Some topics in heavy-ion physics

Aleksi Kurkela
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Universitetet i Stavanger

CERN

Preface

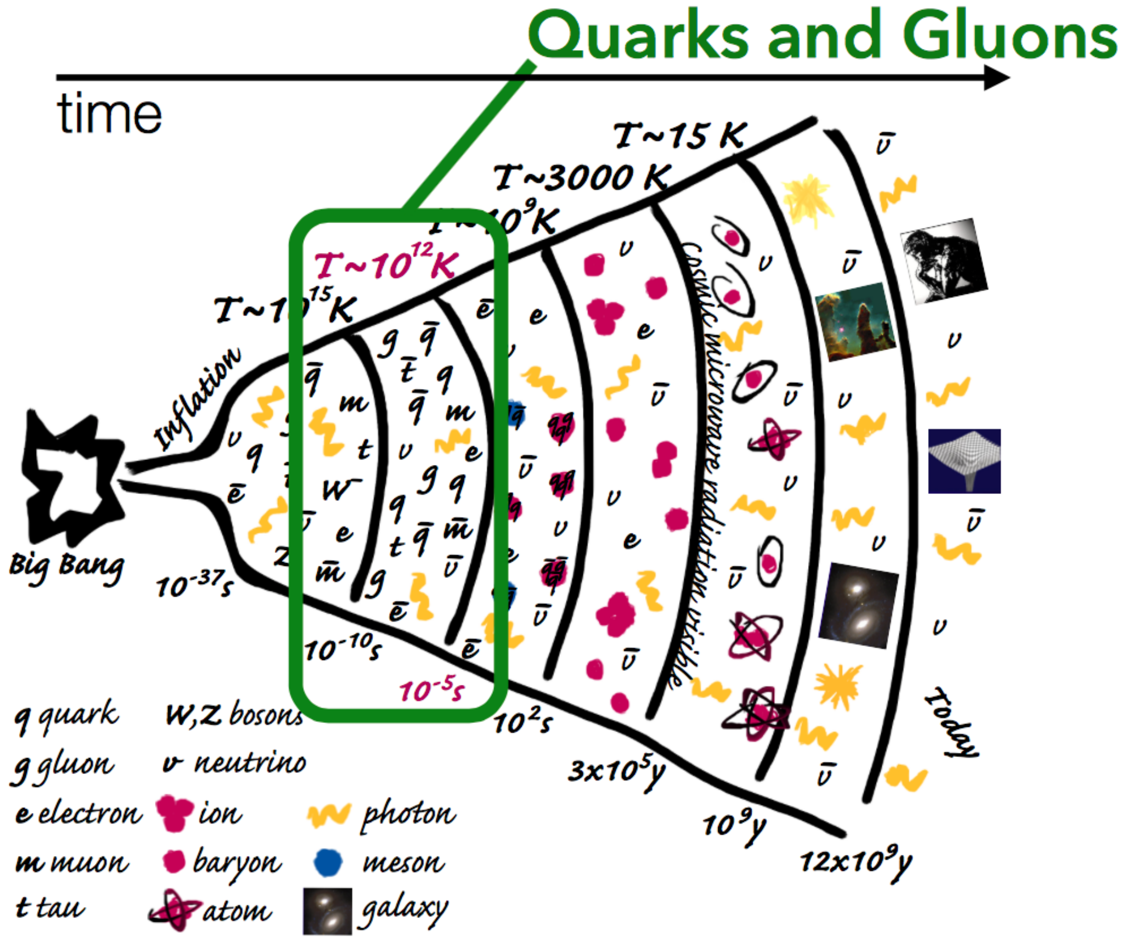
- QCD is a mature theory of strong interactions with a precision frontier
- Fundamental degrees of freedom quarks and gluons, matter normally in hadronic form
- What happens to QCD if the hadronic structure is broken at high temperature?

- Heavy ion collisions offer an experimental venue to create QCD matter at densities only comparable to cores of neutron stars and early universe
- Ongoing large experimental effort at LHC (CERN) with ALICE, ATLAS, CMS, LHCb and at RHIC (BNL) PHENIX, STAR

Preface

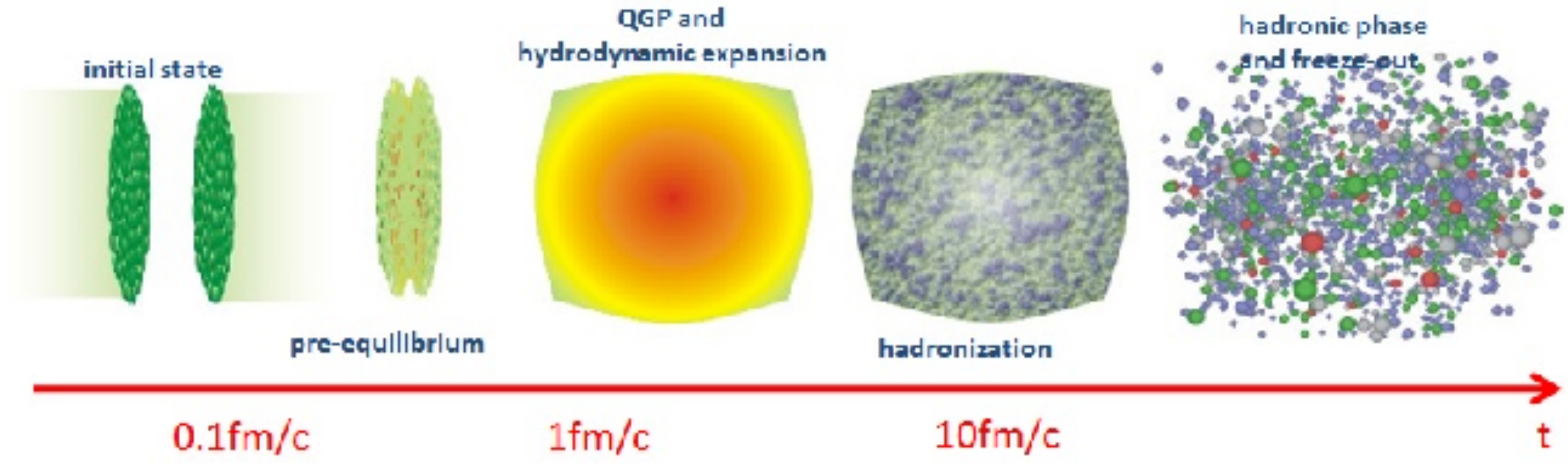
- We want to know: what happens to quantum field theory in extreme conditions. In the presence of a large number of particles, not just perturbations around vacuum.
    - How do collective macroscopic properties arise from microscopic degrees of freedom
    - What are material properties of matter made of quantum fields?
    - Close connection to cosmology: phase transitions, pre/reheating thermal particle production, etc…
    - Close connection to condensed matter physics: cold atoms,

Quark gluon plasma and cosmology



based on 'History of the Universe' by the Particle Data Group, LBNL ©2000

Evolution of heavy ion collision



- Initial condition: Wave function of highly boosted nucleus.
- Initial scattering and particle production (0 - 0.1 fm/c)
- Non-equilibrium evolution and thermalization (0.1-1fm/c)
- Hydrodynamical explosion, expansion, dilution, cool-down (1-10 fm/c)
- Hadronization
- Chemical and kinetic freeze out
- Particle detection (10^{15} fm/c)

References

- Talks:
  - Jan Fiete Grosse-Oetringhaus, CERN-fermilab school 2015
    https://indico.cern.ch/event/353089/contributions/1762268/attachments/
  - Stefan Floerchinger, European School of High Energy Physics 2015
    https://indico.cern.ch/event/381289/contributions/1808002/attachments/
  - Quark Matter student days:
    https://indico.cern.ch/event/355454/timetable/#all.detailed
    - Jean-Yves Ollitrault, Flow
    - Bjoern Schenke, theory overview

Outine

- Basic theoretical concepts
- Particle production in heavy-ion collisions
- Flow
- Fluid dynamics
- QCD kinetic theory and pre-equilibrium dynamics
- Hard probes

Basic theoretical concepts

QCD

- Lagrangian:

$$\mathscr{L} = -\frac{1}{2}\mathrm{tr}\,\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \sum_f \bar{\psi}_f\,(i\gamma^\mu \mathbf{D}_\mu - m_f)\,\psi_f$$

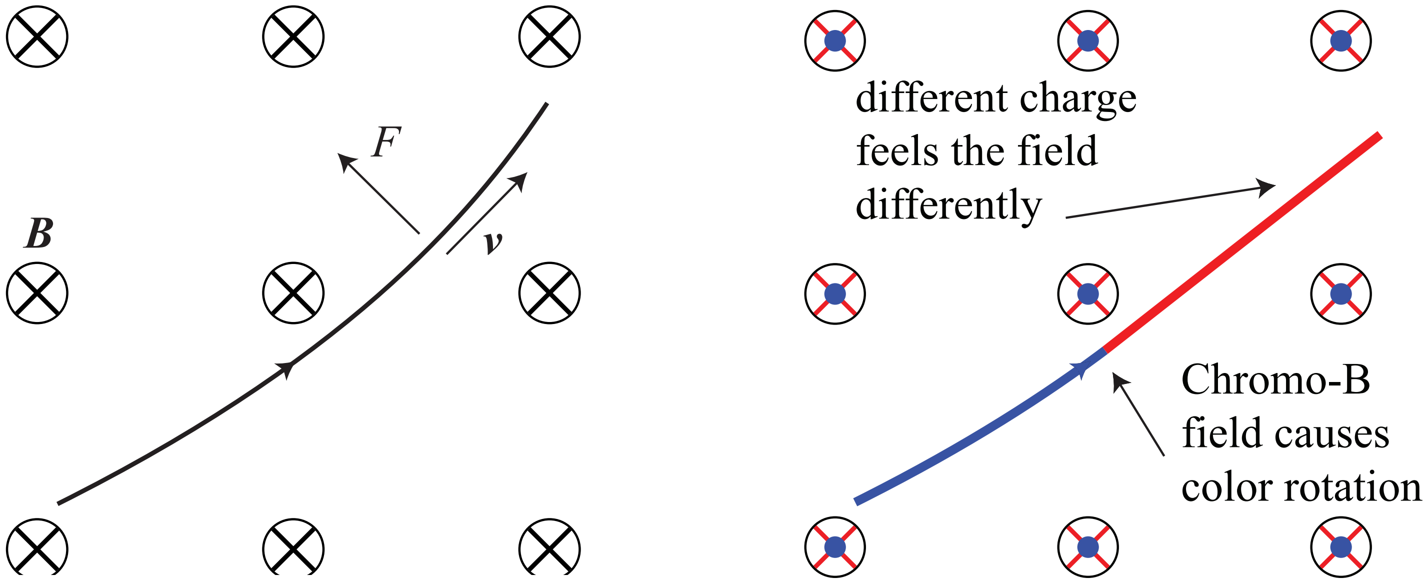
$$\mathbf{F}_{\mu\nu} = \partial_\mu \mathbf{A}_\nu - \partial_\nu \mathbf{A}_\mu - ig[\mathbf{A}_\mu, \mathbf{A}_\nu], \qquad \mathbf{D}_\mu = \partial_\mu - ig\mathbf{A}_\mu$$

- Quark masses:

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

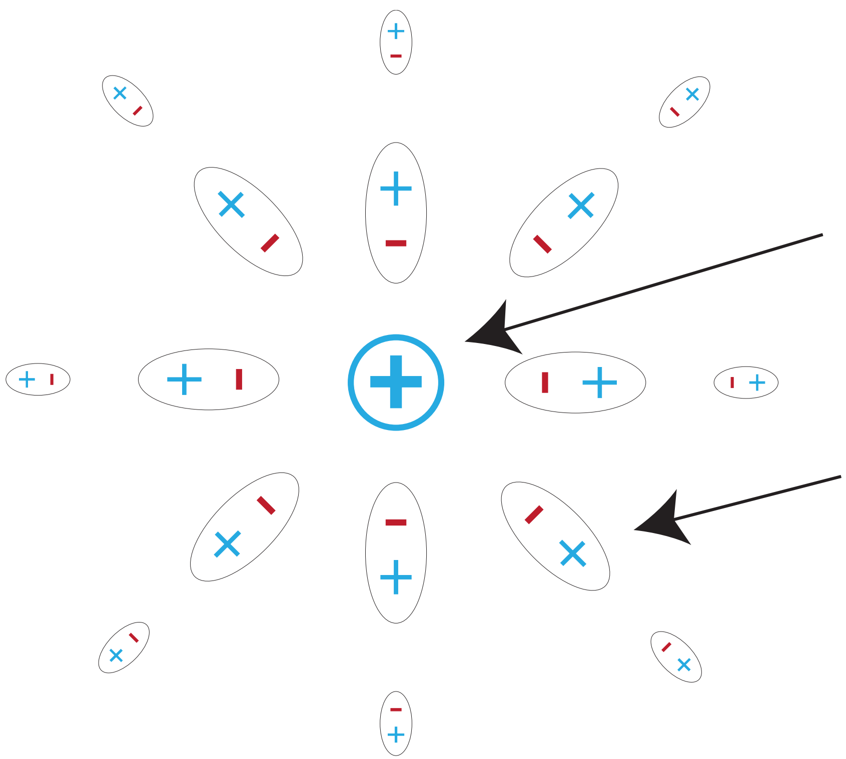
QCD

- Much like QED
  - Quarks like electrons, but come in three colors [rgb]
  - “Chromo-E” and B fields (gluons) like E and B fields (photons) but:
    - E- and B-fields change momentum of particles
    - Chromo-E and -B fields also rotate color (8 different gluon fieds: rg, rb,…)
    - Gluons also carry color (charge), interact together



In QFT vacuum is a medium

- QED: vacuum screens charge, strong at short scales



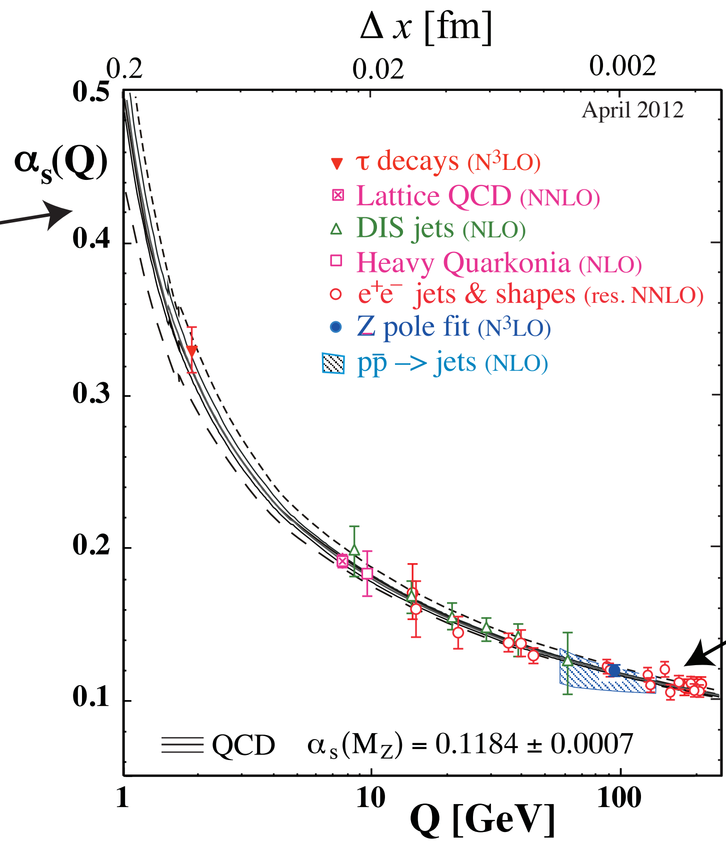
A charge in vacuum

modifies the vacuum around it

In QFT vacuum is a medium

- QED: vacuum screens charge, strong at short scales
- QCD: vacuum “anti-screens”, weaker at short scales
  - Asymptotic freedom: at short scales “free” q and g

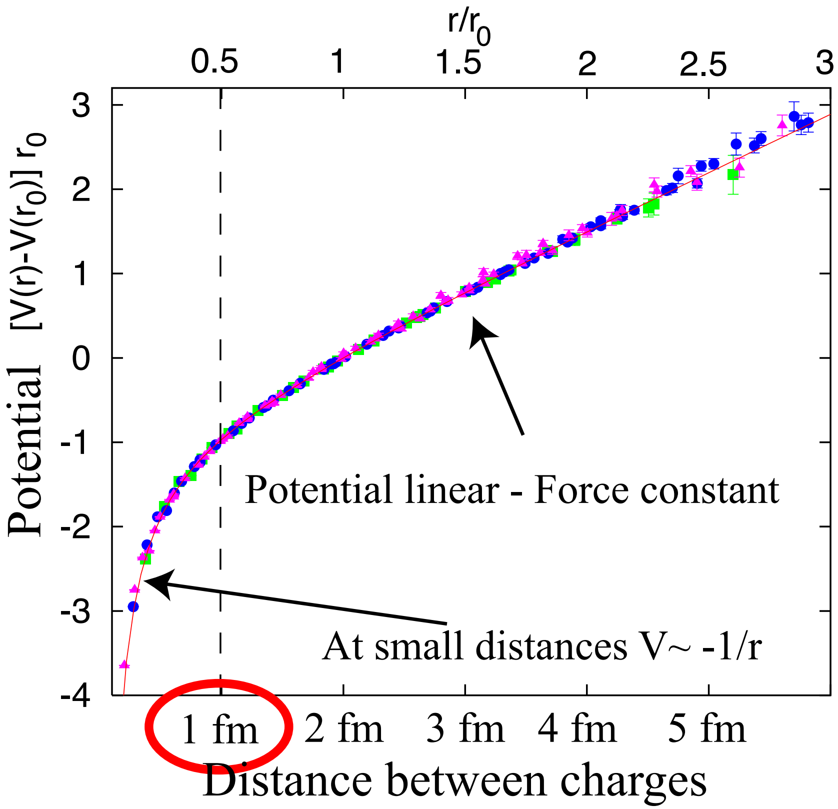
At $\Delta x \sim 10^{-15}$ m, coupling becomes large



Weaker at short distances, “free partons”

Confinement

- Large coupling reflects linear confinement
- At distances $\Delta x \gtrsim 1 fm$, force between color charges independent of distance. “QCD string”



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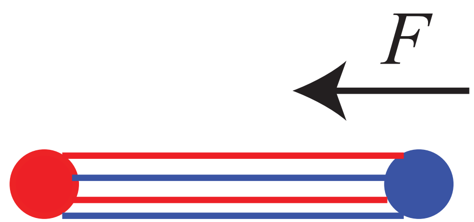

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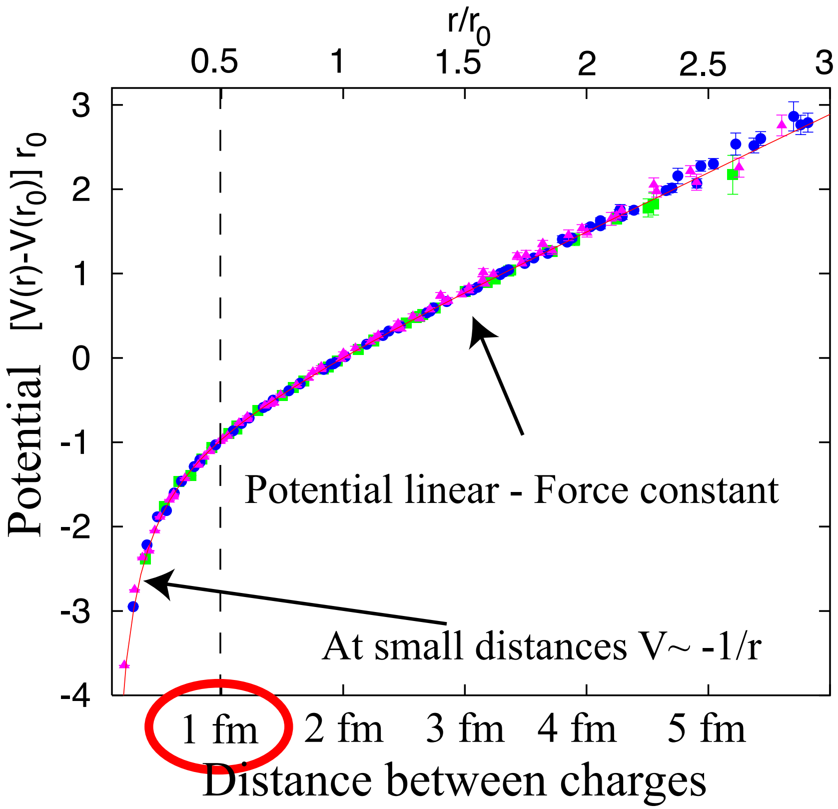

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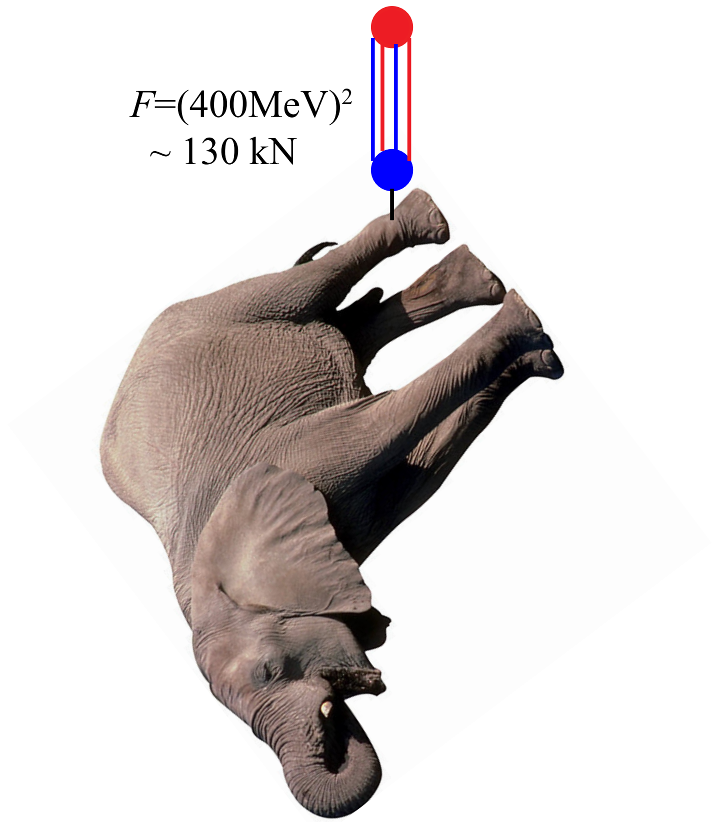
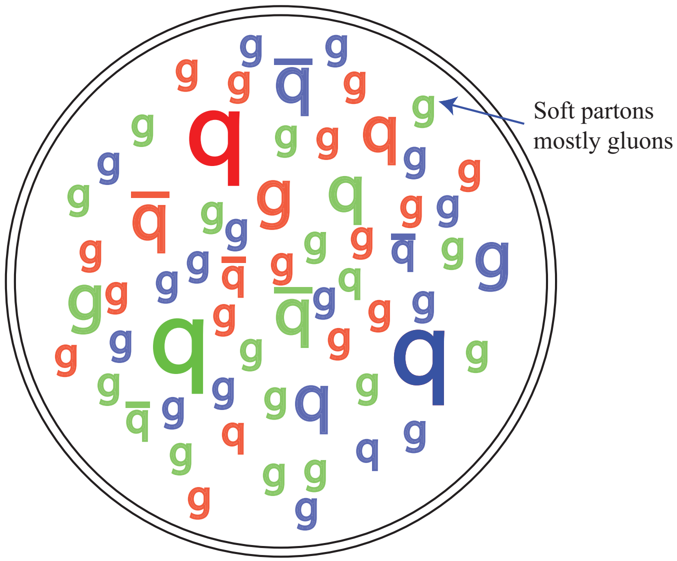
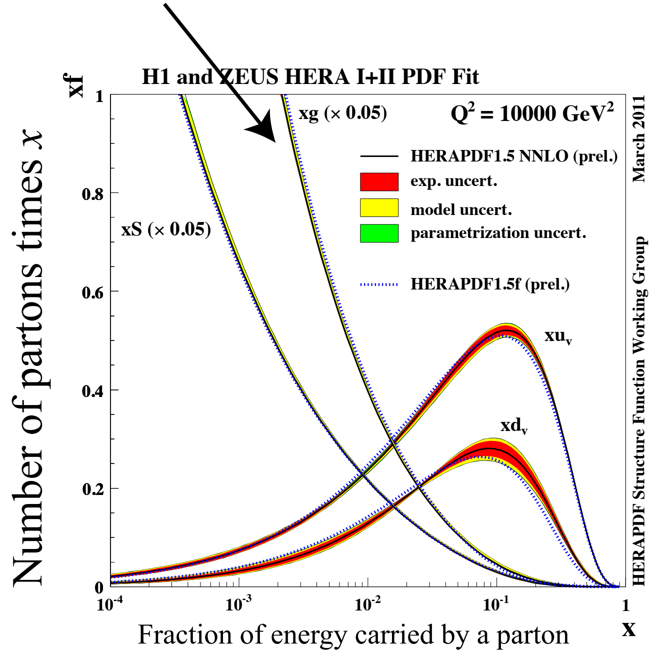


Confinement

- Matter organized in color-neutral lumps: Protons, neutrons, pions, etc. = hadrons
- Quasiparticles of QCD vacuum, not few q and g
- Quark and gluon content can be probed in DIS, pdf's

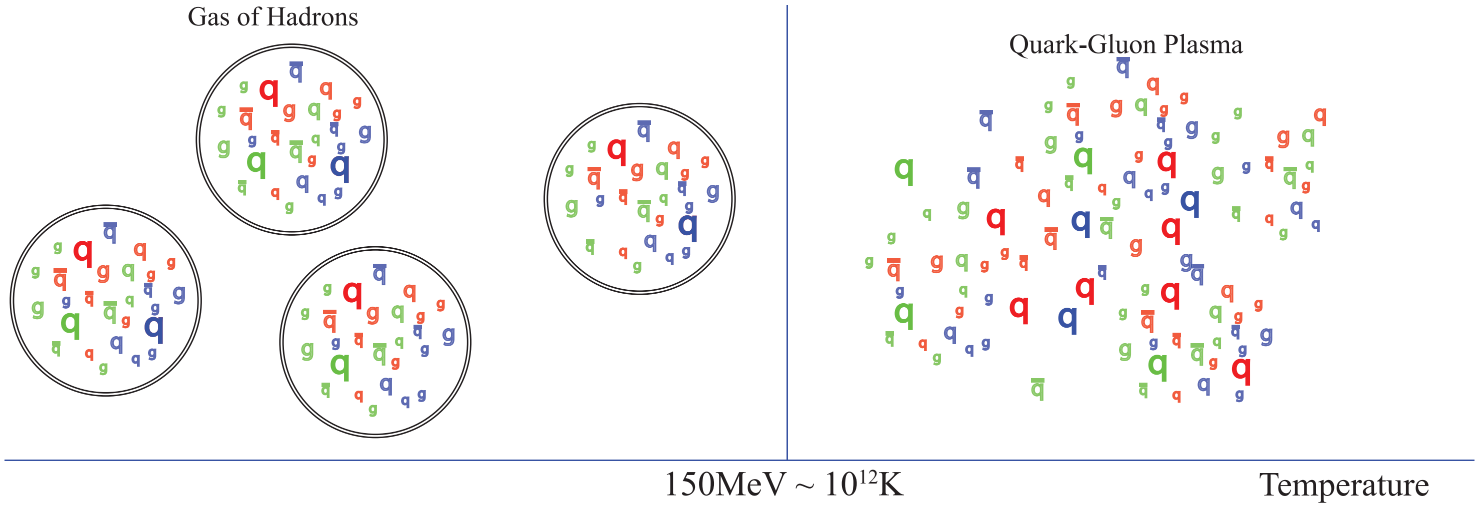


Large number of soft gluons

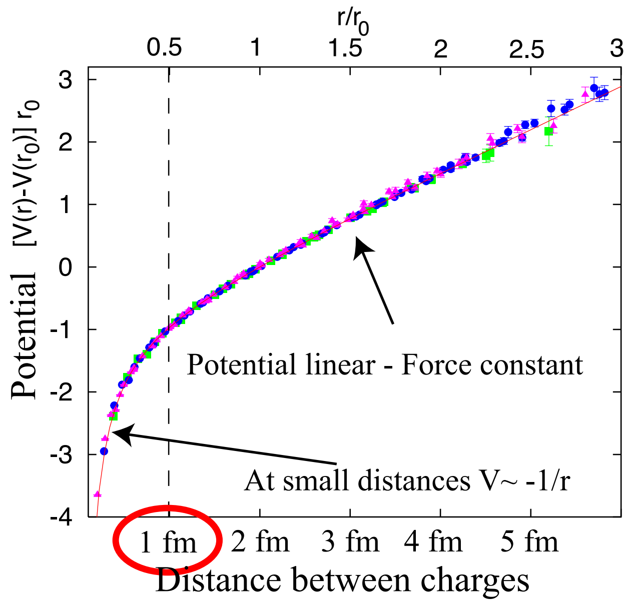


Proton Parton Distribution Functions

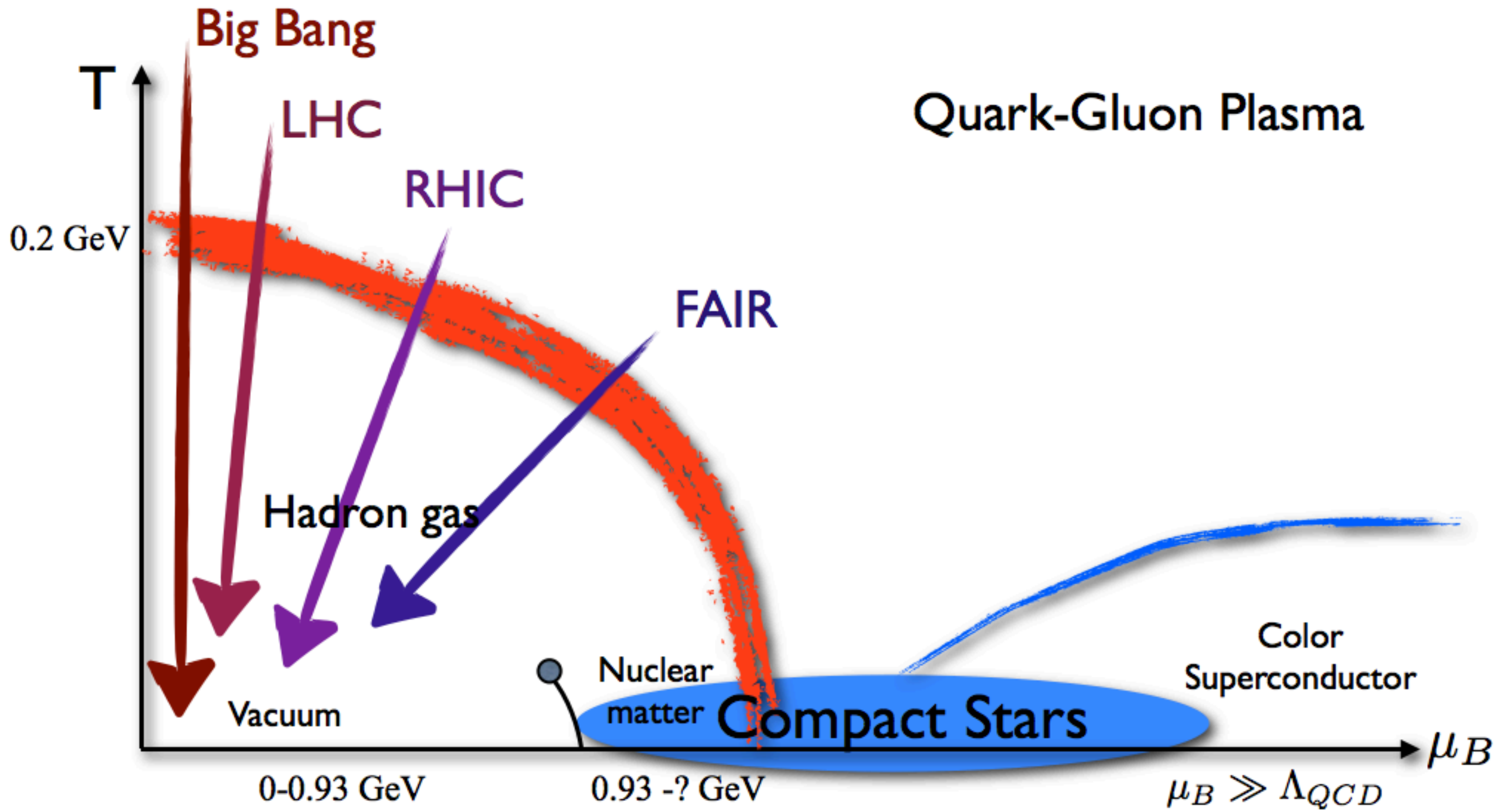
Deconfinement



- At small densities/temperatures: gas of hadrons
- At high densities/temperatures: gas of q and g
- At asymptotically high temperatures, free gas q and g



Phase diagram?



