

# Jet quenching

Martin Spousta

# Zhášení výtrysků

Martin Spousta



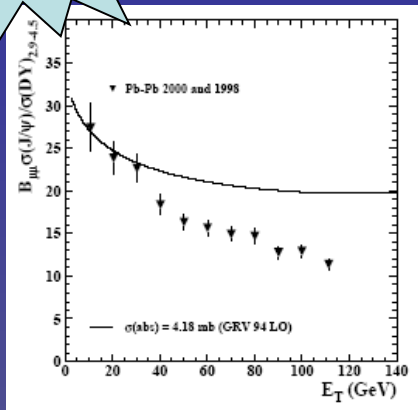
David Gross

HEP2005

# EXPERIMENTAL PREDICTIONS

1. The top quark will be old news and will have a mass of  $160 \pm 20$  GeV ✓
2.  $\epsilon'/\epsilon$  will finally be measured and will not be zero. In addition the three B-factories will have found new manifestations of CP violations. ✓
3. At least 2 light Higgs particles will be found after a few years of running at the SSC. ?
4. There will be convincing evidence for the existence of supersymmetric particles. ?
5. The astrophysicists will finally have determined that  $\Omega = 1$  with an accuracy of 10%. Particle physicists will understand that this mass density is composed of a combination of baryons, axions, neutrinos and neutralinos with various weights (some of which could be zero). ✓ ?
6. The observation of neutrino oscillations will verify the MSW mechanism and be consistent with the solar neutrino problem. ✓
7. There will be evidence of the quark gluon plasma and of a chiral phase transitions in heavy ion collisions. ✓ ?
8. Some number of new Z-mesons will be discovered. ?
9. There will be cloudy evidence of superstrings. ?
10. Finally, the most surprising and strange of all predictions - there will be a real surprise! ✓

NA 50



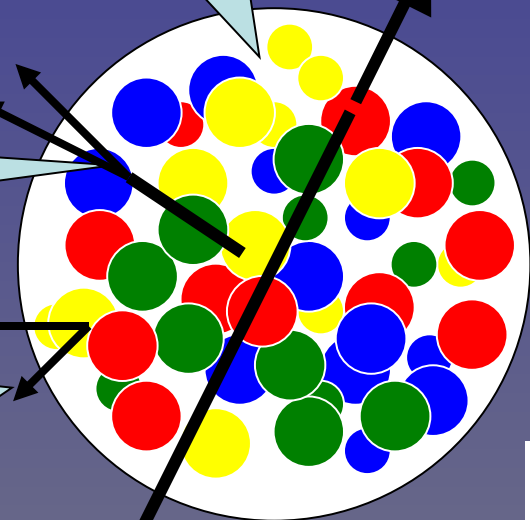
Motivace

Hmota dominovaná gluony

Pb

potlačení J/  
Psi a Upsilon

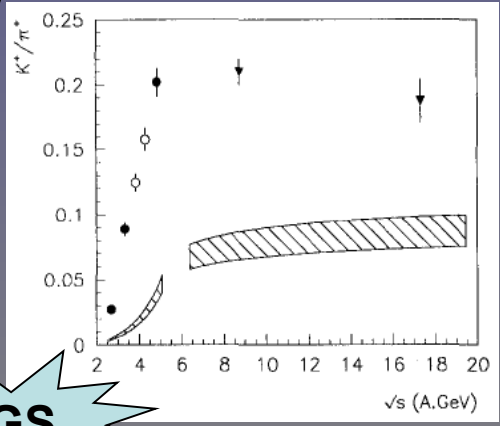
Nárůst počtu podivných částic



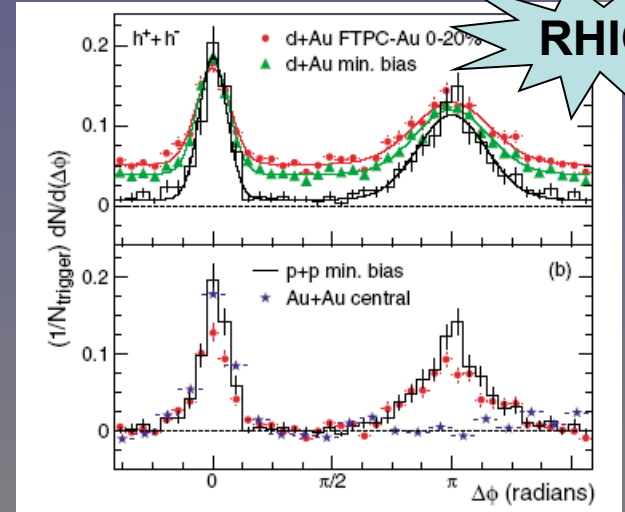
Jet quenching

Pb

RHIC

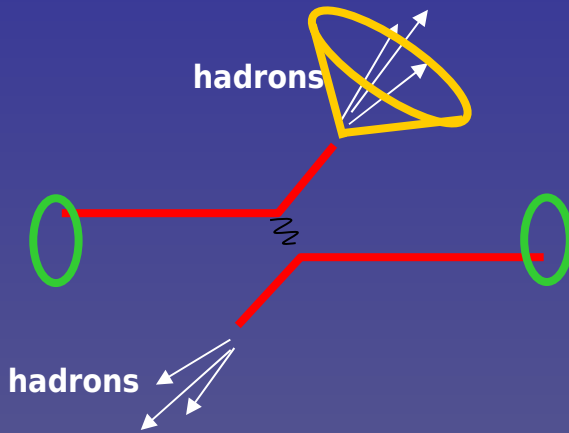


AGS

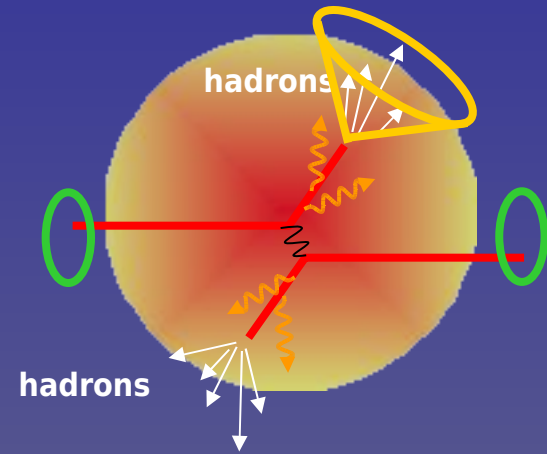


# Základní schéma

*pp*



*AA*



$$\frac{d\sigma_{AB \rightarrow jet}}{dp_T} = \sum_{abc} \iiint dx_a dx_b d\hat{t} G_{a/A}(x_a, Q^2) G_{b/B}(x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}(ab \rightarrow c) D(c \rightarrow jet)$$

$$D_{q \rightarrow h}(x, Q^2) \longrightarrow D_{q \rightarrow h}^{medium}(x, Q^2)$$

Médiem modifikované FF

$$G_{a/A}(x_1, Q^2) G_{b/B}(x_2, Q^2)$$

$$\otimes g(k_a) g(k_b)$$

$$\otimes S_A(x_a, Q^2) S_B(x_b, Q^2)$$

Croninův jev  
Shadowing,  
„EMC efekt“

# Modifikované FF, jeden příklad

Médiem modifikované FF:

$$D_{q \rightarrow h}^{med}(x, Q^2) = \int_0^1 d\epsilon P(\epsilon) \frac{1}{1-\epsilon} D_{q \rightarrow h}\left(\frac{x}{1-\epsilon}, Q^2\right)$$

prům. ztráta energie

$$\epsilon = \frac{1}{E_q} \int_0^{\omega_c} \omega \frac{dI_{med}}{d\omega} d\omega$$

transportní koeficient

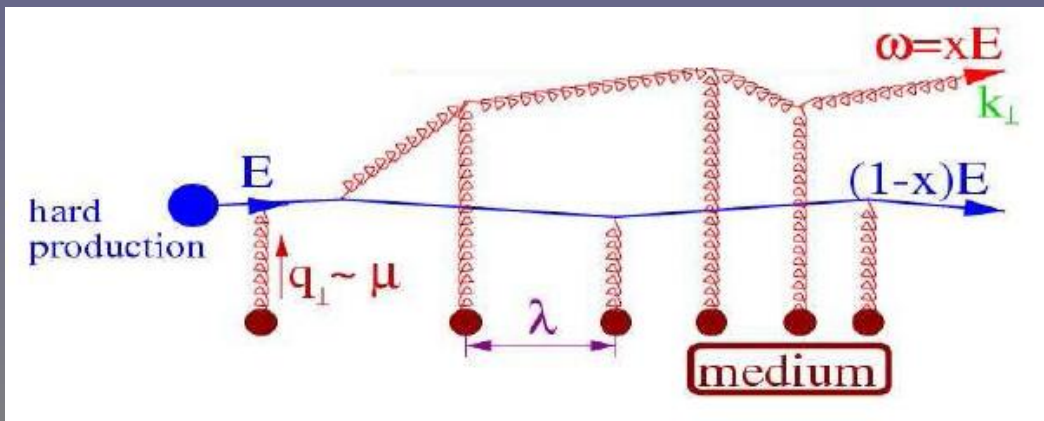
délka dráhy v médiu

$$\epsilon \approx \alpha_s \omega_c = \alpha_s \frac{1}{2} \hat{q} L^2$$

(...)

spektrum vyzařovaných gluonů

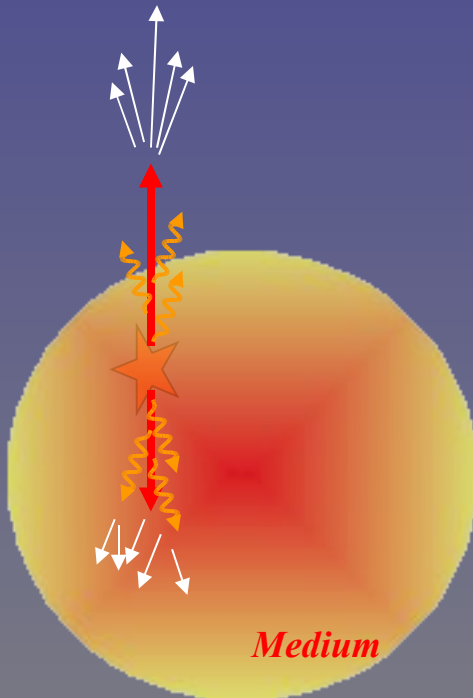
$$\begin{aligned} \omega \frac{dI_{med}}{d\omega d\mathbf{k}} &= \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} 2\text{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d^2\mathbf{u} \\ &\times e^{-i\mathbf{k}_\perp \cdot \mathbf{u}} e^{-\frac{1}{2} \int_{\bar{y}_l}^\infty d\xi n(\xi) \sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \\ &\times \int_{\mathbf{y}=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} D\mathbf{r} \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{\mathbf{r}}^2 - \frac{n(\xi) \sigma(\mathbf{r})}{i2\omega} \right) \right] \end{aligned}$$



Různé přístupy vedoucí k FF (dráhový integrál, přiblížení QFT při konečné teplotě, higher-twist přiblížení, ...)

