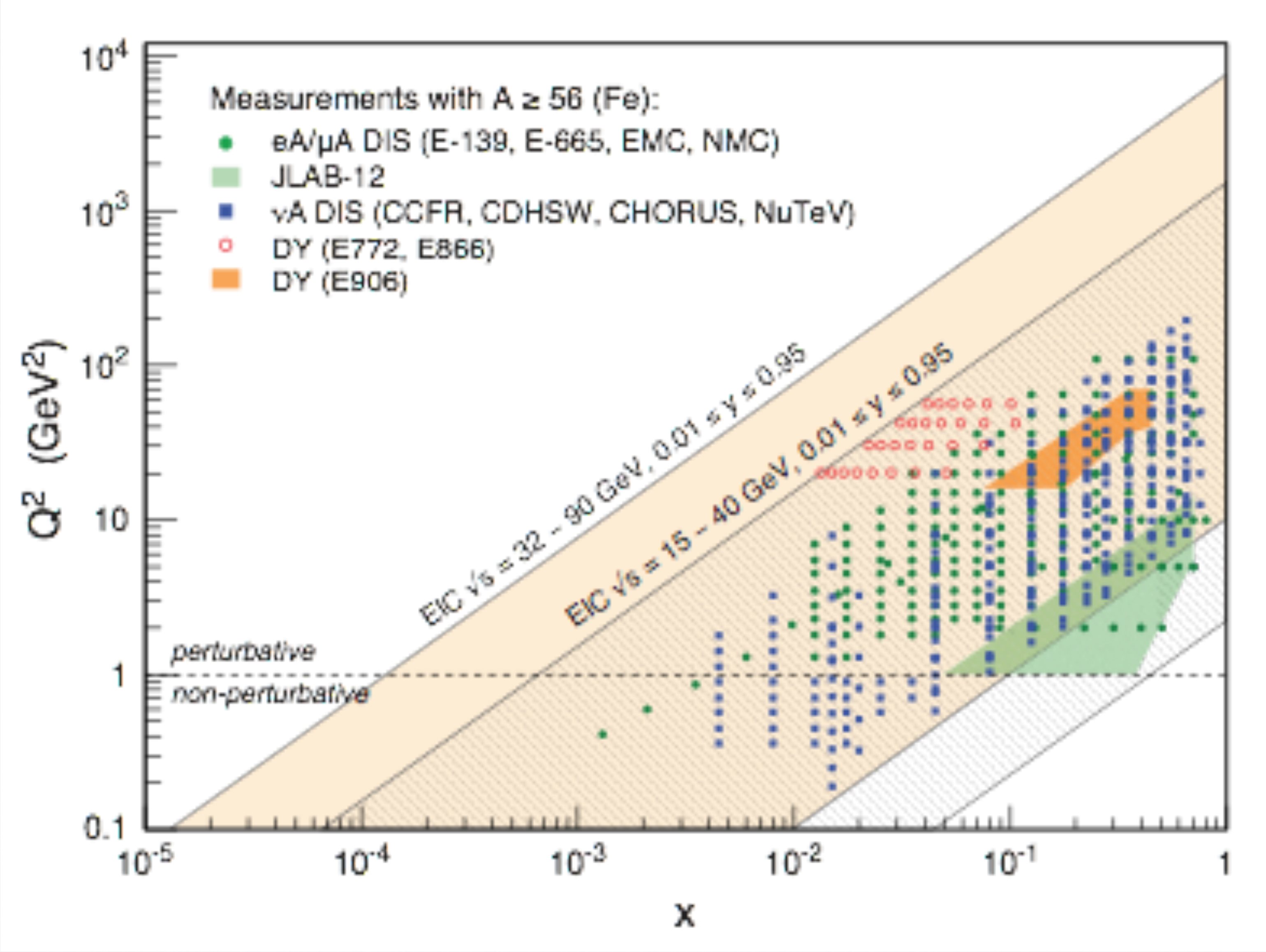
extractions from HERMES data using two different models

