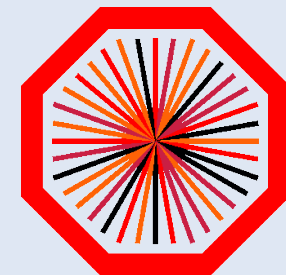


# Probing Cosmic Matter at zero net Baryon Density at the LHC

EBERHARD KARLS  
UNIVERSITÄT  
TÜBINGEN



**ALICE**

A JOURNEY OF DISCOVERY

Benjamin Hess  
University of Tuebingen

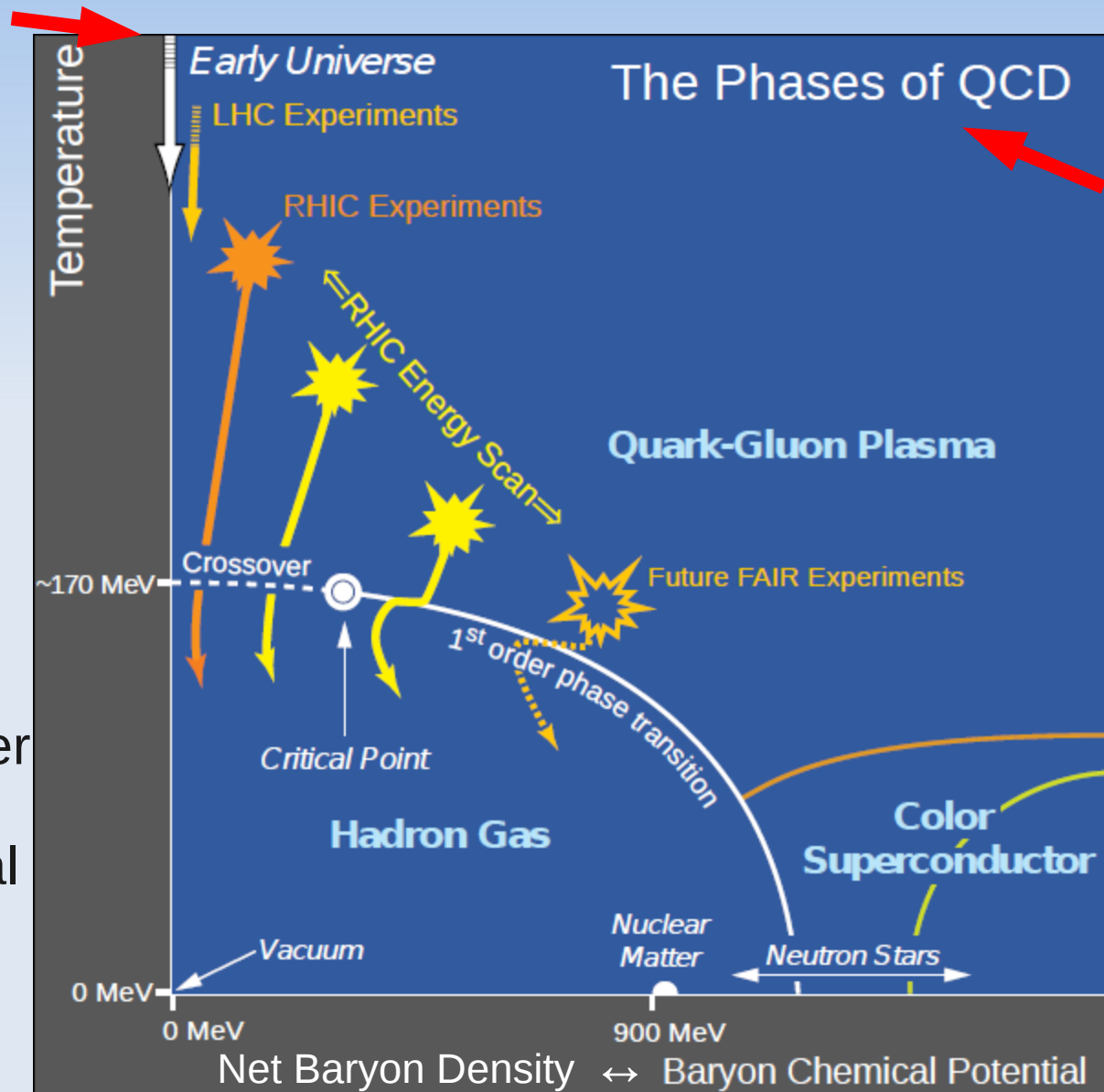
Tuebingen | 12<sup>th</sup> October 2012

# Outline

- Introduction
  - Phases of QCD matter
  - Experimental setup: LHC & ALICE
- (A selection of) signatures of the QGP and experimental results
- Summary and outlook

# Exploring QCD Matter

QGP  $\sim 1\mu\text{s}$   
after the Big Bang



One possibility how it might look like, but not proven by measurement interpretation

Lattice QCD:  
Predicts crossover  
at zero baryon  
chemical potential  
at  $T \sim 170$  MeV

# Large Hadron Collider



3 operation modes/collision types (current values):

- pp:  $\sqrt{s} = 8 \text{ TeV}$  (design: 14 TeV)

- PbPb:  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$  (design: 5 TeV)

- pPb:  $\sqrt{s_{NN}} = 5.023 \text{ TeV}$  **← First collisions in September 2012**

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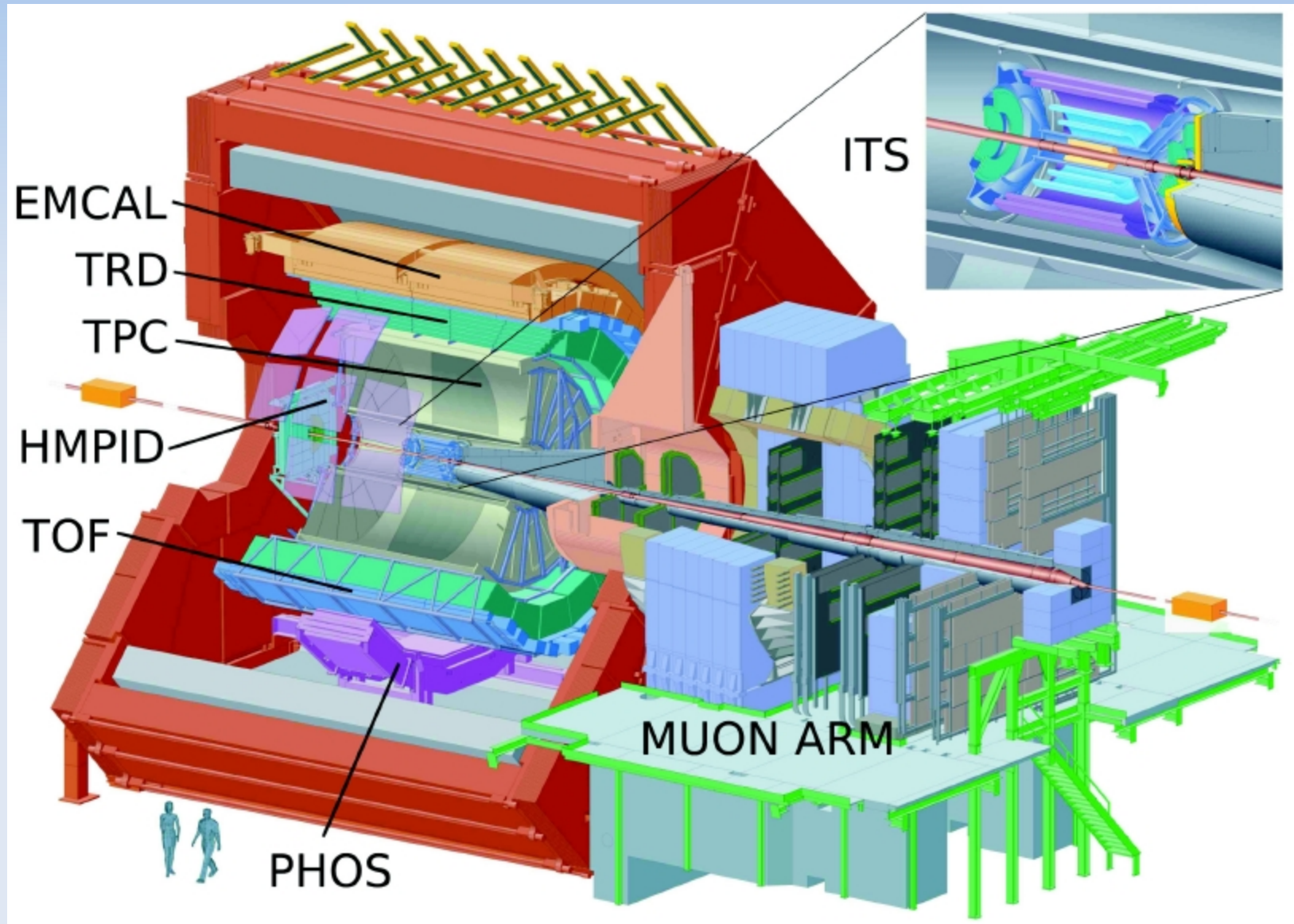
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**All world records!**

**First collisions in  
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# A Large Ion Collider Experiment



# QGP Probes (a selection)

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- Viscosity

(in detail:  $\eta/s$ )