→ různé scénáře pro jet quenching  $\times$  hlavní rysy obdobné:

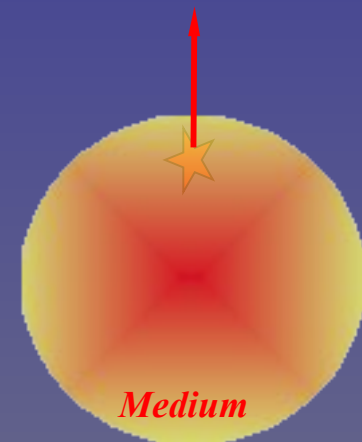
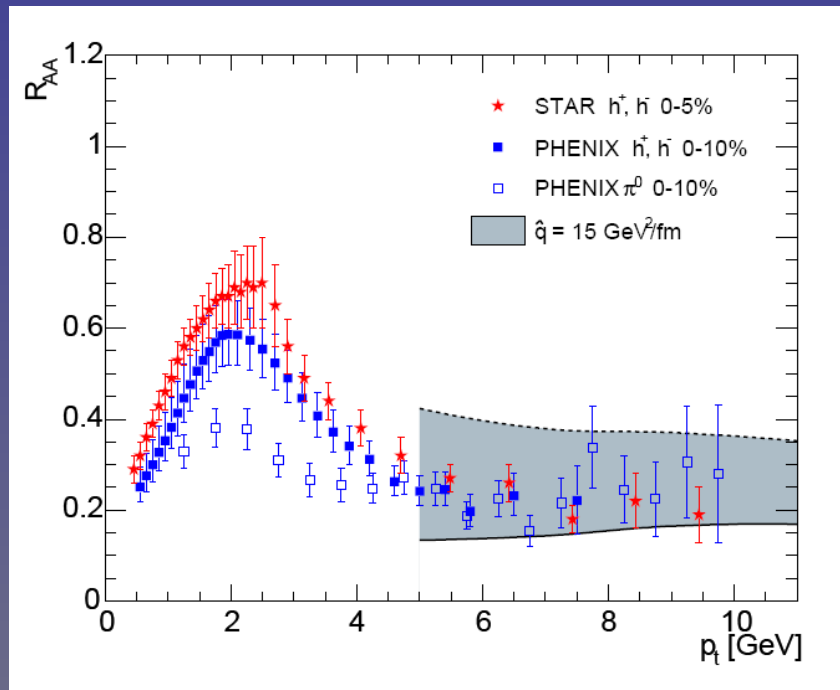
- potlačení hadronů s vysokým  $z = p(\text{hadron}) / p(\text{jet})$
- rozšíření spršky
- nárůst celkové multiplicity částic ve jetu
- potlačení 3-jetové topologie
- energetické ztráty v závislosti na  $m_q$



### Co lze zkoumat

- vlastnosti media v rané fázi (hustota, teplota, počet stupňů volnosti, opacita/viskozita ...)
- mechanismus ztráty energie, způsob hadronizace ve vakuu/v médiu

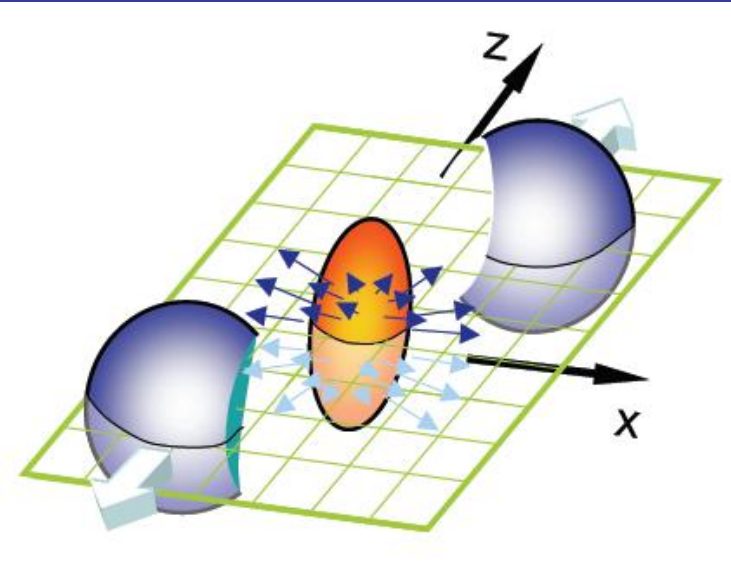
# Co je měřeno na RHIC



$$R_{AA}(p_t) \equiv \frac{1}{\langle N_{\text{coll}} \rangle_{\text{centrality class}}} \times \frac{d^2 N_{AA}/dp_t d\eta}{d^2 N_{pp}/dp_t d\eta}$$

... situace je však komplikovanější

# Globální proměnné

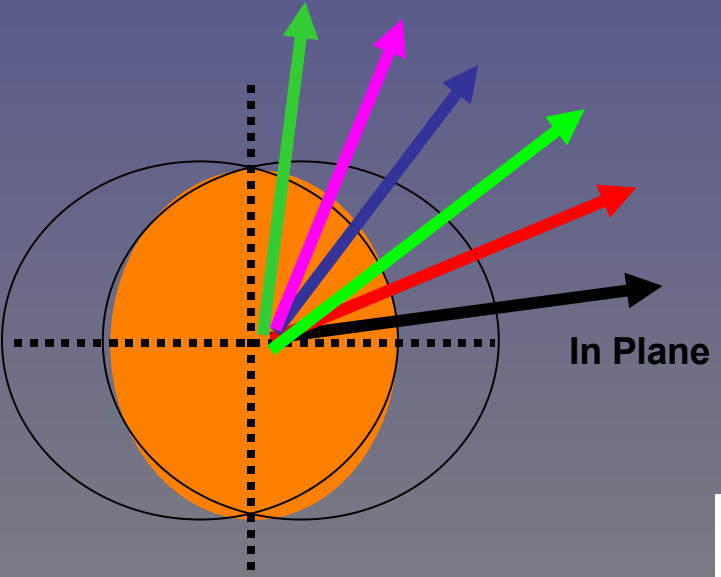


centralita srážky  $\Leftrightarrow$  celková  
 multiplicita nabitých částic  $\Leftrightarrow$   
 celková transverzální energie

azimutální prostorová  
 nesymetrie  $\Leftrightarrow$  azimutální  
 anizotropie spektra hybností  
 hadronů (viz hydrodyn. model)  
 $\rightarrow$  určení interakční roviny

zkoumání  
 závislostí  
 pozorova-  
 ných jetů na  
 délce dráhy  
 v médiu

Out of Plane



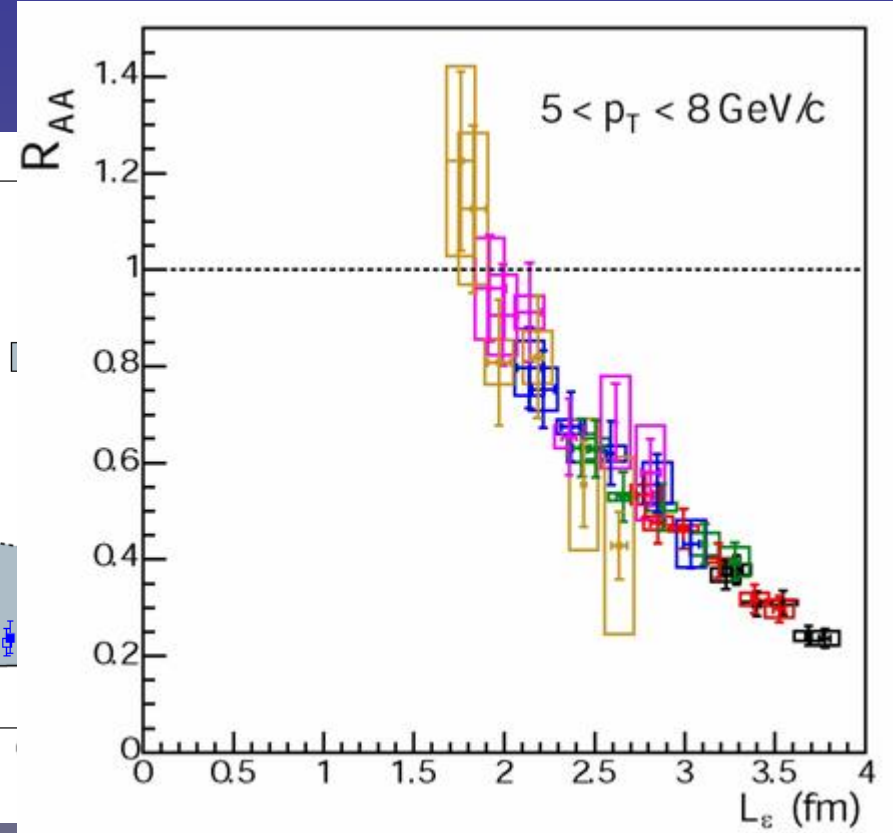
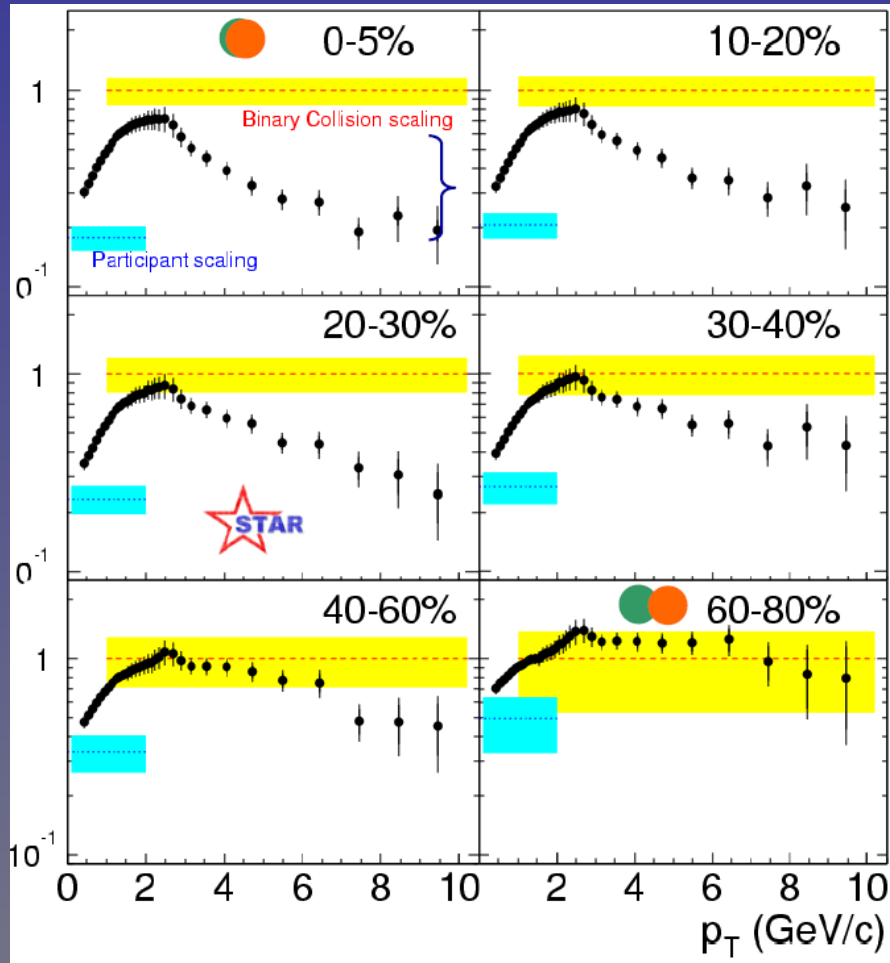
$$b \longleftrightarrow \frac{dN}{d\eta} \longleftrightarrow E_T$$

$$\epsilon_x = \frac{y^2 - x^2}{y^2 + x^2} \longleftrightarrow \epsilon_p = \frac{\int dx dy (T^{xx} - T^{yy})}{\int dx dy (T^{xx} + T^{yy})}$$



$$\frac{dN}{d\eta p_T dp_T d\varphi}(b) = \frac{1}{2\pi} \frac{dN}{d\eta p_T dp_T}(b) (1 + 2v_2 \cos 2\varphi + \dots)$$

