The ALICE Experiment @ the LHC

Measurement of Quarkonia as a Probe for a Quark Gluon Plasma

Moritz Pohl
Goethe Universität Frankfurt

IAP Seminar
2. December 2011

Performance Studies for the Measurement of $\psi(2S)$ via the Decay Channel $\psi(2S) \to J/\psi\ \pi^+\pi^- \to e^+e^-\pi^+\pi^-$ with the ALICE Detector

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Outline

- Physical Motivation
  - Introduction
  - Quark Gluon Plasma
  - Quarkonia
- Infrastructure
  - The LHC
  - ALICE
- Performance Study
  - Simulation
  - Analysis
- Summary and Outlook

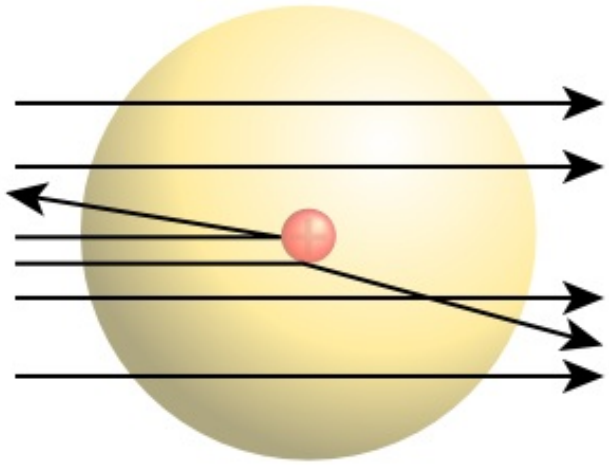
Elements

Natural Philosophy

- Empedokles, 450 b.c.
  Earth, Air, Water, Fire
- Leukipp, 430 b.c.
  Atoms and void as fundamental parts

Modern Physics

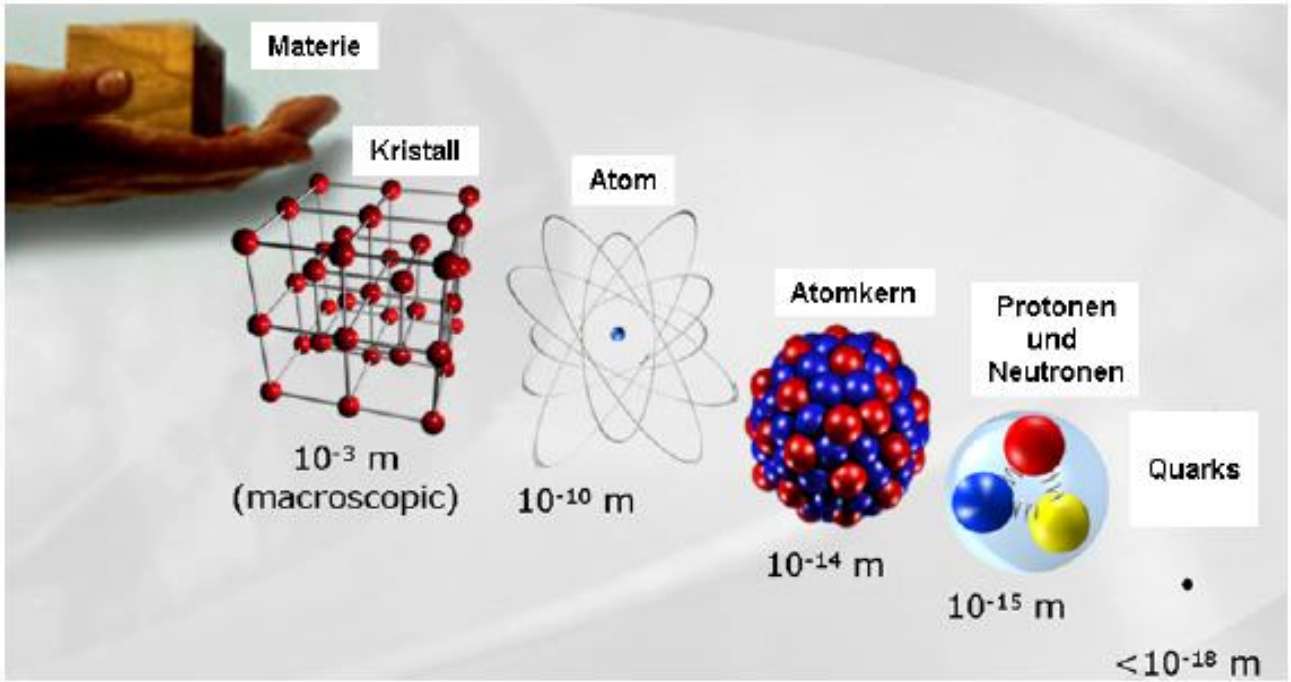
- Thompson, 1897: The electron
- Rutherford, 1909: Strukture of the atom
- Bohr, 1913: Quantum physical model of the atom



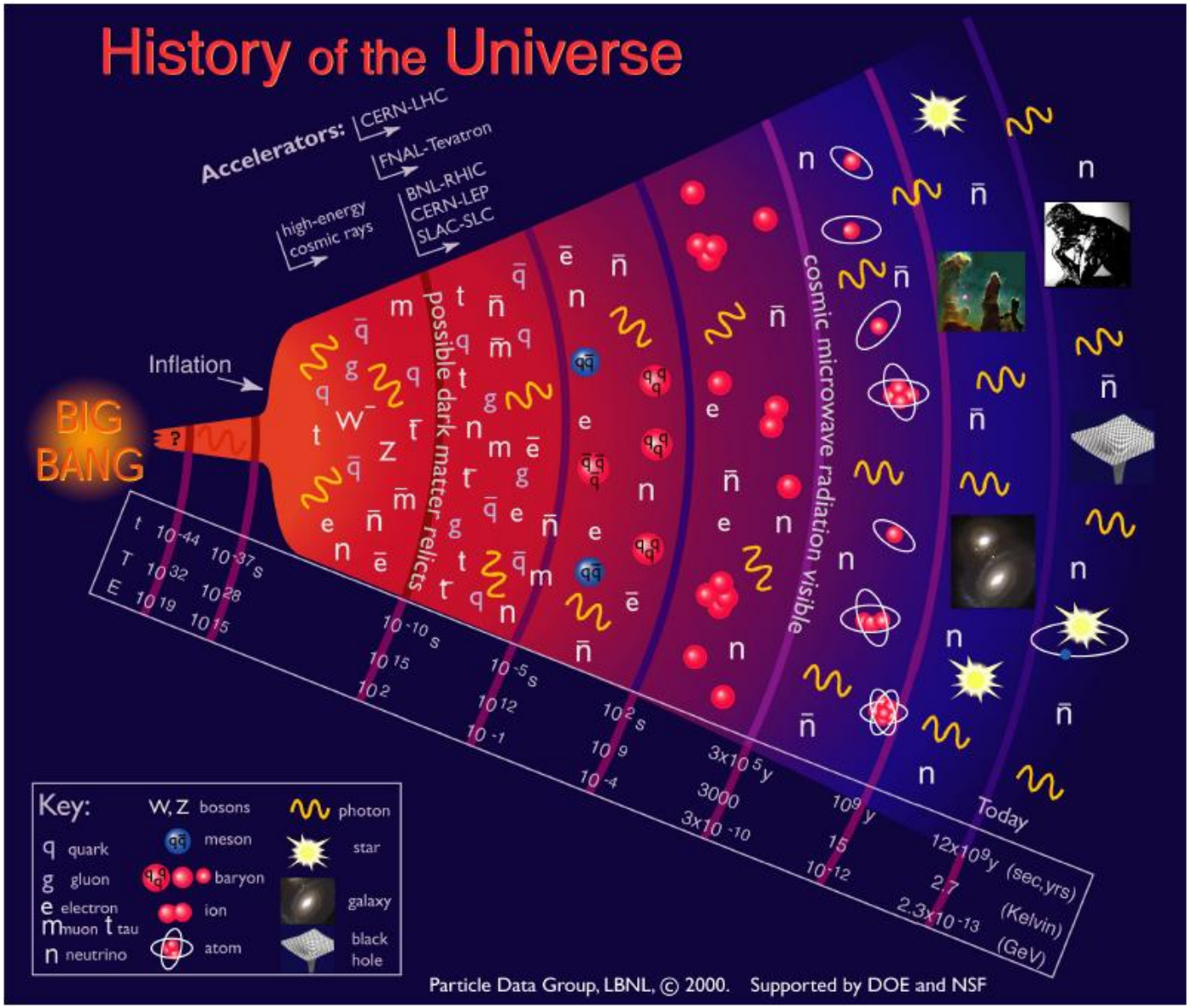
The smallest Component

The Standard Model

- Gell-Mann, 1964: Quark model
- What is the most elemental component?
- How to study?



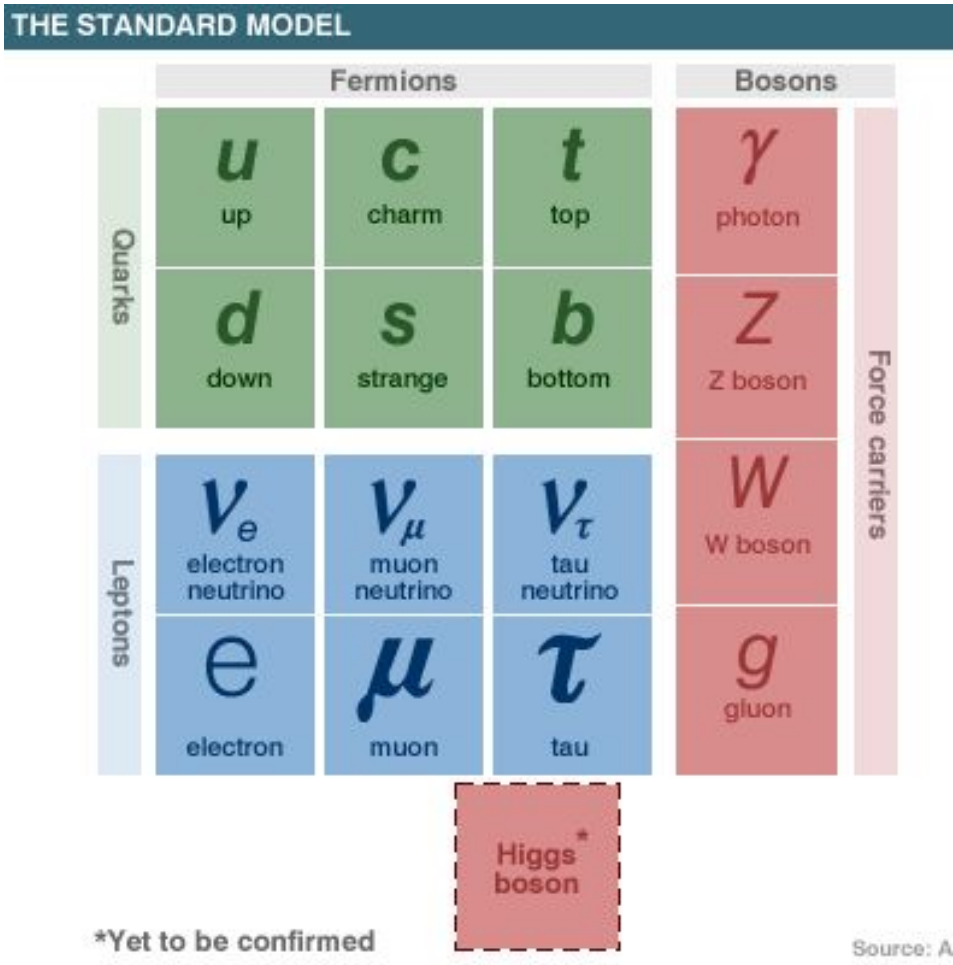
Why to study the QGP?



