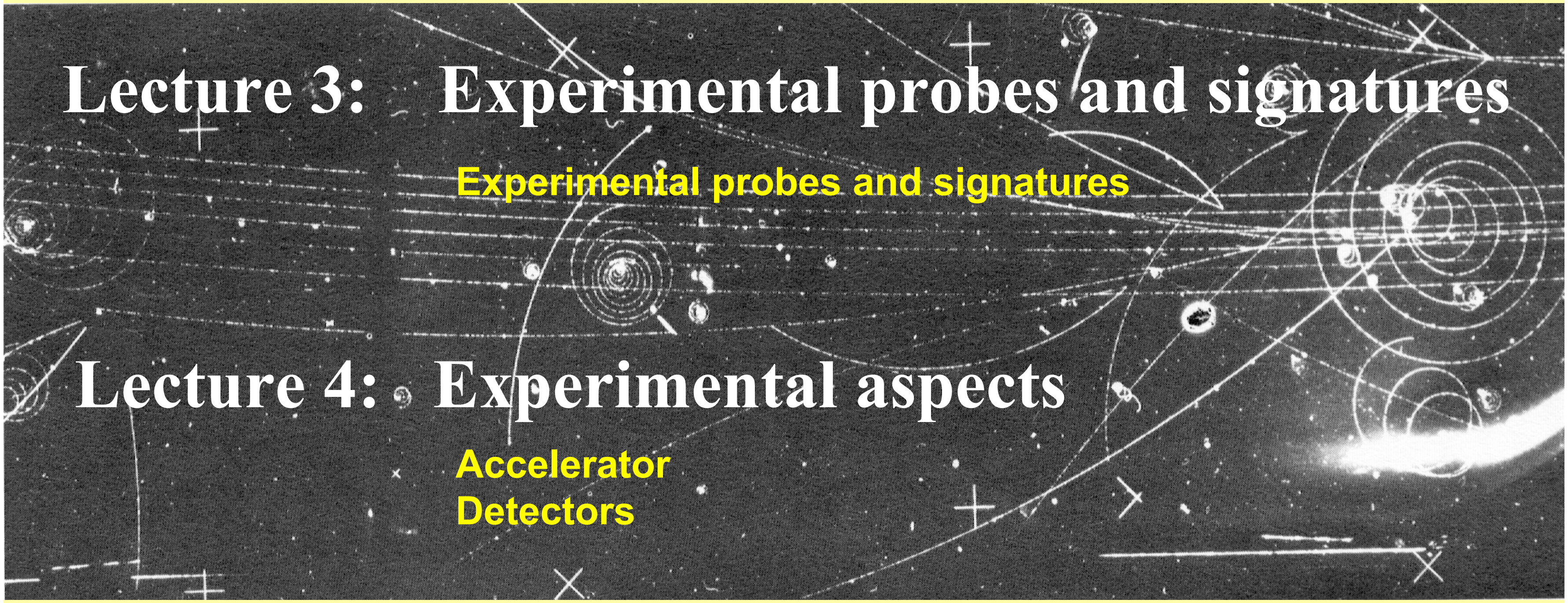
facts



Lecture 3: Experimental probes and signatures

Experimental probes and signatures

Lecture 4: Experimental aspects

Accelerator
Detectors

Signatures of the Quark-Gluon Plasma

Bose-Einstein interferometry

J/ψ suppression

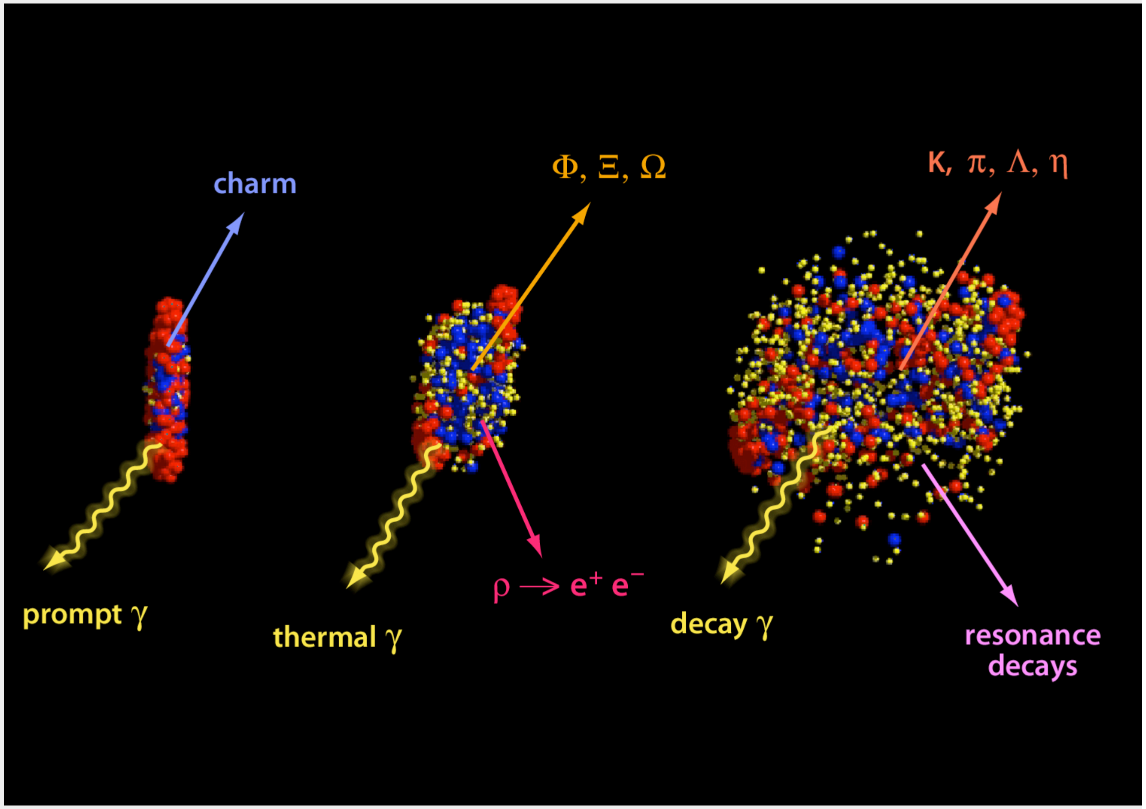
Jet quenching

Collective flow

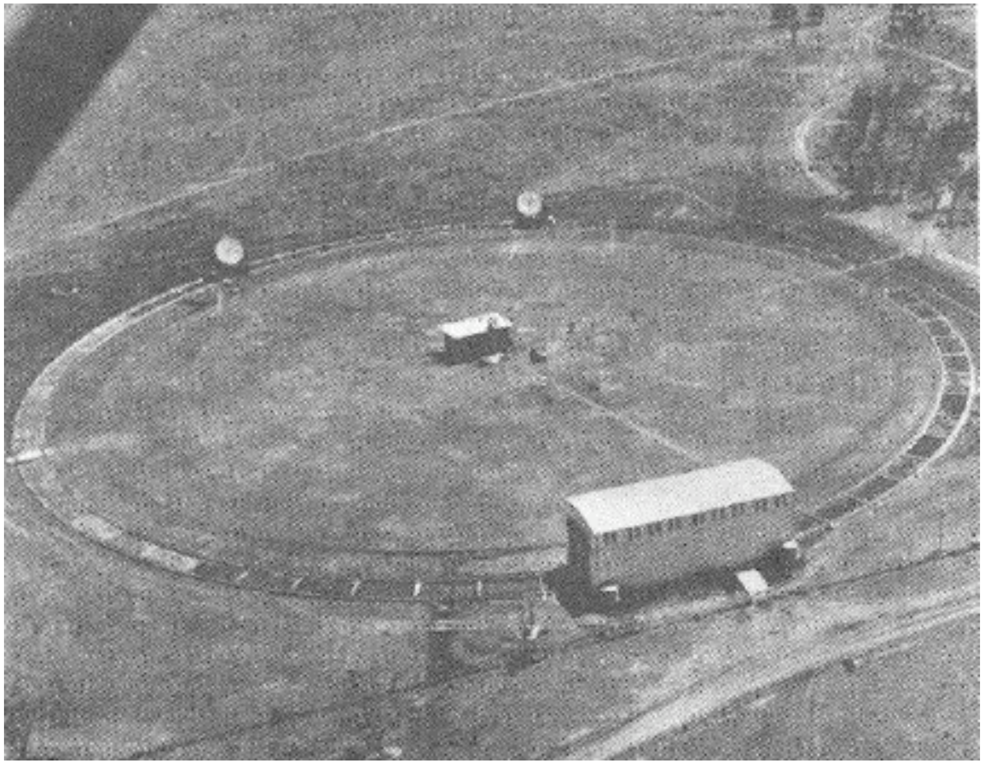
Direct photons

Dilepton production

Strange particle production



Bose-Einstein Correlations

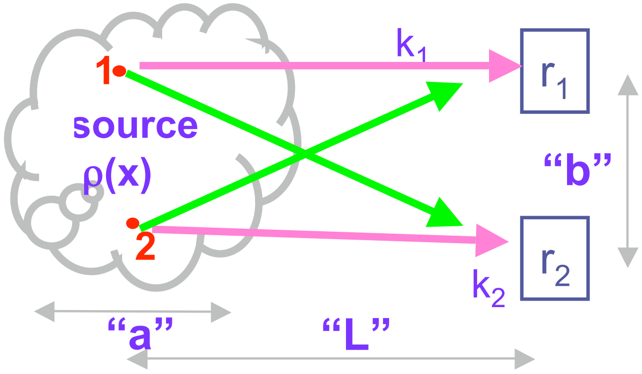


Robert Hanbury Brown and Richard Twiss

HBT Intensity Interferometry

Interference is a phenomenon associated with the superposition of two or more waves.

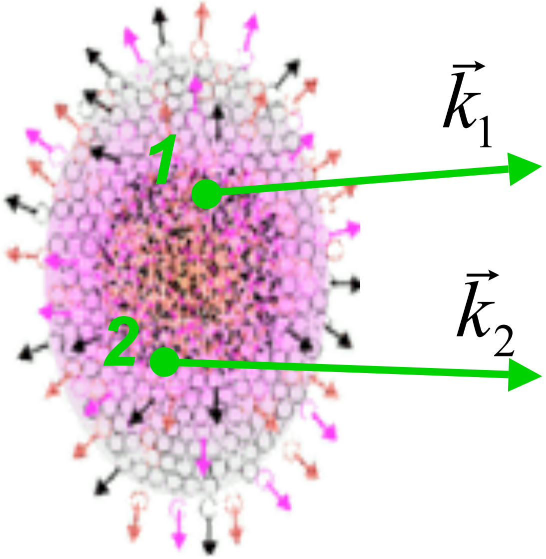
The two-particle correlations arise from the interference of particle wave-functions
… depend on whether the particles are bosons or fermions



The goal of intensity interferometry extract the space-time information of the heavy-ion collision source

with momentum spectra which are the only measureable quantities making use of quantum statistical correlations between the pairs of identical particles.

Handbury, Brown and Twiss measured the diameter of Sirius
Nature 178(1956)1046



emission amplitud of two pions

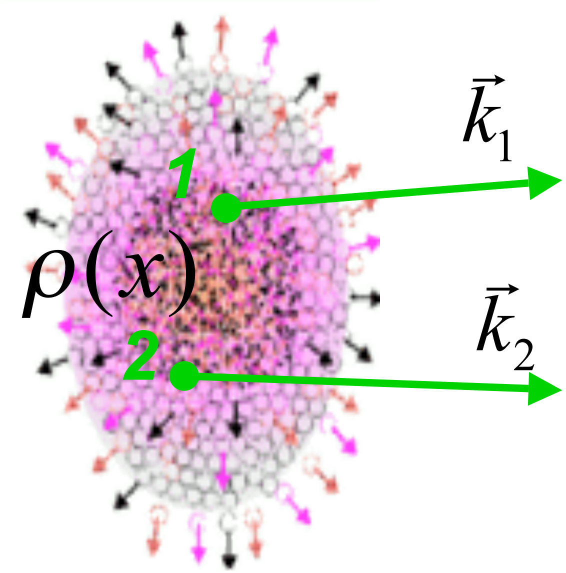
$$A_{\pi\pi} = e^{i\vec{k}_1\vec{r}_1 + i\vec{k}_2\vec{r}_2} + e^{i\vec{k}_1\vec{r}_2 + \vec{k}_2\vec{r}_1}$$

$$\left|A_{\pi\pi}\right|^2 = \left|e^{i\vec{k}_1\vec{r}_1 + i\vec{k}_2\vec{r}_2} + e^{i\vec{k}_1\vec{r}_2 + \vec{k}_2\vec{r}_1}\right|^2$$

$$\left|A_{\pi\pi}\right|^2 = 1 + 1 + e^{i(\vec{k}_1 - \vec{k}_2)\vec{r}_1} + e^{i(\vec{k}_2 - \vec{k}_1)\vec{r}_2}$$

$$\left|A_{\pi\pi}\right|^2 = 2 + 2\cos(qr)$$ where $$q = \left|\vec{k}_1 - \vec{k}_2\right|$$ $$r = \left|\vec{r}_1 - \vec{r}_2\right|$$

$$\frac{\left|A_{\pi\pi}\right|^2}{\left|A_{\pi}\right|\left|A_{\pi}\right|} = 1 + \cos(qr)$$



emission amplitud of two pions

$$A_{\pi\pi} = \rho(x)e^{i\vec{k}_1\vec{r}_1 + i\vec{k}_2\vec{r}_2} + \rho(x)e^{i\vec{k}_1\vec{r}_2 + \vec{k}_2\vec{r}_1}$$

$$\int \rho(x)dx = 1$$

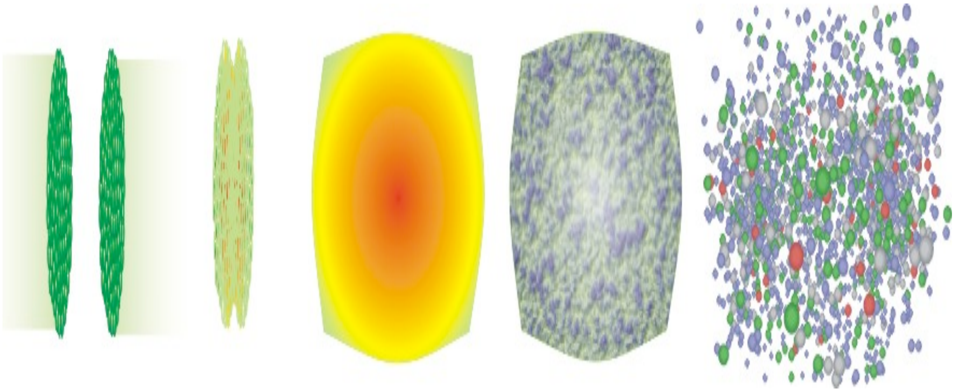
$$\left|A_{\pi\pi}\right|^2 = \rho^*\rho + \rho^*\rho e^{i(\vec{k}_1 - \vec{k}_2)\vec{r}_1} + \rho^*\rho e^{i(\vec{k}_2 - \vec{k}_1)\vec{r}_2}$$

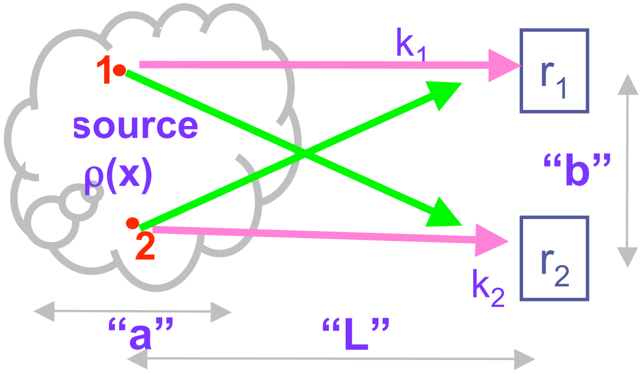
$$\frac{\left|A_{\pi\pi}\right|^2}{\left|A_\pi\right|\left|A_\pi\right|} = 1 + \left|F(\rho)\right|^2$$

where $q = \left|\vec{k}_1 - \vec{k}_2\right|$

$r = \left|\vec{r}_1 - \vec{r}_2\right|$

Probing source geometry through interferometry





The correlation function is defined as the ratio of the probability for the coincidence of k_1 and k_2 relative to the probability of observing k_1 and k_2 separately :

$$\boxed{C(k_1,k_2)} = \frac{P(k_1,k_2)}{P(k_1)P(k_2)} = 1 + \boxed{|F(\rho)|^2}$$

Measurable

Fourier Transform of pion source

Correlation function constructed experimentally, $C_2(q) = A(q) / B(q)$
A (q) → is the pair distribution in momentum difference $q = p_2 - p_1$ for pairs of particles from the same event. B (q) → is the corresponding distribution for pairs of particles from different events.

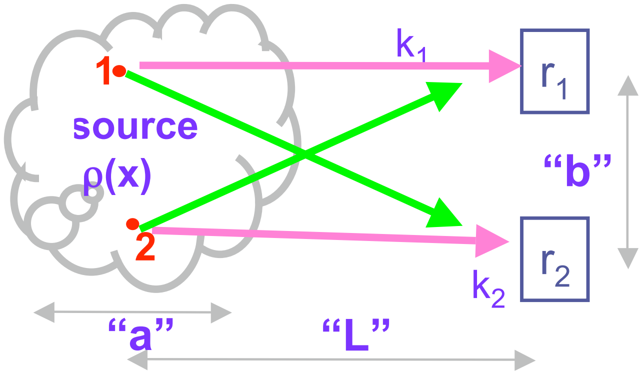
e.g.

