EXCELENCIA
MARÍA
DE MAEZTU

IGFAE
Instituto Galego de Física de Altas Enerxías

USC
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DE SANTIAGO
DE COMPOSTELA

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DE GALICIA

12th International Workshop on Multiple Partonic Interactions at the LHC
LIP, Lisbon, October 15th 2021

Role of MPI to HI

- What can we learn about MPIs in Heavy-Ion collisions?
- What are the current experimental and theoretical challenges?
- Complementary of future LHC data with next machines like FCC, EIC, etc for studying MPI in nuclear targets

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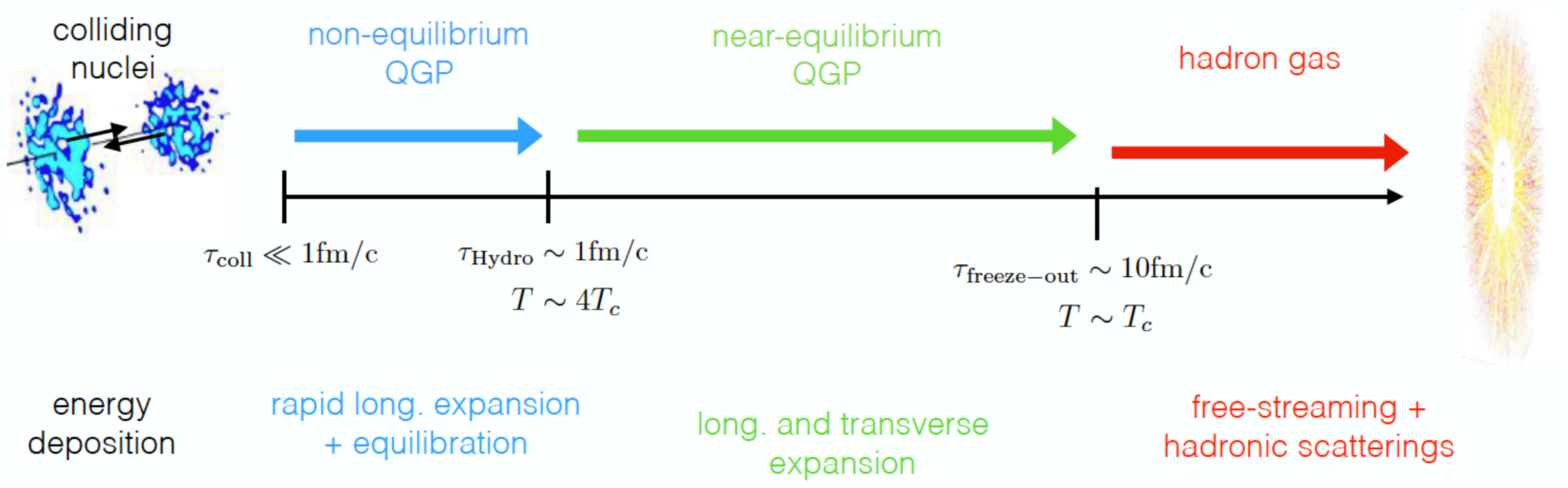
STRONG 2020

AGENCIA ESTATAL DE INVESTIGACIÓN

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMIA Y COMPETITIVIDAD

Picture of a HI collision:



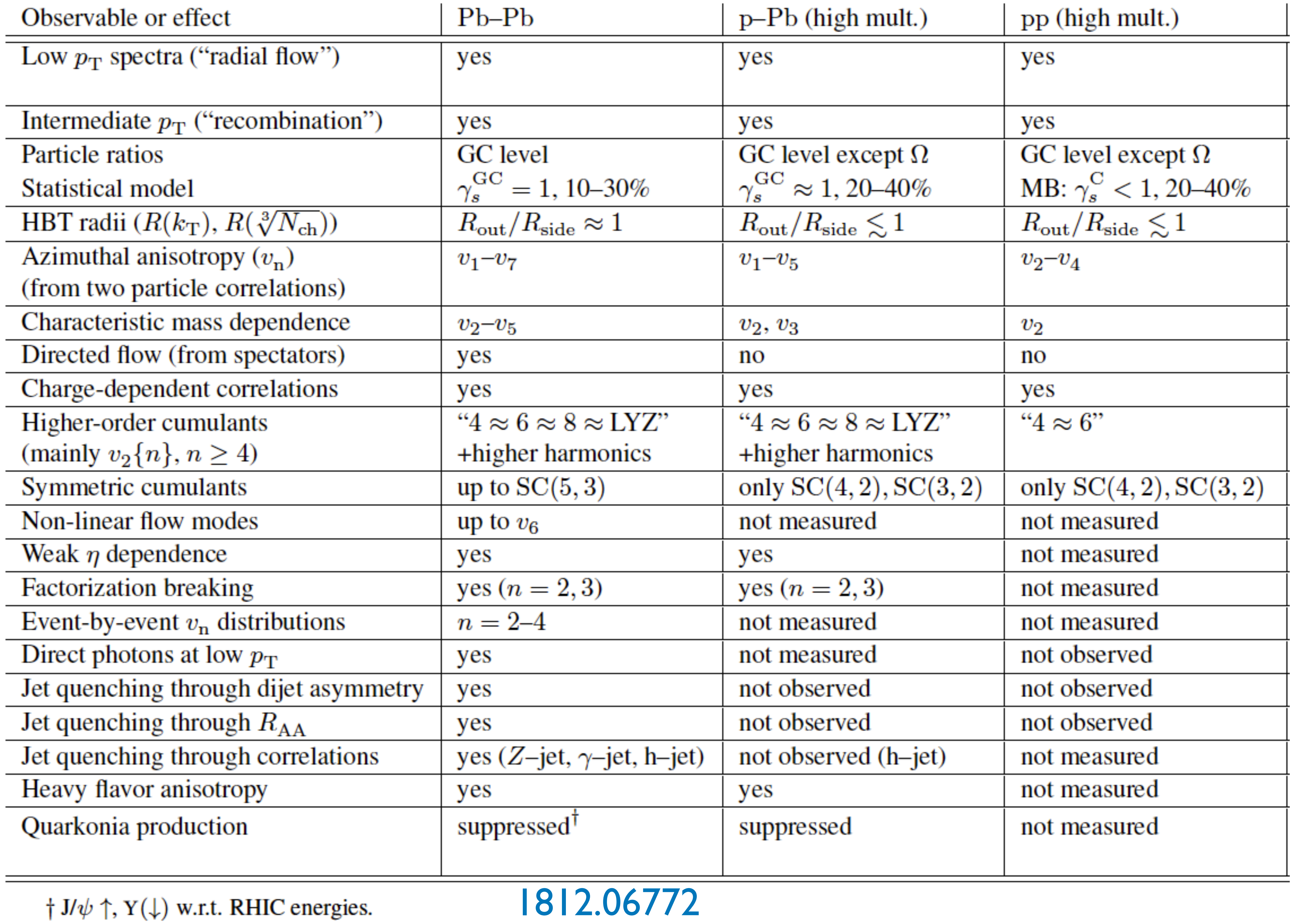
S. Schlichting

Soft/semihard particle production: MPIs built in models e.g. Glauber, CGC,…

Weak (kinetic theory) or strong coupling: AdS/CFT, string interaction (fusion, shoving, CR?,…)

Modification of hadronisation in a dense system: statistical hadronisation/coalescence, rescattering (transport),…

Small systems:



Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
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 MB: $\gamma_s^{C} < 1$, 20–40%