The Standard Model

Subparticles

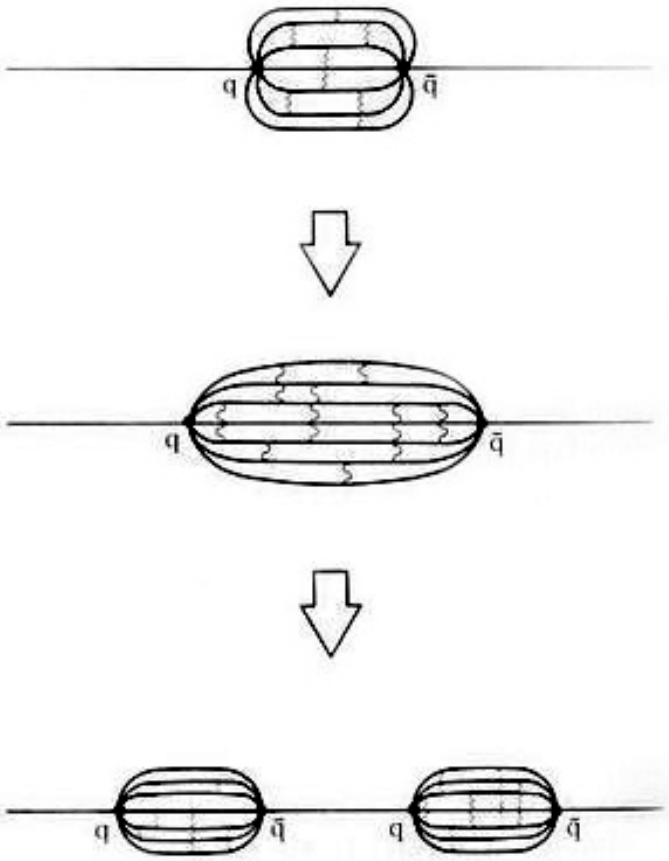
- Leptons
- Quarks
- Hadrons (Neutral)
  - Mesons (2 Quarks)
  - Baryons (3 Quarks)
  - Perhaps others



Confinement

Asymptotic Freedom

- Strong interaction
- Quantum Chromo Dynamic (QCD)
- Quarks and Gluons can not be isolated singularly
- Potential:
  $V_s = -\frac{4}{3}\frac{\alpha_s}{r} + kr$
- „Running“ coupling constant:
  $\alpha_S(Q^2) = -\frac{12\pi}{(33-2n_f)\cdot\ln(Q^2/\Lambda^2)}$



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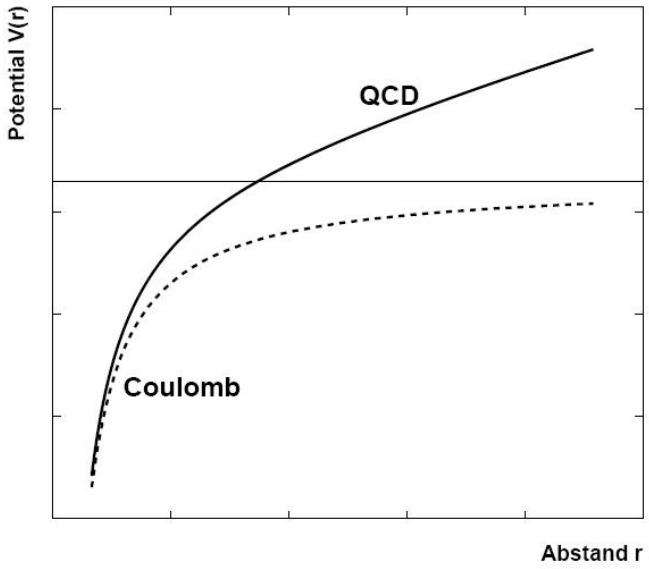
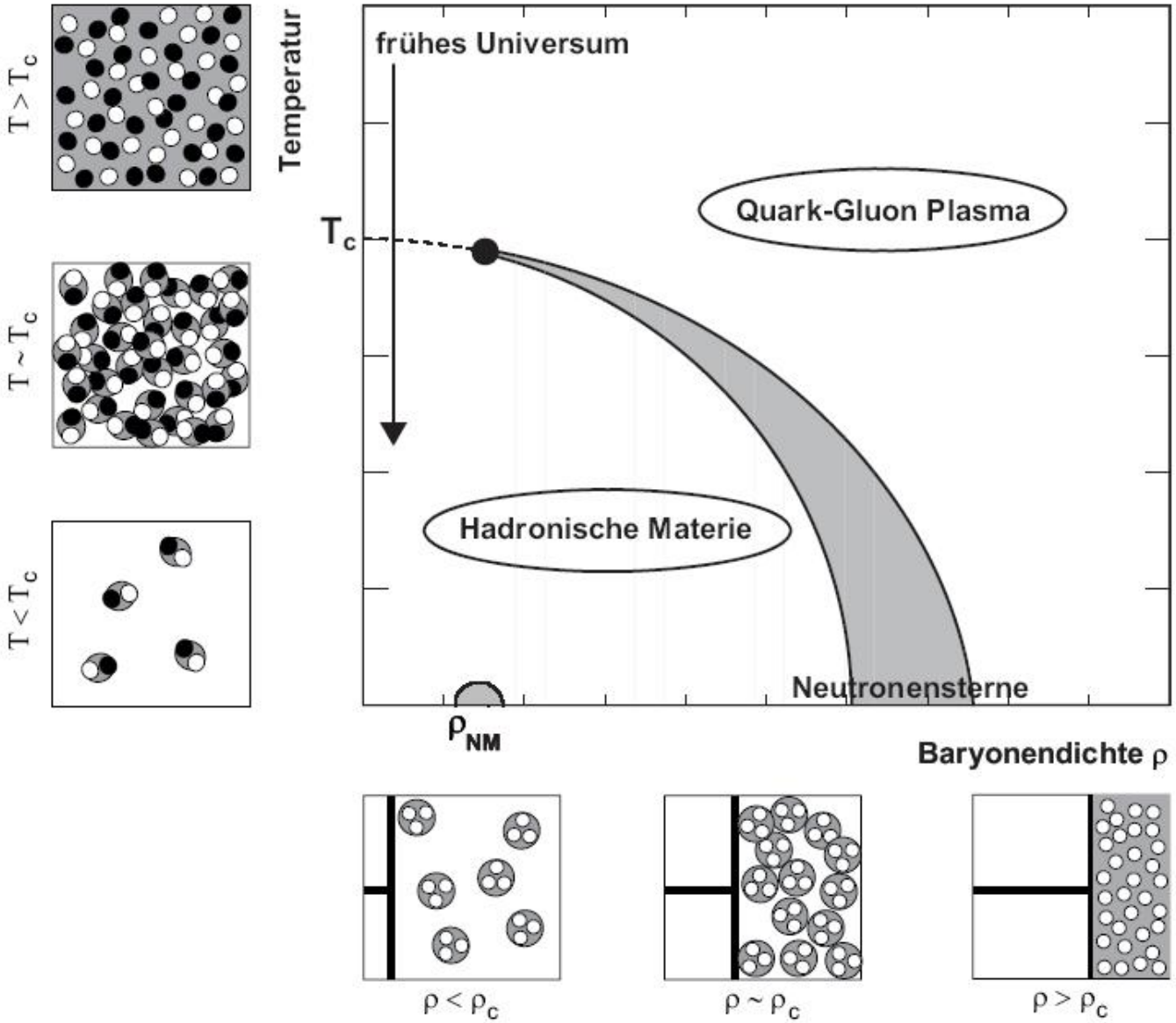


The Quark Gluon Plasma (QGP)

Extreme Matter

- Hadron is state of matter of a quark gluon system $\rightarrow$ Are there other states?
- High temperature (200 MeV) or density ($10^{18}\,\frac{\mathrm{kg}}{\mathrm{m}^3}$) $\rightarrow$ unbound quarks and gluons
- Can this state be reproduced in laboratories?
- Can it be found in the universe?