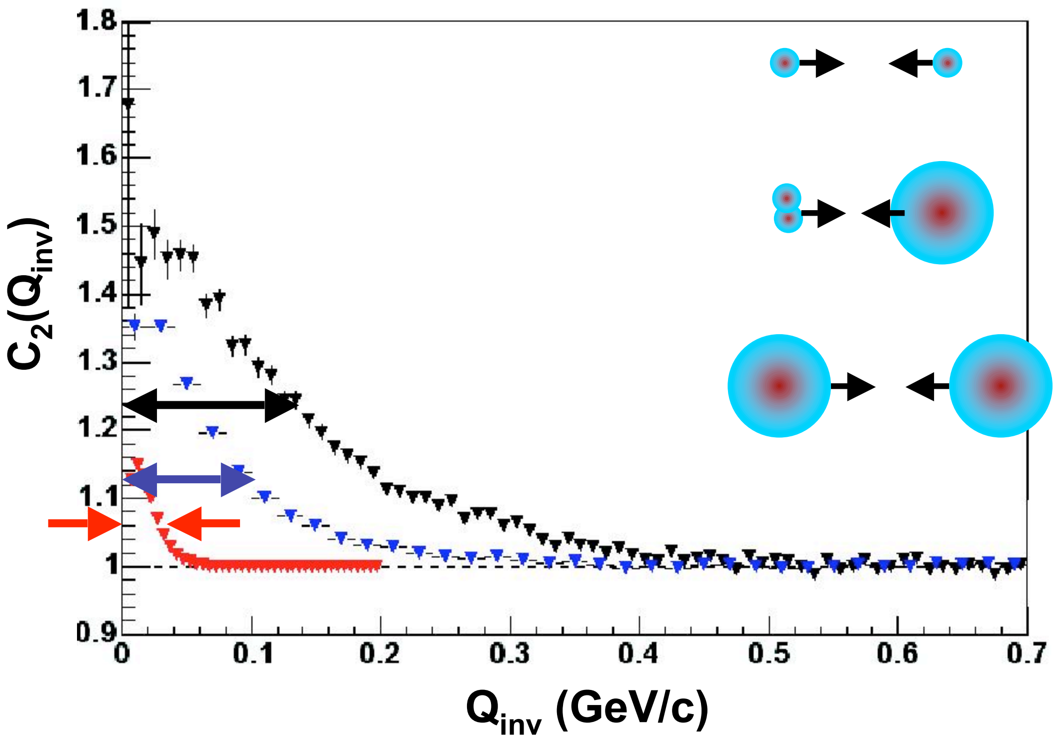
$$\rho(x,y,z) = \frac{N}{4\pi^2 R_x R_y R_z \sigma_t} e^{-\left(\frac{x^2}{2R_x^2}+\frac{y^2}{2R_y^2}+\frac{z^2}{2R_z^2}+\frac{t^2}{2\sigma_t^2}\right)}$$

$$F[\rho](q) = Ne^{-\left(\frac{R_x^2 q_x^2}{2}+\frac{R_y^2 q_y^2}{2}+\frac{R_z^2 q_z^2}{2}+\frac{\sigma_t^2 q_t^2}{2}\right)}$$

$$C(k_1,k_2) = 1 + \left|F(\rho)\right|^2$$

Source geometry

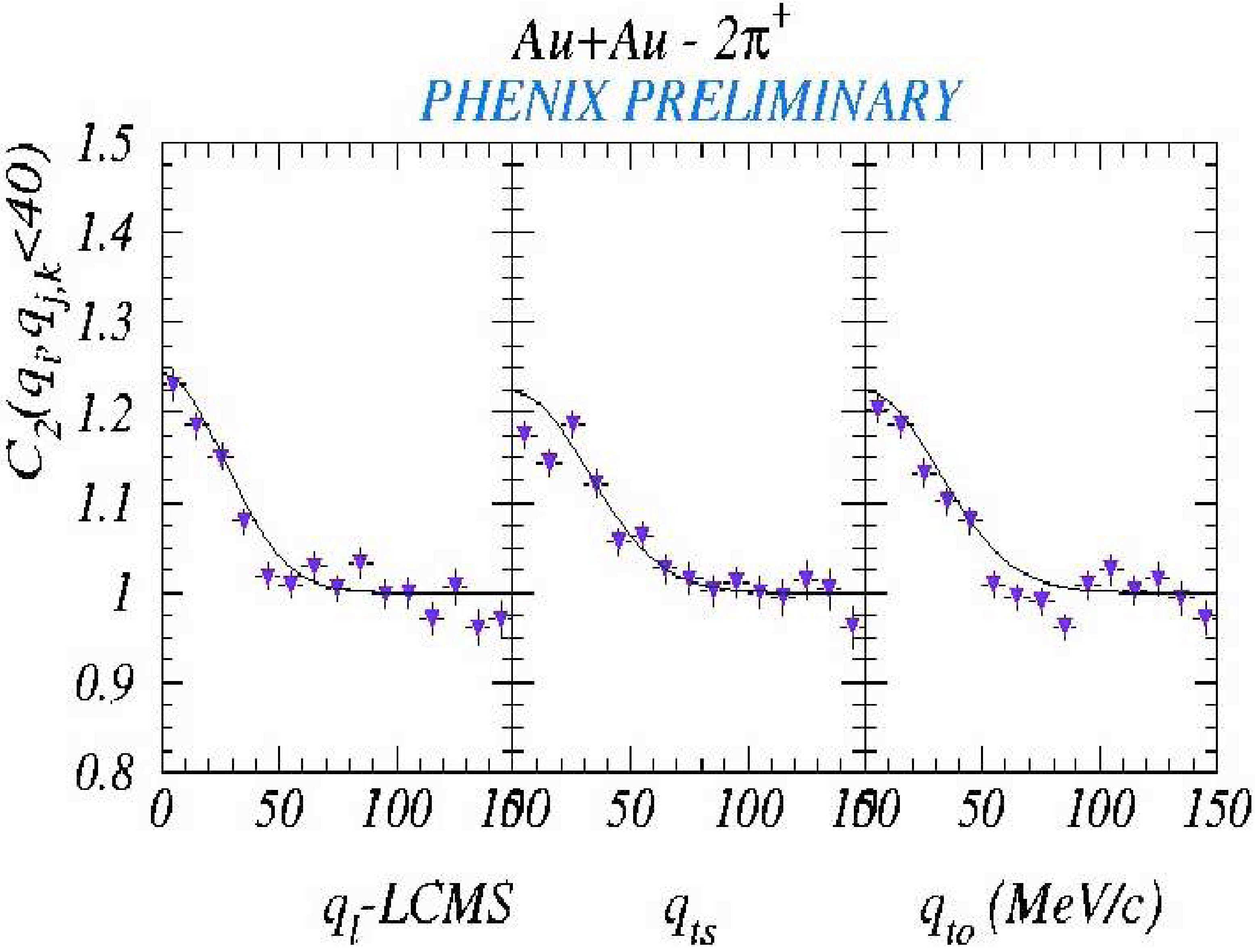




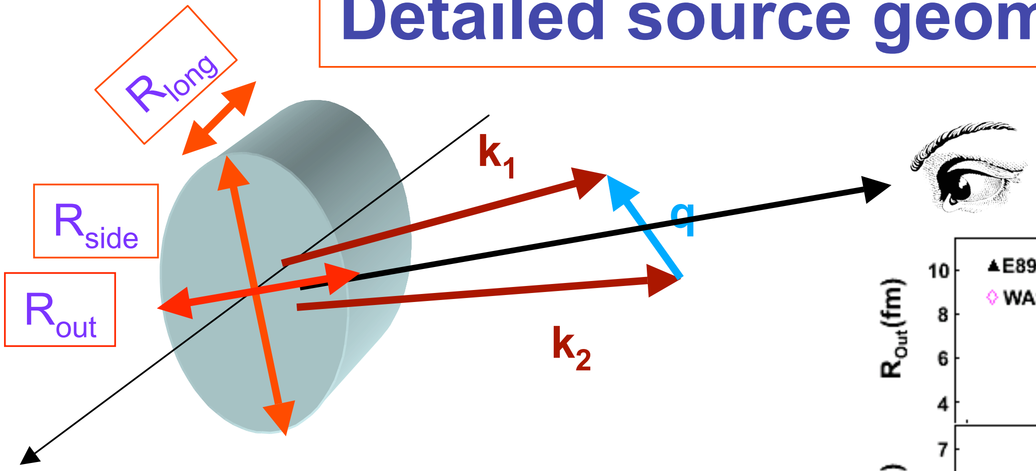
p+p
R ~ 1 fm

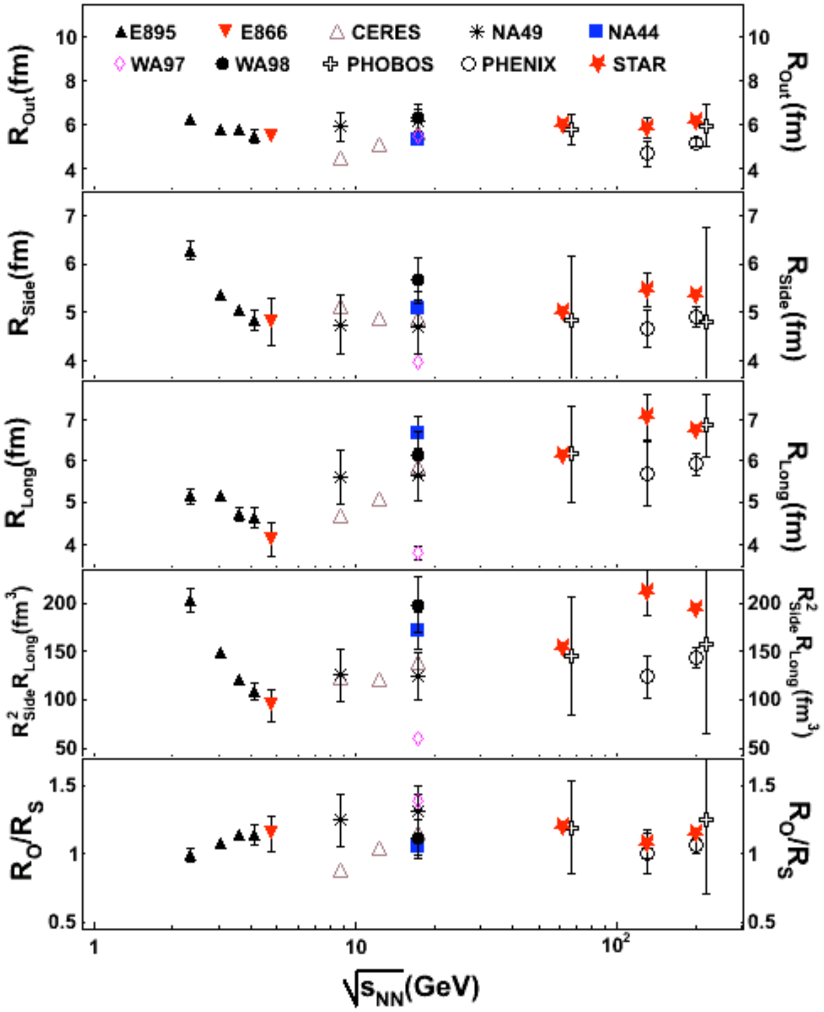
d+Au
R ~ 2 fm

Au+Au
R ~ 6 fm


$Au+Au$ - $2\pi^+$
PHENIX PRELIMINARY
$C_2(q_i, q_{j,k}<40)$
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0
50
100
150
q_l-LCMS
q_{ts}
q_{to} (MeV/c)

Detailed source geometry





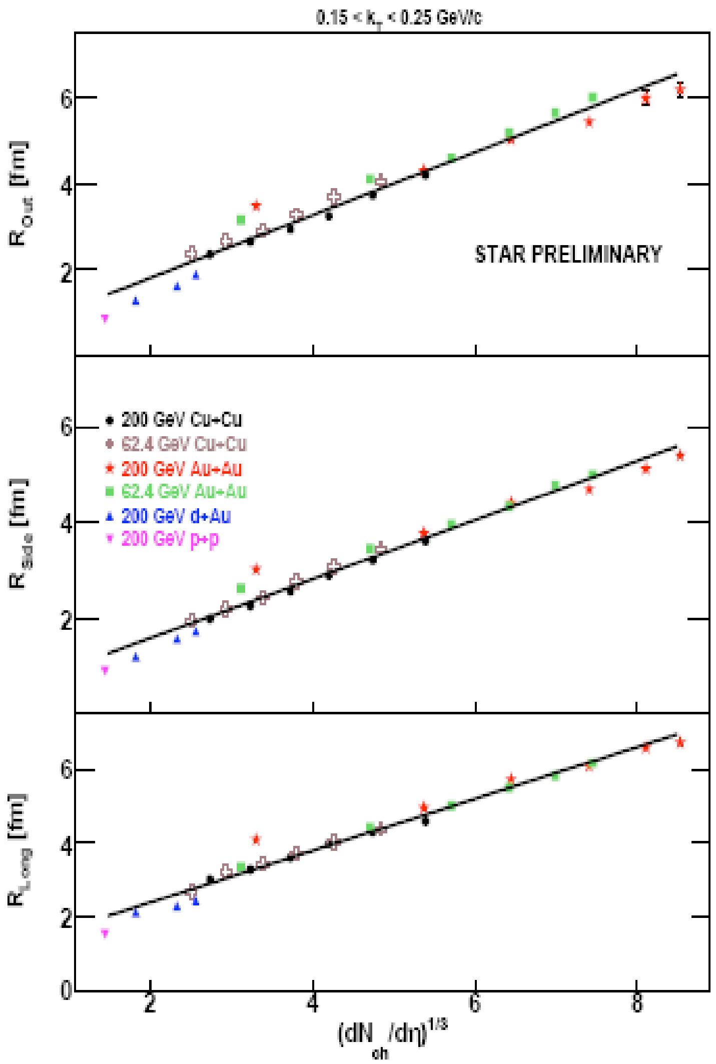
R_{long} – along beam direction

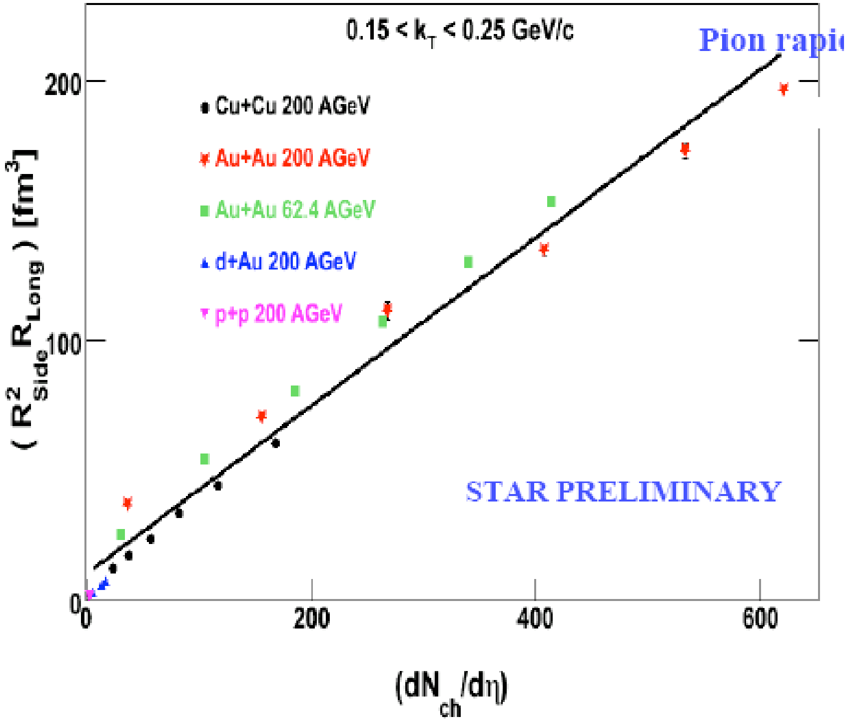
R_{out} – along “line of sight”

R_{side} – ⊥ “line of sight”

Beam energy dependence of pion HBT

STAR





Pion rapidity density is proportional to the freezeout volume => Constant Freezeout Volume (freezeout at a constant density).

Bose Einstein Correlations as a signature

If a Quark Gluon Plasma appears, pions will populate the central rapidity region

Entropy of the QGP = S_{QGP}

The Quark Gluon Plasma will hadronize

Entropy of the hadronization phase = S_{had}

total entropy

$$volume_{QGP} \times S_{QGP} \leq volume_{had} \times S_{had}$$

since $S_{had} < S_{QGP}$ **then** $volume_{had} > volume_{QGP}$

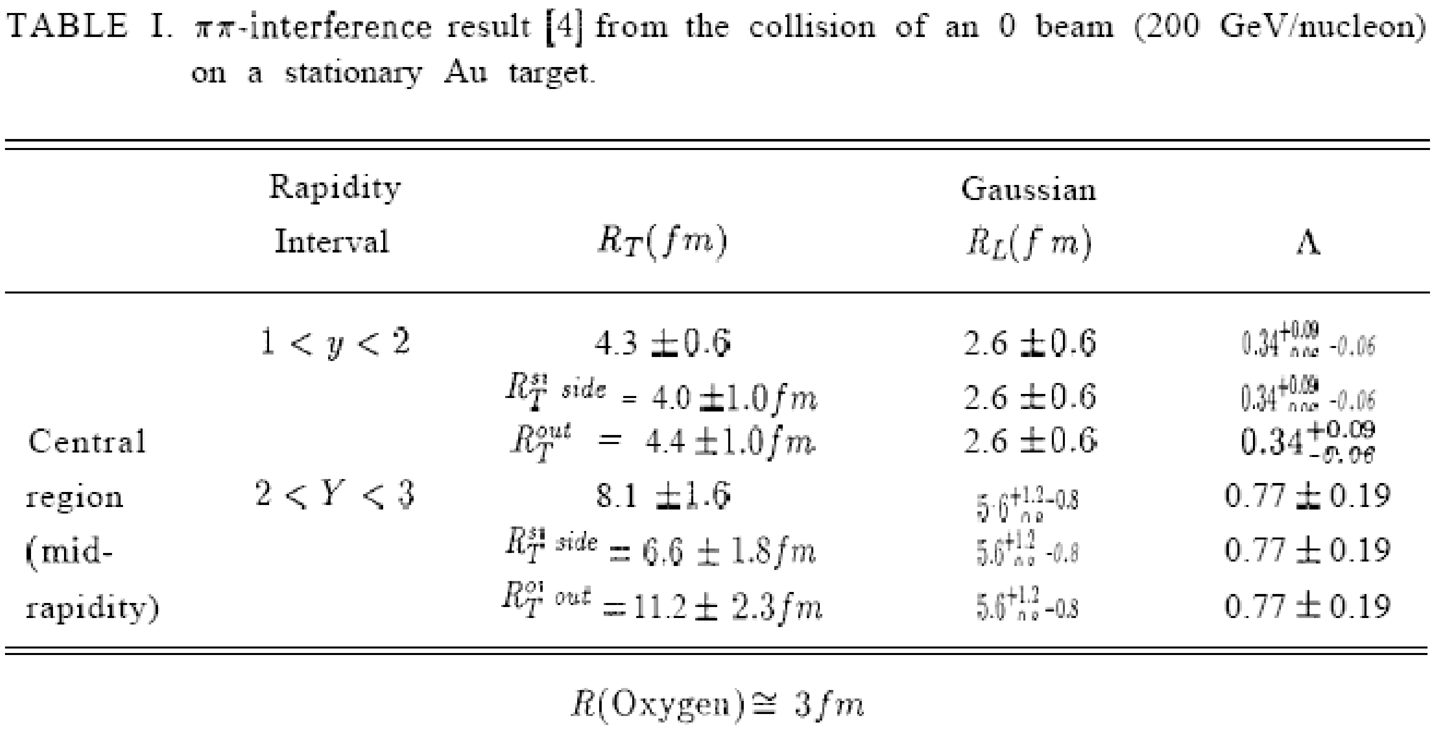


TABLE I. $\pi\pi$-interference result [4] from the collision of an 0 beam (200 GeV/nucleon) on a stationary Au target.