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
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	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_n distributions	$n =$ 2–4	not measured	not measured
Direct photons at low p_T	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

† J/ψ ↑, Υ(↓) w.r.t. RHIC energies.

1812.06772

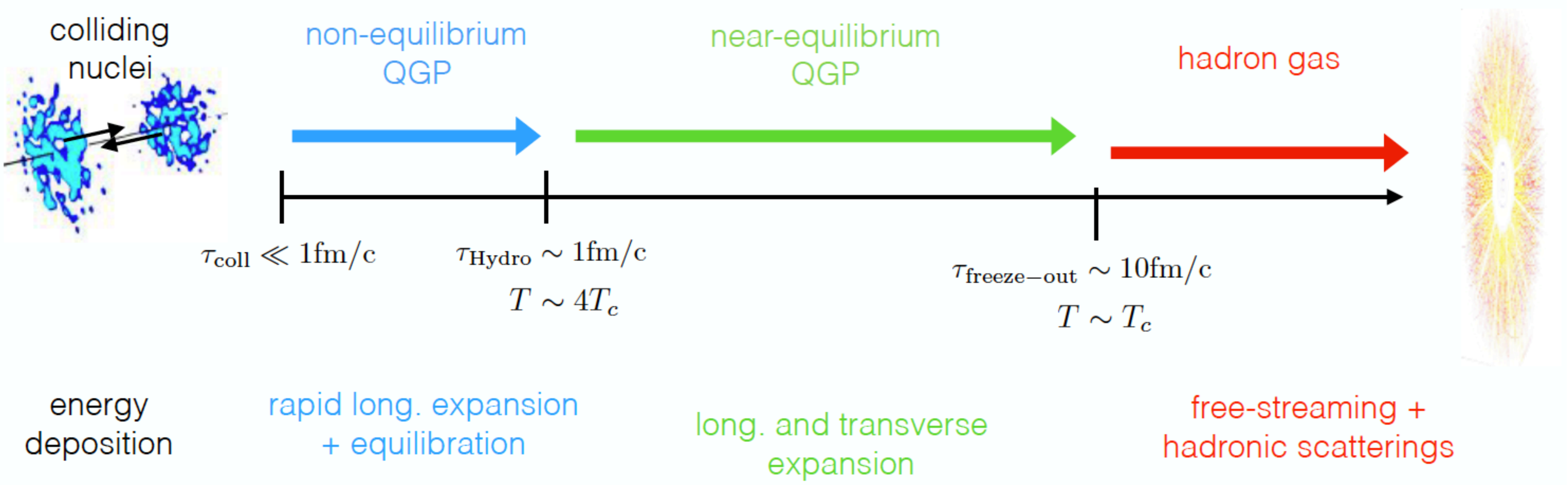
- Many of the observables in AA taken as signatures of QGP are also seen in pp and pA.

