QCD Physics at FAIR -

FAIR - Facility for Antiproton and Ion Research

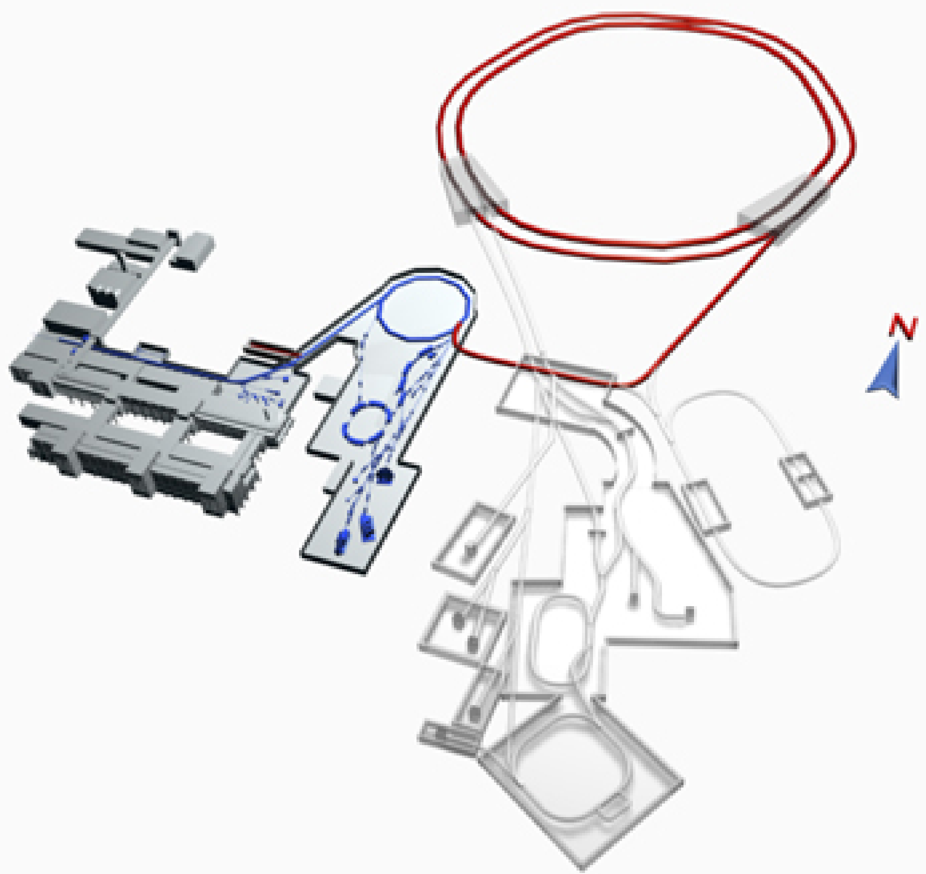
Jim Ritman Forschungszentrum Jülich and Univ. Bochum

Workshop on QCD in Nuclear and Hadronic Physics, CCLRC Daresbury Laboratory

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

FAIR: Facility for Antiproton and Ion Research

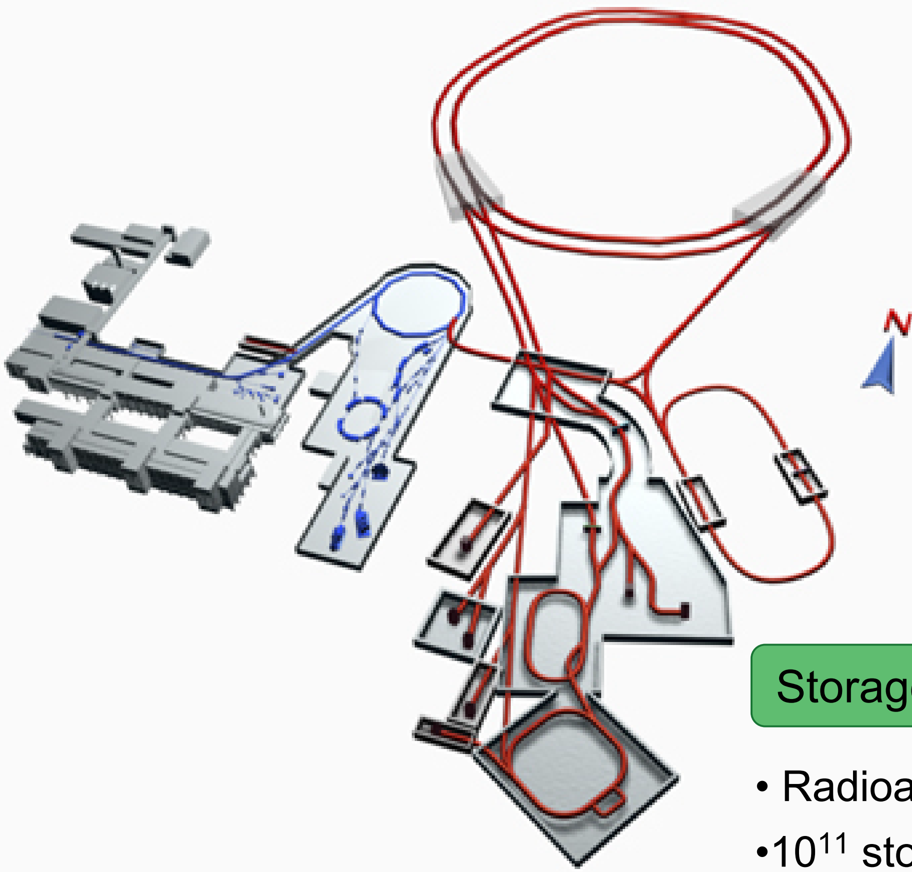
FAIR Will Probe the Intensity Frontier With Secondary Beams



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
  Factor 100-1000 over present in intensity
  x10 faster ramping (0.3 Hz → 3 Hz)
  x10 space charge ($^{238}U^{73+} \rightarrow {}^{238}U^{28+}$)
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons
  75 MeV Linac

FAIR Will Probe the Intensity Frontier With Secondary Beams



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

Storage and Cooler Rings

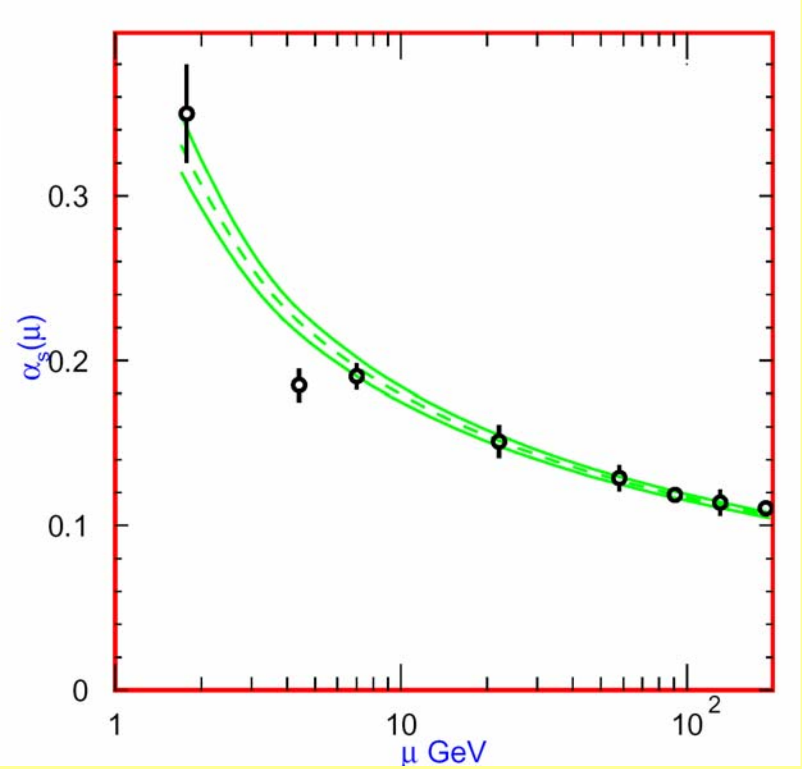
- Radioactive beams
- 10^{11} stored and cooled 1 - 15 GeV/c antiprotons

Technical Challenges include: Storage rings and high energy electron cooling

Strong QCD

QCD Lagrangian

$$L_{\rm QCD} = -\frac{1}{4}F^{(a)}_{\mu\nu}\;F^{(a)\mu\nu} + i\sum_q \overline{\psi}^i_q\,\gamma^\mu\,(D_\mu)_{ij}\,\psi^j_q - \sum_q m_q\,\overline{\psi}^i_q\,\psi_{qi}\;,$$



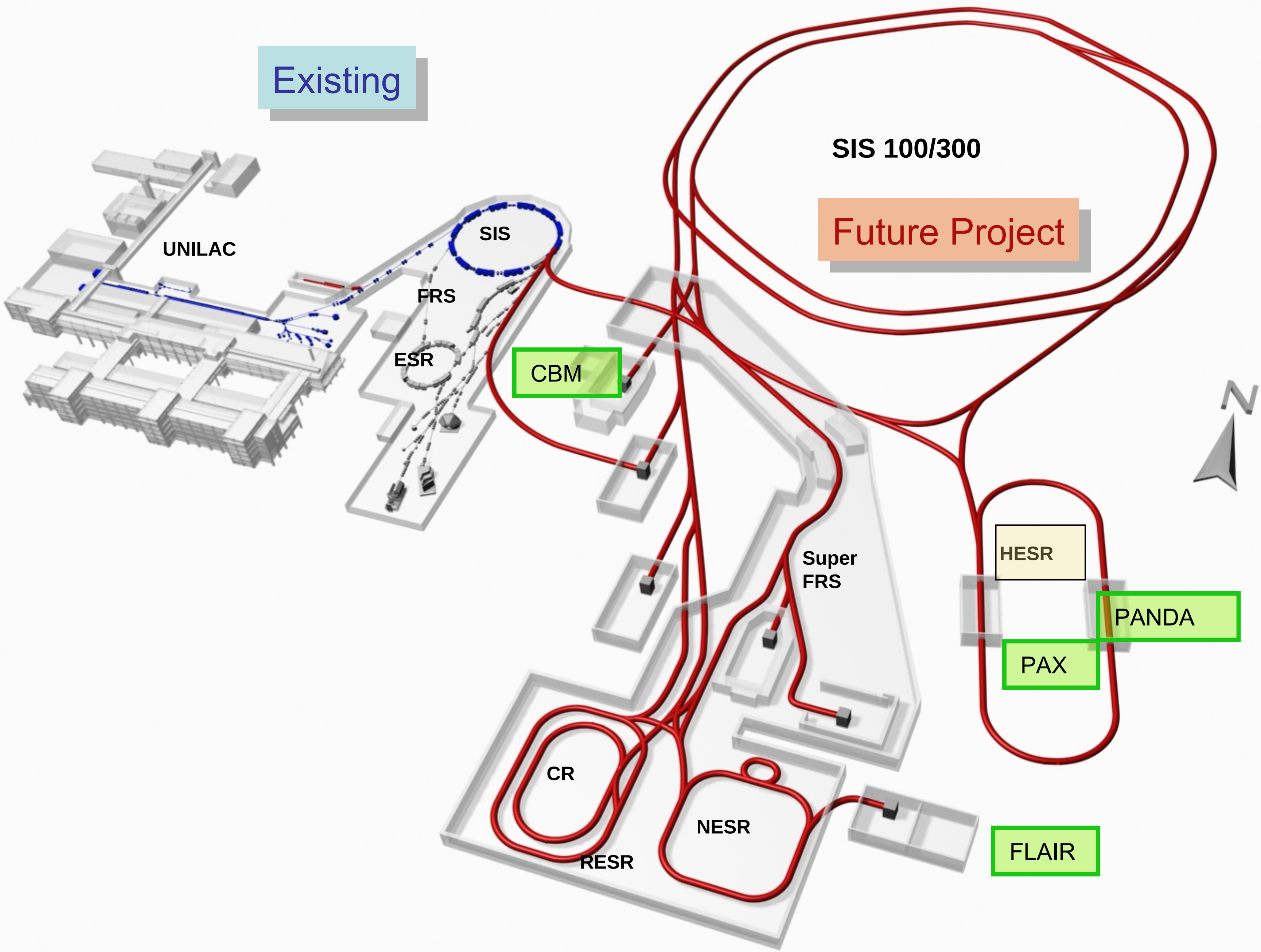
Running coupling const.

- Perturbative at high Q^2
  high precision tests
- New phenomena at low Q^2
  - Broken symmetries
  - Confinement

How do hadrons become the effective degrees of freedom as Q^2 decreases?

QCD Physics at FAIR

- Compressed Baryonic Matter (CBM)
- „High Energy“ Antiprotons (PANDA)
- Polarized Antiprotons (PAX)
- Stopped Antiprotons (FLAIR)



Existing
SIS 100/300
Future Project
UNILAC
SIS
FRS
ESR
CBM
Super
FRS
HESR
PANDA
PAX
CR
NESR
RESR
FLAIR
N

QCD Physics at FAIR

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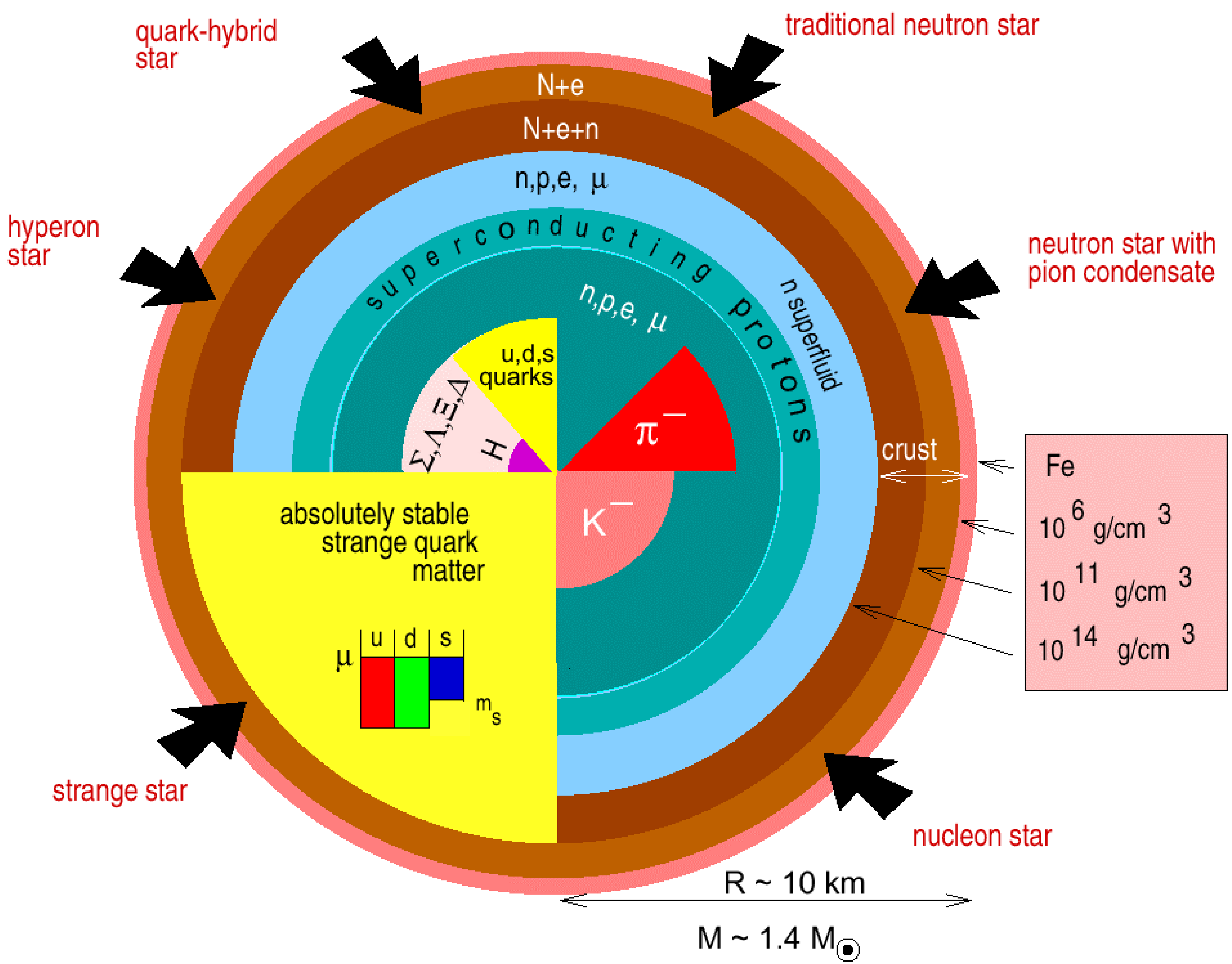
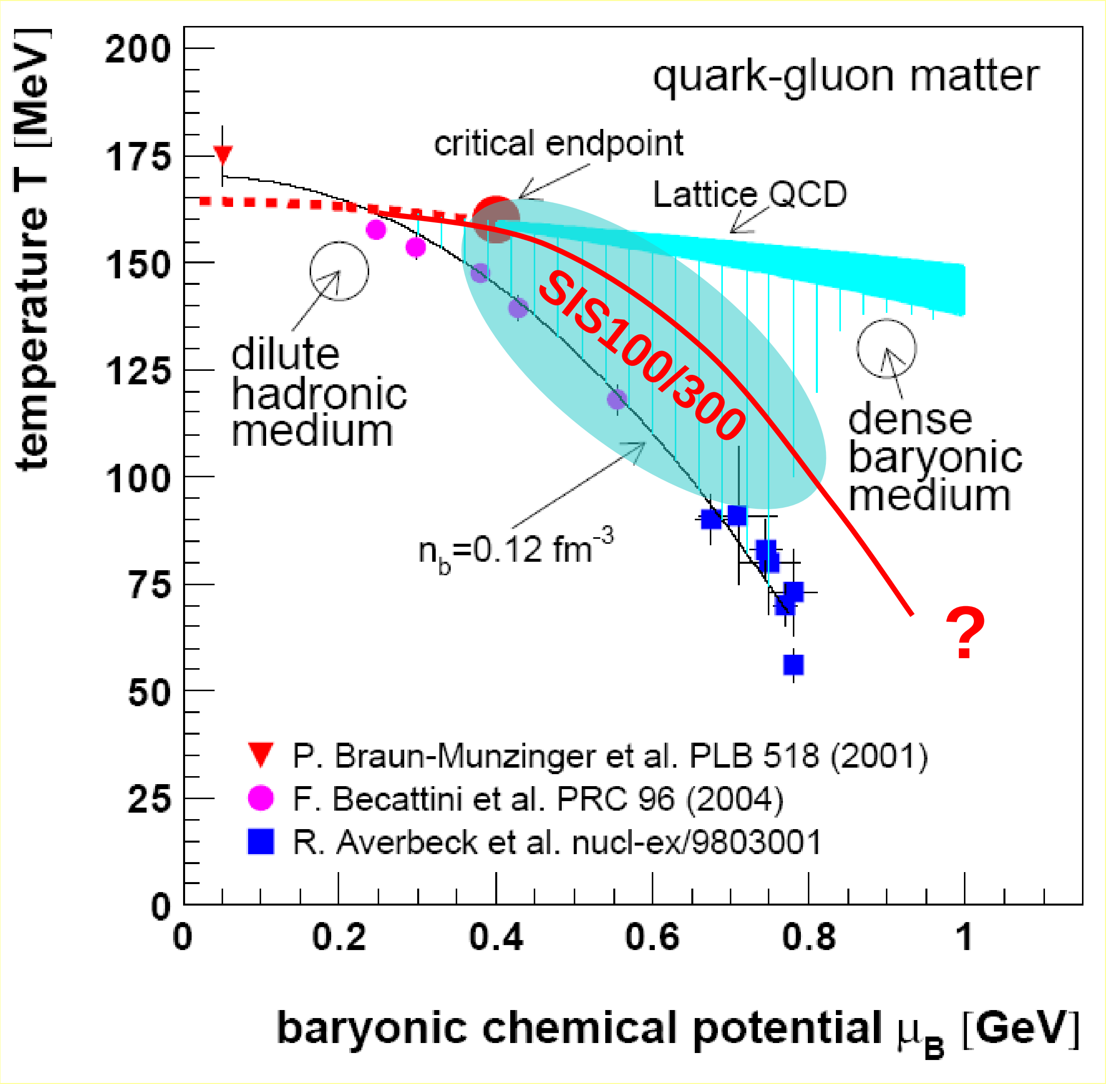
States of strongly interacting matter



