ALICE Experiment @ LHC

A Large Ion Collider Experiment dedicated to heavy-ion collisions however, running also pp program

- Physics motivation
- Experimental conditions
- Physics performance
WHY HEAVY IONS AT THE LHC?
... factor $\sim 30$ jump in $\sqrt{s}$ ...

J. Schukraft QM2001: hotter - bigger - longer lived

<table>
<thead>
<tr>
<th>Central collisions</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s^{1/2}$ (GeV)</td>
<td>17</td>
<td>200</td>
<td>5500</td>
</tr>
<tr>
<td>dN$_{ch}$/dy</td>
<td>500</td>
<td>850</td>
<td>2–8 x10$^3$</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm$^3$)</td>
<td>2.5</td>
<td>4–5</td>
<td>15–40</td>
</tr>
<tr>
<td>$V_f$ (fm$^3$)</td>
<td>10$^3$</td>
<td>7x10$^3$</td>
<td>2x10$^4$</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>&lt;1</td>
<td>1.5–4.0</td>
<td>4–10</td>
</tr>
<tr>
<td>$\tau_0$ (fm/c)</td>
<td>~1</td>
<td>~0.5</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

$\varepsilon_{LHC} > \varepsilon_{RHIC} > \varepsilon_{SPS}$

$V_f_{LHC} > V_f_{RHIC} > V_f_{SPS}$

$\tau_{LHC} > \tau_{RHIC} > \tau_{SPS}$
LHC Energy

For A-A collisions:

\[ E_{\text{cms}} \] = 5500 \text{ A GeV} \\
\[ E_{\text{lab}} \] = \frac{E_{\text{cms}}^2}{(2A \text{ m}_N)} = 1.61 \times 10^7 \text{ A GeV} \\

for lead ions \[ E_{\text{lab \ Pb-Pb}} \] = 3.35 \times 10^9 \text{ GeV} = 3.35 \times 10^{12} \text{ MeV}

Further we need Harald Fritzsch Identity (definition of Anglo-Saxon pound £_{\text{AS}})

\[ 2 \times 10^{-30} \text{ £}_{\text{AS}} = m_e \] (= 0.511 MeV)

and some other definitions (gravitational acceleration \( g \),

\[ g = 1 \text{ in}/\text{tr}^2 \] (1 s = 19.65 tr, trice)

(speed of light \( c \))

\[ c = 6 \times 10^8 \text{ in}/\text{tr} \]

\[ m_e c^2 = 72 \times 10^{-14} \text{ £}_{\text{AS}} \text{ in} \] (= 0.511 MeV)

\[ 1 \text{ MeV} = 1.41 \times 10^{-12} \text{ £}_{\text{AS}} \text{ in} \]

Finally

\[ E_{\text{lab Pb-Pb}} = 1 \text{ £}_{\text{AS}} \times 4.7'' \] (= 0.45 kg \times 12 \text{ cm})
And for pp collisions:

\[ E_{\text{lab \, pp}(14 \text{TeV})} = 0.15 \, \text{AS} \ \text{in} \approx \frac{1}{4} \, \text{AS} \times \frac{1}{2}'' = \frac{1}{8} \, \text{AS} \times 1'' = \ldots \]

For those who don’t like to be seated on a lead ion (and to fly inside LHC vacuum pipe)

\[ E_{\text{cms \, Pb-Pb}} = 5500 \, \text{A GeV} = 1.14 \times 10^9 \, \text{MeV} \]

(HFI, etc.)

\[ E_{\text{cms \, Pb-Pb}} = 10^{-3} \, \text{AS} \times 1.6'' (= 0.45 \, \text{g} \times 4 \, \text{cm}) \]

Still, macroscopic energy !!! (one can actually hear it)

But the size of ions

is by factor more than \(10^{-12}\) smaller
Novel aspects
Qualitatively new regime

- Probe initial partonic state in a novel Bjorken-x range $(10^{-3} - 10^{-5})$:
  - nuclear shadowing,
  - high-density saturated gluon distribution (CGC)
  - effectively moves RHIC forward region to mid-rapidity at LHC

- Larger saturation scale ($Q_S = 0.25A^{1/6}\sqrt{s}$, $\delta = 2.7$ GeV) particle production dominated by the saturation region
Novel aspects

Qualitatively new regime

- 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 ($\gamma$, $Z^0$, $W^\pm$)

