UNRAVELING THE MOST PERFECT LIQUID AT THE LHC

Guilherme Milhano

LIP & IST (Lisbon)
gmilhano@lip.pt

LIP
TÉCNICO LISBOA
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

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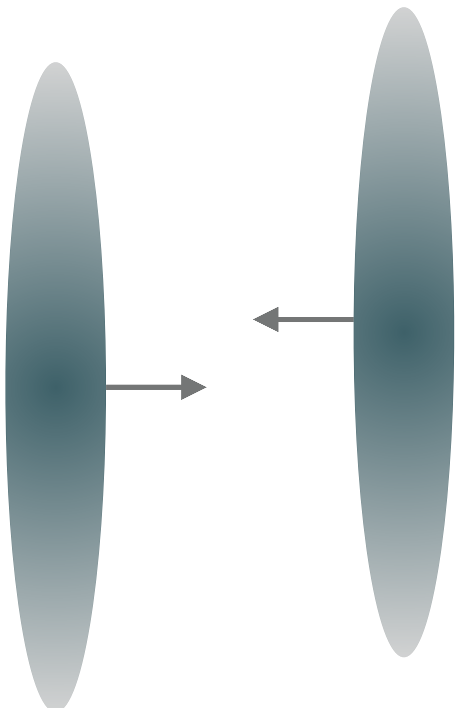
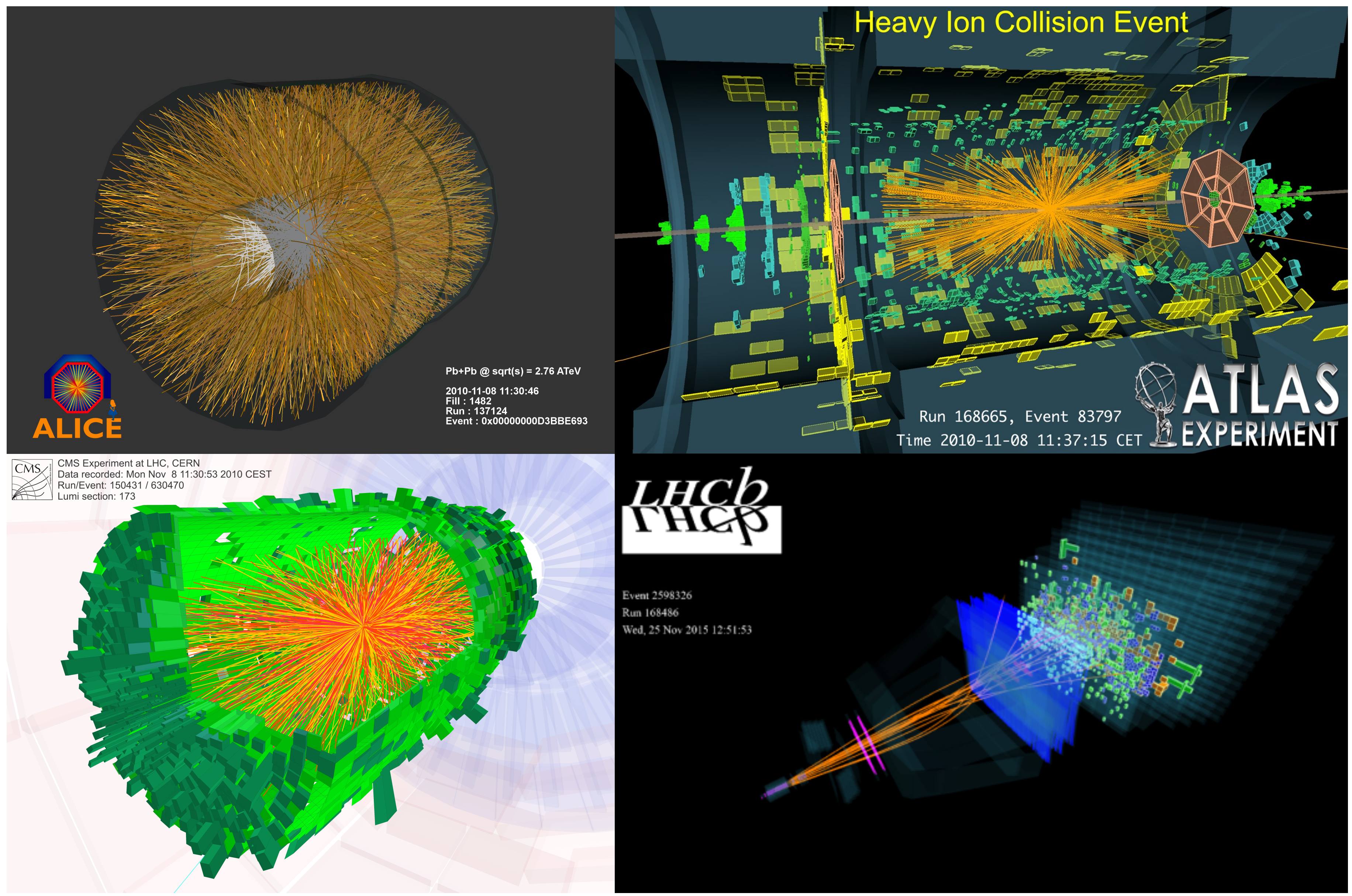
HEAVY-ION PHYSICS [SCOPE]



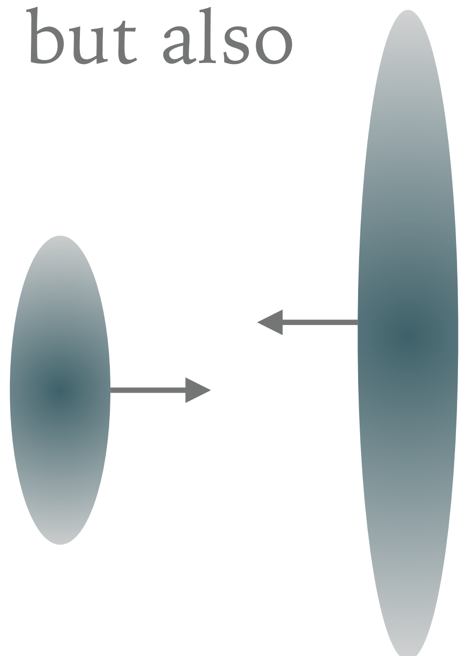
:: the physics of ultra-relativistic collisions of heavy nuclei

PbPb@LHC, {AuAu,CuCu,UU}@RHIC, {PbPb,InIn}@SPS[fixed target], ...



HEAVY-ION PHYSICS [SCOPE]

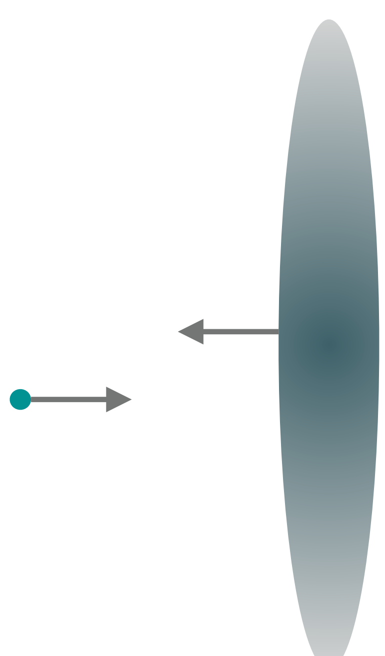
:: but also



:: light[er]-heavy ion collisions

{CuAu, dAu}@RHIC

:: which [obviously] includes



the lightest of all ions

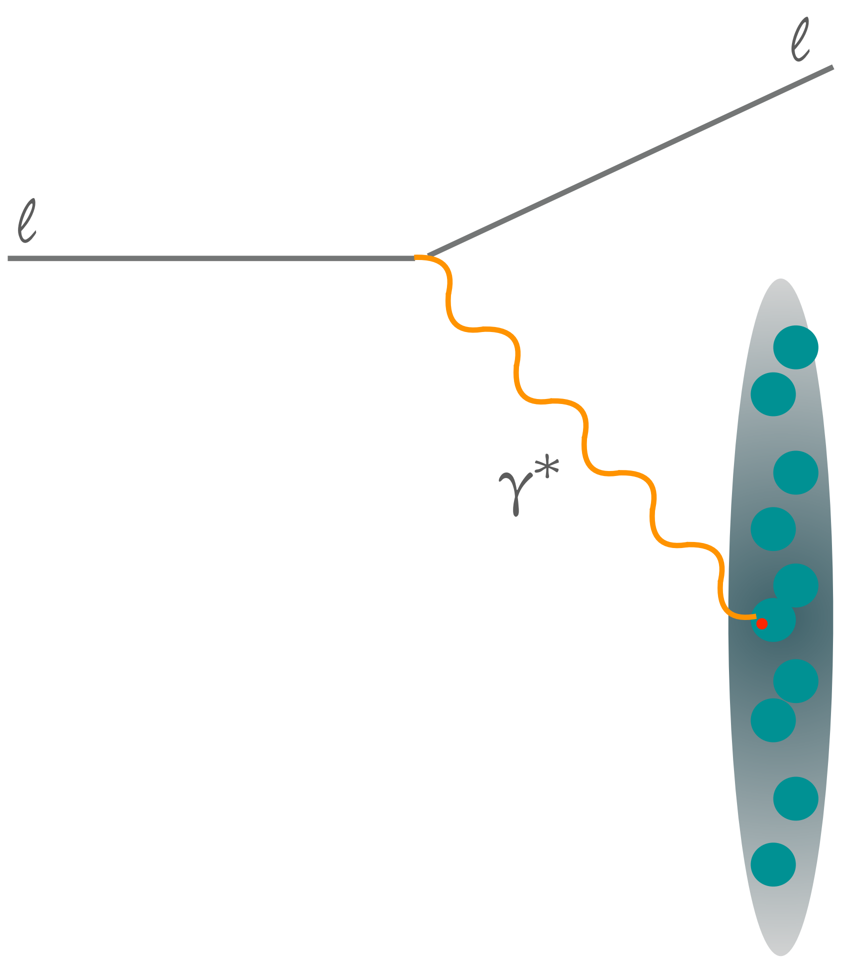
:: proton-nucleus collisions

pPb@LHC

HEAVY-ION PHYSICS [SCOPE]

:: and deep-inelastic scattering off nuclei

[EIC@{BNL/JLAB}, LHeC, FCC-eA] ???



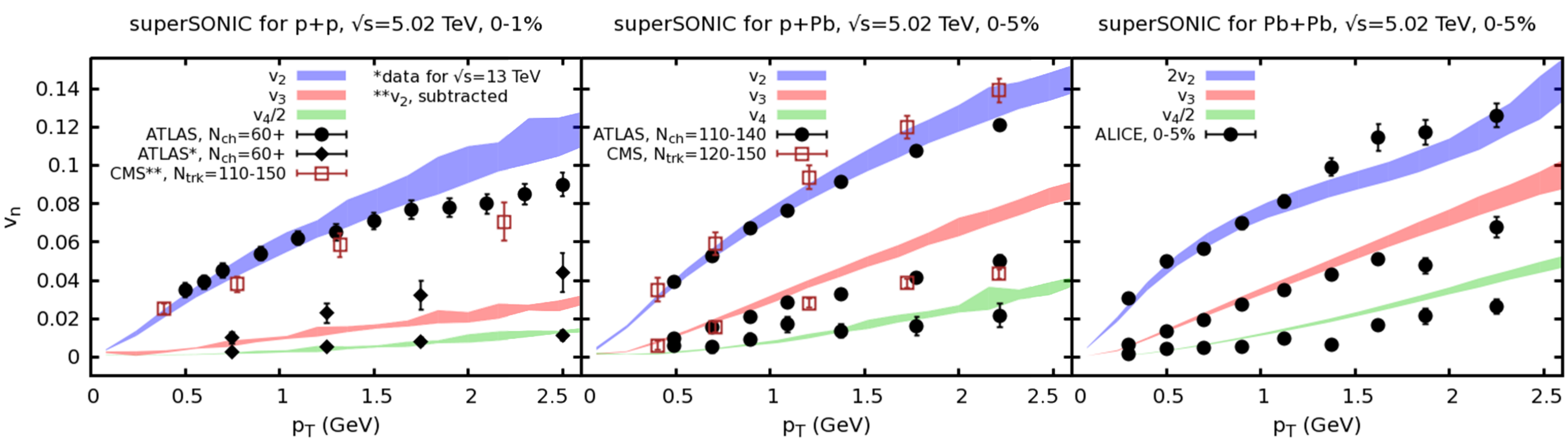
which is essential to know the initial conditions of a heavy-ion collision

:: the structure of the colliding nuclei at all relevant scales [nuclear PDFs]

HEAVY-ION PHYSICS [SCOPE]

:: and, less obviously,

:: whenever 'heavy-ion–like' behaviour is involved



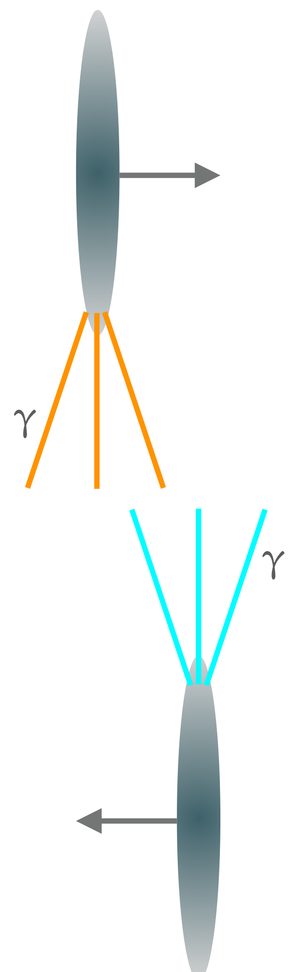
Weller and Romatschke :: 1701.07145 [nucl-th]

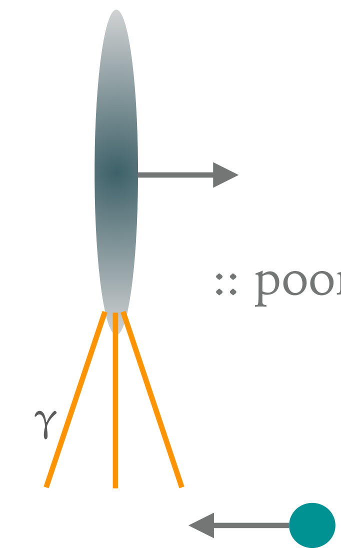
collectivity hallmarks of heavy-ion collisions also observed

in pPb and [high-multiplicity] pp collisions

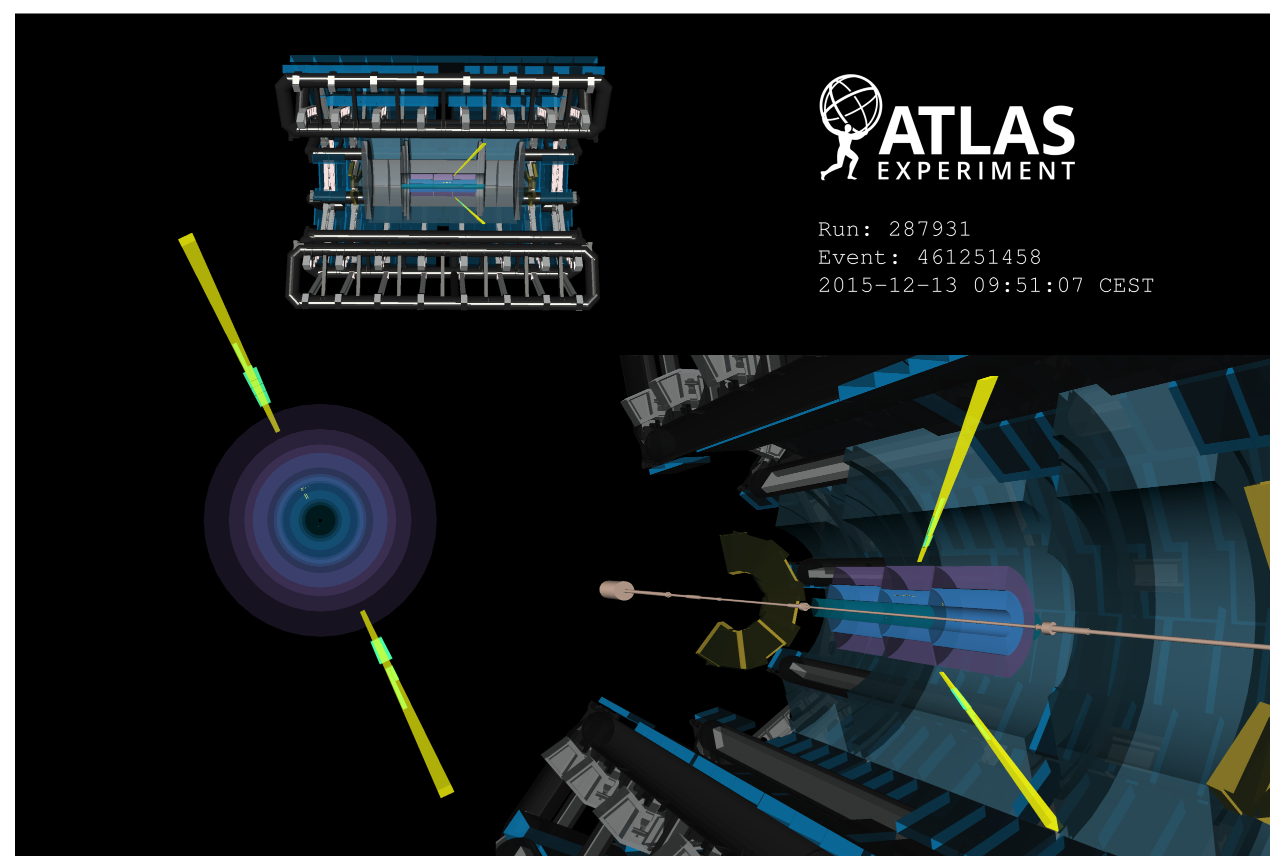
HEAVY-ION PHYSICS [SCOPE]

:: and, even less obviously, nuclei as EM field sources





:: poor [wo]man's DIS

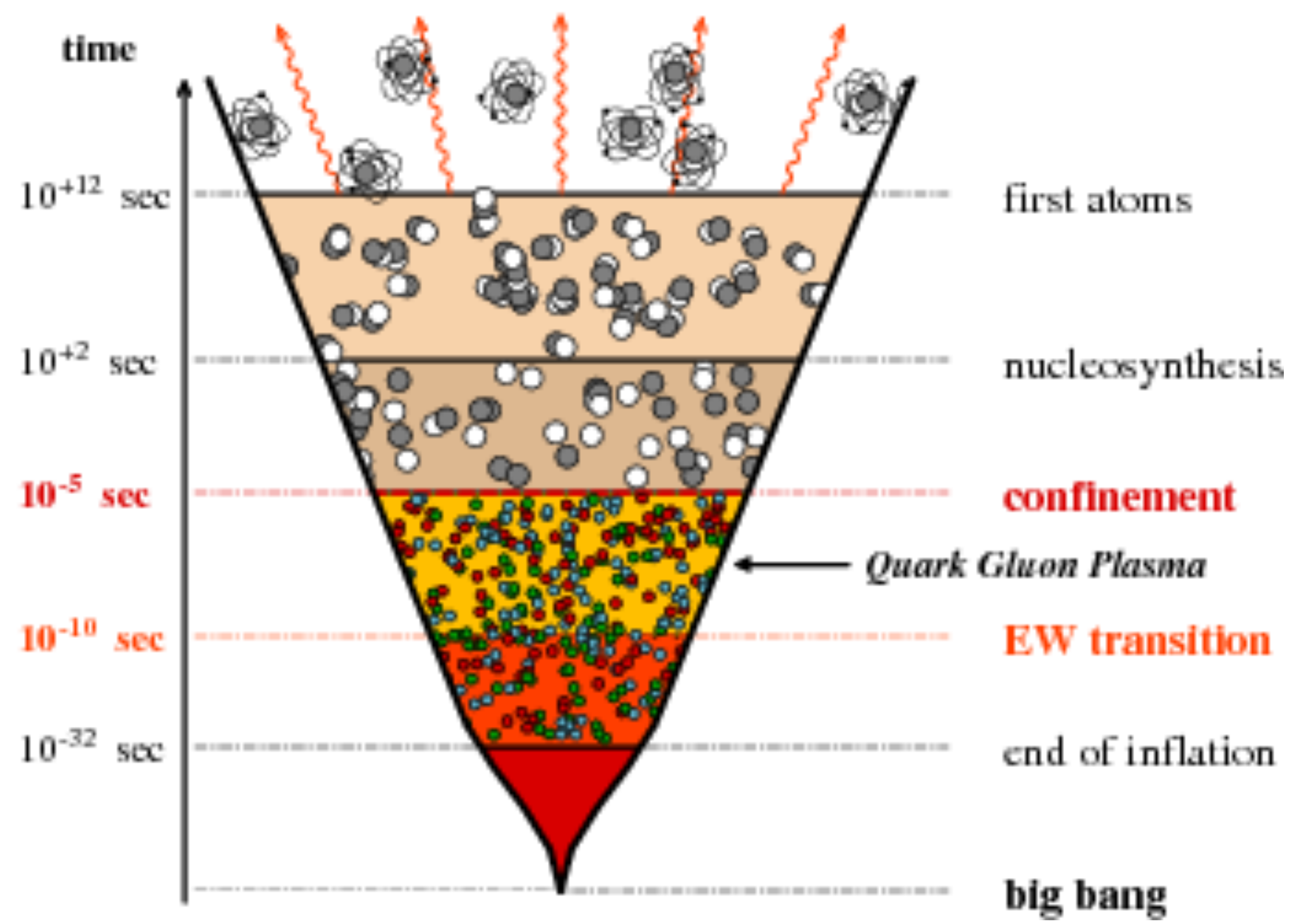


$\gamma\gamma \rightarrow \gamma\gamma$

classically forbidden process

HEAVY-ION PHYSICS [PURPOSE]

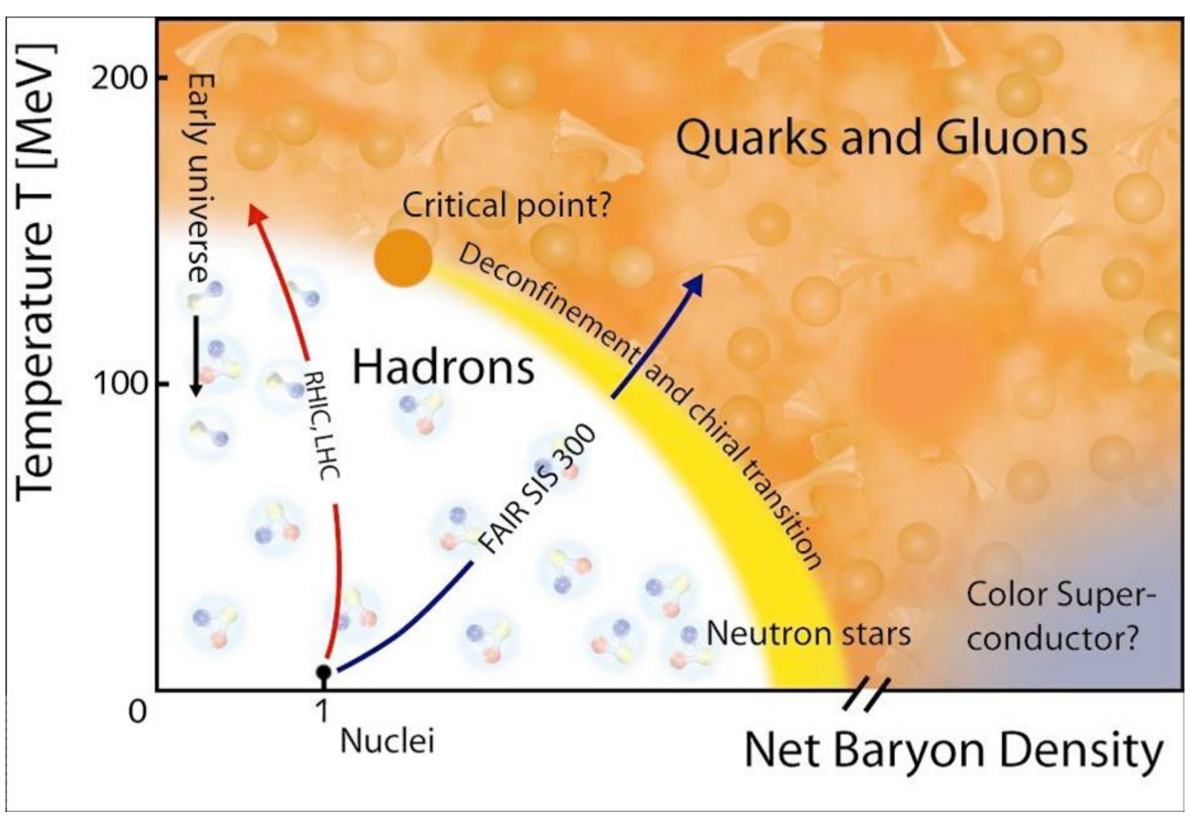
- ✓ explore and understand fundamental properties of matter at the most extreme temperatures [~10^5 higher than the Sun's core] and density achievable in a laboratory
  - ✓ make droplets of early Universe [($10^{-12(-10)}$ to $10^{-6(-5)}$ seconds after the Big Bang] matter