# Co je měřeno na RHIC

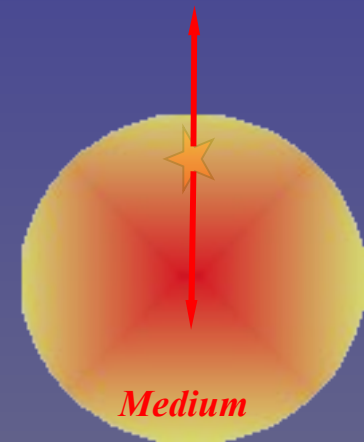
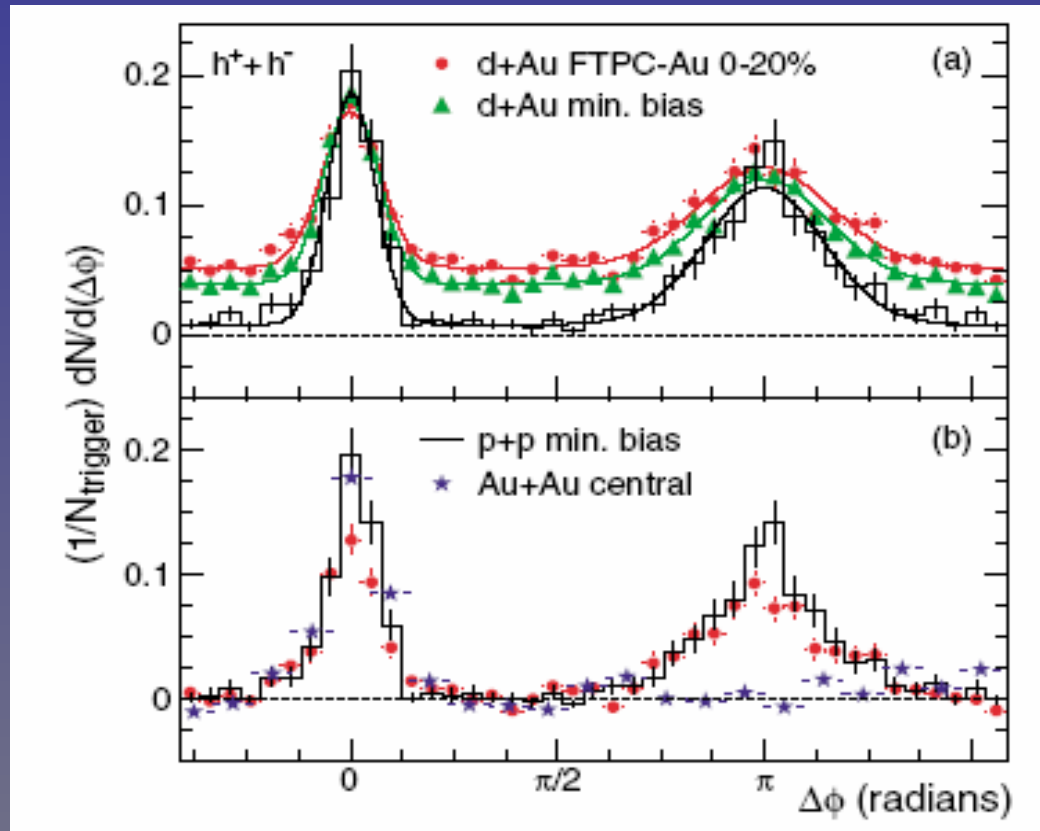




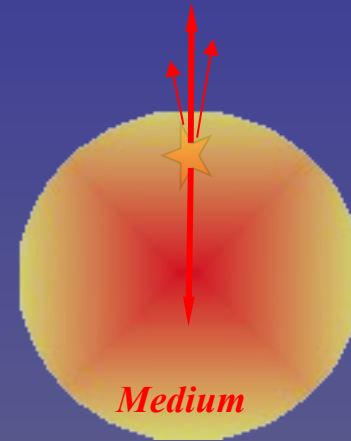
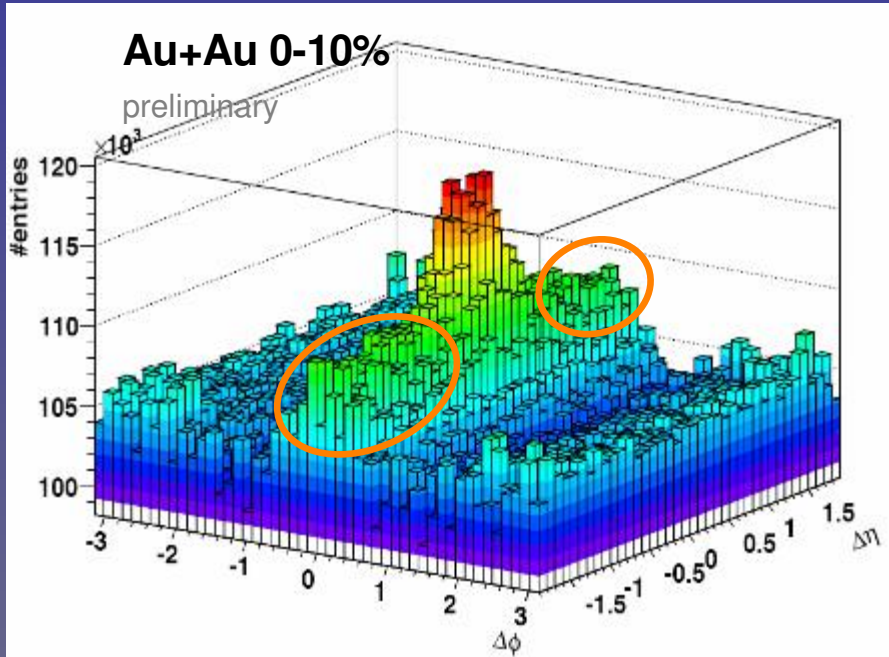
Jana Bielčíková

High  $p_T$  azimuthal and eta correlations with  
strange baryons and mesons at RHIC  
(QM2006)

# Co je měřeno na RHIC

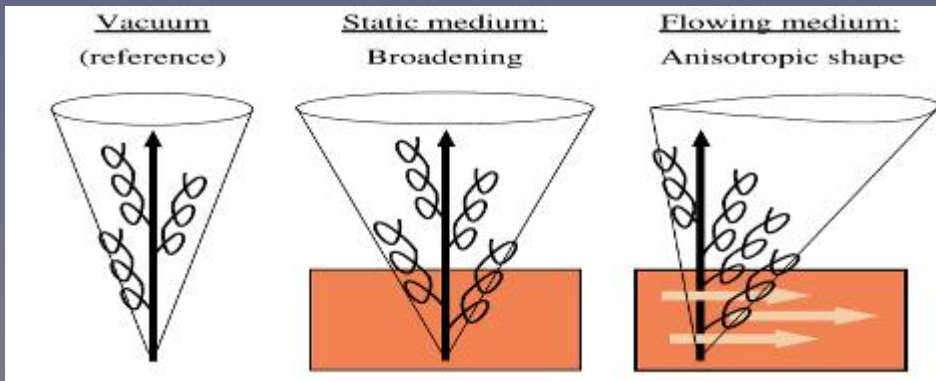


# Co je měřeno na RHIC

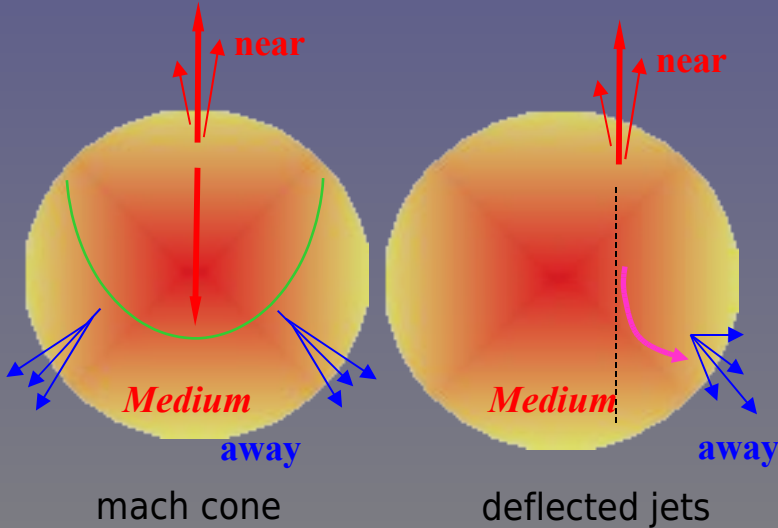
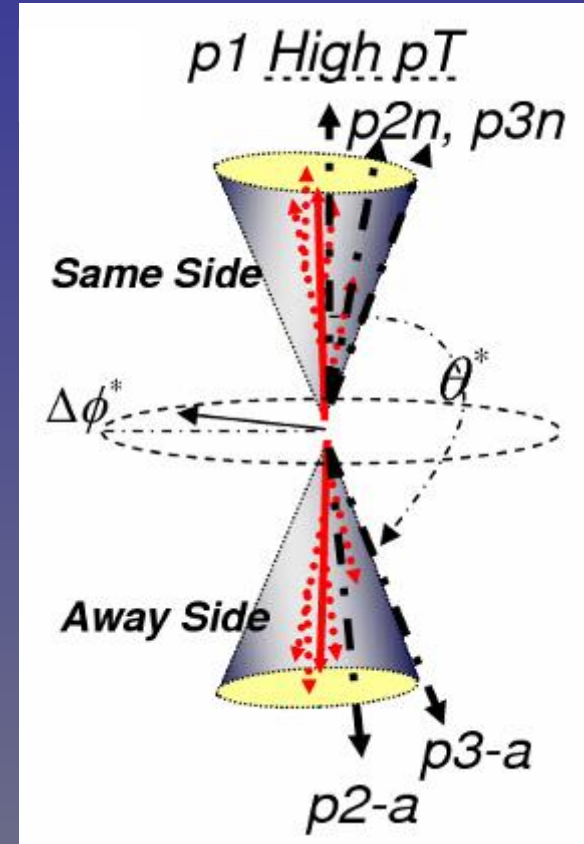
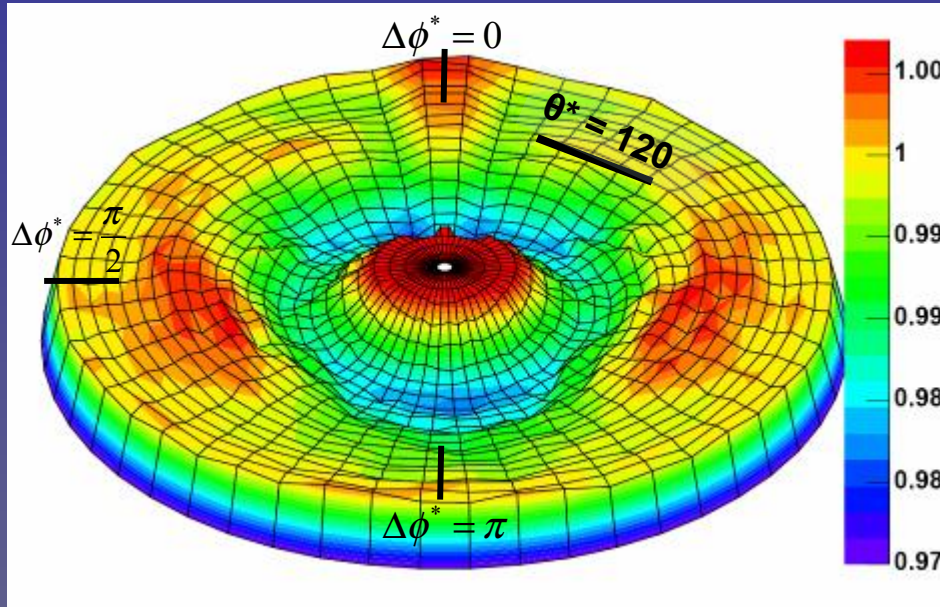


## „Near-side structure“

- pouze gluonové brzdné záření + flowing medium ?
- zahřátí média procházejícím partonem a následná rekombinace partonů z média ?
- ...