![Graph showing cross-section (d\sigma/dy) vs. p_T with different Run-I experiments: LHC, RHIC, SPS. Key values: $\sqrt{s} = 5500 \text{ GeV}$, $200 \text{ GeV}$, $17 \text{ GeV}$, $<k_T^2> = 1.8 \text{ GeV}^2$, $Q^2 = p_T^2$.](image.png)
Moreover

Qualitative improvements:

- Vanishing net baryon density ($\mu_B \rightarrow 0$):
  - closer to early Universe, closer to Lattice QCD

- High energy density $\rightarrow$ maybe approaching the limit of an “ideal” gas of QCD quanta

- Stronger thermal radiation

- Hard probes:
  - Heavy flavours
  - Jets and jet quenching

Dominant processes in particle production
- SPS: soft
- RHIC: soft and semi-hard
- LHC: semi-hard and hard

(F. Karsch)
What multiplicity do we expect?

old estimates: \( \frac{dN_{\text{ch}}}{dy} = 2000 \text{ – } 8000 \),
now we can extrapolate from RHIC data

(from K.Kajantie, K.Eskola)

- ALICE optimized for \( \frac{dN_{\text{ch}}}{dy} = 4000 \), checked up to 8000 (reality factor 2)
but ...

- **The major uncertainties in the energy dependence are still there**
  - only some improvement with the RHIC data!

- **Still no safe way to extrapolate**
  - shadowing/saturation (might decrease charged multiplicity)
  - jet quenching (might increase it dramatically)
  - A-scaling (importance soft vs. hard changes with energy)

- **Simple scaling form RHIC (log–log plot) ~2500**

  → safe guess \( dN_{\text{ch}}/d\eta \sim 1500 – 6000 \)
Experimental conditions @ LHC

- pp commissioning starts after April 2007

- Agreed initial Heavy-Ion programme at LHC

- **Initial few years** (1HI ‘year’ = 10^6 effective s, ~like at SPS)
  - 2 - 3 years Pb-Pb \( \mathcal{L} \approx 10^{27} \text{cm}^{-2}\text{s}^{-1} \)
  - 1 year p - Pb ‘like’ (p, d or \( \alpha \)) \( \mathcal{L} \approx 10^{29} \text{cm}^{-2}\text{s}^{-1} \)
  - 1 year light ions (eg Ar-Ar) \( \mathcal{L} \approx \text{few } 10^{27} \text{ to } 10^{29} \text{cm}^{-2}\text{s}^{-1} \)
  - plus, for ALICE (limited by pileup in TPC):
    - reg. pp run at \( \sqrt{s} = 14 \text{ TeV} \) \( \mathcal{L} \approx 10^{29} \text{ and } < 10^{31} \text{cm}^{-2}\text{s}^{-1} \)

- Later: different options depending on Physics results

- Heavy-ion running is part of LHC initial programme, first run expected by the end of 2008
ALICE Physics goals
(has to cover in one experiment what at the SPS was covered by 6-7 experiments, and at RHIC by 4!!)

Global observables:
- Multiplicities, \( \eta \) distributions
- Degrees of freedom as a function of \( T \): 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 bottomium 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
- PID of hadrons and leptons
- Good secondary vertex reconstruction
- Photon Detection

Use a variety of experimental techniques!
Solenoid magnet 0.5 T
Central tracking system
- ITS
- TPC
- TRD
- TOF
Forward detectors
- PMD
- FMD, T0, V0, ZDC
Specialized detectors
- HMPID
- PHOS
MUON Spectrometer
- absorbers
- tracking stations
- trigger chambers
- dipole magnet
Cosmic-ray trigger
US EMCal (under discussion)

Pb-Scintillator EMCal
$\Delta \eta \times \Delta \phi = 1.4 \times 120^\circ$
~ 1000 Members
(63% from CERN MS)
~30 Countries
~80 Institutes

ALICE Collaboration
ALICE detector acceptance

05/10/2005 Physics Programme of ALICE Experiment K.Safarik

ALICE detector acceptance

Central Detectors

μon arm
PHAon Multiplicity Detector 2.4<η<4
Forward Multiplicity Detector 2.3<η<3.5
-5.4<η<-1.6, 1.6<η<3
A
LICE LAYOUT: TRACKING
(and event characterization)

Inner Tracking System (ITS):
6 Si Layers (pixels, drift, strips)
Vertex reconstruction, dE/dx
-0.9<\eta<0.9

TRD
electron identification, tracking
-0.9<\eta<0.9

TPC
Tracking, dE/dx
-0.9<\eta<0.9
If you thought this was difficult ...

