Heavy-ion collisions at LHC: The Alice Experiment

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Abstract. We present an introduction to heavy-ion collisions at LHC with special emphasis on the ALICE experiment. The lecture is divided in three parts. The first contains a description of the new conditions for the creation of the Quark Gluon Plasma in the laboratory with HIC at the LHC in the context of the 30 years of history of HIC. The second part is a detailed explanation of the different detectors of the ALICE experiment as well as of ALICE capabilities in terms of tracking and particle identification. The last part presents a selection of the ALICE physics capabilities in soft physics, heavy quarks, quarkonia, photons and jets.

References

1. ALICE Collaboration, J. Phys. G **30**, (2004) 1517
2. ALICE Coll., J. Phys. G **32**, (2006) 1295
3. <http://aliceinfo.cern.ch>
4. R.K. Ellis, W.J. Stirling and B.R. Webber, *QCD and Collider Physics*.
5. R. Vogt, *Ultrarelativistic Heavy-Ion Collisions*.
6. P. Braun-Munzinger and J. Stachel, Nature, **448**, (2007) 302
7. W.-M. et al., Journal of Physics G **33** (2006) 1.

Goals of High Energy Heavy-Ion Collisions

- Understand 2 basic properties of the strong interaction: (de)confinement, chiral symm. breaking/restoration
- Probe conditions quark-hadron phase transition in primordial Universe (few μ sec after the Big Bang)
- Study the phase diagram of QCD matter: produce and study the QGP
- Study the regime of non-linear (high density) many-body parton dynamics at small- x (CGC).

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Quantum Chromodynamics (QCD)

• QCD is a gauge field theory that describes the strong interaction of colored quarks and gluons

• QCD potential

$$V = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

- Asymptotic freedom at short distance
- Confinement at large distance

S Bethke, J. Phys. G26 (2000) R27

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Asymptotic Freedom

"What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called 'asymptotic freedom'. The converse is true when the quarks move apart: the force becomes stronger when the distance increases."

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Lattice QCD: deconfinement and chiral symmetry restoration

Lattice provides a first-principles approach to studies of large distances, non-perturbative aspects of QCD

F. Karsch, hep-lat/0106019

χ_L : Polyakov loop susceptibility

χ_m : chiral susceptibility

The maxima of χ_L and χ_m coincide

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Lattice QCD: Pressure and energy density

F. Karsch, hep-lat/0106019

Transition to QGP: $T_c = 175 \pm 15$ MeV; $\epsilon_c = 0.7 \pm 0.2$ GeV/fm³

Above T_c the energy goes into
more degrees of freedom

M. Cheng et al., Phys. Rev. D77 (2008) 014511

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QGP in the laboratory

Key parameters: Bombarding energy and collision centrality

Schematic space-time evolution of a HIC

Different observables sensitive to different reaction stages

History of Heavy Ion Collisions

- **Bevalac (LBL)**
 - fixed target (1975-1986) $\sqrt{s} < 2.4$ GeV
- **SIS (GSI)**
 - fixed target (1989-) $\sqrt{s} < 2.7$ GeV
- **AGS (BNL)**
 - fixed target (1986-1998) $\sqrt{s} < 5$ GeV
- **SPS (CERN)**
 - fixed target (1986-2003) $\sqrt{s} < 20$ GeV
- **RHIC (BNL)**
 - collider (2000-) $\sqrt{s} < 200$ GeV
- **LHC (CERN)**
 - collider (2008-) $\sqrt{s} < 5500$ GeV
- **FAIR (GSI)**
 - fixed target (2014-) $\sqrt{s} < 9$ GeV

Phase diagram of matter

Energy density: Bjorken estimate

$$E_{\text{Bjorken}} = \frac{1}{\pi R^2} \frac{dE_T}{dy}$$

From SPS on
Energy density above transition
value predicted by lattice

THE LHC

The CERN accelerator complex

LINAC2- BOOSTER-PS-SPS-LHC

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The Large Hadron Collider

CMS

ALICE

p+p @ 14 TeV
Pb+Pb @ 5.5A TeV

ATLAS

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Physics questions at LHC

- **ATLAS, CMS, LHCb:**
 - Higgs mechanism
 - Supersymmetry
 - CP violation
- **ALICE:**
 - Chiral Symmetry breaking
 - Origin of mass of hadrons
 - Deconfinement
 - Hadronization
- **ALL:**
 - Understand high energy nuclear interactions (for cosmic ray studies)