	Rapidity Interval	$R_T(fm)$	Gaussian $R_L(fm)$	Λ
Central region (mid-rapidity)	$1 < y < 2$	4.3 ± 0.6	2.6 ± 0.6	$0.34^{+0.09}_{0.06}\ -0.06$
		R_T^{si} side $= 4.0 \pm 1.0 fm$	2.6 ± 0.6	$0.34^{+0.09}_{0.06}\ -0.06$
		$R_T^{out} = 4.4 \pm 1.0 fm$	2.6 ± 0.6	$0.34^{+0.09}_{-0.06}$
	$2 < Y < 3$	8.1 ± 1.6	$5.6^{+1.2}_{0.8}-0.8$	0.77 ± 0.19
		R_T^{si} side $= 6.6 \pm 1.8 fm$	$5.6^{+1.2}_{0.8}\ -0.8$	0.77 ± 0.19
		R_T^{oi} out $= 11.2 \pm 2.3 fm$	$5.6^{+1.2}_{0.8}\ -0.8$	0.77 ± 0.19

$R(\text{Oxygen}) \cong 3 fm$

RHIC:

There is only a weak dependence on the energy

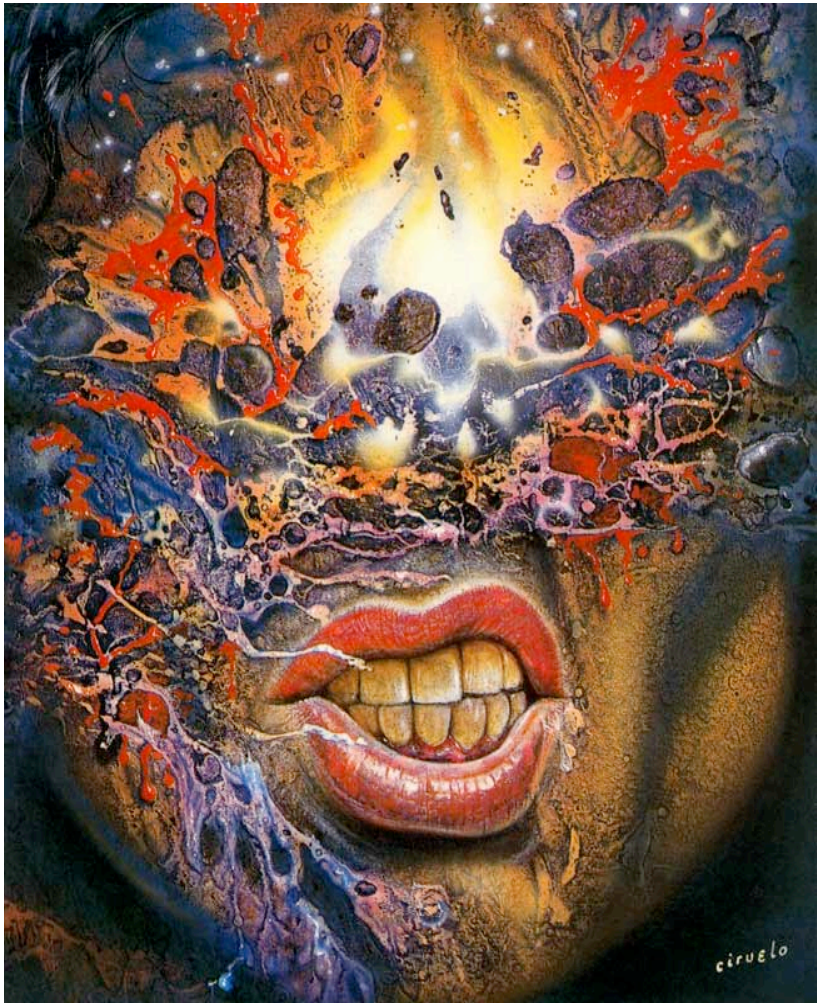
Results more or less what was observed at CERN SPS

$R_{out} / R_{side} \approx 1$ when most models expect $R_{out} / R_{side} \approx 2$

no consistent description of data

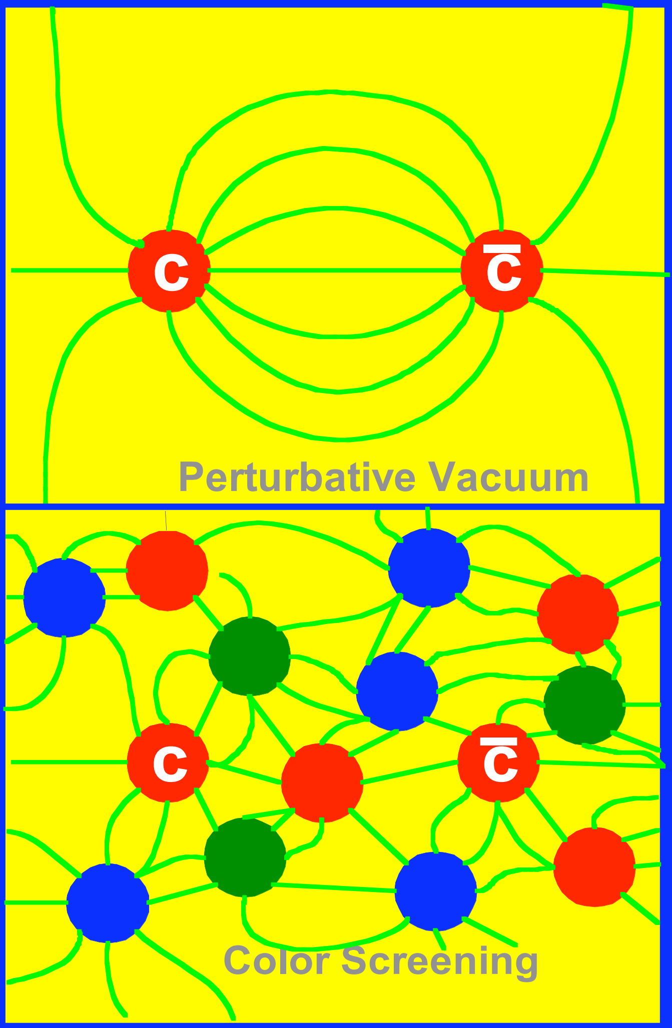
something is missing in our picture of space time

Charm suppression **Strageness enhacement**

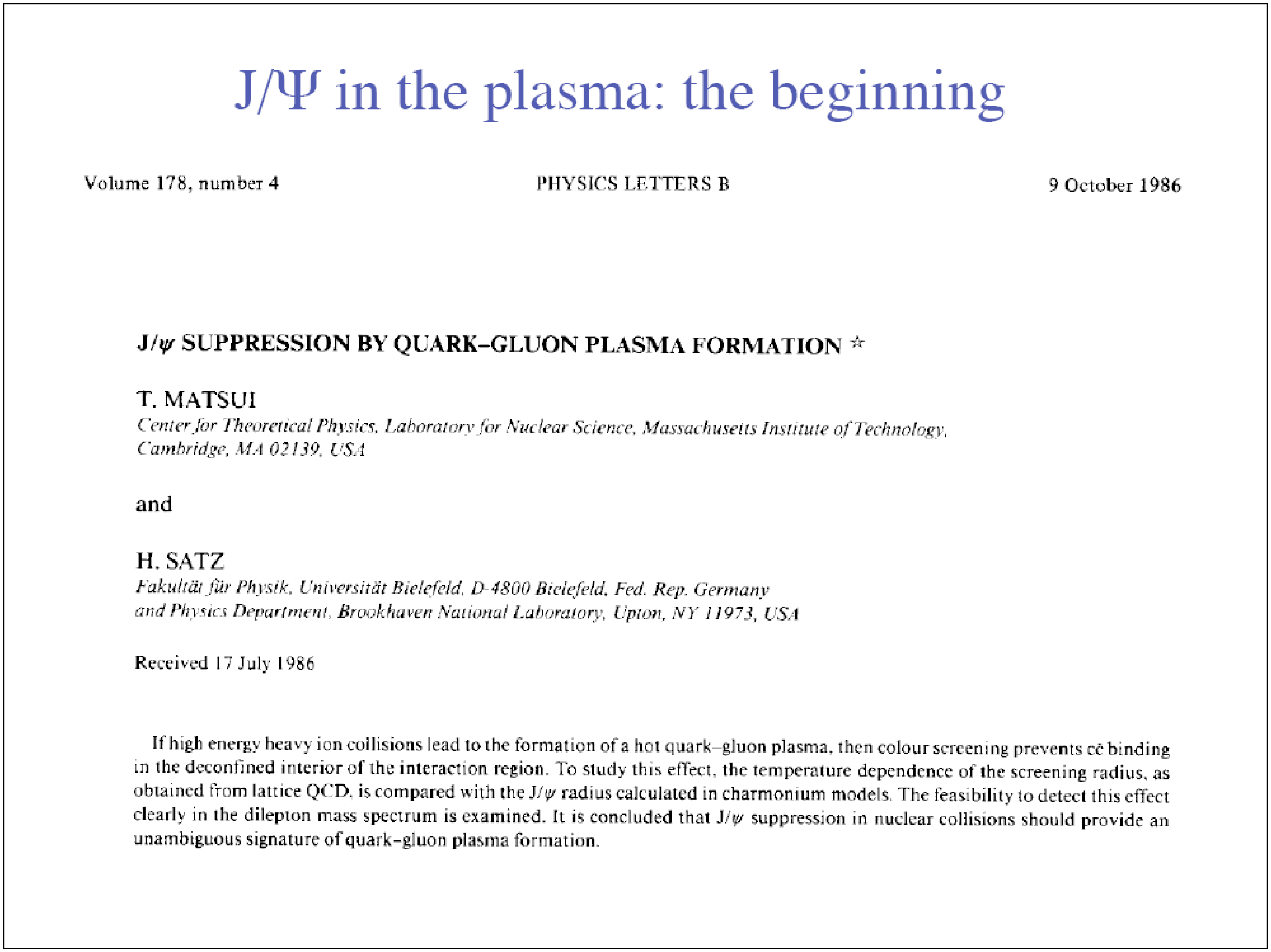


Suppression of the J/Ψ production as a Signature of QGP

- J/Ψ suppression because colour screening hinders the quarks from binding
- J/Ψ interacts inelastically with some dense hadronic matter created in the collision



J/Ψ in the plasma: the beginning



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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

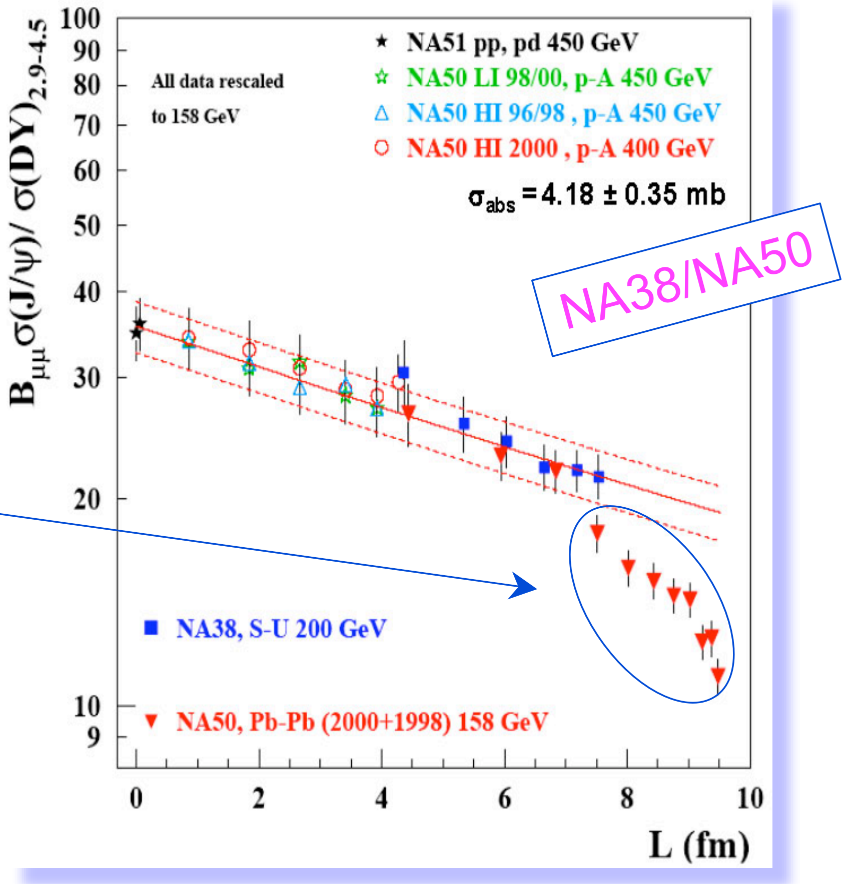
Anomalous suppression

In peripheral Pb-Pb collisions the (J/ψ)/DY ratio is consistent with the normal suppression pattern

In central Pb-Pb collisions (b<8-8.5 fm) a much stronger suppression is observed:

Anomalous suppression

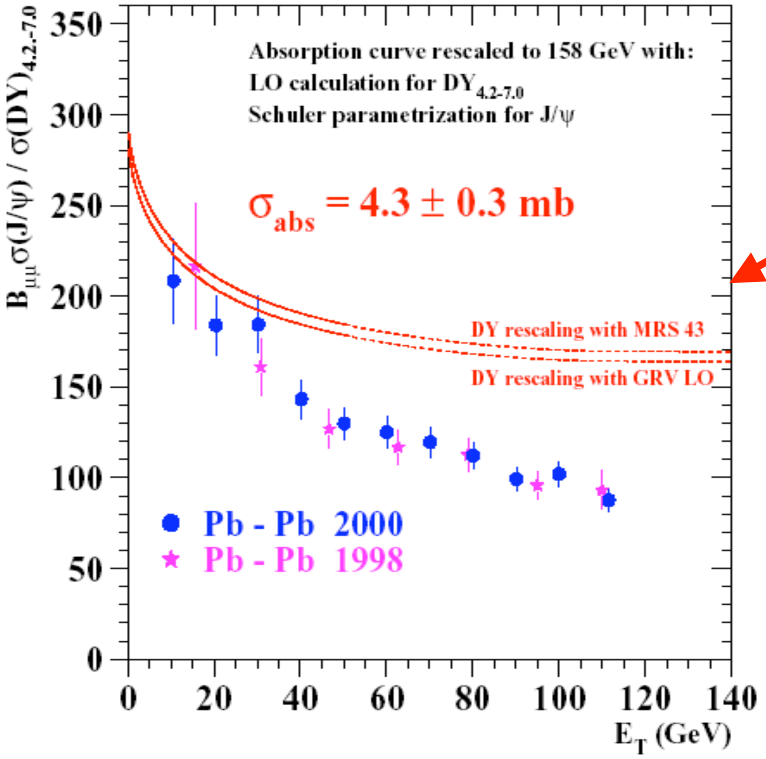
New In-In data follow the same pattern ! (NA60)



Anomalous J/Ψ suppression in A+A

Heavy flavor sector reflects the actual dynamics since heavy hadrons can only be formed in the very early phase of heavy-ion collisions !

- **Anomalous J/Ψ suppression in A+A (NA38/NA50/NA60)**

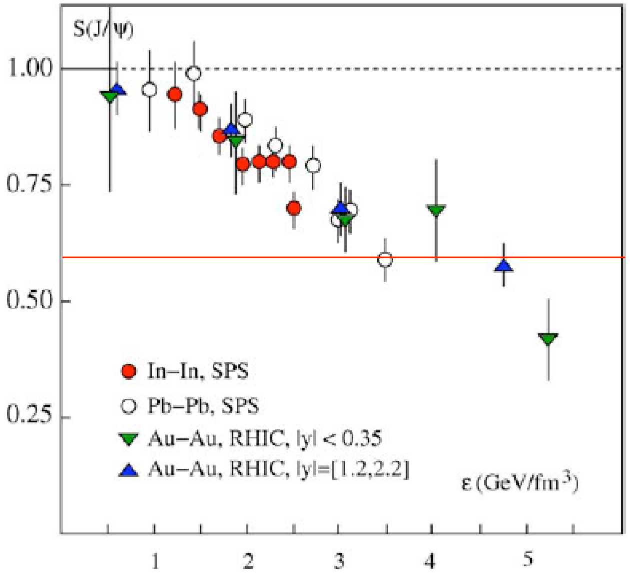


J/Ψ ‚normal' absorption
by nucleons
(Glauber model)
||

Experimental observation: extra suppression in A+A collisions; increasing with centrality

Is that due to Debye screening of the confining potential in a QGP ?

or may be



Multiple rescattering ?

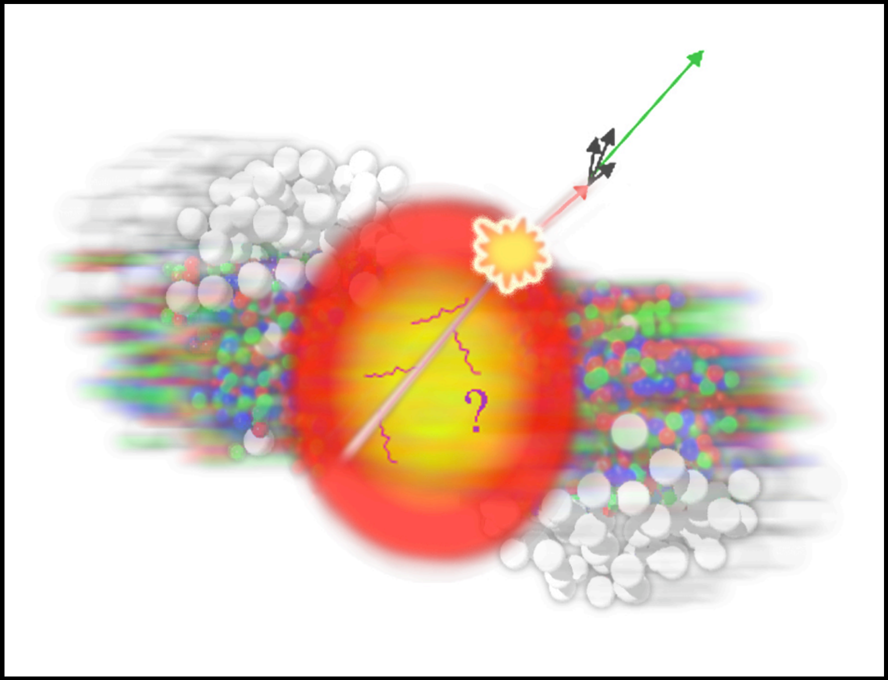
Changes in the gluon distribution function ?

Affected by other decays (excited state decays) ?

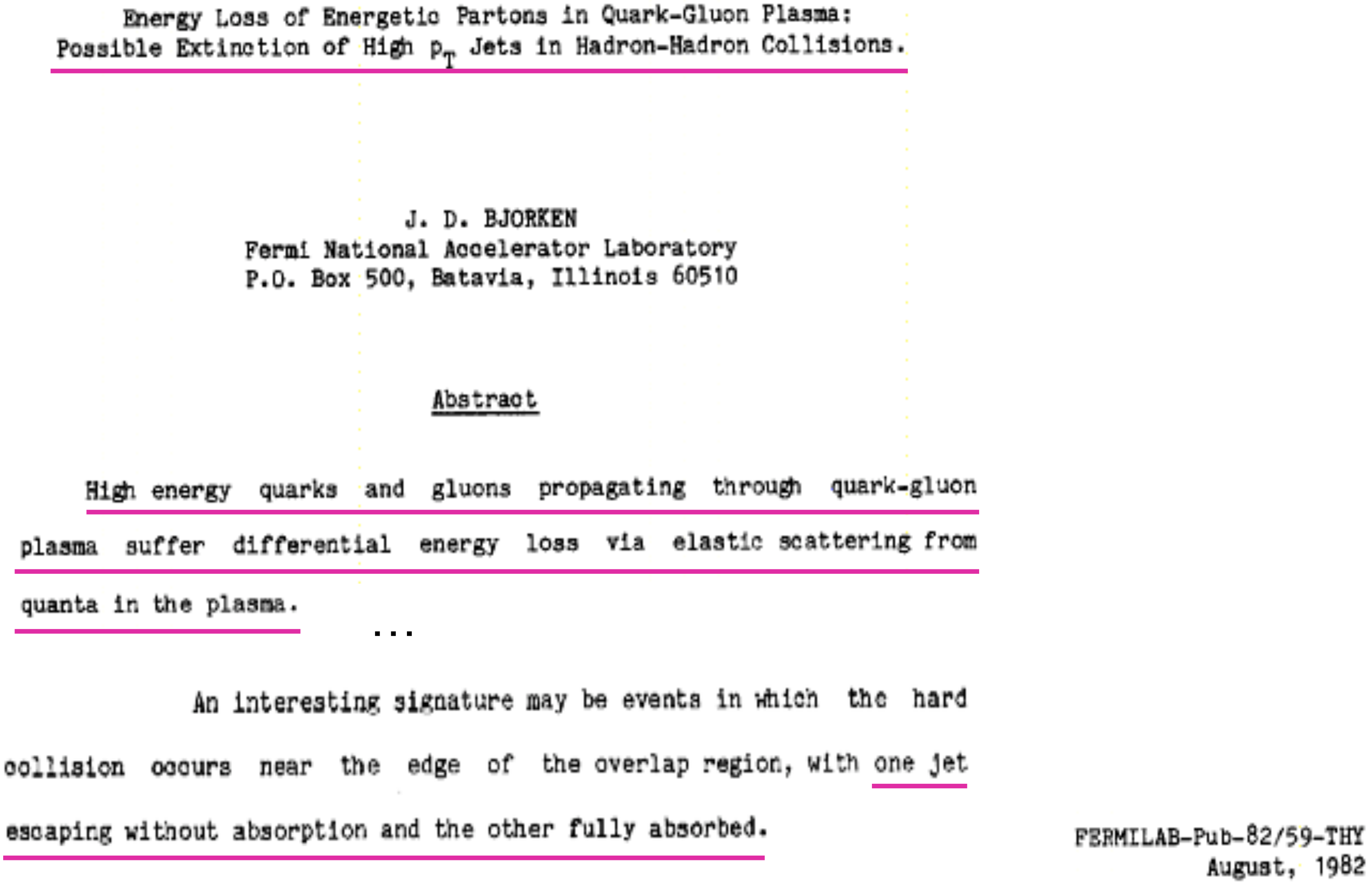
Affected by heavy quark/gluon energy loss ?

