IGFAE
Instituto Galego de Física de Altas Enerxías

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

First Joint Workshop IGFAE / LIP
Braga, May 4th 2018

Small-x Physics

Néstor Armesto
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela
nestor.armesto@usc.es

Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

EXCELENCIA MARÍA DE MAEZTU

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

XUNTA DE GALICIA

Contents:

1. Motivation.

2. A few recent topics:
   - ➜ Nuclear parton densities.
   - ➜ Particle correlations.
   - ➜ NLO calculations.

3. Implication in future experimental programmes.

Note: I am limiting the presentation to activities at IGFAE (in collaboration with LIP when applicable).

From pp to AA:

- Several (QGP-pointing) observables show a (smooth) transition between pp, pPb and PbPb - the only exception being jet quenching in pPb.

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Observable or effect	PbPb	pPb (at high mult.)	pp (at high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[37–42]
Intermed. p_T ("recombination")	yes	yes	yes	[41–47]
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω $\gamma_s^{C} < 1$, 20–40% [2]	[48–51] [52]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$ [3]	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[53–59]
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3	[25–27] [60–67]
Characteristic mass dependence	v_2, v_3 [4]	v_2, v_3	v_2	[67–73]
Directed flow (from spectators)	yes	no	no	[74]
Higher order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$" [5]	[28, 29, 67] [75–83]
Weak η dependence	yes	yes	not measured	[83–90]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[91]
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured	[92]
Event plane and v_n correlations	yes	not measured	not measured	[93–95]
Direct photons at low p_T	yes	not measured	not measured [6]	[96]
Jet quenching	yes	not observed [7]	not measured [8]	[97–105]
Heavy flavor anisotropy	yes	hint [9]	not measured	[106–109]
Quarkonia	$J/\psi \uparrow$, $\Upsilon \downarrow$	suppressed	not measured [8]	[110–116]

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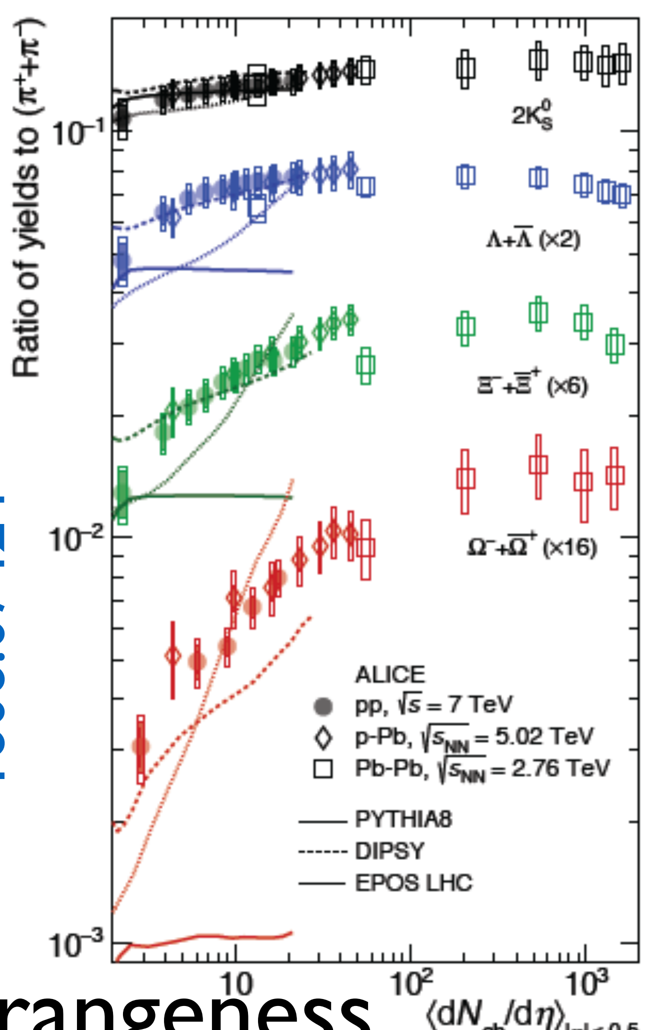

Strangeness

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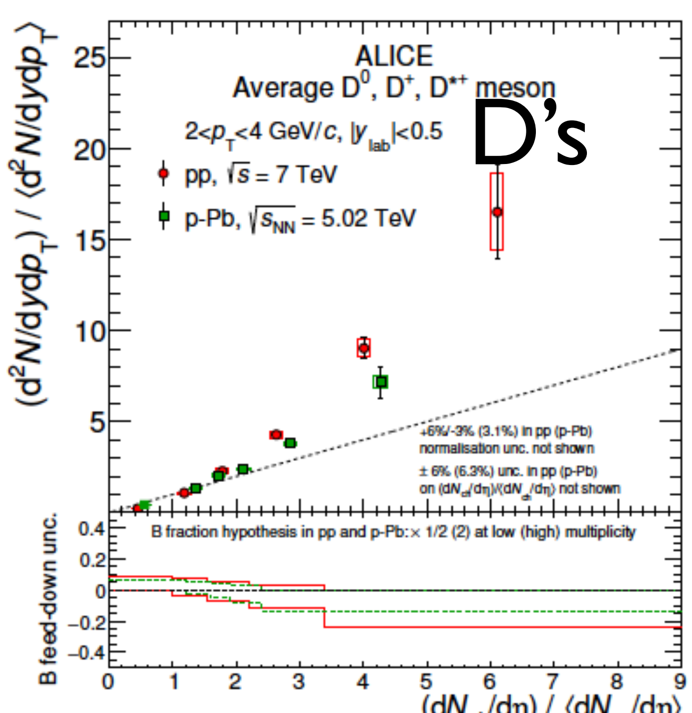

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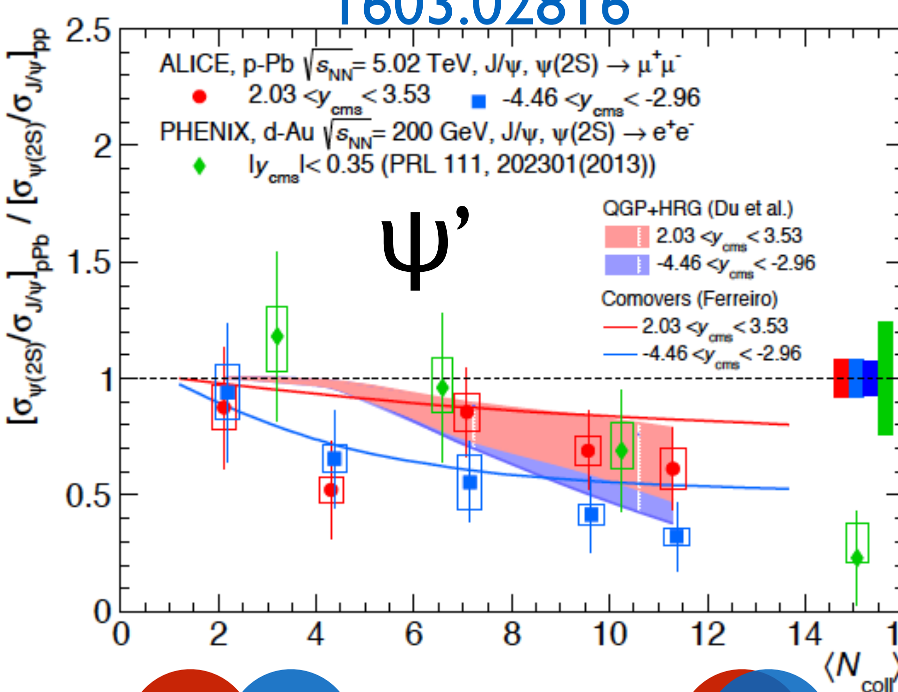

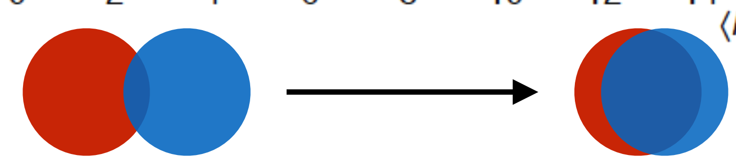

The ridge:

- Particle correlations in pp and pPb at the LHC show features that in AA are attributed to final state interactions describable by hydrodynamics and interpreted as a signal of equilibration.
- Hydro works, although it demands non-trivial inputs, and some limitations in pp.

$$\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle,$$
$$\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle,$$
$$\langle\langle \mathrm{corr}_n\{6\}\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle,$$
$$\langle\langle \mathrm{corr}_n\{8\}\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\rangle\rangle,$$

$$c_n\{2\} = \langle\langle \mathrm{corr}_n\{2\}\rangle\rangle,$$
$$c_n\{4\} = \langle\langle \mathrm{corr}_n\{4\}\rangle\rangle - 2\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^2,$$
$$c_n\{6\} = \langle\langle \mathrm{corr}_n\{6\}\rangle\rangle - 9\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle + 12\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^3,$$
$$c_n\{8\} = \langle\langle \mathrm{corr}_n\{8\}\rangle\rangle - 16\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle\langle\langle \mathrm{corr}_n\{6\}\rangle\rangle - 18\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle^2 + 144\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^2\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle - 144\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^4.$$

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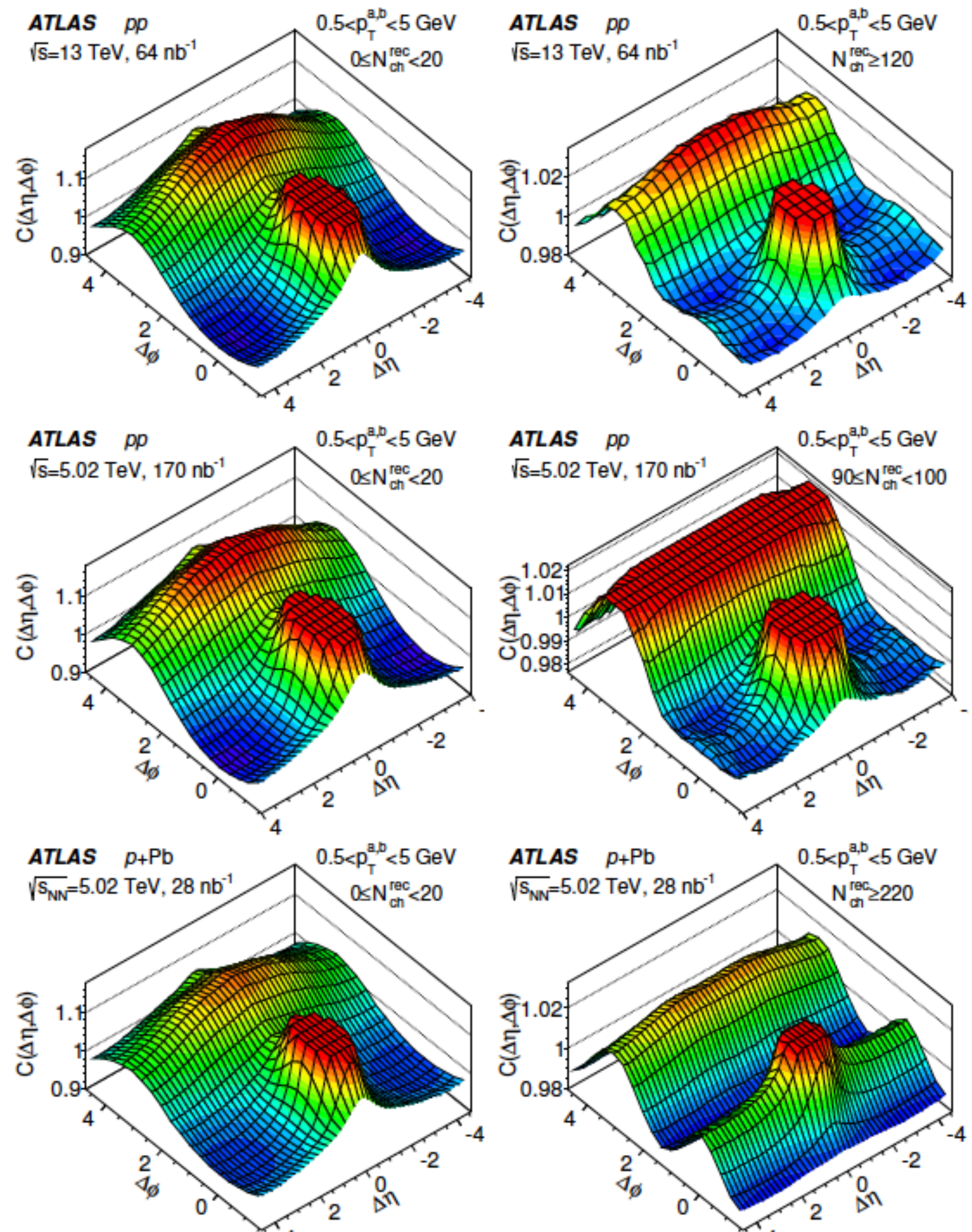

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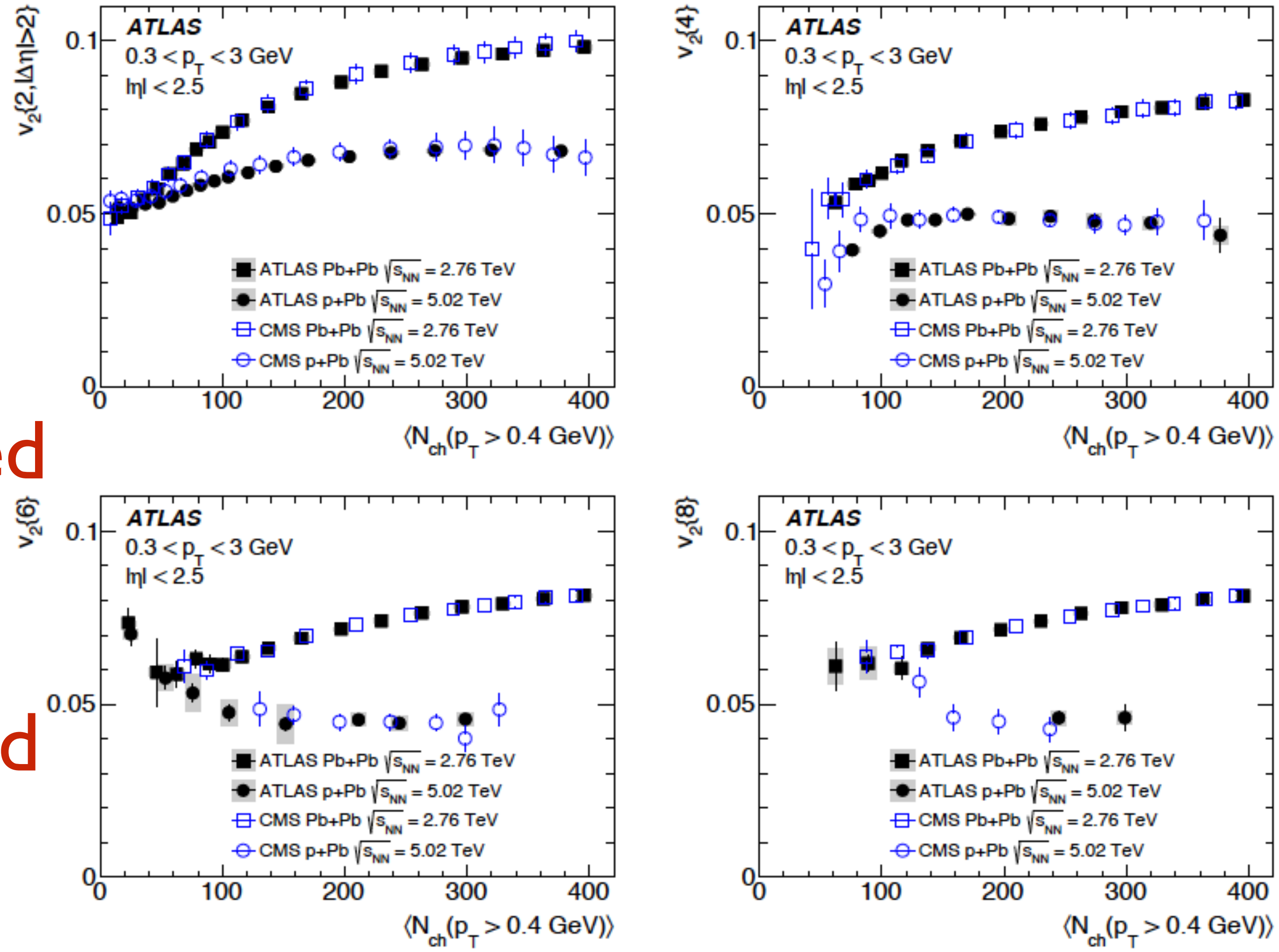