Baryon chemical potential

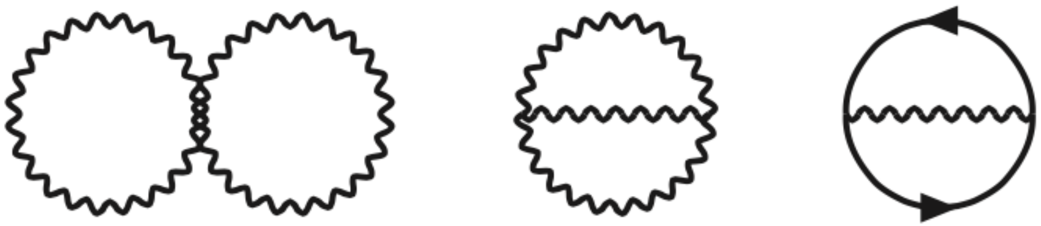
QCD thermodynamics

- At asymptotically high temperature: EoS of non-interacting quarks and gluons

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

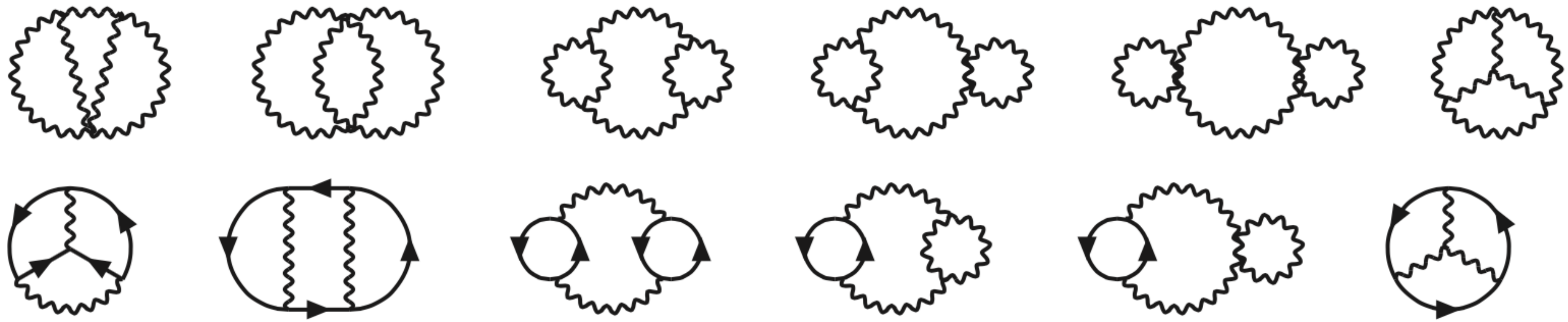
$$N_B = \underbrace{2}_{\text{spin}} \times \underbrace{8}_{\text{color}}, \quad N_F = \underbrace{2}_{\text{spin}} \times \underbrace{2}_{\text{particle/antiparticle}} \times \underbrace{3}_{\text{color}} \times \underbrace{3}_{\text{flavor: u/d/s}}$$

- Corrections through loop diagrams:



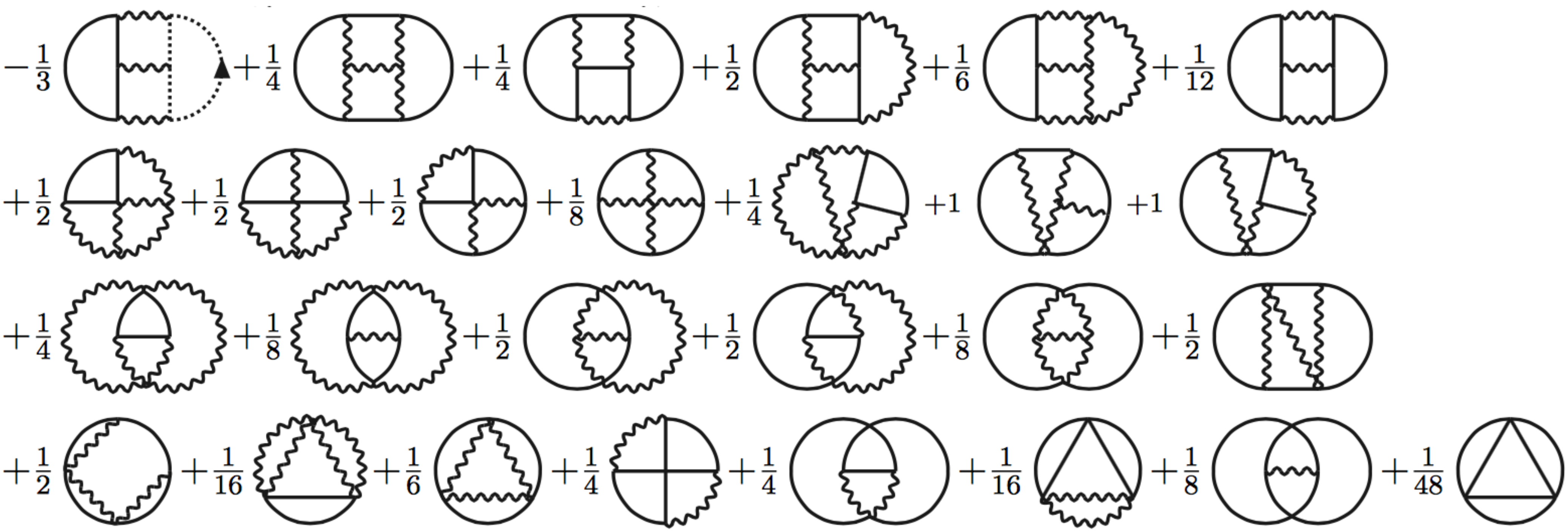
QCD thermodynamics

- …and



QCD thermodynamics

- …and

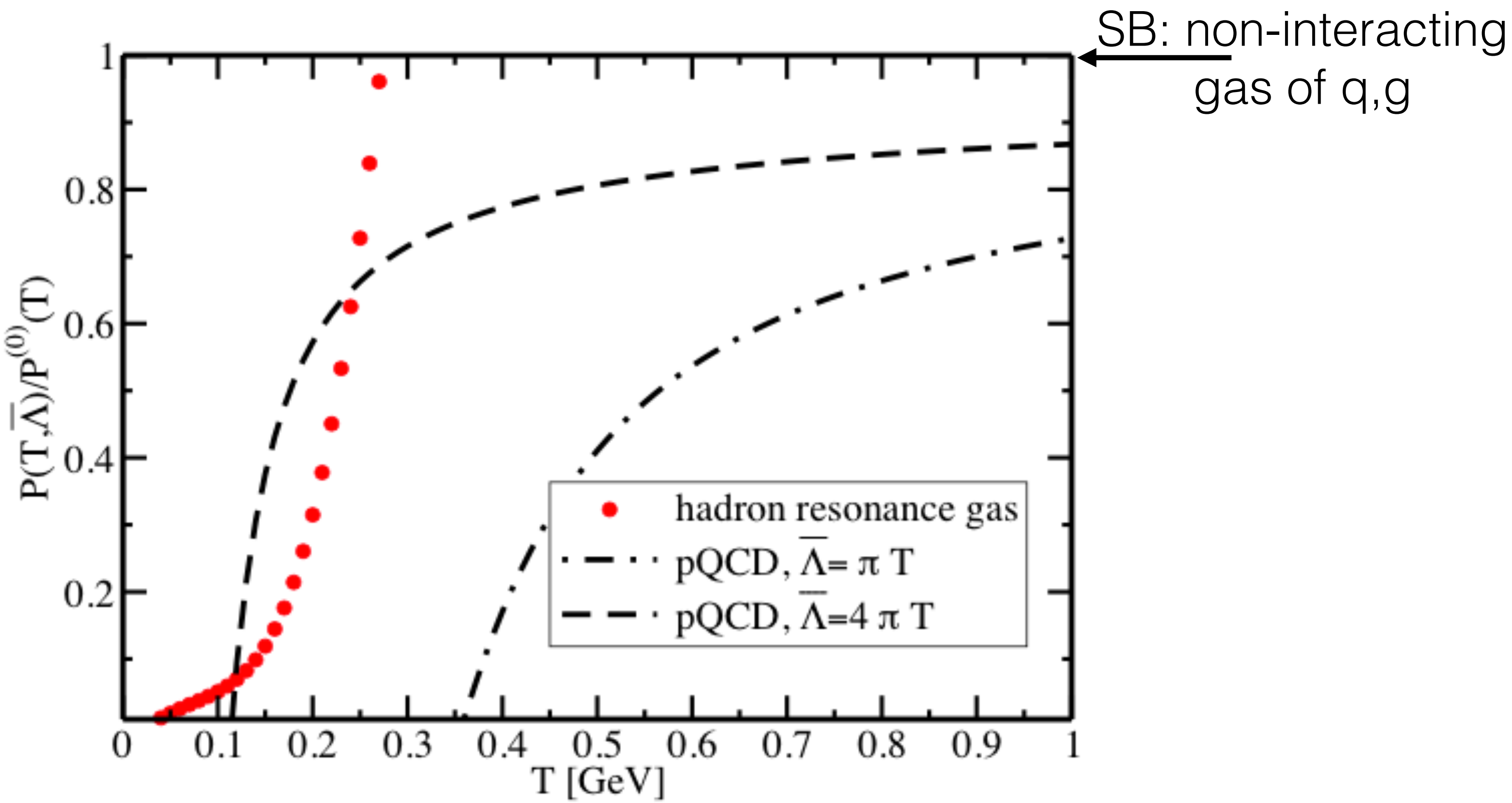


- and so on. Computed to order $p \sim 1 + \alpha_s + \alpha_s^{3/2} + \alpha_s^2 + \alpha_s^{5/2} + \ldots$

NNNNNLO?

QCD thermodynamics

- At small temperatures: non-interacting gas of massive hadrons



- In the middle something else!

Lattice QCD

- (Some) equilibrium thermodynamical information numerically calculable nonperturbatively, directly from Lagrangian.

- Discretization of g and q fields on a space time lattice

- Based on a formal analogy of 3+1D quantum theory (in Minkowski) and 4D statistical field theory (Euclidean).

$$Z = \sum_{\psi} \langle \psi | \hat{\rho} | \psi \rangle \qquad \hat{\rho} = e^{-\hat{H}/T}$$

Looks like time evolution operator with imaginary time: $U(0,t) = e^{-i\hat{H}t}$

$1/T$

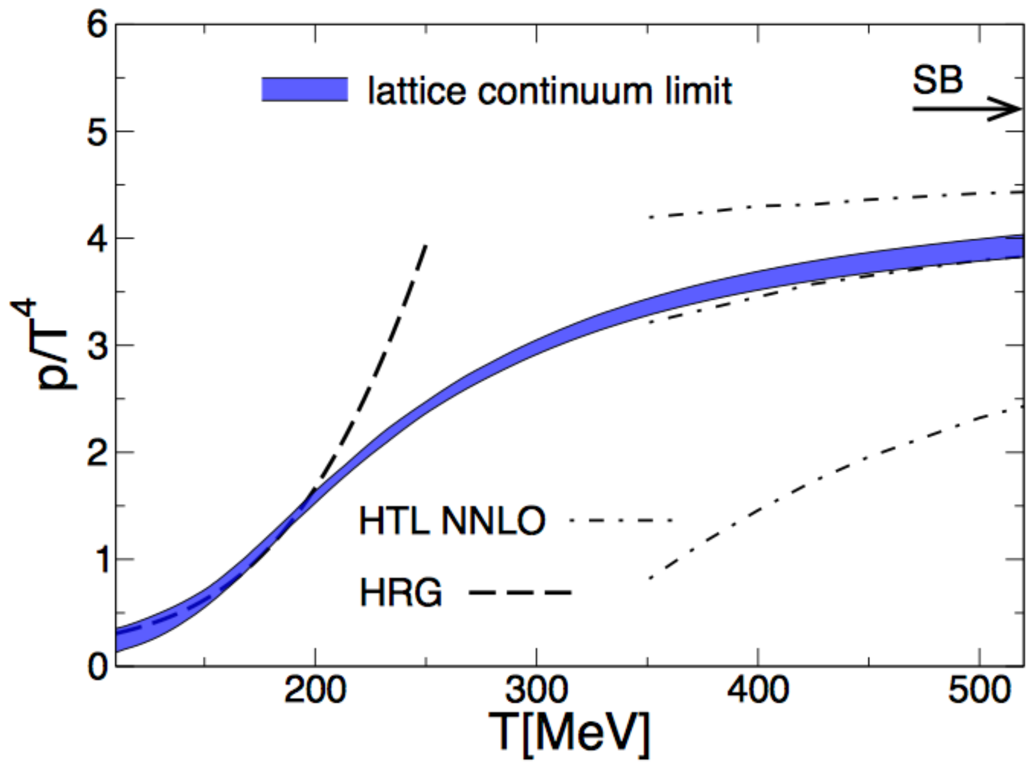
Lattice QCD

- Applicability limited to static quantities (spacelike correlators) in thermal equilibrium. Not sufficient to model the dynamical evolution in heavy-ion collisions

- Can do: Equation of State, speed of sound, screening masses,

- Can't do: Transport coefficients, non-equilibrium evolution, particle production etc..

Equation of State



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- Small temperatures, gas of hadrons
- Large temperatures, ideal gas of q and g
- Pseudocritical temperature of cross-over T_C~200 MeV
- At few T_C, still large corrections from ideal gas
- Deviation from ideal gas qualitatively described by thermal perturbation theory with large error bars

$\mathcal{N} = 4$ Super Yang-Mills theory

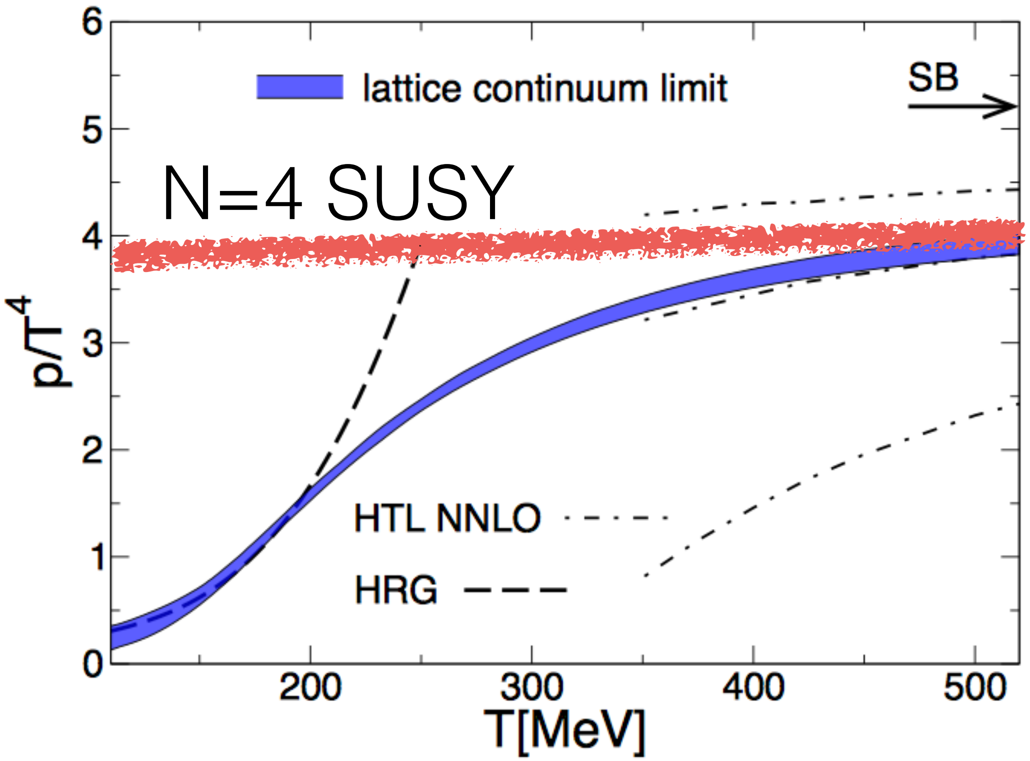
- Not QCD
  - Different particle content! Extra scalar, adjoint fermions, ….
  - Conformal symmetry
  - No confinement, no asymptotic freedom.
- …But can be solved in the ’t Hooft limit using holography (AdS/CFT)

$$N_c \to \infty, \quad \lambda \equiv 4\pi\alpha_s N_c \to \infty$$

  - Offers a solvable theoretical toy model that is as strongly coupled as it gets. “The opposite of ideal gas”

- Not to be taken quantitatively predictive but qualitative insight
  - Most results contain a some kind of rescaling (by # of d.o.f etc)

$\mathcal{N} = 4$ Super Yang-Mills theory



Particle production in Heavy-Ion Collisions

Accelerators

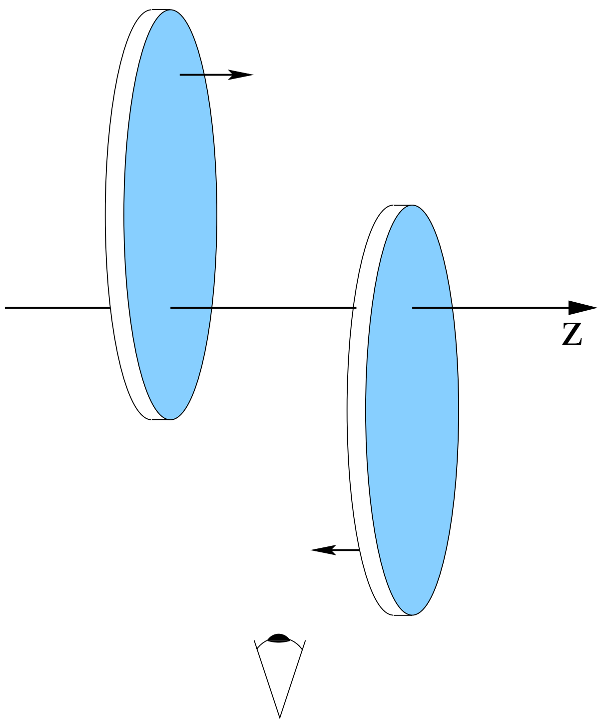
	SPS	RHIC	LHC
√s per nucl. pair (GeV)	17	200	5500
Volume at freeze-out (fm	1200	2300	5000
Energy density (GeV/fm	3-4	4-7	10
Lifetime (fm/c)	4	7	10

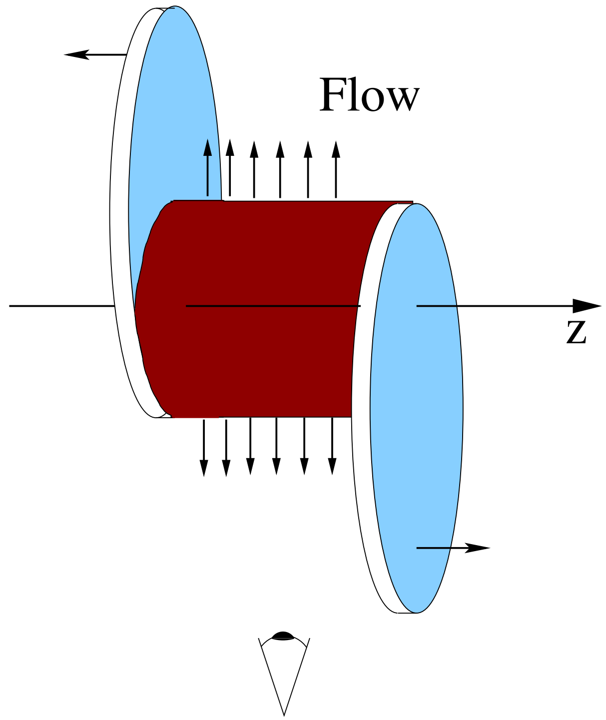
- For HIC, centre-of-mass energy per nucleon-nucleon pair is usually indicated $\sqrt{s_{NN}}$

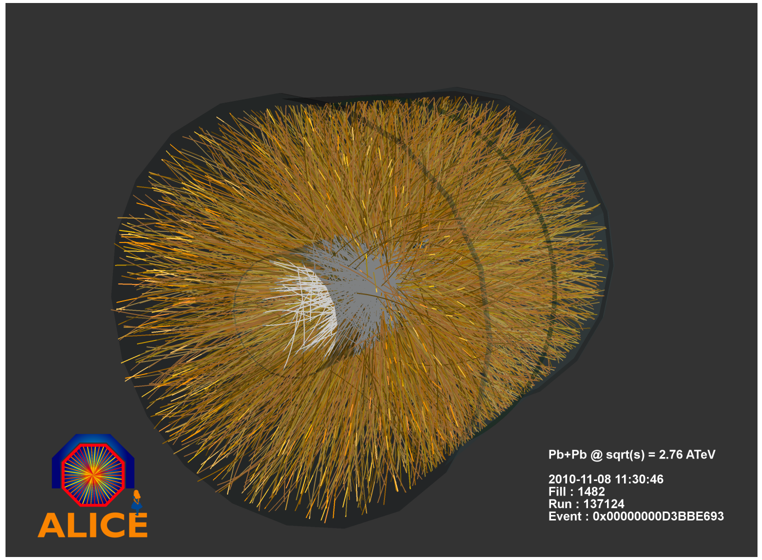
- Total collision energy

$$\sqrt{s} \approx (82 + 126) \times 5.5\mathrm{TeV} \approx 1144\mathrm{TeV}$$

Basic picture

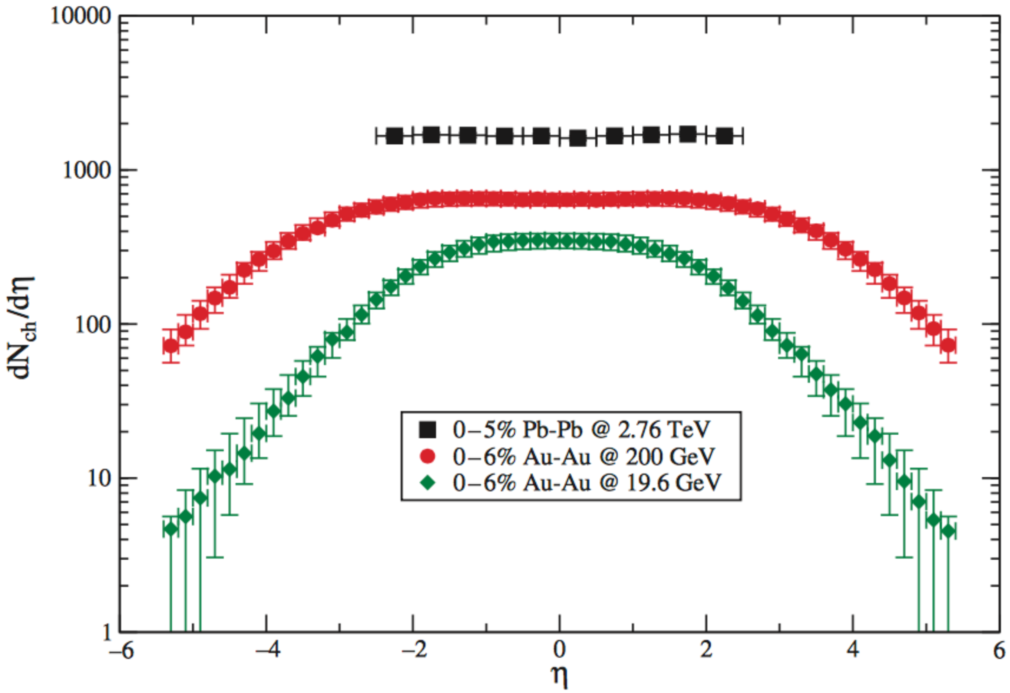


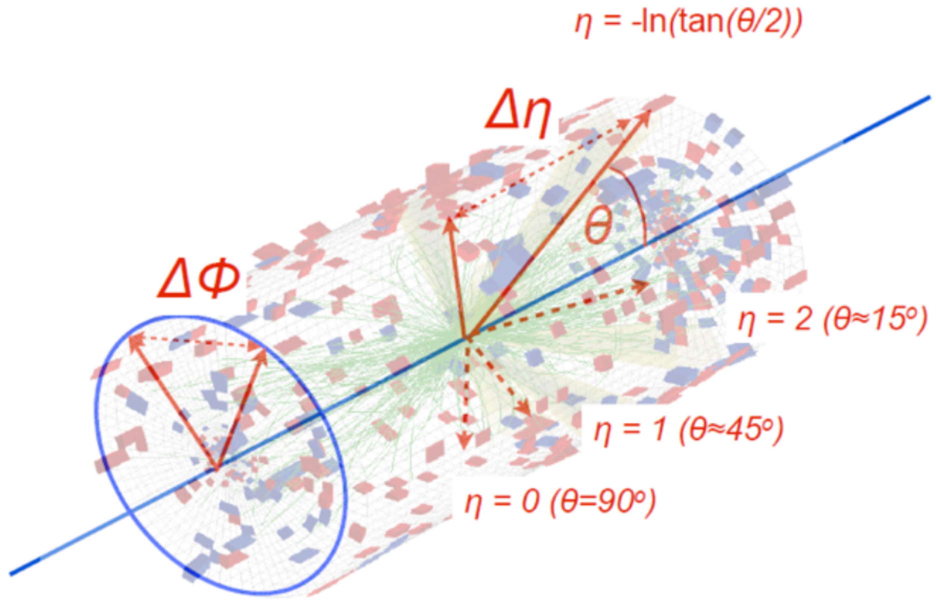




- Most particles and energy continue along beam pipe
- Those that undergo a large angle scattering form a medium and eventually reach detector
- Large Lorentz contraction of the nuclei indicate lack on longitudinal structure: Boost invariance in mid rapidity region

Multiplicities at midrapidity



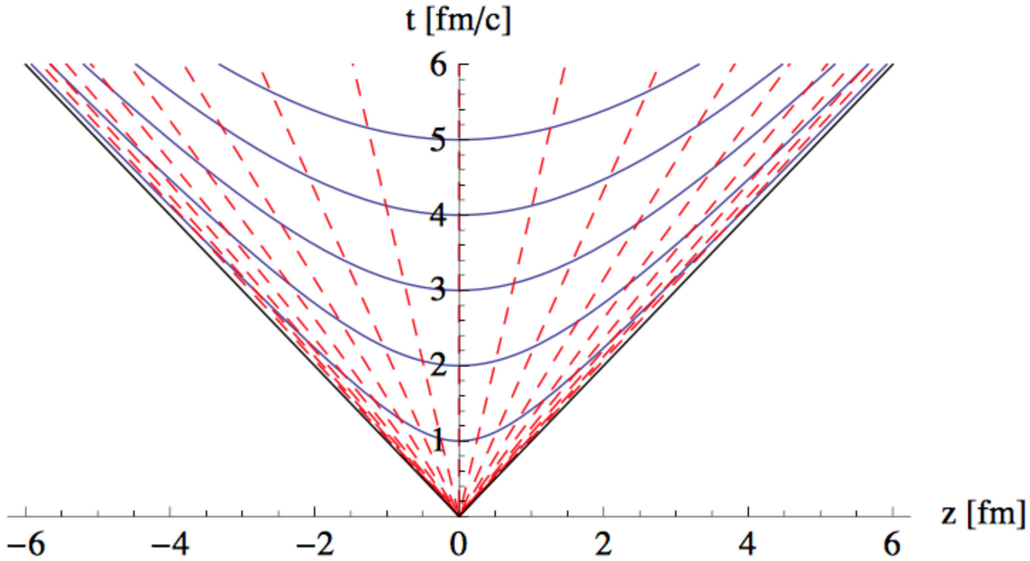


- Number of charged particles found in detector as a function of pseudorapidity eta. Approximately independent of eta
- Not all particles charged: $N_{tot} \approx 1.6 \times N_{ch}$
- Total charged:
    - RHIC: ~5000, LHC: ~25000

Bjoerken estimate

- The multiplicities give an handle on the energy density and temperature of the fireball
- Consider transverse slab at midrapidity
- Energy density per unit (pseudo)rapidity

$$\frac{dE_T}{dy} = \frac{dN}{dy}\langle E_T \rangle$$



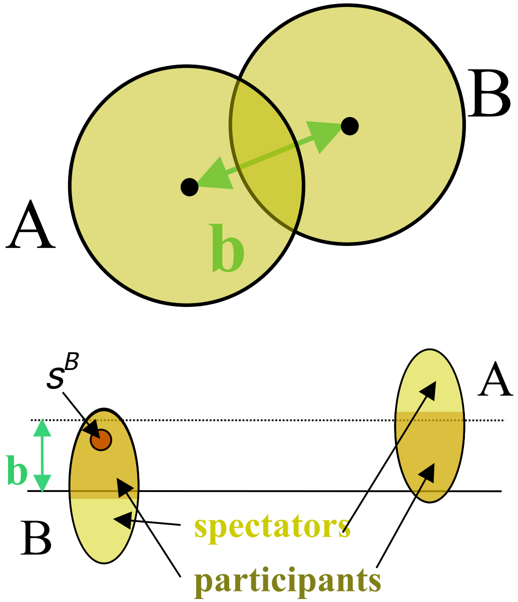
- At a proper time τ_0 this energy is concentrated in a volume

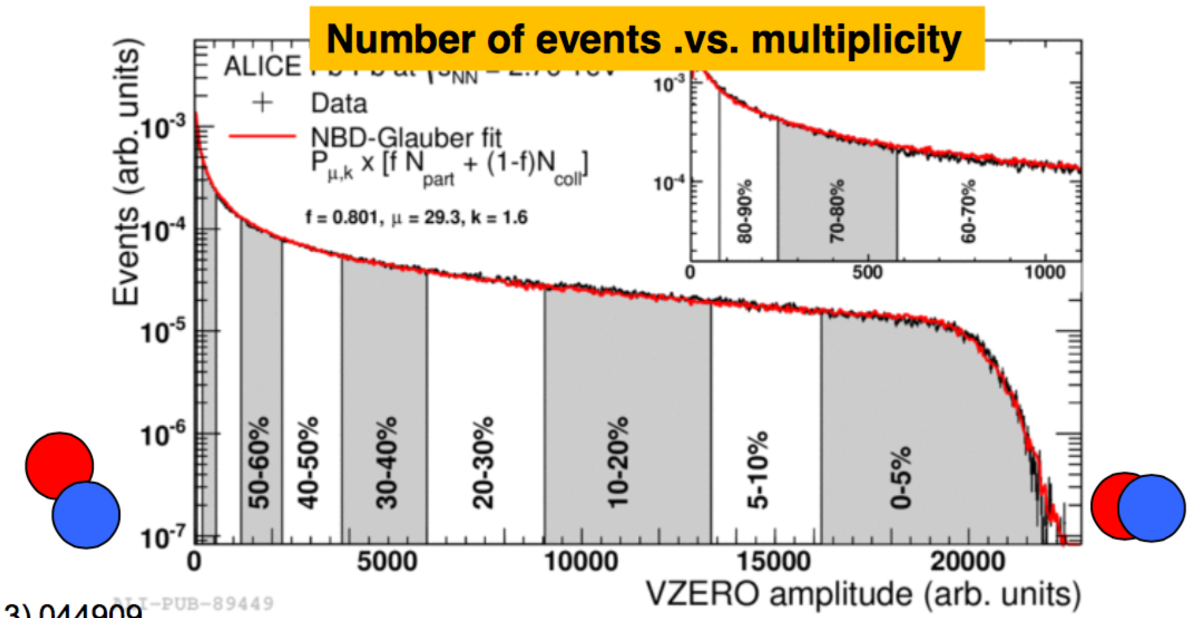
$$\pi R^2 dz = \pi R^2 d\eta \tau_0$$

- The energy density is then

$$\epsilon^{SPS}(\tau_0 = 1fm/c) \approx 3 - 4GeV/fm^3, \quad T \sim 3T_c$$

Collision geometry and impact parameter



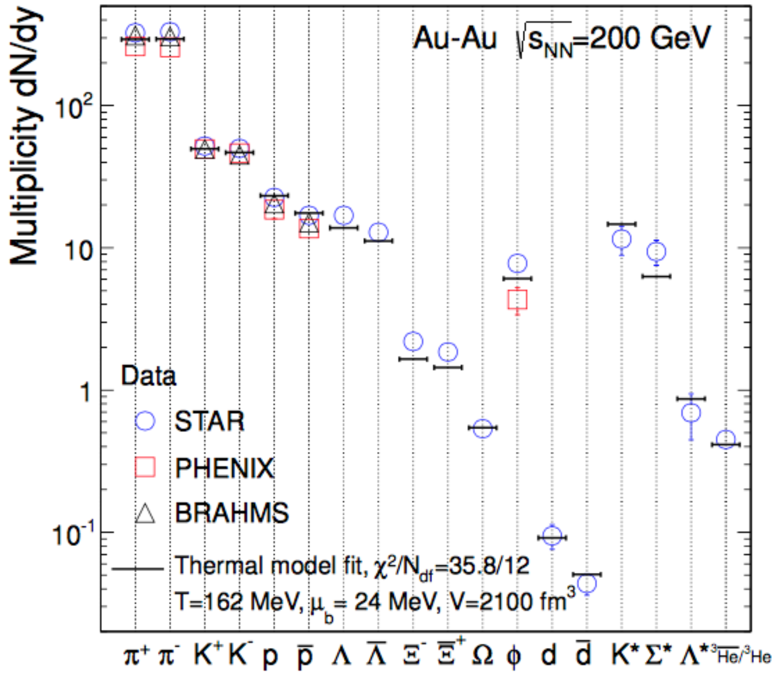


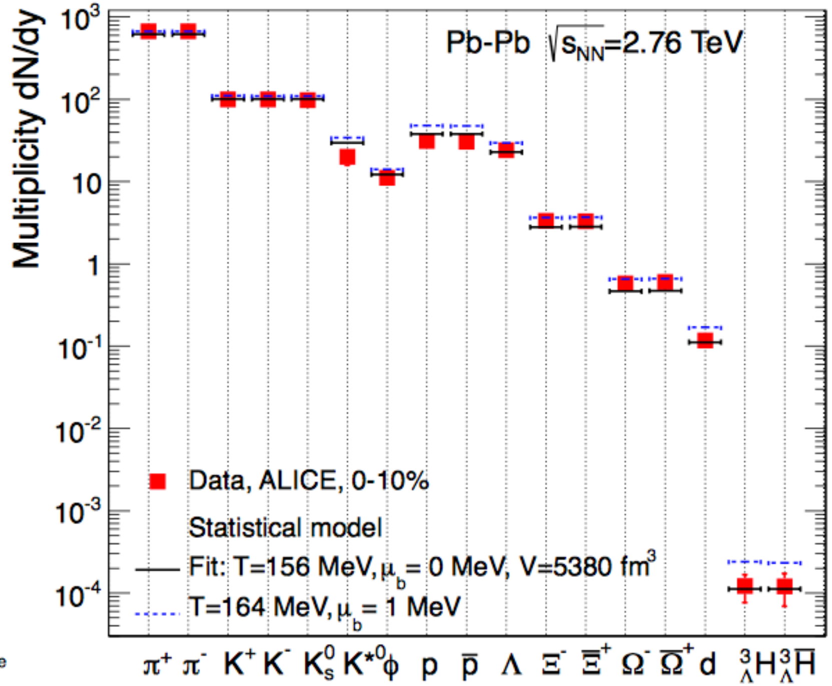
PRC88 (2013) 044909

- Centrality class: percentage of the minimum bias cross section
- Multiplicity distribution explained by collision geometry
  -> Impact parameter b ~ multiplicity