- Viscous hydrodynamics can be applied out of equilibrium (checked both at strong and weak coupling), works outside its domain of applicability.

⇒ Need of clarifying the role of initial state effects.

- MPIs are within any model of multiparticle production: they can be **signal** (e.g. correlations that survive until the final stage of the collision) and **background** (on top of which we see the QGP effects whose modelling needs MPIs in any case e.g. for the initial conditions).

What can we learn about MPIs in HI (or pA)?



colliding nuclei

non-equilibrium QGP

near-equilibrium QGP

hadron gas

$\tau_{\rm coll} \ll 1{\rm fm/c}$

$\tau_{\rm Hydro} \sim 1{\rm fm/c}$

$T \sim 4T_c$

$\tau_{\rm freeze-out} \sim 10{\rm fm/c}$

$T \sim T_c$

energy deposition

rapid long. expansion + equilibration

long. and transverse expansion

free-streaming + hadronic scatterings

S. Schlichting

The initial condition problem: to which extent can we constrain multiparton densities in proton and nuclei and MPI size from the observed (LR) correlations?

Can we get a better understanding of the early phase e.g. through hard probes (1st splittings in jet evolution, relation between $R_{(p)AA}$ and v_2)?

Which observables are less dependent of the final state, i.e. they respond better to the multiparticle production mechanism?

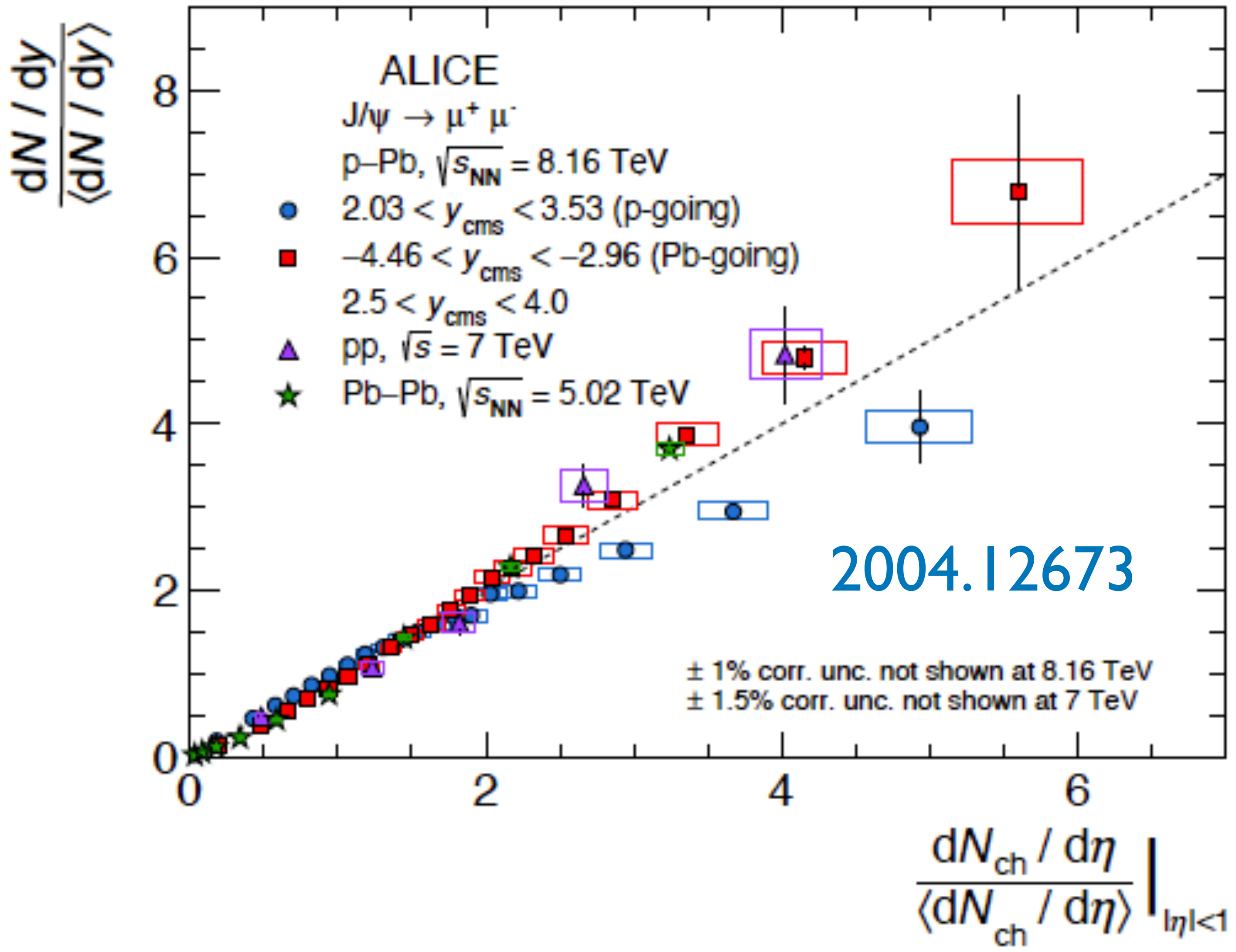
Challenges:

- How can we constrain multiparton densities? Can we design a program analogous to that of PDFs (or TMDs)?

- Better evolution towards small x. What we have, JIMWLK@resumNLO, has several limitations.
- Can we extend the relation between the TMD formalism and the CGC at small x to multiparton densities? We need it if we want to use low energy results for higher energies.

- Is there a relation between different, strong and weak coupling approaches, for the initial stage? As examples:

  ➜ CGC → Glasma → flux tubes → string models.
  ➜ Kinetic theory or AdS/CFT → macroscopic description by viscous hydrodynamics.



2004.12673

- Final state effects, if any, are also enhanced in the nuclear case.

- Centrality dependence of nuclear effects?

Complementarity of future facilities with the LHC:

- Varying A safer than centrality, over all in pA: future O run, lighter ions beyond Run 4?

$$\sigma^{pA}_{CD}(b) = AT(b)\sigma^{pp}_{CD} + A(A-1)\sigma^{pp}_{C}\sigma^{pp}_{D}T^{2}(b) + \cdots, \quad \sigma^{pp}_{C}, \sigma^{pp}_{D} \ll \sigma^{pp}_{in}$$

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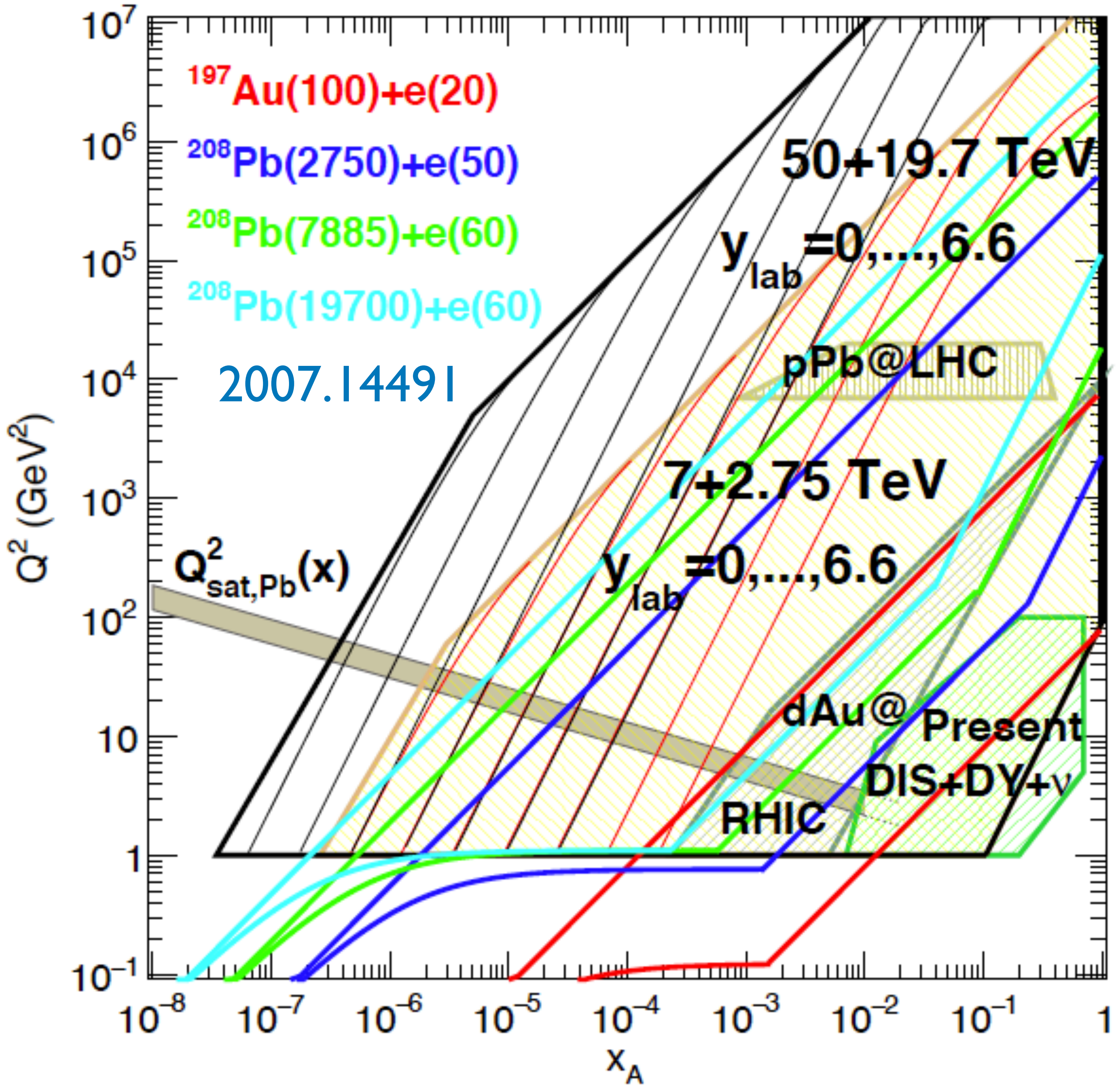
- Intrinsic DPS inside a nucleon-nucleon collision less enhanced by A than internucleon ones: vary A and the pp cross sections (e.g. with cuts or varying the energy) to disentangle different contributions.



- eA cleaner both experimentally and theoretically, but limited in kinematics, need of evolution towards high Q^2 and small x.

- UPCs to examine smaller systems at the LHC. e^+e^- colliders can also offer information, e.g. colour reconnections, double hadron FFs.

- Higher energies and higher luminosities (FCC):
  - ➜ Higher statistics for rarer probes and higher scales (dominance of perturbative splittings?).
  - ➜ Increasing cross sections: larger number of MPIs.

Backup

What nuclear collisions can offer:

- Nuclei offer an additional variable to study MPIs: enhancement by A to be combined with the scale of the process to disentangle between different contributions.
- Varying A safer than centrality, over all in pA: future O run, lighter ions beyond Run 4?

$$\sigma_{CD}^{pA}(b) = AT(b)\sigma_{CD}^{pp} + A(A-1)\sigma_C^{pp}\sigma_D^{pp}T^2(b) + \cdots, \quad \sigma_C^{pp}, \sigma_D^{pp} \ll \sigma_{in}^{pp}$$