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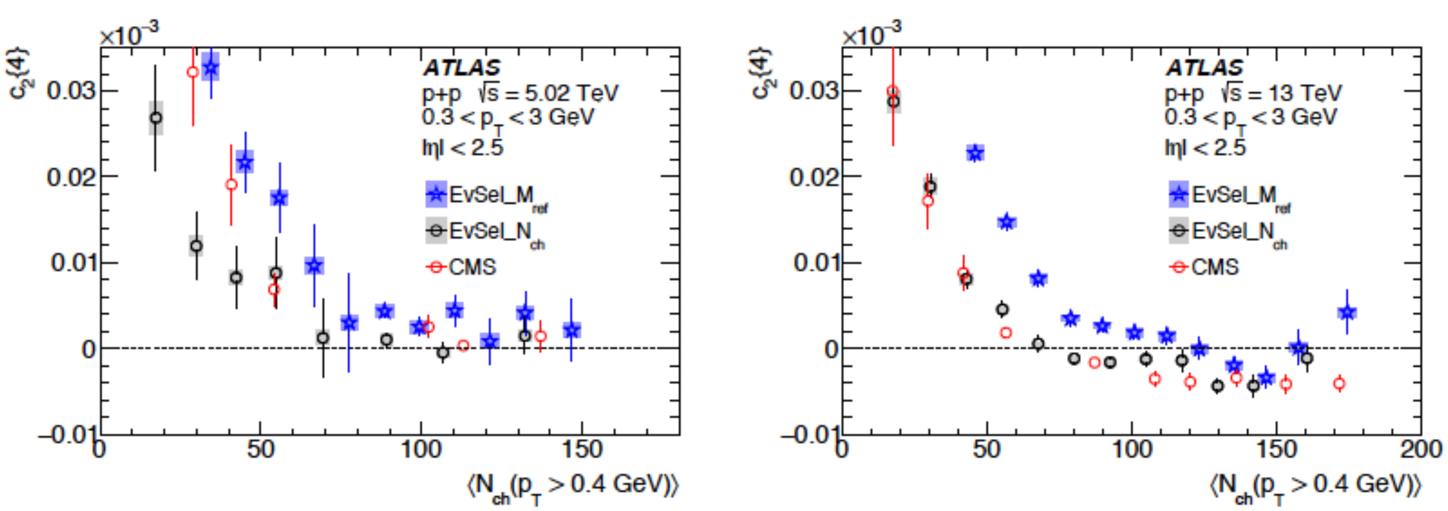

$$v_n\{2\} = \sqrt{c_n\{2\}},$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}},$$
$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4},$$
$$v_n\{8\} = \sqrt[8]{-c_n\{8\}/33}.$$

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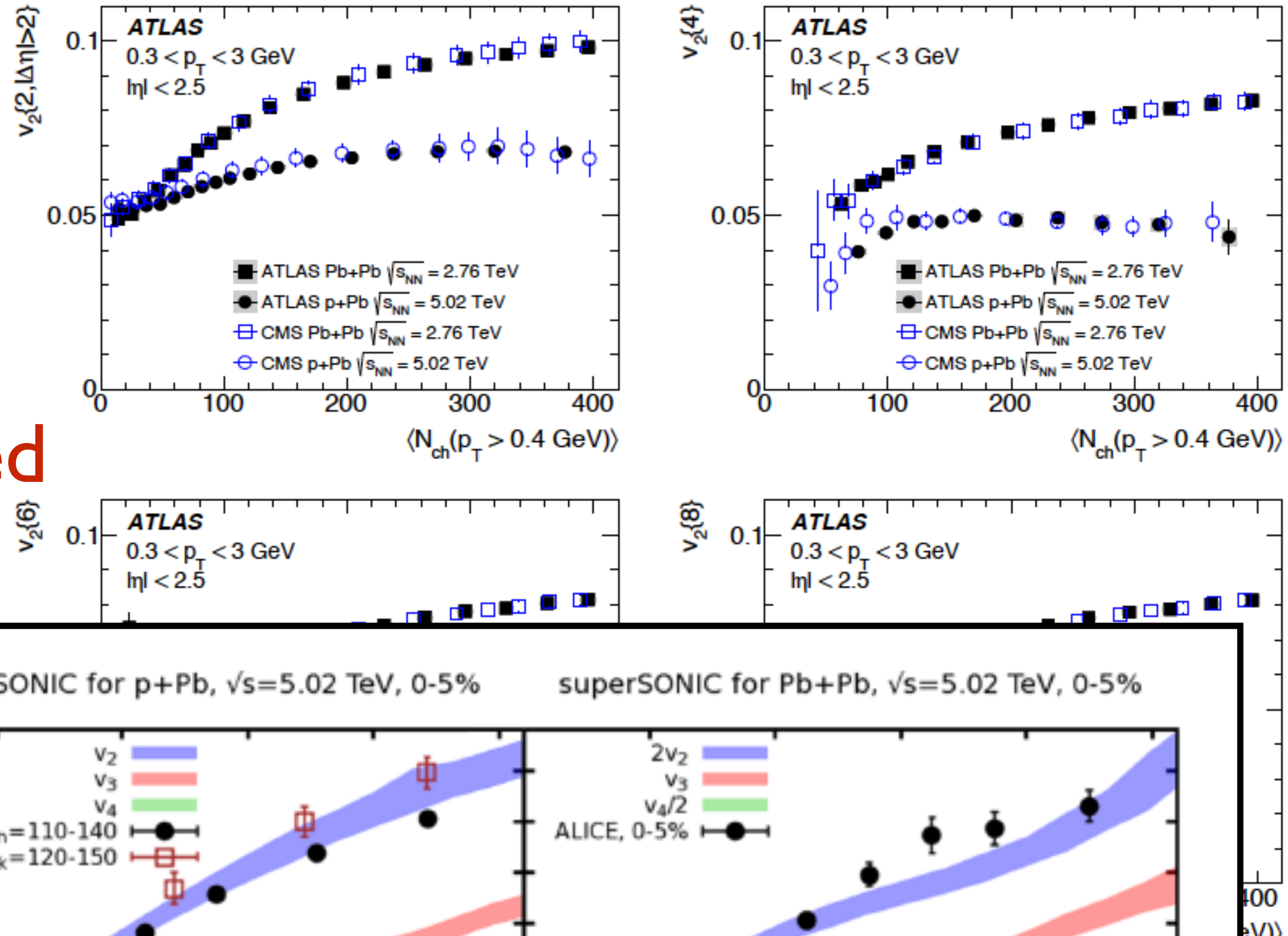
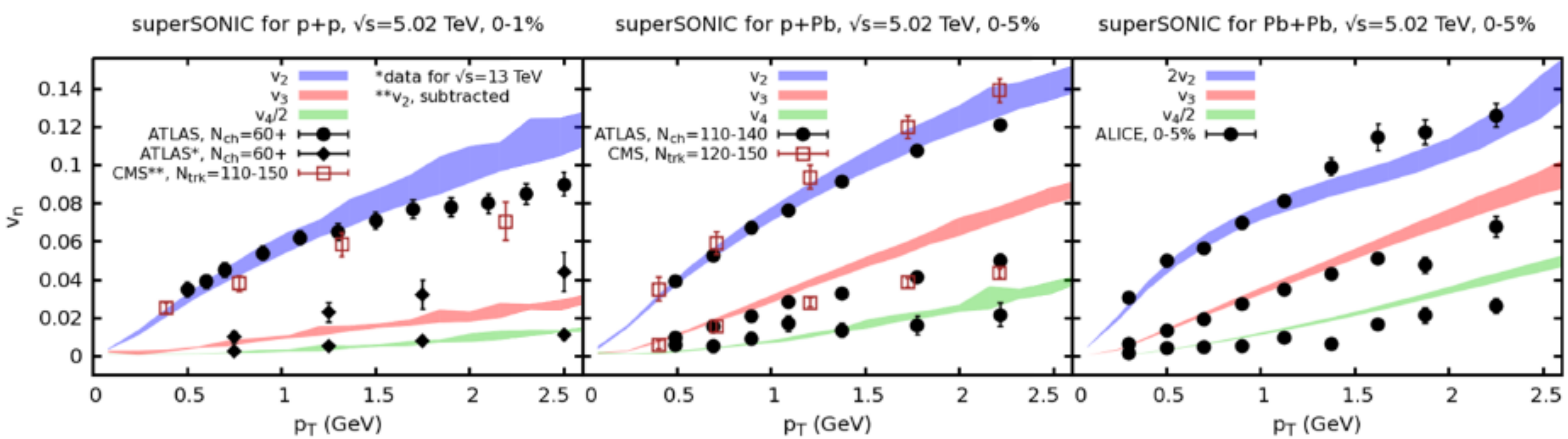




1701.07145, proton as 3 hot spots

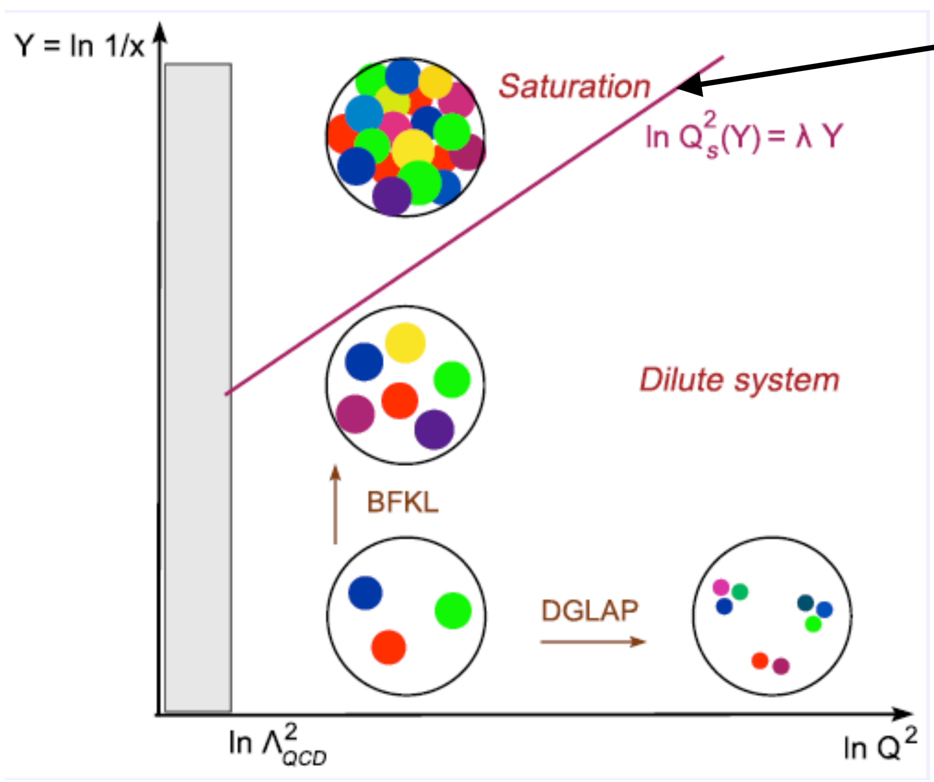
FIG. 2. Elliptic (v_2), triangular (v_3) and quadrupolar (v_4) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at $\sqrt{s} = 5.02$ TeV [58–62]. Simulation parameters used were $\frac{\eta}{s} = 0.08$ and $\frac{\zeta}{s} = 0.01$ for all systems. Note that ATLAS results for v_3, v_4 are only available for $\sqrt{s} = 13$ TeV, while all simulation results are for $\sqrt{s} = 5.02$ TeV.

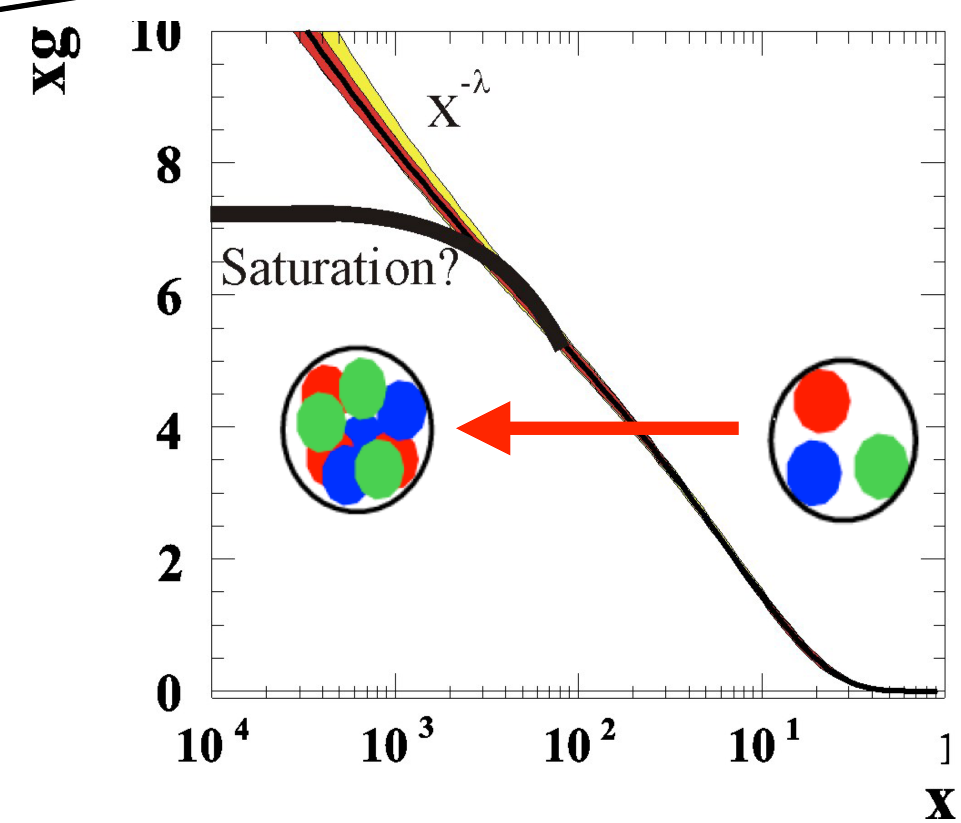
Small x and non-linear dynamics:

• **High-energy QCD**: standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail:

➜ Large logs e.g. $\alpha_s \ln(1/x) \sim 1$: resummation (BFKL,CCFM,ABF,CCSS; **HERA?**).
➜ High density ⇒ linear evolution cannot hold: saturation, either perturbative (CGC) or non-perturbative.