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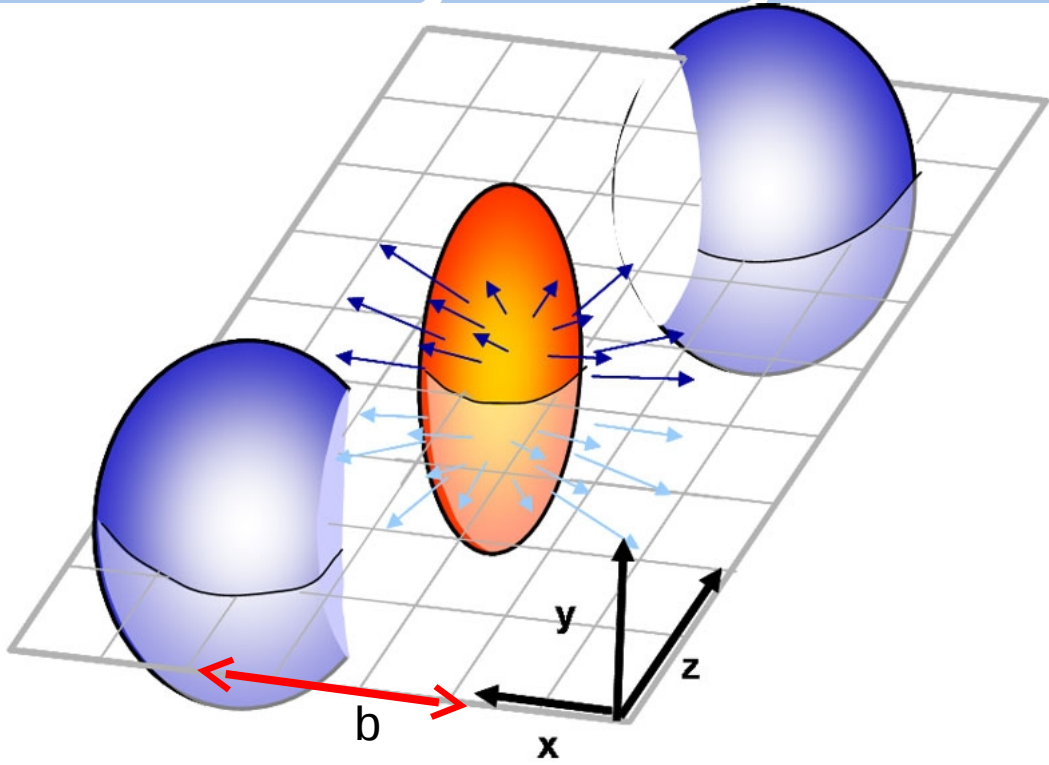
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  - Stopping power  $\Delta E/\Delta x$   
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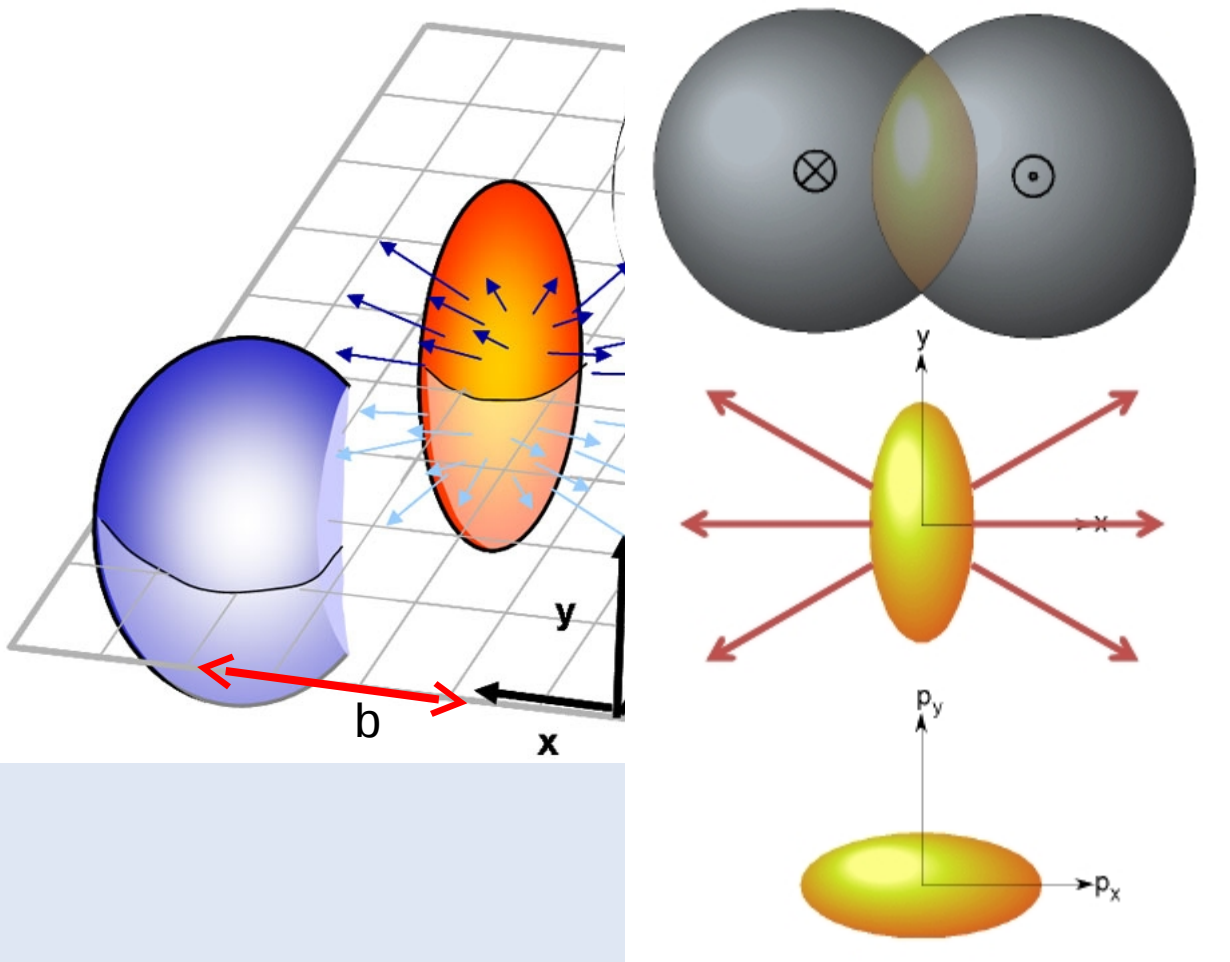
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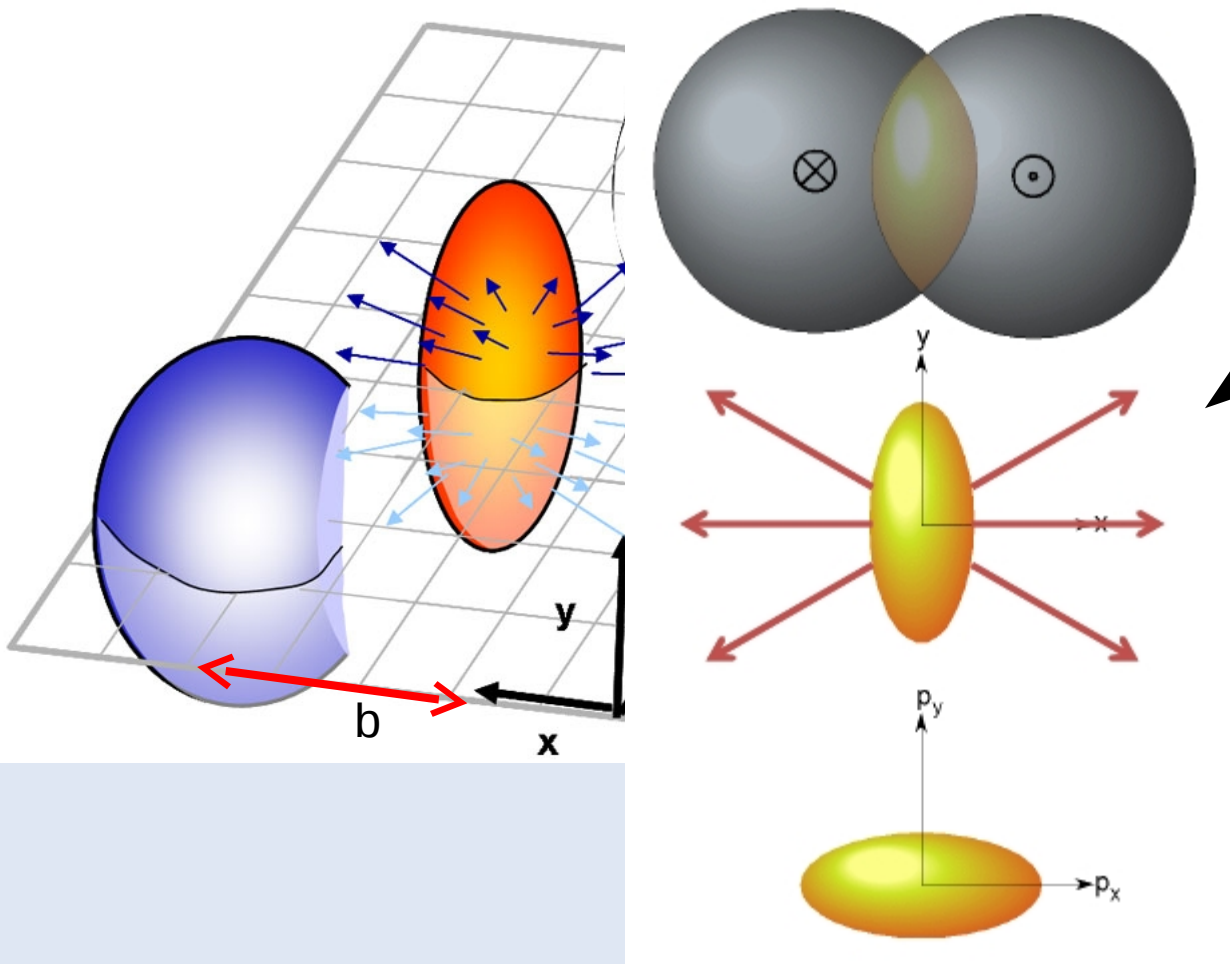
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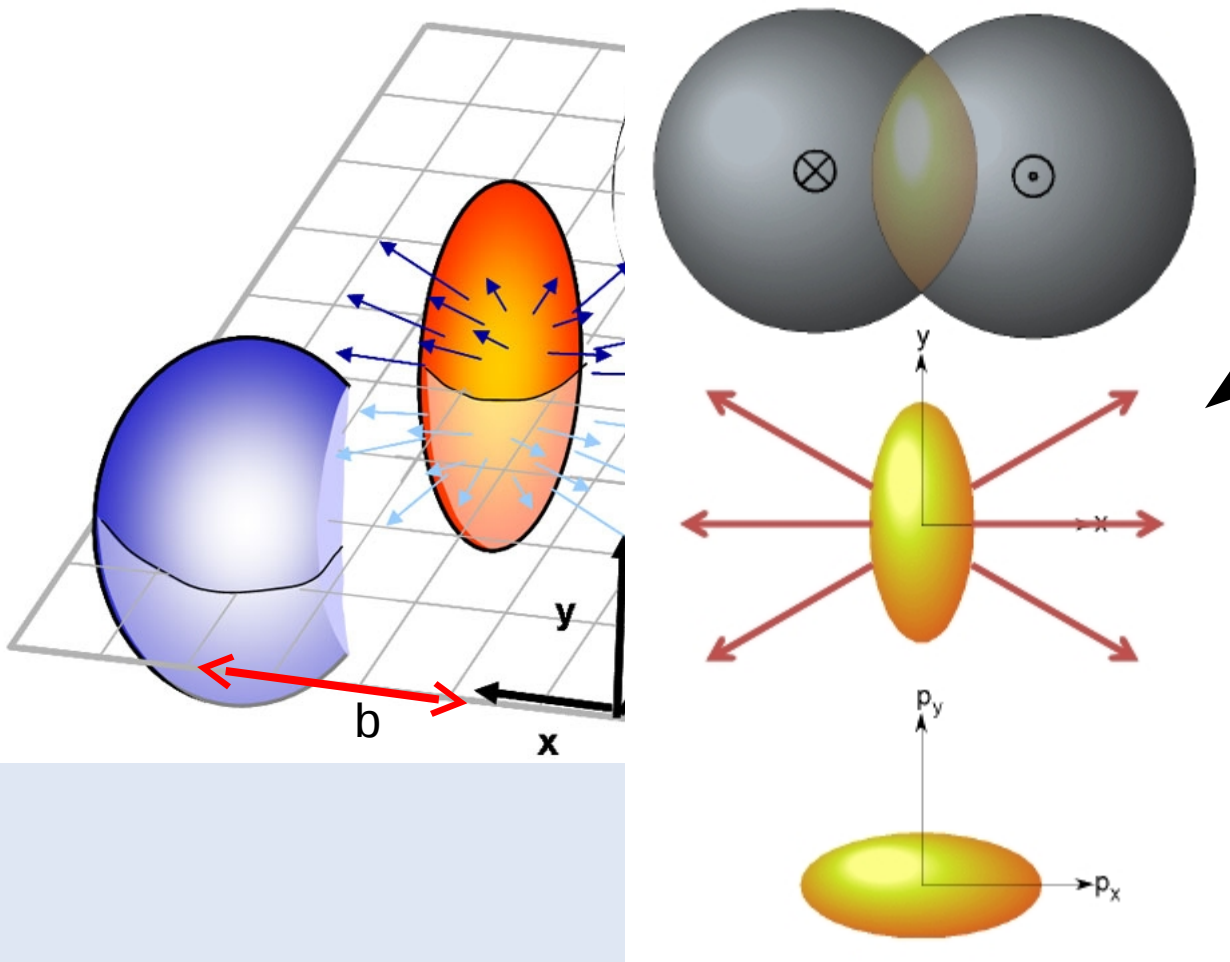


# QGP Probes 1 – Hydrodynamic Behaviour



Geometric anisotropy  
with pressure gradient  
 $dP/dx > dP/dy$  ( $\Delta P > 0$ )

