QCD and Nucleon Structure
Heavy-ions and Quark-Gluon Plasma

10th ICFA Seminar on Future perspectives in High-Energy Physics
2011
Science driving facilities for particle physics

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A. Zaitsev, Protvino, IHEP

Scope

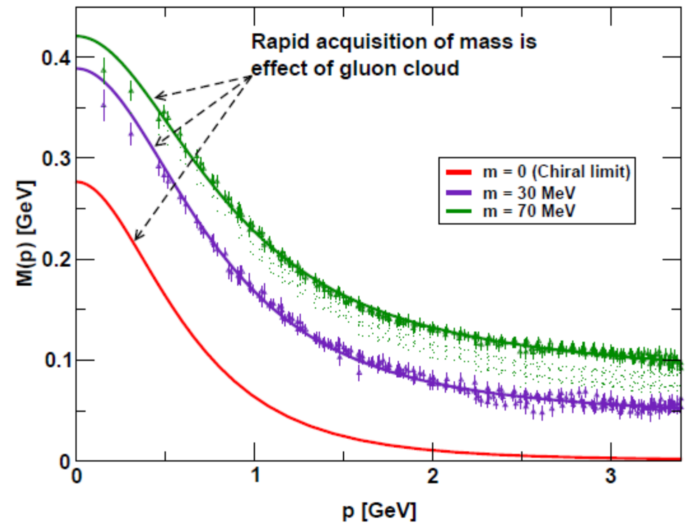
Session 6 QCD and Nucleon Structure

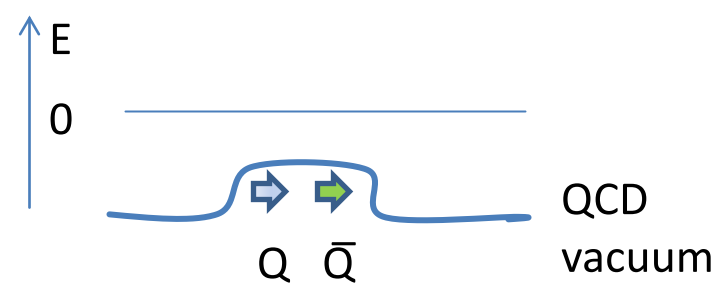
- Nucleon structure
  Sasha Glasov
- Spin effects & Semi-inclusive Deep Inelastic Scattering
  Matthias Burkardt
- High-energy Phenomena
  Robert Thorne
- Hadron Spectroscopy
  Xiaoyan Shen

Session 7 Heavy-ions and Quark-Gluon Plasma

- Strongly Coupled Plasma: Properties and Critical Point Search
  Barbara Jacak
- Opportunities at the the Energy Frontier
  Peter Braun-Munziger
- Nuclear Matter at High Barion Density
  Peter Senger

- Nonperturbative QCD:
  - Mass from nothing (at least 99%)
  - Chiral Symmetry Breaking
  - Confinement
- <0|q q̄ |0>
- QCD vacuum – driving factor
- How to study it?
  - With hadron spectroscopy
  - With nucleon
  - With many quarks
  - With high temperature/pressure