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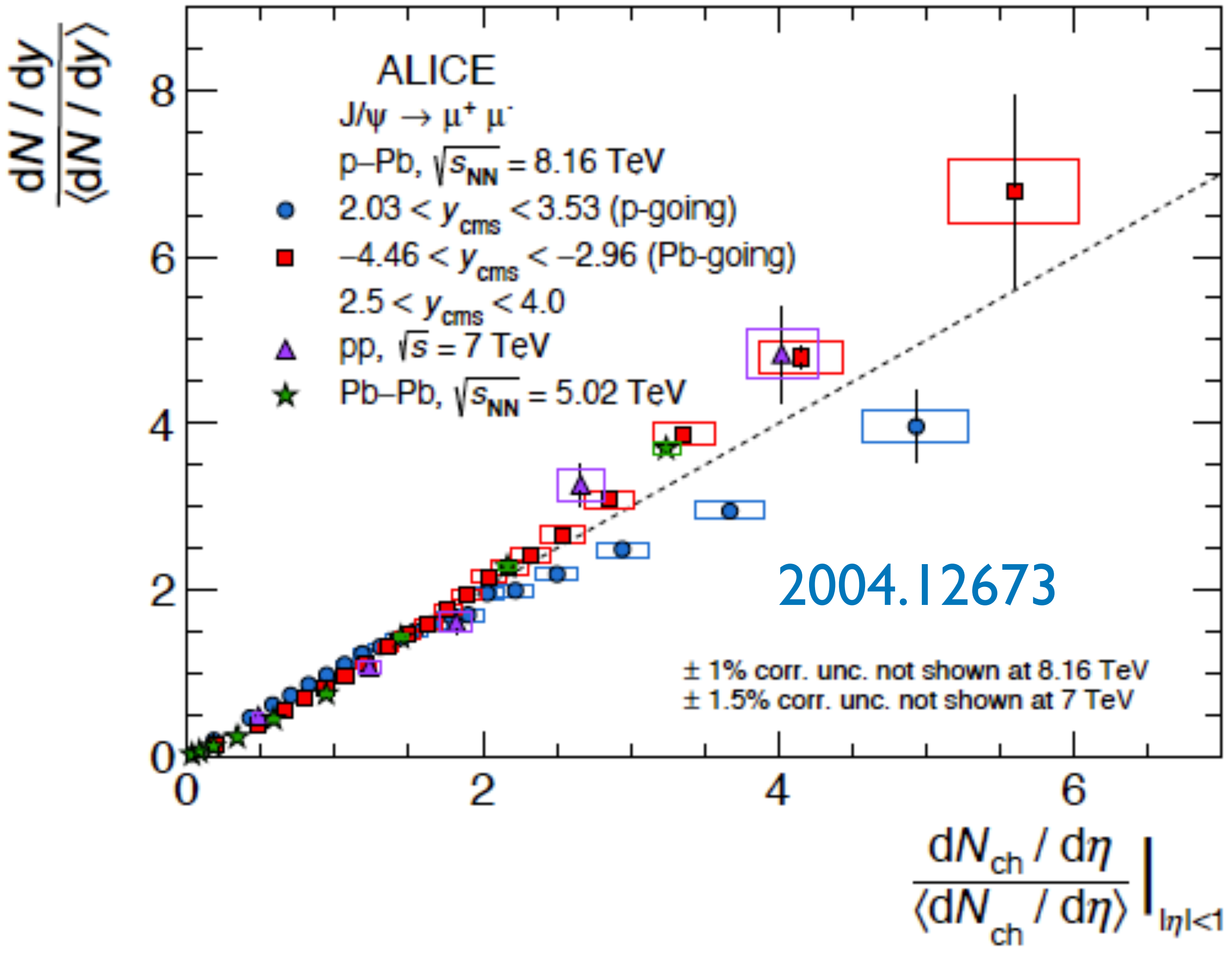
- Final state effects, if any, are also enhanced in the nuclear case.



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$$R_{forward}^{D_1 D_2} = \frac{\sigma_{D_1 D_2}}{\sigma_{D_1 \bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