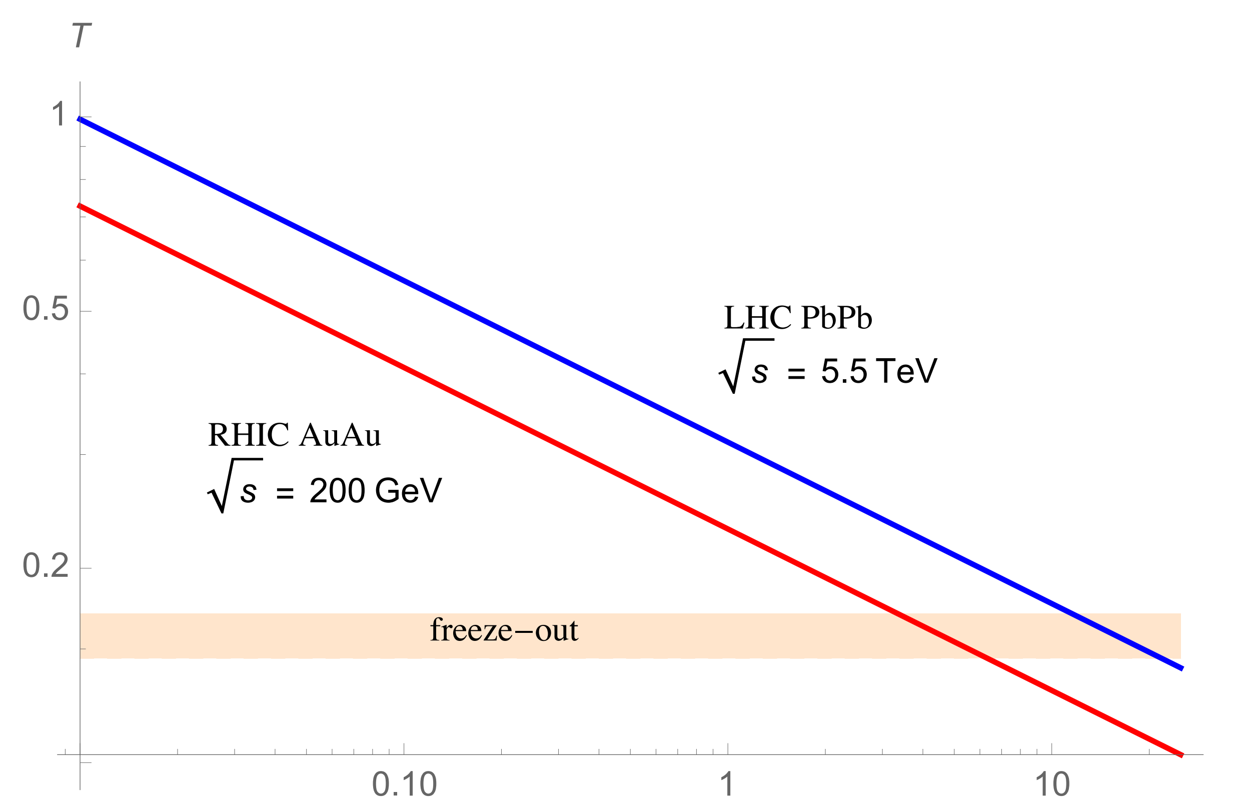


HEAVY-ION PHYSICS [PURPOSE]

✓ explore and understand fundamental properties of matter at the most extreme temperatures [~10^5 higher than the Sun's core] and density achievable in a laboratory

✓ understand QCD beyond 'few-particles' and 'conventional' vacuum :: explore the QCD phase diagram

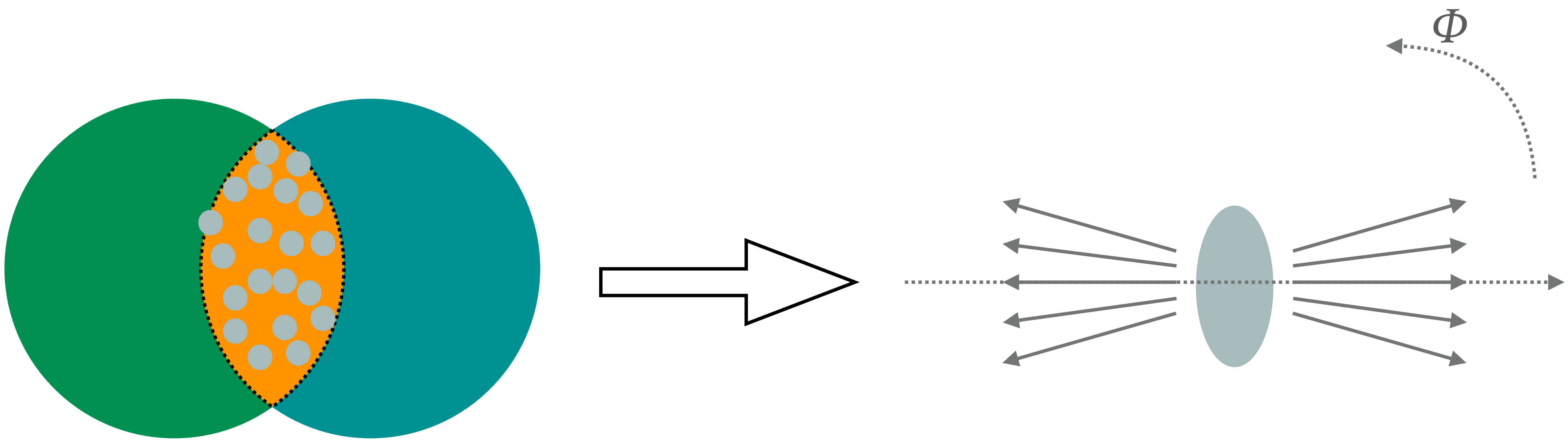




HEAVY-ION PHYSICS [PURPOSE]

- ✓ explore and understand fundamental properties of matter at the most extreme temperatures [$\sim 10^5$ higher than the Sun's core] and density achievable in a laboratory
- ✓ understand QCD beyond 'few-particles' and 'conventional' vacuum :: explore the QCD phase diagram
    - ✓ it so happens that this state-of-matter — a quark-gluon plasma [QGP]— is truly remarkable …

A REMARKABLE PROPERTY OF QGP



[beam axis view of collision]

final state soft particles preferably aligned the collision plane

initial *spatial* anisotropy → final state *momentum* anisotropy
[pressure gradients]

a natural consequence of hydrodynamics

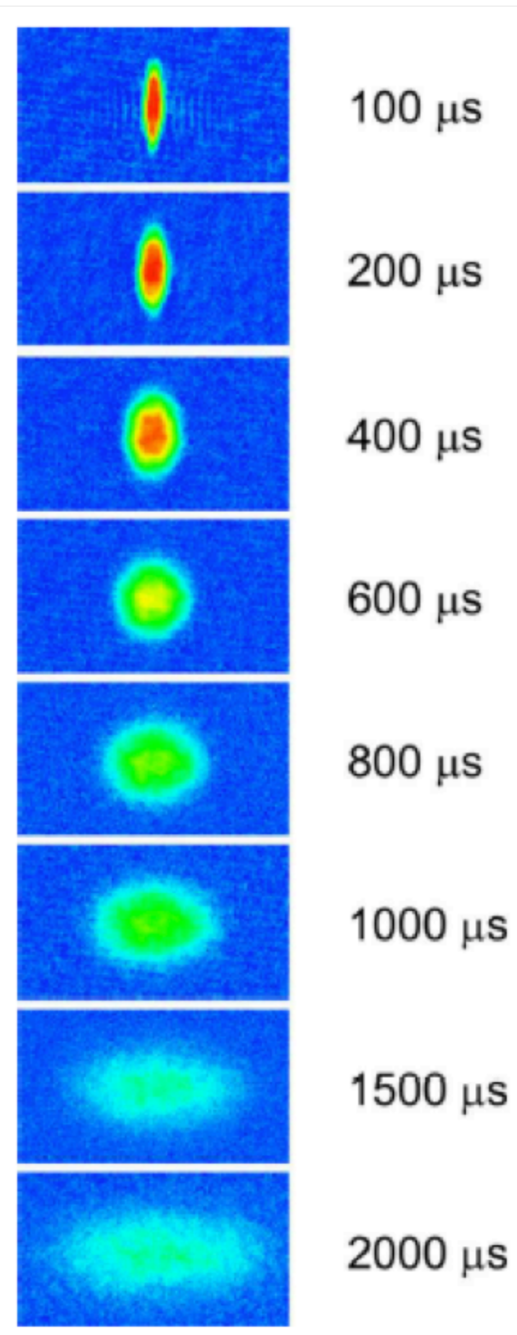
QGP manifests collectivity :: it flows

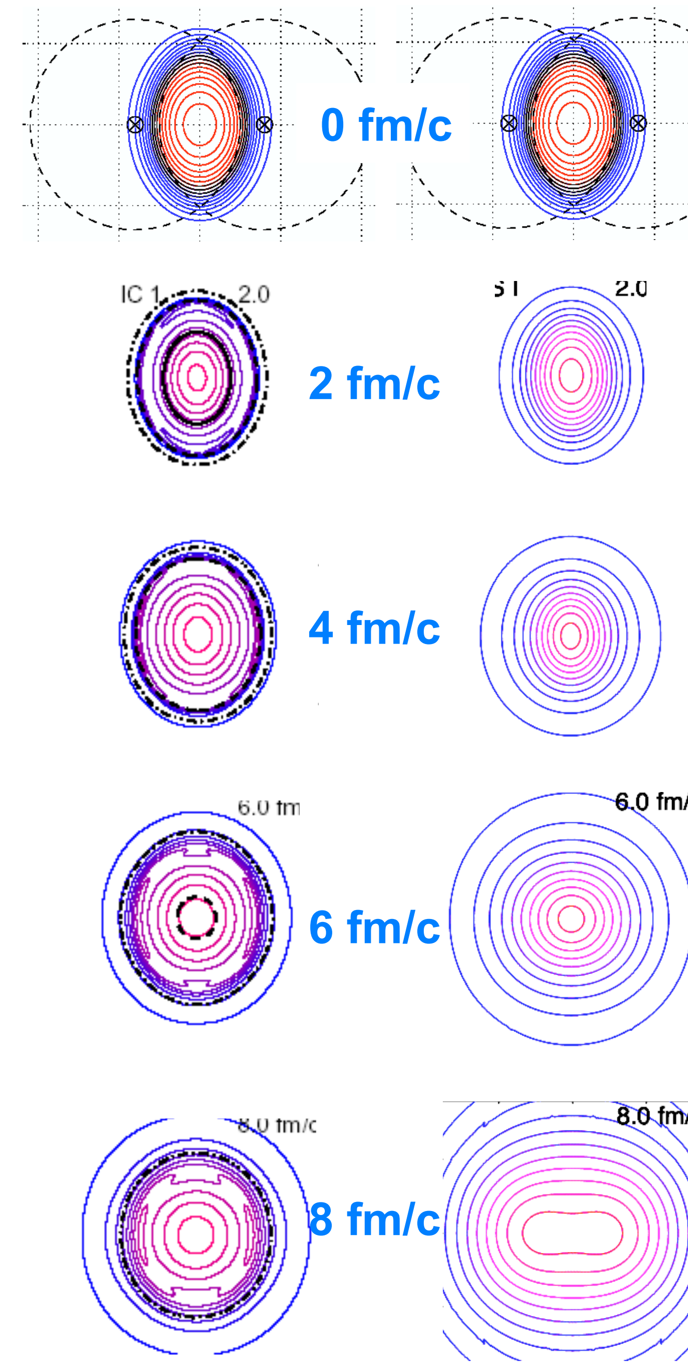
QGP is a nearly perfect liquid :: QGP is strongly coupled

FLOW AND STRONG COUPLING

strong coupled systems flow

O'Hara et al. :: Science 298 (2002)





Kolb and Heinz :: QGP3 (2003)

degenerate Fermi gas of ultracold Li atoms released from anisotropic trap

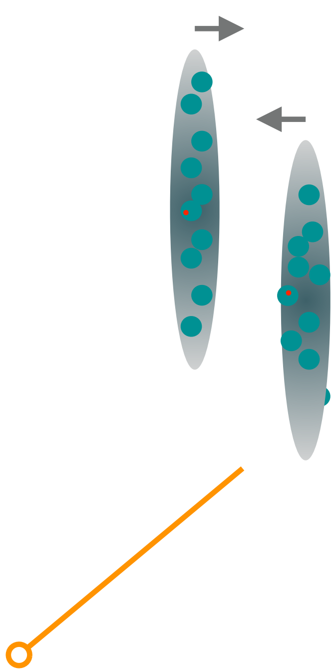
Lisa et al. :: New J.Phys 13 (2011)

HEAVY-ION PHYSICS [PURPOSE]

- ✓ explore and understand fundamental properties of matter at the most extreme temperatures [$\sim 10^5$ higher than the Sun's core] and density achievable in a laboratory
- ✓ understand QCD beyond 'few-particles' and 'conventional' vacuum :: explore the QCD phase diagram
- ✓ understand emergent collective and macroscopic phenomena in a QFT of elementary interactions between fundamental degrees of freedom

timeline of a heavy-ion collision

FROM NUCLEI TO QGP



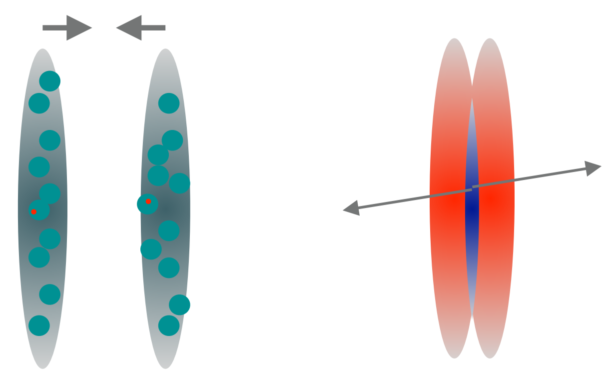
colliding nuclei

:: need to know how likely it is to find energetic quarks and gluons in the nucleons [nuclear PDFs]
:: geometry of collision [how head-on they are] is VERY important

FROM NUCLEI TO QGP

~ 0.1 fm/c
[~10^{-25} s]

time



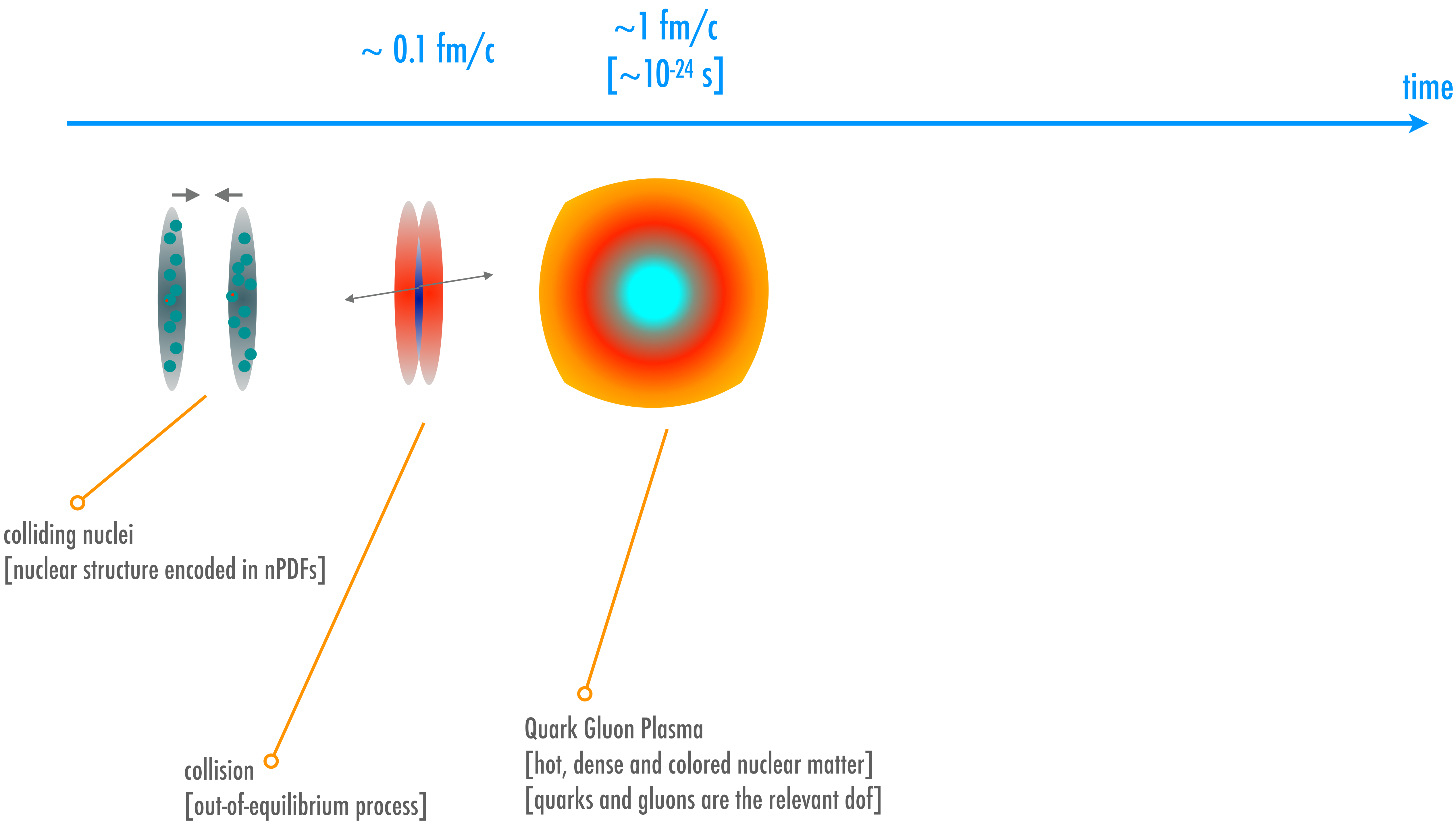
colliding nuclei

collision
[out-of-equilibrium process]

many soft [small momentum exchange] collisions
- responsible for bulk low-momentum particle production
- will quickly hydrodynamize

very few hard [large momentum exchange] collisions
- offspring will slowly relax towards hydrodynamization, yet remain out-of-equilibrium, while propagating through soft soup

FROM NUCLEI TO QGP



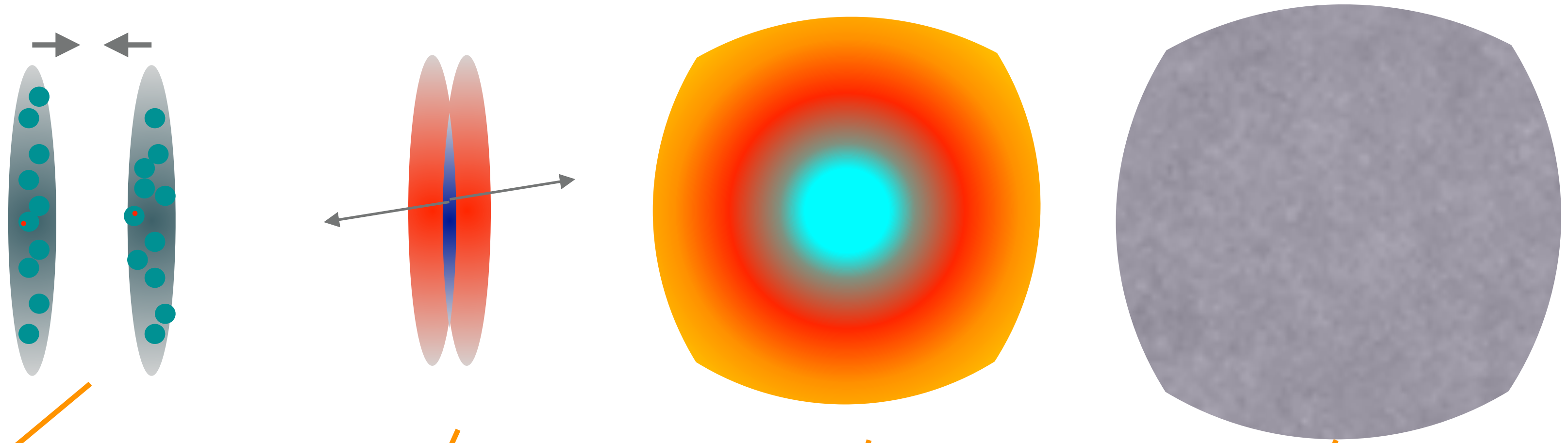
FROM NUCLEI TO QGP TO HADRONS

~ 0.1 fm/c

~1 fm/c
[~10^{-24} s]

~ 10 fm/c

time

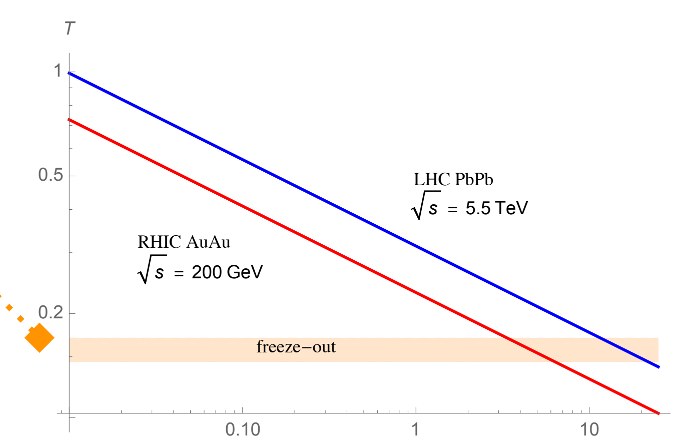


colliding nuclei
[nuclear structure encoded in nPDFs]

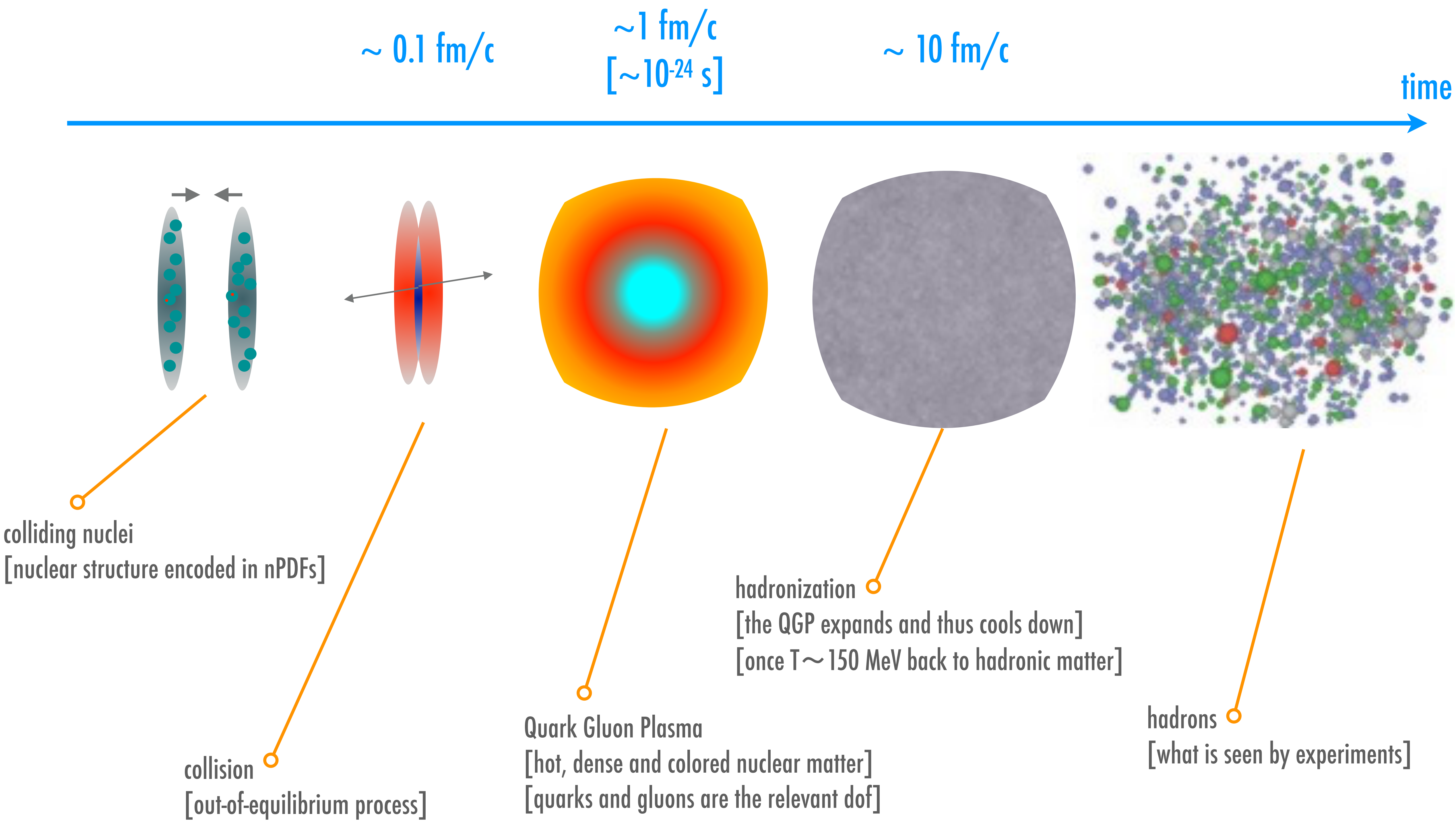
collision
[out-of-equilibrium process]

Quark Gluon Plasma
[hot, dense and colored nuclear matter]
[quarks and gluons are the relevant dof]

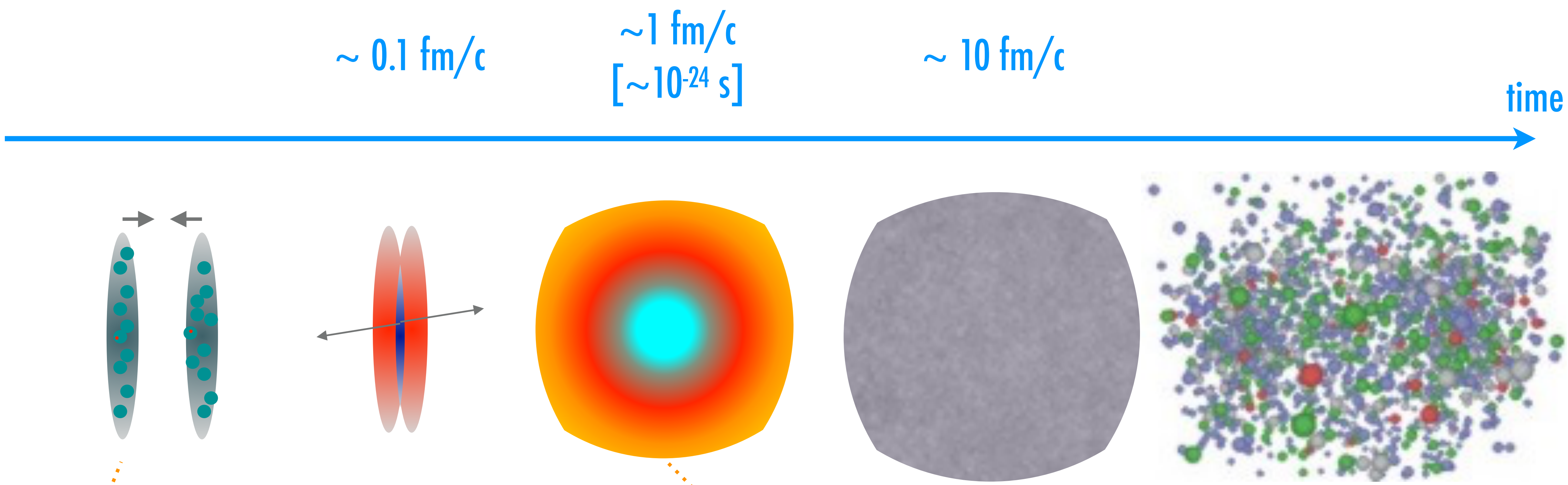
hadronization
[the QGP expands and thus cools down]
[once T ~ 150 MeV back to hadronic matter]



FROM NUCLEI TO QGP TO HADRONS



FROM NUCLEI TO QGP TO HADRONS



what we want to understand

- how we get here?
- what it is?
- how it stops being?

what we can ideally determine/constrain elsewhere
•electron-nucleus EIC/LHeC/FCC-eA
•proton-nucleus [to a lesser extent] LHC/RHIC–sPHENIX

all we have

HOW DOES QGP COME INTO BEING?