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$



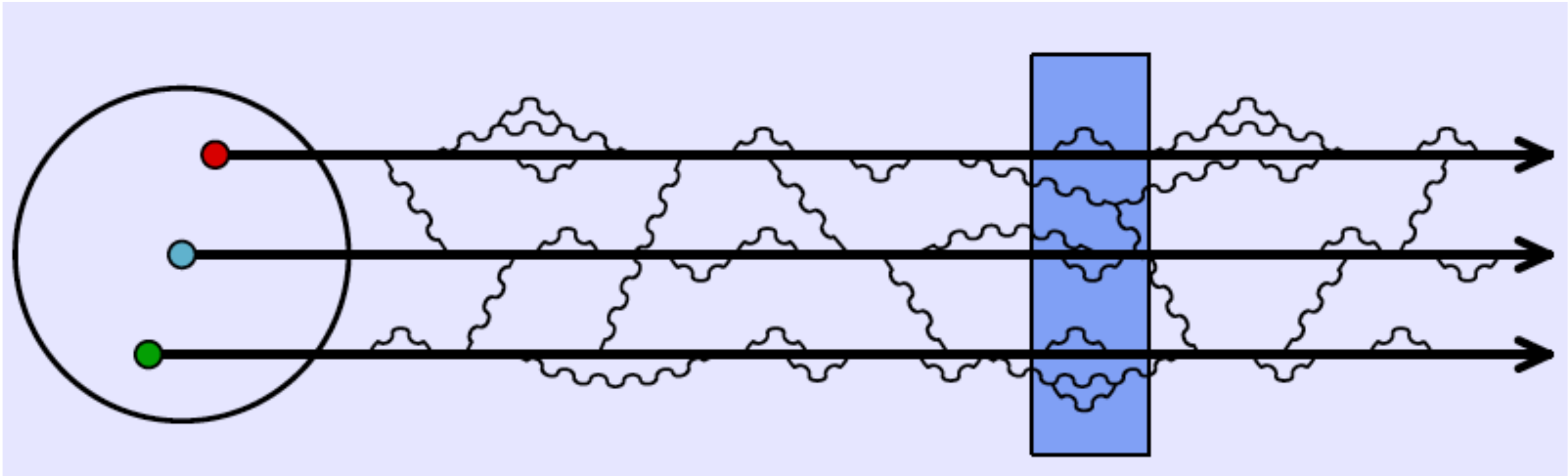


• Non-linear effects are density effects: decrease x and increase A.

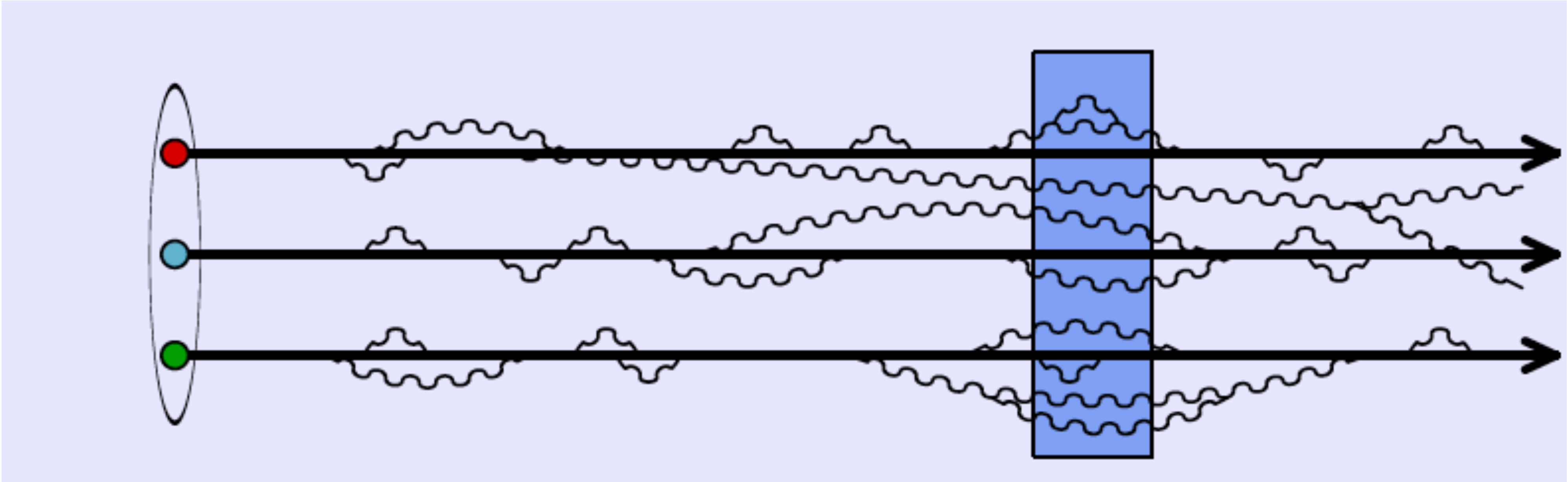
• Determining the dynamics at small x has been a major subject at HERA, and RHIC and the LHC both in pp, pA and AA.

The CGC:

• Low energies: short-lived fluctuations of the components of the wave function when compared with the size of the target.



• High energies: many long lived fluctuations (small-x gluons) that do not self-interact during the scattering time, frozen configuration: fast/slow mode separation in an EFT (CGC), evolution equations.



The CGC:

- Interaction of a frozen configuration of partons through a shock wave, the S-matrix is given by a Wilson line:

$$W(x_\perp) = S(x_\perp) = \mathcal{P}\exp\left[ig\int dx^+ A^-(x^+, x_\perp)\right]$$

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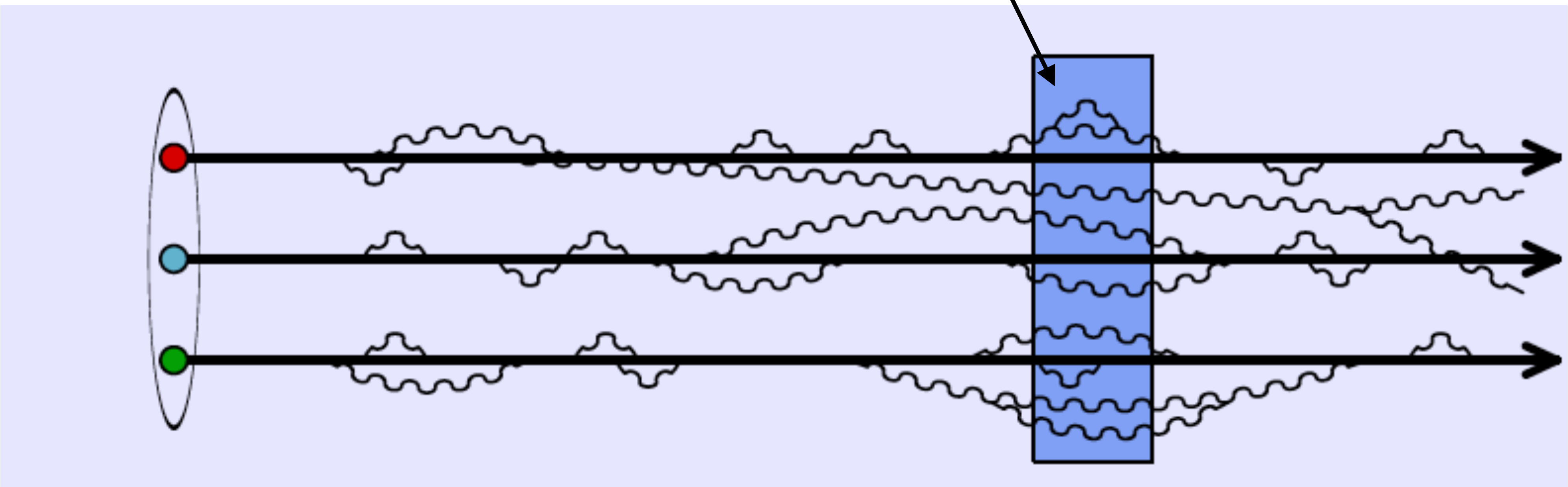
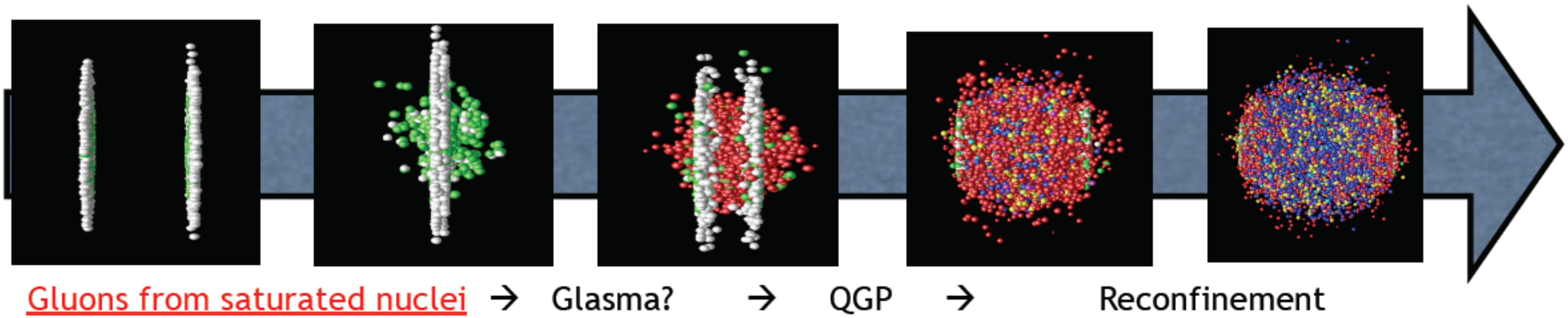


The CGC:

Item	Order	Theory	Pheno-menology	Comments
Evolution eqns.	NLO	✔	~	rcBK and resummations; dilute-dense approx.
DIS impact factor	NLO	✔	✔	dilute-dense approx.
Hadrons at y~0	LO	✔	✔	q and Q , dilute-dense approx.
Forward hadrons	NLO	✔	✔	q and Q, hybrid formalism
Quarkonium at y~0	LO	✔	✔	dilute-dense approx.+NRQCD
Forward quarkonium	LO	✔	✔	hybrid formalism
$\gamma^{(*)}$ at y~0	NLO	✔	✘ at NLO	dilute-dense approx., not yet DY at NLO
Forward $\gamma^{(*)}$	LO	✔	✔	hybrid formalism
Dijets at y~0	LO	✔	✔	dilute-dense approx., partial NLO
Forward dijets	LO	✔	✔	hybrid formalism and high-energy factorisation, partial NLO
Diffractive dijets	NLO	✔	✘ at NLO	dilute-dense approx.
Exclusive vector mesons	NLO	✔	✘ at NLO	dilute-dense approx.
g/q/γ-g/q/γ correlations	LO	✔	✔/✘	glasma graph approx. + some density corrections; hybrid formalism

Implications for heavy-ions:

- Assuming collinear factorisation holds, small -x PDFs poorly known for particle production (even for heavy objects at the FCC).



- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation.

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Available nPDF sets:

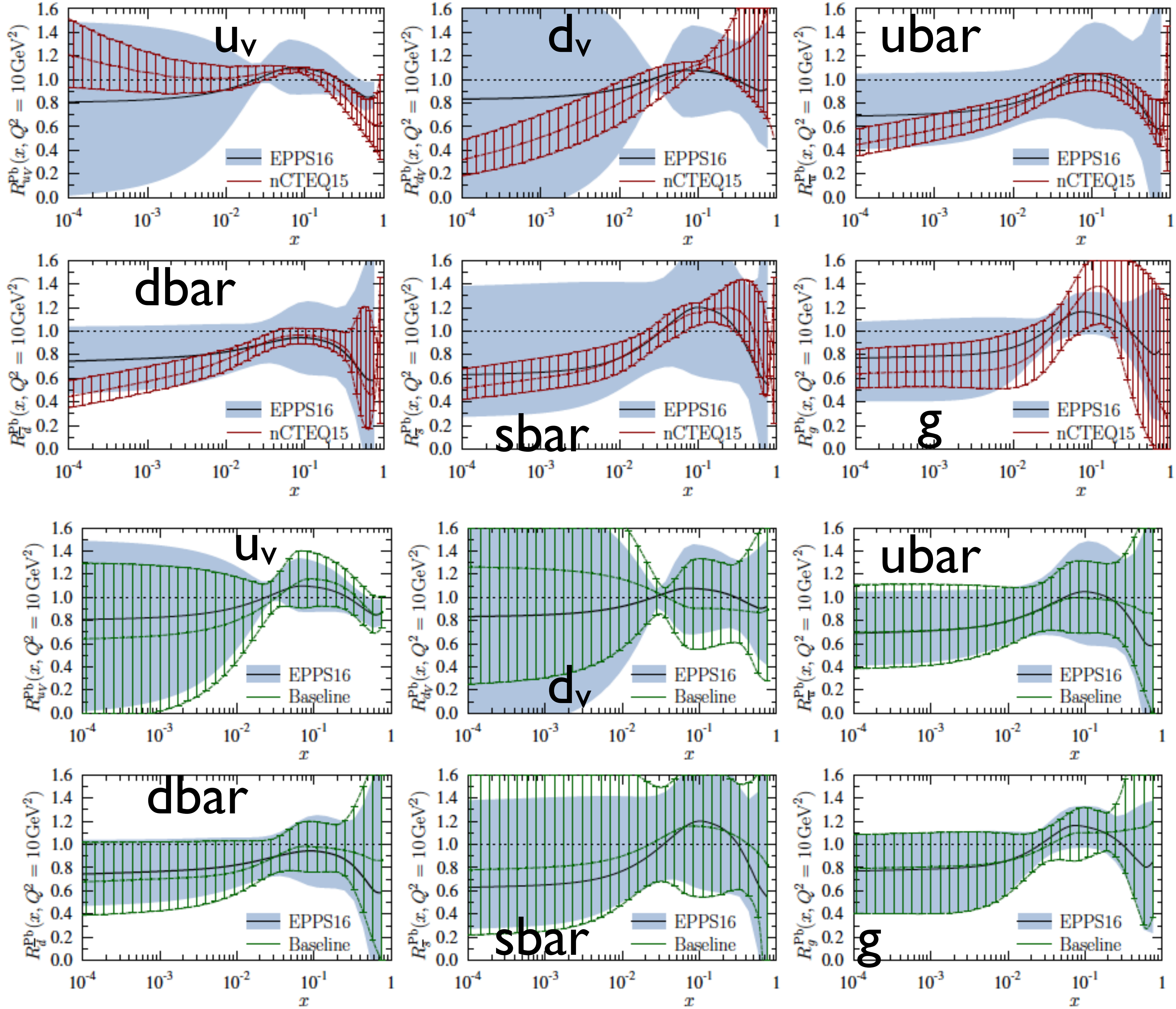
SET		**HKN07** PRC76 (2007) 065207	**EPS09** JHEP 0904 (2009) 065	**DSSZ** PRD85 (2012) 074028	**nCTEQ15** PRD93 (2016) 085037	**KA15** PRD93 (2016) 014036	**EPPS16** EPJC C77 (2017) 163
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	pPb	✘	✘	✘	✘	✘	✔
# data		1241	929	1579	740	1479	1811
order		NLO	NLO	NLO	NLO	NNLO	NLO
proton PDF		MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO
mass scheme		ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS
comments		$\Delta\chi^2$=13.7, ratios, no EMC for gluons	$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data

EPPS16:

Q^2=10 GeV^2

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

- Presently available LHC data seem not to have a large effect: large-x glue (baseline=no ν, no LHC data).



Ridge in the CGC (I):

- Several explanations for the ridge proposed in the CGC:

➜ Assume that the final state carries the imprint of initial-state correlations;

➜ Use that the CGC wave function is rapidity invariant over $Y \propto 1/\alpha_s$ (we resum terms $\alpha_s \ln(1/x) = \alpha_s Y \sim 1$ coming from the $1/x$ soft divergence).