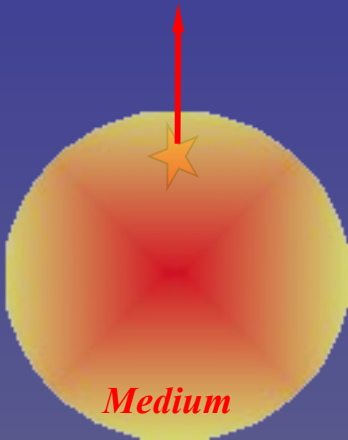


# Co je měřeno na RHIC

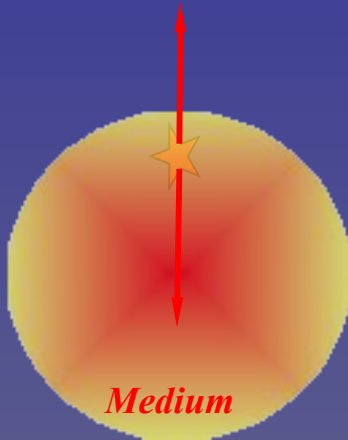


## „Away-side structure“

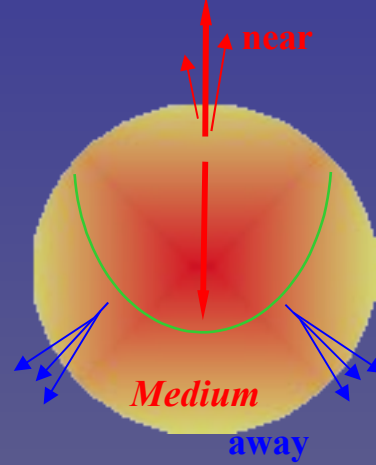
- Machův kužel ?
- „ohyb“ jetu v mediu ?
- ...



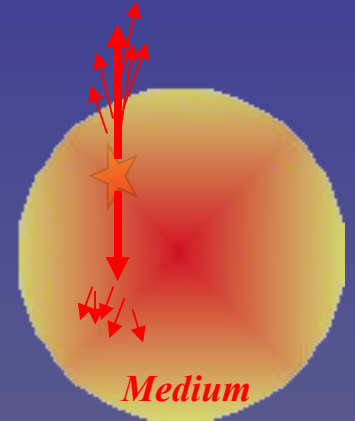
$R_{AA}$



dvou částicové  
korelace



tří částicové  
korelace



tvar *jetu*,  
multiplicita

RHIC

LHC

$$\epsilon = \frac{1}{E_q} \int_0^\infty \omega \frac{dI_{med}}{d\omega} d\omega$$

$$D_{q \rightarrow h}^{med}(x, Q^2) = \int_0^1 d\epsilon P(\epsilon) \frac{1}{1-\epsilon} D_{q \rightarrow h}\left(\frac{x}{1-\epsilon}, Q^2\right)$$

$$\psi(r; R) = \frac{\int E_T dE_T \frac{d^2\sigma}{dE_T dr}}{\int_0^R dr \int E_T dE_T \frac{d^2\sigma}{dE_T dr}}$$

$$\psi(r; R) = \frac{C_F \alpha_s}{2\pi} \left[ \frac{2}{r} \left( 2 \log \frac{1}{Z} - \frac{3}{2} (1-Z)^2 \right) \right]_+$$

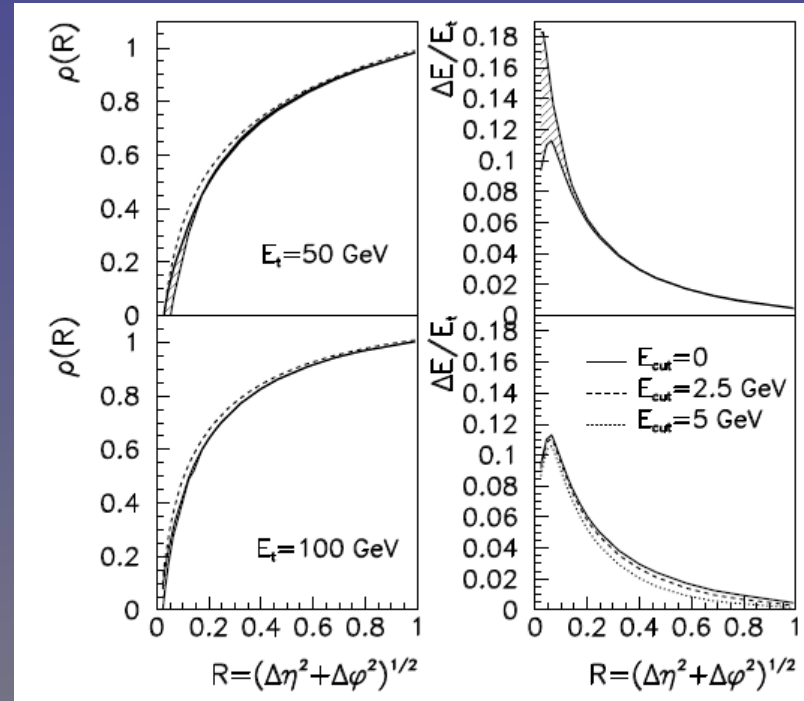
$$\psi(r; R) = \sum_b \frac{\alpha_s}{2\pi} \frac{2}{r} \int_0^{1-Z} dz z P_{a \rightarrow bc}(z) \quad (...)$$

$$\psi(r; R) = \frac{d\Psi(r; R)}{dr}$$

$$\Psi(r; R) = \frac{\sum_i E_{Ti} \theta(r - r_i)}{\sum_i E_{Ti} \theta(R - r_i)}$$

$$\begin{aligned} \omega \frac{dI_{med}}{d\omega dk} &= \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} 2\text{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d^2u \\ &\times e^{-i\mathbf{k}_t \cdot \mathbf{u}} e^{-\frac{1}{2} \int_{\bar{y}_l}^\infty d\xi n(\xi) \sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \quad (...) \\ &\times \int_{\mathbf{y}=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} D\mathbf{r} \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{\mathbf{r}}^2 - \frac{n(\xi) \sigma(\mathbf{r})}{i 2\omega} \right) \right] \end{aligned}$$

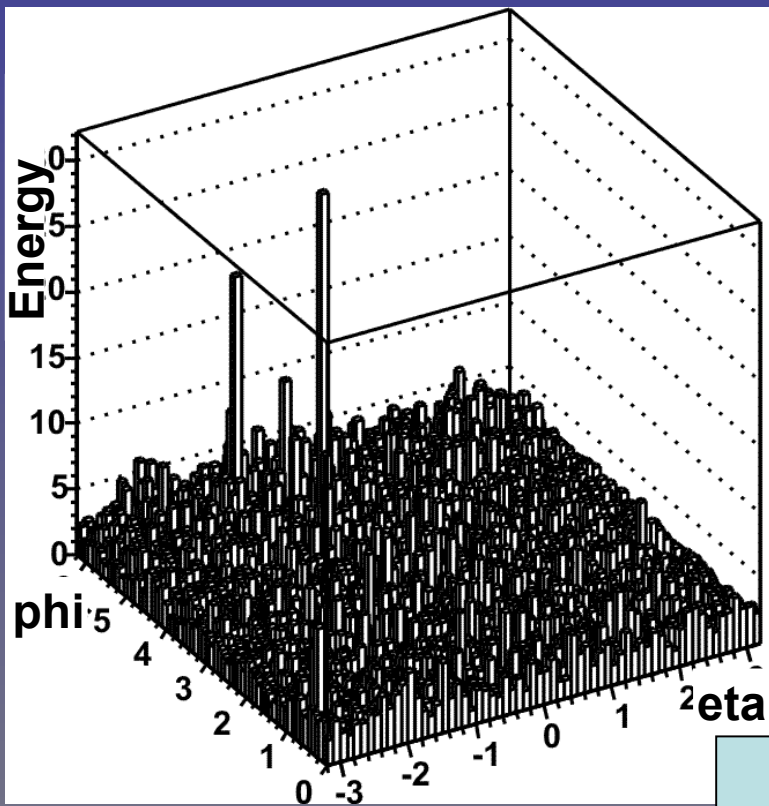
QCD



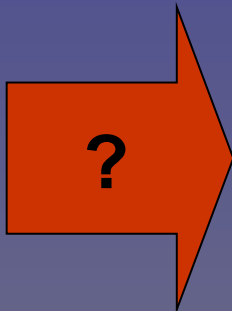
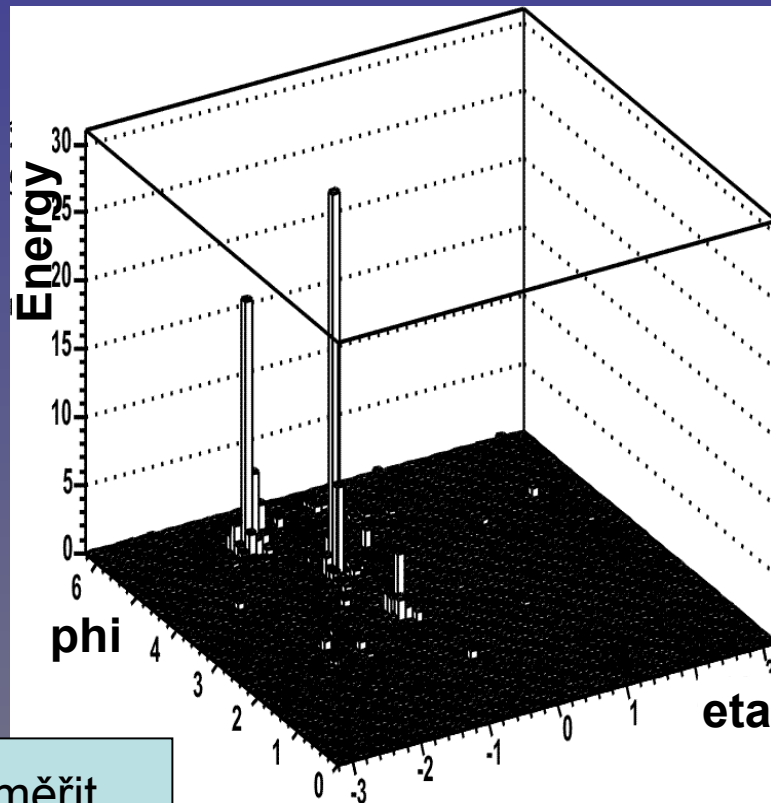
C.A.Salgado, U.Wiedemann