- For precise connection modelling necessary

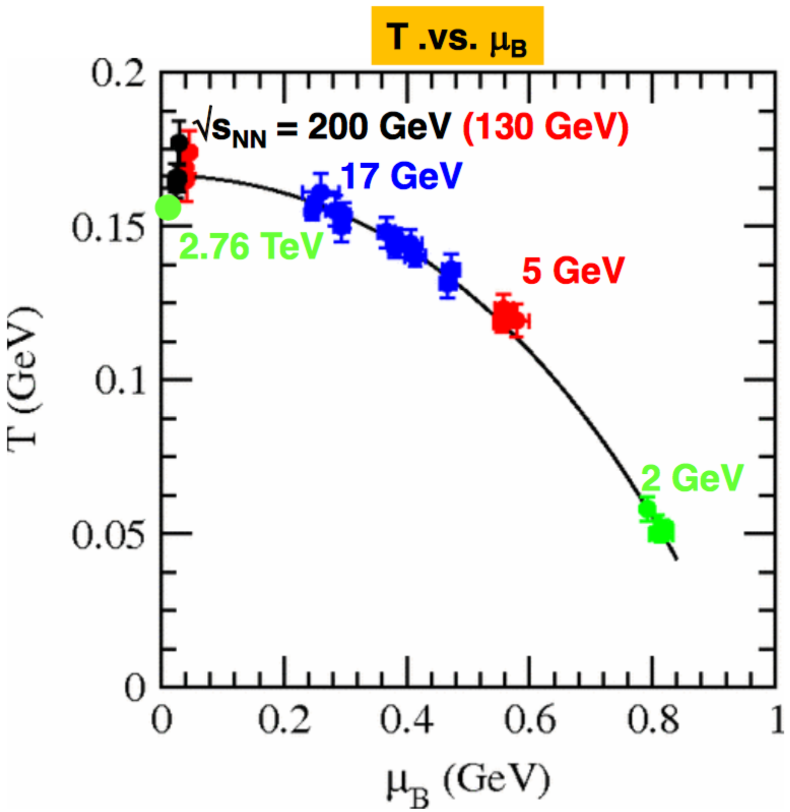
Freeze-out and identified particle multiplicities

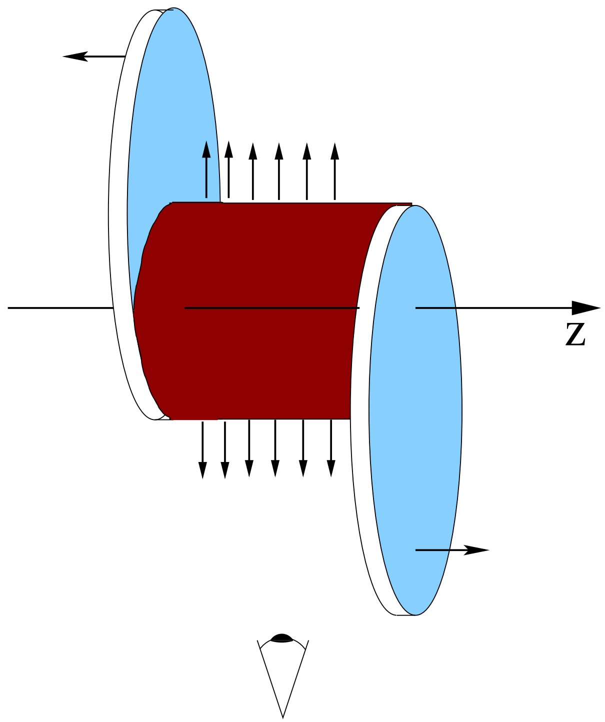




- Multiplicities of identified particles well described by statistical model:
    - Hadron gas in thermal and chemical equilibrium
    - Includes all hadronic resonances known to particle data group
    - Interpretation: 1) Matter close to local thermal eq.,
      2) cools and interactions fail to keep in thermal
      3) Multiplicities frozen to the moment of freeze-out (cf. CMB)
- Evidence of formation of thermalized plasma

Freeze-out and identified particle multiplicities

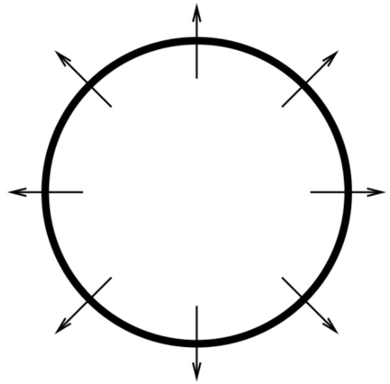




- Different beam energies correspond to different chemical potentials
- Increasing energy leads to reduced baryochemical potential
  - Transport of baryon number from nuclei to mid rapidity more and more difficult

Flow

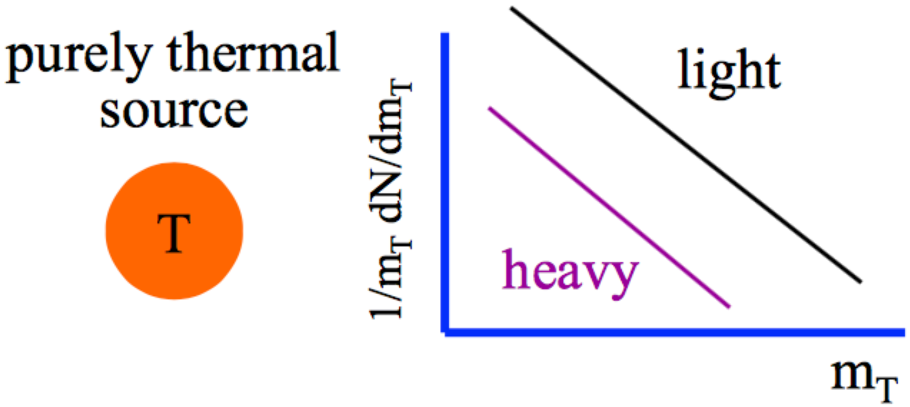
Radial flow:



- The explosion of the fire ball leads to *radial flow*
- Emission from thermal source, $\sim e^{-E/T}$

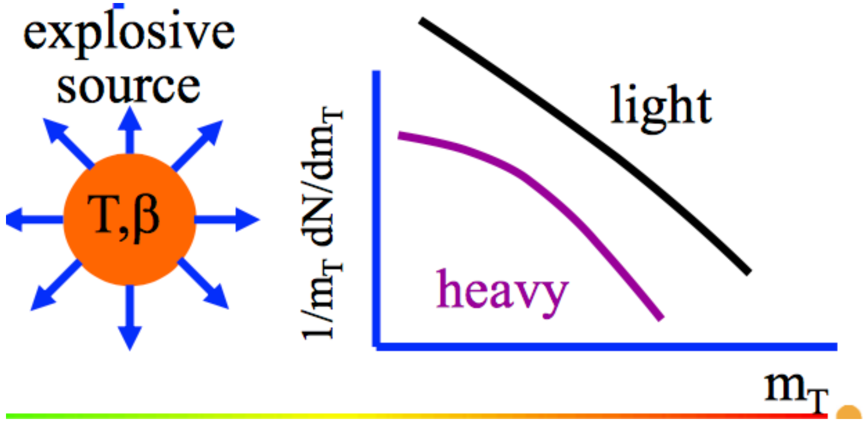
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = Cm_T K_1\left(\frac{m_T}{T}\right)$$

$$\approx C'\sqrt{m_T}\, e^{-m_T/T} \quad \text{für} \quad m_T >> T$$



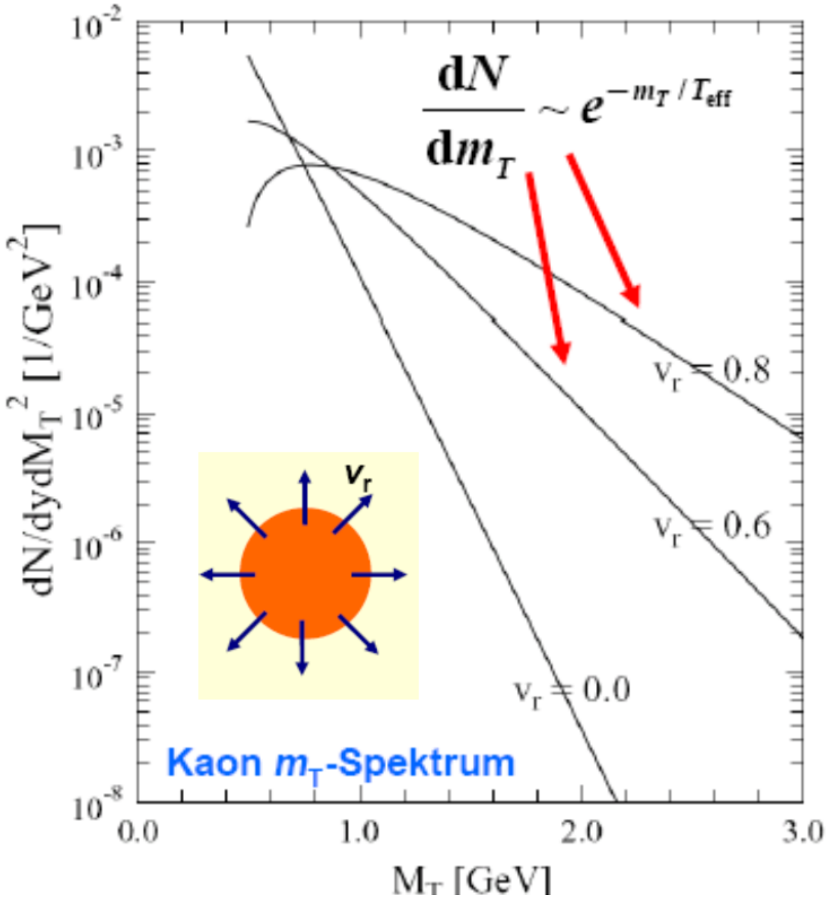
- Shape of the spectrum independent of masses

- Explosive source will blueshift the spectrum
  - Spectrum depends on mass
  - and on the expansion velocity



Radial flow:

- “Blast wave model”: Hydrodynamics inspired model with a symmetric average geometry
- The inverse slope determines the velocity



$$T_{eff} = T\sqrt{\frac{1+v_r}{1-v_r}}$$

Radial flow:

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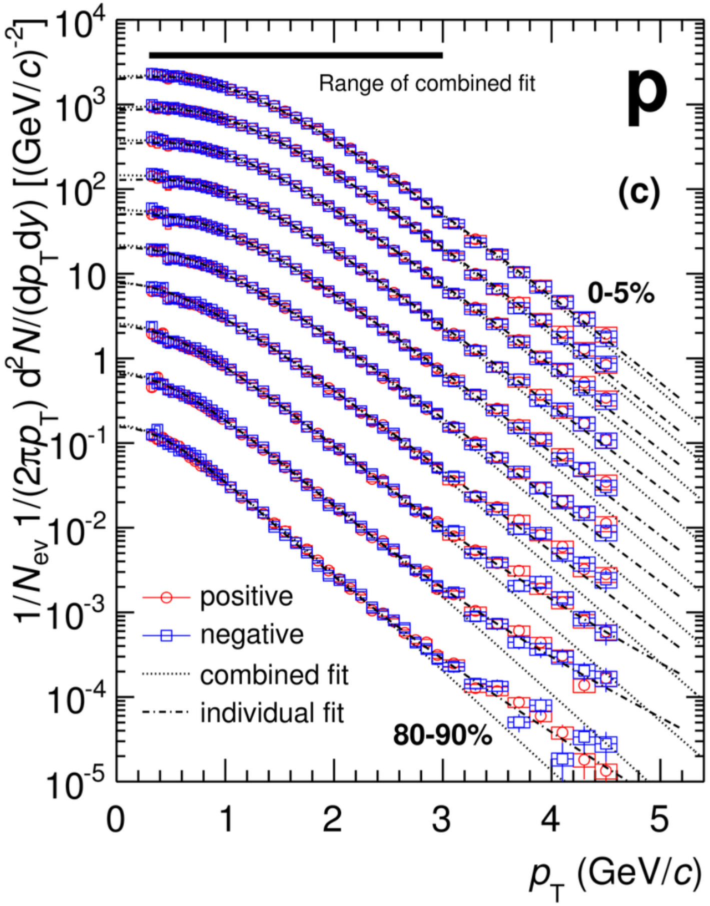
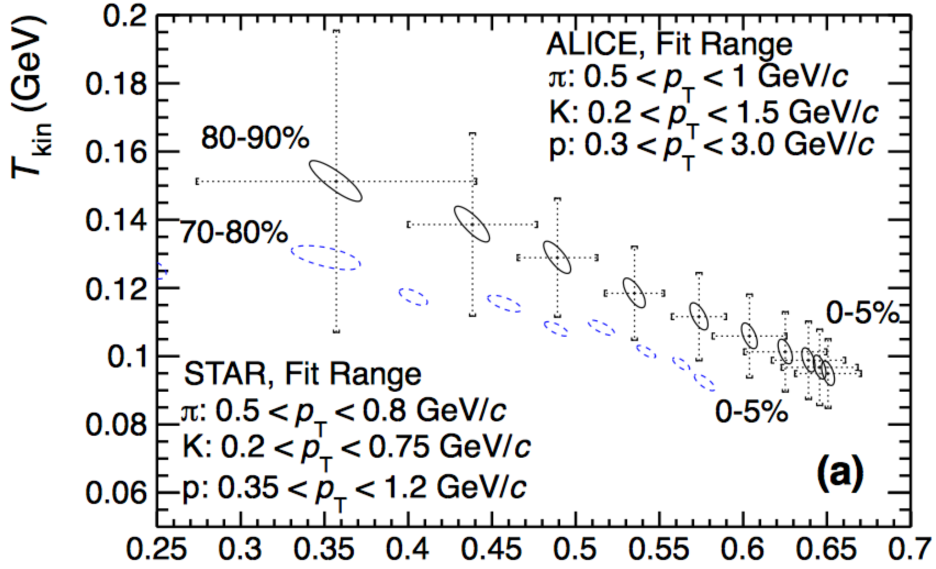


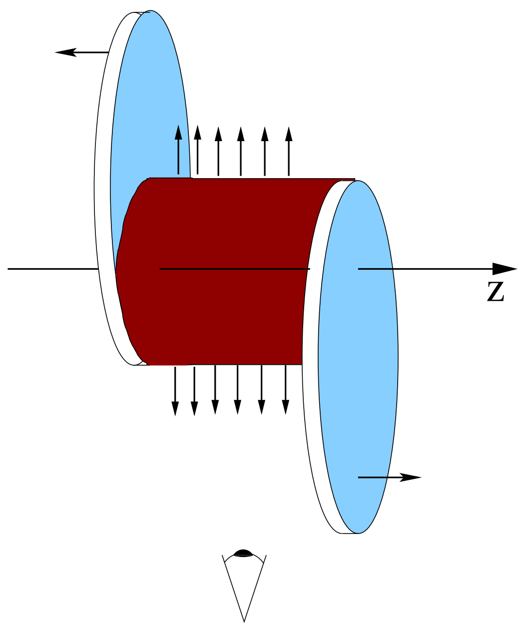


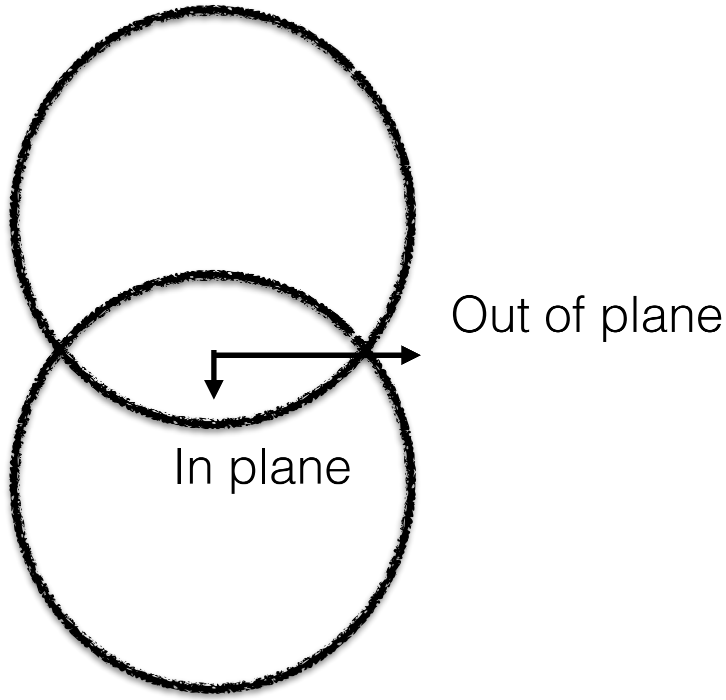
Expansion velocity $\langle \beta_T \rangle$

- The inverse slope determines the velocity

Elliptic flow:

- Nuclear overlap area anisotropic in non-central collisions:
  Symmetry direction defines *reaction plane*





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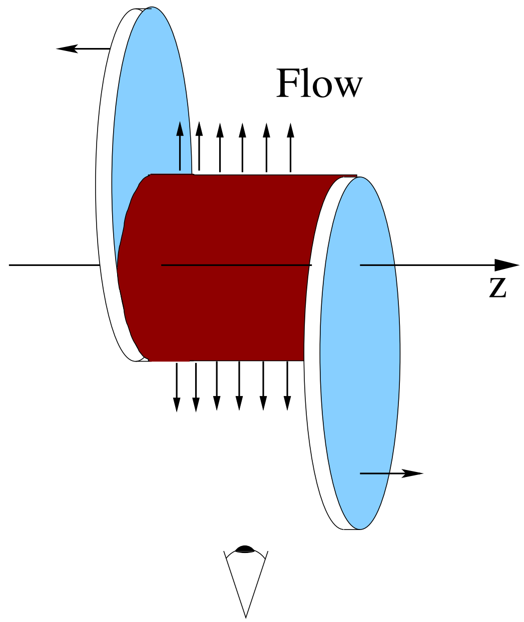
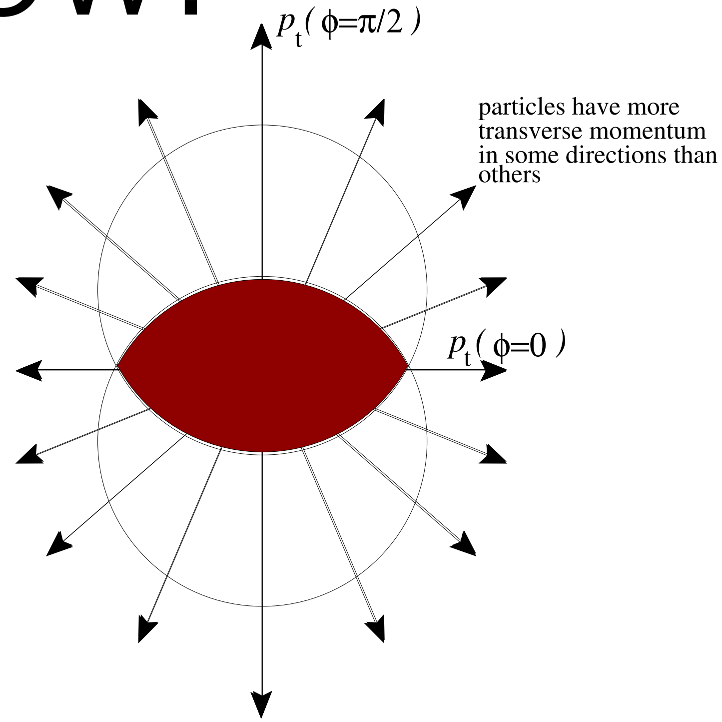
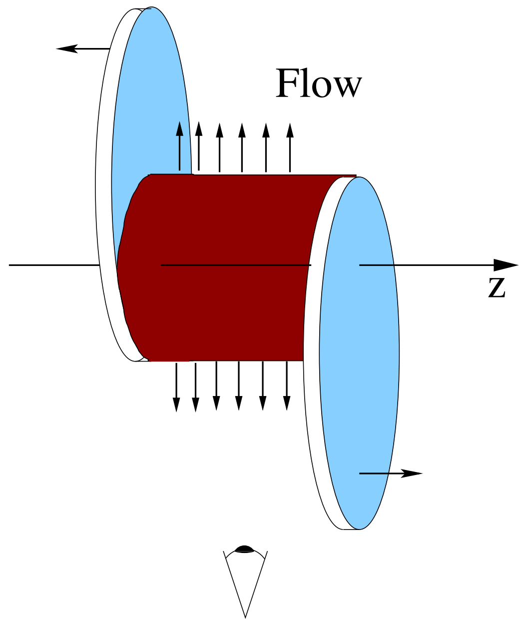
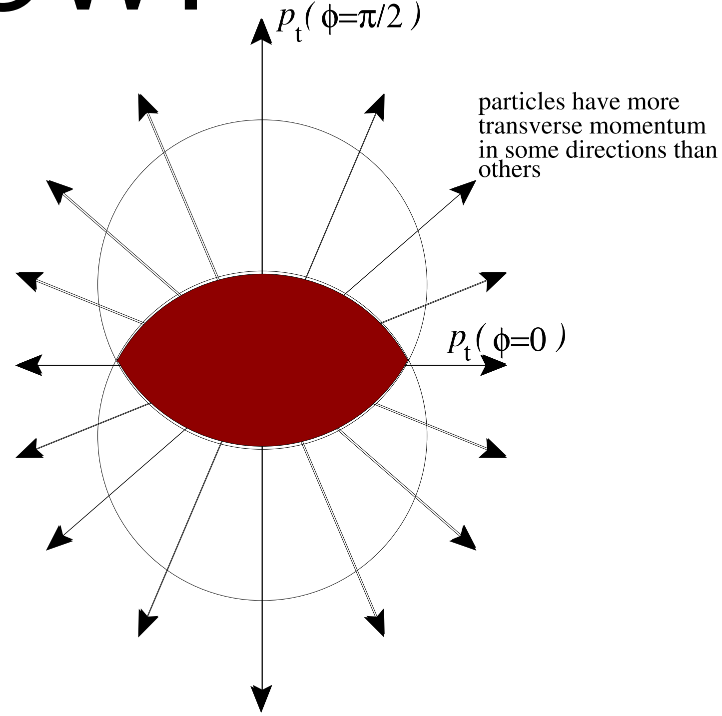




- Hydrodynamical flow converts spatial anisotropy to momentum anisotropy:
  - Pressure gradients larger in the reaction plane
  - Leads larger fluid velocity in this direction, more particles

Elliptic flow:



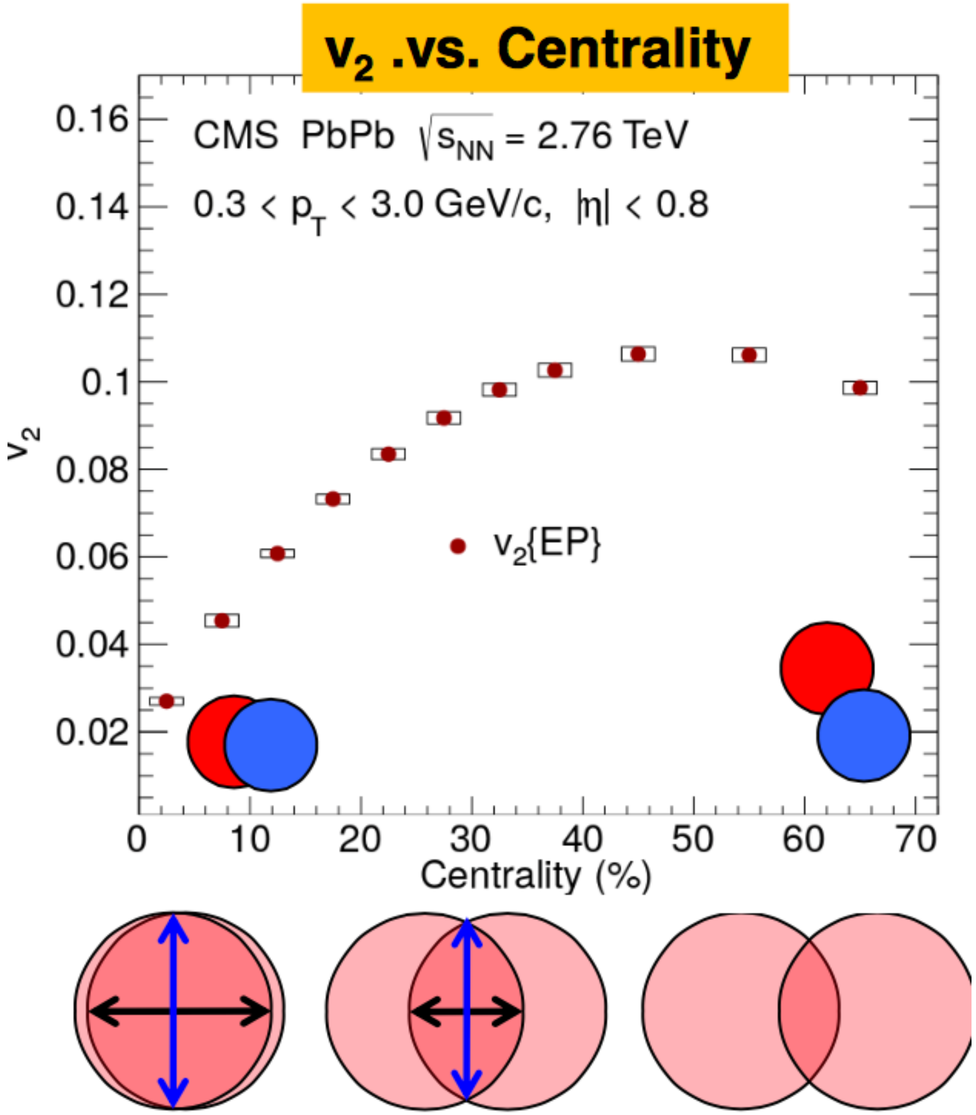


- Quantify anisotropy using Fourier expansion of the azimuthal coordinate:

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

Reaction plane

Elliptic flow



CMS, PRC 87(2013) 014902

- Strong centrality dependence, largest for 40-50%
- Very small spatial anisotropy in central collisions
- Large anisotropy in midcentral collisions
- Small overlap region in peripheral collisions

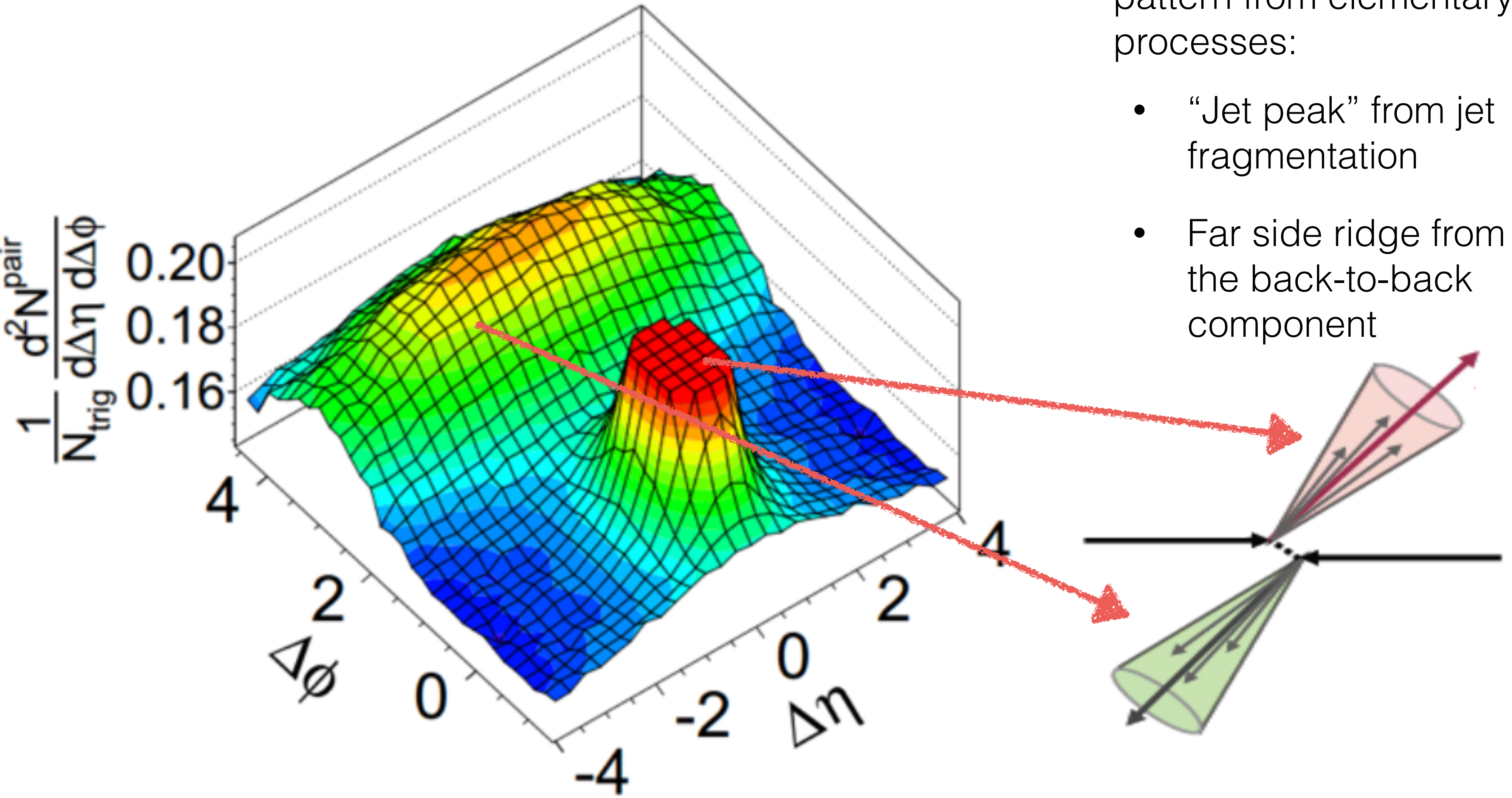
Elliptic flow

- Estimation of the reaction plane even-by-event difficult if multiplicities are small
- Another way to look at same data, pair correlations

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

Elliptic flow

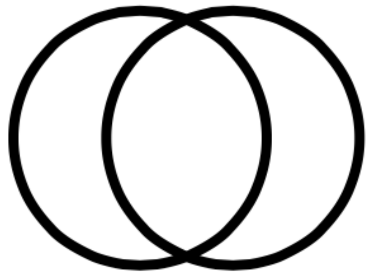
- Pair correlations in p-p:

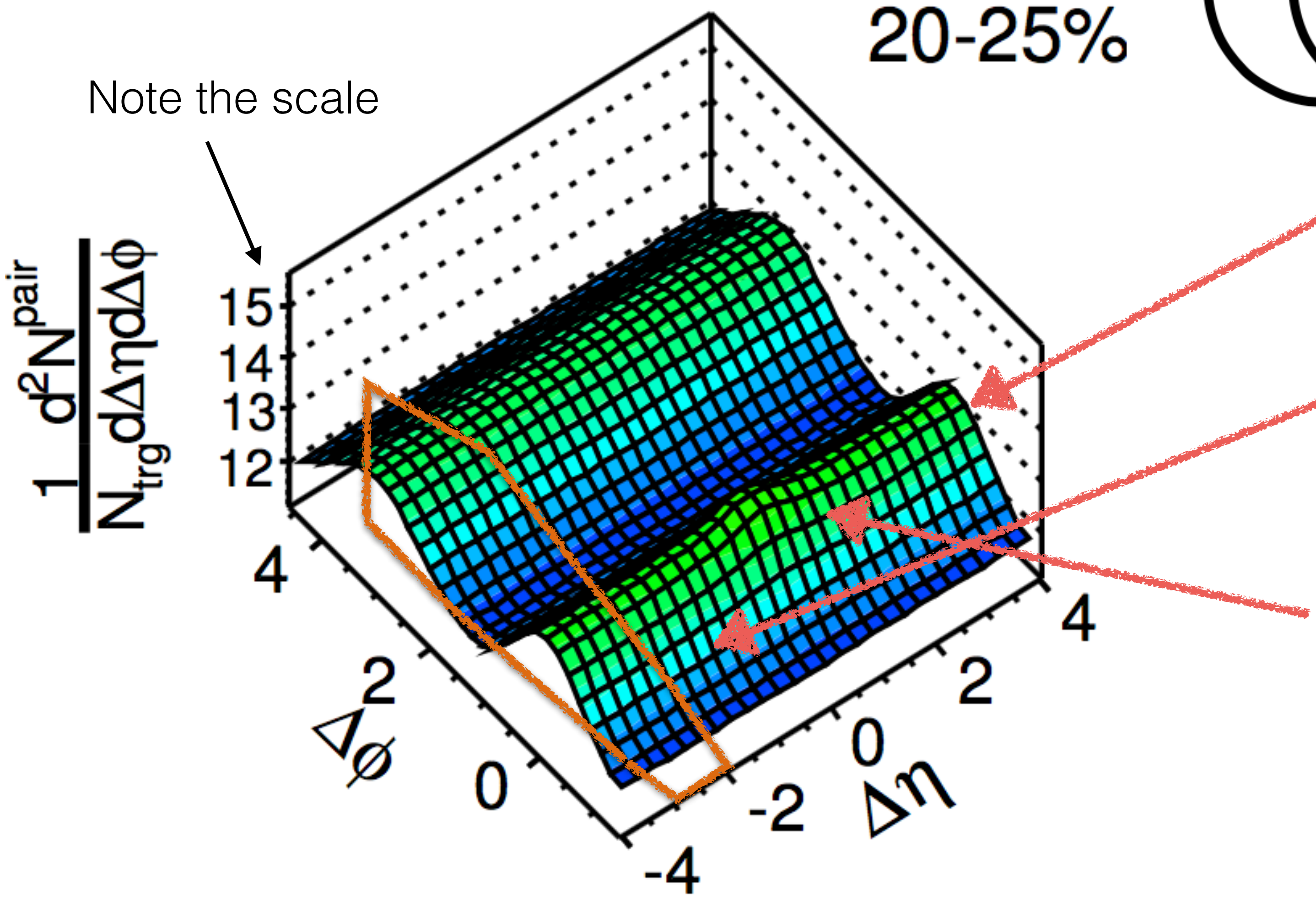


- Nontrivial correlation pattern from elementary processes:
  - "Jet peak" from jet fragmentation
  - Far side ridge from the back-to-back component