- ✓ how does a rapidly expanding, violently out-of-equilibrium system, reach some form of equilibrium state amenable to a 'macroscopic' treatment?
  - ✓ (thermalization, isotropization, hydrodynamization, equation-of-statization) are all different names that imply some stronger or weaker sort of equilibrium

- ✓ this is a very tough open problem

understanding QGP can be invaluable for
understanding strongly coupled systems in general

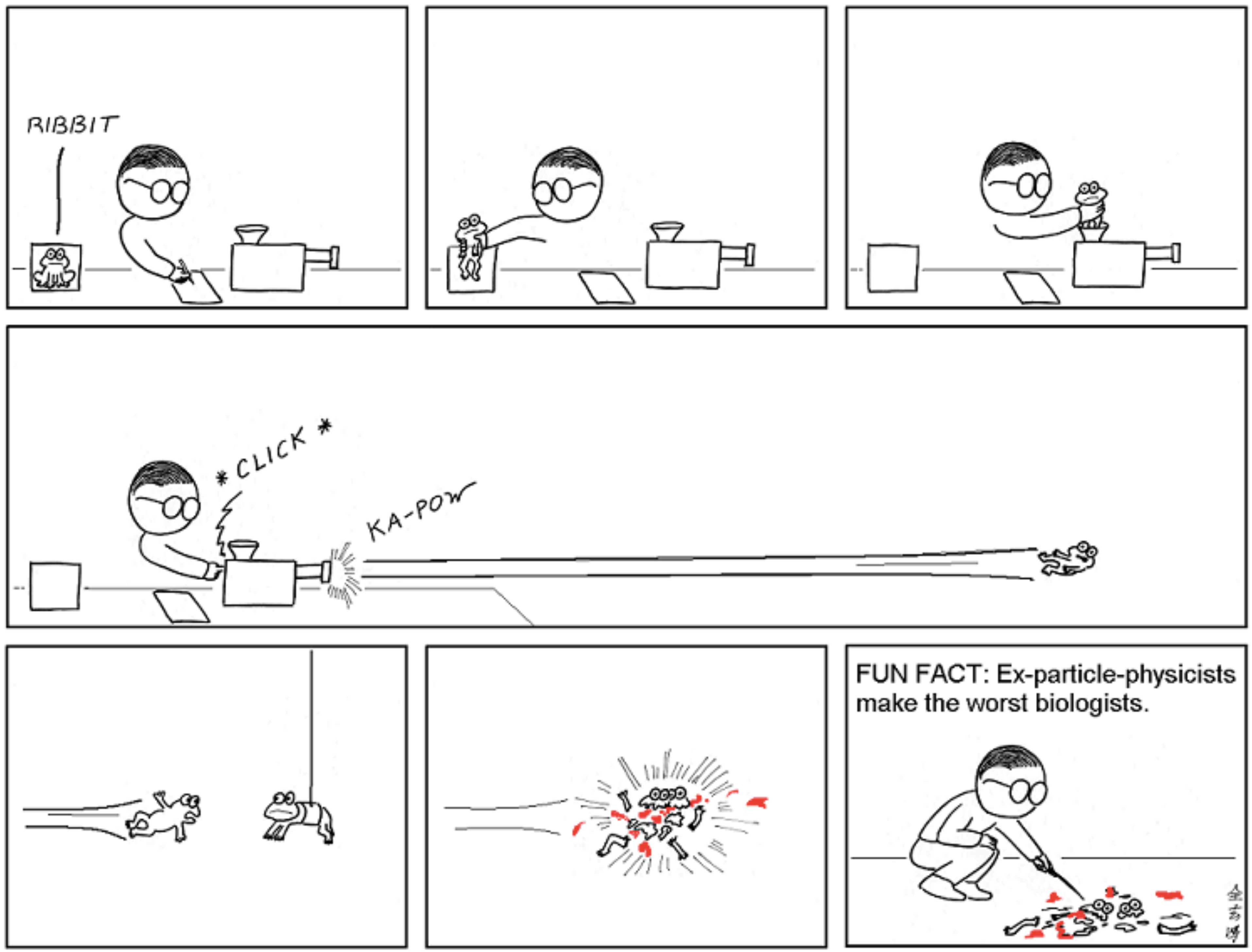
[and vice-versa]

QGP is the only strongly coupled system of
Standard Model microscopic degrees of freedom

HOW TO PROBE ANYTHING

HOW TO PROBE ANYTHING

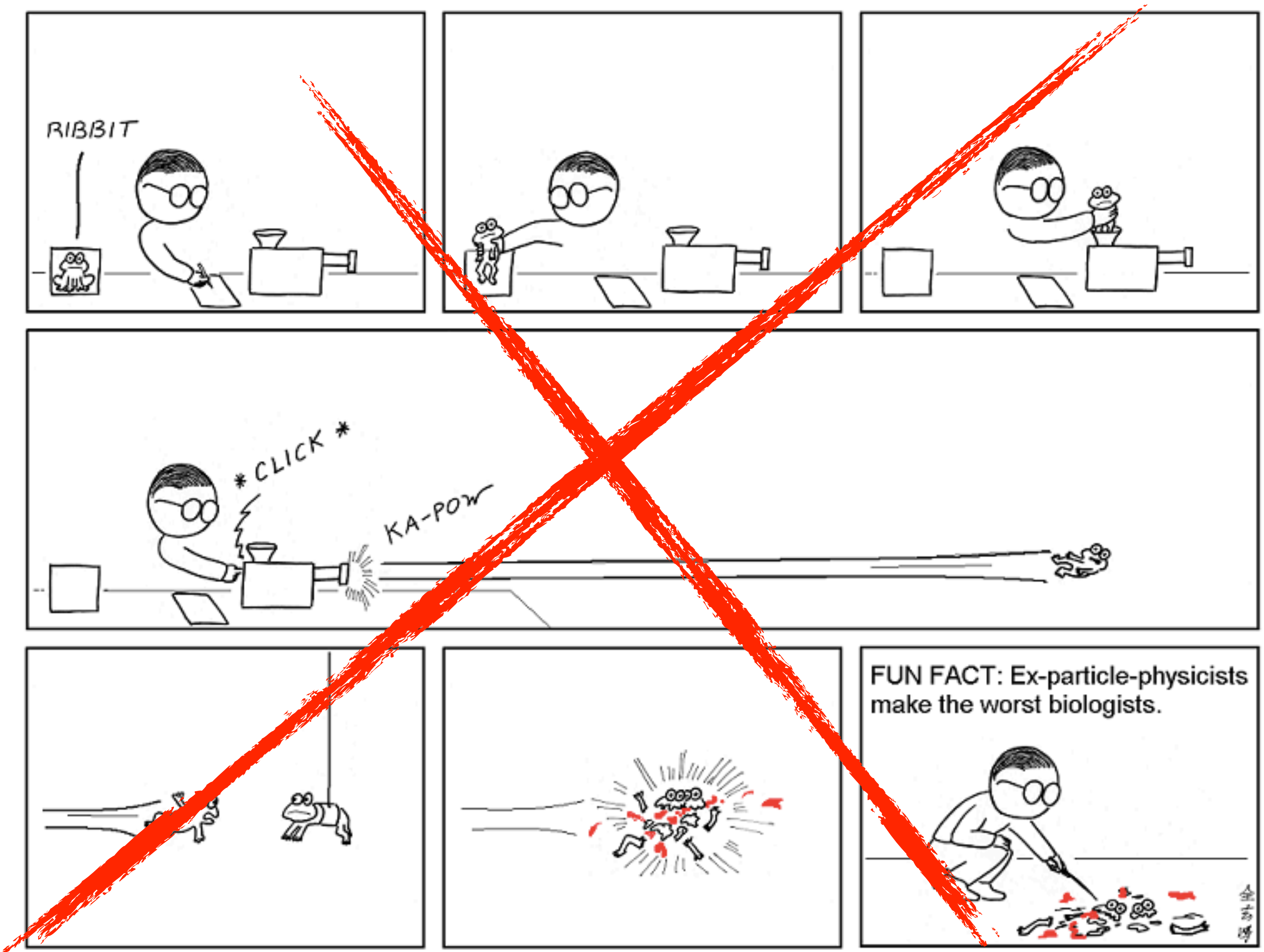
scatter something off it



Abstruse Goose

HOW TO PROBE ANYTHING

scatter something off it

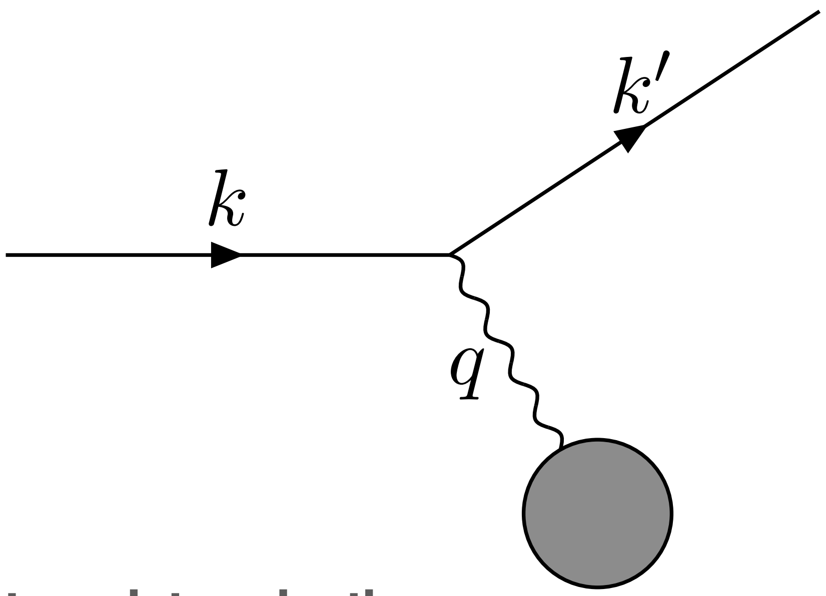


cannot [easily] understand a frog from scattering it off another frog

Abstruse Goose

HOW TO PROBE ANYTHING

scatter something you understand off it



deep inelastic scattering is the golden process for proton/nucleus structure determination

dial $Q^2 = -q^2 = -(k' - k)^2$ to probe distances $\lambda = \hbar/Q$

QGP too short-lived for external probes to be of any use

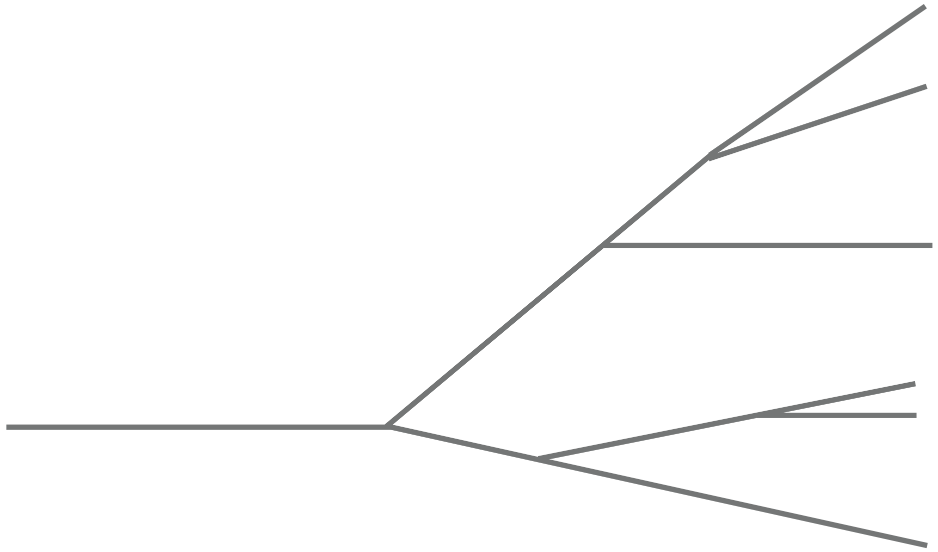
:: to mimic DIS paradigm need multi-scale probes produced in the same collision as the QGP

→ jets

WHAT IS A JET ?

jet is a **jet** is a jet is a jet

[theory view]
the offspring of the QCD
branching of a hard parton



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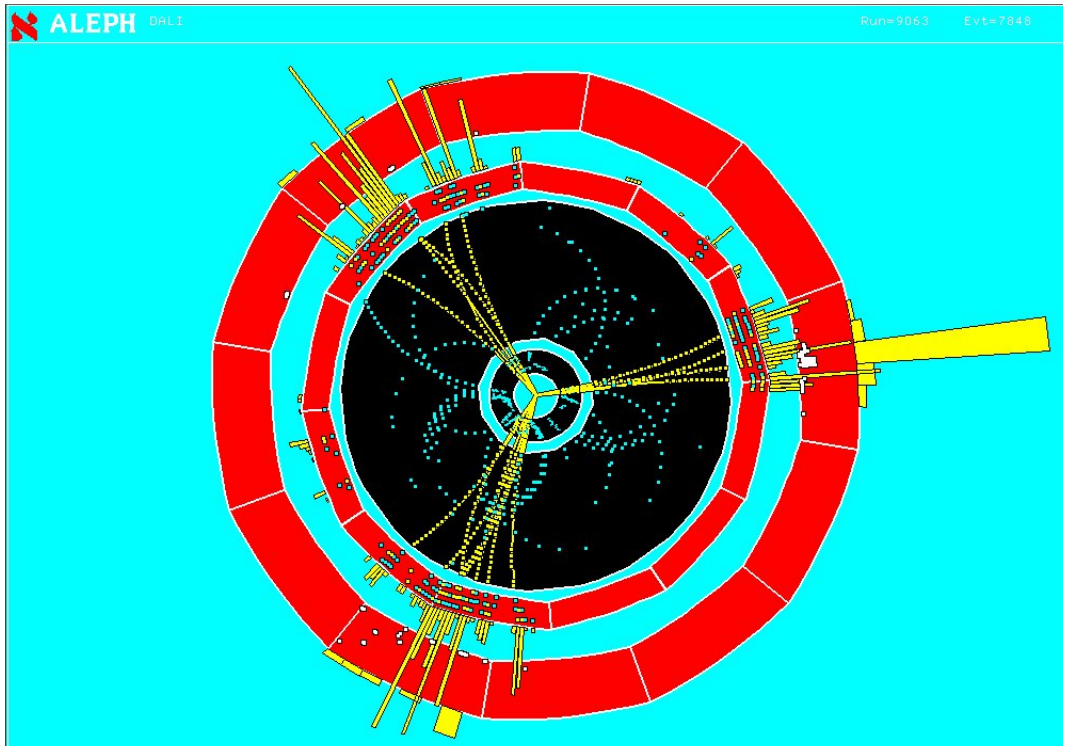


[experimental view]
collimated bunch of particles

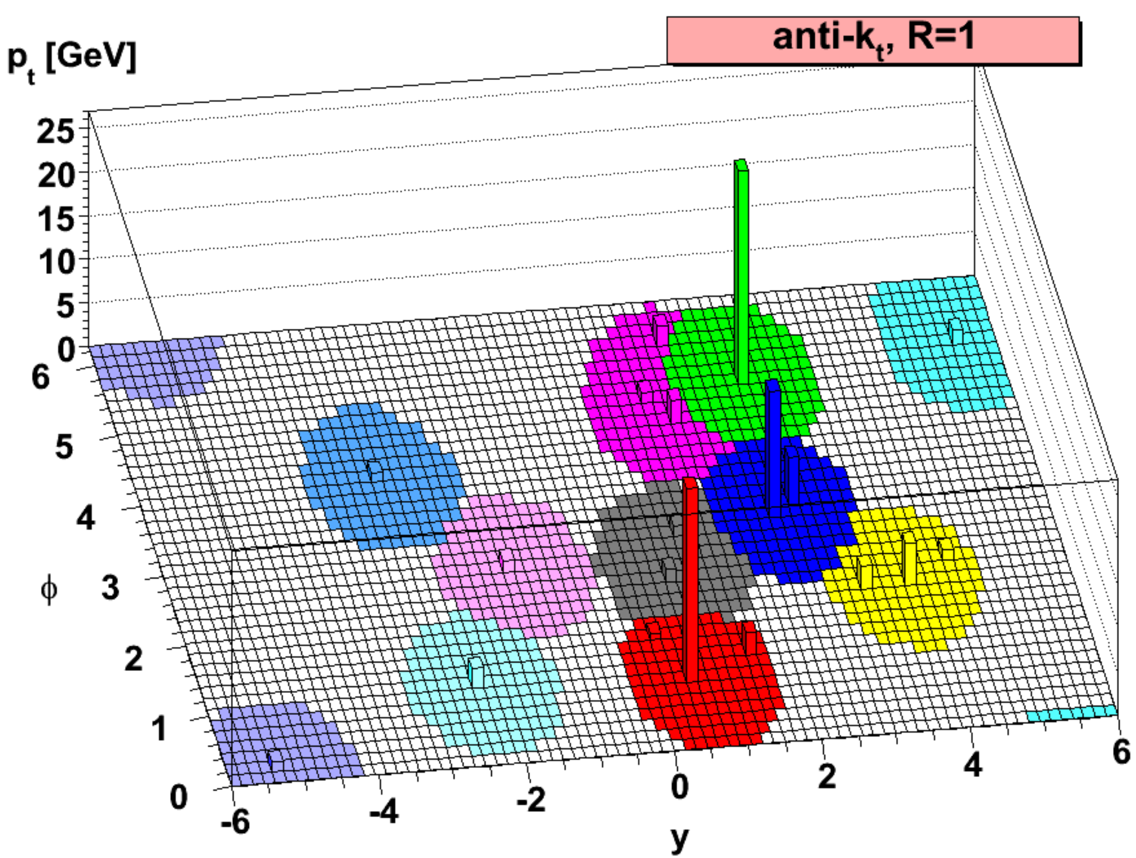
WHAT IS A JET ?

jet is a **jet** is a **jet** is a **jet**

[theory view]
the offspring of the QCD branching of a hard parton

[experimental view]
collimated bunch of particles

[strictly]
defined by a jet algorithm



WHAT IS A JET ?

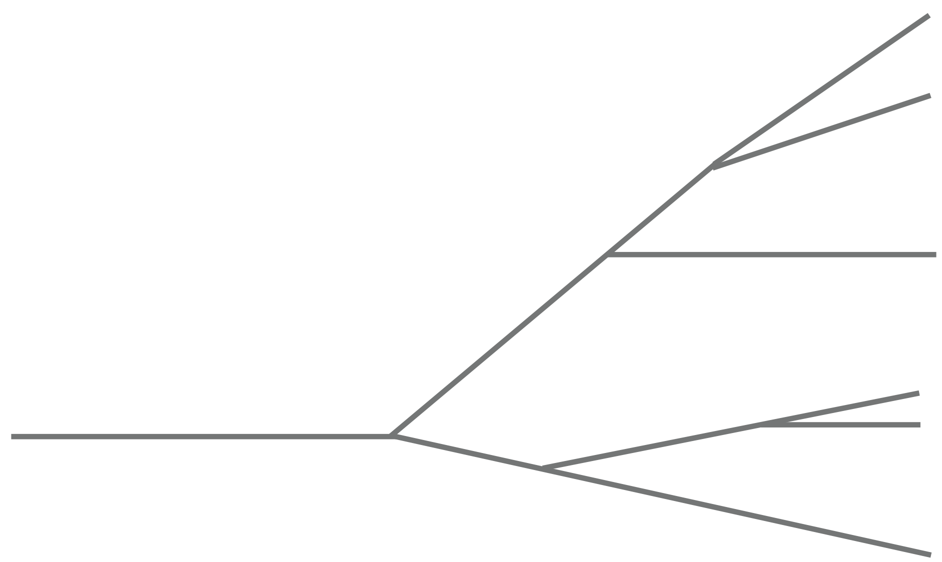
jet is a jet is a jet is a jet

UNIQUE AMONGST QGP PROBES

- multi-scale
  :: broad range of spatial and momentum scales involved in jet evolution in QGP
- multi-observable
  :: different observable jet properties sensitive to different QGP scales and properties
- very well understood in vacuum
  :: fully controlled benchmark
- feasible close relative of a standard scattering experiment

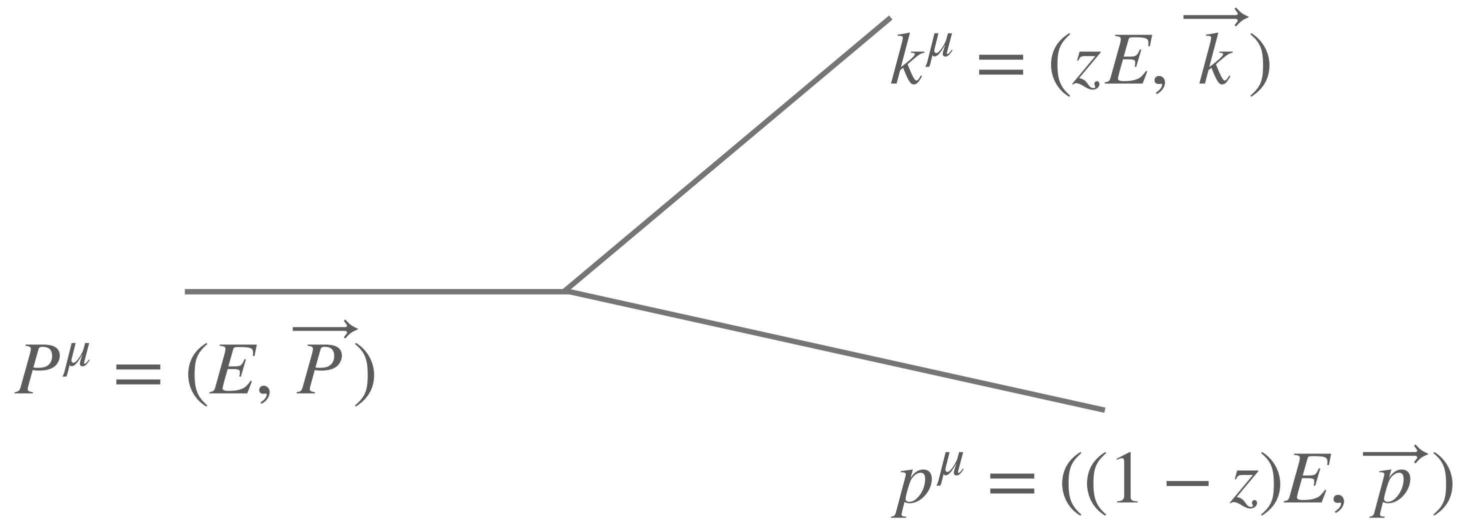
HOW A JET IS BORN

- ✓ rare very energetic collisions of partons [quarks or gluons] within the overall collision produce very energetic [and virtual] back to back partons
- ✓ these partons will split [one parton becomes two partons]
- ✓ each daughter can again split …



how long does it take for a parton to split?

