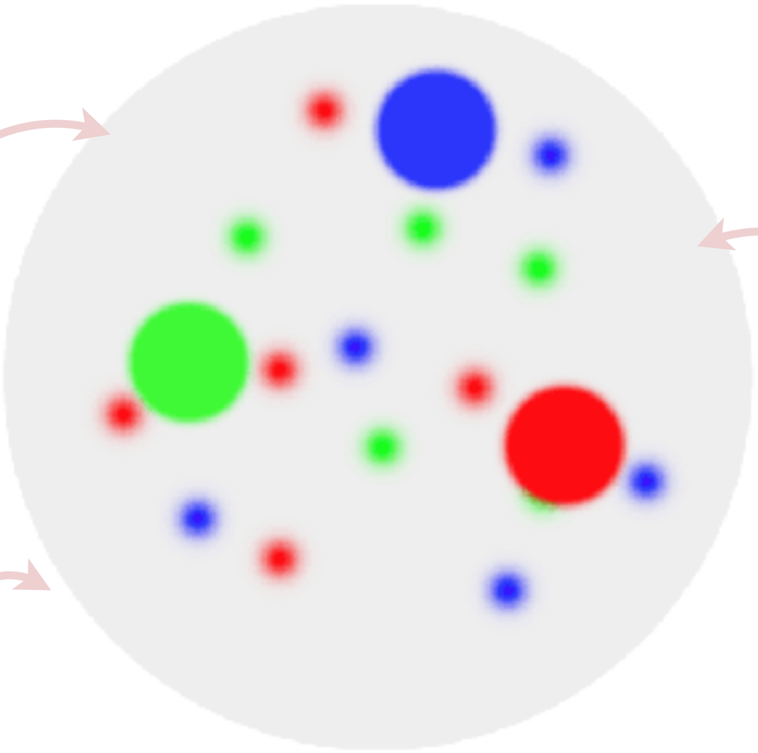
HEAVY ION PHYSICS

Konrad Tywoniuk

University of Oslo, Spring workshop on nuclear and particle physics, CERN 09.04.2018

A snapshot of a proton



"fractional charge"

2/3 e: up, charm and top
1/3 e: down, strange and bottom

confinement

the quarks are tightly bound by the gluons inside "colorless" objects, so called **hadrons**

"fuzziness"

QCD is a **quantum field theory** (creation & annihilation of particles)

$$\Delta x \Delta p \gtrsim h$$

Millennium Prize Problem #7

Yang–Mills Existence and Mass Gap. Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in [45, 35].

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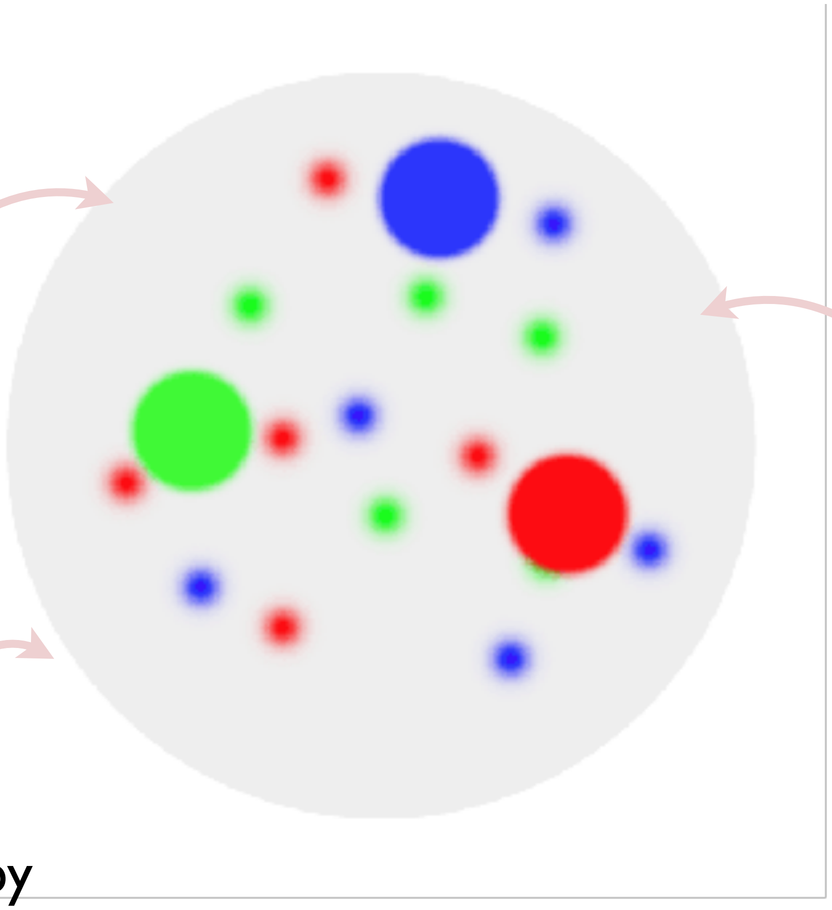

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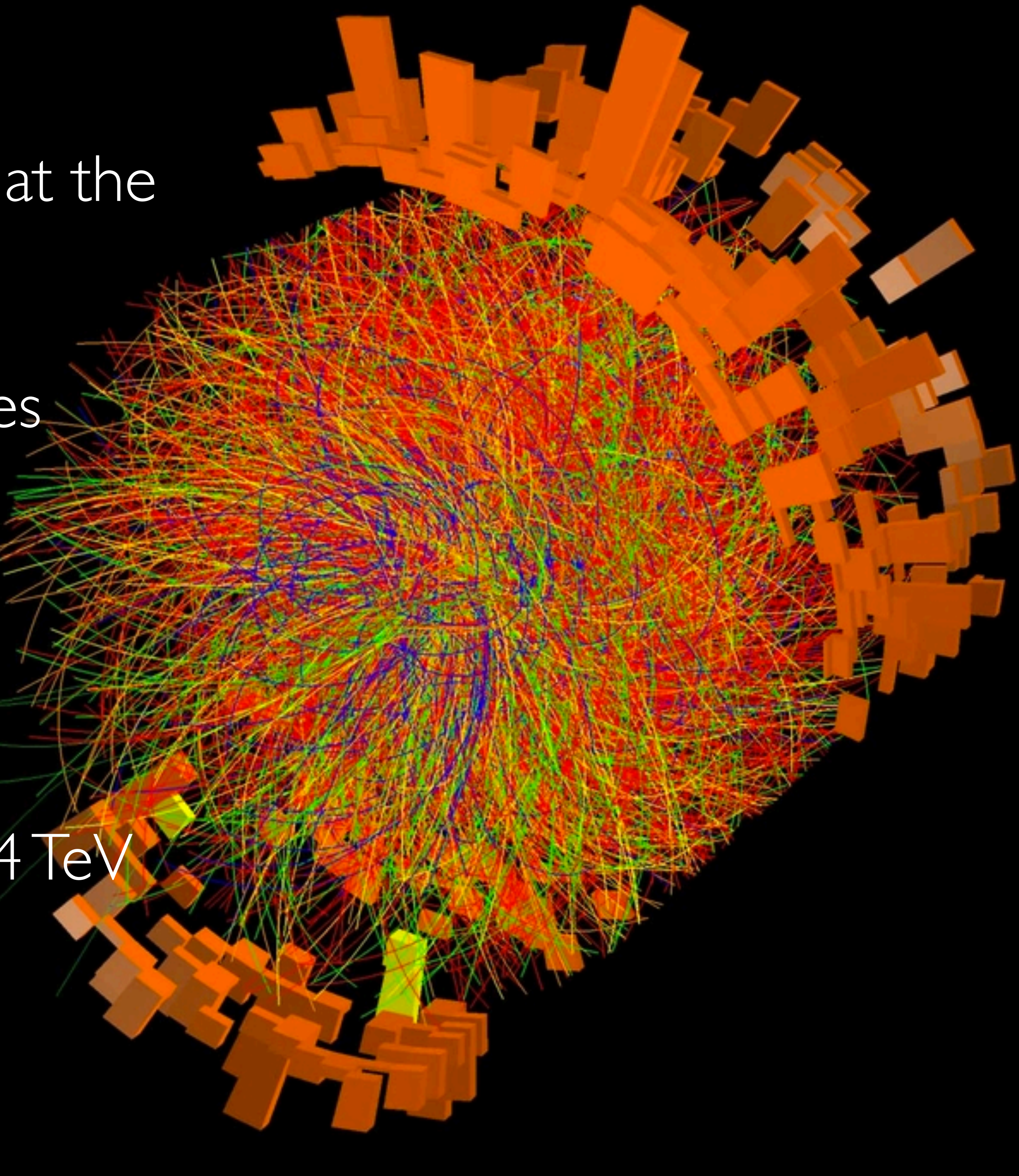
ALICE @ CERN



in: two lead (Pb208) ions at the speed of light

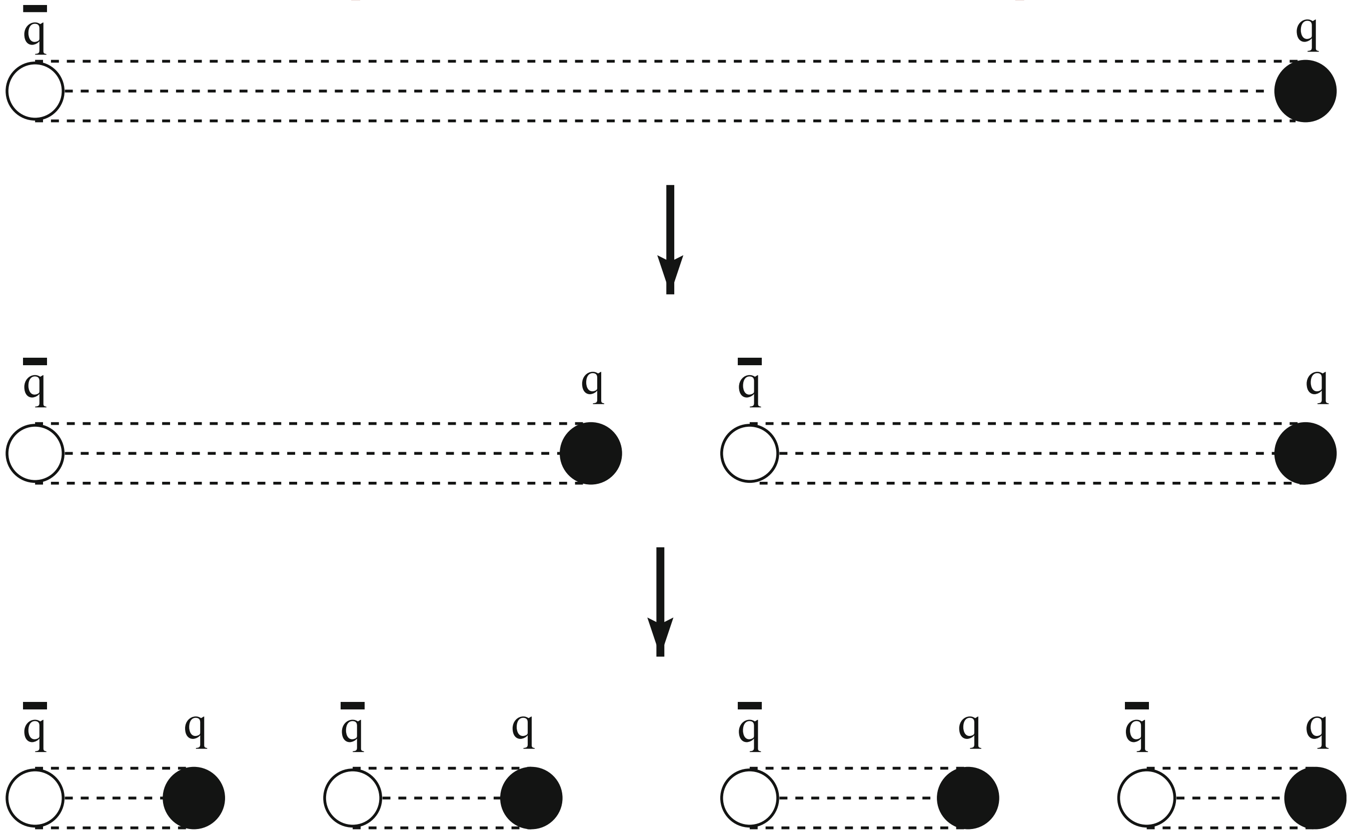
out: ~ 10.000 particles

Temperature 10^{12}K

Lifetime 10^{-23}s

Total collision energy 574 TeV

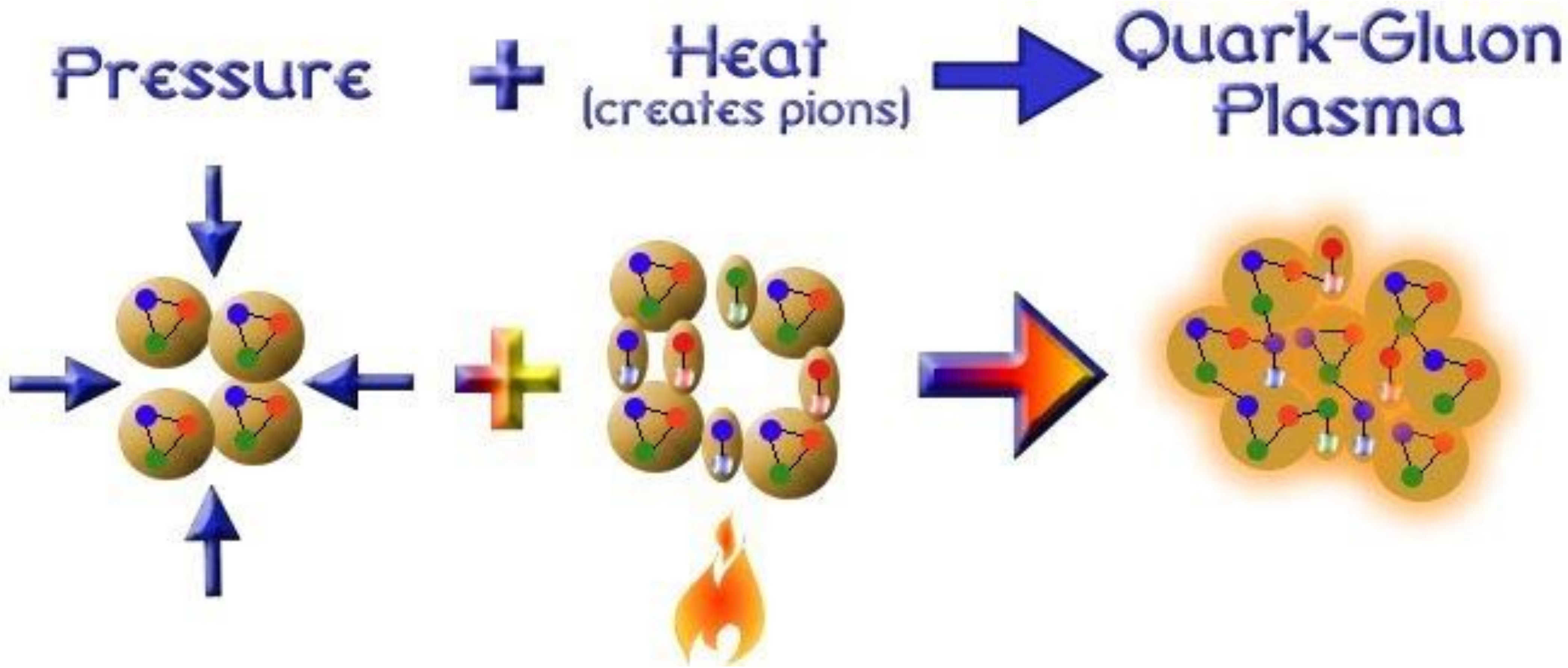
How are particles produced?



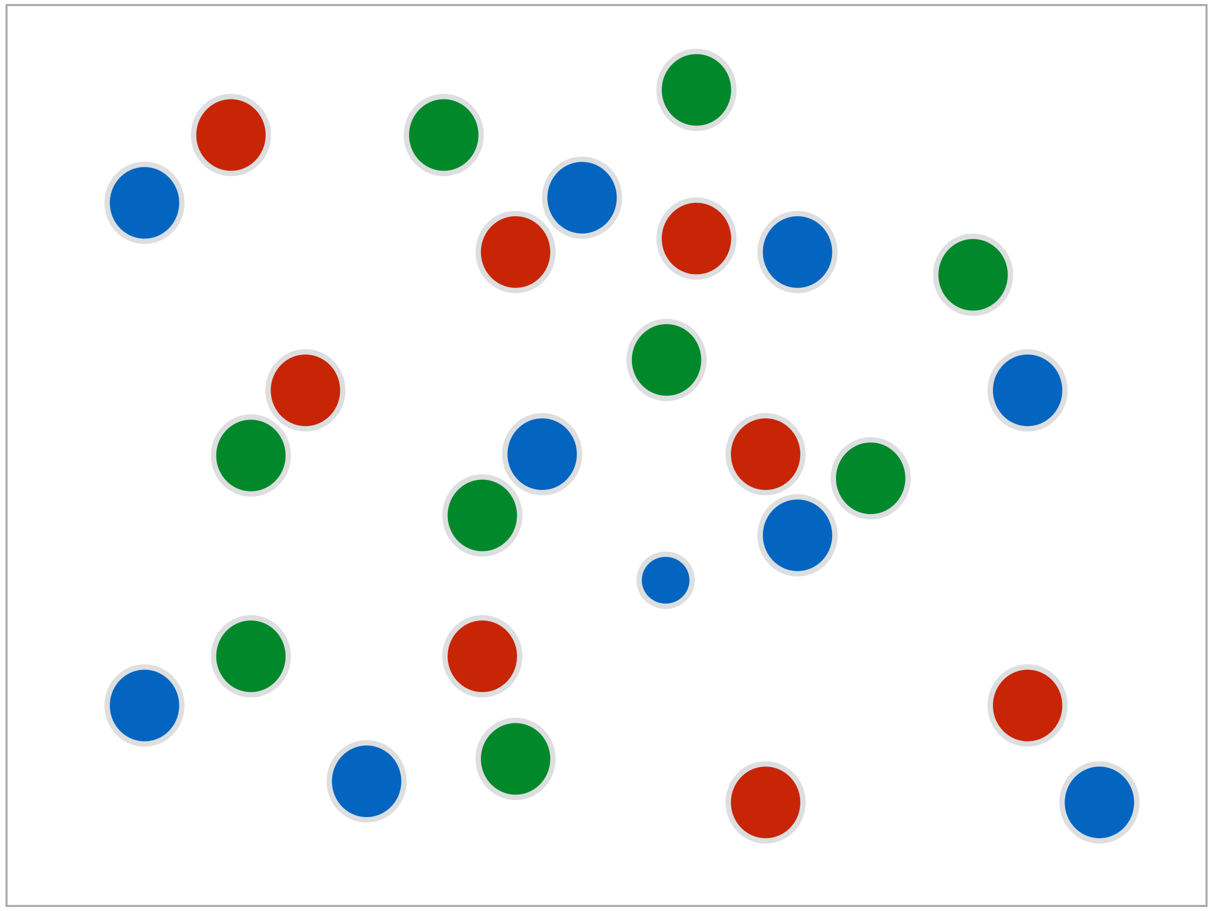
$$V(r) = -\frac{\alpha}{r} + \sigma r$$

- tube of (color) electrical flux
- $\sqrt{\sigma}$ = 420 MeV is the so-called string tension
- string breaks due to light quarks!
- short-distance regime: Coulomb interaction

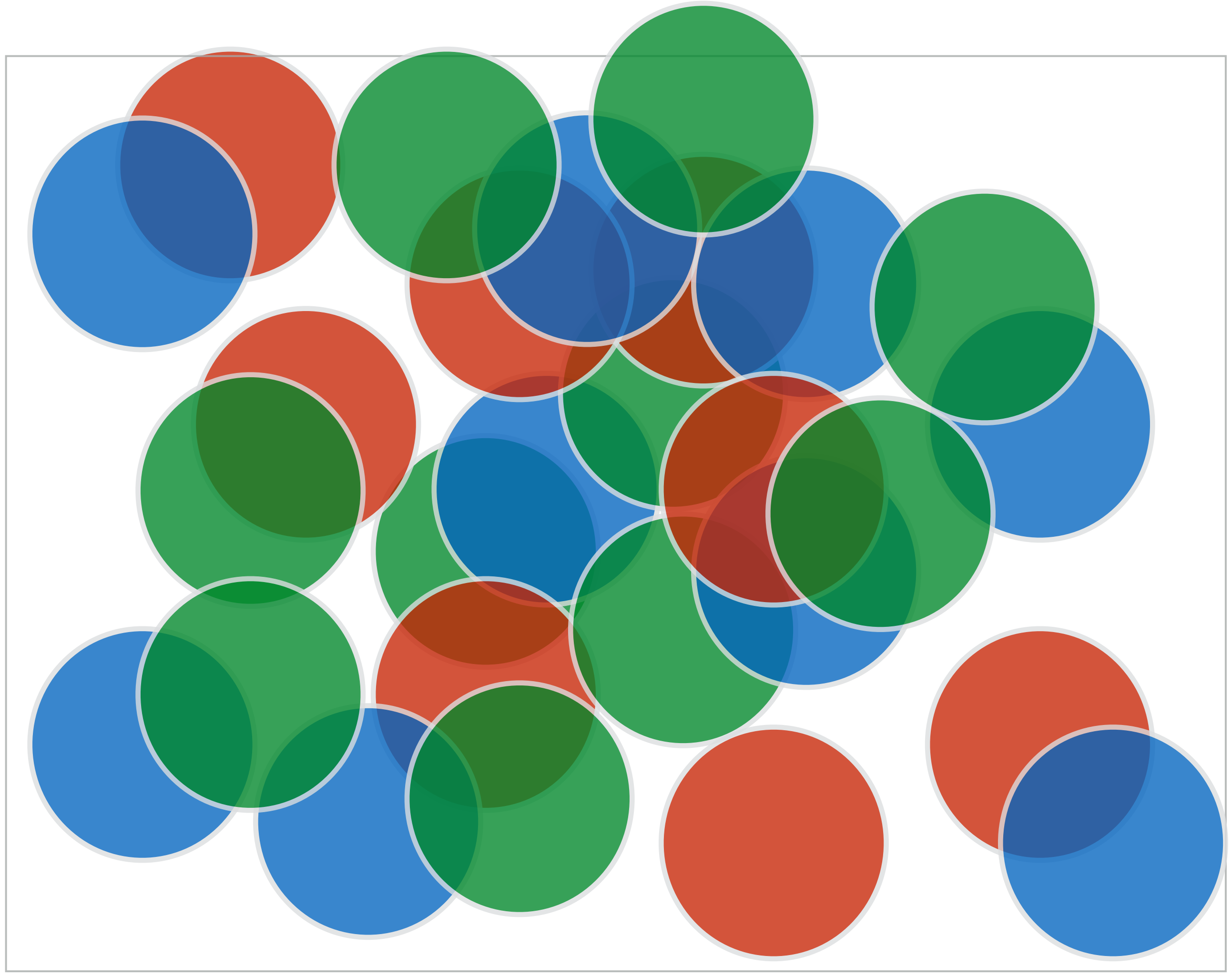
Main idea



What is the QGP?



dilute gas of quasi-particles?



strongly correlated system?