Elliptic flow v_2

- Pair correlations in Pb-Pb:



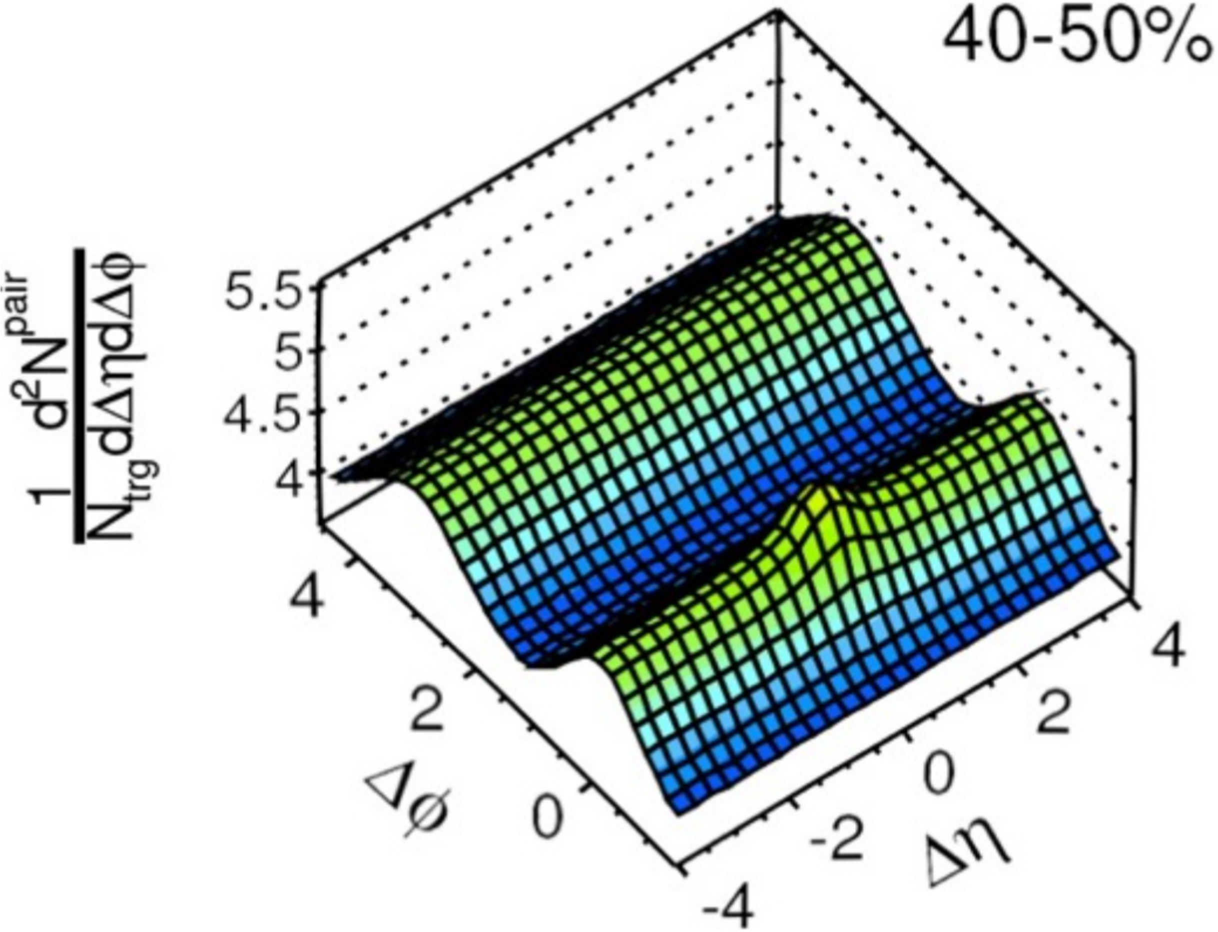


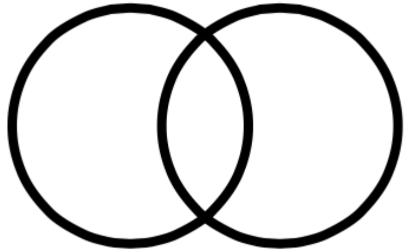
- Ridge: large rapidity correlation from boost invariance
- Azimuthal structure from flow, dominated by v_2
- Tiny remainder of a jet peak

CMS 1201.3158

Elliptic flow v_2

- Pair correlations in Pb-Pb:



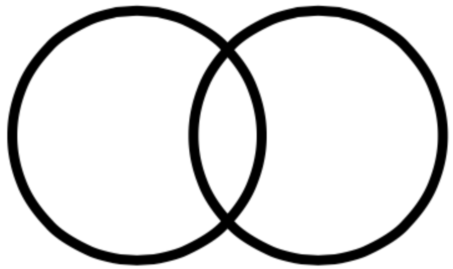


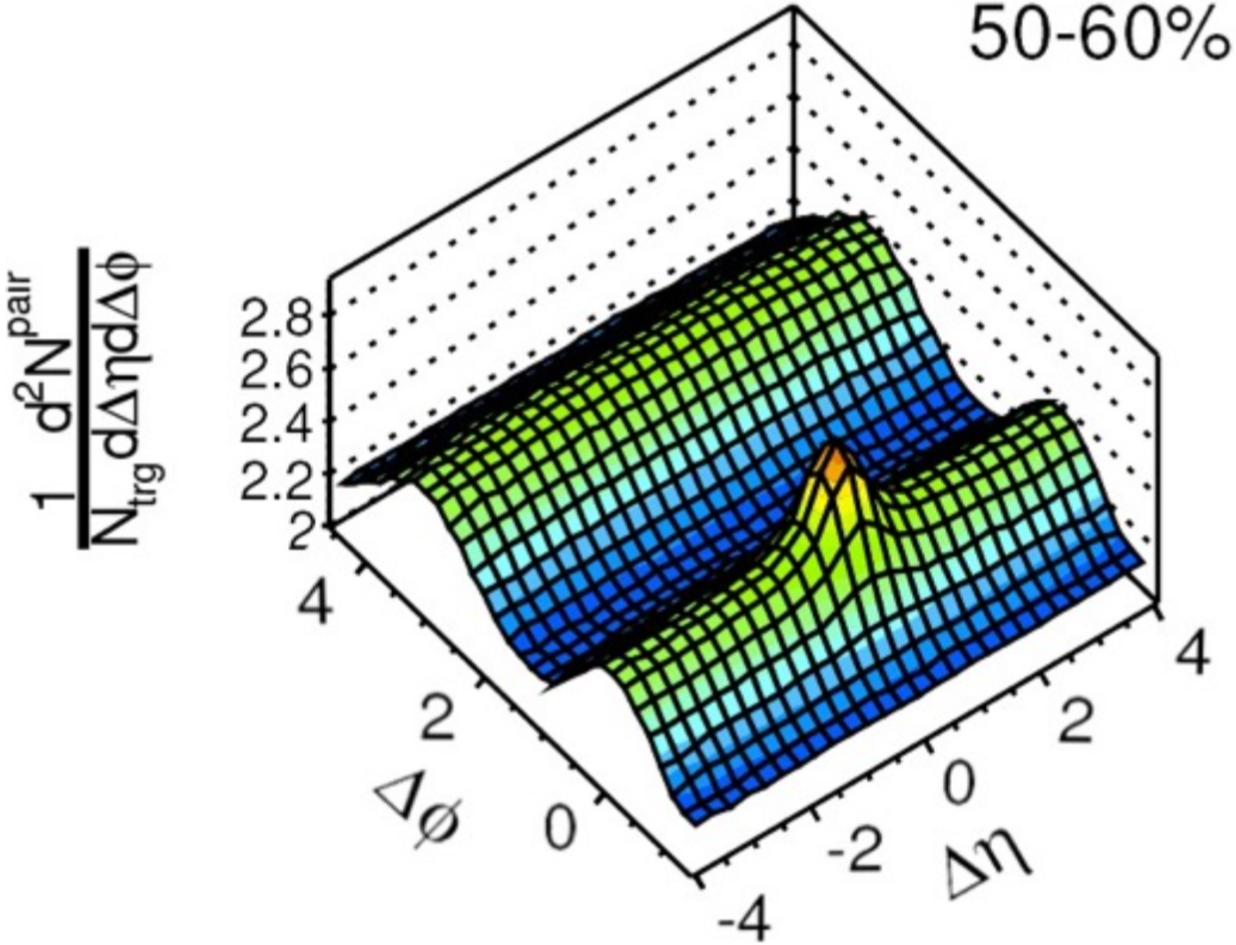
CMS 1201.3158

Elliptic flow v_2

- Pair correlations in Pb-Pb:

50-60%



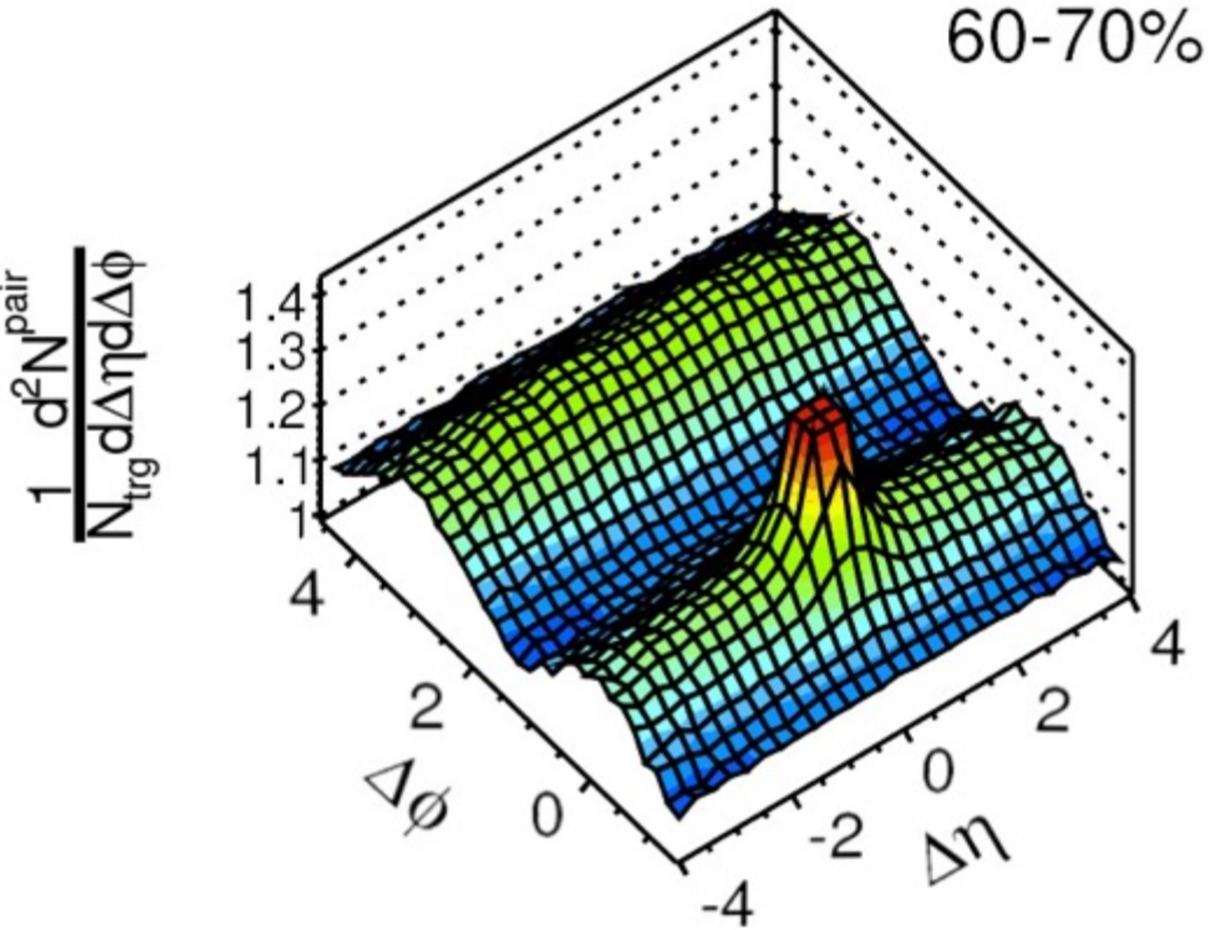


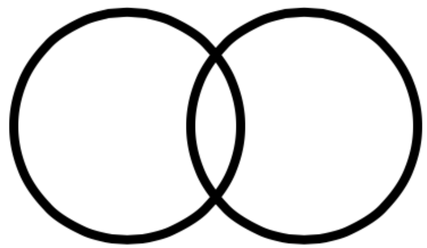
- Only the $\Delta\phi$ structure evolves as function of centrality

CMS 1201.3158

Elliptic flow v_2

- Pair correlations in Pb-Pb:



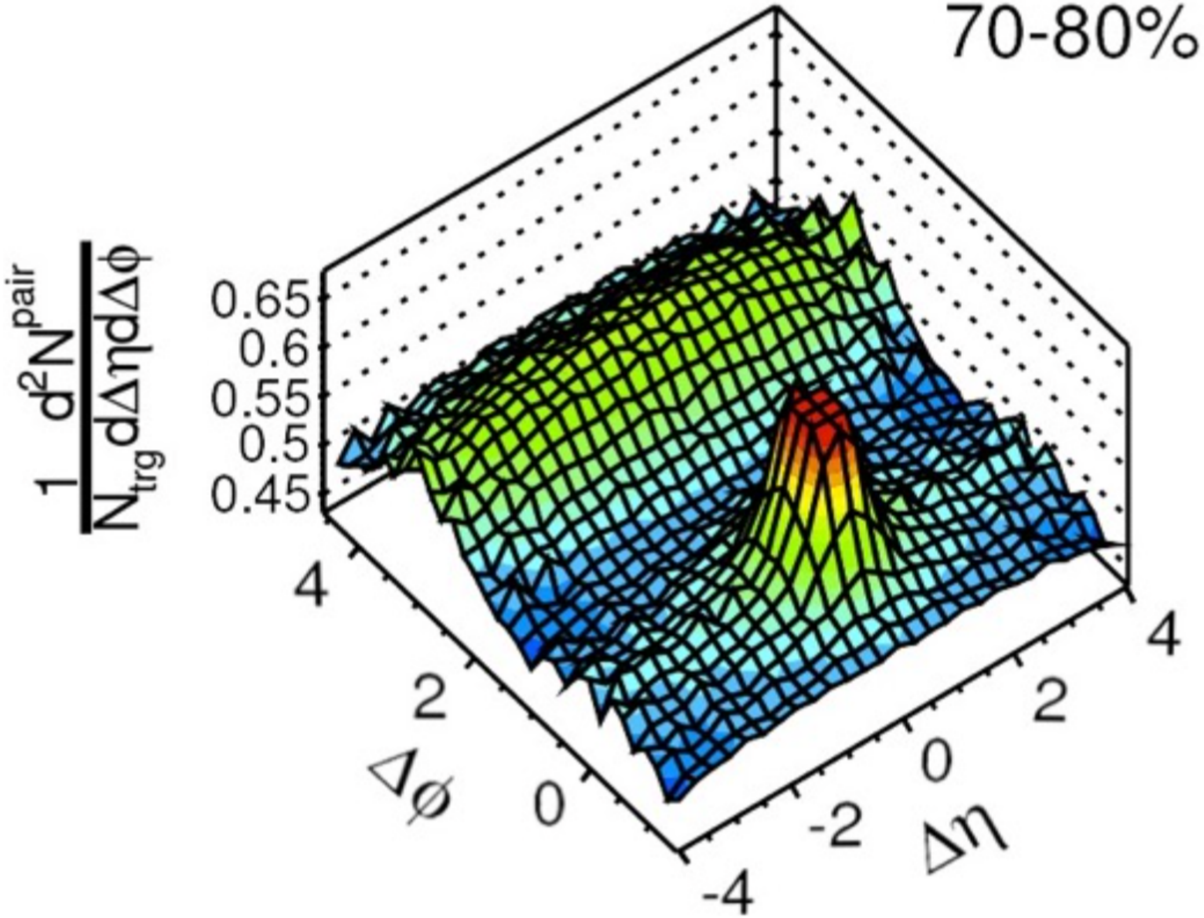


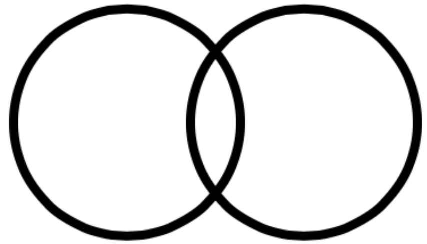
- Only the $\Delta\phi$ structure evolves as function of centrality

CMS 1201.3158

Elliptic flow v_2

- Pair correlations in Pb-Pb:



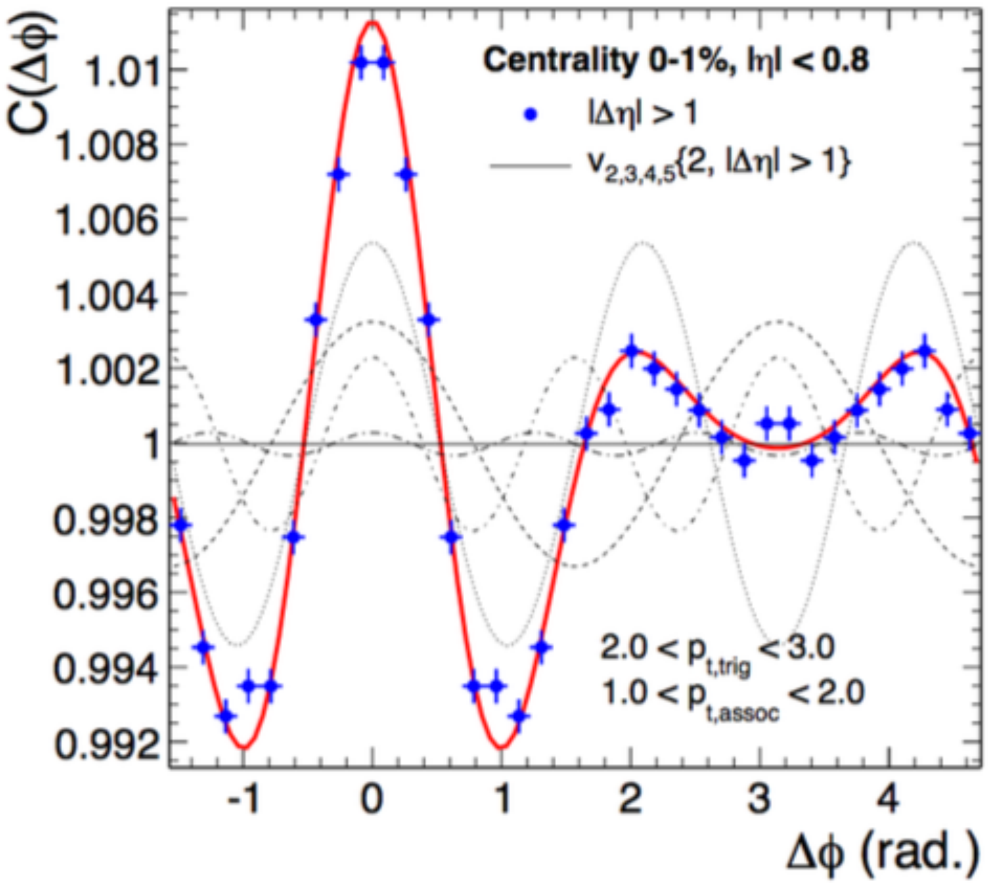


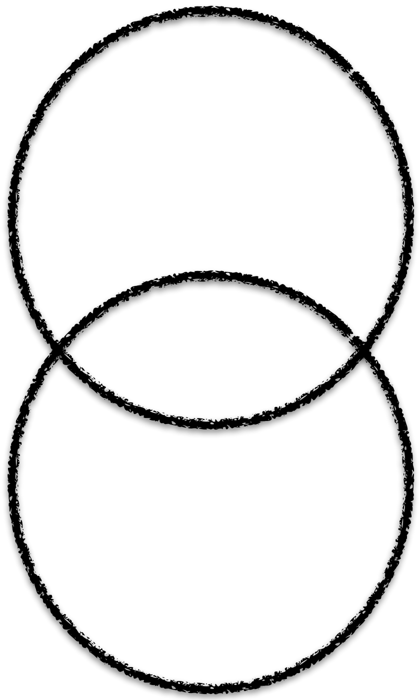
- Most peripheral collisions look like p-p collisions again with "near-side jet"

CMS 1201.3158

Triangular flow v_3

- Naively the geometry has a $\phi \to \phi + \pi$ symmetry
- Expect $v_3, v_5, \ldots$ to be zero





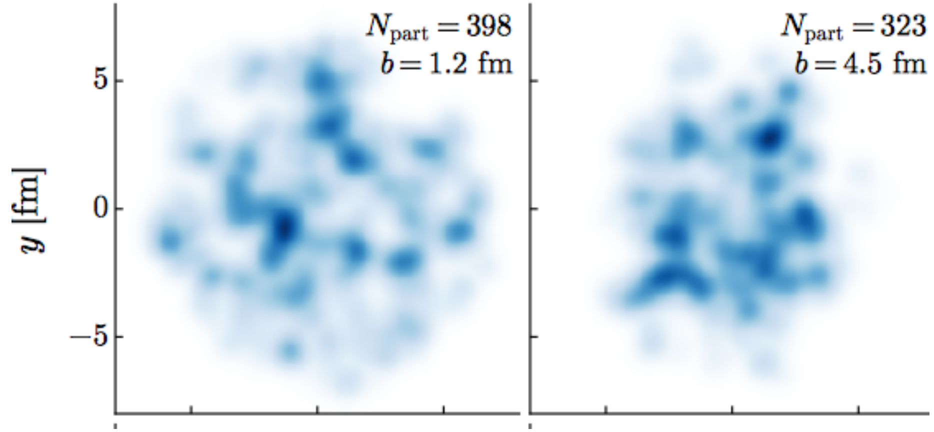
- All coefficients seem to be non-zero!

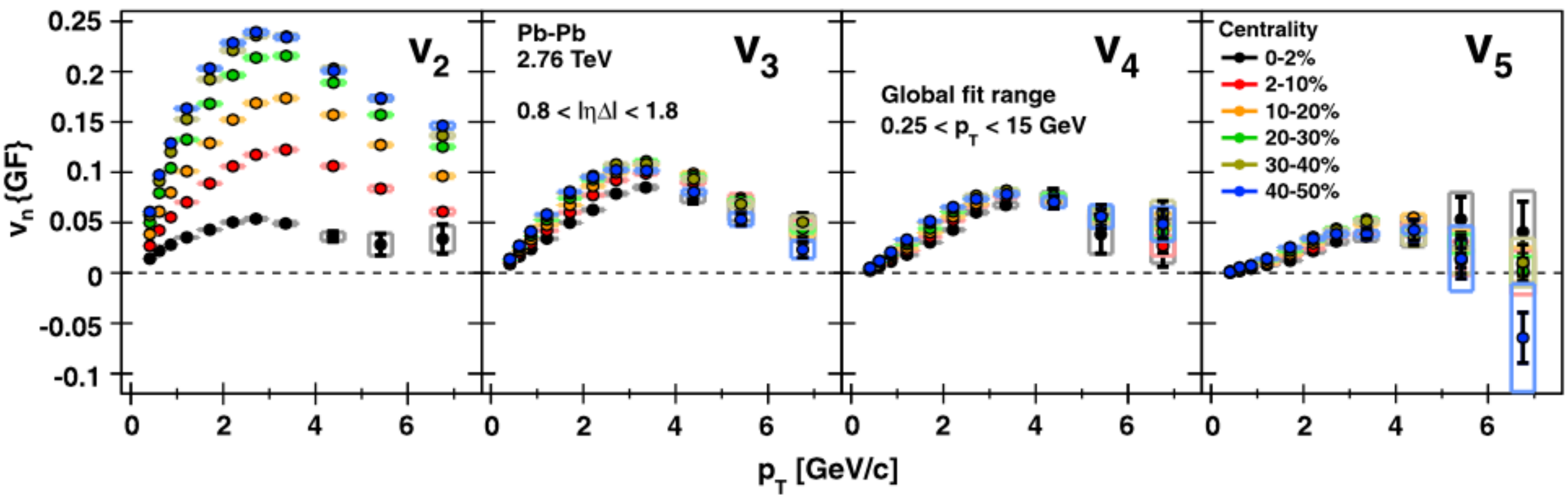
Triangular flow

- Nuclear geometry not smooth, event-by-event fluctuations of locations of nuclei

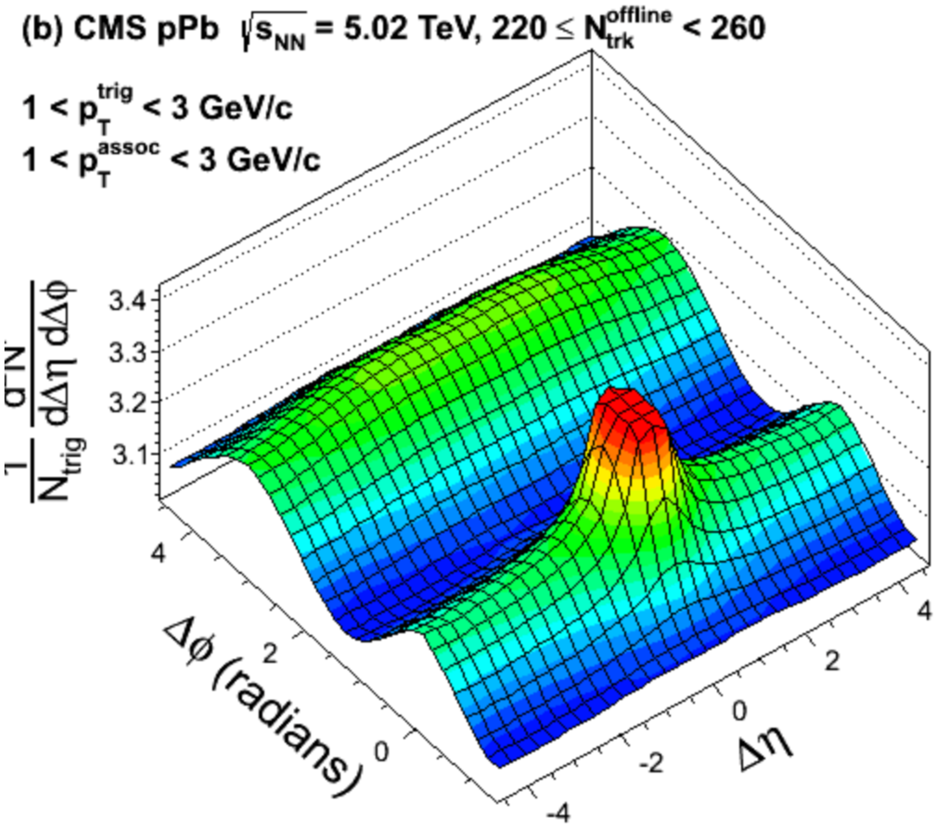
- Triangular flow driven by fluctuations

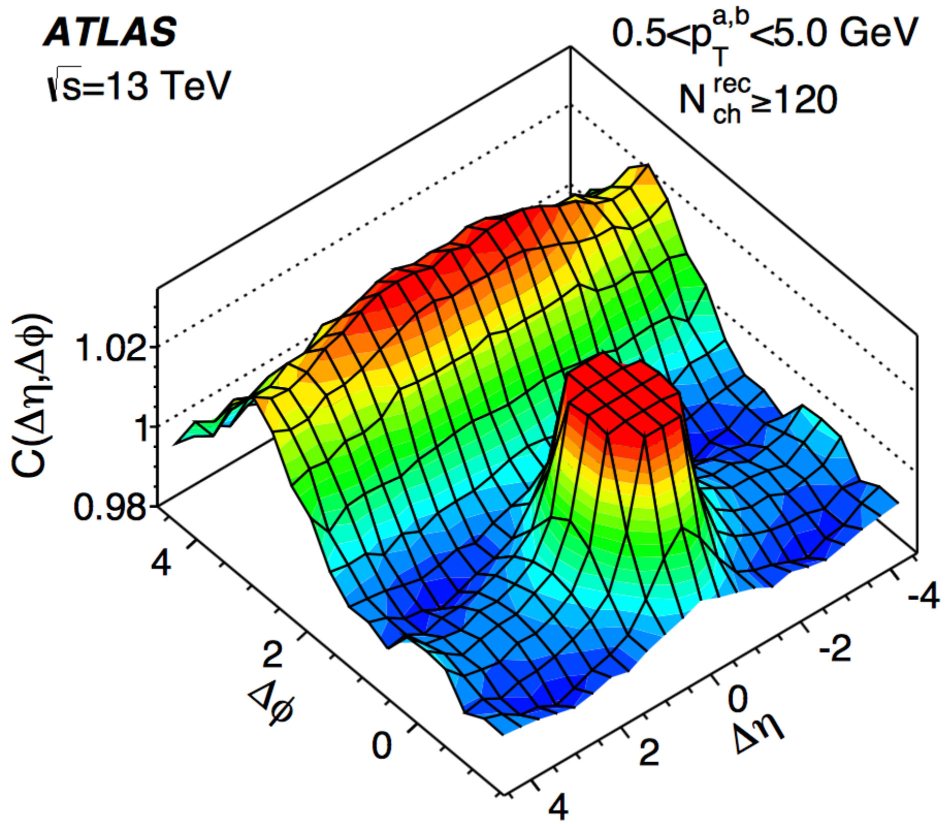
- Picture corroborated by insensitivity to centrality:





Flow in small systems





- Ridge-like pattern clearly visible in p-Pb collisions! A formation of a very small liquid?
- Ridge even present at very high multiplicity p-p collisions! What to make out of this? Flow in p-p? At most a very small correction…

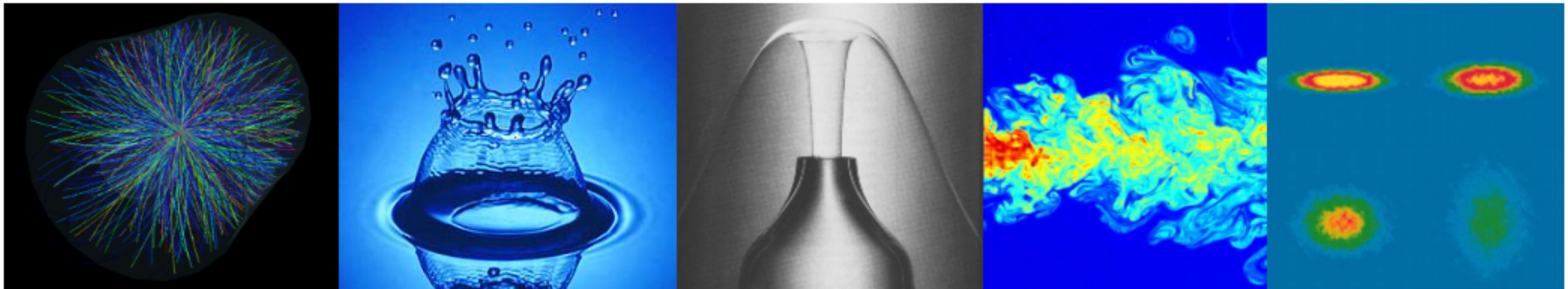
Fluid dynamics

Fluid dynamics

- Hydrodynamics is a low energy effective theory describing long distance, late time behaviour of averaged macroscopic features of the system
  - Applicable to a very generic set of theories
  - Assumes that matter is close to local thermal equilibrium
  - Microscopic details of the theory are encapsulated by the inputs of hydrodynamics:
    - EoS, shear viscosity η, bulk viscosity ζ, …

Microscopic theory → Hydrodynamics → Thermodynamics

Local equilibration   Global equilibration



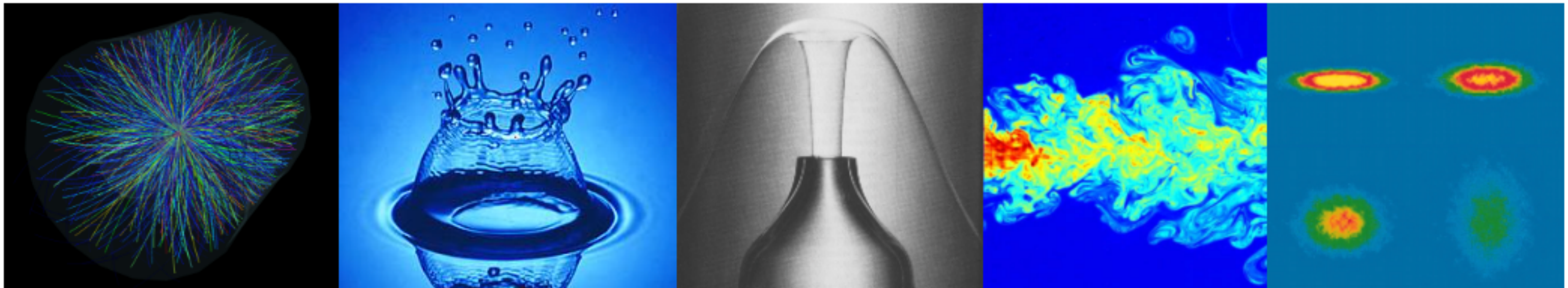
Fluid dynamics

- Requirement: no explicit or spontaneous breaking of Lorentz symmetry
  - Distances larger than mean free path, times larger than scattering rate:

$$\Delta x \gg l_{mfp}, \Delta t \gg \tau_{sc}$$

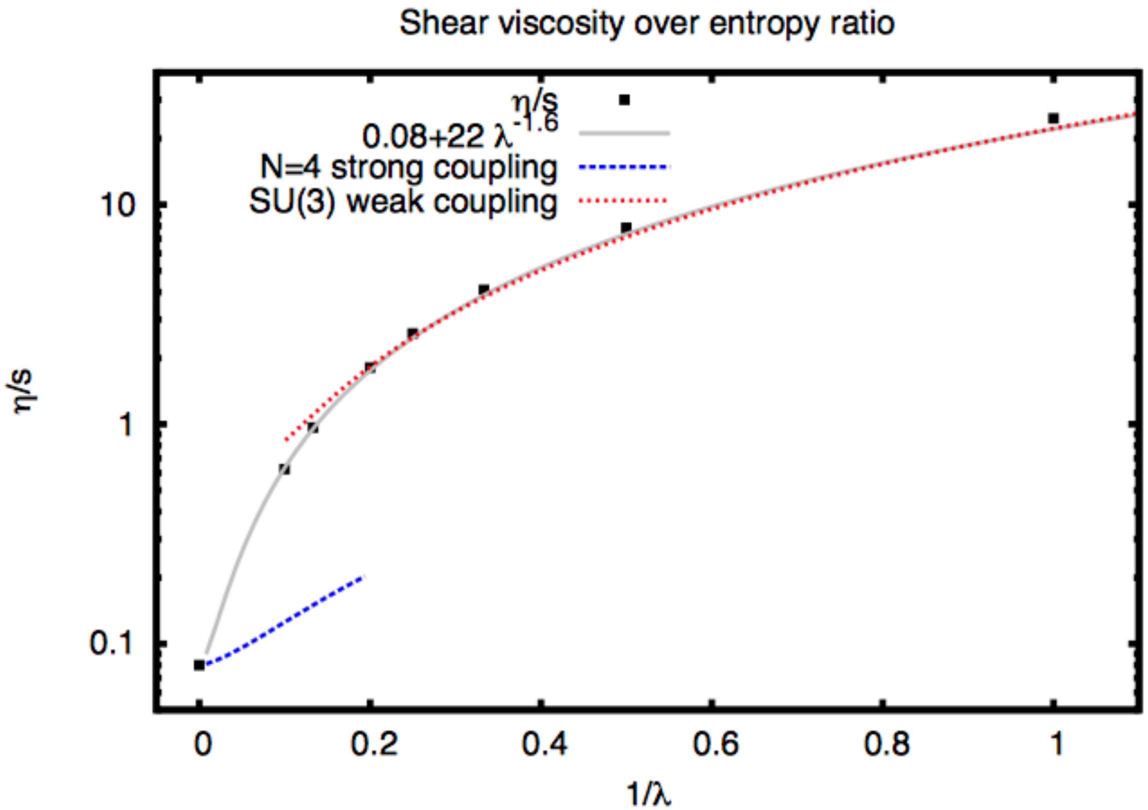
  - Systems with sufficiently smooth variation

$$\partial_i \epsilon \ll l_{mfp}^{-1} \epsilon$$



Fluid dynamics

- Strategy in heavy ion collisions:
  - Determine the material properties of QGP by varying the material properties and matching to data
  - Compare the deduced material properties with approximate analytical calculations



BRSSS 0902.3663

Fluid dynamics

- Consider matter in global thermal equilibrium, described by an energy momentum tensor

$$T^{\mu\nu}$$

- What can the energy momentum tensor look like?
- Energy momentum tensor rank-2 tensor. Must be constructed from available rank-2 tensors and vectors
- Available structures are

$g^{\mu\nu}$ metric

u^{μ} flow velocity, defining rest frame of the fluid

- The coefficients of the operators from comparing with thermodynamics

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

- In thermal equilibrium energy density and pressure related through the equation of state (available from lattice!)