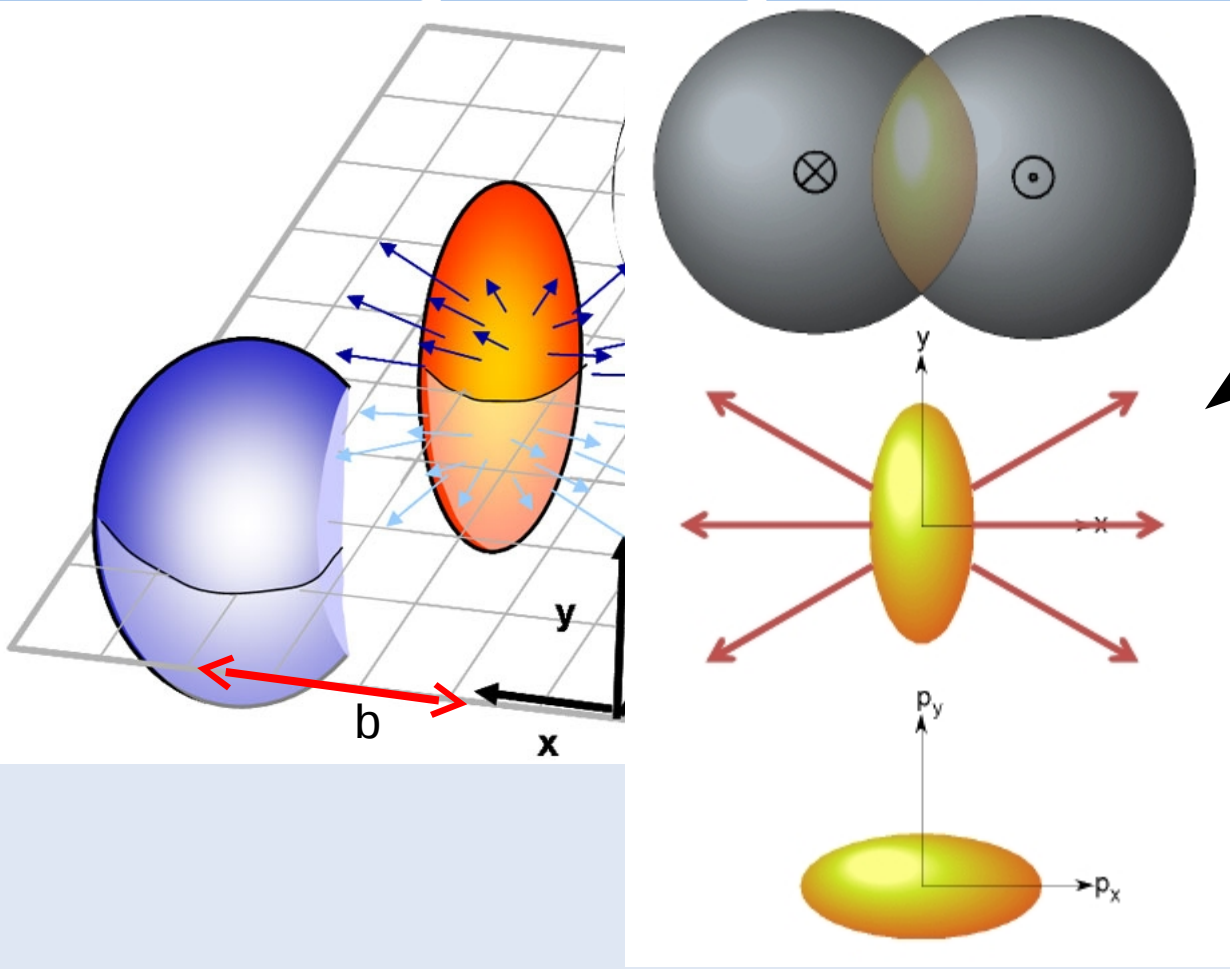
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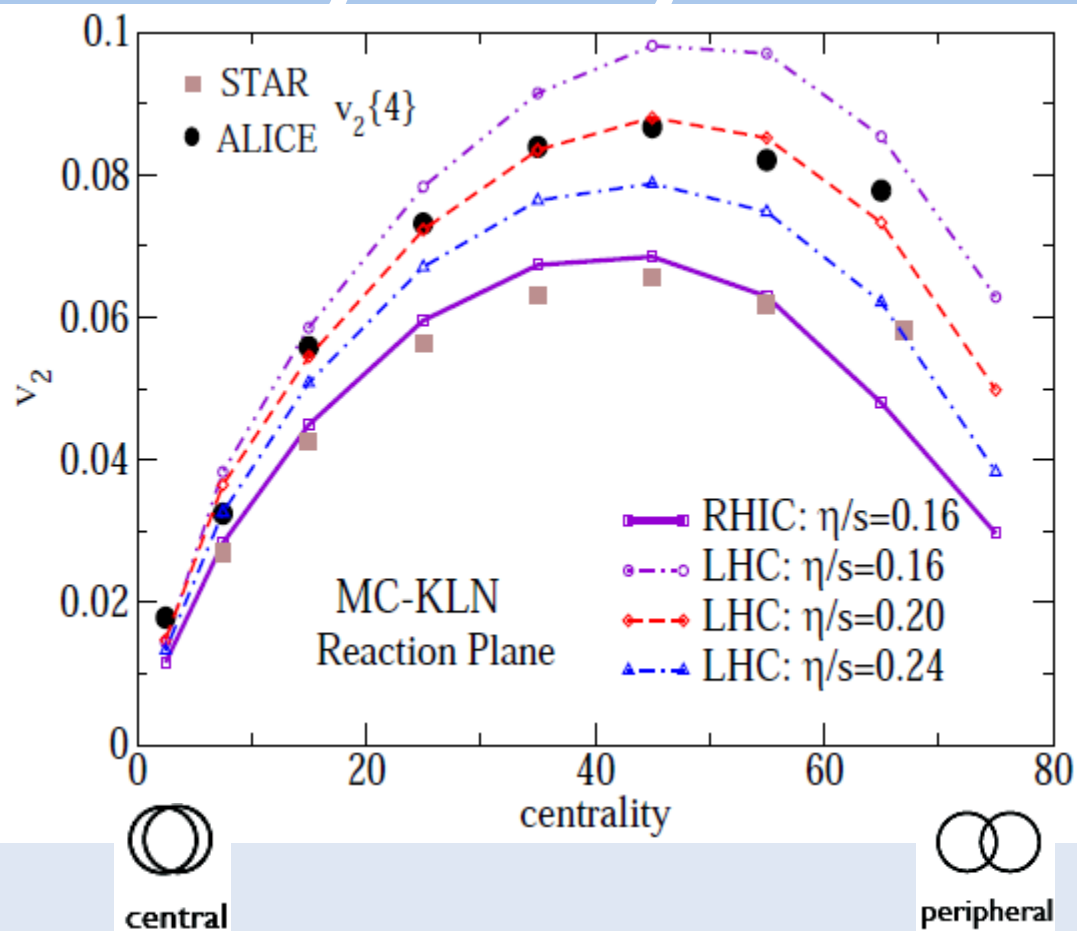
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↓  
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- Anisotropy in p-space characterised by parameter  $v_2$   
(obtained from azimuthal particle distribution)
- $v_2$  from hydrodynamical models with viscosity ( $\eta/s$ ) as input

# QGP Probes 1 – Hydrodynamic Behaviour ...

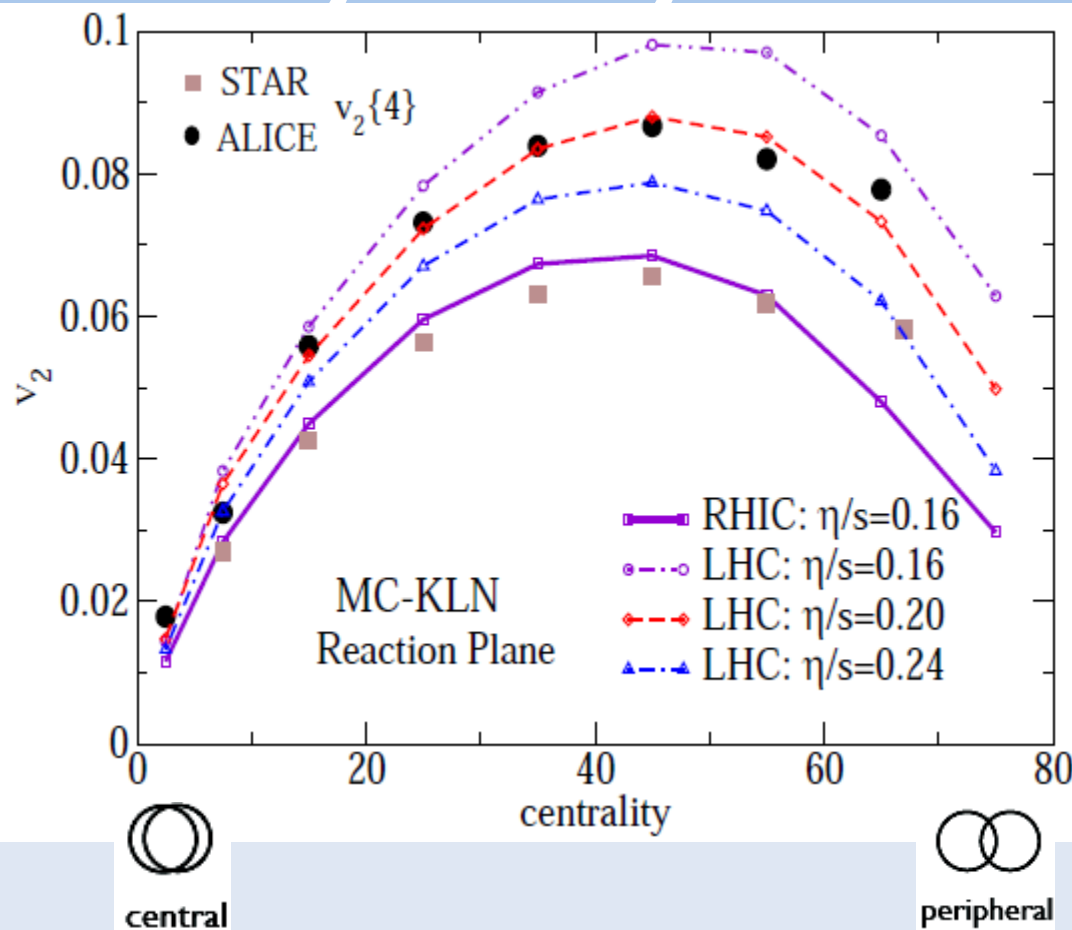
U. Heinz arXiv:1106.6350





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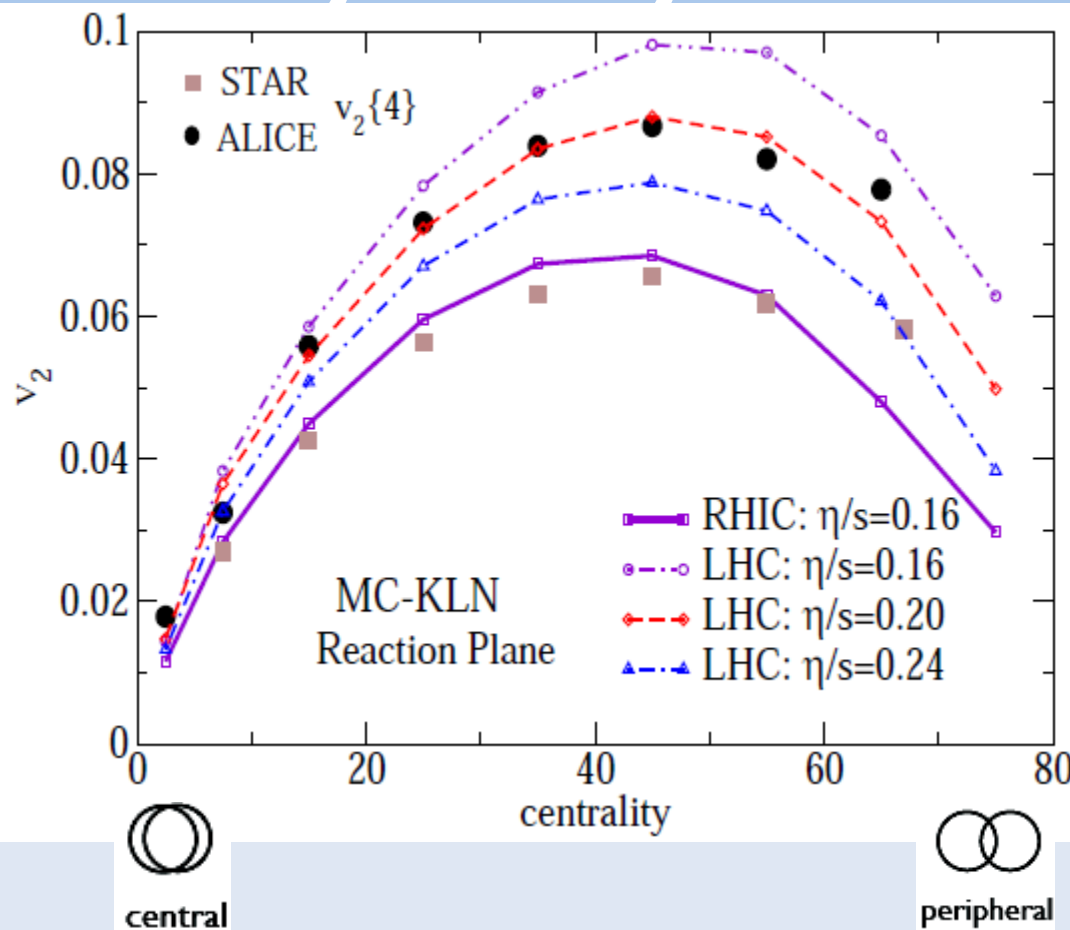
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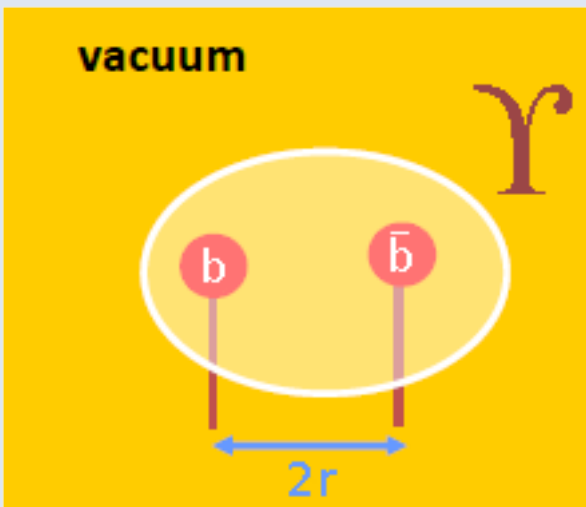
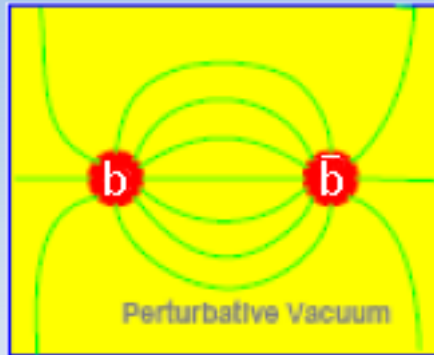
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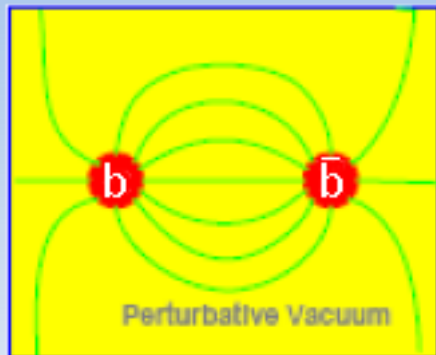
Expected: Extremely hot and dense matter + asymptotic freedom  
=> Small coupling => Behaviour like a gas

Surprising result: Perfect liquid (strong coupling, minimal viscosity)