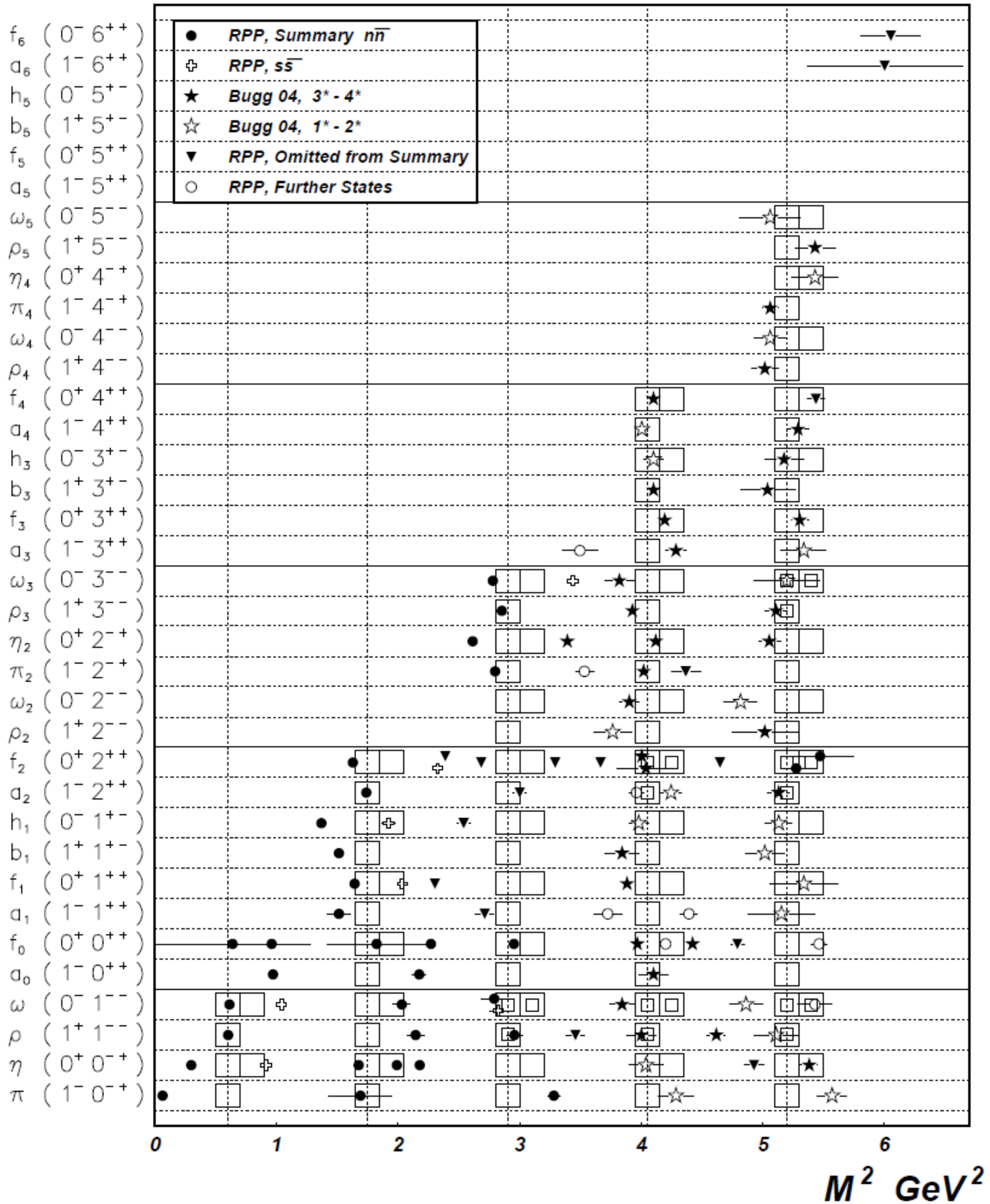


Light mesons (excitations, exotics)

High excitations:

- the resonance masses follows simple laws, typical for string models
- most of these states are not well established
- many base characteristics are unknown, including masses, widths, branching ratios etc.

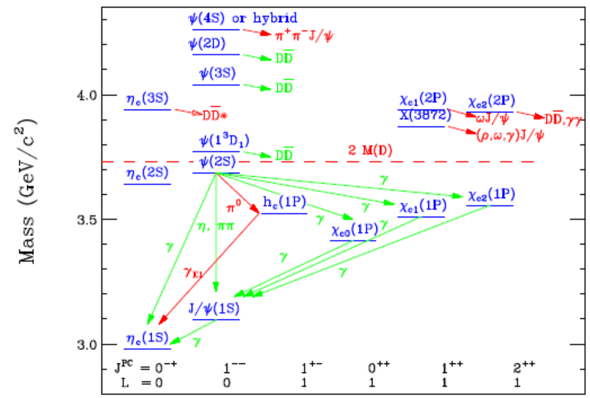
Exotic states: non ($q\tilde{q}$, qqq) objects. Some observations point to the existence of exotic objects.

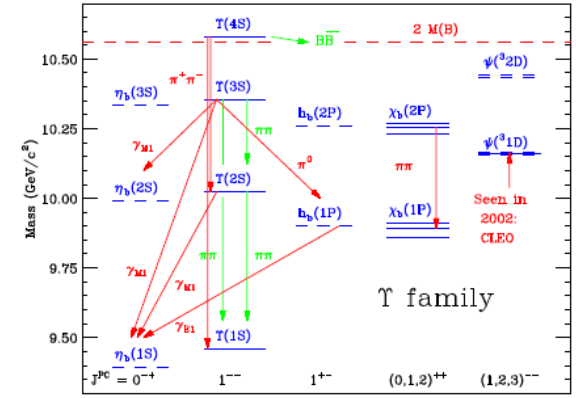


Mesons

New opportunities:

- Nearly “infinite” statistics in some channels:
  - COMPASS, VES π p→ exclusive diffraction N~10^{10}
  - BES III ~ 10^9 J/Ψ
  - Super c-tau ~10^{11} J/Ψ
  - CEBAF
  - Φ (also η/η`) factory
- Problems to be solved:
  - PWA upgrade
  - p̅ p↑ scan
- Heavy quark spectroscopy
  - Fast developing field
  - Threshold physics, exotics?
  - LHcB, BELLEII, SuperB, ……





The X family:
X(3872)→ J/Ψπ+π−
JPC = 1++ or 2−+
X(3914-3940)
The 1−− Y family:
4008, 4260, 4360, 4660
Charged Z states:
4050, 4240, 4430

Baryons

- Experimental data do not demonstrate a number of states predicted by quark models
- some states looks like exotics
- New methods are welcome
- Good field for low energy machines

New opportunities:

High statistics $\gamma^* \to X \bar{X}$:
BES III, Super c-tau

Heavy-light barions:
bcs, bcu bbu etc. : LHCb

In addition to standard beams (π+-, K+-, γ , γ*) one can use reggeons with arbitrary IG JPC like $\pi^- \to \eta$ R(IG JPC=1-0++):
IHEP, Protvino

