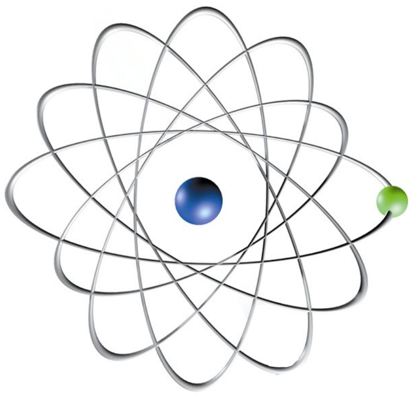
Some Concepts about Heavy Ion Reactions

- Chiral Symmetry
- Sideward and Elliptic Flow
- Phase Diagram of Nuclear Matter
- Jets (Suppresion)
- RAA

the mass of composite systems

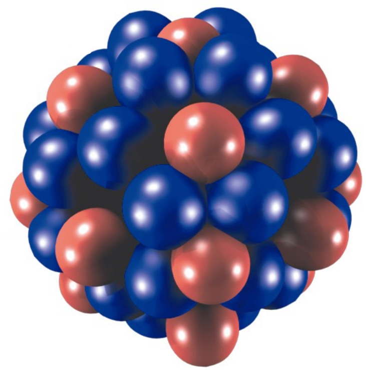
atom
10^{-10} m



$M \approx \Sigma\, m_i$

binding energy
effect $\approx 10^{-8}$

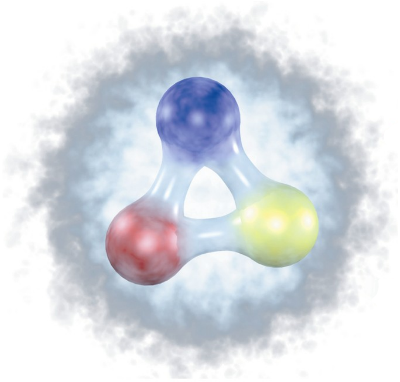
atomic nucleus
10^{-14} m



$M \approx \Sigma\, m_i$

binding energy
effect $\approx 10^{-3}$

nucleon
10^{-15} m

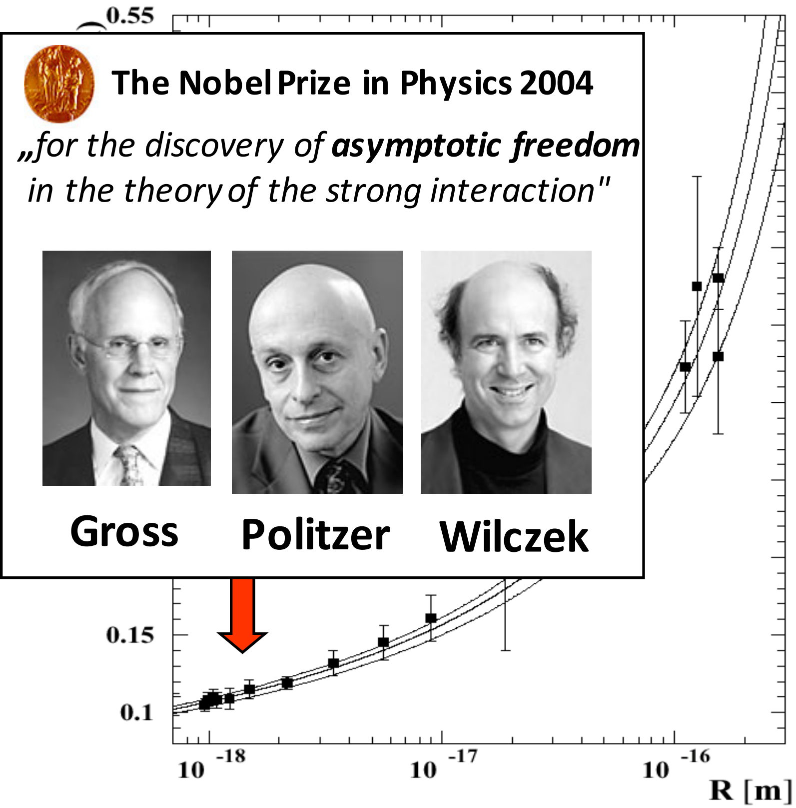


$M \gg m_i$

<u>nucleon:</u> mass not determined by sum of constituent masses
$m = E/c^2$; „mass without mass“ (Wilczek)
mass given by energy stored in motion of quarks
and by energy in colour gluon fields

how is the mass of the nucleon generated?

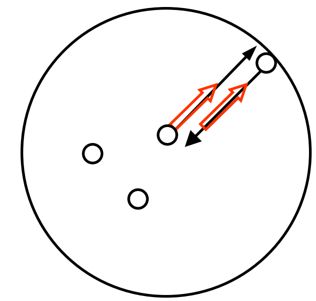
m_N = 938 MeV >> $m_q \approx$ 5 – 10 MeV

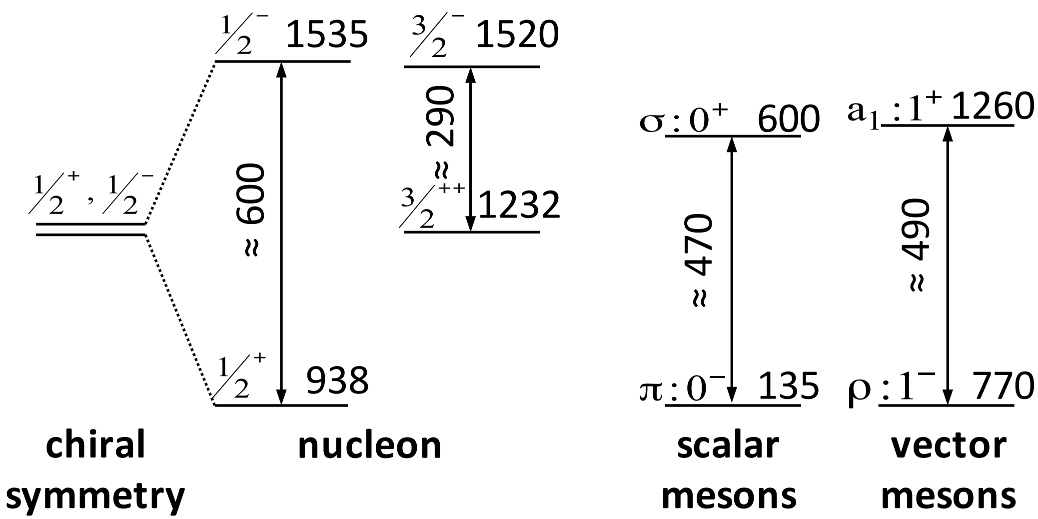


the interaction among quarks has to become so strong that it overcomes their quantum mechanical resistance to localization (Wilczek)

the role of chiral symmetry breaking

- chiral symmetry = fundamental symmetry of QCD for massless quarks
- chiral symmetry broken on hadron level

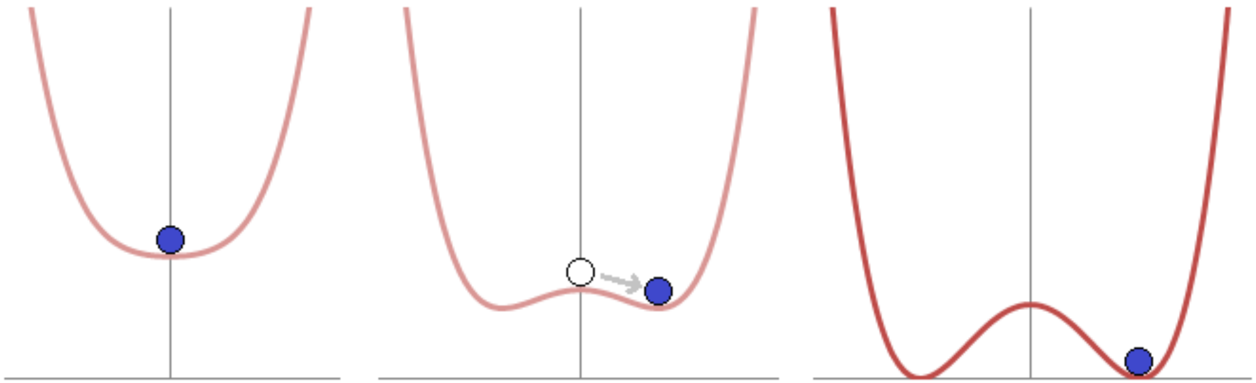




mass split comparable to hadron masses !

Chiral Symmetry

Strong interaction is the same for left- and right-handed quarks and for all the flavours



Spontenous Chiral Symmetry Breaking

Vacuum state of the QCD Lagrangian is not 0 and hence does not have the same symmetries has the Lagrangian

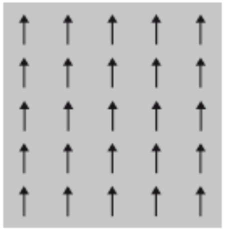
Quark Condensate $$\langle \bar{q}q \rangle \approx -(240\,\mathrm{MeV})^3 \times N_f$$

The Usual Example

- interaction between microscopic magnetic dipoles (spins) does not prefer any direction

$$H_{\mathrm{int}} = g \sum_{i \neq j} \vec{s}_i \cdot \vec{s}_j$$

$\longrightarrow$ rotational invariance



- in contrast ground state (unexcited solid state) has preferred direction

$\longrightarrow$ breaking of rotational invariance

S. Leupold Lectures HADES Summer School

Spontaneous Chiral Symmetry Breaking

Vacuum state of the QCD Lagrangian is not 0 and hence does not have the same symmetries has the Lagrangian

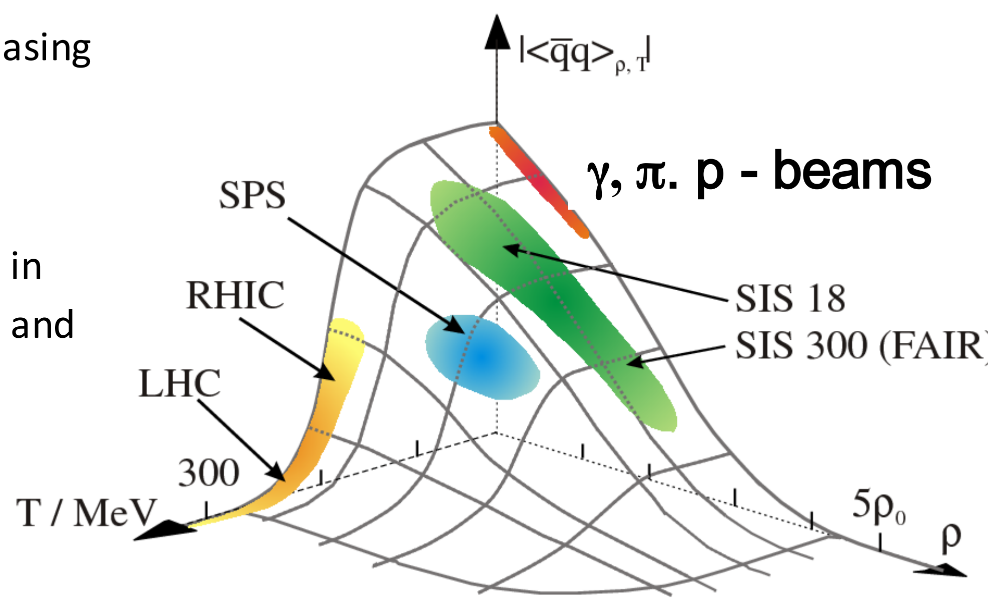
Quark Condensate $\langle \bar{q}q \rangle \approx -(240\,\mathrm{MeV})^3 \times N_f$

F. Kling, W. Weise NPA (1998)

Theory predicts a drop of the $\langle q\bar{q} \rangle$ for increasing T and ρ -> hadron collisions

How to measure the drop experimentally?

The $\langle q\bar{q} \rangle$ is linked to the hadron properties in nuclear matter that could also depend on T and ρ



Explicit Symmetry Breaking

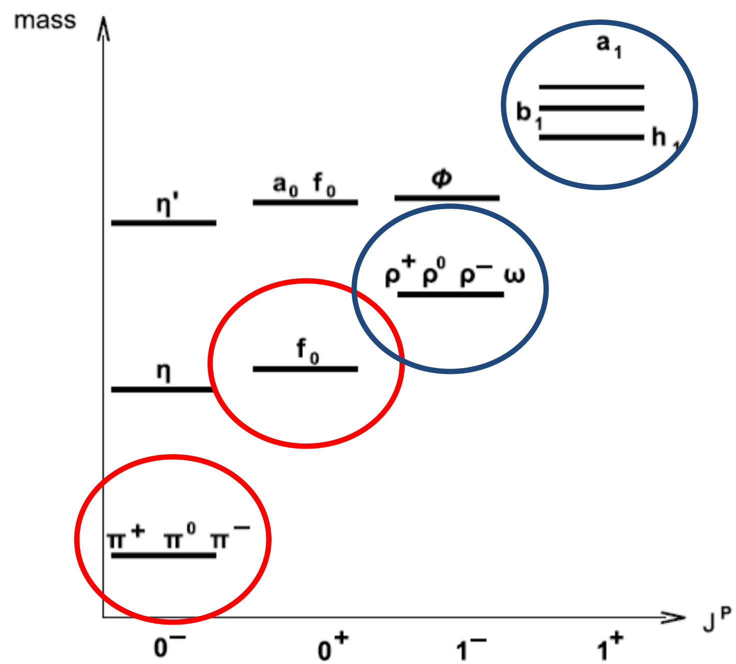
Mass term in the QCD Lagrangian due to the non-0 quark masses

QCD lagrangian: $L_{QCD} = L_0 + m_q \bar{q} q$

L_0 invariant under chiral transformations (L,R)
Small explicit breaking

$$SU_L(N_f) \times SU_R(N_f) = SU_V(N_f) \times SU_A(N_f)$$

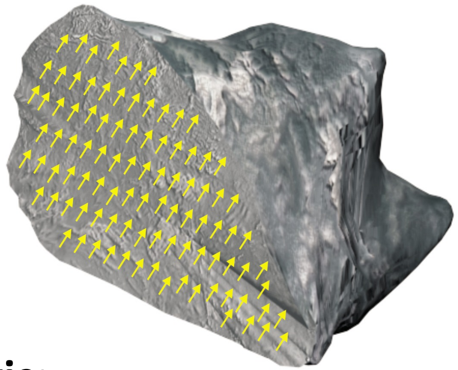
→Isopin/Parity partners should be degenerate to restore the symmetry
The isospin partner might become degenerate with increasing T and ρ

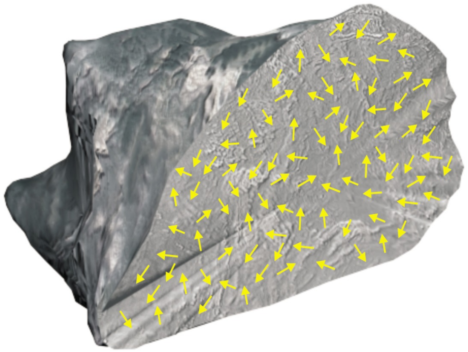


η and η‘ are two different particles in vacuum -> do their masses approach to each other when the density increases?

phase transition: ferromagnetism → paramagnetism

restoration of full rotational symmetry



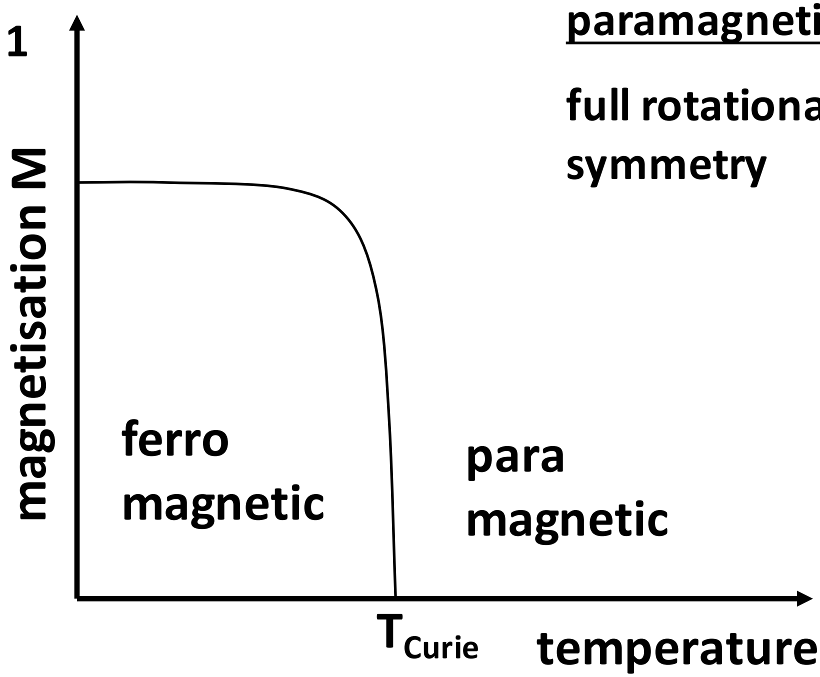


ferromagnetic:

rotational symmetry about 1 axis

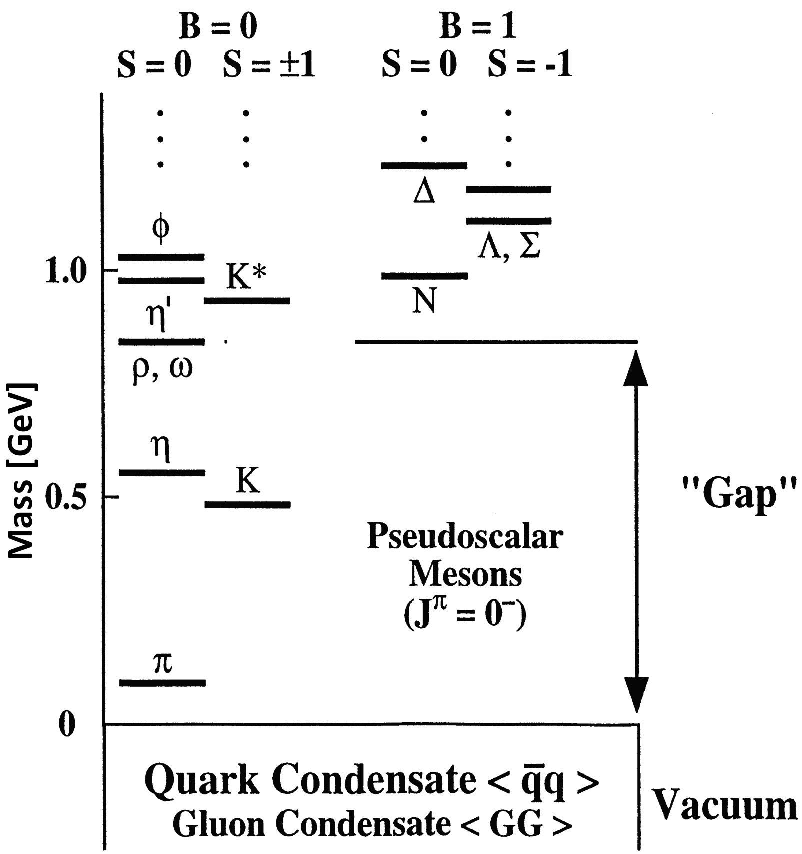
paramagnetic:

full rotational symmetry



V. Metag, Uni. Giessen

hadron masses



- hadrons = excitations of the QCD vacuum
- QCD-vacuum: complicated structure characterized by condensates
- in the nuclear medium: condensates are changed

→ change of the hadronic excitation energy spectrum

G.E.Brown and M. Rho, PRL 66 (1991) 2720

$$\frac{m^*}{m} \approx \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \approx 0.8 \left(\rho \approx \rho_0\right)$$

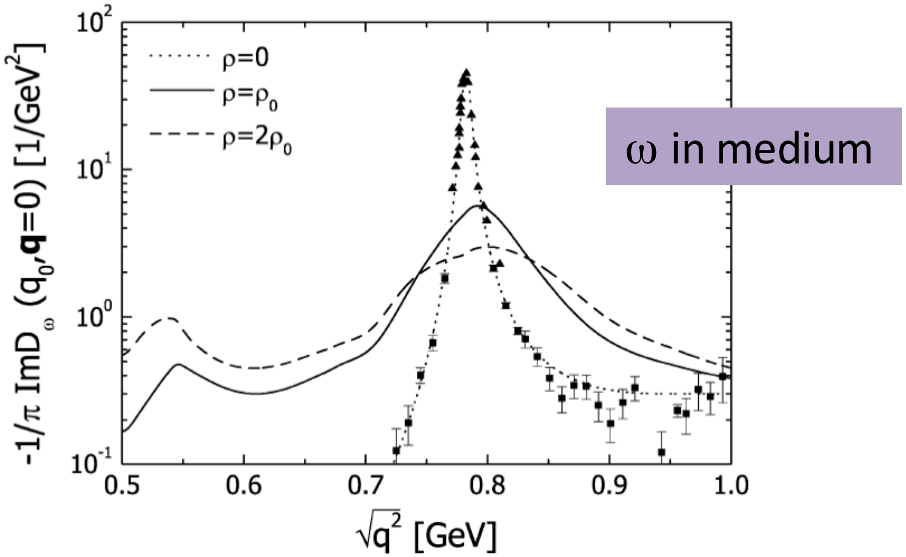
T.Hatsuda and S. Lee, PRC 46 (1992) R34

$$\frac{m_V^*}{m_V} = \left(1 - \alpha \frac{\rho_B}{\rho_0}\right) \; ; \; \alpha \approx 0.18$$