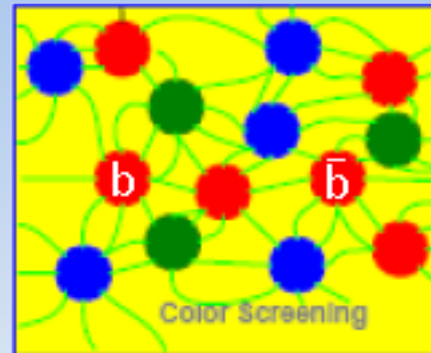
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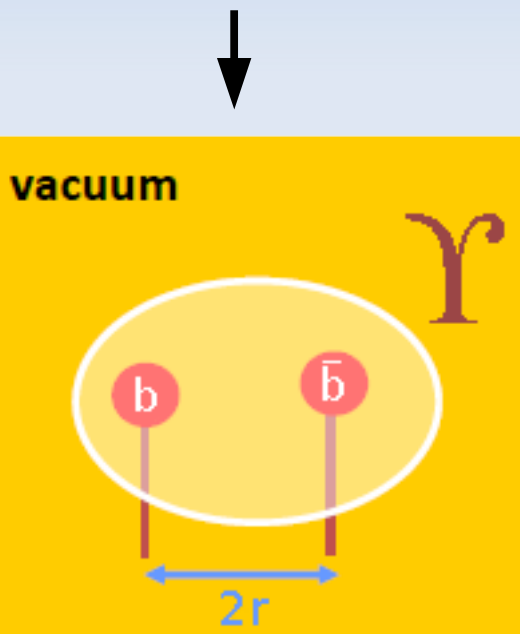
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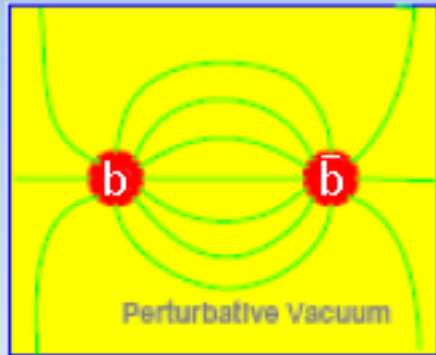
Add QGP



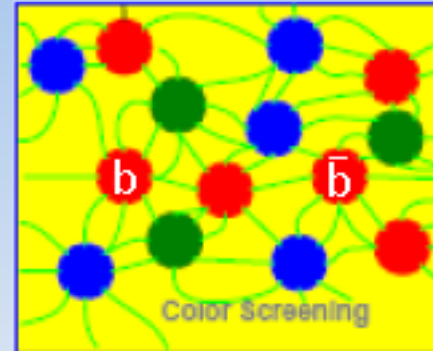
Screening is characterised by Debye-screening length  $\lambda_D(T)$



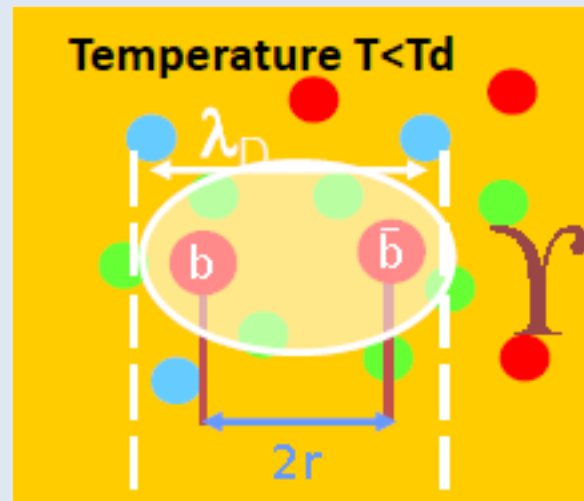
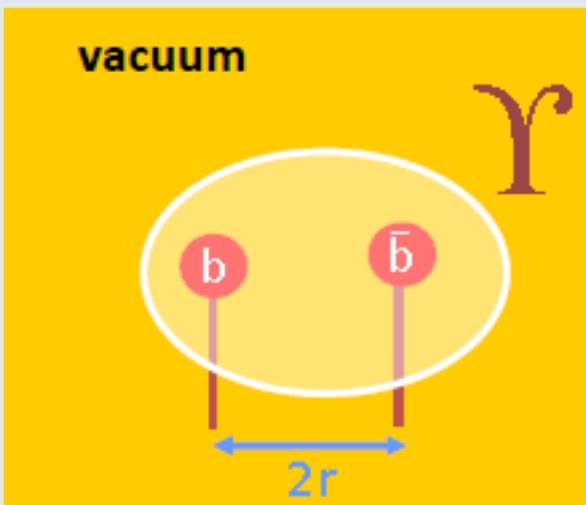
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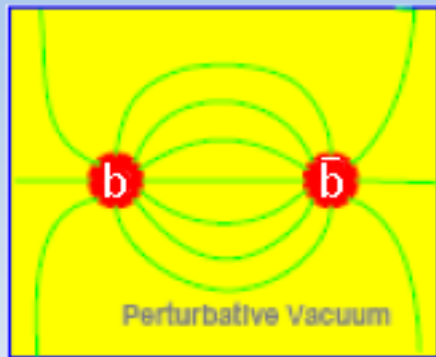
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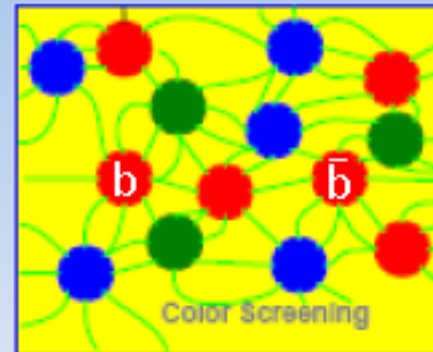
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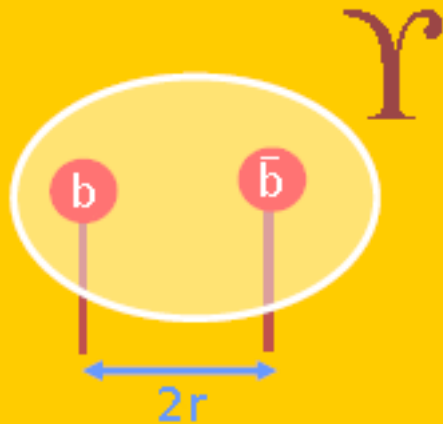
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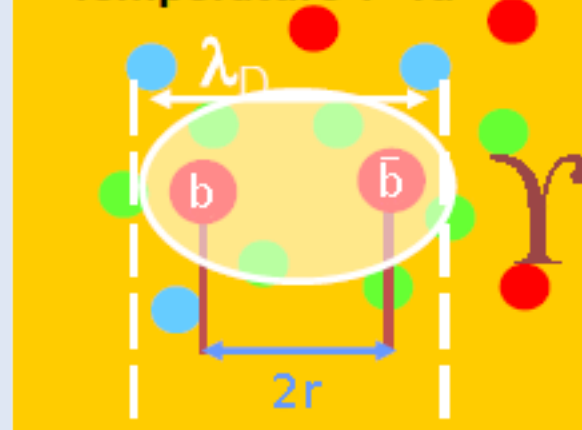
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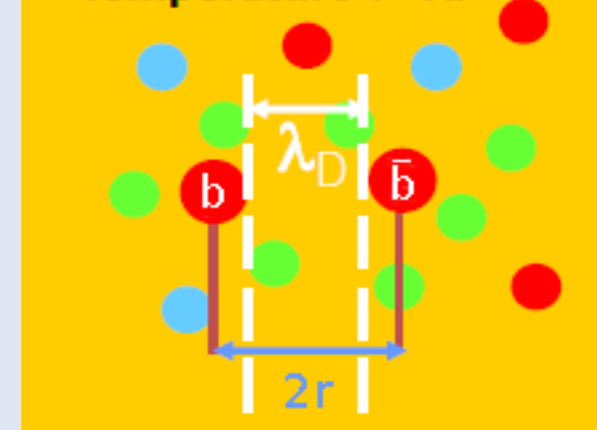
vacuum



Temperature  $T < T_d$



Temperature  $T > T_d$



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- Different quarkonia states (e.g. radial excitations) have different binding radii:

State	$\Upsilon(1S)$	$\Upsilon'(2S)$	$\Upsilon''(3S)$
Mass $m$ [GeV/c <sup>2</sup> ]	9.46	10.02	10.36
Binding energy $\Delta E$ [GeV]	1.10	0.54	0.20
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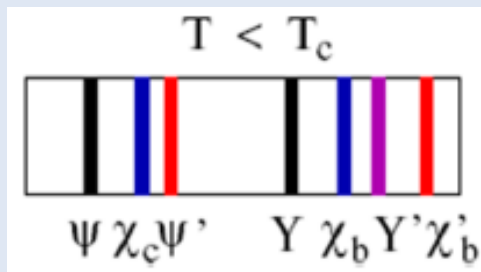
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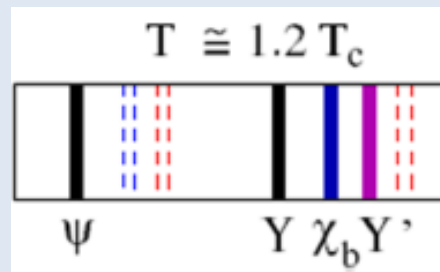
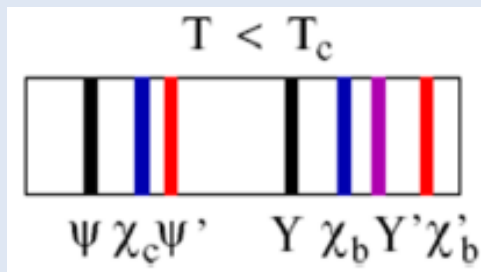
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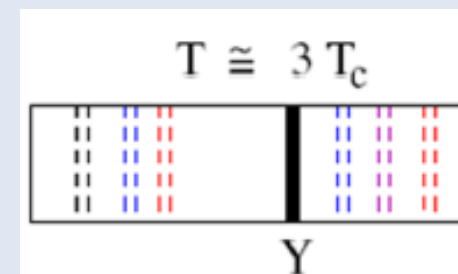
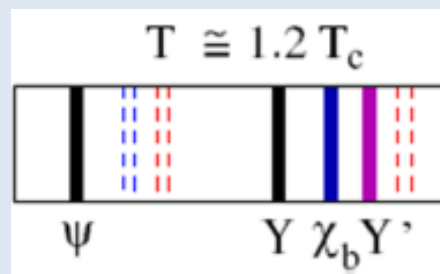
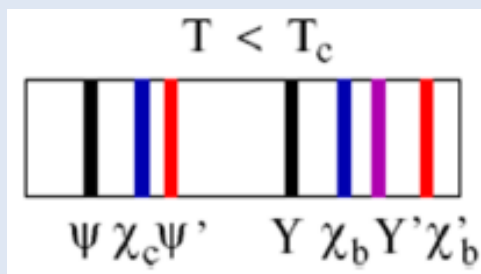