NA49 experiment:
A Pb-Pb event
and this was even more difficult ...

A central Au-Au event
@ ~130 GeV/nucleon
... then what about this!
Tracking performance

TPC and ITS tracking efficiency – better than 90%
Track reconstruction in TPC-ITS

\( p_T \) resolution

- The track momentum is measured (mainly) by TPC.

- With ITS: resolution improves by a factor \( \sim 10 \) for high \( p_T \) tracks.

\[ \begin{align*}
   \text{Lever arm larger by 1.5 accounts for a factor } \sim 2 \\
   \text{Remaining effect due to high resolution of points measured in ITS} \\
   \text{More improvement comes including the TRD in the tracking}
\end{align*} \]
Tracking-II: Momentum resolution

resolution ~ 9% at 100 GeV/c
excellent performance in hard region!
ALICE PID

- π, K, p identified in large acceptance (2π * 1.8 units η) via a combination of dE/dx in Si and TPC and TOF from ~100 MeV to 2 (p/K) - 3.5 (K/p) GeV/c
- Electrons identified from 100 MeV/c to 100 GeV/c (with varying efficiency) combining Si+TPC+TOF with a dedicated TRD
- In small acceptance HMPID extends PID to ~5 GeV
- Photons measured with high resolution in PHOS, counting in PMD, and in EMC

Alice uses ~all known techniques!
Under study: extension of PID to even higher momenta

- Combine TPC and TRD dE/dx capabilities (similar number of samples/track) to get statistical ID in the relativistic rise region

8<p<10 GeV/c
LHC Experiments

Single particle spectra
Correlation studies
Jet reconstruction

T = Λ_{QCD} \quad Q_s

Bulk properties

Hard processes
Modified by the medium

ALICE

CMS&ATLAS

(pid)

p_t (GeV/c)

0 1 2 10 100

05/10/2005 Physics Programme of ALICE Experiment K.Safarik
Parton Energy Loss

\[ \langle \Delta E \rangle = \int_0^{\omega_c} d\omega \frac{\omega dN}{d\omega} \propto \alpha_s C_R \hat{q} L^2 \]

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

Medium transport coefficient
\( \propto \) gluon density and momenta

Parton Energy Loss

**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 ($\pi$, K, p, $\Lambda$, etc.) + partons (charm, beauty) at high $p_t$

- Suppression of mini-jets
  - same-side / away-side correlations

- Change of fragmentation function for hard jets ($p_t >> 10$ GeV/c)
  - Transverse and longitudinal fragmentation function of jets
  - Jet broadening → reduction of jet energy, dijets, $\gamma$-jet pairs

- $p+p$ and $p+A$ measurements crucial
Heavy Quarks – dead cone

- Heavy quarks with momenta $< 20–30 \text{ GeV}/c \rightarrow \nu << c$

- Gluon radiation is suppressed at angles $< m_Q/E_Q$

  
  “dead-cone” effect

  - Due to destructive interference
  - Contributes to the harder fragmentation of heavy quarks

Yu.L.Dokshitzer and D.E.Kharzeev: dead cone implies lower energy loss

- D mesons quenching reduced

- Ratio $D$/hadrons (or $D/\pi^0$) enhanced and sensitive to medium properties

Detection strategy for $D^0 \rightarrow K^- \pi^+$

- Weak decay with mean proper length $c\tau = 124 \, \mu m$
- Impact Parameter (distance of closest approach of a track to the primary vertex) of the decay products $d_0 \sim 100 \, \mu m$

- STRATEGY: invariant mass analysis of fully-reconstructed topologies originating from (displaced) secondary vertices
  - Measurement of Impact Parameters
  - Measurement of Momenta
  - Particle identification to tag the two decay products
Track reconstruction in TPC-ITS

\( d_0 \) measurement

Measurement of impact parameters is crucial for secondary vertex reconstruction.