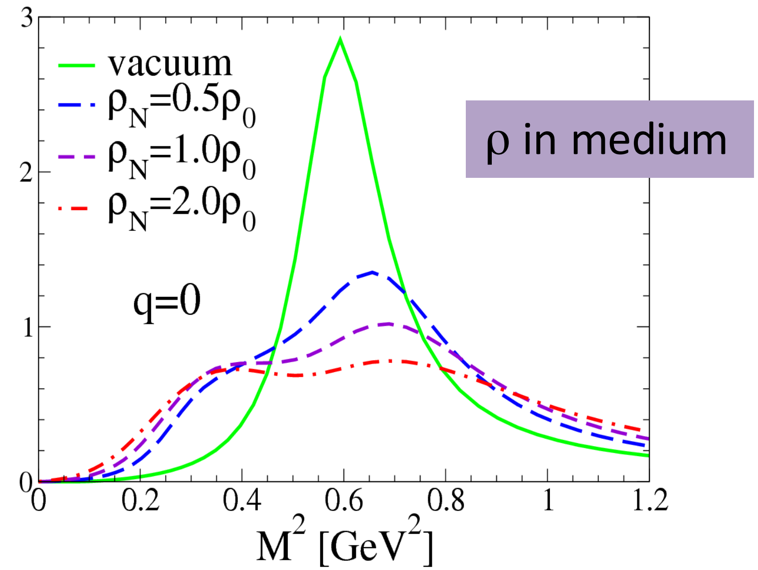
⇒ widespread experimental activities to search for in-medium modifications of hadrons

Hadron In-Medium Modification

P.Mühlich et al.,NPA 780 (2006) 187



Urban et al.,1998



There are several scenarios.. 2 examples:

Old One: Brown-Rho scaling (1992)

$$m = m_0\left(1 - \alpha\frac{\rho}{\rho_0}\right)$$

One of the new: QCD Sum-Rules

$$-Q^2\int ds\frac{\mathrm{Im}\Pi_{Had}(s)}{(s+Q^2)s^2} = A(Q^2) + \frac{1}{Q^4}\left(B\cdot\langle\bar{q}q\rangle_{med} + C\cdot\langle G^2\rangle + \ldots\right) + \frac{1}{Q^6}\left(D\cdot\langle q^4\rangle + \ldots\right) + \ldots$$

S. Leupold et al. Int.J.Mod.Phys.E19:147-224,2010

Tools to study the in-medium modifications of hadrons:

possible in-medium modifications of hadrons:

- in-medium mass shift

  (partial restoration of chiral symmetry, meson-baryon coupling)

- in-medium broadening of hadron resonances

  (meson-baryon coupling, collisional broadening)

- Transparency Ratio

  (imaginary part of the interacting potential)

- Momentum and Energy Shift

  (real part of the interacting potential)

- hadron-nucleus bound states

  (meson-nucleus attractive potential)

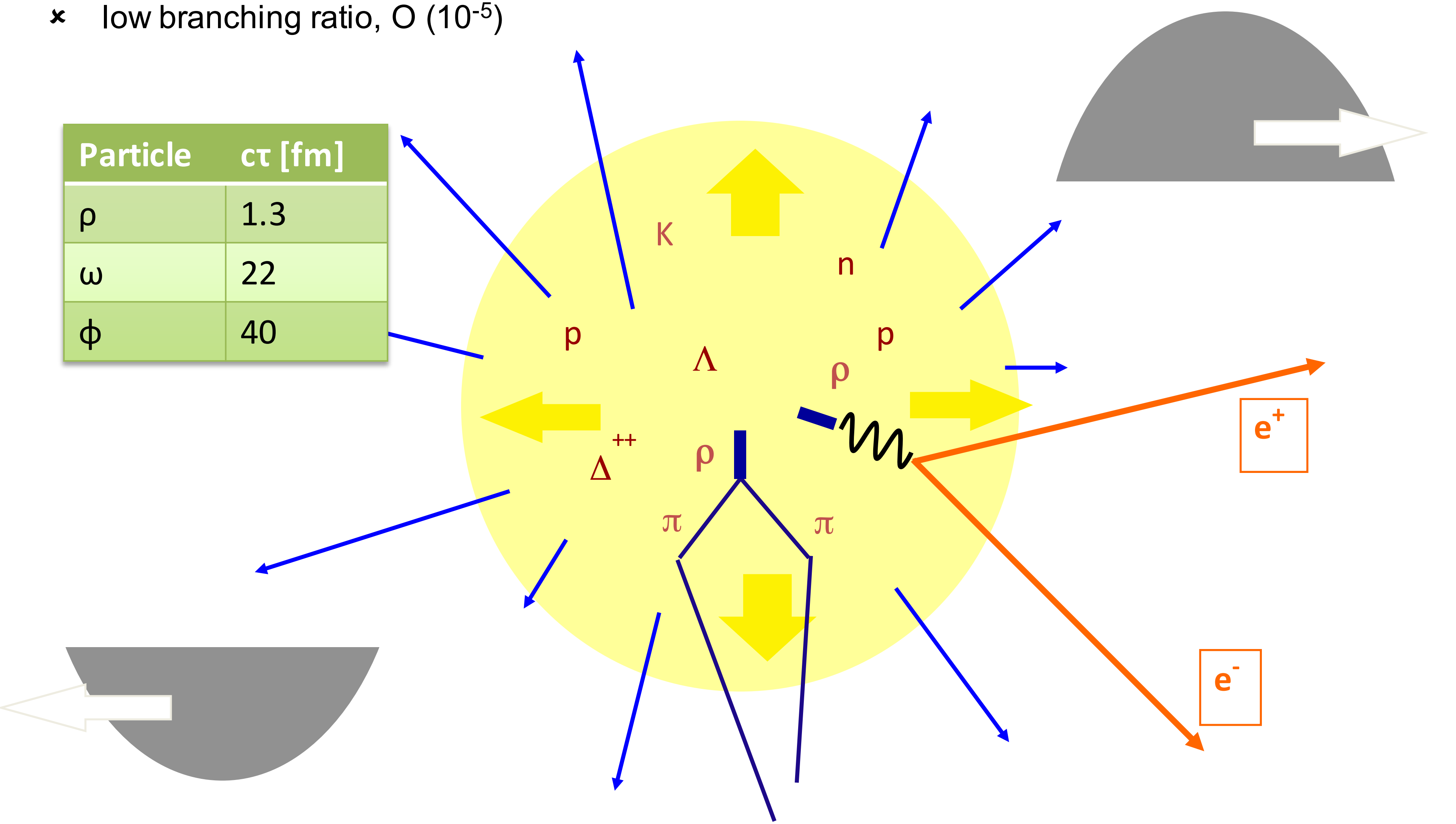
In-Medium Mass Shifts

Vector Meson in Medium

Penetrating probes:

- information from the early stage
- low branching ratio, O (10^{-5})

Particle	cτ [fm]
ρ	1.3
ω	22
ϕ	40



experimental approach:

reconstruction of invariant mass from 4-momenta of decay products:

$$m_\omega(\rho, T, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

dilepton spectroscopy: $\rho, \omega, \phi \rightarrow e^+e^-$

essential advantage: no final state interactions !!

Information on medium modifications of mesons

from heavy-ion collisions

advantage:
sizable effects due to high
densities and temperatures

disadvantage:
any signal represents an integration
over the full space-time history of the
heavy-ion collision with strong
variations in densities and temperatures

from elementary reactions

advantage:
well controlled conditions:
important for theoretical interpretation
no time dependence of baryon density:
$\rho_B \neq \rho_B(t); T=0;$

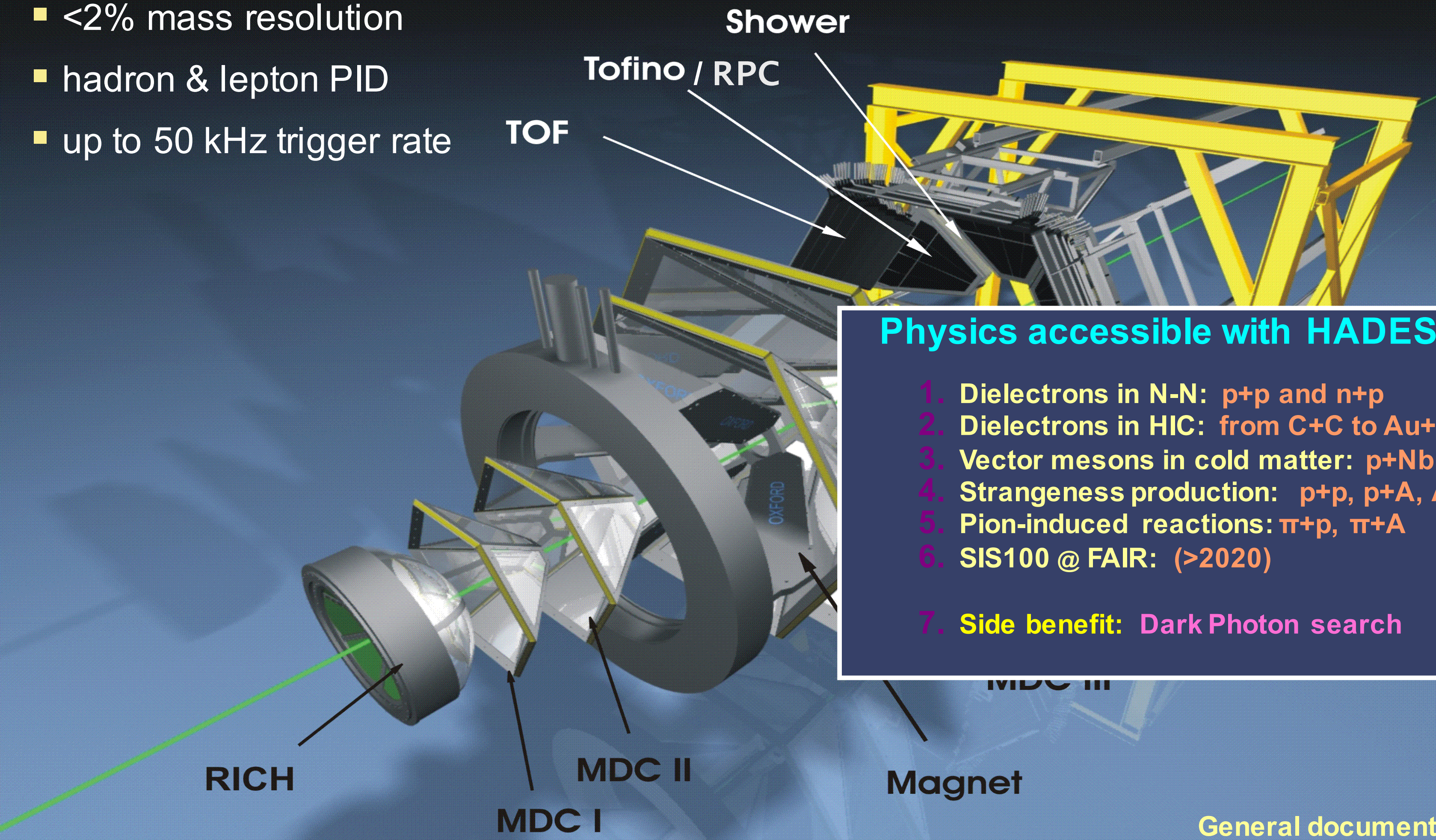
disadvantage:
small medium effects since
$\rho \leq \rho_0$ and T=0

The HADES experiment at GSI

HADES

High Acceptance DiElectron Spectrometer

- large acceptance
- <2% mass resolution
- hadron & lepton PID
- up to 50 kHz trigger rate



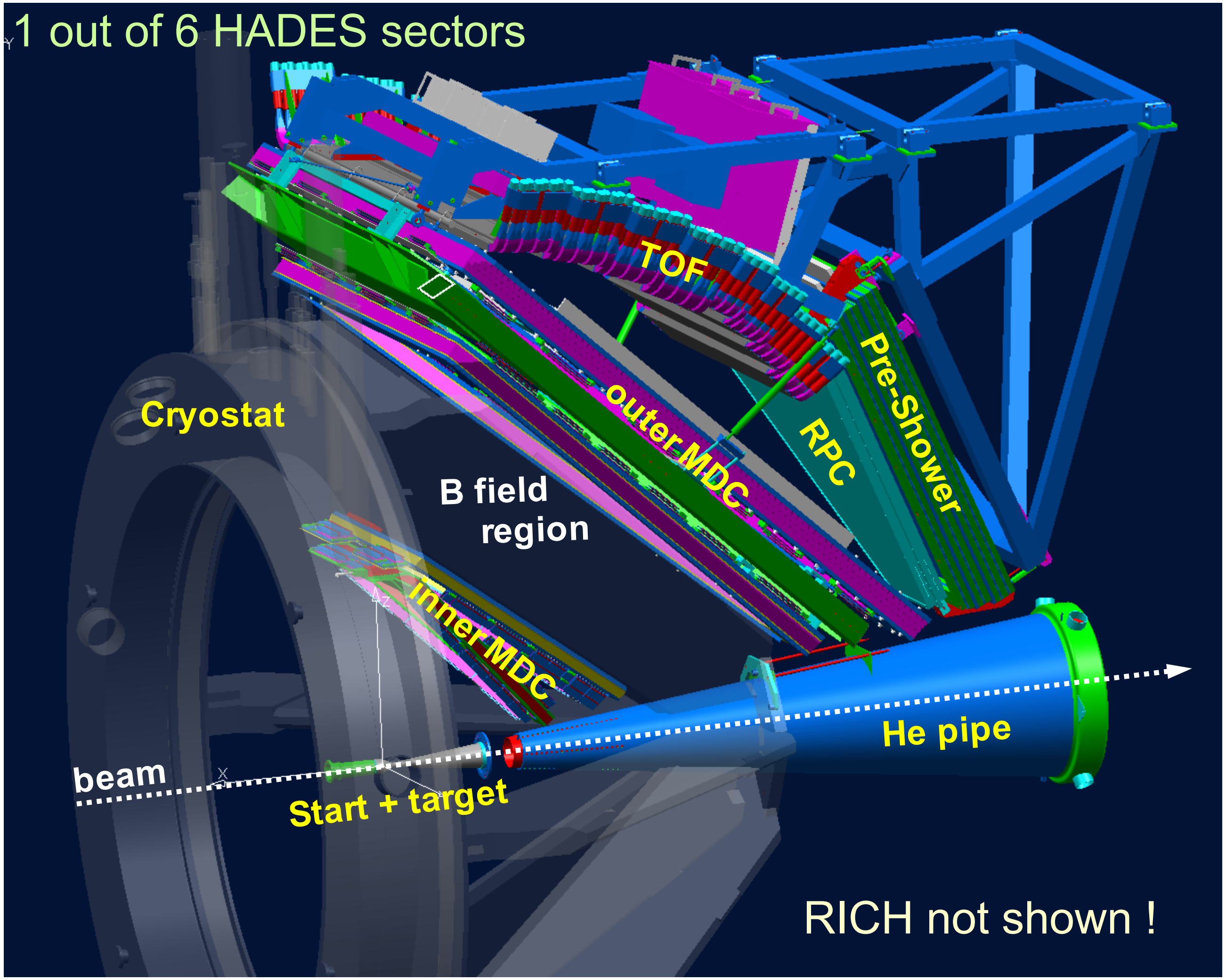
Physics accessible with HADES:

1. Dielectrons in N-N: p+p and n+p
2. Dielectrons in HIC: from C+C to Au+Au
3. Vector mesons in cold matter: p+Nb
4. Strangeness production: p+p, p+A, A+A
5. Pion-induced reactions: π+p, π+A
6. SIS100 @ FAIR: (>2020)

7. Side benefit: Dark Photon search

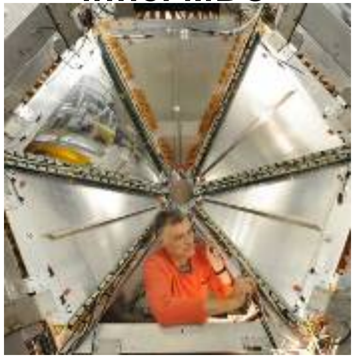
General documentation at:
http://www-hades.gsi.de

Technical layout of HADES



HADES + FW

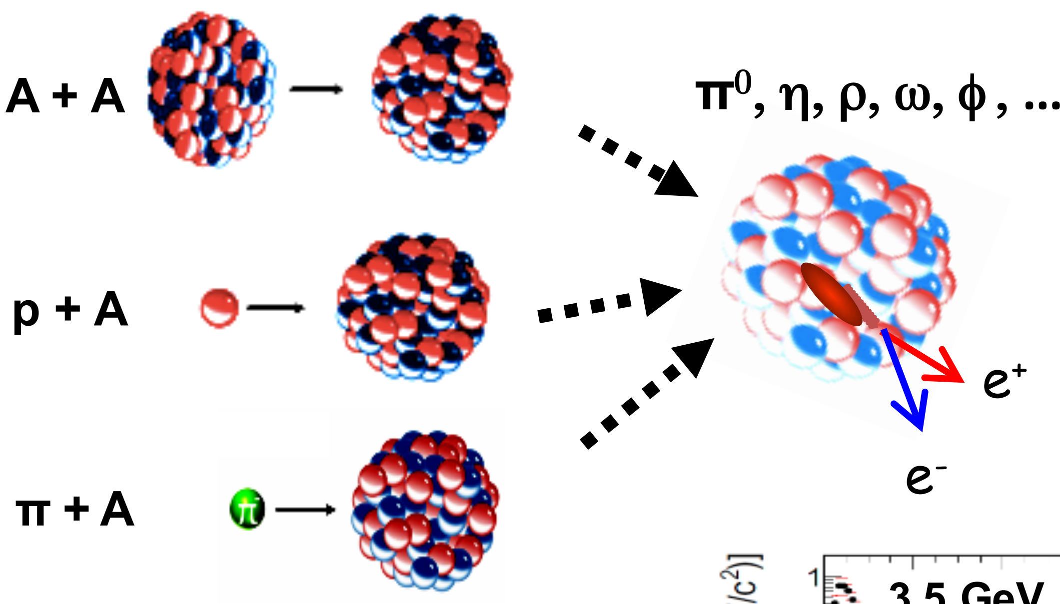
inner MDC



RICH readout

e^+e^- spectroscopy in few-GeV reactions

HADES

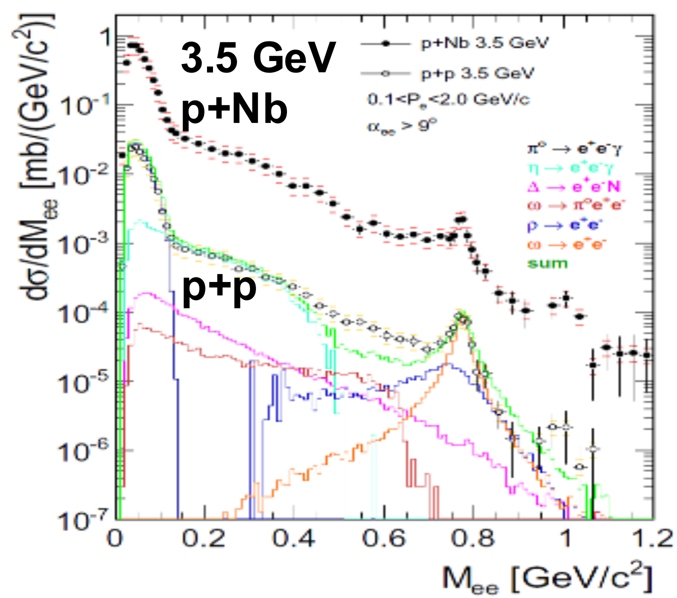


Modus operandi:

1. produce meson
2. let decay into leptons
3. detect products
4. reconstruct inv mass

Pair invariant mass:

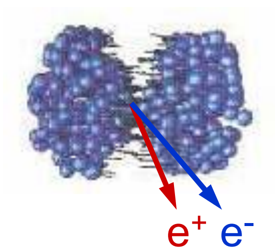
$$M_{ee} = \sqrt{(p_1 + p_2)^2}$$



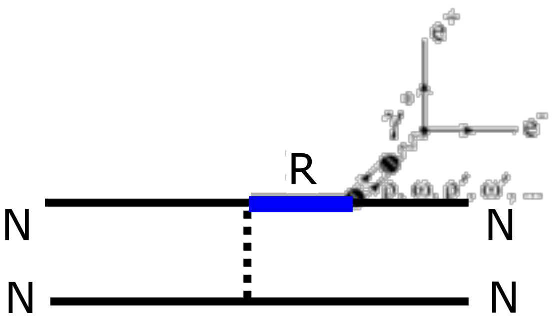
typical pair spectrum

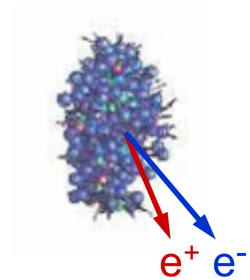
Dilepton sources in HI collisions

Dileptons are emitted in all phases of the collisions…

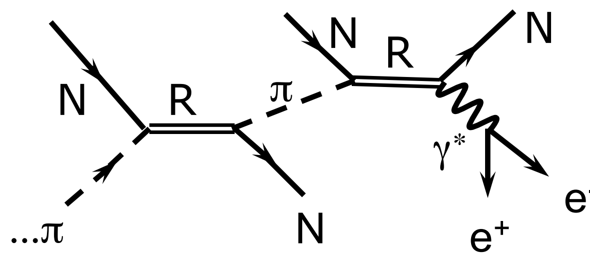


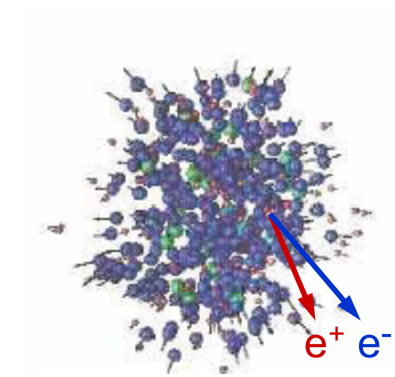
first chance collisions
elementary N-N collisions