Heavy ion collisions at LHC

	SPS	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	17	200	5500
dN_{ch}/dy	430	730	1000-4000
τ_{QGP}^0 (fm/c)	1	0.2	0.1
T/T_c	1.1	1.9	3.0-4.7
ϵ (GeV/fm ³)	3	5	15-60
τ_{QGP} (fm/c)	≤ 2	2-4	≥ 10
τ_f (fm/c)	~ 10	20-30	15-60
V_f (fm ³)	few 10 ³	few 10 ⁴	few 10 ⁵

faster
hotter
denser
longer

bigger

Heavy Ion collisions at LHC

Cross-sections of interesting probes expected to increase by factors

~ 10 (cc) to

$\sim 10^2$ (bb) to

$\sim > 10^5$ (very high p_T jets); Hard probes of the medium accessible at LHC

Direct photons are abundantly produced at LHC

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Hard processes at LHC

Hard processes contribute significantly to the total AA cross-section ($\sigma_{\text{hard}}/\sigma_{\text{tot}} = 98\%$):

Bulk properties dominated by

hard processes;

Very hard probes are abundantly produced.

Weakly interacting probes become accessible ($g, Z^0, W^\pm$).

K. Kajantie, Nucl Phys. A 715(2003) 432

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Physics topics of ALICE

- Event characterization
Multiplicity, centrality
- Bulk properties of the hot and dense medium (dynamics of hadronization)
Hadron ratios, hadronic resonances
- Chiral symmetry restoration
Short lived resonance masses
- Space-time fireball description and fireball expansion dynamics
Momentum correlations (HBT), Radial and anisotropic flow
- Heavy quark production
Charmonium and bottomonium (Debye screening, recombination(?))
- Partonic energy loss in QGP
Jet reconstruction, Jet quenching, high pt spectra, inclusive high p_t suppression, open charm
(Mass/color dependence of E loss)
- Fluctuation phenomena
Event-by-Event analysis
-

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ALICE: The dedicated HI Experiment

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ALICE Collaboration

> 1000 Members
~ 30 Countries
~ 100 Institutes

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The Inner Tracking System

6 Layers of silicon detectors for precision tracking in $|\eta| < 0.9$

- Three technologies to keep occupancy $\sim 2\%$ from $R_{\min} \sim 4 \text{ cm}$ (80 tracks/cm^2) to $R_{\max} \sim 40 \text{ cm}$ ($< 1 \text{ tracks/cm}^2$)

SPD-Silicon Pixel
SDD-Silicon drift
SSD-Silicon Strip

~ 12.5M channels,
Analogue readout
for dE/dx

- 3-D reconstruction ($< 100 \mu \text{ m}$) of the Primary Vertex
- Secondary vertex Finding (Hyperons, D and B mesons)
- Particle identification via dE/dx for momenta $< 1 \text{ GeV}$
- Standalone reconstruction of very low momentum tracks ($< 100 \text{ MeV}$)

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The ITS assembly

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The Time Projection Chamber

Main tracking detector (charged particles)
of the ALICE Central Barrel

Inner and Outer
Containment Vessels
(150 mm, CO₂)

•very thin & lightweight FC ~3% X₀

•high track density & small space
charge

drift gas, chamber lay-out, field
strips, ..