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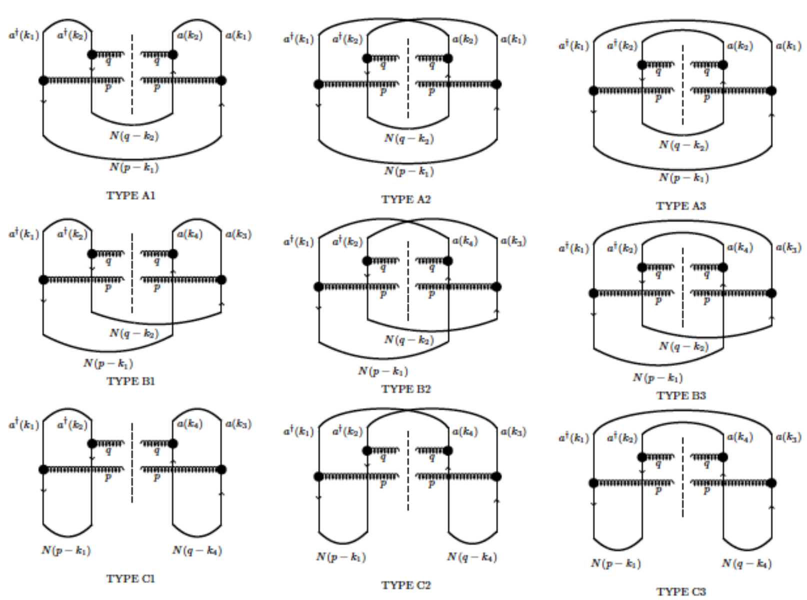

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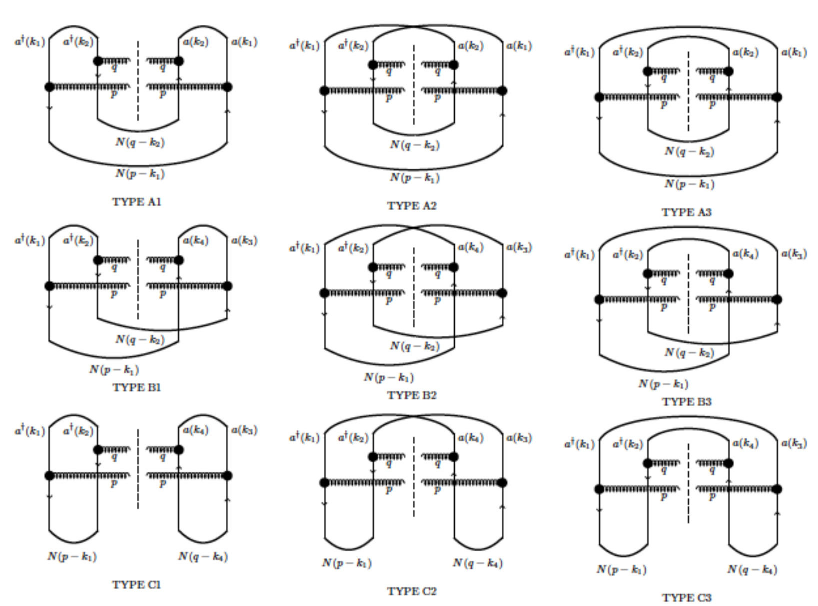
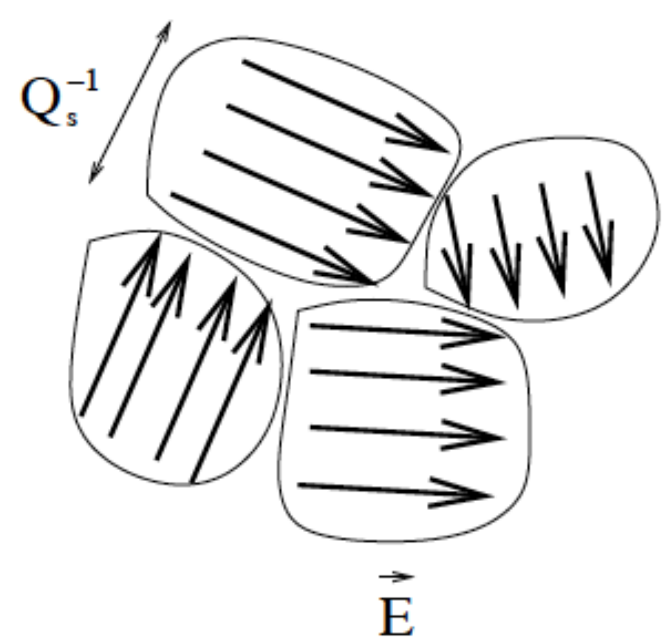


- Local anisotropy of target fields (Kovner-Lublinsky, Dumitru-McLerran-Skokov).



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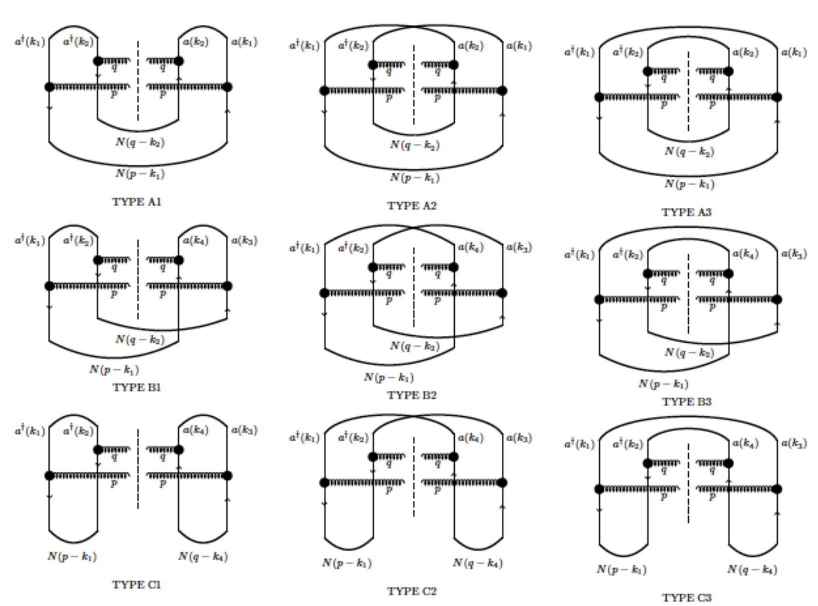

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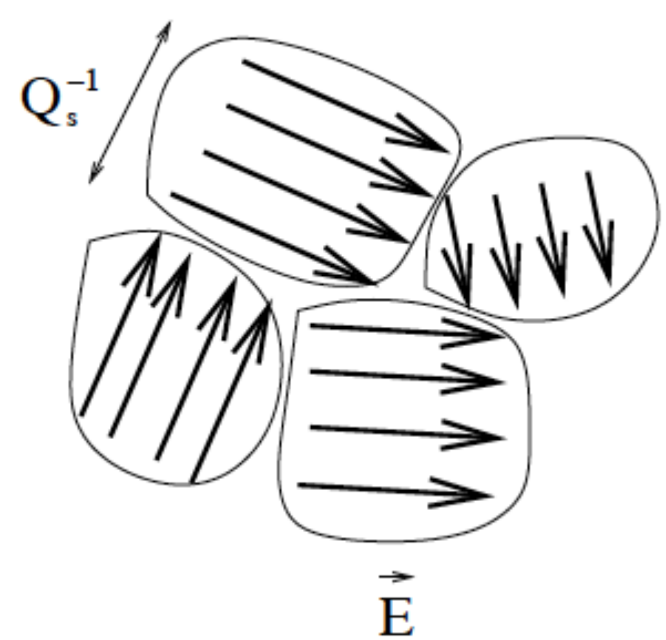
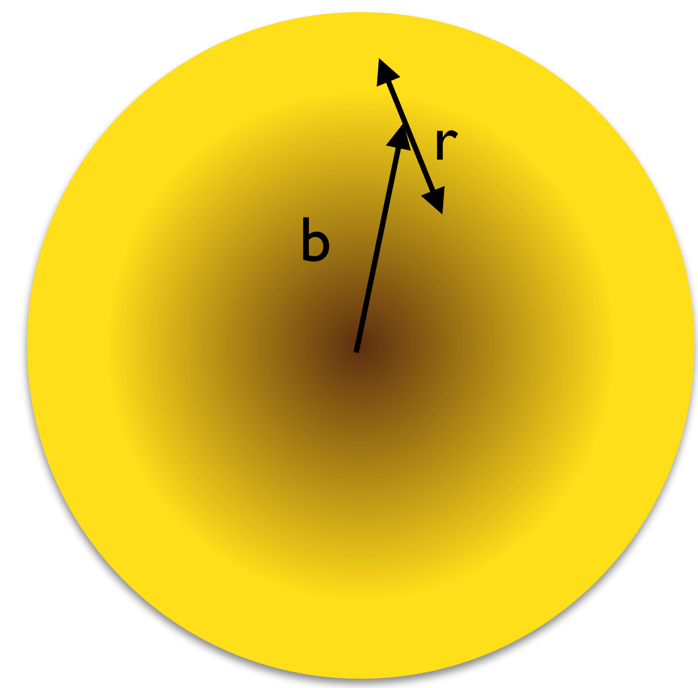


- Spatial variation of partonic density (Levin-Rezaeian-Gotsman).



Ridge in the CGC (II):

• The appearance of the ridge in the final state, within the glasma graph approach, can be traced to the Bose enhancement of gluons in the (rapidity invariant) wave function:

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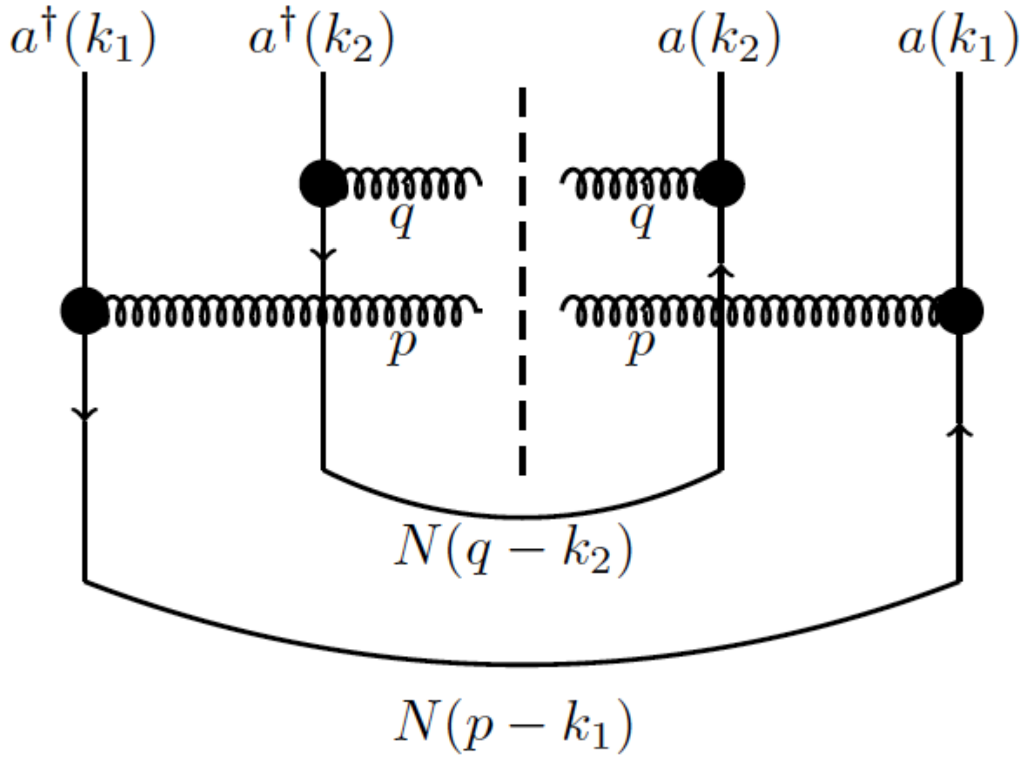
1509.03223



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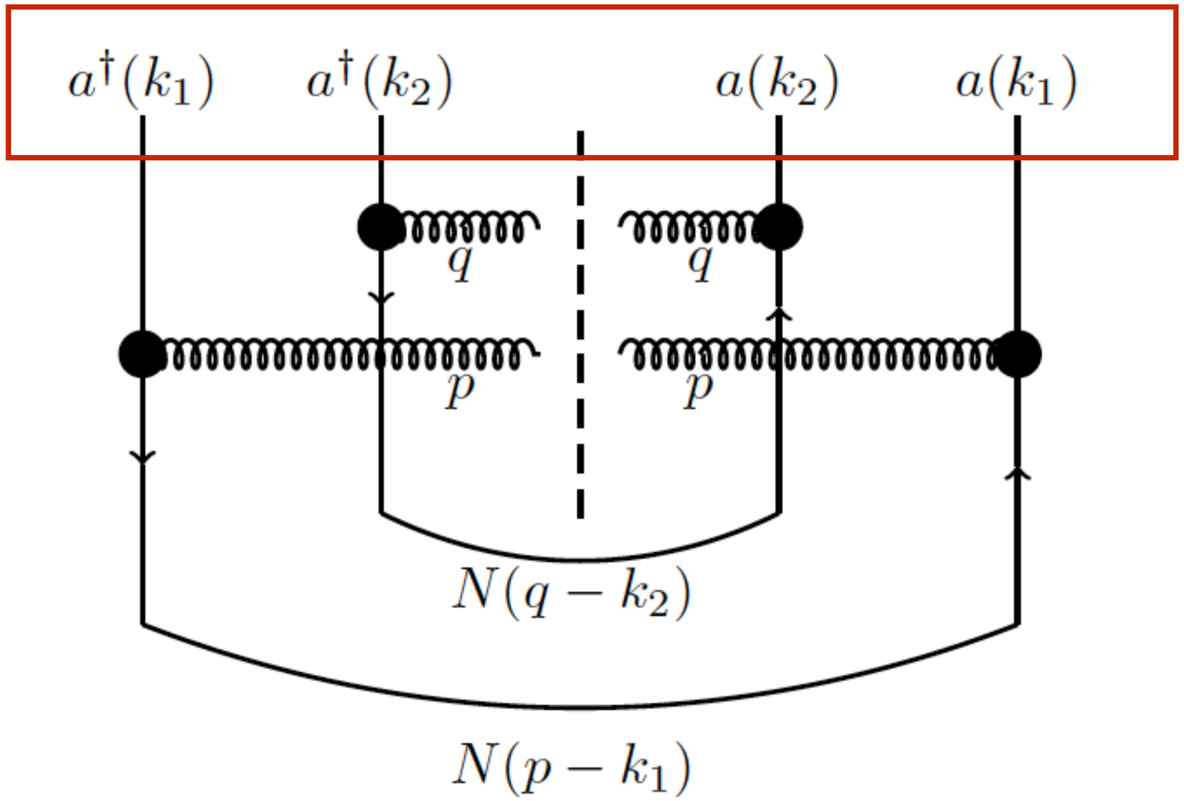

gluons in the WF

1503.07126, 1509.03223

$$[a^i_a(k), a^{\dagger j}_b(p)] = (2\pi)^2 \delta_{ab} \delta^{ij} \delta^{(2)}(k-p)$$

$$a^i_a(k) \equiv \frac{1}{\sqrt{Y}} \int_{|\eta<Y/2|} \frac{d\eta}{2\pi}\, a^i_a(\eta, k)$$