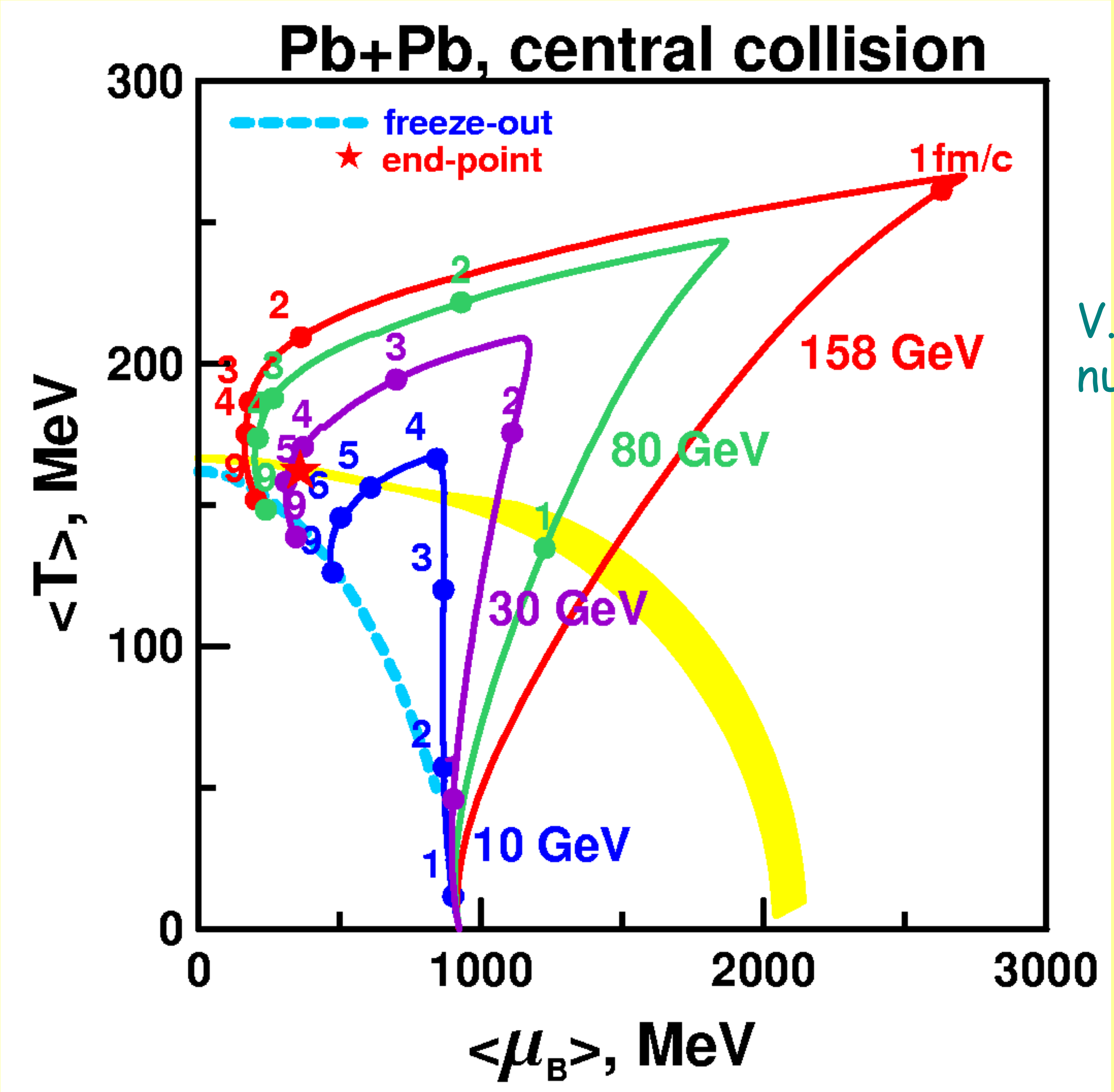
asma

Mapping the QCD phase diagram with heavy-ion collisions



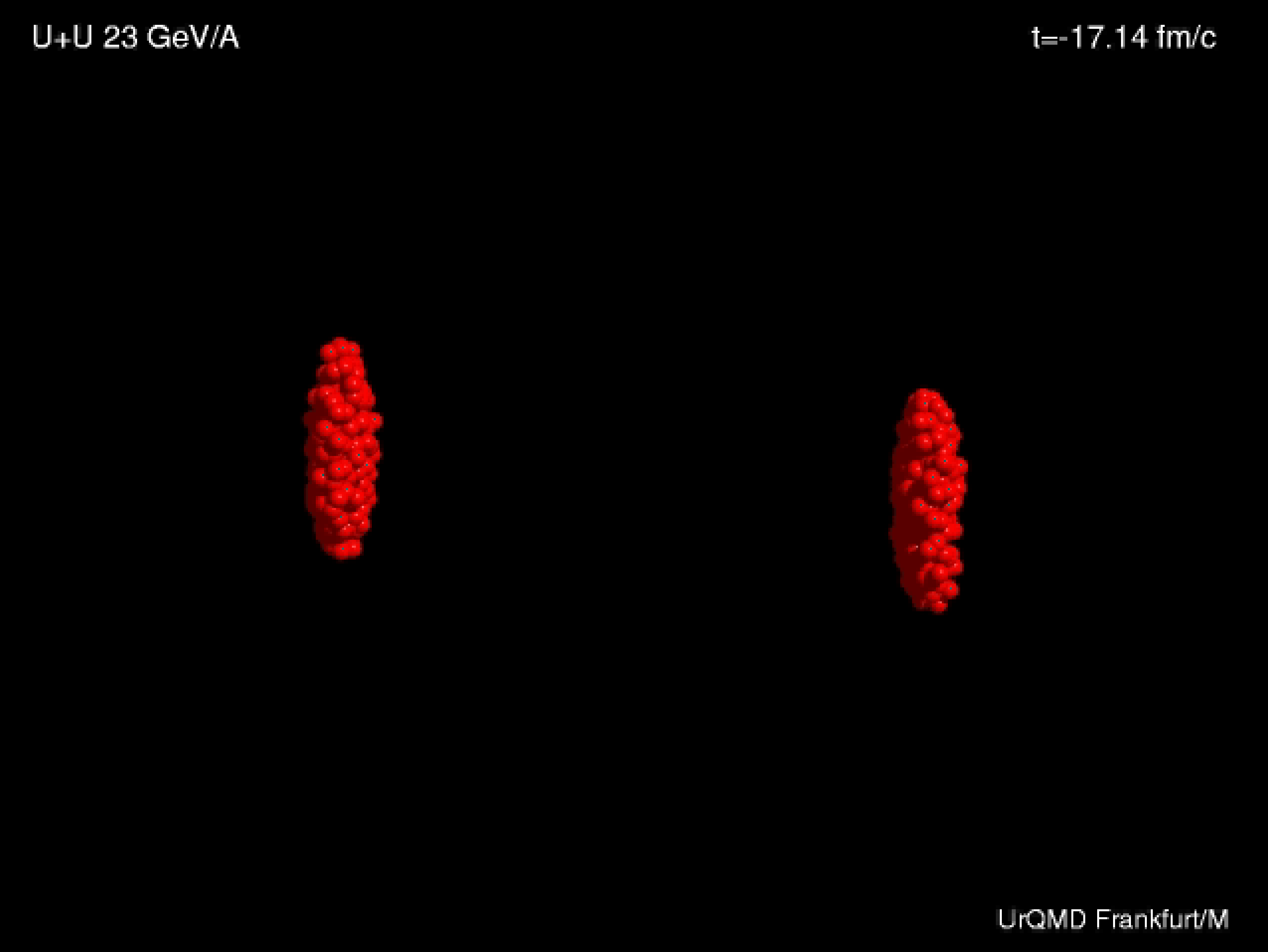
Critical endpoint:
Z. Fodor, S. Katz, hep-lat/0402006
S. Ejiri et al., hep-lat/0312006

"Trajectories" (3 fluid hydro)



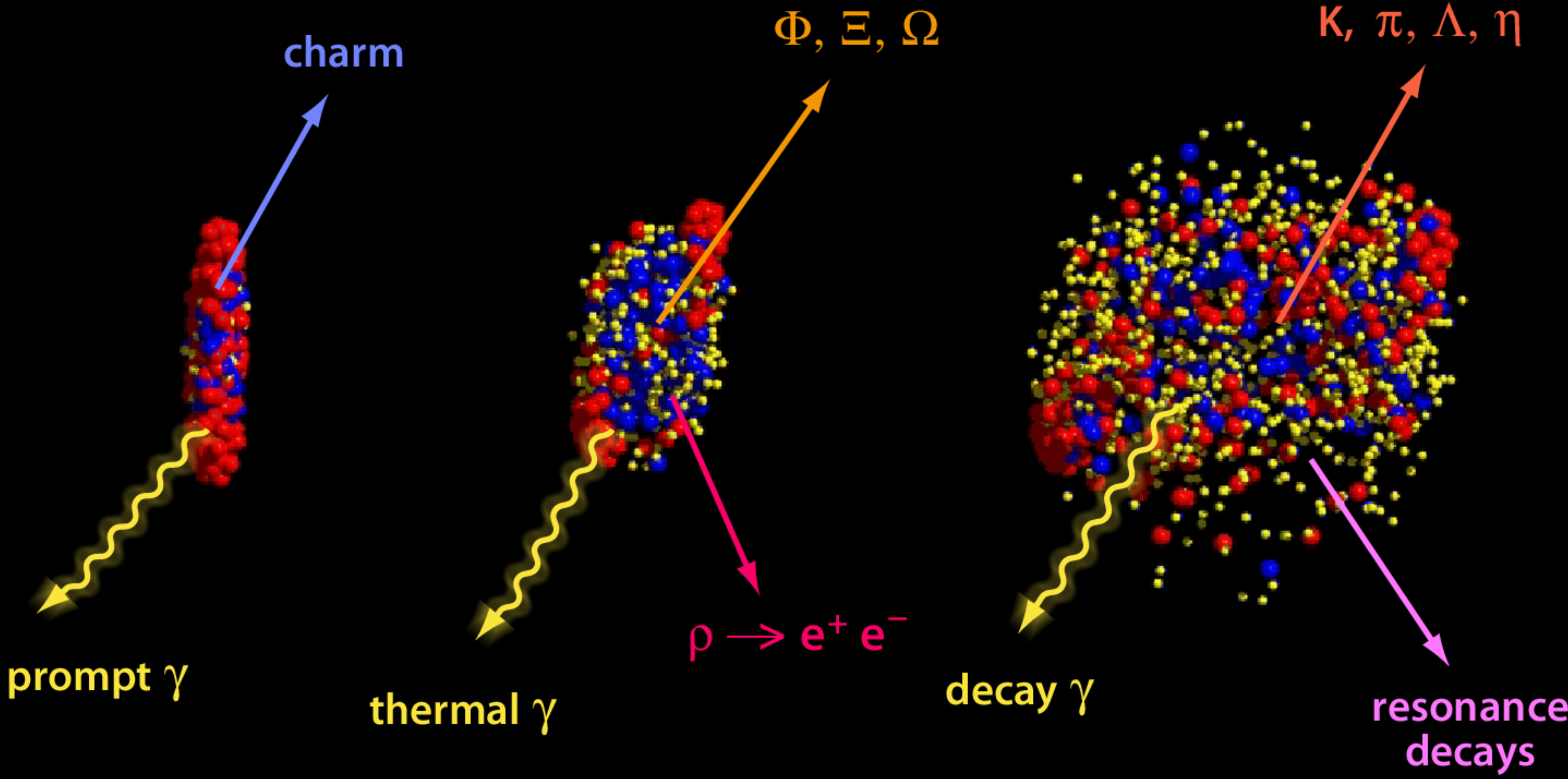
Hadron gas EOS

V.Toneev, Y. Ivanov et al.
nucl-th/0309008


U+U 23 GeV/A
t=-17.14 fm/c
UrQMD Frankfurt/M

Diagnostic probes

U+U 23 AGeV



CBM physics topics and observables

- In-medium modifications of hadrons
  - ↳ onset of chiral symmetry restoration at high ρ_B

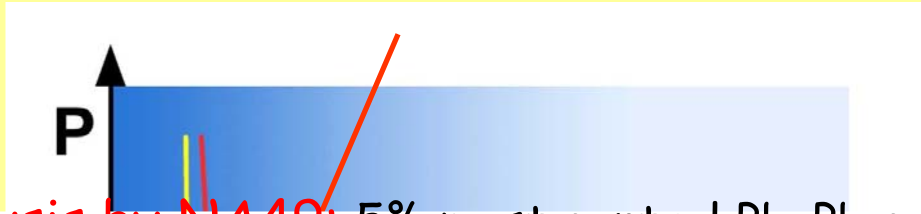
    measure: $\rho, \omega, \phi \rightarrow e^+e^-$

    open charm (D mesons)
- Strangeness in matter (strange matter?)
  - ↳ enhanced strangeness production ?