What is the production mechanism at RHIC energies (color singlet mode, color octet mode, color evaporation model) contribution from gluon fusion, heavy quark fragmentation, gluon fragmentation ?

Jet quenching



"Jet Quenching" – J.D.Bjorken 1982



Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma.

...

An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

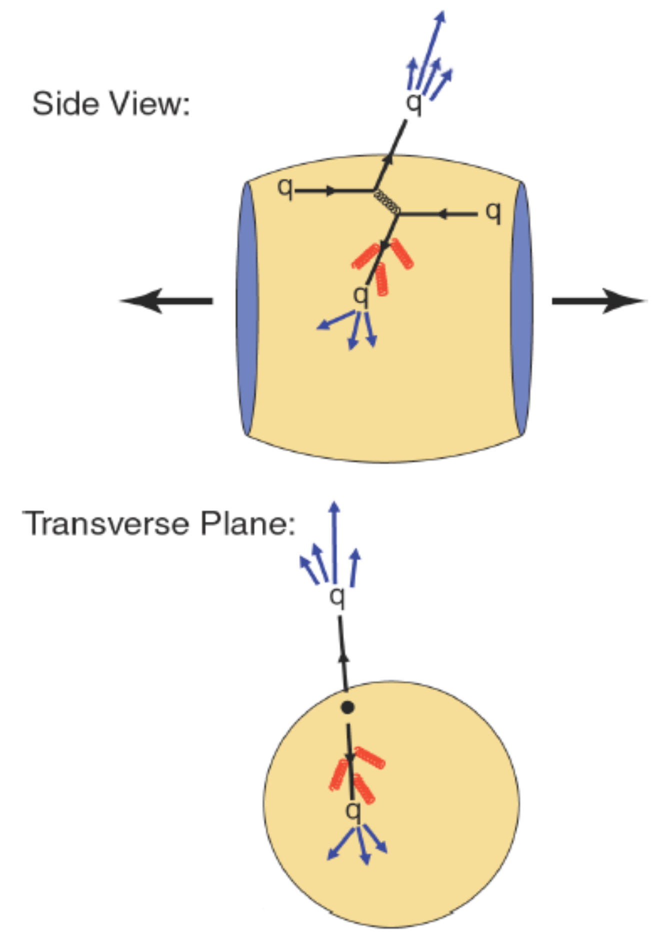
FERMILAB-Pub-82/59-THY
August, 1982

Jet Quenching as a Signature of QGP

leading particle

hadrons

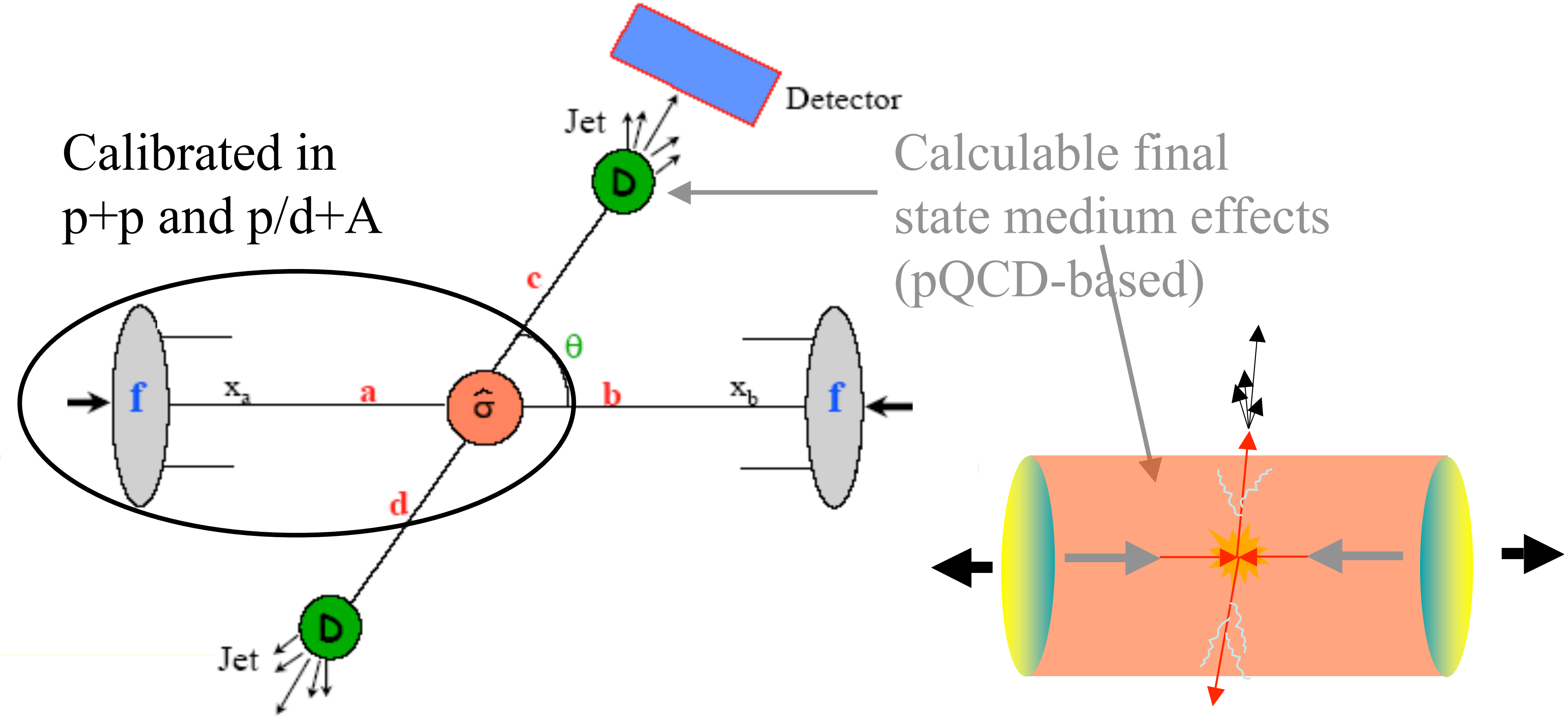
- Hard scatterings (HS) in nucleon collisions produce jets of particles
- In a colour deconfined medium the partons (quarks+gluons) strongly interact and loose energy (~GeV/fm) by gluon radiation
- HS near the surface can give a jet in one direction, while the other side is quenched



leading particle

hadrons

Hard probes of QCD matter

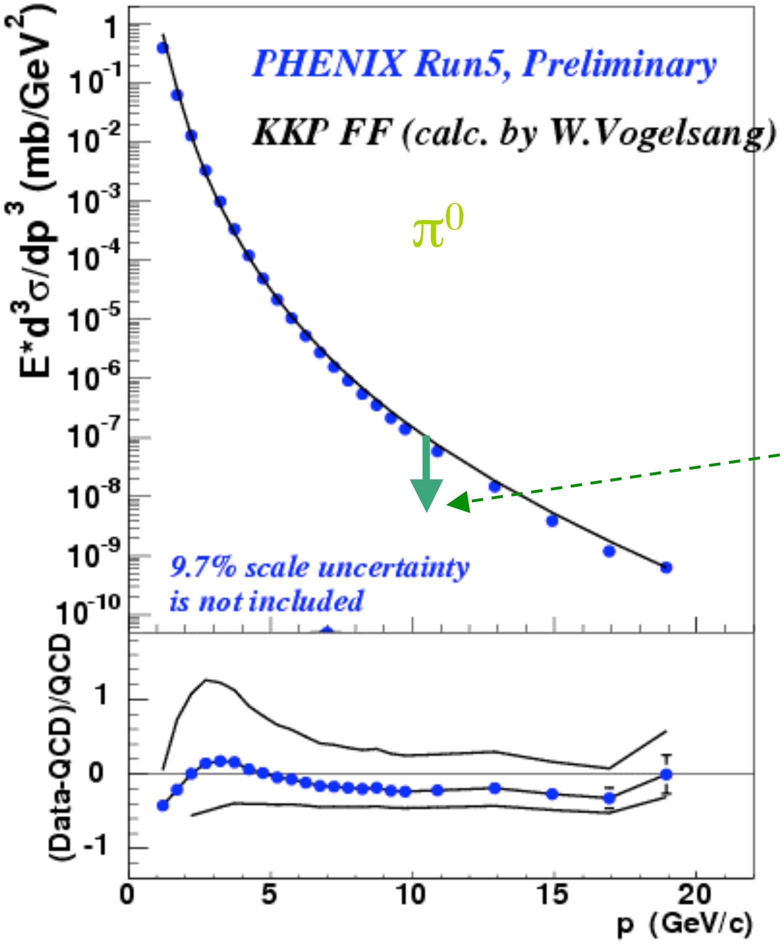


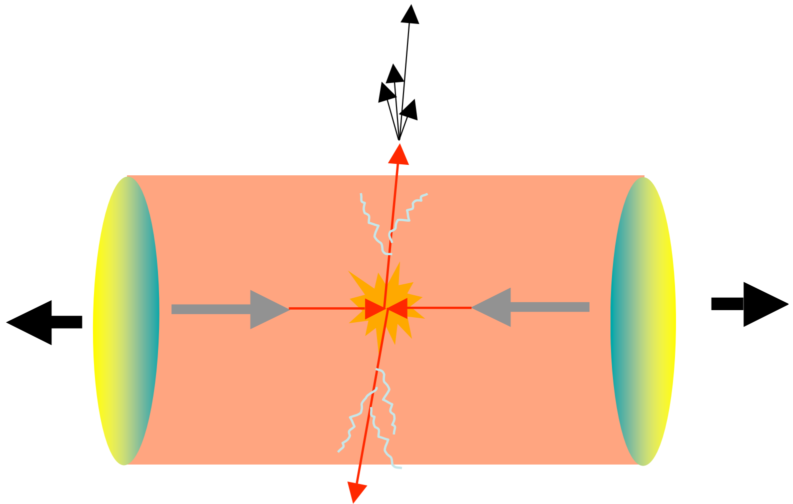
Calibrated in
p+p and p/d+A

Calculable final
state medium effects
(pQCD-based)

Calculable interactions of energetic partons with the medium
⇒ calibrated, penetrating *tomographic* probes

Jet quenching: hadron suppression





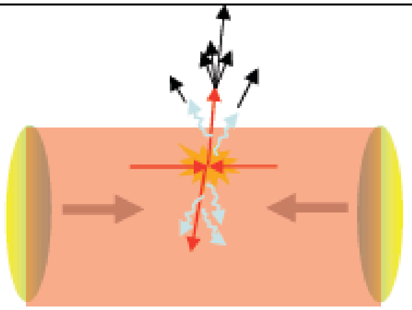
Energy loss ⇒ softening of fragmentation ⇒ suppression of leading hadron yield

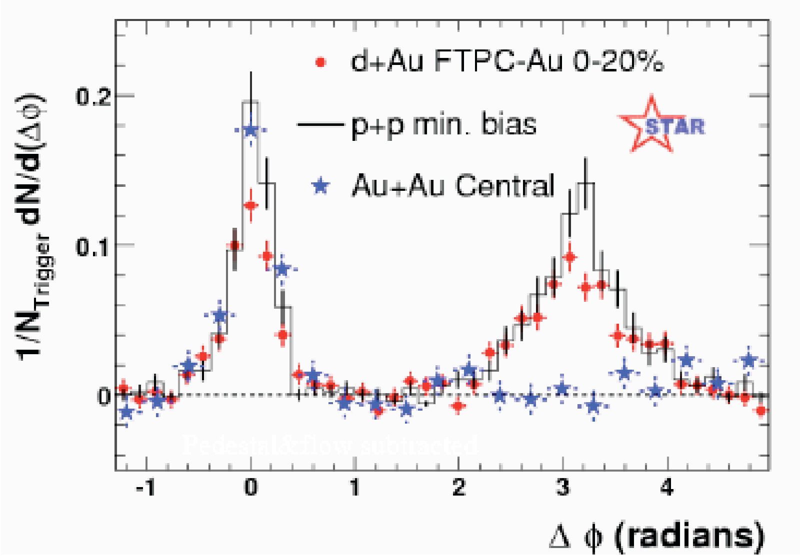
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Binary collision scaling

p+p reference

Jets Modified by the Medium

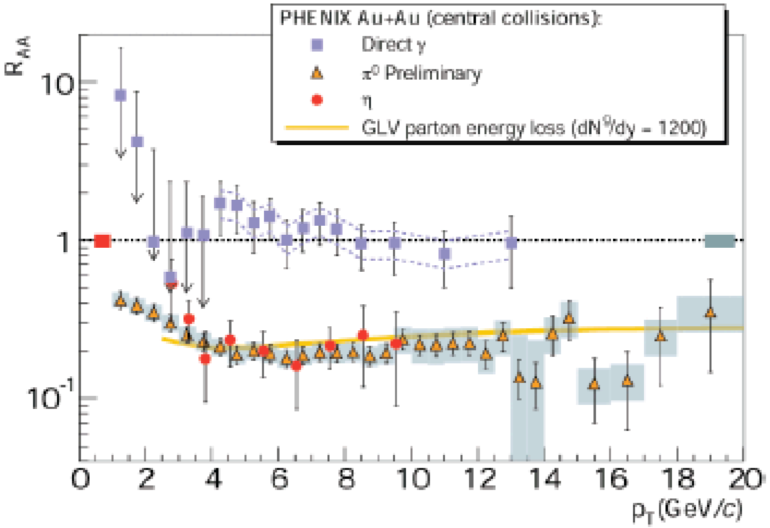




Away side suppression

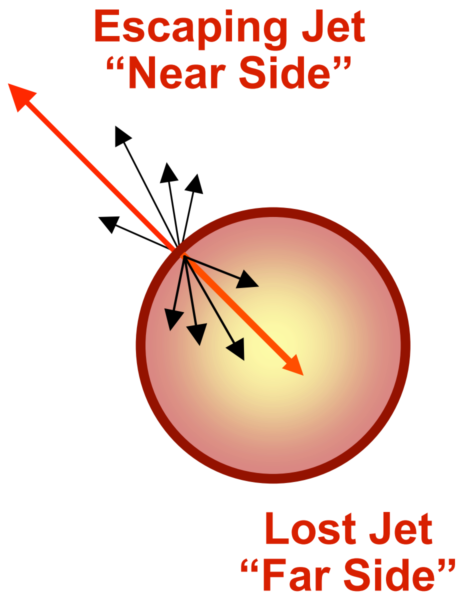
$4 < p_T(\text{trig}) < 6$ GeV/c

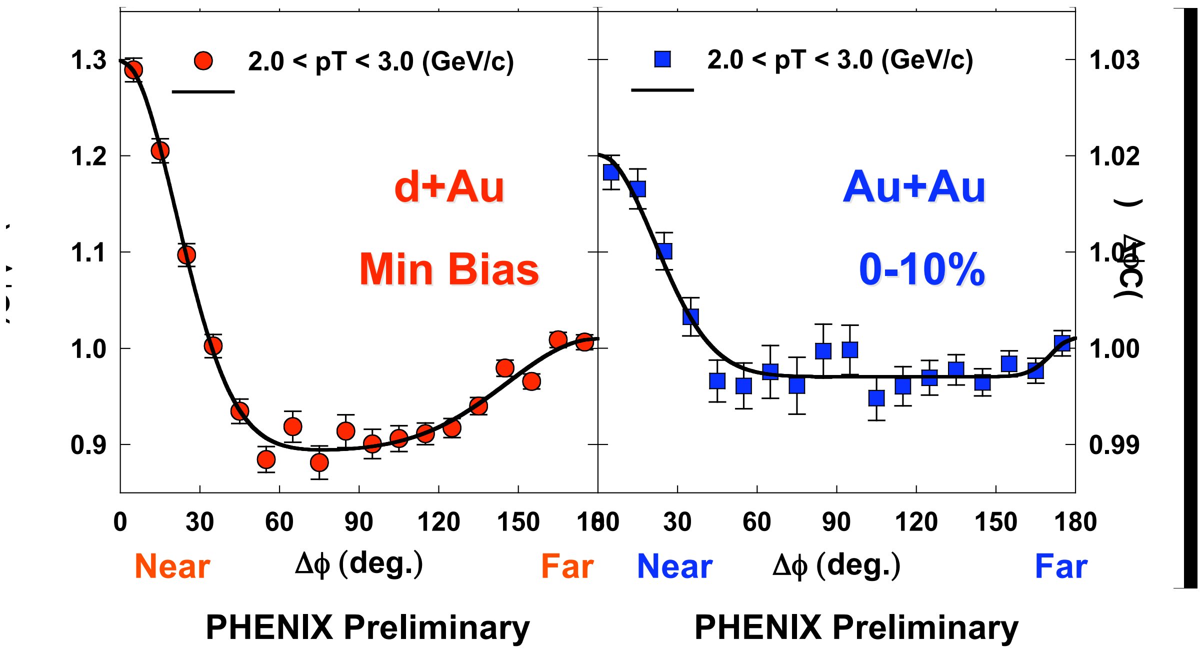
$p_T(\text{assoc}) > 2$ GeV/c



PHENIX

The “Away-Side” Jet



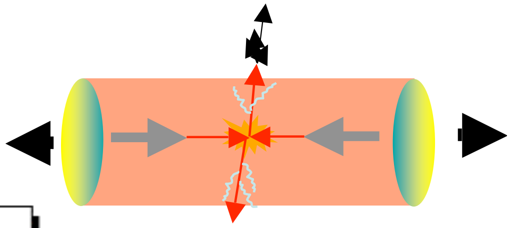


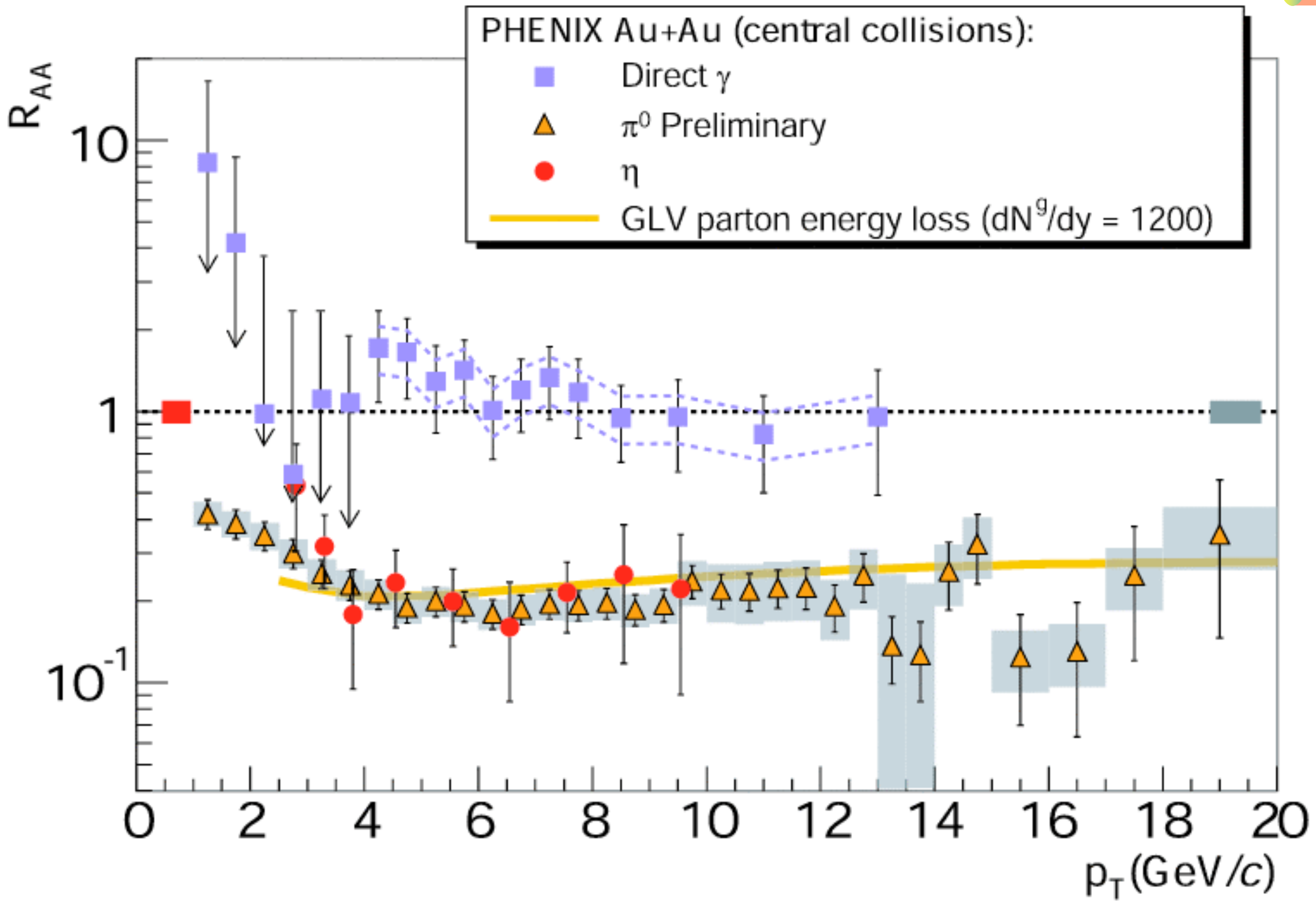
- Jets produced on the periphery of the collision zone coming out should survive.
- However, their partner jet will necessarily be pointed into the collision zone and be absorbed.