<table>
<thead>
<tr>
<th>( d_0 ) resolution vs ( p_\text{r(\phi)} )</th>
<th>( A_{\text{meas}} )</th>
<th>11.59</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{\text{scatt}} )</td>
<td>65.76</td>
<td></td>
</tr>
<tr>
<td>( B )</td>
<td>1.878</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( d_0 ) resolution vs ( p (z) )</th>
<th>( A_{\text{meas}} )</th>
<th>34.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{\text{scatt}} )</td>
<td>170.1</td>
<td></td>
</tr>
<tr>
<td>( B )</td>
<td>1.226</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sigma(d_0) = \sqrt{A_{\text{meas}}^2 + A_{\text{scatt}}^2} \]

\[ \sigma(d_0) = \sqrt{A_{\text{meas}}^2 + A_{\text{scatt}}^2} \]

Fit function:

\[ \sigma(d_0) = \sqrt{A_{\text{meas}}^2 + A_{\text{scatt}}^2} \]

\[ \sigma(d_0) = \sqrt{A_{\text{meas}}^2 + A_{\text{scatt}}^2} \]
Selection of D⁰ candidates

- **Secondary vertex**: from minimization of distance between the 2 tracks.
- **After reconstruction and rejection of (π, π) pairs**: \(|M[K, π] - M(D₀)| < 3σ = 36 MeV/c).

\[
S/B = 4.6 \times 10^{-6}
\]

- **Geometric & Kinematic selection**: (track dist. < 300 μm, \(p_T^{K, π} > 800\) MeV/c) increases \(S/B\) by a factor 100:

\[
S/B \approx 10^{-4}
\]

- **Displaced vertex selection**: pair of tracks with large impact parameters & good pointing of reconstructed D₀ momentum to the primary vertex increases \(S/B\) by a factor 1000:

\[
S/B \approx 0.1
\]

- For \(d₀^K \times d₀^π \ll 0\), \(\cos θ_{\text{pointing}} \approx 1\)

- \(d₀^K \times d₀^π \ll 0\) increase \(S/B\) by factor \(\sim 10^3\).
Hadronic charm

Combine ALICE tracking + secondary vertex finding capabilities ($\sigma_{d0} \sim 60 \mu m @ 1 GeV/c p_T$) + large acceptance PID to detect processes as $D^0 \rightarrow K^-\pi^+$ ~1 in acceptance / central event ~0.001/central event accepted after rec. and all cuts

Results for $10^7$ PbPb ev. (~1/2 a run)

$S/\sqrt{B+S} \sim 37$
Charm in hadronic decay pp

Similar study for $10^9$ pp minimum bias collisions

Acceptance practically down to the $p_t \to 0$ (as for heavy-ion)
Charm in $pp (D^0 \rightarrow K\pi)$

Sensitivity to NLO pQCD params

$\sqrt{s} = 14$ TeV

$m_c, \frac{\mu_F}{\mu_0}, \frac{\mu_R}{\mu_0}, PDF_S$

$d^2\sigma^{D^0}/dp_t dy$ [mb/(GeV/c)]

$p_t [GeV/c]$ down to $p_t \sim 0$!
$D^0 \rightarrow K\pi$ in pPb

Statistical and systematic errors

- Triangles: Statistical error
- Circles: $p_t$-dep. syst.
- Triangles: $p_t$-indep. syst.
- Squares: $D^0$ from b
- Triangles: B.R. $D^0 \rightarrow K\pi$
- Pentagons: Systematic error
- Rectangles: MC corrections
- Hexagons: $\sigma_{\text{inel}}$ (TOTEM) + centr.

Graphs:
- Left: Relative error [%] vs. $p_t$ [GeV/c]
- Right: $d^2\sigma/dp_t dy$ [mb/(GeV/c)] vs. $p_t$ [GeV/c]

Legend:
- Blue: p-Pb, $\sqrt{s_{NN}} = 8.8$ TeV
- Yellow: (minimum bias)
Sensitivity on $R_{AA}$ for $D^0$ mesons

Low $p_t$ (< 6–7 GeV/c)
- Nuclear shadowing
- $k_t$ broadening
- ? thermal charm

‘High’ $p_t$ (6–15 GeV/c)
- Here energy loss can be studied
  (it’s the only expected effect)
D quenching \((D^0 \rightarrow K^-\pi^+)\)

- Reduced

- Ratio \(D/\text{hadrons} \) (or \(D/\pi^0\)) enhanced and sensitive to medium properties

\[
R_{AA} = \frac{1}{N_{\text{coll}}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}
\]
D/hadrons ratio (2)

\[ p_t^{\text{hadron}} = z \ p_t^{\text{parton}} \]

\[ (p_t^{\text{hadron}})' = p_t^{\text{hadron}} - z \ \Delta E \]