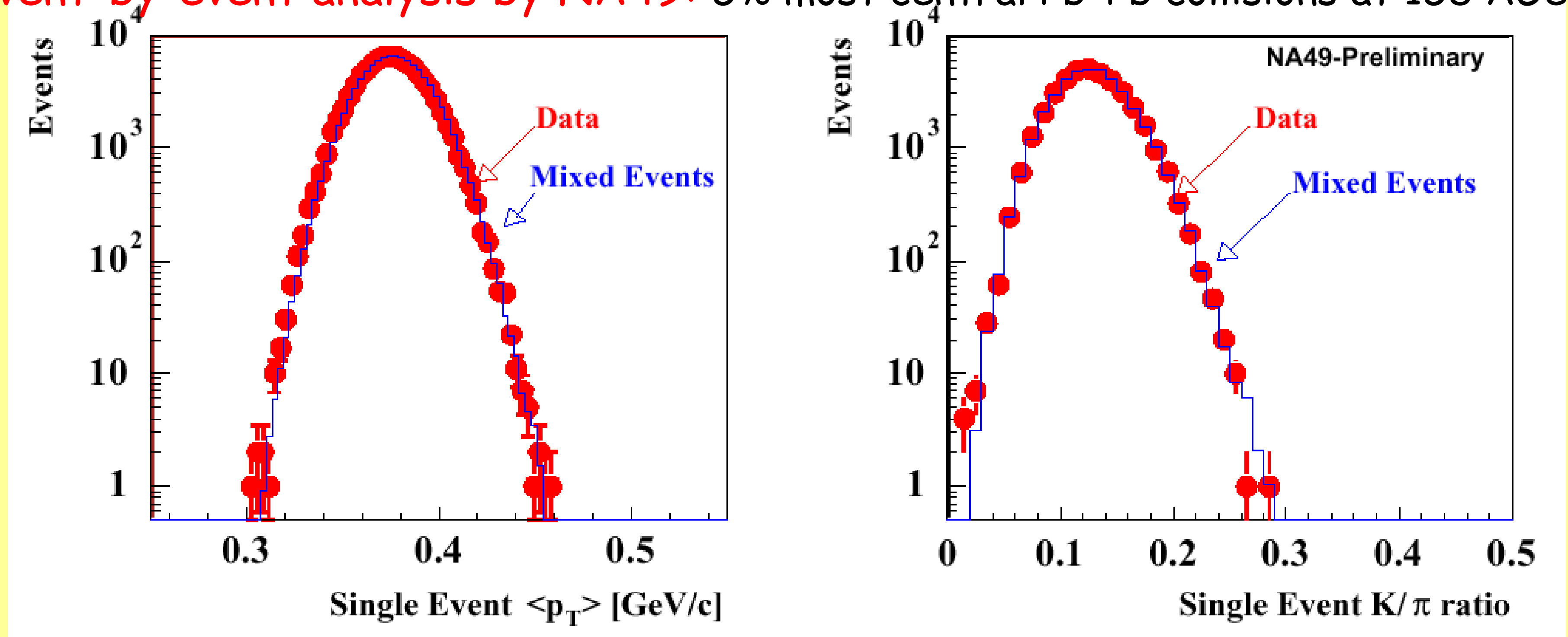
    measure: K, $\Lambda, \Sigma, \Xi, \Omega$
- Indications for deconfinement at high ρ_B
  - ↳ anomalous charmonium suppression ?

    measure: J/ψ, D
- Critical point
  - ↳ event-by-event fluctuations
- Color superconductivity
  - ↳ precursor effects ?

The critical point



Event-by-event analysis by NA49: 5% most central Pb+Pb collisions at 158 AGeV

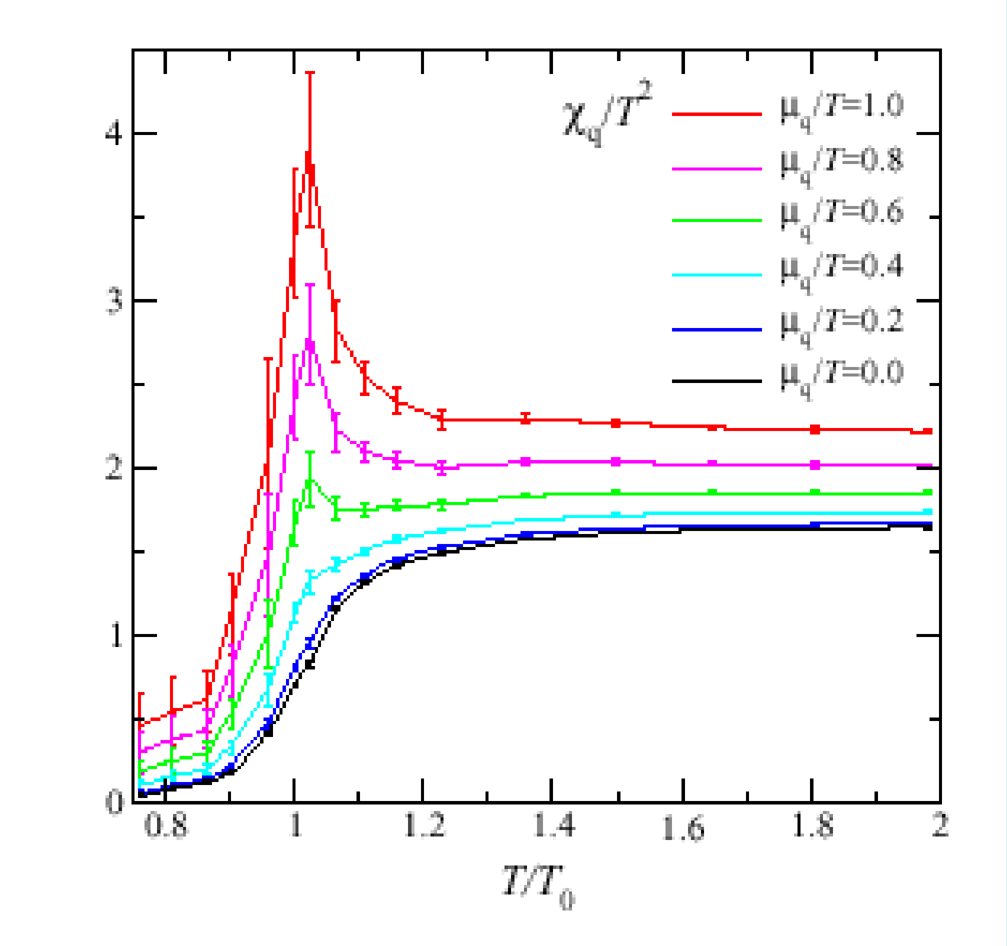


above T_c: no phase boundary

At the critical point:
Large density fluctuations,
critical opalescence

Fluctuations on the Lattice

C. R. Allton et al, hep-lat 0305007

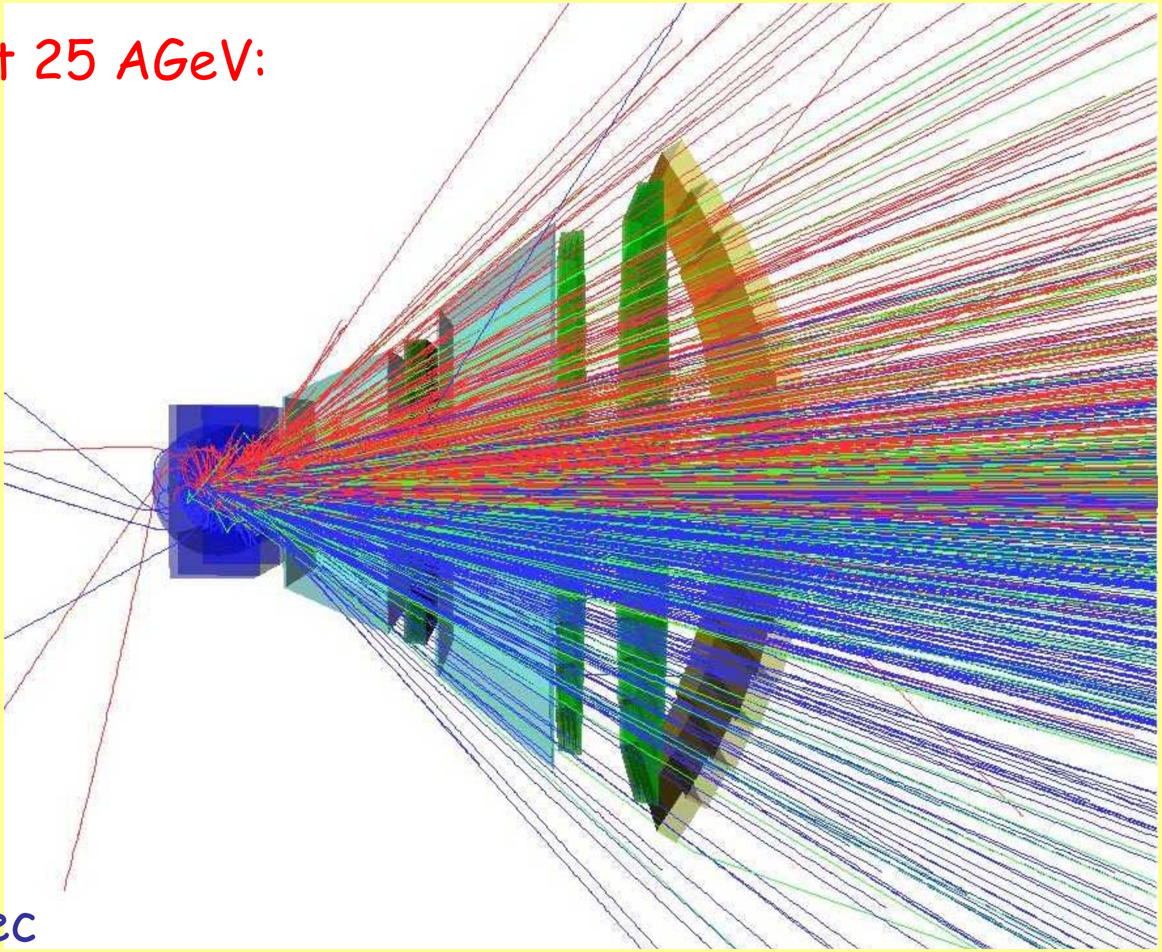


Lattice QCD :
maximal baryon number density fluctuations at T_C for $\mu_q = T_C$ ($\mu_B \approx 500$ MeV)

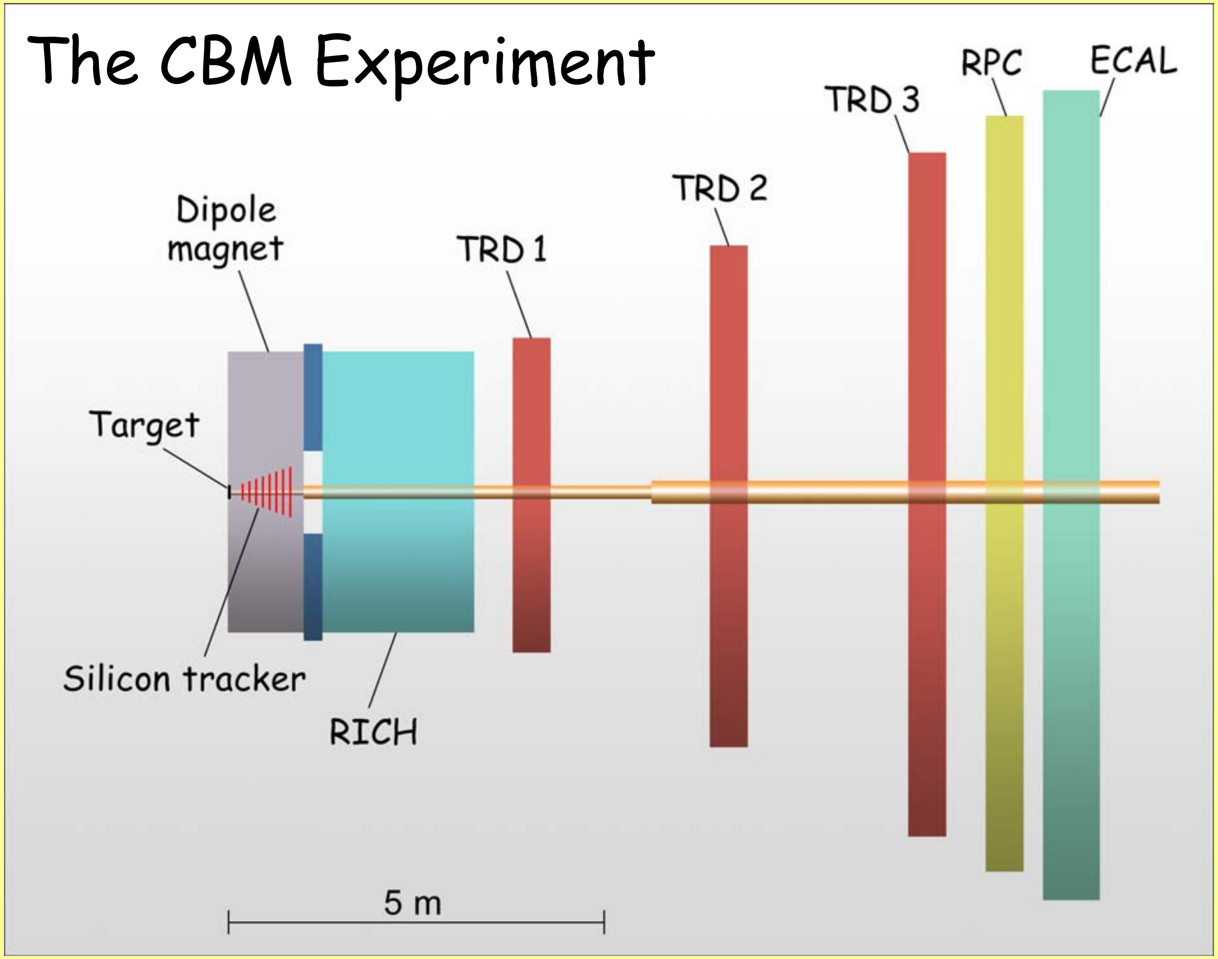
Experimental challenges

Central Au+Au collision at 25 AGeV:
URQMD + GEANT4

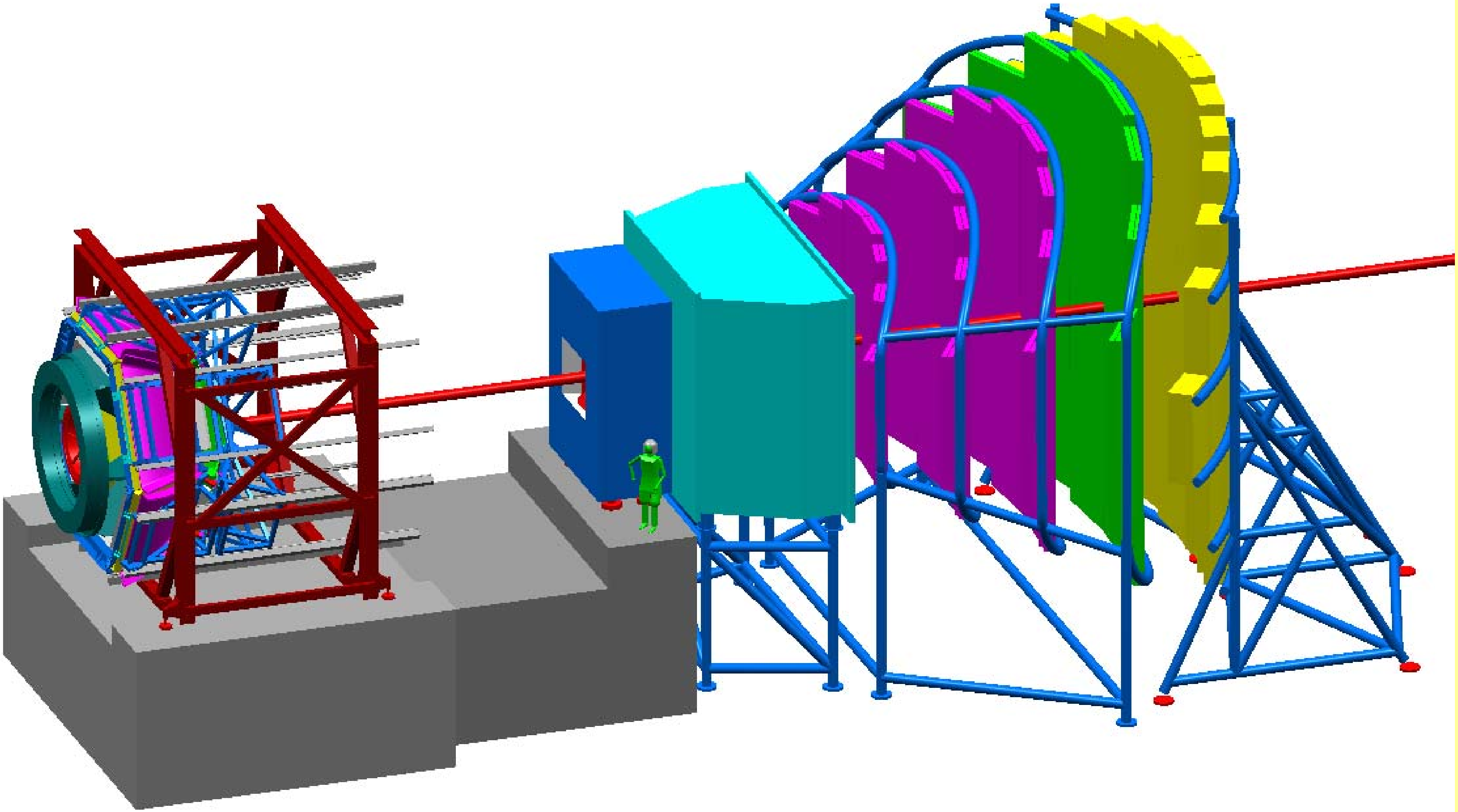
160 p
400 π^-
400 π^+
44 K^+
13 K^-



- 10^7 Au+Au reactions/sec
  (beam intensities up to 10^9 ions/sec, 1 % interaction target)
- determination of (displaced) vertices with high resolution ($\approx$ 30 μm)
- identification of electrons and hadrons



- Radiation hard Silicon (pixel/strip) Tracking System in a magnetic dipole field
- Electron detectors: RICH & TRD & ECAL: pion suppression better 10^4
- Hadron identification: TOF-RPC
- Measurement of photons, π, η, and muons: electromagn. calorimeter (ECAL)
- High speed data acquisition and trigger system



CBM Collaboration : 41 institutions, > 300 Members

Croatia:
RBI, Zagreb

China:
Wuhan Univ.

Cyprus:
Nikosia Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IReS Strasbourg

Hungaria:
KFKI Budapest
Eötvös Univ. Budapest

Korea:
Korea Univ. Seoul
Pusan National Univ.