SPLITTING TIME



✓ splitting time = life-time of boosted virtual mother state

$$t_f = \frac{1}{M_{\mathrm{virt}}} \frac{E}{M_{\mathrm{virt}}}$$

relativistic time-dilation

uncertainty principle

$$M_{\mathrm{virt}}^2 = P^2 = (p+k)^2 = p^2 + k^2 + 2p \cdot k \simeq 2z(1-z)E(1-\cos\theta)$$

SPLITTING TIME

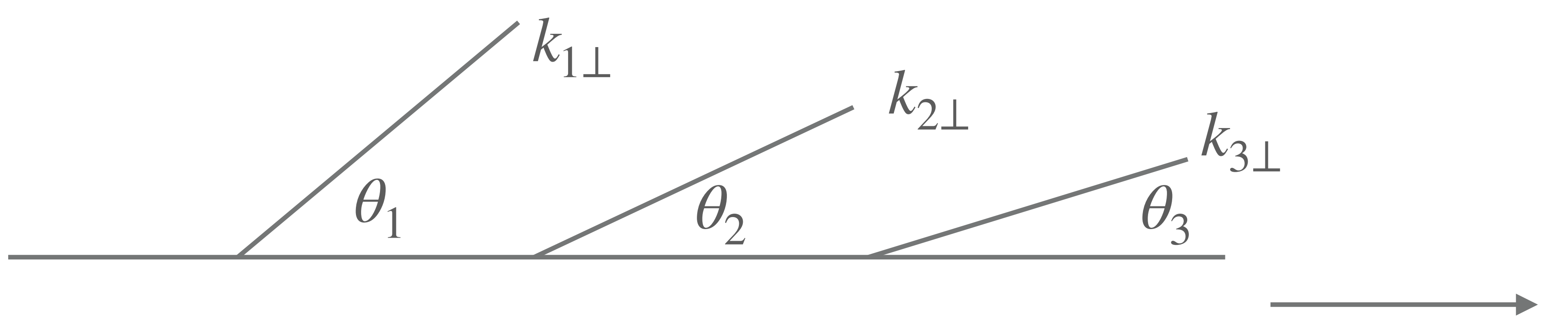
✓ for soft small-angle emissions

$$t_f = \frac{1}{zE\theta^2} = \frac{1}{\omega\theta^2} = \frac{\omega}{k_\perp^2}$$

$$\omega = zE$$
$$k_\perp = zE\theta = \omega\theta$$

✓ if one considers only primary soft emissions [radiated particles will not radiate further] we get a simple, and rather accurate, prototype of a jet

- ✓ emissions are ordered in angle :: large angle emissions happen early :: small-angle happens late $\theta_1 \gg \theta_2 \gg \theta_3$
- ✓ emissions are ordered in transverse momentum $k_{1\perp} \gg k_{2\perp} \gg k_{3\perp}$



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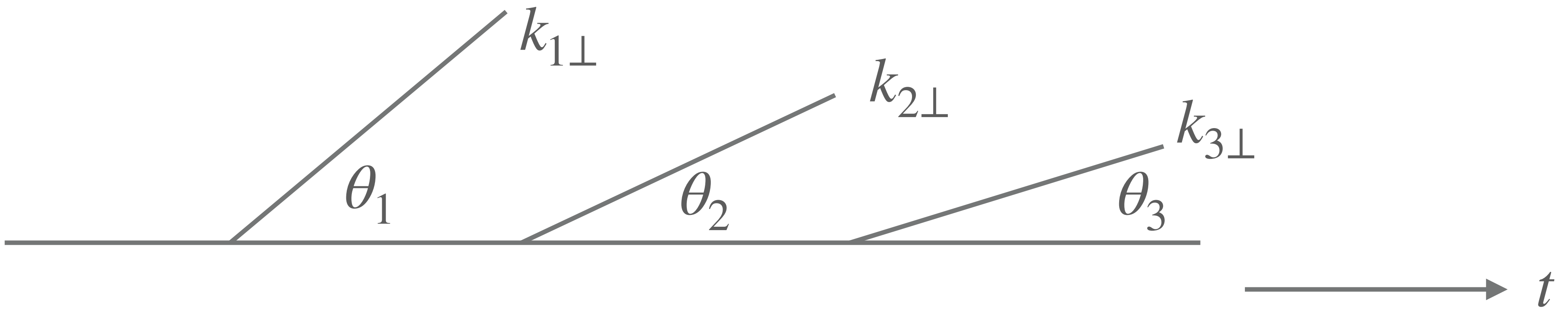


jets involve a broad range of scales

INTERACTION WITH QGP

✓ QGP provides external source of transverse momentum

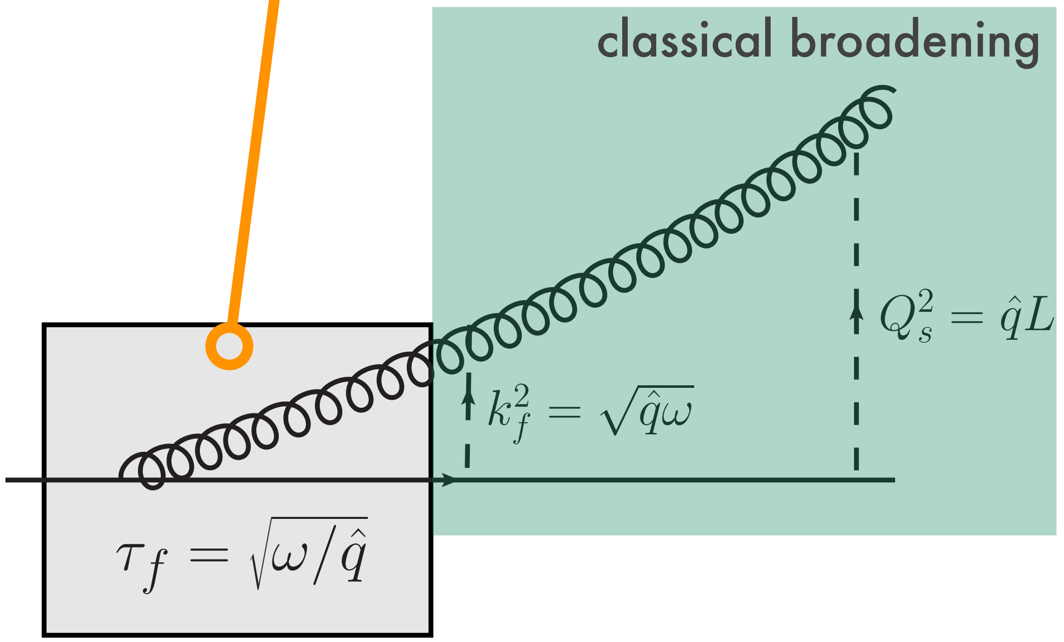
$$t_f = \sqrt{\frac{\omega}{\hat{q}}}$$

$$k_\perp^2 = \hat{q}L$$

✓ jet structure is modified by QGP

$$\mathcal{R}_q^{\text{med}} \approx 4\omega \int_0^L dt' \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t') \sin\left(\frac{\boldsymbol{k}'^2}{2k_\text{f}^2}\right) e^{-\frac{\boldsymbol{k}'^2}{2k_\text{f}^2}}$$

quantum emission/broadening during formation time



PROBING QGP WITH JETS

- ✓ modern jet analysis techniques allow us to correlate specific modifications of jets with specific properties of the QGP-jet interaction
  - ✓ these involve the theoretical description of the interaction from QCD first principles; the use of techniques borrowed from string theory; the development of simulation codes, the identification of the 'right' observables; the very selective grooming of the jets; the use of Machine Learning techniques; …
- ✓ understanding how parts of the jet relax into QGP amounts to understanding how the QGP was born in the first place

this research programme has only started a few years ago

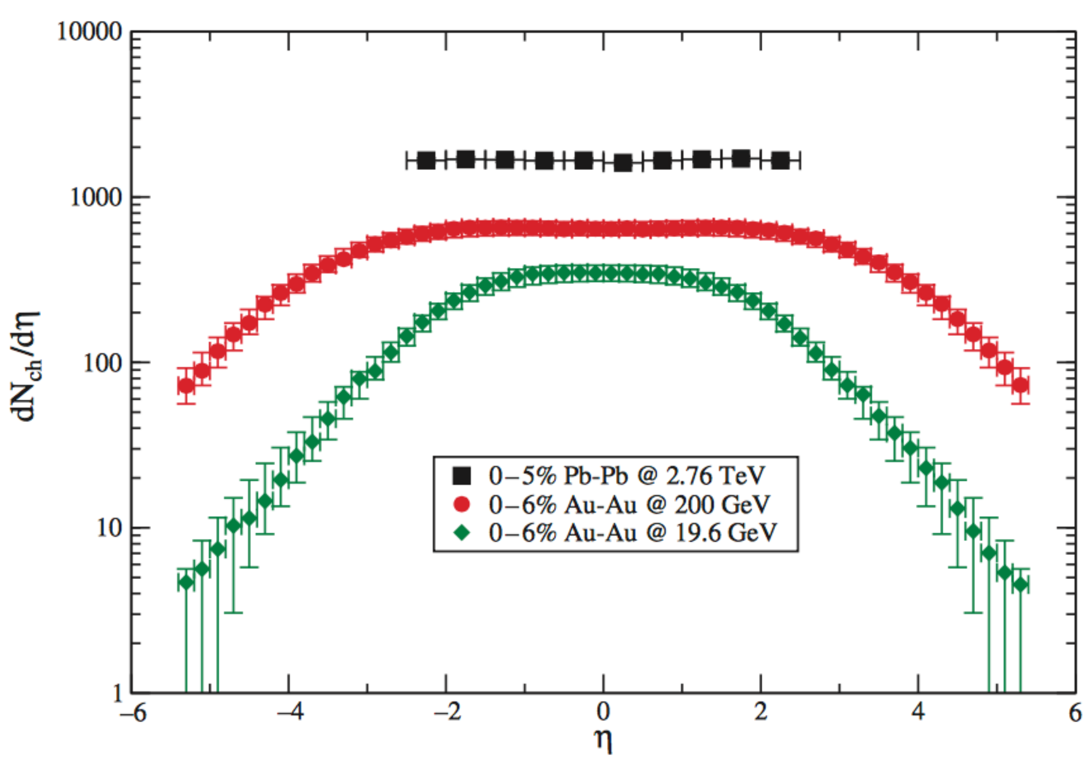
:: most remains to be done and understood ::

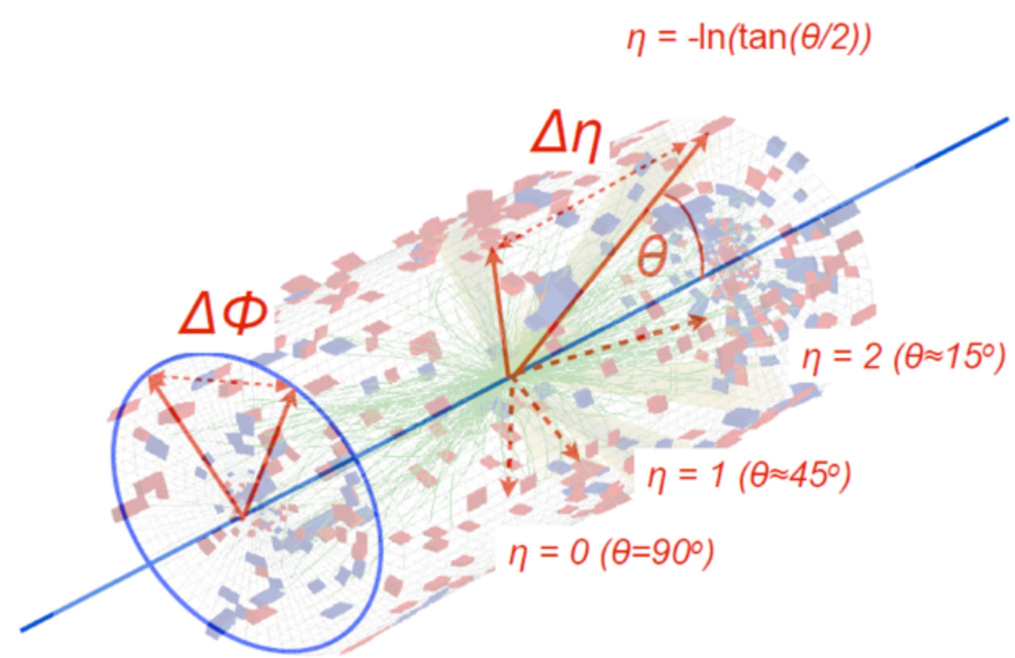
BACKUPS

HEAVY ION COLLISIONS

	SPS	RHIC	LHC	FCC
$\sqrt{s_{NN}}$ [TeV]	0.017	0.2	2.76 (5.5)	39
volume at freezout [fm³]	1200	2300	5000 (6200)	11000
$\varepsilon(\tau=1 fm/c)$ [GeV/fm³]	3-4	4-7	12-13 (16-17)	35-40
lifetime [fm/c]	4	7	10 (11)	13

:: all this can be estimated from the number of particles produced at mid-rapidity





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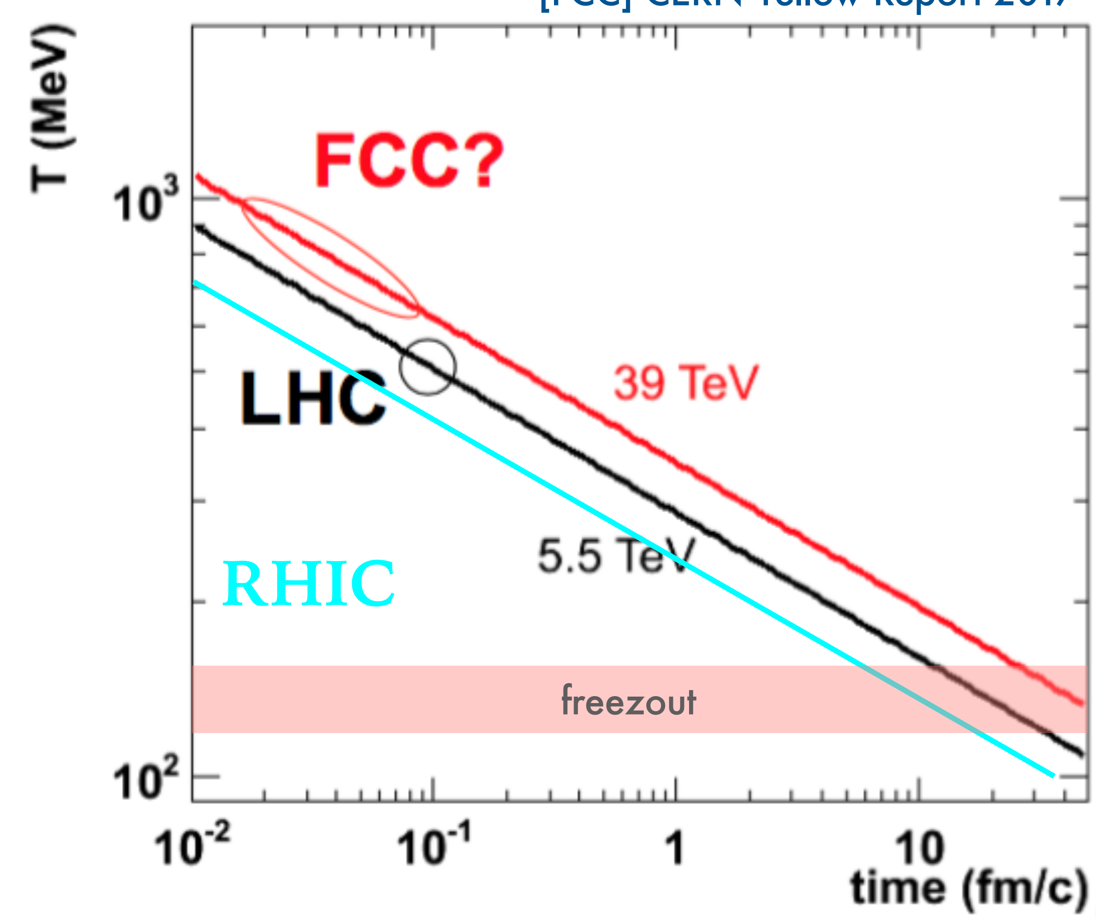
QGP is short-lived

[FCC] CERN Yellow Report 2017



in heavy ions $\sqrt{s}$ given per nucleon pair

$$\sqrt{s_{NN}} = \frac{Z}{A}\sqrt{s_{pp}}$$

:: for PbPb [LHC 14TeV] :: 82/208 x 14 = 5.5 TeV

QCD IN ONE SLIDE

:: each quark flavour [u,d,c,s,b,t] exists in 3 colours [r,g,b]

:: quark carries one colour index :: fundamental representation of SU(3) [triplet]

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \left(i\gamma^\mu \partial_\mu - m\right)\psi_a$$

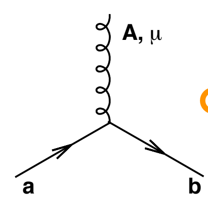
kinetic term :: quark propagation

not gauge invariant

:: need to introduce gauge field [gluon] to fulfil gauge invariance

:: gluon carries two colour indices :: adjoint representation of SU(3) [octet]

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \left(\bar{\psi}_a \left(i\gamma^\mu \partial_\mu - m\right)\psi_a - g_s \bar{\psi}_a \gamma^\mu t^C_{ab} A^C_\mu \psi_b\right)$$



interaction term quark-gluon vertex

gauge field

:: once new field available, include all further gauge invariant terms

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \left(\left(i\gamma^\mu \partial_\mu - m\right)\delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu\right)\psi_b - \frac{1}{4} F^A_{\mu\nu} F^{\mu\nu,A}$$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C$$

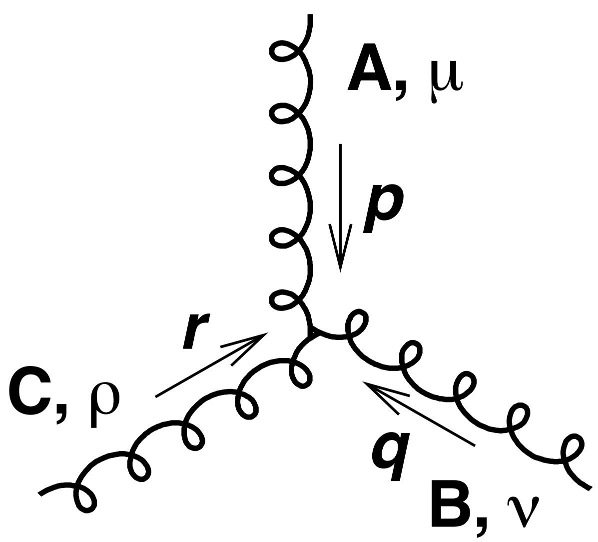
Lagrangian structure fixed by requirement of $SU(3)_{\text{colour}}$ gauge symmetry

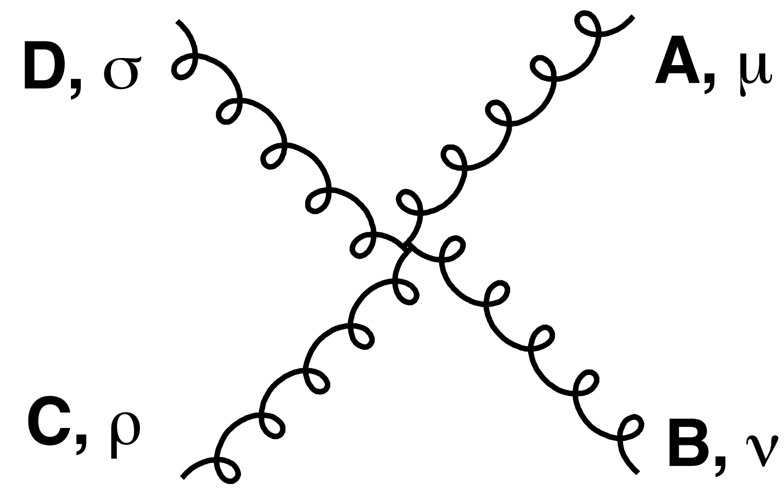
WELL, TWO…

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^A_{\mu\nu} F^{\mu\nu,A} + \sum_{\text{flavours}} \bar{\psi}_a \Big((i\gamma^\mu \partial_\mu - m)\delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu \Big) \psi_b$$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C$$

gluon propagator + gluon self-interactions





Quark masses

Up	2.3 MeV	Charm	1275 MeV	Top	173 GeV
Down	4.8 MeV	Strange	95 MeV	Bottom	4180 MeV

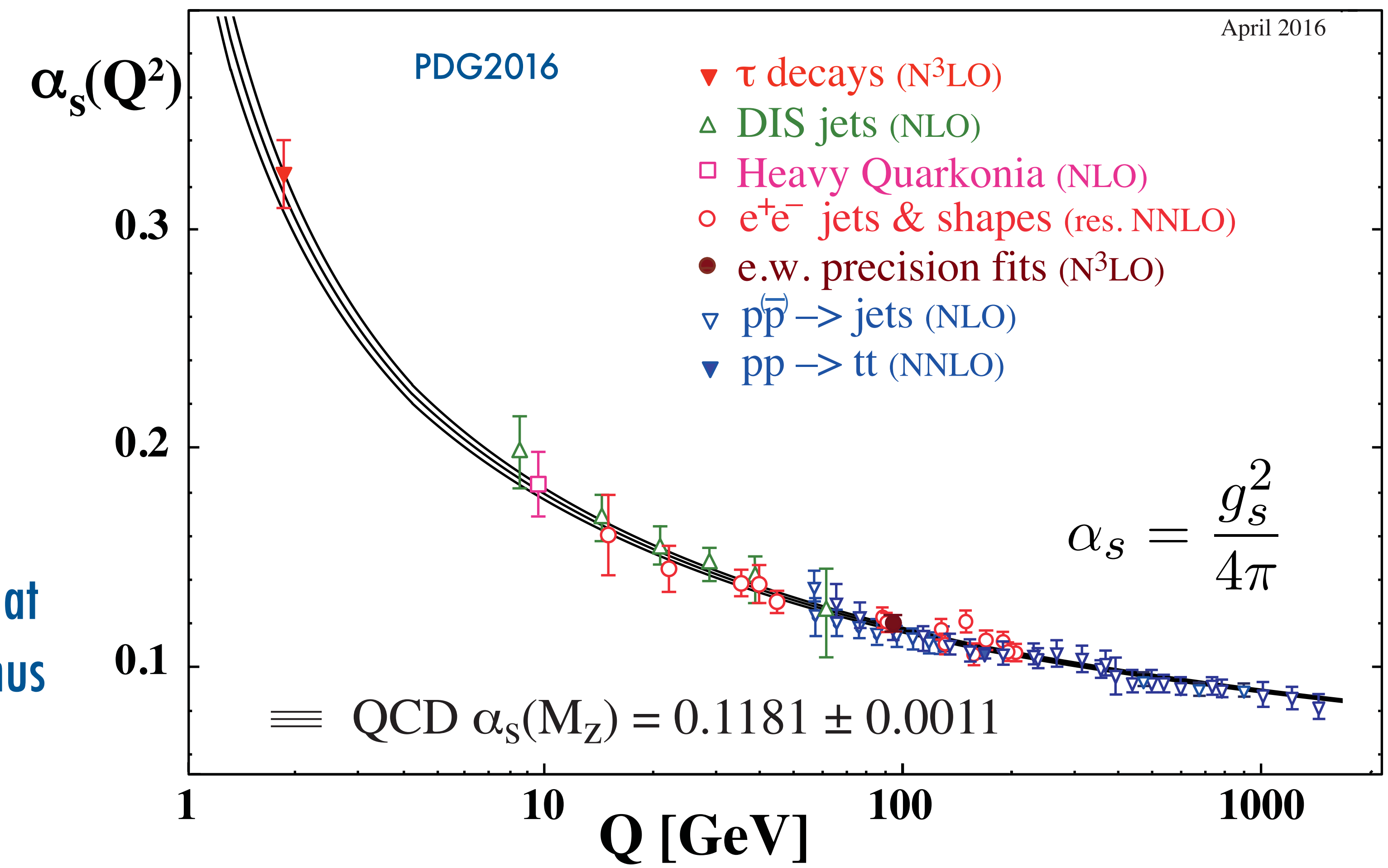
ASYMPTOTIC FREEDOM AND CONFINEMENT

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^{A}_{\mu\nu} F^{\mu\nu, A} + \sum_{\text{flavours}} \bar{\psi}_a \Big((i\gamma^\mu \partial_\mu - m)\delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu \Big) \psi_b$$

✓ renormalization [cancellation of divergences in higher order corrections] makes the coupling scale dependant