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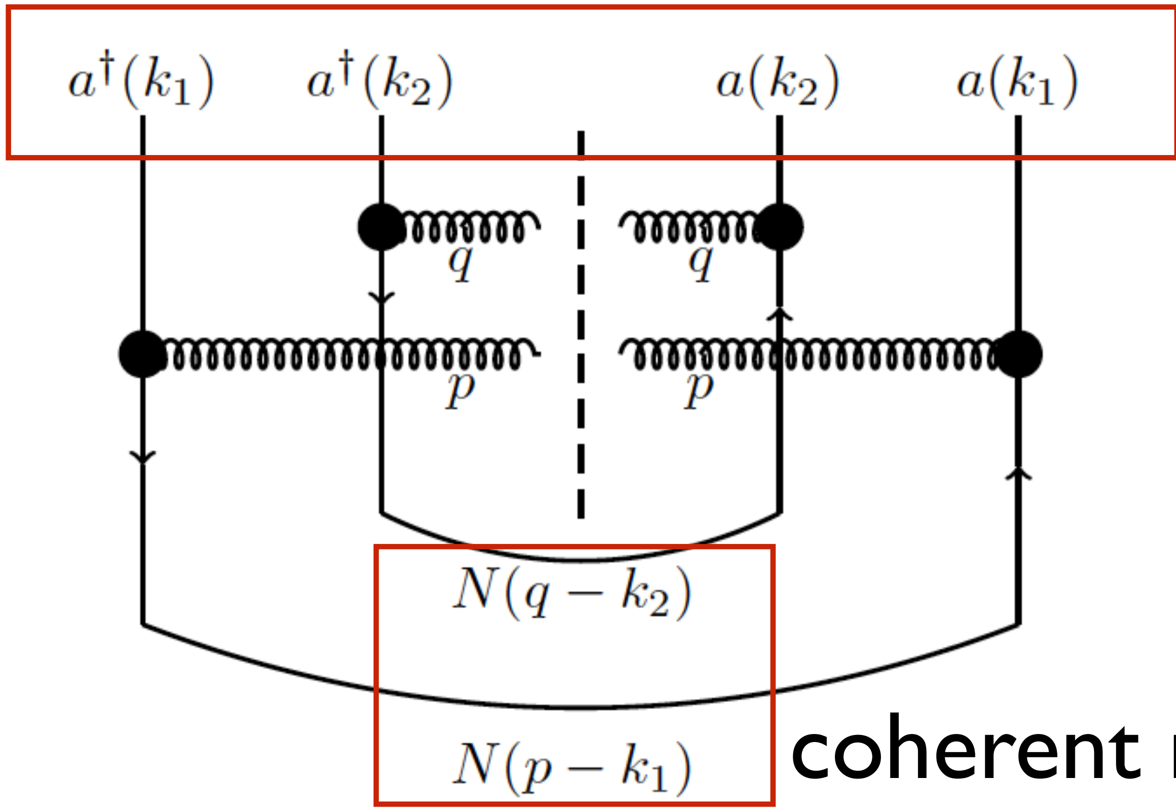

gluons in the WF

coherent rescattering on the target - S-matrix

1503.07126, 1509.03223

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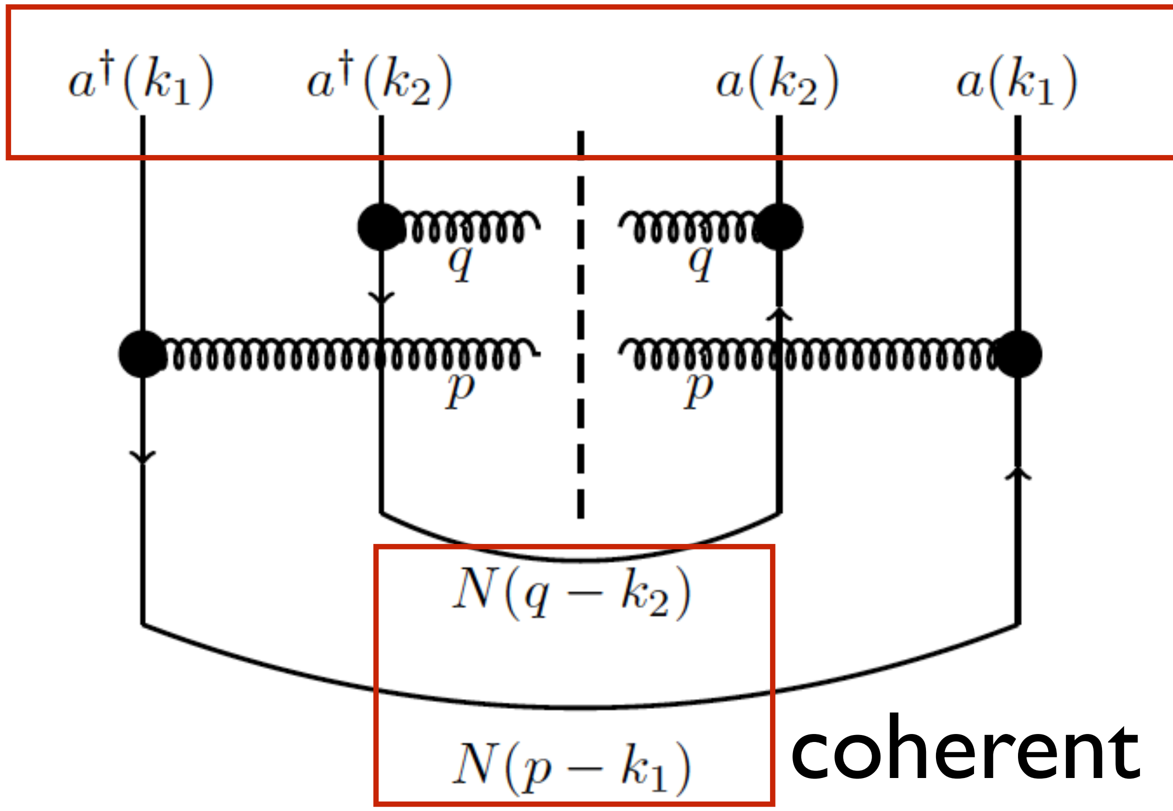

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$$C \int_{k_1,k_2} \langle in| a^{\dagger i}_a(k_1) a^{\dagger j}_b(k_2) a^k_a(k_1) a^l_b(k_2) |in\rangle \left[\delta^{ik} - \frac{k_1^i k_1^k}{p^2}\right] \left[\delta^{jl} - \frac{k_2^j k_2^l}{q^2}\right] N(p-k_1) N(q-k_2)$$

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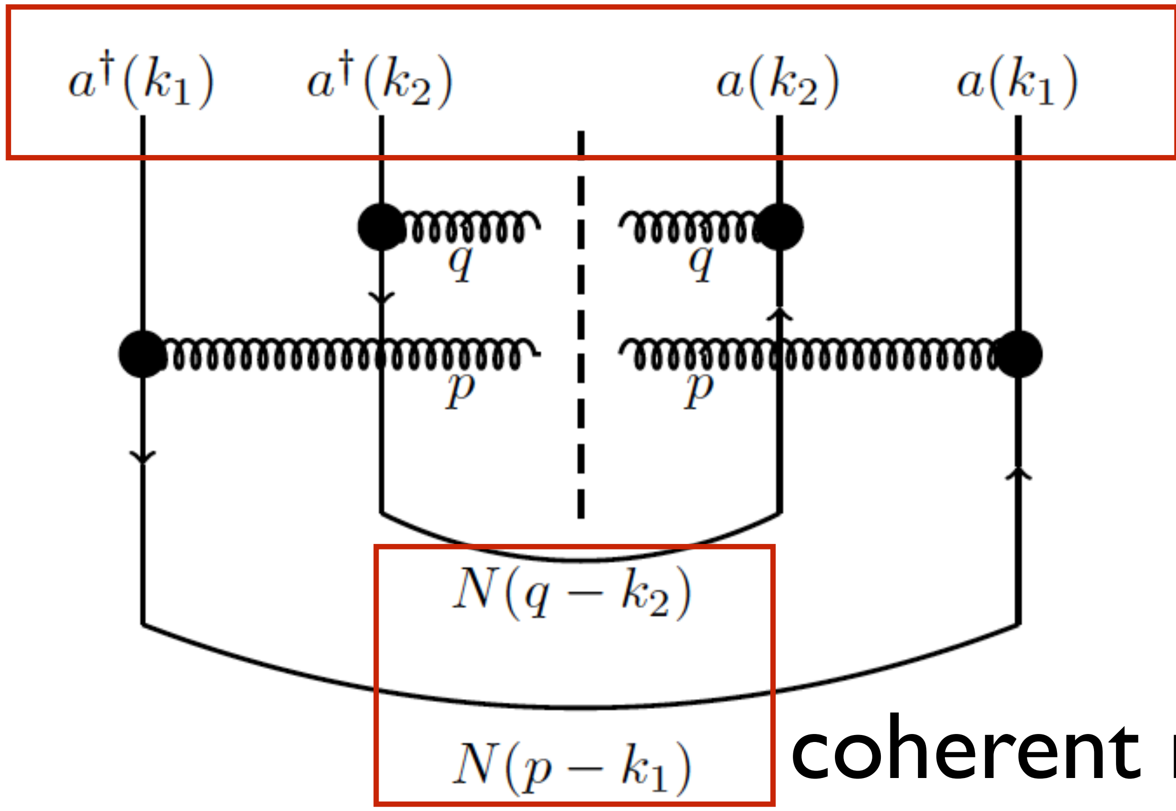

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coherent rescattering on the target - S-matrix

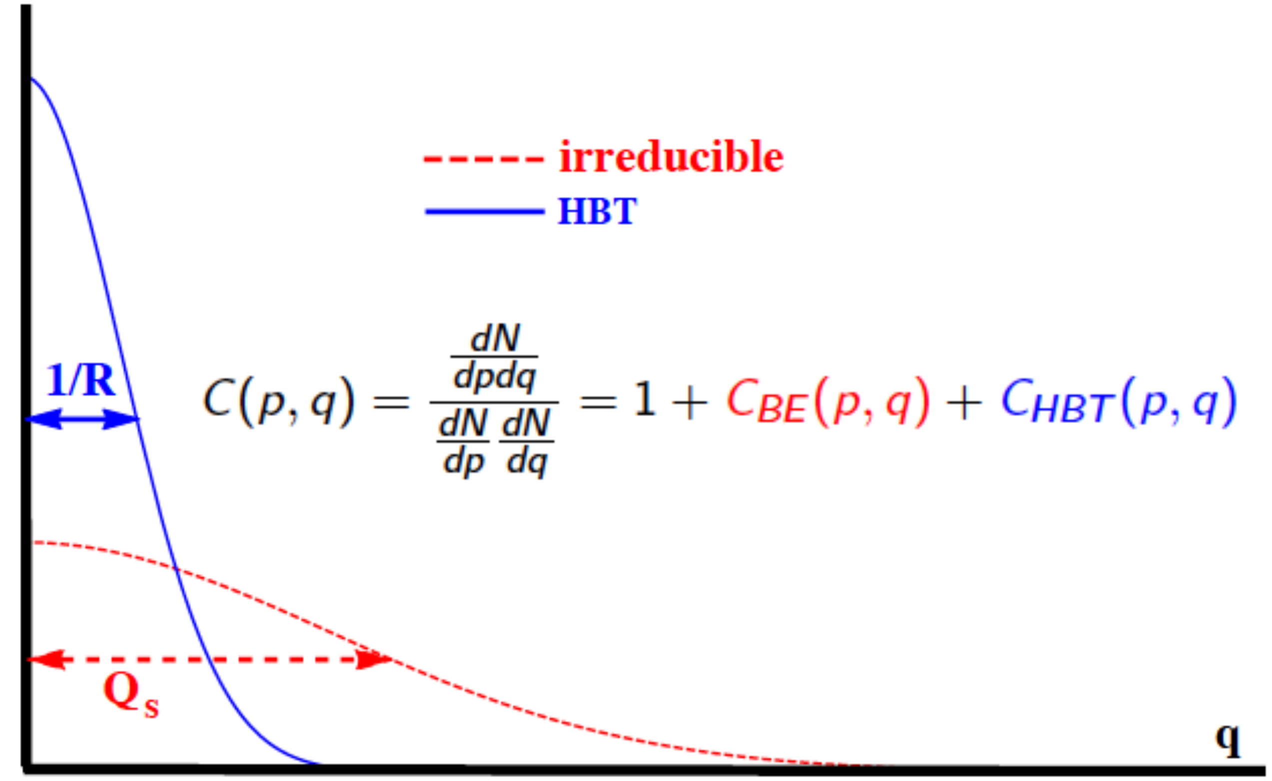
$$C \int_{k_1,k_2} \langle in | a_a^{\dagger i}(k_1) a_b^{\dagger j}(k_2) a_a^k(k_1) a_b^l(k_2) | in \rangle \left[\delta^{ik} - \frac{k_1^i k_1^k}{p^2}\right]\left[\delta^{jl} - \frac{k_2^j k_2^l}{q^2}\right] N(p-k_1)N(q-k_2)$$

$$D(k_1,k_2) = S^2(N_c^2-1)^2 \frac{k_1^i k_1^k k_2^j k_2^l}{k_1^2 k_2^2} \frac{g^4\mu^2(k_1)\mu^2(k_2)}{k_1^2 k_2^2} \left\{1 + \frac{1}{S(N_c^2-1)}\left[\delta^{(2)}(k_1-k_2) + \delta^{(2)}(k_1+k_2)\right]\right\}$$

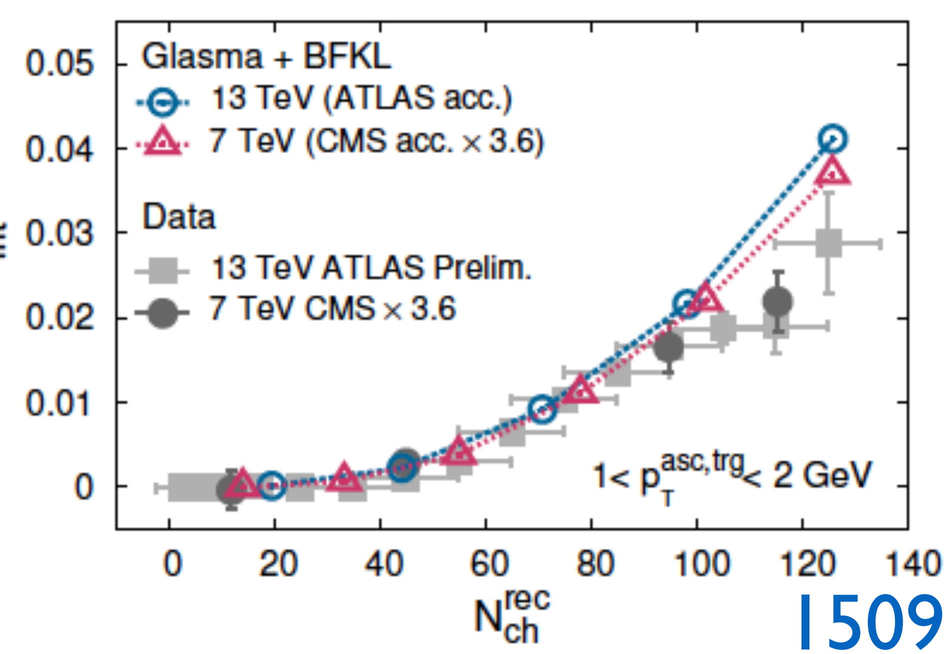
$$a^*(k) = a(-k)$$

Ridge in the CGC (III):

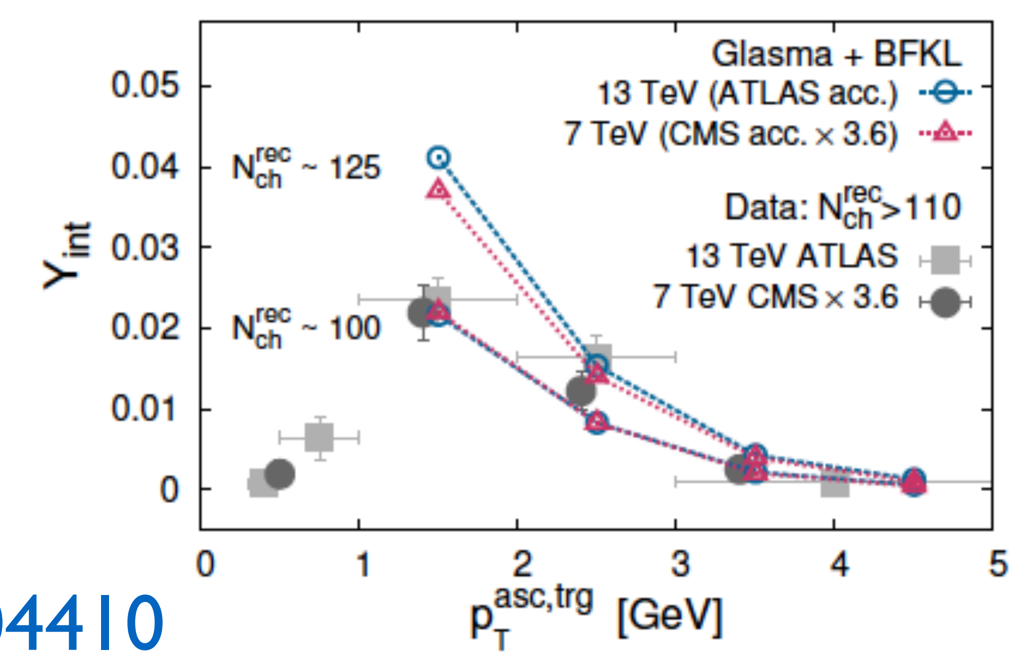
- It can be extended for quarks giving Pauli blocking (1610.03020): short range anticorrelation in the near side ridge.
- It contains information both on the 'source' size $1/Q_s$ (BE, suppressed by the number of sources), and on the size of the distribution of 'sources' R (HBT).