JLab Hall A, Phys. Rev. Lett. 99 (2007) 242501

Hermes Coll., JHEP 06 (2008) 066

Problem of model dependent extractions

QCD in nuclei

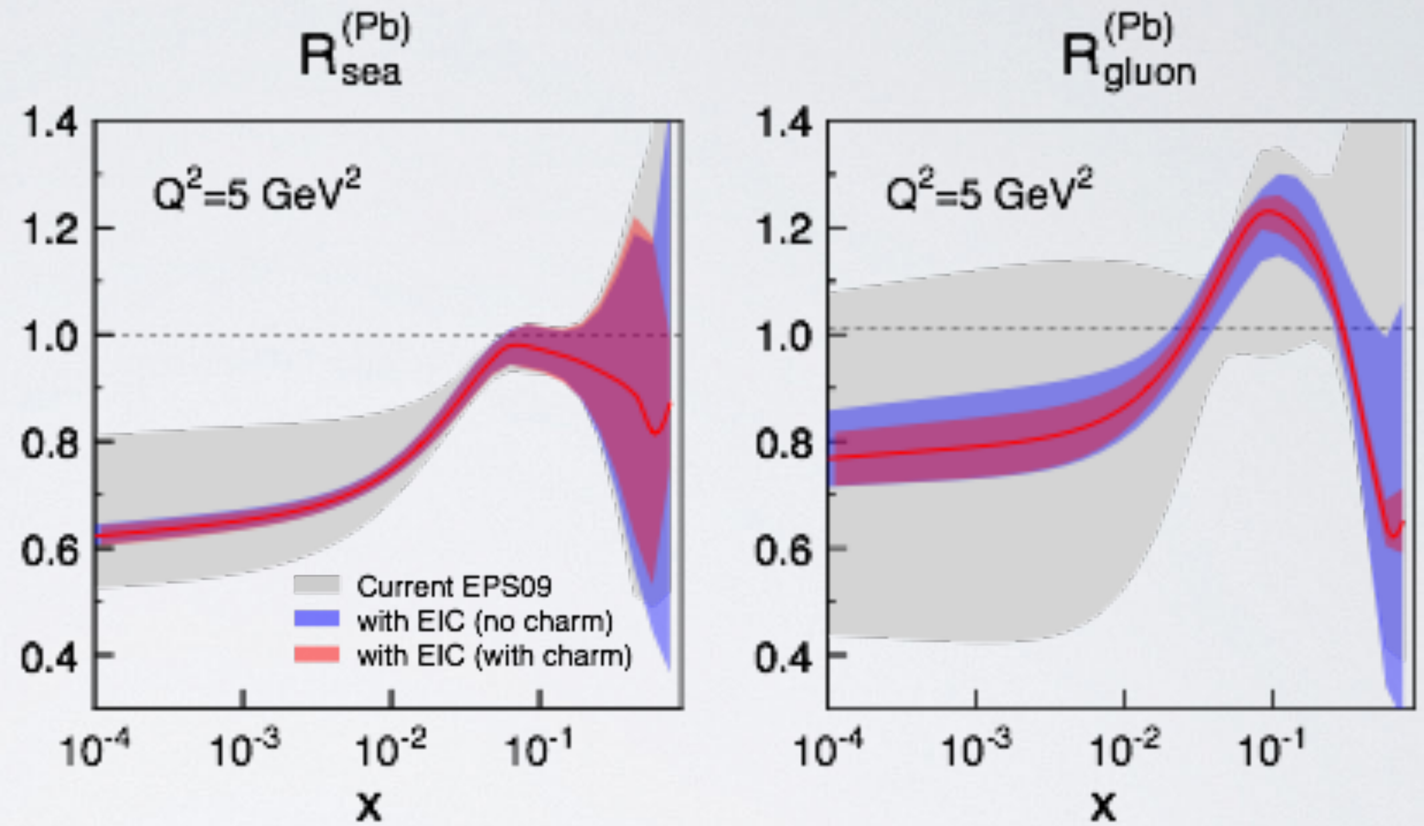


nuclear PDF

Simulations of DIS $F_{2,L}(x,Q^2)$ at EIC kinematics

$$R = \frac{\text{PDF (Pb)}}{\text{PDF (p)}}$$

nuclear modification factor for partons



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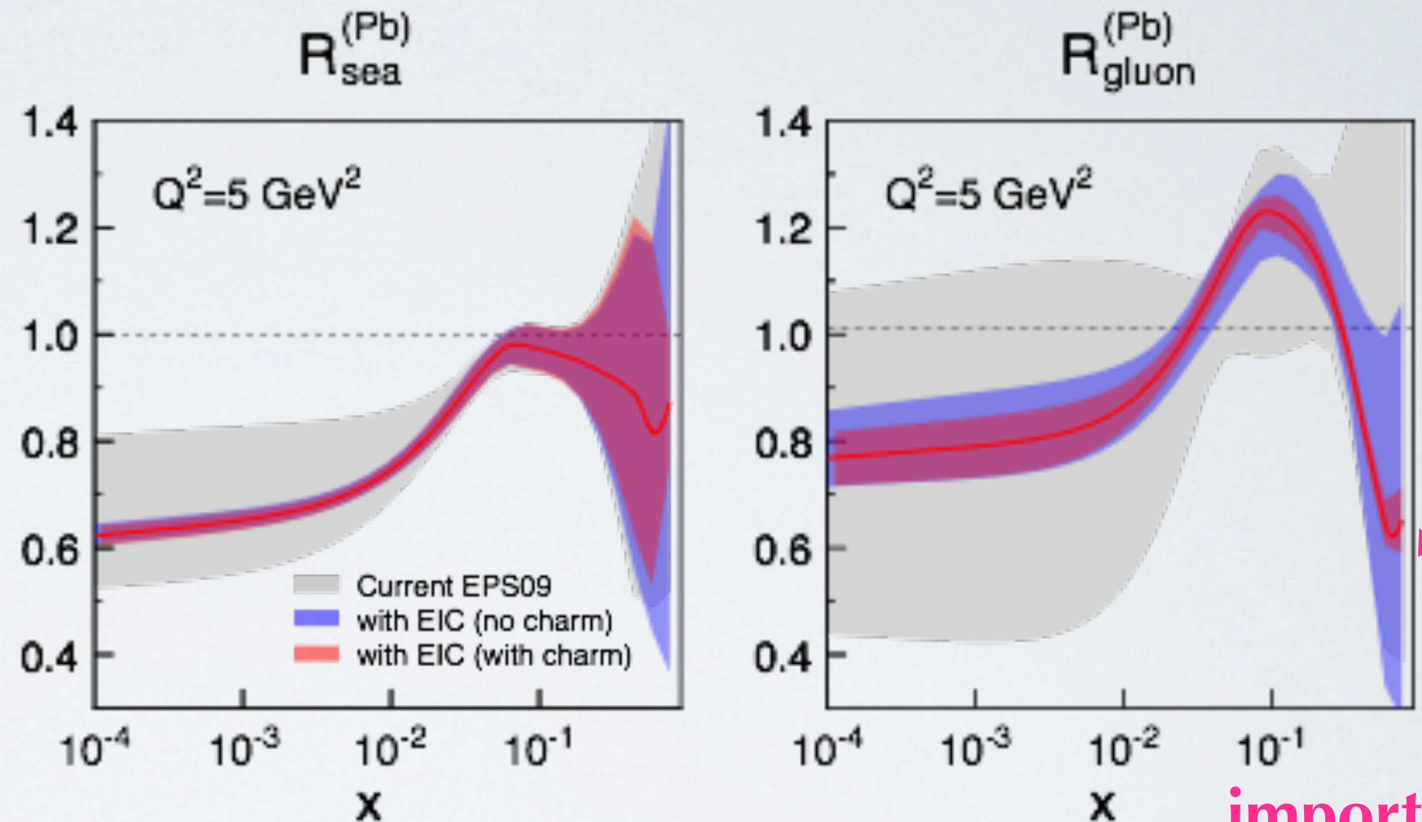

importance of F_2^{charm} for high-x gluon

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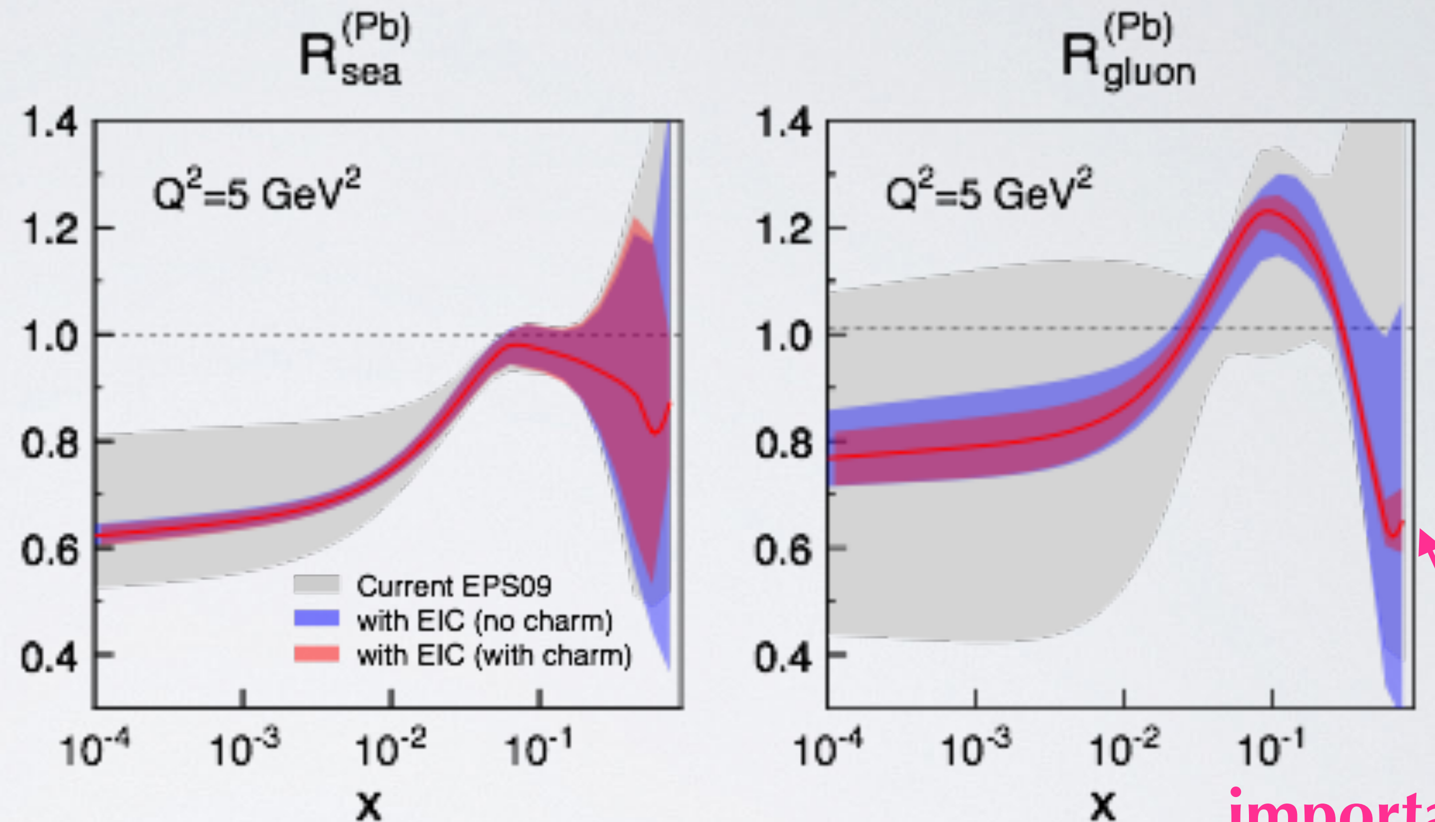
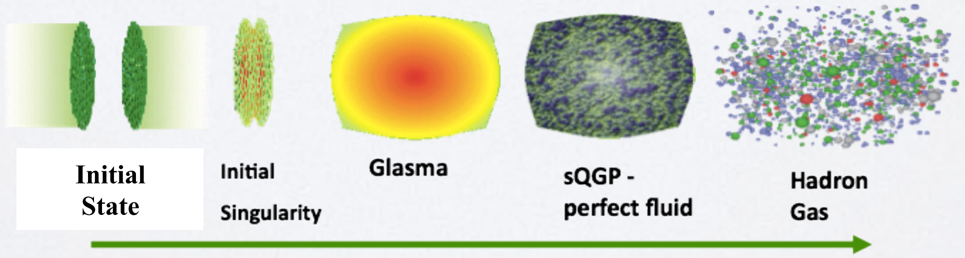