Norway:
Univ. Bergen

Germany:
Univ. Heidelberg, Phys. Inst.
Univ. HD, Kirchhoff Inst.
Univ. Frankfurt
Univ. Kaiserslautern
Univ. Mannheim
Univ. Marburg
Univ. Münster
FZ Rossendorf
GSI Darmstadt

Poland:
Krakow Univ.
Warsaw Univ.
Silesia Univ. Katowice

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest

Russia:
CKBM, St. Petersburg
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHE, JINR Dubna
LPP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP, Moscow State Univ.
St. Petersburg Polytec. U.

Spain:
Santiago de Compostela Univ.

Ukraine:
Shevshenko Univ. , Kiev

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Hadron Structure with panda

Charmonium:

- Quark confining potential

Search for Exotic Hadrons

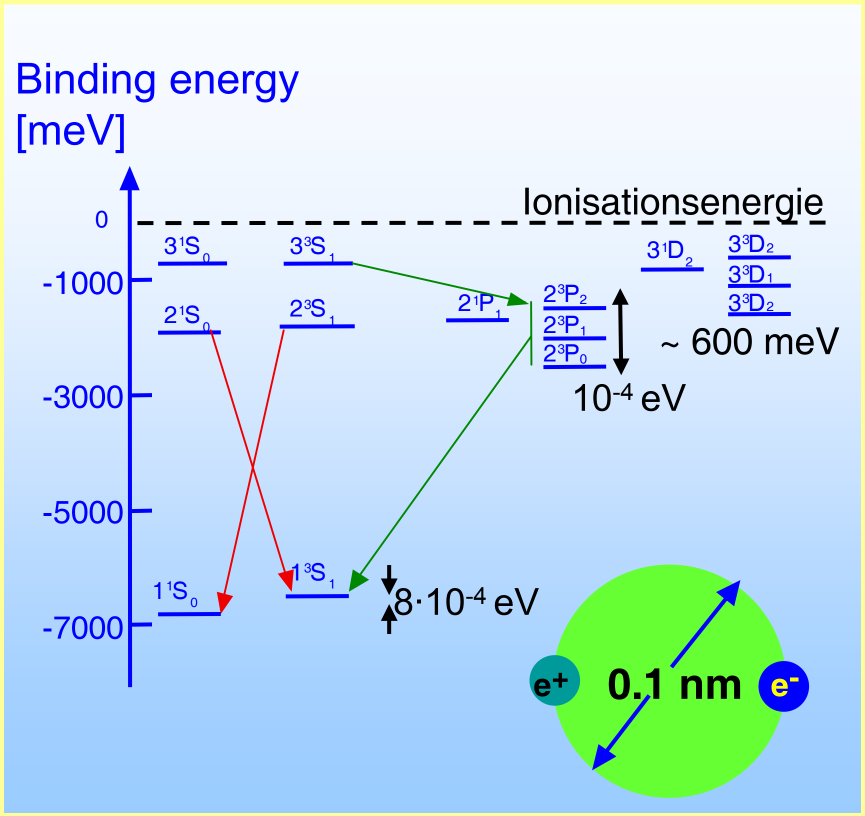
- Glueballs
- Hybrids

Charm Production in pbar A

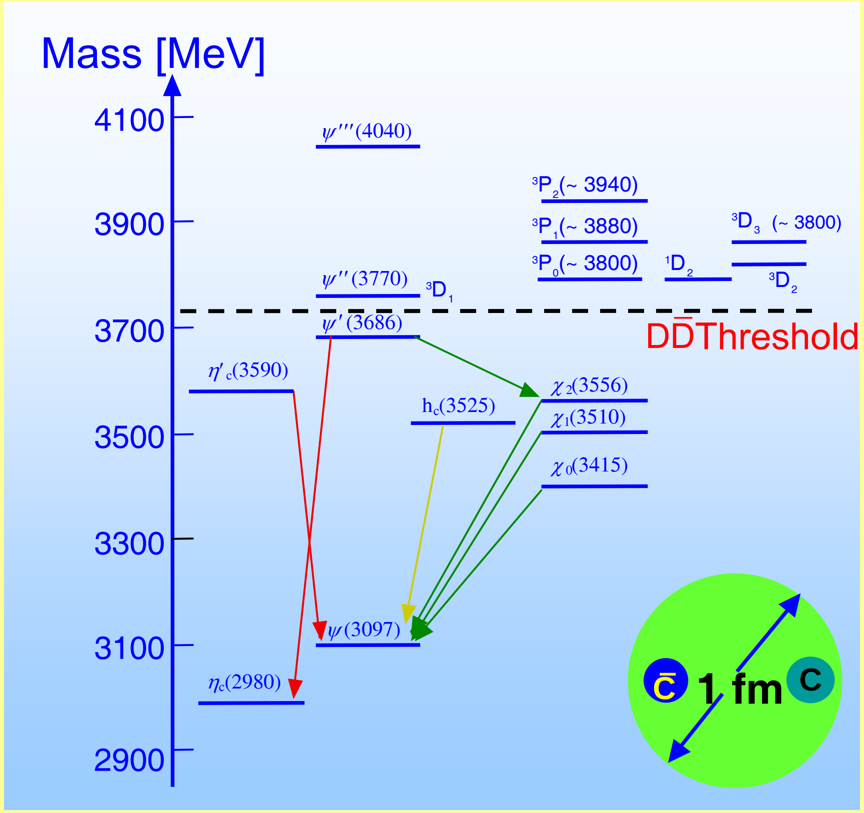
- Charmonium

Charmonium – the Positronium of QCD

- Positronium

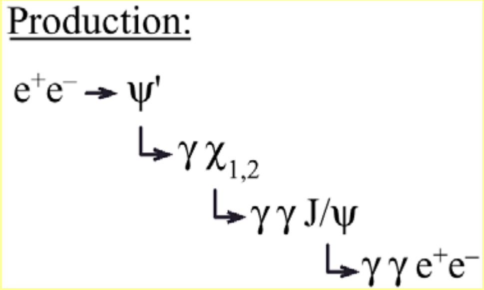


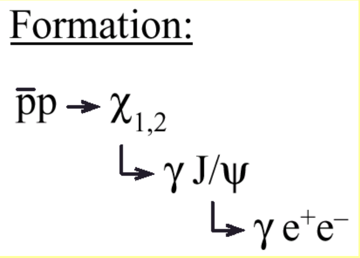
- Charmonium



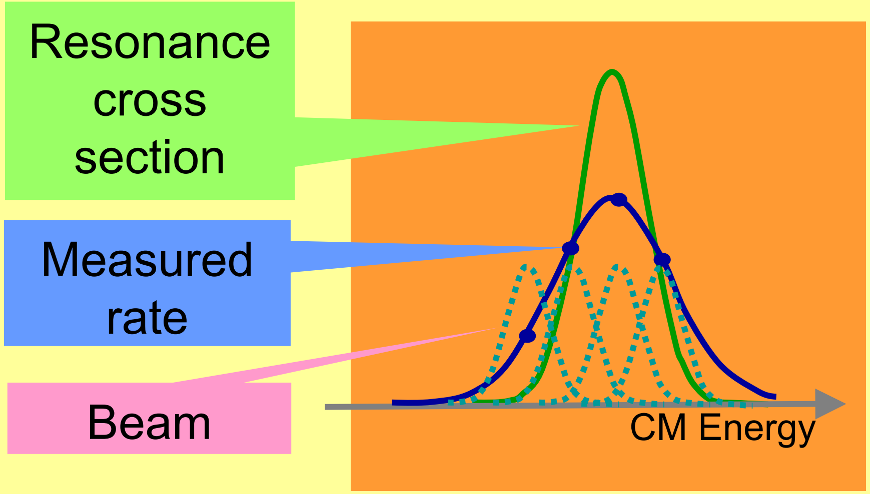
Why Antiprotons?

- e+e- annihilation via virtual photon: only states with $J^{pc} = 1^{--}$

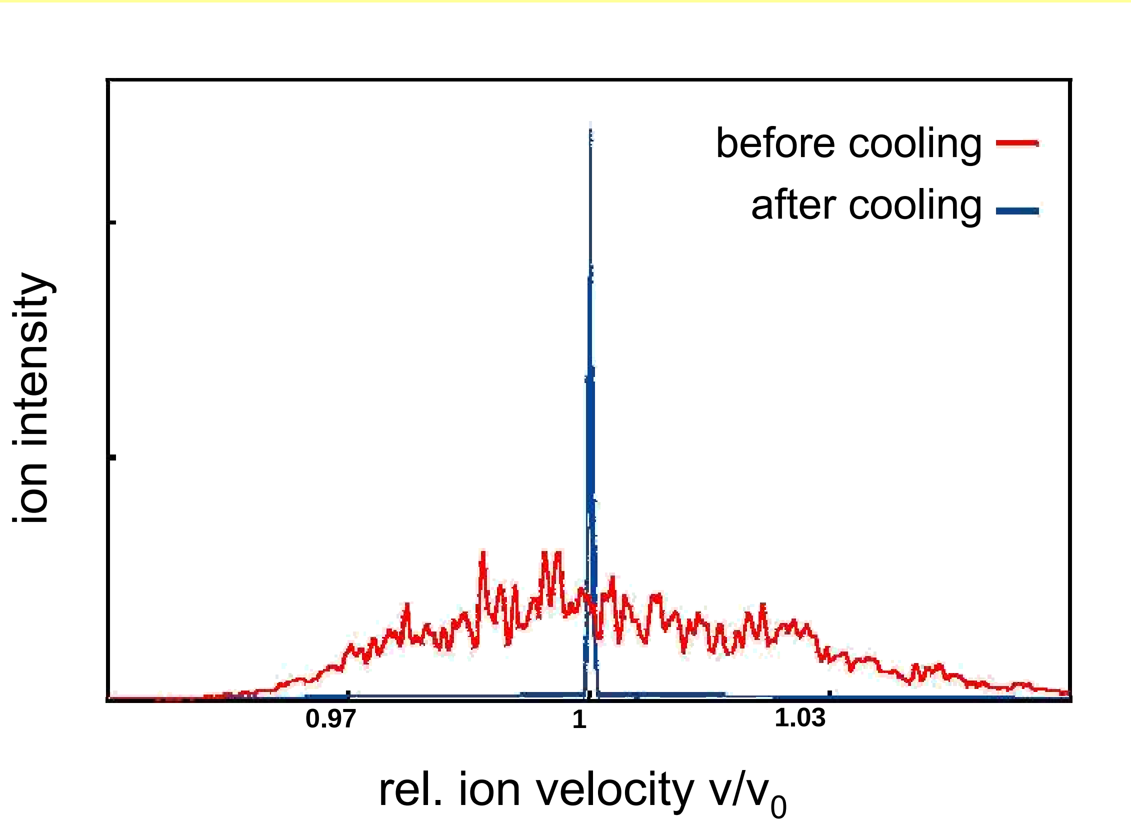




- In $p\bar{p}$ annihilation all mesons can be formed
- Resolution of the mass and width is only limited by the beam momentum resolution



Why Antiprotons?



$/\psi$

$\hookrightarrow \gamma\,\gamma\, e^+e^-$

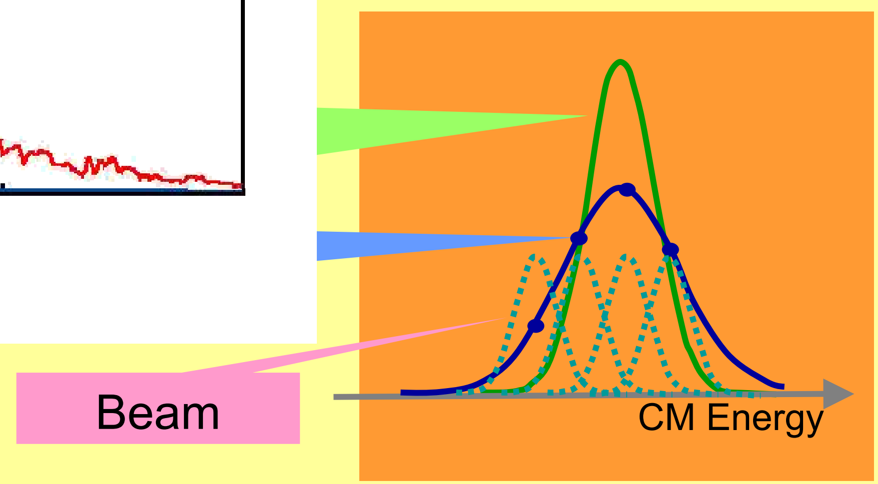
Formation:

$\bar{p}p \rightarrow \chi_{1,2}$

$\hookrightarrow \gamma\, J/\psi$

$\hookrightarrow \gamma\, e^+e^-$

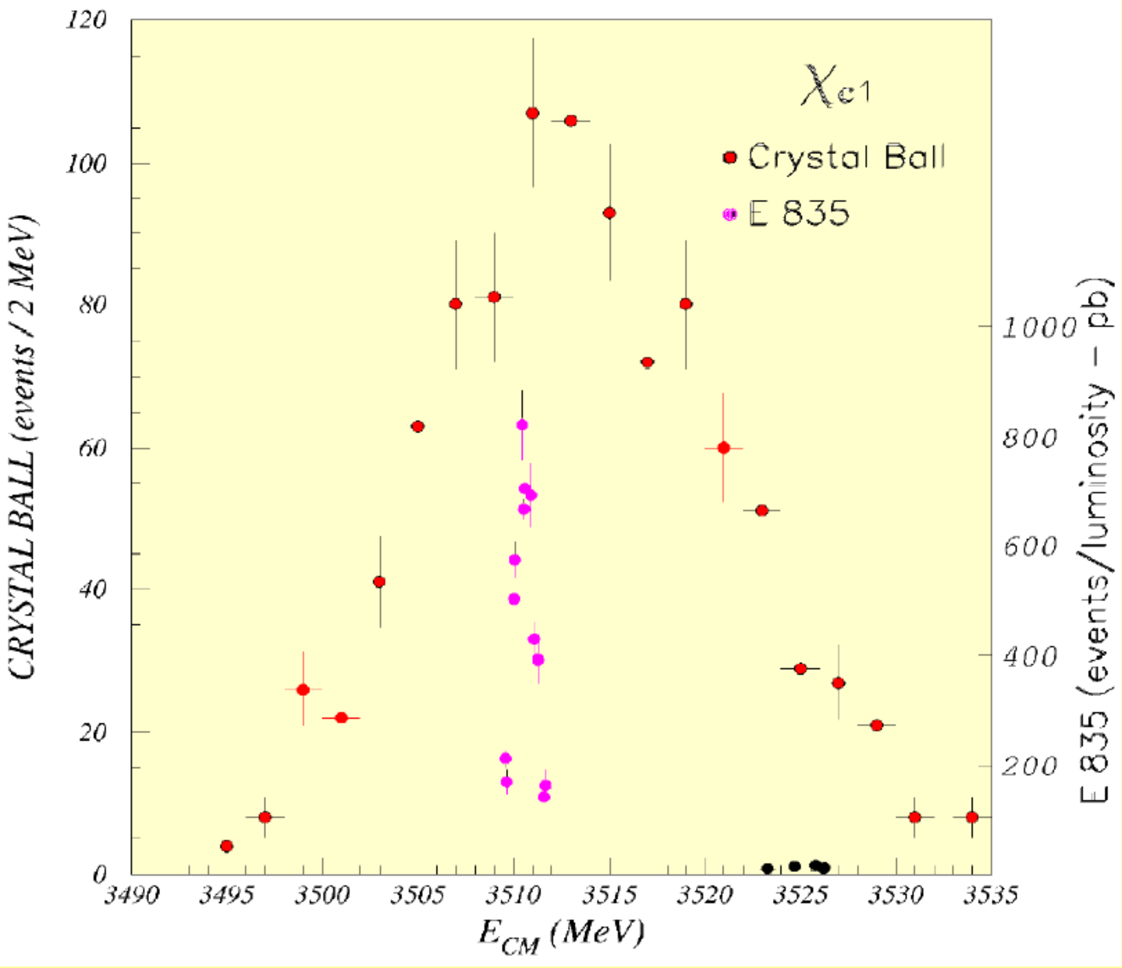
by the beam momentum resolution



High Resolution

- Crystal Ball: typical resolution ~ 10 MeV
- Fermilab: 240 keV

$\Rightarrow \Delta p/p < 10^{-4}$ needed



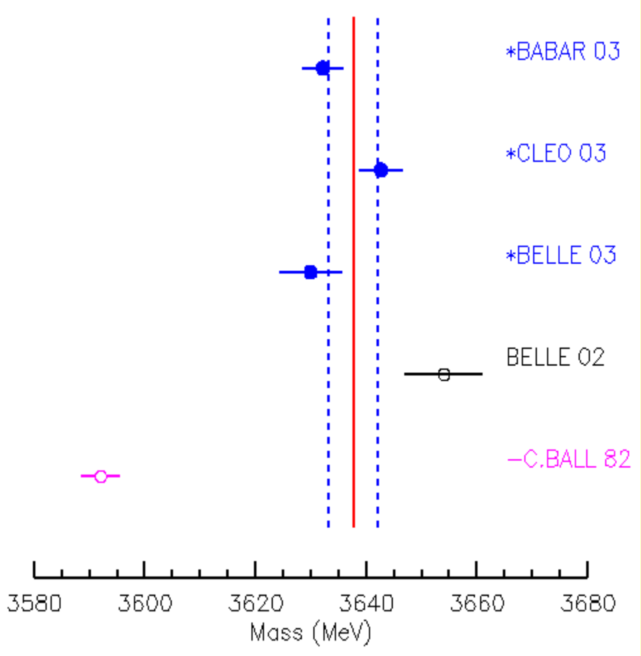
Open Questions

$\eta_c\ (1^1S_0)$

experimental error on M > 1 MeV

Γ hard to understand in simple quark models

$\eta_c'\ (2^1S_0)$



Crystal Ball result way off

study of hadronic decays

$h_c(^1P_1)$

Spin dependence of $Q\overline{Q}$ potential

Compare to triplet P-States

LQCD ←→ NRQCD

$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

Open Questions

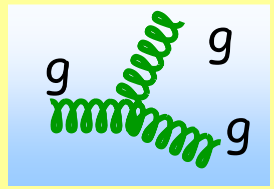
States above the $D\overline{D}$ threshold