- Peripheral Au+Au similar to d+Au
- Central Au+Au shows distinct reduction in far side correlation.
- Away-side Jet is missing in Au+Au

Jet quenching I: hadrons are suppressed, photons are not

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$





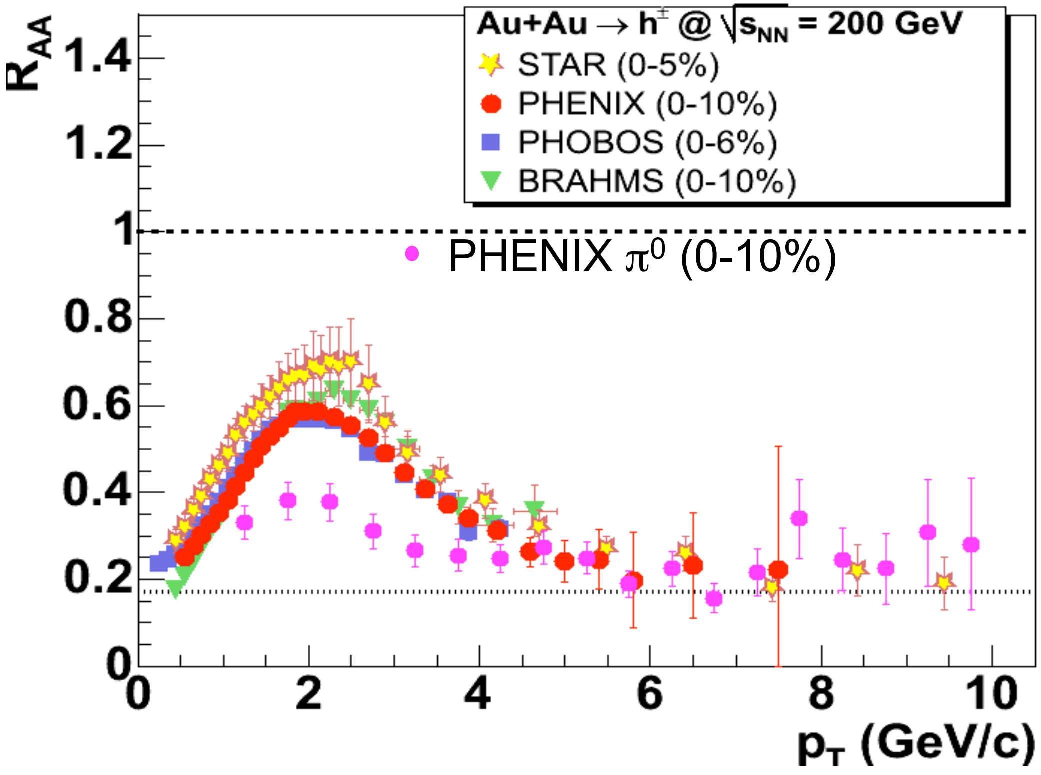
Photons (color-neutral)

Jets (color-charged)

Discoveries at RHIC:high-p_t suppression

- Nuclear modification factor of p_t distributions:

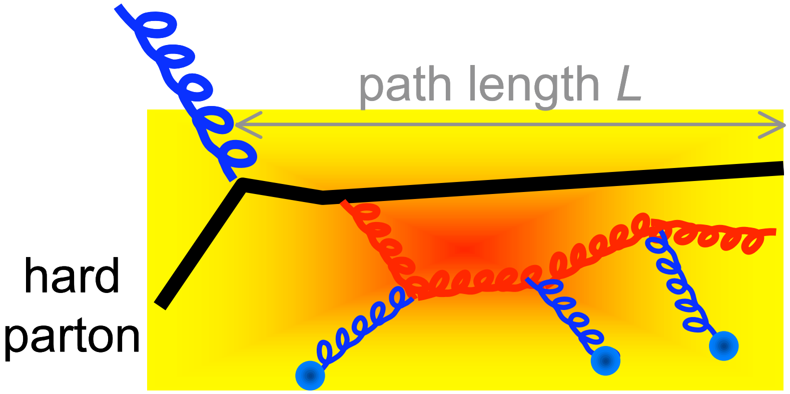
$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle_C} \times \frac{\mathrm{d}^2 N_{AA}^C / \mathrm{d}p_t \mathrm{d}\eta}{\mathrm{d}^2 N_{pp} / \mathrm{d}p_t \mathrm{d}\eta}$$



factor 5
suppression!

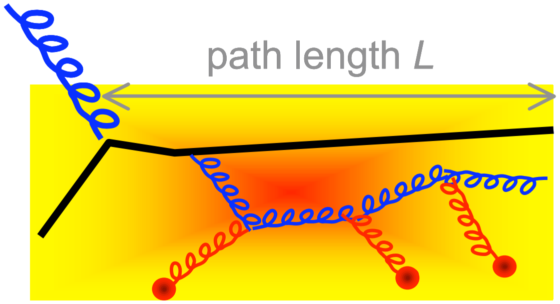
Parton Energy Loss

- Partons travel ~4 fm in the high colour-density medium
- Bjorken (`82): energy loss due to elastic scattering
- Successive calculations (`92 →): a QCD mechanism dominates, ***medium-induced gluon radiation***
- *Coherent wave-function gluon acummulates k_T due to multiple inelastic scatterings in the medium; it decoheres and is radiated*



Bjorken, Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Pegne, Schiff, Levai, Vitev, Zhakarov, Wang, Salgado, Wiedemann,…

Calculating Parton Energy Loss



$$\langle \Delta E \rangle \approx \int \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s\, C_R\, \hat{q}\, L^2$$

(BDMPS)

Casimir coupling factor:
4/3 for quarks
3 for gluons

Medium transport coefficient
∝ gluon density and momenta

Probe the medium

- To analyse RHIC data, need more than mean ΔE
- Quenching weights: energy loss probability distributions

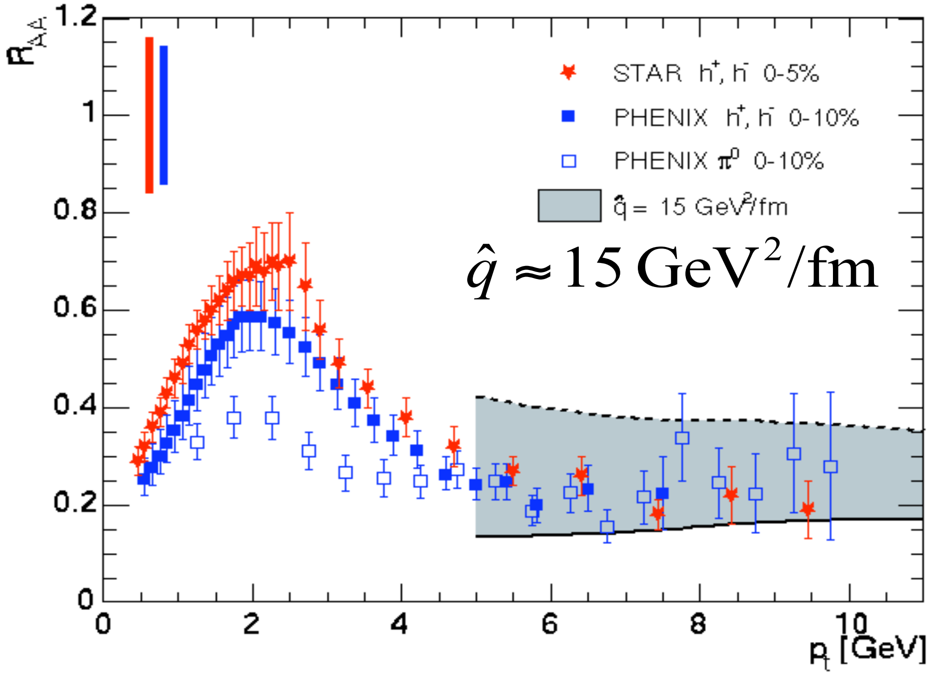
$$P(\Delta E; C_R, \hat{q}, L)$$

- Main limitation: calculated in $E \to \infty$ approx. ➡ uncertainties

R.Baier, Yu.L.Dokshitzer, A.H.Mueller, S.Peigne' and D.Schiff, (BDMPS), Nucl. Phys. **B483** (1997) 291.
C.A.Salgado and U.A.Wiedemann, Phys. Rev. **D68** (2003) 014008 [hep-ph/0302184].

Model vs RHIC data

- Density ($\hat{q}$) “tuned” to match R_{AA} in central Au-Au at 200 GeV
- Extrapolations
  - in centrality: according to Glauber-model collision geometry
  - in $\sqrt{s}$: assuming $\hat{q} \propto N^{gluons}/\text{volume} \propto (\sqrt{s})^{0.6}$ (saturation model)



Caveat:

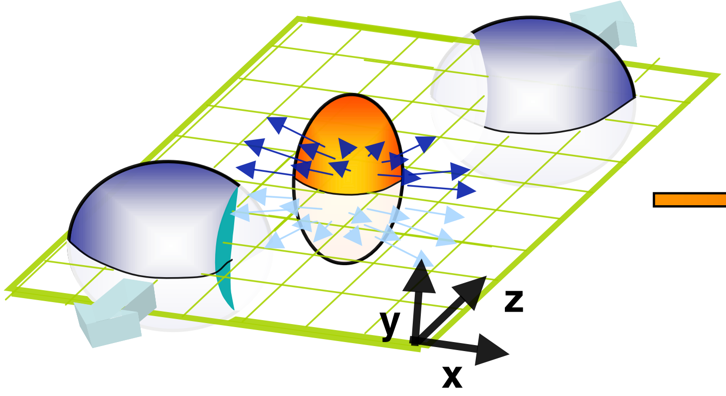
- No initial-state effects and in-medium hadronization: results given for $p_t > 5$ GeV
- Band represents theoretical uncertainty

➡ naturally matches p_t-independence of suppression at high p_t

Saturation model: K.J.Eskola, et al, Nucl. Phys. **B570** (2000) 379 [hep-ph/9909456].

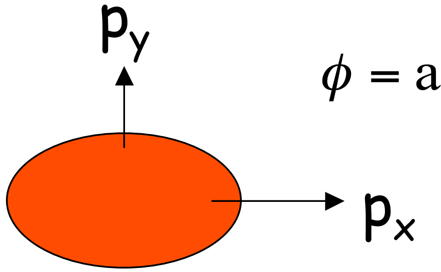
Collective flow

Collective Flow of QCD Matter



$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy



$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

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

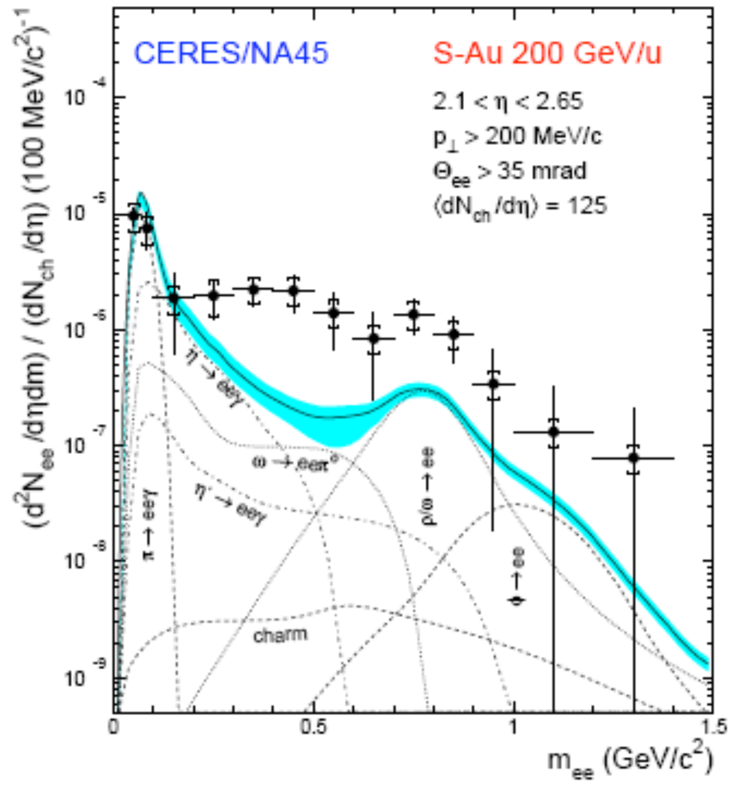
Final momentum anisotropy

Reaction plane defined by
“soft” (low p_T) particles

Elliptic flow $$\frac{dN}{d\phi} \propto 1 + 2\boxed{v_2}\cos[2(\phi - \Psi_R)]$$

Dilepton production

Dilepton spectra

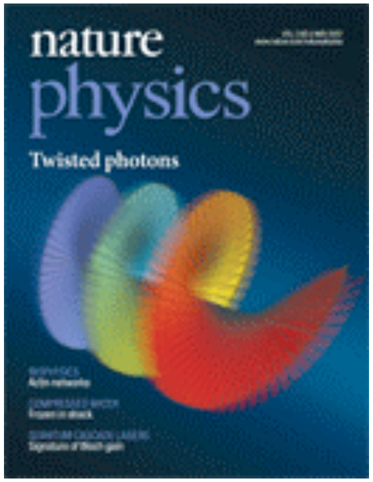


Heavy Ions and String Theory

News and Views
***Nature Physics* 3**, 297 - 298
(2007)

Heavy-ion collisions: Where string theory meets reality?

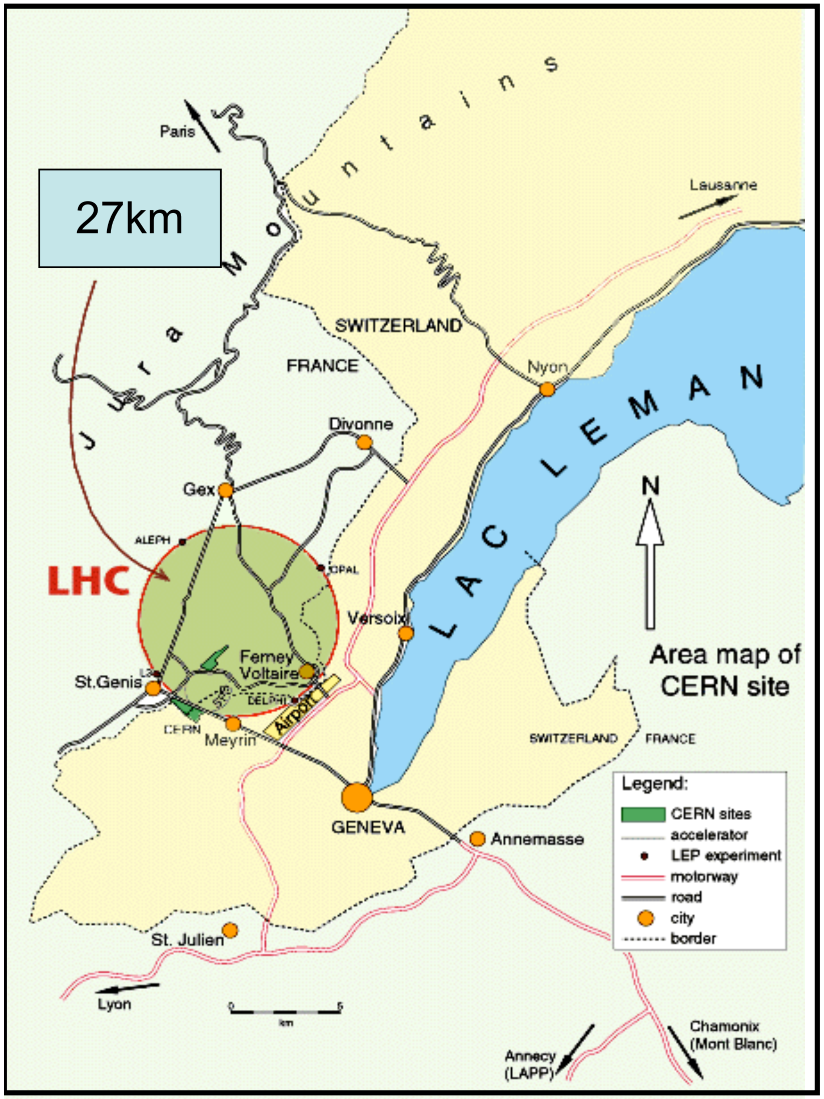
Makoto Natsuume

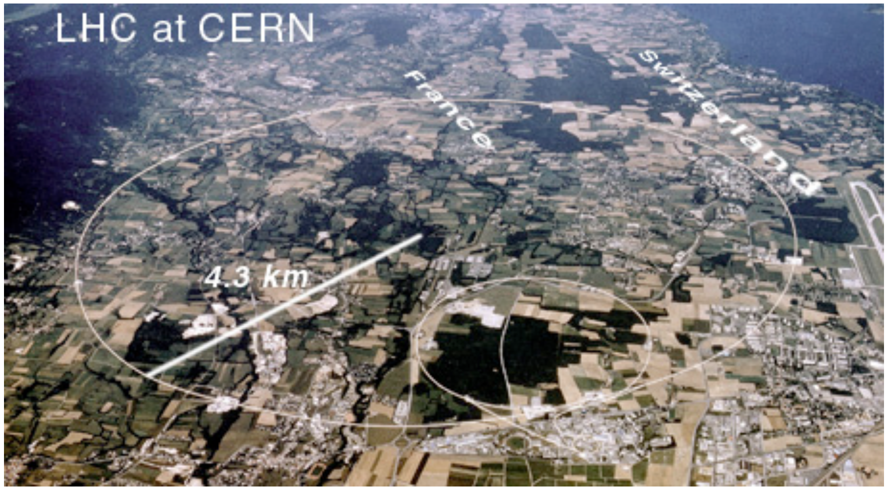


Heavy ion **collisions and black holes in Anti-de Sitter space.**
John R. Ellis (CERN) . CERN-TH-98-391, Oct 1998. 18pp.
Invited talk at RHIC Physics and Beyond: Kay Kay Gee Day, Upton, NY, 23 Oct 1998.
In *Brookhaven 1998, RHIC physics and beyond* 35-52.
e-Print: **nucl-th/9902061**