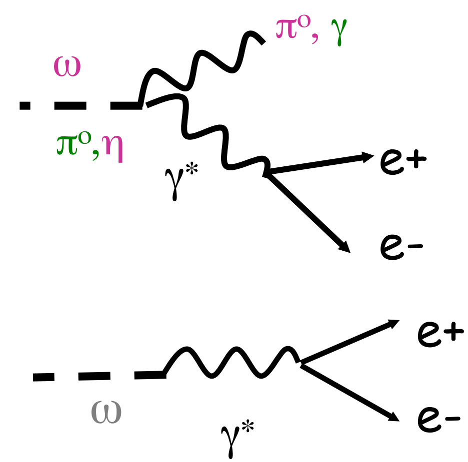


hot and dense phase
multistep production
of resonances and mesons



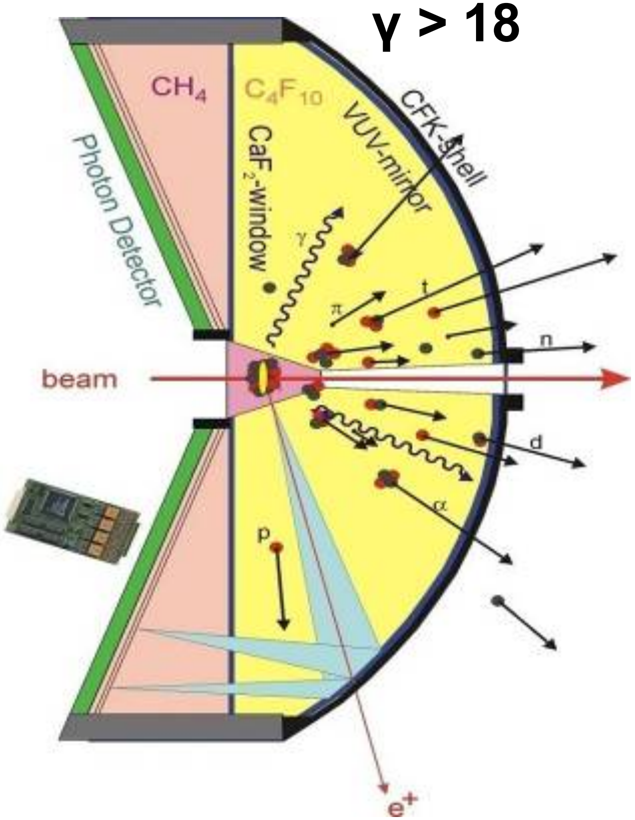


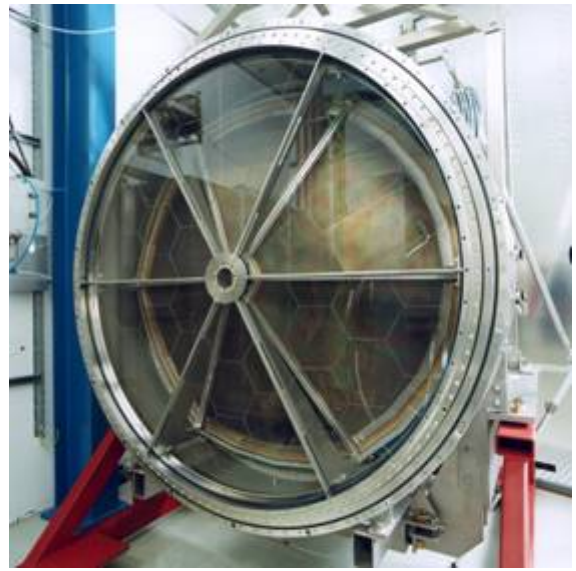
freeze –out
decays of long-lived
mesons: π^0, η, ω



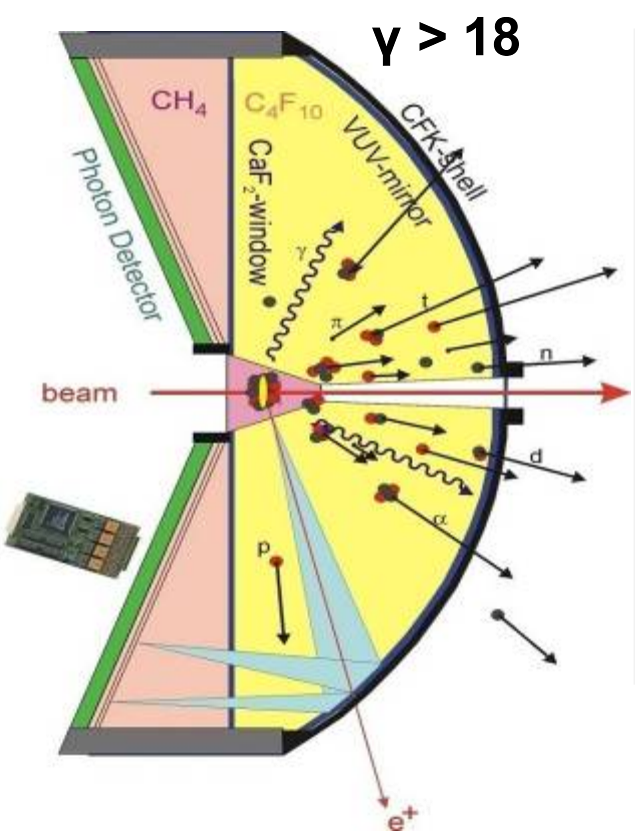
The RICH: excellent lepton ID

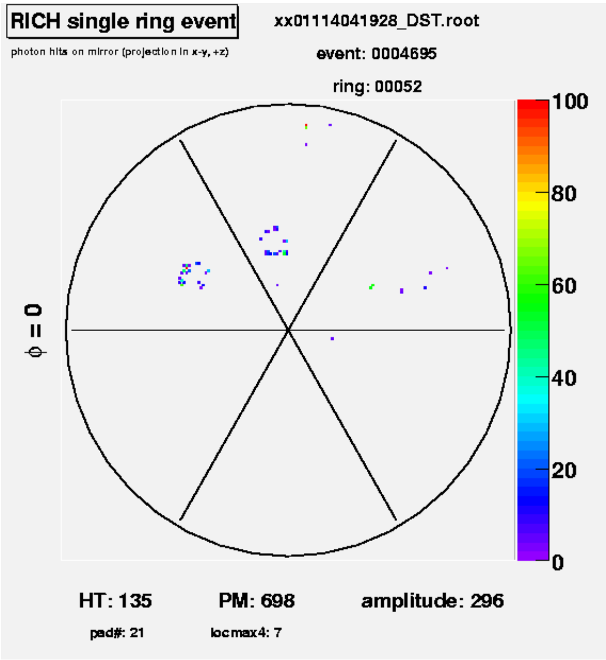
γ > 18

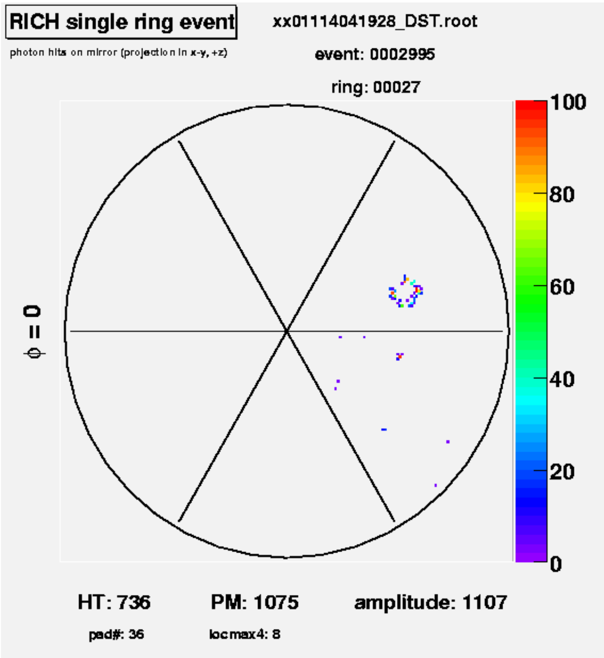




The RICH: excellent lepton ID

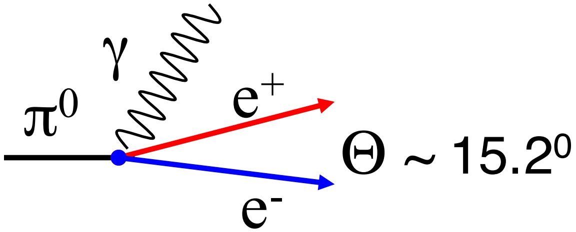


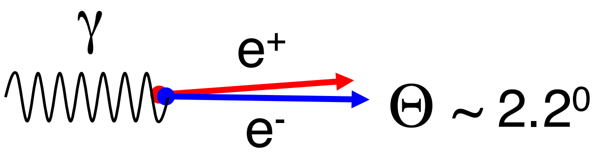




π^0 Dalitz pair

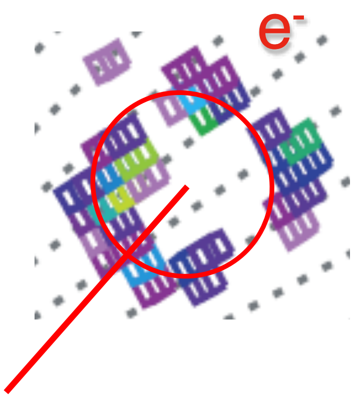
γ conversion pair





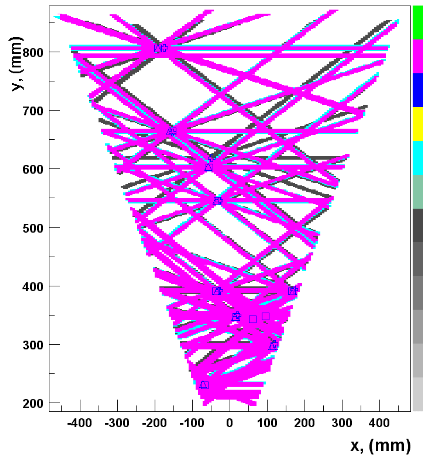
Electron/positron identification

RICH pattern



+

MDC hit finder & hit/track matching



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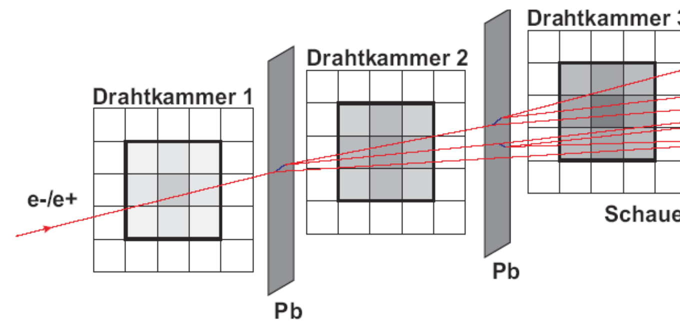
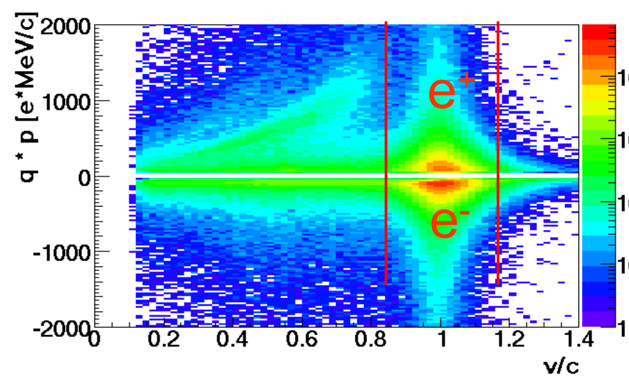
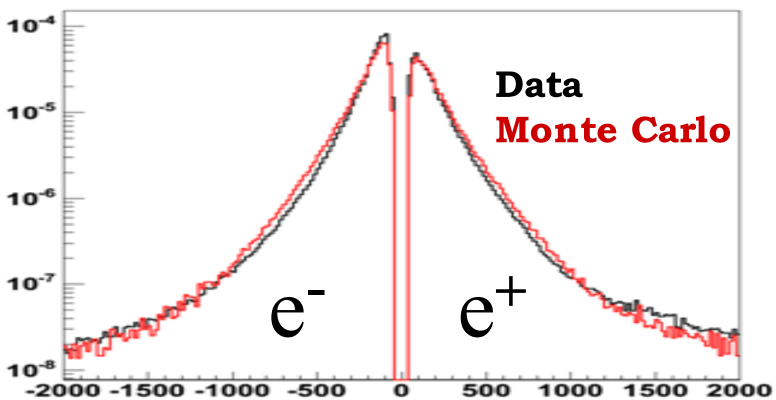
Pre-Shower condition



velocity vs. momentum

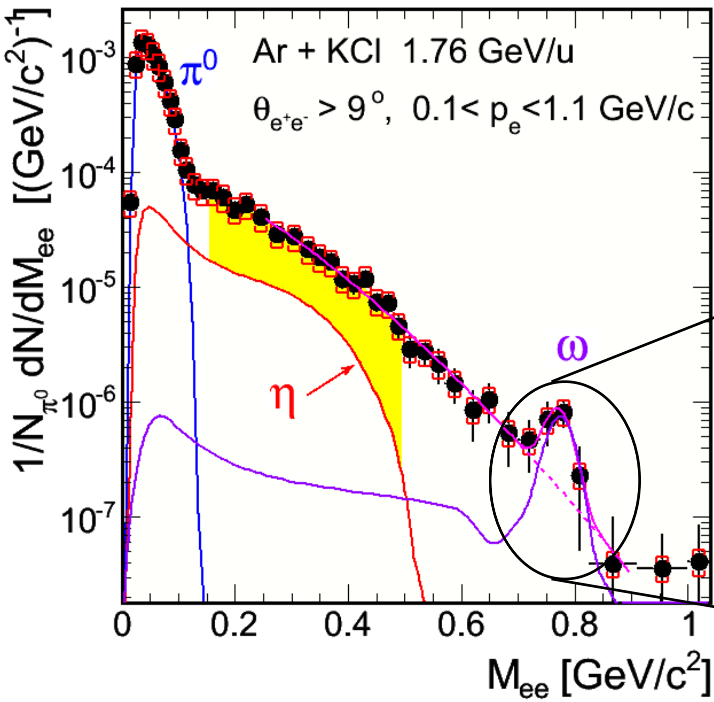


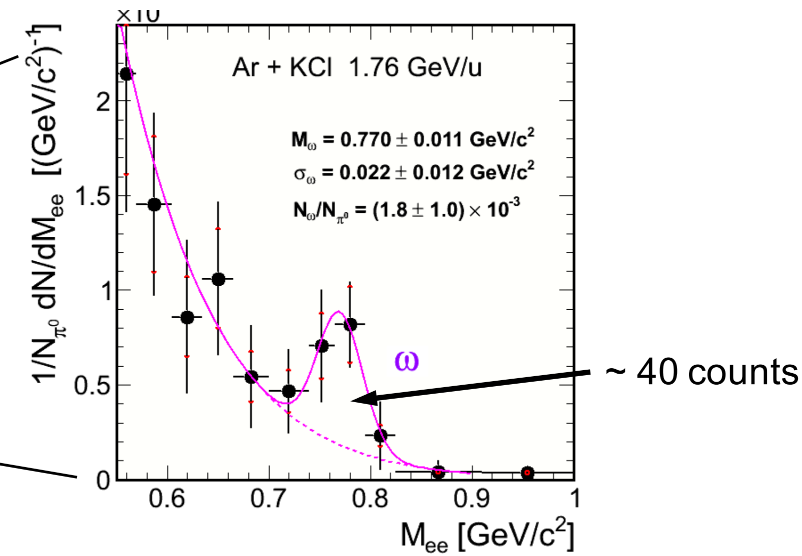


Momentum * charge [MeV/C]

Performance: Dielectron production in Ar+KCl

- Again, strong overshoot above the cocktail of long-lived sources!
- First ω peak seen at SIS energies!





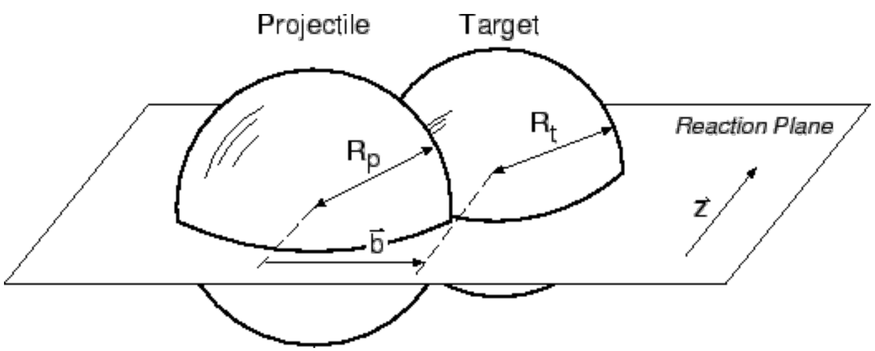
Long-lived sources:
π^0, η, and ω

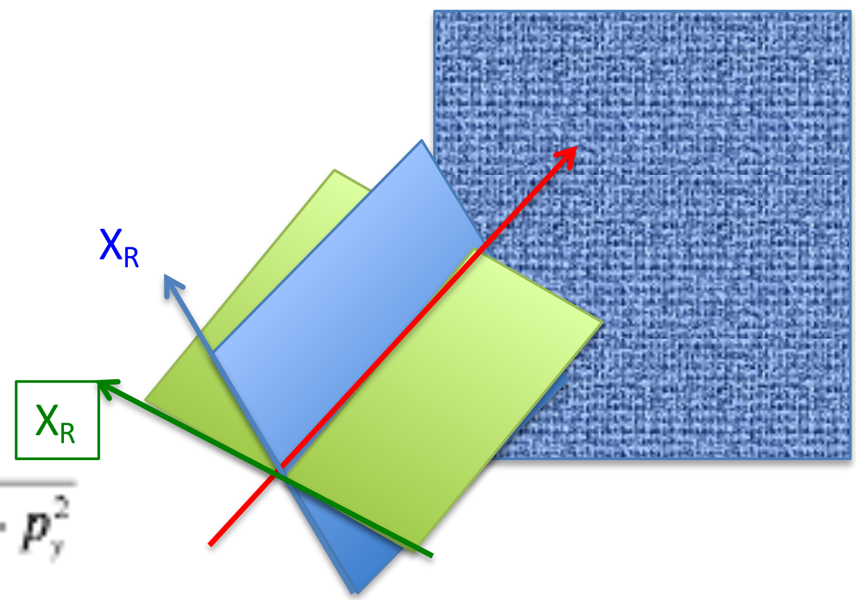
► $M_{LVL1}(\omega) = (6.5 \pm 2.8) \cdot 10^{-3}$

±20 % sys.

Flow: Sideward and Elliptic

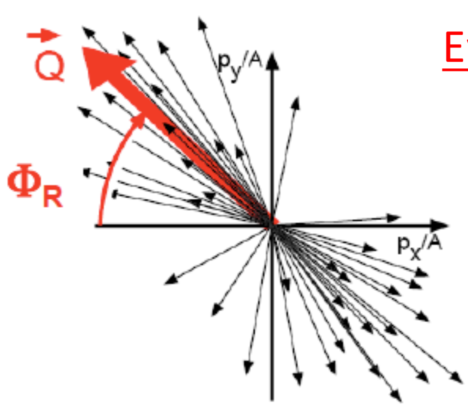
Reaction Plane and angular variables





? Which is the angle ψ_R

Q= Sum of the P_t of all particles $p_T = \sqrt{p_x^2 + p_y^2}$



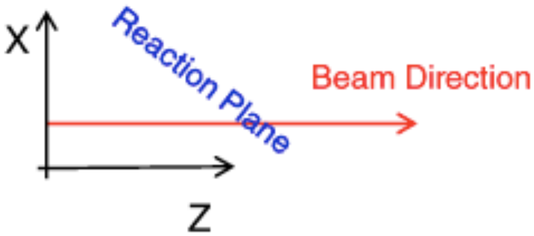
Event Plane!!

