Measuring the Properties of the QGP

Conditions

- $\mu$
- $T_i$
- CNM effects
- Initial State

Properties

- Screening length
- $\eta/s$
- $\mathrm{d}E/\mathrm{d}x$

Stefan Bathe for PHENIX, QM2011
What I will show you today

- $v_2$ of thermal direct photons
  - Constrains $T_i$ and $\tau_0$
- CNM effects in $d+Au$
  - Density dependence of shadowing from $J/\psi$
  - Reconstructed jets
  - Low-x suppression from forward di-hadron correlations
- $v_3$
  - Disentangle initial state from $\eta/s$
  - Implications for 2-particle correlations
- E loss
  - Path-length dependence
- Results from energy scan
Measuring the Properties of the QGP

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- $\mu \sim 0$
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Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

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- $\eta/s$
- dE/dx

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Direct Photon Excess in Au+Au

\[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \]

NLO Vogelsang

\[ p+p \]

PRL 104, 132301 (2010)

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Direct Photon Excess in Au+Au

- Direct photon excess above $p+p$ spectrum
- Exponential (consistent with thermal)
- Inverse slope = $220 \pm 20$ MeV
- $T_i$ from hydro
  - 300 . . . 600 MeV
  - Depending on thermalization time

$\sqrt{s_{NN}} = 200$ GeV

$p+p$

PRL 104, 132301 (2010)

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Critical $d$+Au Check

New:
- no exponential excess in $d$+Au

Poster: Y. Yamaguchi

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Direct photon $v_2$ further constrains $T_i$

**Expected $v_2$:**
- Prompt photons: 0 (time zero)
- Thermal photons
  - Early (flow not built up)
  - Late (like hadrons)

**Diagram:**
- Thermal photons
  - Au+Au at 200 AGeV
  - $b = 6$ fm

Reference:
- Chatterjee, Srivastava
- PRC79, 021901 (2009)

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Direct Photon $v_2$

Statistical subtraction

inclusive photon $v_2$
- decay photon $v_2$
= direct photon $v_2$

$$v_2^{\text{dir.}} = \frac{R_\gamma v_2^{\text{inc.}} - v_2^{BG}}{R_\gamma - 1}$$
Direct Photon $\nu_2$

- $\pi^0$ $\nu_2$ similar to inclusive photon $\nu_2$
- Two possibilities
  - A: there are no direct photons
  - B: direct photon $\nu_2$ similar to inclusive photon $\nu_2$
- Key: precise measurement of direct photon excess

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Direct Photon $v_2$

- Direct photon $v_2$ large ($\sim 15\%$) at $p_T = 2.5$ GeV
- $v_2 \to 0$ where prompt photons dominate
Theory Comparison: Direct Photon $v_2$

- Models under-predict direct photon $v_2$
- Measurement further constrains $T_i$ and $\tau_i$
- Challenge to theorists

Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

Plenary: S. Esumi (flow), Tue
Parallel: E. Kistenev (direct photons) Thu

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Measuring the Properties of the QGP

Conditions

- $\mu \approx 0$
- $T_i = 300-600$ MeV
- CNM effects
- Initial State

Properties

- Screening length
- $\eta/s$
- $dE/dx$

Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300\text{-}600 \text{ MeV}$
- CNM effects
- Initial State

Properties

- Screening length
- $\eta/s$
- $dE/dx$

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Cold Nuclear Matter Effects

- Important for interpretation of HI data
  - Measure Cold Nuclear Matter (CNM) effects in d+Au collisions
- RHIC versatile
  - Can collide any nuclear species on any other

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J/ψ in d+Au: Shadowing non-linear

- EPS09 shadowing with linear dependence on nuclear thickness matches for central collisions
- Overpredicts suppression for peripheral collisions
- $R_{CP}$ shows this clearly
- Thickness (impact parameter) dependence of shadowing is non-linear!