- thermal (static) properties of QCD

equilibrium

- collective & dynamic properties of QCD

non-equilibrium

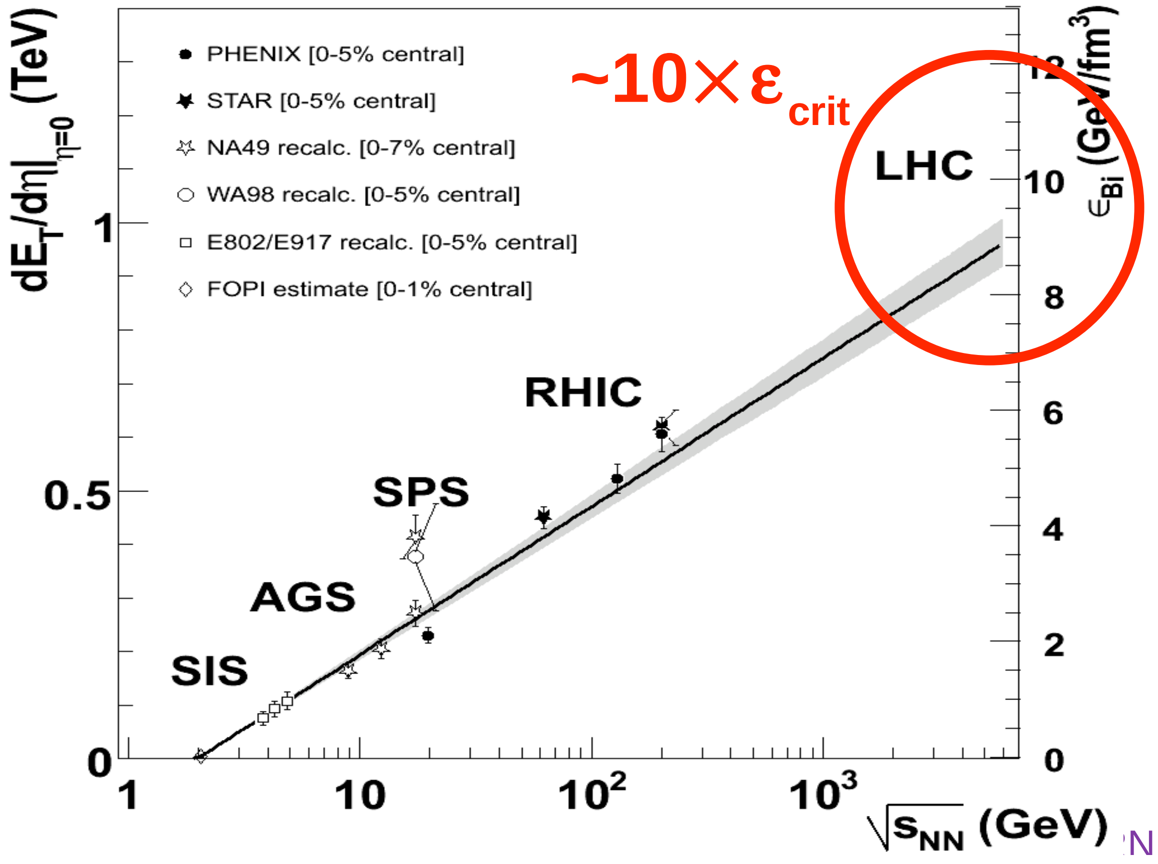
- two paradigms: gas or fluid

strongly or weakly interacting

Collisions & colliders

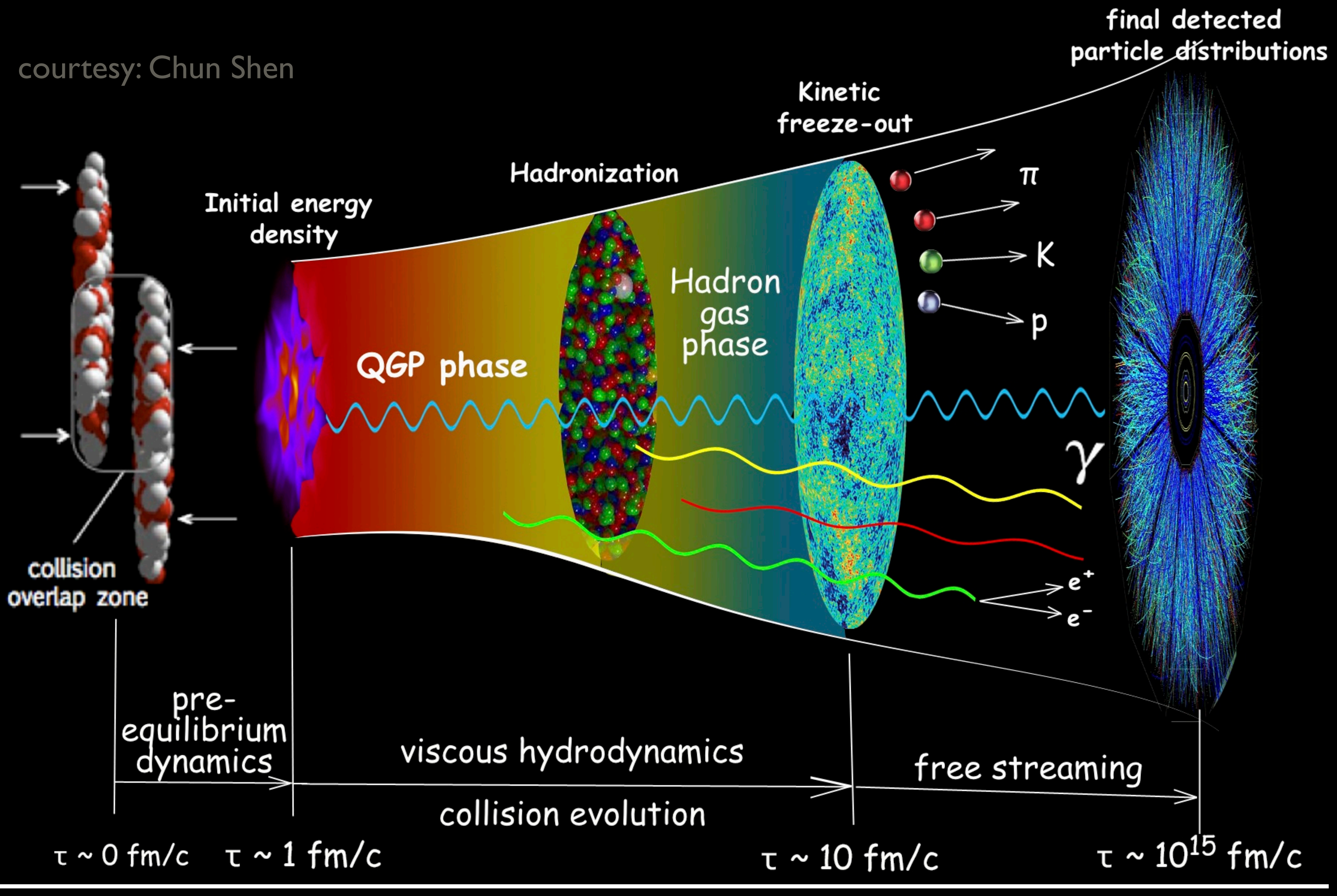
	AGS	AGS	SPS	SPS	SPS	RHIC	RHIC	LHC
Start year	1986	1992	1986	1994	1999	2000	2001	2009
$\mathrm{A}_{\max}$	^{28}Si	^{197}Au	^{32}S	^{208}Pb	^{208}Pb	^{197}Au	^{197}Au	^{208}Pb
$\mathrm{E}_P^{\max}$ [A GeV]	14.6	11	200	158	40	0.91×10^4	2.1×10^4	1.9×10^7
$\sqrt{s_{\mathrm{NN}}}$ [GeV]	5.4	4.7	19.2	17.2	8.75	130	200	5500
$\sqrt{s_{\mathrm{AA}}}$ [GeV]	151	934	614	3.6×10^3	1.8×10^3	2.6×10^4	4×10^4	1.2×10^6
$\Delta y/2$	1.72	1.58	2.96	2.91	2.22	4.94	5.37	8.77

- long history, new frontiers
- energy deposited in central detector (particles) indicate initial energy density
- higher collision energy, higher initial temperature, longer-lived QGP



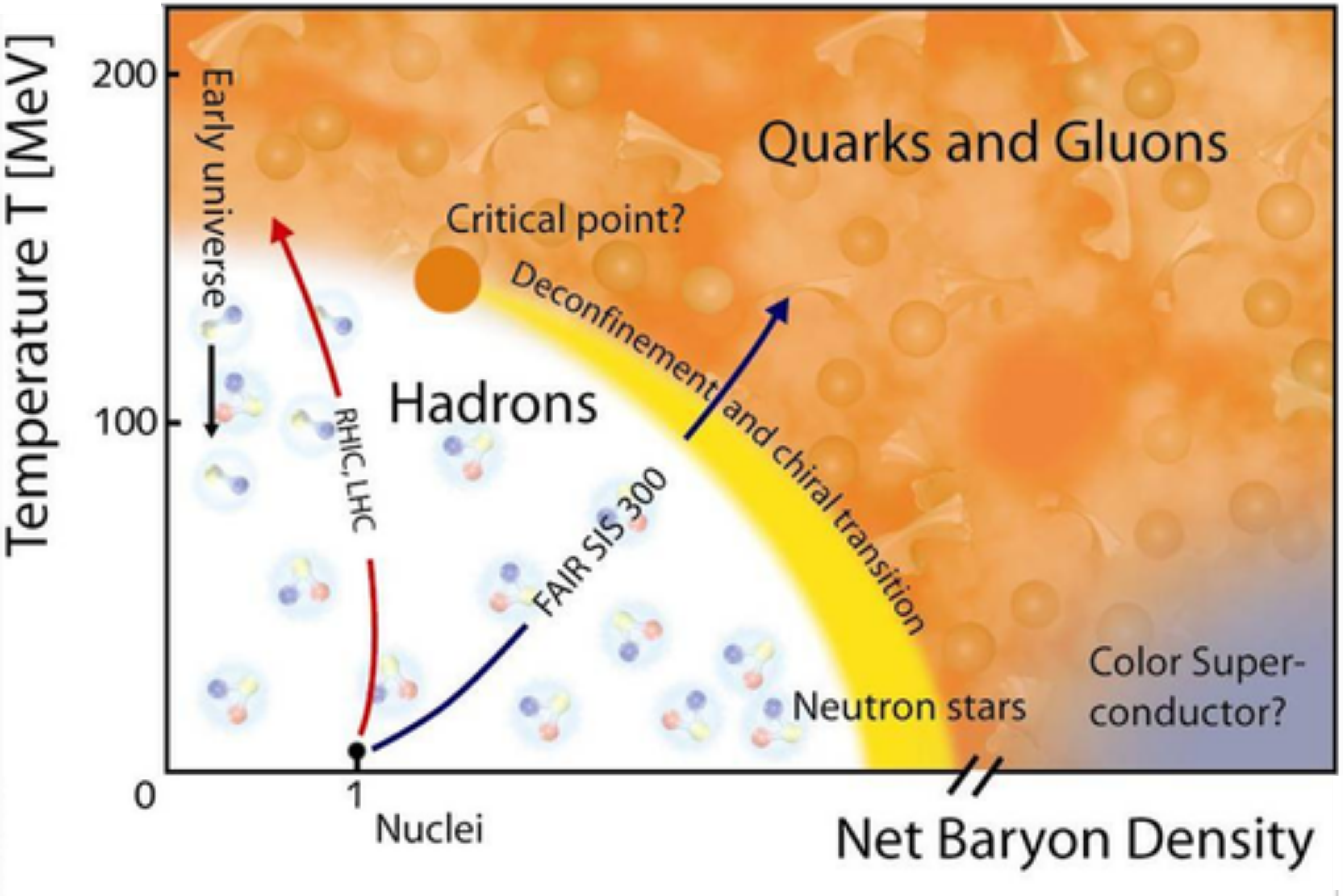
Evolution of the collision

courtesy: Chun Shen



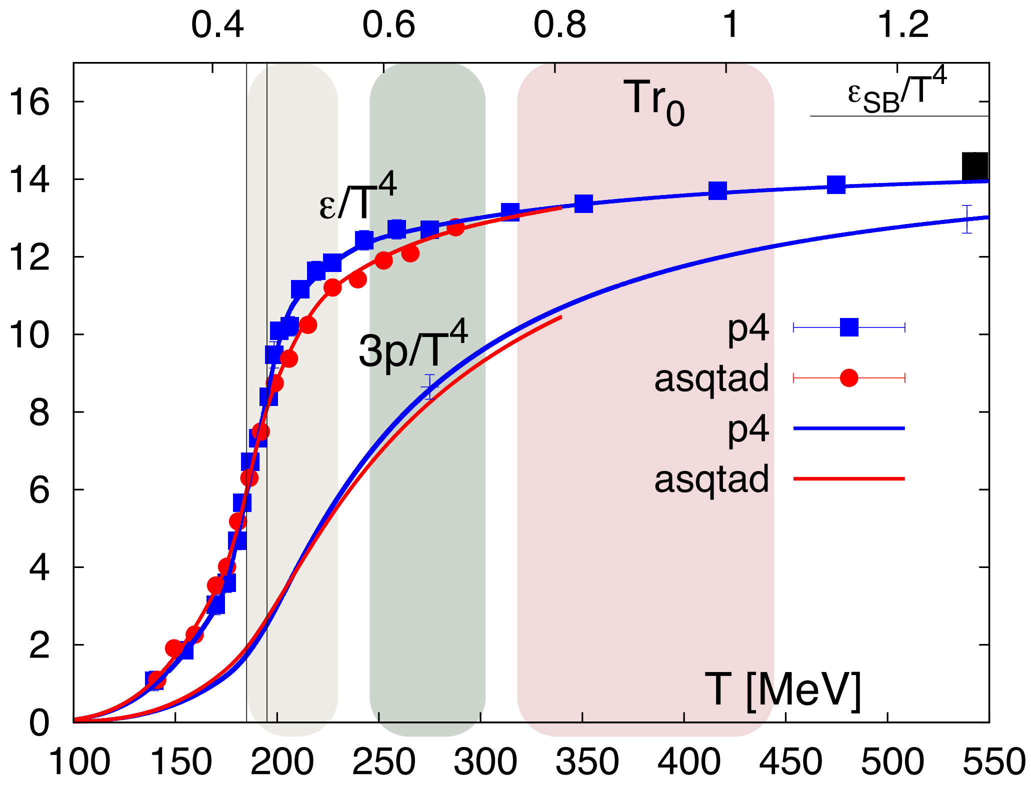
phenomenology demands precise description of each phase…

Hot & dense nuclear matter



QCD thermodynamics

A rapid rise of energy density (pressure, entropy etc) is observed (μ_B=0).



Bazavov et al., PRD 80 (2009) 014504

Energy regimes: **SPS**, **RHIC** & **LHC**

Number of pions (d_π=3):

$$n_\pi = d_\pi \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{1}{e^{E_\mathbf{p}/T}-1}$$

Free parton gas:

$$e_{SB} = e_{\rm glue} + e_{\rm quark}$$

$$e_{\rm glue} = d_{\rm glue}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{E_\mathbf{p}}{e^{E_\mathbf{p}/T}-1}$$

$$e_{\rm quark} = d_{\rm quark}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{E_\mathbf{p}}{e^{E_\mathbf{p}/T}+1}$$