Beam Direction=z

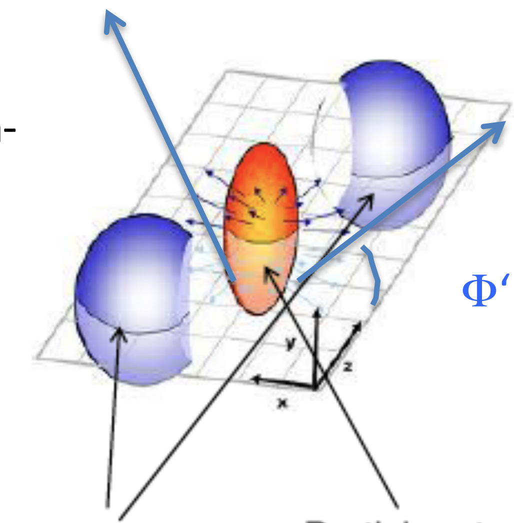
$\phi' = \phi - \Psi r$

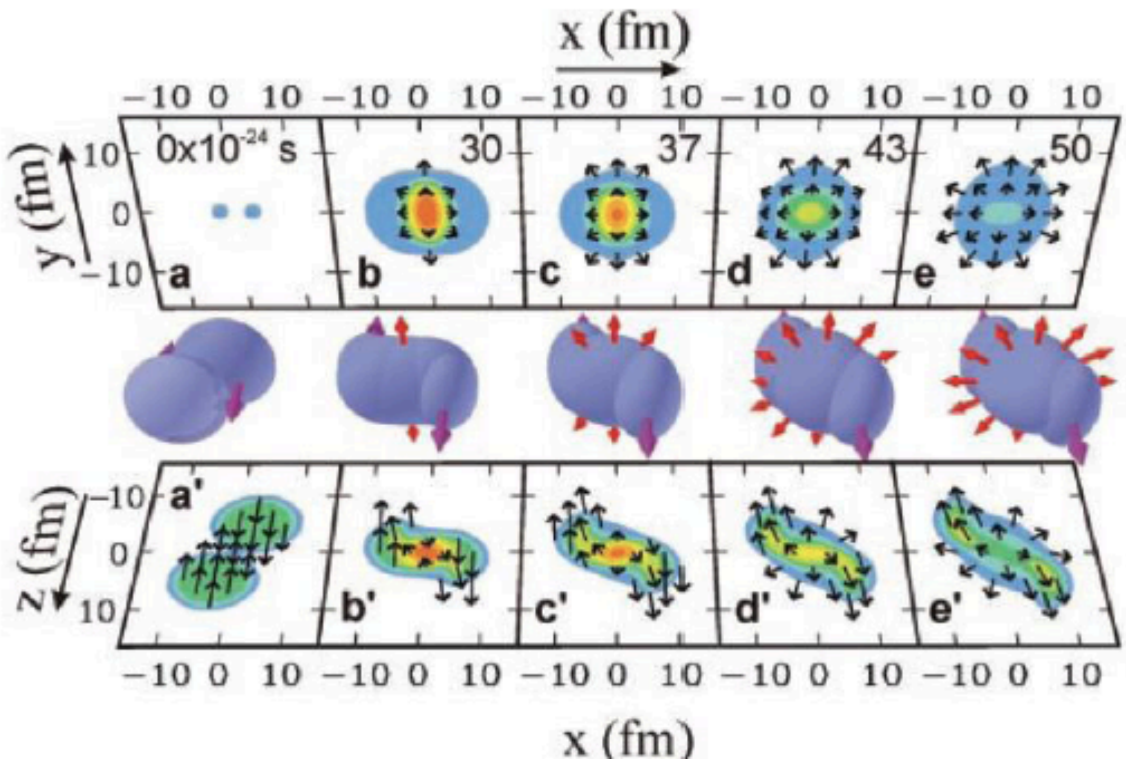
ϕ = Azimuthal Emission angle of one particle

Flow: Sideward and Elliptic



Different pressure gradient in in-plane and out-of-plane.
Expansion in in-plane





High Pressure Area in the collison zone:
Specator shade angular areas

Flow: Sideward and Elliptic

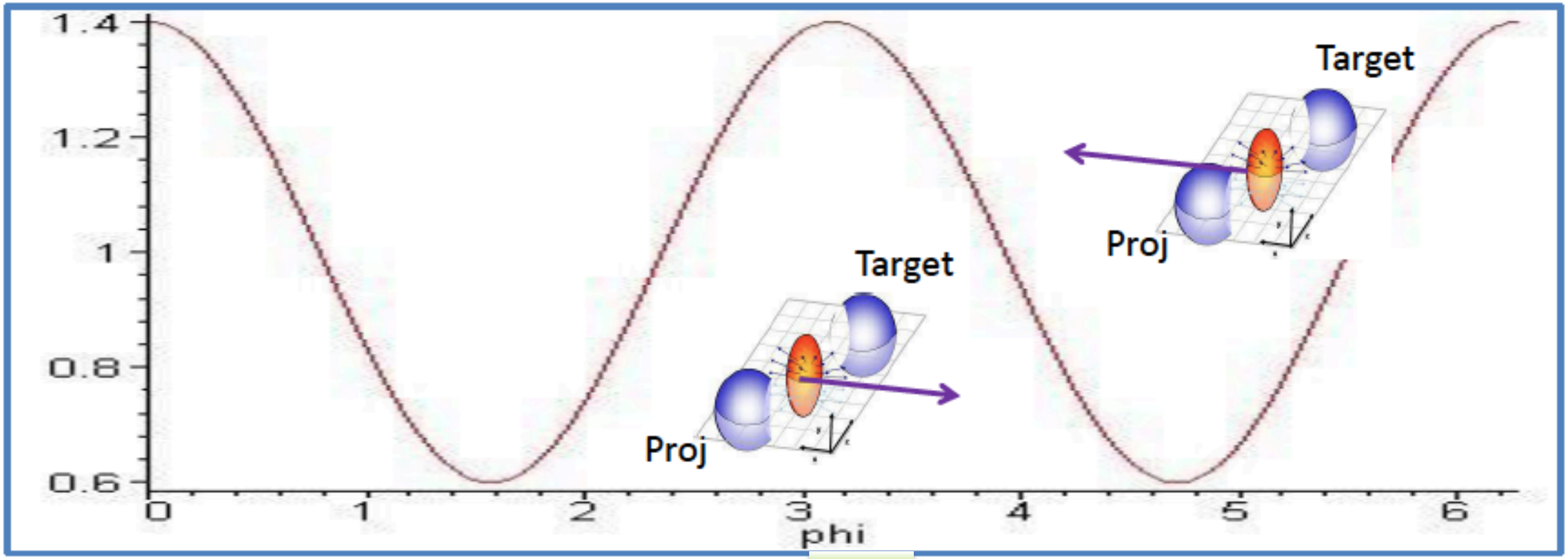
S. Voloshin, Y. Zhang, *hep-ph/9407082*
J.Y. Ollitrault, *nucl-ex/9711003*

$$\frac{dN}{d(\phi-\psi_R)} \sim 1+\sum_n 2v_n \cos[n(\phi-\psi_R)].$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

N=2 Eliptic flow

$v_2 = \langle \cos(2\phi) \rangle$



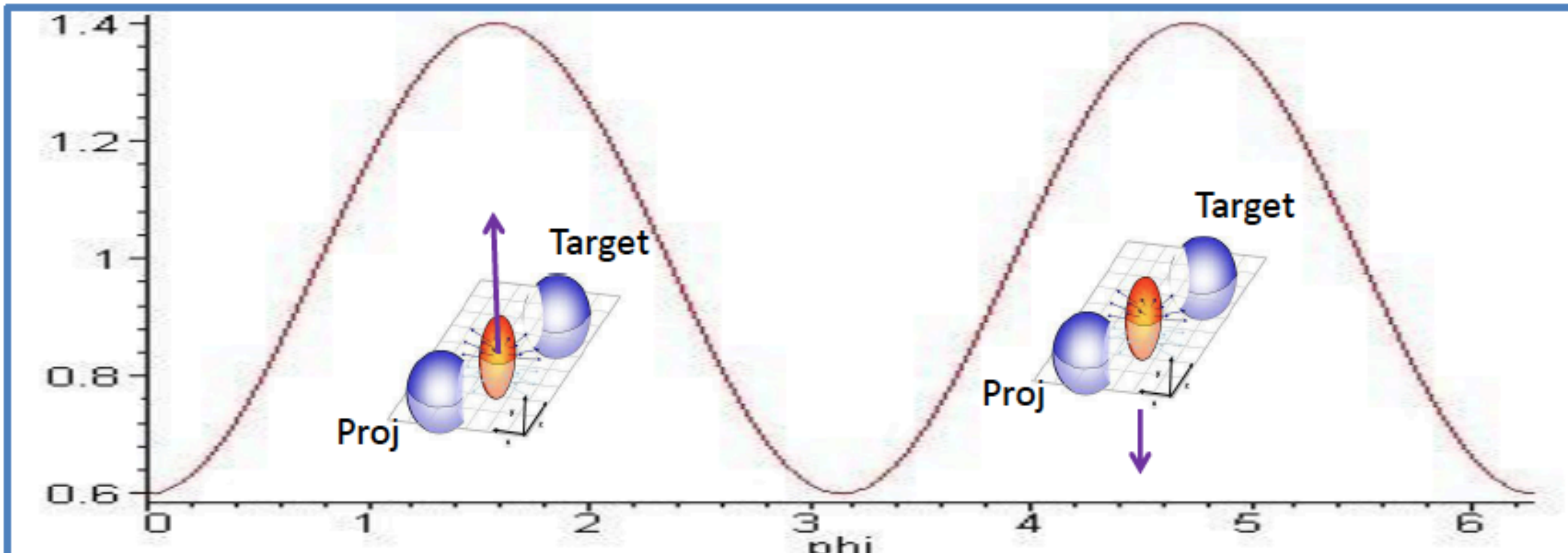
V2=0.2; Enhancement in reaction plane

Flow: Sideward and Elliptic

$$\frac{dN}{d(\phi-\psi_R)} \sim 1+\sum_n 2v_n \cos[n(\phi-\psi_R)].$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\phi \rangle$$

N=2 Eliptic flow



V2=-0.2; Enhancement out of reaction plane

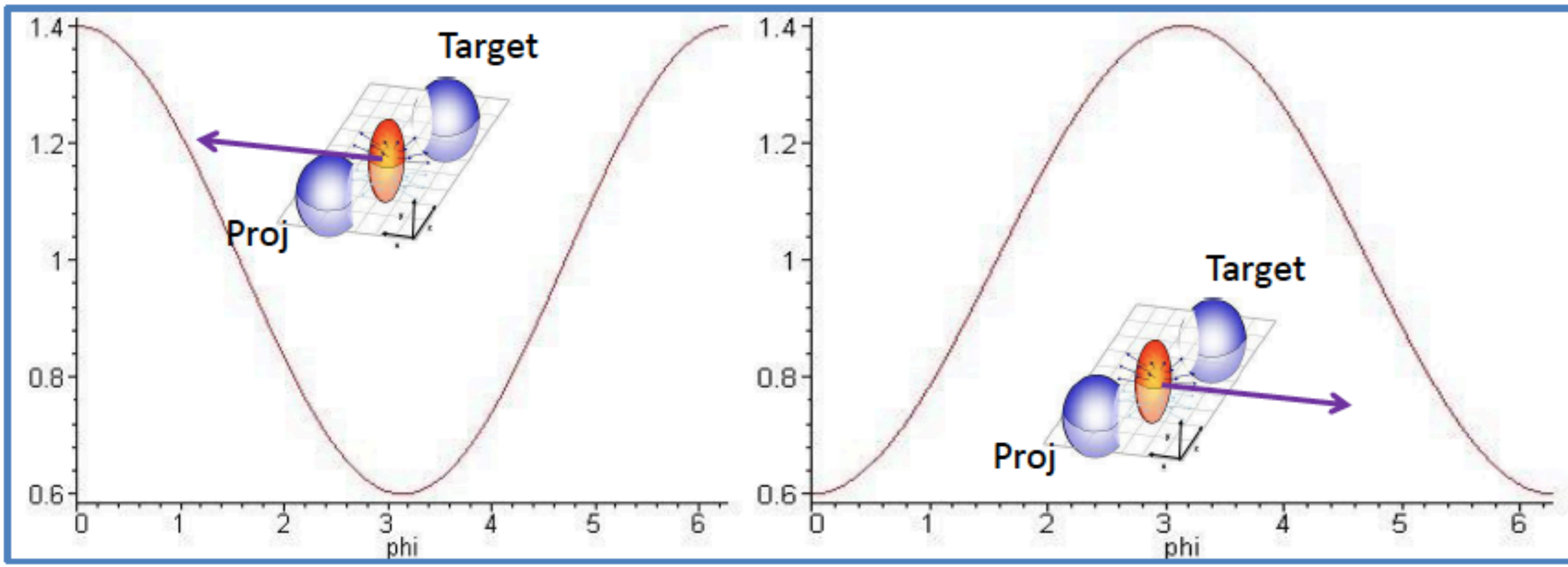
Flow: Sideward and Elliptic

$$\frac{dN}{d(\phi - \psi_R)} \sim 1 + \sum_n 2v_n \cos[n(\phi - \psi_R)].$$

For a fixed rapidity interval

N=1 in-plane flow

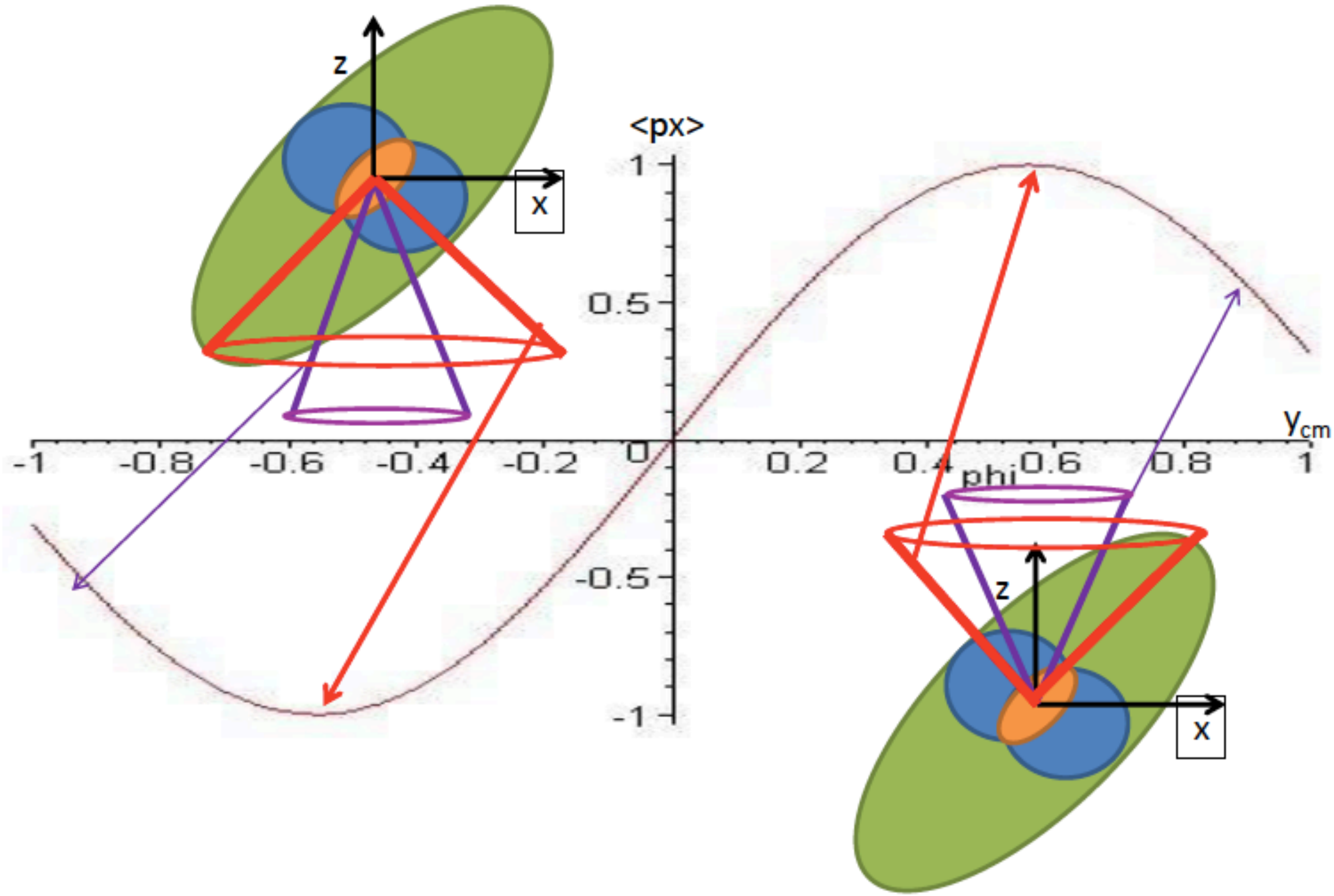
$v_1 = <\cos(\phi)> = <p_x>$



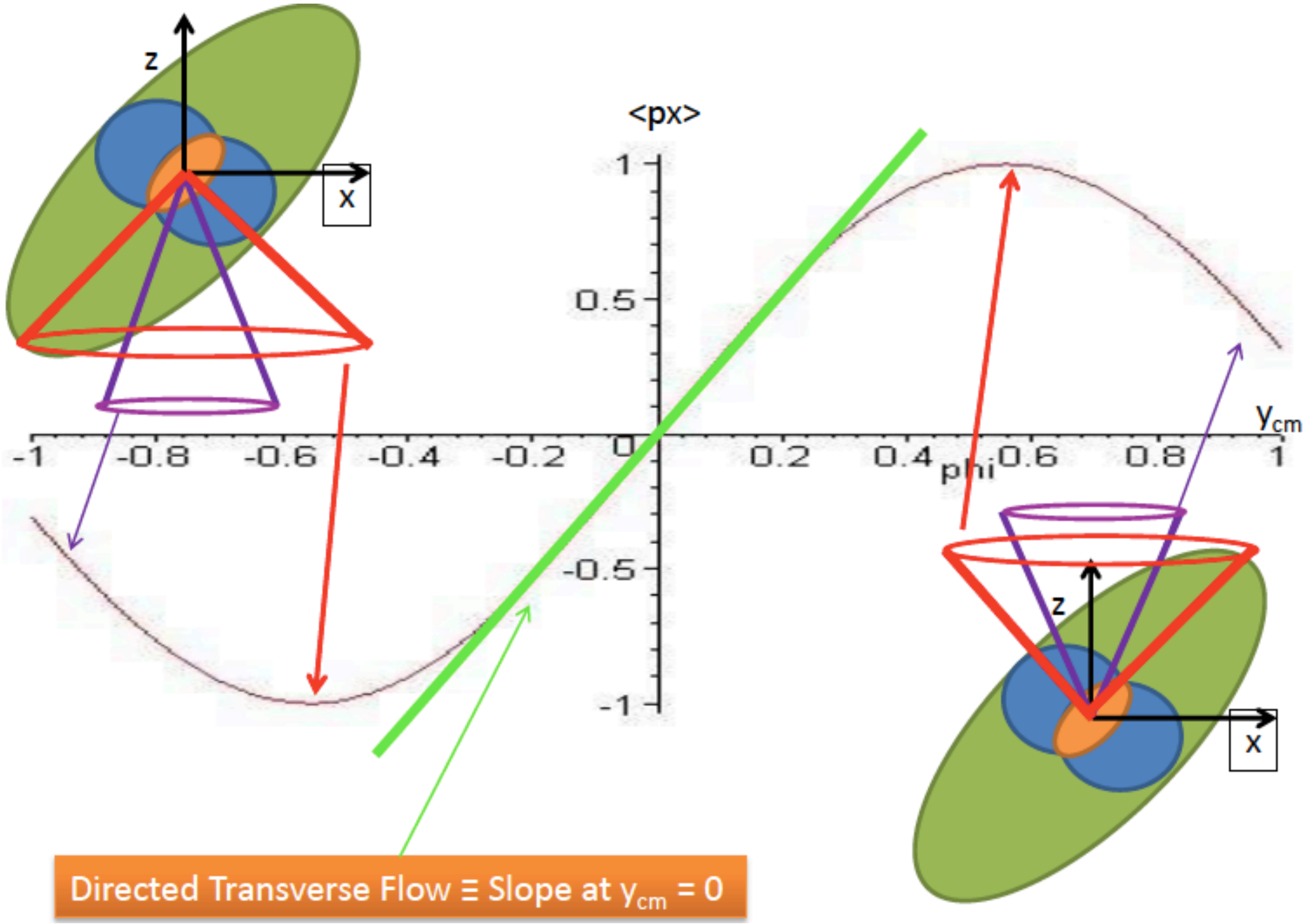
V1=0.2; Enh. in Proj. Direction

V1=-0.2 ; Enh. in Target Direction

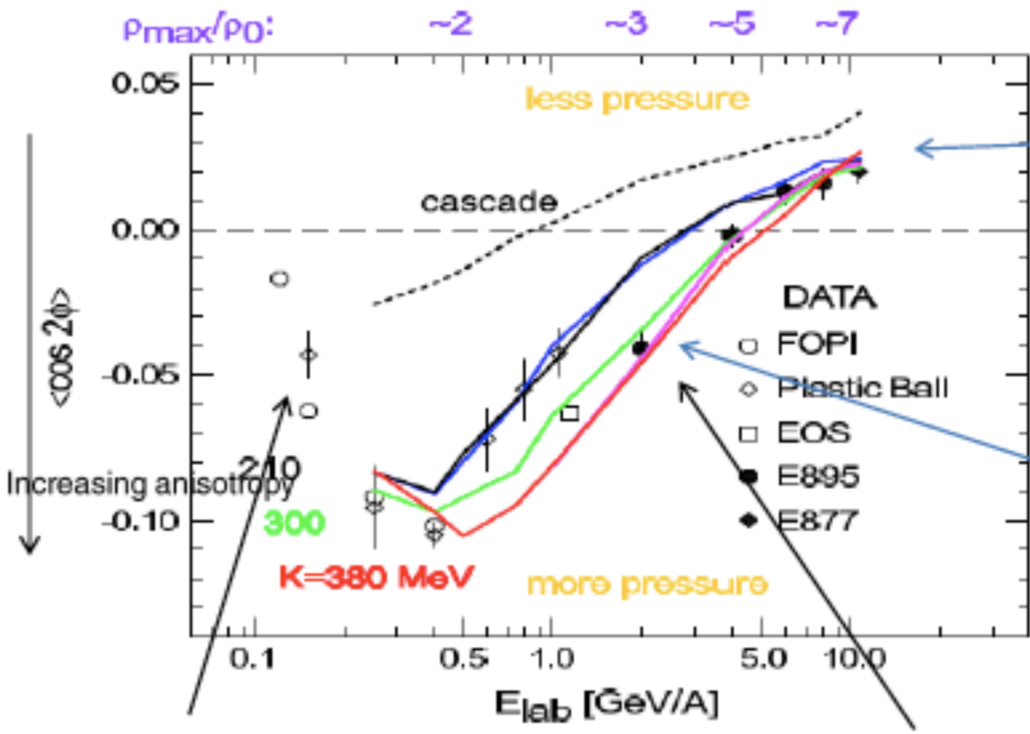
Flow: Sideward and Elliptic



Flow: Sideward and Elliptic



Elliptic Flow



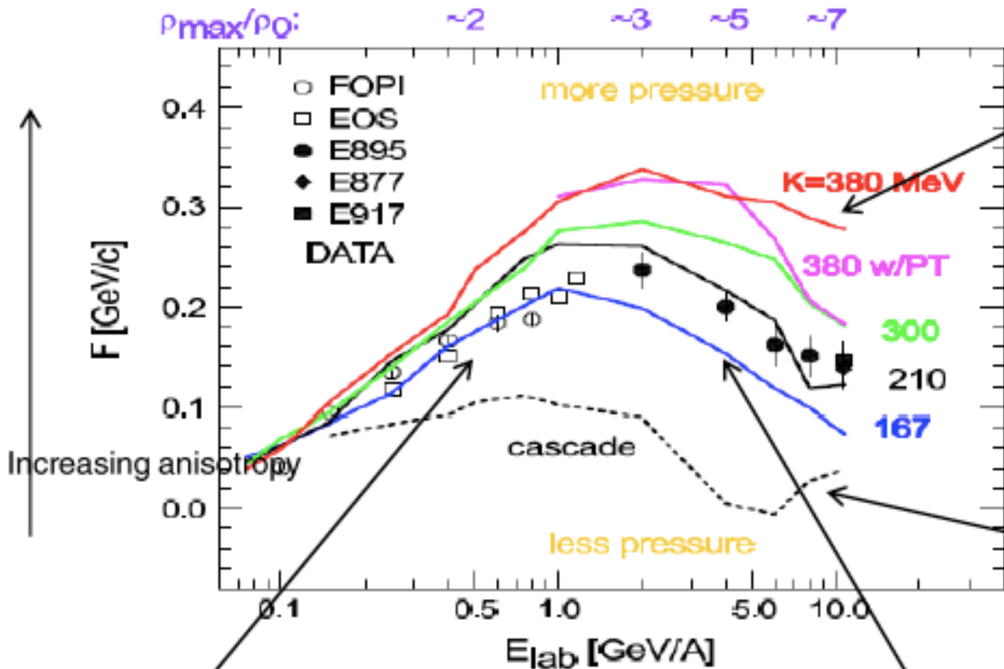
Emission in-plane

Emission out of plane
In-plane shadowed by spectators

Increasing density => Increasing emission

Increasing velocity = decreasing shadowing time of the spectators

Sideward Flow



High incompressibility (high pressure gradient) can not describe data

Positive v1: Enhancement to Proj Direction

Neglected Mean Field

Increasing density (increasing pressure)+decreasing shadowing time of spectators → anisotropy increases