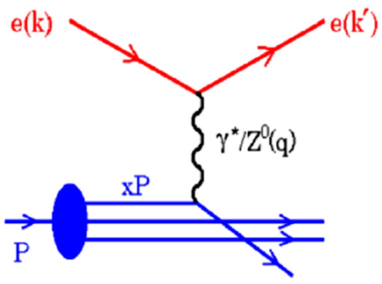
Nucleon structure

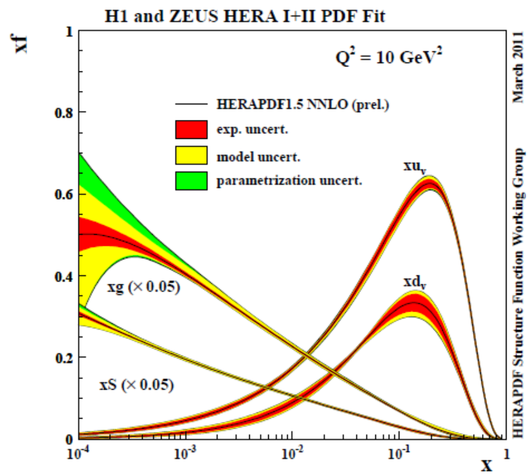
Parton Distribution Functions

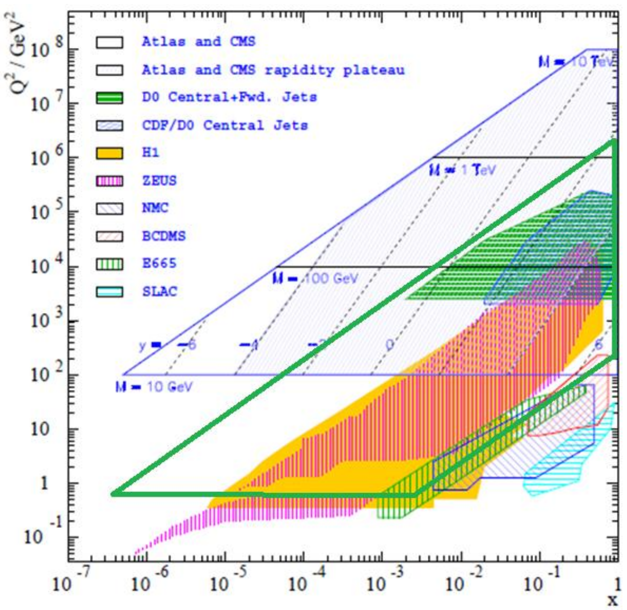
- Neutral current Deep Inelastic Scattering (DIS) cross section
- $F_2(x,Q^2)$, $F_l(x,Q^2)$, $F_3(x,Q^2)$

- New facilities:
- CEBAF 12 GeV (2014)
- EIC (√s (~100 GeV); L~10^{34}cm-1 s-1) ?
- LHeC (√s (~1.5 TeV); L~10^{33}cm-1 s-1) ?

- CEBAF 12 GeV: high x, Q2~6 GeV^2 for W>2 GeV
- Much increased luminosity for EIC and LHeC colliders compared to HERA.
- Increased center of mass energy for the LHeC allows for accurate measurements in EW regime
- Very low X (saturation?)







Nucleon structure

Generalized Parton Distributions (GPD)

- GPD provide correlated information on longitudinal momentum *xp and* transverse spatial position *r⊥*
- Several GPDs: *H, H̃, E, Ẽ ,*
- Basic method:

Deeply Virtual Compton Scattering (DVCS)

- DVCS interfere with BH processes →beam charge/polarization asymmetry

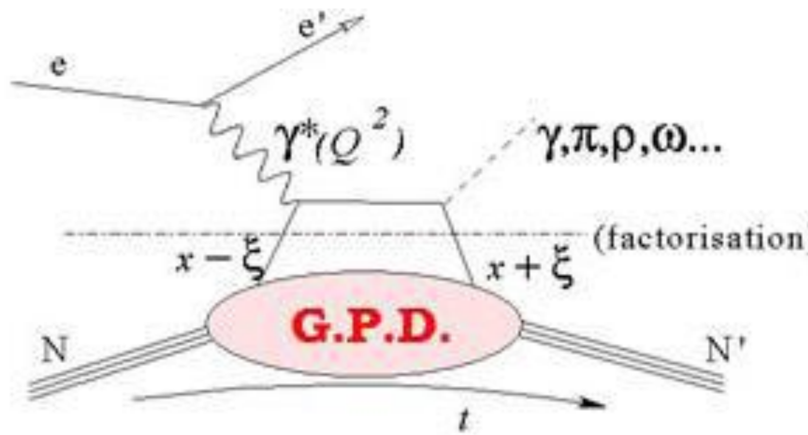
First measurements: CEBAF

Plans:

- CEBAF 12 GeV
- COMPASS longitudinally polarized μ± beams with the energy of Eμ = 160 GeV. COMPASS covers unexplored region at medium X