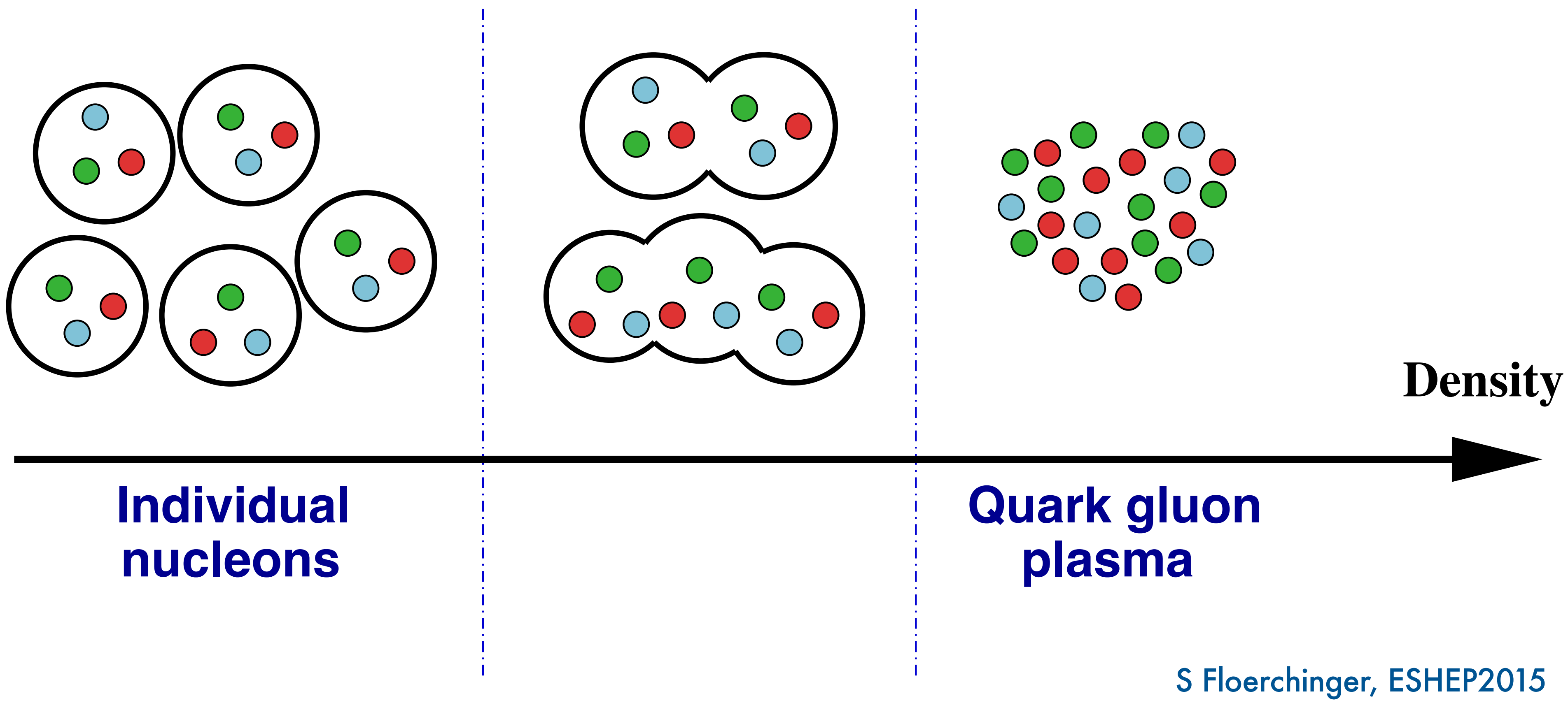
✓ self-interacting gauge fields lead to asymptotic freedom

:: quarks and gluon can only behave freely at high momentum scales [small distances] thus always observed confined within hadrons



DECONFINEMENT

✓ temperature/energy density acts as scale to free quarks and gluons beyond the nucleon radius

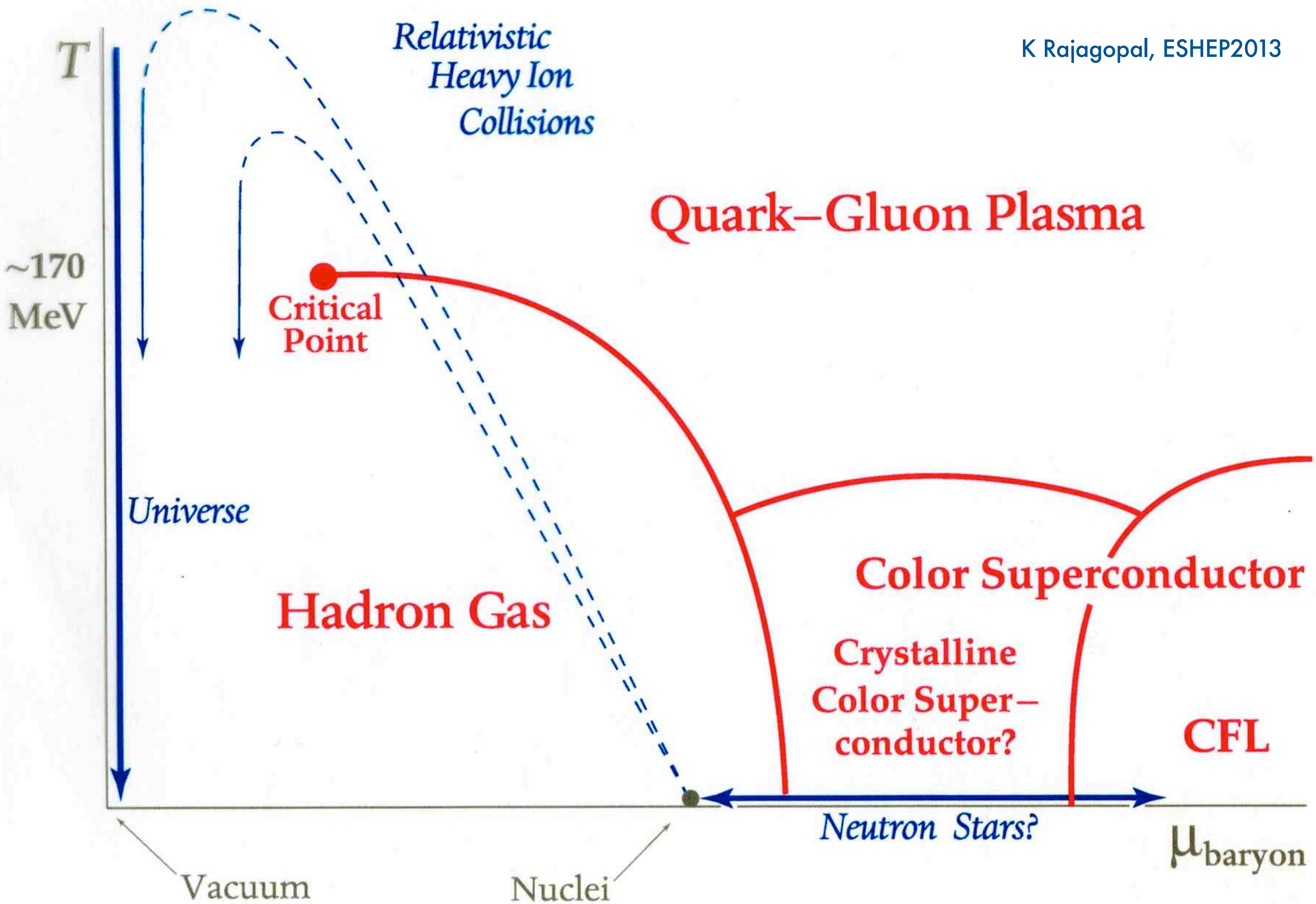


:: at high temperature/energy density quark and gluons deconfined

:: no sharp transition [cross-over]

QCD PHASE DIAGRAM

K Rajagopal, ESHEP2013



QCD THERMODYNAMICS

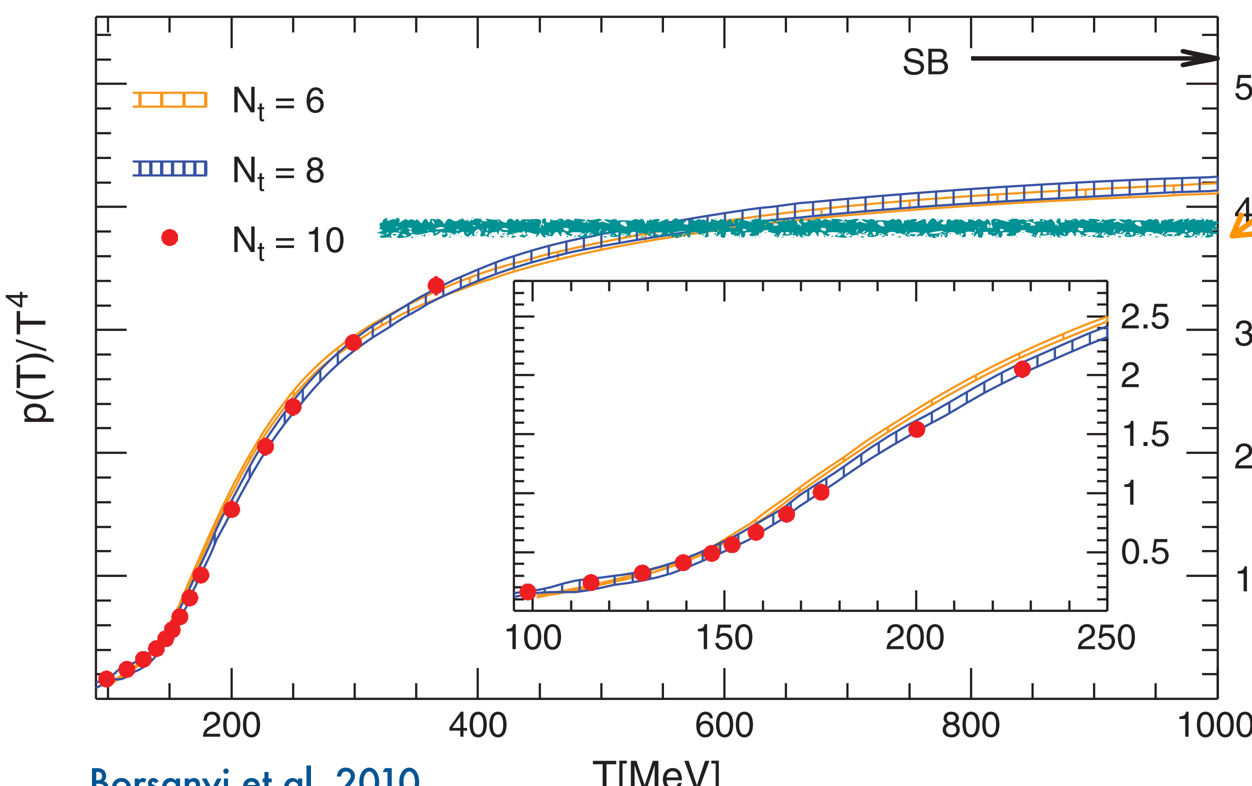
pressure of gas of NB massless bosons and NF massless fermions [SB]

$$p(T) = \frac{\pi^2}{90}\left(N_B + \frac{7}{8}N_F\right)T^4$$

$$N_B = 2 \times 8, \quad N_F = 2 \times 2 \times 3 \times 3$$

spin, color; spin, particle/antiparticle, color, flavor: u/d/s

lattice QCD [first principles calculation]



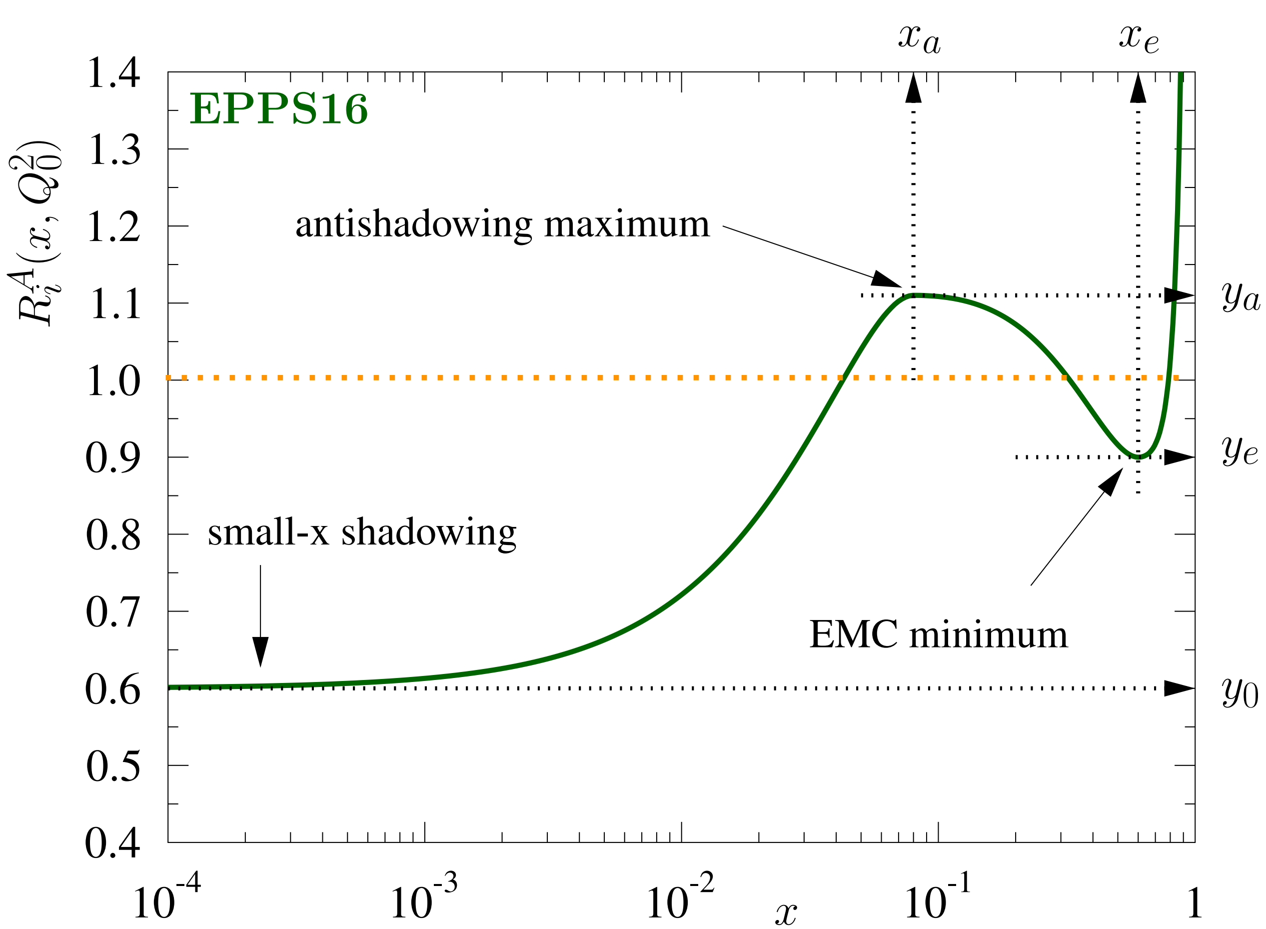
Borsanyi et al. 2010

N=4 SYM [not QCD] :: strongly [∞] coupled as different as it gets from ideal gas

NUCLEAR PARTON DISTRIBUTION FUNCTIONS [nPDF]

- ✓ nuclei are not a simple superposition of nucleons
    - ✓ parton distributions in a bound nucleon are different than those of a free proton/neutron

$$f_i^{\mathrm{p}/A}(x,Q^2) = R_i^A(x,Q^2) f_i^{\mathrm{p}}(x,Q^2)$$



HOW TO SEE THE QGP

✓ soft particle correlations :: flows, …

- ✓ sensitive to global QGP properties
- x analogous behaviour in high multiplicity pA and pp confounds straightforward interpretation [very personal opinion]

✓ electroweak bosons

- ✓ oblivious to QGP [benchmark]

✓ quarkonia/heavy flavour

- ✓ sensitive to temperature
- x underconstrained vacuum benchmark

✓ energetic hadrons

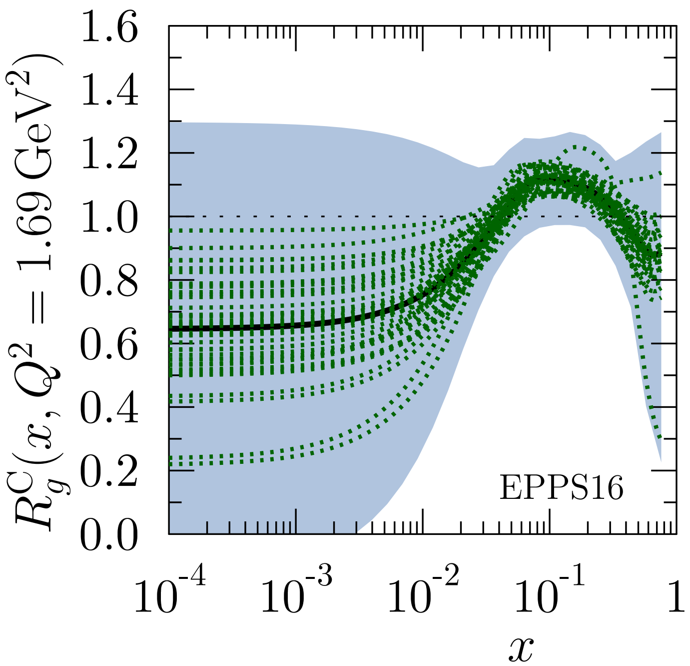
- ✓ the parton(s) they originate from traverse and interact with QGP
- x very sensitive to hadronization

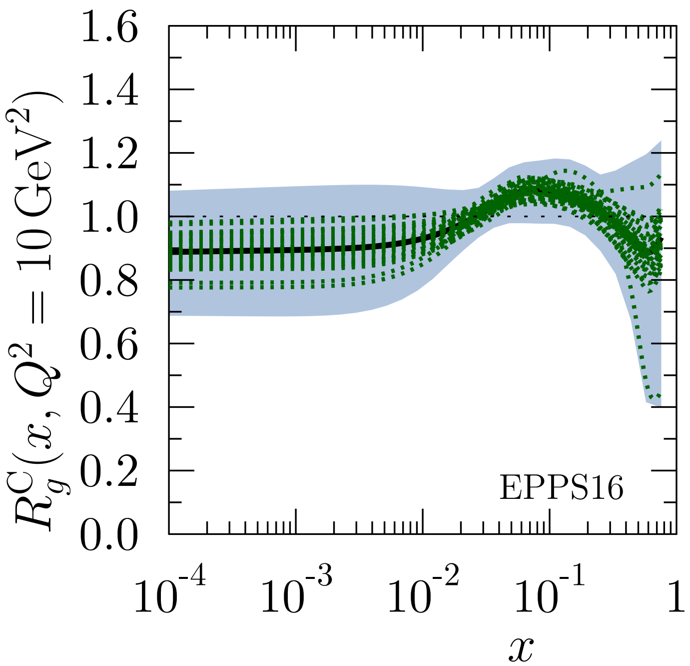
✓ jets

- ✓ multi-scale sensitivity to QGP
- ✓ vacuum benchmark under excellent theoretical control
- x need to deal with large and fluctuating contamination from underlying event

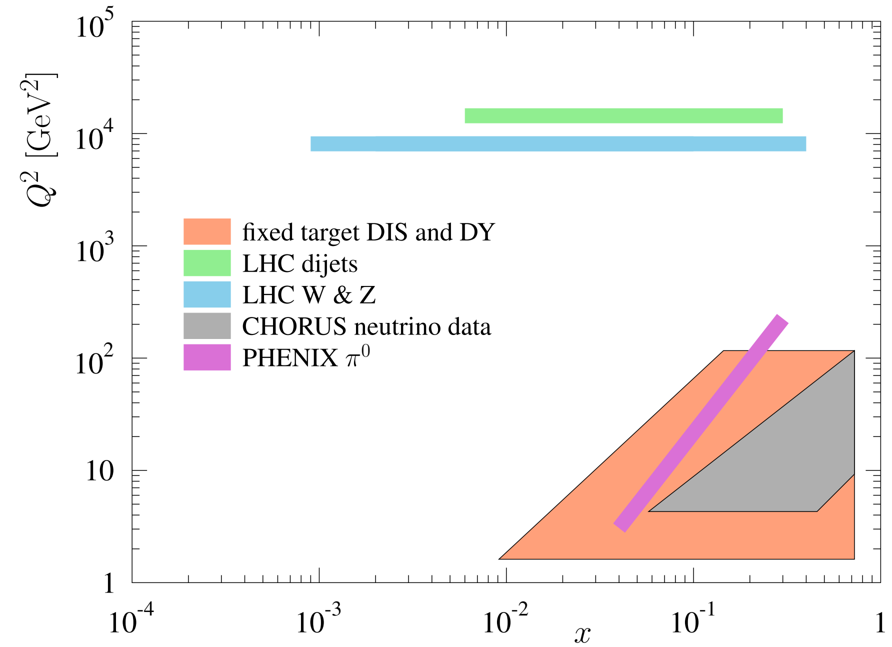
NUCLEAR PARTON DISTRIBUTION FUNCTIONS [nPDF]

✓ modifications less important at higher momentum scales [more important for soft processes that for hard]





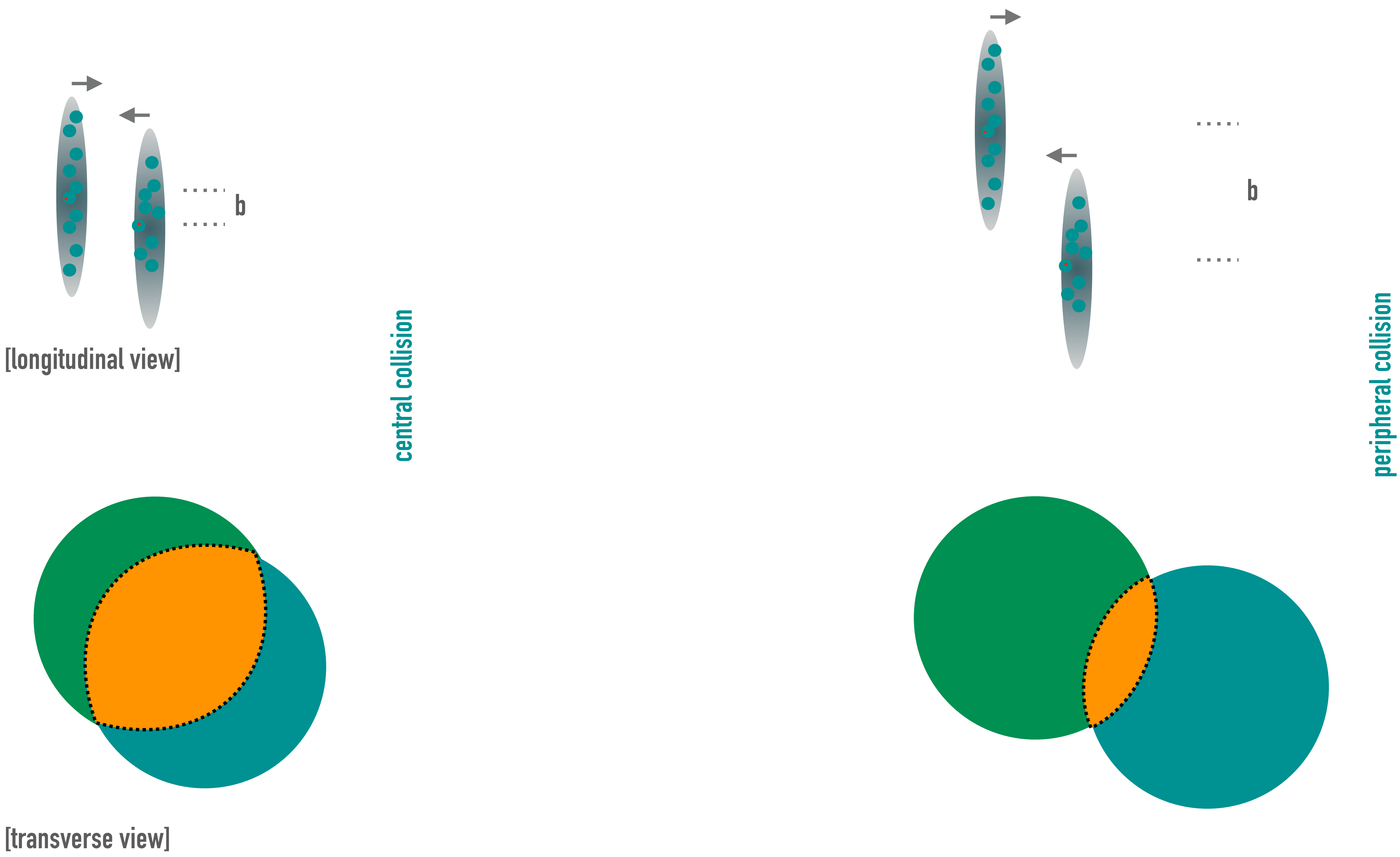
$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$$



:: constraining data is sparse [uncertainties larger than ideal]

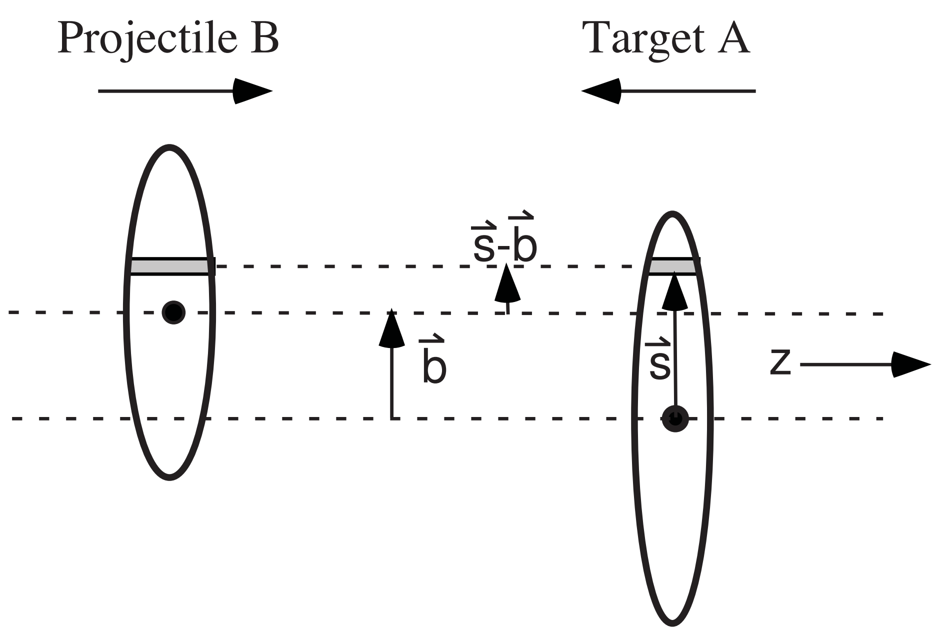
COLLISION GEOMETRY

✓ impact parameter of collision defines initial geometry [size and shape of overlap]