Increasing density (increasing pressure)+very short shadowing time of spectators → anisotropy reduces

Phase Diagramm of Nuclear Matter

Nuclear Equation of State

Outline

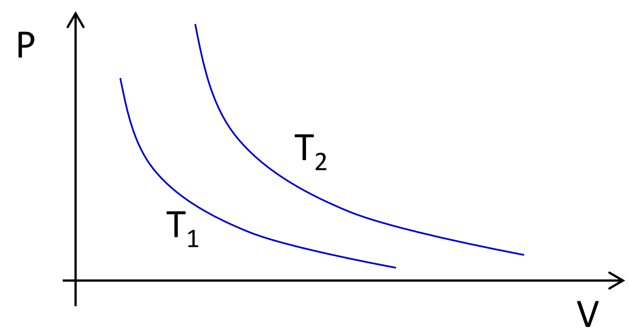
1. Reminders on Thermodynamics
2. Nuclear Equation of State
   a) Importance of the EoS for the understanding of the universe
   b) Approach from Nuclear Physics (EoS around ρ_0)
   c) Approach from Heavy Ion Physics (EoS for $\rho>\rho_0$)

Equation of State

How a system behaves depends on its equation of state.
The equation of state connects the different state variables to each other.
E.g.:
P=P(T,V,N) ; E=E(T,V,N); μ(T,V,N) etc.

Example: **ideal gas**

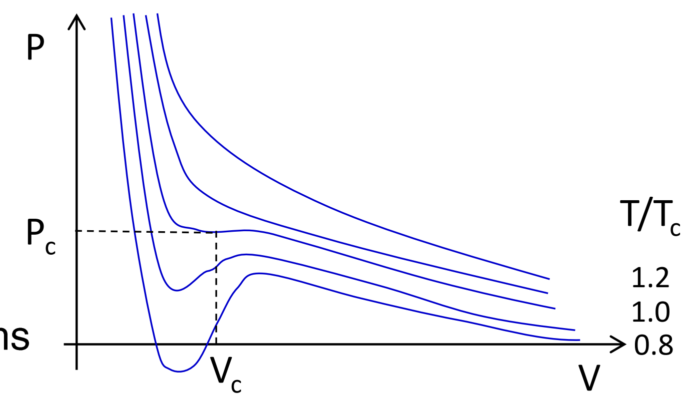
$$P = \frac{N k_b T}{V}$$



Example: **classical gas**
(interaction included)

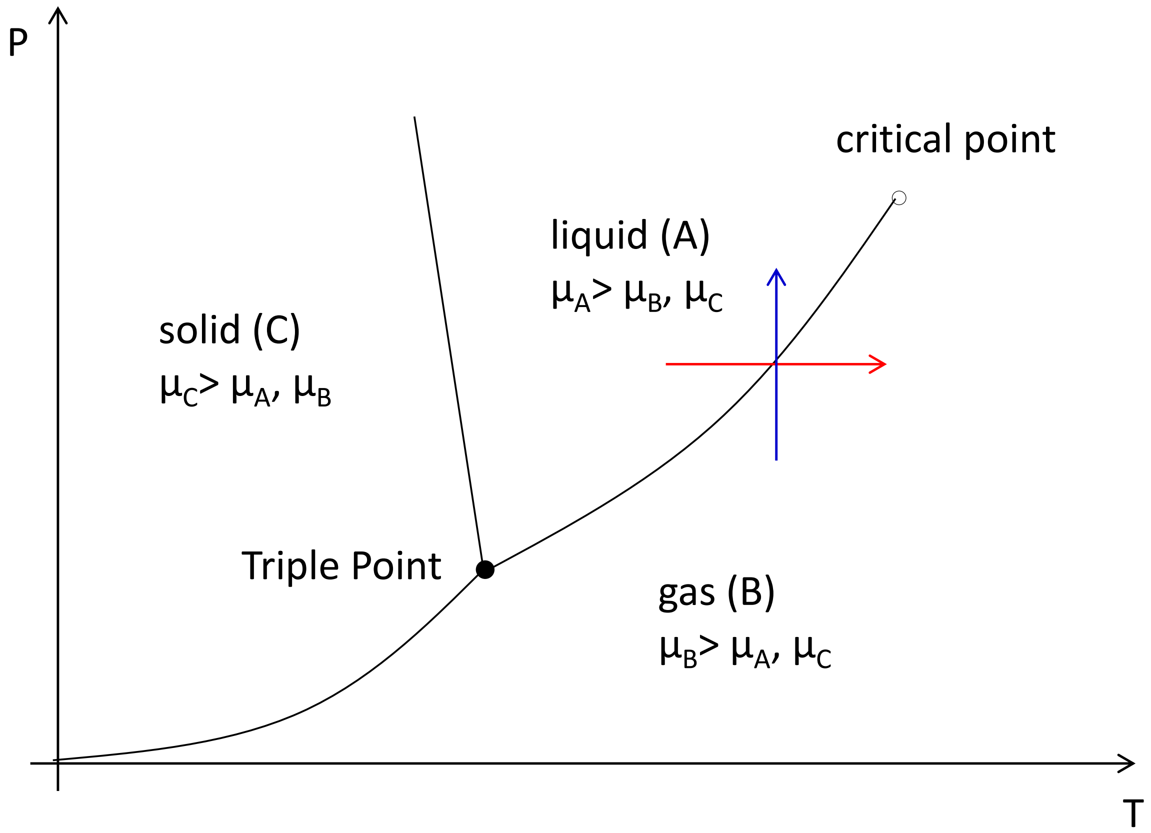
$$P = \frac{k_b T}{v - b} - \frac{a}{v^2}$$

Phase transition to liquid phase
occurs when thermal Energy ($k_b T$)
smaller than attractive Potential between atoms



Phase Diagram

Example of a phase diagram is given by the different phases of water



In general always the phase with the **lowest** chemical potential is present.

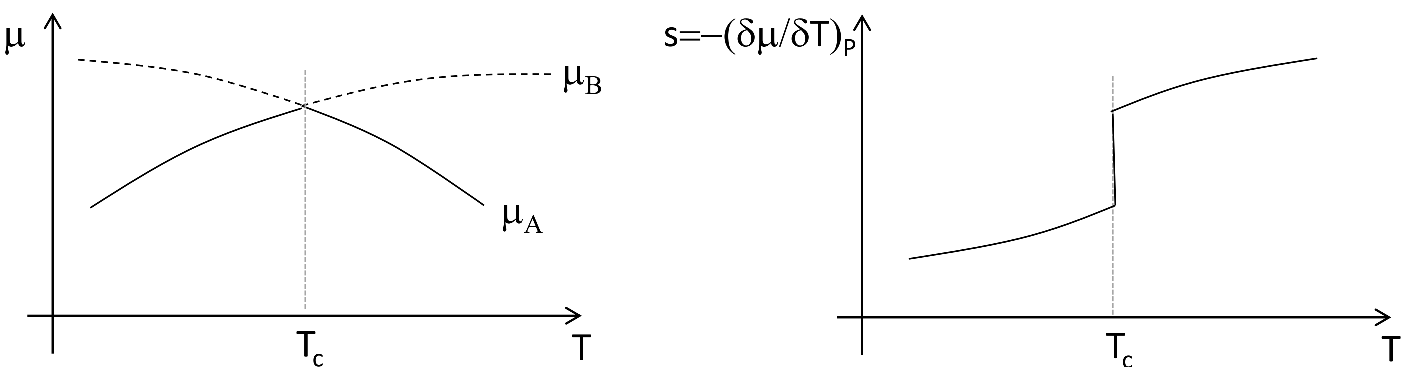
Phase Diagram

By going from left to right one crosses the phase boarder from the liquid (A) to the gaseous (B) phase at **constant pressure.** At the boarder the two phases are in equilibrium, i.e. their chemical potentials are equal:

$$\mu_A(T,P) = \mu_B(T,P) \quad \Rightarrow \quad Phaseboarder: \quad P = P(T)$$

This does not have to be true for the derivatives of the chemical potential:

$$\left(\frac{\partial \mu_A(T,P)}{\partial T}\right)_P \neq \left(\frac{\partial \mu_B(T,P)}{\partial T}\right)_P \Rightarrow s_A \neq s_B$$

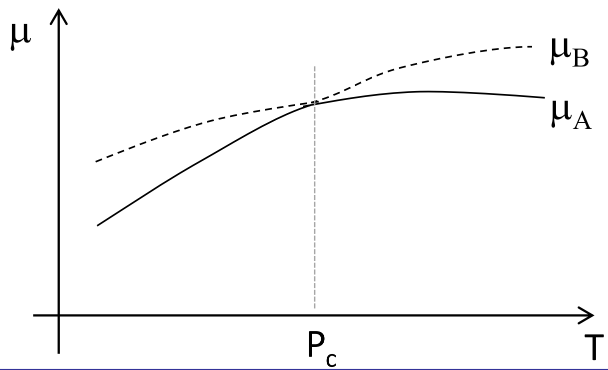


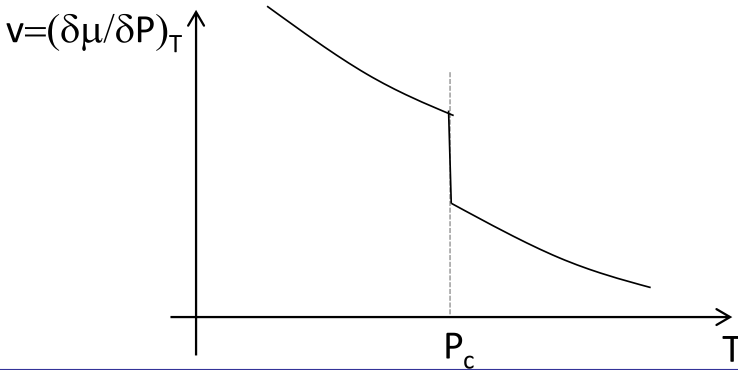
Phase Diagram

By going from down to up one crosses the phase boarder from the gas (B) to the liquid (A) at **constant temperature.** At the boarder the two phases are again in equilibrium, i.e. their chemical potentials are equal:

The first derivatives of the chemical potential is:

$$\left(\frac{\partial \mu_A(T,P)}{\partial P}\right)_T \neq \left(\frac{\partial \mu_B(T,P)}{\partial P}\right)_T \Rightarrow v_A \neq v_B$$





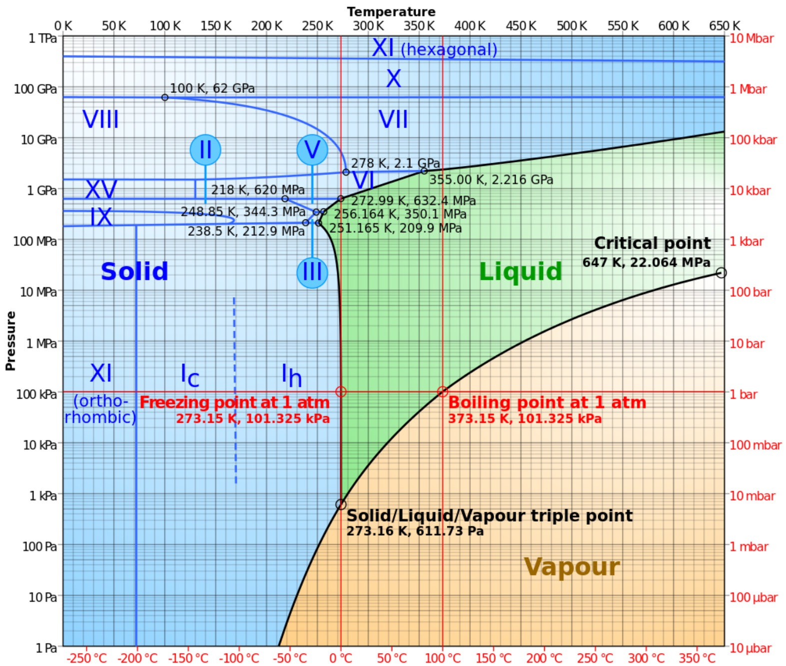
Phase Transitions

- The first derivative has a jump → 1. Order Phase Transition
- By moving to higher temperatures in the water Phase Diagram one reaches the critical point
  - Jumps in Entropy and Volume go to 0
  - 2. Order phase transition
- Moving to even higher Temperatures, derivatives to all order become static → **Cross Over!**

- A state variable, which shows a characteristic change at the Phase Transition is called the **Order Parameter**.
  - e.g. the volume in the case of water
  - e.g. the magnetization in case of a ferro magnet (2. Order Phase Transition)
  - e.g. Entropy (heat) for transition from QGP to hadron gas
    $S_{QGP} \approx N_{color}^2$; $S_{HG} \approx N_{color}^0$

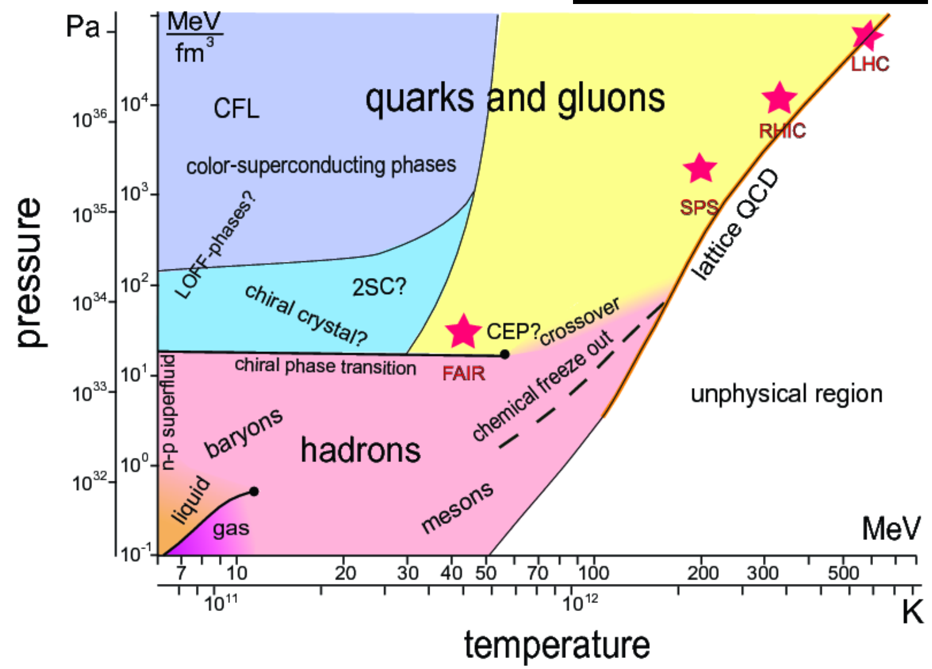
Phase Diagrams

Water (Electromagnetism)



Quark Matter (QCD)

arXiv:1111.5475 [hep-ph]



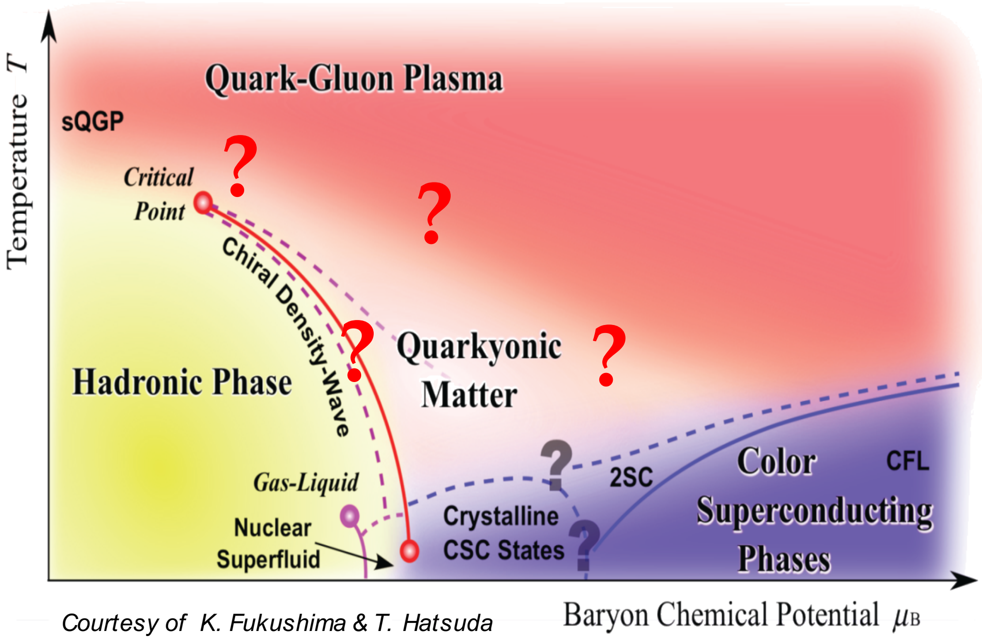
- Can we establish/study a QCD phase diagram with
1. Phase transitions?
2. Critical point?
3. Other phases of matter, e.g. Quarkyonic?

The QCD Phase Diagram

Basic motivation: Exploration of the QCD phase diagram

- Hadron gas phase at low T and/or μ_B
- We expect from QCD lattice calculations a cross over at high energies
- QGP at high T and/or μ_B
  → R_{CP}, NCQ scaling of v_2,...
- First order phase transition?
  → HBT, v_1 analyses
- Critical point?
  → Fluctuation analyses (net-protons)
- Chiral symmetry restoration?
  → Di-leptons
- Quarkyonic matter?
  → ???