$$R_{backward}^{D_1 D_2} = 0.391 \pm 0.019 \pm 0.025$$

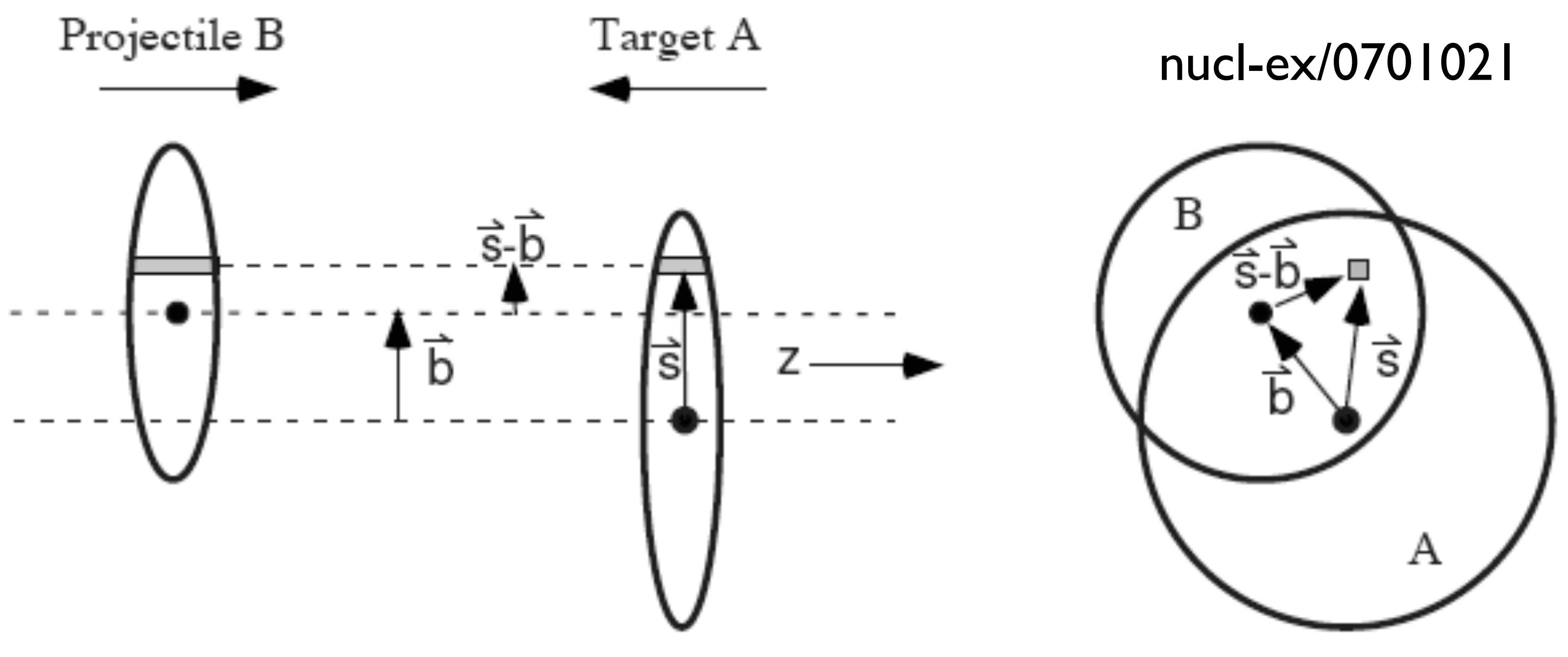
$$R_{pp}^{D^0 D^0} = 0.109 \pm 0.008$$

LHCb, A. F. Bursche

- MPI is nothing less than the business of multiparticle production…

MPIs were always there (I):

- The Glauber-Gribov model is a QFT result, based on the factorisation of the nuclear scattering amplitudes, that results in a probabilistic interpretation.



a) Side View b) Beam-line View

nucl-ex/0701021

$$\sigma_{in}^{pA(AB)}(b) = 1 - \left[1 - \sigma T_{A(B)}(b)\right]^{A(B)} = \sum_{n=1}^{A(B)} C_n^{A(B)} \left[\sigma T_{A(B)}(b)\right]^n \left[1 - \sigma T_{A(B)}(b)\right]^{A(B)-n}$$

$$\langle N_{coll}(b)\rangle \sigma_{in}^{pA(AB)}(b) = A(B)\sigma T_{A(B)}(b), \quad \langle N_{coll}\rangle = \frac{A(B)\sigma}{\sigma_{in}^{pA(AB)}} \propto \frac{A(B)}{A^{2/3}(+B^{2/3})}$$

$$P(n,m,\vec{b},\vec{s}) = \frac{1}{\sigma} C_n^A \left[\sigma T_A(s)\right]^n \left[1 - \sigma T_A(s)\right]^{A-n} C_m^B \left[\sigma T_B(\vec{b}-\vec{s})\right]^n \left[1 - \sigma T_B(\vec{b}-\vec{s})\right]^{B-m}$$

$$\langle N_A(\vec{b},\vec{s})\rangle = \sum_{n=1}^{A} n \sum_{m=1}^{B} P(n,m,\vec{b},\vec{s}) = A T_A(s) \sigma_{in}^{pB}(\vec{b}-\vec{s}), \quad \langle N_A\rangle \propto \frac{AB^{2/3}}{A^{2/3}+B^{2/3}}$$

- It lies at the root of the extension of MC models to the nuclear case: DPM example

$$\frac{dN}{dy} = N_A(b,s)\frac{dN_1}{dy} + N_B(b,s)\frac{dN_2}{dy} + N_{coll}(b,s)\frac{dN_3}{dy}, \quad N_A \geq N_B$$

dN_i/dy depending on the # of inelastic collisions n (strings, parton interactions) per NN collision, with nucleon multiparton densities in a factorised form $\rho^{(n)}(x_1,\ldots,x_n) = \prod_{i=1}^{n} \rho^{(1)}(x_i)\ \delta(\sum_{j=1}^{n} x_j)$.