COLLISION GEOMETRY [GLAUBER MODEL]

- ✓ impact parameter cannot be measured, it has to be related to observables through modelling
- ✓ optical [analytical] Glauber model allows for the computation of the [average] number of participants and collisions for a given impact parameter



* overlap function [overlap area for which a nucleon in A can interact with a nucleon in B

$$\hat{T}_{AB}(\mathbf{b}) = \int \hat{T}_A(\mathbf{s})\, \hat{T}_B(\mathbf{s}-\mathbf{b}) d^2 s$$

* probability for n interactions

$$P(n, \mathbf{b}) = \binom{AB}{n} \left[\hat{T}_{AB}(\mathbf{b})\, \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^n \left[1 - \hat{T}_{AB}(\mathbf{b})\, \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{AB-n}$$

*number of participants

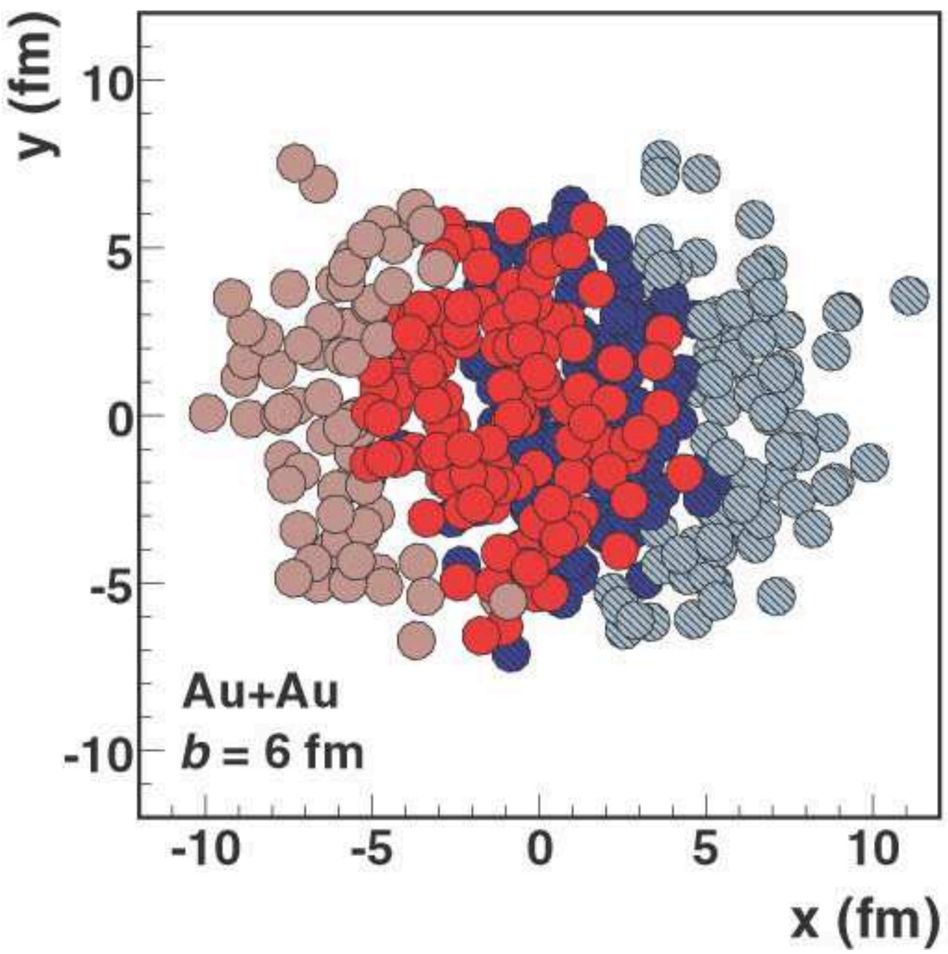
$$\begin{aligned} N_{\mathrm{part}}(\mathbf{b}) &= A \int \hat{T}_A(\mathbf{s}) \left\{1 - \left[1 - \hat{T}_B(\mathbf{s}-\mathbf{b})\, \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^B\right\} d^2 s + \\ & B \int \hat{T}_B(\mathbf{s}-\mathbf{b}) \left\{1 - \left[1 - \hat{T}_A(\mathbf{s})\, \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^A\right\} d^2 s, \end{aligned}$$

*number of nucleon-nucleon collisions

$$N_{\mathrm{coll}}(b) = \sum_{n=1}^{AB} n P(n, b) = AB \hat{T}_{AB}(b)\, \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

COLLISION GEOMETRY [GLAUBER MC]

✓ to account for fluctuations, a 'Glauber MC' is used



+ take nucleon-nucleon cross-section from pp measurents

+ distribute nucleons in nuclei by sampling Wood-Saxons distribution

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Density in the center

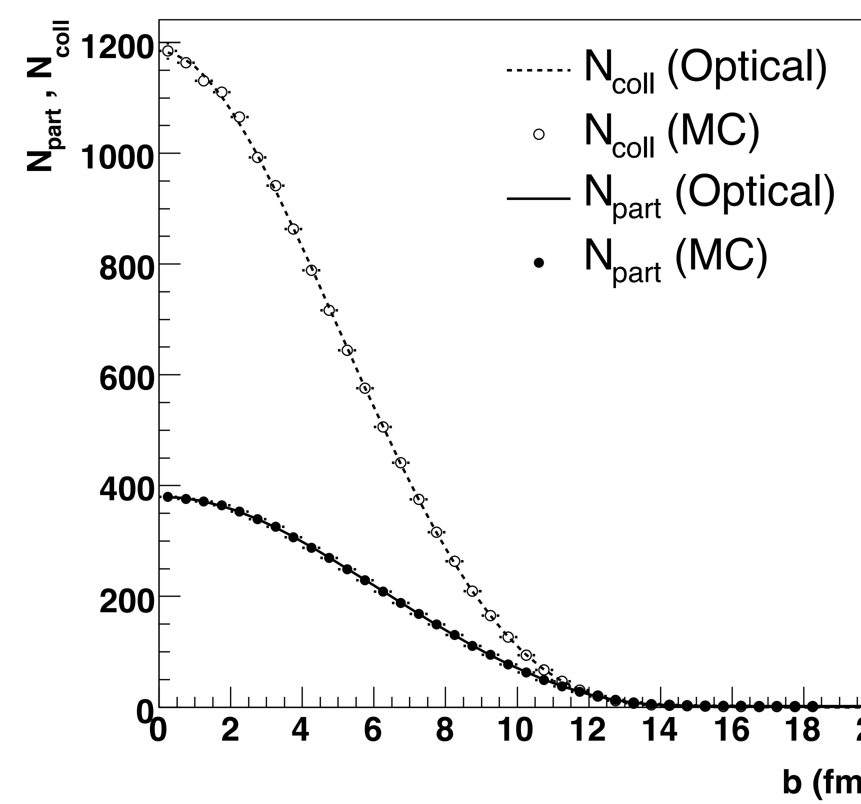
Skin depth a

✓ N_{part} ~ number of nucleons

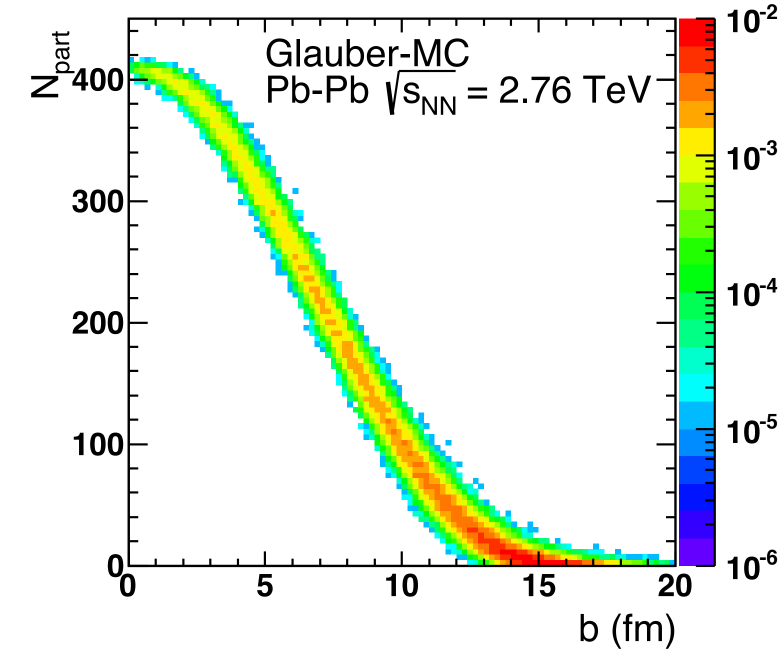
✓ N_{coll} ~ (number of nucleons) ^ (4/3)

✓ soft [low p_t] observables ~ N_{coll}

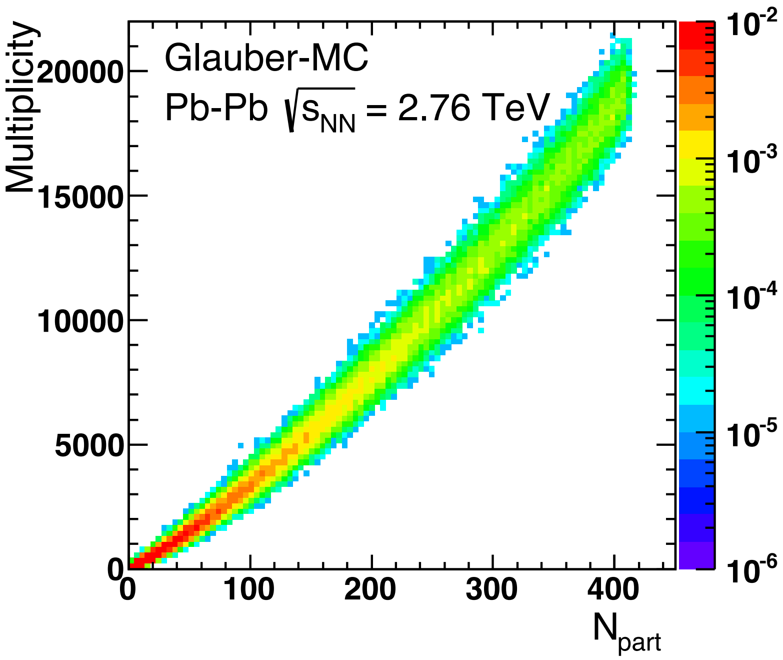
✓ hard [high p_t] observables ~ N_{part}



COLLISION GEOMETRY [MEASUREMENT]



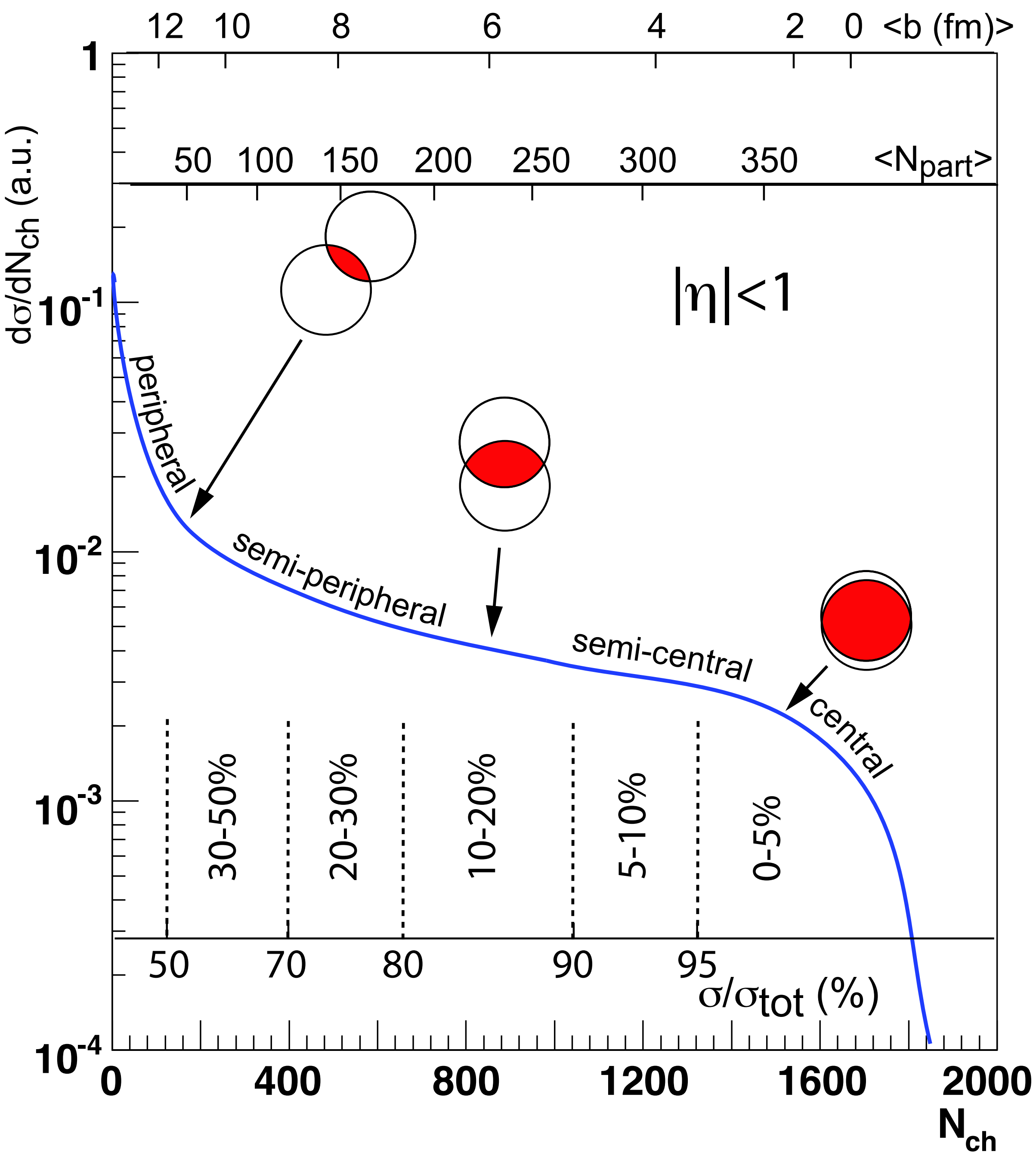
N_{part} [also N_{coll}] tightly correlated with impact parameter



activity [multiplicity or calorimetric energy] computed from model[s] for particle production tightly correlated with N_{part}

:: centrality can be inferred from activity or, alternatively, from spectators [not so simple in proton-nucleus where large fluctuations fuzz the correlations]

COLLISION GEOMETRY [MEASUREMENT]

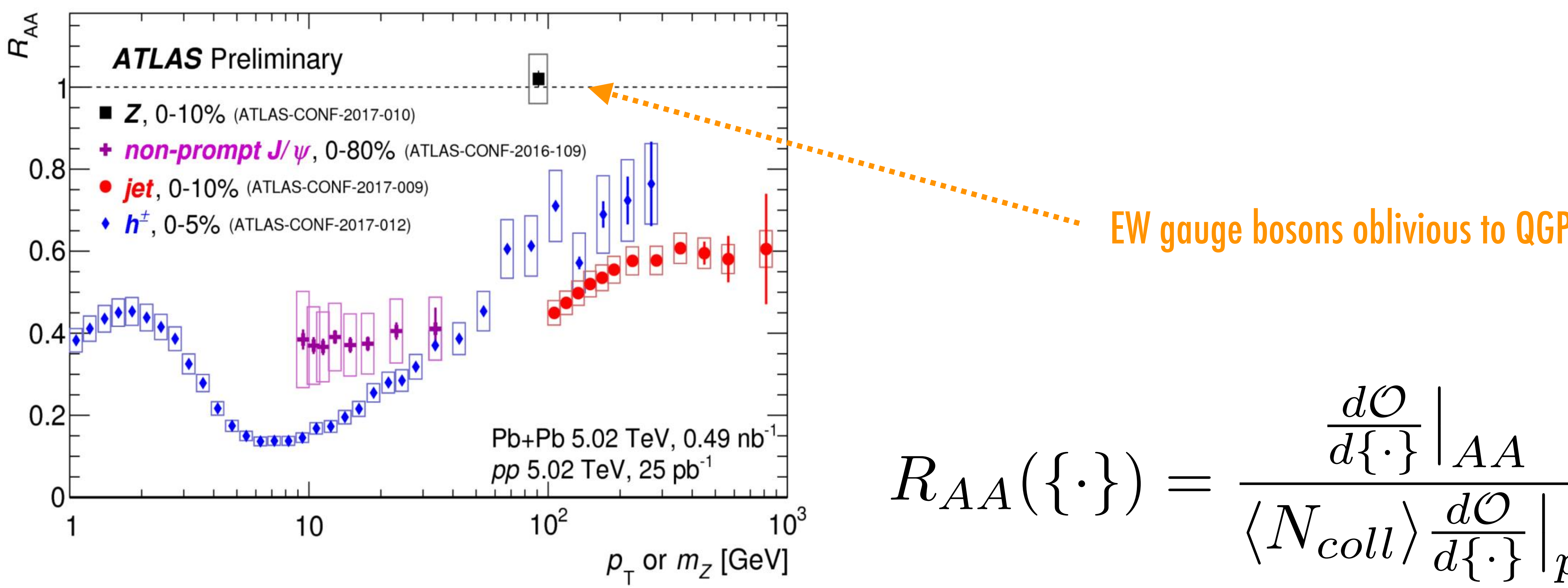


- ✓ centrality defined as percentile ranges of minimum-bias cross section

NUCLEAR MODIFICATION RATIOS [R_{AA}]

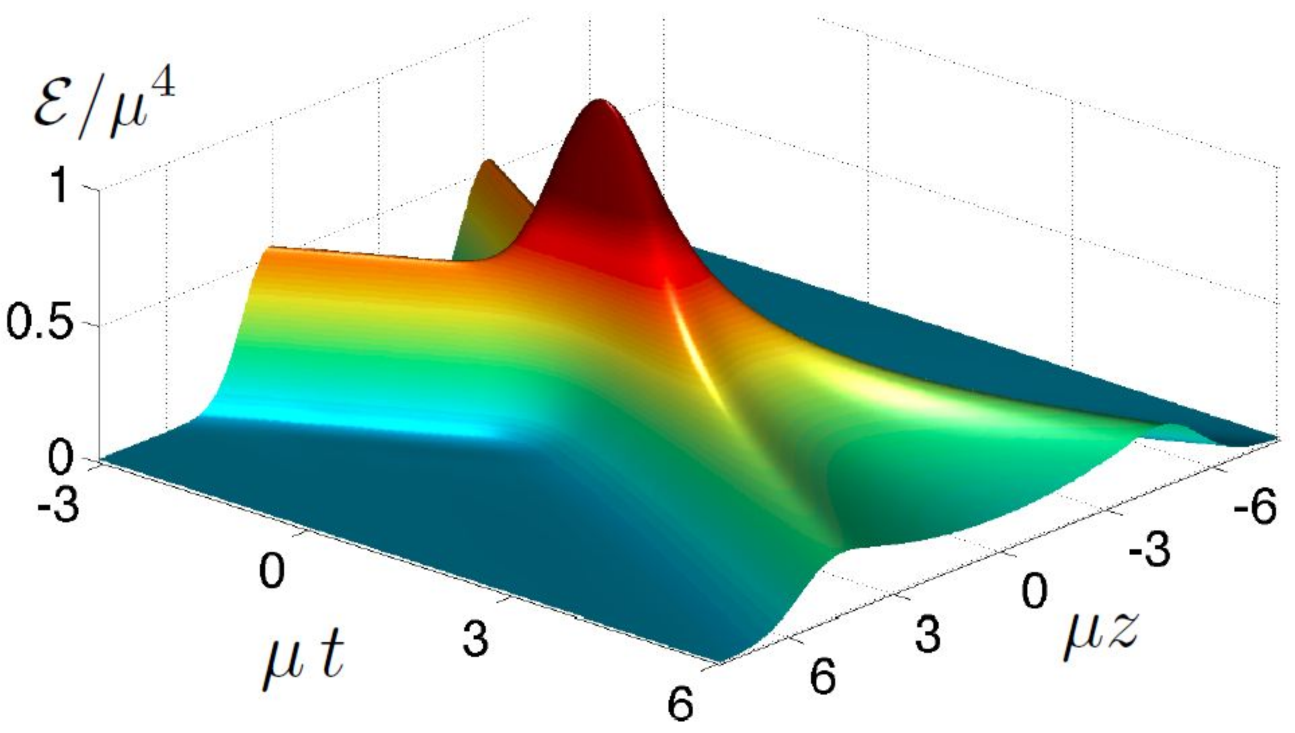
✓ a standard procedure to seek for QGP effects is to take ratios[PbPb over pp] of a given measured quantity [cross-section, yield, …]

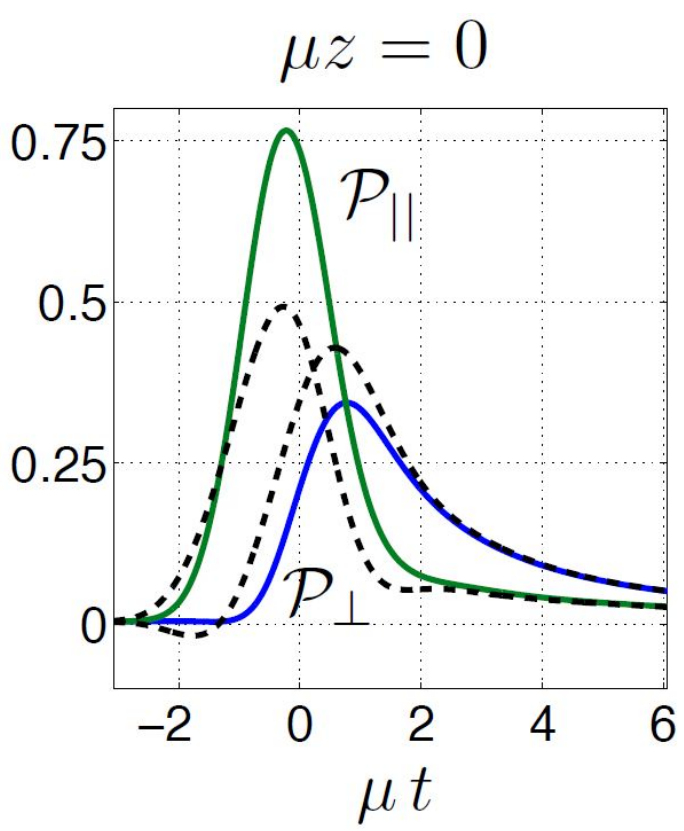
- ✓ pp result must be scaled by the number of collisions [Glauber]
- ✓ deviations from unity signal effects beyond incoherent superposition of nucleon-nucleon collisions



$$R_{AA}(\{\cdot\}) = \frac{\frac{d\mathcal{O}}{d\{\cdot\}}\Big|_{AA}}{\langle N_{coll}\rangle \frac{d\mathcal{O}}{d\{\cdot\}}\Big|_{pp}}$$

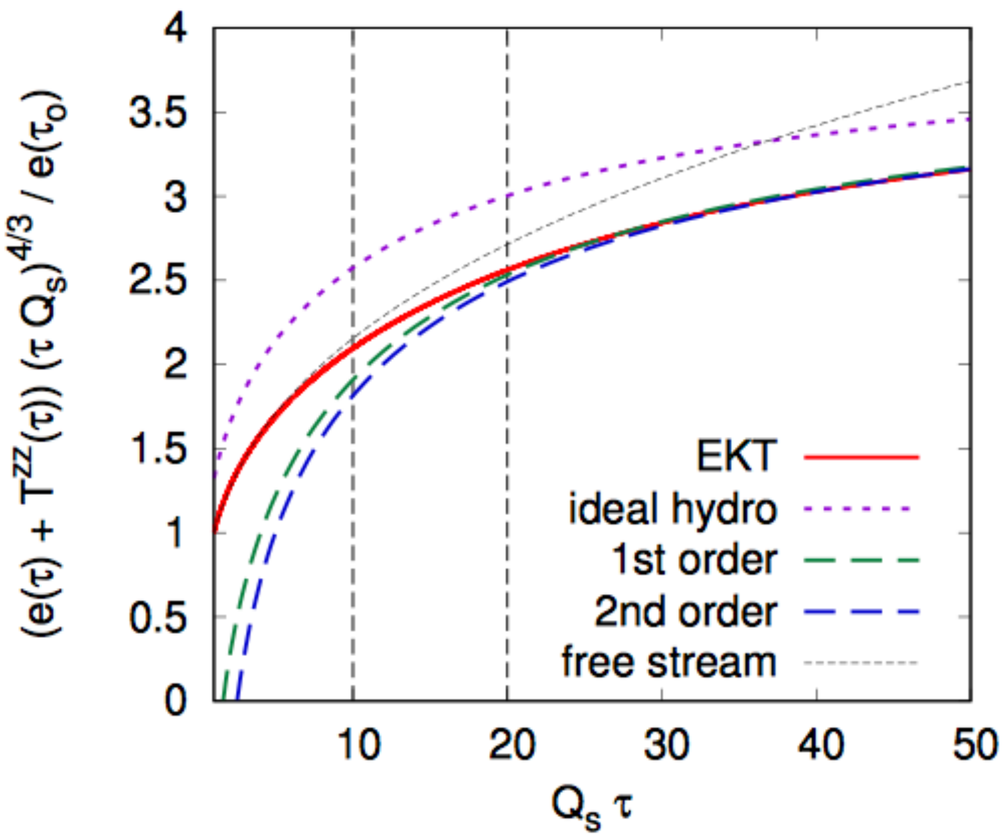
HOW DOES QGP COME INTO BEING?