Experimental aspects

Accelerator

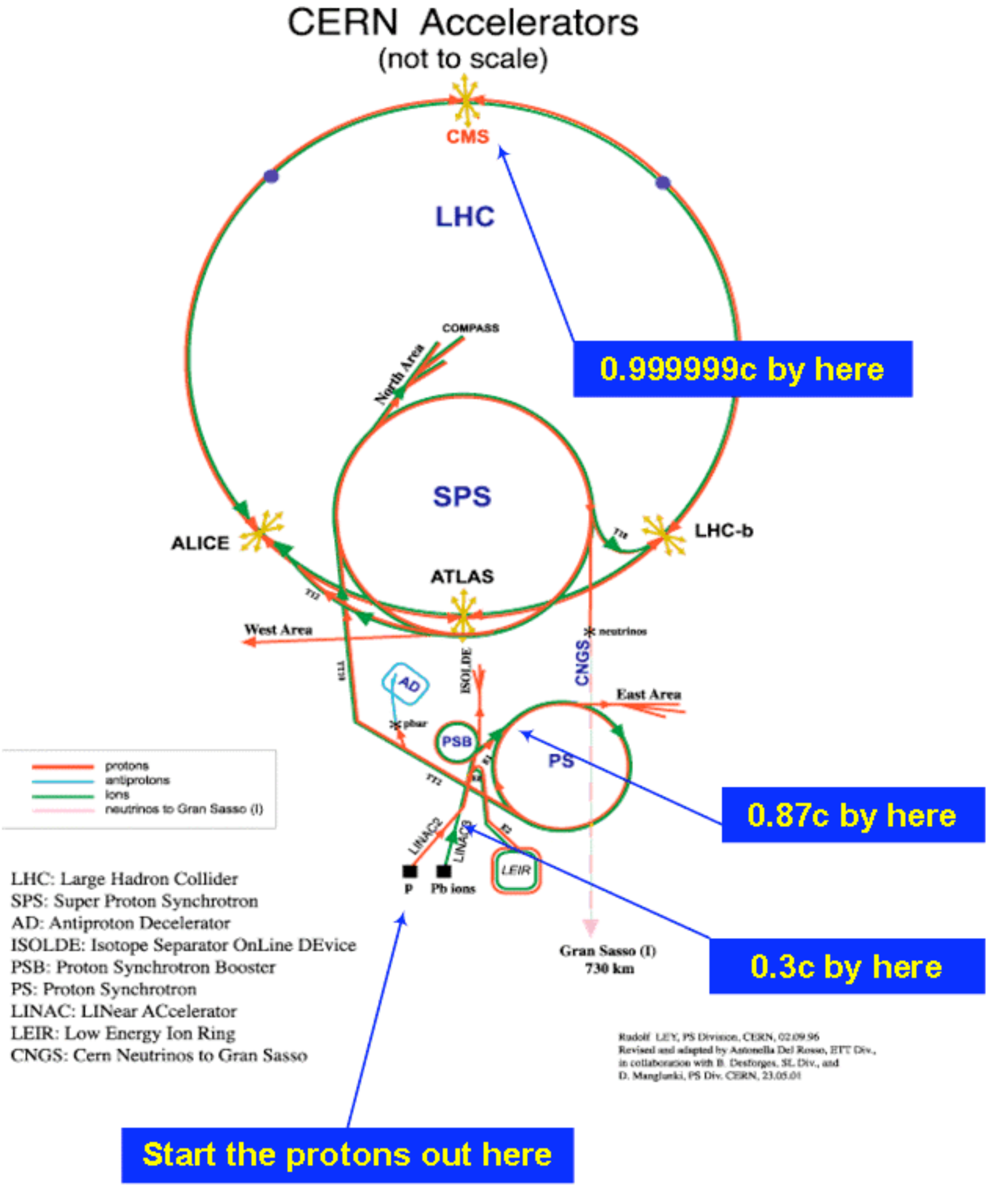




Note : √s limited by needed bending power.

LHC : 1232 superconducting dipoles with
B = 8.4 T working at 1.9 Kelvin (the largest cryogenic system in the world)

Accelerators and LHC experiments at CERN



protons
antiprotons
ions
neutrinos to Gran Sasso (I)

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

0.999999c by here

0.87c by here

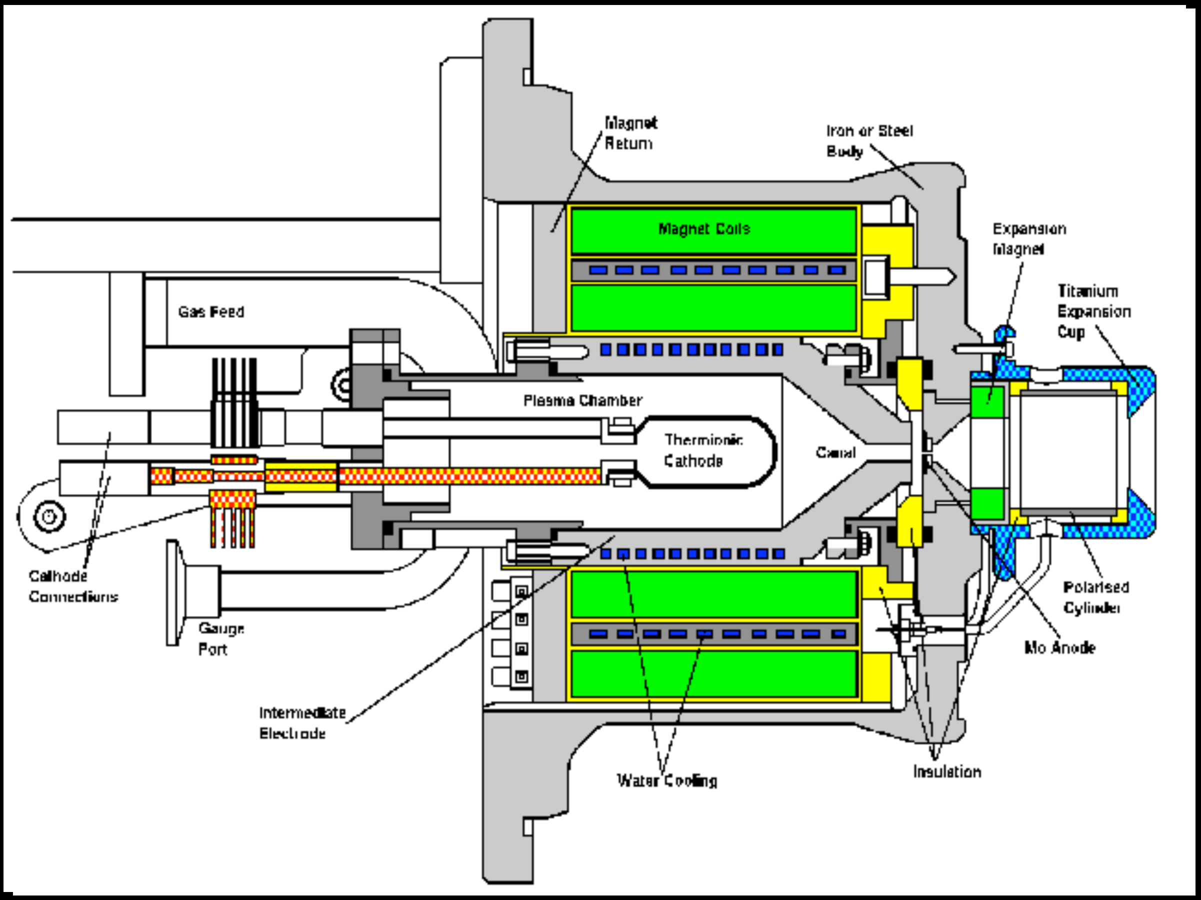
0.3c by here

Start the protons out here

Energies:

Linac	50 MeV
PSB	1.4 GeV
PS	28 GeV
SPS	450 GeV
LHC	7 TeV

Proton source   duoplasmatron



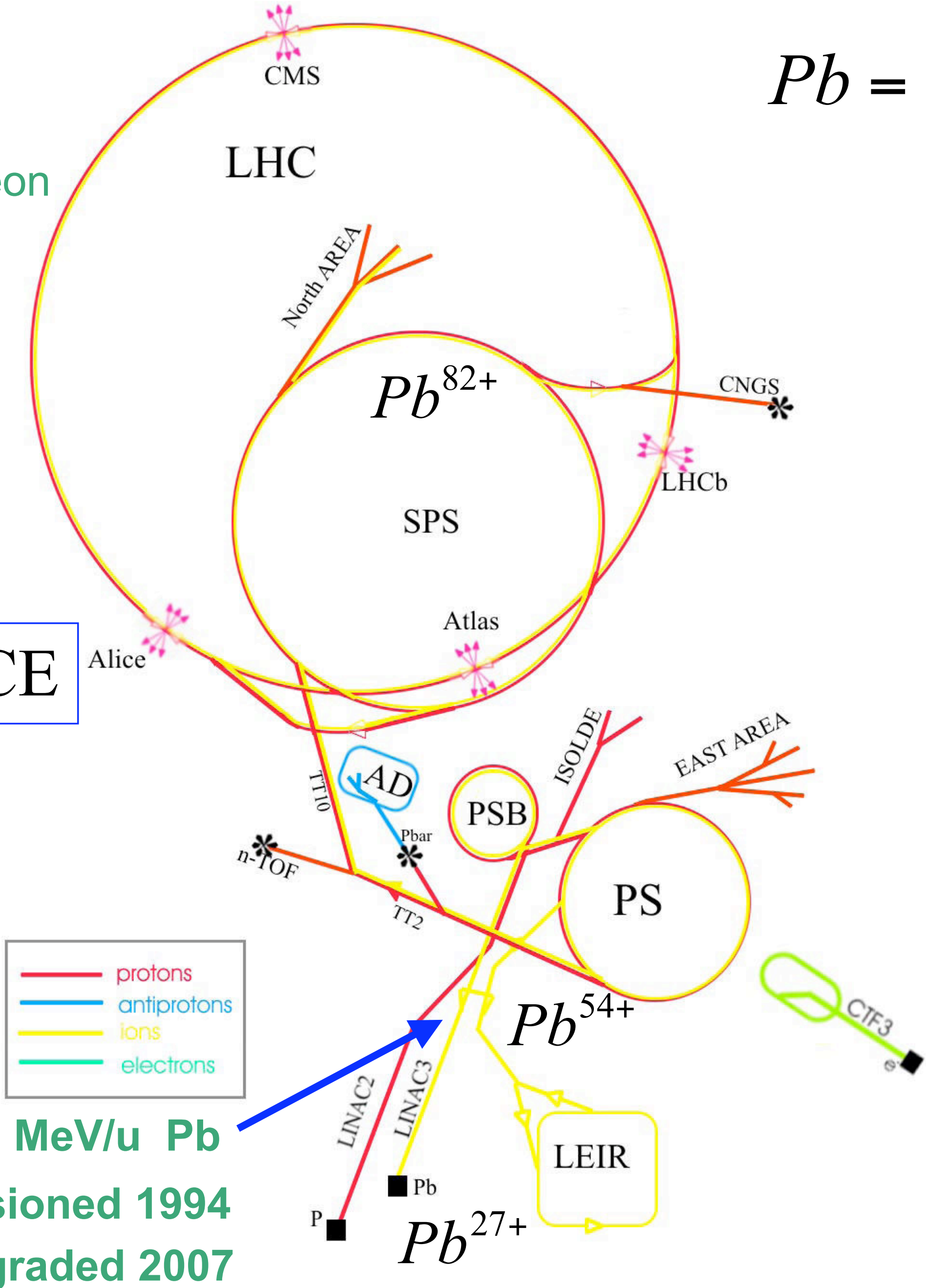
$$Pb = 82p + 125n$$

fully stripped
Pb ions

Pb^{82+}

2.76 TeV/nucleon

ALICE



Pb^{54+}

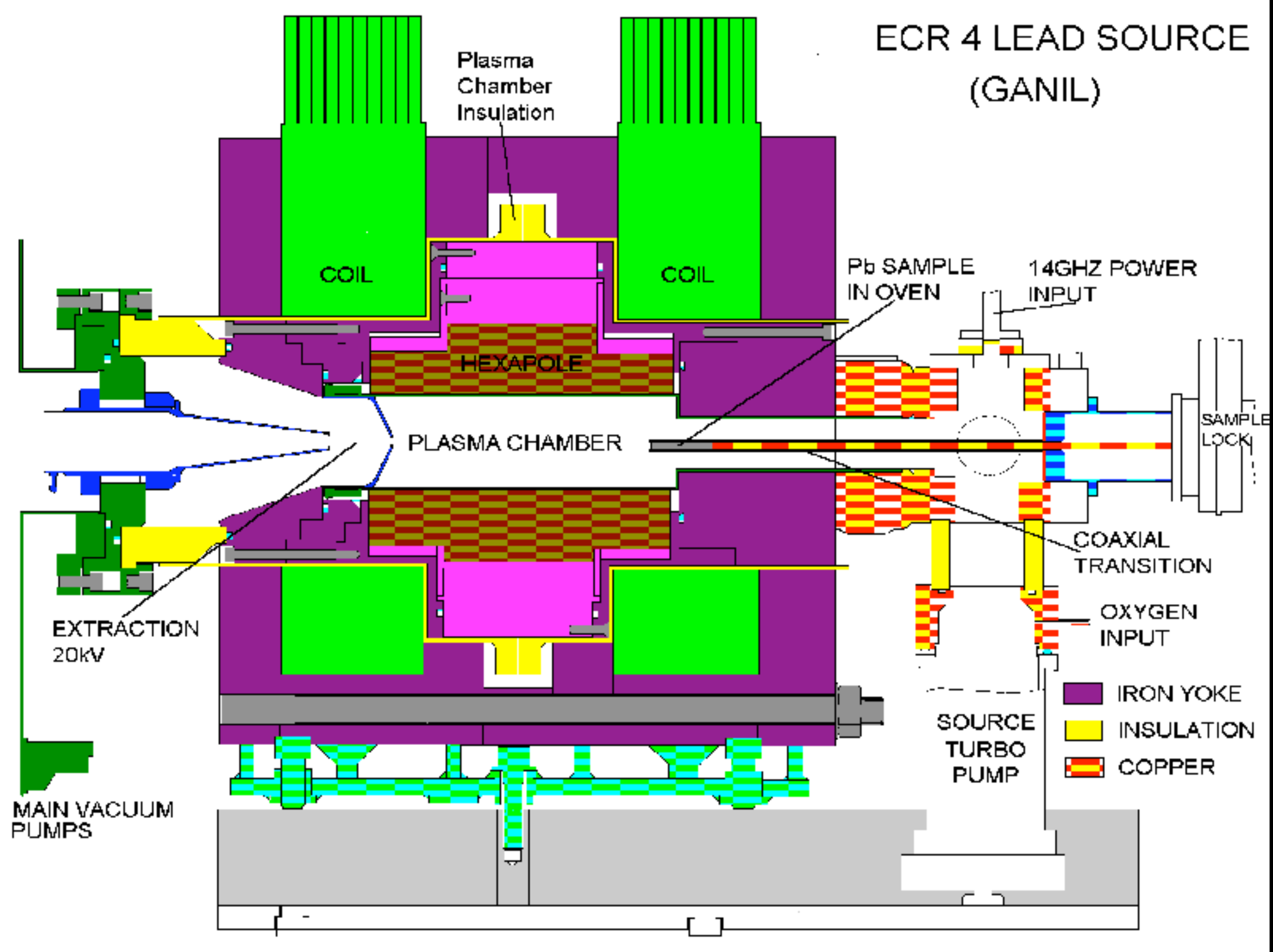
Pb^{27+}

4.2 MeV/u Pb

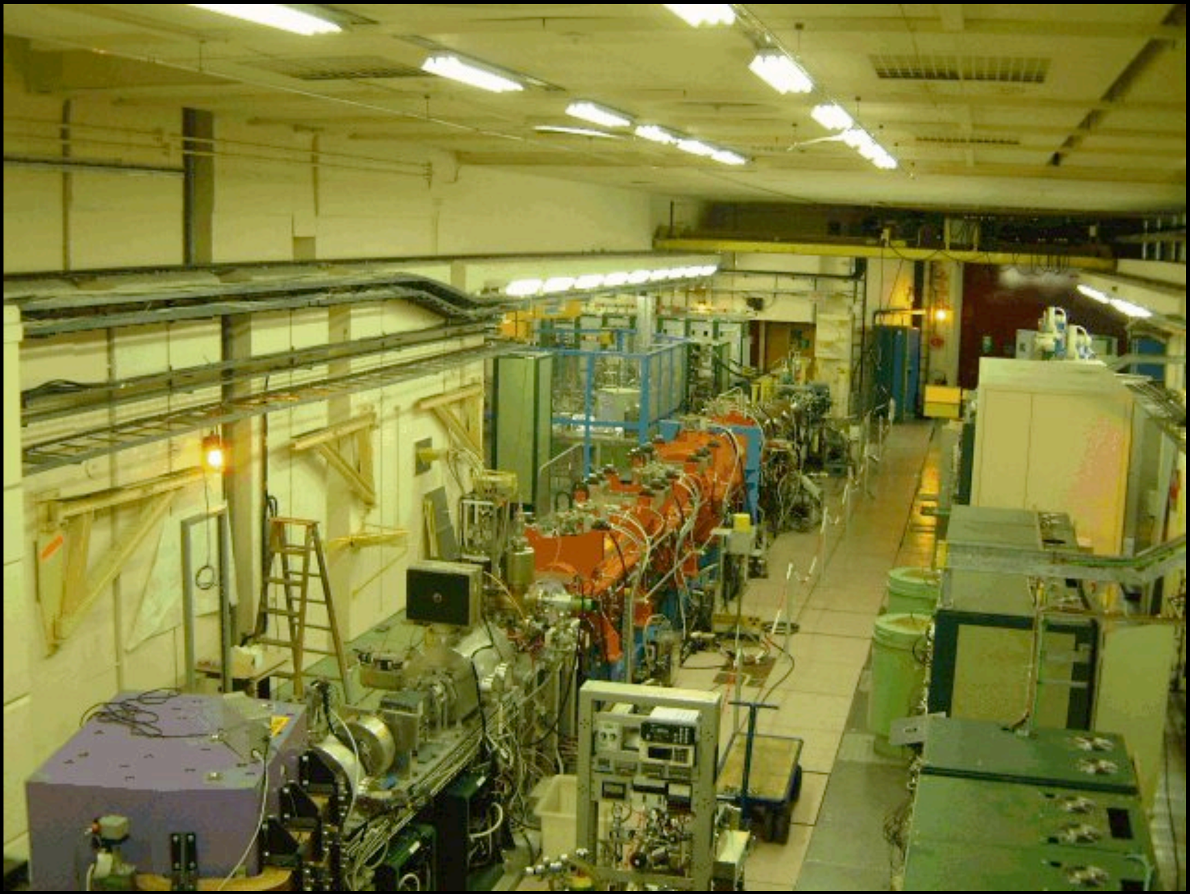
commissioned 1994

upgraded 2007

Electron Cyclotron Resonance ECR



Heavy ion linac



LHC approved by the CERN Council on december 1994

... as a 2-stage project:			
	First Stage	10 TeV	2004
	Second Stage	14 TeV	2008

Conceptual Design Report “Yellow Book” october 1995 first machine built at CERN with substantial contribution from non-Member states