Fluid dynamics

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

fluid flow velocity

- Now, introduce a small deviation from equilibrium, such that the energy density and the flow velocities are smooth functions of the coordinate

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

- If the gradients are smooth enough, the system still stays in *local thermal equilibrium.*

- Then, independent of the microphysics, the evolution of energy momentum tensor is dictated by energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0 \longrightarrow \begin{aligned} u^\mu \partial_\mu \epsilon + (\epsilon + p) \nabla_\mu u^\mu &= 0, \\ (\epsilon + p) u^\mu \nabla_\mu u^\nu + (g^{\nu\mu} + u^\nu u^\mu)\, \partial_\mu p &= 0. \end{aligned}$$

Ideal hydrodynamics!

Fluid dynamics

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

- In the nonerativistic limit $u^\mu \approx (1, 0, 0, v)$, $\epsilon \approx \rho$ mass density

$$u^\mu \partial_\mu \approx \partial_t + \vec{v}\cdot\vec{\partial} + \mathcal{O}(|\vec{v}|^2) \qquad (g^{i\nu} + u^i u^\nu)\partial_\nu \approx \partial^i + \mathcal{O}(|\vec{v}|)$$

Euler equations:

$$\partial_t \vec{v} + \left(\vec{v}\cdot\vec{\partial}\right)\vec{v} \;=\; -\frac{1}{\rho}\vec{\partial}p\,,$$
$$\partial_t \rho + \rho\,\vec{\partial}\cdot\vec{v} + \vec{v}\cdot\vec{\partial}\rho \;=\; 0\ .$$

Fluid dynamics

- Perturb the system now with larger gradients. Energy momentum tensor receives corrections to the thermal form $\Delta^{\mu\nu} = (g^{\mu\nu} + u^\mu u^\nu)$

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + p\Delta^{\mu\nu} + \Pi^{\mu\nu}$$

"viscous" stress tensor

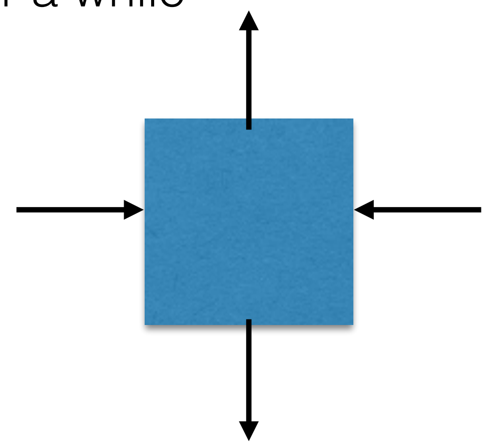
- Customary to decompose to traceless and remainder

$$\Pi^{\mu\nu} = \pi^{\mu\nu} + \Delta^{\mu\nu}\Pi$$

"Shear stress" "Bulk viscous pressure"

- Bulk viscous pressure: Perform rapid compression to fluid, for a while pressure below thermodynamical pressure

- Shear stress: Anisotropic pressure caused be flow



Fluid dynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + p\Delta^{\mu\nu} + \Pi^{\mu\nu}$$

$$\Pi^{\mu\nu} = \pi^{\mu\nu} + \Delta^{\mu\nu}\Pi$$

- Viscous stress tensor must be also constructed from $g^{\mu\nu}, u^\mu$ and from additional gradient vector ∂_μ
- Hydrodynamical gradient expansion: grade terms in powers of ∂_μ
  Constitutive equations:
  - No derivatives: Ideal hydro, $\Pi^{\mu\nu} = 0$
  - One derivative: "viscous hydro"

$$\Pi = -\zeta \nabla_\mu u^\mu + \ldots,$$

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

Bulk viscosity   Shear viscosity   = 1st order transport coefficients

- Two derivatives: "2nd order hydro", $\tau_\pi, \lambda_1, \lambda_2, \lambda_3, \ldots$

Fluid dynamics

- Transport coefficients properties of equilibrium system and can in principle be obtained from microscopic theory.

$$G^R_{xy,xy}(\omega,0) \equiv \int dt\, dx\, e^{i\omega t}\, \Theta(t) \left\langle \left[T_{xy}(t,x), T_{xy}(0,0) \right] \right\rangle_{eq}$$

$$\eta \equiv -\lim_{\omega \to 0} \frac{1}{\omega} \mathrm{Im} G^R_{xy,xy}(\omega,0)$$

- Correlation function required at non-zero frequency (corresponding to time-like separation of the operators). No reliable lattice calculation available.

- Has been calculated in
  - perturbative QCD using effective kinetic theory methods (more in this later)

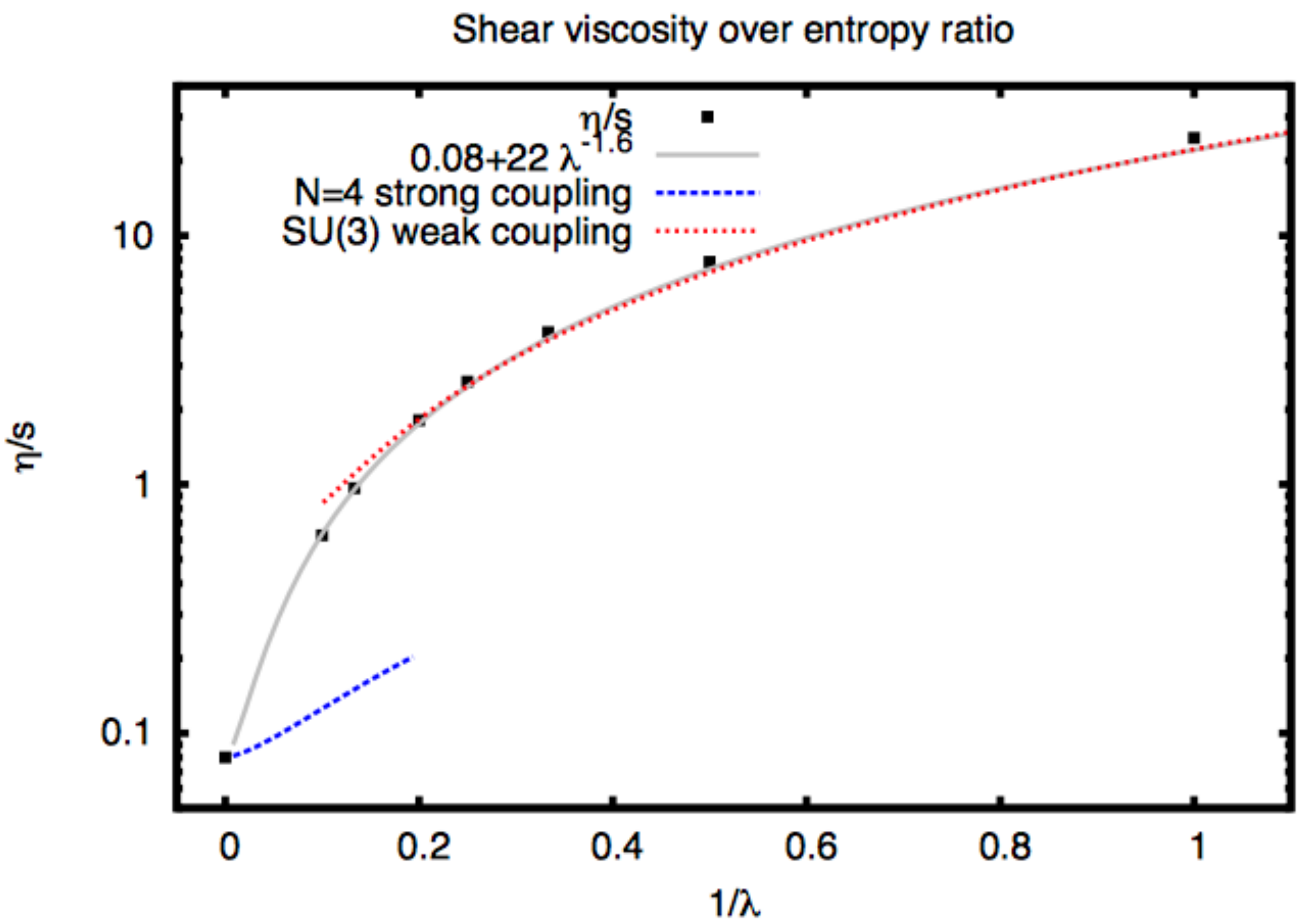
$$\frac{\eta}{s} = \frac{34.784}{\lambda^2 \log(4.789/\sqrt{\lambda})} \qquad \lambda = g^2 N_c$$

  - In N=4 Super-Yang Mills theory at the limit of large N_c and large 't Hooft coupling $\lambda = g^2 N_c$

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

- Bulk viscosity vanishes for both theories

Fluid dynamics

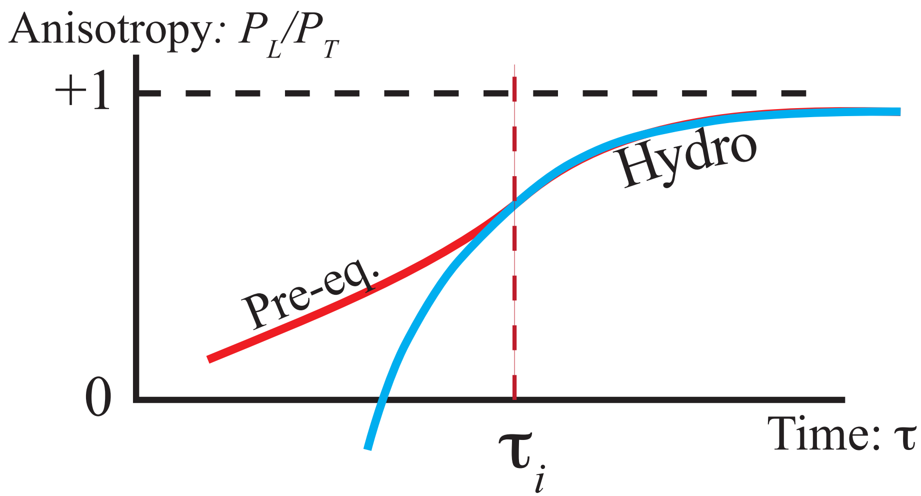


Viscosity as a measure of the interaction strength of the plasma

Fluid dynamics

- Hydrodynamical equations can be solved at some given initial conditions
  - Viscous hydro in fact acausal, need a “resummation” Israel-Stuart theory

- The collision geometry is such that the gradients diverge at early times, and corrections to ideal hydro become large
- The hydrodynamical simulation then has to be initialized at a time τ_i, when the system is sufficiently close to local thermal equilibrium
- It is not completely understood what the correct initial conditions are for heavy ion collisions, they affect any determination of transport coefficients



Bjoerken boost invariance

- Bjoerken's guess:

$$v_z(t,x,y,z) = z/t$$

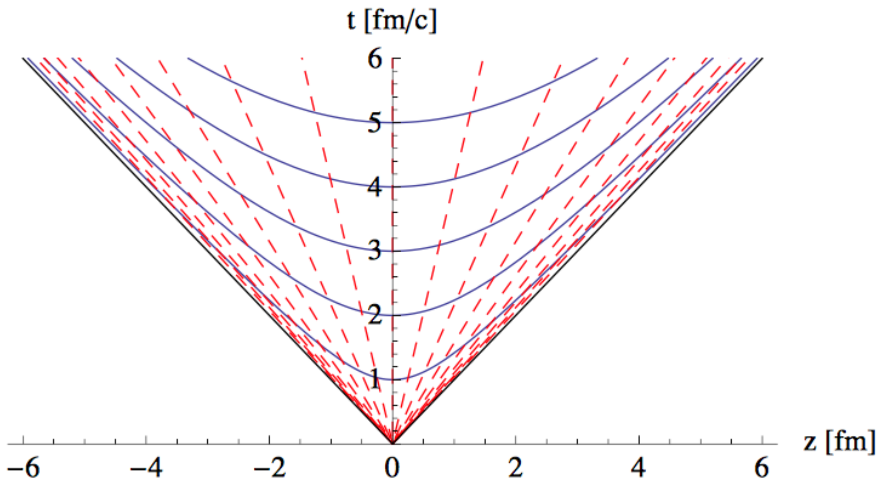
- Leads to boost invariance in z-direction
- Coordinates:

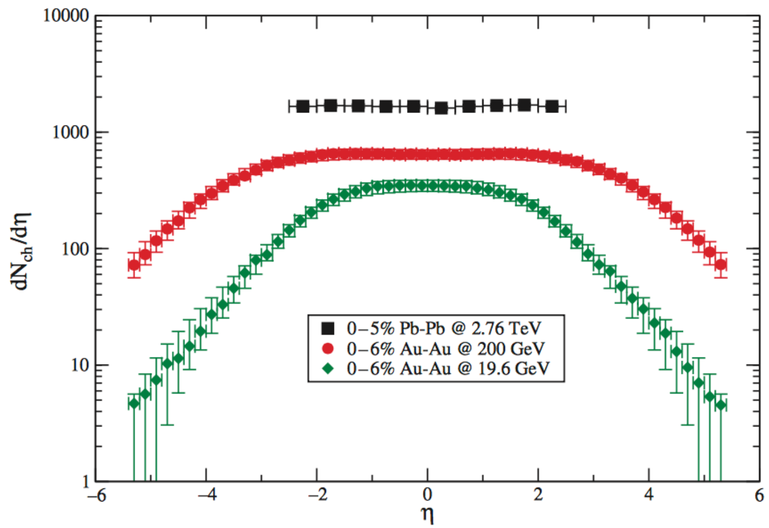
$$\tau = \sqrt{t^2 - z^2}$$
$$\eta = arctanh(z/t)$$

- Quantities independent of η

$$\epsilon = \epsilon(\tau, x, y)$$

- Boost symmetry an idealization but it is reasonable accurate close to midrapidity





Bjoerken model

- Further assuming translational invariance, the system can be solved analytically

- A simple model of the inner region of central collision at early times

- Start with initial condition (no transverse flow)

$$\epsilon = \epsilon(\tau_0), \qquad u^\mu = (1,0,0,0)$$

- The viscous (first order) hydro equations simplify to

$$\partial_\tau \epsilon + (\epsilon + p)\frac{1}{\tau} - \left(\tfrac{4}{3}\eta + \zeta\right)\frac{1}{\tau^2} = 0$$

- Solution depends on equation of state and viscosities $p(\epsilon), \eta(\epsilon), \zeta(\epsilon)$

- In terms of effective temperature $\epsilon \sim T^4$

$$\partial_\tau T + \frac{T}{3\tau}\left(1 - \frac{4\eta/3 + \zeta}{sT\tau}\right) = 0$$

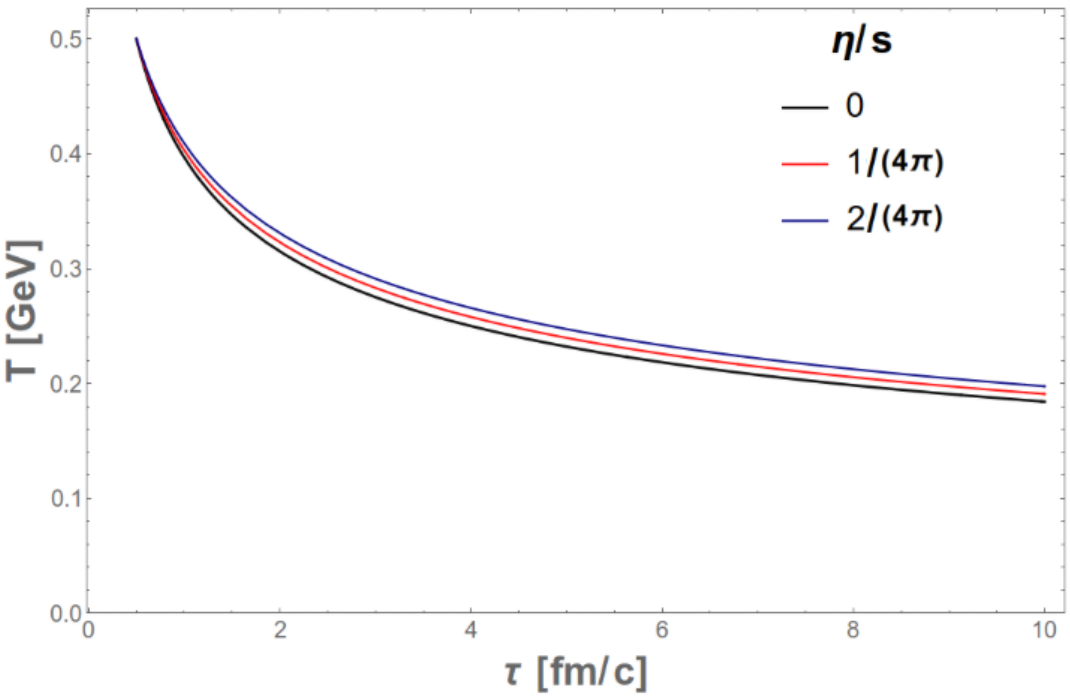
Bjoerken model

- Solution for constant η/s, and $\zeta = 0$, and ideal EoS $\epsilon = 3p$

$$T(\tau) = T(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1/3}\left[1 + \frac{2}{3\tau_0 T(\tau_0)}\frac{\eta}{s}\left(1 - \left(\frac{\tau_0}{\tau}\right)^{2/3}\right)\right]$$

Ideal hydro

Viscous correction

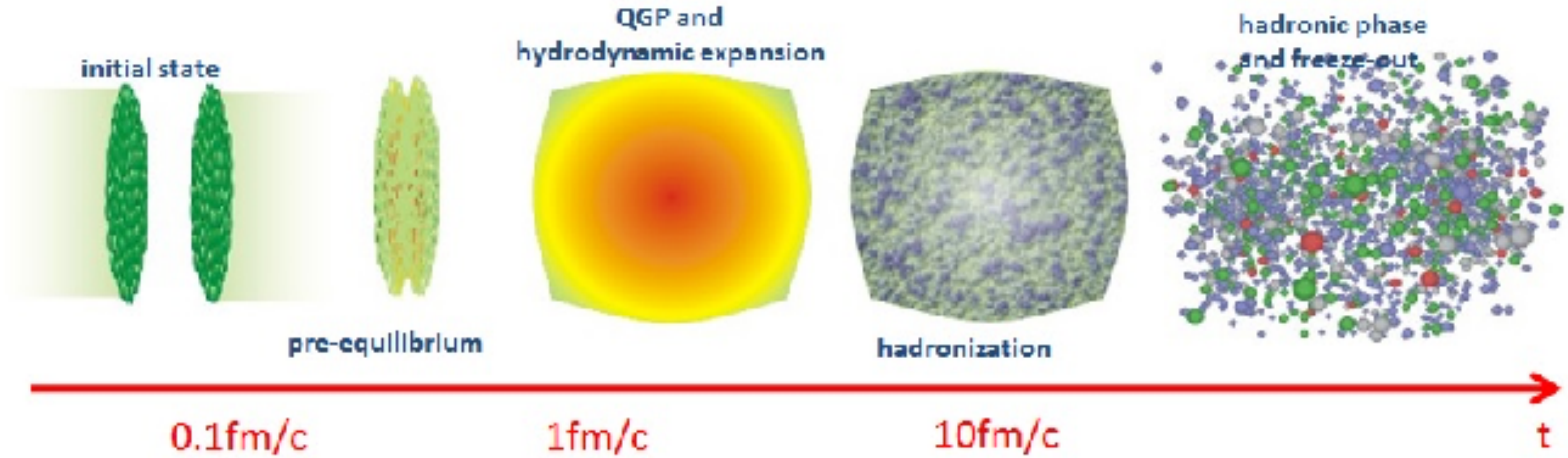


Total entropy

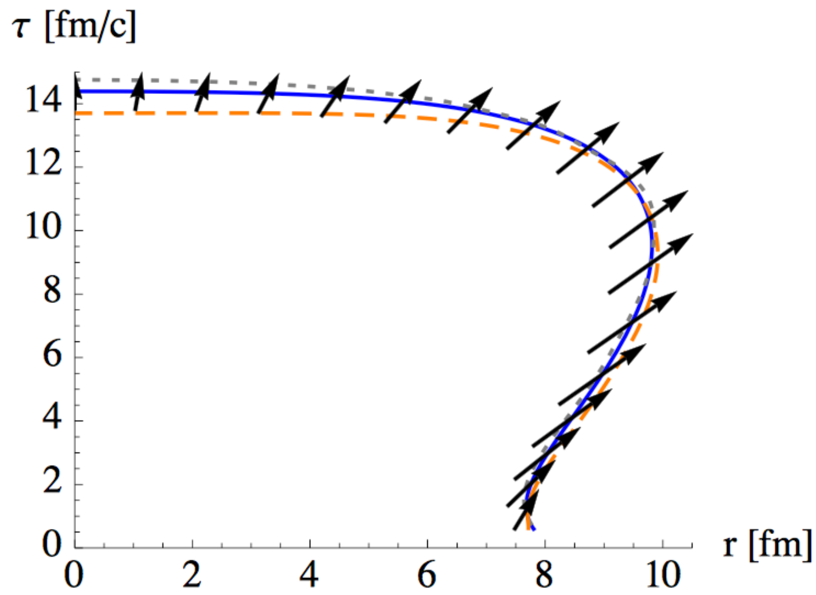
$$\tau s = \tau \frac{\epsilon + P}{T} \sim T^3 \tau$$

- No entropy generation by ideal hydro
- Small amount of entropy generation (heating) from viscous effects

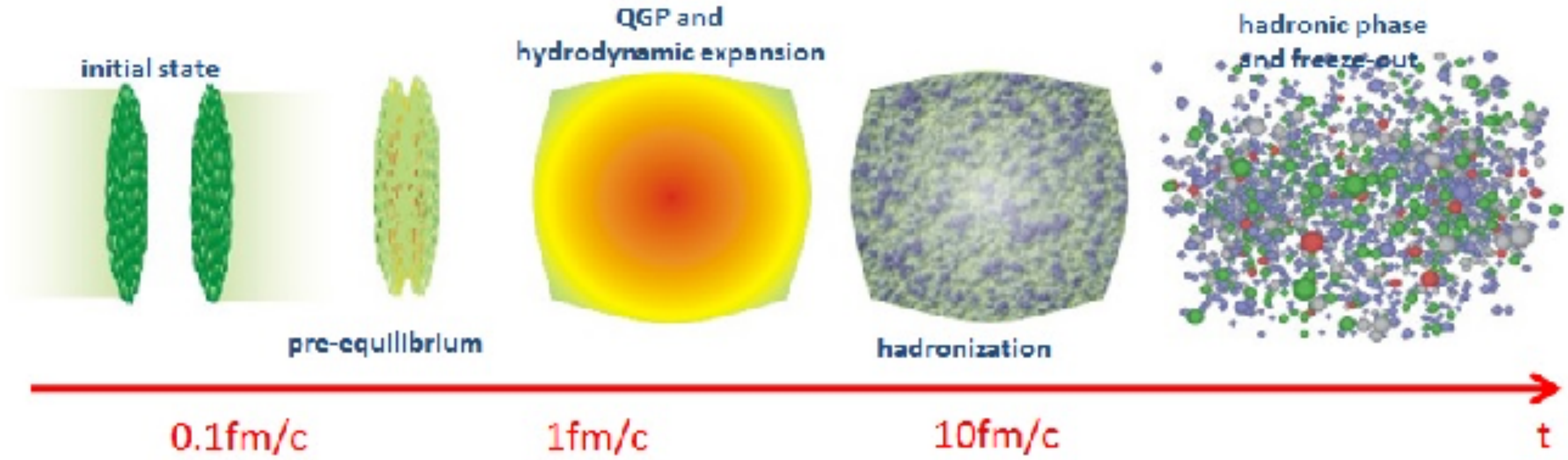
Kinetic freeze-out



- Eventually temperature low and scattering becomes infrequent, the fluid dynamics smoothly goes to free streaming of hadrons -> kinetic Freeze-out
- Freeze-out takes place at $T \lesssim T_c$
  perhaps can get away from hadronization

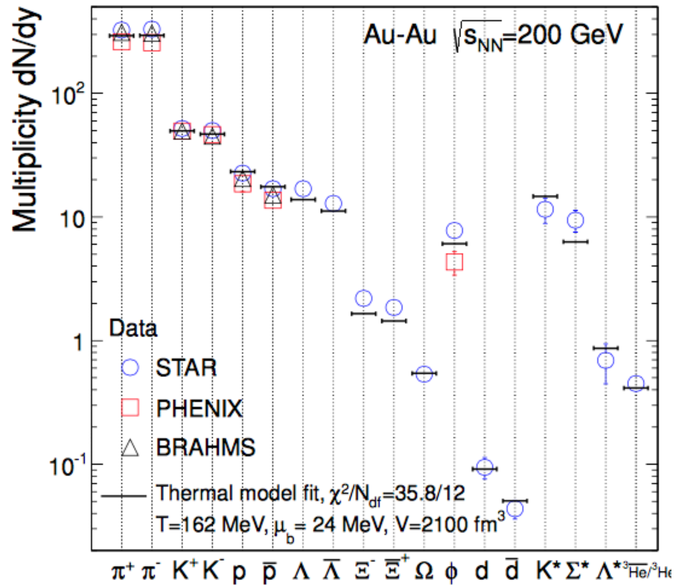


Kinetic freeze-out



- Eventually temperature low and scattering becomes infrequent, the fluid dynamics smoothly goes to free streaming of hadrons -> kinetic Freeze-out
- Freeze-out takes place at $T \lesssim T_c$ perhaps can get away from hadronization
- Guess what the particle distribution is based on hydrodynamical fields

$$f_i = c_i \, e^{\frac{u_\mu(x) p^\mu}{T(x)}}$$



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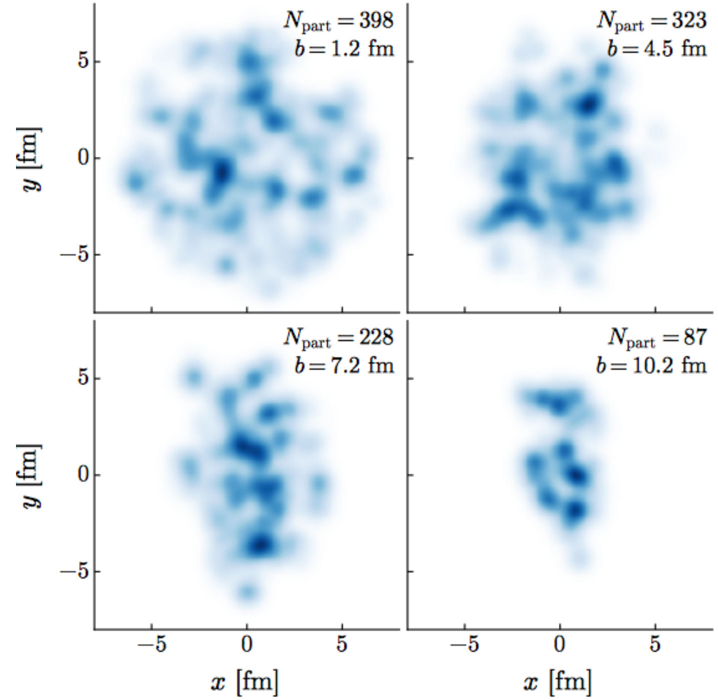
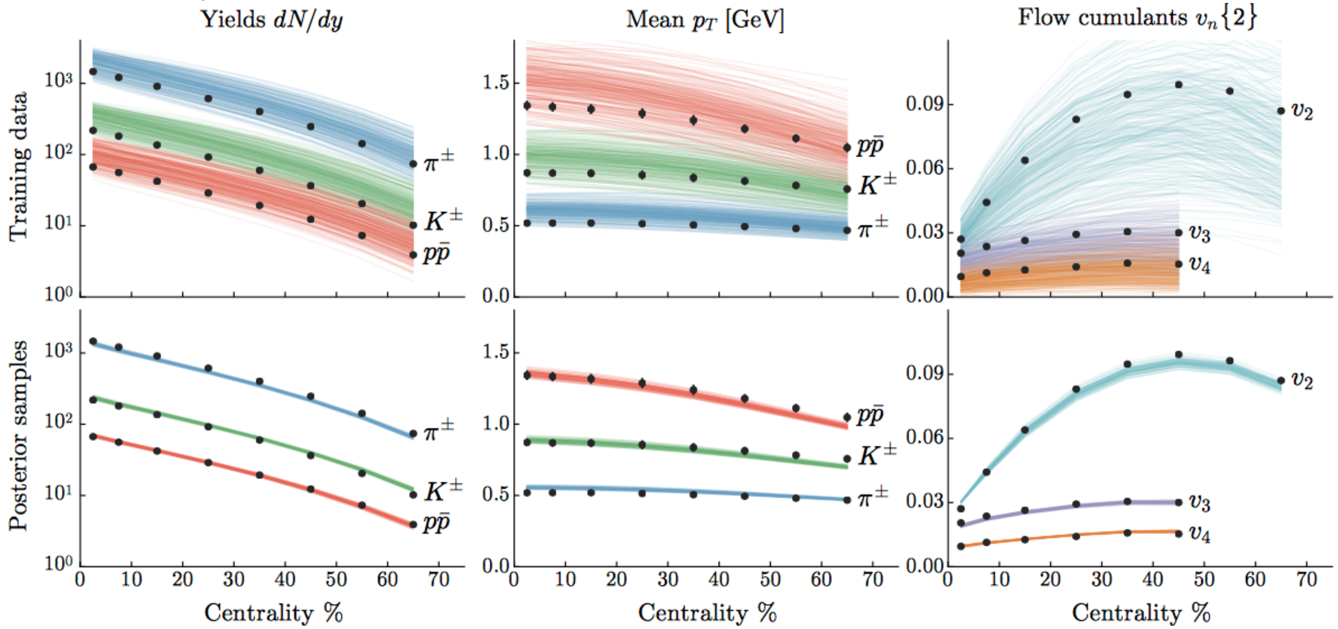
Parameter estimation

- Massively parallel numerical hydro simulations with realistic initial conditions
- Wide range of hydrodynamical parameters

$$(\eta/s)(T) = \begin{cases} (\eta/s)_{\min} + (\eta/s)_{\text{slope}}(T - T_c) & T > T_c \\ (\eta/s)_{\text{hrg}} & T \leq T_c \end{cases}$$

- A large set of observables
- Bayesian analysis to determine the most likely parameter values