Suspended field
defining strips
400 V / cm

845 < r < 2466 mm
Drift length 2 x 2500 mm
Drift gas Ne-CO₂-N₂ (86/9/5)
Gas volume 95 m³
557568 readout pads

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The TPC

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The TPC installation

January 2007

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Moving of the ITS over the SPD

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The Transition Radiation Detector

e-identification

- 18 supermodules
 - 6 radial layers
 - 5 longitudinal stacks
- ⇒ 540 chambers
 ⇒ 750m² active area
 ⇒ 28m³ of gas

Each chamber:

≈ 1.45 × 1.20m²

≈ 12cm thick (incl. Radiators and electronics)

in total 1.18 million read out channels

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ALICE TRD principle

Charged particles at $\gamma > 1000$ give T.R. photons ($< 30\text{KeV}$).
They are absorbed by high-Z gas (Xe, CO_2) mixture

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TRD assembly and installation

4 SM's are installed

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The Time Of Flight System

Large array at $R \sim 3.7$ m, covering $|\eta| < 0.9$ and full ϕ , requirements:

- Time resolution < 100 ps
- Very high granularity, $O(10^5)$ channels to keep occupancy $< 15\%$

Active surface ~ 150 m²

TOF basic element:
double-stack Multigap RPC strip
7.4x120 cm² active area
segmented into 96 readout pads

Extensive R&D, from TB data:

- Intrinsic Resolution ~ 40 ps
- Efficiency $> 99\%$

Full TOF: 1638 strips, arranged in 18 ϕ sectors, each of 5 modules along z

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TOF supermodule

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The High Momentum Particle ID Detector

SINGLE-ARM proximity-focus RICH, active surface $\sim 11 \text{ m}^2$ at $R \sim 4.7 \text{ m}$

- **RADIATOR:**
15 mm liquid C₆F₁₄ ($n \approx 1.2989$ @ 175 nm),
 $p_{th} = 1.21 \text{ m (GeV/c)}$

- **PHOTON + MIP DETECTION:**
MWPC with CH₄ with analogue pad r/o
($\sim 160 \times 10^3$ channels), photon
conversion on a layer of CsI (Q.E.
 $\approx 25\%$ @ 175 nm)

Largest scale application of CsI photocathodes

1 Astrophysics, A. Marin (Dubna July 2008)

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The HMPID detector during installation

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PHOTON SPECTROMETER

- Dense like lead and transparent like crystal to stop photons
- PbWO_4 crystal (17920 crystals in total)
 - $R_0=2.2$ cm, $X_0=8.9$ mm, $\rho =8.28$ g/cm³,
 - $n=2.16$, size: $22 \times 22 \times 180$ mm³

PHOS has 5 modules installed at 4.6 m apart from the ALICE interaction point.

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The Muon arm

Muon spectrometer is dedicated to the (di-)muons measurement ($2.5 < \eta < 4$)

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Muon arm assembly

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Forward Detectors

20.0

Zero Degree Calorimeter

- 6 small & dense calorimeters
 - 8 m (em calo) and 116 m (ZP, ZN) from IP
 - trigger on impact parameter (spectators)
 - v_1 measurement
 - unbiased event plane
 - impact parameter also in pA ('grey & black' tracks)
 - effective A^s dependences

	Proton ZDC (ZP)	Neutron ZDC (ZN)	EM ZDC
Dimensions (cm ³)	12x21x150	7x7x100	7x7x21
Absorber	brass	W-alloy	lead
Fibre angle wrt LHC axis	0°	0°	45°
Fibre Ø (µm)	550	365	550

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Centrality determination in ALICE

Event by event determination of the centrality :
Zero degree hadronic calorimeters (ZDC) +
electromagnetic calorimeters (ZEM)
EZDC , EZEM → Nspec → Npart → Impact parameter (b)

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ALICE charged particle acceptance

- **Minimum Bias trigger** provided by a coincidence between **V0 counters** ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$).
- We expect a $dN/d\eta$ excellent measurement in the **central region** thanks to the **ITS + TPC** detector
- V0 and FMD in the forward region.