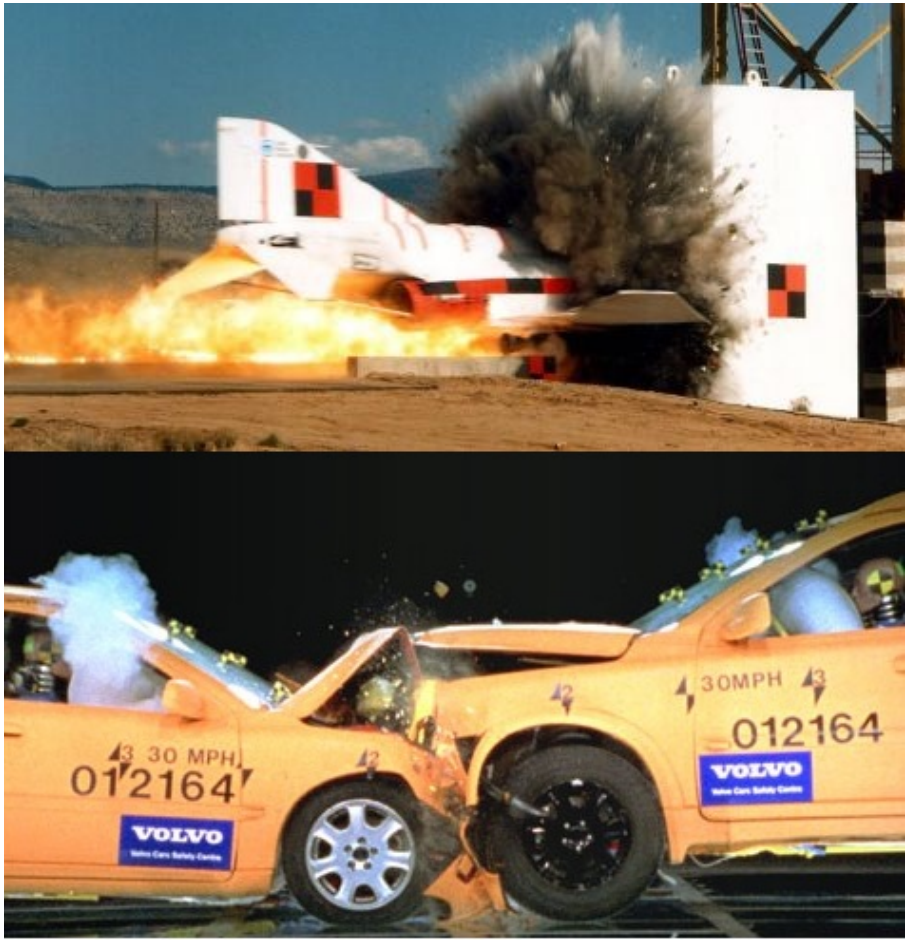
The Quark Gluon Plasma Phase Diagram



QGP in Experiment

How To

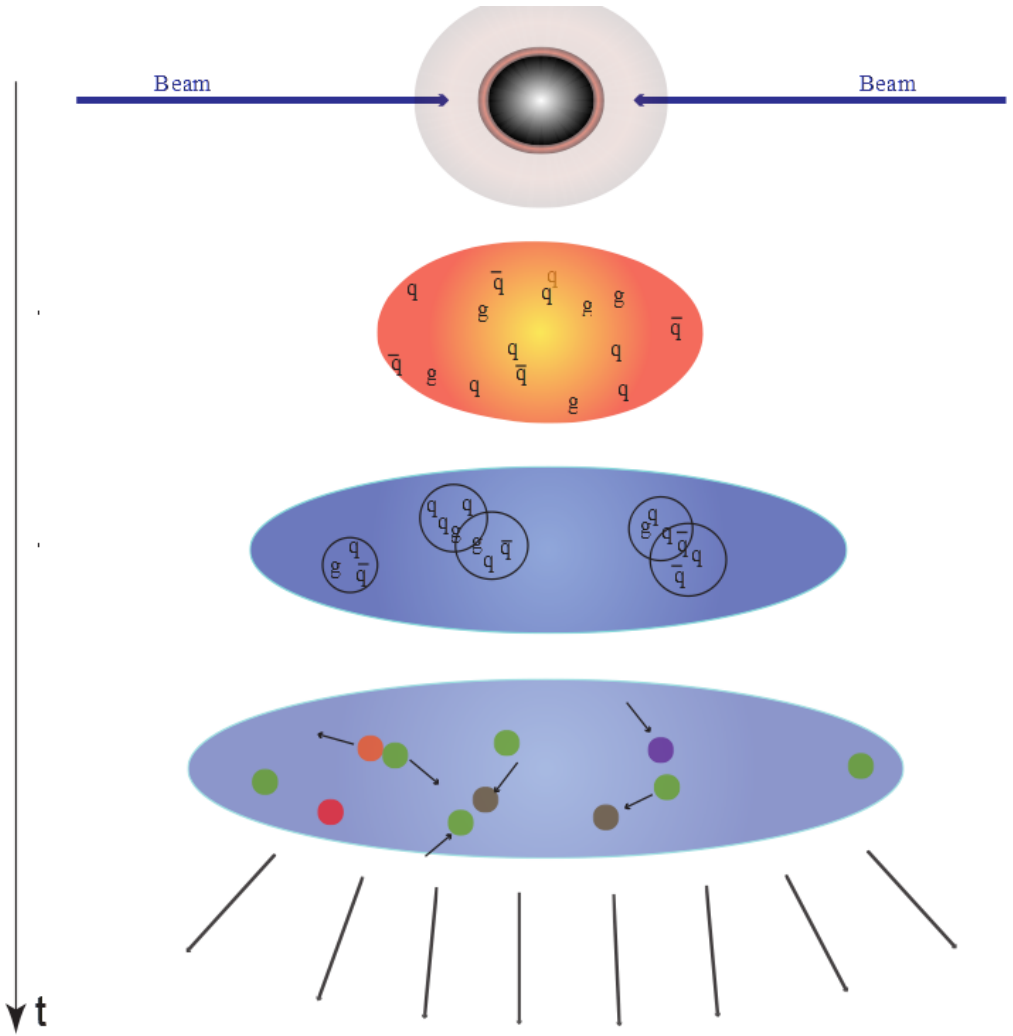
- Have the right idea and money
- Build infrastructure
- Accelerate ions to 99.9999% c
- Fixed target or collision experiment



QGP in Experiment II

Sequence of a Heavy Ion Collision

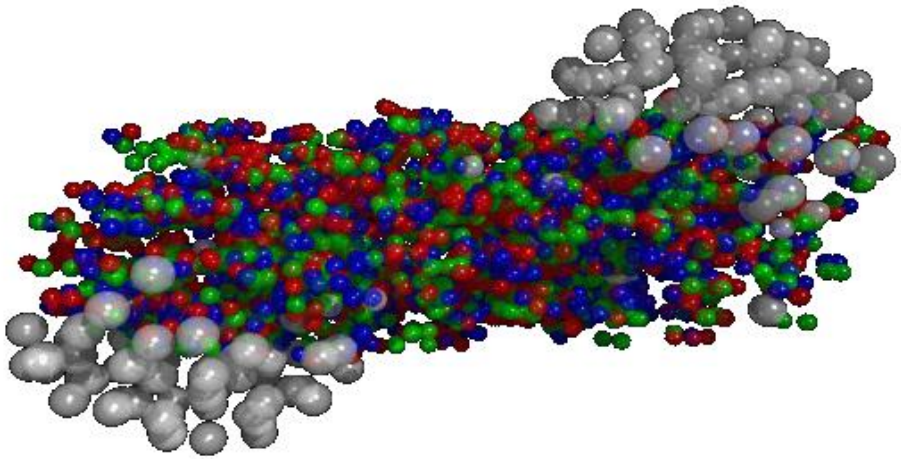
- Fireball
- QGP
- Hadrongas
- Chemical freeze out
- Thermical freeze out



Signatures of a QGP

Observables

- Transverse momentum p_{T}
- Transverse energy E_{T}
- Multiplicity of particles
- Photons (prompt, thermal)
- Leptones
- Jet quenching
- Productionrate of heavy quarks
  $\rightarrow$ Quarkonia

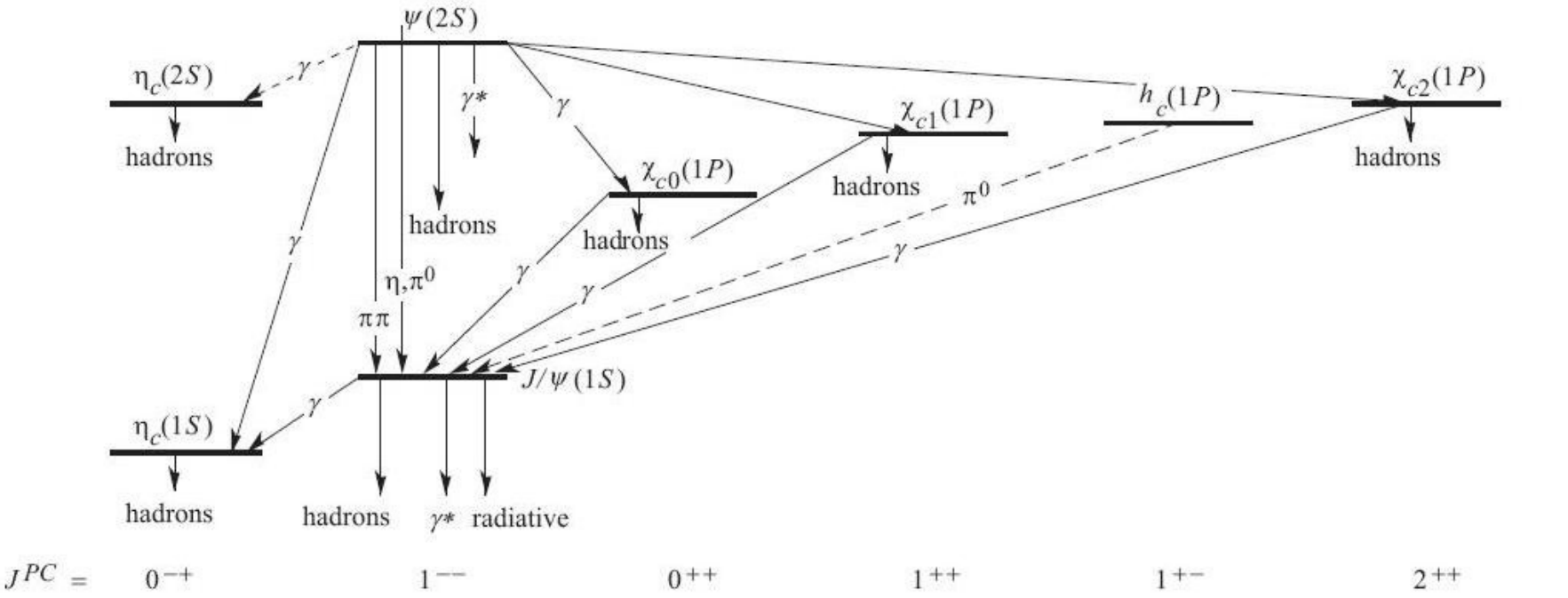


Quarkonia

Long Life Resonances

- System of heavy quarks
- Bottomonia: $b\bar{b}$
- Charmonia: $c\bar{c}$
- Small decay width: J/ψ 87 keV; ψ(2S) 277 keV
  $\rightarrow$ Long lifetimes, treated like particles
- Different decay channels. Most common measured: Di-leptonic

Charmonia

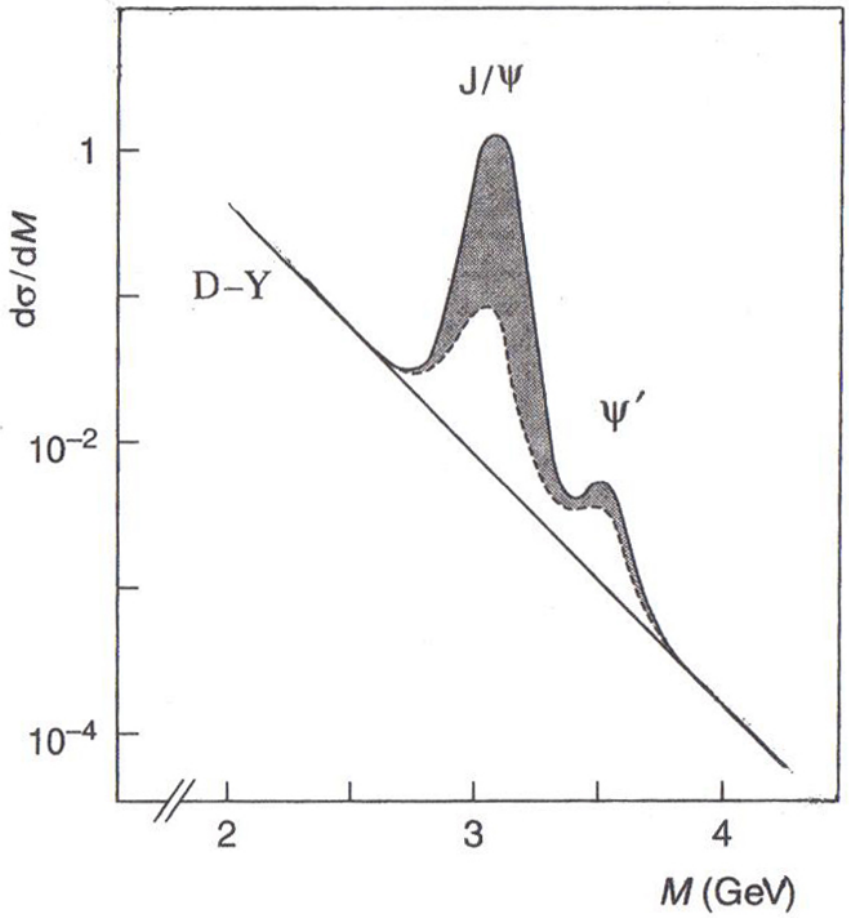


Particle Data Group 2010

Quarkonia Supression

Screening in a QGP

- Analog to debye screening
- Color charge is dominating
- Color charge screening by free gluons → Decrease of charmonium numbers
- $V^{\mathrm{eff}}_{Q\bar{Q}}(r,T) \approx -\frac{4}{3}\frac{\alpha_s}{r}e^{r/\lambda_{\mathrm{D}}(\mathrm{T})}$
- Compare to drell Yan Process (scaled pp to NN)
- Quarkonia thermometer