- Higher vector states not confirmed $\Psi(3S)$, $\Psi(4S)$
- Expected location of 1st radial excitation of P wave states
- Expected location of narrow D wave states
- Only $\Psi(3770)$ seen
- Sensitive to long range Spin-dependent potential

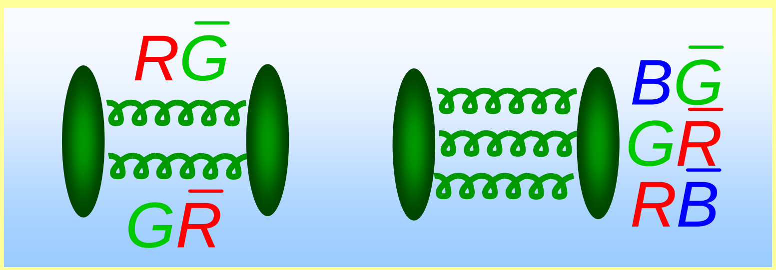
State	Predicted energy (MeV)	Experiment data (MeV)
$1\,^3S_1$	3097	3096.88 ± 0.04
$1\,^1S_0$	2987	2978.8 ± 1.9^a
$2\,^3S_1$	3686	3686.00 ± 0.09
$2\,^1S_0$	3620	3594.0 ± 5.0
$1\,^3P_2$	3554	3556.17 ± 0.13
$1\,^3P_1$	3512	3510.53 ± 0.12
$1\,^3P_0$	3412	3415.1 ± 1.0
$1\,^1P_1$	3527	3526.14 ± 0.24
$1\,^3D_3$	3843	
$1\,^3D_2$	3819	
$1\,^3D_1$	3789	3769.9 ± 2.5
$1\,^1D_2$	3820	

Glueballs

Self interaction between gluons



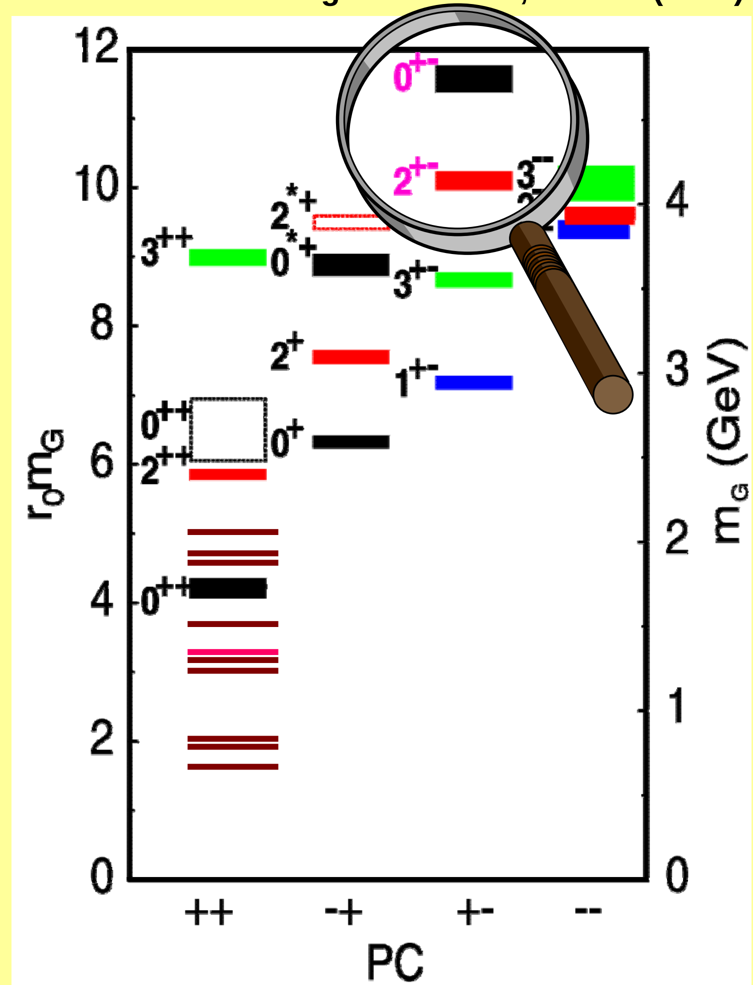
⇒ Construction of color-neutral hadrons with gluons possible



exotic glueballs don‘t mix with mesons ($q\bar{q}$)

0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+},...

C. Morningstar PRD60, 034509 (1999)

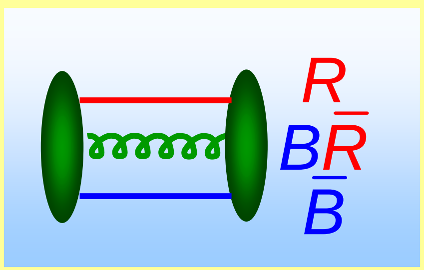


Charm Hybrids $c\bar{c}g$

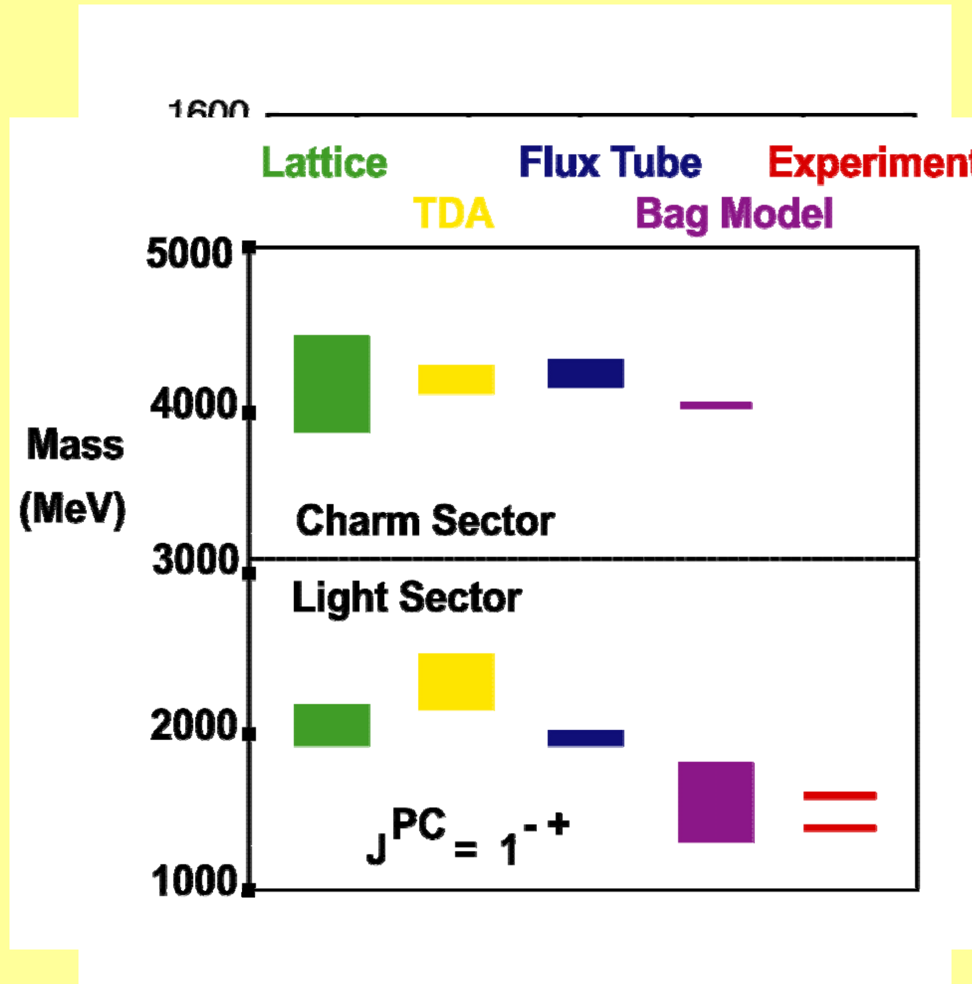
Prediction in QCD:

Collective gluon excitation

(Gluons contribute to quantum numbers)



Ground state:
$J^{PC} = 1^{-+}$ (spin exotic)



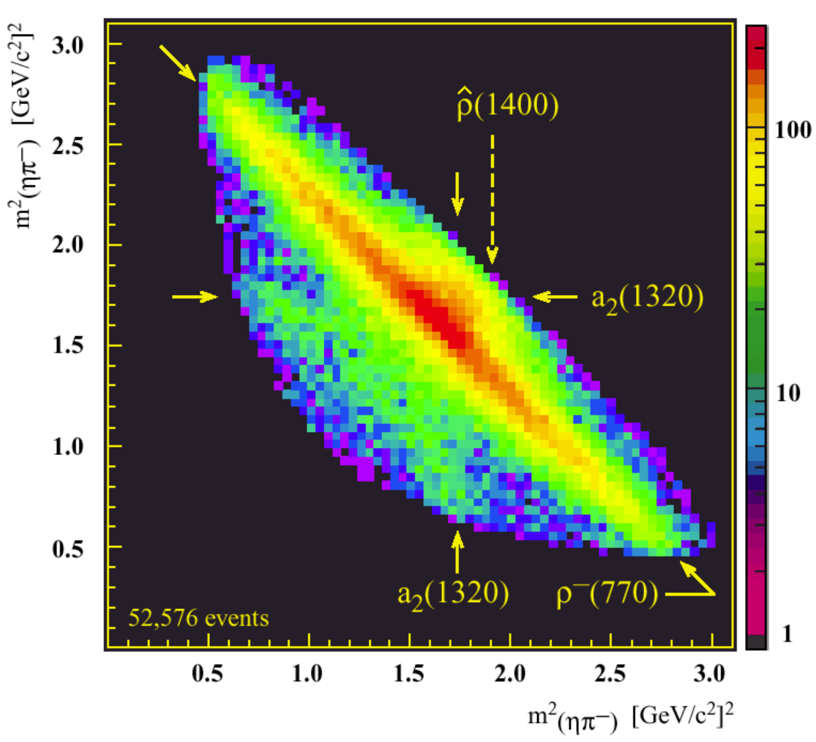
Partial Wave Analysis

Partial wave analysis as important tool

Example of 1^{-+} **(**CB@LEAR**)**
$\bar{p}d \rightarrow X(1^{-+})+\pi+p,\ X \rightarrow \eta\ \pi$

Strength ~ $q\bar{q}$ States !

Signal in production but not in formation is interesting !

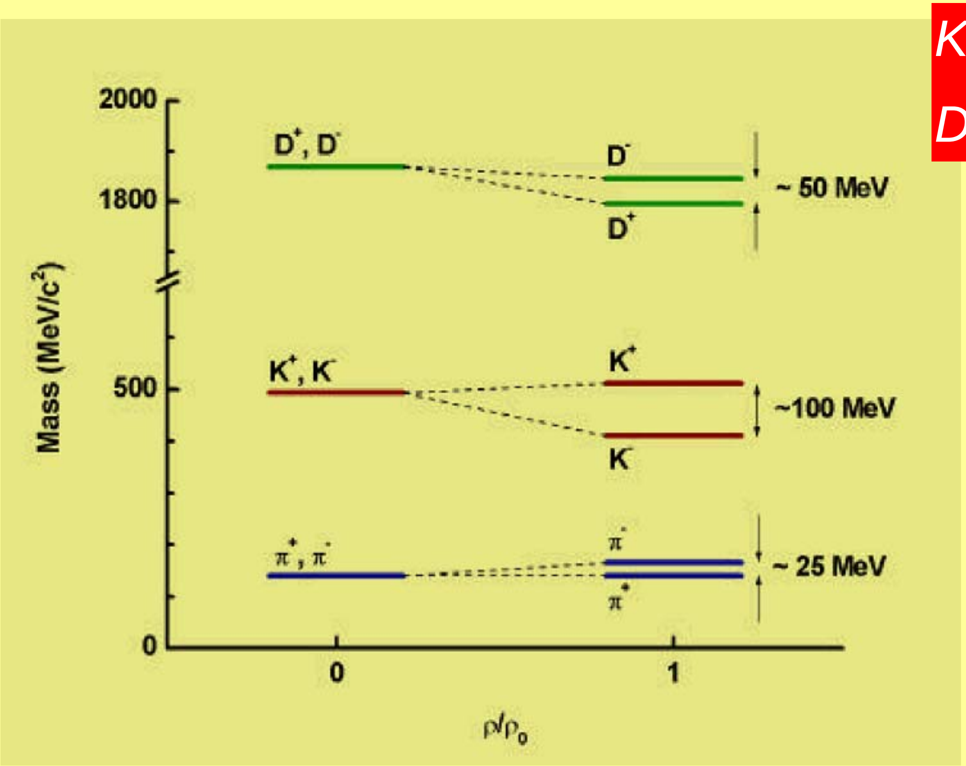


Hadron Properties at Finite Density

Mass splittings because charge conjugation symmetry broken at $n_B \neq 0$

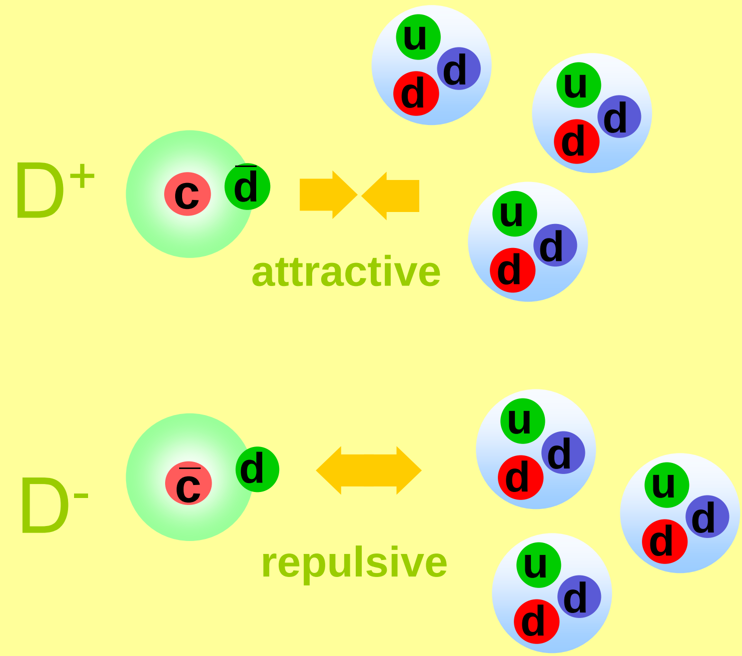
Overall attraction of Kaons due to scalar interaction: KN sigma term

Mass splitting due to vector interaction: Weinberg-Tomozawa



$K^-(s\bar{u}):\ m_s/m_u \approx 40$

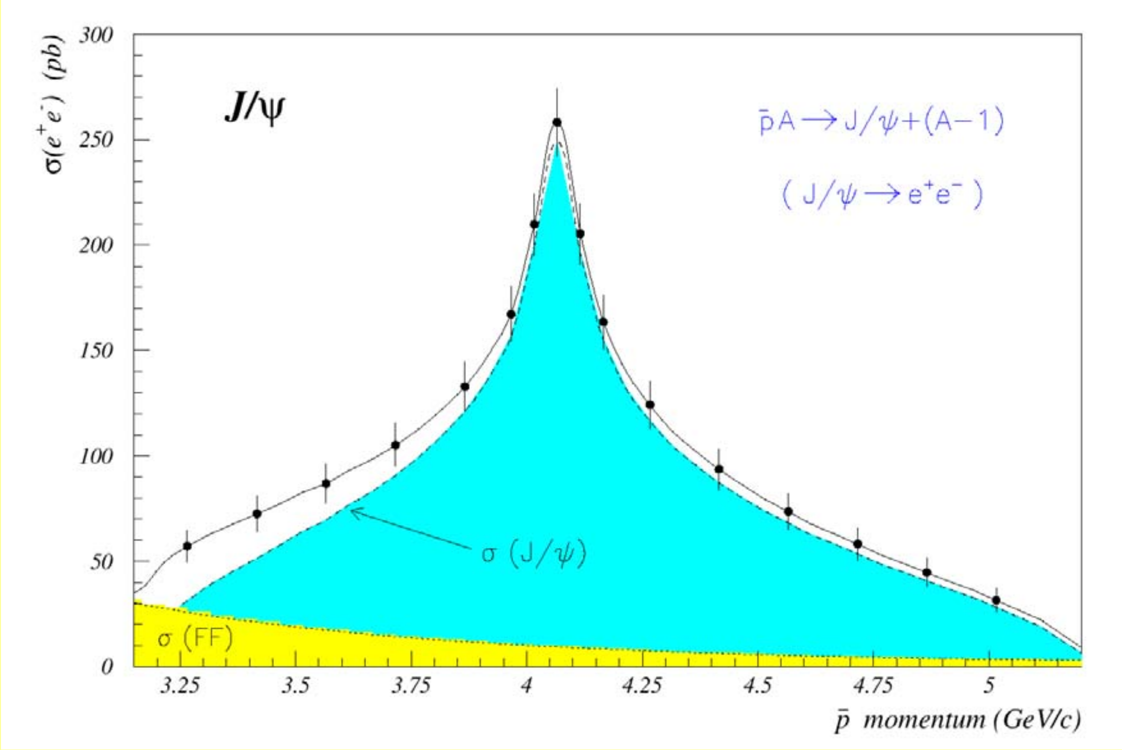
$D^+(c\bar{d}):\ m_c/m_d \approx 200 \Rightarrow$ **Quark atom**