Near side integrated yield



1509.04410



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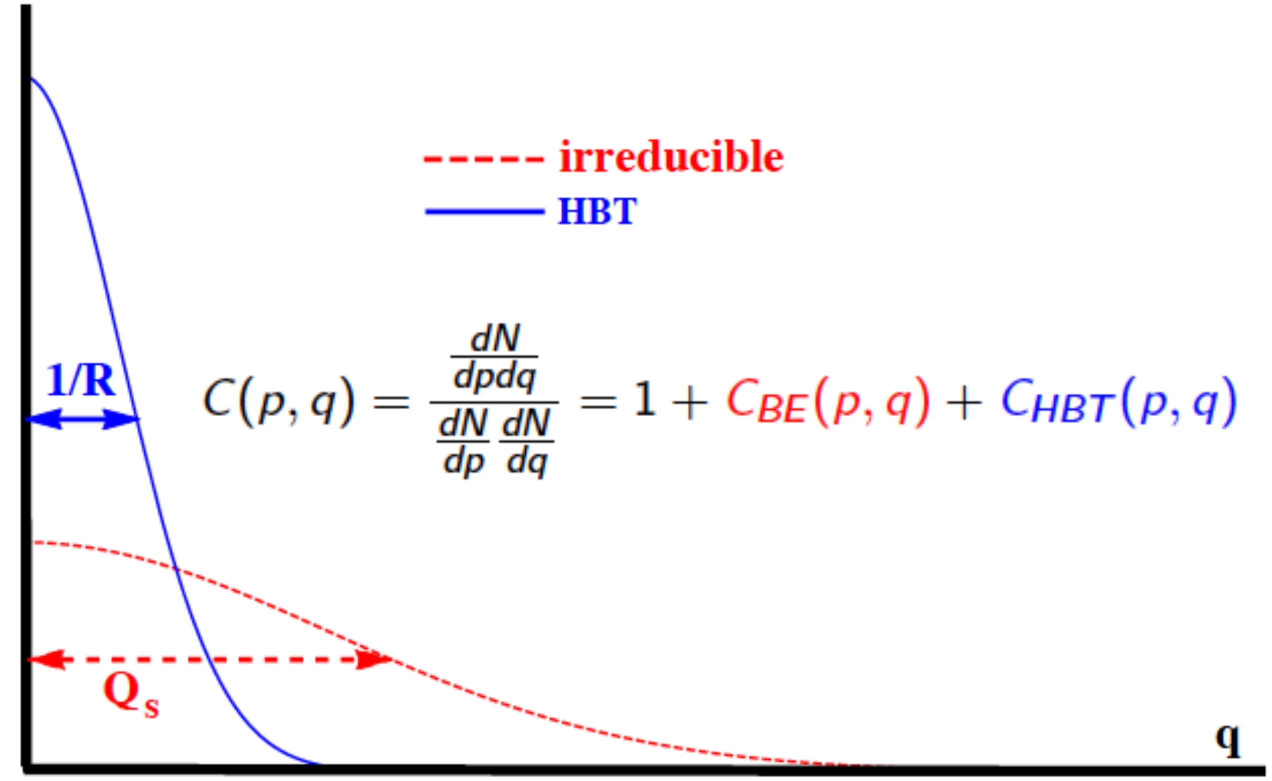


- Limitations:

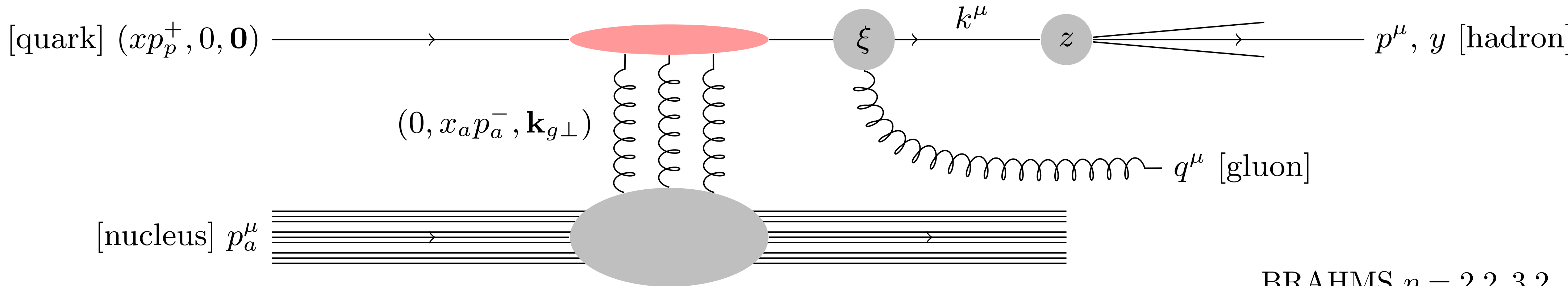
  ➜ S-matrices for rescattering of partons with the target are expanded in colour fields ⇒ low density approximation

  (extended to dilute-dense 1804.02910, more to come soon).

  ➜ Gaussian (MV) isotropic colour correlations taken ⇒ correlations subleading in N_c, no odd harmonics, $c_2\{4\}>0$. $\langle \rho^a_T(k)\rho^b_T(p)\rangle_T = (2\pi)^2\lambda^2(k)\delta^{ab}\delta^{(2)}(k+p)$

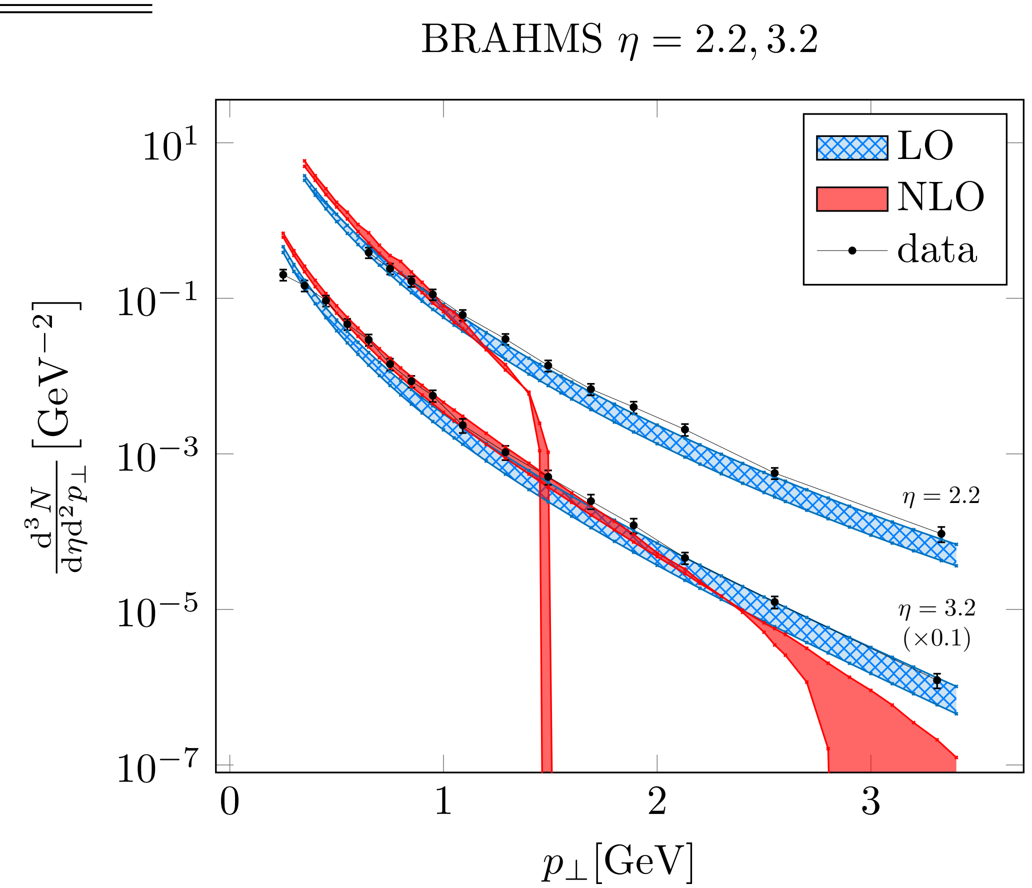
NLO particle production:

- Light and heavy production computed at NLO in the hybrid formalism: collinear parton through a dense target, forward η, yields LO DGLAP PDFs/FFs and LO BK dipoles. [Chirilli-Xiao-Yuan+Stasto-Zaslavsky-Wanatabe, Altinoluk-Kovner+Armesto-Beuf-Lublinsky, Kang-Vitev-Xing, Ducloue-Lappi-Mantysaari-Zhu]



- Negative results at large rapidities from the original CXY calculation, with dependence on the choice of dipole.

➜ Note: hybrid valid for $p_T^2/s_0 \ll 1$.



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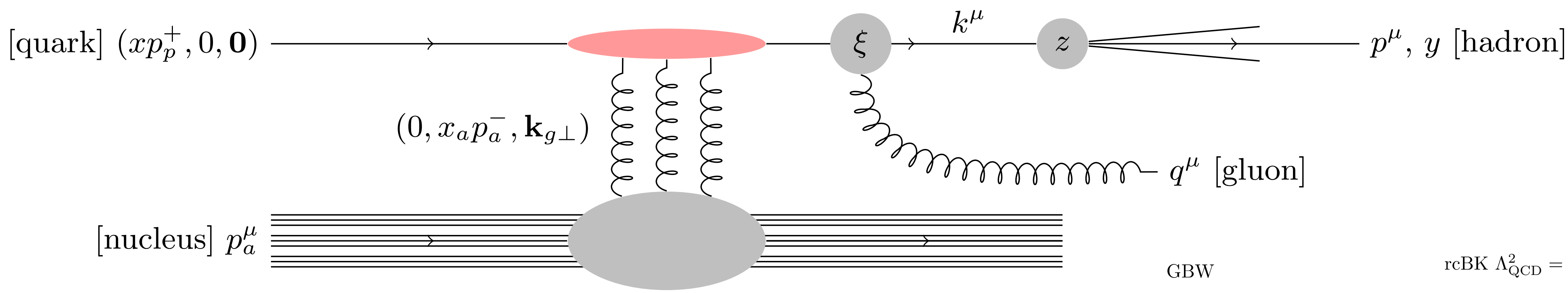
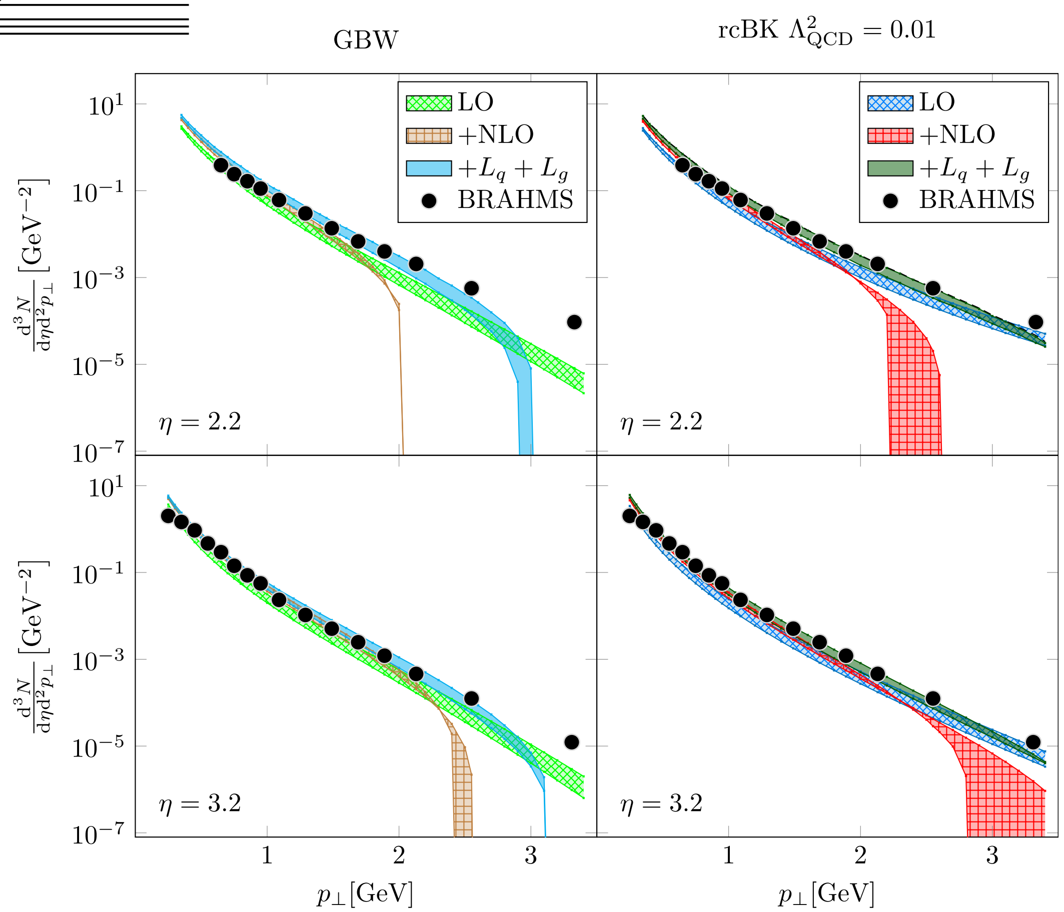


- Only fluctuations that are long lived are resolved coherently by the target: Ioffe time restriction, equivalent to P- ordering from the target nucleus.

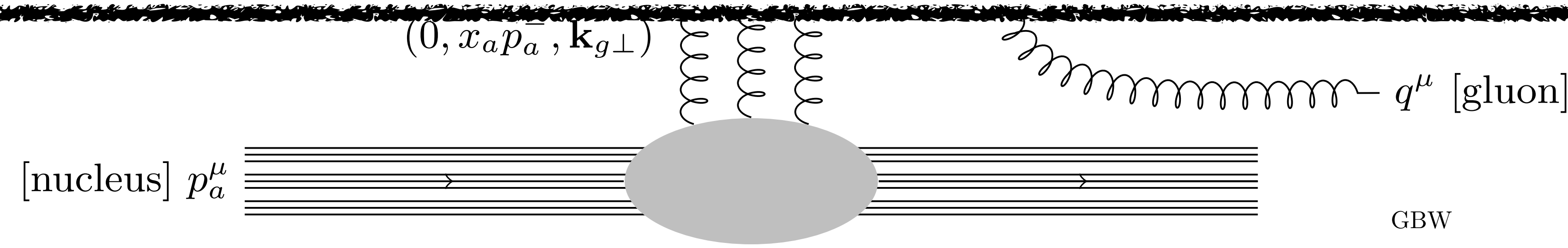


$$P^-_{pair} = \frac{k_\perp^2}{2\xi(1-\xi)x_B P^+} < P^-_T \Longrightarrow t_{Ioffe} = \frac{2\xi(1-\xi)x_B P^+}{k_\perp^2} > \tau = \frac{2P^+}{s_0}$$

NLO particle production:

• Work ongoing to cure deficiencies of NLO BK and of single particle production through resummations [Iancu-Mueller-Tryantafillopoulos, Lappi-Ducloue-Zhu].