# Co budeme vidět na LHC energiích?

Těžko-iontová srážka s jety

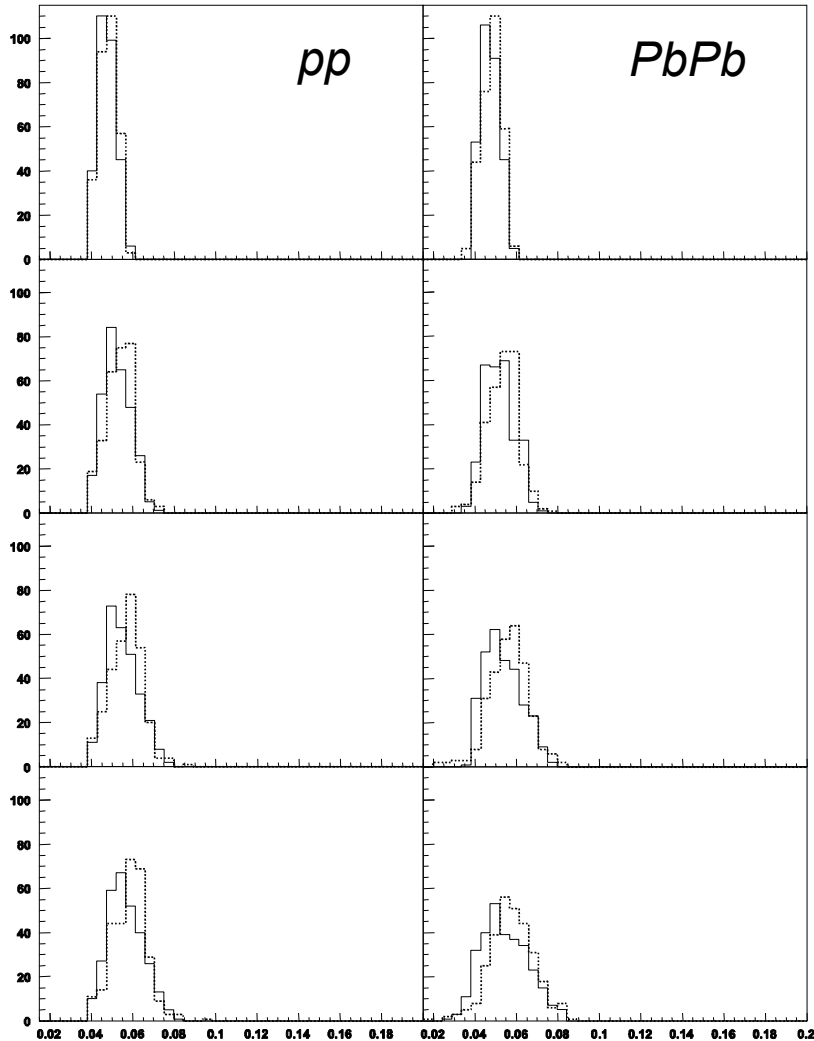


“Čisté”  $pp$  jety



... možnost měřit  
„opravdové“ jety,  
ale jak se vyrovnat  
s pozadím?

# Vhodné pozorovatelné



... radiální momenty

$$r^{[n]}(R) = \frac{\sum_{i:r_i \leq R} r_i^n E_{Ti}}{\sum_{i:r_i \leq R} E_{Ti}}$$

HYDJET HIJING Pythia  
Herwig

Generation

HepMC

Rome-Final ATLAS-CSC-01-02-00  
ATLAS-DC3-07

Simulation

G4 Hits

Digitization

G4 Digits

Reconstruction

ESD

CBNT SAN AAN  
Analysis

Real Data

Calo Towers  
(0.1 x 0.1)

Tower Building

Calo Cells

Physics Jets

In-situ  
Calibration  
(underlying event,  
physics environment)

Tower Noise  
suppression

Jet Finding  
KT

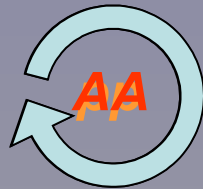
Calo Jets  
(not calibrated)

Jet Calibration  
(e/h, inactive mat.)

Calo Jets  
(calibrated)

Jet E<sub>T</sub> Scale  
Corrections  
(noise, pile up,  
algorithm effects)

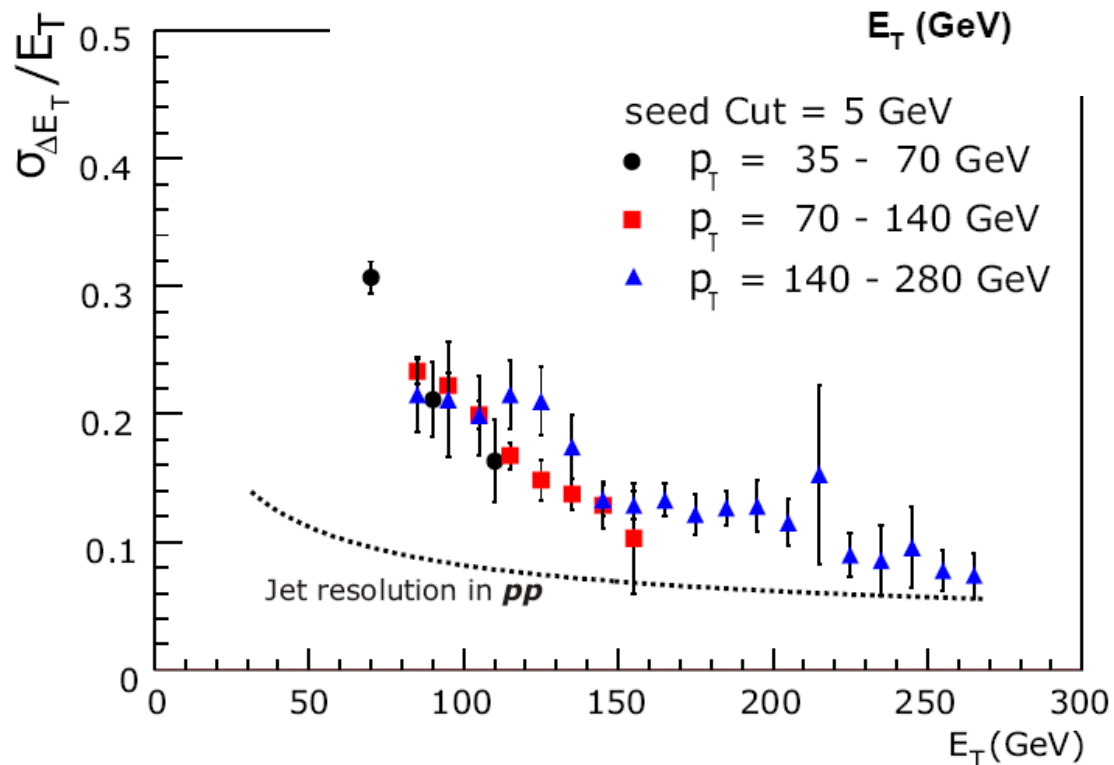
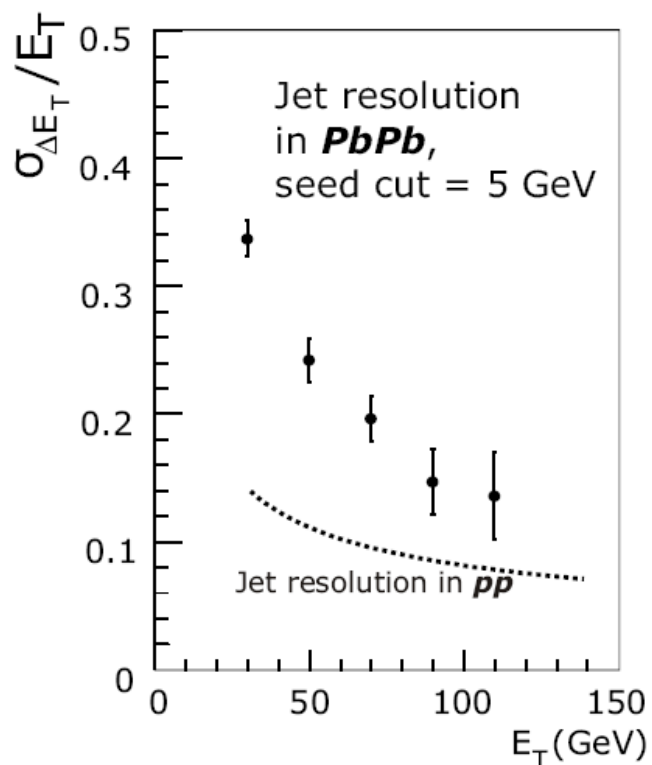
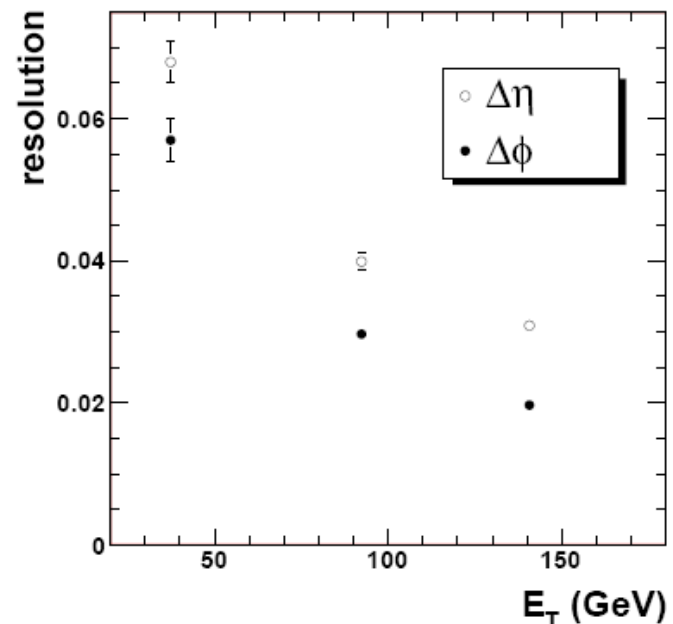
Physics Jets



# Vhodné algoritmy

Cone 0.4, 0.7

rozlišení pozice jetu →  
 rozlišení energie jetu ↓



# Základní idea fitovacího algoritmu:

Najít osu jetu, vyintegrovat energii kolem této osy a získaný jet shape i s pozadím fitovat

$$F(R) = \int_0^{2\pi} d\varphi \int_0^R r dr \left( \psi(r) + c_{background} \right)$$

... substituce:

$$\eta, \phi \rightarrow r, \varphi$$

Jet Shape

příspěvek pozadí

V první aproximaci uvažovat jet jako gaussovský peak:

$$F(R) = \int_0^{2\pi} d\varphi \int_0^R r dr \left( c_1 e^{-\frac{r^2}{c_2}} + c_3 \right) = \pi c_1 c_2 \left( 1 - e^{-\frac{R^2}{c_2}} \right) + \pi c_3 R^2$$

... v tomto přiblížení je energie jetu dána součinem konstant  $c_1 c_2$  a šířka jetu je charakterizována konstantou  $c_2$ :

$$E = \lim_{R \rightarrow \infty} \pi c_1 c_2 \left( 1 - e^{-\frac{R^2}{c_2}} \right) = \pi c_1 c_2$$