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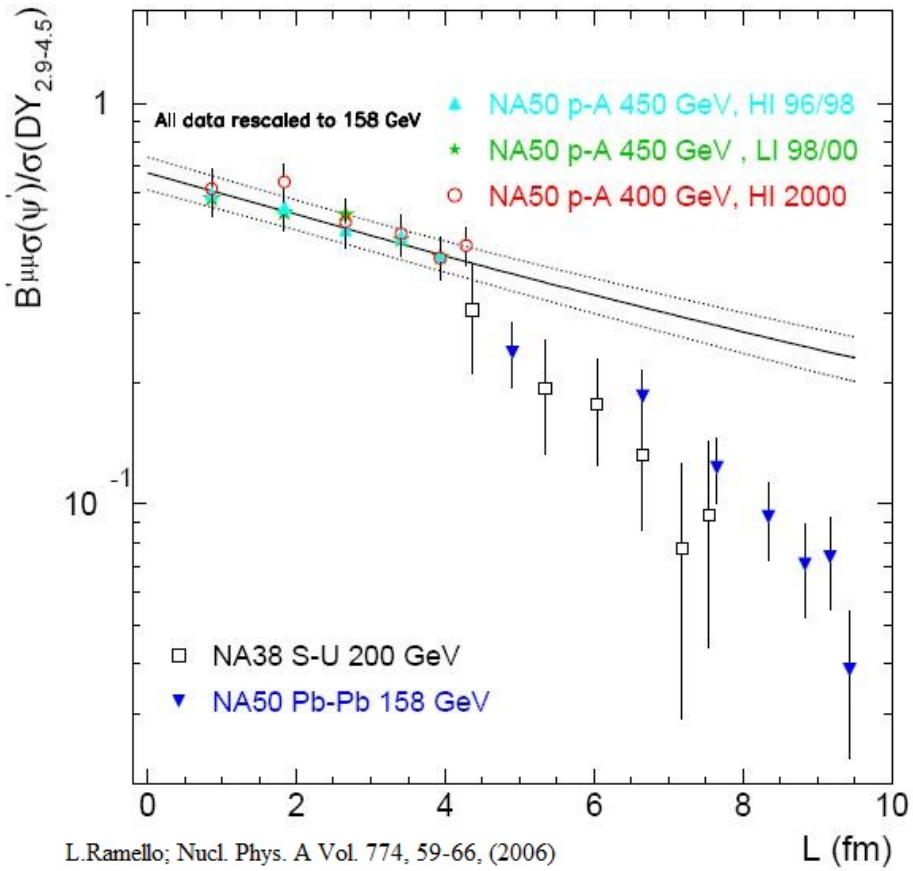


L.Ramello; Nucl. Phys. A Vol. 774, 59-66, (2006)

The $\psi(2S)$ Meson

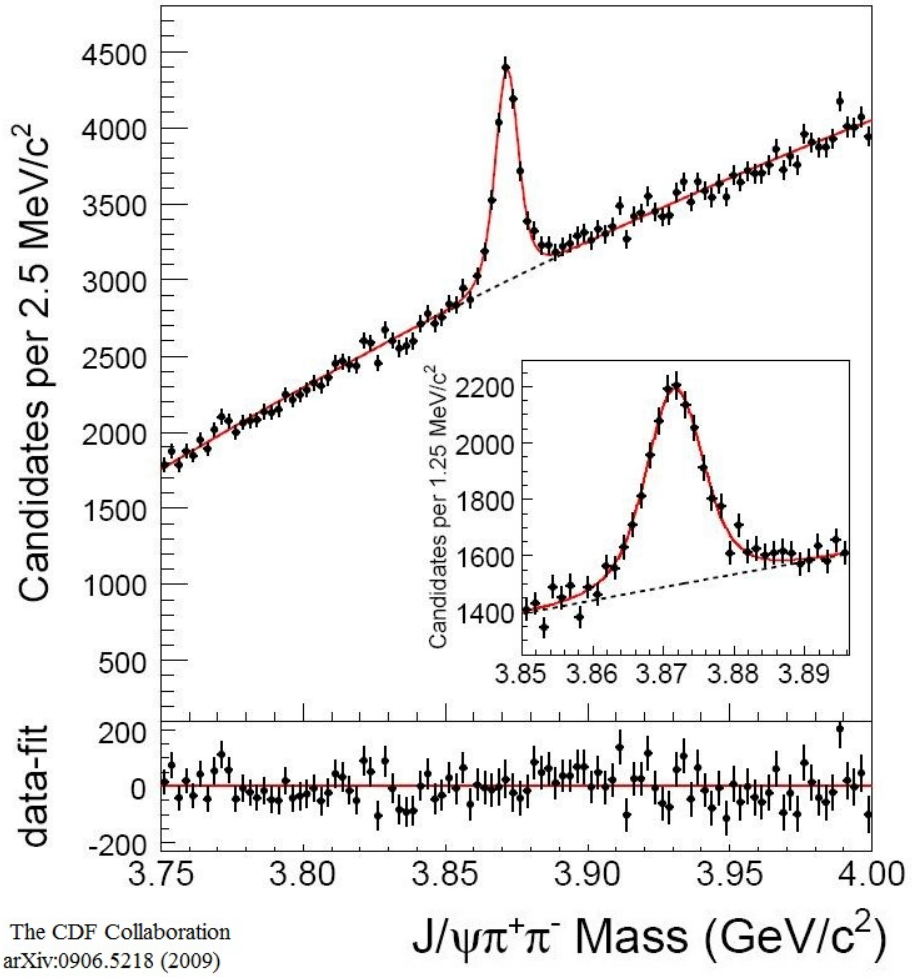
Why measure $\psi(2S)$

- Mass: 3.686 GeV/c^2
- Charmonium: $c\bar{c}$ system
- Production of charmonia is an promising signature of a QGP
- Understanding of excited charmonia states is crucial for J/ψ analysis
- Branching ratio for $\psi(2S) \to J/\psi\ \pi^+\pi^- \to e^+e^-\pi^+\pi^-$ is $\approx 2\%$; nearly three times higher than the dileptonic br
- The exotic X(3872) particle exhibits the same decay channel

The X(3872) Particle

What shouldn't be there...

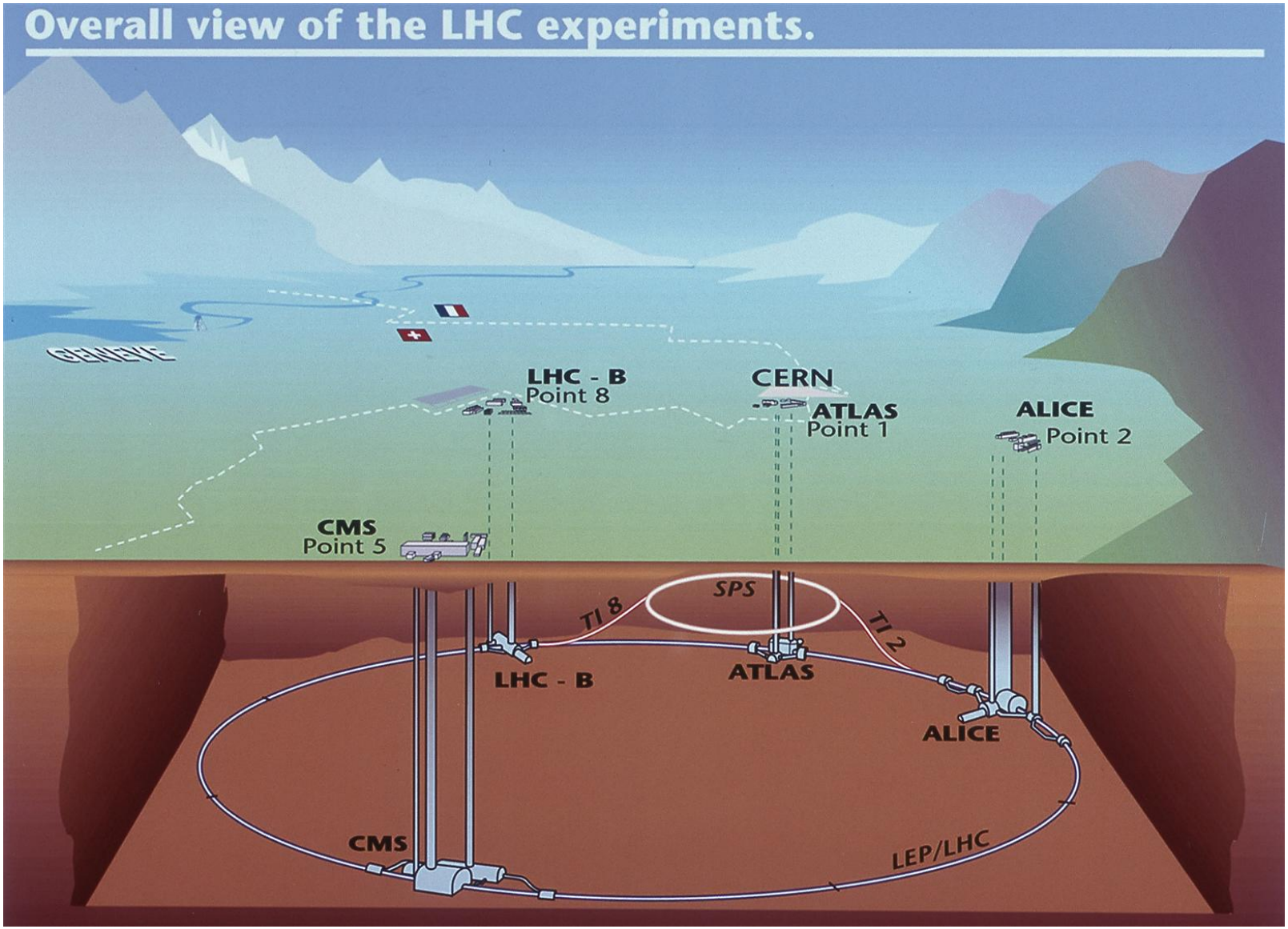
- Belle experiment in 2003:Peak in invariant mass of $J/\psi\ \pi^+\pi^-$
- CDF 2009: $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions
- Quantum numbers not confirmed; 1^{++} or 2^{-+}
- No plausible charmonium state
- Diverse theories: slightly bound diquark-antiquark system $(cu\bar{c}\bar{u})$; $\bar{D}^{*0}D^0$ molecule....