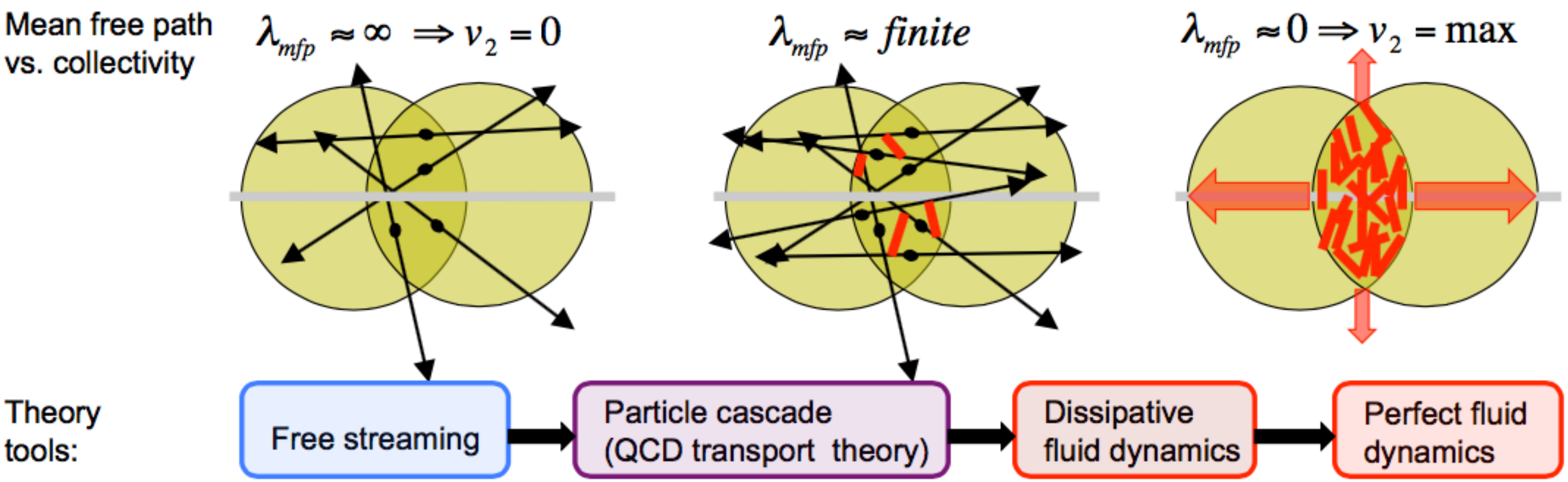




Parameter	Calibrated to: Identified	Charged
Normalization	$120._{-8.}^{+8.}$	$132._{-11.}^{+11.}$
p	$-0.02_{-0.18}^{+0.16}$	$0.03_{-0.17}^{+0.16}$
k	$1.7_{-0.5}^{+0.5}$	$1.6_{-0.5}^{+0.6}$
w [fm]	$0.48_{-0.07}^{+0.10}$	$0.51_{-0.09}^{+0.10}$
η/s min	$0.07_{-0.04}^{+0.05}$	$0.08_{-0.05}^{+0.05}$
η/s slope [GeV^{-1}]	$0.93_{-0.92}^{+0.65}$	$0.65_{-0.65}^{+0.77}$
ζ/s norm	$1.2_{-0.3}^{+0.2}$	$1.1_{-0.5}^{+0.5}$
T_{switch} [GeV]	$0.148_{-0.002}^{+0.002}$	—

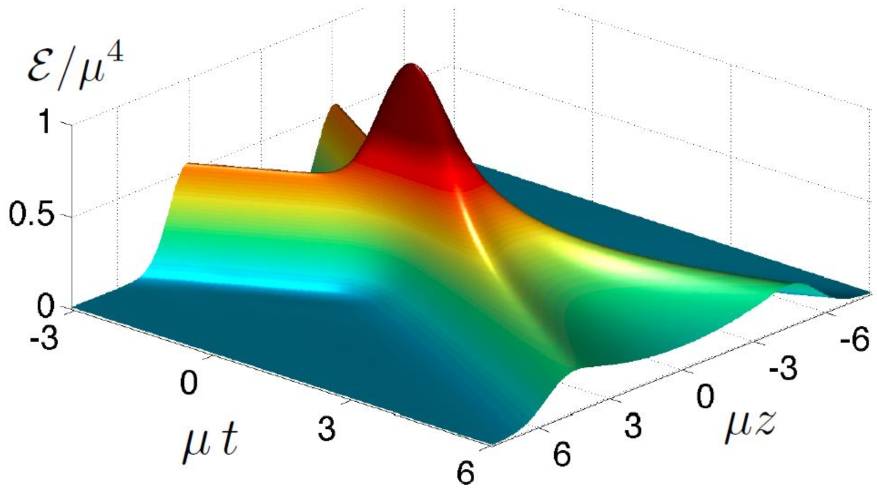
QCD kinetic theory and pre-equilibrium dynamics

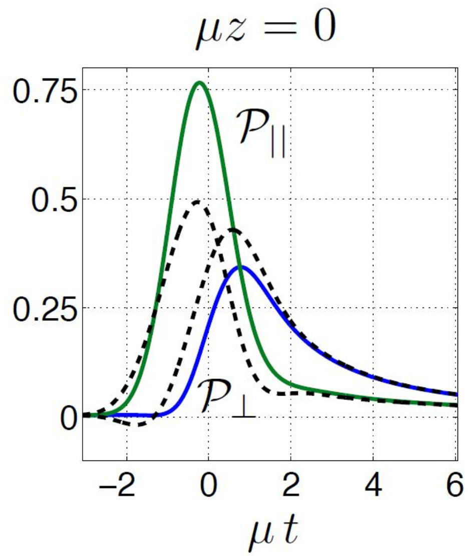
Pre-equilibrium dynamics



- At early times, large gradients. Hydrodynamics fails.
- The longer it takes for a pressure to build up, less radial flow, less v2 etc
- Affects determination of transport coefficients
- Neglected or crudely modelled in most of the current large scale simulations
  - Free streaming, classical YM fields etc…
  - Results sensitive to the initialisation time of hydrodynamical simulation

Pre-equilibrium dynamics



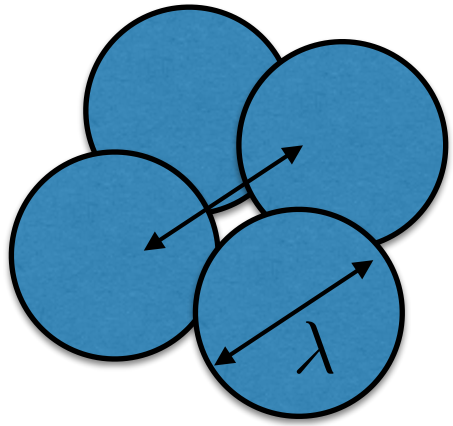


- Pre-equilibrium evolution can be solved for N=4 SUSY at strong coupling,
  - Collision of shock waves in 5 dimensions
  - Onset of hydrodynamics associated with creation of a black whole in the 5th dimension
  - Hydrodynamical flow reached in the mid rapidity region rapidly

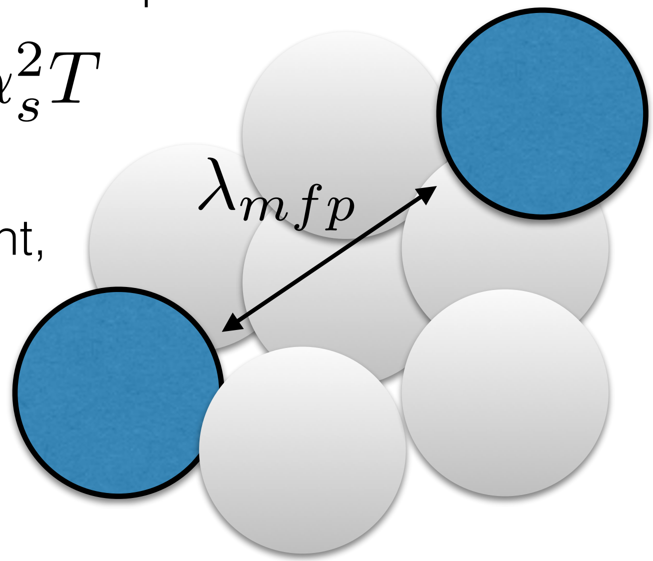
$$\tau_{therm} \sim 1/T$$

QCD kinetic theory

- Consider thermal QCD matter at weak coupling $\alpha_s \to 0$
- Typical scales:
  - Typical momentum $p \sim T$
  - Interparticle distance $\Delta x \sim 1/T$
  - Thermal wavelength $\lambda \sim 1/p \sim 1/T$



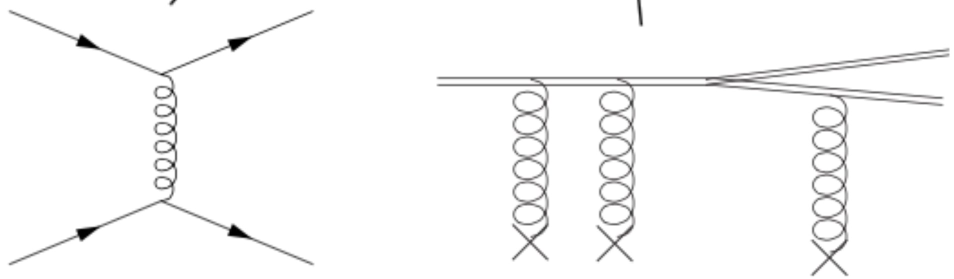
- At weak coupling, scattering only with α_s fraction of particles
  - Mean free path $\lambda_{mfp} \sim 1/\alpha_s^2 T$



- Scale separation implies kinetic theory treatment, can be derived from the Lagrangian in
- Approach to hydrodynamics and transport, jet quenching etc.
- Recent effort to elevate to NLO

QCD kinetic theory

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f] \qquad f = \frac{dN_{gluon}}{d^3p\,d^3x}$$



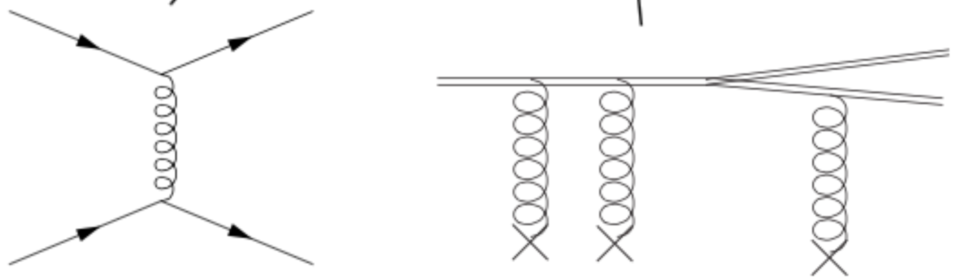
- Evolution equation for (color averaged) quark and gluon distribution
- Contains effective 2to2 and n to (n+1) processes
- Both terms have a non-trivial structure arising from the underlying physical divergences of the underlying processes
- The scattering kernels contain information of a dynamically generated scale

$$m^2_{screen} \sim \int d^3p \frac{f(p)}{p} \sim \alpha T$$

  - Plasma rearranges to screen color charge, $1/m_{screen}$ related to how far a color-electric charge is visible

QCD kinetic theory

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f] \qquad f = \frac{dN_{gluon}}{d^3p d^3x}$$



$$C_{2\leftrightarrow 2}[f] = \int_{k,p',k'} |M|^2 \left[f_p f_k (1+f_{p'})(1+f_{k'}) - f_{p'} f_{k'} (1+f_p)(1+f_k) \right]$$

Effective matrix element

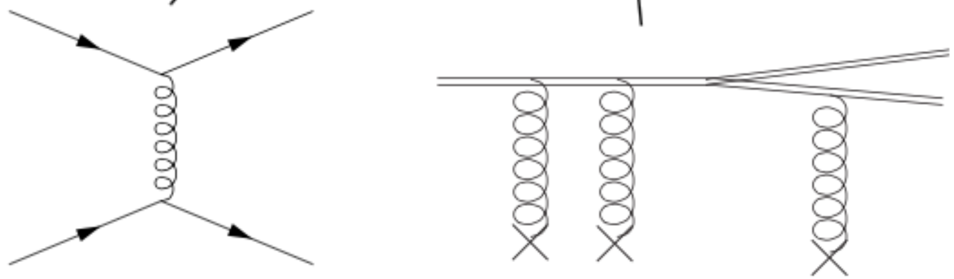
Initial state factors

Phase space integral

Quantum mechanical final state factors
+ bose enhancement (- for fermions)

QCD kinetic theory

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f] \qquad f = \frac{dN_{gluon}}{d^3p\,d^3x}$$

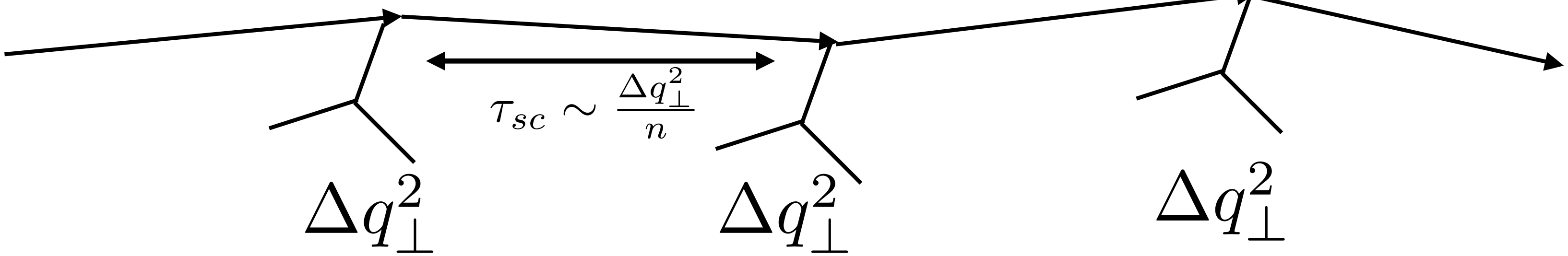


$$C_{2\leftrightarrow 2}[f] = \int_{k,p',k'} |M|^2 \left[f_p f_k (1+f_{p'})(1+f_{k'}) - f_{p'} f_{k'} (1+f_p)(1+f_k)\right]$$

- Naively $\quad |M|^2 = 9 + \frac{(t-u)^2}{s^2} + \frac{(s-u)^2}{t^2} + \frac{(s-t)^2}{u^2}$
- However, in *t* and *u* channels Coulombic IR divergence:
  - Total scattering rate: $\quad \int |M|^2 \int_p f_p(1+f_p) \sim n \int d^2q_\perp \frac{\alpha_s^2}{(q_\perp^2)^2}$
  - Regulated by the screening: $\quad \longrightarrow \frac{1}{(q_\perp^2 + m_{screen}^2)^2}$

QCD kinetic theory

- What does the infrared sensitivity mean?
- Consider a hard particle travelling in medium and undergoing uncorrelated kicks ("collisional energy loss")

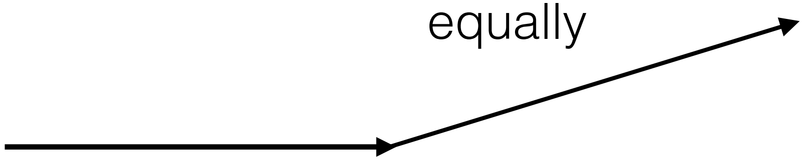
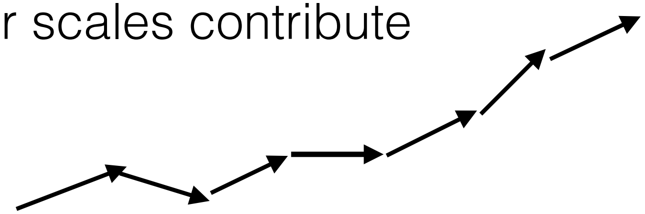


- Total momentum transfer from uncorrelated kicks:

$$Q_\perp^2 \sim \sum_i \Delta q_\perp^2 \sim \frac{\tau}{\tau_{sc}} \Delta q_\perp^2 \equiv \hat{q}\tau$$

$$\hat{q} \sim \alpha^2 n \int d^2 q_\perp \frac{q_\perp^2}{(q_\perp^2)^2} \sim \alpha^2 n \log(T/m_{screen})$$

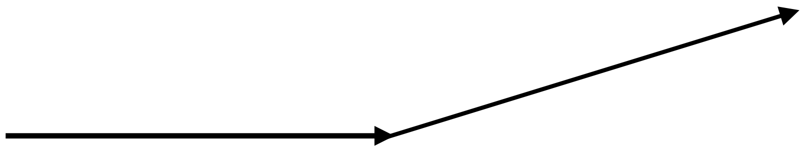
  - All momentum transfer scales contribute equally

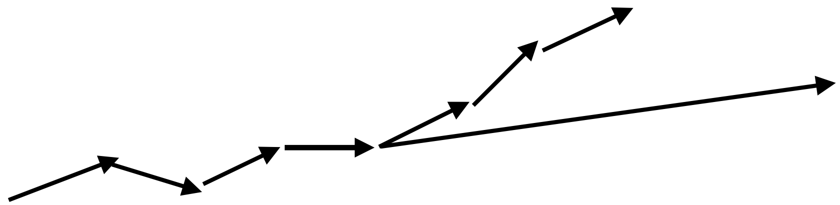



Equally probable

QCD kinetic theory "EKT"

- What does fast soft scattering imply?
- With each scattering, α_s probability of radiation

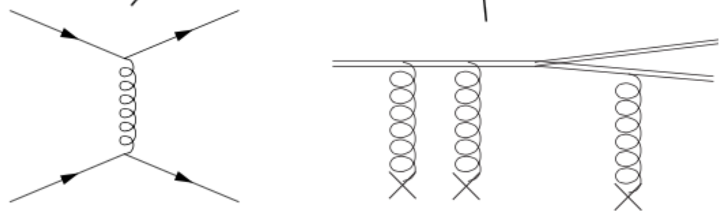




$$\tau_{sc}(\Delta q_\perp^2 \sim T^2) \sim \frac{1}{\alpha^2 T} \qquad \tau_{split}(\Delta q_\perp^2 \sim T^2) \sim \frac{1}{\alpha_s}\tau_{sc}(m^2) \sim \frac{1}{\alpha}\frac{1}{\alpha T}$$

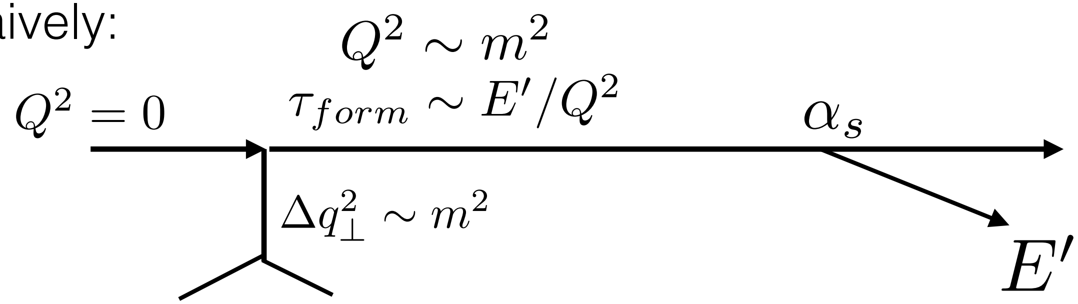
- Elastic scattering and collinear splitting equally fast, both need to be included

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$



QCD kinetic theory “EKT”

- Collinear splitting and Landau-Pomeranchuk-Migdal suppression
- Naively:



- The soft scattering and the splitting far apart in time, diagram factorizes

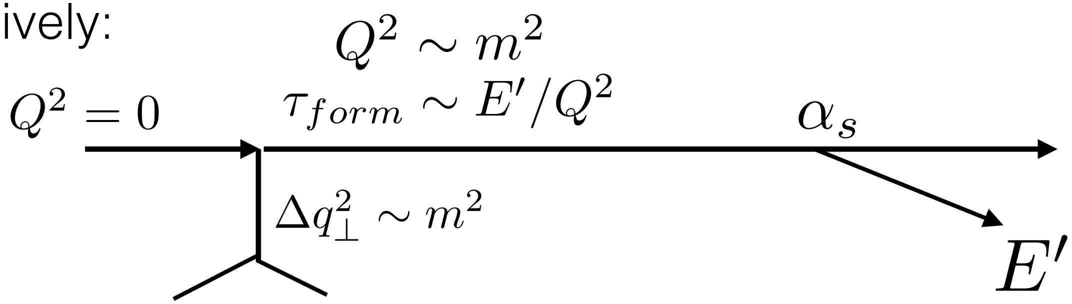
$$C_{1\leftrightarrow 2} \sim \int dp\, \gamma^{p}_{k,p-k}\left[f_p(1+f_k)(1+f_{p-k}) - f_k f_{p-k}(1+f_p)\right]$$

$$\gamma \sim \frac{1}{\tau_{sc}(m^2)} \times \frac{1}{p}$$

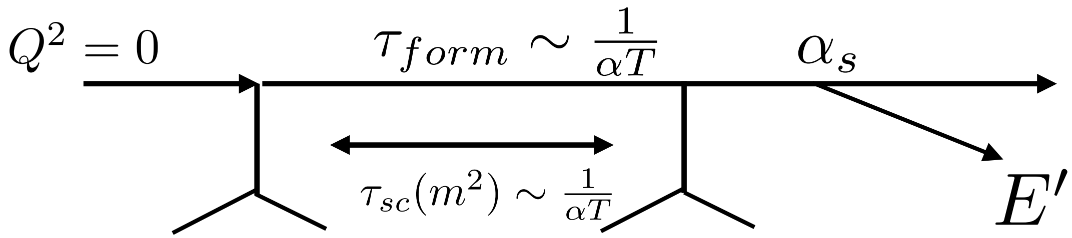
  - Bether-Heitler rate

QCD kinetic theory "EKT"

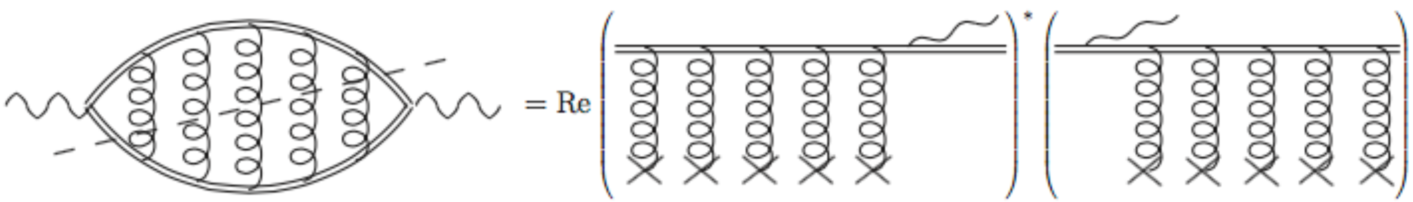
- Collinear splitting and Landau-Pomeranchuk-Migdal suppression
- Naively:



- The soft scattering and the splitting far apart in time, diagram factorizes
- However, if $E' \gtrsim T$, several scatterings during formation

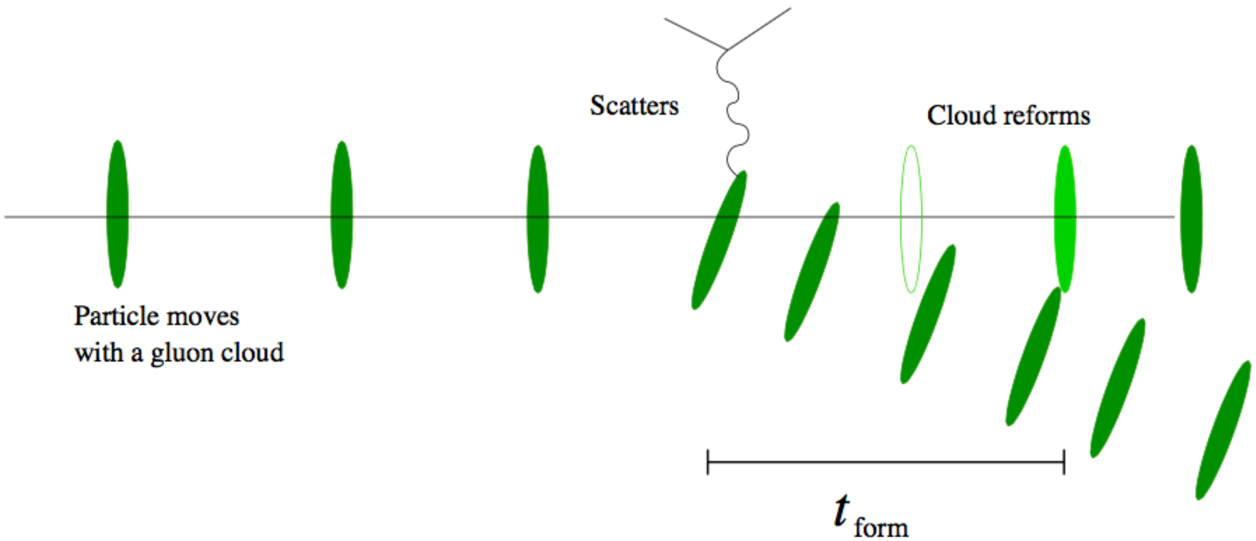


- Leads to interference between diagrams: LPM suppression



QCD kinetic theory “EKT”

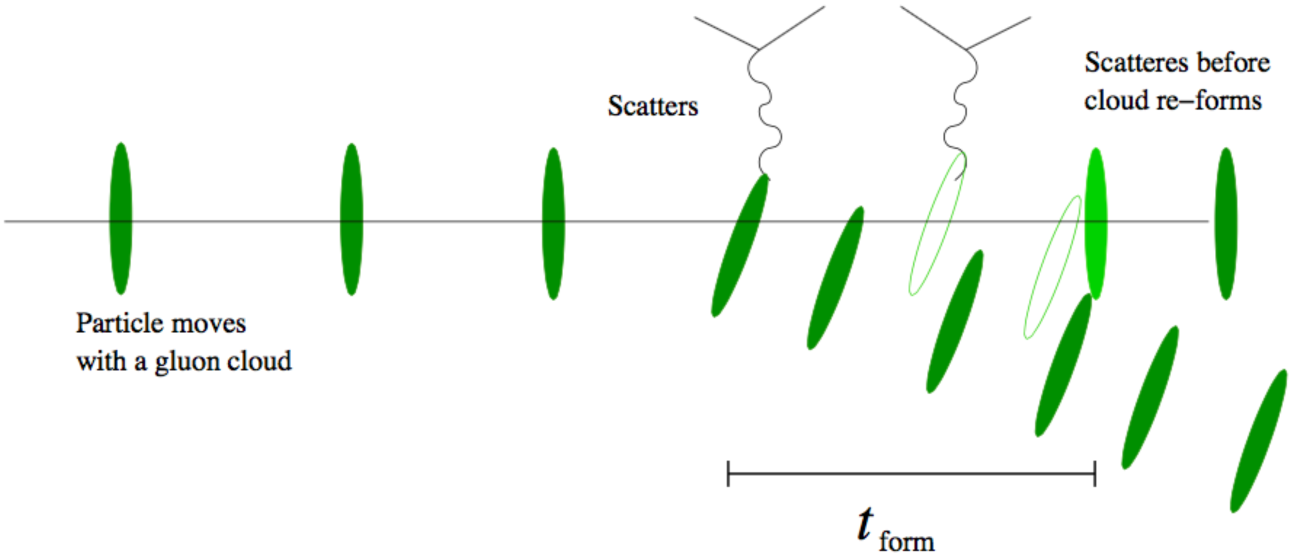
- Landau-Pomeranchuk-Migdal suppression qualitatively



$$t_{form} \sim \frac{trans.size}{trans.vel} \sim \frac{1/q_\perp}{q_\perp/E'} \sim \frac{E}{q_\perp^2}$$

QCD kinetic theory “EKT”

- Landau-Pomeranchuk-Migdal suppression qualitatively



$$\tau_{form} \sim \frac{trans.size}{trans.vel} \sim \frac{1/q_\perp}{q_\perp/E'} \sim \frac{E}{q_\perp^2}$$

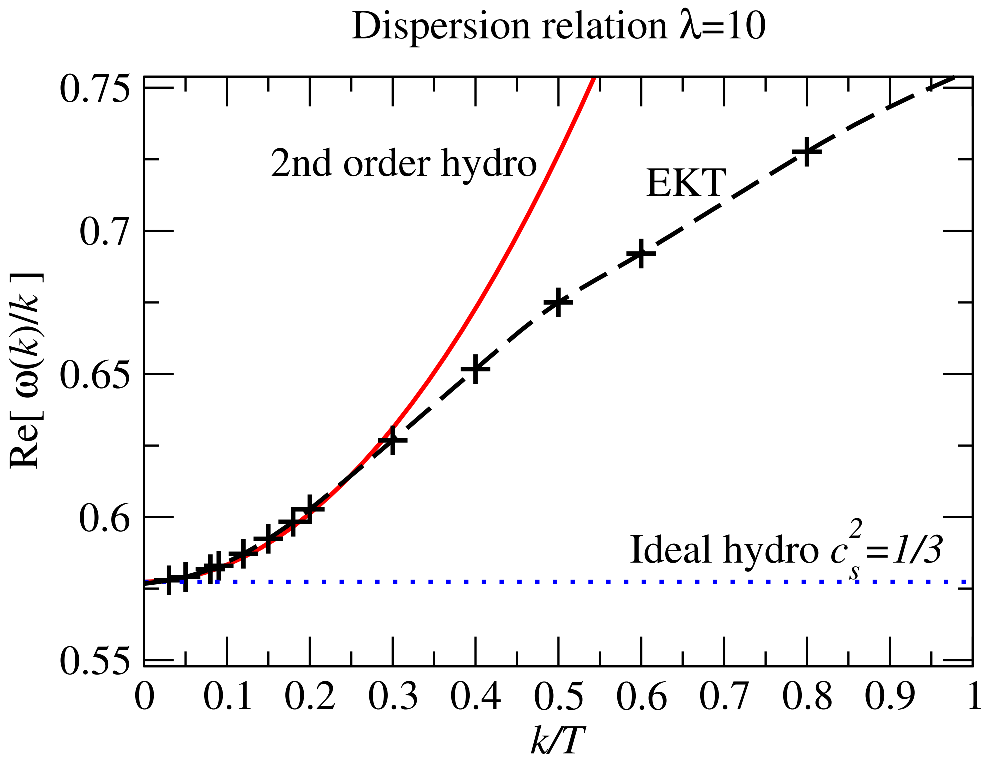
- If a new scattering occurs while the emission has not formed, it is not resolved. The two scattering act as a single scattering -> reduced rate

- Assuming that the net effect during τ_{form} from multiple scatterings is

$$q_\perp^2 \sim \hat{q}\tau_{form} \Rightarrow \tau_{form} \sim \frac{E}{\hat{q}\tau_{form}} \sim \sqrt{\frac{E}{\hat{q}}}$$

$$\tau_{sc} \sim \frac{1}{\alpha_s}\tau_{form} \sim \frac{1}{\alpha_s}\sqrt{\frac{E}{\hat{q}}}$$

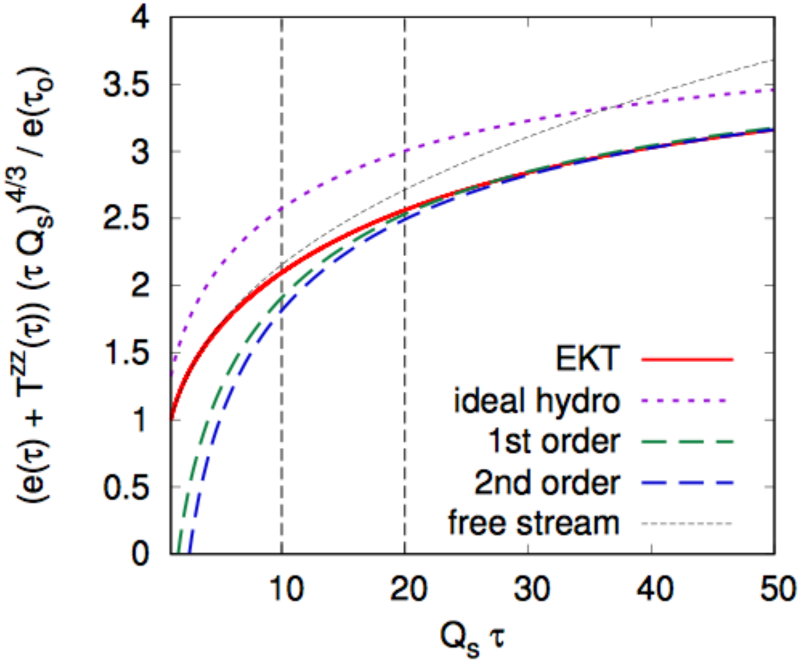
QCD kinetic theory



$$\omega = c_s k + \frac{4}{3}\frac{\eta}{e+p}\left(c_s\tau_\pi - \frac{2}{3c_s}\frac{\eta}{e+p}\right)k^3$$

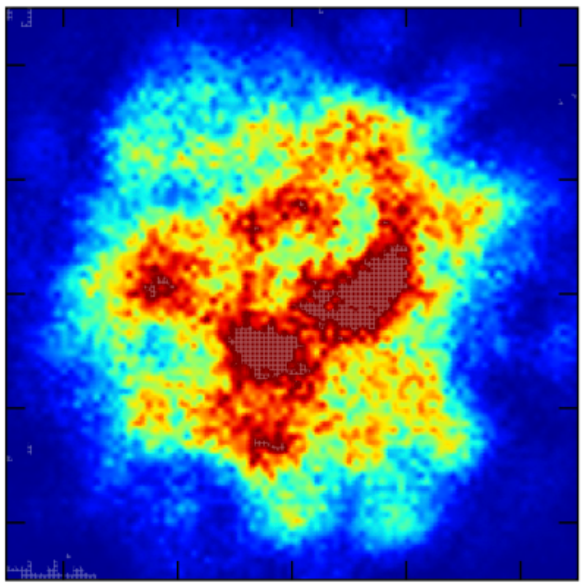
- Dispersion relation of sound reproduces ideal hydro for long wave lengths (small gradients)
- Deviations from hydrodynamics for small wavelengths

