New Developments of EPOS 2

Tanguy Pierog\textsuperscript{1},
K. Werner\textsuperscript{2}, Y. Karpenko\textsuperscript{2}, S. Porteboeuf\textsuperscript{2}

\textsuperscript{1} Institut für Kernphysik, Karlsruhe, Germany
\textsuperscript{2} - SUBATECH, Nantes, France

XVI\textsuperscript{th} ISVHECRI, Chicago, USA

June the 30\textsuperscript{th} 2010
Outline

- The EPOS model
  - Baryons and remnants

- New developments
  - 3D Hydrodynamical calculation
  - New Parton Distribution Function (PDF)
  - LHC data

- Preliminary results
  - LHC
  - Consequences on air shower development
The EPOS Model

EPOS* is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing: for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms): used for air shower!

EPOS first designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

*T.Pierog, S. Porteboeuf and K. Werner
Baryons and Remnants

Parton ladder string ends:

  - 2 strings approach:
    - $\bar{\Omega} / \Omega$ always > 1
    - But data < 1 (Na49)

- EPOS
  - No “first string” with valence quarks: all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega} / \Omega$ always < 1

Decay (excited)
New Developments (1)

EPOS approach: use theory to fix the framework and adapt the details to be as close as possible to all possible data.

Collective effects (hydro) needed for heavy ions

- Important even for pp and pA
  - explain $<p_t>$ vs mult. (flow), strangeness, baryon pt shape, etc...
  - replace former effective treatment needed to describe these data (medium dependent string parameters)

- In EPOS 2: detailed 3D hydro calculation
  - For CR same simplified calculation of collective effects as in EPOS 1.x but with flow extrapolation based on calculation instead of low energy data (large uncertainty).
Hydro in EPOS 2

Features
- Flux-tube initial condition
- Event-by-event treatment
- 3D core-corona procedure
- Tree flavor cross-over EoS (X3F)
  \[ p = p_Q + \lambda (p_H - p_Q), \quad \lambda = \exp \left( -\frac{T - T_c}{\delta} \right) \theta(T - T_c) + \theta(T_c - T) \]
- 3 + 1D hydro
- Complete hadron set (latest PDG)
- Hadronic cascade (HC), here UrQMD

Checks: Centrality dependence of
- Yields and pt spectra of identified particles
- \( v_2 \) and pt dependence of \( v_2 \) of identified particles
- Particle correlations (eta-phi, HBT (in progress), ...)

The EPOS model

New developments

Preliminary results
The EPOS model

New developments

Preliminary results

Check with Heavy Ions: AuAu@RHIC

- Early freeze-out (166 MeV) + hadron cascade

First Real Hydro in ap-p@1.8 TeV: Radial Velocity

> Apply same parameters as for AuAu@RHIC (except flux tube radius = free parameter)

![Radial Velocity Plots](image-url)

- τ = 0.6
- τ = 1.0
- τ = 1.4
- τ = 1.7
- τ = 2.1
- τ = 2.5

**rad velocity [% of c] (eta_s=0) C1**
The EPOS model

New developments

Preliminary results

**<p_t> vs multiplicity ap-p@1.8 TeV : EPOS 2**

- Using small flux tube size
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

No collective effects

**hydro+hadronic cascade**

No collective effects

|\eta|<1  |p_t|>0.4

<table>
<thead>
<tr>
<th>mean p_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>1.8</td>
</tr>
<tr>
<td>1.6</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

| 0  |
| 5  |
| 10 |
| 15 |
| 20 |
| 25 |
| 30 |

Charged

Ks

**λ**
New Developments (2)

EPOS approach: use theory to fix the framework and adapt the details to be as close as possible to all possible data.

- New fragmentation function based on initial parton type in jets (gluon or quark)
  - Natural change of baryon and strangeness production with energy

- Needs for LHC
  - Proper PDF needed for hard scattering (Jet, etc …)
  - In EPOS 2:
    - \( F_2 \) data from HERA used in global fit (same parameters for cross-section, PDF and multiplicity …)
    - Hard diffraction
    - New parameters taken into account LHC data
      - Preliminary results
The EPOS model

New developments

Parton Distribution Function

- PDF based and DGLAP and initial soft parametrization

Preliminary results
LHC data (1)

- Higher average multiplicity due to reduced screening

Preliminary results

The EPOS model

New developments

Preliminary
LHC data (1)

- Higher average multiplicity due to reduced screening
The EPOS model

New developments

LHC data (2)

- Multiplicity tale still not long enough
- $P$ now too high?
  - Only lack of low pt particles?