Theory calculations:
- Eskola, Paukkunen, Salgado, JHEP04, 065
- Vogt, PRC71, 054902
- Kharzeev, Tuchin, NPA770, 40
- Kharzeev, Tuchin, NPA735, 248

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Reconstructed Jets in $d+Au$
Reconstructed Jets in $d+Au$

PHENIX Preliminary

$d+Au$, $\sqrt{s_{NN}} = 200$ GeV

Jet $R_{cp}$ in central $d+Au$ modified
- caution: this is not $R_{dA}$!
- consistent with $\pi^0 \ R_{cp}$
- anti-shadowing?

Parallel: N. Grau (gamma-hadron, jets) Tue
Poster: D. Perepelitsa (jets in dAu)
Forward di-hadron correlations

\[ \sqrt{s_{NN}} = 200 \text{ GeV}, \text{d}+\text{Au}, \text{p}+\text{p} \rightarrow \text{Cluster} + \pi^0; \quad 3.0 < \eta_{\text{clus}}, \eta_{\pi^0} < 3.8 \]

Pocket formula:

\[ x_{Au}^{\text{frag}} = \frac{<p_{T1}> e^{-\eta_1} + <p_{T2}> e^{-\eta_2}}{\sqrt{S}} \]

\[ J_{dA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{dA}^{\text{pair}}}{\sigma_{pp}^{\text{pair}}} / \frac{\sigma_{dA}}{\sigma_{pp}} \]

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Color Glass Condensate?

new forward EM calorimeter

|\eta| = 3.0-3.8
Initial state low-x gluon suppression

\[ \sqrt{s} = 200 \text{ GeV} \, p+p, \, d+Au \rightarrow h + \pi^0 + X \]

Di-hadron suppression factor

\( J_{dA} \)

\( 10^{-1} \)

\( 1 \)

smaller \( x \)

Forward-Forward

Mid-Forward

peripheral

Stefan Bathe for PHENIX, QM2011
Initial state low-x gluon suppression

\[ \sqrt{s} = 200 \text{ GeV } p+p, d+Au \rightarrow h + \pi^0 + X \]

Di-hadron suppression factor

- Forward-Forward
- Mid-Forward

Peripheral

Central smaller \( x \)

\( J_{dA} \)

Parallel: M. Chiu (small \( x \) dAu correl) Thu
Poster: Z. Citron (small \( x \) dAu correlations)

Di-hadrons suppressed at low \( x \)

Important for interpretation of HI results

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Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300-600$ MeV
- CNM effects
  - non-linear shadowing
  - low-x suppression
  - anti-shadowing?

Properties

- Screening length
- $\eta/s$
- $dE/dx$

Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300-600$ MeV
- CNM effects: non-linear shadowing, low-x suppression, anti-shadowing?
- Initial State

Properties

- Screening length
- $\eta/s$
- $dE/dx$

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Initial State determines flow strength

Glauber

CGC

Radial gluon distribution

2-D density profile

Initial state determines $v_2$ strength (largest uncertainty)

Disentangle initial conditions from flow strength

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$v_3$ has fluctuations origin

weak centrality dependence of $v_3 \Rightarrow$ fluctuations origin

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$v_3$ disentangles initial state and $\eta/s$

$V_2$ described by Glauber and CGC

Theory calculation: Alver et al. PRC82,034913

PHENIX
Glauber
KLN

PHENIX
arXiv:1105.3928

$1.75 < p_T < 2.0 \text{ GeV/c}$

arXiv:1105.3928v1

$N_{\text{part}}$

0 50 100 150 200 250 300 350

0 0.05 0.1 0.15 0.2 0.25

Glauber

- Glauber initial state
- $\eta/s = 1/4\pi$

KLN

- CGC initial state
- $\eta/s = 2/4\pi$

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Two models
$v_3$ disentangles initial state and $\eta/s$

**$v_2$ described by Glauber and CGC**

Theory calculation: Alver et al. PRC82,034913

**$v_3$ described only by Glauber**

Theory calculation: Alver et al. PRC82,034913

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Two models

- **Glauber**
  - Glauber initial state
  - $\eta/s = 1/4\pi$

- **MC-KLN**
  - CGC initial state
  - $\eta/s = 2/4\pi$

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$v_3$ disentangles initial state and $\eta/s$