$$\int dx H_q(x,\xi,t) = F_1^q(t)$$

$$\int dx E_q(x,\xi,t) = F_2^q(t)$$

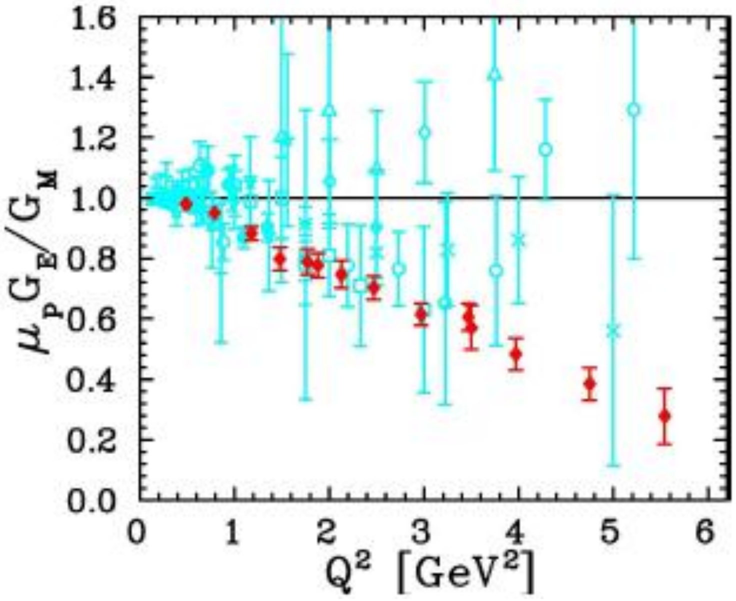


Nucleon structure
Form-factors

- New information on proton structure:
- $GE(Q^2) \neq GM(Q^2)$ different charge, magnetization distributions
- Connection to GPDs: spin-space-momentum correlations

- At CEBAF12
  $GE(Q^2)/GM(Q^2)$ will be measured up to Q^2=12 GeV^2

- PANDA: time-like proton formfactors will be measured up to q^2=15 GeV^2



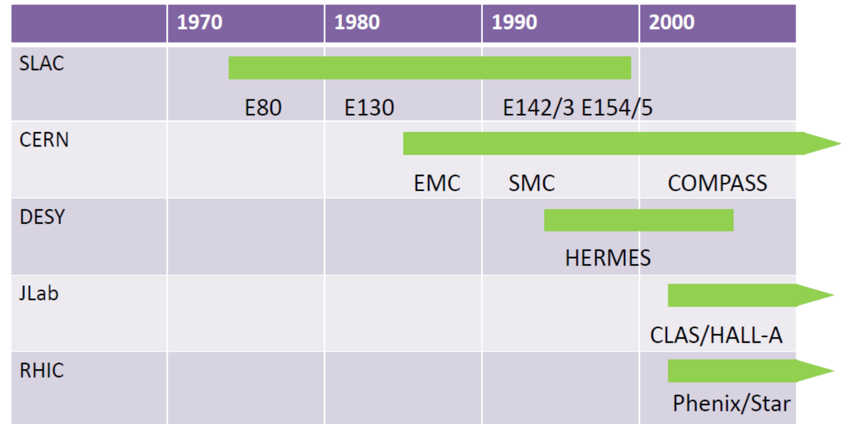
Spin
Longitudinal spin physics

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

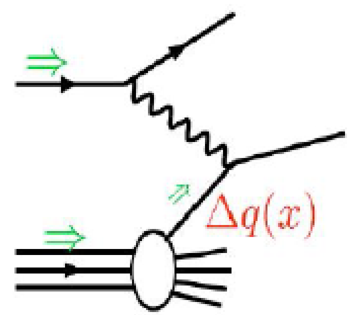
small — poorly known — unknown

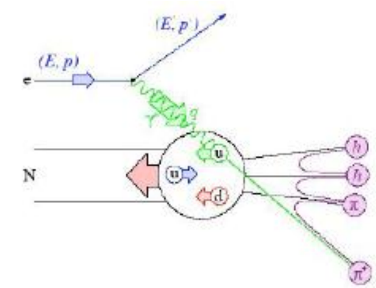
Methods:

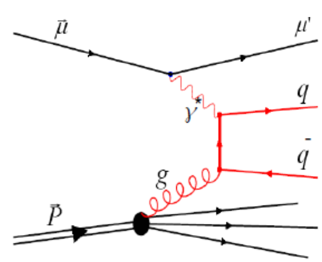
- Deep Inelastic Scattering →$\Delta\Sigma$
- Semi-inclusive DIS (e.g. charm production) →ΔG
- Polarized protons inclusive scattering →ΔG :
  RHIC $\vec{p} + \vec{p} \rightarrow \pi^+, \pi^-, \pi^0, \gamma$, Jet
- $\vec{p} + \vec{p} \rightarrow W^{+-} + X \rightarrow \Delta\Sigma$
- New experiments planned at JLAB, COMPASS, RHIC
- Good prospects for EIC , LHeC

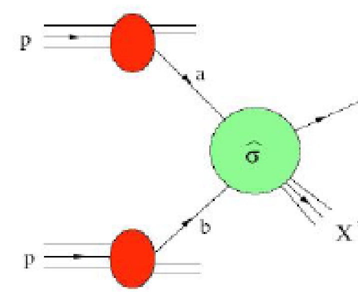


D.Peshekhonov







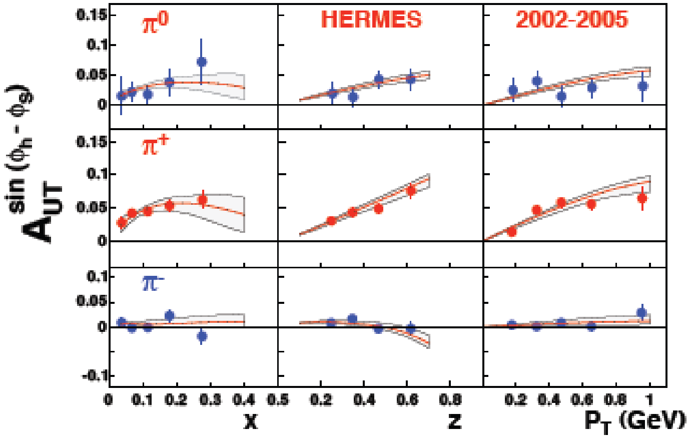


Spin

Transverse-momentum dependent parton distributions (TMD)