The ALICE EXPERIMENT

ALICE - Global Tracking

Parallel Kalman Filtering

After cluster finding, start iterative process through all central tracking detectors, ITS+TPC+TRD:

- Primary Vertex Finding in ITS
- Track seeding in outer TPC
- Propagation to the vertex, tracking in ITS
- Back-propagation in TPC and in the TRD
- Extrapolation and connection with outer PID detectors
- Final refit inwards (for V0, 1-prong decays)

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Tracking/Physical efficiency

Challenge in high-particle density environment

Efficiency normalized to number of generated particles at primary vertex within the central acceptance $|\eta| < 0.9$
 protons - large absorption
 kaons - decays on flight

For realistic particle densities
 $dN/dy = 2000 - 4000$
 combined efficiency well above 90%
 and fake track probability below 5%

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Momentum resolution

Robust, redundant tracking from $< 100 \text{ MeV}/c$ to $> 100 \text{ GeV}/c$
 Very little dependence on dN/dy up to $dN/dy \approx 8000$

at low momentum dominated by
 - ionization-loss fluctuations
 - multiple scattering

at high momentum determined by
 - point measurement precision
 - and the alignment & calibration

PID in ALICE

• excellent particle ID up to ~ 50 to $60 \text{ GeV}/c$

• Most ($2\pi \times 1.8$ units η) of the hadrons ($dE/dx + \text{ToF}$), leptons (dE/dx , TOF, transition radiation) and photons (high resolution EM calorimetry, conversions);

• Track and identify from very low ($< 100 \text{ MeV}/c$) up to very high p_T ($> 100 \text{ GeV}/c$);

• Identify short lived particles (hyperons, D/B meson) through secondary vertex detection;

PID: Energy loss (dE/dx) in the TPC

Bethe-Bloch formula

$$\frac{\overline{\Delta E}}{\Delta x} = 2C \frac{m_e c^2}{\beta^2} \frac{Zz^2}{A} \rho \frac{V_1}{V_2} \ln \frac{\Phi_2 \gamma^2 \beta^2 m_e c^2 E_{\max}}{I_0^2} \frac{K}{B} \beta^2 - \frac{\epsilon}{2} - \frac{\delta(\beta) b}{2} \frac{b}{3}$$

~6.5% resolution for central Pb+Pb collisions

PID: dE/dx in the ITS

- Based on specific ionization (dE/dx) in the SDD and SSD (4 layers)
- Add information to the PID given by the TPC (combined-Bayesian PID)
- Identify tracks not reconstructed by the TPC:
 - Low momentum
 - Out of TPC acceptance
 - Dead zones of TPC (between sectors)

Mass separation with TOF

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PID: Pion efficiency with TRD

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Identified particle spectra

Estimated p_t range for particle identification for 10^7 central Pb-Pb events (1-year data taking)

π, K, p : 0.1 - 0.15 $\langle p_t \rangle$ 50 GeV/c

Weak or strong decaying particles: up to 10-15 GeV/c

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ALICE running strategy

- Regular pp runs at 14 TeV. First run at 10 TeV
- Initial heavy-ion programme:
 - Pb-Pb pilot run
 - 1-2 years Pb-Pb
 - 1 year pPb like collisions
 - 1-2 years Ar-Ar
- Later options:
 - dedicated pp at 5.5 TeV
 - another intermediate mass A-A system
 - possibly another pA system

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ALICE running conditions

System	$\sqrt{s_{NN,max}}$ (TeV)	Δy	σ_{geom} (b)	$\mathcal{L}_{low}$ ($\text{cm}^{-2} \text{s}^{-1}$)	$\mathcal{L}_{high}$ ($\text{cm}^{-2} \text{s}^{-1}$)
Pb-Pb	5.5	0	7.7	1.0×10^{27}	
Ar-Ar	6.3	0	2.7	2.8×10^{27}	1.0×10^{29}
O-O	7.0	0	1.4	5.5×10^{27}	2.0×10^{29}
N-N	7.0	0	1.3	5.9×10^{27}	2.2×10^{29}
$\alpha\alpha$	7.0	0	0.34	6.2×10^{29}	
dd	7.0	0	0.19	1.1×10^{30}	
pp	14.0	0	0.07	1.0×10^{29}	5.0×10^{30}
pPb	8.8	0.47	1.9	1.1×10^{29}	
pAr	9.4	0.40	0.72	3.0×10^{29}	
pO	9.9	0.35	0.39	5.4×10^{29}	
dPb	6.2	0.12	2.6	8.1×10^{28}	
dAr	6.6	0.05	1.1	1.9×10^{29}	
dO	7.0	0.00	0.66	3.2×10^{29}	
α Pb	6.2	0.12	2.75	7.7×10^{28}	
α Ar	6.6	0.05	1.22	1.7×10^{29}	
α O	7.0	0.00	0.76	2.8×10^{29}	