**$v_2$ described by Glauber and CGC**

Theory calculation: Alver et al. PRC82,034913

**$v_3$ described only by Glauber**

Theory calculation: Alver et al. PRC82,034913

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Two models

- **Glauber**
  - Glauber initial state
  - $\eta/s = 1/4\pi$

- **MC-KLN**
  - CGC initial state
  - $\eta/s = 2/4\pi$

---

Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon
$v_3$ explains double-hump

- $v_2$ correction only
- double-hump

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$v_3$ explains double-hump

- $v_2$ correction only
  - double-hump

- $v_2$, $v_3$, $v_4$ correction
  - double-hump disappeared
  - Peak still broadened

Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon

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Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300-600$ MeV
- CNM effects
  - non-linear shadowing
  - low-x suppression
  - anti-shadowing?
- Initial State $\rightarrow$ Glauber

Properties

- Screening length
- $\eta/s \rightarrow 1/4\pi$
- $dE/dx$

Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300-600$ MeV
- CNM effects: non-linear shadowing, low-x suppression, anti-shadowing?
- Initial State: Glauber

Properties

- Screening length
- $\eta/s \rightarrow 1/4\pi$
- $dE/dx$

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Path-length dependence of E loss

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

$R_{AA}$ explained by both models
Path-length dependence of E loss

\( \nu_2 \) not explained by pQCD (even with fluctuations & saturation)

Theory calculations:
Wicks et al., NPA784, 426
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Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

\( R_{AA} \) explained by both models
Path-length dependence of $E$ loss

$v_2$ not explained by pQCD (even with fluctuations & saturation)

$v_2$ explained by cubic path length dependence (like AdS/CFT)

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
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$R_{AA}$ explained by both models
Path-length dependence of E loss

\( \nu_2 \) not explained by pQCD (even with fluctuations & saturation)

\( \nu_2 \) explained by cubic path length dependence (like AdS/CFT)

\( \nu_2 \) data favors \( \frac{dE}{dx} \sim l^3 \) (like AdS/CFT)

\( R_{AA} \) explained by both models

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

Plenary: M. Purschke (R_AA) Wen
Parallel: N. Grau (gamma-hadron, jets) Tue
Parallel: D. Sharma (light vector mesons) Mon
Poster: M. Tannenbaum (E loss RHIC vs. LHC)
\( \gamma-h: \) fragmentation function in Au+Au

\[
\xi = - \ln \left( \frac{p_T^h}{p_T^\gamma} \right)
\]

\( p+p \) consistent with \( e^++e^- \)

Au+Au consistent with E loss model

Tasso: Braunschweig et al., Z. Phys. 320 C47, 187
MLA: Borghini, Wiedemann, hep-ph/0506218

Parallel: N. Grau (gamma-hadron, jets) Tue
Poster: M. Tannenbaum (E loss RHIC vs. LHC)
Measuring the Properties of the QGP

Conditions

- $\mu \sim 0$
- $T_i = 300$-$600$ MeV
- CNM effects
  - non-linear shadowing
  - low-x suppression
  - anti-shadowing?
- Initial State
  - Glauber

Properties

- Screening length
  - $\eta/s \to 1/4\pi$
- $dE/dx \to l^3$

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Measuring the Properties of the QGP

Conditions

\( \mu \approx 0 \)

\( T_i = 300-600 \text{ MeV} \)

CNM effects
non-linear shadowing
low-x suppression
anti-shadowing?

Initial State
? \rightarrow \text{Glauber}

Properties

Screening length
\( \frac{\eta}{s} \rightarrow \frac{1}{4\pi} \)

\( \frac{dE}{dx} \rightarrow l^3 \)
$v_2, v_3, v_4$ independence of $\sqrt{s_{NN}}$ (for 39, 62, 200 GeV)

Just like at 200 GeV, disentangle initial state and $\eta/s$

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$v_2$ saturation with $\sqrt{s_{NN}}$

$\rho_T = 1.7$ GeV

$\rho_T = 0.7$ GeV

Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon
Parallel: X. Gong (energy scan: bulk) Fri
Poster: S. Mizuno (PID v3)

Bathe for PHENIX, QM2011
\( s_{NN} \) dependence of energy loss

- \( R_{AA} \) suppressed also at 39 GeV
- \( R_{AA} \) at 62 GeV approaches 200 GeV level at high \( p_T \)

Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

Conditions

\( \mu \sim 0 \)

\( T_i = 300-600 \text{ MeV} \)

CNM effects

non-linear shadowing

low-x suppression

anti-shadowing?