- The TMDs depend on the intrinsic motion of partons inside the nucleon and allow the reconstruction of the nucleon structure in momentum space.
- The 'simplest' TMD is the unpolarized function f^q_1 (x, k⊥)
- f^q_1 (x, k⊥; s_q,S) may depend on all possible combinations of the pseudo-vectors s_q,S and the vectors k⊥,P which are allowed by parity invariance. At leading order in 1/Q, there are eight such combinations, leading to the eight independent TMDs.
- How to measure TMD's? → SIDIS

The hadrons from the fragmentation of a scattered quark, 'remembers' the original motion of the quark.



First measurements by HERMES and COMPASS

New measurements planned at CEBAF12 (valence quarks) and COMPASS.

p↑ p↑ semi-inclusive (π0, jets) at RHIC

Good prospects for EIC and LHeC.

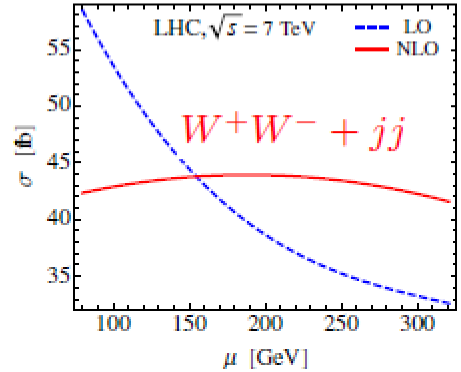
High energy phenomena

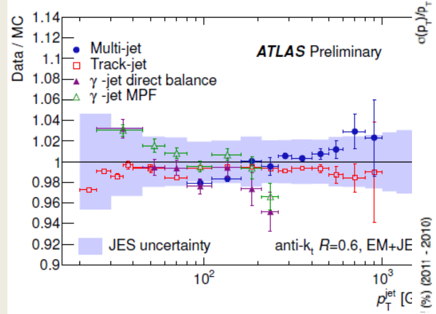
Jets

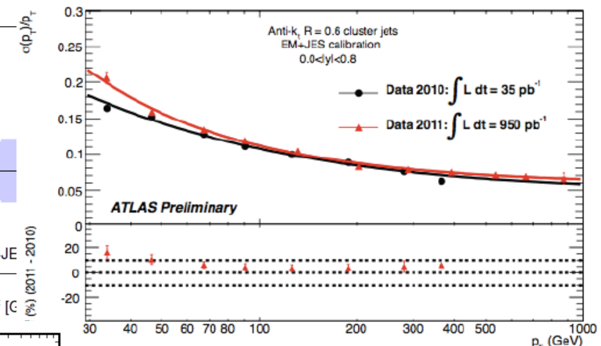
- Progress in calculations (NLO, NNLO)
- Anti-kT algorithm with resolution parameter R=0.4 – 1.2
  - reconstruct jets with simple cone-like geometrical shape from calorimeter clusters or charged particle tracks
  - infrared and co-linear safe
- Jet energy calibration is validated in-situ. The uncertainty is below 2.5% (ATLAS).
- Jet energy resolution (~6% at E=1 TeV)
- α_s
- PDF

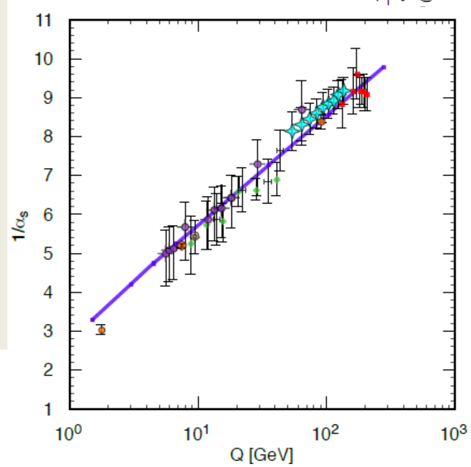
- Hard QCD evolving to high precision science