LHC machine parameters

Table 2.3. LHC machine parameters for pp and Pb-Pb runs for ALICE.

	pp	Pb-Pb
Energy per nucleon (TeV)	7	2.76
β at the IP: β^* (m)	10	0.5
R.m.s. beam radius at IP: σ_t (μm)	71 ^a	15.9
R.m.s. bunch length: σ_l (cm)	7.7	7.7
Vertical crossing half-angle (μrad) for pos. (neg.) μ -spectr. dipole polarization	150 (150)	150 (100)
No. of bunches	2808	592
Bunch spacing (ns)	24.95	99.8
Initial number of particles per bunch	1.1×10^{11}	7.0×10^7
Initial luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	$< 5 \times 10^{30}$	$10^{27\text{b}}$

^a For low-intensity runs β^* could be 0.5 m and $\sigma_t = 15.9 \mu\text{m}$ as in Pb-Pb.

^b Early operation will be with 62 bunches and $\beta^* = 1$ m, which yields an initial luminosity of $5.4 \times 10^{25} \text{ cm}^{-2} \text{s}^{-1}$.

Soft Physics

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Charged-particle Multiplicity Density

Integrated multiplicity distributions from Au-Au/Pb-Pb collisions and scaled pp collisions

$dN_{ch}/dy = 2600$

saturation model

Eskola hep-ph/050649

$dN_{ch}/dy = 1200$

$\ln(\sqrt{s})$ extrapolation

- ALICE designed (before RHIC) for $dN_{ch}/dy = 3500$
design checked up to $dN_{ch}/dy = 7000$

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Charged-particle Multiplicity Density

N. Armesto, arXiv:0804.4158.
LHC predictions: An overview

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Thermal Model and particle abundancies

- Assume chemically equilibrated system at freeze-out (constant T_{ch} and μ)
- Composed of non-interacting hadrons and resonances
- Given T_{ch} and μ 's, particle abundancies (n_i 's) can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

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Equilibrium versus non equilibrium at LHC

ALICE Estimates : Equilibrium vs Non Eq. particle ratios

And many other questions: strangeness enhancement % energy
Correlation volume ($N_{part} \rightarrow GC, N_{bin} \rightarrow \text{hard processes}$) ? Evolution in pp ?

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Resonances (ρ , ϕ , K^* , ...)

Short-lived resonances:

- Time difference between chemical and kinetic freeze-out
- In medium modifications of mass, width, comparison between hadronic and leptonic channels $\rightarrow$ partial chiral symmetry restoration

- Reconstruction by invariant mass spectrum, background subtracted (like-sign method).
- Mass resolutions $\sim 1.5 - 3$ MeV . p_T stat. limits from 8 (ρ) to 15 GeV/c (ϕ , K^*)

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Reaction plane

- The initial spatial anisotropy is transformed into momentum anisotropy
- Analyze in terms of response of the system to initial pressure
- Deduce (model) thermalizing time, EOS

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Energy dependence of flow

eccentricity vs. particle multiplicity in overlap region

hydrodynamical limit
reached at RHIC
→ 'ideal fluid'

- clear predictions from hydrodynamics
- sensitive to equation-of-state

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Predictions of v_2 for LHC

N.Borghini and U.A.Weidemann,
J.Phys.G 35 (2008) 023001

Hirano et al.,
nucl-th/0701075v2

Heavy quarks and Quarkonia

Charm and beauty at LHC

- Measure parton energy loss in QGP
- Test of pQCD
- Cross sections needed to understand quarkonia production in HIC