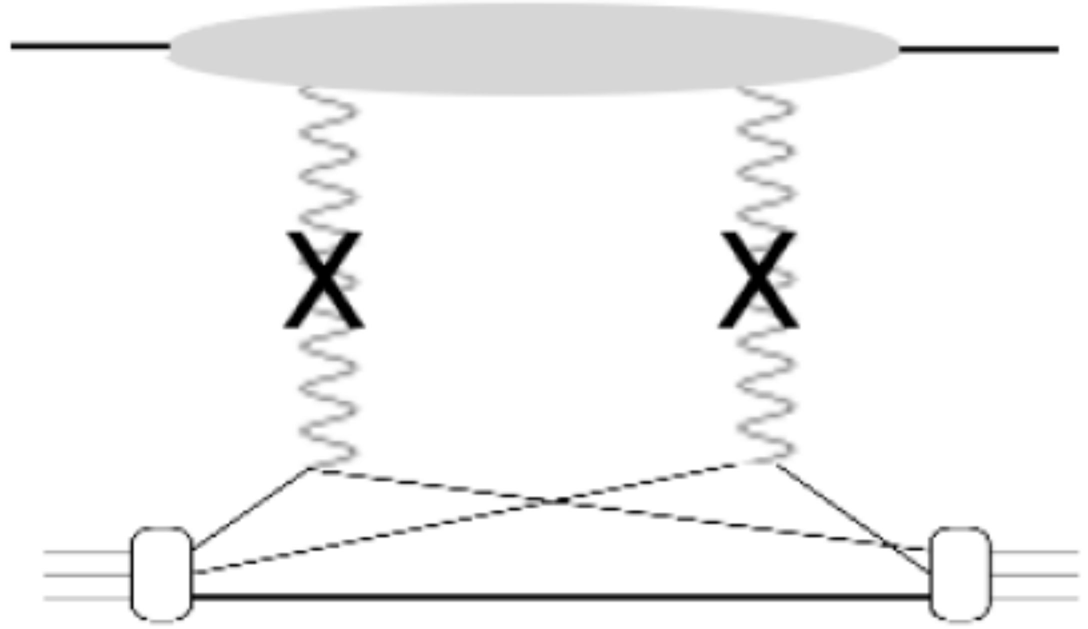
MPIs were always there (II):

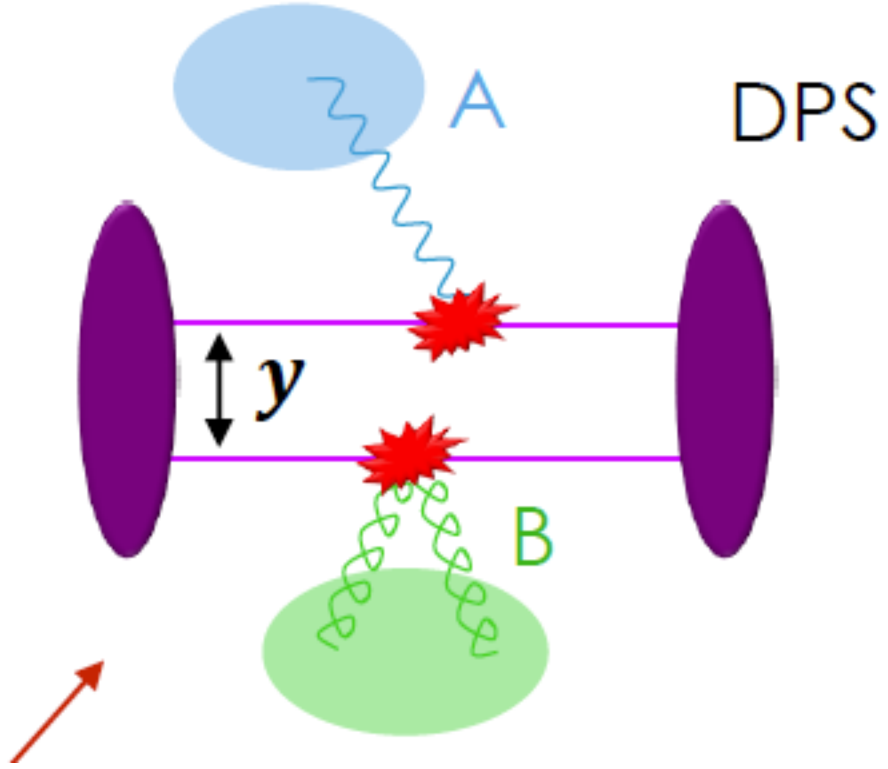
- The minijet cross section $\sigma_{minijet} = f_A(x_i) \otimes f_B(x_j) \otimes \hat{\sigma}(x_i x_j s)$ requires an IR cutoff and increases with increasing collision energy, becoming larger than the inelastic cross section σ_{inel} and thus breaking the unitarity of the theory. Some solutions adopted in MCs:

  ➜ Energy dependent IR cutoff (quite equivalent to a saturation momentum).
  ➜ Unitarise the cross section (usually through an eikonal expression):

$$\sigma = 2\int d^2B \left(1 - e^{-\chi(B,s)}\right), \qquad \chi_h(B,s) = \frac{\sigma_h}{8\pi b_h} \exp\left[-\frac{B^2}{4b_h}\right],$$

- Unitarity implies that there is multiple scattering which in turn implies multiple parton interactions.





J. Gaunt