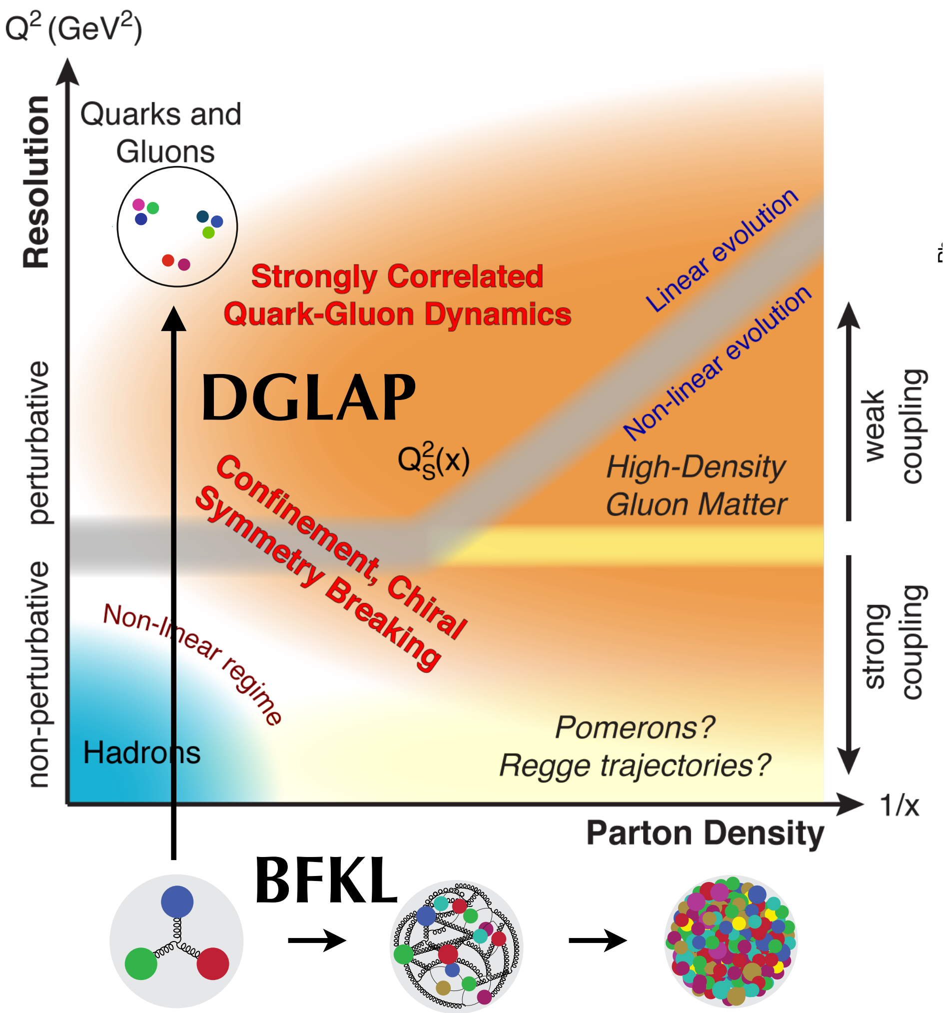
importance of F_2^{charm} for high-x gluon

- **complementary to LHC data**:
  - test universality of nPDF
  - reduce QCD uncertainties in BSM searches
  - energy loss (jet quenching) in eA vs. AA: QGP vs. gluon saturation



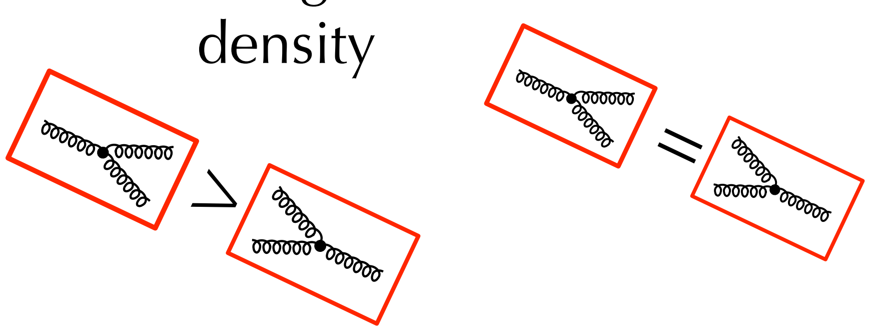
Saturation at high nuclear density

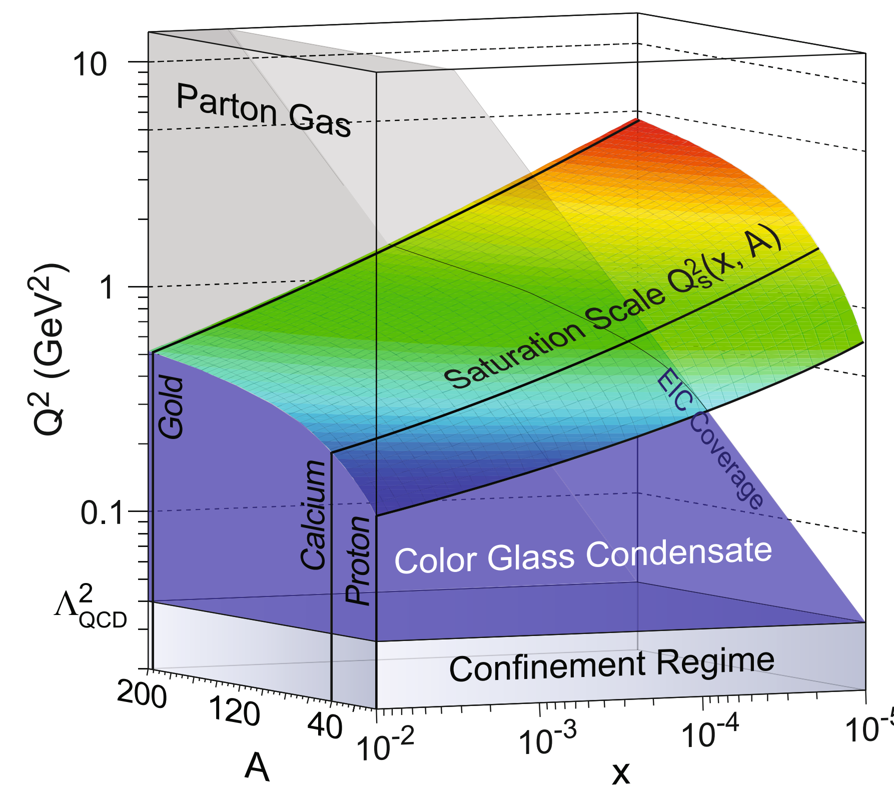
Where is onset of high-density regime?