J/Ψ Absorption in Nuclei

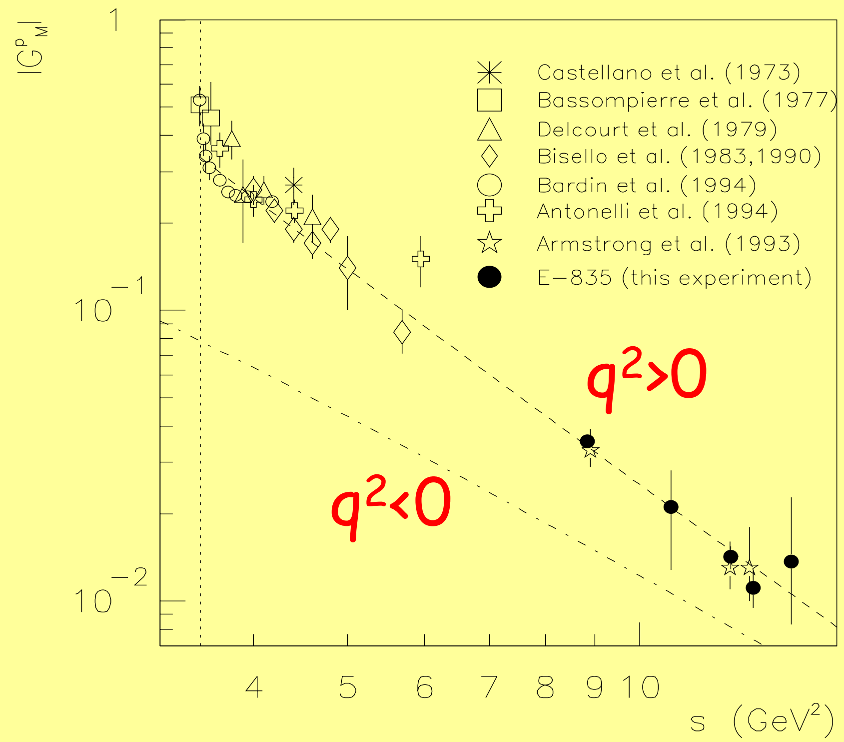
J/Ψ absorption cross section in nuclear matter

$\bar{p} + A \rightarrow J/\Psi + (A\text{-}1)$



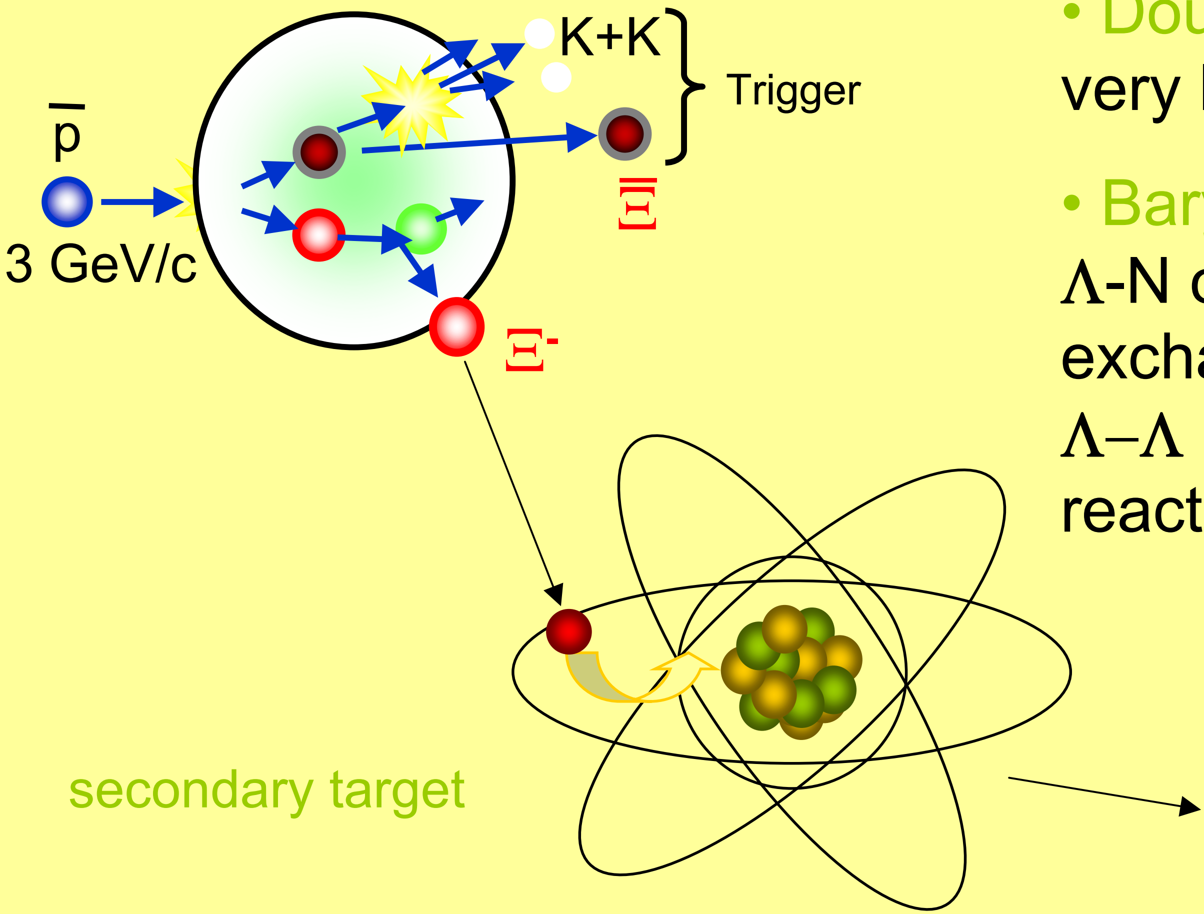
Proton Form Factors at large Q^2

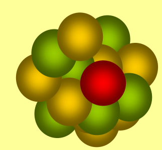
The time like FF remains about a factor 2 above the space like. These differences should vanish in pQCD, thus the asymptotic behavior has not yet been reached at these large values of $|q^2|$.
(HESR up to s ~ 25 GeV^2)



Strange Baryons in Nuclear Fields

Hypernuclei open a 3rd dimension (strangeness) in the nuclear chart

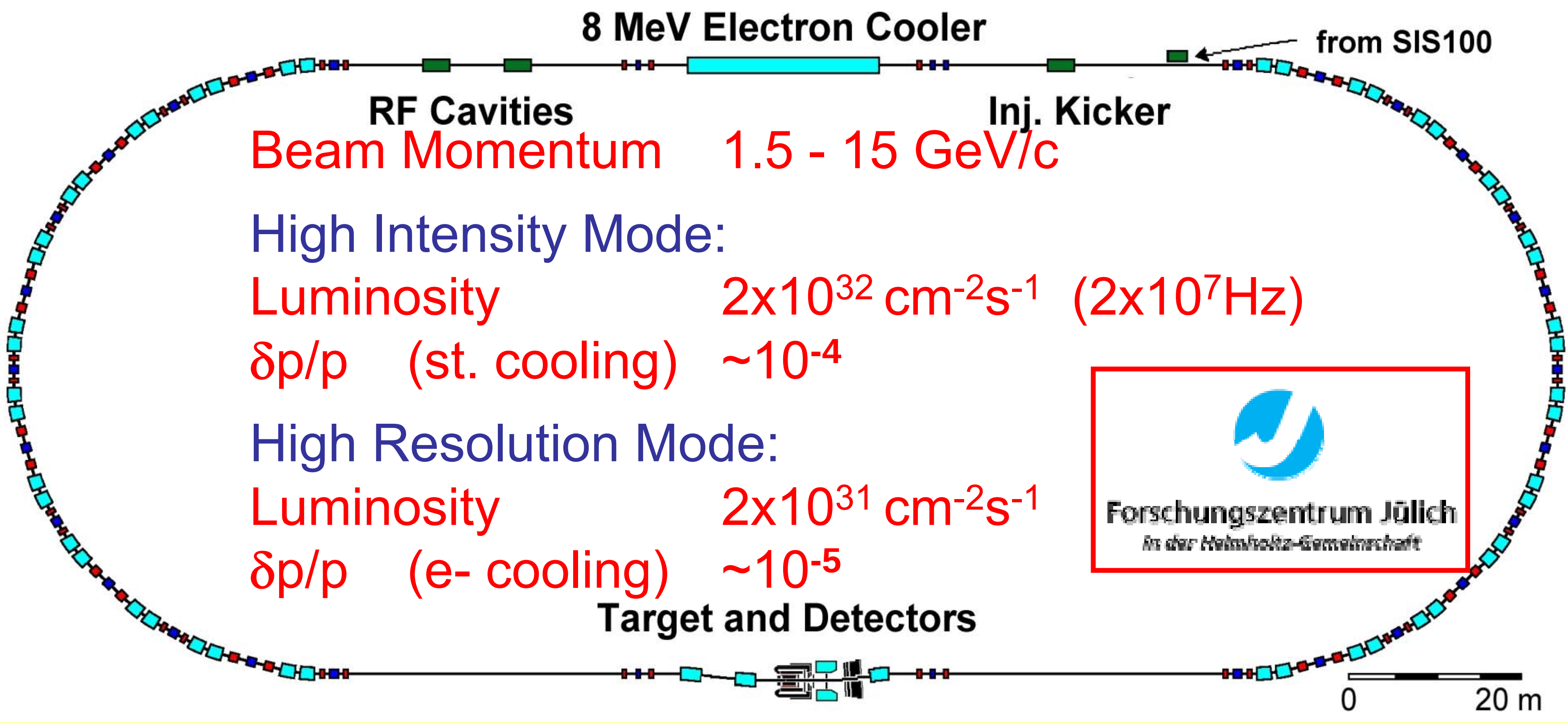




- Double-hypernuclei: very little data
- Baryon-baryon interactions: Λ-N only short ranged (no 1π exchange due to isospin) Λ–Λ impossible in scattering reactions

Ξ^-(dss) **p**(uud) ⇒ Λ(uds) Λ(uds)

HESR: High Energy Storage Ring



Beam Momentum 1.5 - 15 GeV/c

High Intensity Mode:

Luminosity $2x10^{32}$ $cm^{-2}s^{-1}$ $(2x10^{7}Hz)$

$\delta p/p$ (st. cooling) $\sim 10^{-4}$

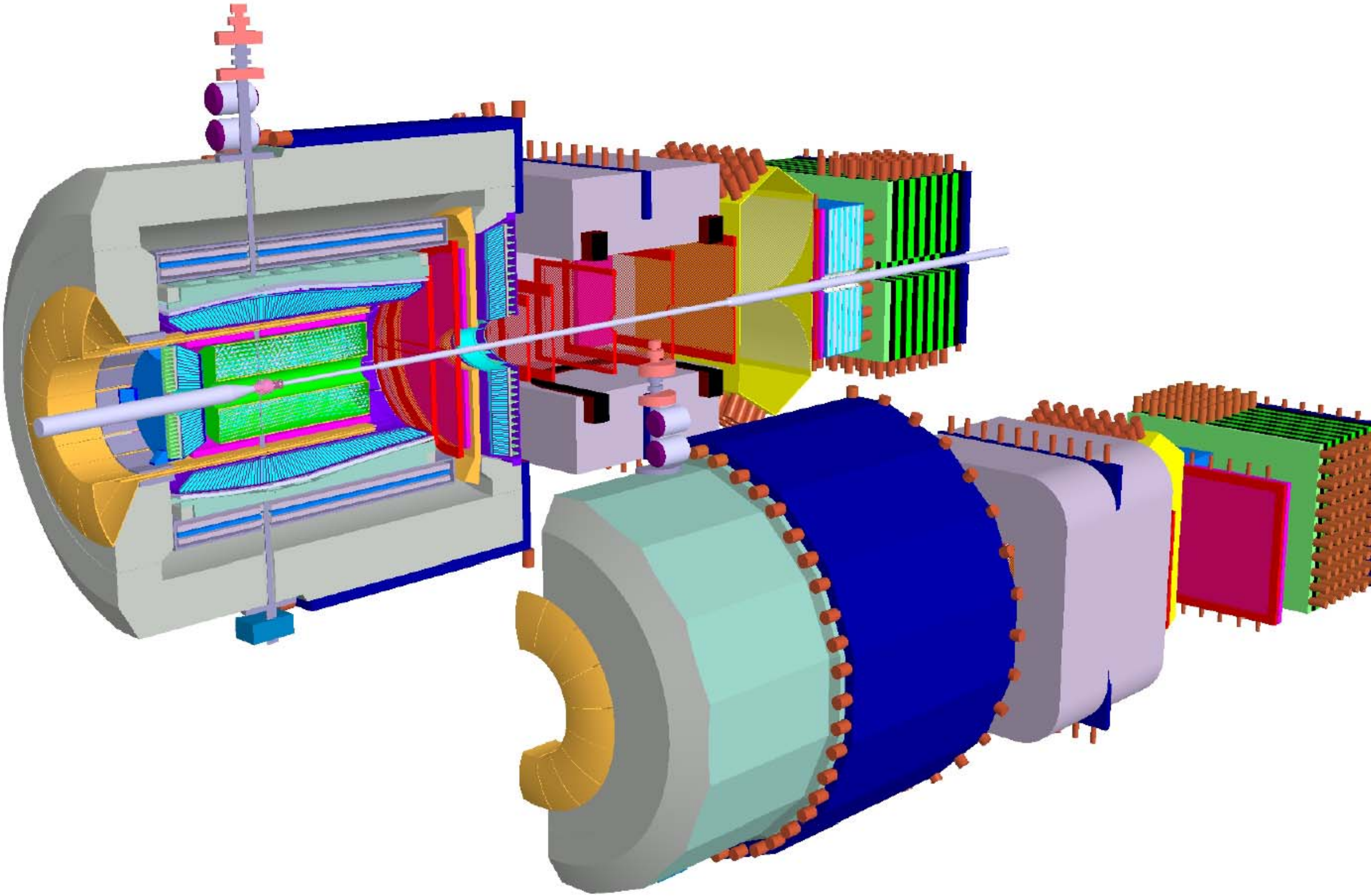
High Resolution Mode:

Luminosity $2x10^{31}$ $cm^{-2}s^{-1}$

$\delta p/p$ (e- cooling) $\sim 10^{-5}$

Forschungszentrum Jülich

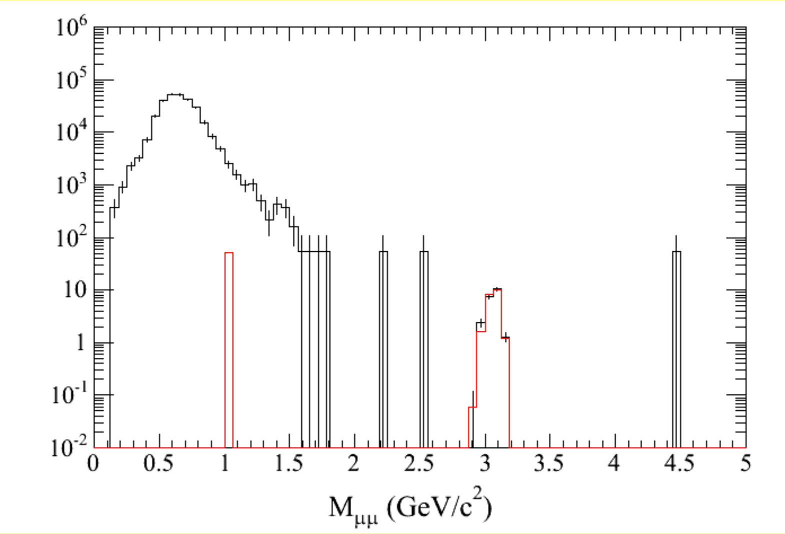
In der Helmholtz-Gemeinschaft

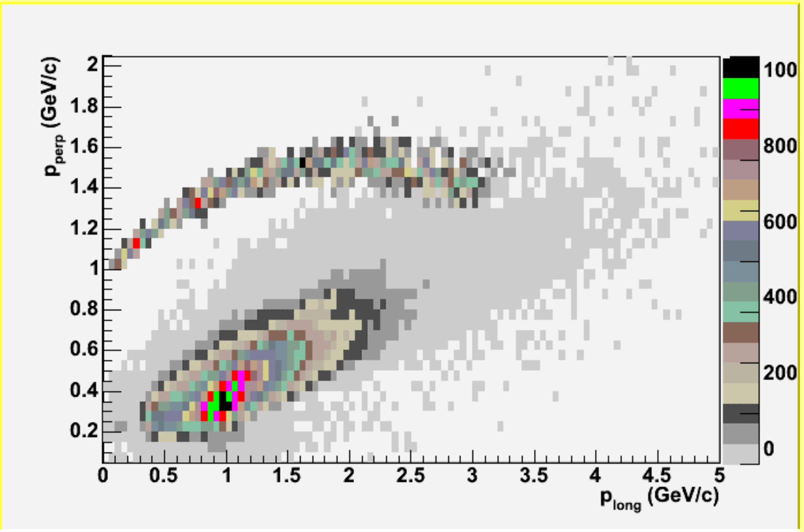


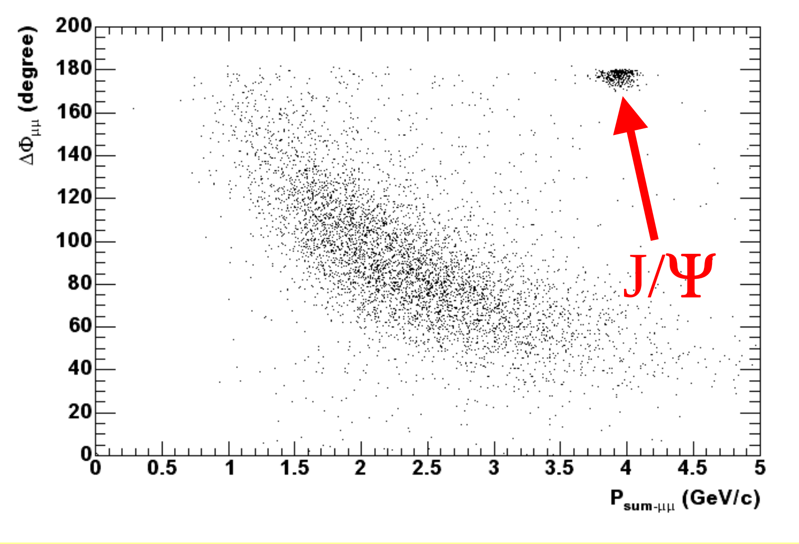
Picture: P. Rosier-IPN Orsay

Dimuon Spectrum in $\bar{p}$+Cu

- Beam momentum "on resonance"
- Full background simulations
  (result scaled up)
- Muons from J/Ψ have high Pt
- J/Ψ has low Pt (coplanar)