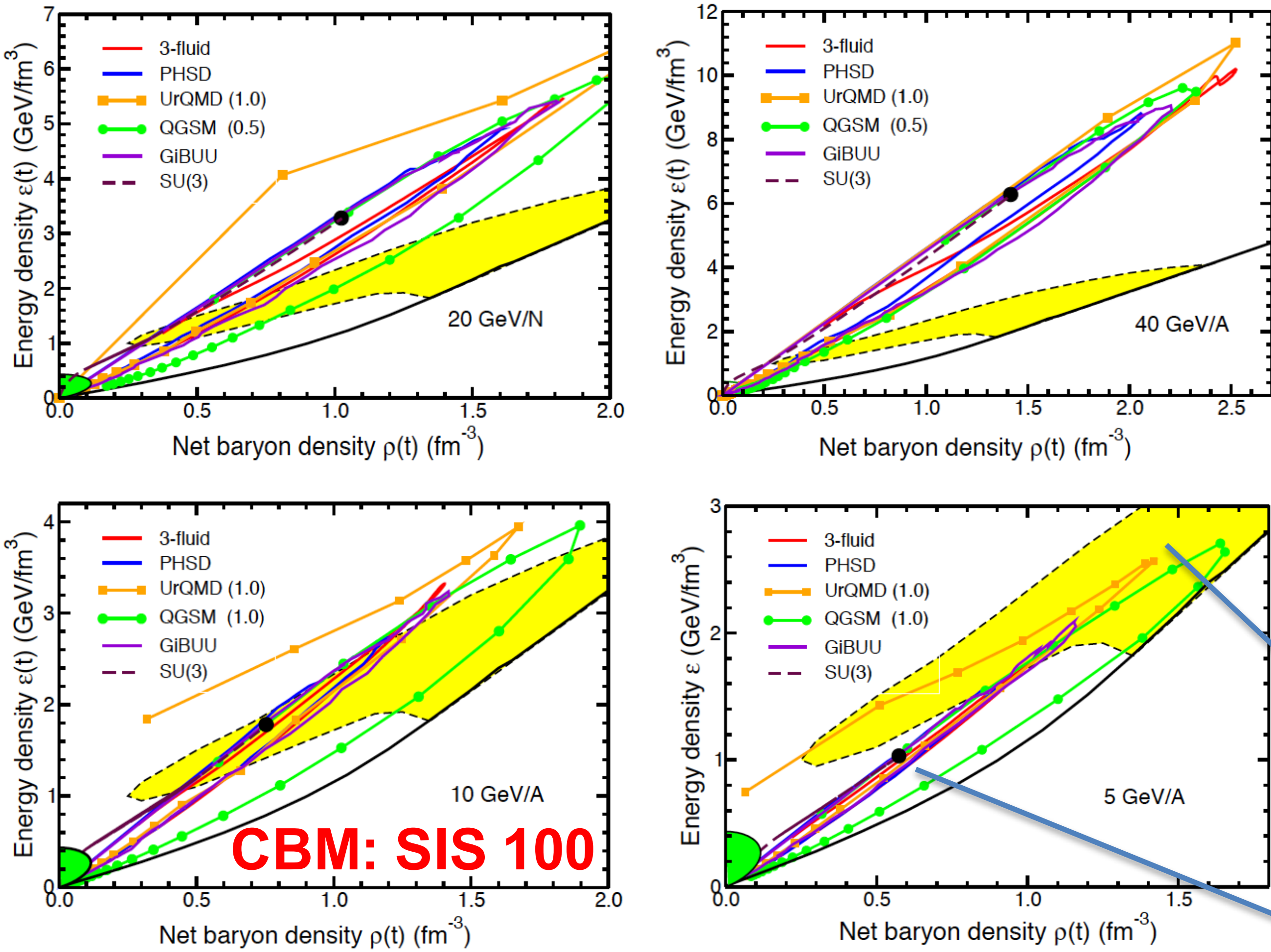
Rept.Prog.Phys. 74 (2011)



? QCD critical point
? QCD phase transition
? Quarkyionic matter
? QGP phase

Phase Space Trajectories

Phys.Rev. C75 (2007) 034902



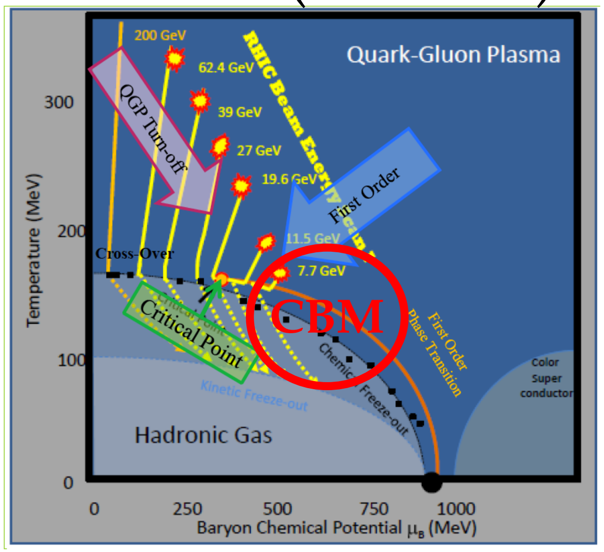
- Coexistence region crossed the longest for trajectories at 10 GeV
- Optimal test of phase transition region at SIS100 energies!

Phase Coexistence region

Critical Point

The Beam Energy Scan Programs

RHIC (Collider)

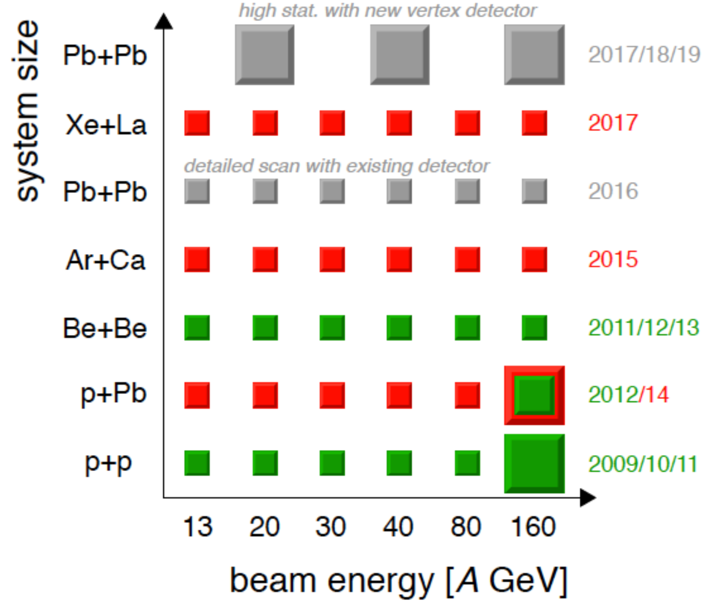


D. Cebra

$\sqrt{s_{NN}}$ (GeV)	*MB Events in 10^6
7.7	4.3
11.5	11.7
14.5	24**
19.6	35.8
27	70.4
39	130.4
62.4	67.3

*Au+Au minimum bias events at STAR usable for analysis

SPS (Fixed target)

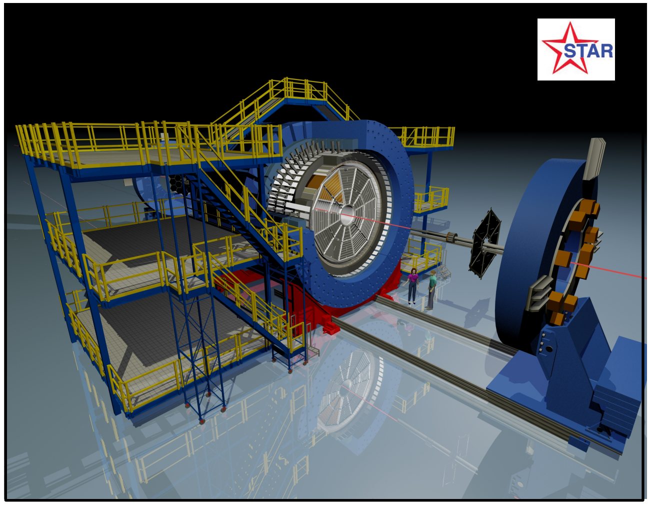


$\sqrt{s_{NN}}$ = 5-17 GeV

- Two dimensional scan in energy and system size → Criticality
- p+p and p+Pb reference runs
- High statistic runs with vertex tracker from 2017

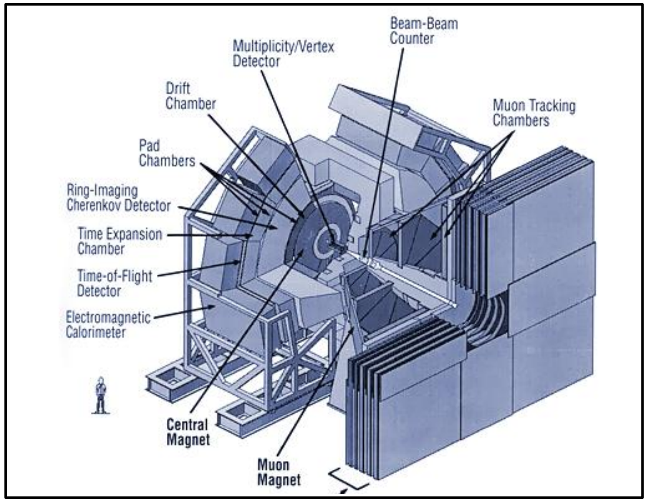
Present Experiments

STAR



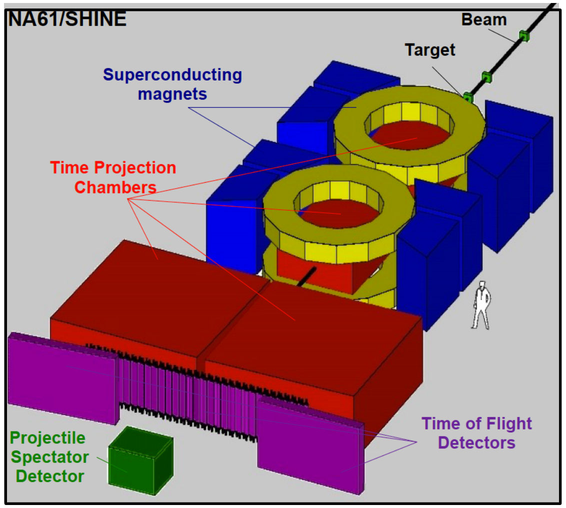
- $7.7 < \sqrt{s_{NN}} < 200$ GeV
- Excellent PID
- Full azimuthal coverage
- Energy scan started: 2010

PHENIX



- $7.7 < \sqrt{s_{NN}} < 200$ GeV
- High granularity calorimeter
- Energy scan started: 2010

NA61/SHINE

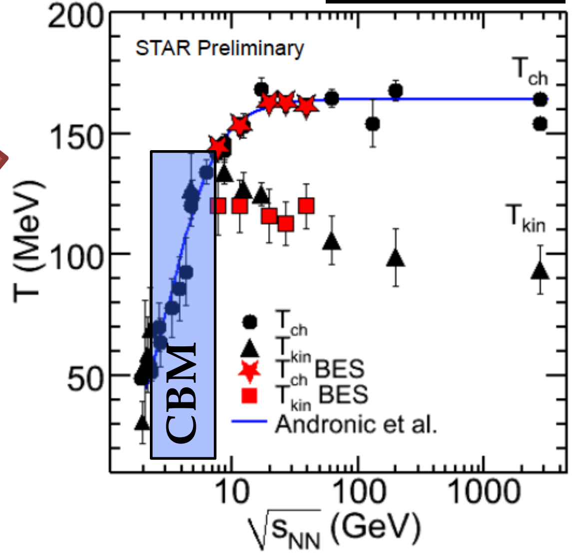


- $\sqrt{s_{NN}}$ = 5-17 GeV
- Full forward ToF
- Energy scan started: 2009

Relatively low statistics at lowest energies (~ few million events)
→Focus mainly on bulk observables
→→ For rare probes and lower energies CBM/HADES is needed!

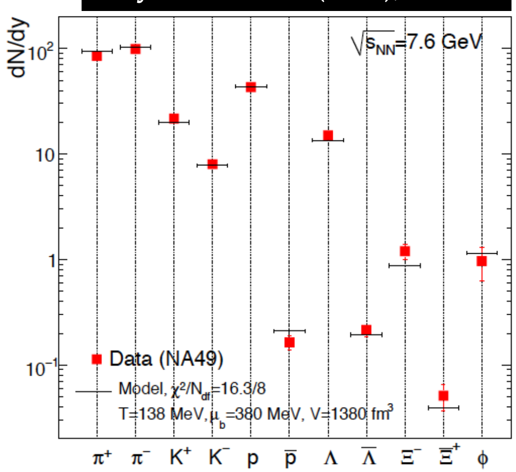
Freeze-Out Systematics

STAR QM 2014



$T_{chemical}$: Statistical hadronization model

Phys.Lett. B673 (2009), 142-145



Where are we in the phase diagram?

- Saturation of T_{chem} above ~10 GeV
- Splitting between T_{chem} and T_{kin} starts at ~6 GeV

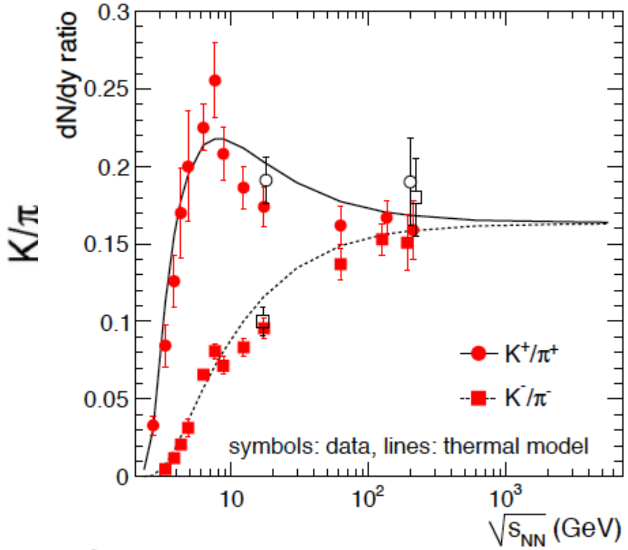
- Connected to a phase change?

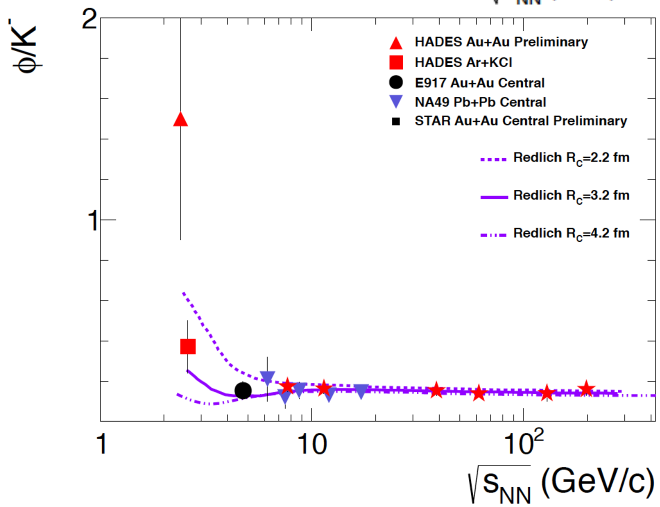
- Maximum baryon density reached at ~8 GeV
  → pions processes become more important

Lattice chemical freeze-out parameters:
S. Mukherjee. arXiv:1211.7048 [nucl-th]
A. Bazavov et al., Phys. Rev. Lett. 109, 192302 (2012)
S. Borsanyi et al., Phys. Rev. Lett. 111, 062005 (2013)

Particle Ratios

J.Phys. G38 (2011)





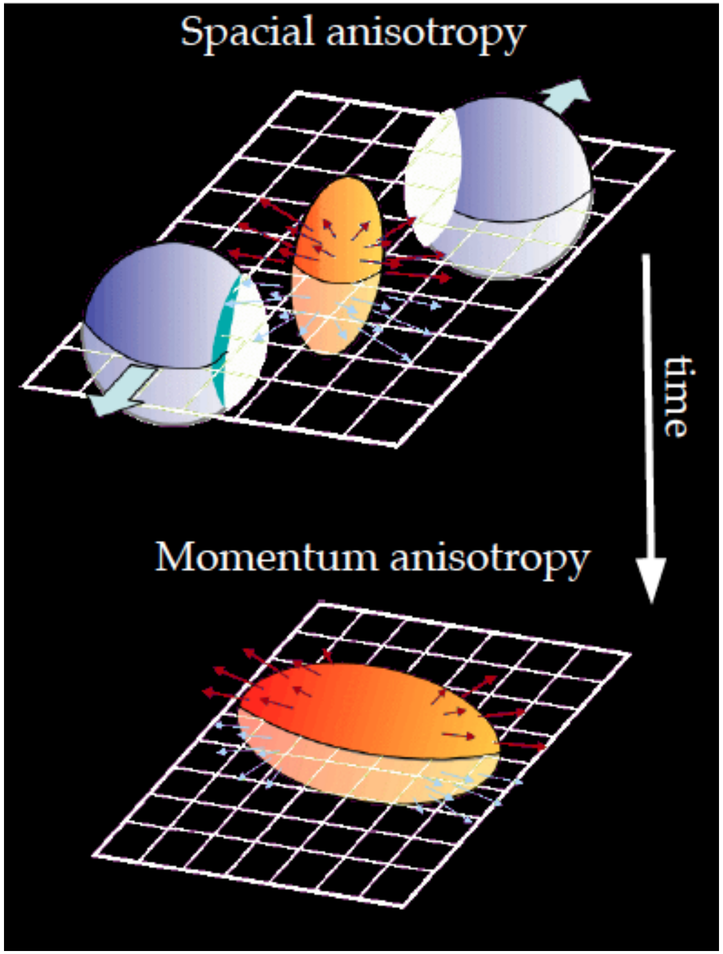
- Pronounced structures in particle ratios at ~ 5-10 GeV
  → indications for a phase transition?

- Net-baryon density has a maximum at ~ $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out (Λ/π)
  + Associate production channels like N+N → N + Λ + K^+
- Canonical strangeness suppression at low energies?
- Statistical hadronization model can describe the various structures, **EXCEPT** multi=strange particles
  → Ξ
  → What about Ω?

HADES, QM 2014

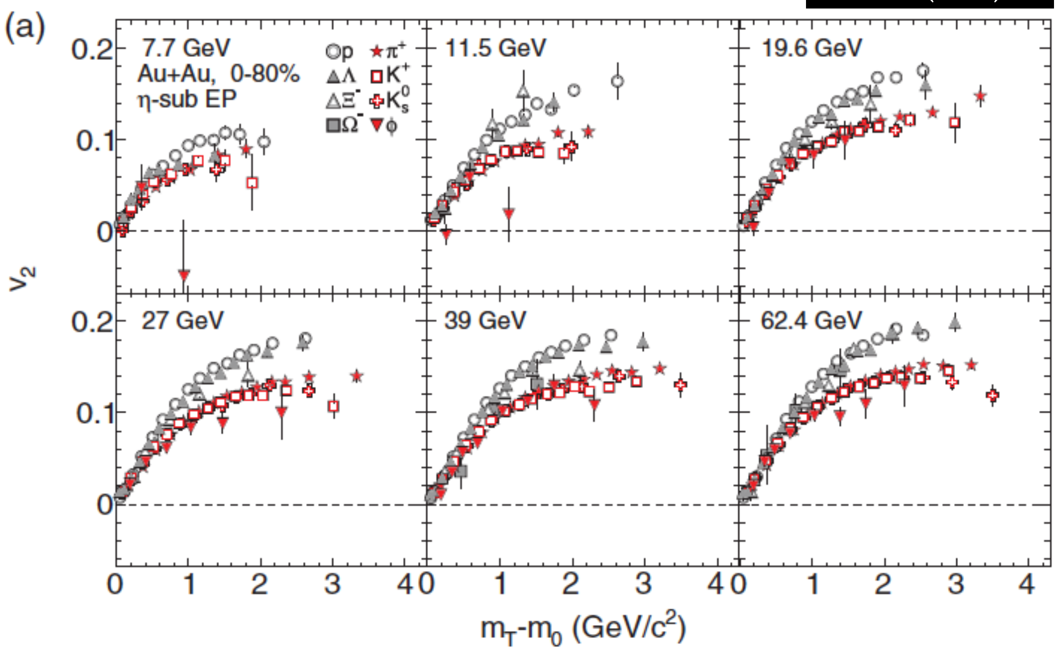
Hwa & Yang, Phys. Rev. C 75, 054904 (2007)

Collective Behavior



Hydrodynamic evolution

Phys. Rev. C 88, 014902 (2013)

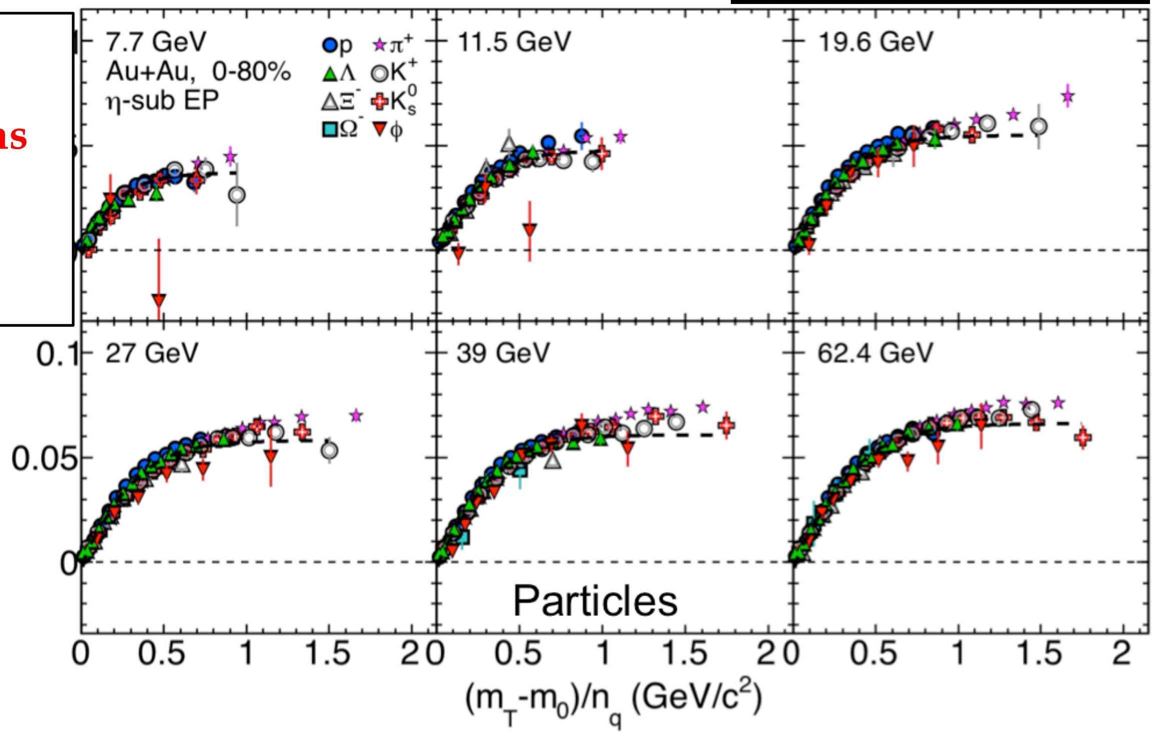


- v_2 is strength of correlation with event plane
- Baryon-**meson** splitting
  → signature for partonic degrees of freedom?
- This signature should go away in a hadronic environment
  → **SIS 100 energies**
  → **QGP at < 8 GeV?**

v_2 NCQ Scaling of Particles

Phys. Rev. C 88, 014902 (2013)

What happens at 2-8 GeV?