$E$

variance

$$\sigma = \sqrt{\sigma_\eta^2 + \sigma_\phi^2}$$

$$\sigma_\eta^2 = \frac{1}{E_T} \sum_i (\eta_i - \bar{\eta})^2 E_{T,i}$$

$$\sigma_\phi^2 = \frac{1}{E_T} \sum_i (\phi_i - \bar{\phi})^2 E_{T,i}$$

osa jetu

$$\sqrt{c_2}$$

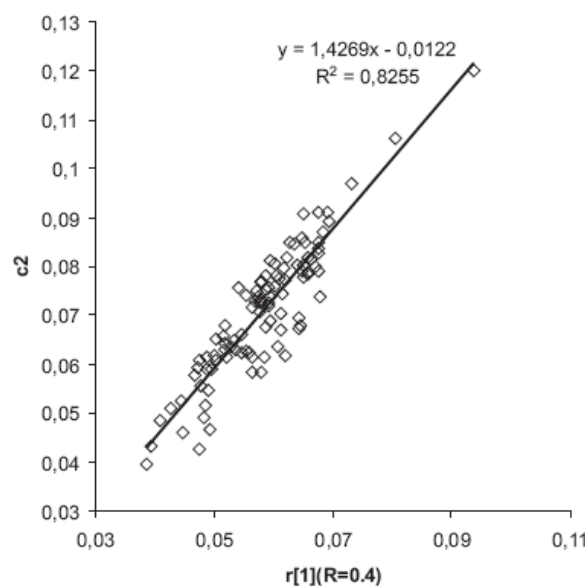
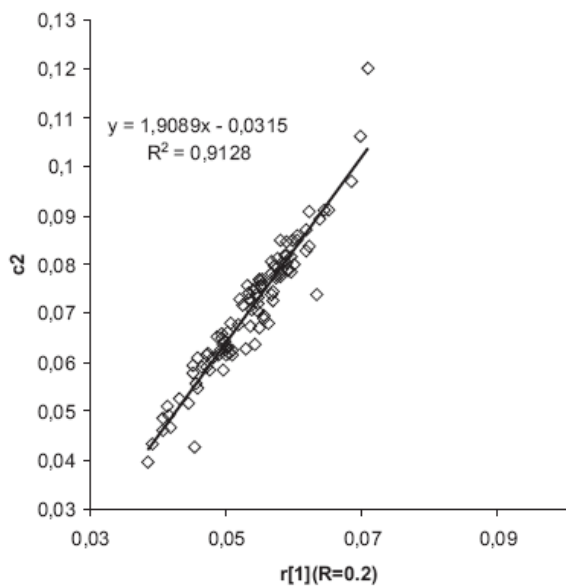
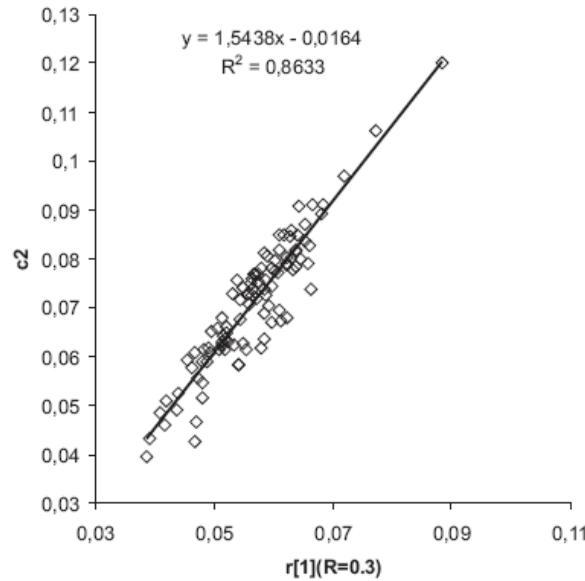
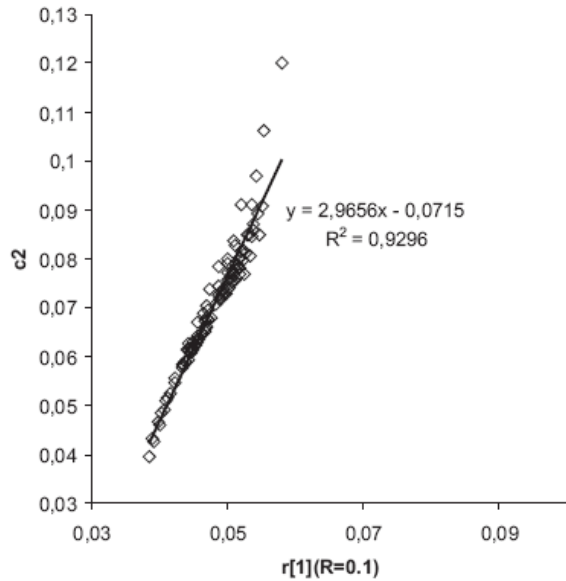
variance



experiment

teorie

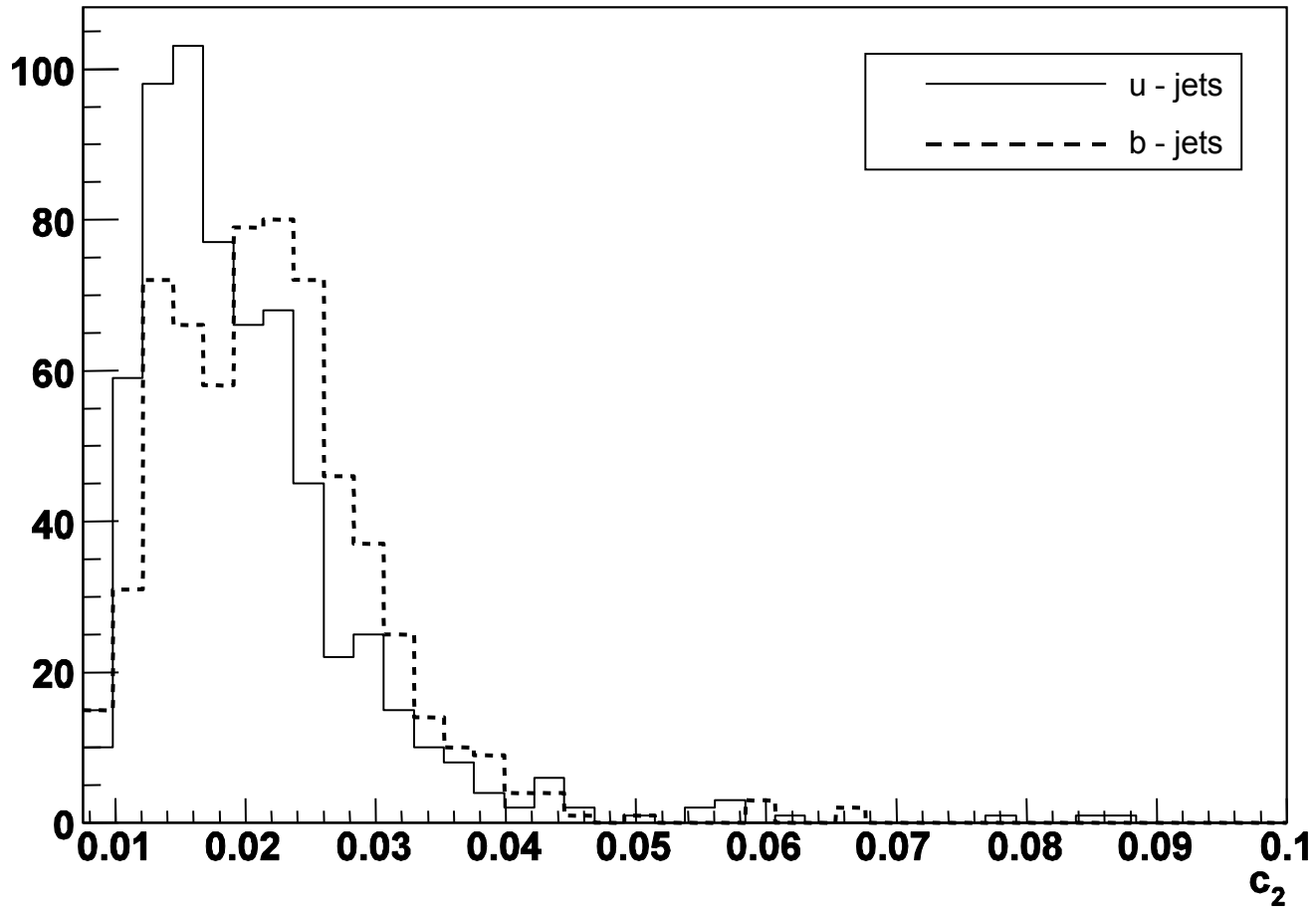
# Souvislost mezi momenty a parametrem c2



$$r^{[n]}(R) = \frac{\sum_{i:r_i \leq R} r_i^n E_{Ti}}{\sum_{i:r_i \leq R} E_{Ti}}$$