MNR code (NLO): Mangano, Nason, Ridolfi, NPB373 (1992) 295.

system, $\sqrt{s}$	pp, 14 TeV (c/b)	Pb-Pb (0-5%), 5.5 TeV
$\sigma_{NN}^{Q\bar{Q}}$ [mb]	11.2 / 0.5	4.3 / 0.2
$N_{tot}^{Q\bar{Q}}$	0.16 / 0.007	115 / 4.6

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Heavy quarks as medium probes: Energy Loss

q: colour triplet
u,d,s: $m \approx 0$, $C_R = 4/3$
(difficult to tag at LHC)
g: colour octet
g: $m = 0$, $C_R = 3$
> E loss, dominant at LHC
Q: colour triplet
c: $m \sim 1.5$ GeV, $C_R = 4/3$
small m, tagged by D's
b: $m \sim 5$ GeV, $C_R = 4/3$
large mass, < E loss

QCD medium

Parton Energy Loss by

- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\epsilon_{QGP}; C_R, m, L)$$

$$\text{pred: } \Delta E_g > \Delta E_{c \approx q} > \Delta E_b$$

$$\rightarrow R_{AA}^\pi < R_{AA}^D < R_{AA}^B$$

Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

Djordjevic, Gyulassy, Wicks, nucl-th/0512076

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Physics Analysis

• Hadronic decays:

- $D^0 \rightarrow K^- \pi^+$, $D^{*+} \rightarrow K^- \pi^+ \pi^+$, $D_s \rightarrow K K^*$, $D_s \rightarrow \phi$
 π , ...

• Leptonic decays:

- Single lepton analysis:
 - Open charm, open beauty, electro-weak bosons;
- Invariant mass analysis of lepton pairs:
 - BB, DD, BD_{same}, J/Ψ, Ψ', Υ family, B → J/Ψ + anything;
- Multi-lepton analysis :

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Charm reconstruction: $D^0 \rightarrow K^- \pi^+$

- Large combinatorial background ($dN_{ch}/dy=6000$ in central Pb-Pb!)
- Main selection: displaced-vertex selection
 - pair of opposite-charge tracks with large impact parameters
 - good pointing of reconstructed D^0 momentum to the primary vertex

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D⁰ -meson Performance

S/B~10%
significance ~40
(1 month PbPb running)

Beauty via displaced electrons

- ALICE has excellent electron identification capabilities
- Displaced electrons from B decays can be tagged by an impact parameter cut

Beauty via displaced J/ψ

- ALICE has excellent electron identification capabilities
- Displaced di-electrons from B decays can be tagged by an impact parameter cut

Expected p_t coverage

1 year at nominal luminosity
(10^7 central Pb-Pb events, 10^9 pp events)

Calibrating the probe ($pp, \sqrt{s} = 14 \text{ TeV}$)

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t} \quad \text{measured at 14 TeV, then scaled by pQCD to 5.5 TeV}$$

Expected sensitivity in comparison to pQCD:

$D^0 \rightarrow K\pi$

$B \rightarrow e + X$

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Charm and Beauty E Loss : R_{AA}

E loss calc.:
Armesto, Dainese, Salgado, Wiedemann

1 year at nominal luminosity
(10^7 central Pb-Pb events, 10^9 pp events)

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Quarkonia at LHC: ψ (cc) & Υ (bb)

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Statistical Hadronization Model (PLB 652 (2007) 259)

Clear signal for generation of charmonia due to statistical hadronization at the phase boundary

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Quarkonia in the electron channel

- Electron Identification (TRD+TPC);
- Tracking : ITS+TPC+TRD;
- 2×10^8 central PbPb events (no e-trigger).

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Quarkonia in the muon channel

PbPb cent, 0 fm<b<3 fm

State	S[10³]	B[10³]	S/B	S/(S+B) ^{1/2}
J/ψ	130	680	0.20	150
ψ'	3.7	300	0.01	6.7
γ(1S)	1.3	0.8	1.7	29
γ(2S)	0.35	0.54	0.65	12
γ(3S)	0.20	0.42	0.48	8.1

Yields for baseline

- γ(1S) & γ(2S) : 0-8 GeV/c
- J/ψ high statistics: 0-20 GeV/c
- ψ' poor significance
- γ(3S) ok, but 2-3 run needed.