PANDA Collaboration : 46 institutions, > 340 Members

Austria
SMI, Vienna
Belarus
Belarus State Univ., Minsk
NCPHEP, Minsk
China
IHEP Beijing
IMP Lanzhou
France
IPN, Orsay
Gemany
FZ-Juelich
GSI-Darmstadt
Univ. Bochum
Univ. Bonn
Univ. Dresden
Univ. Erlangen-Nurnberg
Univ. Frankfurt
Univ. Giessen
Univ. Mainz
Tech. Univ. Munich
Univ. Muenster
Univ. Tuebingen

Italy
Univ. Brescia
Univ. and INFN, Catania
Univ. and INFN, Ferrara
INFN Frascati
INFN Genova
Politecnico, Univ., and INFN, Milano
Univ. and INFN, Pavia
Univ. Piemonte Orientale Alessandria and INFN, Torino
Univ. and INFN, Torino
IFSI Torino
Politecnico Torino
Univ. and INFN Trieste
Poland
Univ. Cracow
Univ. Katowice
SINS, Warsaw
Warsaw Univ., Otwock-Swierk

Russia
VBLHE, JINR
LPP, JINR
LIT, JINR
LNP, JINR
Kabardian-Balkarian State Univ. IAMA, Nal'chik
BINP, Novosibirsk
IHEP, Protvino
TSU, Tomsk
PNPI, Gatchina, St. Petersburg
Spain
Univ. Valencia
Sweden
KTH, Stockholm
Stockholms Univ.
TSL, Uppsala
Univ. Uppsala
Switzerland
Univ. Basel
United Kingdom
Univ. Edinburgh
Univ. Glasgow
USA
Northwestern Univ.

QCD Physics at FAIR

- Compressed Baryonic Matter (CBM)
- „High Energy“ Antiprotons (PANDA)
- Polarized Antiprotons (PAX)
- Stopped Antiprotons (FLAIR)

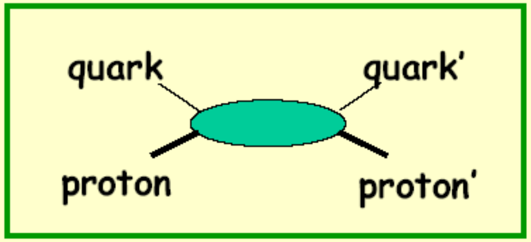
Central Physics Issue

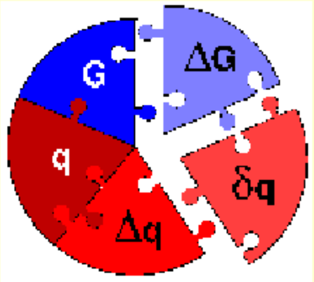
Transversity distribution of the nucleon:

- last leading-twist missing piece of the QCD description of the partonic structure of the nucleon
- directly accessible uniquely via the double transverse spin asymmetry A_{TT} in the Drell-Yan production of lepton pairs
- theoretical expectations for A_{TT} in DY, 30-40%
  - transversely polarized antiprotons
  - transversely polarized proton target
- definitive observation of $h_1^q(x,Q^2)$ of the proton for the valence quarks

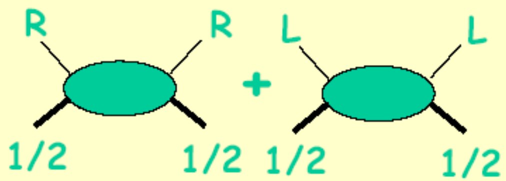
Leading Twist Distribution Functions

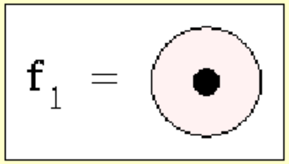
Probabilistic interpretation in helicity base:





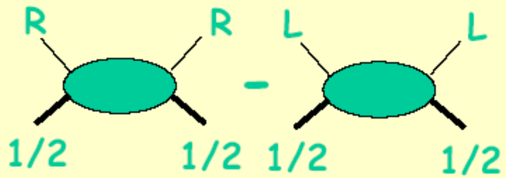
$f_1(x)$

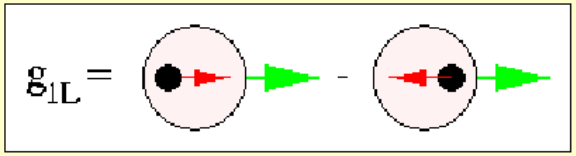




q(x) spin averaged (well known)

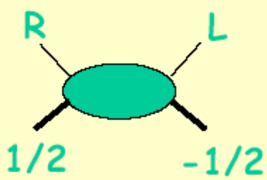
$g_1(x)$





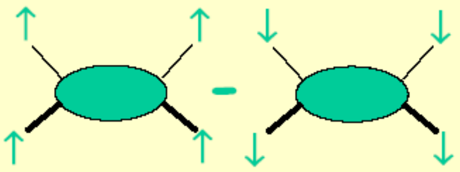
Δq(x) helicity diff. (known)

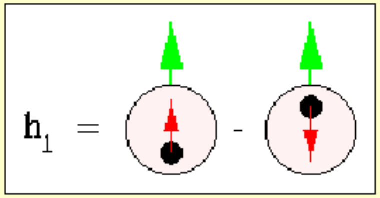
$h_1(x)$



No probabilistic interpretation in the helicity base (off diagonal)

Transversity base
$u_\uparrow = 1/\sqrt{2}(u_R + u_L)$
$u_\downarrow = 1/\sqrt{2}(u_R - u_L)$

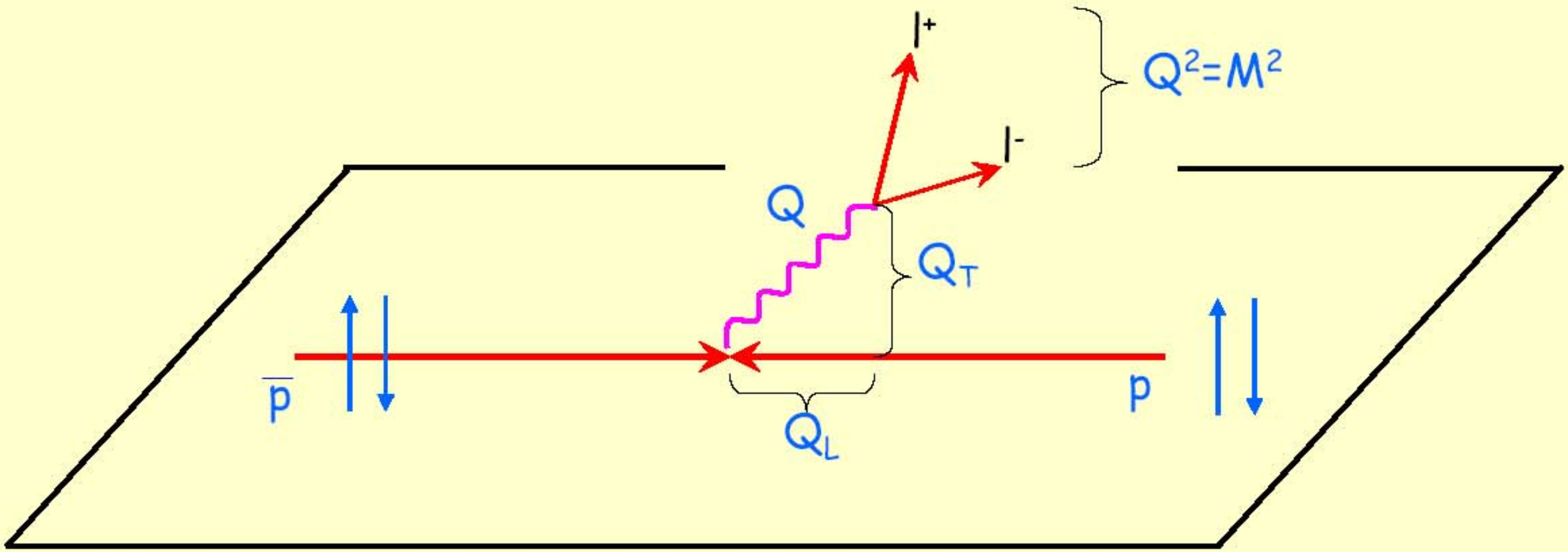




δq(x) helicity flip (unknown)

Transversity in Drell-Yan processes

Polarized Antiproton Beam → Polarized Proton Target
(both transversely polarized)



$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

$q = u, \bar{u}, d, \bar{d}, \ldots$

M invariant Mass of lepton pair

A_{TT} for PAX kinematic conditions

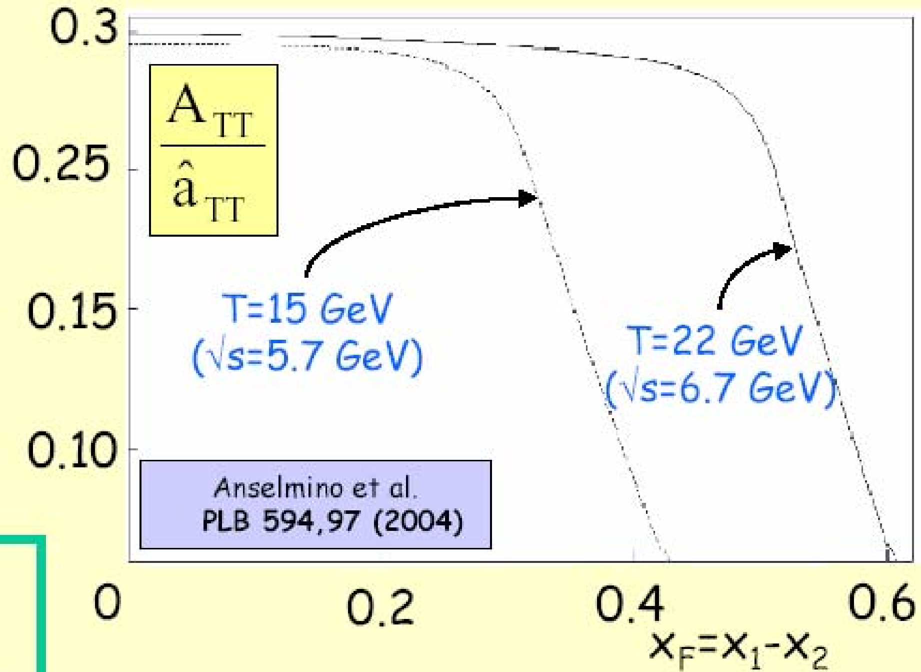
RHIC: $\tau = x_1 x_2 = M^2/s \sim 10^{-3}$
→ Exploration of the sea quark content (polarizations small!)
A_{TT} very small (~ 1 %)

PAX: $M^2 \sim 10$ GeV^2, $s \sim 30\text{-}50$ GeV^2, $\tau = x_1 x_2 = M^2/s \sim 0.2\text{-}0.3$
→ Exploration of valence quarks ($h_1^q(x,Q^2)$ large)

$A_{TT}/a_{TT} > 0.3$
Models predict $|h_1^u| \gg |h_1^d|$

$$A_{TT} = \hat{a}_{TT} \frac{h_1^u(x_1,M^2)h_1^u(x_1,M^2)}{u(x_1,M^2)u(x_1,M^2)}$$

$$(\text{where } \bar{q}^{\bar{p}} = q^p = q)$$



Similar predictions by Efremov et al.,
Eur. Phys. J. C35, 207 (2004)

Main contribution to Drell-Yan events at PAX from $x_1 \sim x_2 \sim \sqrt{\tau}$: deduction of x-dependence of $h_1^u(x,M^2)$

Other Physics Topics

- Single-Spin Asymmetries
- Electromagnetic Form Factors
- Hard Scattering Effects
- Soft Scattering
  - Low-t Physics
  - Total Cross Section
  - pbar-p interaction

Polarization Buildup: Optimum Interaction Time

statistical error of a double polarization observable (A_{TT})

$$\delta_{A_{TT}} = \frac{1}{P \cdot Q \cdot \sqrt{N}}$$

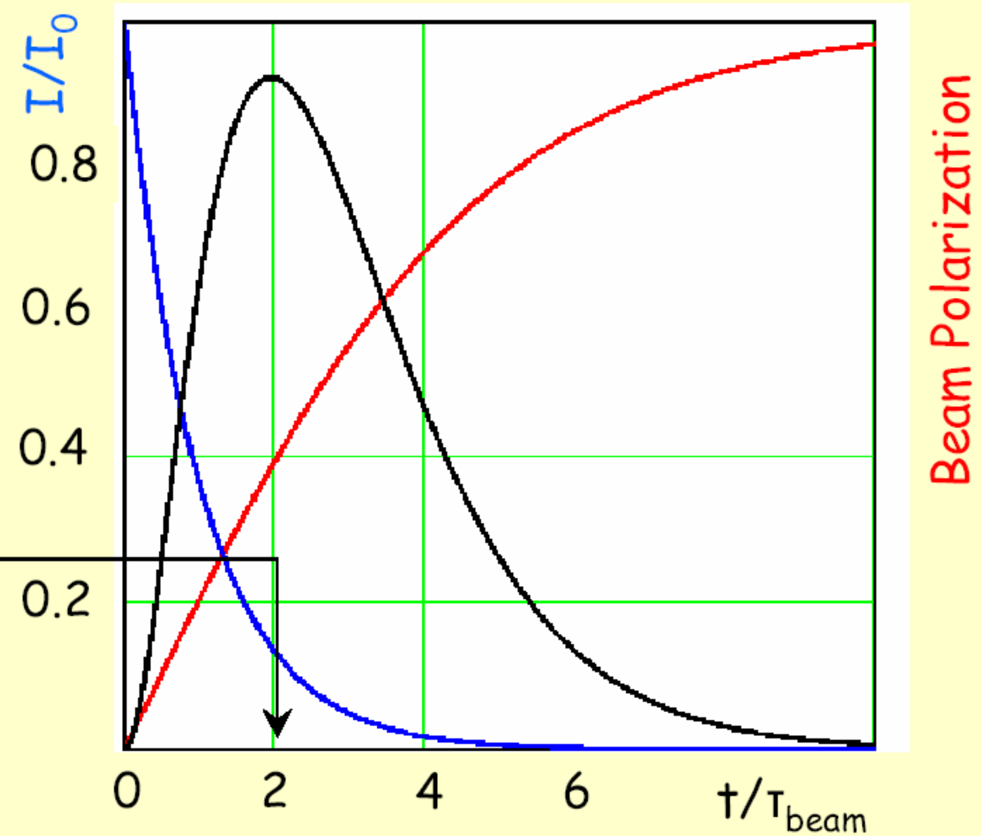
(N ~ I)