$$d_{\rm glue} = 2\times 8$$

spin, color

$$d_{\rm quark} = 2\times2\times3\times3$$

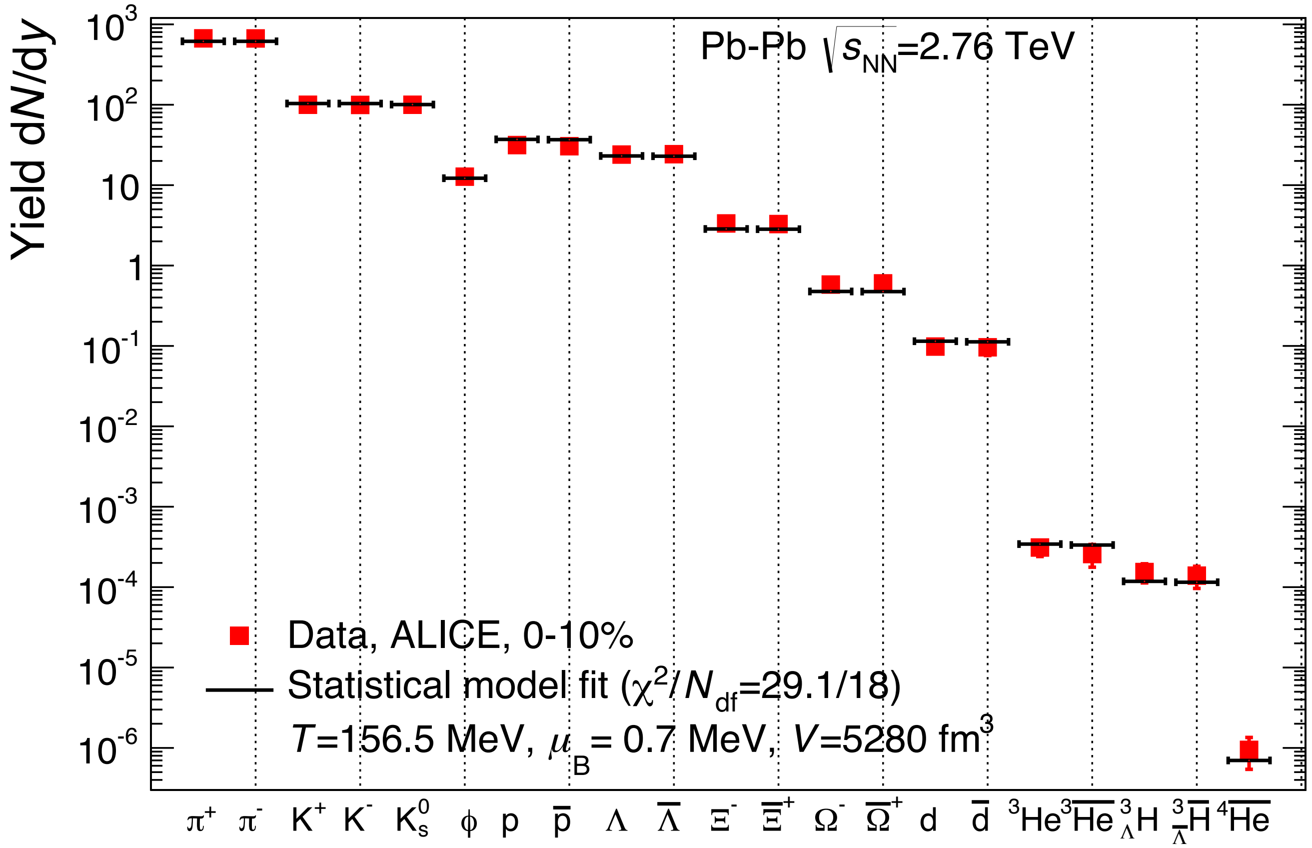
spin, quark/antiquark, color, flavor

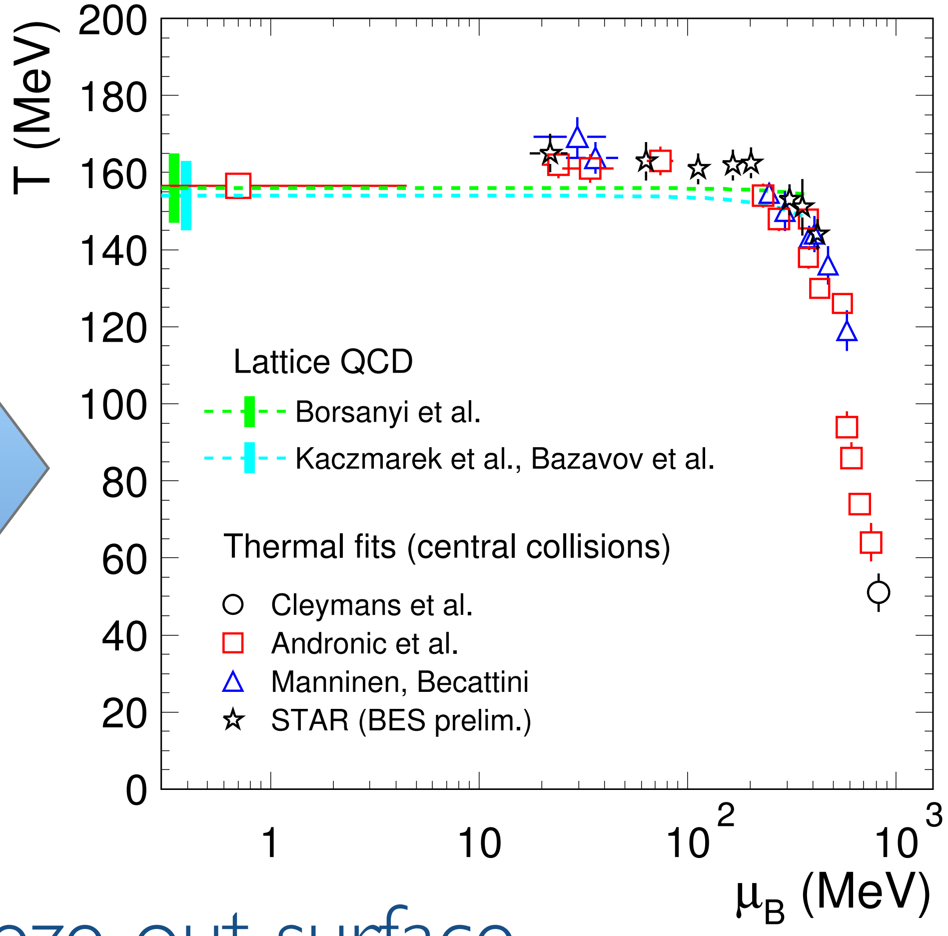
Do not reach Stefan-Boltzman limit — interactions survive!

Statistical model

Grand canonical partition function $$\ln Z_i(V,T,\mu_Q,\mu_B,\mu_S) = \pm(2s_i+1)\frac{V}{2\pi^2}\int_0^\infty dp\, p^2 \ln\left[1 \pm \lambda_i \exp(-\beta\omega_i)\right]$$

Fugacities: $$\lambda_i(T,\mu_Q,\mu_B,\mu_S) = \exp\left[\beta(\mu_Q Q_i + \mu_B B_i + \mu_S S_i)\right]$$





Thermal properties at the freeze-out surface.
Hadron yields are in chemical equilibrium.

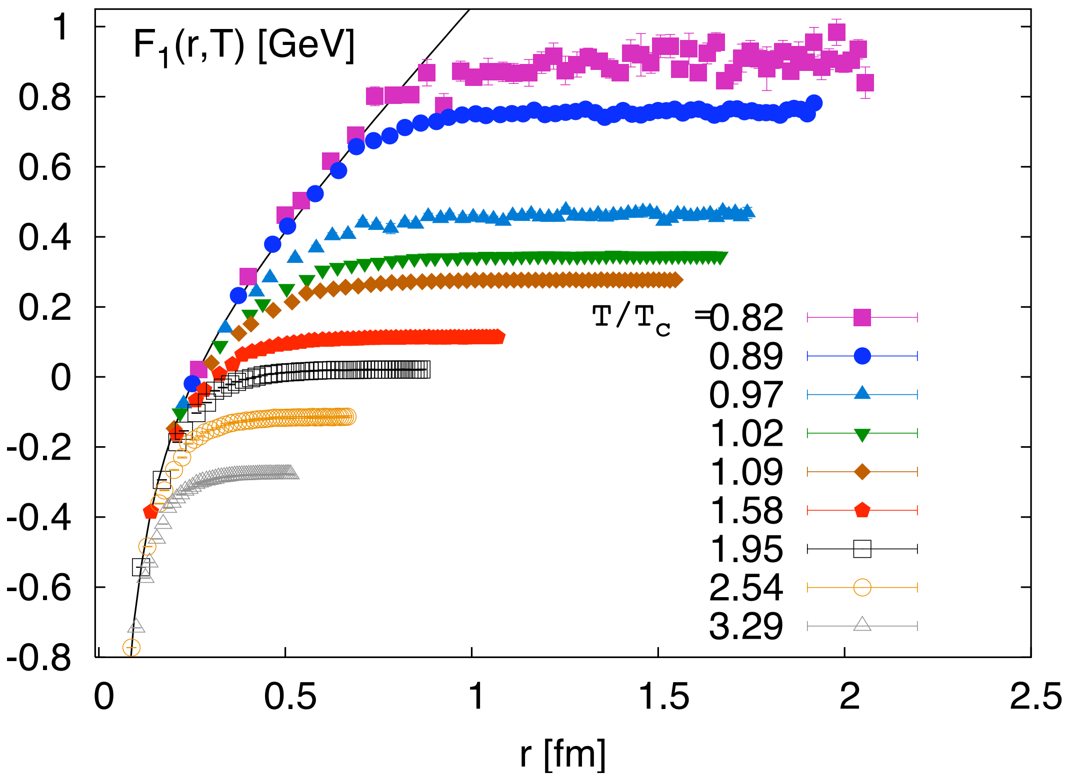
Question:

By fitting the data, do we prove that there is thermal equilibrium in heavy-ion collisions?
What is the criterium to make such a statement?

What is the meaning of the parameter "T" and chemical potentials?

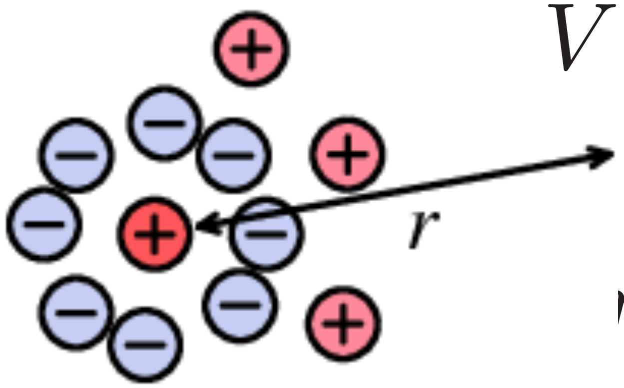
Debye screening

At asymptotically high T (g≪1): plasma particles with soft momenta (~gT) are dressed by fluctuations (~T).



Kaczmarek 0710.0498[hep-lat]

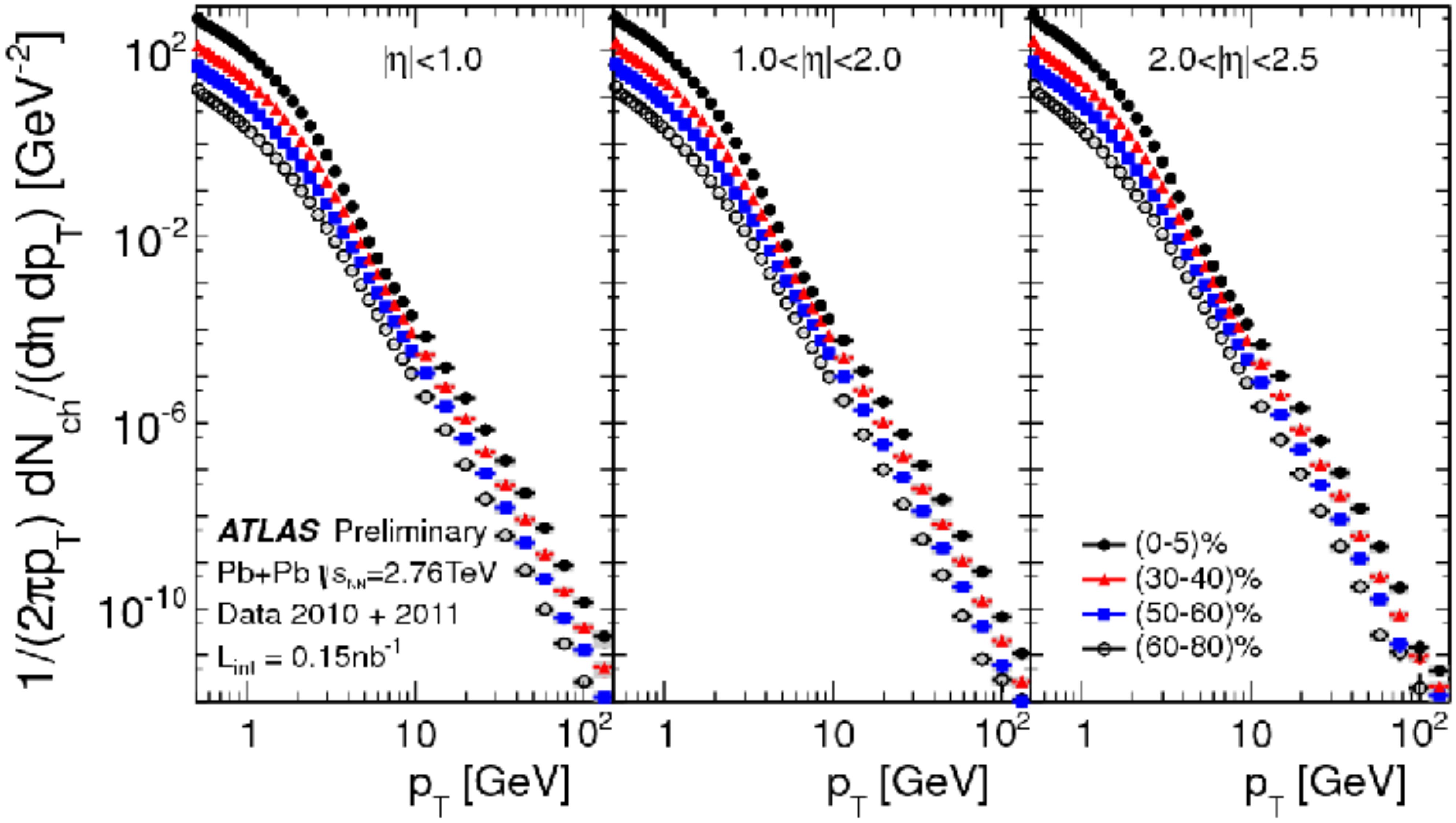
$$V(r) = -\frac{\alpha}{r} + \sigma r$$



$$V(r) = \frac{\alpha'}{r} e^{-m_D r}$$

$$m_D = \# gT$$

Charged particle spectrum



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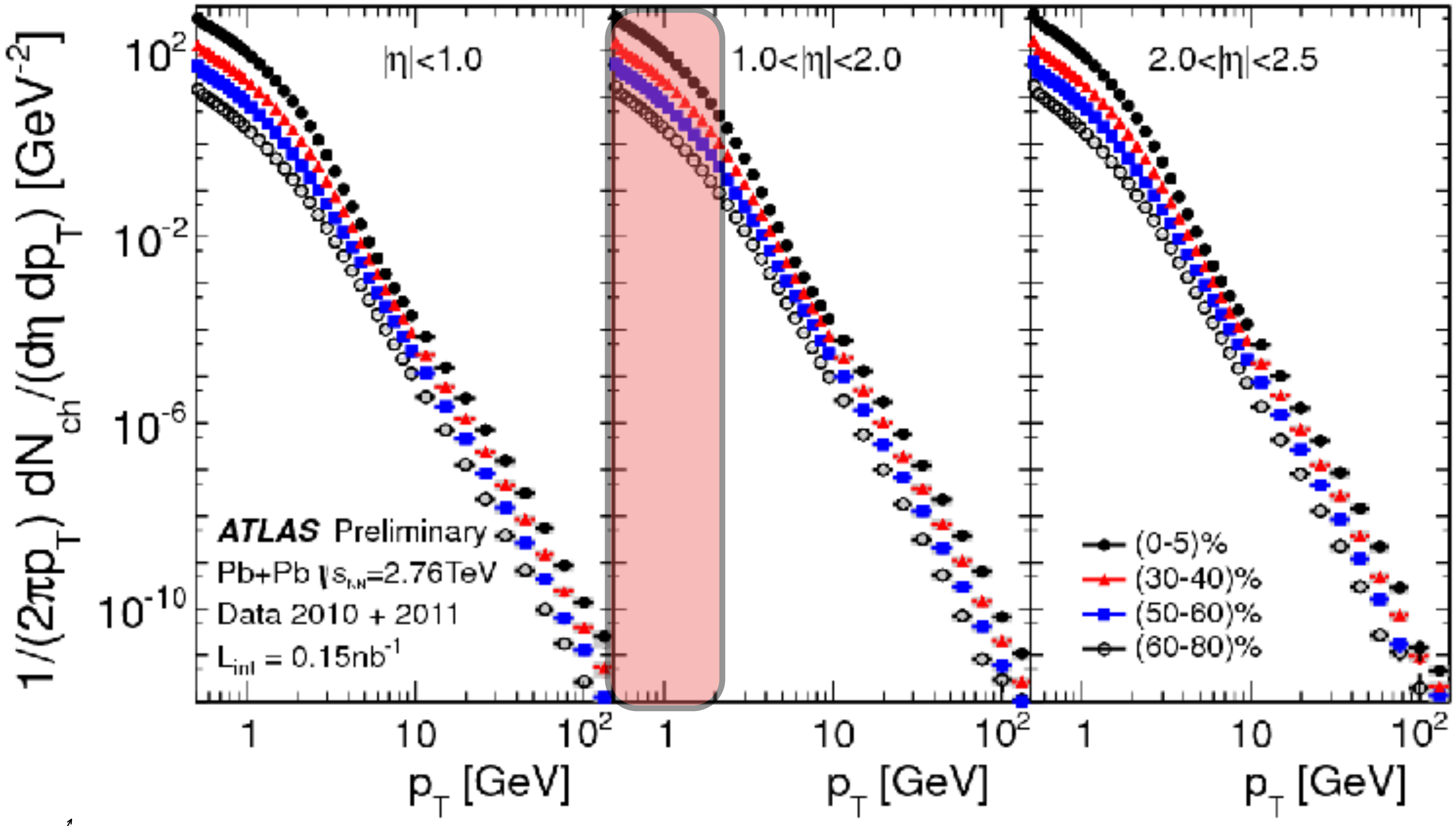
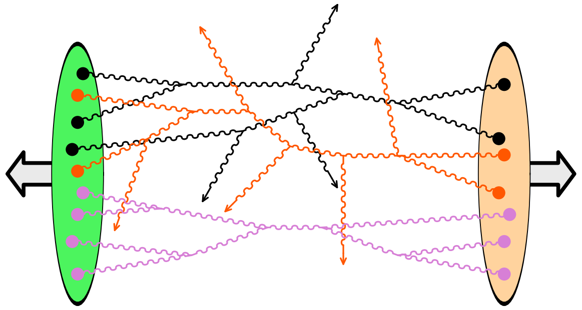
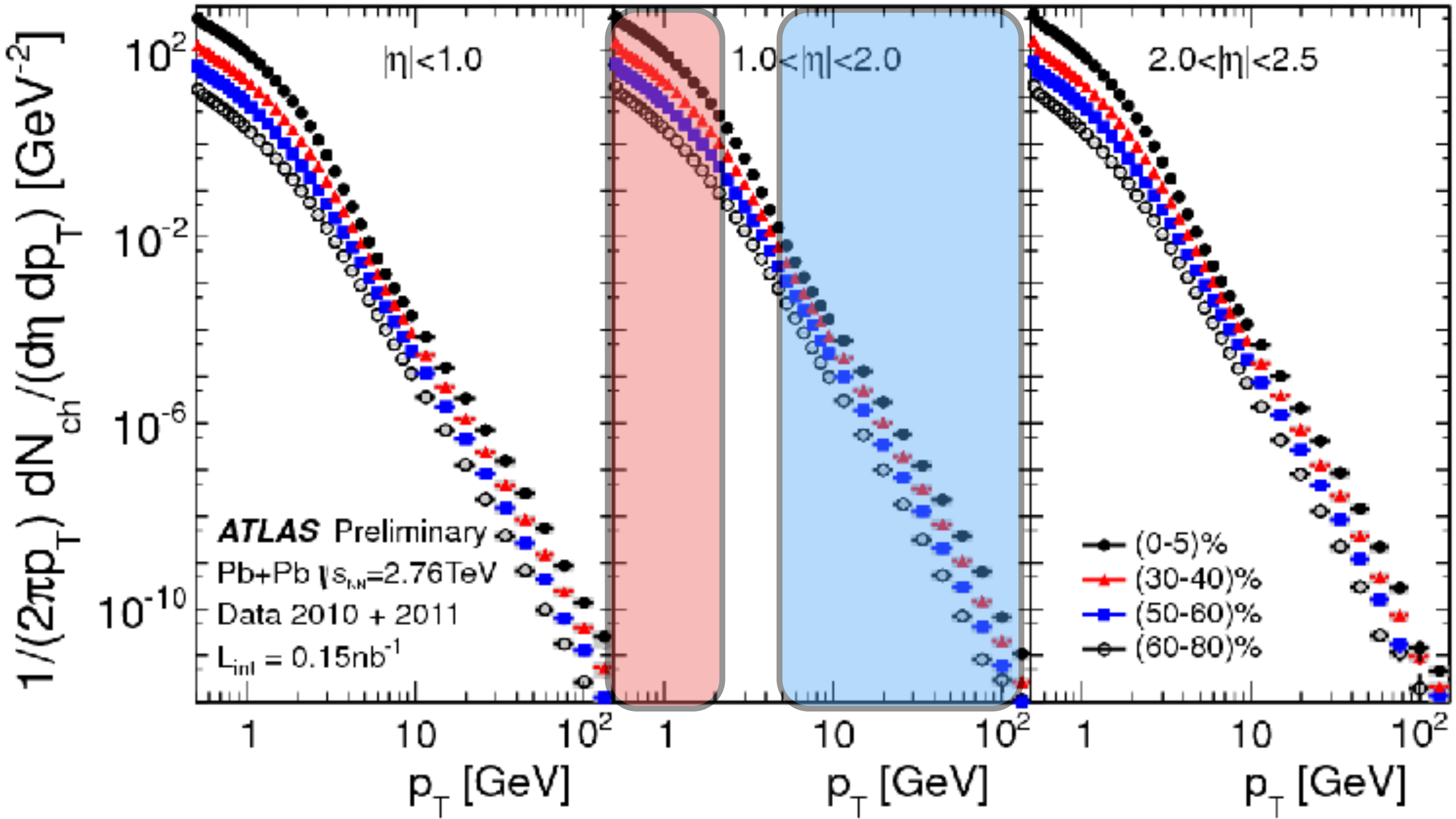
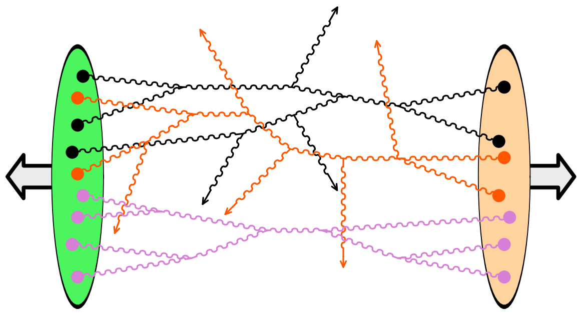




soft probes
dense regime
exponential

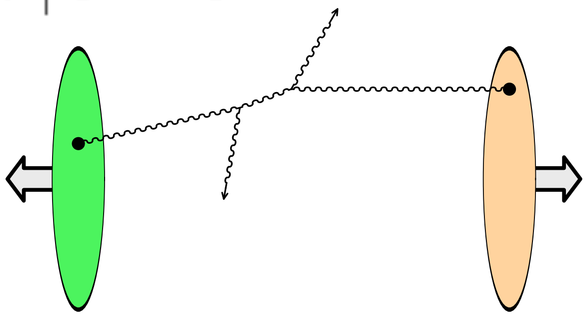
Charged particle spectrum





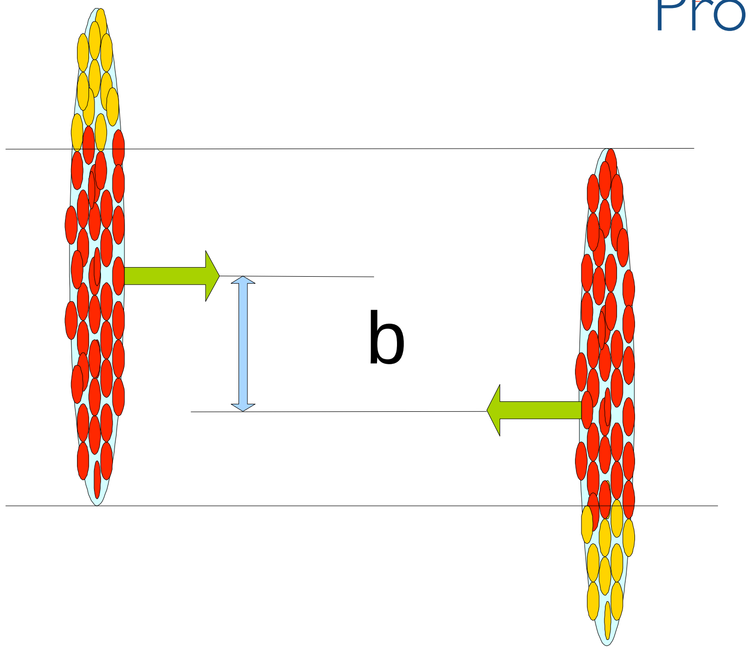
soft probes
dense regime
exponential

hard probes
dilute regime
power-like



Part 1: flow

The Glauber model



Probabilistic model of the collision.