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Quarkonia Performance

Bkg input: $dN_{ch}/dy=4000$ in central Pb-Pb. $S/\sqrt{S+B}$ for 1 month

Particle	Charmonia $\mu^+\mu^-$	Charmonia e^+e^-	Bottomia $\mu^+\mu^-$	Bottomia e^+e^-
Bkg-subtracted mass plot				
acc. η				
M res.	65 MeV	35 MeV	90 MeV	90 MeV
S	J/ψ 150, ψ' 7	J/ψ 245	Υ 30, Υ' 12, Υ'' 8	Υ 21, Υ' 8
$\sqrt{s}$ per B	ψ , $?\psi'$	ψ , $??\psi'$	Υ , Υ' , $?\Upsilon''$	Υ , $?\Upsilon'$, no Υ''
p_t	J/ψ 0-20 GeV	J/ψ 0-10 GeV	Υ 0-8 GeV	--

Photons, Jets and high p_t

Direct photon

Why direct photons?: Exit medium unscattered
Carry information on the entire history of the collision

qq Compton Scattering

qq
Annihilation

Bremsstrahlung

Thermal photons from QGP and hadron gas

Photons from Jet re-interaction in the medium

...in a large background from π^0 and η decays

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Photon sources in A-A collisions at LHC

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How many direct photons, jets?

Large sample of direct LO γ -jet for $p_T < 30 \text{ GeV}/c$ in PHOS and $p_T < 50 \text{ GeV}/c$ in EMCal ...and in central Barrel

... but $\gamma/\pi^0 = 0,01-0,1$ for $p_T > 20 \text{ GeV}/c$
We need a good γ/π^0 PID

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Photon Production: different sources

Turbide, Gale, Jeon, and
Moore

PRC (2004) 014906

Photons are abundantly produced at LHC

Jet-photon conversion in the plasma dominates $8 < p_T < 14 \text{ GeV}$

Primordial hard NN scattering dominant for $p_T > 20 \text{ GeV}$ at LHC

How can we distinguish different photon sources?

- Prompt : $R_{AA} = 1$, $v_2=0$ (azimuthal anisotropy)
- Fragmentation: $R_{AA}<1$, $v_2>0$
- Thermal, Bremsstrahlung, Jet Conversion: $R_{AA}>1$, $v_2<0$

$R_{AA} > 1$ and $v_2 < 0$
Unambiguous signature
of medium produced
photons

W.Liu, R.J.Fries nu-th/0801.0453

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Identifying prompt γ in ALICE (PHOS)

Isolation method

- pp
 - $R = 0.3$, $\Sigma p_T < 2 \text{ GeV}/c$
 - Efficiency: 69%
 - Background rejection: 1/170
 - First year (10 pb⁻¹)
 - 3000 γ ($E_\gamma > 20 \text{ GeV}$)
- PbPb
 - $R = 0.2$, $p_{T, \text{thresh}} = 2 \text{ GeV}/c$
 - Efficiency: 50%
 - Background rejection: 1/14
 - One month of running
 - 2000 γ ($E_\gamma > 20 \text{ GeV}$)

Y. Mao, Poster QM2008,
ALICE-INT-2007-021

G. Conesa et al., NIM A 580(2007) 1446,
NIM A 585(2008) 28

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Direct photons

Sensitivity of subtraction method

- [1] N. Arneodo, (ed.) et al. F.Arleo et al.,
J.Phys.G35:054001, 2008
 2+1 hydro, T_h 650 MeV, reach RHG EOS
 pQCD: CTEQ6.5M + nDSg, AKK-m_s=50 GeV
 [2] F. Arleo et al., (Yellow Report) **hep-ph/0311131**
 pQCD: CTEQ5M, KKP(BFG) for γ ,
 EKS98-Eloss(0 for γ)
 [3] S.Tubide et al., **Phys.Rev.C72:014906,2005**