• Extension to photons+jets and the relation with the TMD factorisation formalism (1802.01398).



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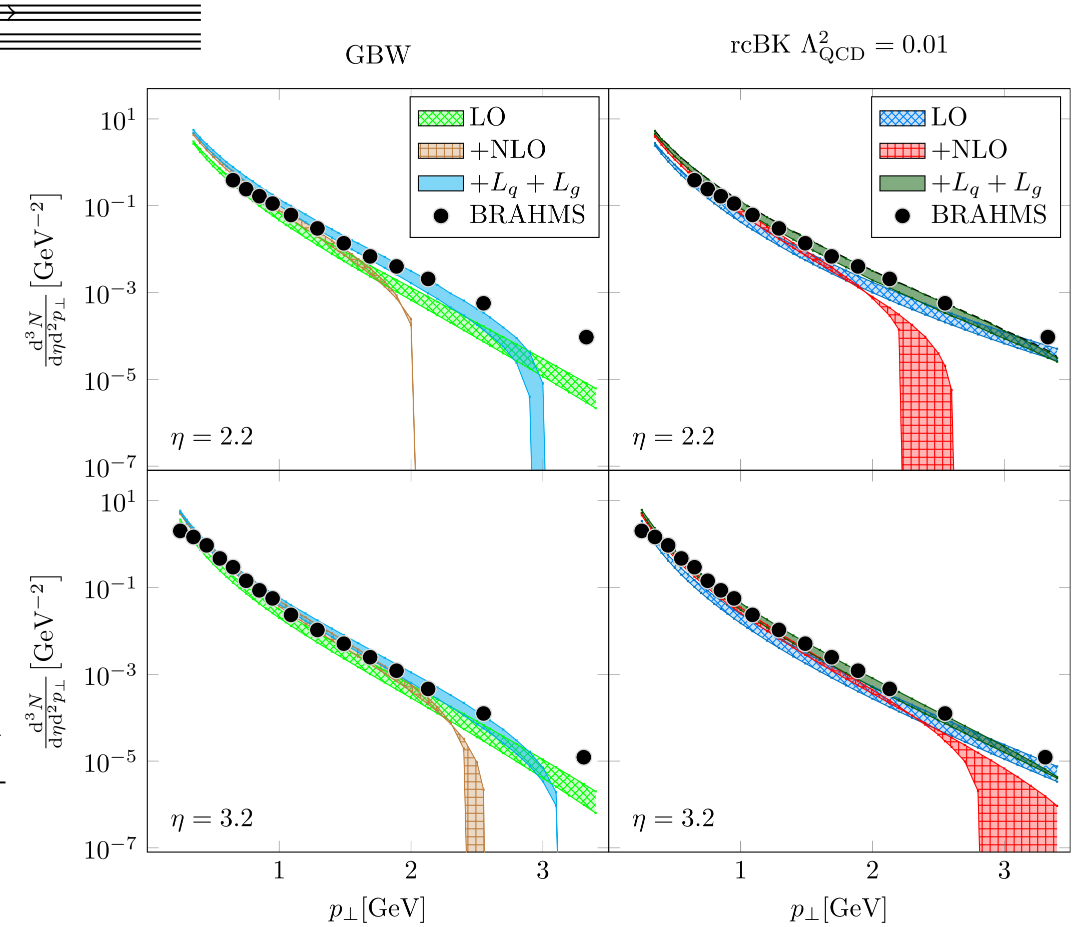

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Contents:

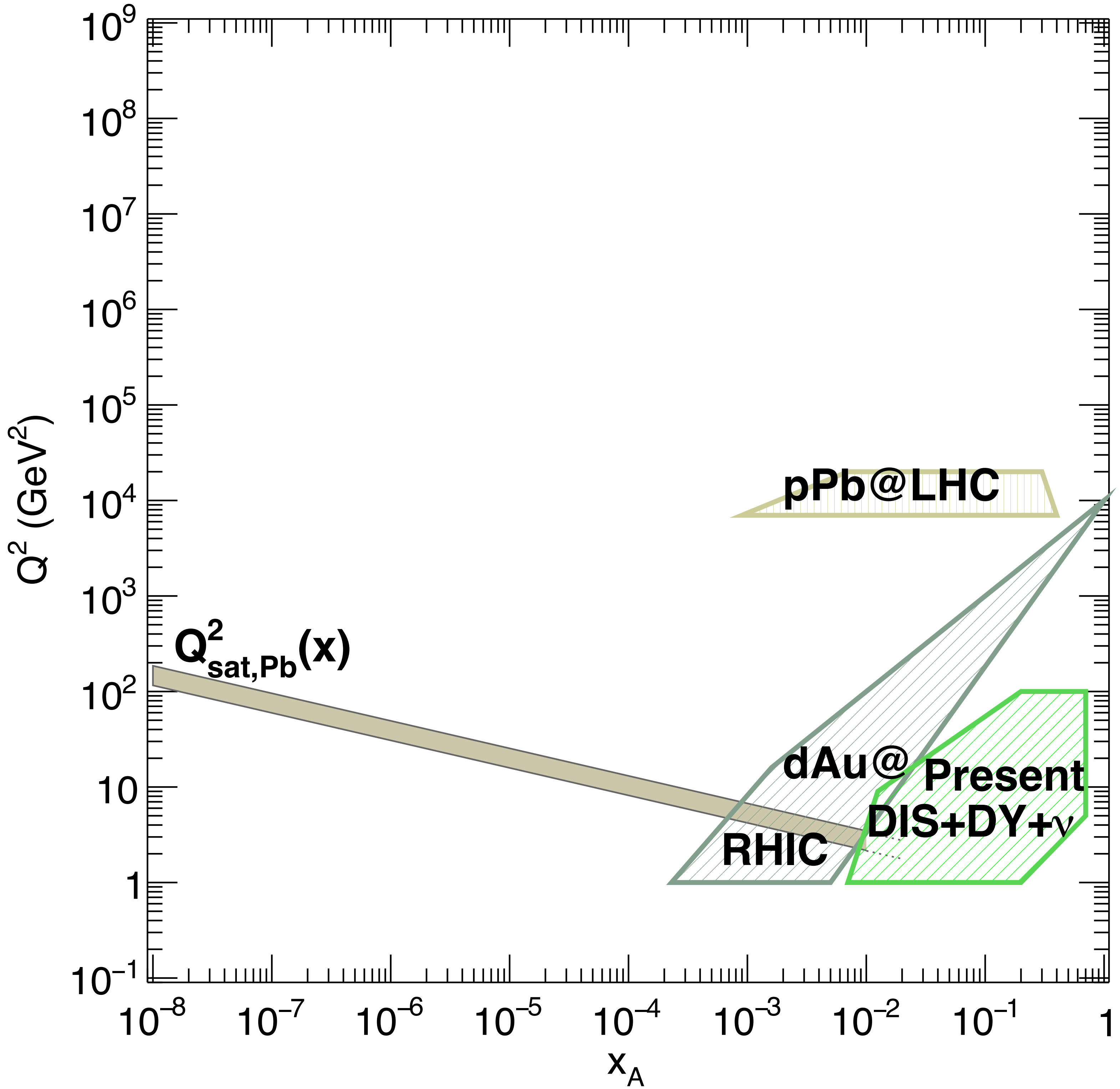
1. Motivation.

2. A few recent topics:
   - ➜ Nuclear parton densities.
   - ➜ Particle correlations.
   - ➜ NLO calculations.

3. Implication in future experimental programmes.

Note: I am limiting the presentation to activities at IGFAE (in collaboration with LIP when applicable).

Our implication:



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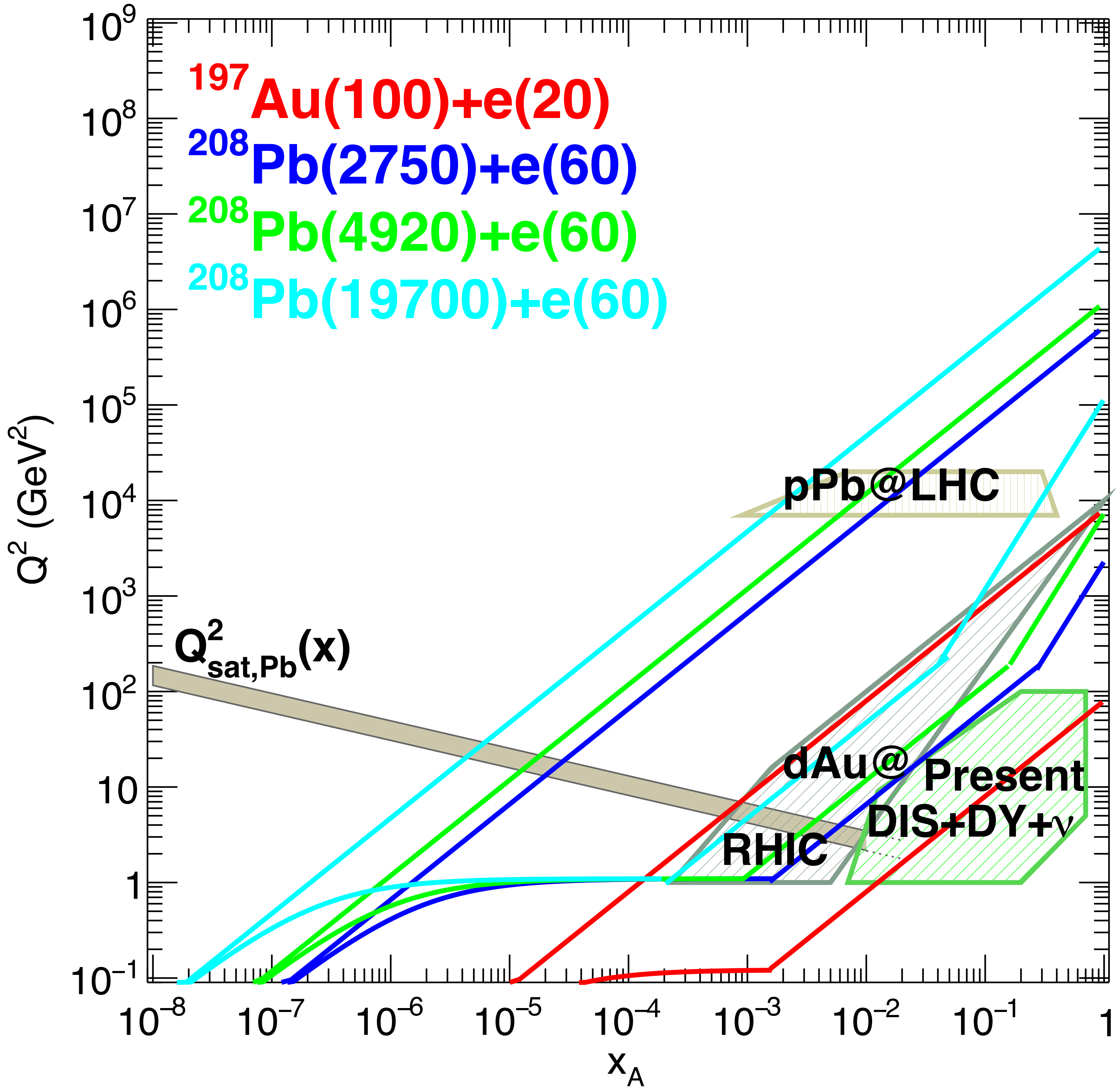

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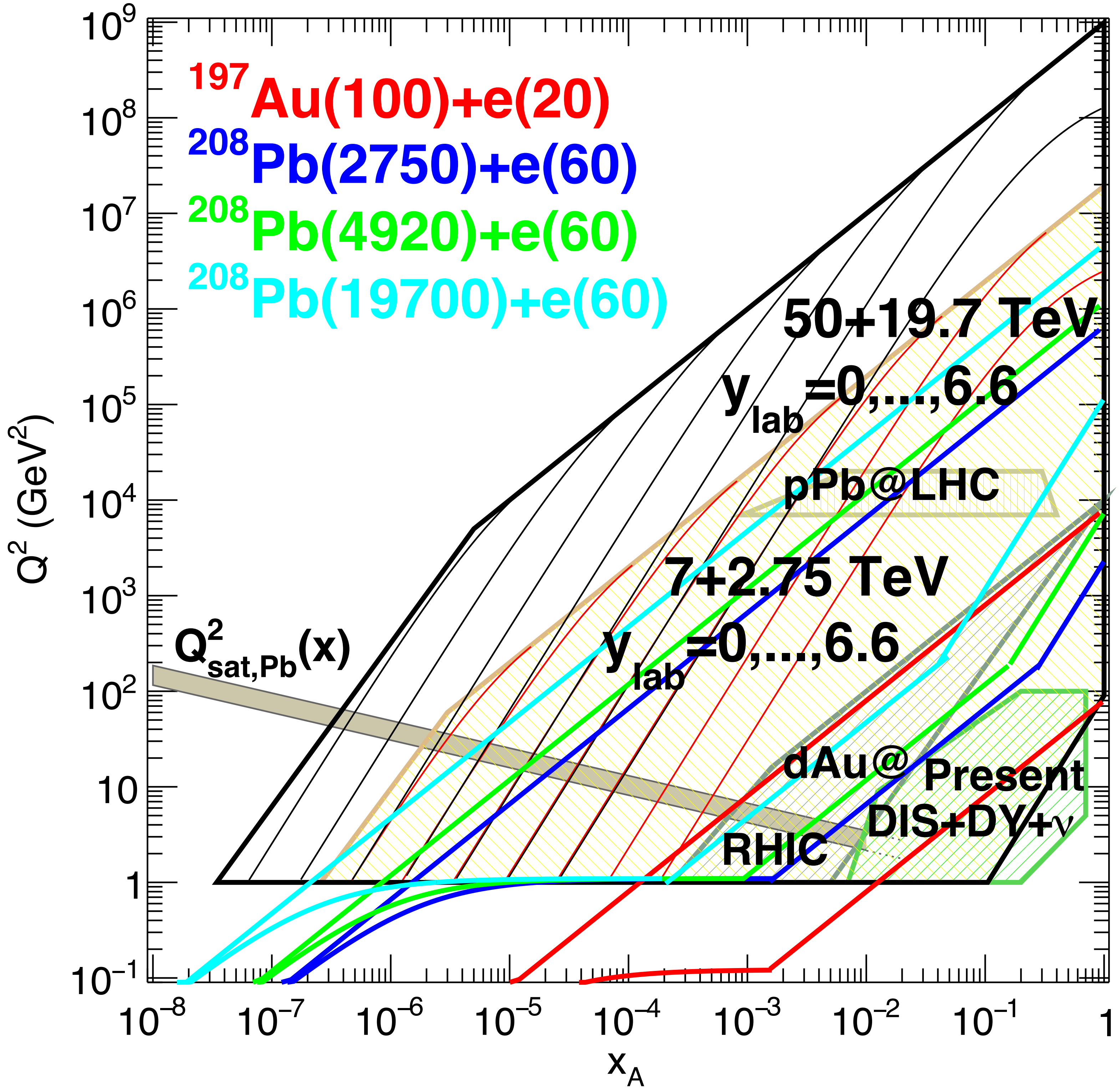