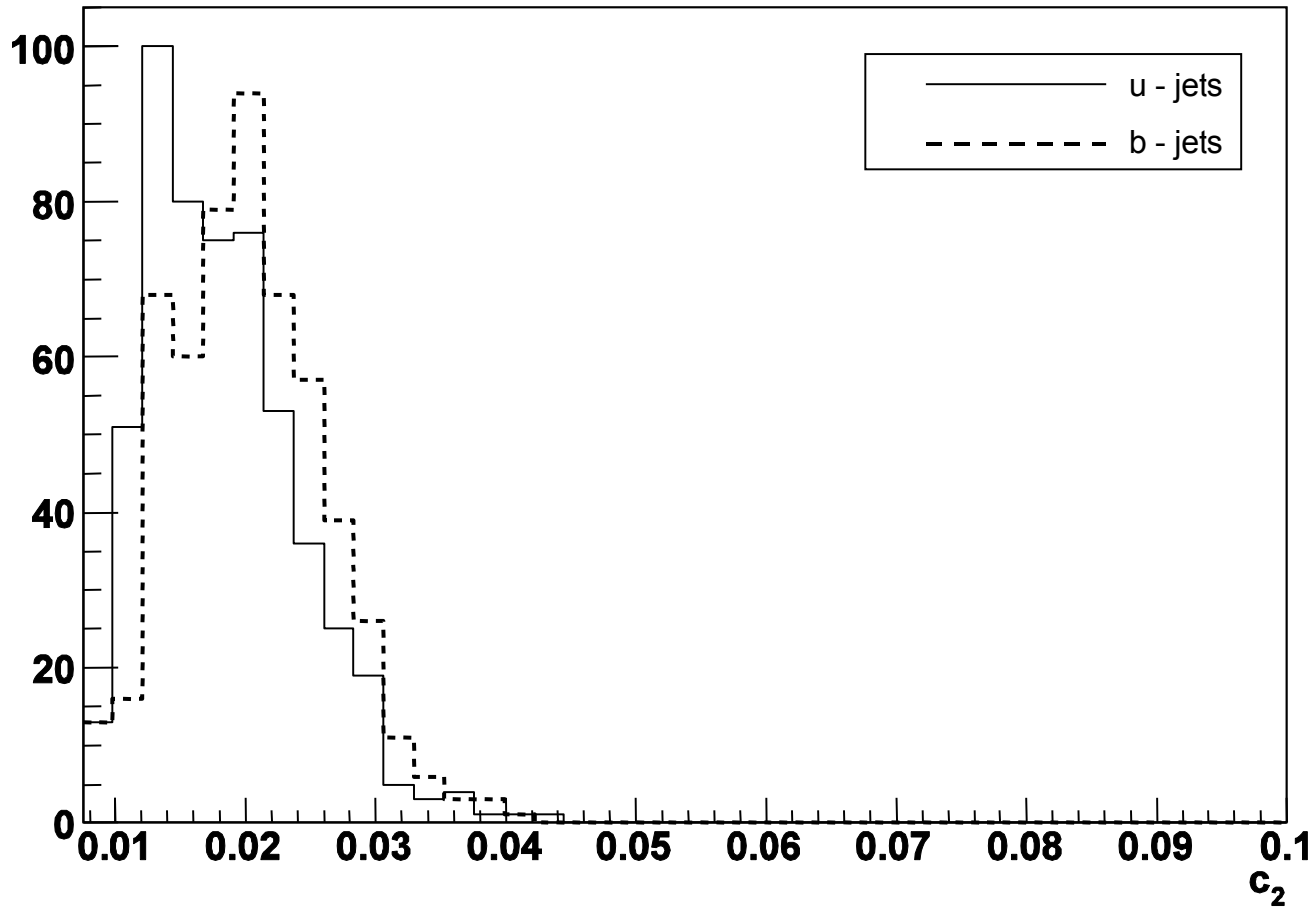
# Pythia, Fitting

## Jet width histogram

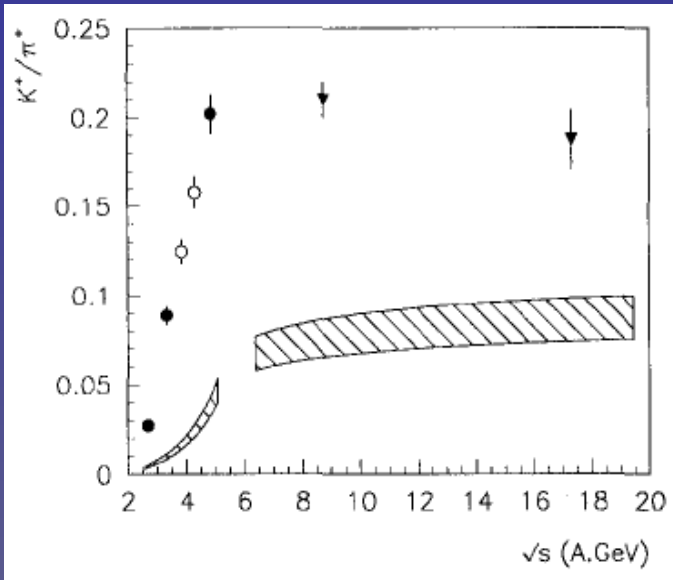


# Pythia+Hijing, Fitting+Chi2

## Jet width histogram



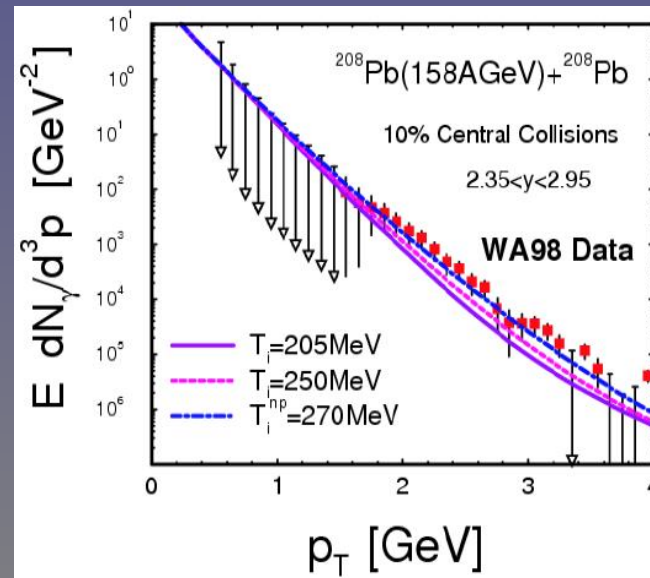
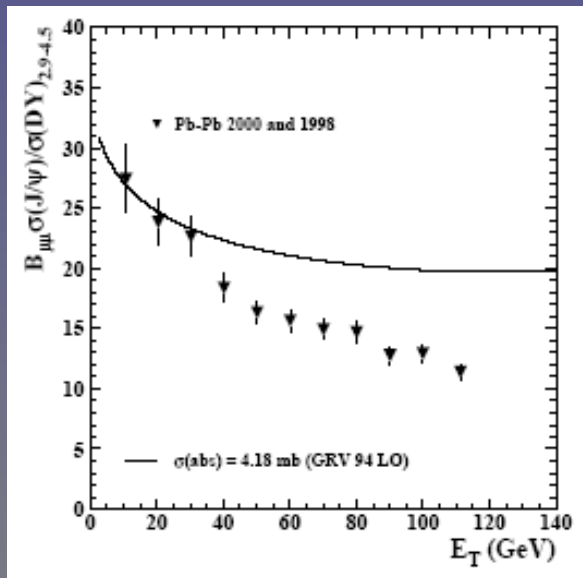
# Další nástroje na výzkum QGP



← zvýšení produkce podivných částic

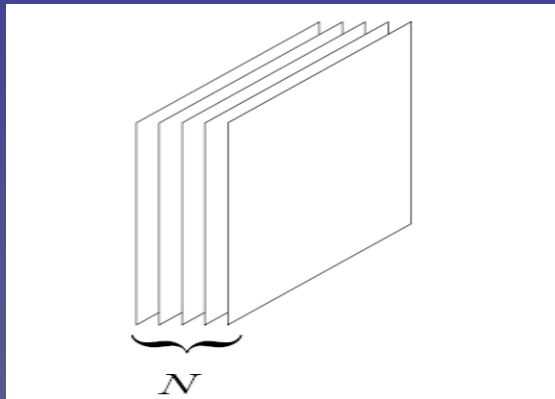
potlačení produkce kvarkonií

měření přímých fotonů

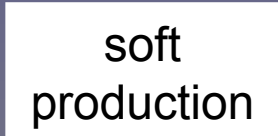
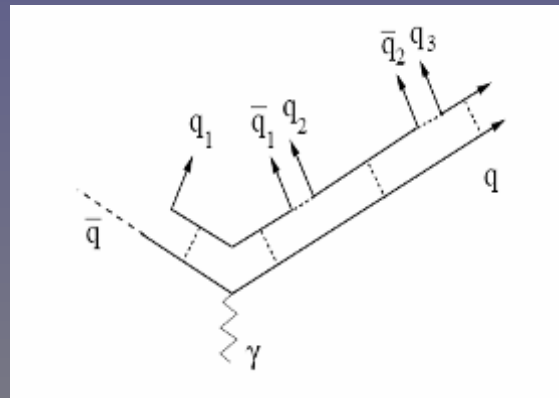
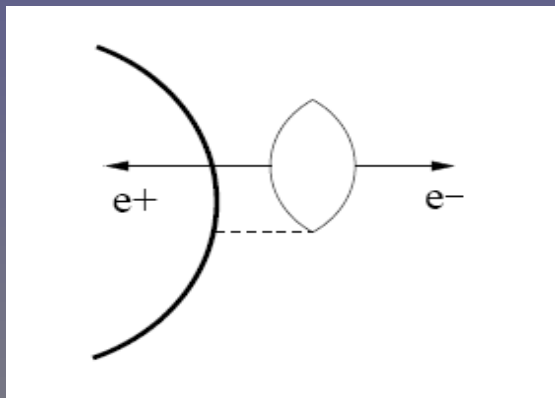


# „Nekonformní“ přístupy

QCD asymptoticky volná  $\rightarrow \alpha_s$  malá na velkých předaných impulzech,  
 problémy s výpočty termodynamických veličin v rámci pQCD, ...  
 x aplikace matematického aparátu teorie strun



OTR – černá díra – hmota uvězněna v omezené oblasti prostoročasu  $\Leftrightarrow$   
 QCD – hadrony – barevné konstituenty uvězněny uvnitř hadronu



## Proč se zabývat jety ve srážkách těžkých iontů

- Lze zkoumat vlastnosti media v rané fázi srážky (hustota, teplota, počet stupňů volnosti, opacita/viskozita ...)
- Lze zkoumat mechanismus ztráty energie, způsob hadronizace ve vakuu / v médiu
- Lze proměřovat fázový diagram jaderné hmoty
- Experiment přináší neočekávané výsledky
- QGP je pohled do minulosti ...

Více informací ...

QM2006 - <http://www.sinap.ac.cn/qm2006/scientific.html>

PoS(HEP2005)414 - [http://pos.sissa.it/archive/conferences/021/414/HEP2005\\_414.pdf](http://pos.sissa.it/archive/conferences/021/414/HEP2005_414.pdf)

Jet Quenching (GLV) - hep-ph/9907461

Jet Quenching (BDMPS) - hep-ph/9607355

Jet Quenching, Jet Shape & Jet multiplicites (SW) - hep-ph/0310079

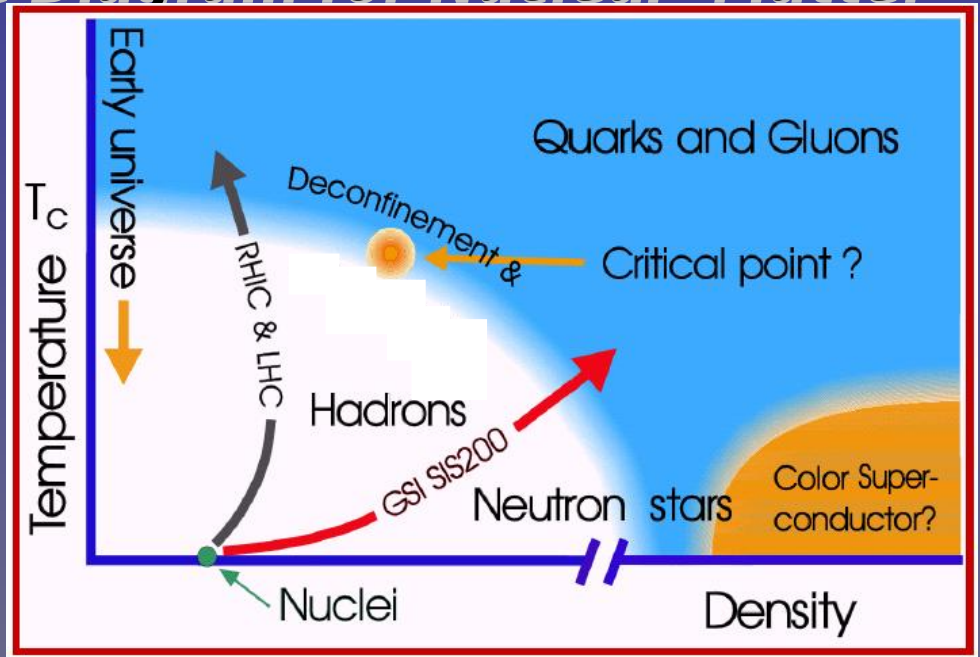
Jet Quenching & AdS/CFT - hep-ph/0605178

...