rise of gluon density

saturation





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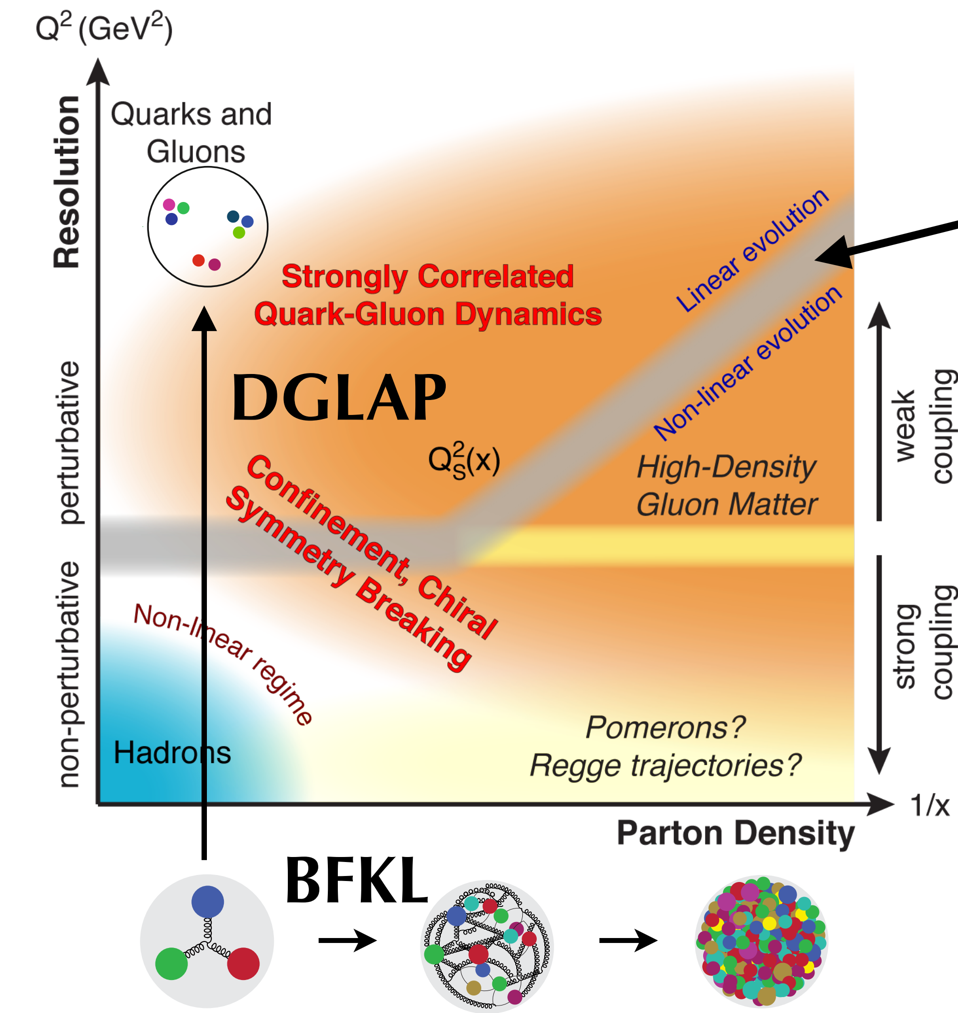
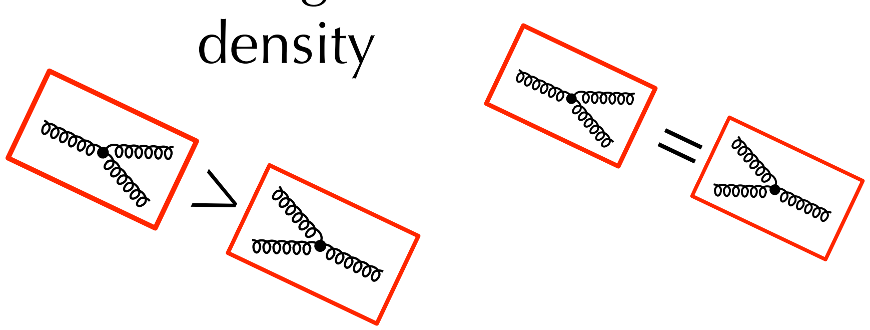


saturation scale
$Q_s(x,A) \gg \Lambda_{QCD}$

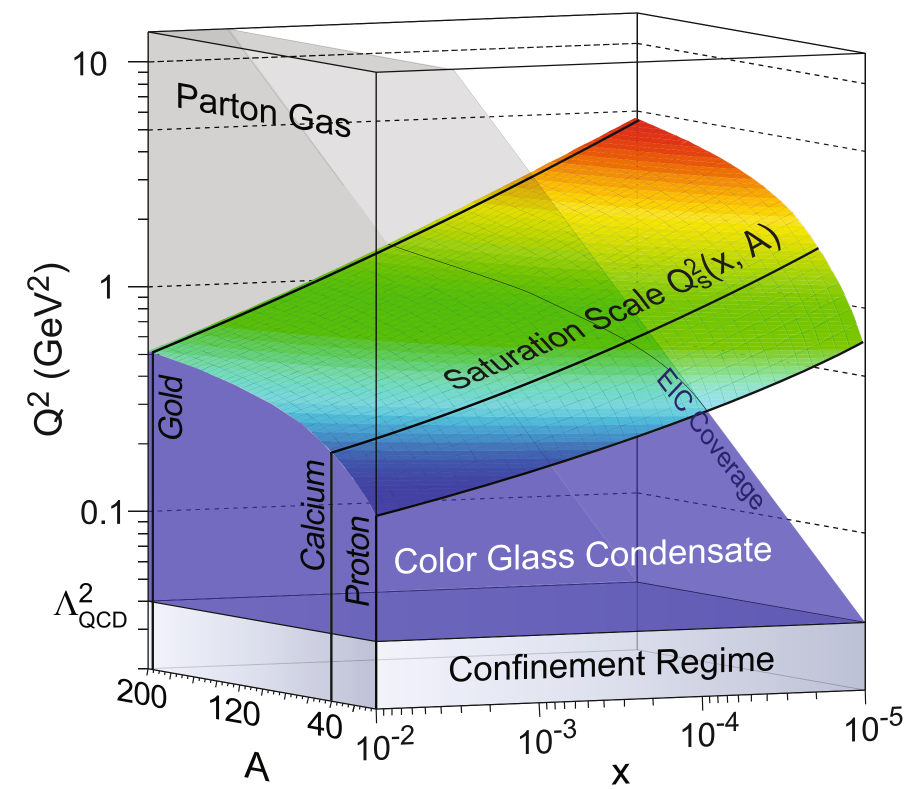
rise of gluon density

saturation



Color Glass Condensate (CGC)