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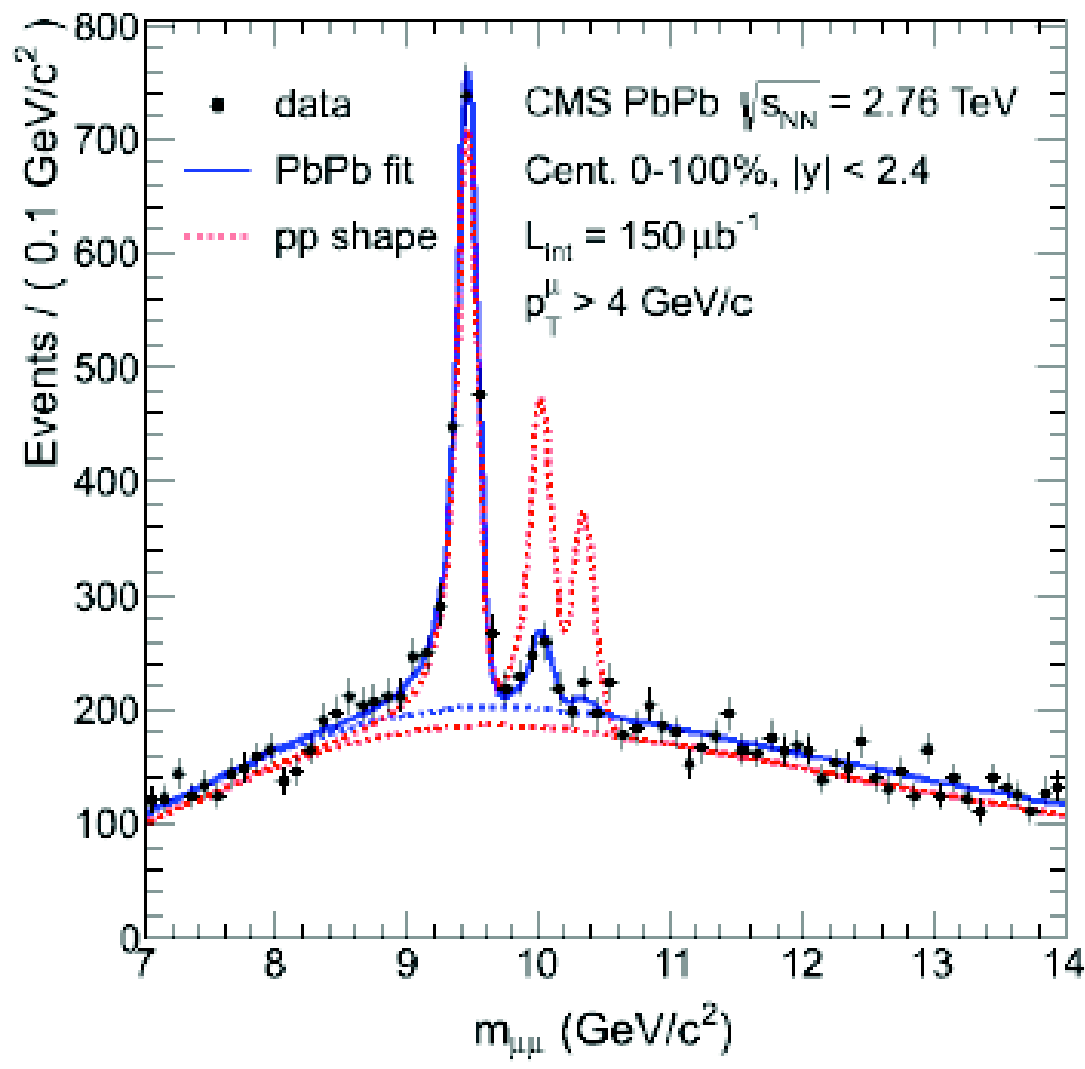
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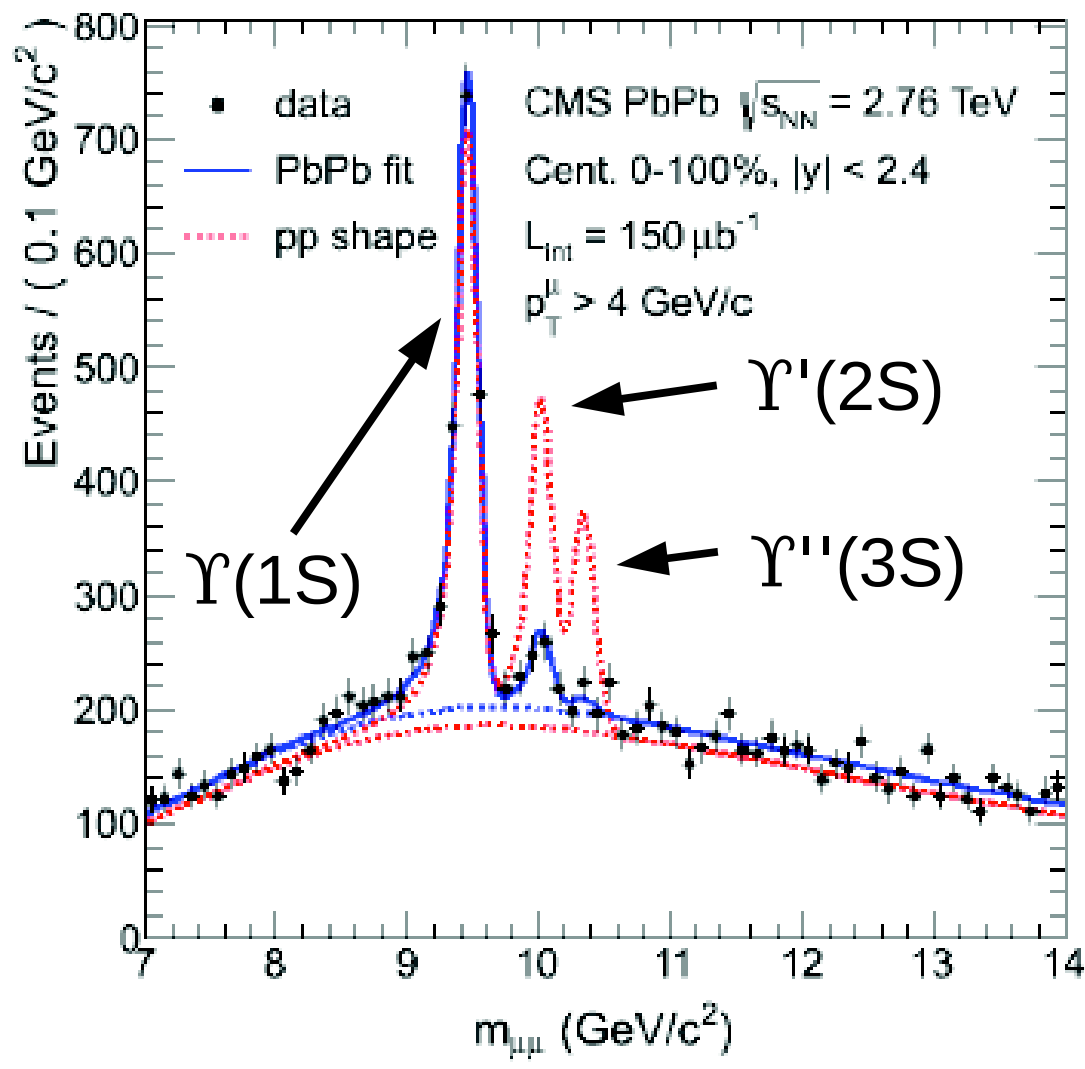


# QGP Probes 2 - Quarkonia Suppression ...



T. Dahms (CMS Collaboration),  
Talk at Hard Probes 2012

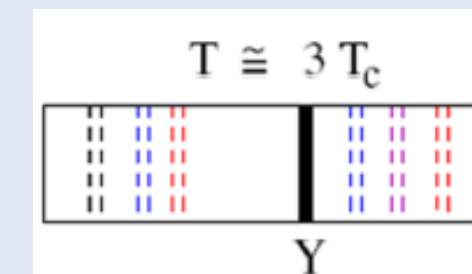
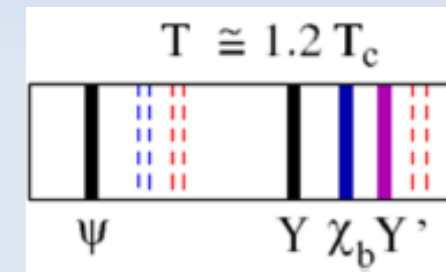
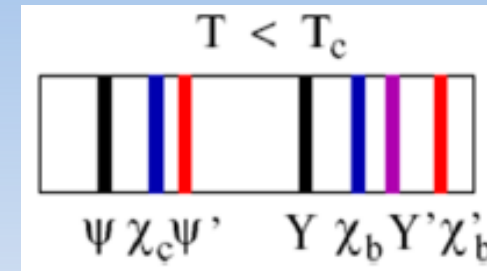
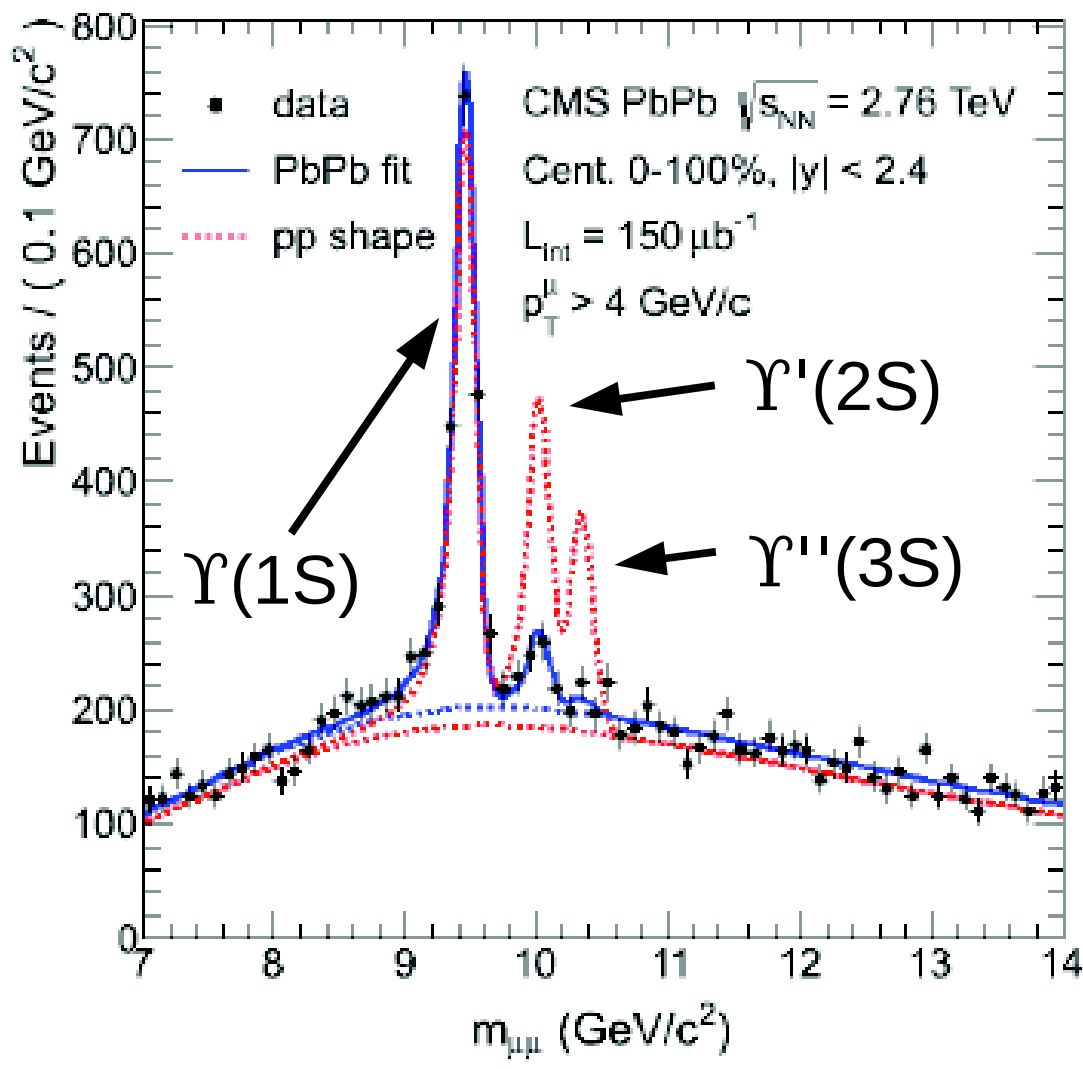
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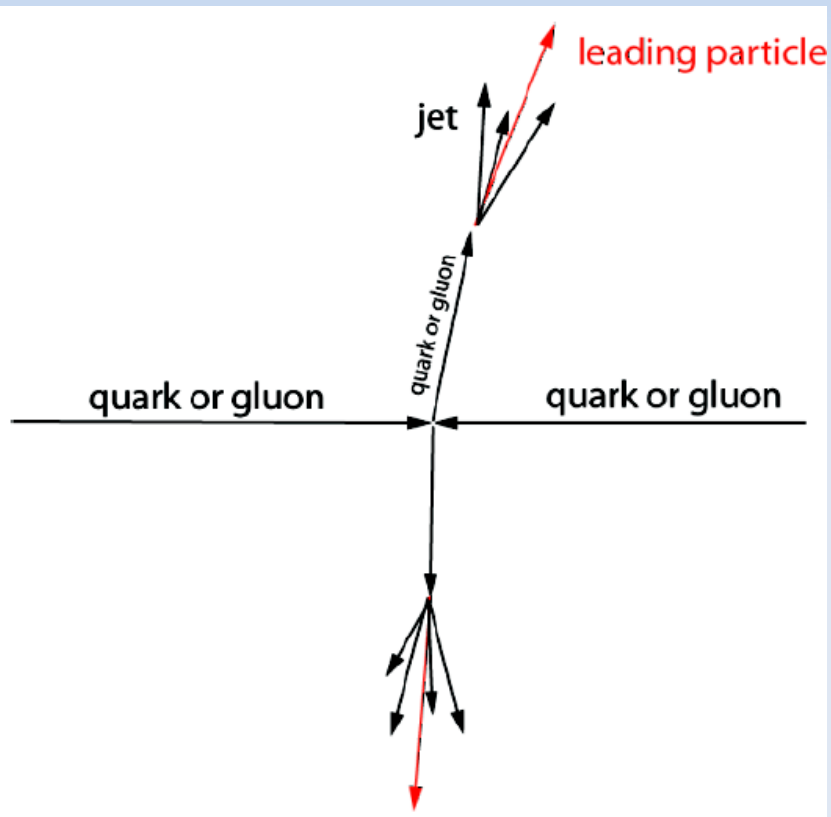