- NCQ-scaling holds for particles and anti-particles separately at all energies → Partonic degrees of freedom?

NCQ = Number of Constituent Quark

- High m_T-m_0 not measured at lower energies
- Do ϕ-mesons or multi-strange particles deviate?
- NCQ scaling should break down at even lower energies (2-5 GeV)!

Jet Suppresion

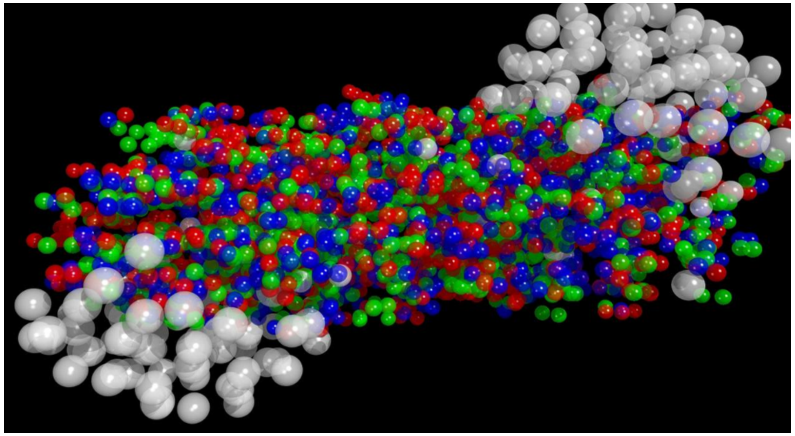
Probe the medium

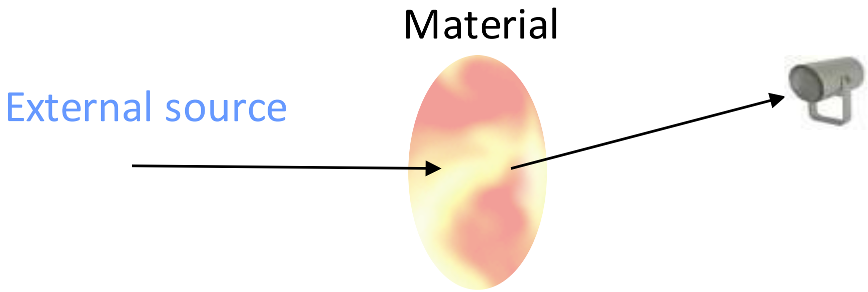
- Goal:

  Understand the property of QGP

- Problem: the lifetime of QGP is so short ($O(fm/c)$) such that it is not feasible to probe it with an external source.

- Solution: Take the advantage of the large cross-sections of high p_T jets, $\gamma/W/Z$, quarkonia at the LHC energy, use hard probes produced with the collision.



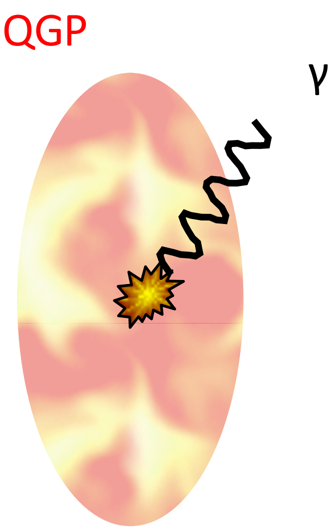


Y.G. Lee, QM Lectures 2012

Three types of hard probes

Electroweak probes

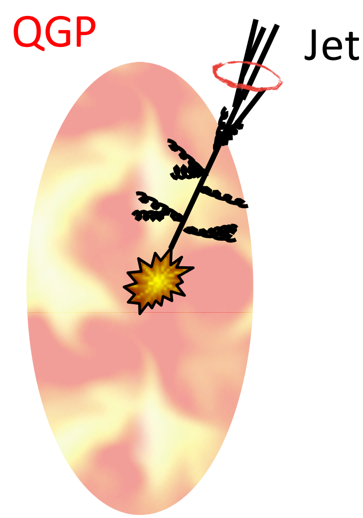
W/Z bosons, high p_T γ



Probe the initial state

Quarks and gluons

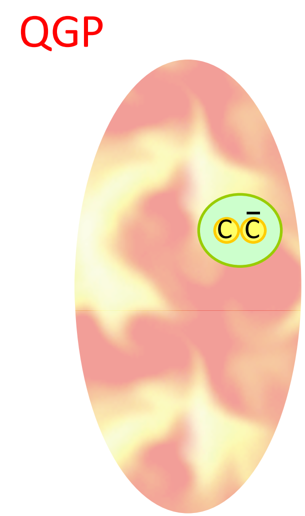
Jets



Probe the opacity of QGP

Quarkonium

J/ψ, Υ family



Sensitive to
the temperature of QGP

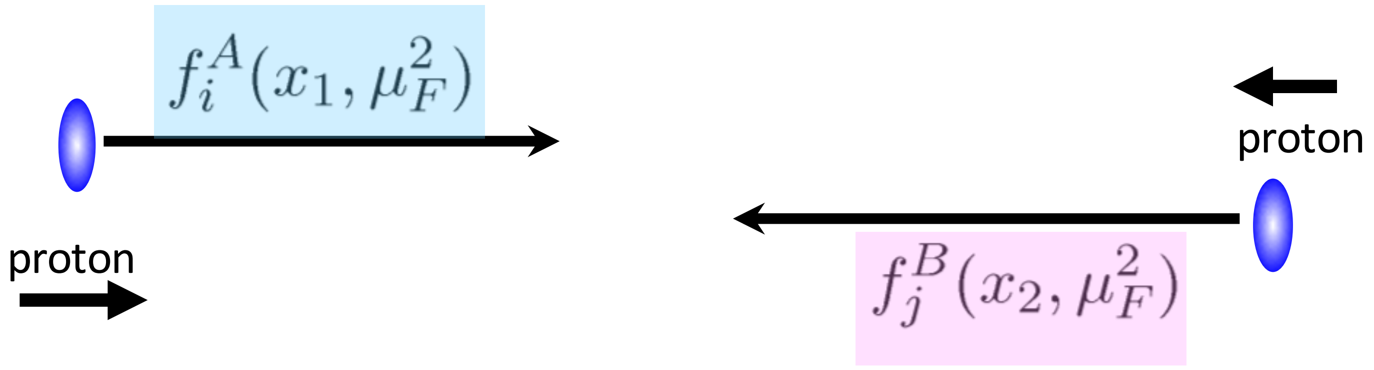
Y.G. Lee, QM Lectures 2012

Factorization

Factorization

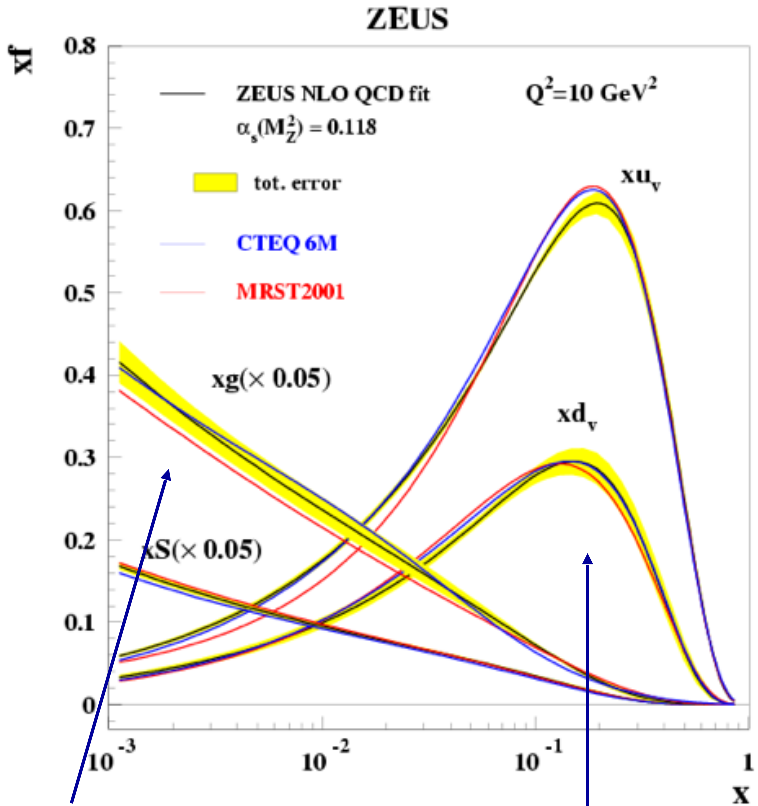
$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Parton Distribution Function (PDF)



Parton density distribution

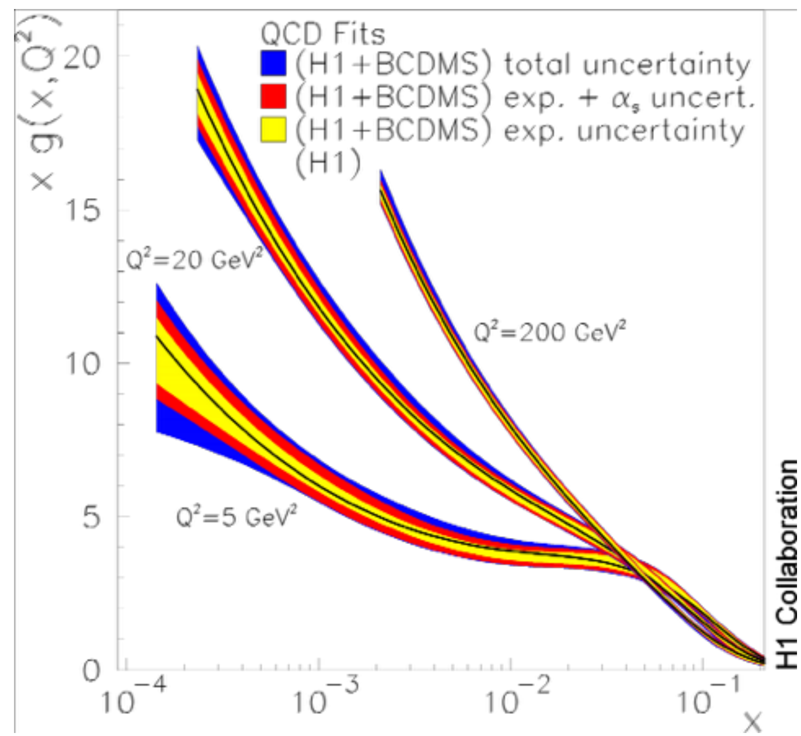
Low Q^2: valence structure



Soft gluons

Valence quarks (p = uud)
x ~ 1/3

Q^2 evolution (gluons)

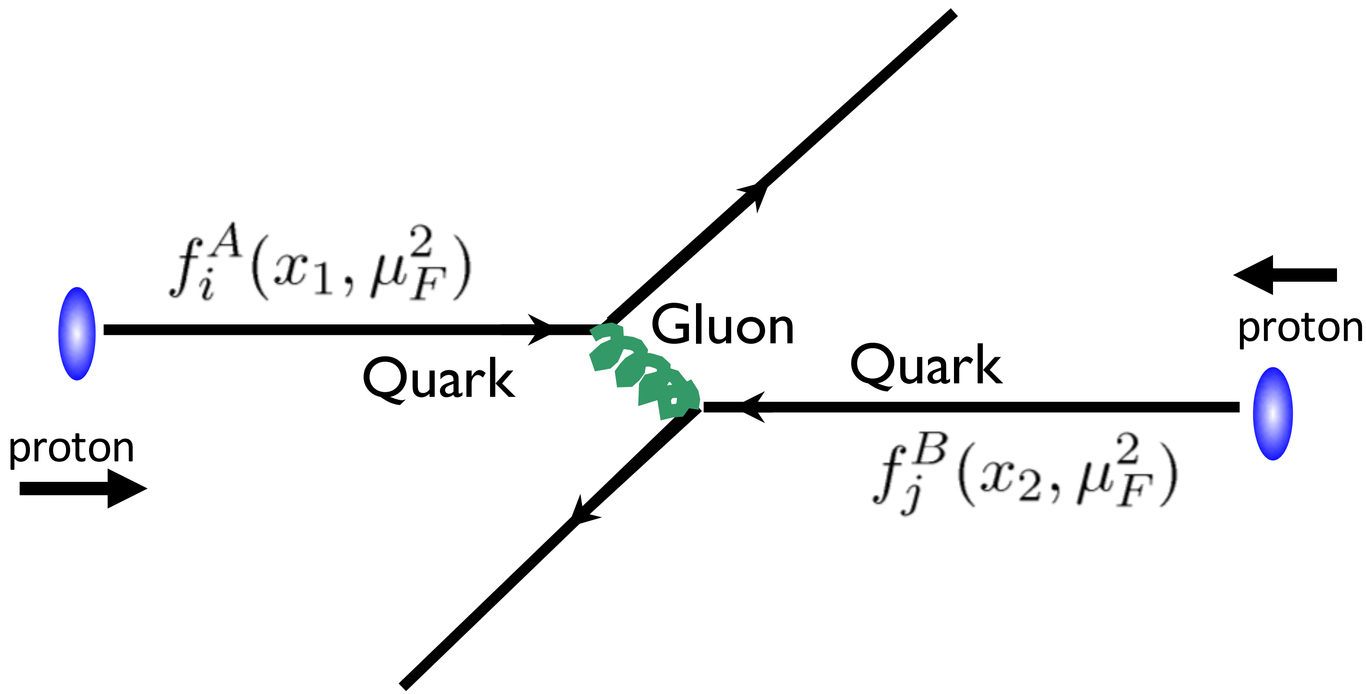


Gluon content of proton rises quickly with Q^2

Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Parton Distribution Function (PDF)   Cross-section of 2→2 process



Y.G. Lee, QM Lectures 2012

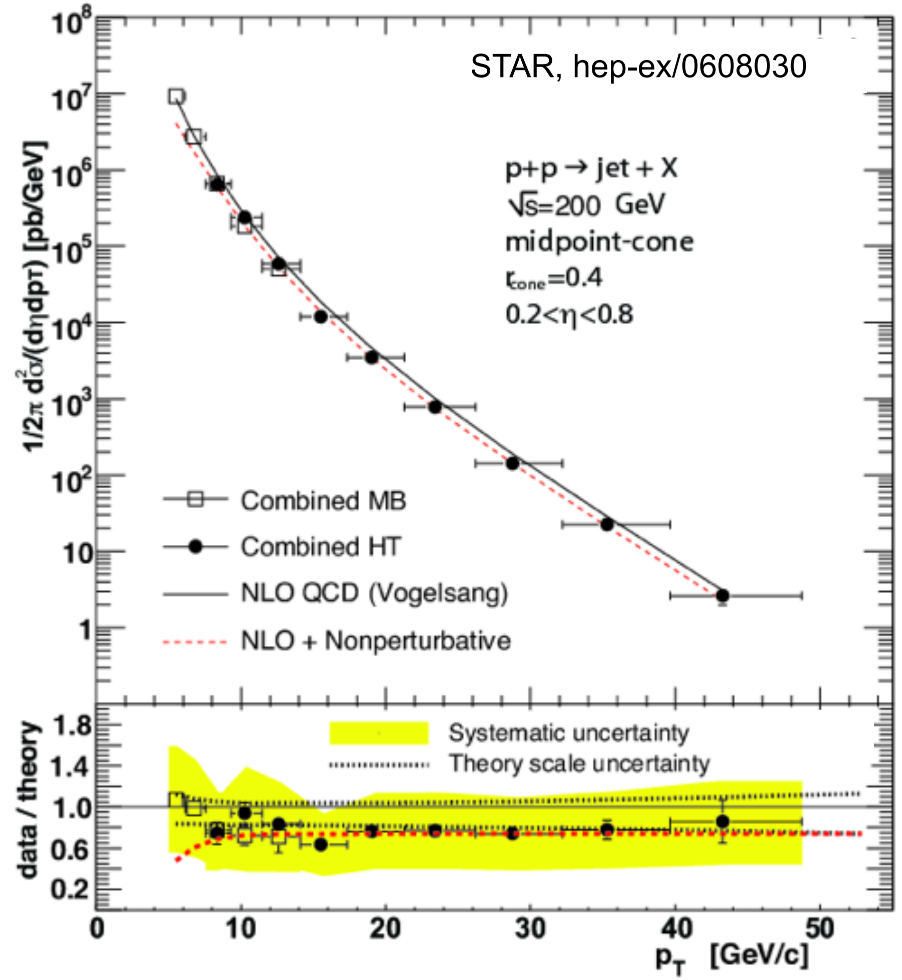
Testing QCD at RHIC with jets

RHIC: p+p at √s = 200 GeV
(recent run 500 GeV)

Jets also measured at RHIC

NLO pQCD also works at RHIC

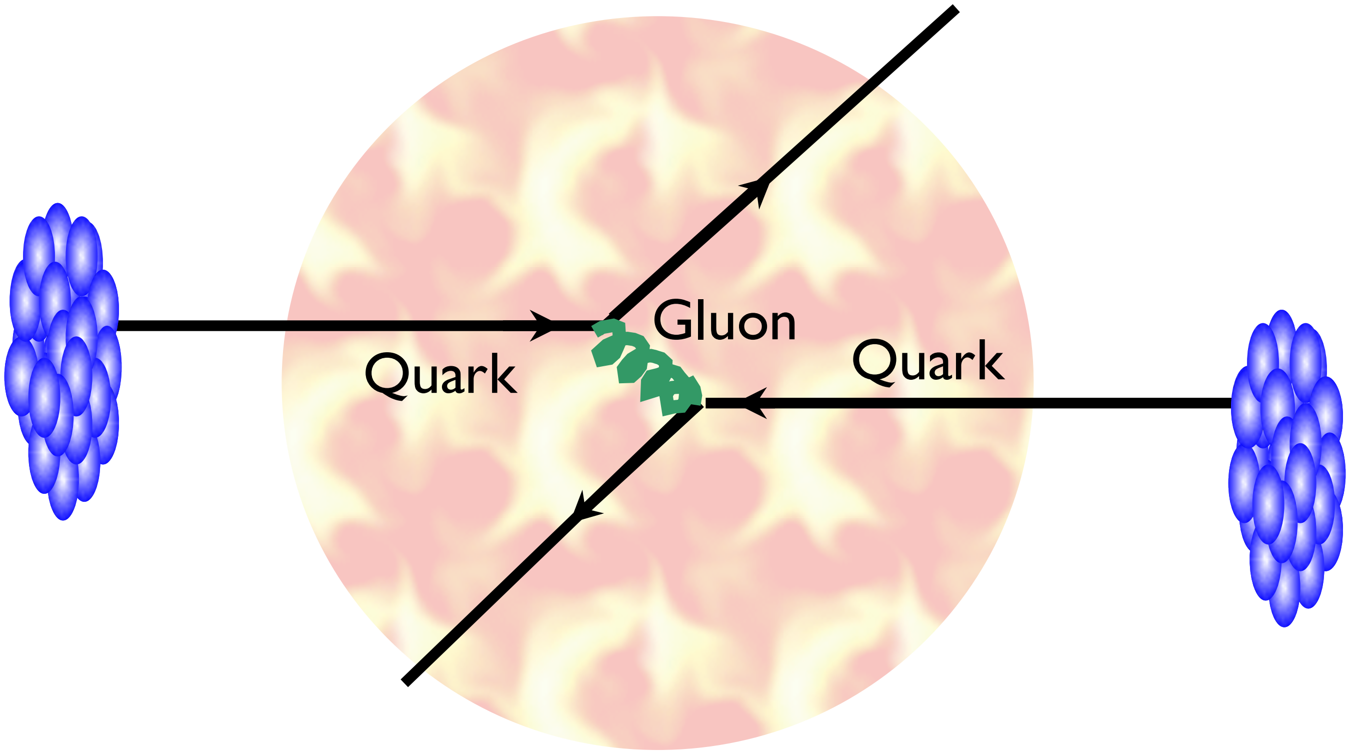
However: signficant uncertainties in energy scale, both ‘theory’ and experiment



Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Nuclear Parton Distribution Function (nPDF)   Cross-section of 2→2 process

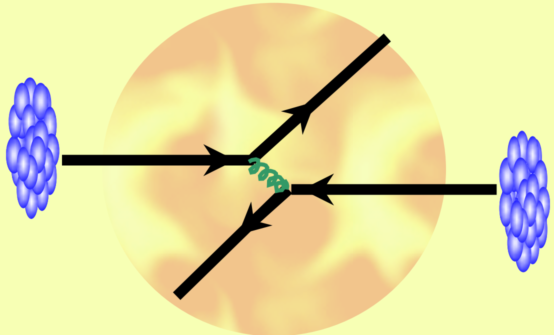


Y.G. Lee, QM Lectures 2012

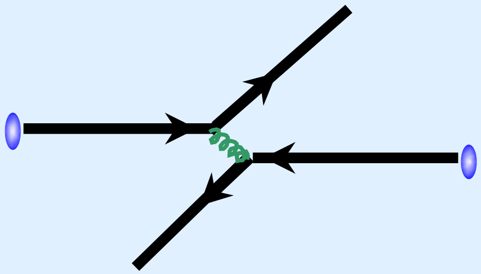
How do we extract the medium effect in PbPb collisions?