Nuclear thickness: $T_A(\boldsymbol{b}) = \int_{-\infty}^{\infty} dz \rho(z, \boldsymbol{b})$

Optical approximation:

$$\int d\boldsymbol{s}\, T_A(\boldsymbol{b}) T_B(\boldsymbol{b} - \boldsymbol{s}) \sigma_{NN}^{\text{inel}} \equiv T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}$$

Probability of n scatterings at impact parameter b:

$$P(n, \boldsymbol{b}) = \binom{AB}{n} \left[1 - T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}\right]^{AB-n} \left[T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}\right]^{n}$$

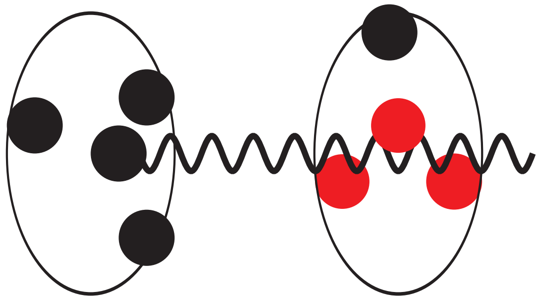
Sum over probabilities = cross section:

$$\begin{aligned} \sigma_{AB}^{\text{inel}} &= \int d^2b \left[1 - (1 - T_{AB}(\mathbf{b}) \sigma_{NN}^{\text{inel}})^{AB}\right] \\ &\simeq \int d^2b \left\{1 - \exp\left[-AB T_{AB}(\mathbf{b}) \sigma_{NN}^{\text{inel}}\right]\right\} \end{aligned}$$

Centrality determination

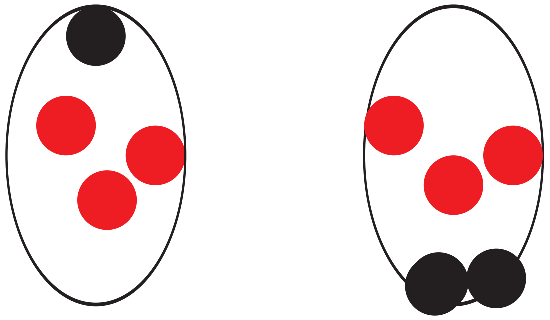
Number of collisions:

$$N_{\rm coll}^{AB}(\boldsymbol{b}) = \sum_{n=0}^{A} nP(n,\boldsymbol{b}) = ABT_{AB}(\boldsymbol{b})\sigma_{NN}^{\rm inel}$$

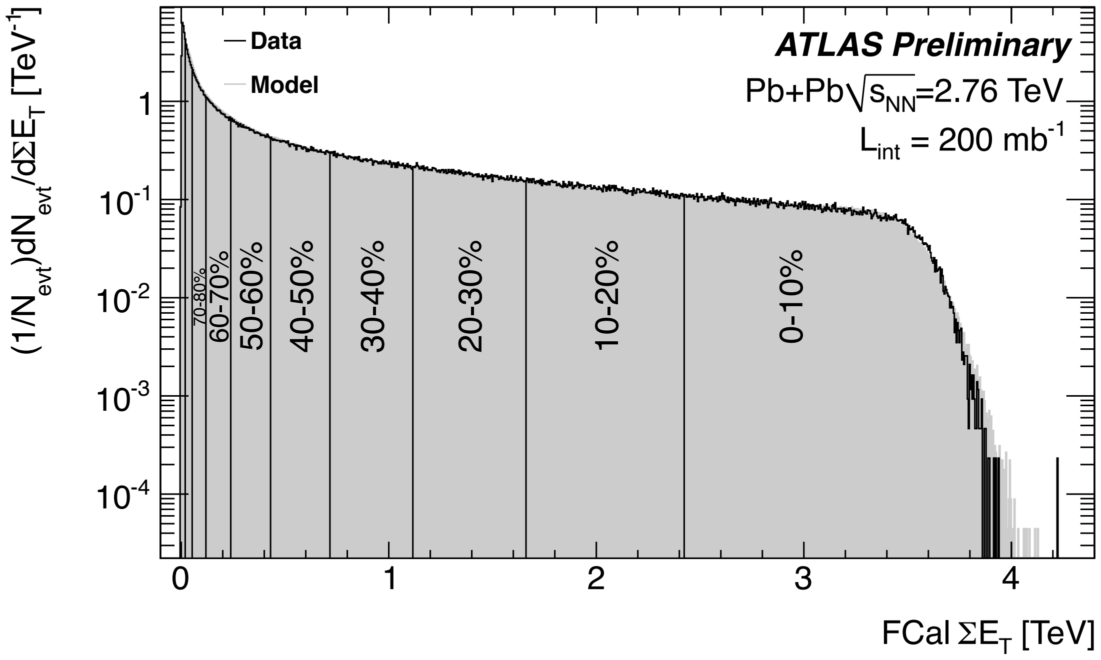


Number of participants:

$$N_{\rm part}^{A}(\boldsymbol{b}) = \int d\boldsymbol{s}\, B\, T_B(\boldsymbol{s})\sigma_{pA}^{\rm inel}(\boldsymbol{b}-\boldsymbol{s})$$
$$= \int d\boldsymbol{s}\, B\, T_B(\boldsymbol{s}) \exp\left[-AT_A(\boldsymbol{b}-\boldsymbol{s})\sigma_{NN}^{\rm inel}\right]$$



- events are (typically) categorized
  - soft :: $N_{\rm part}$
  - hard :: $N_{\rm coll}$
- how does energy or entropy scale with $N_{\rm part}$ & $N_{\rm coll}$ — not clear

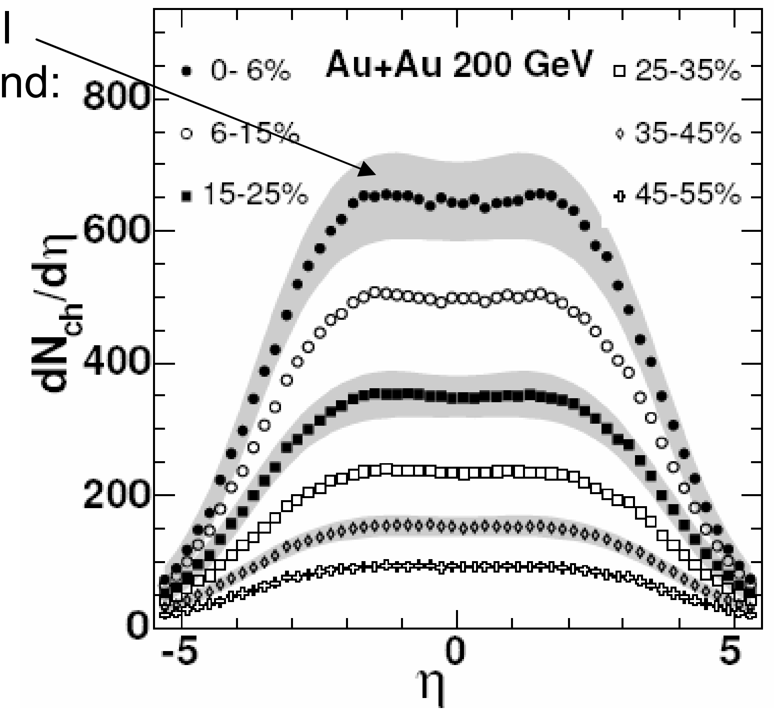


Question:

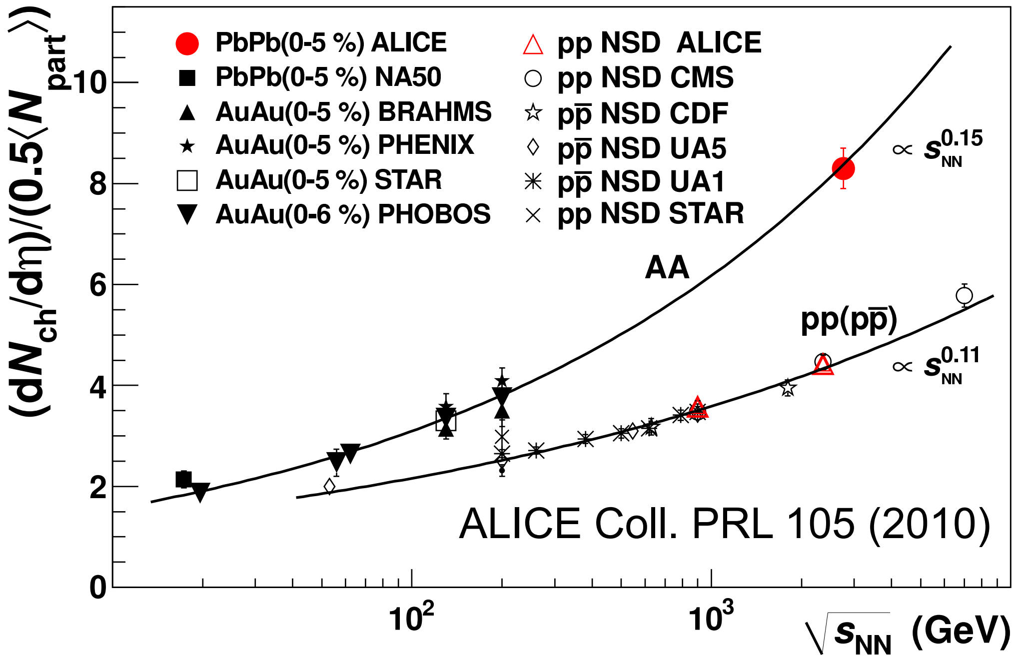
In a proton-nucleus collision, what is the relation between the number of collisions and the number of participants?

Deposited energy

6% most central
collisions (grey band:
syst. error)



At mid rapidity
particles have
$\langle p_T \rangle \sim 500$ MeV



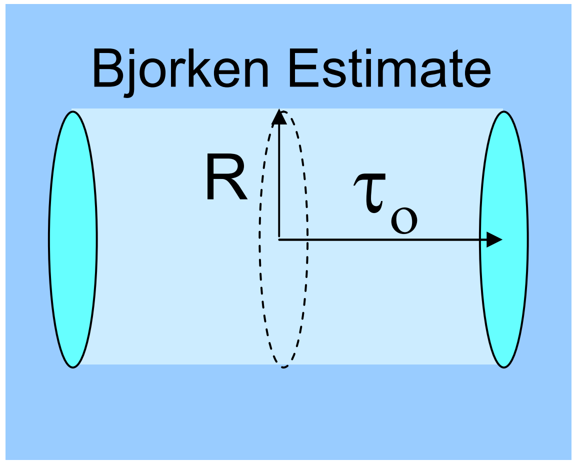
ALICE Coll. PRL 105 (2010)

- particle density is a measure of energy density
- almost flat distribution in pseudo-rapidity
- factor of 2 from SPS to RHIC and another from RHIC to LHC

$$\frac{\mathrm{d}E}{\mathrm{d}\eta} \simeq \langle E \rangle \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} \times \frac{3}{2} \simeq 6 - 12 \times 0.5\,\mathrm{GeV} \times \frac{N_{\mathrm{part}}}{2}$$

$$\frac{N_{\mathrm{part}}}{2} \sim 170$$

Bjorken energy density estimate



At high energies most the matter is mostly transparent; QGP is formed in the wake.

$$\eta_s = \frac{1}{2}\log\frac{t+z}{t-z} \simeq \frac{1}{2}\log\frac{p+p_z}{p-p_z} = \eta$$

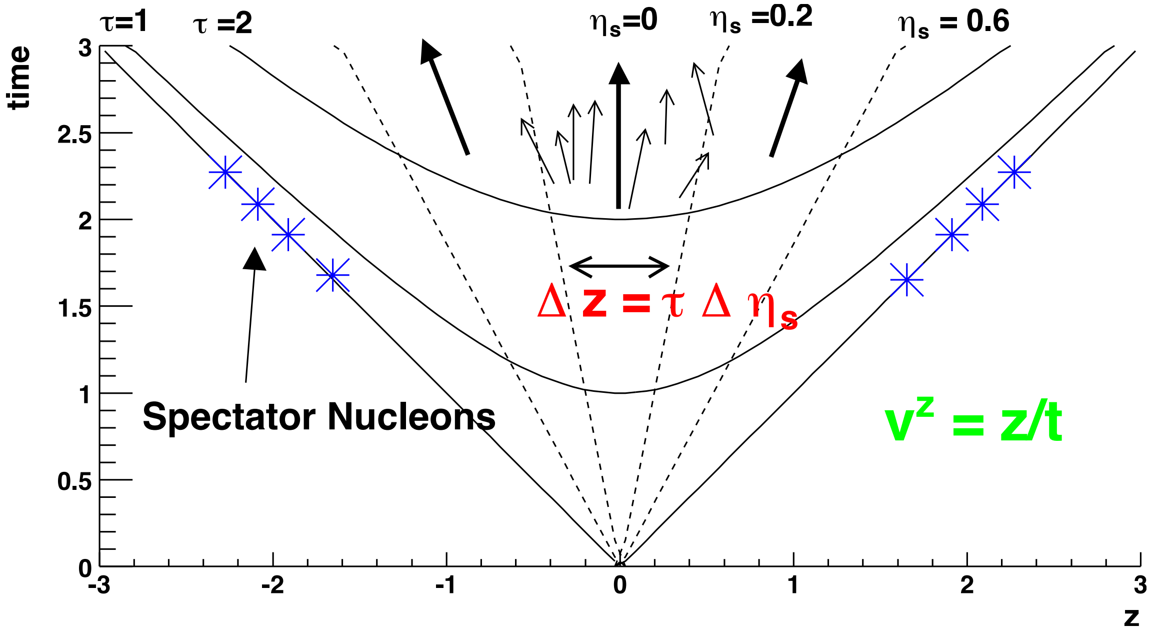
Matter at certain rapidity are created in the same space-time slice.

$$\epsilon_{\rm Bj} \simeq \frac{1}{\pi R^2}\frac{\Delta E}{\Delta z} \simeq \frac{1}{\pi R^2 \tau_0}\frac{\Delta E}{\Delta \eta}$$

- using τ_0=1 fm and R=6 fm

$$\epsilon_{\rm Bj} \sim 5-10\,\frac{\rm GeV}{\rm fm^3}$$

$$\rho_{\rm cold} = 0.15\frac{\rm GeV}{\rm fm^3}$$



Enough energy density to melt the nucleons!

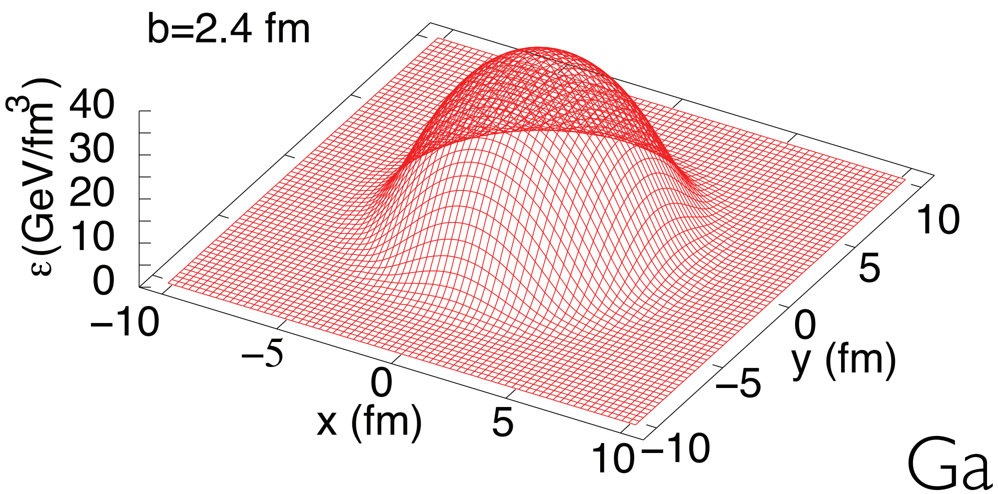
Initial conditions

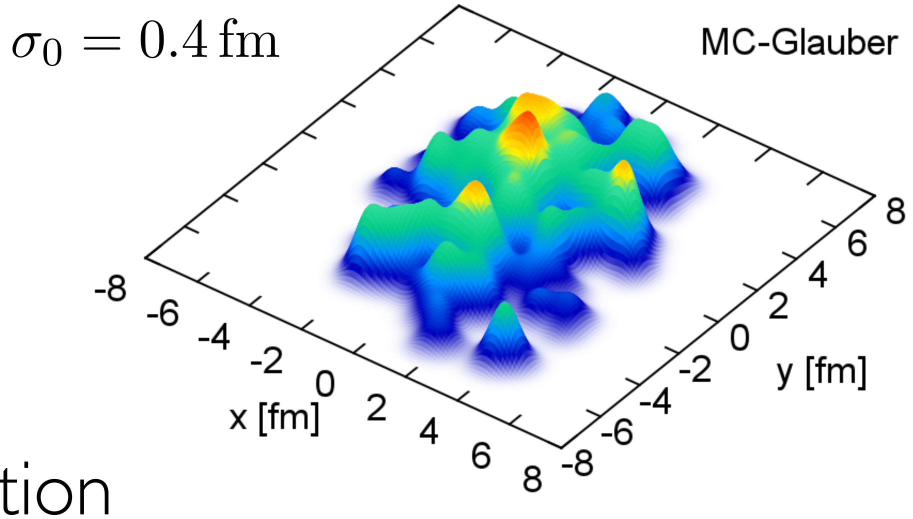
Smooth distribution of wounded nucleons (participants)

$$N_{\rm part}(x,y,b) = T_A(x+b/2,y)\left[1-\left(1-\sigma_{\rm inel}^{NN}T_B(x-b/2,y)\right)^B\right] + T_B(x-b/2,y)\left[1-\left(1-\sigma_{\rm inel}^{NN}T_A(x+b/2,y)\right)^A\right]$$

Binary collisions per area: $N_{\rm coll}(x,y,b) = \sigma_{\rm inel}^{NN}T_A(x+b/2,y)T_B(x-b/2,y)$

$$\epsilon \propto \frac{dN_{\rm ch}}{d\eta} = \alpha N_{\rm part} + \beta N_{\rm coll}$$