Iancu, Leonidov, McLerran, P.L. ***B510*** *(01) 133*



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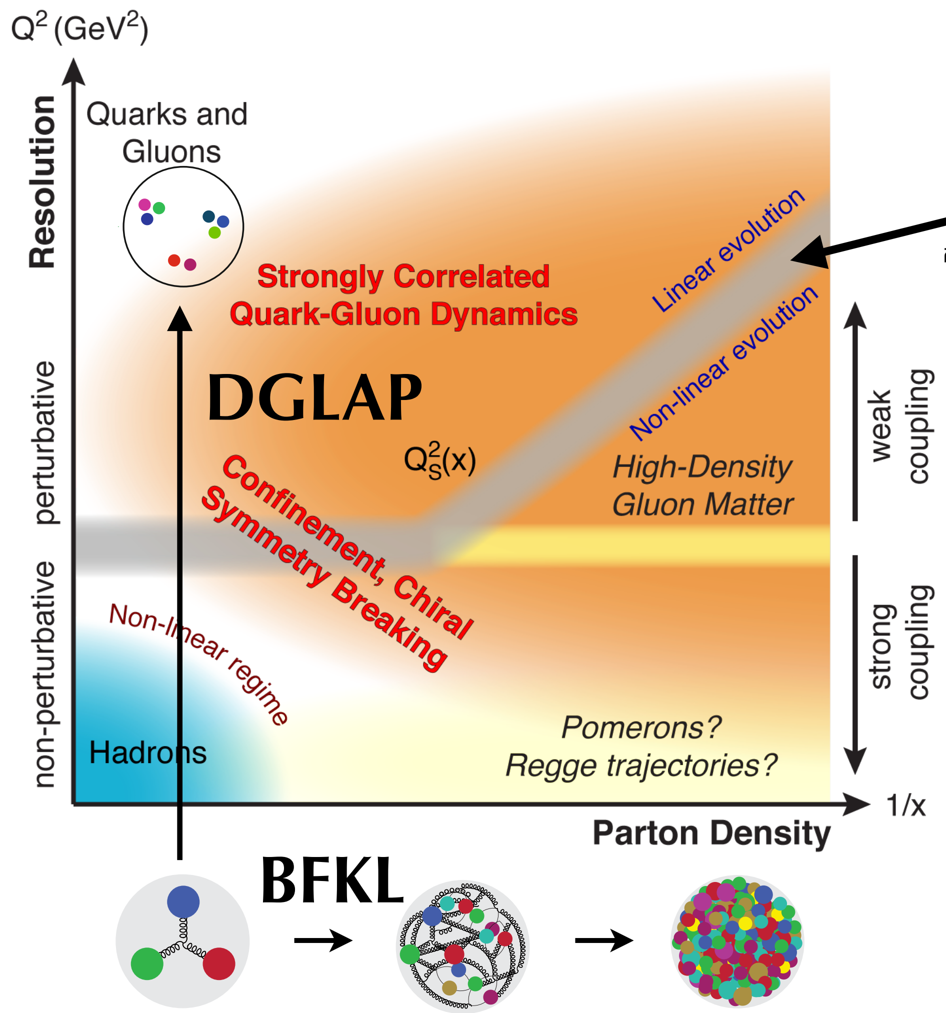

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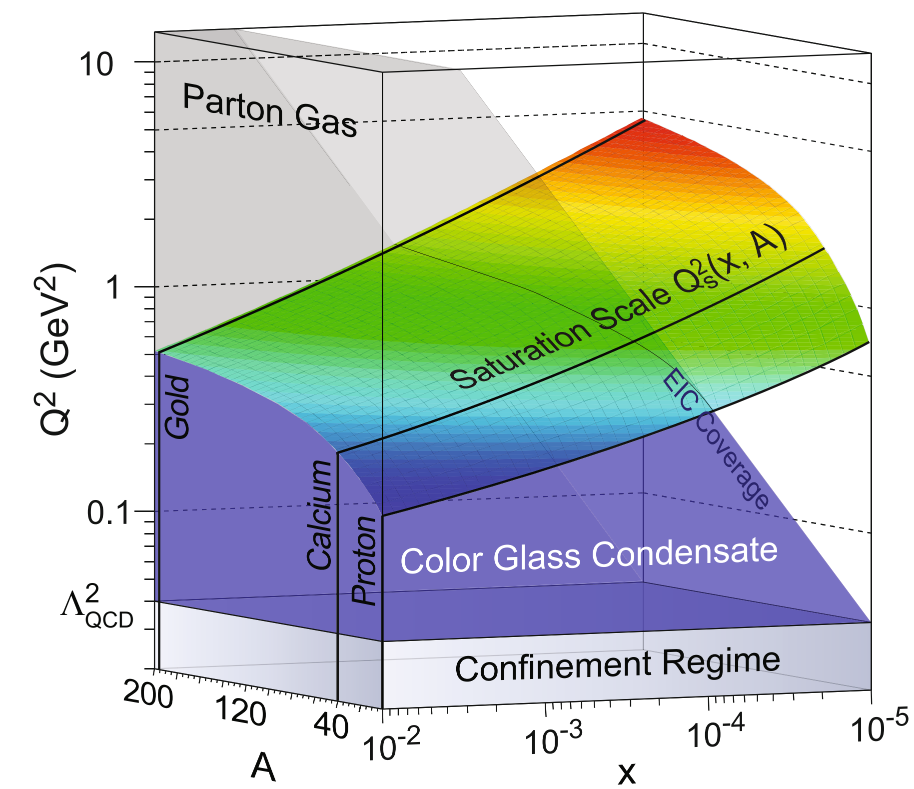
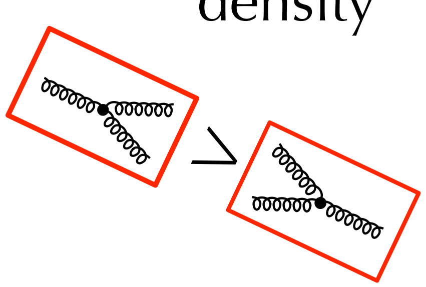
Color Glass Condensate (CGC)