Initial State

\( \rightarrow \text{Glauber} \)

Properties

Screening length

\( \eta/s \rightarrow 1/4\pi \)

d\(E/dx \rightarrow l^3 \)

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Near-Term Future: Silicon Vertex Detector

**Status**
- VTX successfully commissioned in 2011 $p+p$ run
- VTX taking data in Au+Au now!

**Physics**
- $R_{AA}$ of $c, b$ separately
- $v_2$ of $c, b$ separately
- Jet tomography ($\text{di-hadron}, \gamma-h, c-h, c-\bar{c}$)

Data: $p+p@500$ GeV, 2011

Stefan Bathe for PHENIX, QM2011
Near-Term Future: Silicon Vertex Detector

**Status**

- VTX successfully commissioned in 2011 $p+p$ run
- VTX taking data in Au+Au now!

Data: Au+Au@200 GeV, 2011

**Physics**

- $R_{AA}$ of $c$, $b$ separately
- $v_2$ of $c$, $b$ separately
- Jet tomography (di-hadron, $\gamma-h$, $c-h$, $c-\bar{c}$)

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What I could not cover in this talk

- $T_i$
  - **Plenary**: S. Esumi, Tue
  - **Parallel**: E. Kistenev (direct photons) Thu
  - **Poster**: Y. Yamaguchi (direct photons dAu)

- $v_3$, jet shape, $\eta/s$
  - **Plenary**: S. Esumi, Tue
  - **Parallel**: R. Lacey (v3, jet shape) Mon
  - **Parallel**: X. Gong (energy scan: bulk) Fri
  - **Poster**: S. Mizuno (PID v3)

- Chiral Symmetry
  - **Parallel**: M. Makek (Results from HBD) Thu

- Heavy Flavor
  - **Plenary**: C. Luiz da Silva, Fri
  - **Parallel**: A. Sen (quarkonia) Tue
  - **Parallel**: M. Durham (open heavy flavor) Fri
  - **Poster**: S. Whitaker (Upsilon RAA)
  - **Poster**: A. Takahara (J/psi photoproduction)
  - **Poster**: H. Thewman (high $p_T$ single e in $p+p$)

- Energy Loss
  - **Plenary**: M. Purschke (R_AA) Wen
  - **Parallel**: N. Grau (gamma-hadron, jets) Tue
  - **Parallel**: N. Novitsky (energy scan) Fri
  - **Parallel**: D. Sharma (light vector mesons) Mon
  - **Poster**: M. Tannenbaum (E loss RHIC vs. LHC)
  - **Poster**: O. Chvala (RAA in 39 and 62 GeV)
  - **Parallel**: D. Sharma (light vector mesons) Mon

- Cold nuclear matter
  - **Parallel**: M. Chiu (small x dAu correl) Thu
  - **Parallel**: J. Kamin (dAu dileptons) Fri
  - **Poster**: Z. Citron (small x dAu correlations)
  - **Poster**: D. Perepelitsa (jets in dAu)

- Future
  - **Parallel**: A. Sickles (Decadal Plan) Thu
  - **Poster**: M. Chiu (Fast TOF, 10 ps)
  - **Poster**: M. Kurosawa (VTX (pixel))
  - **Poster**: T. Hachiya (VTX (pixel))
  - **Poster**: R. Akimoto (VTX (pixel))
Conclusions

- $v_2$ of thermal direct photons **large**
  - Further constrains $T_i$ and $\tau_0$
- CNM effects in $d+$Au
  - **Non-linear** density dependence of shadowing from $J/\psi$
  - **Reconstructed jet** $R_{cp}$ modified
  - **Low-x suppression** from forward di-hadron correlations
- $v_3$
  - **Disentangle initial state from $\eta/s$**
  - **Double-hump disappears** in 2-particle correlations
- **Energy loss**
  - **Cubic** path-length dependence
- **Energy Scan**
  - $v_2$ **saturation** 39 GeV
  - $R_{AA}$ **suppressed** also at 39 GeV

Thank you!