European Organization for Nuclear Research

- Staff: 8000 + 2500
- 85 Countries
- 575 Universities
- Located at the border of swiss and france near Geneva
- Biggest research facility in the world

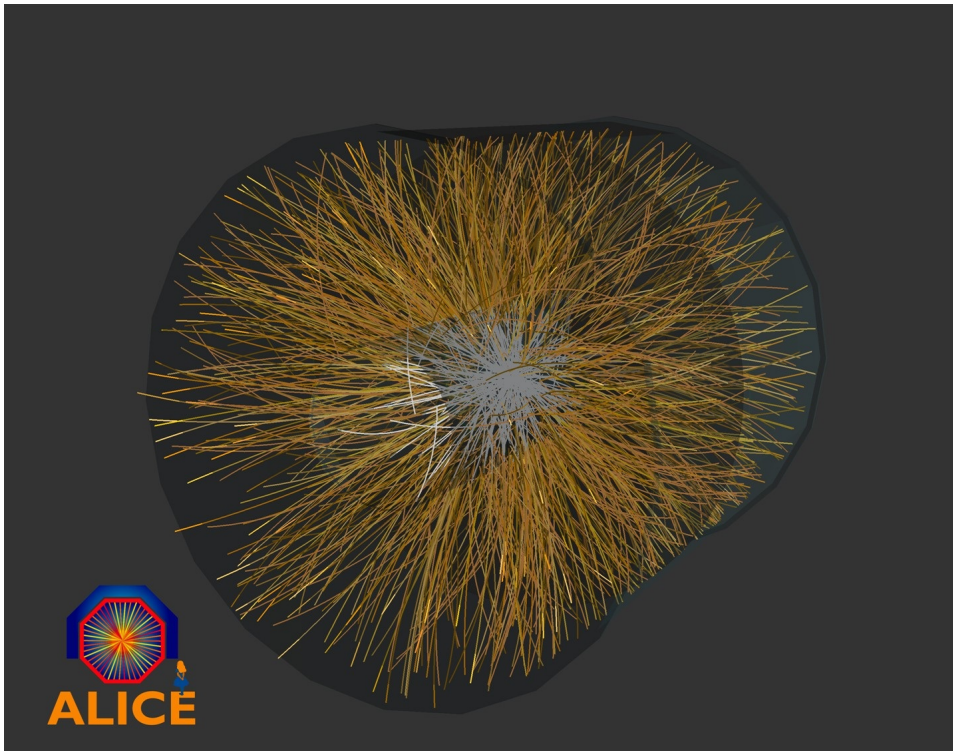
The Large Hadron Collider @ CERN



The Large Hadron Collider @ CERN

Facts

- Perimeter 26.7 km
- Cost $3{\cdot}10^9$ Euro
- Magneticfield up to 8 Tesla
- ATLAS, CMS, LHCb, TOTEM, ALICE
- 2800 Bunches with 10^{11} protons
- Max. collisionenergy: pp collisions $\sqrt{s} = 14$ TeV, in PbPb $\sqrt{s} = 5.5$ TeV
- World record 11.2010: PbPb collision with $\sqrt{s} = 2.76$ TeV

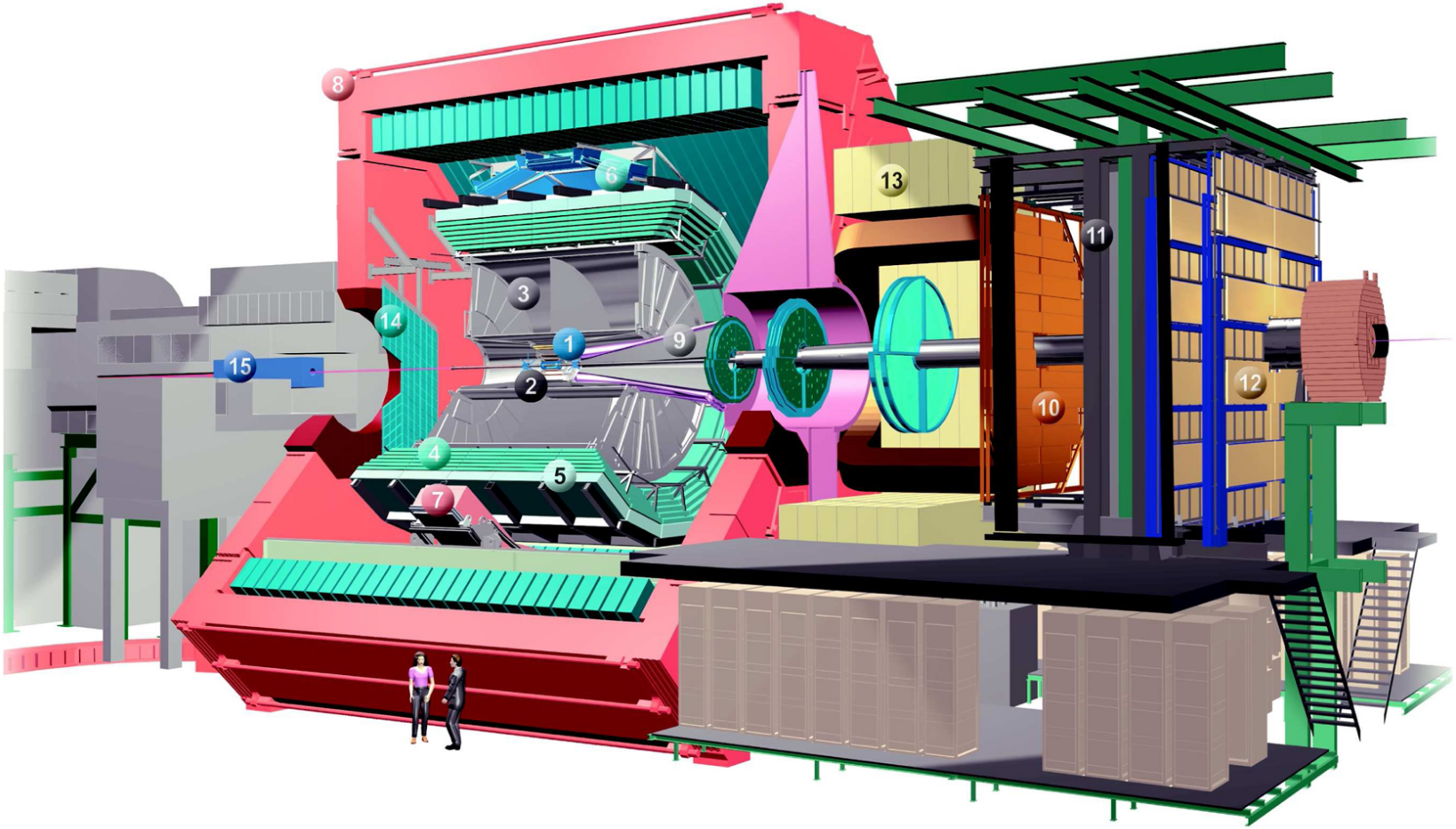


The ALICE Experiment at the LHC

A Large Ion Collider Experiment (ALICE)

- General-purpose heavy-ion detector
- Focus on QGP studies in heavy-ion collisions
- pp data as reference
- 10.000 Tons
- Different detectors
- More than a 1000 scientists
- Datarate 1,25 GB/s

The ALICE Experiment at the LHC

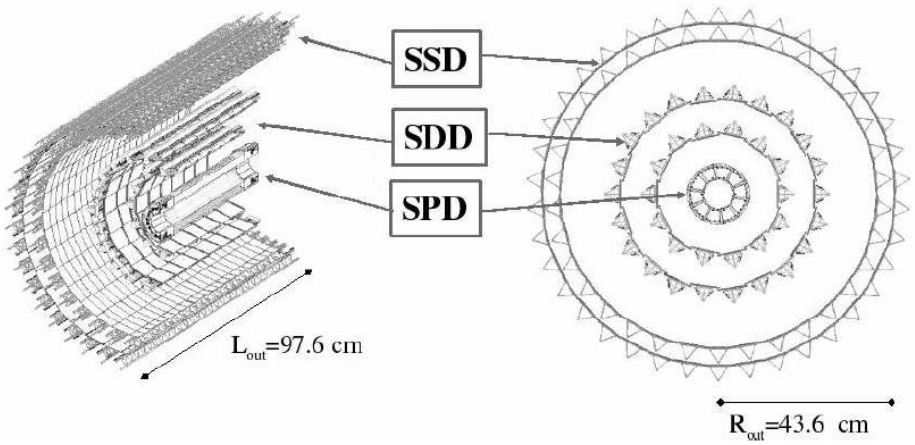


1. ITS (Inner Tracking System)
2. FMD (Forward Multiplicity Detector)
3. TPC (Time Projection Chamber)
4. TRD (Transition Radiation Detector)
5. TOF (Time-of-Flight Detector)
6. HMPID (High-Momentum Particle Identification Detector)
7. PHOS CPV (Photon Spectrometer Charged Particle Veto Detector)
8. L3 Magnet
9. Absorber
10. Tracking Chambers
11. Muon Filter
12. Trigger Chambers
13. Dipole Magnet
14. PMD (Photon Multiplicity Detector)
15. Compensator Magnet

Central Barrel Detectors I

Inner Tracking System (ITS)

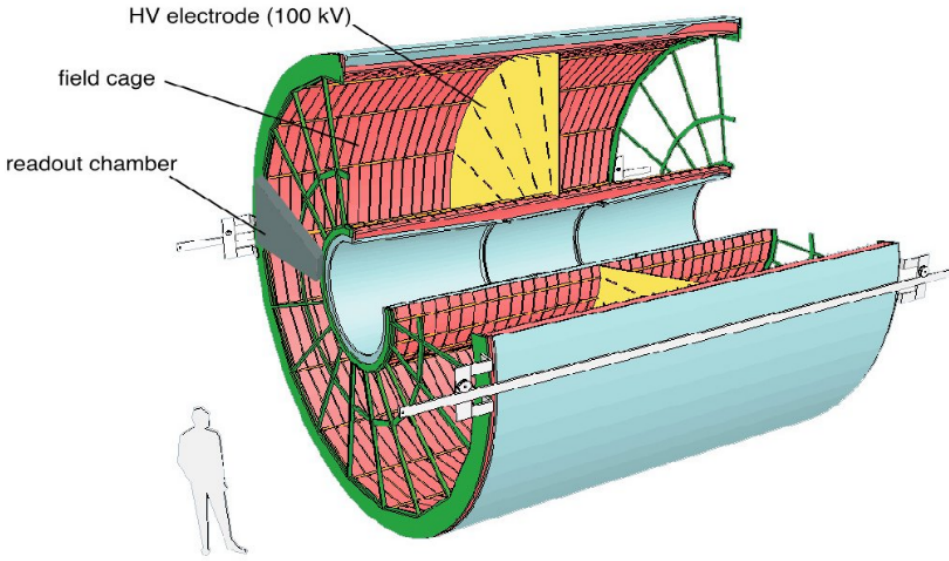
- 97.6 x 43.6 cm
- Detection surface 6.28m^2
- Resolution better than 100 μm
- Localization of primary & secondary vertices
- Subsystems: SPD, SDD, SSD