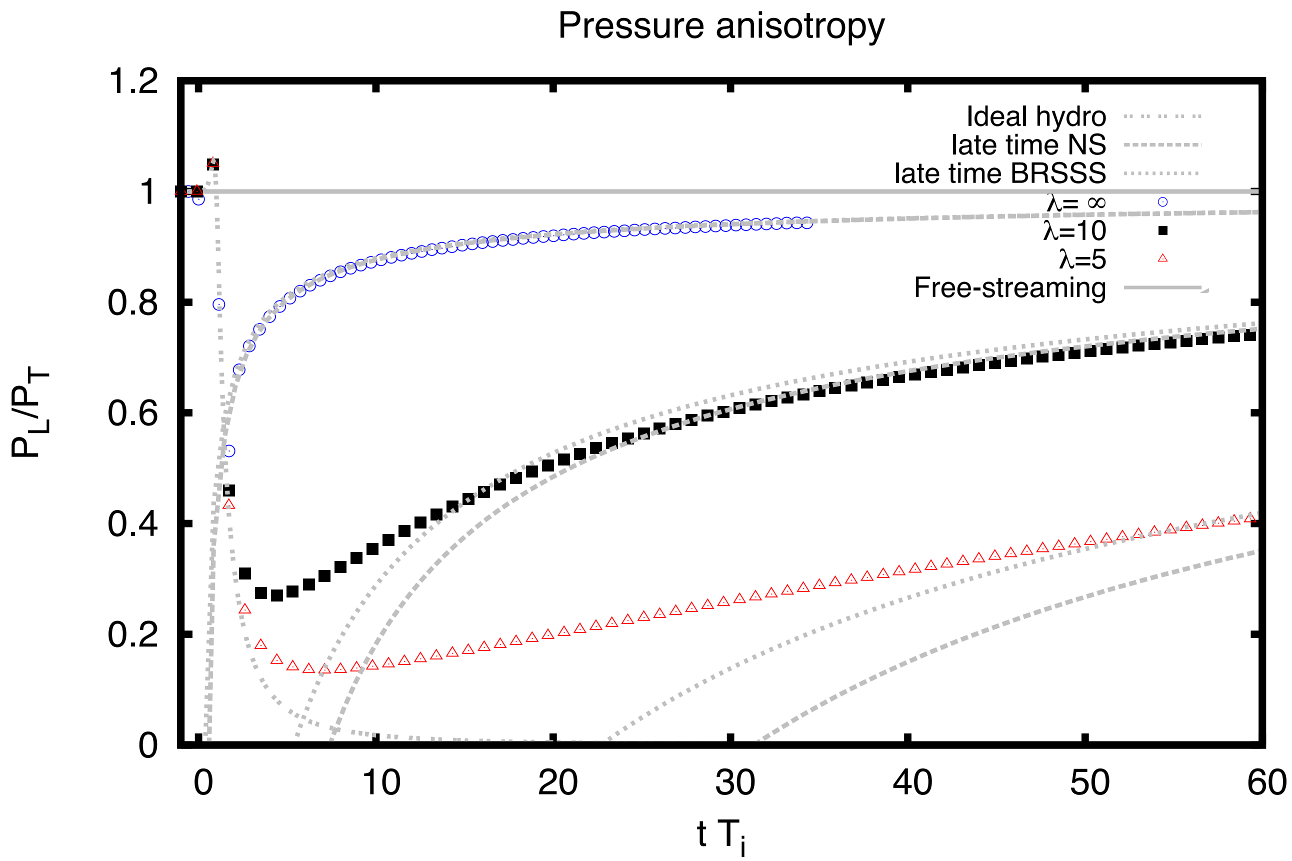




- ✓ towards-equilibrium dynamics can be solved in N=4 SYM at strong coupling [AdS/CFT correspondence comes in handy]
  - ✓ collision of shockwaves in 5d
  - ✓ hydrodynamization related to creation of BH in 5th dim
  - ✓ hydrodynamical behaviour reached very quickly [τ∼1/T]
- ✓ unfortunately N=4 SYM is not QCD

HOW DOES QGP COME INTO BEING?





✓ kinetic theory [weak coupling] can describe the dynamics bringing out-of-equilibrium initial condition towards hydrodynamical behaviour

✓ note that hydrodynamics appears to become applicable well before when it naively should [$P_L \sim P_T$]

- ✓ deep theoretical challenge cutting across many fields of physics

HYDRODYNAMICS

- ✓ description of long-distance [low momentum], long-time, strongly coupled dynamics in terms of macroscopic quantities [eq. of state, shear/bulk viscosities, relaxation times, etc.]
- ✓ incredibly successful in heavy-ion collisions
  - ✓ QGP is a fluid

IDEAL HYDRODYNAMICS

:: energy momentum tensor for fluid in global thermal equilibrium

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + p\,(g^{\mu\nu} + u^\mu u^\nu)$$

velocity field

metric

:: thermodynamical equation of state

$$p = p(\epsilon)$$

pressure

energy density

:: ideal fluid ➞ local thermal equilibrium

$$u^\mu = u^\mu(x) \qquad\qquad \epsilon = \epsilon(x)$$

:: energy-momentum conservation ➞ hydrodynamical evolution equations

$$\nabla_\mu T^{\mu\nu} = 0 \implies \quad u^\mu \partial_\mu \epsilon + (\epsilon + p)\nabla_\mu u^\mu = 0$$

$$(\epsilon + p) u^\mu \nabla_\mu u^\nu + (g^{\nu\mu} + u^\nu u^\mu)\partial_\mu p = 0$$

VISCOUS HYDRODYNAMICS

:: more general energy momentum tensor

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + (p + \pi_{\mathsf{bulk}})(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

bulk viscous pressure

shear stress [transverse and traceless]

deviations from ideal hydro

:: can be organized as a derivative [gradient] expansion

$$\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$$

$$\pi_{\mathsf{bulk}} = -\,\zeta \nabla_\mu u^\mu + \ldots\,,$$

$$\pi^{\mu\nu} = -\,2\eta \left(\tfrac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta} + \tfrac{1}{2}\Delta^{\mu\beta}\Delta^{\nu\alpha} - \tfrac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta} \right) \nabla_\alpha u_\beta + \ldots$$

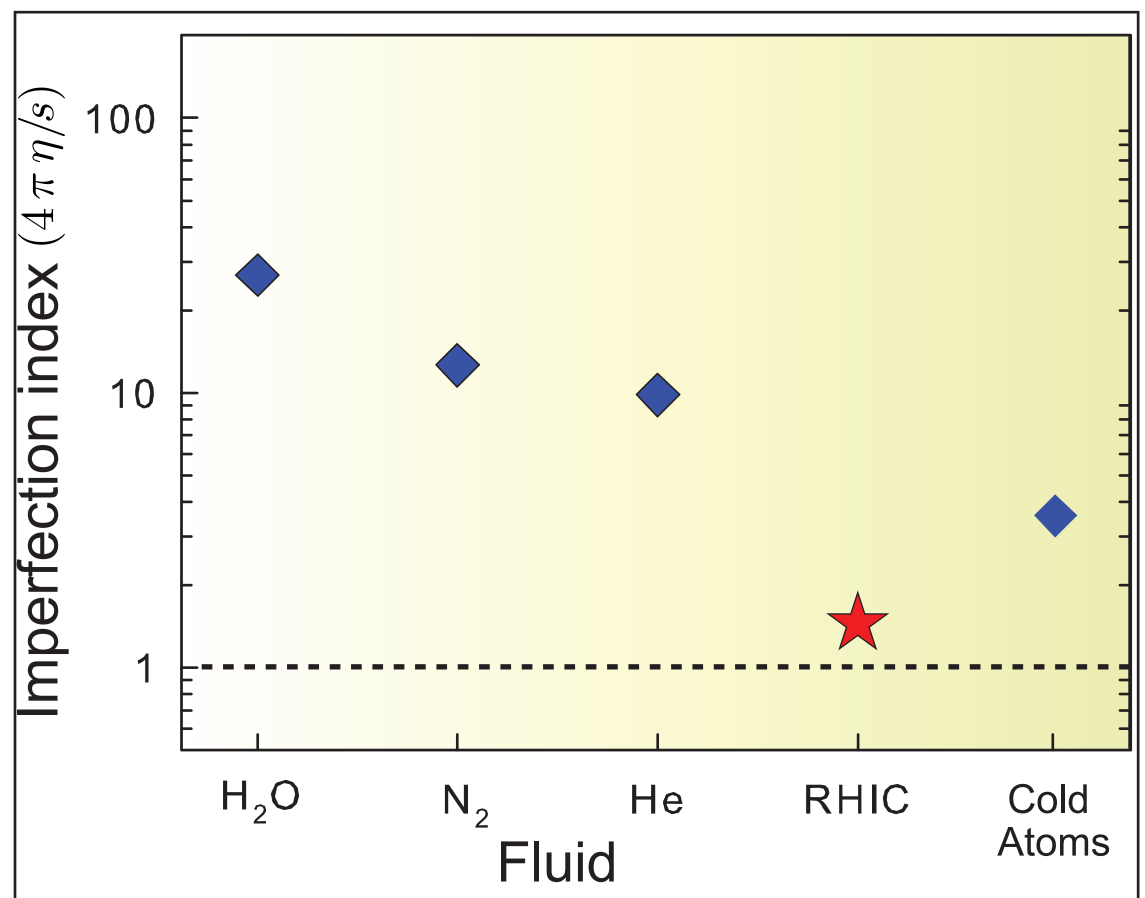
:: at first order, dependence on bulk viscosity [$\zeta = \zeta(\varepsilon)$] and shear viscosity [$\eta = \eta(\varepsilon)$]

:: at higher orders, further coefficients…

:: increasingly complicated evolution equations [to be solved numerically]

TRANSPORT PROPERTIES

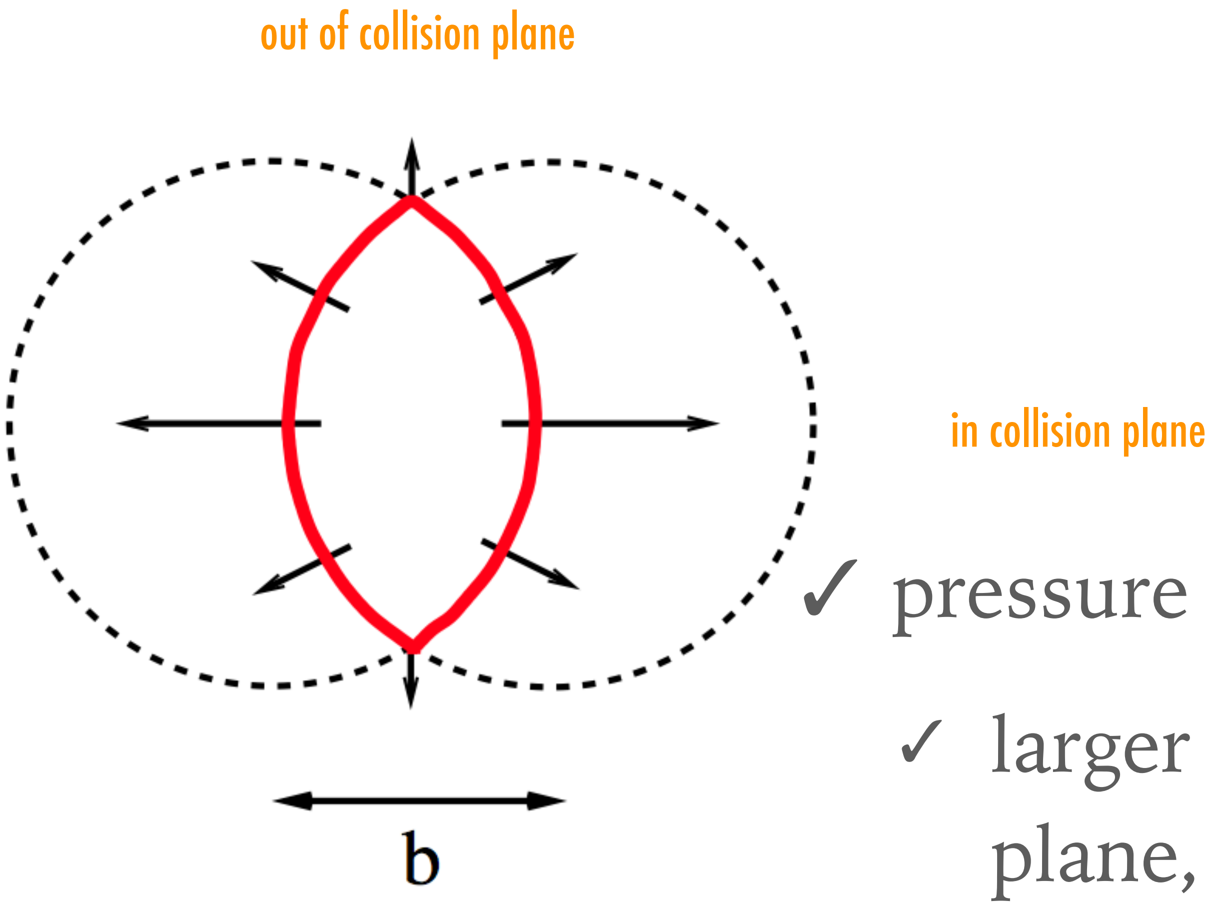
- ✓ viscosity is due to transport of momentum
  - ✓ large η/s requires momentum to be transported over distances $s^{-1/3}$ by well-defined quasiparticles
  - ✓ for small η/s there are no quasi-particles
- ✓ QGP has very small η/s
- ✓ efficient momentum transport converts spatial properties [asymmetries] into momentum asymmetries



universal lower bound ?

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

FLOW



✓ pressure gradients larger in reaction plane

✓ larger fluid velocity along reaction plane, more particles fly in this direction

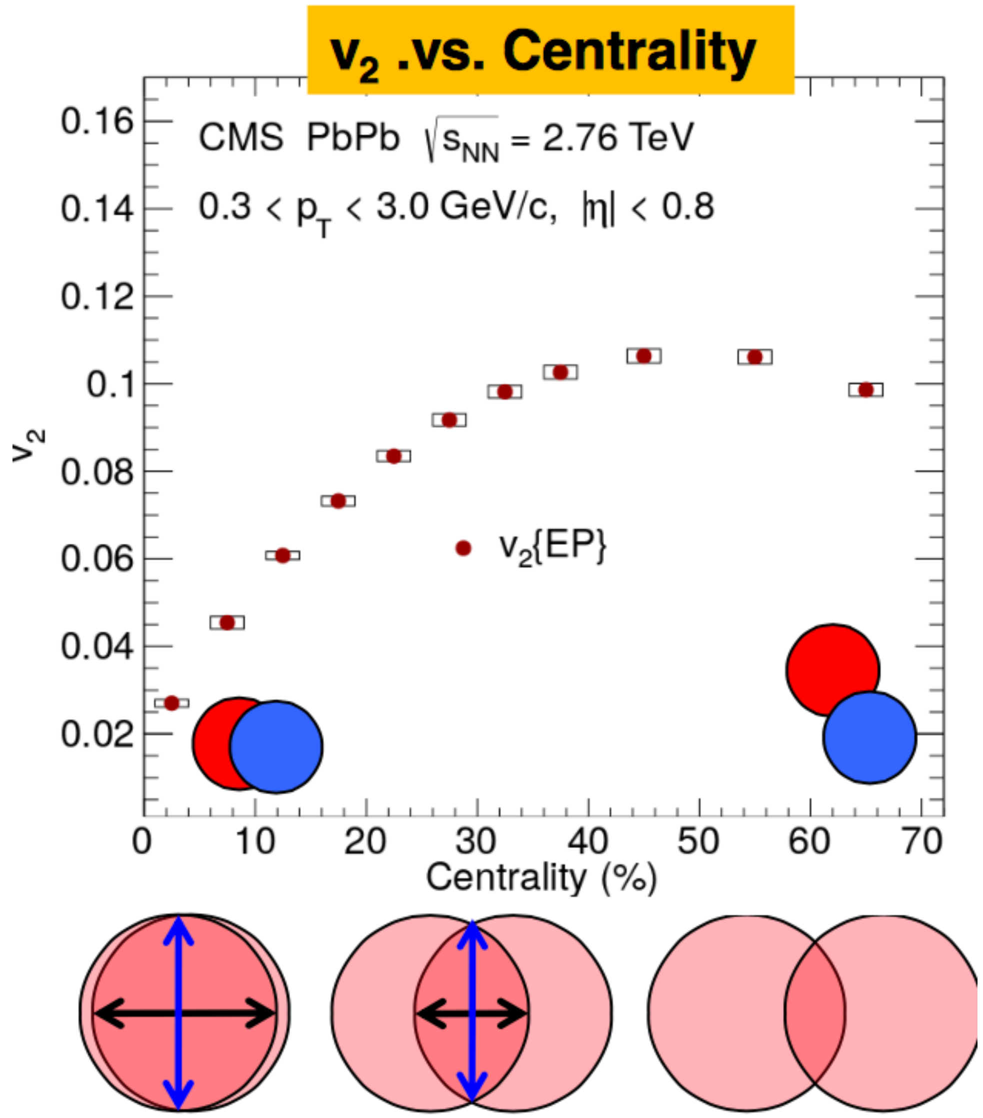
:: quantify effect by measuring particle distribution in azimuth

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_m v_m \cos\left(m\left(\phi - \psi_R\right)\right)\right]$$

:: v_2 measures ellipticity of momentum distribution

:: odd-coefficients [v_3, …] vanish by $\phi \to \phi + \pi$ symmetry

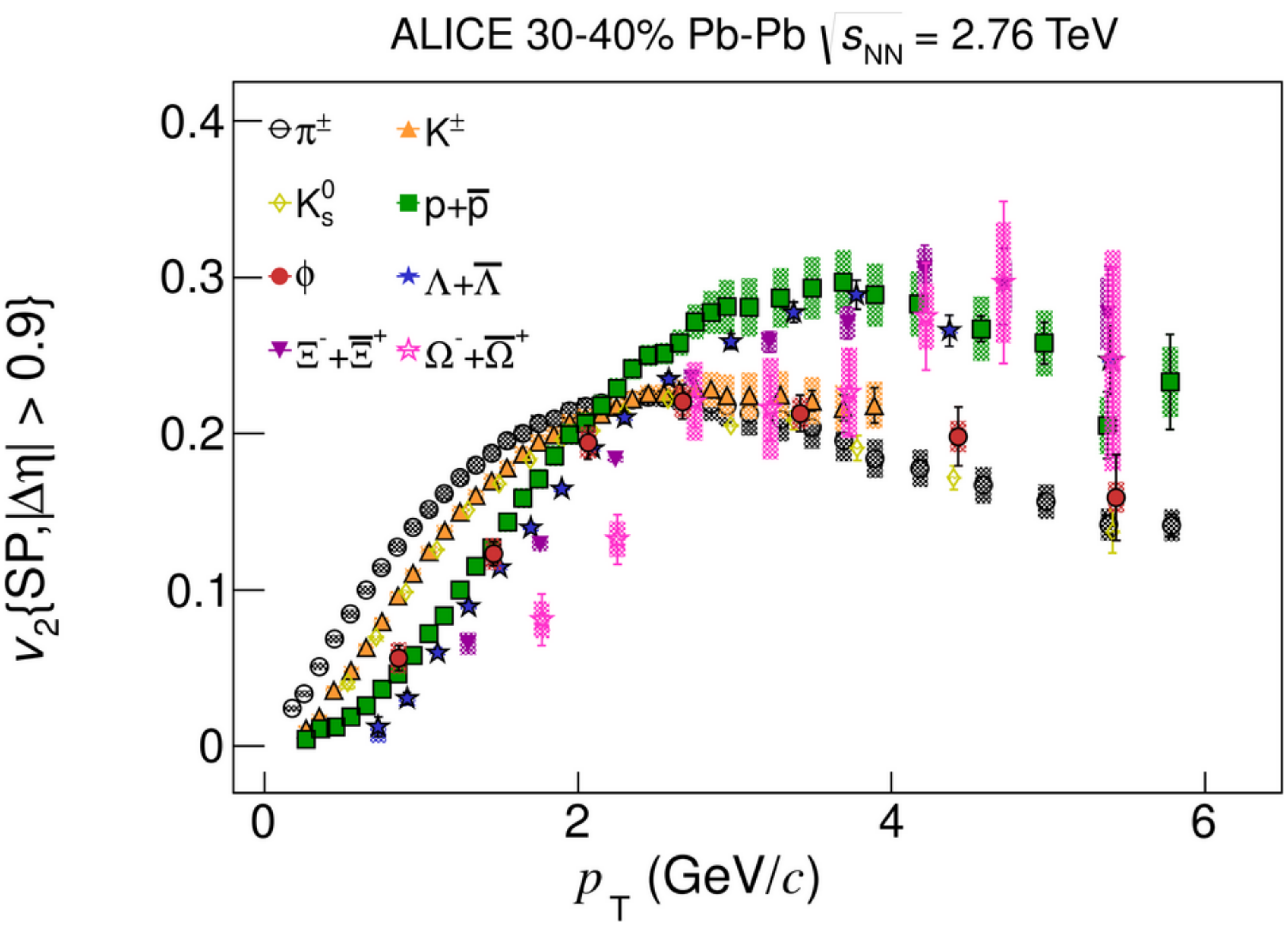
ELLIPTIC FLOW



CMS, PRC 87(2013) 014902

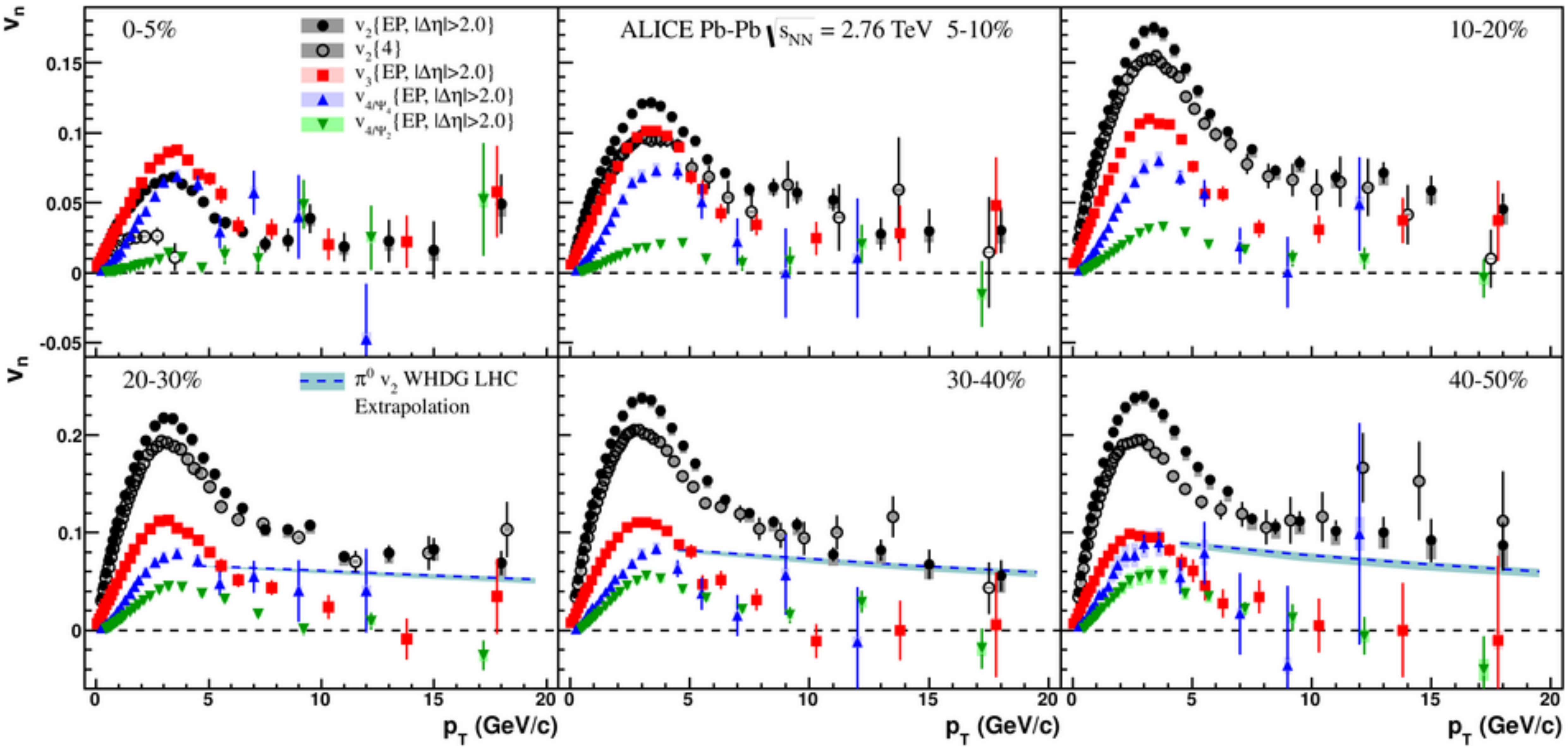
- ✓ strong centrality dependence
  - ✓ small for central [no-spatial asymmetry]
  - ✓ maximum for mid-central
  - ✓ smaller again for very peripheral [small QGP]