Stefan Bathe for PHENIX, QM2011
Backup
Jet-$\pi^0$ comparison $d+Au$

- $\pi^0 R_{cp}$ calculated from published $R_{dA}$
- Consistent in overlapping $p_T$ range

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Confirmation from $d+Au$ and $Cu+Cu$

- Fraction of direct photons compared to pQCD

No excess in $d+Au$ (no medium)

Excess also in $Cu+Cu$

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Inclusive Photon $v_2$

- Measured with EMCal

**Issue:**
- Hadronic contamination at low $p_T$
  - Hadrons deposit only fraction of energy
  - depends on hadron species
  - Difficult to estimate

- Confirmed with external conversion
  - No hadronic contamination

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Direct photon excess $R_\gamma$

- Key to this analysis
  - Precise measurement of $R_\gamma$ through internal conversion
  - 20% direct photon fraction
  - $\Rightarrow$ direct photon similar to inclusive photon $v_2$ (or $\pi^0 v_2$)

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Correlations at Forward Rapidity

- $J_{dA}$ suppressed in central d+Au

Caveat:
- Double parton interactions (DPI) enhanced in d+Au
  - may be dominant process for large forward rapidity (rather than 2->2 process)
- Then xfrag not sensitive to rapidity

Pocket formula:

$$x_{Au}^{\text{frag}} = \frac{<p_{T1}> e^{-\eta_1} + <p_{T2}> e^{-\eta_2}}{\sqrt{s}}$$
Direct photon flow calculation

30-35 % most central Au+Au@200 GeV
upper curve: \( m_q = 0.1 \) GeV
lower curve: \( m_q = 0.3 \) GeV

thermal only

Hadrons
PHENIX
PRL98, 162301

thermal + prompt

V. Pantuev, arXiv:1105.NNNN
-expanding fireball in longitudinal and radial direction
- photons are produced from matter which flows
- Doppler

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\( T_i \) from hydro

- 300 \ldots 600 MeV
- Depends on thermalization time, \( \tau_0 \)
- anti-correlation: \( T_i \leftrightarrow \tau_0 \)

Theory calculations:
- d’Enterria, Peressounko, EPJ46, 451
- Huovinen, Ruuskanen, Rasanen, PLB535, 109
- Srivastava, Sinha, PRC 64, 034902
- Turbide, Rapp, Gale, PRC69, 014903
- Liu et al., PRC79, 014905
- Alam et al., PRC63, 021901(R)

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What is the initial Temperature, $T_i$?

- Integrate over space-time evolution
- Early photons
  - Large temperature
  - Large inverse slope
- Late photons
  - Low temperature, but large velocity boost
    - Also large inverse slope
- \( \Rightarrow \) Need model for quantitative answer

Figures: K. Mendoza, U. Colorado

Stefan Bathe for PHENIX, QM2011
Measuring the Properties of the QGP

Conditions

\[ \mu \approx 0 \]

\[ T_i = 300-600 \text{ MeV} \]

CNM effects

Initial State

Properties

Screening length

\( \eta/s \)

dE/dx

Stefan Bathe for PHENIX, QM2011
Factorizing initial state and viscosity

- $v_2$ described by both models
  - Glauber
    - Glauber initial state
    - $\eta/s = 1/4\pi$
  - KLN
    - CGS initial state
    - $\eta/s = 2/4\pi$
- $v_3$ described by only one model
  - Glauber
    - Glauber initial state
    - $\eta/s = 1/4\pi$

Data:
PHENIX, arXiv:
Models:
JG.-L. e. a. Ma (2010), 1011.5249.

Stefan Bathe for PHENIX, QM2011