QCD kinetic theory

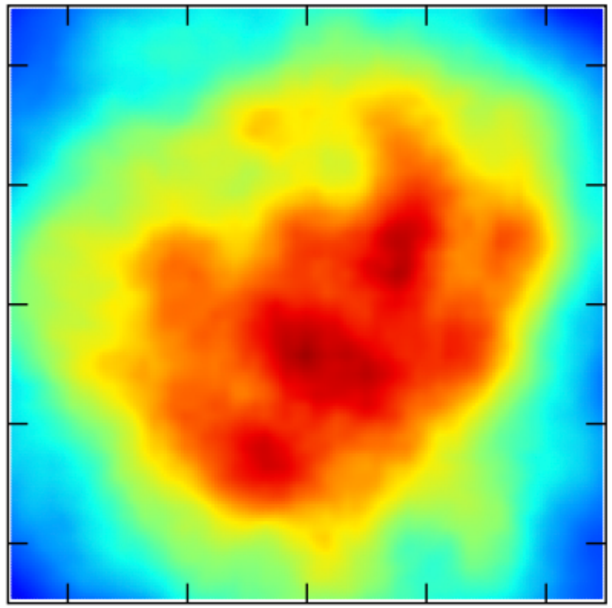


- The kinetic theory interpolates between free streaming and hydrodynamics

- Can be used to bring the initial condition to time where fluid dynamics is applicable

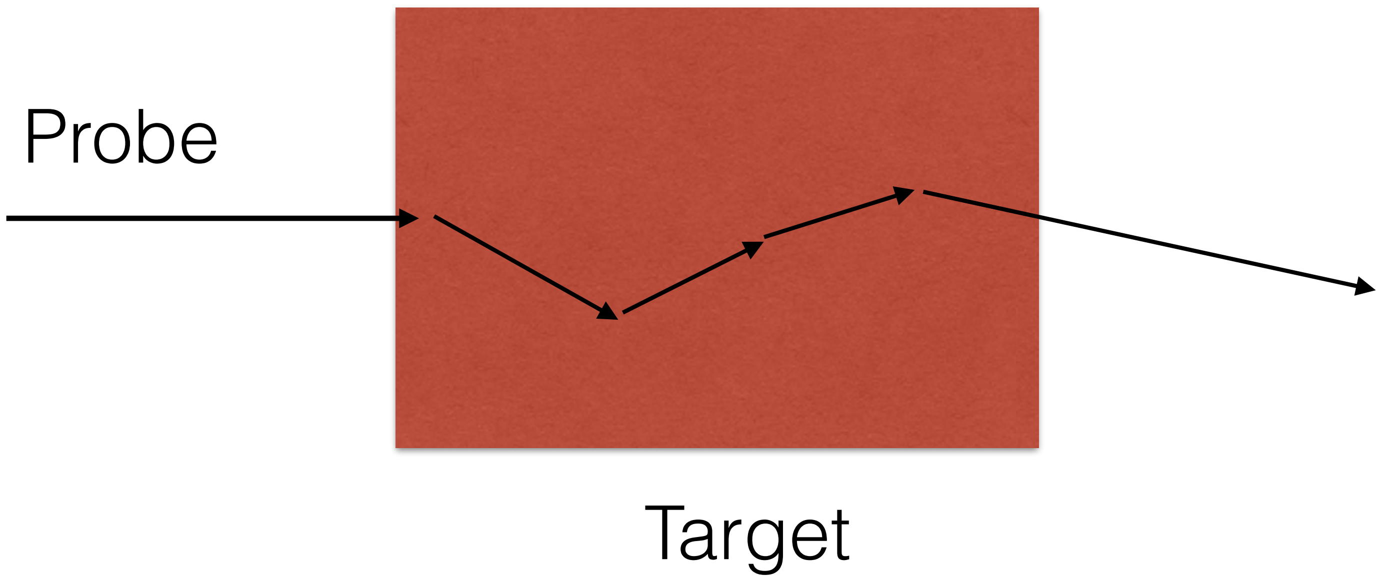


Pre-equilibrium smearing and generation of *preflow*



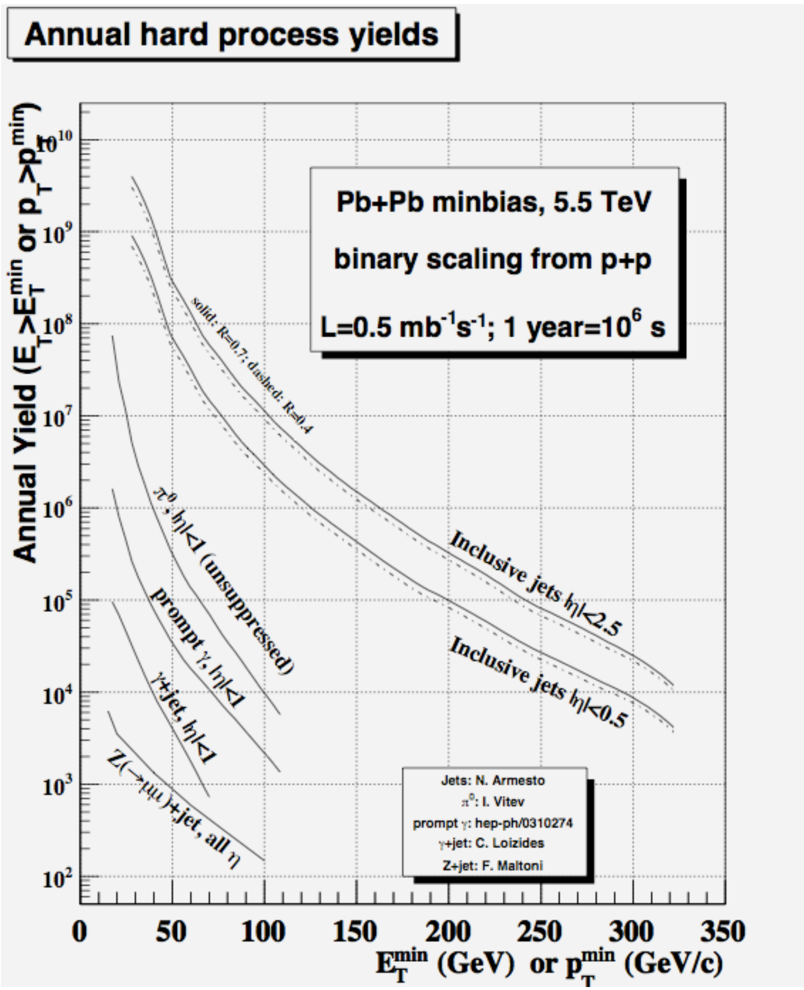
Hard probes

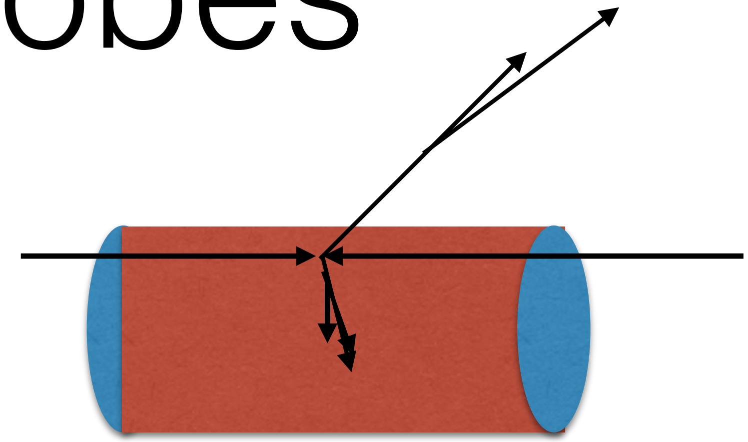
Hard probes



- Classic experiment: shoot a probe through medium to learn about the properties of the medium

Hard probes

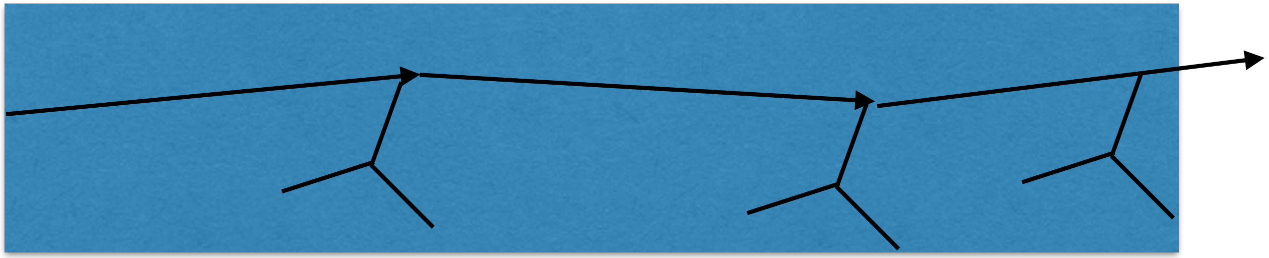




- Hard probes=
  Rare hard processes embedded in the hot plasma "self generated probes"
- Emission rates of hard particles largely unmodified by the medium and well known. "Calibrated probes"
- Created abundantly at the LHC

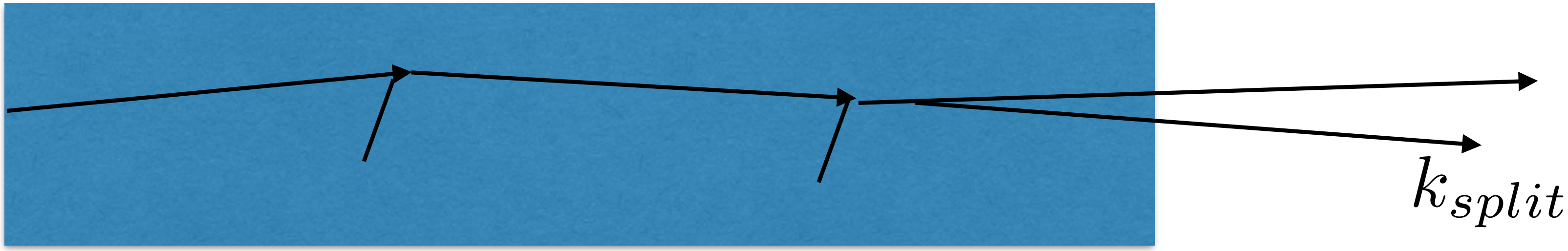
Jet quenching

- Thermal background + jet is a non-equilibrium system -> use EKT (AMY)
- Several other formalisms, all do basically the same. Slightly different kinematical approximations. BDMPS, Z, AMY,…
- Key question: How fast an energetic parton loses energy when traversing medium of length L
  - 2 to 2 scattering: collisional energy loss: $\Delta E \sim \hat{e} L$
    - Drag coefficient $\hat{e}$ related to $\hat{q} = 2T\hat{e}$ by Einstein relation



- 1 to 2 splitting: radiational energy loss: $\Delta E \sim \hat{q} L^2$

Radiational energy loss



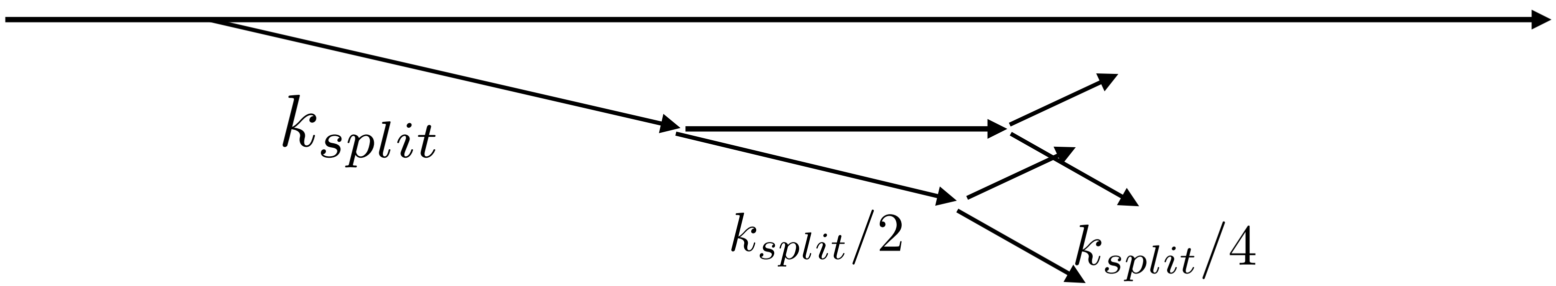
- Relevant rate LPM suppressed

$$\tau_{split}^{-1} \sim \alpha_s \tau_{form}^{-1} \sim \alpha\sqrt{\frac{\hat{q}}{p}}$$

- After a traversing length L, the hardest splitting is given by

$$L \sim \tau_{split}(k_{split}) \qquad k_{split} \sim \alpha_s^2 \hat{q} L^2$$

Radiational energy loss



- Those particles that have had time time to be emitted have time to re-split again

$$\tau_{split}(k_{split}) > \tau_{split}(k_{split}/2) > \tau_{split}(k_{split}/4)$$

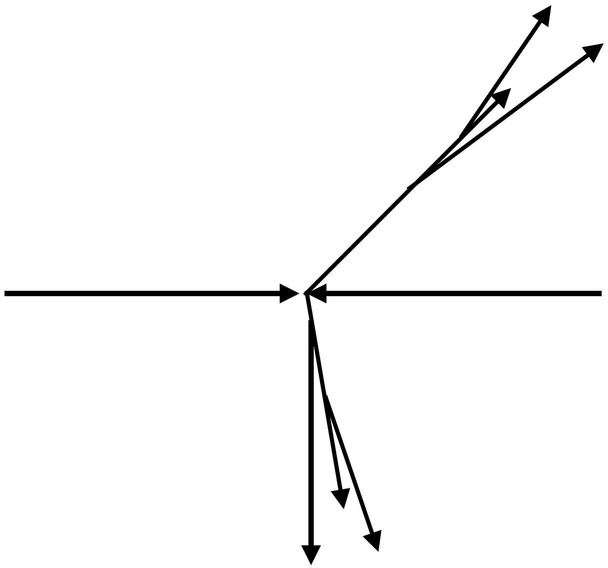
- Emitted particles undergo a radiational cascade until all the energy reaches the thermal scale

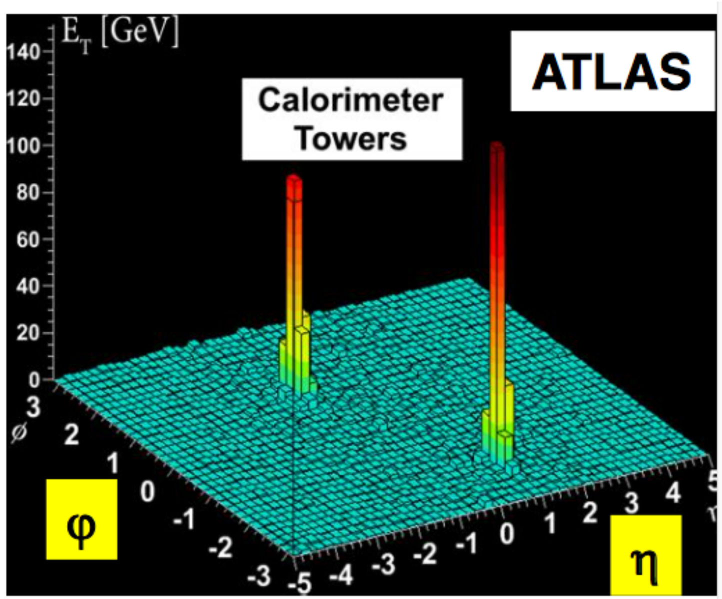
- Soft particles undergo large angle scattering more easily and can escape the jet cone

- The jet is fully quenched when $L = \tau_{split}(E), \quad L \sim \sqrt{\frac{E}{\alpha^2 \hat{q}}} \sim \frac{1}{\alpha^2 T}\sqrt{\frac{E}{T}}$

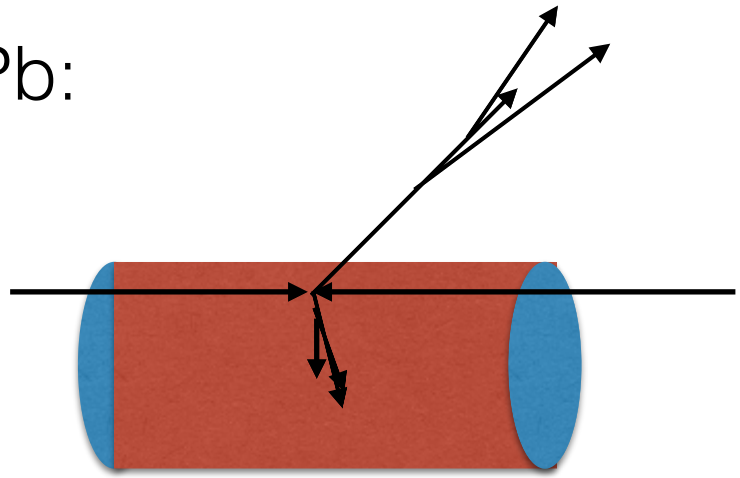
A Back-to-back jet

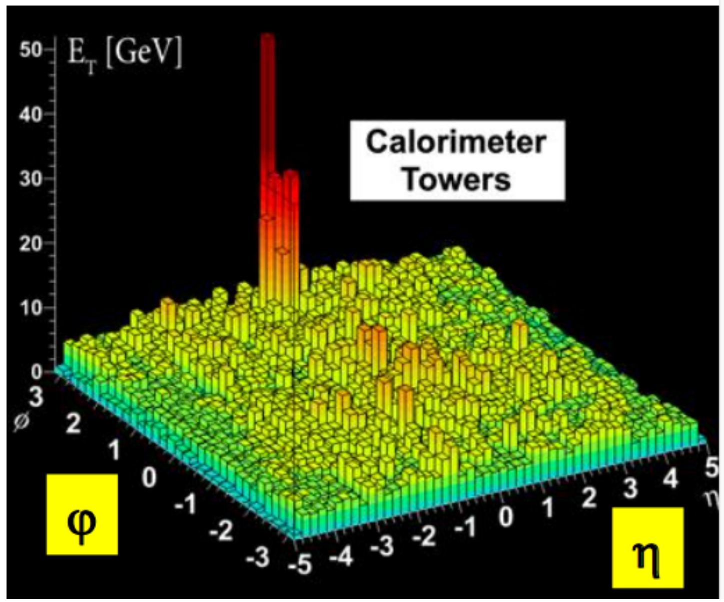
pp:



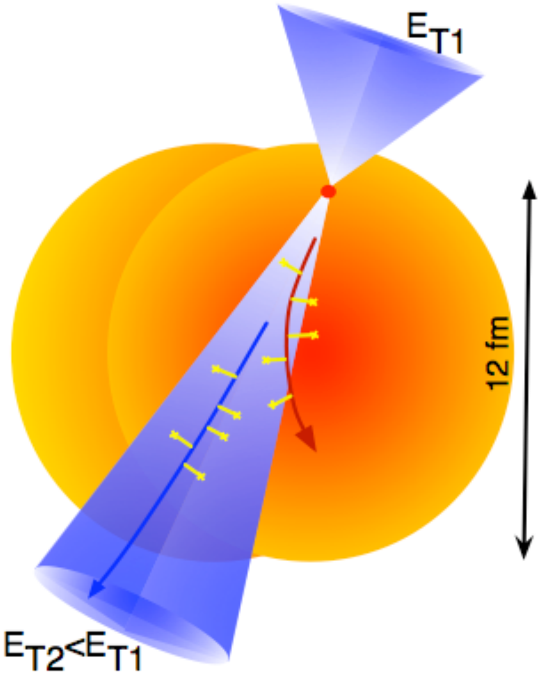


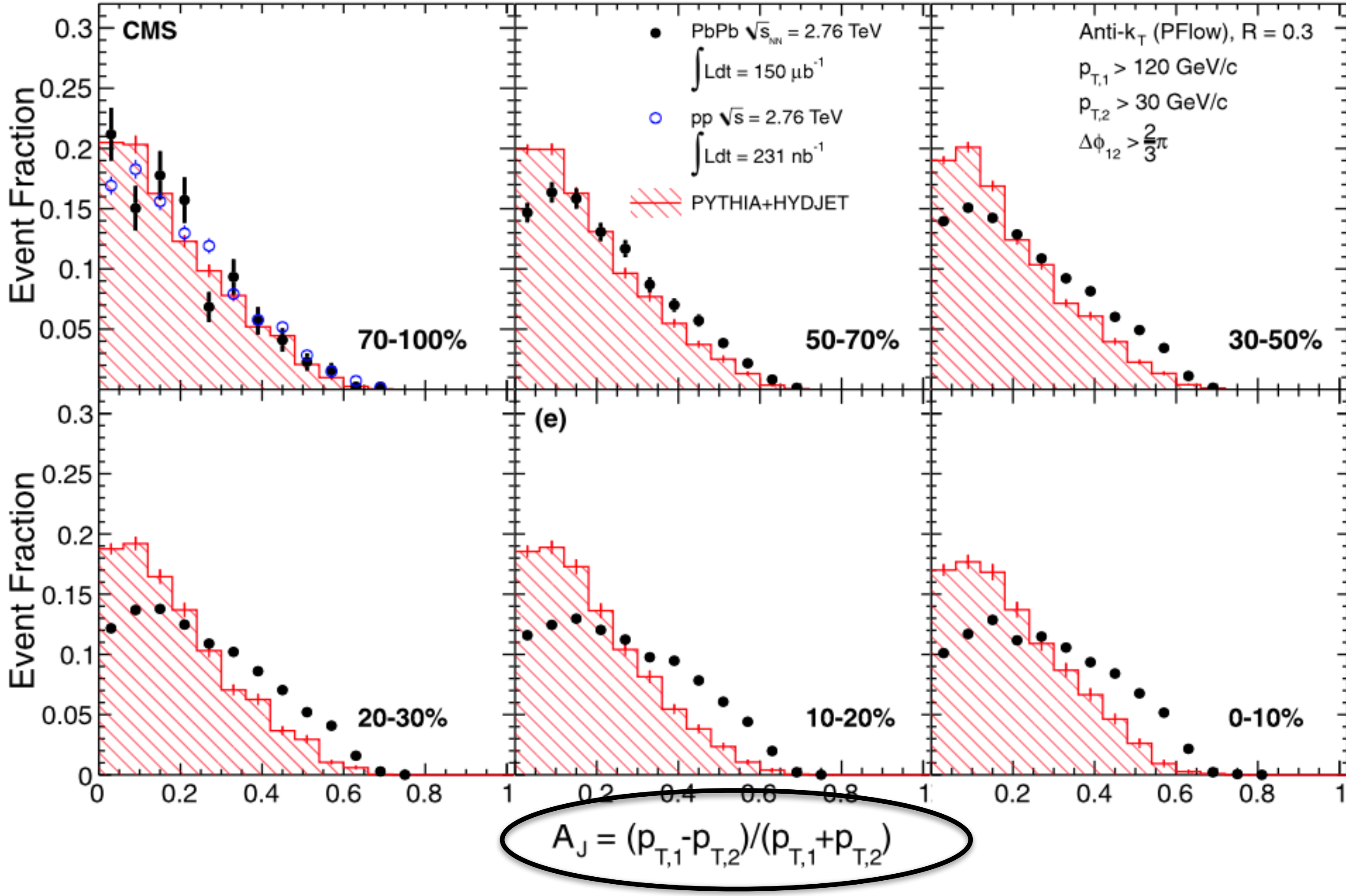
PbPb:





Dijet asymmetry



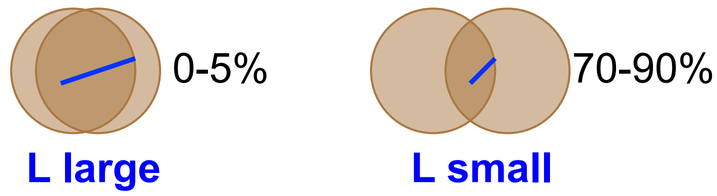


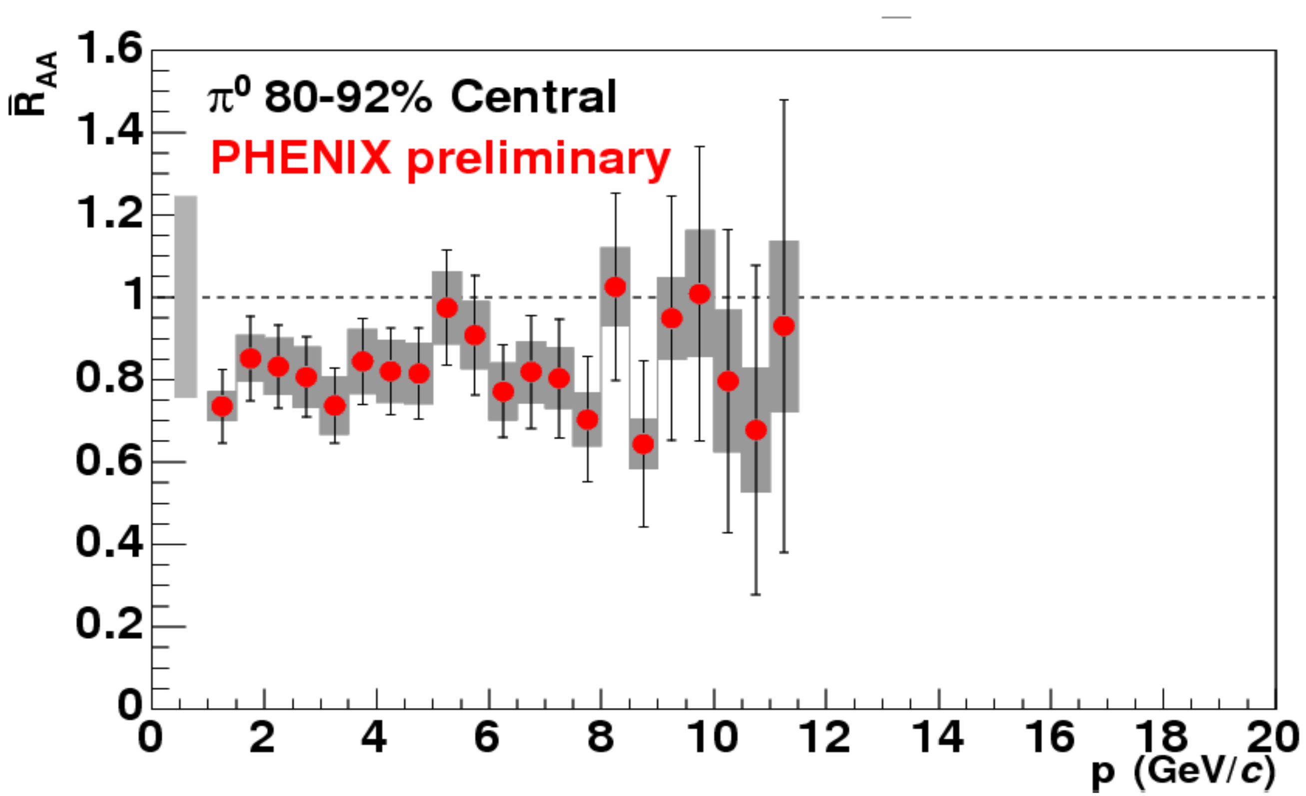
- Periphreral events have an unmodified AJ
- In pp, asymmetry arises from 3-jet events
- Asymmetry much enhanced in central AA

Nuclear modification factor

- Suppression of leading hadron production compared to pp baseline

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{n_{coll}\ dN^{NN}/dp_T}$$





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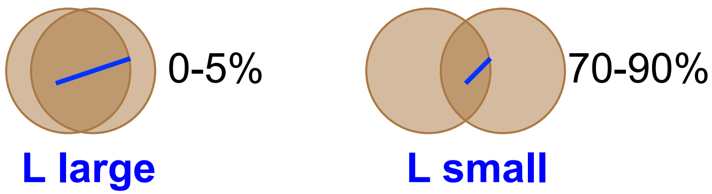

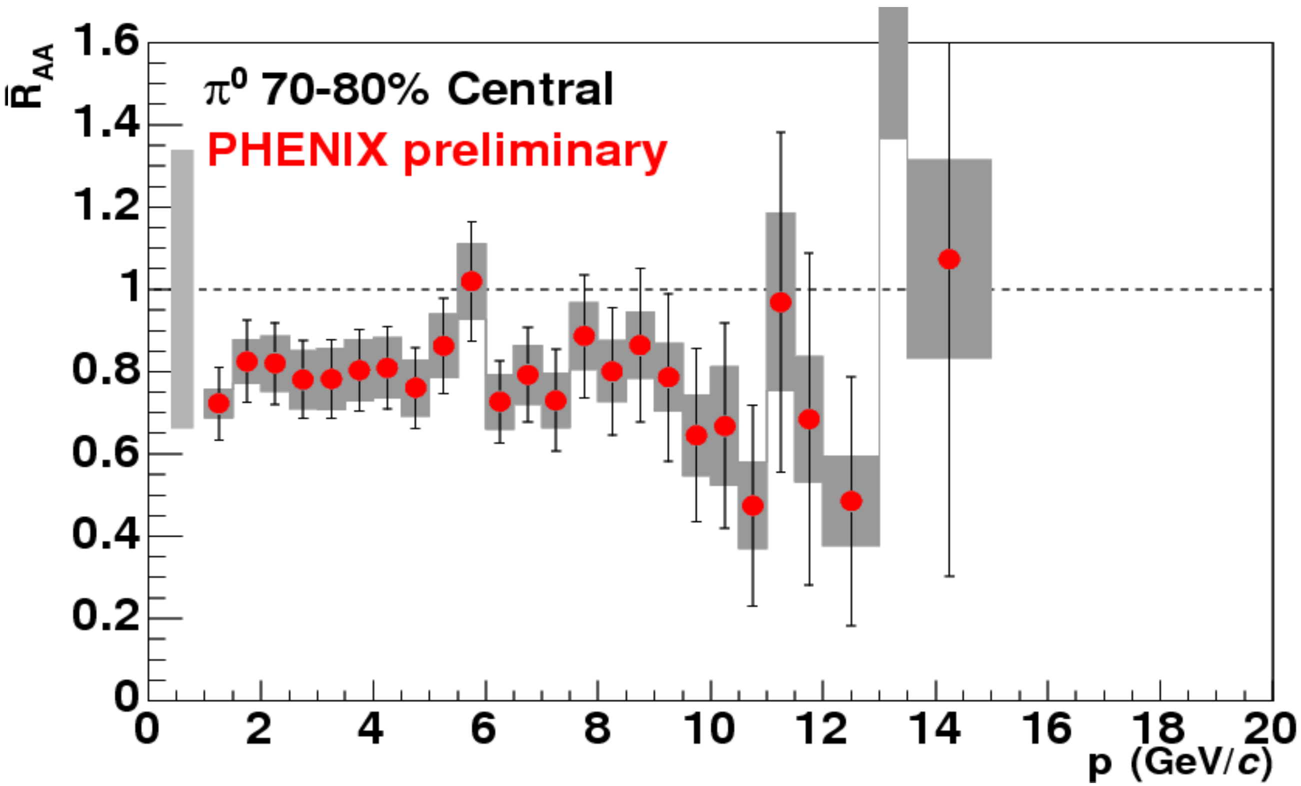

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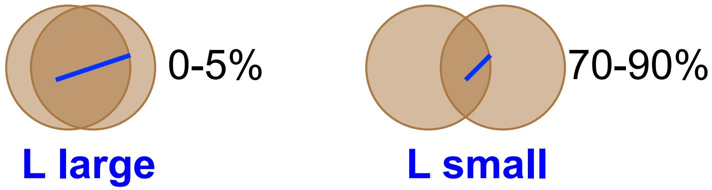

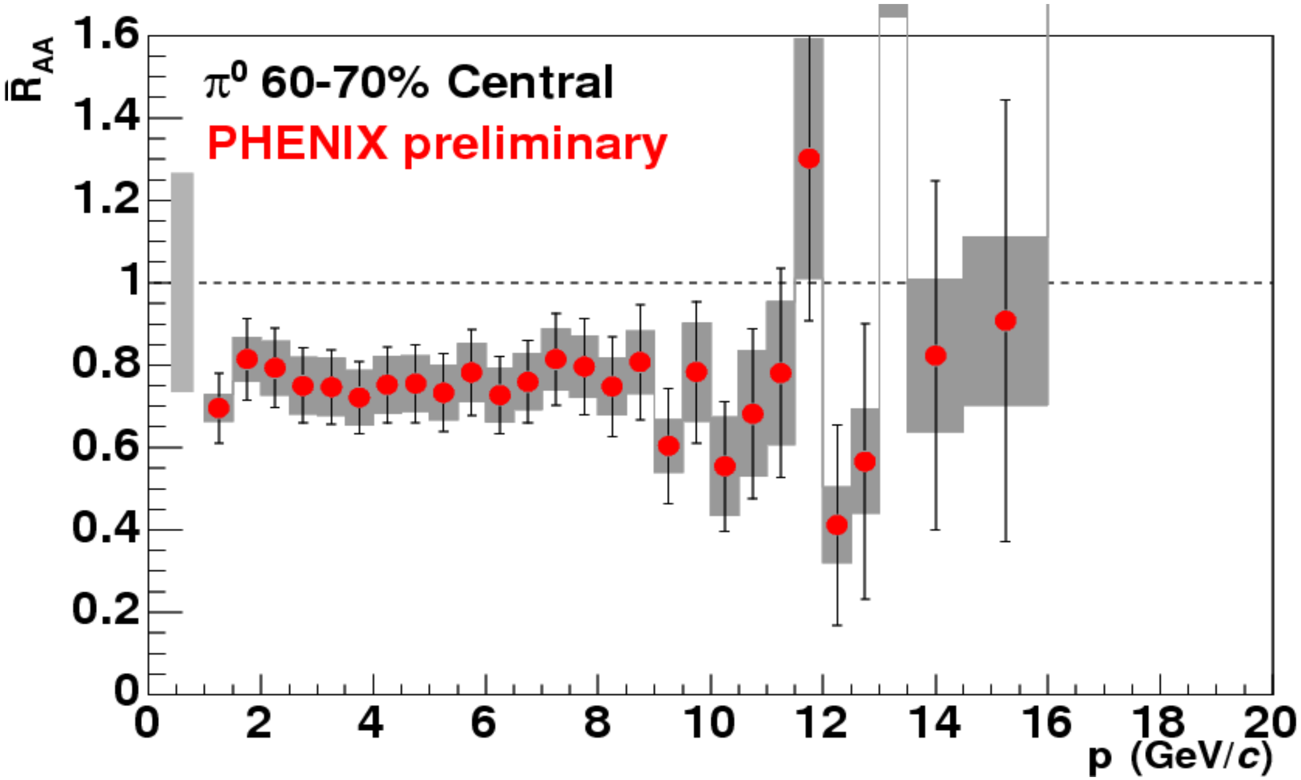

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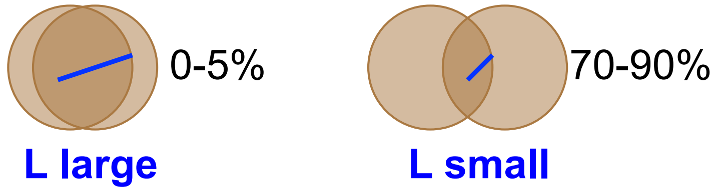