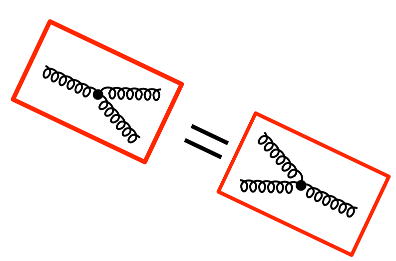
*Iancu, Leonidov, McLerran, P.L. **B510** (01) 133*



rise of gluon density

saturation





Advantage of having ion beams:
same Q_s reached for higher x / lower √s

Saturation scale

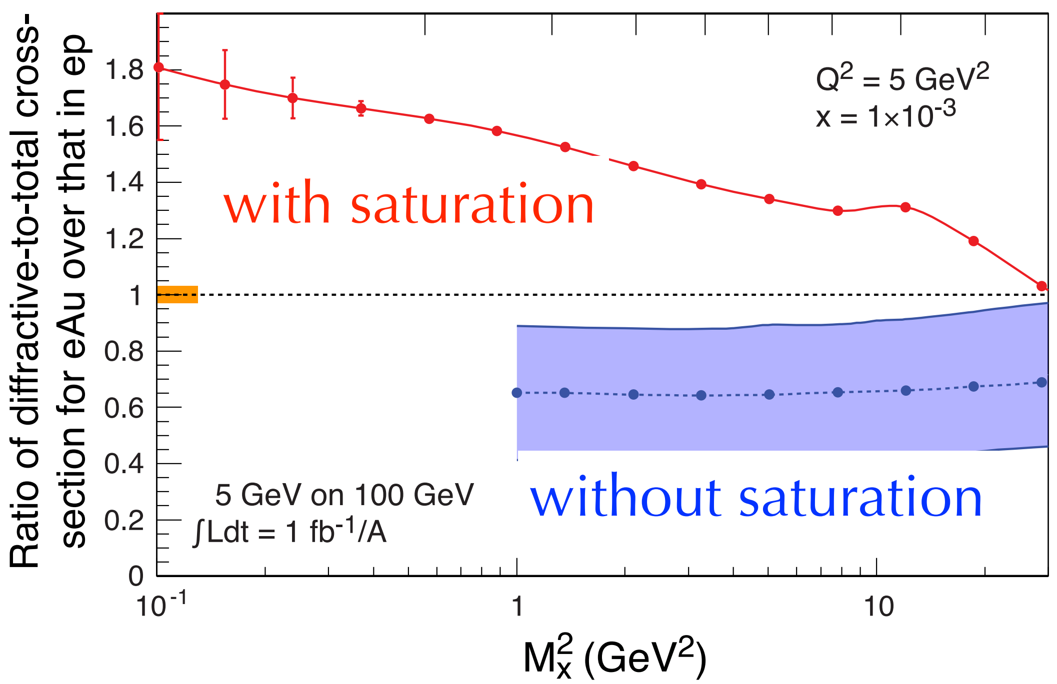
$$[Q_s(x,A)]^2 \sim \left(\frac{A}{x}\right)^{\frac{1}{3}}$$

EIC can “intercept” $Q_s(x,A)$

Importance of diffraction

Diffraction : a powerful probe of onset of QCD

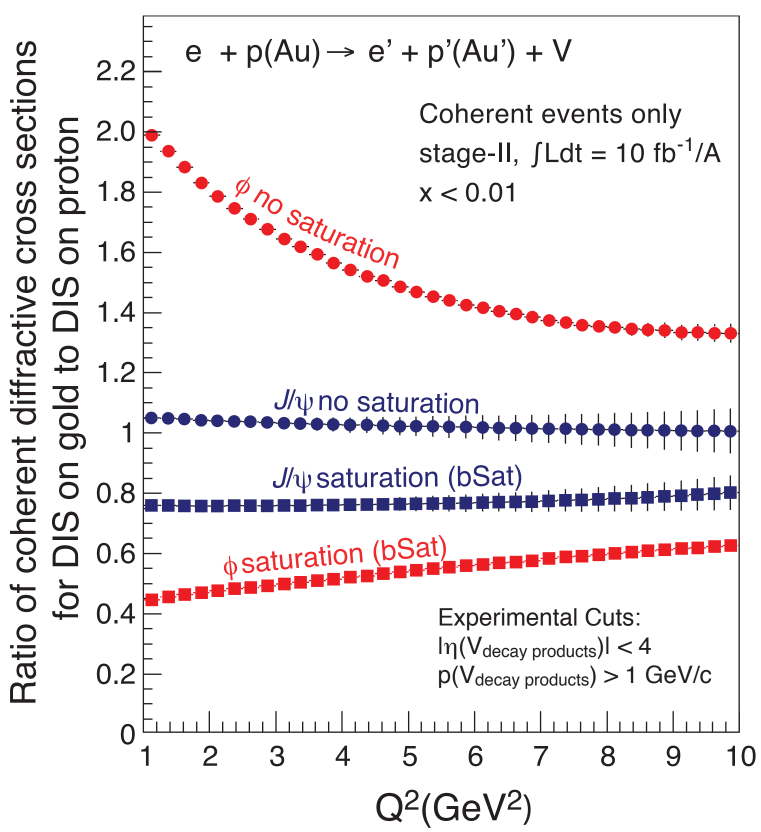
$\sigma_{diff} \sim [g(x,Q^2)]^2$ non-linear dynamics in saturation



$$\frac{\sigma_{diff}\text{ (e-Au)}}{\sigma_{tot}\text{ (e-Au)}} \Big/ \frac{\sigma_{diff}\text{ (e-p)}}{\sigma_{tot}\text{ (e-p)}}$$

Study the saturation limit

→ proximity to "black body" limit in DIS



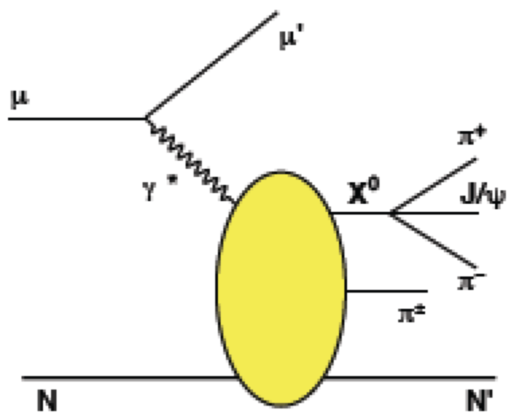
diffractive vector meson production

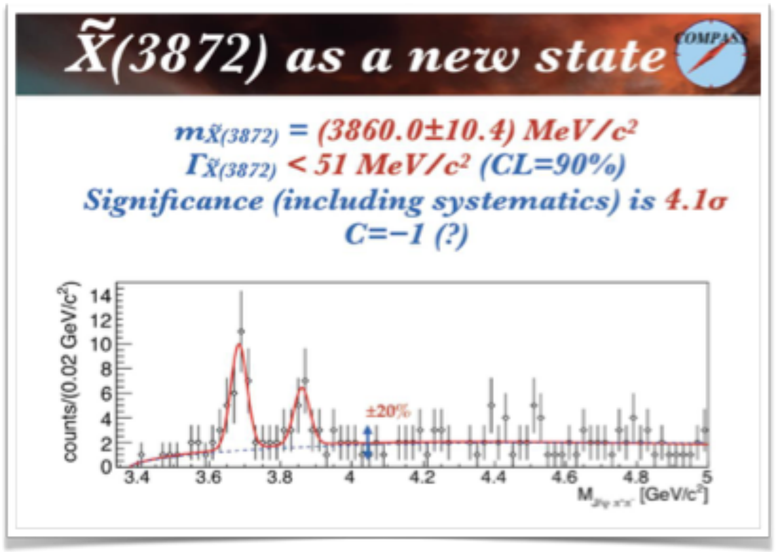
σ_{diff}^{V} (Au) / σ_{diff}^{V} (p)