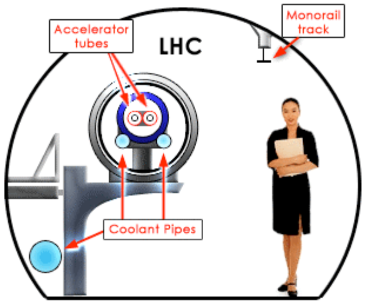
Canada, India, Japan, Russia, USA

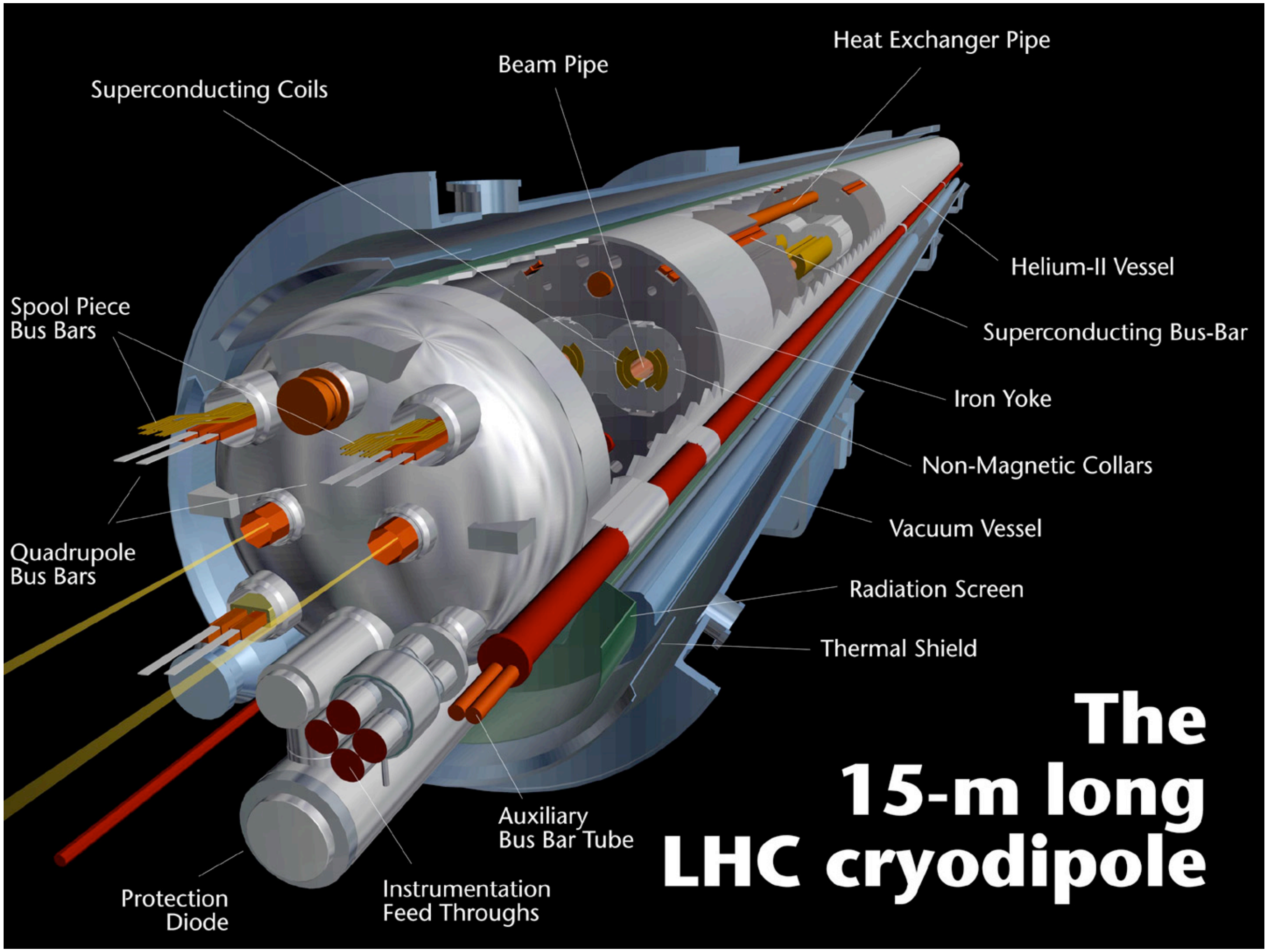
0.5 million US dollars each

1232 needed

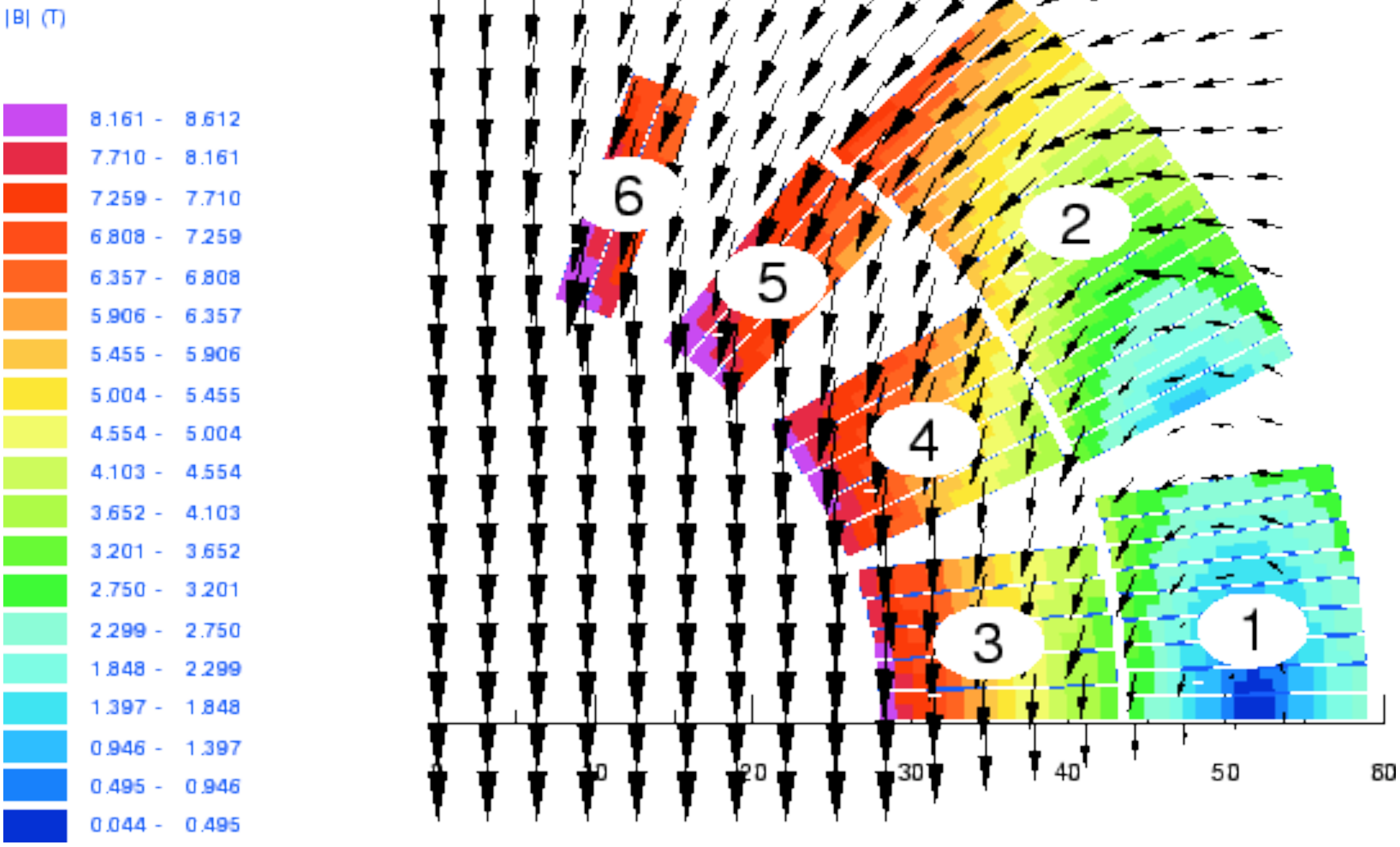
Dipole Magnet


MAFI


Accelerator tubes
LHC
Monorail track
Coolant Pipes


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Quadrupole Bus Bars
Vacuum Vessel
Radiation Screen
Thermal Shield
Auxiliary Bus Bar Tube
Instrumentation Feed Throughs
Protection Diode
The 15-m long LHC cryodipole

Magnetic Field

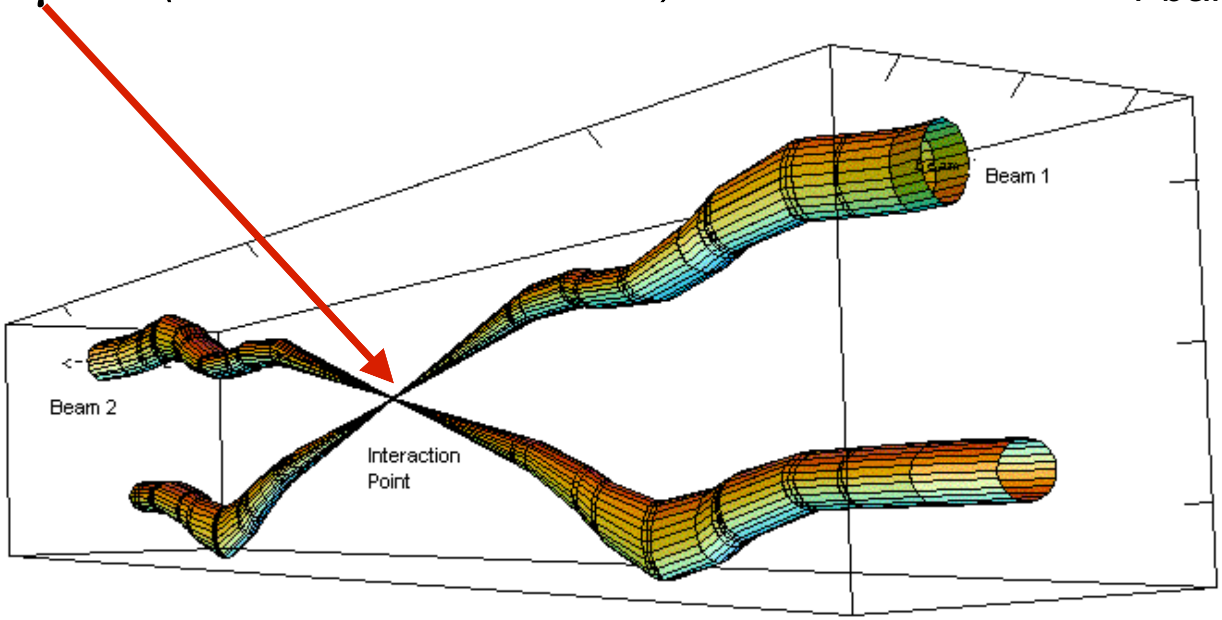


total proton - proton cross section at 7 TeV $\approx$ 110 mbarn

$$\boxed{\sigma_{inel} = 60mb}$$

$64\mu m$ *(width of a human hair)*

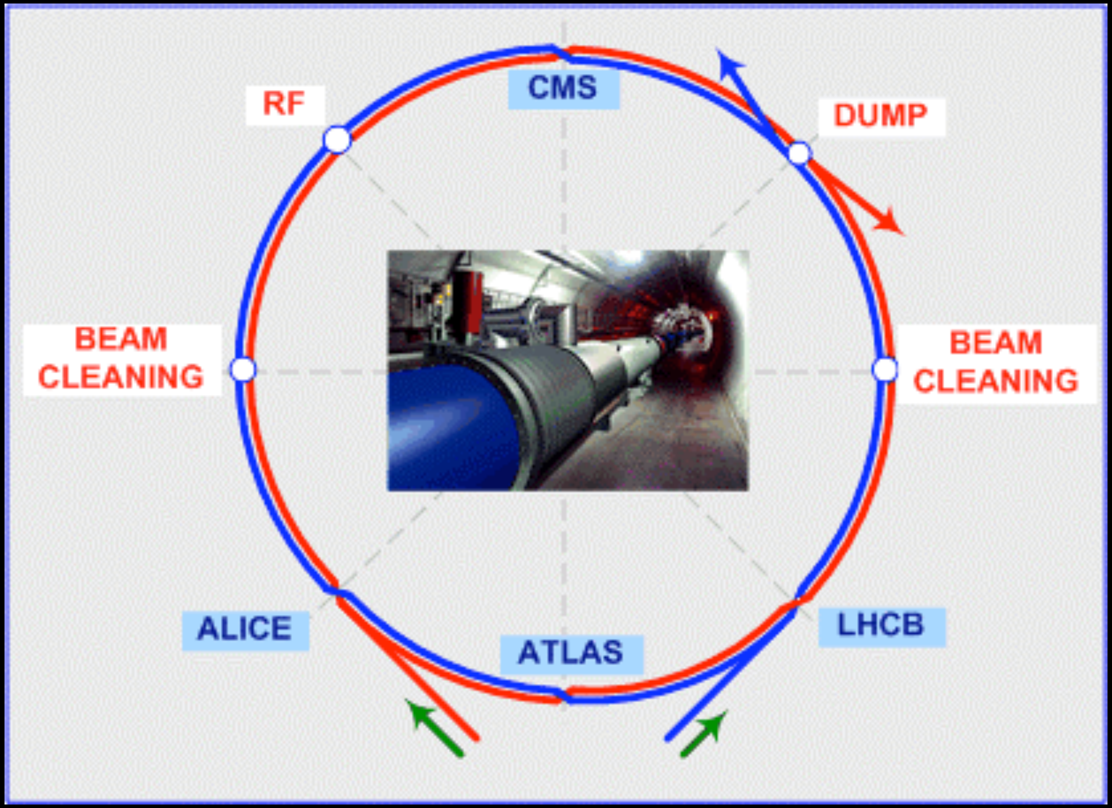
1 barn $=10^{-24}$ cm



Relative beam sizes around IP1 (Atlas) in collision

event rate = $\underbrace{\textbf{luminosity}}$ **x** $\underbrace{\textbf{cross section}}$

event rate = $10^{34} \bullet 60 \bullet 10^{-3} \bullet 10^{-24}$ **= 600 millions/sec**



injected at 450 GeV, accelerated to 7 TeV

For our fully-stripped ${}_{208}\mathrm{Pb}^{82+}$ nuclei ("ions")
in the same magnetic field as 7 TeV protons:

$$
\begin{aligned}
E_{\mathrm{Pb}} &= Z\,E_{\mathrm{p}} = 82\times 7\ \text{TeV} = 7Z\ \text{TeV} = 574\ \text{TeV} \\
&= A\,E_{n} = 208\times 2.76\ \text{TeV} = 2.76A\ \text{TeV} = 574\ \text{TeV} \\
&= 82\times(\text{kinetic energy of mosquito at 1m/s}) \\
&= (\text{kinetic energy of 1 mm diameter grain of sand at 40 km/h})
\end{aligned}
$$

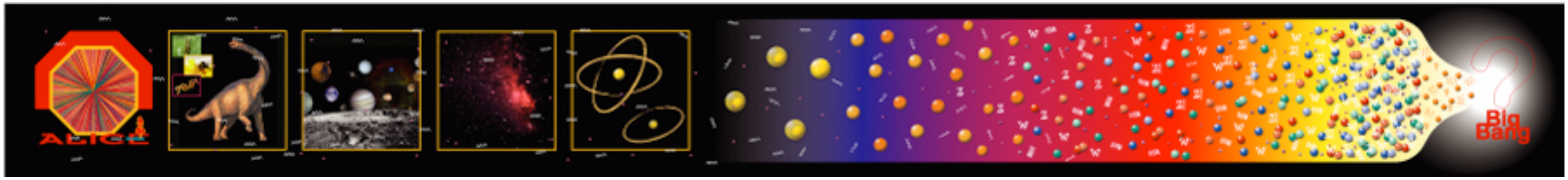
Key Parameters of "Early" Pb Ion Beam (from LHC Design Report)

Parameter	**Units**	**Early Beam**	**Nominal**
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2} s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3
		Only possibility for 2009 or early 2010	Goal for 2-3 years (?) beyond

At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Experimental aspects

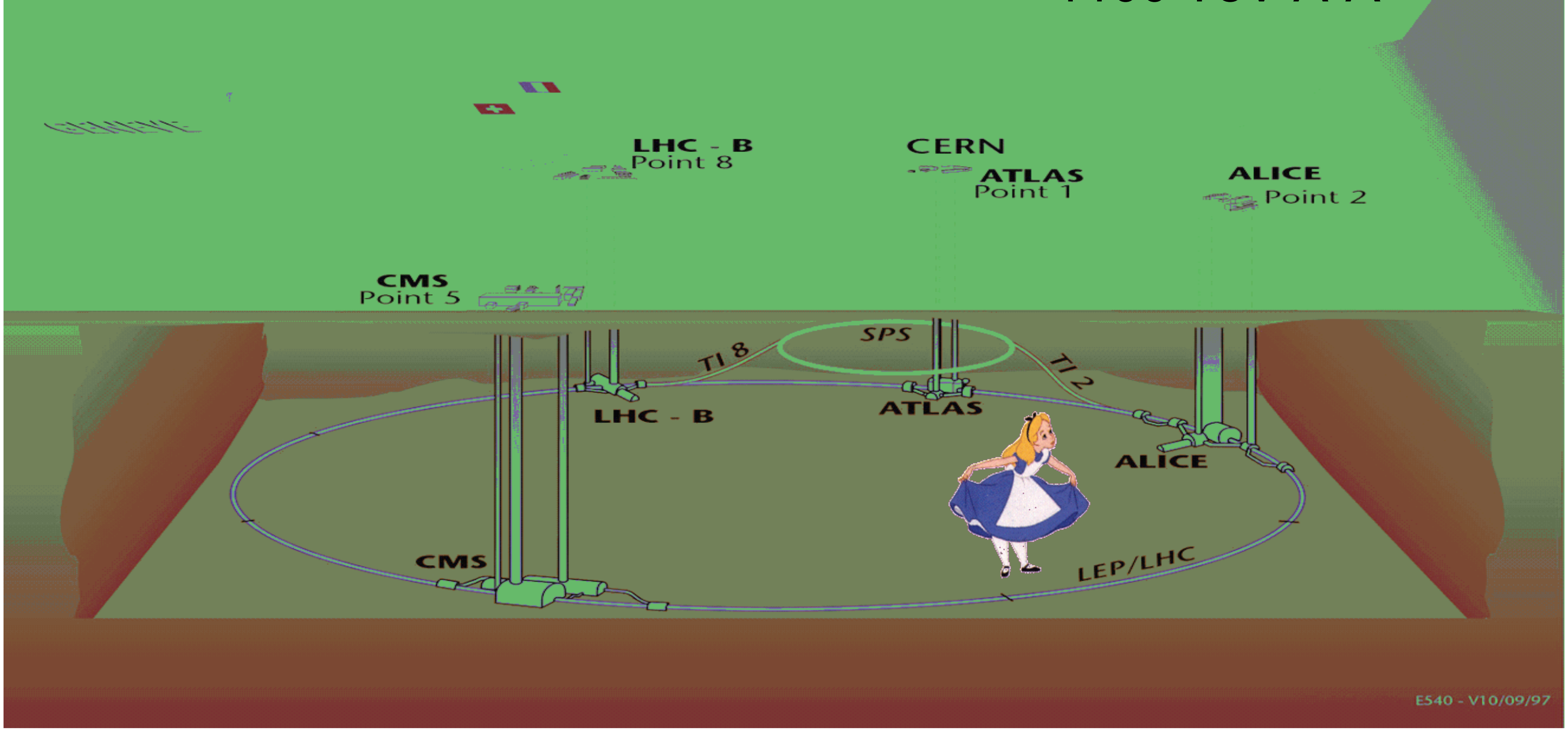
Detector



$\sqrt{S}$ = 14 TeV p-p

$\sqrt{S}$ = 5.5 TeV/nucleon A-A

= 1100 TeV A-A



5.5 TeV x 100 nucleones x 2 (cms) = 1100 TeV

ALICE Physics goals all aspects in the same experiment!