Central Barrel Detectors II

Time Projection Chamber (TPC)

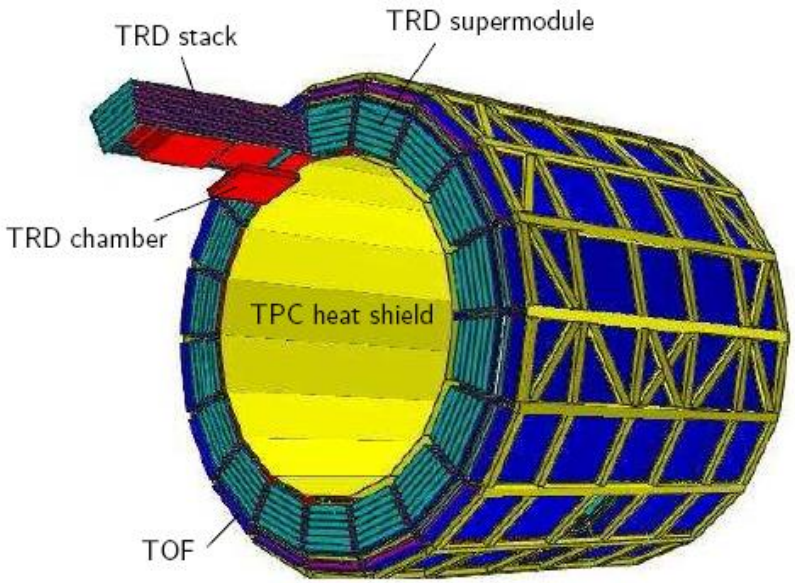
- 5 x 1.60 m
- Active volume 88 m^3
- Gasmixture: 85.7% Ne, 9.5% CO_2, 4.8% N_2
- Main tracking detector
- Particle identification (PID)
- Max. drift time 92 μs
- 557.568 Read out pads
- Possible detection range 0.1 - 100 GeV/c



Central Barrel Detectors III

Transition Radiation Detector (TRD)

- 18 super-modules with 30 submodules made of 6 stacks
- 85% Xe + 15% CO_2
- Sandwich material, 3 layers
- Electrons cause radiation, pions don't
- Electron/Pion separation, 100:1 with momentum bigger than 1 GeV/c
- Trigger
- Not completed today



Simulation and Reconstruction

Simulation

- Recreat detector geometry with software
- Take efficiencies and into account
- Calculate interactions and tracks for particles
- Calculate detector response

Reconstruction

- Find tracks in the detectors
- Calculate kinematic
- Independet from simulation
- Reconstructed data from simulation and real measurement are comparable

Monte-Carlo Data Sets

$\psi(2S)$ Signal

- Pure $\psi(2S)$ MC sample
- 0.84 M $\psi(2S)$ decaying exclusively via $\psi(2S) \to J/\psi\ \pi^+\pi^- \to e^+e^-\pi^+\pi^-$

Background

- 1.2 M minimum bias pp collisions at $\sqrt{s} = 7$ TeV
- Pythia6 MC production with Perugia0 tune

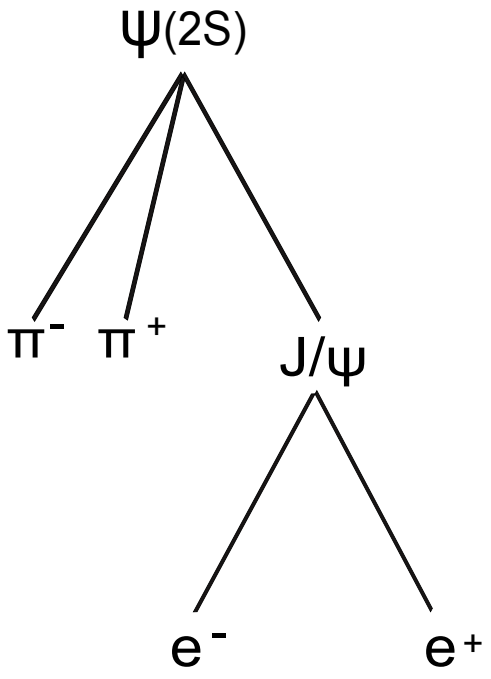
Reconstruction Chain

Track selection

- Fully reconstructed data
- Track quality cuts
- PID via parametrization of TPC & TRD Signal

$\psi(2S)$ Reconstruction

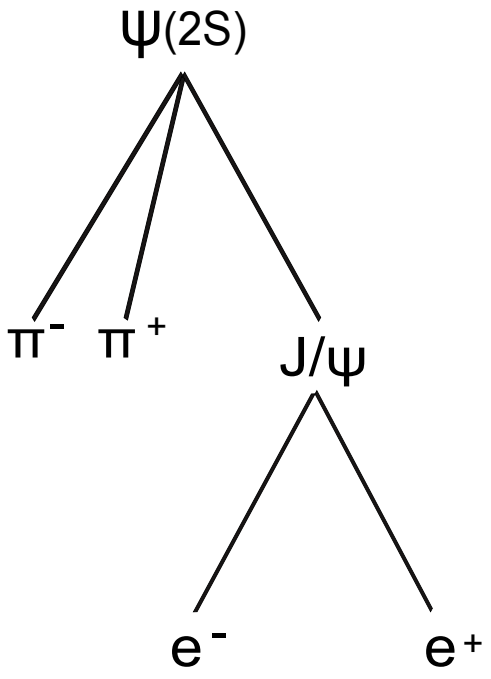
- Reconstruct $e^+e^- \rightarrow J/\psi$
- Select J/ψ candidates via invariant mass
- Combine with $\pi^+\pi^-$ pairs



Reconstruction Chain

Analysis

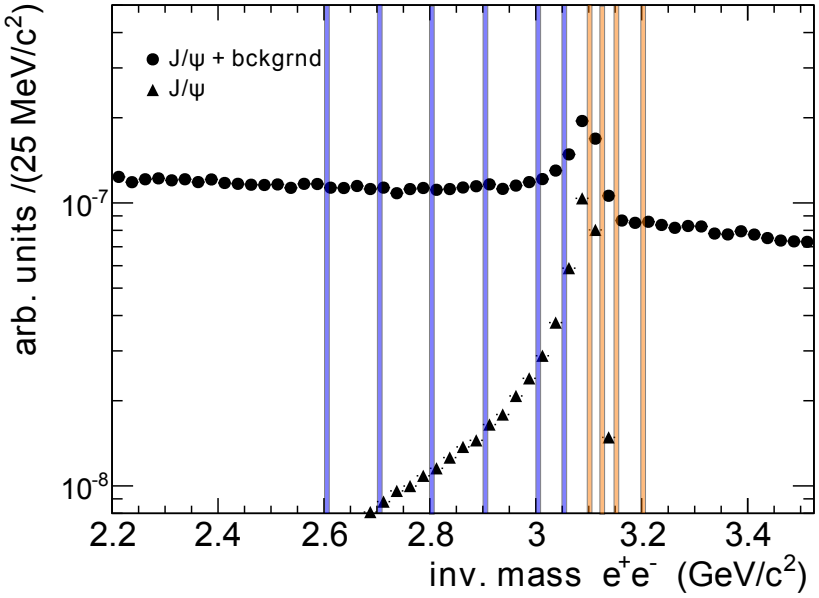
- Calculate reconstruction efficiency
- S/B & significance for min. bias pp collisions at $\sqrt{s} = 7$ TeV
  - Cut on e^+e^- p_{T}



Selection of J/ψ Candidates

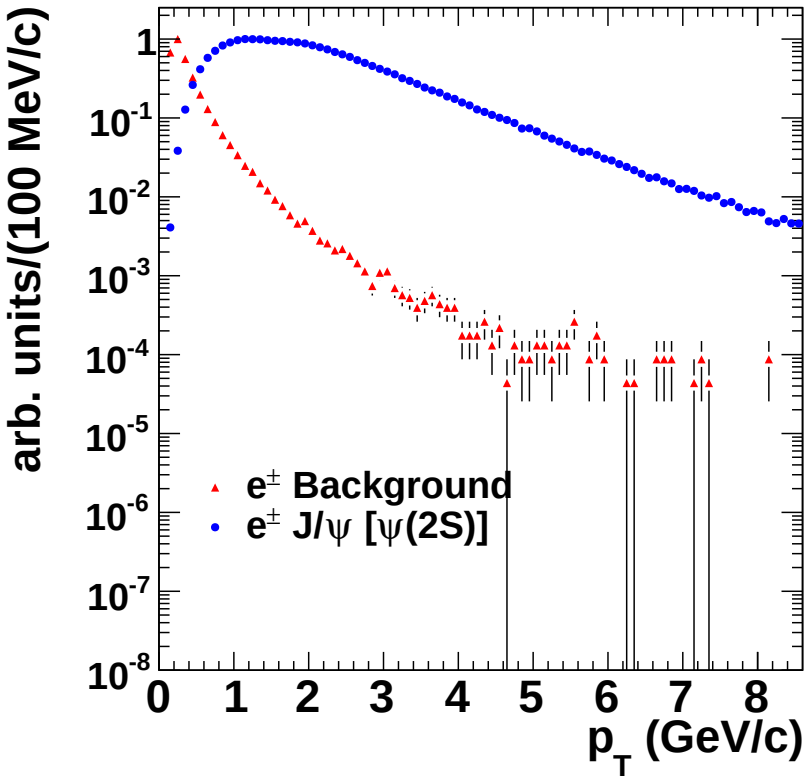
Mass window

- Select J/ψ candidates via the invariant mass
- Reduce background via this selection
- vary upper and lower limit
- $\rightarrow$ different mass windows



Cut on Transverse Momentum of e^+e^-

- Study kinematics of the decay products to find differences
- Compare p_{T} of e^+e^- from J/ψ of $\psi(2S)$ decays to those from background
- Vary min. p_{T} of e^+ and e^- from 0 to 2.0 GeV/c