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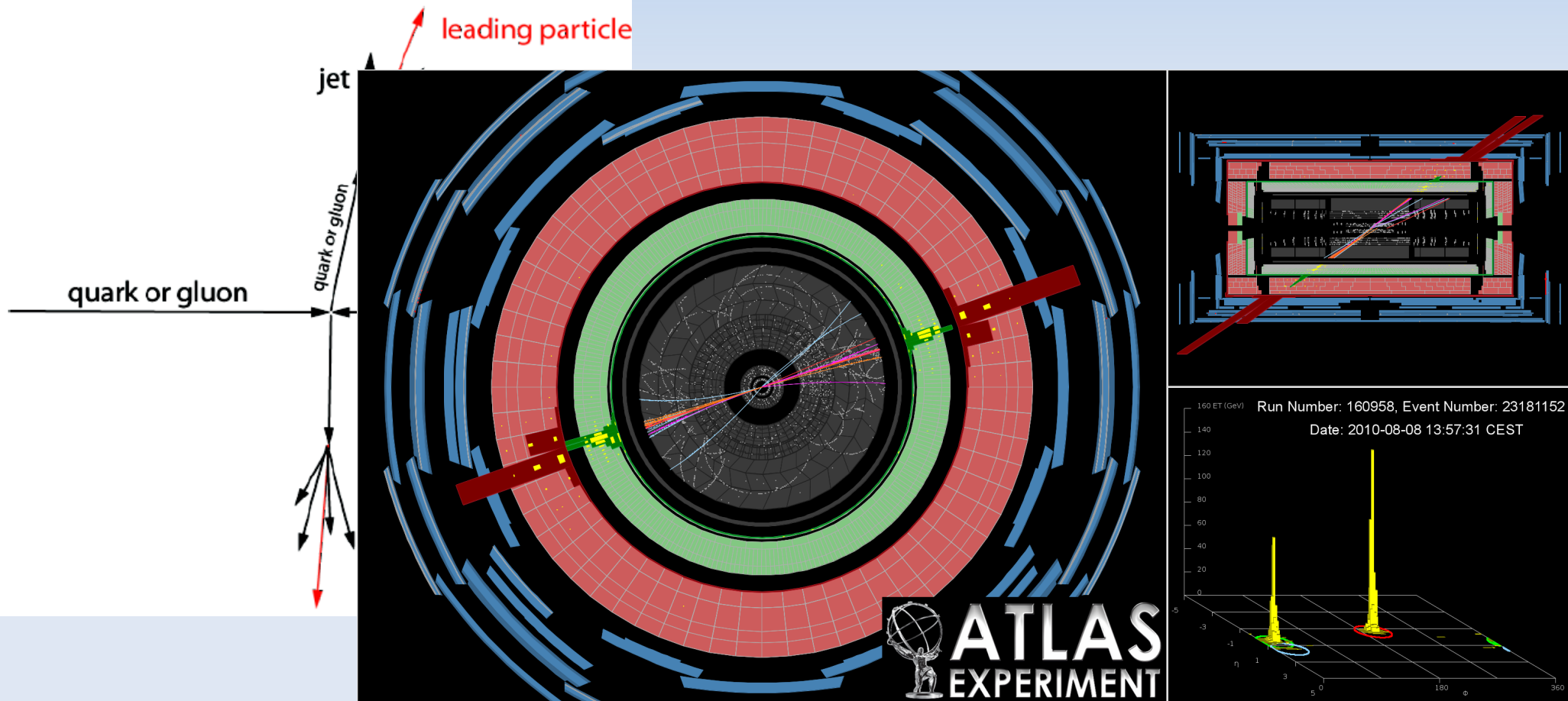
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In **pp collisions**, initial hard scattering produces back-to-back di-jet....



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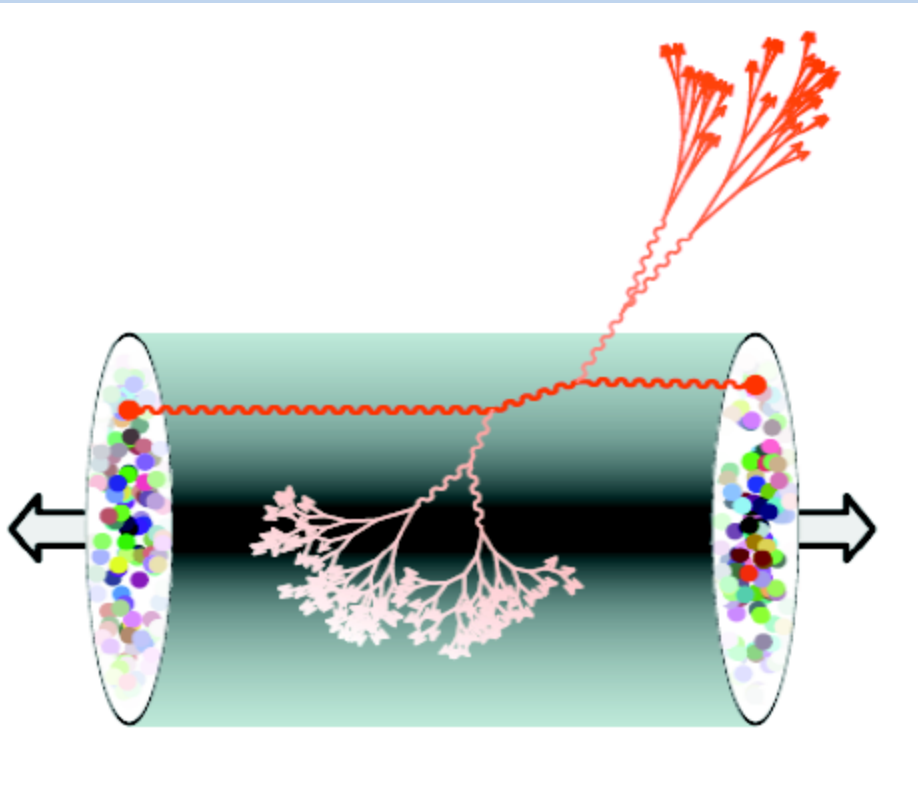
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ATLAS Experiment © 2012 CERN

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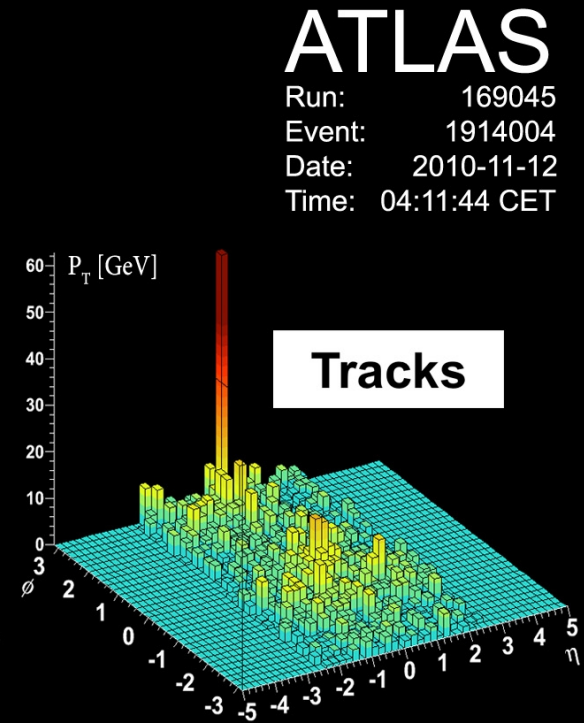
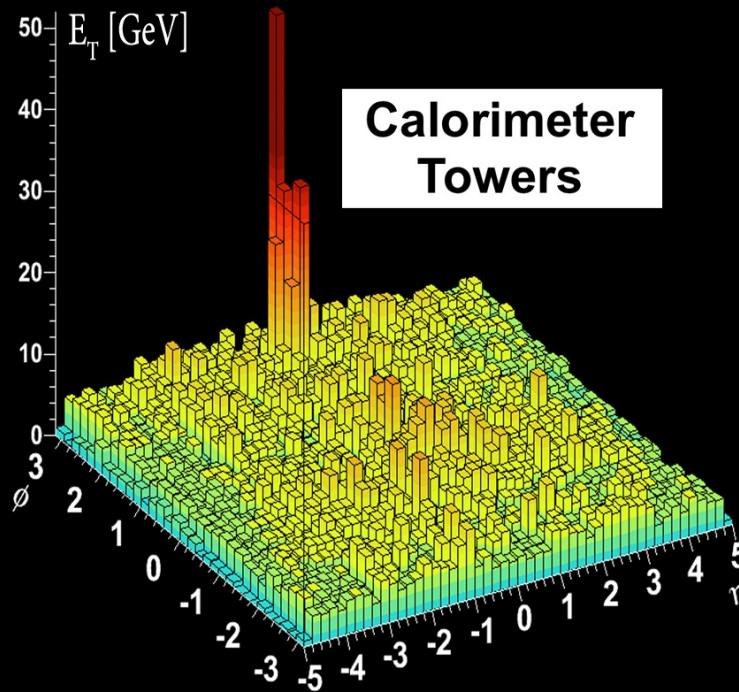
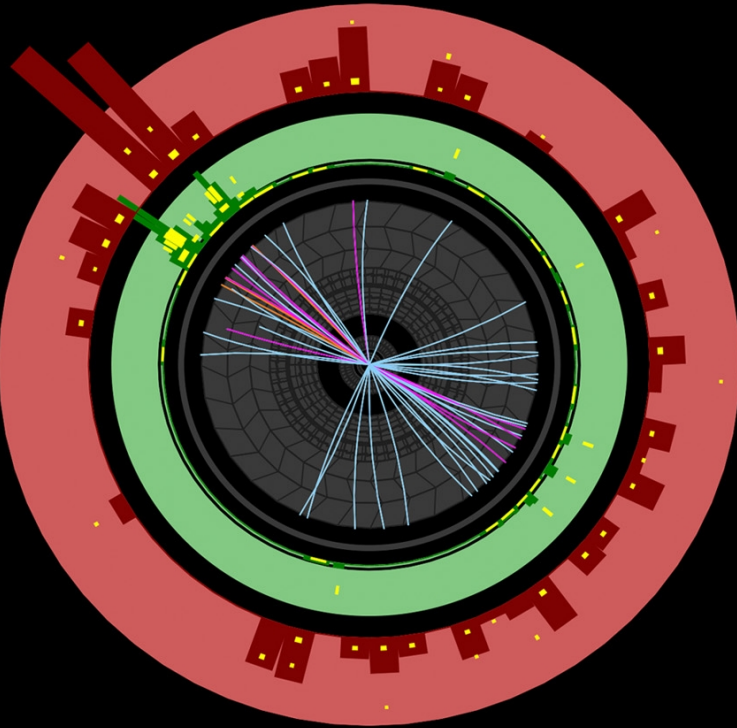
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**ATLAS**  
Run: 169045  
Event: 1914004  
Date: 2010-11-12  
Time: 04:11:44 CET

# Summary and Outlook

- Some form of QGP is produced in ultra-relativistic heavy-ion collisions
- A number of experiments has studied the QGP over several years - studies still ongoing
- A variety of probes exists to constrain / determine the parameters of the QGP
- History continues:
  - Upgrades of RHIC and LHC experiments and colliders
  - New facilities like FAIR under construction to map out the QCD phase transition at finite net baryon densities

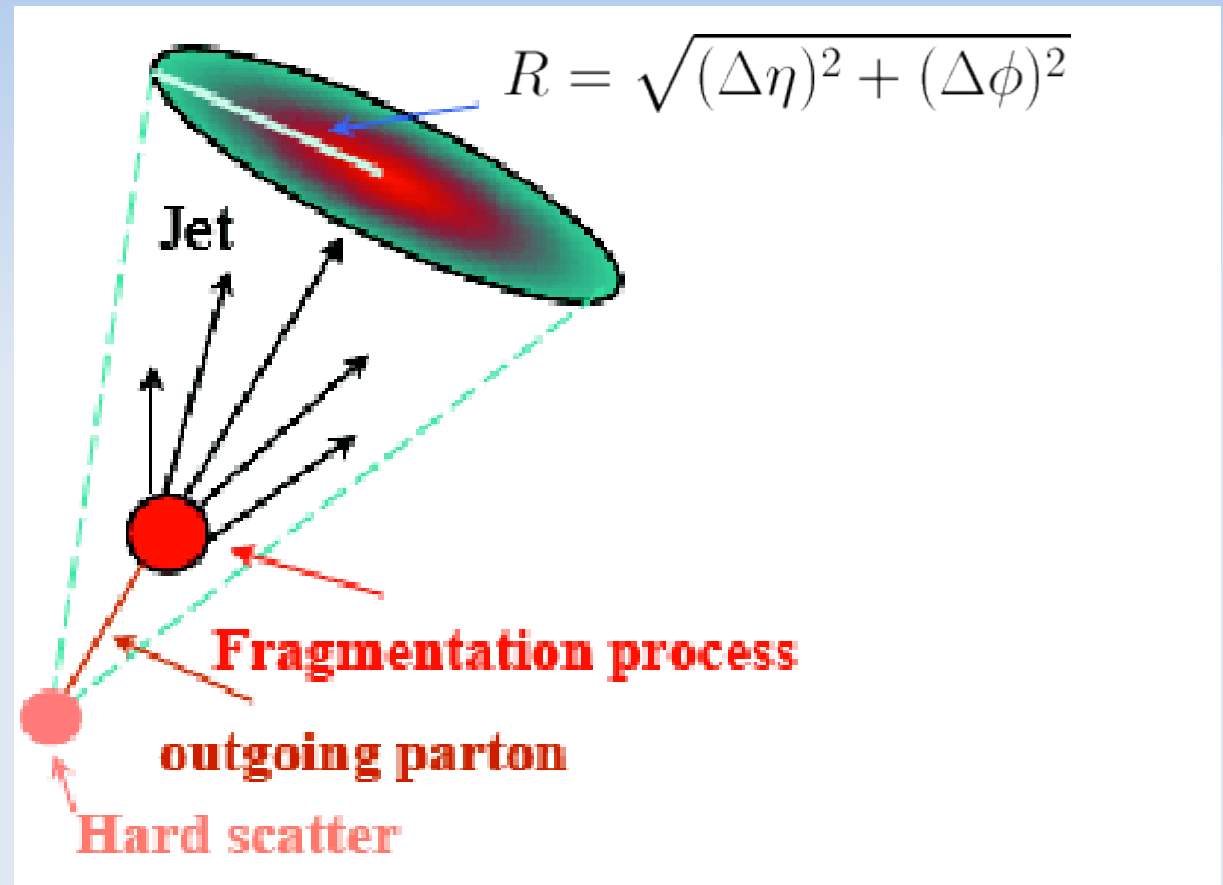
# Backup

# Jets as a QGP Probe 1

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=> Need suitable probes
- Focus here: Jets!