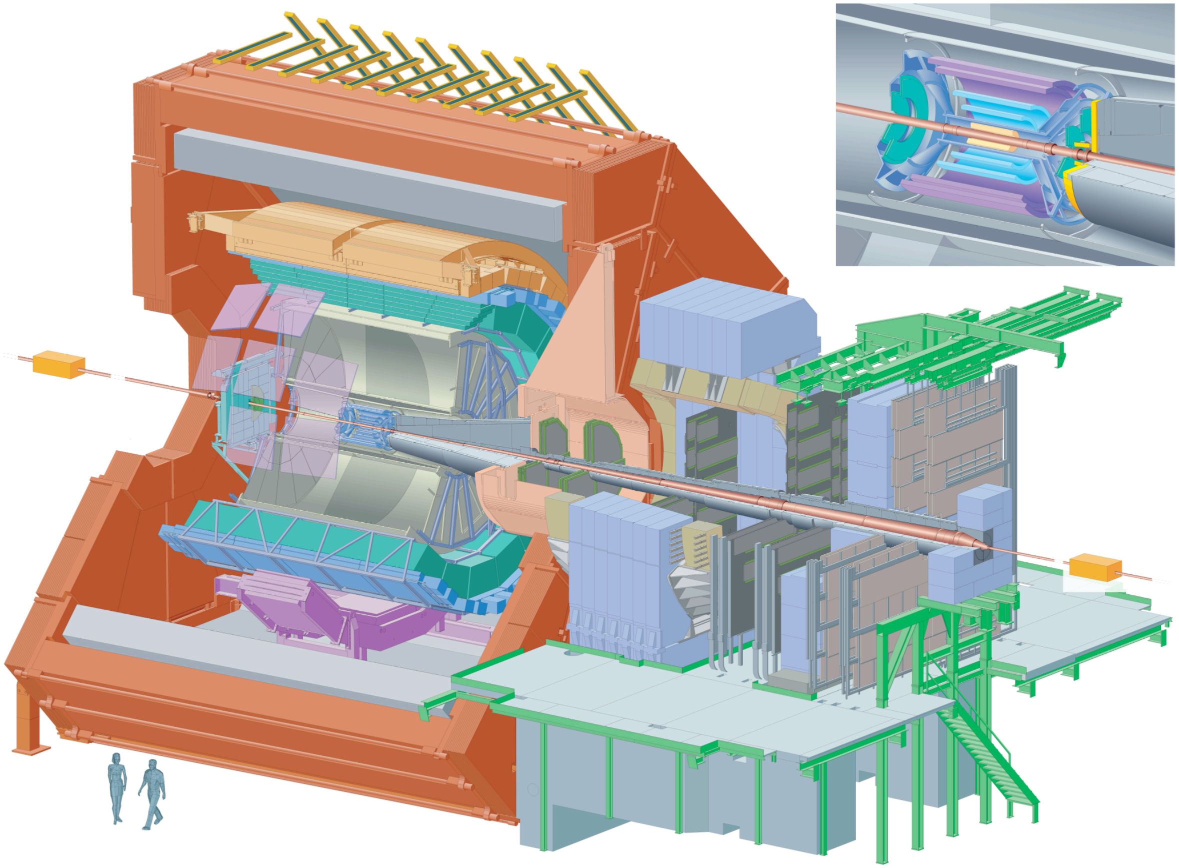
- **Global observables:**
Multiplicities, η distributions
- **Degrees of freedom as a function of Temperatue**
hadron ratios and spectra, dilepton continuum, direct photons
- **Early state manifestation of collective effects:** elliptic flow
- **Energy loss of partons in quark gluon plasma:**
jet quenching, high pt spectra, open charm and open beauty

- **Deconfinement:**
charmonium and bottonium spectroscopy
- **Chiral symmetry restoration:**
neutral to charged ratios, res. decays
- **Fluctuation phenomena - critical behavior:**
event-by-event particle comp. and spectra
- **Geometry of the emitting source:**
HBT, impact parameter via zero-degree energy flow
- **pp collisions in a new energy domain**

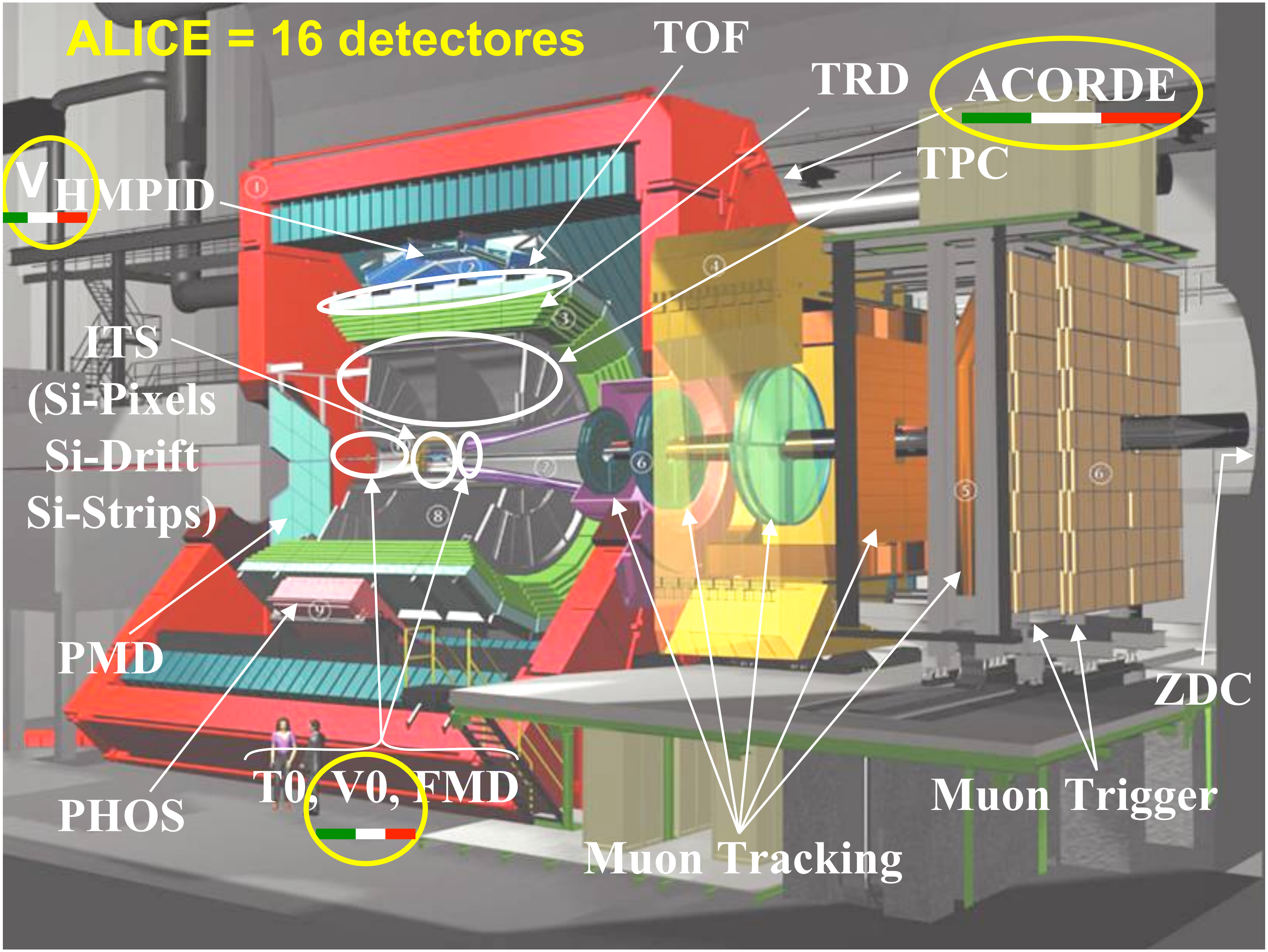
- ➢ Large acceptance
- ➢ Good tracking capabilities
- ➢ Selective triggering
- ➢ Excellent granularity

- ➢ Wide momentum coverage
- ➢ P.I.D. of hadrons and leptons
- ➢ Good sec. vertex reconstr.
- ➢ Photon Detection

use a variety of experimental techniques!



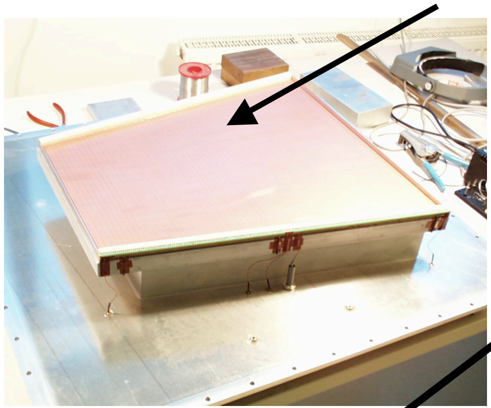
ALICE = 16 detectores

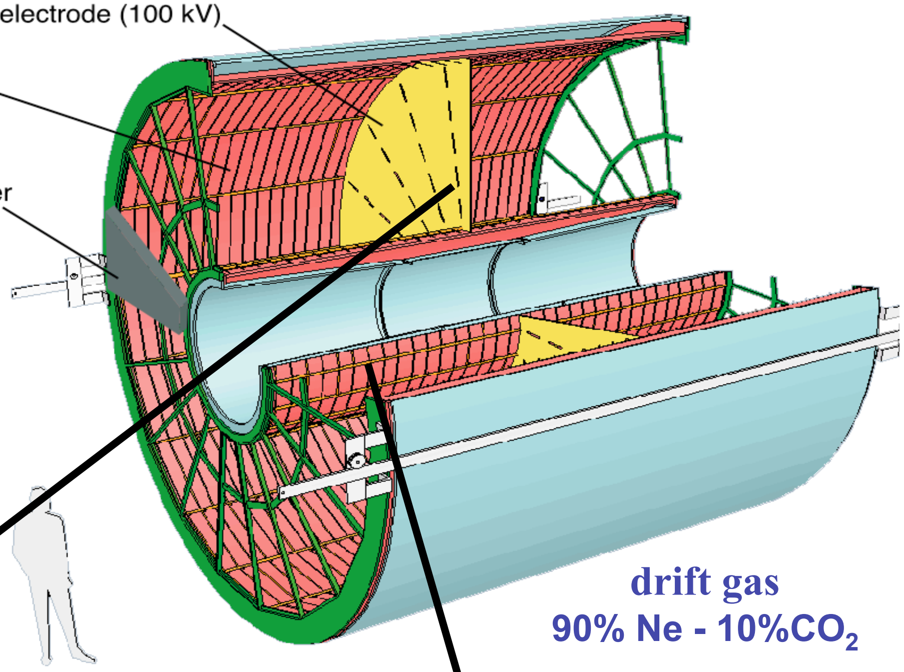


Time Projection Chamber
largest ever: 88 m^3,
570 k channels

for tracking and PID via dE/dx

$-0.9 < \eta < 0.9$





drift gas
90% Ne - 10%CO_2

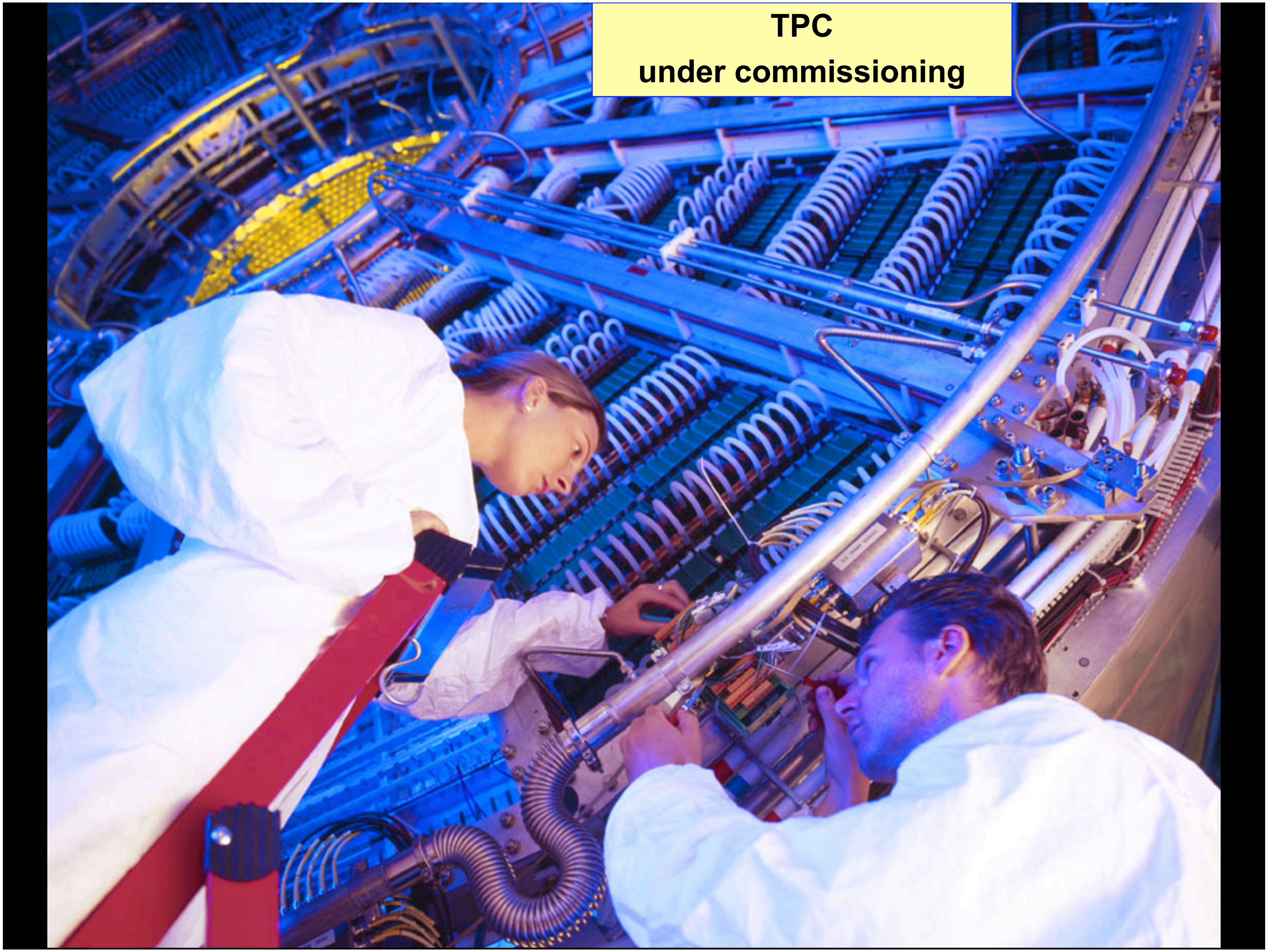
Central Electrode Prototype

25 µm aluminized Mylar on Al frame

~ 3 m diameter

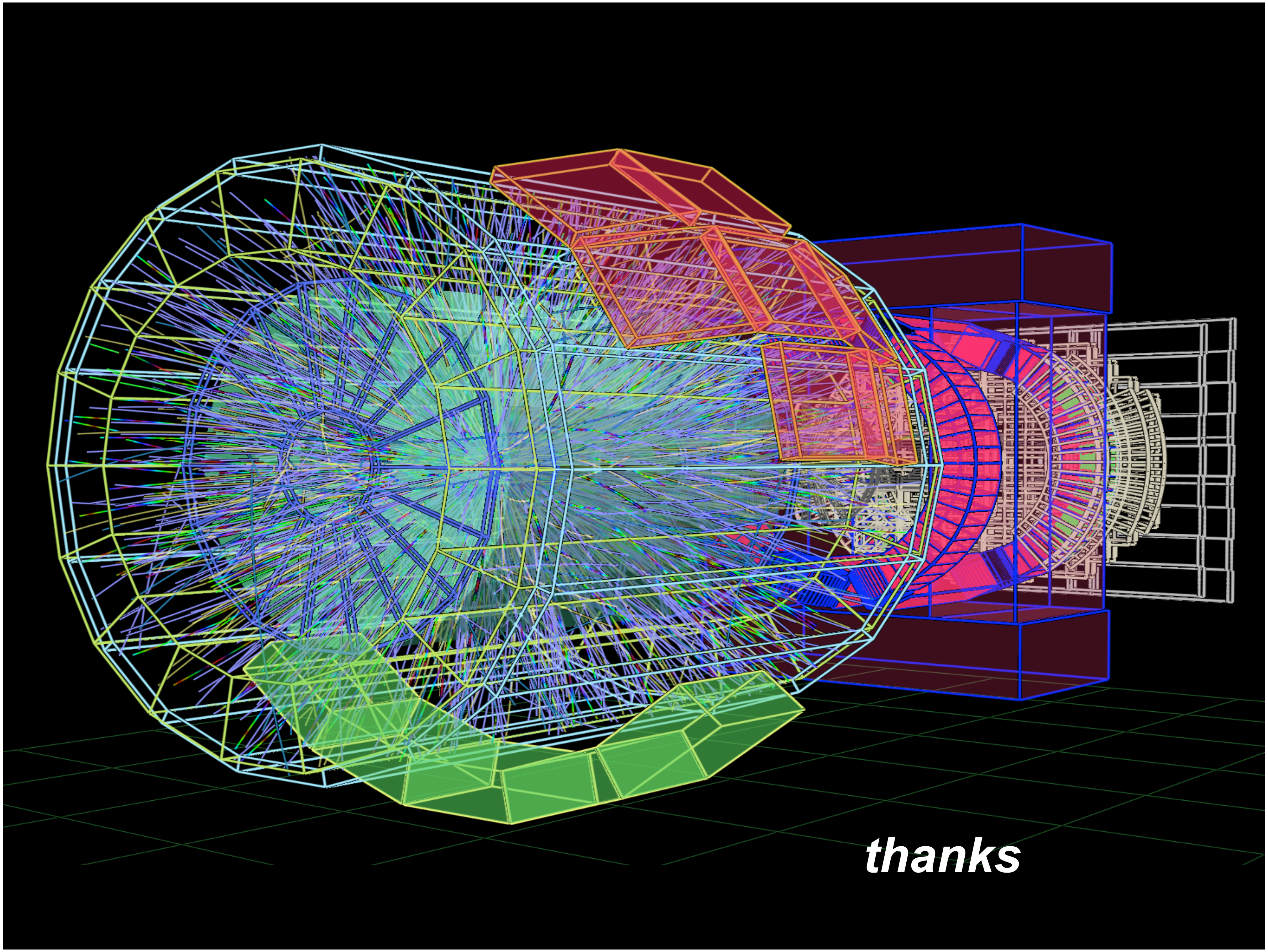
Field Cage   Inner Vessel

TPC
under commissioning



Summary

- LHC is the ultimate machine for Heavy Ion Collisions
  - very **significant step** beyond RHIC
  - excellent conditions for **experiment & theory** (QCD)
- ALICE is a powerful next generation detector
  - first truly **general purpose** HI experiment
    - addresses most relevant observables: from super-soft to ultra-hard
  - many **advances** in technology
- Both the experiment and the machine are getting ready … Physics at last is coming



thanks