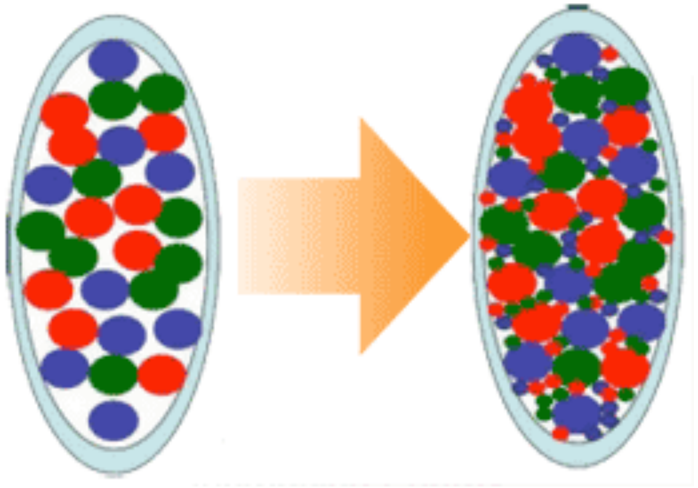



$\sigma_0 = 0.4\,{\rm fm}$

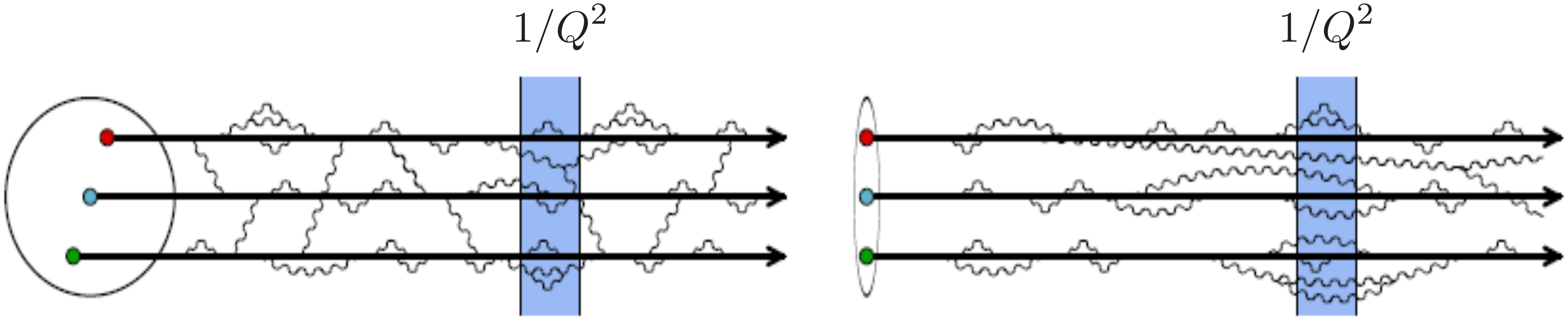
Gaussian randomization

Inner life of nucleons

- the structure of the hadrons changes with energy
- partonic degrees of freedom starts taking over
- space-time picture changes
- related to the physics of infrared & collinear divergences

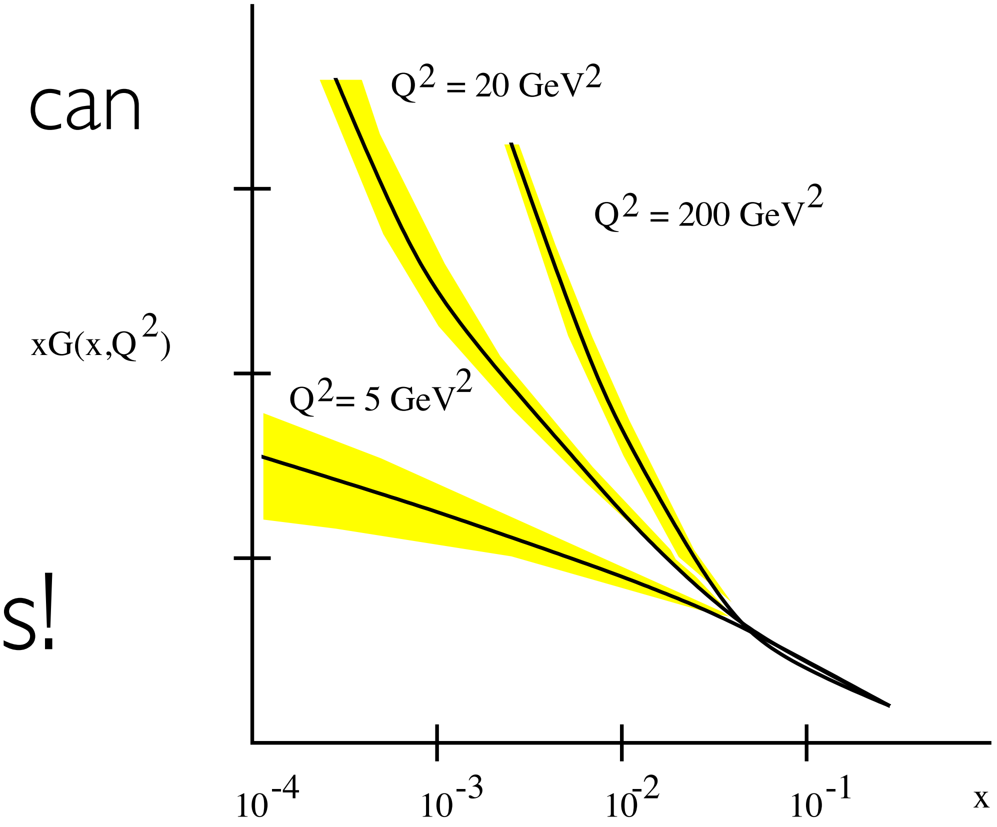


Digging out gluons



Lorentz time dilation: soft fluctuations can live over long timescales.

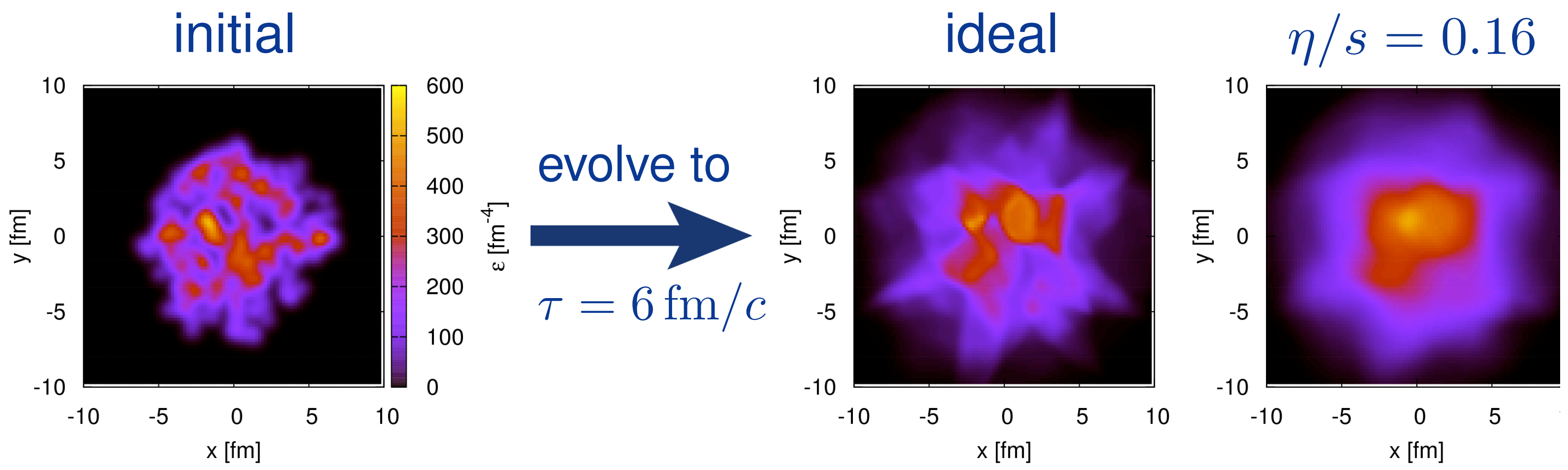
Lifetime vs. interaction time.



Parton distribution functions!

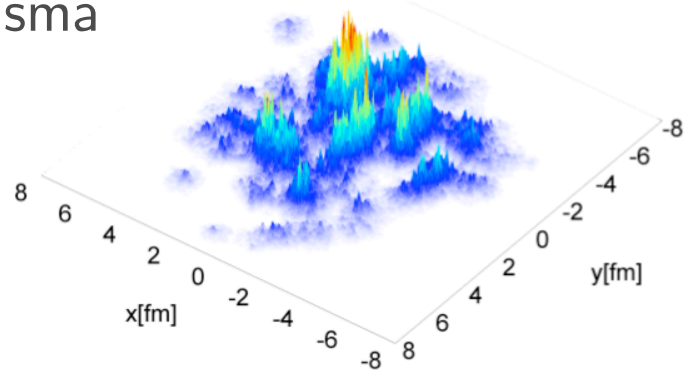
Evolving the state

- initial color charge & energy density: sensitivity to size of initial-state fluctuations
- provides initial conditions for hydrodynamics
- can pin down the shear viscosity from observables

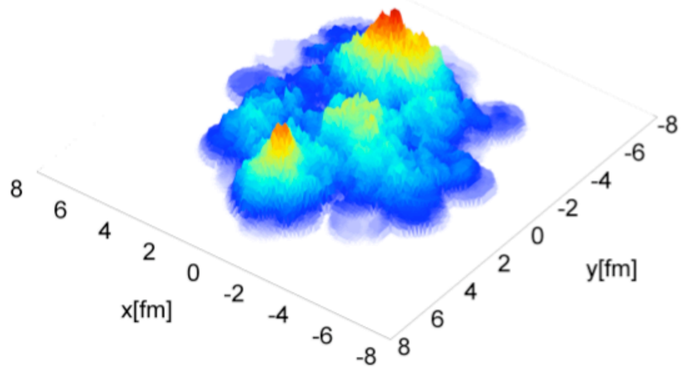


MUSIC B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)

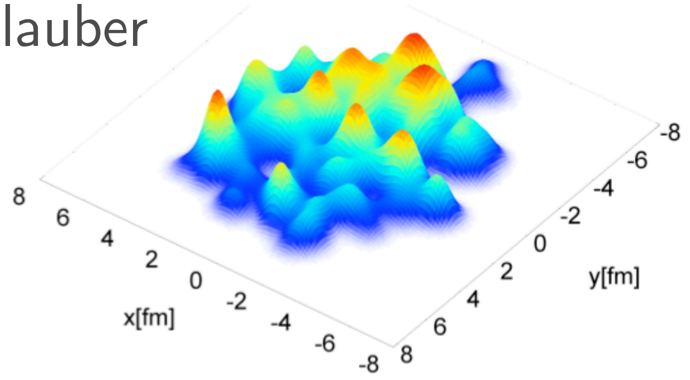
IP-Glasma



MC-KLN

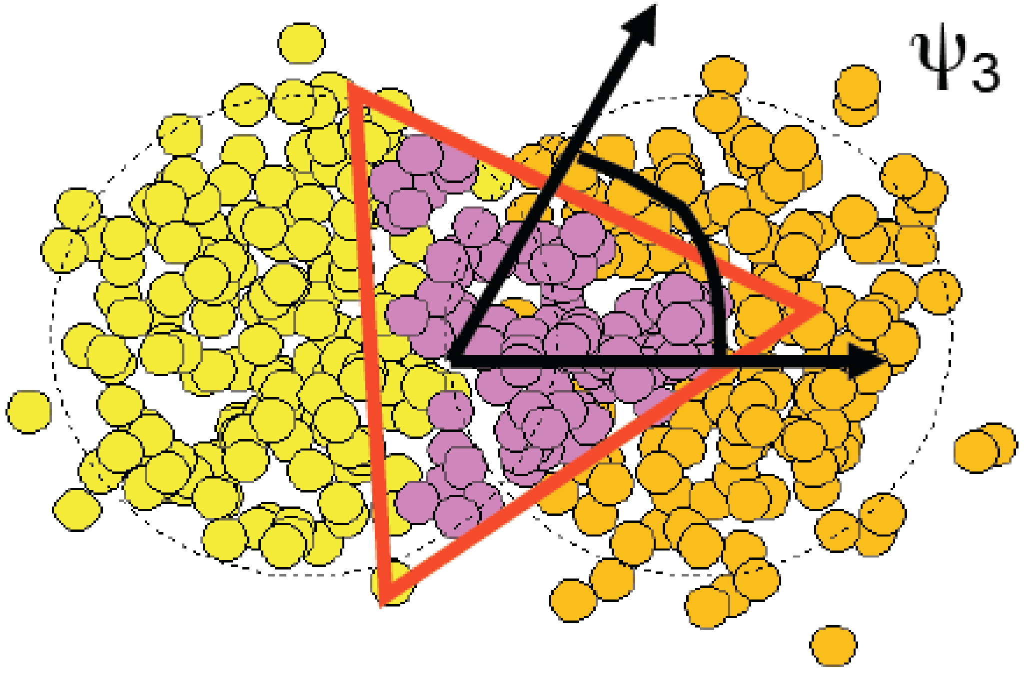


MC-Glauber



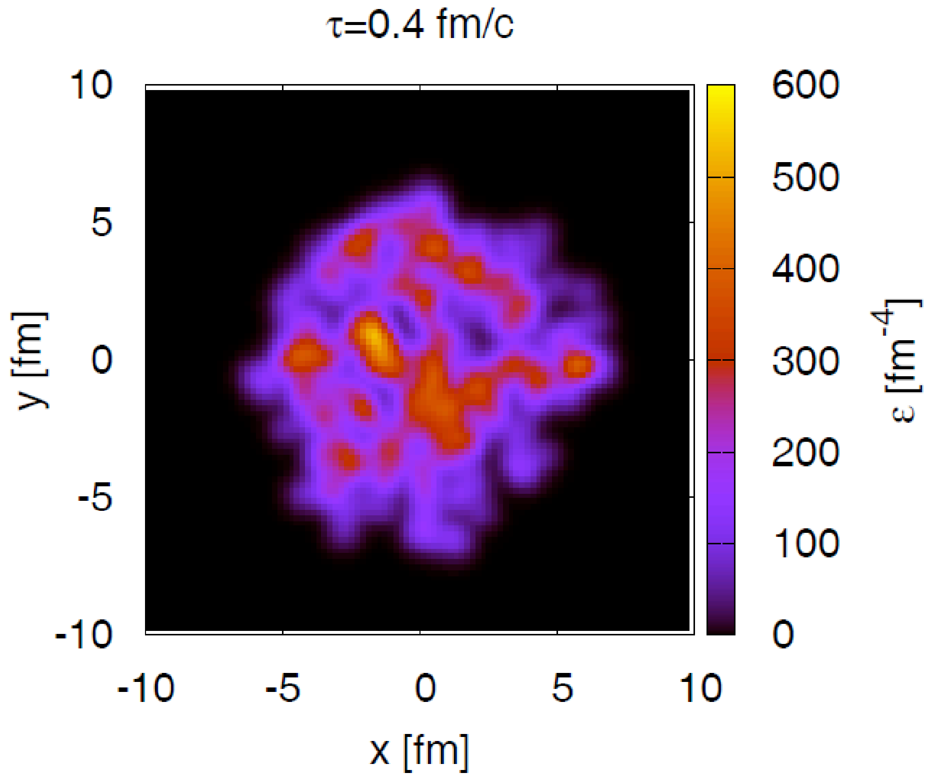
Schenke, Tribedy, Venugopalan
1206.6805, PRL 108 (2012)

Fluctuations from initial state



Glauber Model

B. Alver, G. Roland, PRC81 (2010) 054905



Viscous Hydro.

B. Schenke, S. Jeon, C. Gale PRL 106, 042301

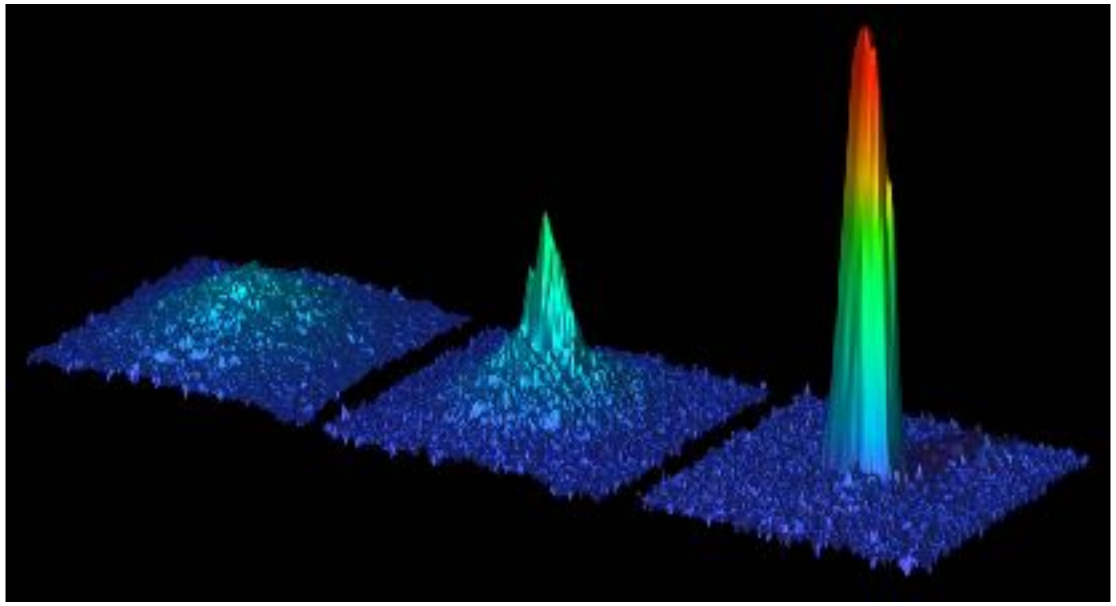
$$\frac{dN^{(i)}}{dy\,p_T dp_T\,d\phi_p}(b) = \frac{dN^{(i)}}{dy\,p_T dp_T}(b)\left(1+2\sum_{n=1}^{\infty} \boldsymbol{v_n^{(i)}(y,p_T;b)}\cos(\phi_p-\Psi_n^{(i)})\right)$$

flow coefficients

Hydrodynamics

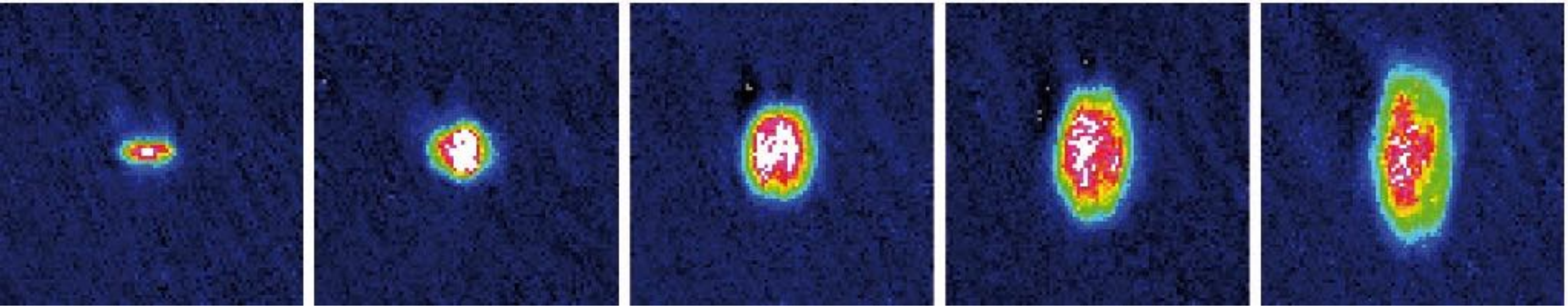
- is energy & momentum (& charge) conservation!
- it applies when the mean-free path is much shorter than the size of the system
- since our system is very energetic we have to use special relativity to define relativistic hydrodynamics…

Hydrodynamics for cold atoms



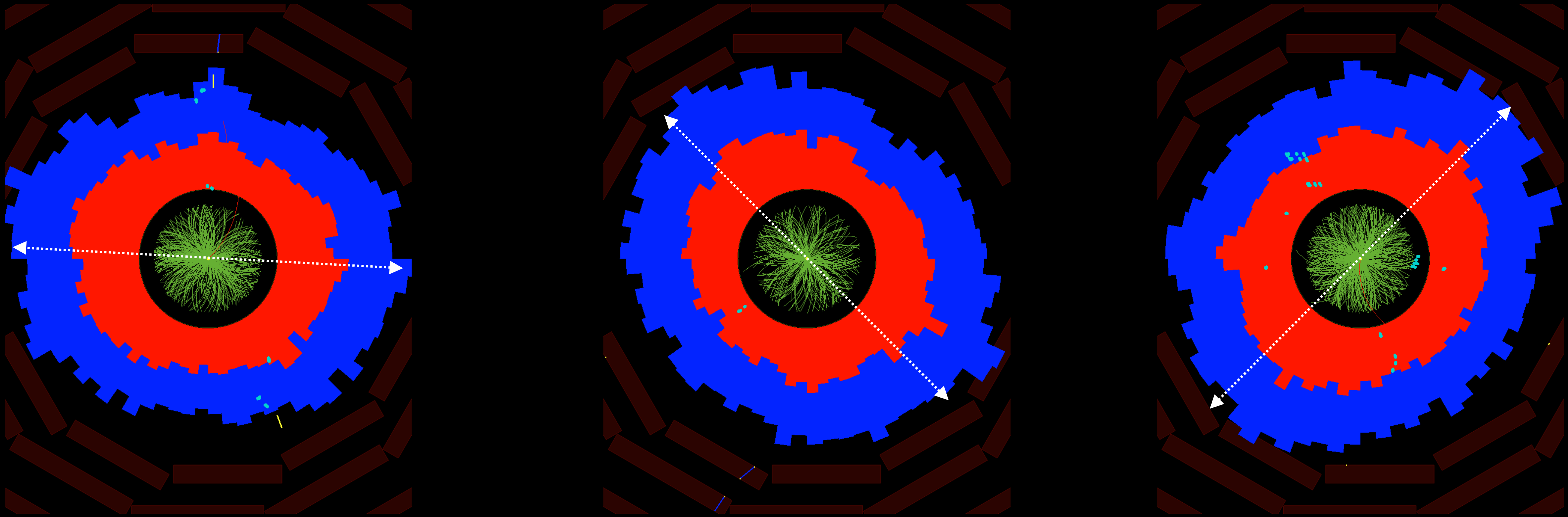
^{84}Sr BEC

Schreck et al, PRL 103 (2009) 200401



initial spatial anisotropy transforms to final-state momentum anisotropy due to strong correlations in the system