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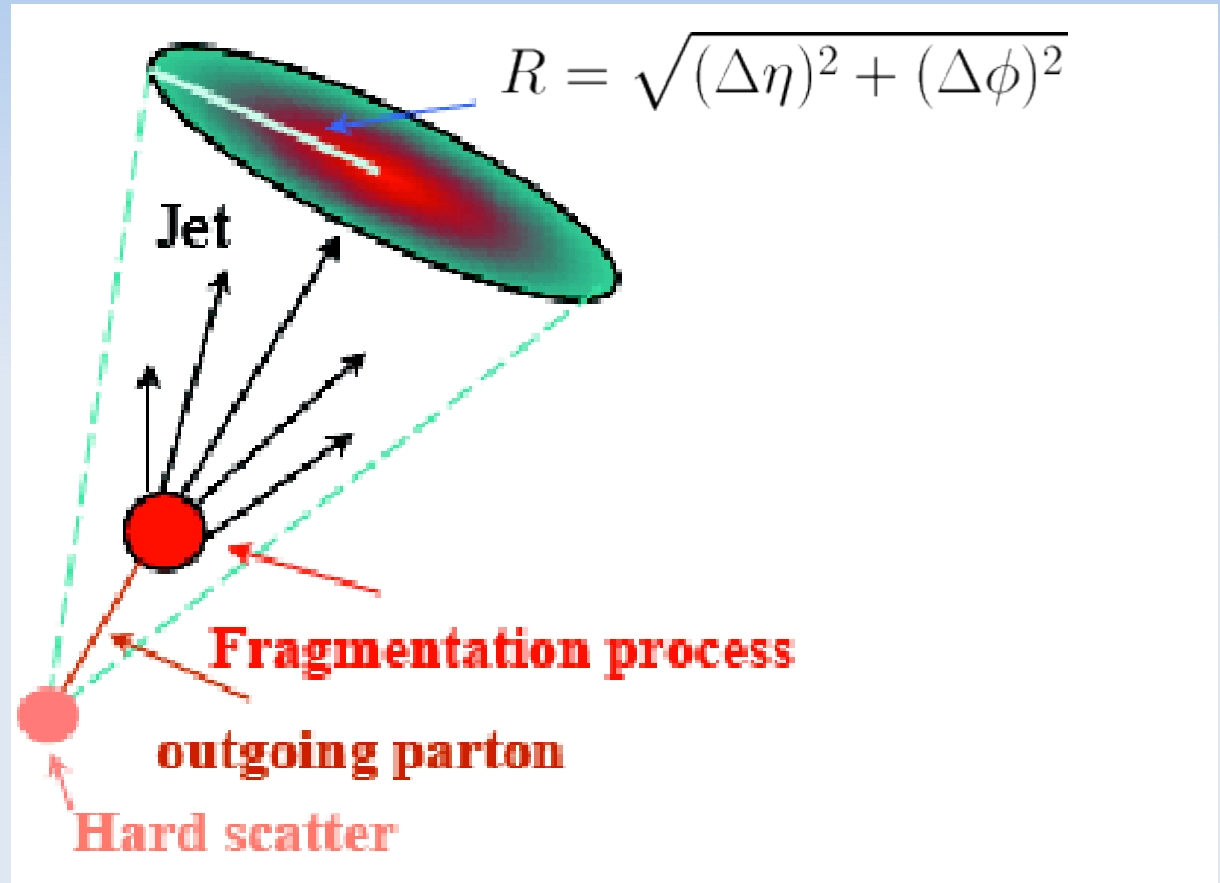


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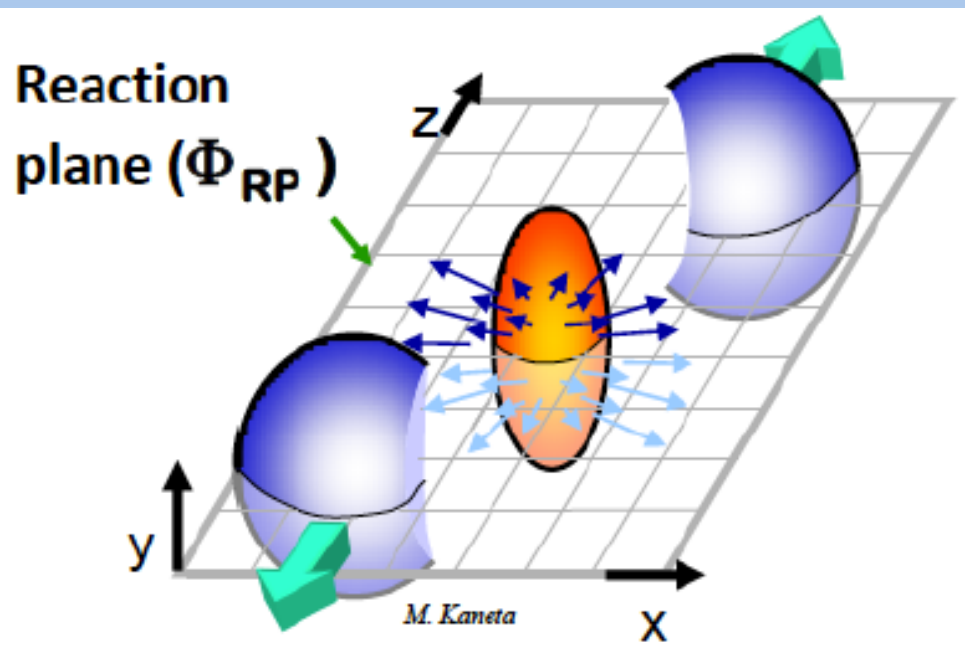
- Advantage: Good comparability with theory, since initial parton momentum  $\sim$  jet momentum
- In particular powerful, if jet particles are identified!

# Particle Flow

## - Particle Flow:

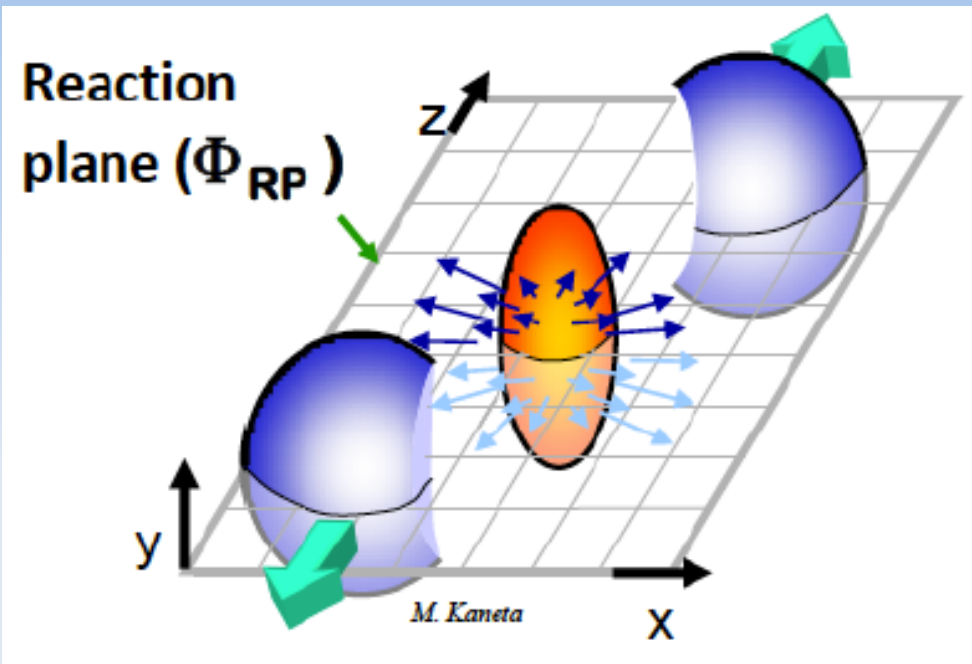
- Azimuthal distribution of particles in plane  $\perp$  to beam direction
- Perform Fourier decomposition and compare with models
- => Allows to determine  $\eta/s$  of created matter

# Particle Flow





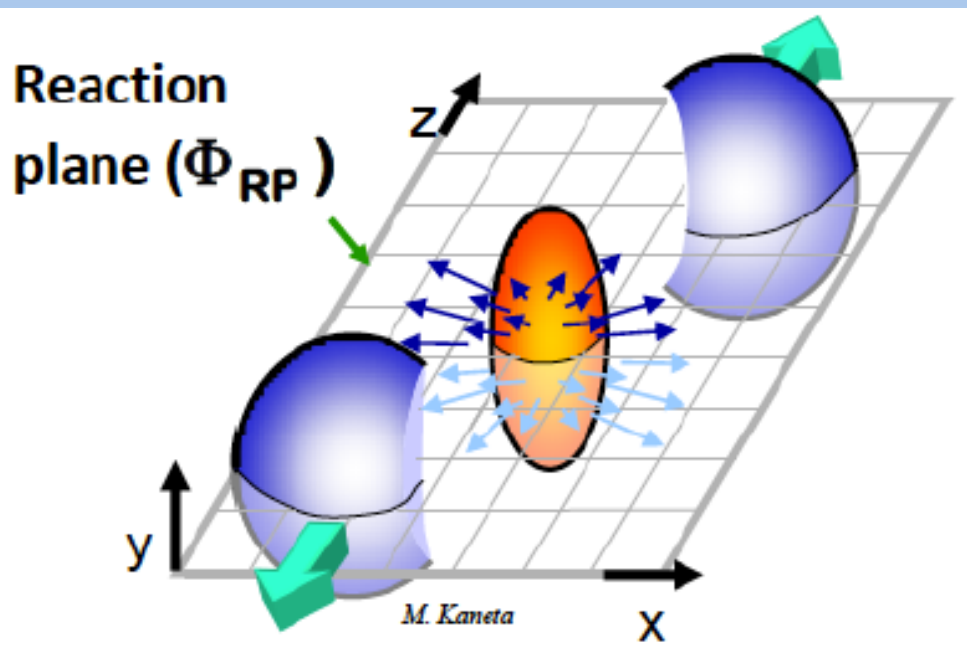
# Particle Flow



$$\frac{dN}{d\phi} \propto \mathbf{1} + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

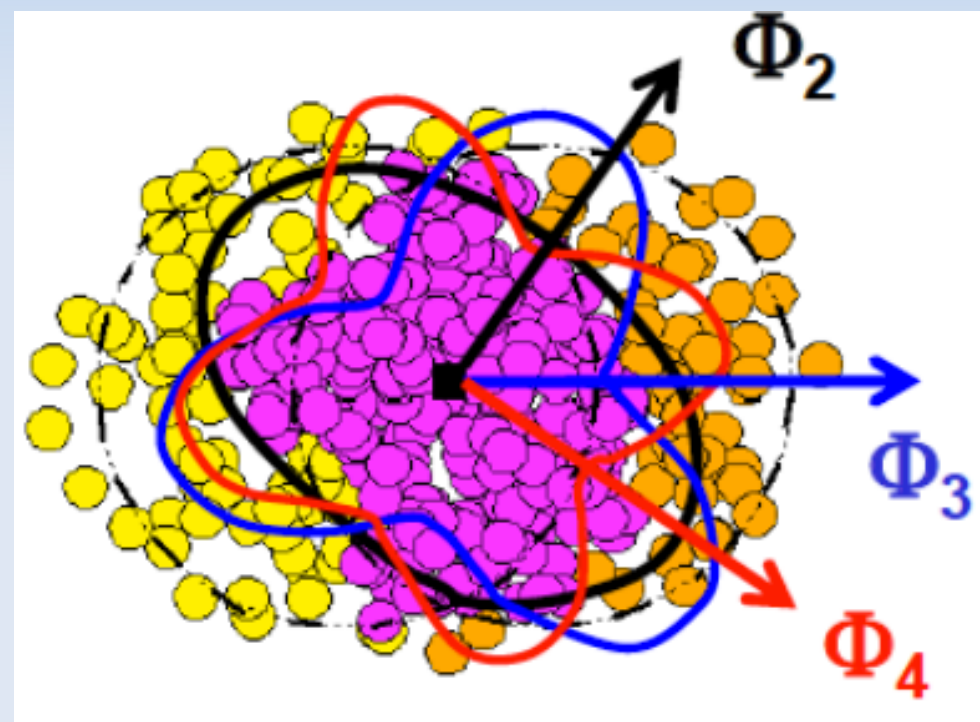
$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