Energy loss observed in \( R_{AA} \) is not \( \Delta E \) but \( z\Delta E \)

\[ z_{c \rightarrow D} \approx 0.8; \quad z_{\text{gluon} \rightarrow \text{hadron}} \approx 0.4 \quad (\text{for } p_t > 5 \text{ GeV}/c) \]

\[ \Delta E_c = \frac{\Delta E_{\text{gluon}}}{2.25} \quad (\text{w/o dead cone}) \]

\[ z_{c \rightarrow D} \ \Delta E_c \approx 0.9 \quad z_{\text{gluon} \rightarrow \text{hadron}} \ \Delta E_{\text{gluon}} \]

\[ \text{Without dead cone, } R_{AA}^D \approx R_{AA}^h \]
**Beauty: semi-leptonic decays**

*Detection strategy*

$d_0$ and $p_T$ distributions for “electrons” from different sources:

Distributions normalized to the same integral in order to compare their shapes.
Semi-electronic Beauty detection

simulation results

Signal-to-total ratio and expected statistics in $10^7$ Pb-Pb events

- $p_T > 2$ GeV/c, $200 < |d_0| < 600 \, \mu m$

- 90% purity

- 40,000 e from B
Estimation of uncertainties on the $p_T$ - differential cross section of beauty electrons

*Final B-decay electron $p_T$ distribution*

---

**E loss calculations:**
Extraction of a minimum-$p_T$-differential cross section for B mesons

Using UA1 MC method (*), also adopted by ALICE μ

The B meson cross section per unit of rapidity at midrapidity with $p_T^B > p_T^{min}$ is obtained from a scaling of the electron-level cross section measured within a given electron phase space $\Phi^e$

\[
\frac{d\sigma^B}{dy}(p_T^B > p_T^{min}) = \sigma^{e,\text{beauty}}(\Phi^e)_{\text{meas}} \times \frac{d\sigma^B}{dy}(p_T^B > p_T^{min}) \times \frac{\sigma^B(\Phi^e)}{MC}
\]

The phase space used is $\Phi^e \equiv \{\Delta p_T, \Delta \eta, \Delta d_0\}$ where $\Delta p_T$ are the previously used bins, $\Delta \eta = [-0.9, 0.9]$ and $\Delta d_0 = [200,600]$ µm

C. Albajar et al., UA1 Coll., Phys Lett B256 (1991) 121
Extraction of a minimum-$p_T$-differential cross section for B mesons

Using electrons in
$2 < p_T < 16$ GeV/c

obtain B-meson
$2 < p_T^{\text{min}} < 23$ GeV/c

E loss calculations:
N. Amesto, A. Dainese,
C.A. Salgado, U.A. Wiedemann,
hep-ph/0501225

\begin{itemize}
\item stat
\item $p_T$-dep. syst
\item 11\% norm. err. (not shown)
\end{itemize}
Semi-electronic Beauty detection + X

$p_T$ quark distribution

Under study $B \rightarrow e X$ and use charged particle in $X$ with displaced vertex – b jet tagging

Analysis of the electron $p_T$ distribution useful for beauty production cross section measurement. But, what about the quark $p_T$ distribution?

Example: $B \rightarrow e + D^0 (\rightarrow K+\pi) + X$
Beauty from muon raw yields

- Fits with fixed shapes from the Monte Carlo & beauty amplitude as the only free parameter (next: tray c also free)
- Uses 3 different data samples

(Very) large statistics is expected

<table>
<thead>
<tr>
<th>$p_t$ (GeV/c)</th>
<th>1.5 - 2</th>
<th>2 – 2.5</th>
<th>2.5 - 3</th>
<th>3 - 4</th>
<th>4 - 5</th>
<th>5 - 6</th>
<th>6 - 9</th>
<th>9 - 12</th>
<th>12 - 15</th>
<th>15 - 20</th>
<th>20 - 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\mu$ from b</td>
<td>2.7 $10^6 \pm 620$</td>
<td>1.8 $10^6 \pm 675$</td>
<td>1.1 $10^6 \pm 636$</td>
<td>1.0 $10^6 \pm 684$</td>
<td>4 $10^5 \pm 474$</td>
<td>1.7 $10^5 \pm 326$</td>
<td>1.3 $10^5 \pm 294$</td>
<td>2.1 $10^4 \pm 123$</td>
<td>5 $10^3 \pm 60$</td>
<td>1.8 $10^3 \pm 38$</td>
<td>474 ± 30</td>
</tr>
</tbody>
</table>