Heavy-ion collisions "by eye"

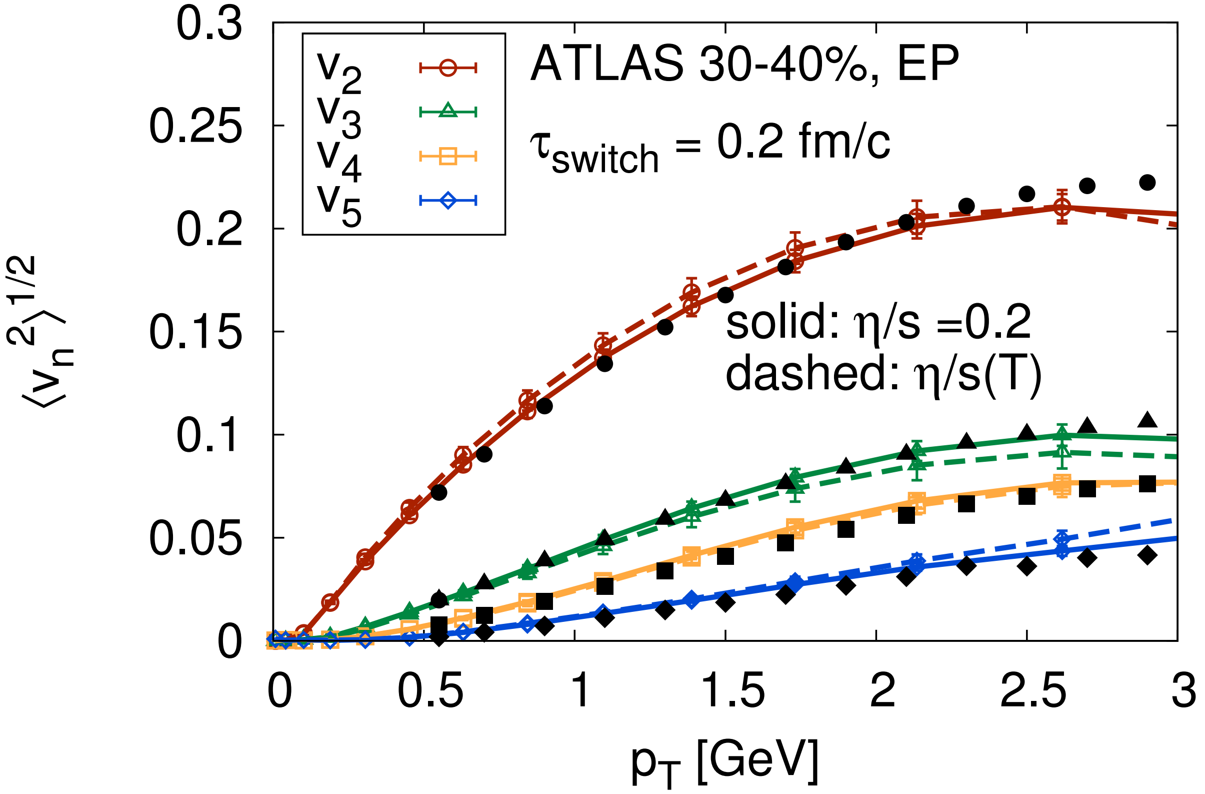


~15% modulatio event by event.

QGP flow measurements

Initial space anisotropy results in particles being produced in different directions in a modulated fashion.

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu}$$

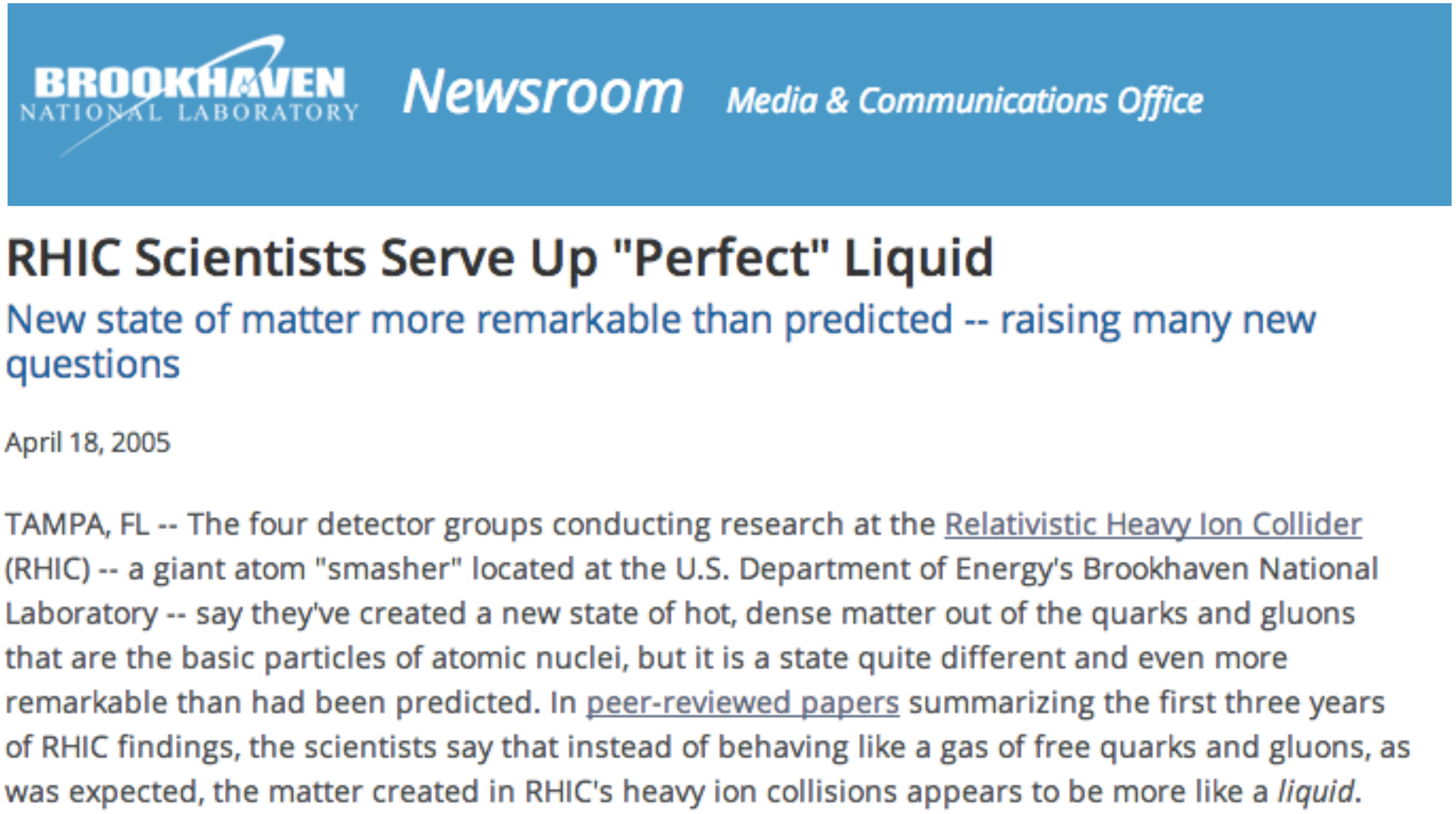


Extracted from data:

$$\frac{\eta}{s} \simeq 0.08 \pm 0.05$$

Schenke, Jeon, Gale PRC82 (2010), PRL 106 (2011)

- ~400 times smaller than for water: QGP the "most perfect fluid"
- toward precision measurements of transport coefficients



BROOKHAVEN NATIONAL LABORATORY Newsroom Media & Communications Office

RHIC Scientists Serve Up "Perfect" Liquid

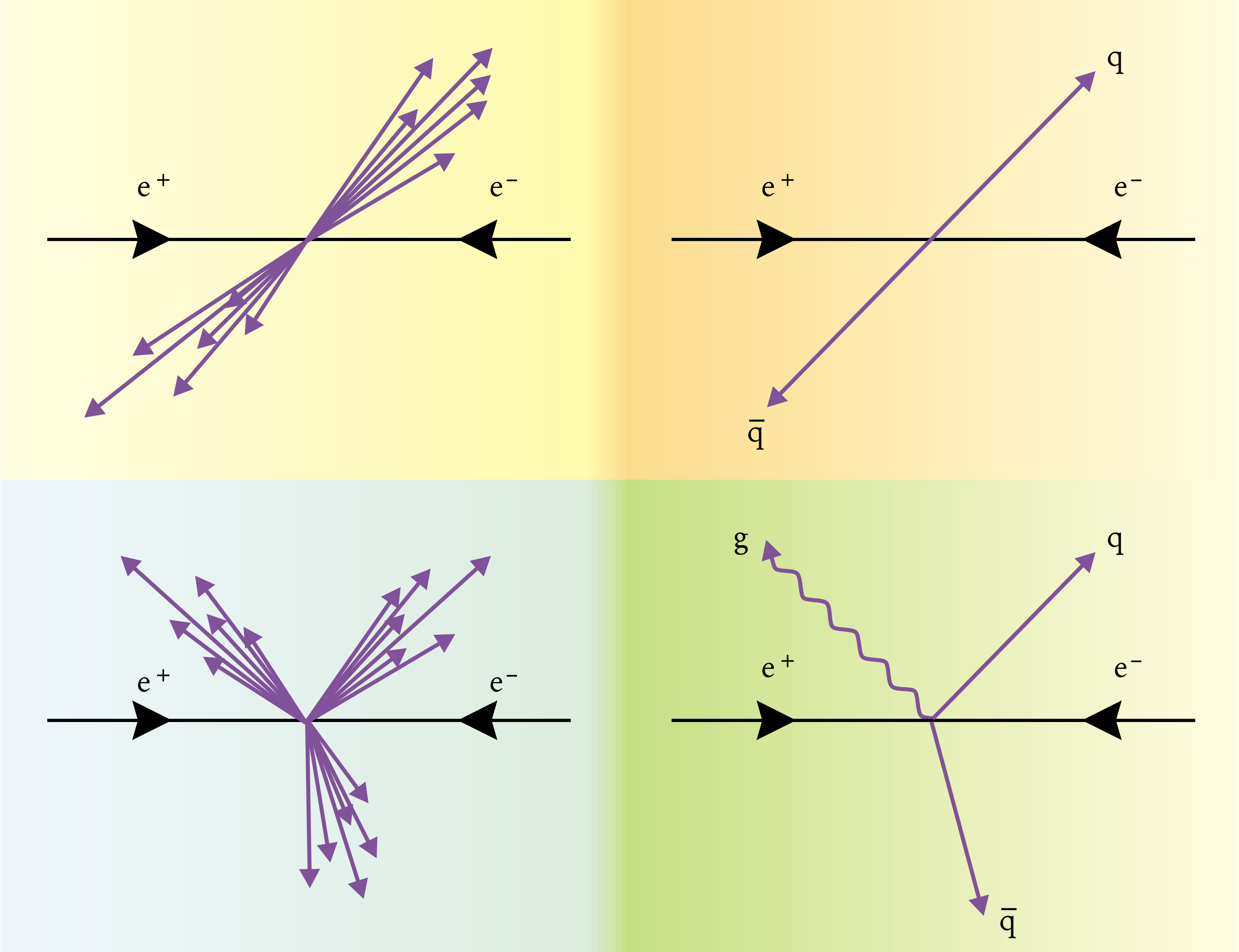
New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

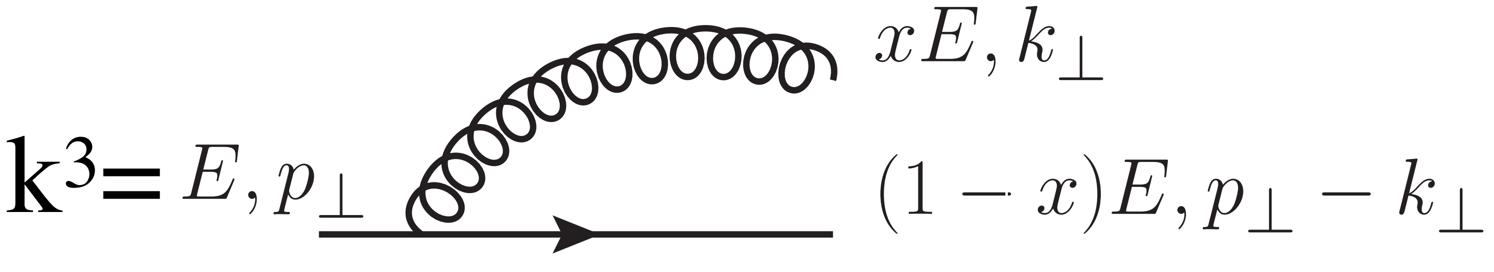
Part 2: jet quenching

QCD jets



- what we see as sprays of particles in the detector are originating from "one quark/gluon"
- a way to probe the quarks and gluons
- defining a jet is a contract between theory and experiment (jet algorithms)

$$E = \sqrt{k_\perp^2 + (k^3)^2}$$

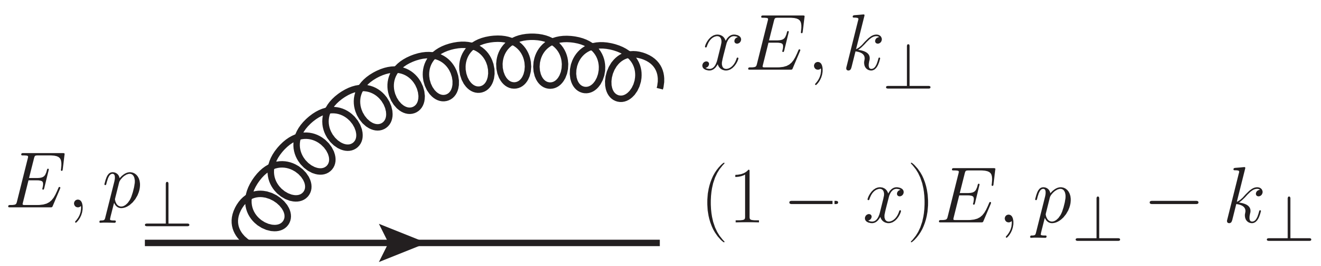


Question:

Using QM, is there a way to say that a splitting takes time?

Hint: recall Heisenberg…

Radiation time



$$E = \sqrt{k_\perp^2 + (k^3)^2}$$

$$\begin{aligned}\Delta E &= \sqrt{x^2E^2 + \boldsymbol{k}^2} + \sqrt{(1-x)^2E^2 + (\boldsymbol{k}+\boldsymbol{p})^2} - \sqrt{E^2+\boldsymbol{p}^2} \\ &\approx xE + \frac{\boldsymbol{k}^2}{2xE} + (1-x)E + \frac{(\boldsymbol{k}+\boldsymbol{p})^2}{2(1-x)E} - E - \frac{\boldsymbol{p}^2}{2E} \\ &= \frac{(\boldsymbol{k}+x\boldsymbol{p})^2}{2x(1-x)E} \\ &= \frac{\boldsymbol{k}^2}{2\omega}\end{aligned}$$

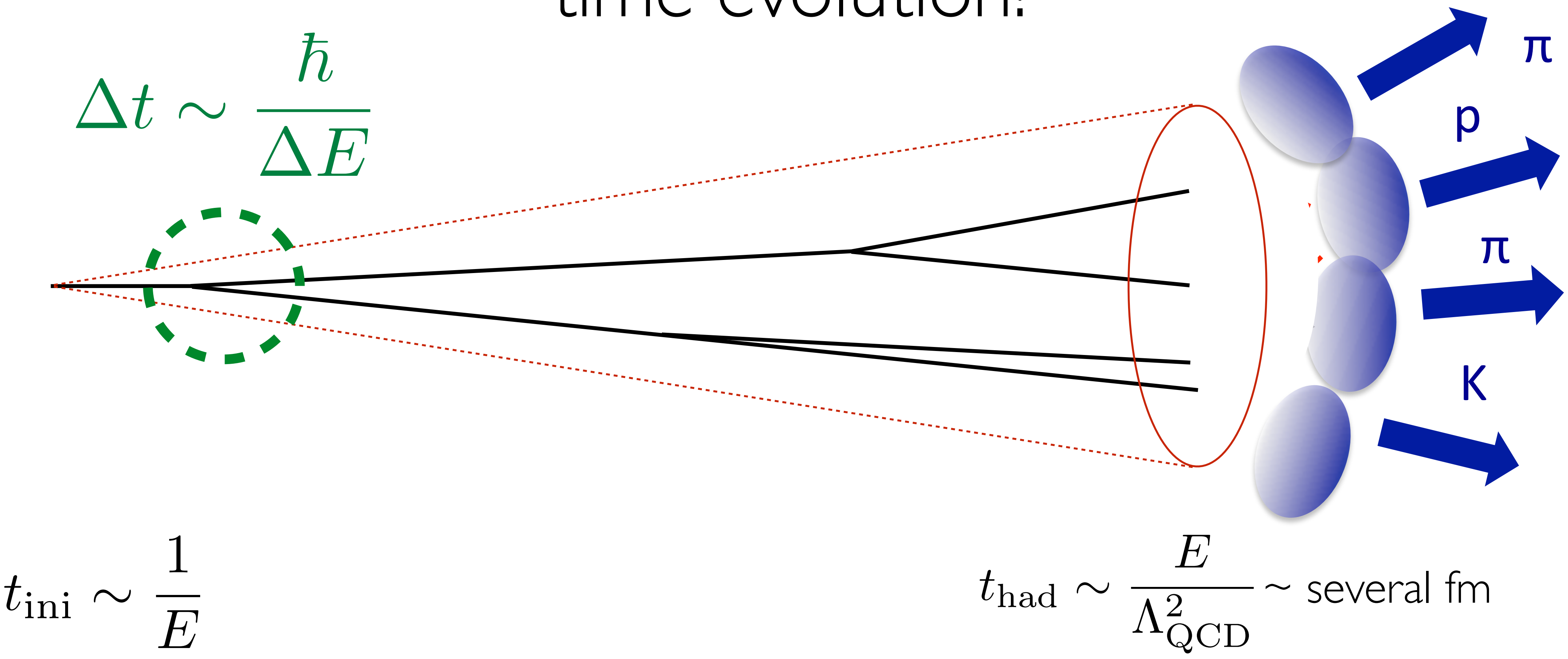
$\boldsymbol{p} = 0$

$$t_\mathrm{f} \sim \Delta t \sim \frac{1}{\Delta E} \sim \frac{2\omega}{\boldsymbol{k}^2}$$

$$t_\mathrm{f} \sim \frac{1}{\omega\theta^2}$$

Jet evolution

Jets are extended objects with interesting space-time evolution!