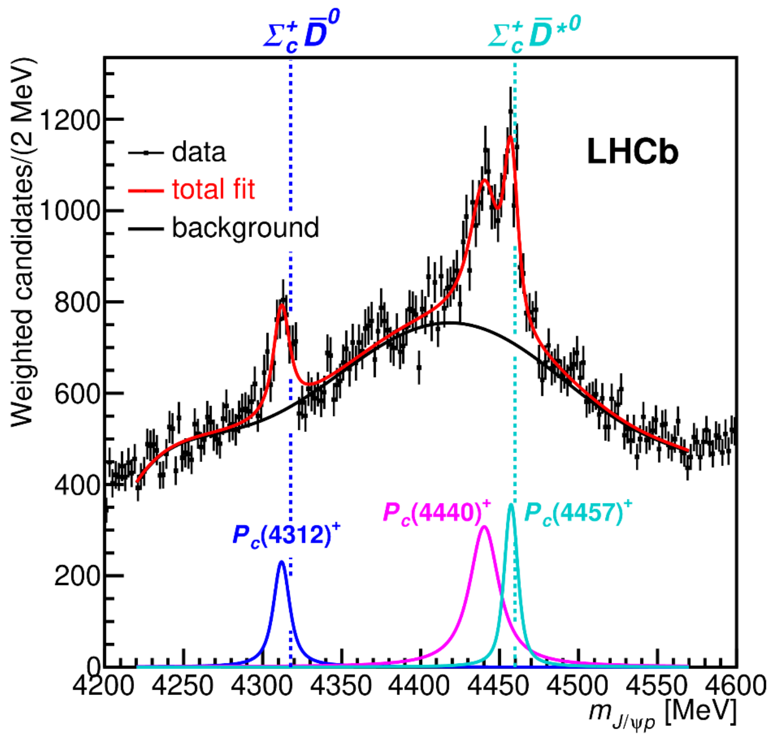
Q^2 dependence of saturation

Hadron spectroscopy @ EIC

New multiquark states to confirm:
X(3872) and ΣD pentaquark







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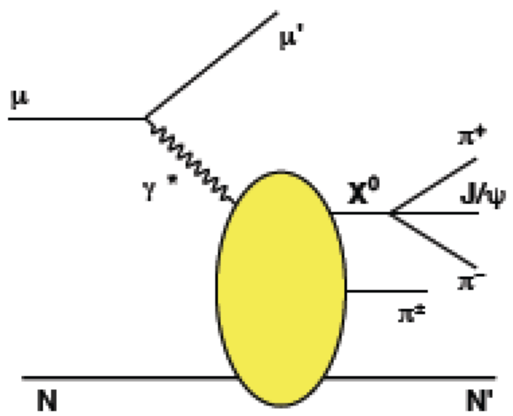
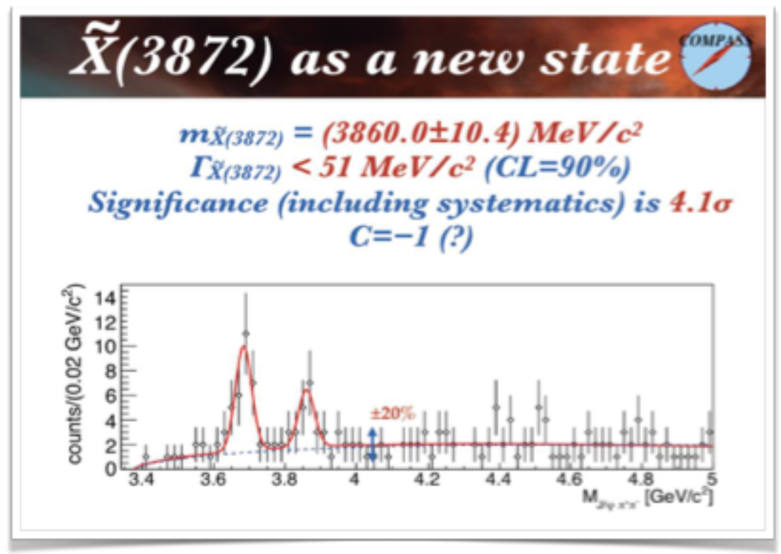
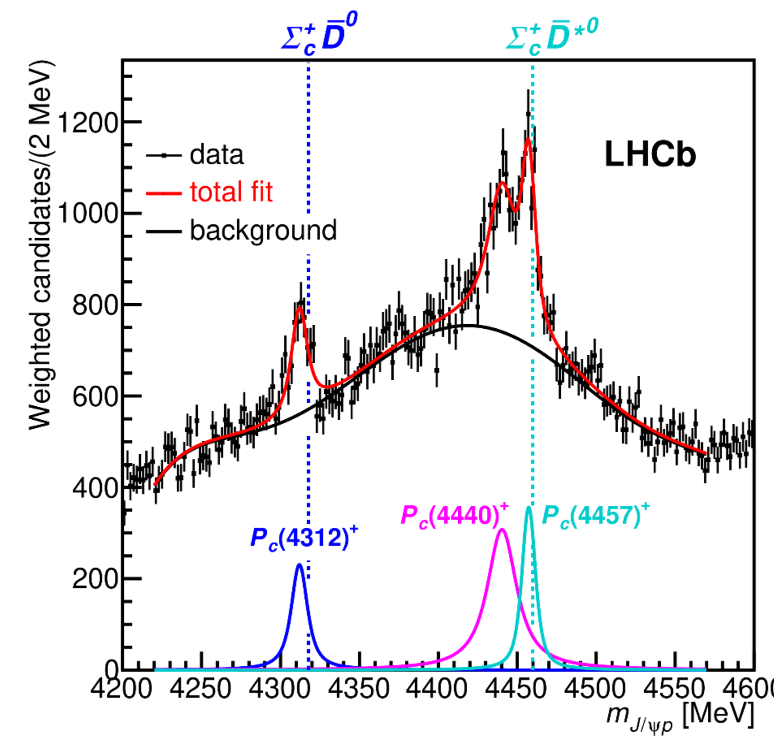
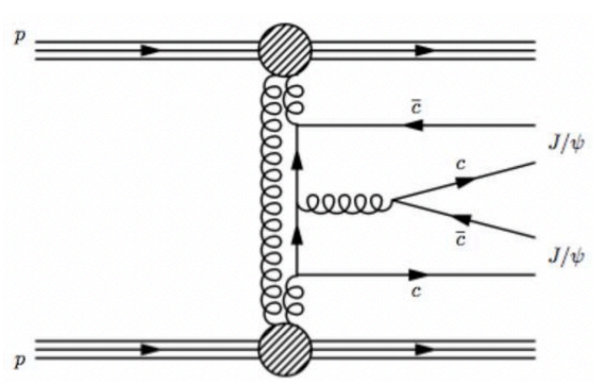
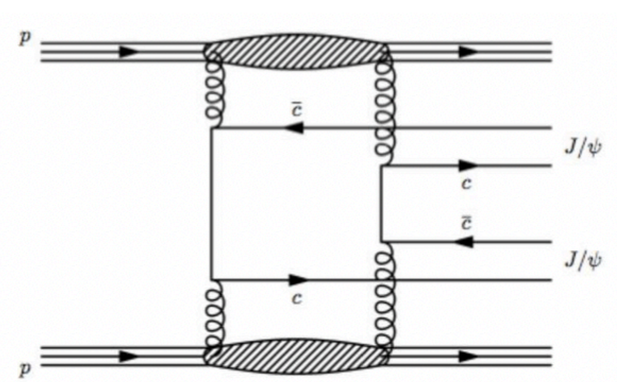