$\mathcal{L} = 5 \times 10^{26} \text{cm}^{-2}\text{s}^{-1}$
Jet reconstruction

- Jets are produced copiously

\[
\begin{align*}
\text{pt (GeV)} & \quad 2 & \quad 20 & \quad 100 & \quad 200 \\
100/\text{event} & \quad 1/\text{event} & \quad & \quad 100K/\text{year} \\
\end{align*}
\]

4 \times 10^8 central PbPb collisions/month

6 \times 10^5 events

<table>
<thead>
<tr>
<th>\text{ET threshold}</th>
<th>\text{N_jets}</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 GeV</td>
<td>2 \times 10^7</td>
</tr>
<tr>
<td>100 GeV</td>
<td>6 \times 10^5</td>
</tr>
<tr>
<td>150 GeV</td>
<td>1.2 \times 10^5</td>
</tr>
<tr>
<td>200 GeV</td>
<td>2.0 \times 10^4</td>
</tr>
</tbody>
</table>
50 – 100 GeV jets in Pb–Pb

At large enough jet energy – jet clearly visible
But still large fluctuation in underlying energy

η–φ lego plot with $\Delta\eta \times \Delta\phi$

Central Pb–Pb event (HIJING simulation) with 100 GeV di-jet (PYTHIA simulation)
Energy fluctuation in UE

Mean energy in a cone of radius R coming from underlying event

Fluctuation of energy from an underlying event in a cone of radius R
More quantitatively ...

Intrinsic resolution limit for $E_T = 100$ GeV

For $R < 0.3$:

$\Delta E/E = 16\%$ from Background

(conservative $dN/dy = 5000$)

$14\%$ from out-of-cone fluctuations
Jet quenching

- Excellent jet reconstruction... but challenging to measure medium modification of its shape...

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

Medium induced redistribution of jet energy occurs inside cone

C.A. Salgado, U.A. Wiedemann hep-ph/0310079
Irreducible limits on jet energy resolution

- **Small radius of jet cone (R = 0.3)**
  - we don’t see 30% of energy
  - underlying event fluctuation $\sim 15$ GeV – 15% for 100 GeV jet

- **Larger jet-cone radius (R = 0.7)**
  - we don’t see 10% of energy
  - underlying event fluctuation $\sim 45$ GeV – 45% for 100 GeV jet

- **We cannot just add non-seen energy outside jet cone**
  - as is usually done in pp where jet shape is known
  - that depends on energy distribution which we have to study

- **It’s impossible to know jet energy better than 25 – 30% (for 100 GeV jets)**
  - we are now at 34 %, pretty close…
Jet structure observables at the LHC

**How close can we get to the ideal case**

- Measure unquenched parton energy by measuring the jet energy.
- Determine energy loss and transverse heating by measuring the fragmentation function and $k_T$ spectra.

\[ \Delta E = 20 \text{ GeV} \]

\[ z = \frac{p_L}{E} \]

\[ \Delta E = 20 \text{ GeV} \]

Energy-Loss Spectrum

- $E = 100$ GeV

Unquenched
Quenched (AliPythia)
Quenched (Pyquen)
Limit experimental bias ...

- By measuring the jet profile inclusively.
  - Low-\(p_T\) capabilities are important since for quenched jets sizeable fraction of energy will be carried by particles with \(p_T < 2\) GeV.

- Exploit \(\gamma\)-jet correlation
  - \(E_\gamma = E_{\text{jet}}\)
  - Caveat: limited statistics
    - \(10^3\) smaller than jet production
  - Does the decreased systematic error compensate the increased statistical error?
  - Certainly important in the intermediate energy region \(20 < E_T < 50\) GeV.
Jet structure observables: $k_T$

- Unmodified jets characterized by $\langle k_T \rangle = 600$ MeV $\sim \text{const}(R)$.
- Partonic energy loss alone would lead to no effect or even a decrease of $\langle k_T \rangle$.
  - Transverse heating is an important signal on its own.
- Relation between $R$ and formation time of hard final state radiation.
  - Early emitted final state radiation will also suffer energy loss.
  - Watch for $R$ – dependence of $\langle k_T \rangle$!
Prompt $\gamma$ spectrum (1 year running)
Fragmentation functions: $\gamma \text{ jet}$

\[ R_{FF} = \frac{F_{AA}}{(F_{pp} A^2)} \]

$R_{FF} = 1$ in the absence of medium effects.
ALICE already exists
Summary

Looking forward to fill the empty space