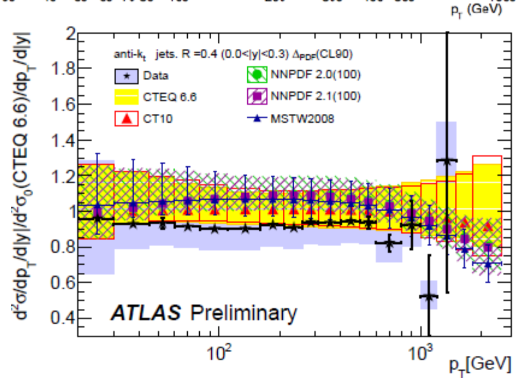
NLO











The phase diagram of strongly interacting matter

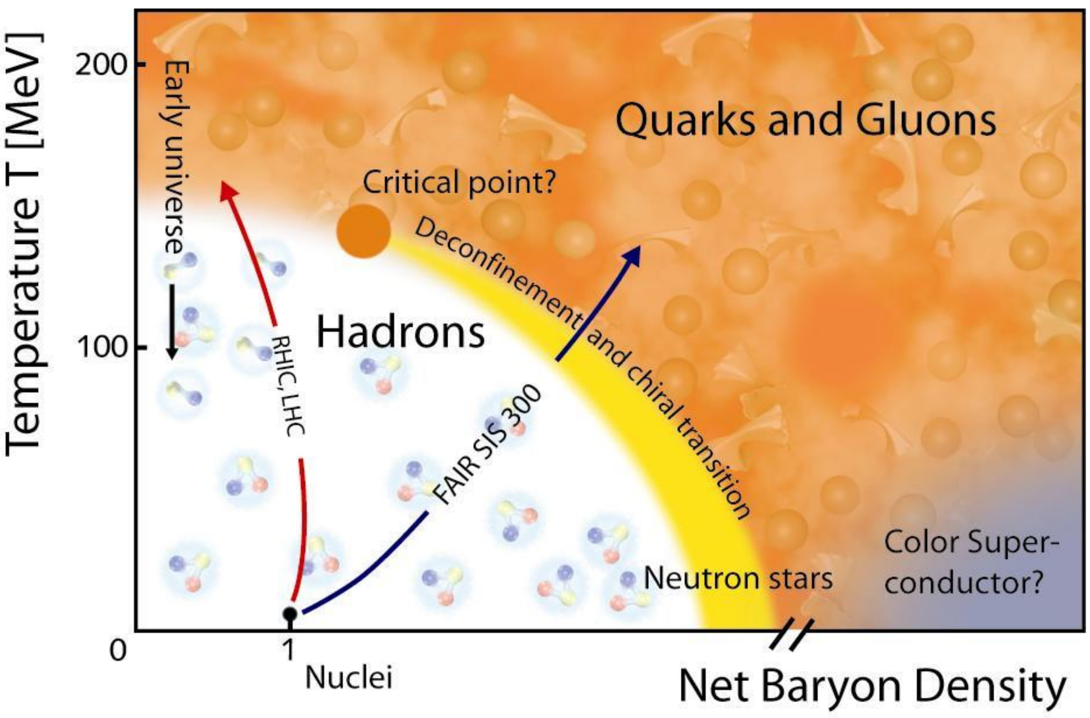
- RHIC data have shown robust collective flows: that confirms that QGP above the critical line is in a strongly coupled regime.

- Goals:
- Exploring the QCD phase diagram with heavy-ion collisions:

- RHIC & LHC:

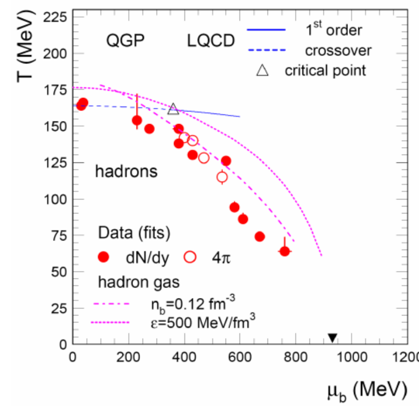
  high temperatures, very small net-baryon density
- SPS (low energies), FAIR, NICA:

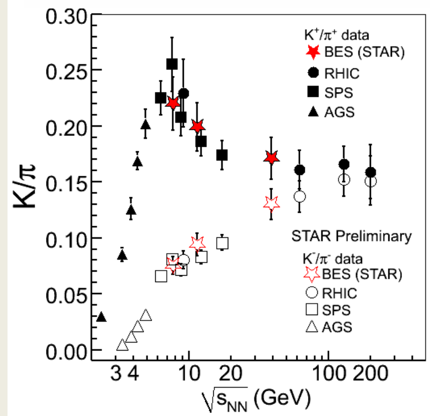
  moderate temperatures, very high net-baryon density



Heavy nuclei at high density

- Questions @ methods
- phase transition at high density r_B
  - excitation function and flow of strangeness
  - excitation function and flow of charm (e.g. melting of J/ψ and ψ')
  - excitation function of low-mass lepton pairs
- QCD Critical point
  - excitation function of dynamical event-by-event fluctuations
- Equation of State at high density
  - collective flow of hadrons
  - particle production at threshold energies (multistrange hyperons, open charm)
- chiral symmetry restoration at high ρ_B
  - in-medium modifications of hadrons





Facilities:

RHIC low energy-scan:
bulk observables
f=1 - 800 Hz

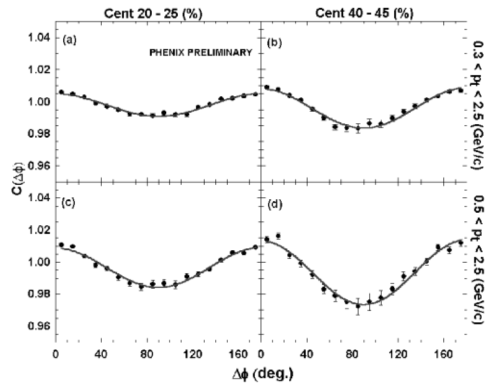
NA49/61@SPS:
bulk observables
f= 80 Hz

MPD&NICA:
bulk observables
f = 10^3 Hz

CBM&FAIR: bulk and rare observables
f = 10^7 Hz

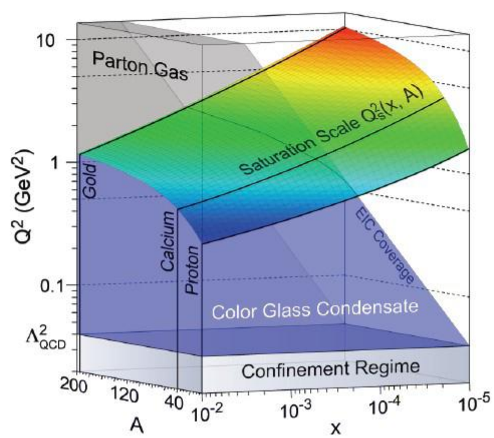
Strongly coupled plasma

- Questions & methods
- Coupling scale & quasiparticle search
  - charm hard (not thermal) probe
  - c vs. b in QGP
- Parton-plasma interaction
  - Jets ≤ 50 GeV, γ-jet
  - Ejet, l, q_{mass}, angle dep. of dE/dx
  - Jet virtuality ~ medium scale
- Screening length
  - as function of √s, p_T , Ronium
- Termalization mechanism
  - γdir yield, spectra & flow
- QCD in cold, dense (initial) state
  - y dependence in d+Au
- Gluon saturation scale
  - DIS (γ* A)



$dN/d\phi \sim 1 + 2\, v2(pT) \cos(2\phi) + \dots$

"elliptic flow"



Facilities:

Luminosity x10 at RHIC
Large acceptance in both STAR&PHENIX

rare probe scan:
50<√s <200 GeV &
asymmetric systems

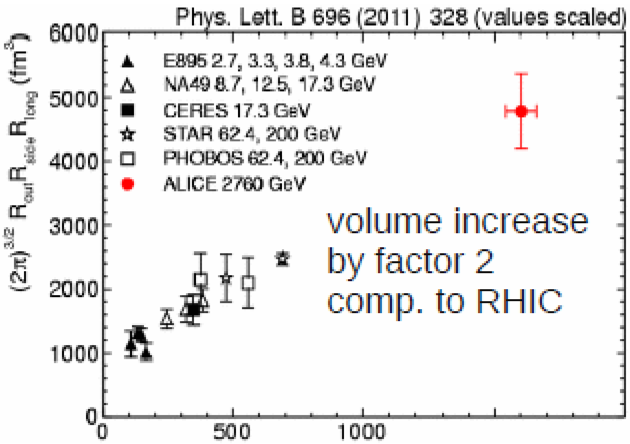
EIC:
either eRHIC & BNL
or ELIC & JLaB

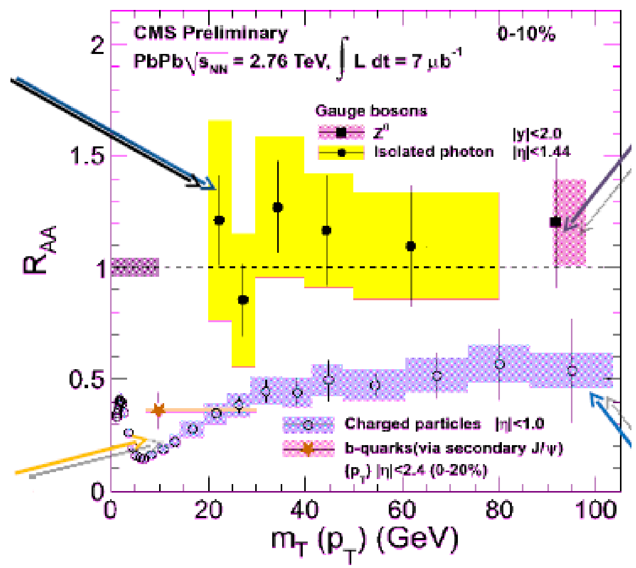
In distant future:
LHeC & CERN

QGP matter at LHC

why LHC?

- much larger energy (> 20 x RHIC)
- very large volumes, temperatures, densities
- copious production of jets and heavy quarks
  - enough heavy quarks and resolution to study complete J/ and Y family together with open charm and beauty
- electro-weak probes
- use of quantitative tools (pQCD) possible