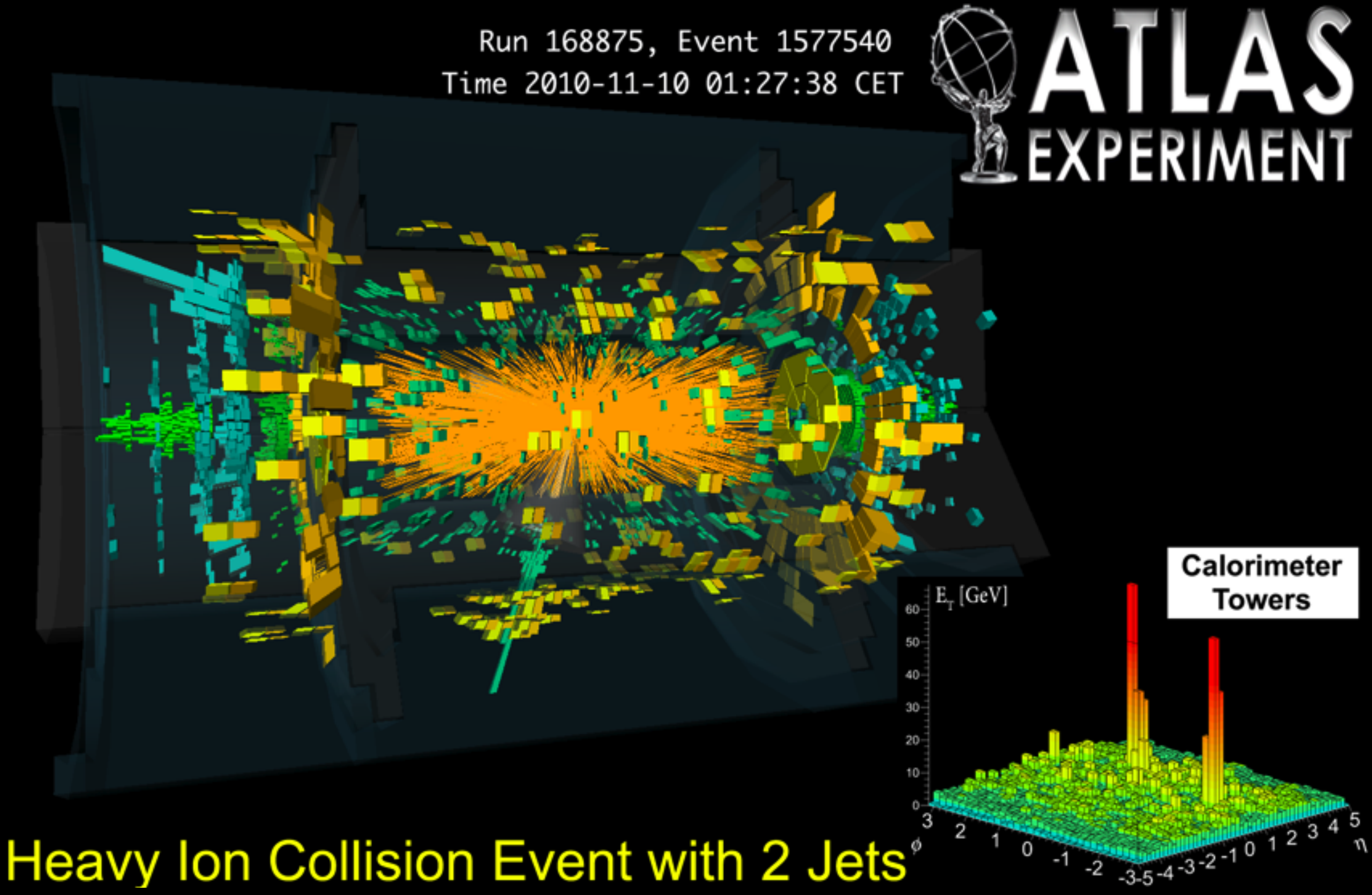


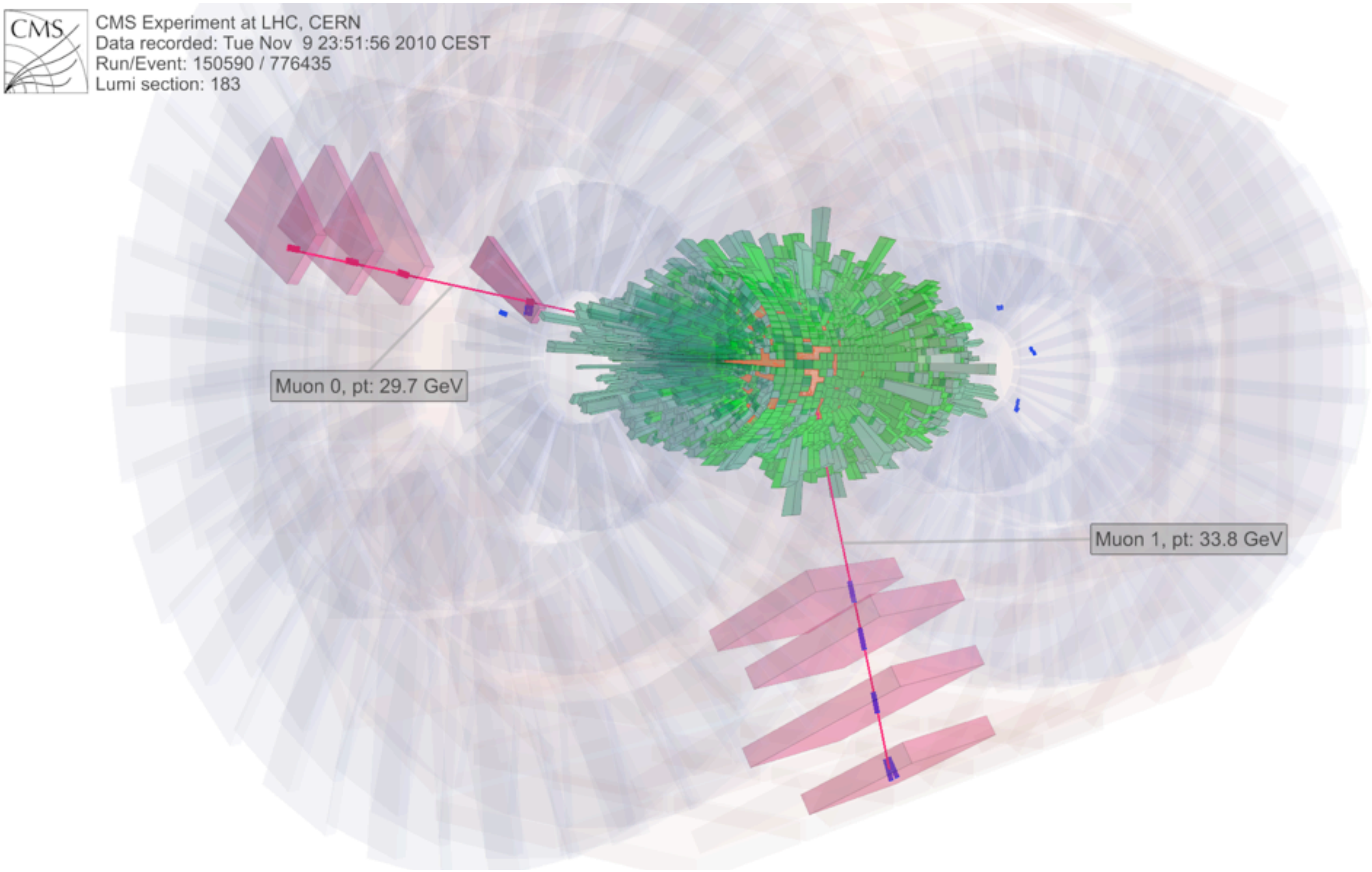
$$\Delta t \sim \frac{\hbar}{\Delta E}$$

$$t_{\rm ini} \sim \frac{1}{E}$$

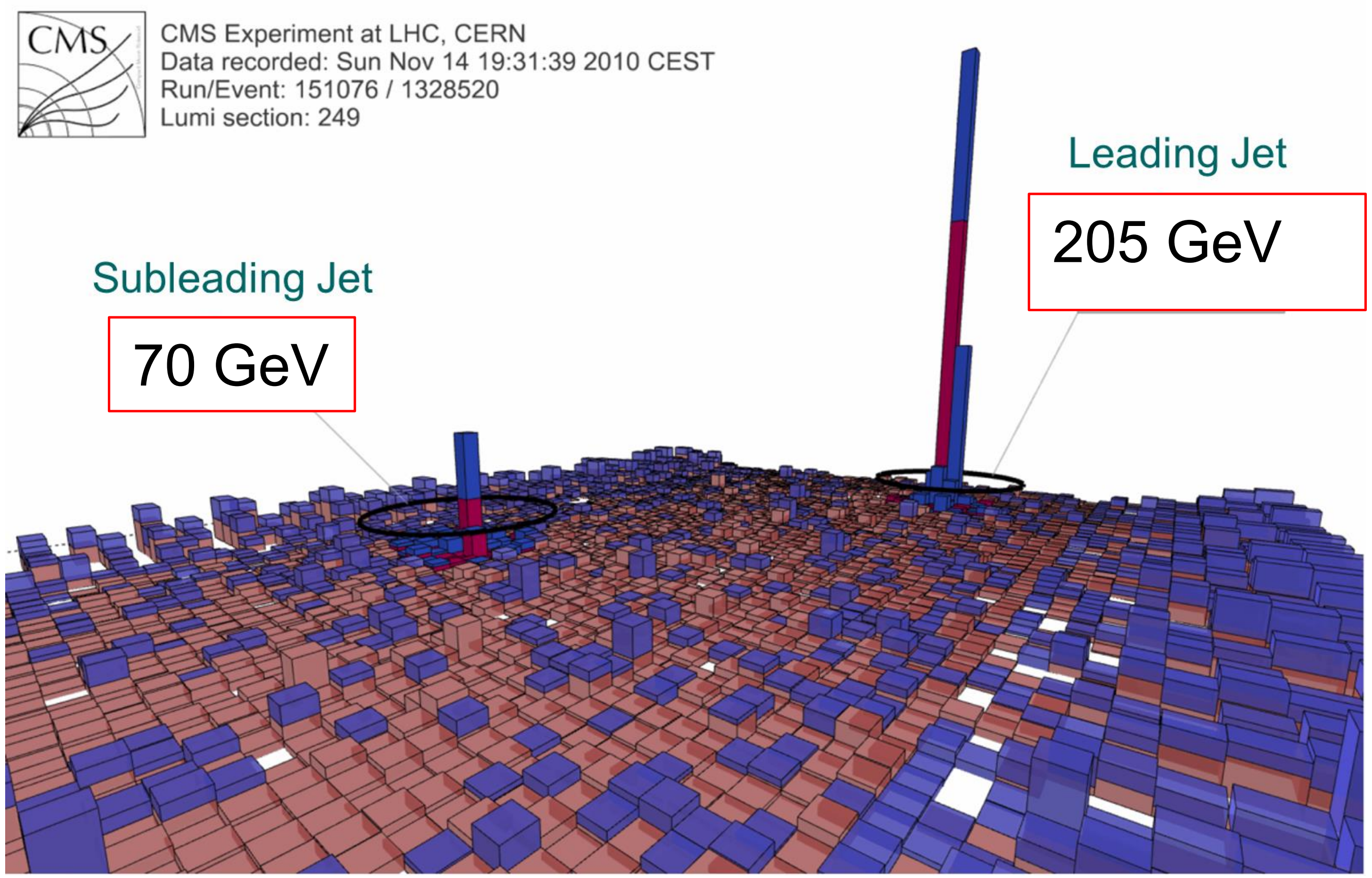
$$t_{\rm had} \sim \frac{E}{\Lambda^2_{\rm QCD}} \sim \text{several fm}$$

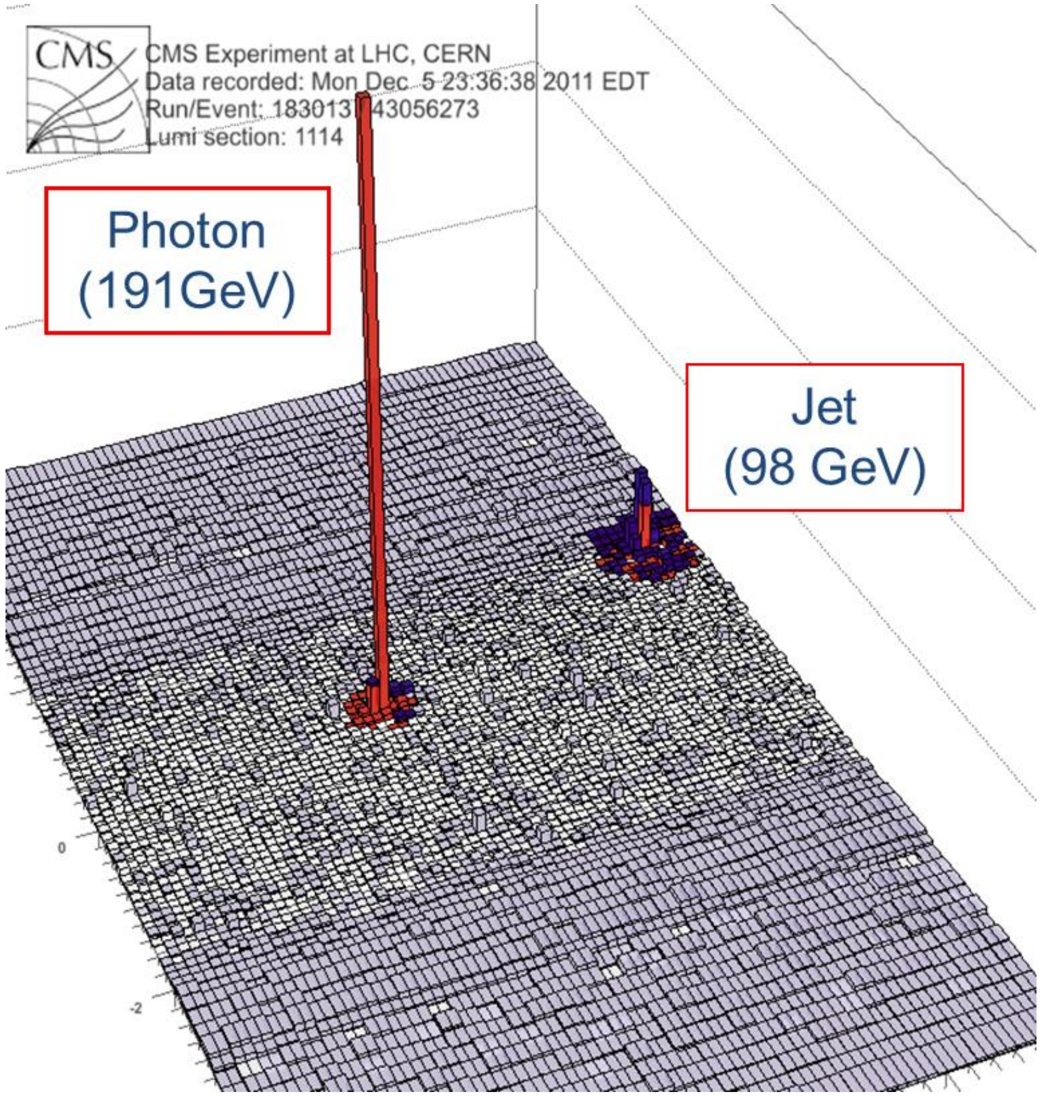
Heavy-ions “by eye” 2





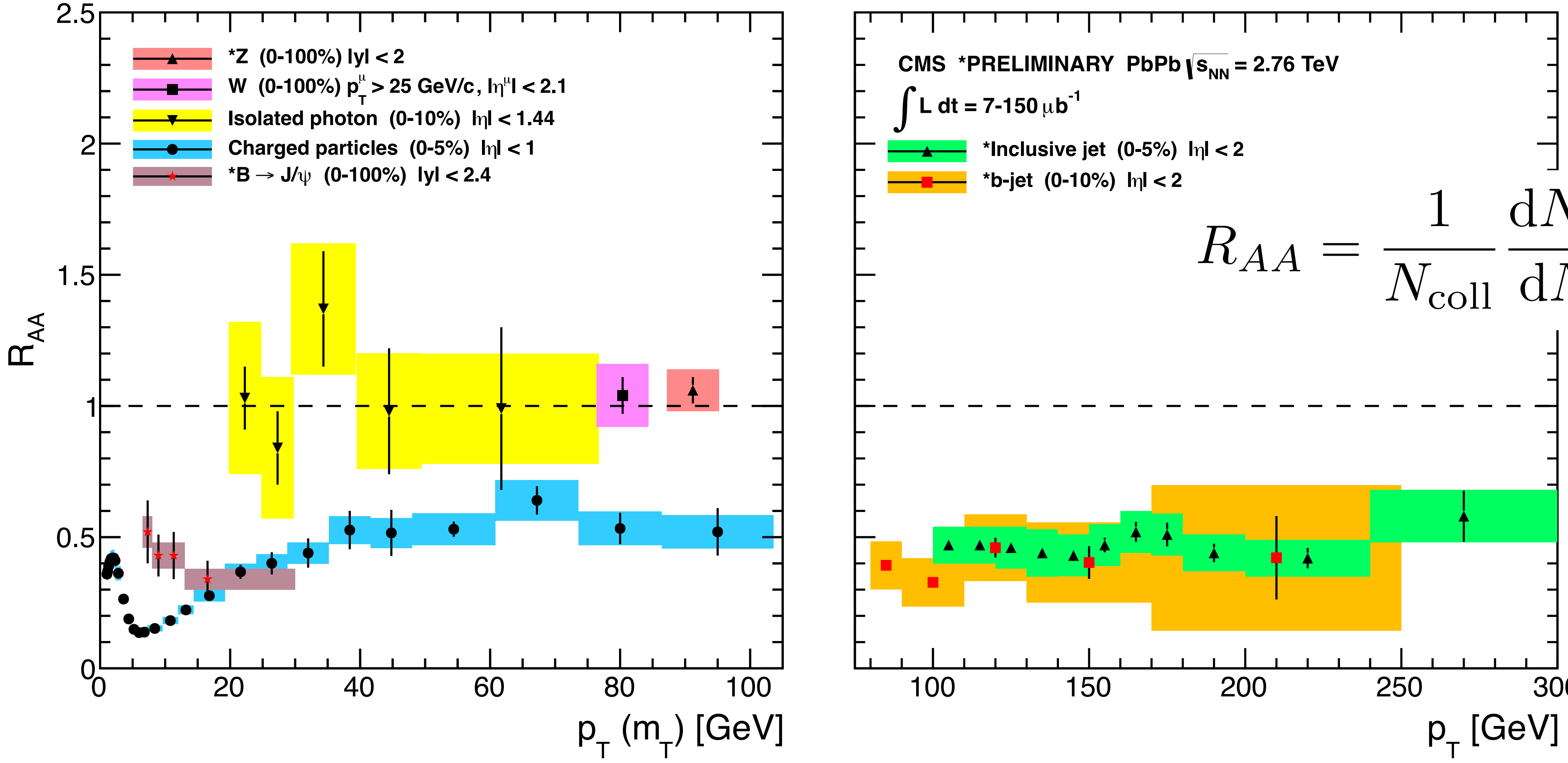
First observed Z-production event in heavy-ion collisions!





Jet quenching!

Nuclear suppression factor

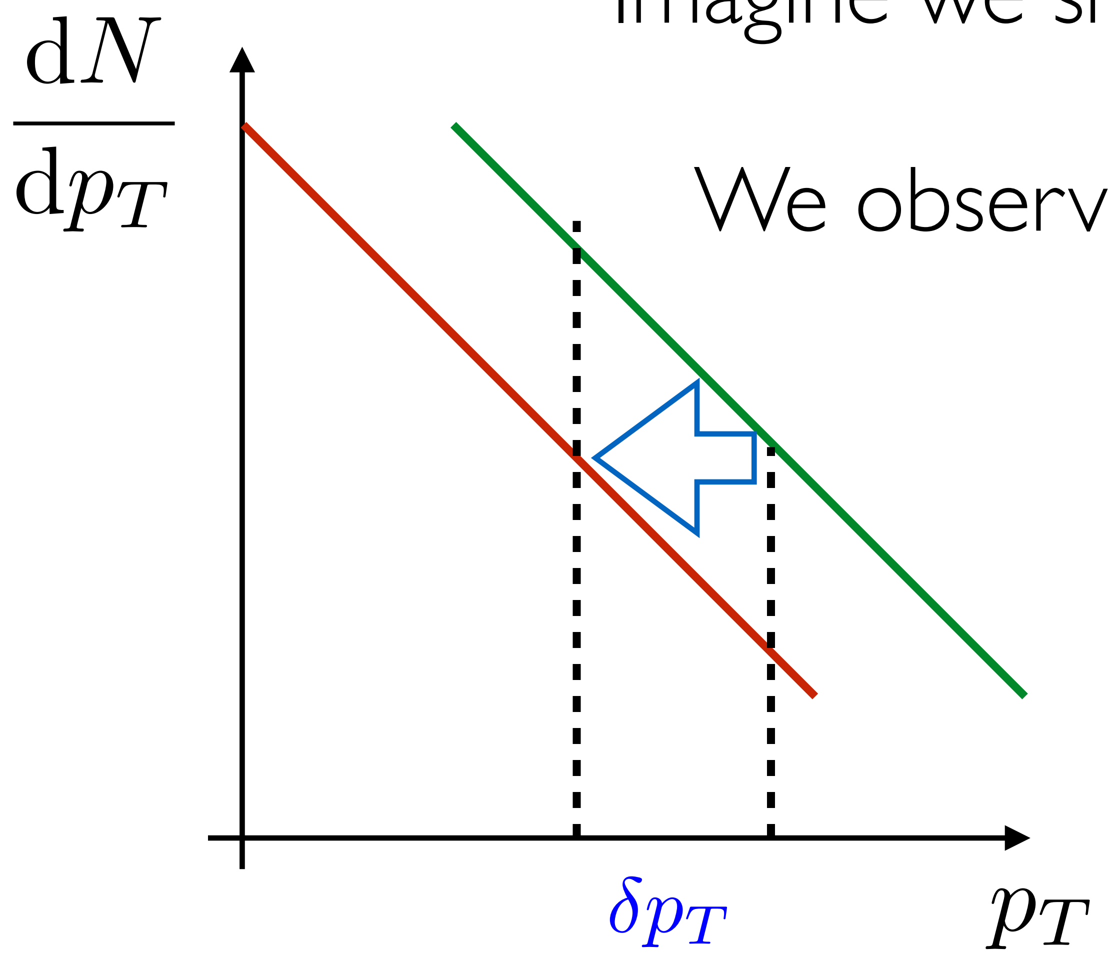


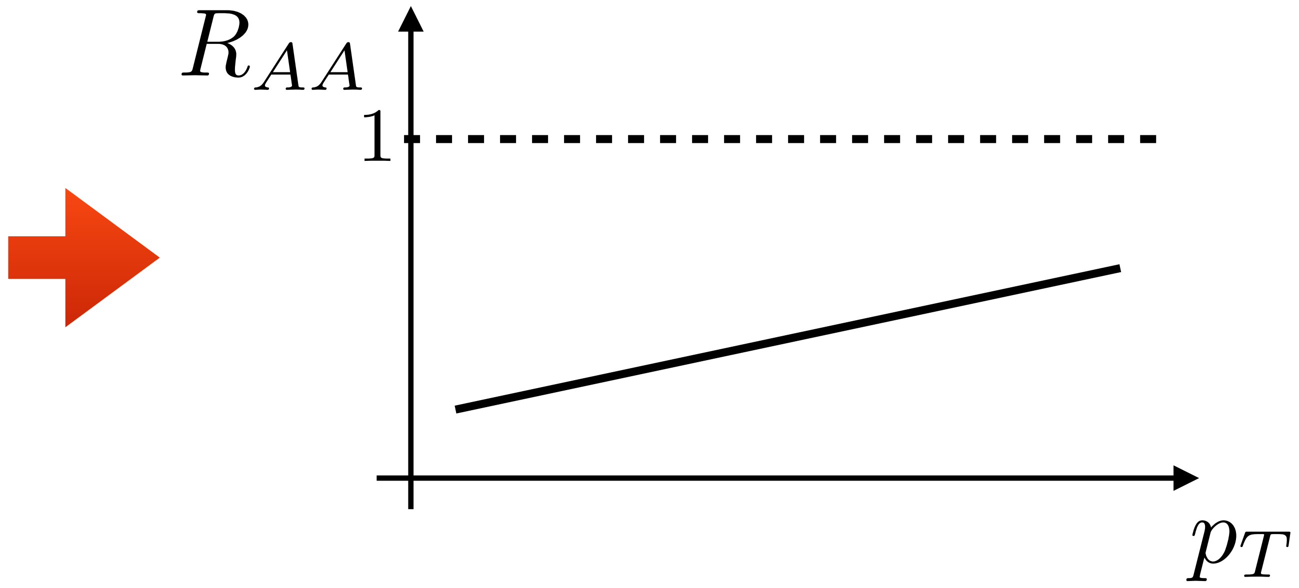
$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{{\rm d}N_{AA}/{\rm d}p_T}{{\rm d}N_{pp}/{\rm d}p_T}$$

- final-state effect (not observed in control experiment pA)
- affects hadronic probes (sensitive to color deconfinement)
- significant suppression!