Measuring time t to achieve a certain error

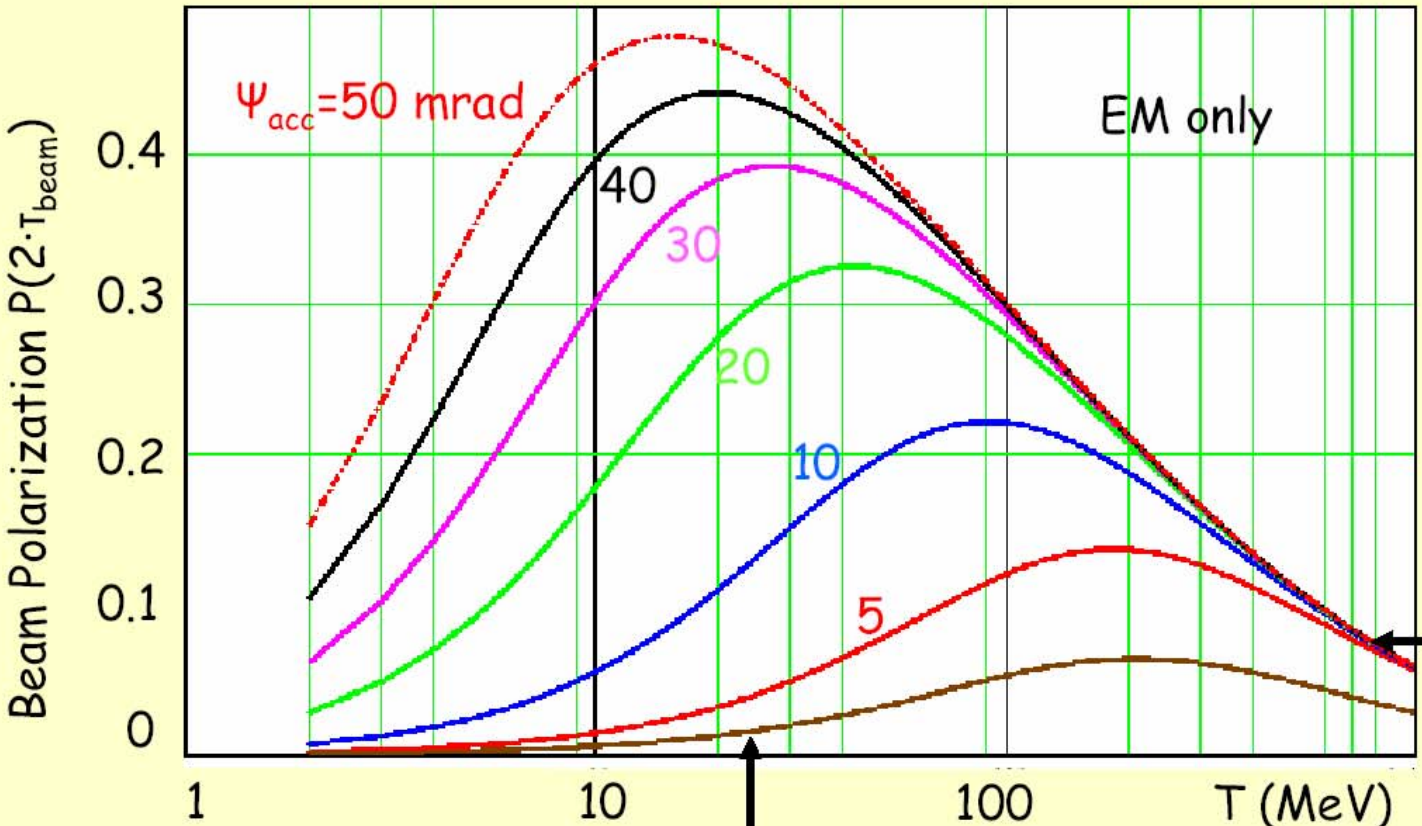
$$\delta_{A_{TT}} \sim FOM = P^2 \cdot I$$

Optimimum time for Polarization Buildup given by maximum of FOM(t)

$$t_{filter} = 2 \cdot \tau_{beam}$$



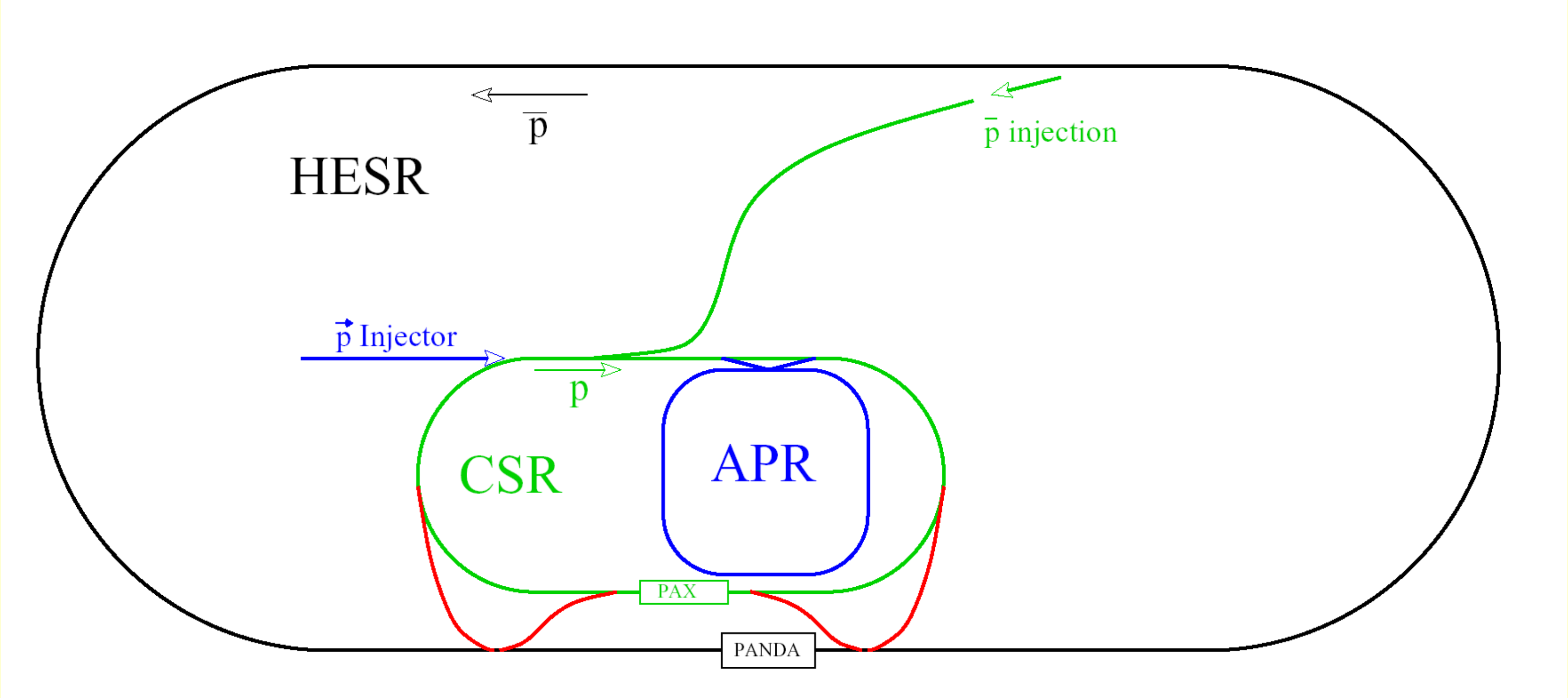
Beam Polarization



Filter Test: T = 23 MeV
Ψ_{acc} = 4.4 mrad

Buildup in HESR (800 MeV)

F. Rathmann et al.,
PRL 94, 014801 (2005)



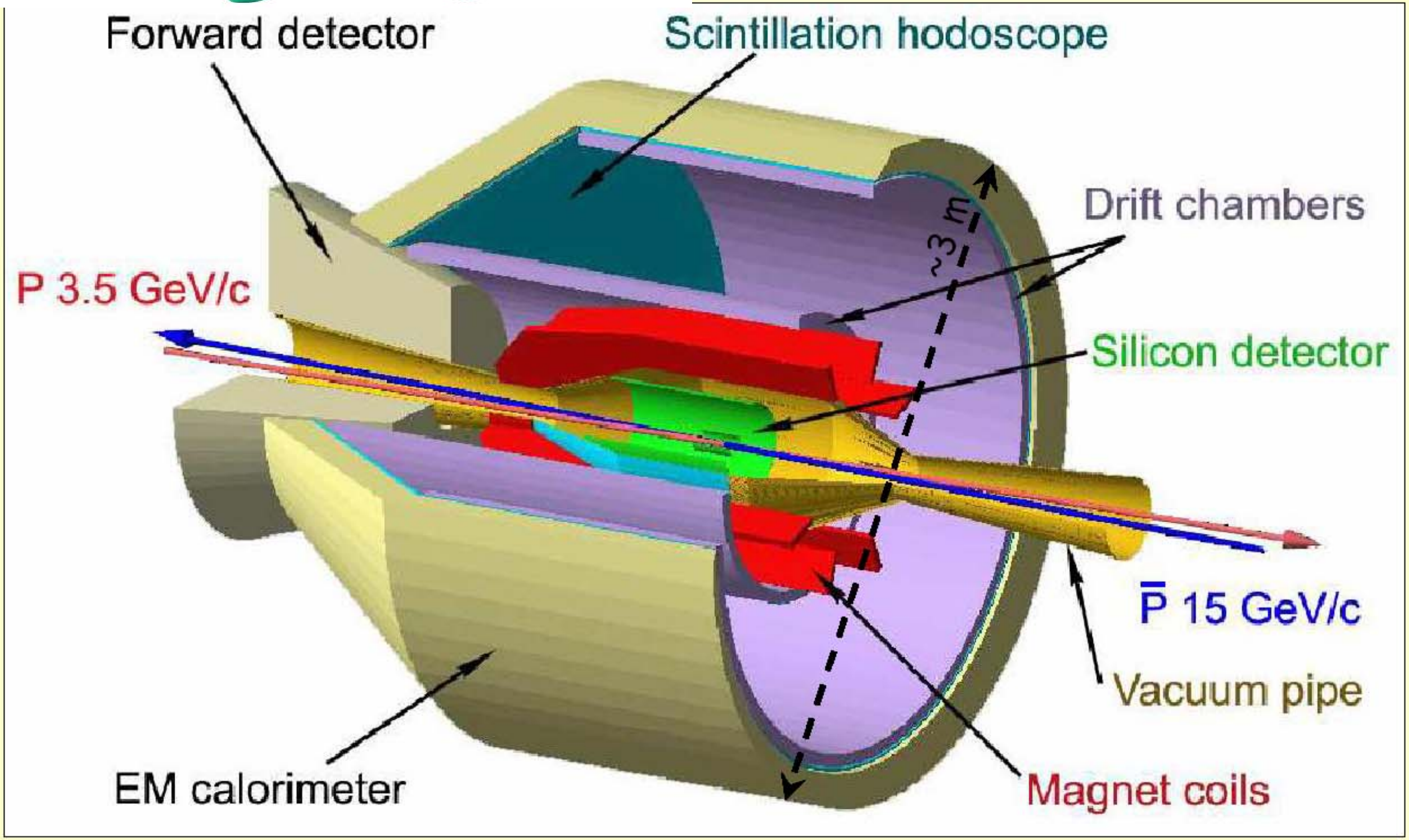
- CSR (green)   Cooler Storage Ring
  unpol. Pbar beam (pol. target) at 3.5 GeV/c

- APR (blue) Anti-Proton-Polarizer
  double spin measurements at 3.5 GeV/c

- Asymmetric collider
  15 GeV/c pbar on 3.5 GeV/c protons (both polarized)

Conceptual Detector Design

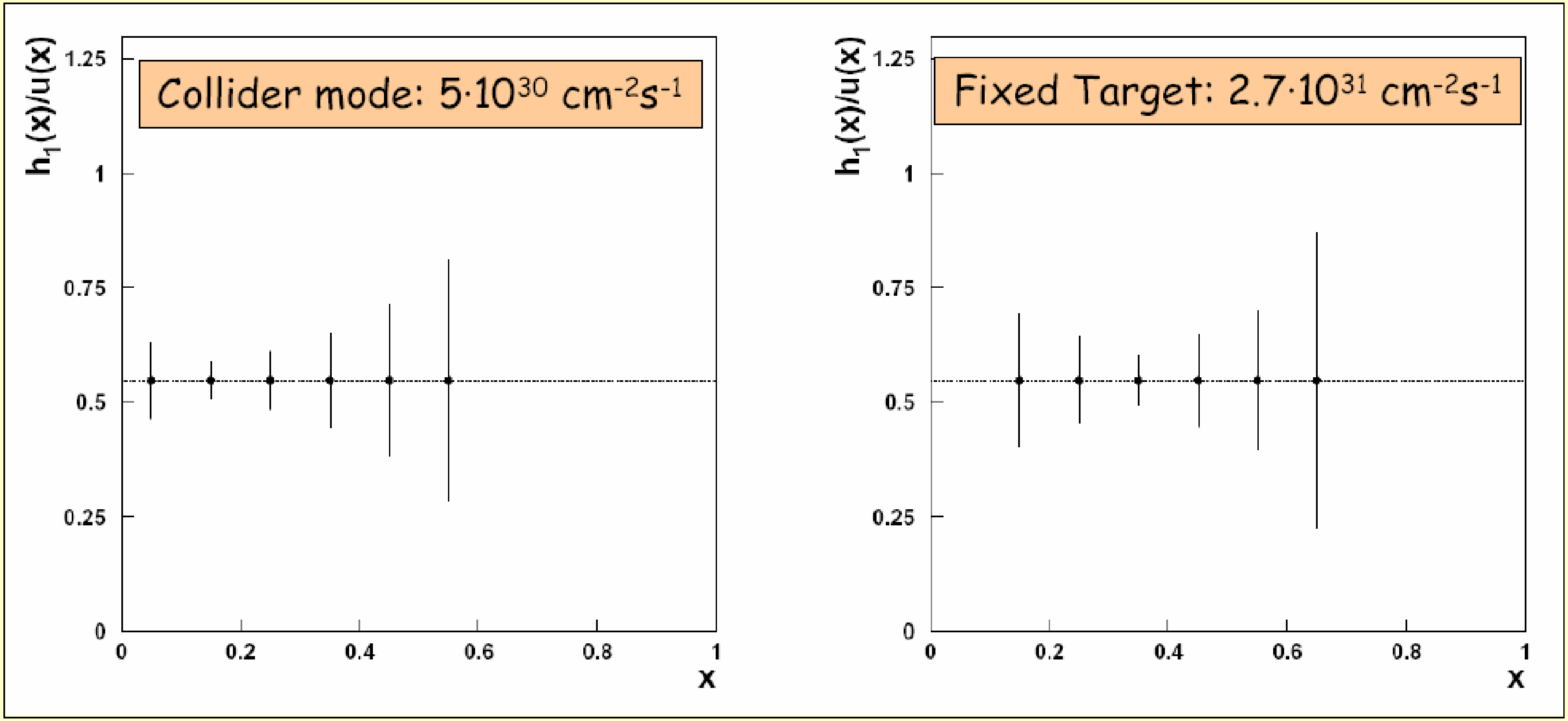
Polarized Antiproton EXperiments



Expected precision of the h_1 measurement

One year of data taking at 50 % efficiency (180 days), $A_{TT}/a_{TT} = 0.3$

$$A_{TT}(x, \overline{x}) = \hat{a}_{TT} \frac{h_1(x)}{u(x)} \frac{h_1(\overline{x})}{u(\overline{x})}$$



170 PAX Collaborators, 27 Institutions (17 inside, 17 outside EU)

Yerevan Physics Institute, Yerevan, Armenia
Department of Subatomic and Radiation Physics, University of Gent, Belgium
University of Science & Technology of China, Beijing, P.R. China
Department of Physics, Beijing, P.R. China
Centre de Physique Theorique, Ecole Polytechnique, Palaiseau, France
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
Nuclear Physics Department, Tbilisi State University, Tbilisi, Georgia
Forschungszentrum Jülich, Institut für Kernphysik Jülich, Germany
Institut für Theoretische Physik II, Ruhr Universität Bochum, Germany
Helmholtz-Institut für Strahlen- und Kernphysik, Bonn, Germany
Physikalisches Institut, Universität Erlangen-Nürnberg, Germany
Department of Mathematics, University of Dublin, Dublin, Ireland
University del Piemonte Orientale and INFN, Alessandria, Italy
Dipartimento di Fisica, Universita di Cagliari and INFN, Cagliari, Italy
Instituto Nationale di Fisica Nucleare, Ferrara, Italy
Dipartimento di Fisica Teorica, Universita di Torino and INFN, Torino, Italy
Instituto Nationale di Fisica Nucleare, Frascati, Italy
Dipartimento di Fisica, Universita di Lecce and INFN, Lecce, Italy
Unternehmensberatung und Service Büro (USB), Gerlinde Schulteis & Partner GbR, Langenbernsdorf, Germany
Soltan Institute for Nuclear Studies, Warsaw, Poland
Petersburg Nuclear Physics Institute, Gatchina, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Lebedev Physical Institute, Moscow, Russia
Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia
Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Dubna, Russia
Laboratory of Particle Physics, Joint Institute for Nuclear Research, Dubna, Russia
Budker Institute for Nuclear Physics, Novosibirsk, Russia
High Energy Physics Institute, Protvino, Russia
Institute of Experimental Physics, Slovak Academy of Sciences and P.J. Safarik University, Faculty of Science, Kosice, Slovakia
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RIKEN BNL Research Center, Brookhaven National Laboratory, USA
University of Wisconsin, Madison, USA
Department of Physics, University of Virginia, Virginia, USA

Summary

- FAIR is approved, $\bar{p}$ beam expected 2013
- Highly compressed baryonic matter
- Charmonium (D) spectroscopy
- QCD exotics
- Polarized antiprotons for transversity