ELLIPTIC FLOW [MASS DEPENDENCE]



✓ heavier particles flow less strongly

HIGHER HARMONICS



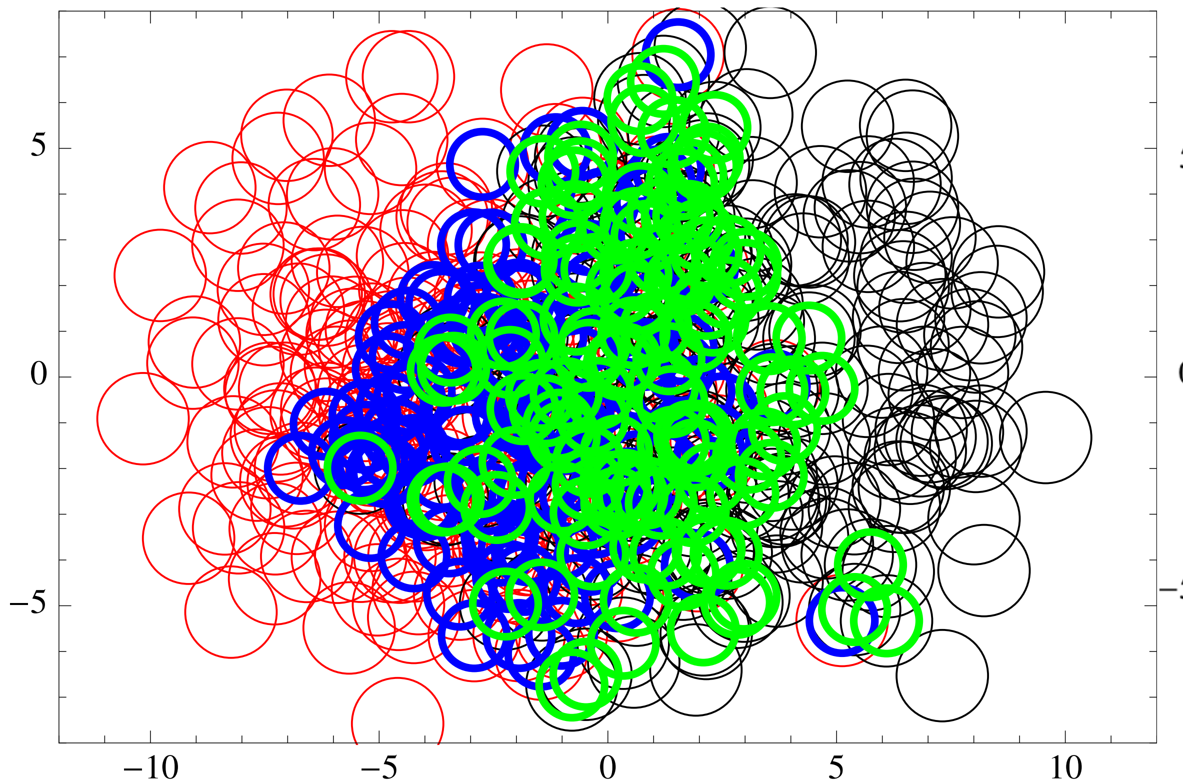
✓ all flow coefficients are non-zero

✓ odd ones should vanish by symmetry: what is going on?

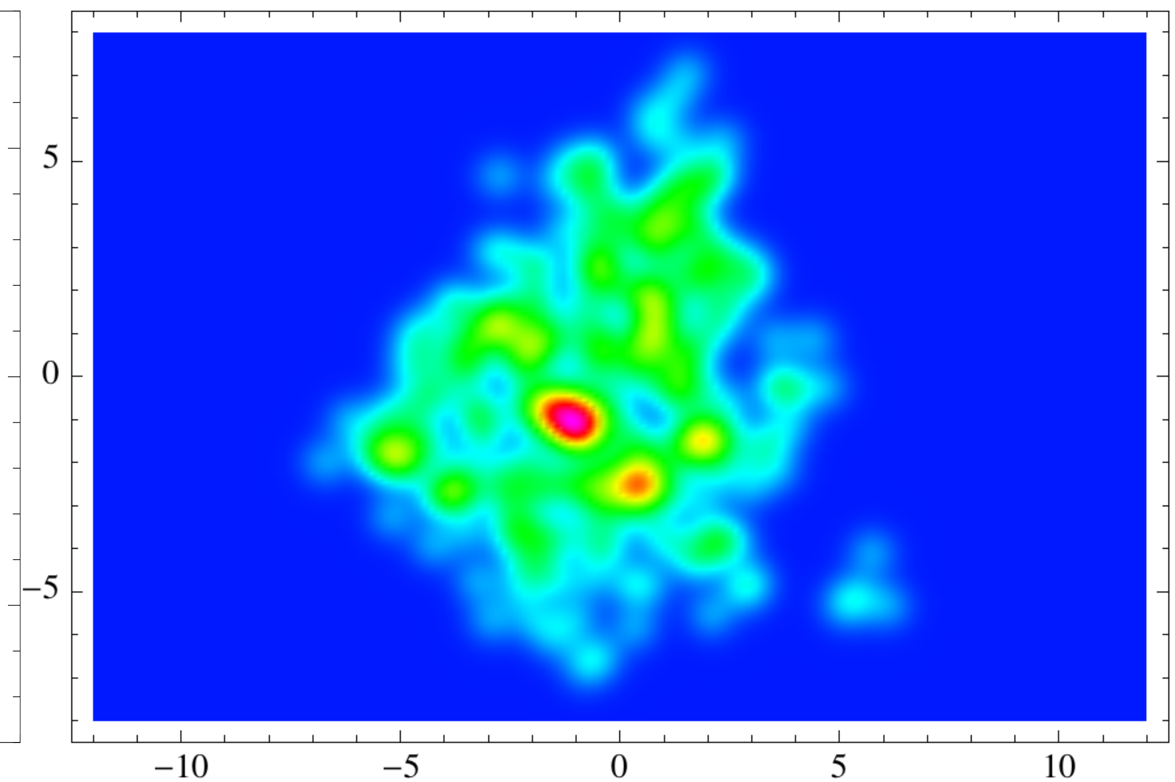
EVENT-BY-EVENT FLUCTUATIONS

✓ symmetry argument for vanishing of odd harmonics applies only for event-averaged geometry

✓ importance of event-by-event fluctuations of initial configuration [MCGlauber, several other alternatives]

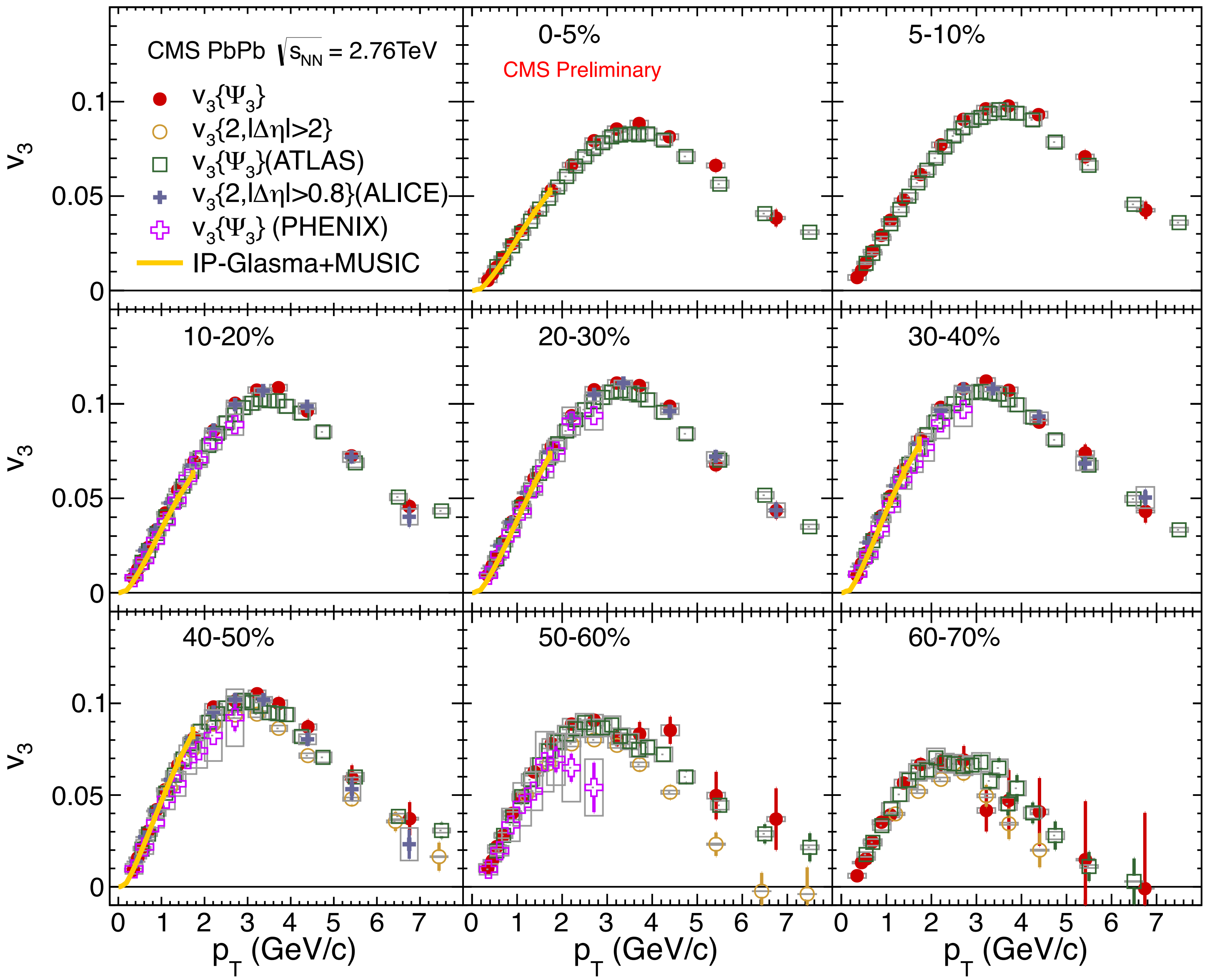


MCGlauber



IP-Glasma

EVENT-BY-EVENT FLUCTUATIONS



✓ fluctuation dominance leads to centrality independence

PARTICLE CORRELATIONS

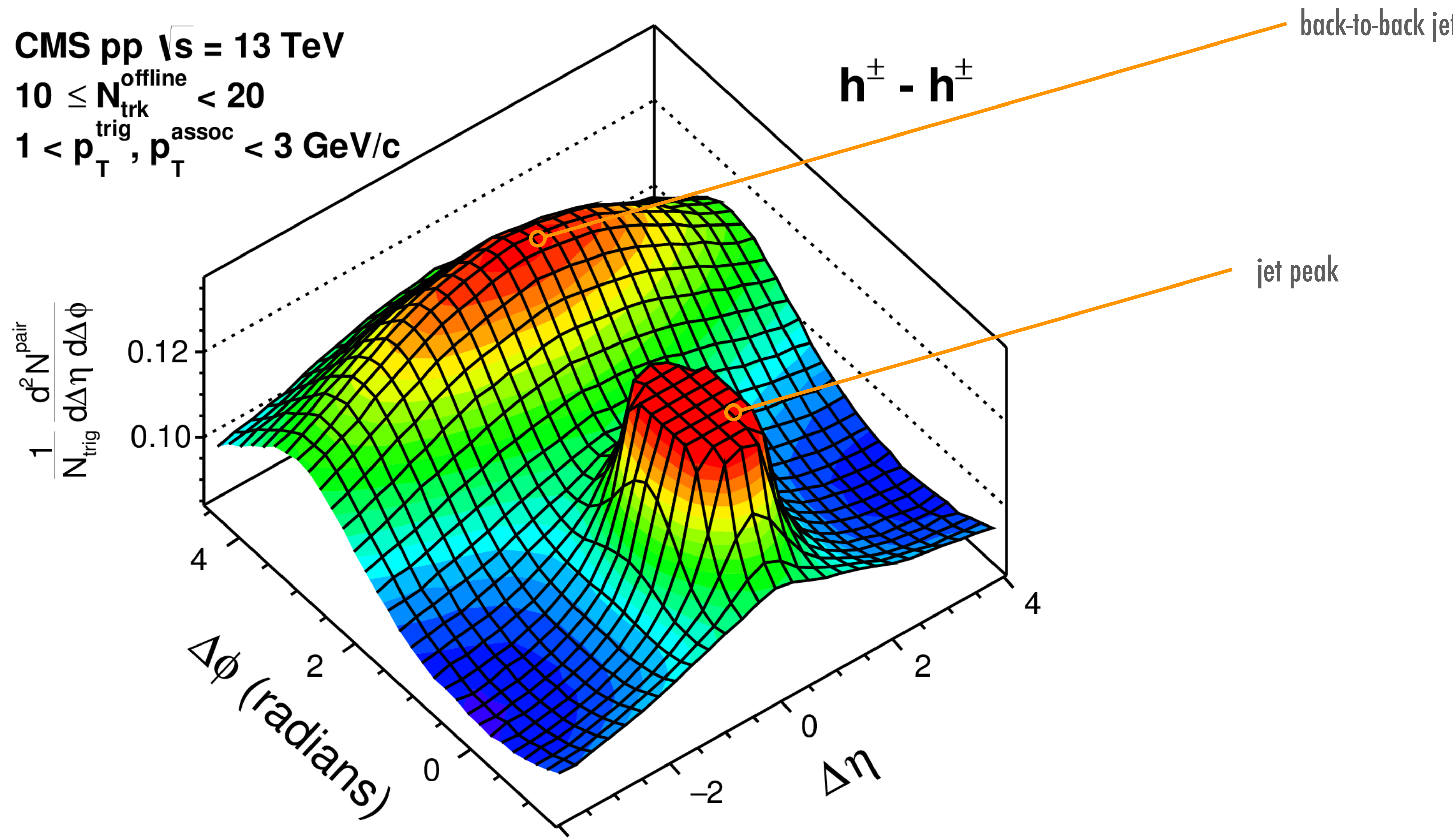
✓ determination of reaction plane is not straighforward [particularly so if low multiplicity]

✓ same flow information can be obtained from pair correlations

$$C(\phi_1, \phi_2) = \frac{\left\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \right\rangle_{\text{events}}}{\left\langle \frac{dN}{d\phi_1} \right\rangle_{\text{events}} \left\langle \frac{dN}{d\phi_2} \right\rangle_{\text{events}}} = 1 + 2 \sum_m v_m^2 \cos(m(\phi_1 - \phi_2))$$

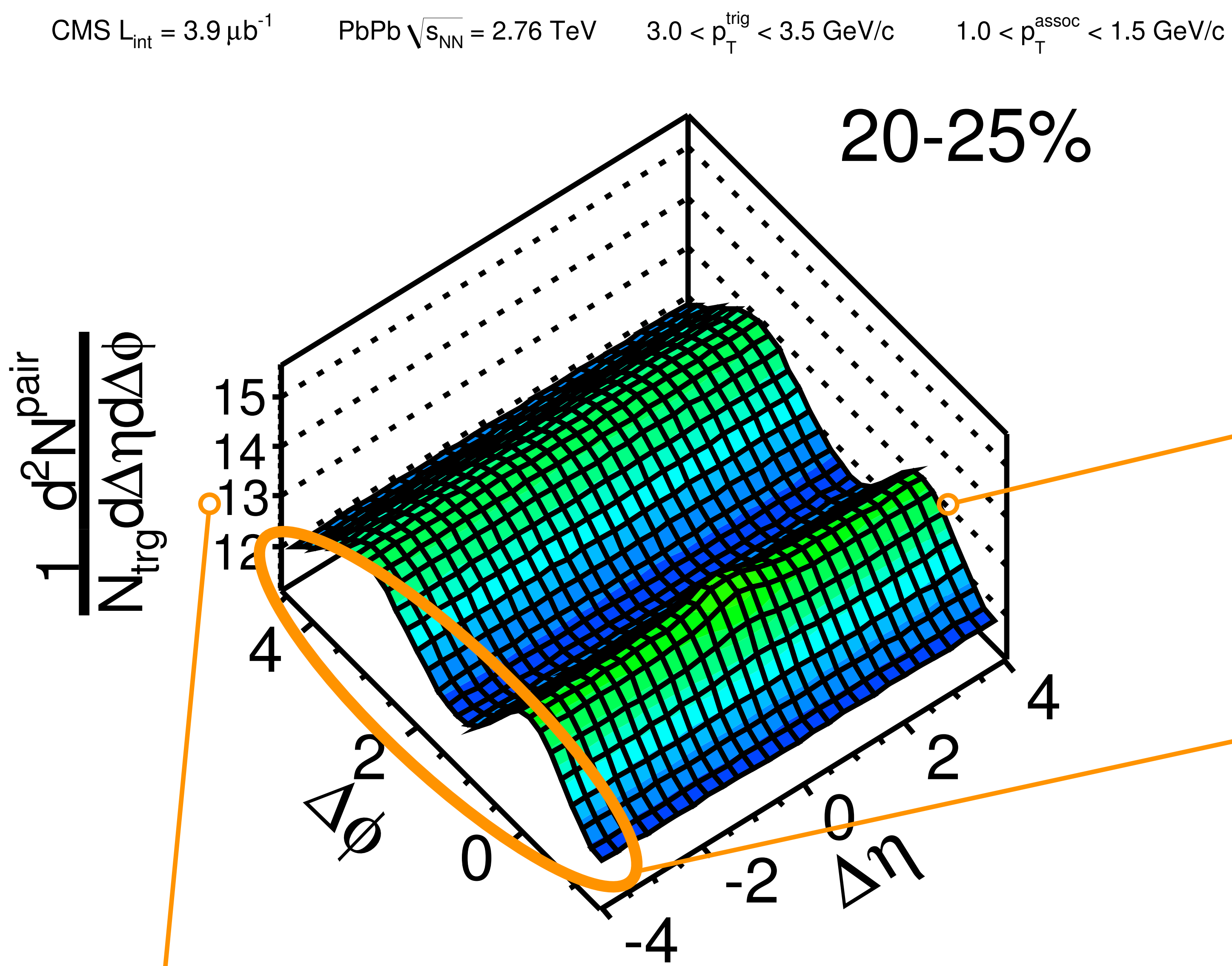
PARTICLE CORRELATIONS

:: pair correlations in [minimum bias] pp



PARTICLE CORRELATIONS

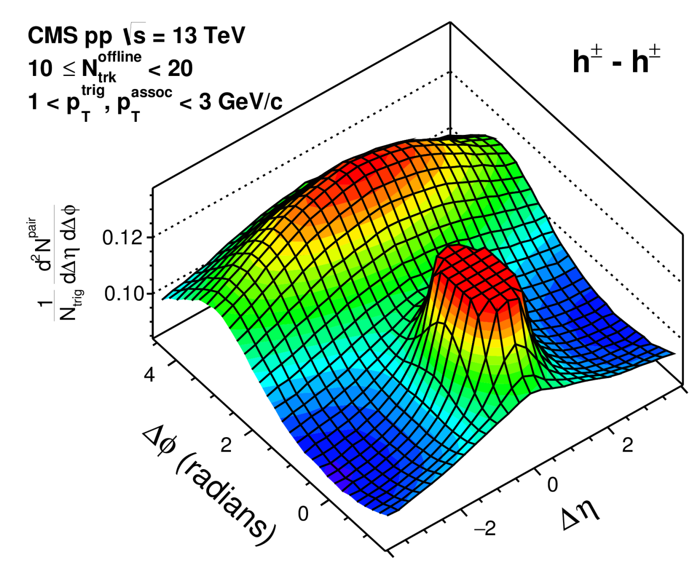
:: pair correlations in PbPb



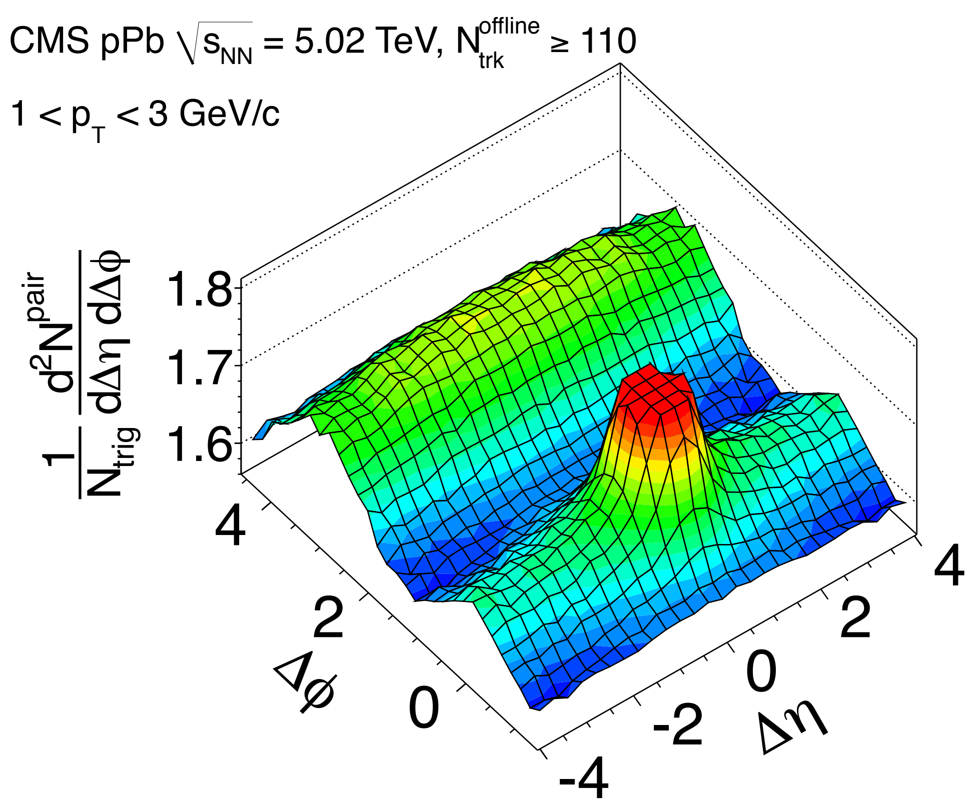
ridge: long range rapidity correlation [boost invariance]

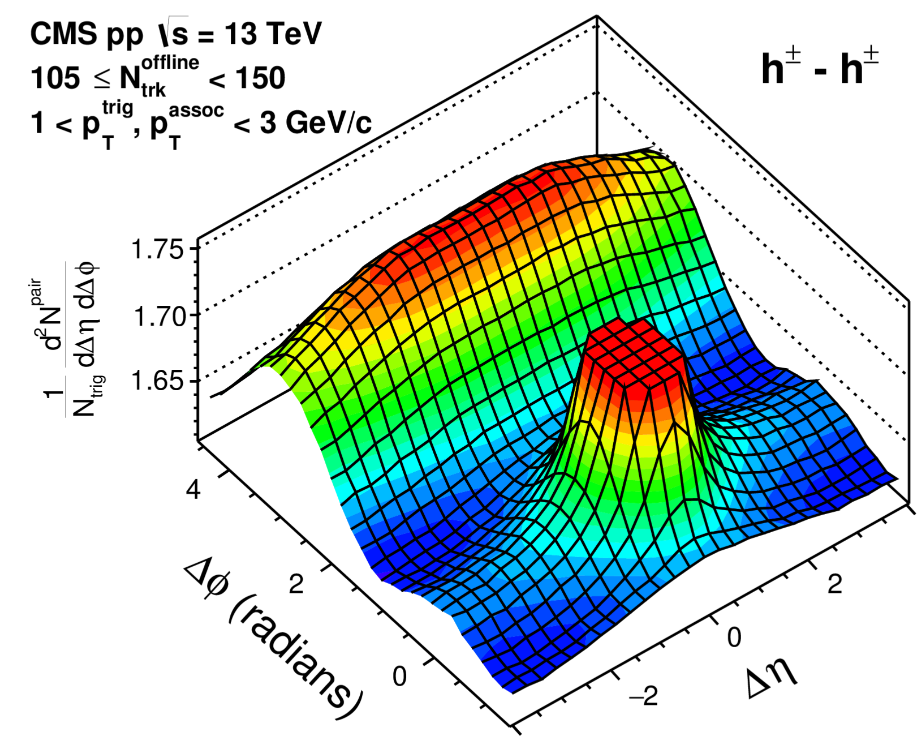
azimuthal structure from flow

note the magnitude



COLLECTIVITY IN SMALL SYSTEMS





- ✓ flow pattern also present in proton-nucleus
  - ✓ tiny droplet of QGP ?
- ✓ flow pattern also present in [high-multiplicity] proton-proton
  - ✓ QGP ???
- ✓ alternative [initial state correlations] explanations exist
  - ✓ do they also work for nucleus-nucleus ? [very difficult to get required magnitude]