Energy loss

Imagine we shoot a well-controlled flux of particles into the plasma.
We observe a shifted spectrum & suppression.





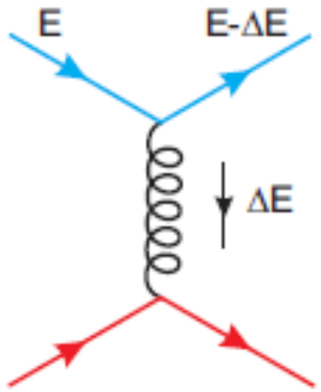
$$\frac{\mathrm{d}N_{AA}(p_T)}{\mathrm{d}p_T} = \frac{\mathrm{d}N_{pp}(p'_T = p_T + \delta p_T)}{\mathrm{d}p'_T} \times \left| \frac{\mathrm{d}p'_T}{\mathrm{d}p_T} \right|$$

☞ medium scattering encoded in shift parameter extracted from data!

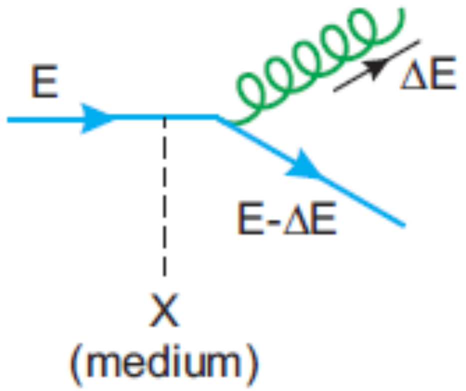
What is responsible?

- surprisingly not direct energy loss with constituents of the plasma but radiative
- **q̂ is the jet transport parameter**

Collisional energy loss



Radiative energy loss



$$\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_T^2\,\mathrm{d}y} = \int_0^\infty \mathrm{d}\epsilon\, \boxed{P(\epsilon)}\, \frac{\mathrm{d}\sigma_{\mathrm{vac}}(p_T+\epsilon)}{\mathrm{d}p_T^2\,\mathrm{d}y}$$

quenching weight!

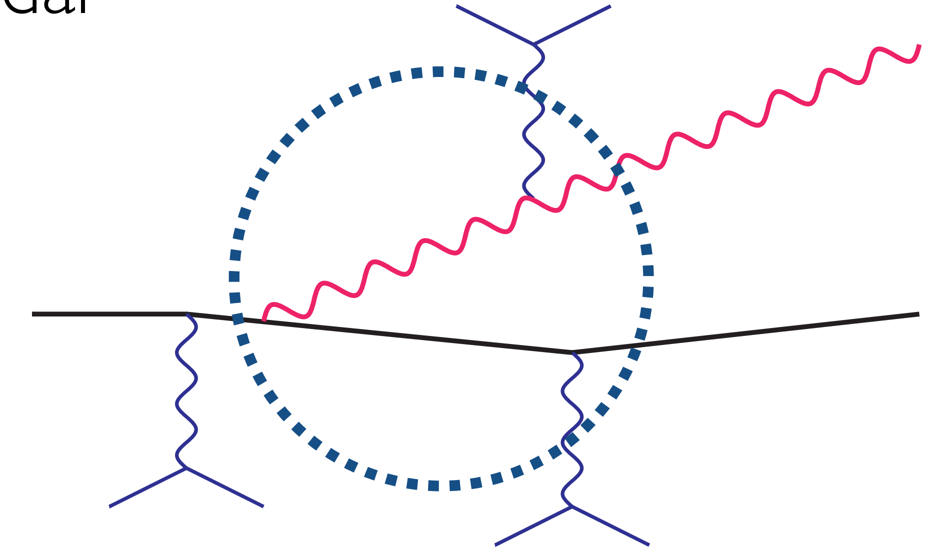
Question:

Why are radiative more efficient than elastic?

Can you think about another case, in vacuum, where we have strong energy-loss effects for relativistic particles?

The LPM effect

Landau-Pomeranchuk-Migdal



momentum broadening $\langle k_\perp^2 \rangle \sim \hat{q} t$

modified splitting kinematics $t_\mathrm{f} = \dfrac{\omega}{k_\perp^2} \sim \sqrt{\dfrac{\omega}{\hat{q}}}$

Q: can you solve it?

coherent spectrum

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \frac{L}{t_\mathrm{f}} = \frac{\alpha_s C_R}{2\pi} \sqrt{\frac{\hat{q} L^2}{\omega}}$$

$$\omega \frac{\mathrm{d}I_\mathrm{incoh}}{\mathrm{d}\omega} \sim \alpha_s \frac{L}{\lambda_\mathrm{mfp}}$$

$$t_\mathrm{f} = \frac{1}{\omega \theta^2}$$

solve for ϑ: $$\theta = \left(\frac{\hat{q}}{\omega^3} \right)^{1/3}$$

Strong energy loss

Multiplicity of gluons $N(\omega) = \int_{\omega}^{\infty} \mathrm{d}\omega' \, \frac{\mathrm{d}I}{\mathrm{d}\omega} = 2\bar{\alpha}\sqrt{\frac{\hat{q}L^2}{\omega}}$

Energy loss: $\Delta E = \int_0^{\infty} \mathrm{d}\omega \, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = 2\bar{\alpha}\hat{q}L^2$

goes like L^2, significant for large medium!

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goes like L², significant for large medium!

rare, small-angle emission $\omega_c = \hat{q}L^2$

$$\theta_{\mathrm{br}}(\omega_c) \sim \sqrt{\frac{1}{\hat{q}L^3}} \equiv \theta_c$$

copious, large-angle emissions $\omega_s = \bar{\alpha}^2\hat{q}L^2$

$$\theta_{\mathrm{br}}(\omega_s) \sim \frac{1}{\bar{\alpha}^{3/2}}\theta_c$$

Probability of losing energy

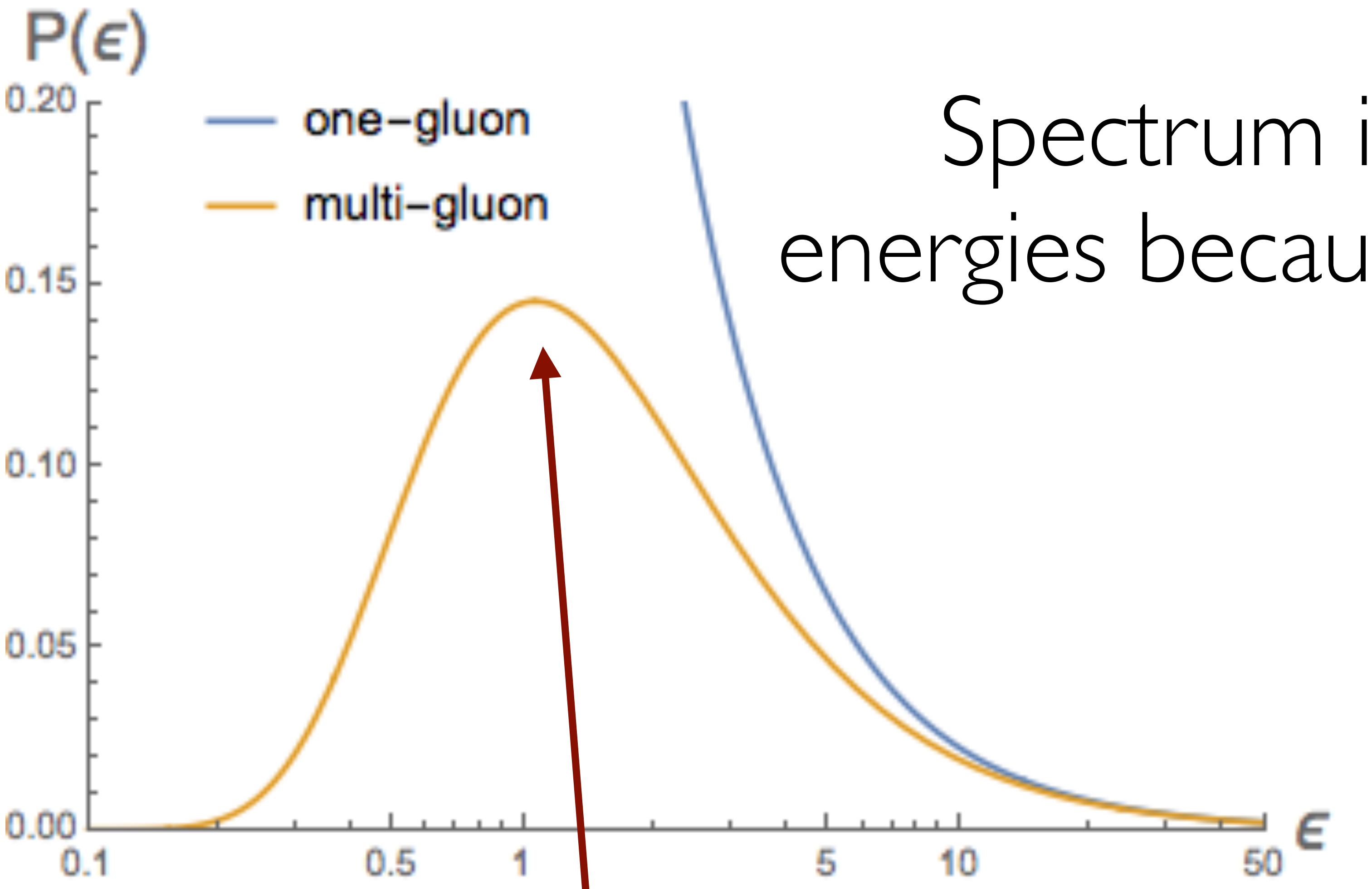
For one-gluon emission $P(\epsilon) = \delta(\epsilon)\left(1 - \int_0^\infty \mathrm{d}\omega\, \frac{\mathrm{d}I}{\mathrm{d}\omega}\right) + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$

Resumming multi-gluon emission (assuming they are independent)

$$P(\epsilon) = \mathrm{e}^{-\int \mathrm{d}\omega\, \mathrm{d}I/\mathrm{d}\omega} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int \mathrm{d}\omega_i\, \frac{\mathrm{d}I}{\mathrm{d}\omega_i} \delta\left(\epsilon - \sum_{j=1}^{n} \omega_j\right)$$

Poisson distribution!

Quenching weight



Spectrum is suppressed at small energies because of the high multiplicity.

$$\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_T} = A\, p_T^{-n}$$

E-loss dominated by max of distribution!

$$\delta p_T = \sqrt{\frac{8\pi\bar{\alpha}^2\hat{q}L^2\, p_T}{n}}$$

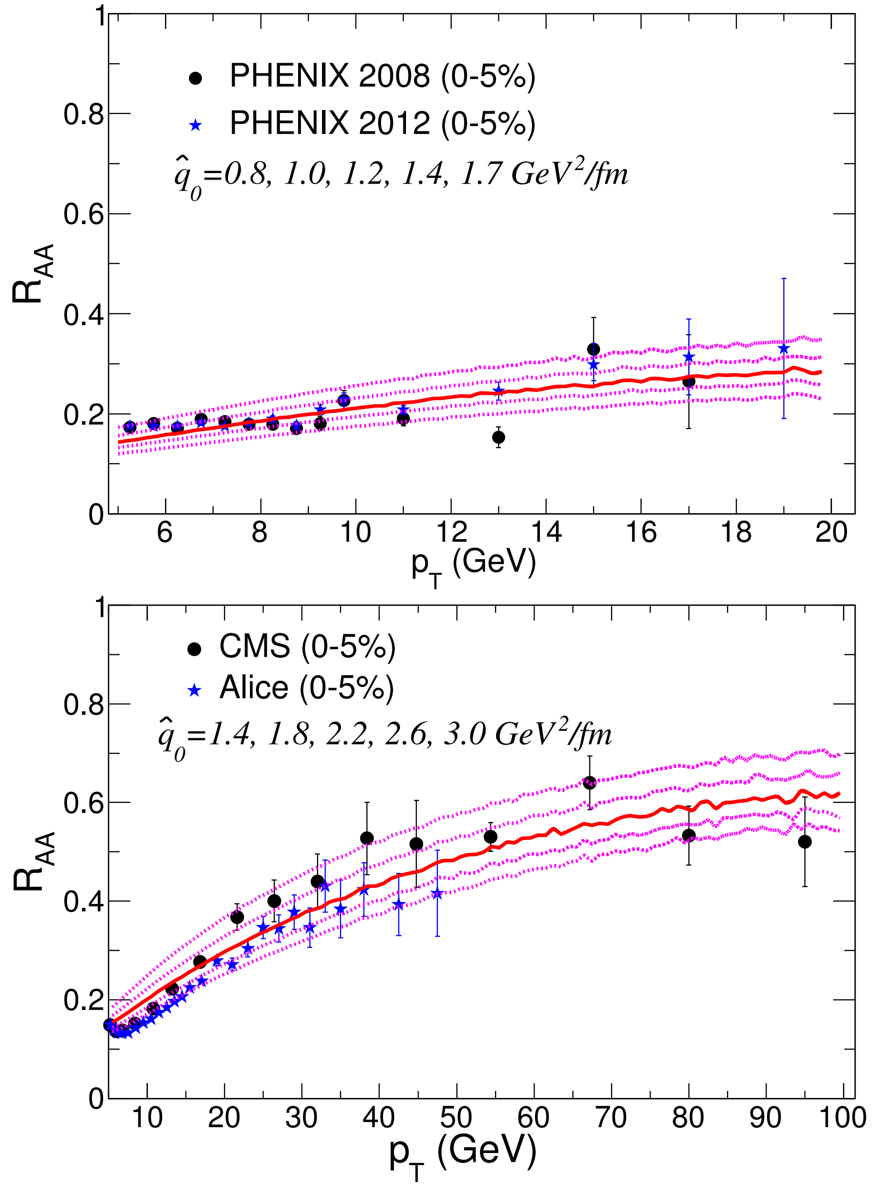
Question:

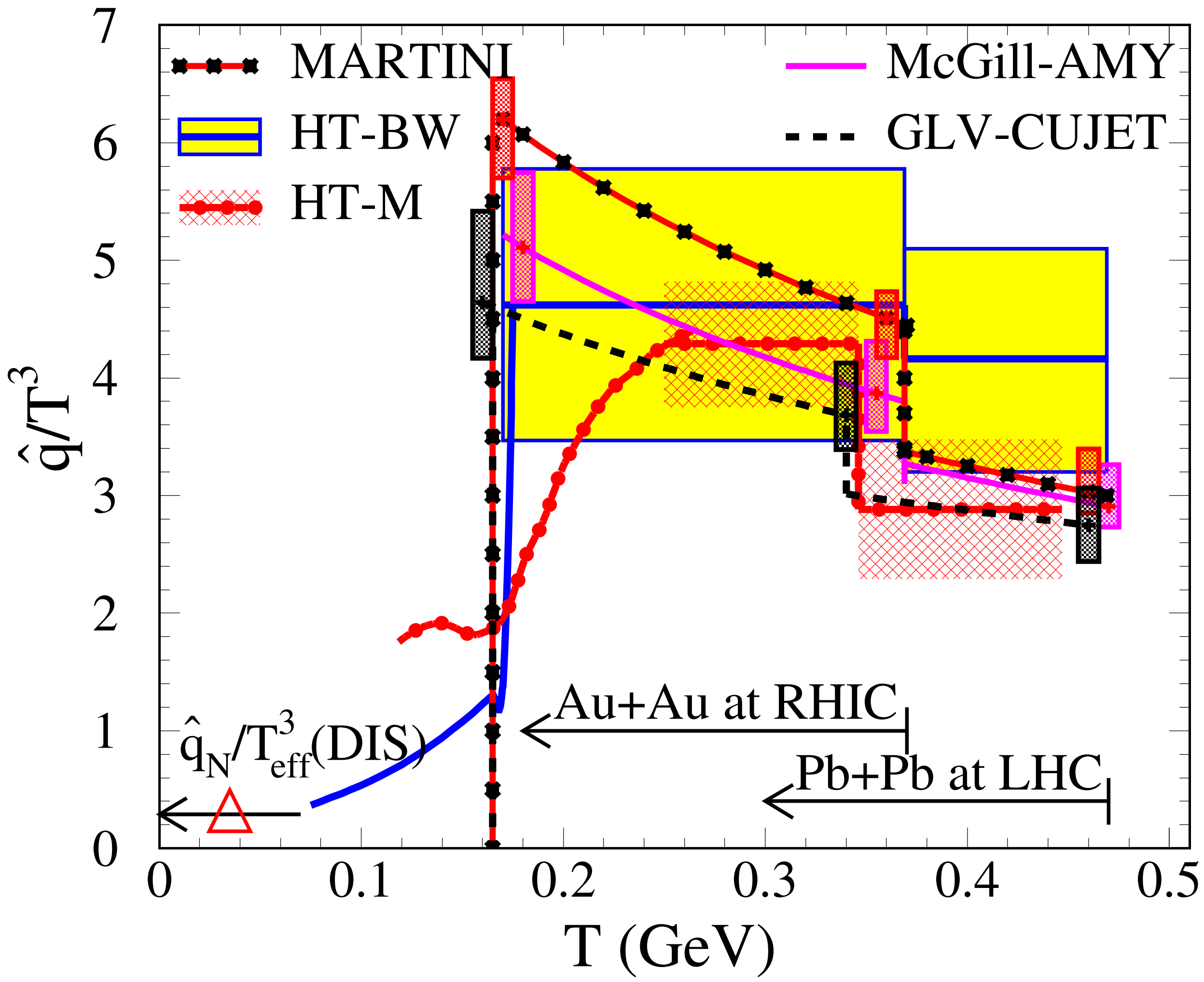
$$\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_T} = A\,p_T^{-n}$$

For a power-law spectrum and a fixed δp_T, what happens to RAA at large p_T?

What happens to an exponential spectrum?

Extracting q̂ from data





Summary

- heavy-ion collisions study nuclear matter in extreme conditions
- two main experimental features: flow and jet quenching
- flow measurements give evidence for strong collectivity & hydrodynamical behavior
- jet quenching demonstrates that this dense state couples to perturbative probes (microscopic description)