Upper p_T limit is defined by

- Available statistics
- Ability to separate π^0 and single photons ~ 50 GeV

D. Peressounko, Hard Probes 2008

ense Matter in Heavy Ion Collisions and Astrophysics, A. Marin (Dubna July 2008)

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Jets and Jet quenching (I)

- Jets : reflect interactions of partons in partonic matter
- Effects
 - Reduction of single inclusive high p_T particles
 - Parton specific (stronger for gluons than quarks)
 - Flavour specific (stronger for light quarks)
 - Measure identified hadrons (p, K, p, Λ , etc.) + heavy partons (charm, beauty) at high p_T
 - Change of fragmentation function for hard jets ($p_T \gg 10$ GeV/c)
 - Transverse and longitudinal fragmentation function of jets
 - Jet broadening $\rightarrow$ reduction of jet energy, dijets, g-jet pairs

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Jets and Jet Quenching (II)

Experimental Consequences

- Measurement of Jet Energy is important
 - Initially ALICE measures only charged particles and electromagnetic energy in PHOS
 - Large EM Calorimeter under construction and will provide significant performance bonus
- Measurement of Jet Structure very important
 - Requires good momentum analysis from $\sim 1\text{ GeV}/c$ to $\sim 100\text{ GeV}/c$
 - ALICE excels in this domain
- pp and pA measurements essential as reference for physics in cold nuclear matter

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Jet quenching

- Excellent jet reconstruction... but challenging to measure global medium modification ...

Medium induced redistribution of jet energy occurs inside cone

- $E_t = 100\text{ GeV}$ (reduced average jet energy fraction inside R):
 - Radiated energy $\sim 20\%$
 - $R=0.3 : DE/E=3\%$

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Why photon-tagged jets?

- Medium effects redistribute ($\propto q_t^{\wedge}$) the parton energy, E_{jet} inside the hadron jet (multiplicity, j_T).
- Redistribution can be best measured with the Fragmentation Function... *If we know E_{jet} .*

- HI environment hinders precise reconstruction of E_{jet} .

If we measure $E_{\gamma} \approx E_{jet}$

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Full Simulation and Reconstruction Jet Spectra

Reconstruction efficiency dominated
by smearing of the spectrum
Charged jets: 33%
Charged + neutral: 68%

Charged Jets

Charged + EMCal

Statistics for 1 month of PbPb running

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Jet Production at LHC

- Initial measurements up to 100 GeV (untriggered charged jets only)
- Detailed study of fragmentation possible
- Sensitive to energy loss mechanism
- Accuracy on transport coefficient $\langle q \rangle \sim 20\%$

$p_{\text{t,jet}} >$ (GeV/c)	jets/event Pb+Pb	accepted jets/ month
5	$3.5 \cdot 10^2$	$4.9 \cdot 10^{10}$
50	$7.7 \cdot 10^{-2}$	$1.5 \cdot 10^7$
100	$3.5 \cdot 10^{-3}$	$8.1 \cdot 10^5$
150	$4.8 \cdot 10^{-4}$	$1.2 \cdot 10^5$
200	$1.1 \cdot 10^{-4}$	$2.8 \cdot 10^4$

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ALICE: Photon-Tag Jets Fragmentation Function

Y. Mao, Poster QM2008,
ALICE-INT-2007-021

G. Conesa et al., NIM A 580(2007) 1446,
NIM A 585(2008) 28

Imbalance distribution

Isolated photons and background subtracted

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ALICE: γ -tagged FF R_{AA}

Systematic errors due
to jet(π^0)-jet background

$$R_{AB} = \frac{dN_{AB}^P}{\langle T_{AB} \rangle_C \times d\sigma_{NN}^P}$$

G. Conesa et al., NIM A 580(2007) 1446,
NIM A 585(2008) 28

Sensitive to medium modifications at low z

if larger than ~5%

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THE END

<http://www.lhcountdown.com/>

Thanks to the ALICE collaborators

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