Diffractive double J/ψ production
through $\gamma\gamma$ collisions





Hadron spectroscopy @ EIC

New multiquark states to confirm:
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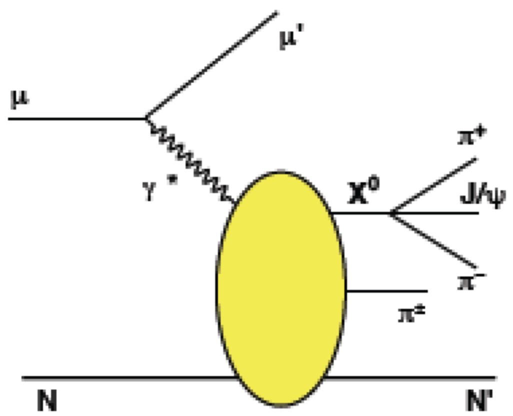

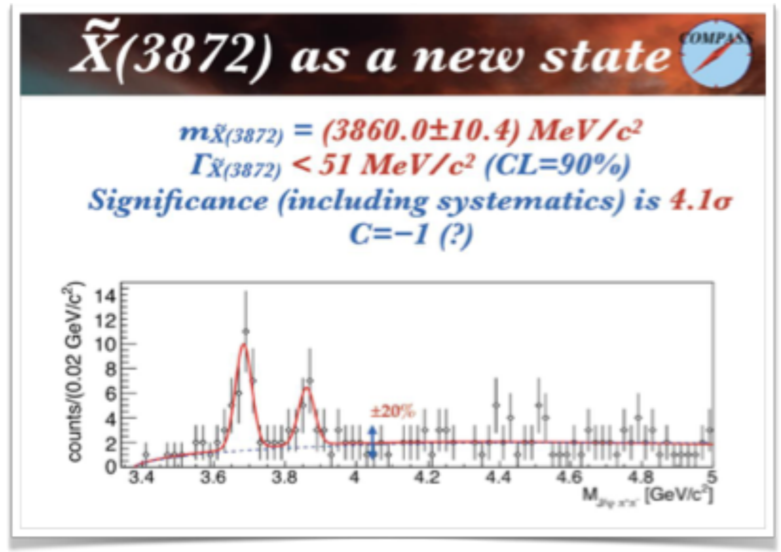

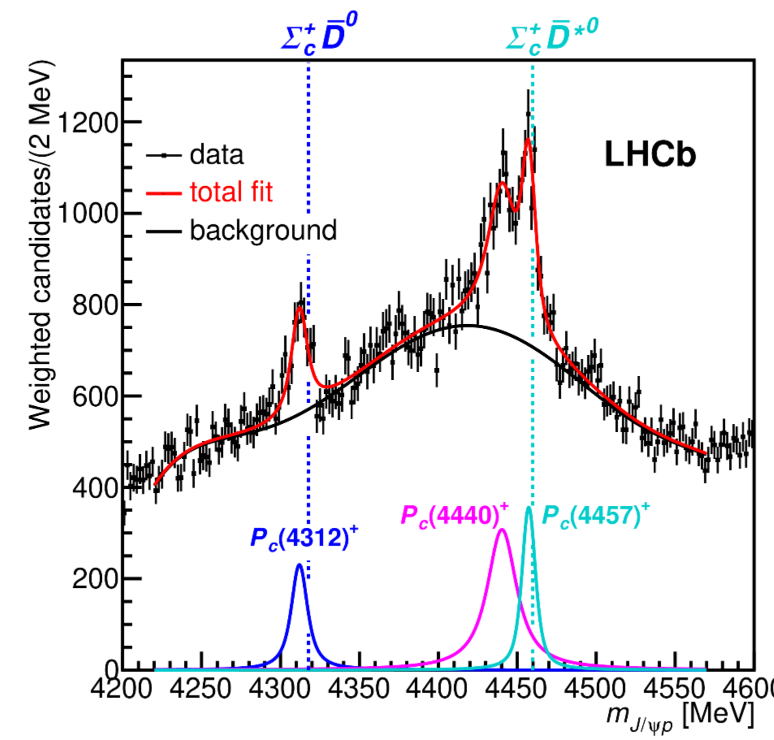

Diffractive double J/ψ production
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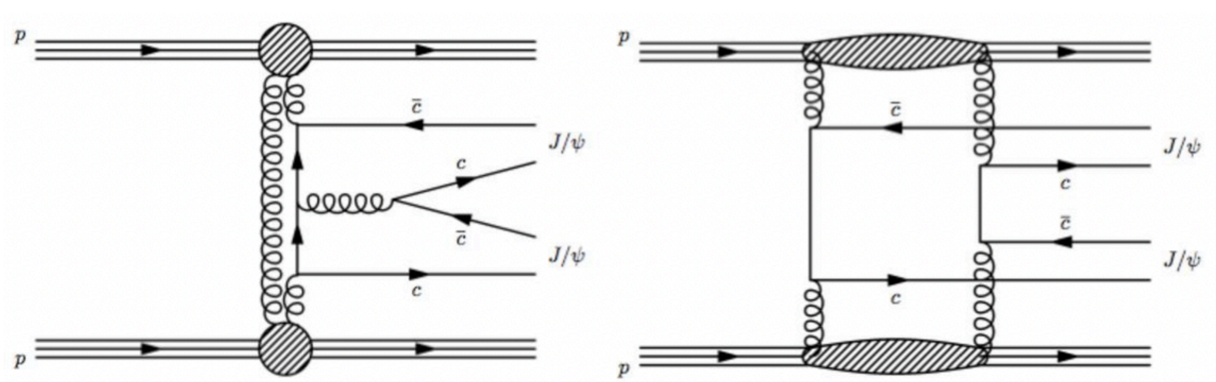
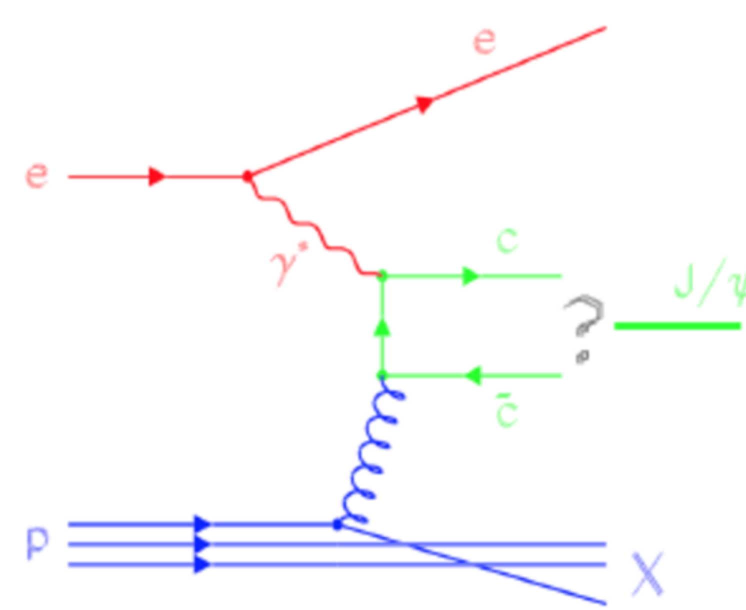


Open heavy flavour



Conclusions

- EIC is addressing fundamental (open) questions on structure of nucleons and nuclei:
  - spin and flavor structure of nucleons and nuclei
  - 3D-imaging (tomography) in momentum and spatial space
  - description of matter at extreme parton densities

- The answers to these questions are relevant both "per se" and for precision measurements / New Physics discoveries

- Apologies for not having discusses many topics in detail: many interesting slides on each of these topics (and more!) at

- **Thanks for your attention!**