QCD and Nucleon Structure: Facility Matrix

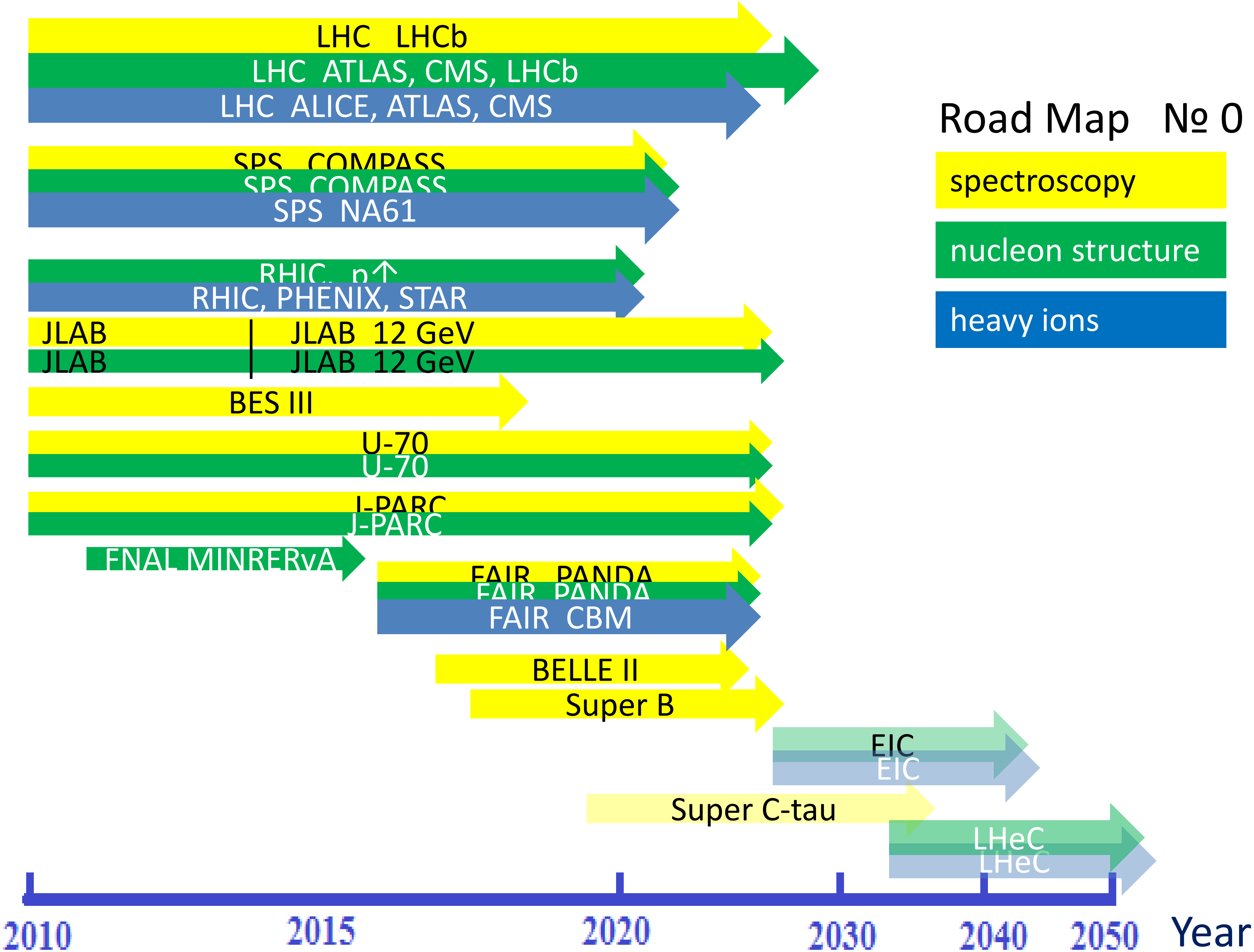
TOPIC/FACILITY	BNL/RHIC	JLab 12 GeV	CERN/Compass	FAIR/PANDA	Fermilab/MI	CERN/LHC	JPARC/Hadron Hall	IHEP Protvino U70	BEPC/BES	DAPHNE/KLOE	KEK/BELLEII	SuperB	EIC	LHeC
Nucleon Structure														
Parton Distribution Functions														
Form Factors of the nucleon														
Gen. Parton Dists														
Spin and Semi-Inclusive														
Long Spin Phys, gluons, Orbital														
Transverse Momentum Dist														
High Energy Phen.														
Jets														
Multiparton interactions														
Diffraction														
Soft physics (multiplicity etc.)														
Very low x, gluon saturation														
Hadron Spectroscopy														
Mesons														
Baryons														

Heavy Ions/QGP

	SPS	RHIC	LHC	RHIC Up	LHC Up	Fair	Nica	LHeC	EIC
High Baryon Density									
phase transition/EoS at large ρ_B									
QCD Critical point									
chiral sym. restoration at large ρ_B									
High Temperature									
dynamical evolution, freeze-out									
viscosity, T_c, c_s,, Quasi-Particles, ...									
Parton energy loss				rare	rare				
Debye screening mass				rare	rare				
Initial State									
CGC/saturation/nuclear PDF		pA	pA	pA					

RHIC Upgrade: Luminosity at low Energy, Detectors
LHC Upgrade: > x 5-10 integrated Lumi., Detectors
pA: proton-Nucleus **rare**: low x-section signals
EoS: Equation of State ρ_B: Baryon Density **CGC:** Color Glass Condensate
T_c: Phase Transition Temperature: c_S: Speed of Sound

Spare slides


LHC LHCb
LHC ATLAS, CMS, LHCb
LHC ALICE, ATLAS, CMS
Road Map № 0
spectroscopy
nucleon structure
heavy ions
SPS COMPASS
SPS COMPASS
SPS NA61
RHIC, p↑
RHIC, PHENIX, STAR
JLAB | JLAB 12 GeV
JLAB | JLAB 12 GeV
BES III
U-70
U-70
J-PARC
J-PARC
FNAL MINRERvA
FAIR PANDA
FAIR PANDA
FAIR CBM
BELLE II
Super B
EIC
EIC
Super C-tau
LHeC
LHeC
2010
2015
2020
2030
2040
2050
Year