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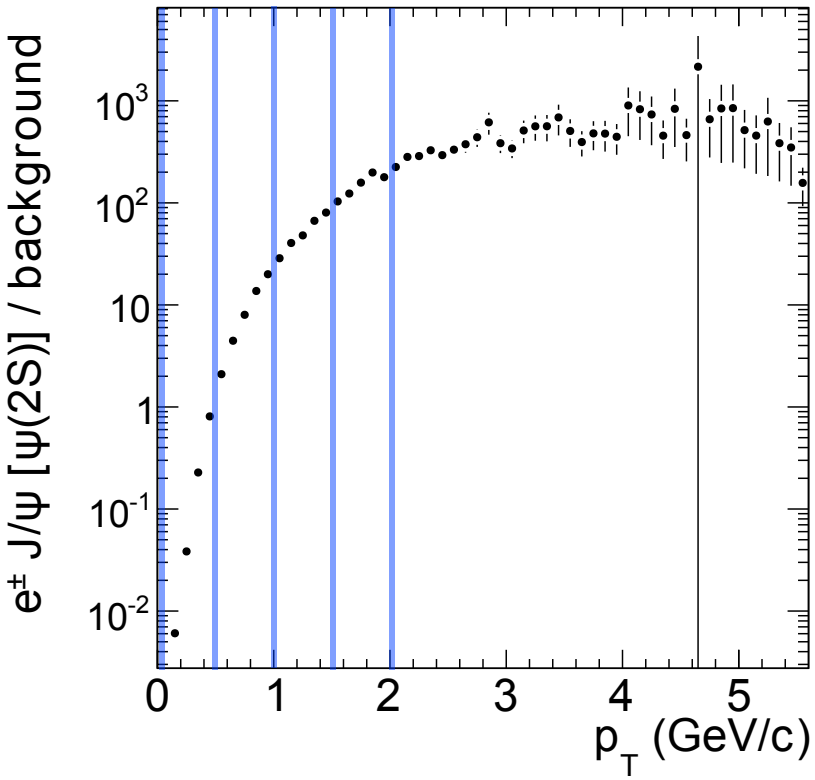
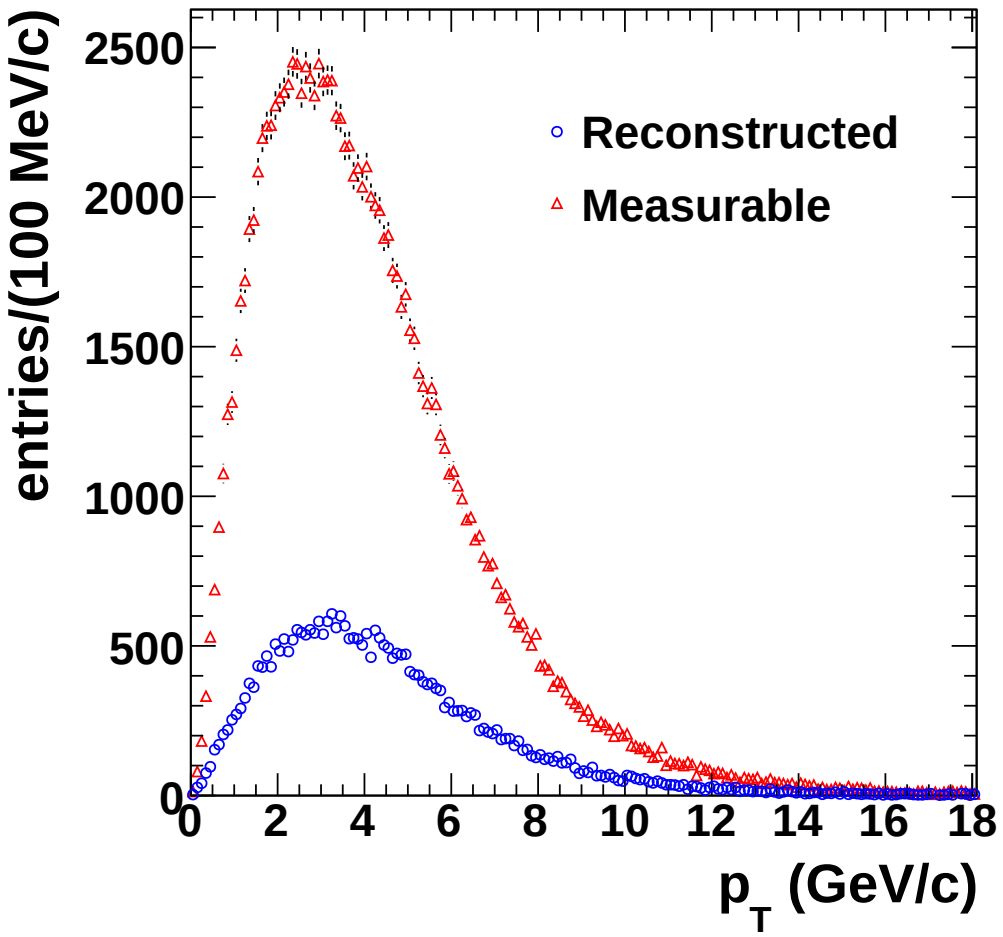


Reconstruction Efficiency

- $\mathrm{E}_{\psi(2\mathrm{S})} = \frac{\text{reconstructed}}{\text{measureable}}$
- reconstructed: $e^+e^-\pi^+\pi^-$ from the same $\psi(2S)$ decay
- measurable: $e^+e^-\pi^+\pi^-$ in $|\eta| < 0.84$
- Include mass windows
- Include p_T cut for $e^\pm$
- $\mathrm{E}_{\psi(2S)} \approx 14\%$ (2.7 - 3.15 GeV/c, min. p_T e^+, e^- 1 GeV/c)



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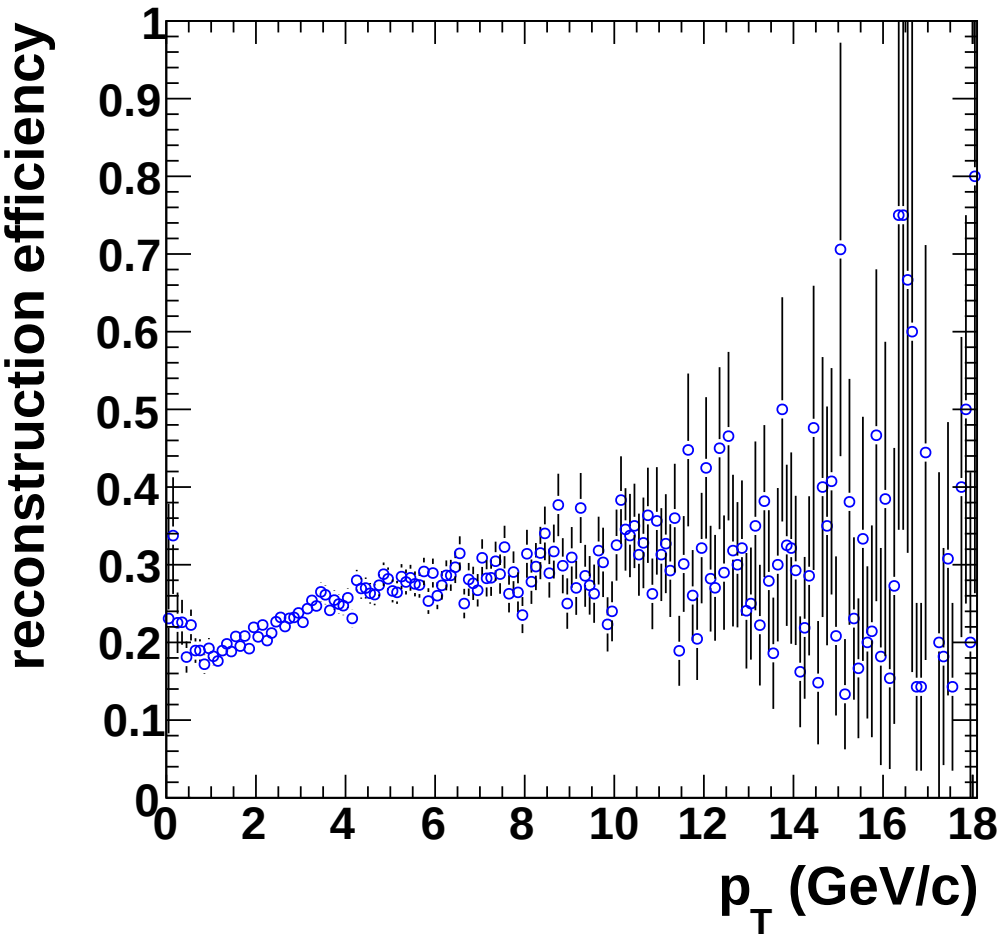

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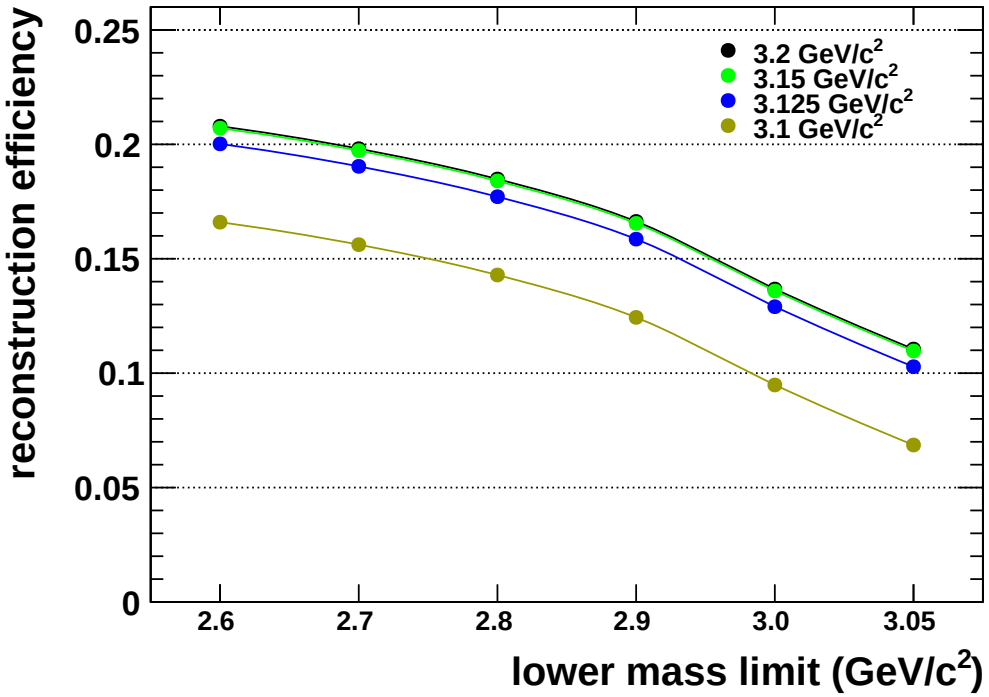