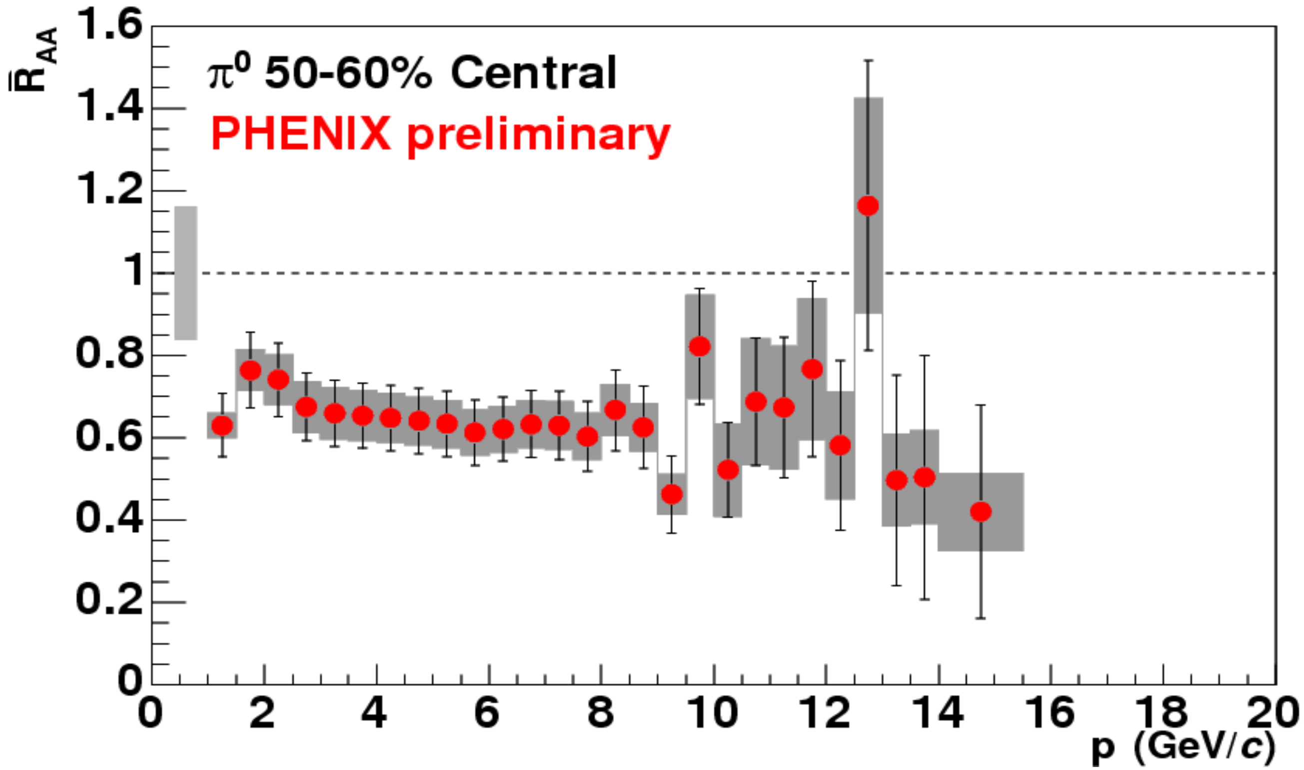

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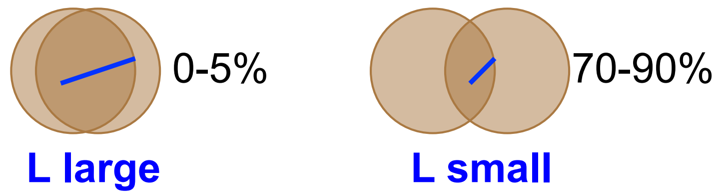

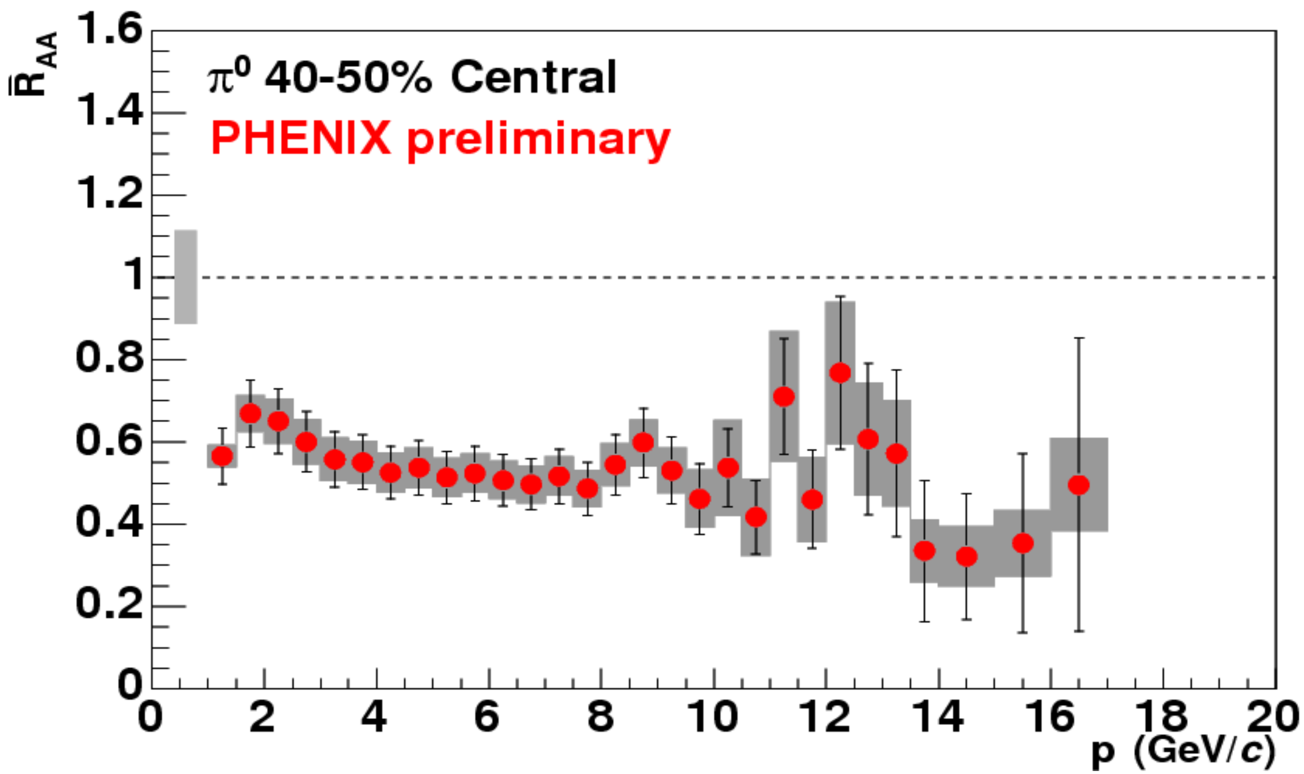

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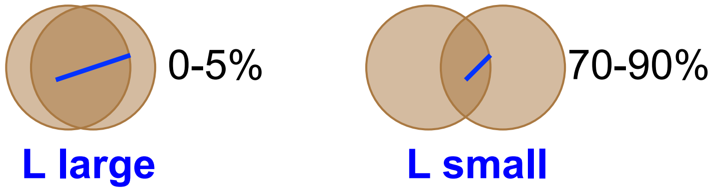

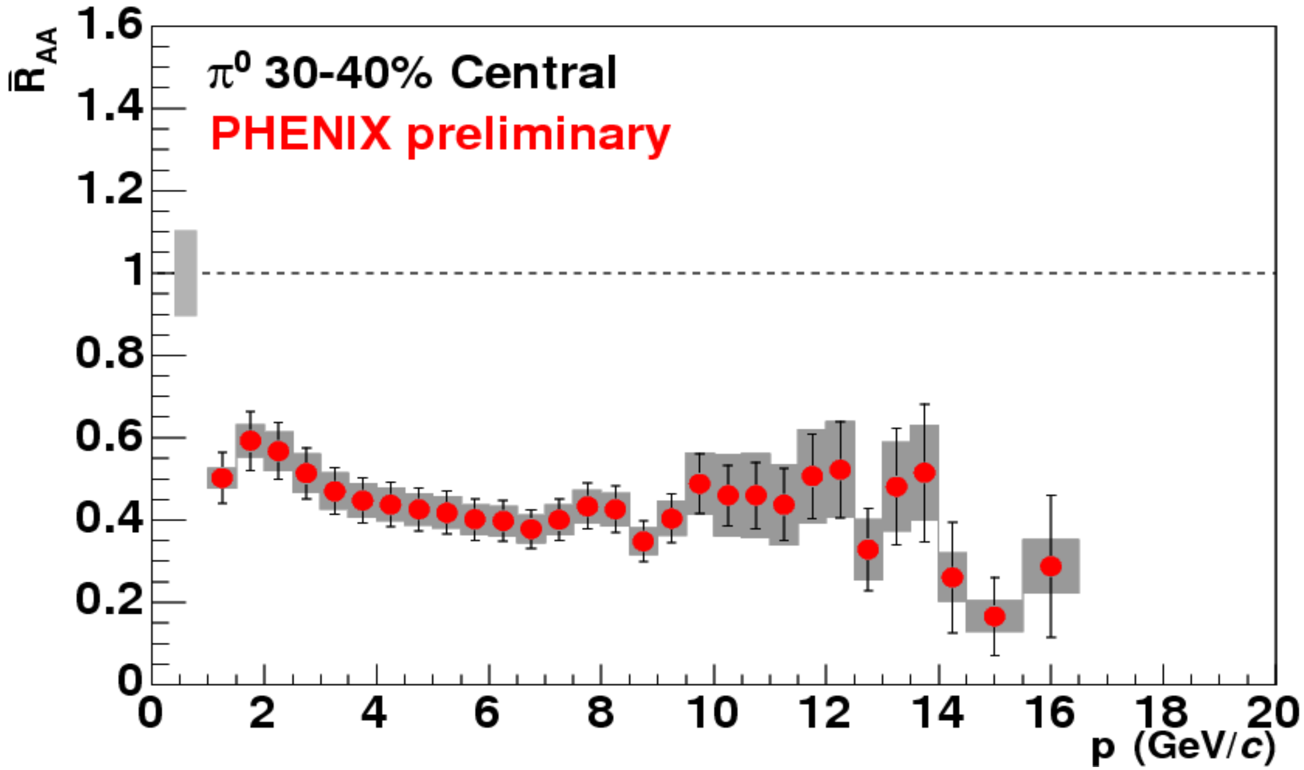

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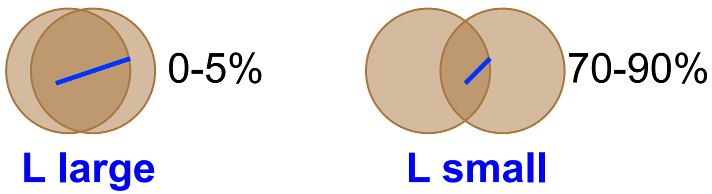

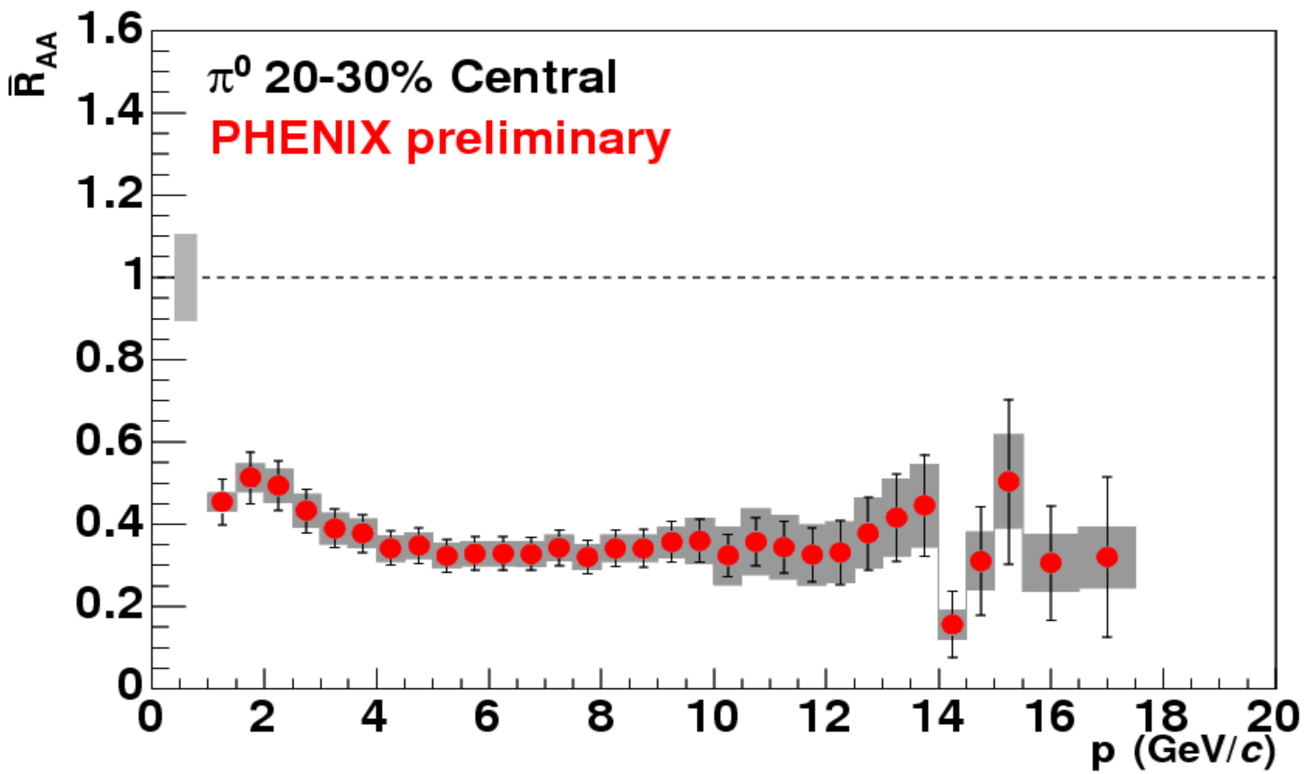

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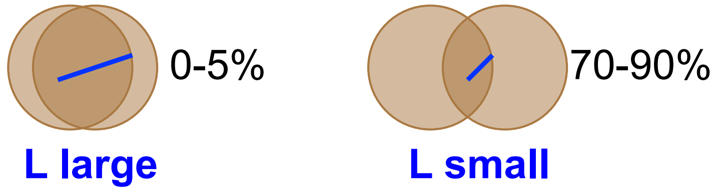

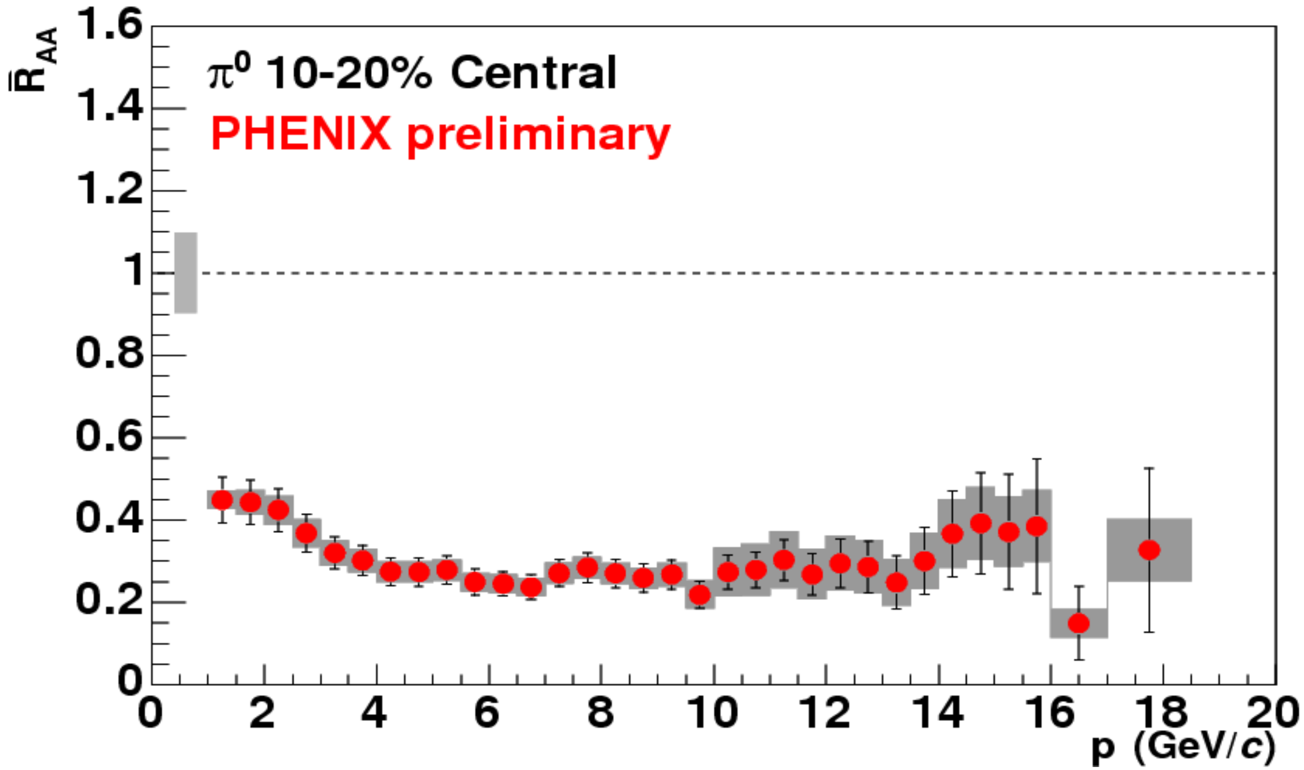

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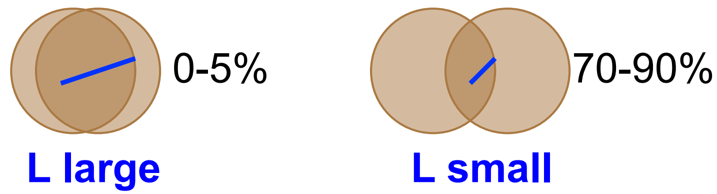

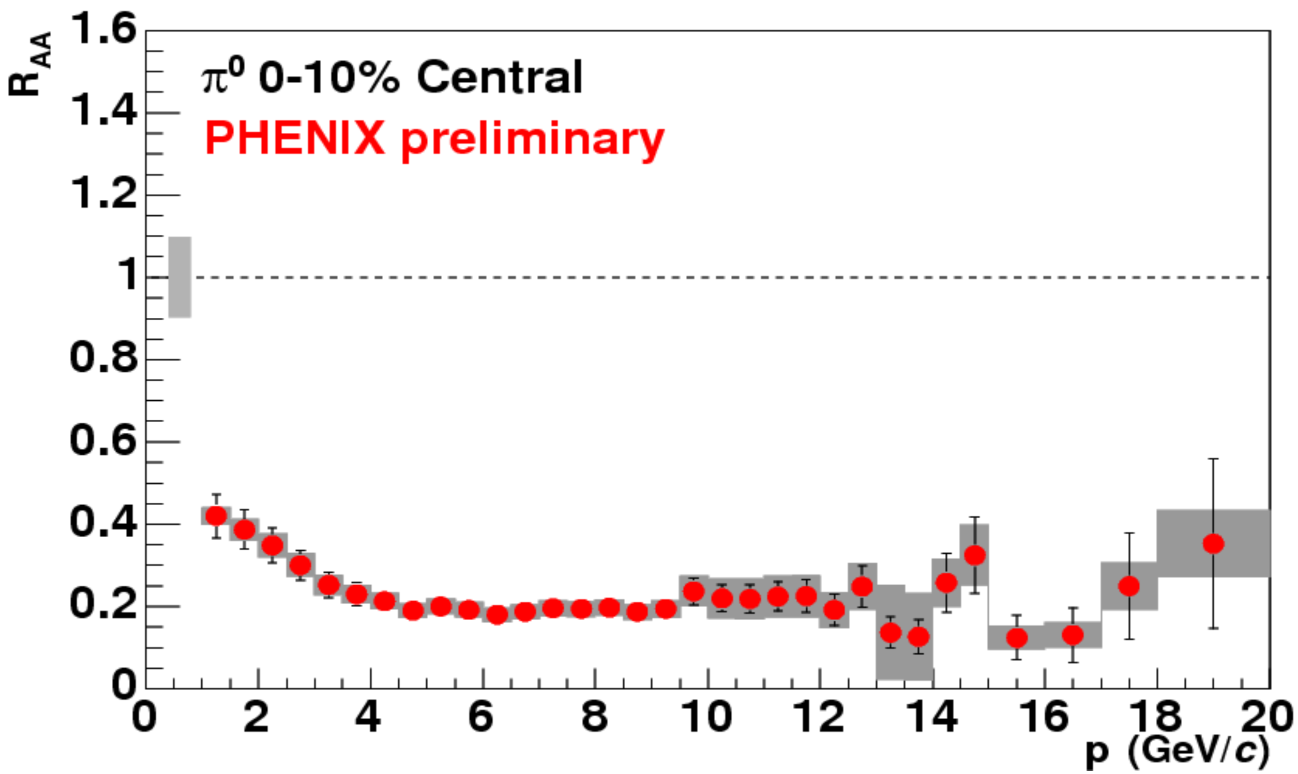

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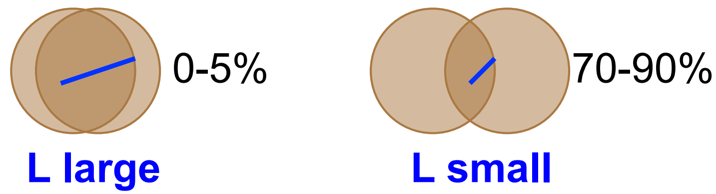
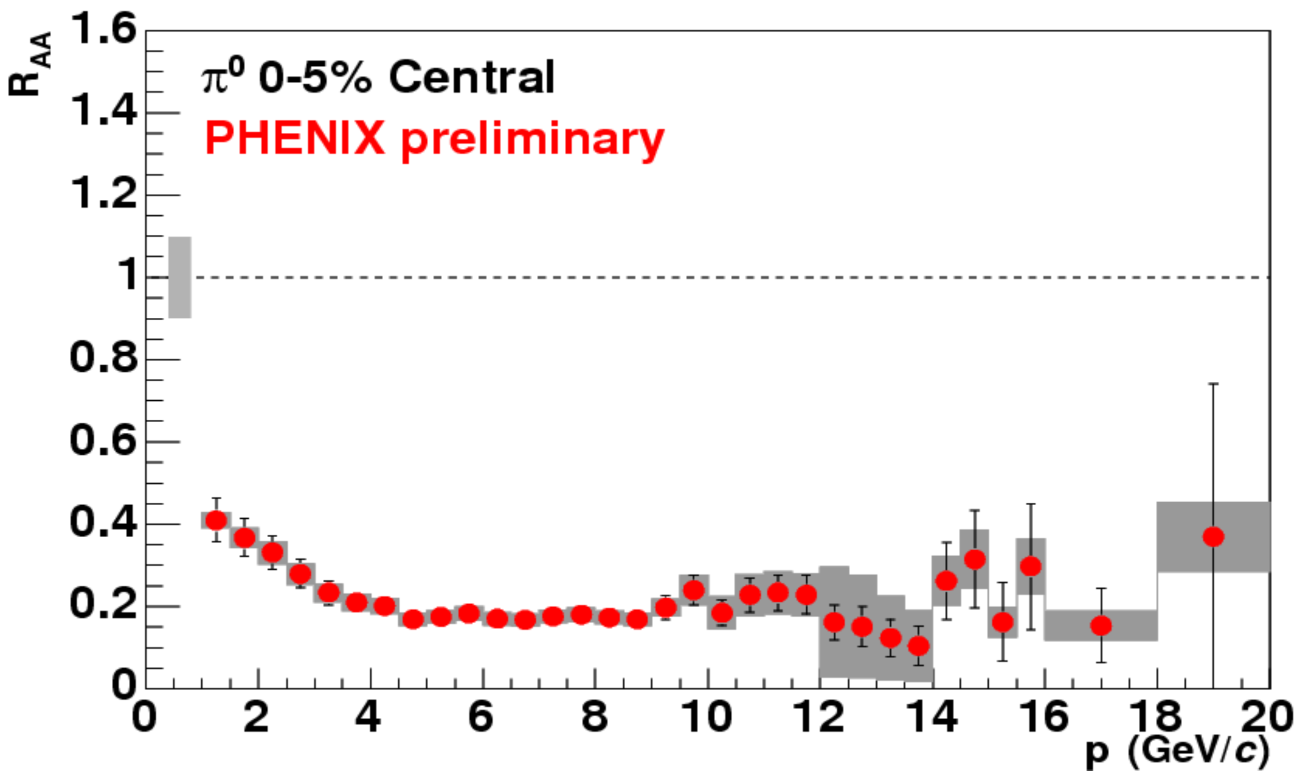
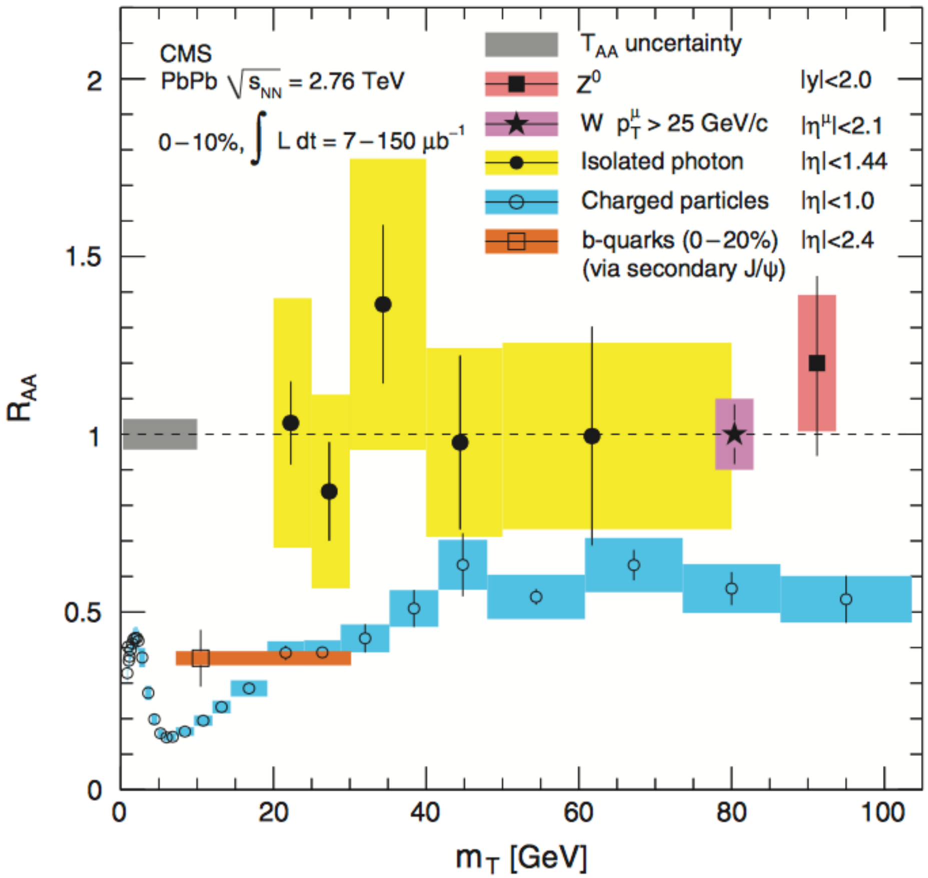




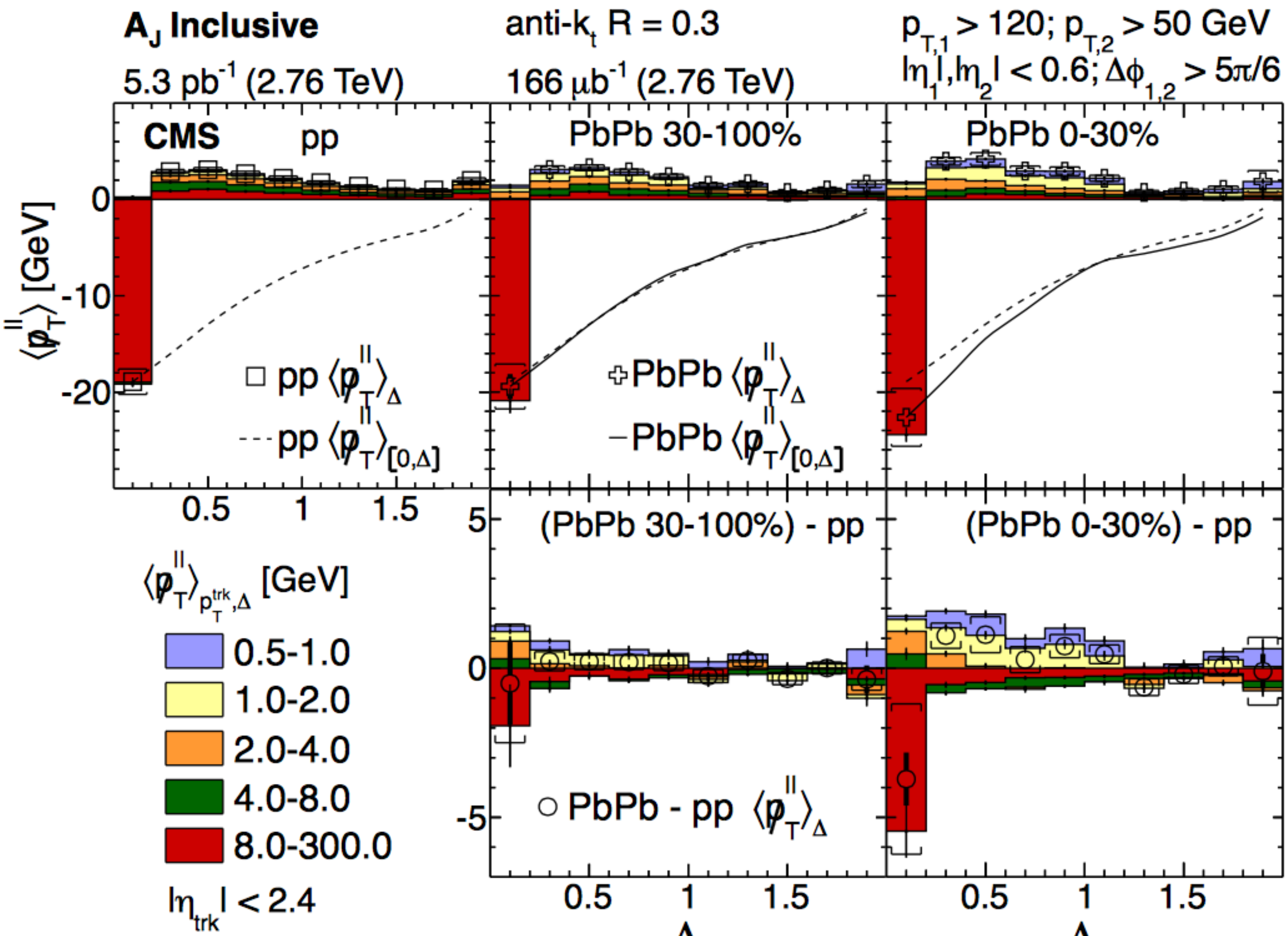
Nuclear modification factor

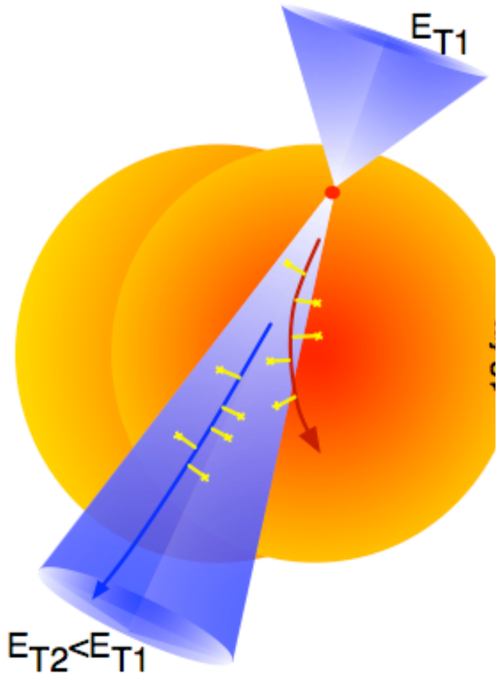


- Uncolored particles are not quenched: Photons, Z, W

Jet modification

- The energy must go somewhere!





Conclusions

- Heavy-ion collisions allow us to test our understanding of quantum field theory in extreme conditions.
- Many different and independent features of heavy-ion collisions point to the formation of a fire ball that evolves like a liquid
- The dynamical description of the collision is getting increasingly quantitative and precise
- The most striking feature of the liquid is that is seems to be strongly coupled with a very low specific shear viscosity $\eta/s \sim 0.2$