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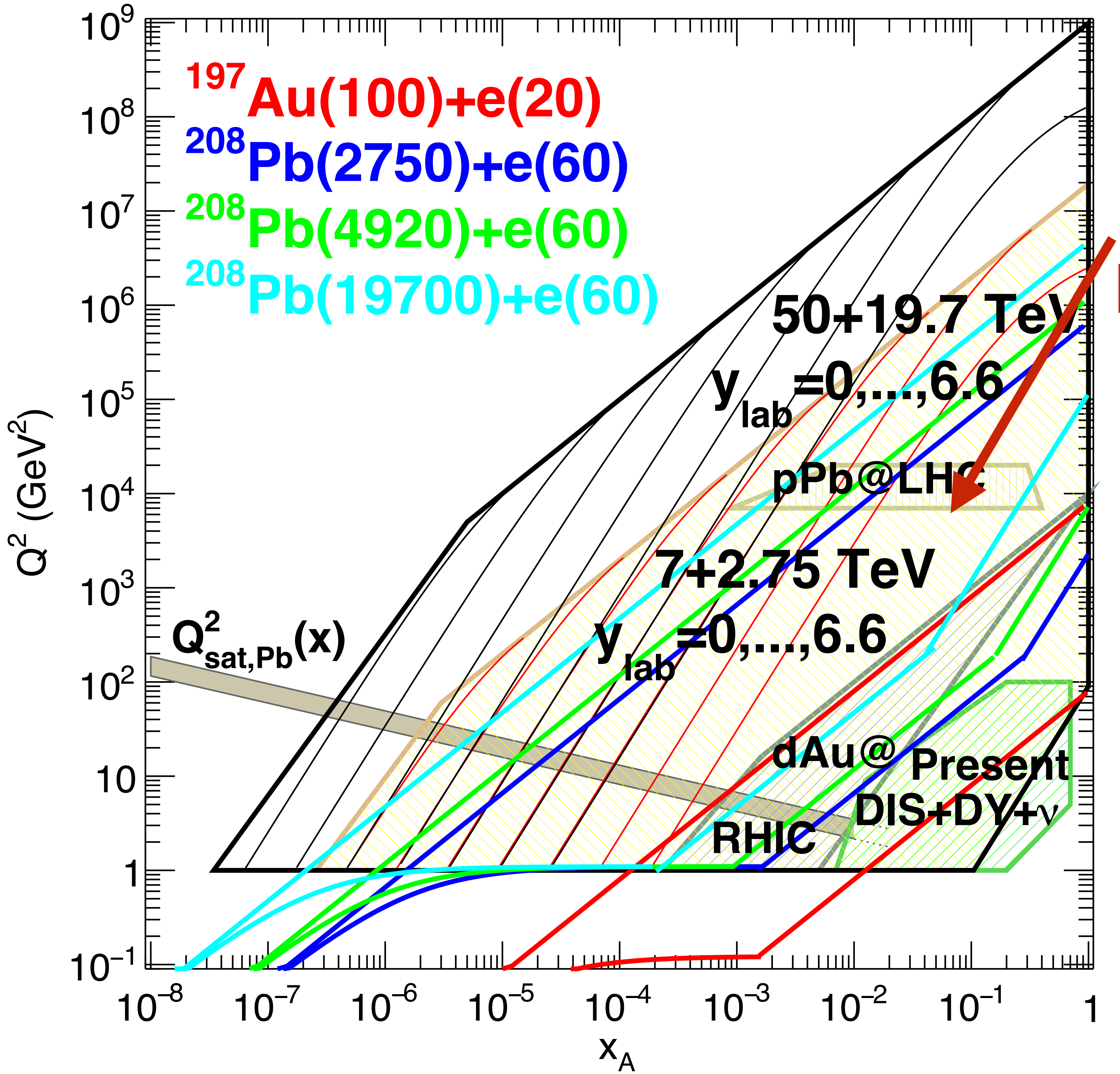

HL-LHC and fixed target programmes at the LHC

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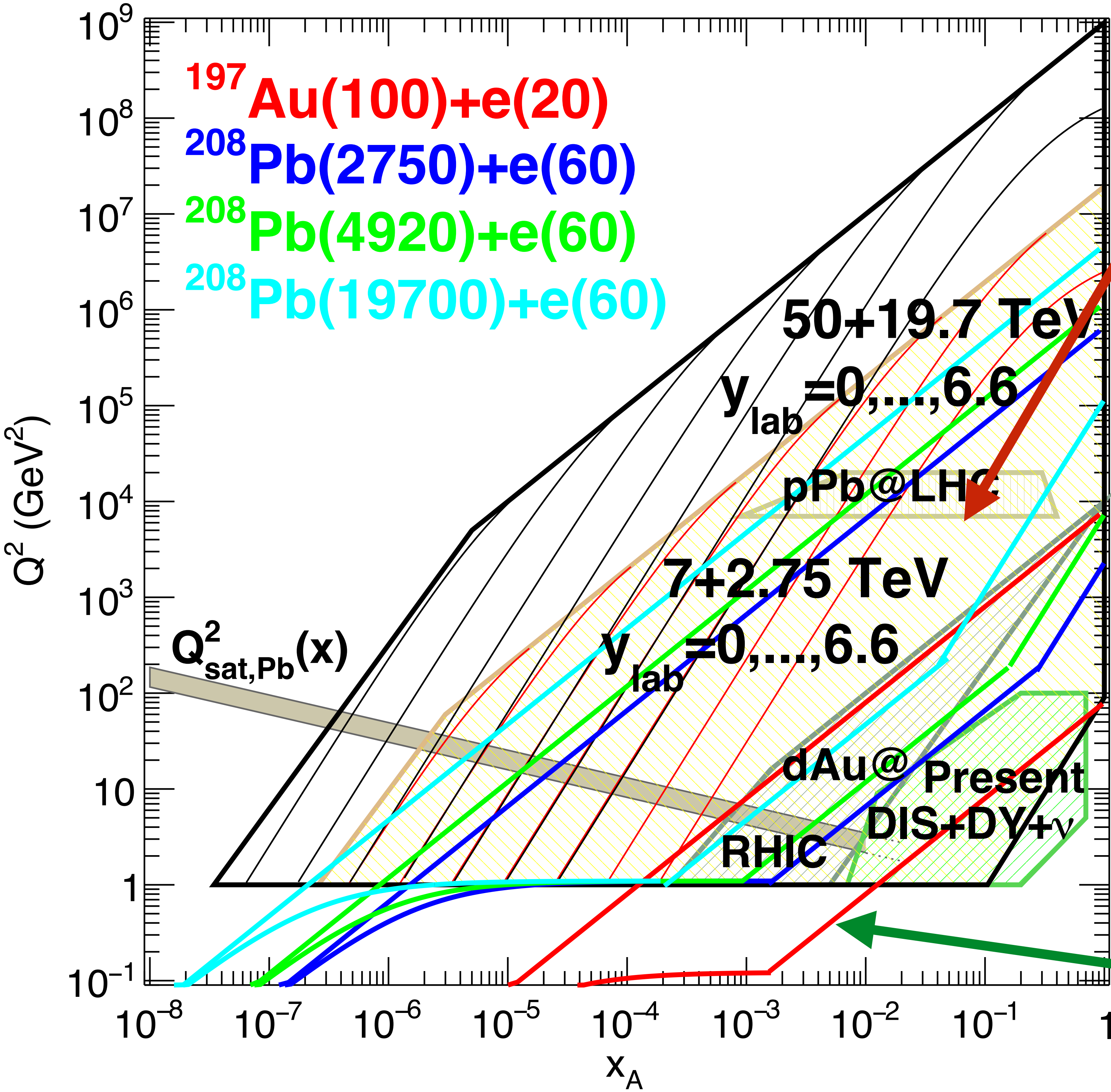

HL-LHC and fixed target programmes at the LHC

EIC

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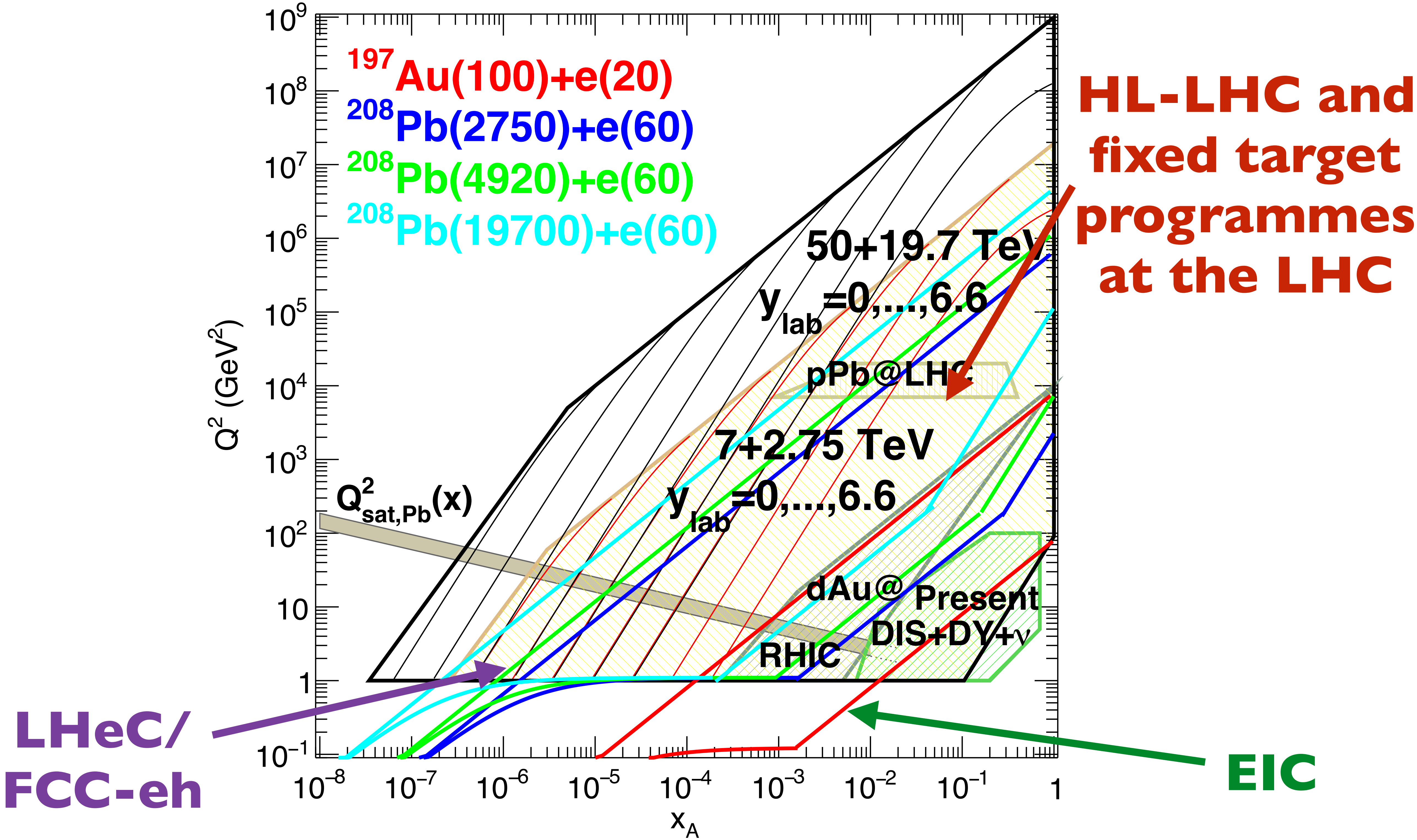

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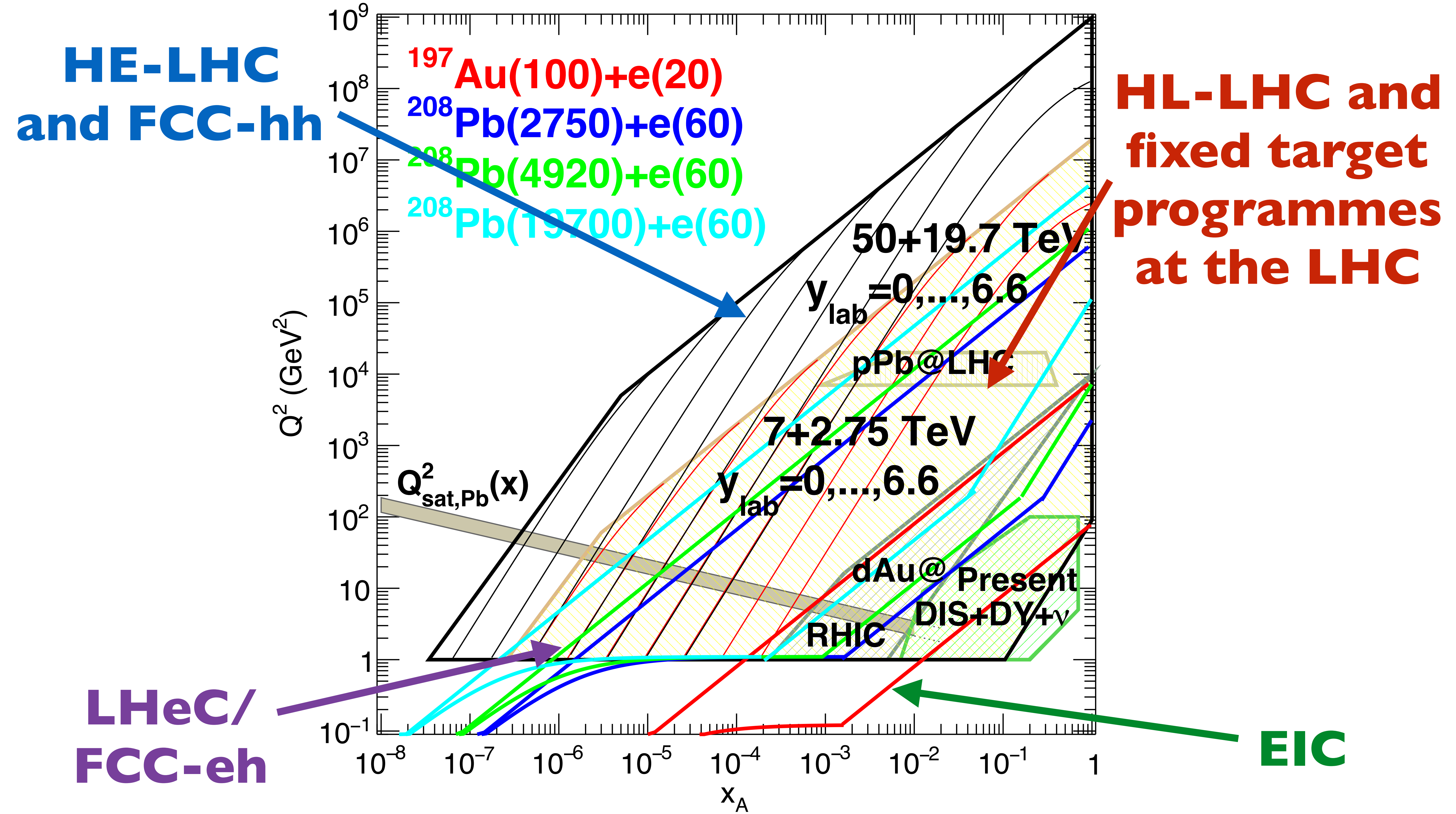

Summary:

- Small-x physics is a hot topic both from the theoretical point of view: high-energy behaviour in Quantum Field Theory, and from an experimental point of view: pp, pA, AA and electron-ion colliders.
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➜ Thank you to the organisers for their invitation and arranging all this.

➜ Thanks to people at LIP, particularly Guilherme and Liliana, for a long collaboration.

➜ Thank you very much for your attention!!!