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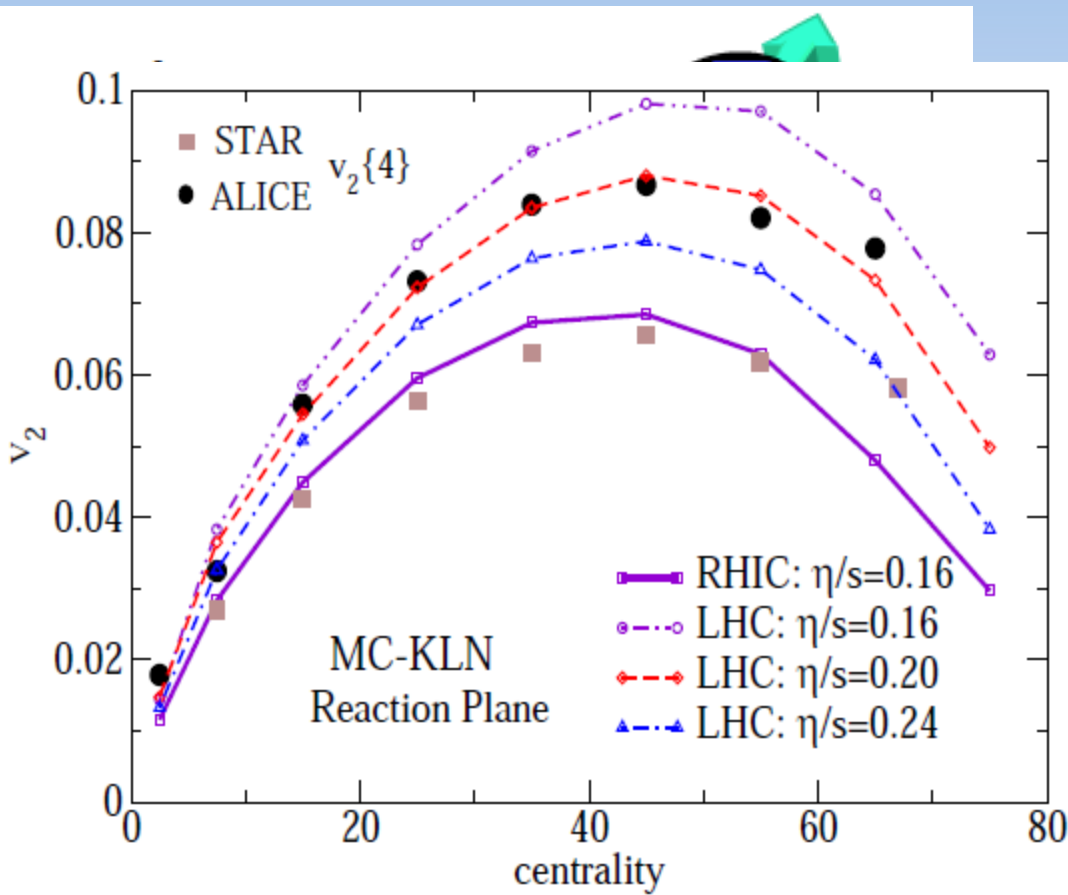


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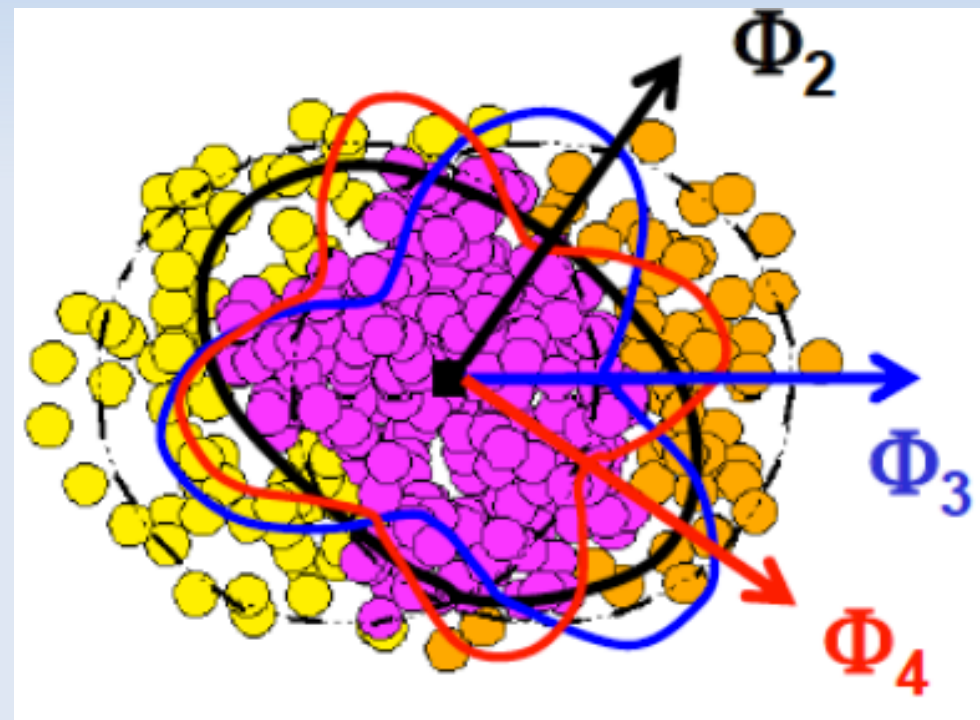


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U. Heinz arXiv:1106.6350:

At LHC energies,  $v_2$  sensitive to details of initial shear stress profile => Not clear, whether  $\eta/s$  really increases with temperature

# Some History 1

## - 2000: First QGP hints at SPS (CERN):

*“[...] a new state of matter has been created [...] at energy densities which exceed by more than a factor 20 that of normal nuclear matter [...]. This state of matter [...] features many of the characteristics of the theoretically predicted quark-gluon plasma [...].”*

(CERN press release PR01.00)

## - 2003, 2005: First QGP studies at RHIC (BNL):

*“[...] Analysis of data from collisions of gold nuclei [...] has shown a peculiar effect, called "jet quenching" [...]. This effect is one possible signature of quark-gluon plasma formation, but other possible interpretations need to be examined.”*

(BNL press release January 13, 2003)

*“[...] created a new state of hot, dense matter out of the quarks and gluons [...]. 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 [...].”*

(BNL press release April 18, 2005)

# Some History 2

- **2011: Further QGP studies at LHC (CERN):**

*“[...] evidence that the matter created in lead ion collisions is the densest ever observed [...]. Confirmed the RHIC experiments' finding that QGP behaves almost like an ideal fluid [...]. Jet quenching [...] reported [...]”*

(CERN press release PR04.11)

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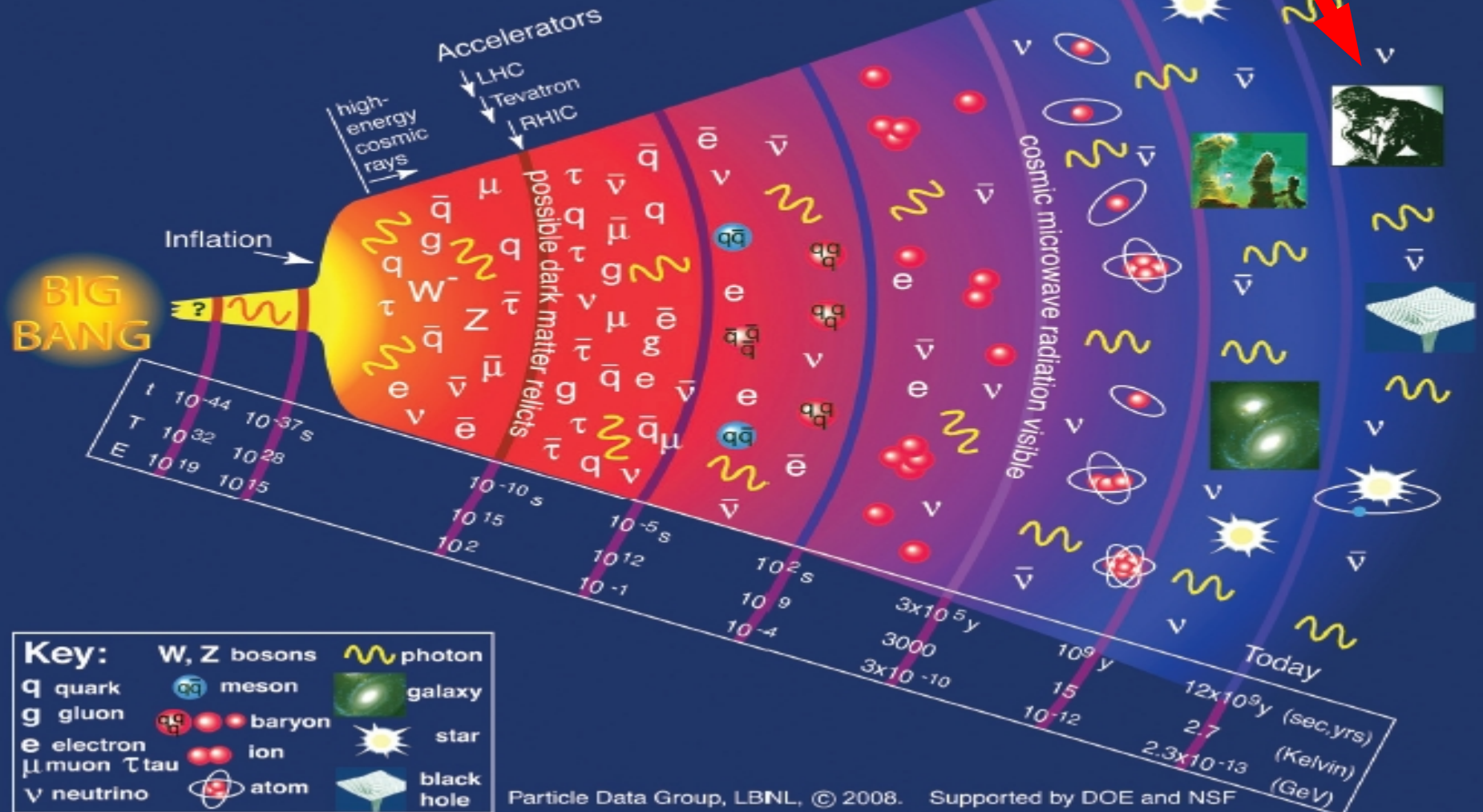
- **2013 and beyond:**

Remains to be seen...

# Some Older History

## History of the Universe

Going from here....

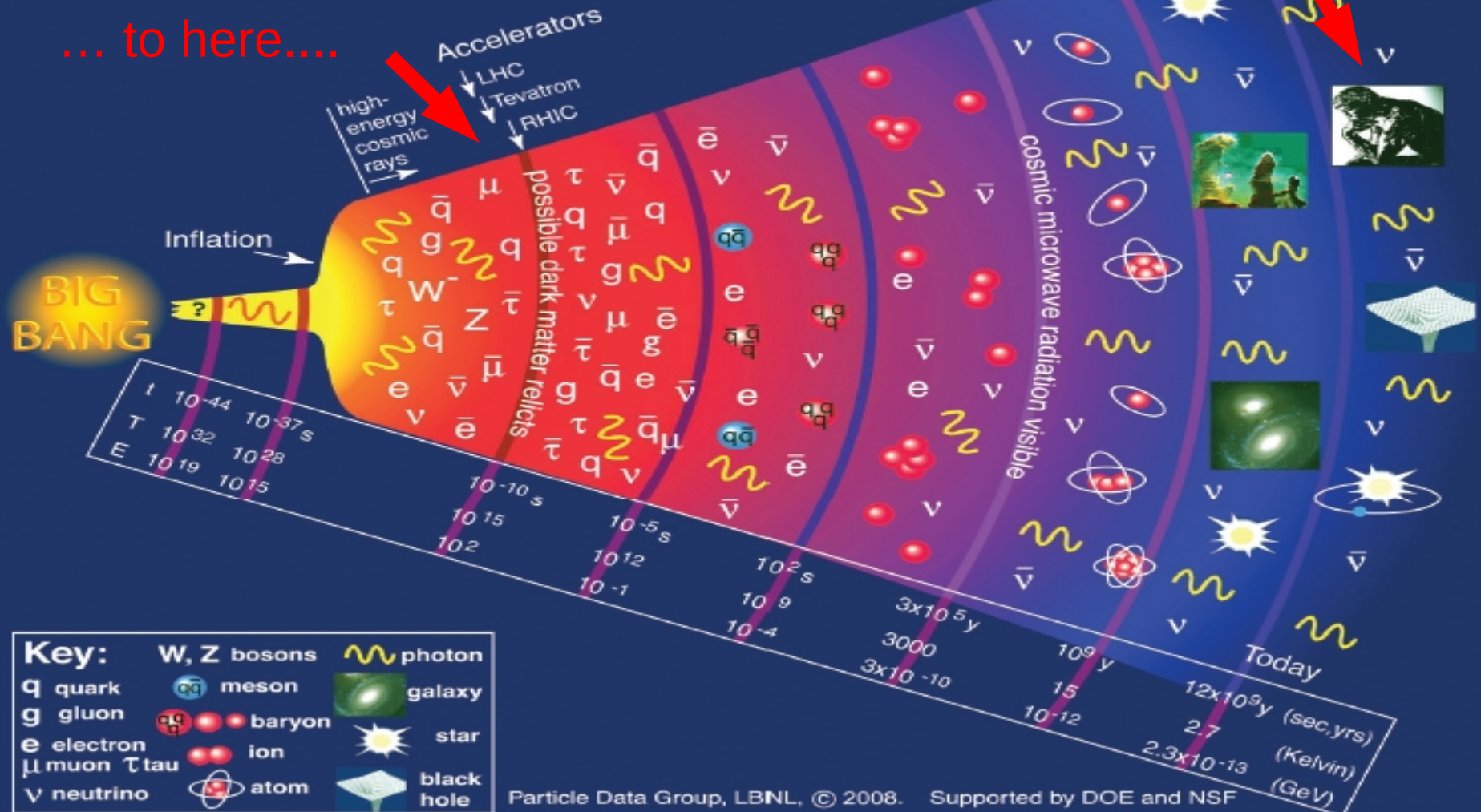


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... to here....





# Some Older History

## History of the Universe