$p + p \rightarrow \text{chrg at 7000 GeV}$

$|\eta| < 1$

$P(n)$ vs multiplicity $n$

$\frac{d^2N}{d^2p_t}$ vs $p_t (\text{GeV/c})$

MC/CMS

Preliminary
Air Shower Development

Change in multiplicity seen in $<X_{\text{max}}>$

$\sim 10 \text{ gr/cm}^2$
Summary

On-going developments: EPOS 2

- Real hydrodynamical evolution
- Hard scattering (PDF and Jets) correctly described
- First test with LHC data
  - Good in average
  - Inconsistency pt/multiplicity: more checks needed
- No dramatic change for air shower development

Next step:

- Selection of hard processes
- Both at the same time: underlaying events
Air Shower Development

- Muons affected by baryon production

![Graph showing energy vs. muon to electron ratio for different models like SIBYLL 2.1, EPOS 2 Preliminary, EPOS 1.99, and QGSJET II-3 for iron and protons.](image-url)
<p>Since 2007 collective effects in EPOS for any system:

- Minimum energy density needed to start formation of “core clusters”
- Microcanonical decay with additional flow
- Flow parametrized from SPS HI, RHIC HI and Tevatron ap-p
</p>

More development on collective effects in pp from other groups:
D'Enterria et al. (arXiv:0910.3029), Solana et al. (arXiv:0911.4400), Chaudhuri (arXiv:0912.2578), ...

K. Werner
Hydro in pp: Initial Conditions

- Initial conditions from multiple interactions:
  - Energy density comparable to AuAu@RHIC
  - Size comparable to size of fluctuations in AuAu@RHIC

- We propose (and we do) for pp:
  - Hydrodynamical expansion + statistical decay based on EPOS flux tube initial conditions (event-by-event)
Initial Conditions ap-p@Tevatron

energy density [GeV/fm³] (τ = 0.6 fm) C 1
First Real Hydro in ap-p@1.8 TeV : Tau

- Apply same parameters as for AuAu@RHIC (except flux tube radius = free parameter)

energy density [GeV/fm$^3$] (eta_s=0) C 1

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>1.0</td>
<td>25</td>
</tr>
<tr>
<td>1.4</td>
<td>9</td>
</tr>
<tr>
<td>1.7</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>1.2</td>
</tr>
<tr>
<td>2.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
The EPOS model

New developments

Preliminary results

Initial Conditions AuAu@RHIC

energy density \([\text{GeV/fm}^3]\) (\(\tau = 0.6\text{fm}\)) C 1
**EoS**

**Hirano:** QG & resonance gas $\Rightarrow$ 1st order PT, PCE, $\mu_B = \mu_S = \mu_Q = 0$

**Q3F:** QG & “complete” resonance gas $\Rightarrow$ 1st order PT, excl volume correction, $\mu_B$, $\mu_S$, $\mu_Q$ considered, parameters as in Spherio

**X3F:** crossover: $p = p_Q + \lambda(p_H - p_Q)$, $\lambda = \exp(-\frac{T-T_c}{\delta})\theta(T - T_c) + \theta(T_c - T)$

The EPOS model

New developments

Preliminary results

AuAu : Kaon

![Graphs showing kaon production in AuAu collisions](image)

solid lines: with hadronic cascade
dotted lines: w/o cascade
AuAu : Lambda

for better visibility:

pt spectra scaled by

1/2 (10-20%)
1/4 (20-40%)
1/8 (40-60%)
AuAu : Di-hadron correlation

AuAu 0-10%, $3 < p_t^{\text{trig}} < 4 \text{ GeV/c}$
$2 < p_t^{\text{assoc}} < p_t^{\text{trig}}$
The EPOS model

New developments

Preliminary results

p-p : Other Possible Observable

Ratio for different energies

14 TeV
10 TeV
5.5 TeV
1.8 TeV

hydro

“Bulk” in full line

“Jet” in dotted lines

200 GeV
Pt distribution CDF $\text{ap-p}@1.8$ TeV with Hydro
Pt distribution CDF $ap-p@1.8$ TeV without Hydro

$|\eta| < 1 \quad N_{ch} = 1, 5, 10, 15$

The EPOS model
New developments
Preliminary results