One typical way is to compare PbPb data to pp reference measurement

PbPb measurements



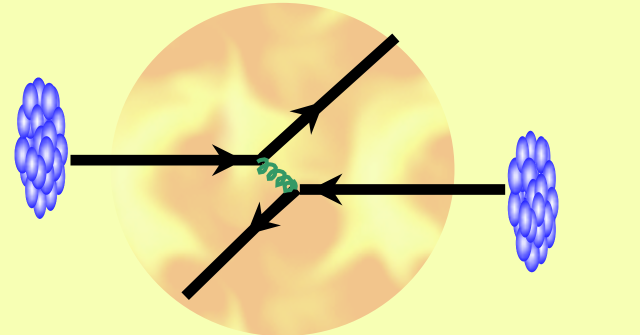
pp reference



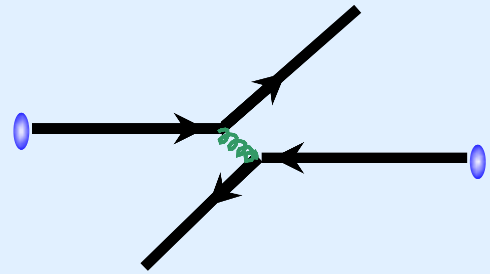
How do we extract the medium effect in PbPb collisions?

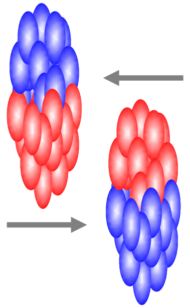
One typical way is to compare PbPb data to pp reference measurement

PbPb measurements



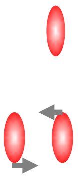
pp reference



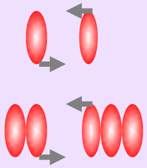


N_{part} → Number of participating nucleons

N_{coll} → Number of binary scatterings



Example:

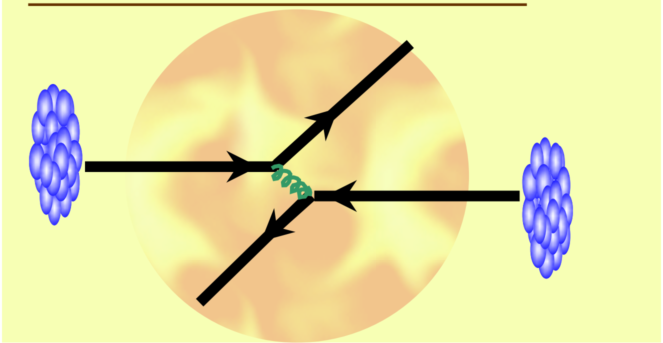


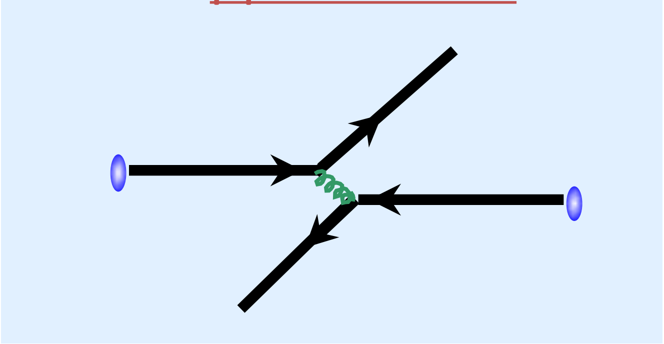
$N_{part} = 2$ $N_{coll} = 1$

$N_{part} = 5$ $N_{coll} = 6$

How do we extract the medium effect in PbPb collisions?

One typical way is to compare PbPb data to pp reference measurement





'Nuclear modification factors'

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

N_{coll} → Averaged number of binary scattering

Can also be written as $1/T_{AA}$

$$T_{AA} = \frac{N_{coll}}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per AA collision"

Reduces the uncertainty from pp inclusive cross-section

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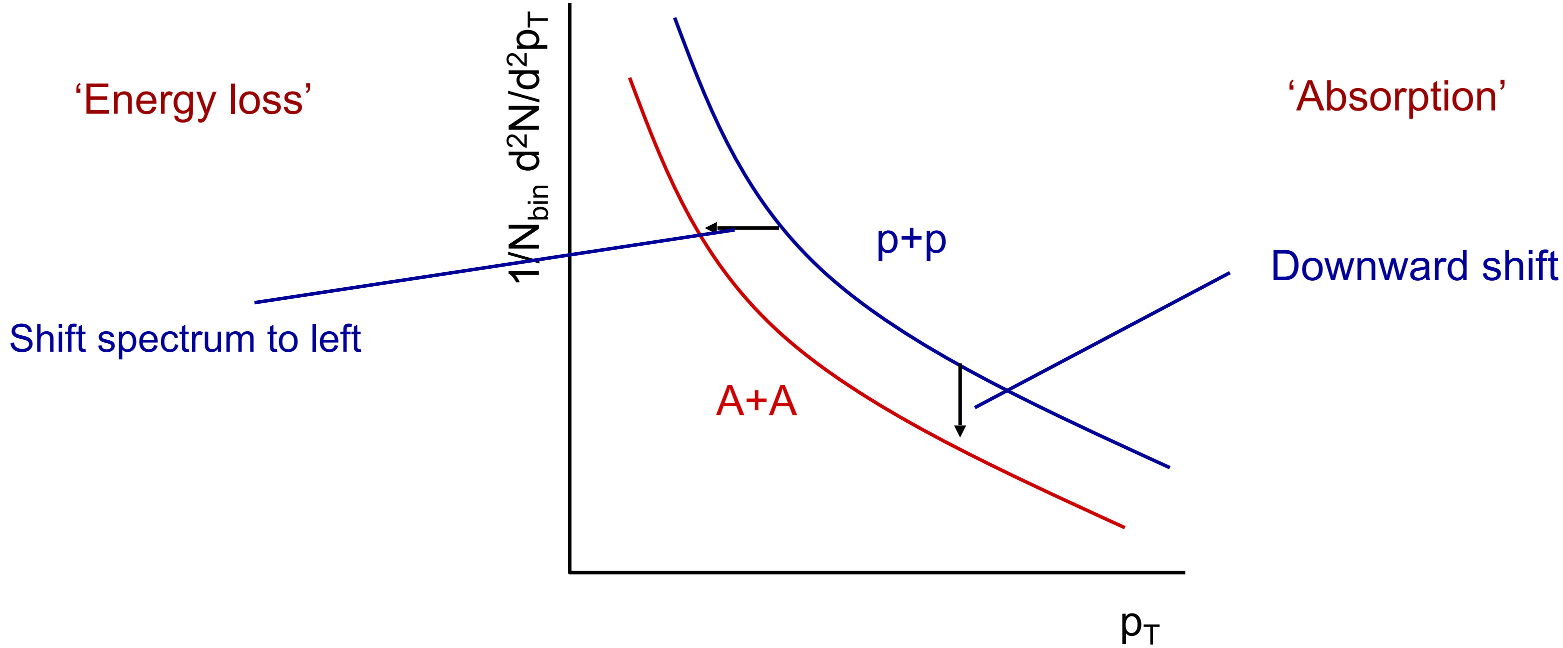
Nuclear modification factor R_{AA}

$$R_{AA} = \frac{dN/dp_T\big|_{Pb+Pb}}{N_{coll}\, dN/dp_T\big|_{p+p}}$$



Measured R_{AA} is a ratio of yields at a given p_T
The physical mechanism is energy loss; shift of yield to lower p_T

From RHIC to LHC

RHIC: 200 GeV
LHC: 2.76 TeV
per nucleon pair

Energy ~24 x higher

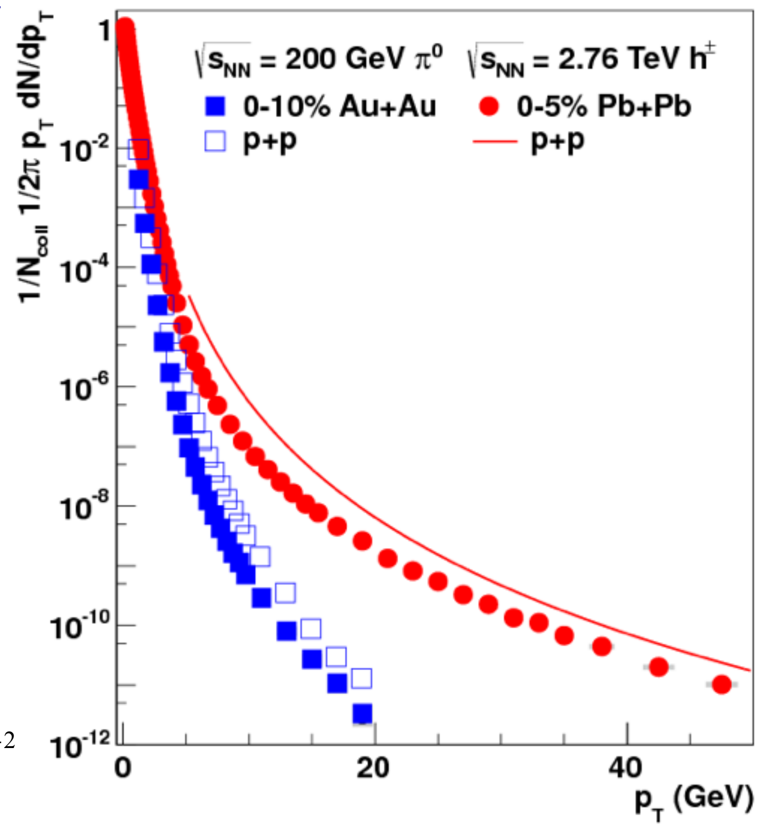
LHC: spectrum less steep,
larger p_T reach

$$\frac{1}{2\pi\ p_T}\frac{dN}{dp_T} \propto p_T^{-n}$$

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

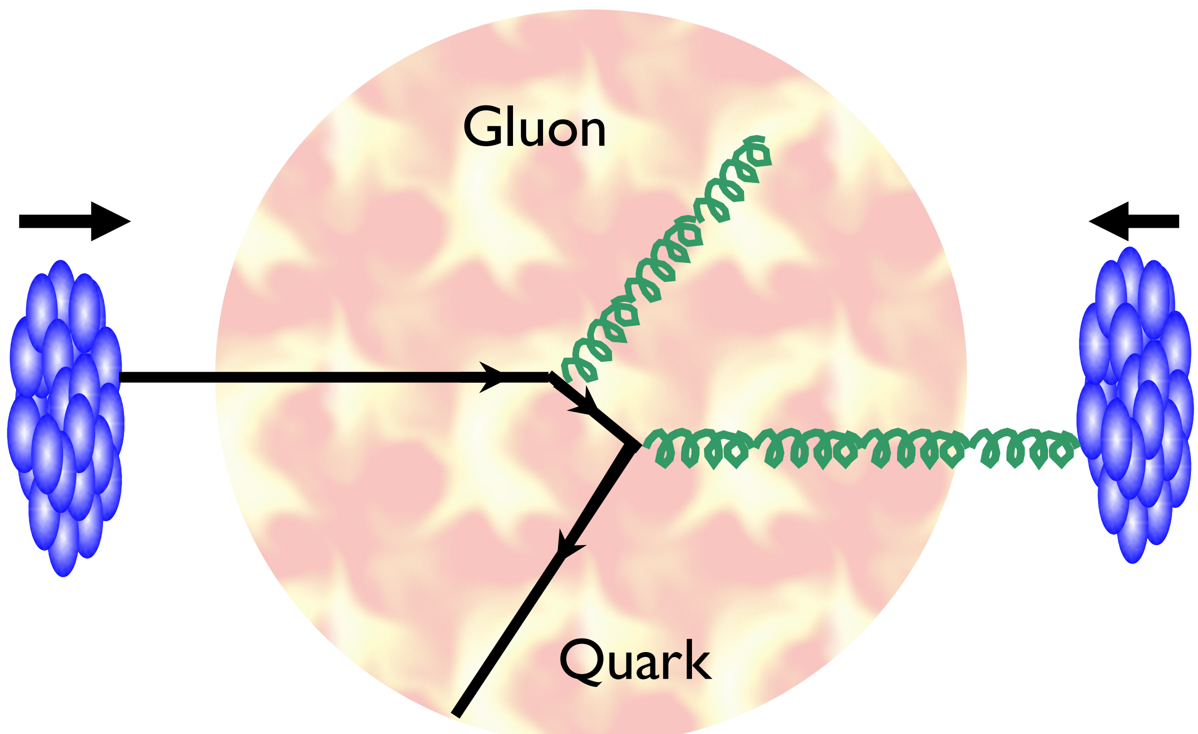
$$R_{AA} \approx \left(1-\frac{\Delta E}{E}\right)^{n-2}$$



R_{AA} depends on n, steeper spectra, smaller R_{AA}

How about quarks and gluons?

- Want to measure quarks and gluons which carry color charge and see how they interact with QGP



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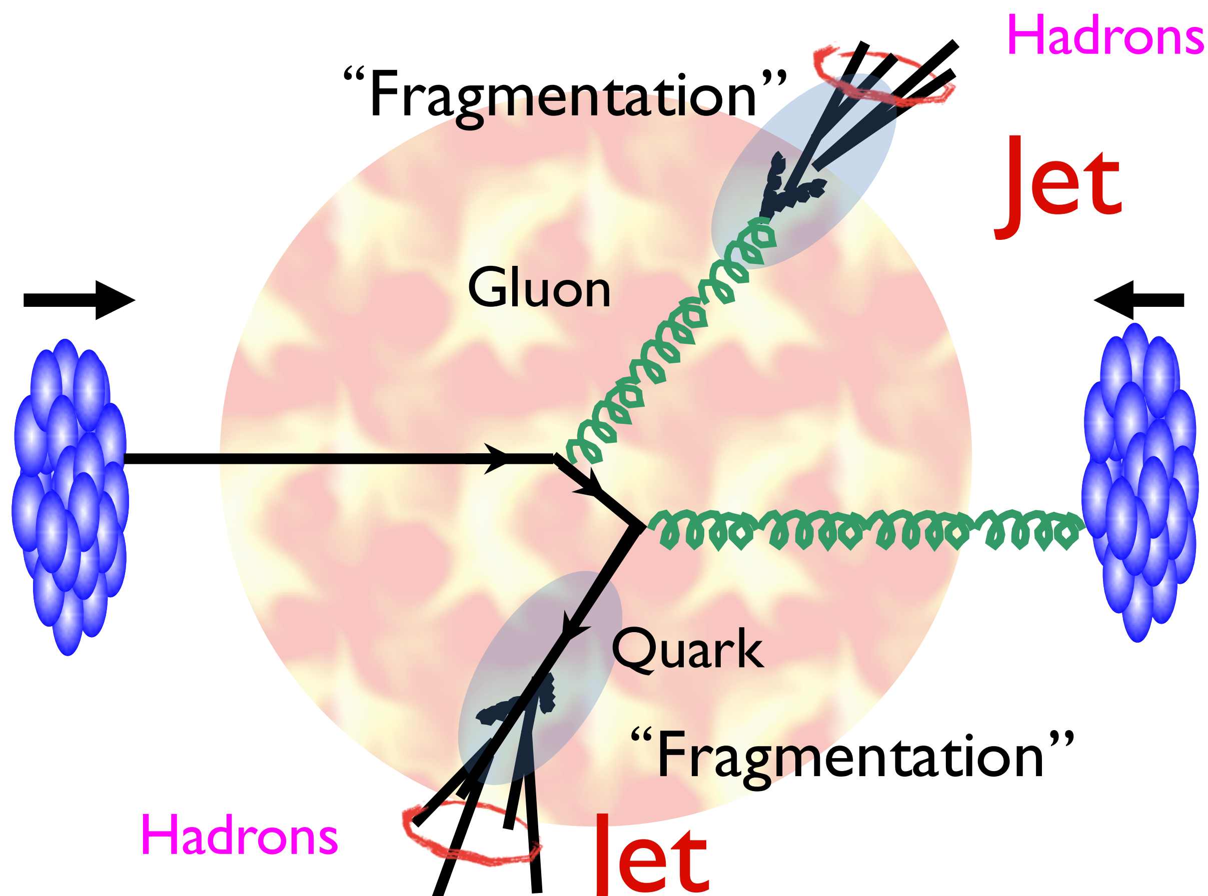
How about out going quarks and gluons?

- Want to measure quarks and gluons which carry color charge and see how they interact with QGP
- → Practically: measure hadrons and jets



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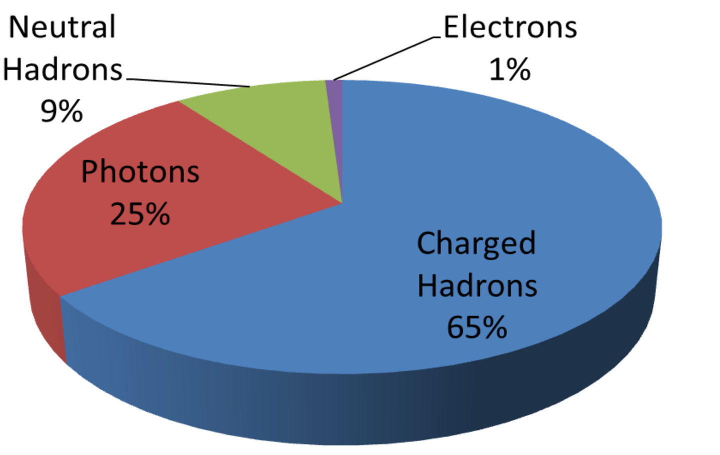
Jet composition

On average, charged hadrons carry 65% of the jet momentum

Measure the known part

Correct the rest by MC simulation



A typical high p_T jet

Optimize the use of calorimeter and tracker

Example: "Particle Flow" in CMS

Goal:

- Make use of the redundancy of measurements from calorimeter and tracker
- Improve the sensitivity to low p_T particles in jet

→Reduce the dependence on MC (ex: PYTHIA)

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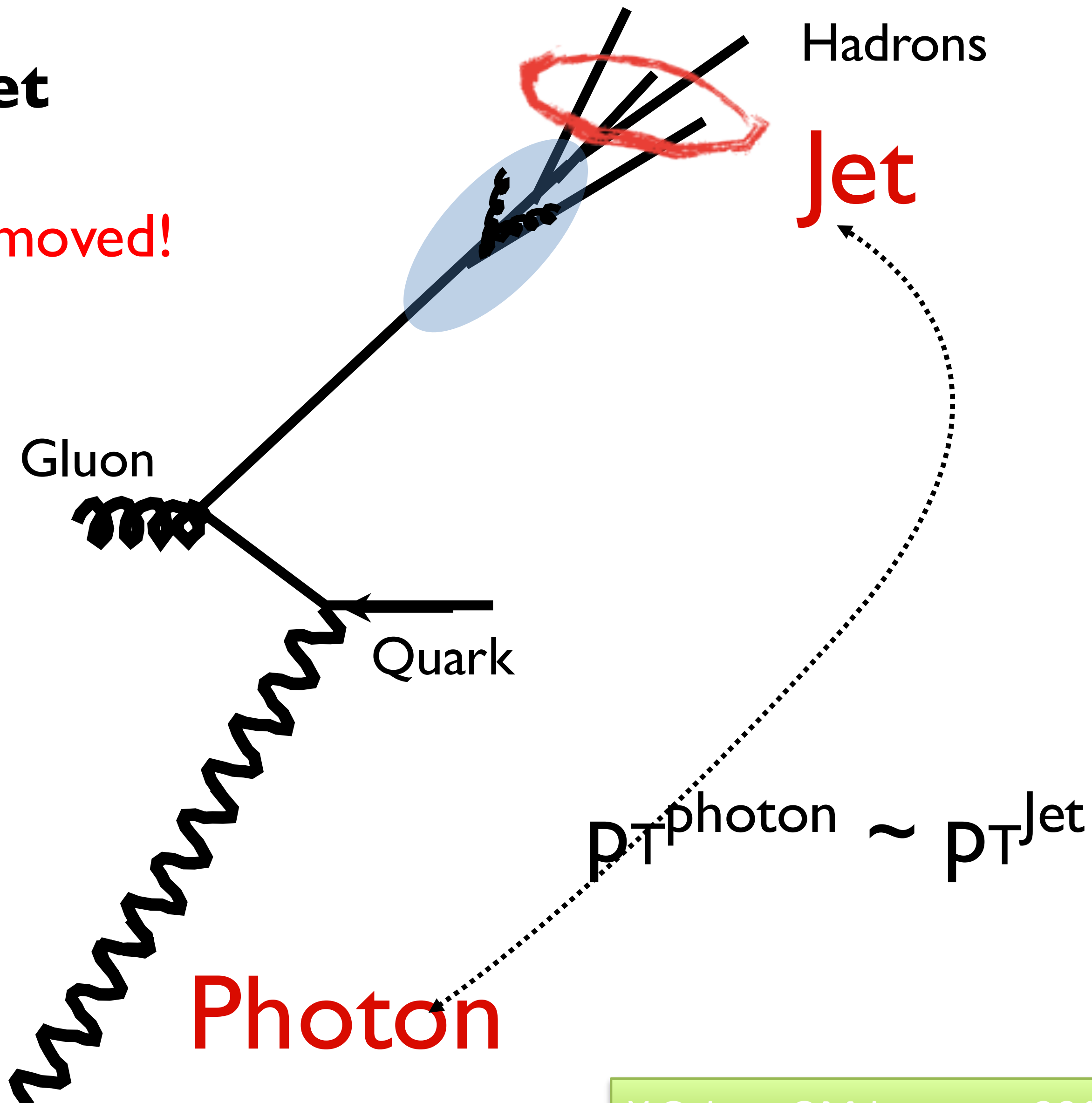
How about correlate photons and jets?

photon+jet

Surface bias is removed!

"quark-gluon compton scattering"



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