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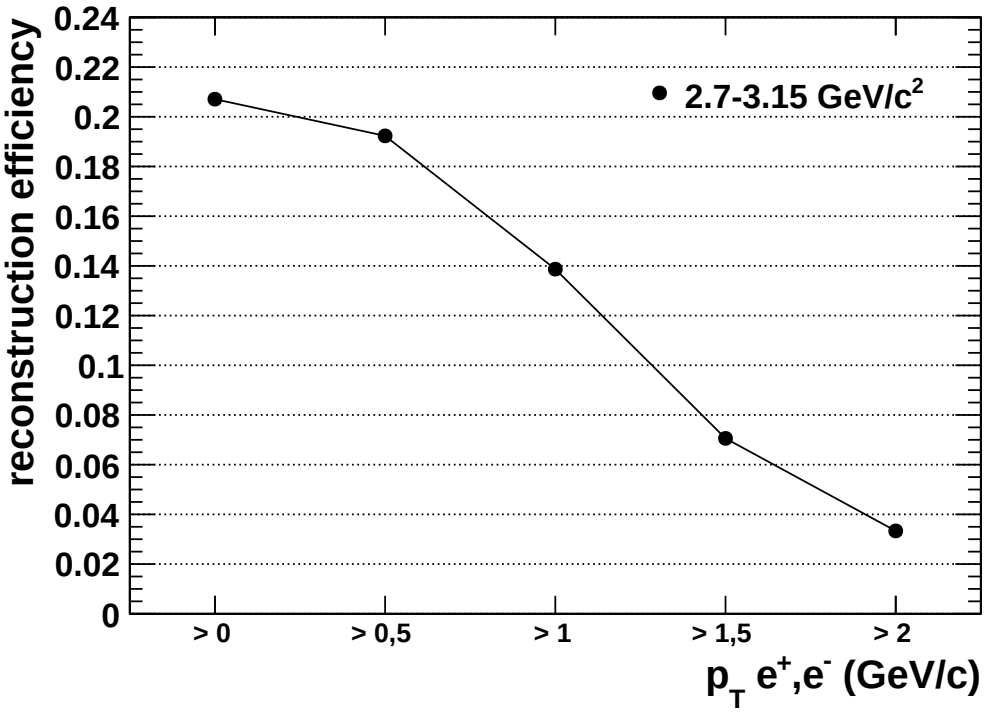
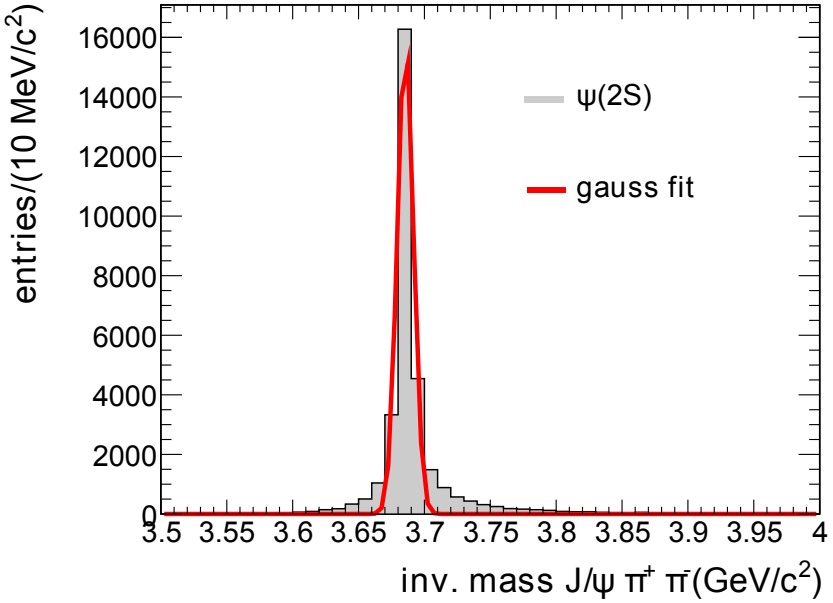


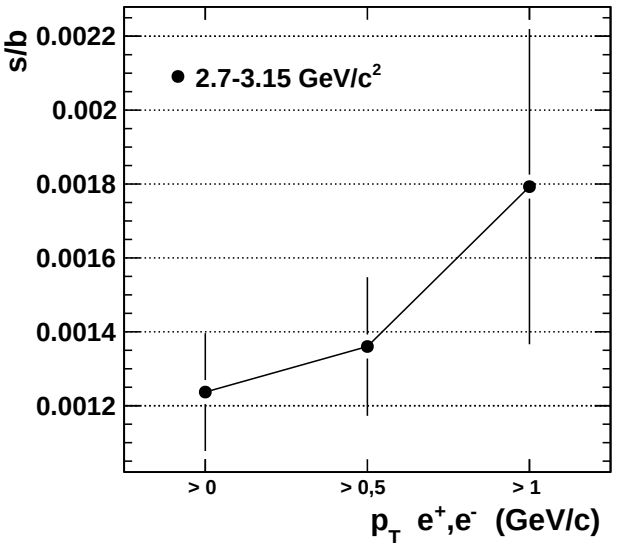
Invariant Mass

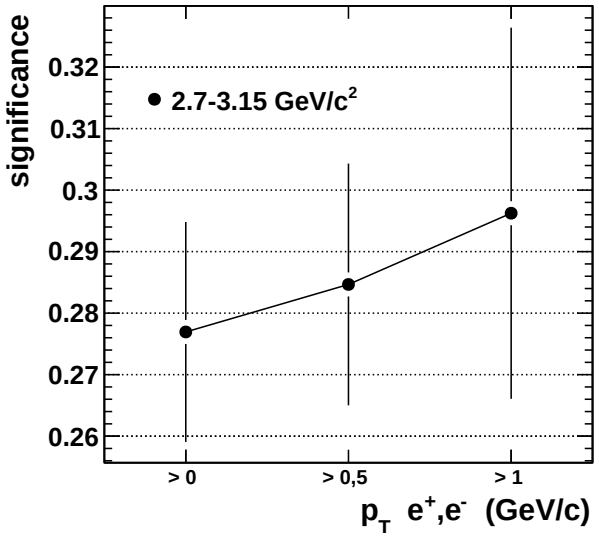
- reconstructed $J/\psi\ \pi^+\pi^-$ from same $\psi(2S)$
- Pure $\psi(2S)$ MC signal
- Gauss fit
- Mass resolution ≈ 7 MeV/c^2



Signal to Background / Significance

- For 10^9 pp events (minimum bias, $\sqrt{s} = 7$ TeV, min. p_{T} e^+, e^- 1 GeV/c):
  - Signal to background ratio: $(1.8 \pm 0.4) \cdot 10^{-3}$
  - Significance: $(2.96 \pm 0.30) \cdot 10^{-1}$





Summary

ALICE

- The LHC is the biggest accelerator ever
- ALICE is capable to proof and study the QGP
- It offers unique opportunities
- Significant results published since autumn 2010

For the $\psi(2S)$ Analysis

- Good mass resolution ≈ 7 MeV/c^2
- Reconstruction efficiency $\approx 14\%$
- Signal to background ratio: $(1.8 \pm 0.4) \cdot 10^{-3}$
- Significance for 10^9 pp events: $(2.96 \pm 0.30) \cdot 10^{-1}$

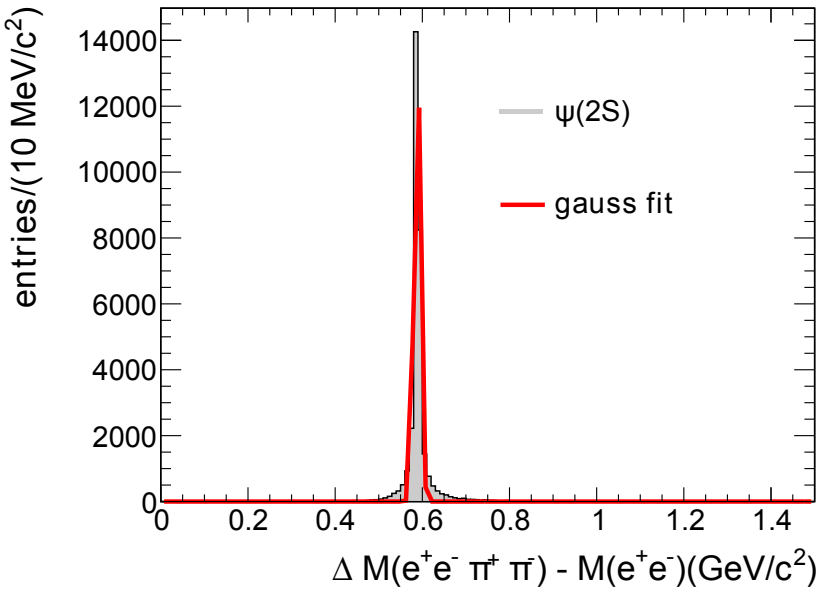
Outlook

- LHC and the installed detectors are unique, and will provide the scientific community with challenges and information for years
- With completed TRD and LHC at maximum intensity ALICE will reach a break through in QGP studies
- For the ψ(2S) Analysis:
  - S/B improvement needs further studies
  - Study kinematics of the decay products
  - TRD as trigger, enhance signal

Thank you for your attention.

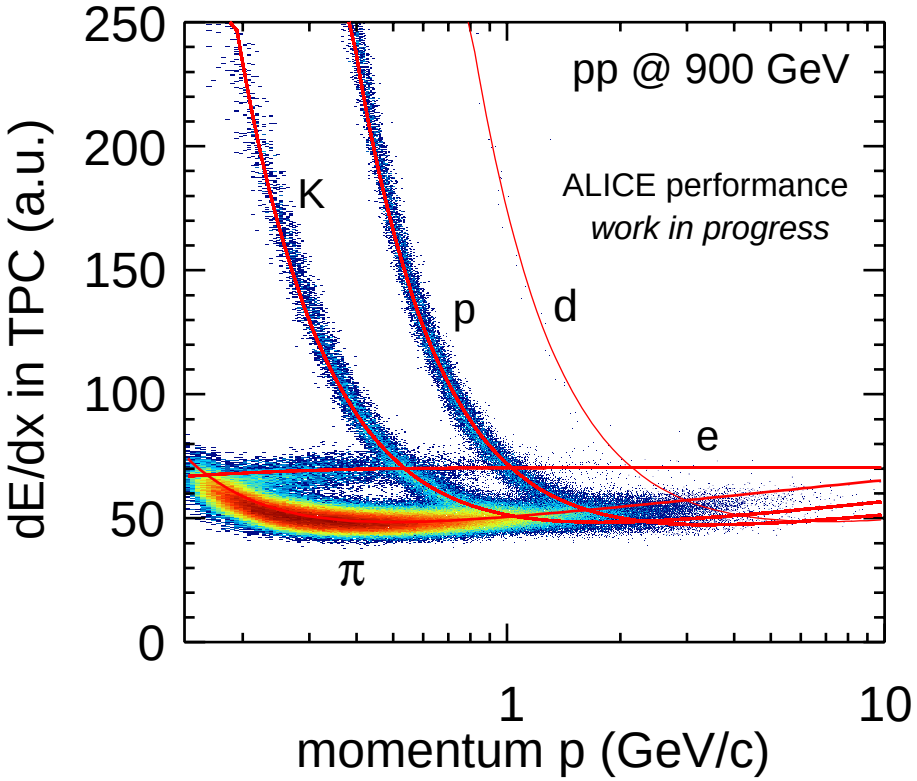
Invariant Mass Spectra

- reconstructed $J/\psi\ \pi^+\pi^-$ from same $\psi(2S)$
- ΔM : $M(e^+e^-\pi^+\pi^-) - M(e^+e^-)$
- Gauss fit
- Mass resolution ≈ 7 MeV/c^2



PID with the TPC

- Bethe Bloch formula for energy deposit in gas
- $-\left(\frac{dE}{dx}\right) = K \cdot z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} ln \frac{2m_e \cdot c^2 \cdot \beta^2 \cdot \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$



Parametrization of the PID

- Contamination of electrons with pions
- Function with variables $\epsilon_\pi(p_\mathrm{T}, \theta, \phi)$