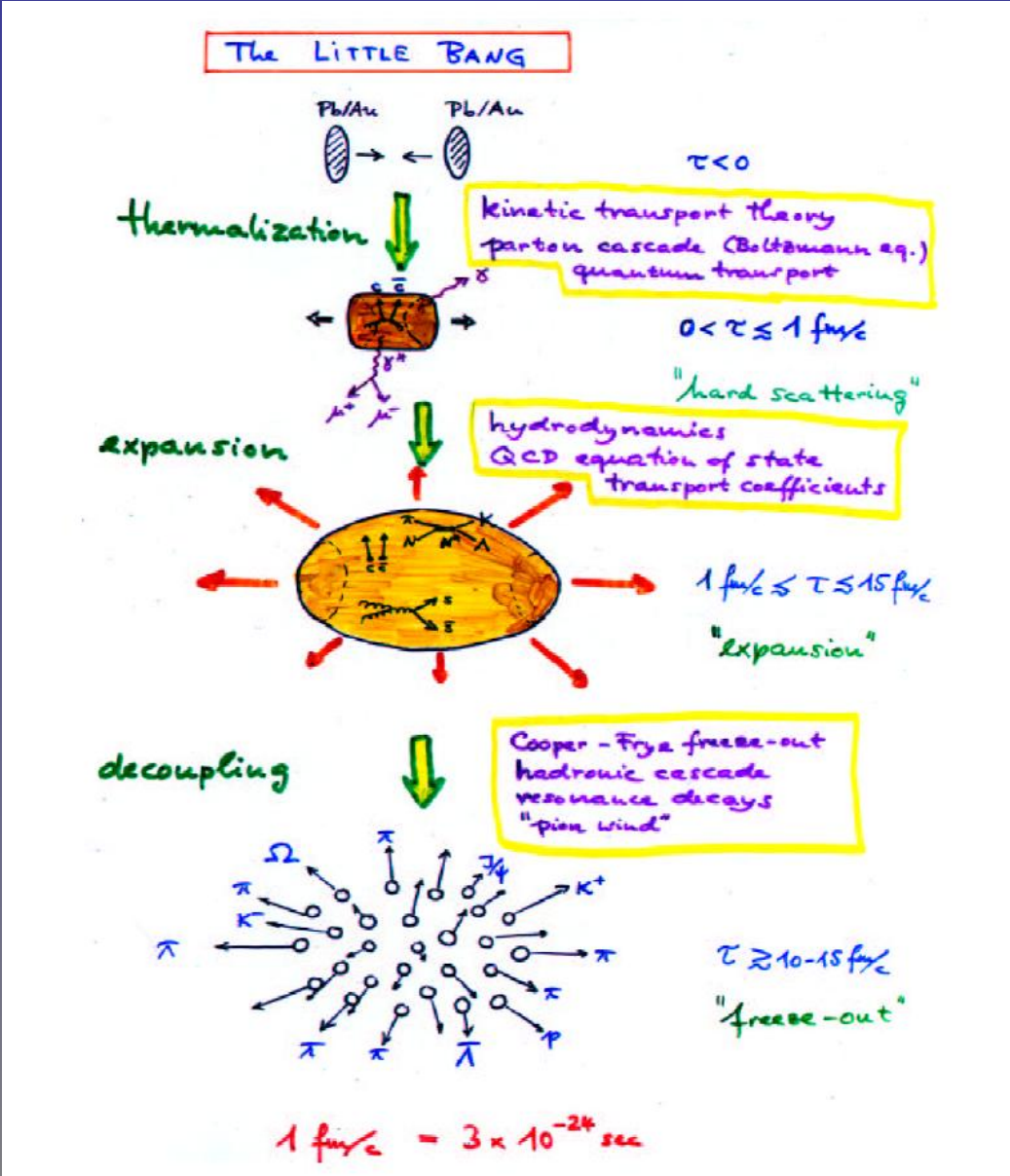
# Založní snímky

# Fázový diagram jaderné hmoty

## Phase Diagram for Nuclear Matter

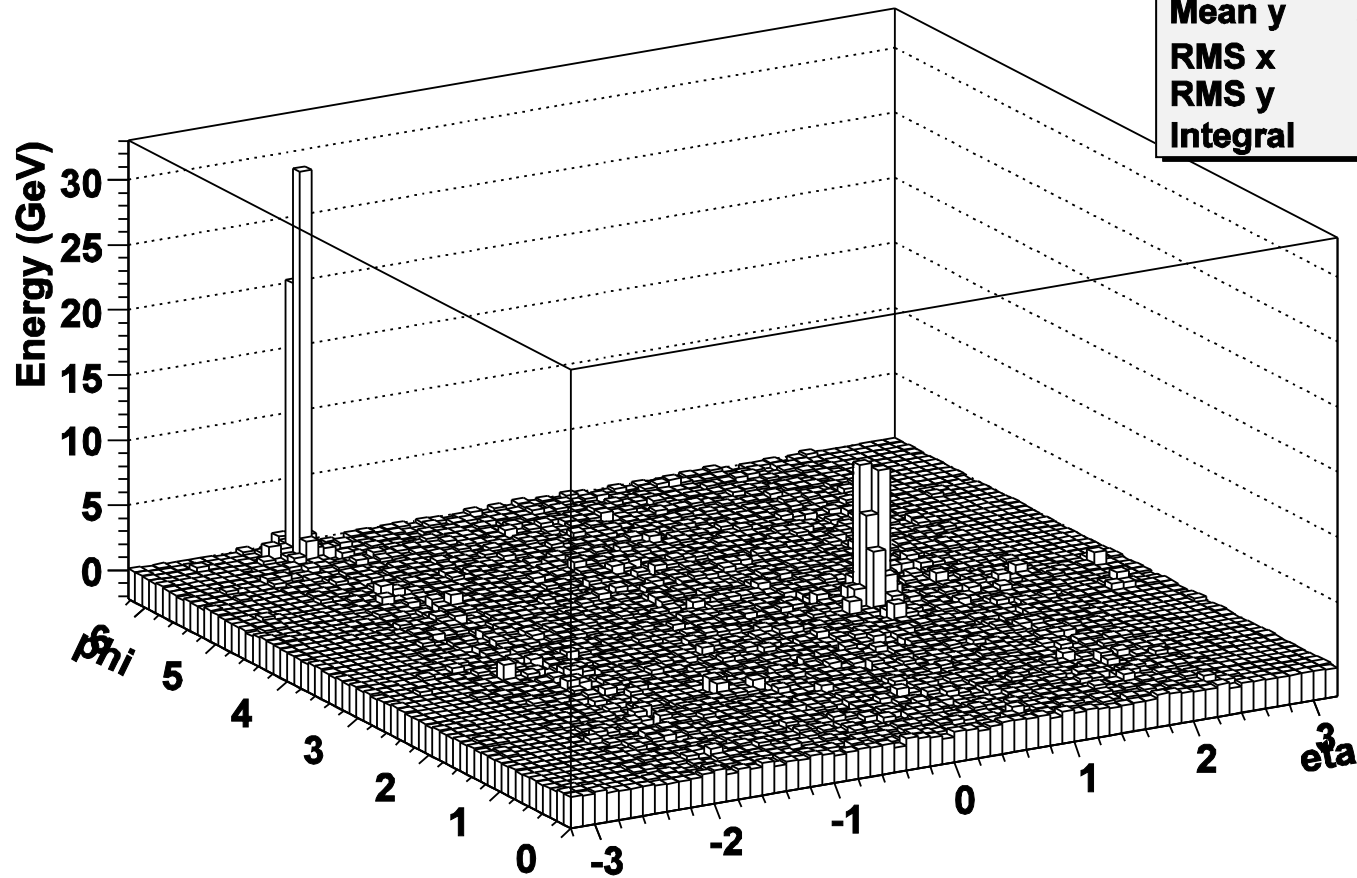


# QGP – pohled do minulosti ...



# Pythia

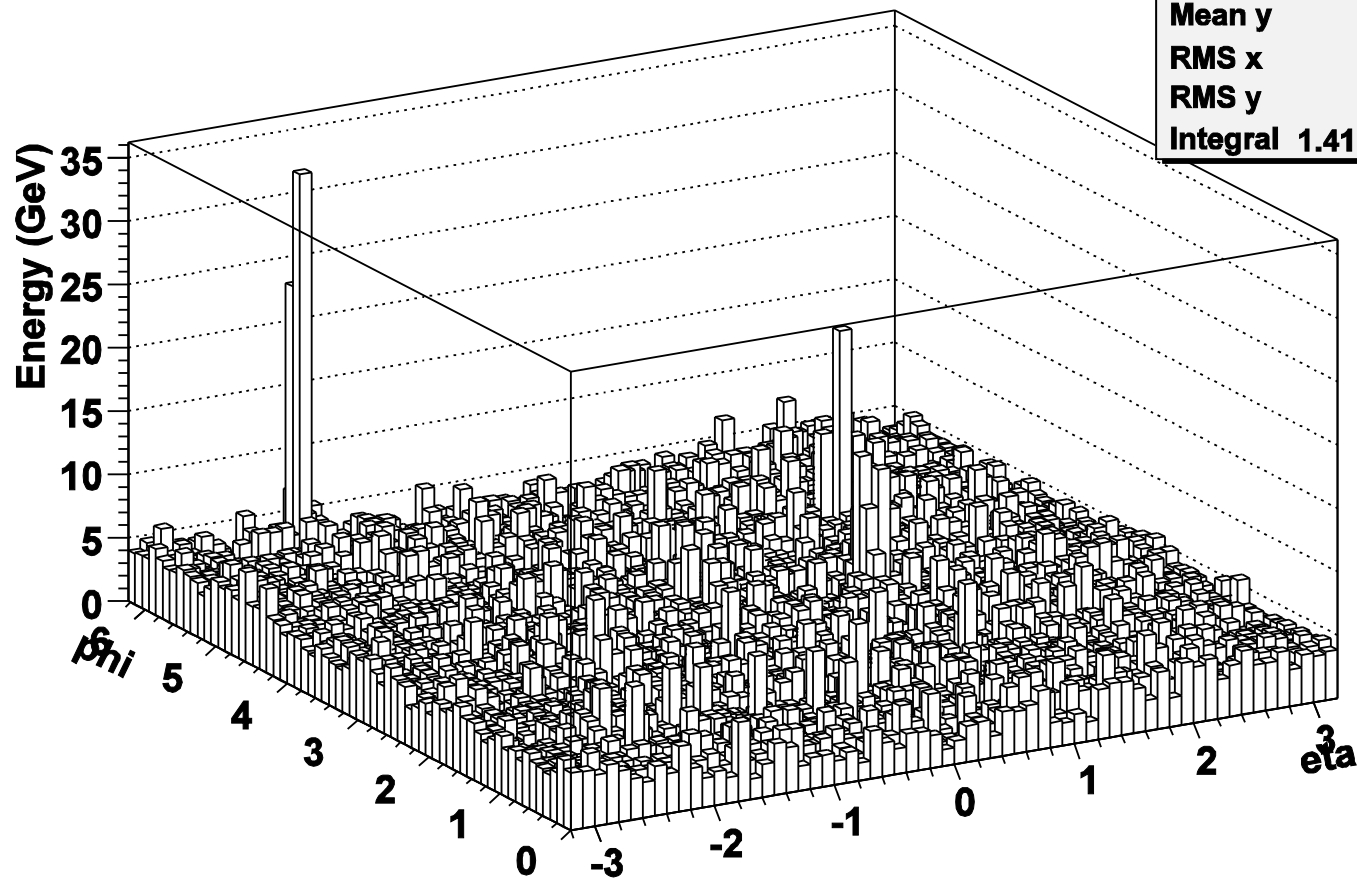
All Towers



Entries	4096
Mean x	-0.1882
Mean y	3.369
RMS x	1.587
RMS y	1.82
Integral	192

# Merged

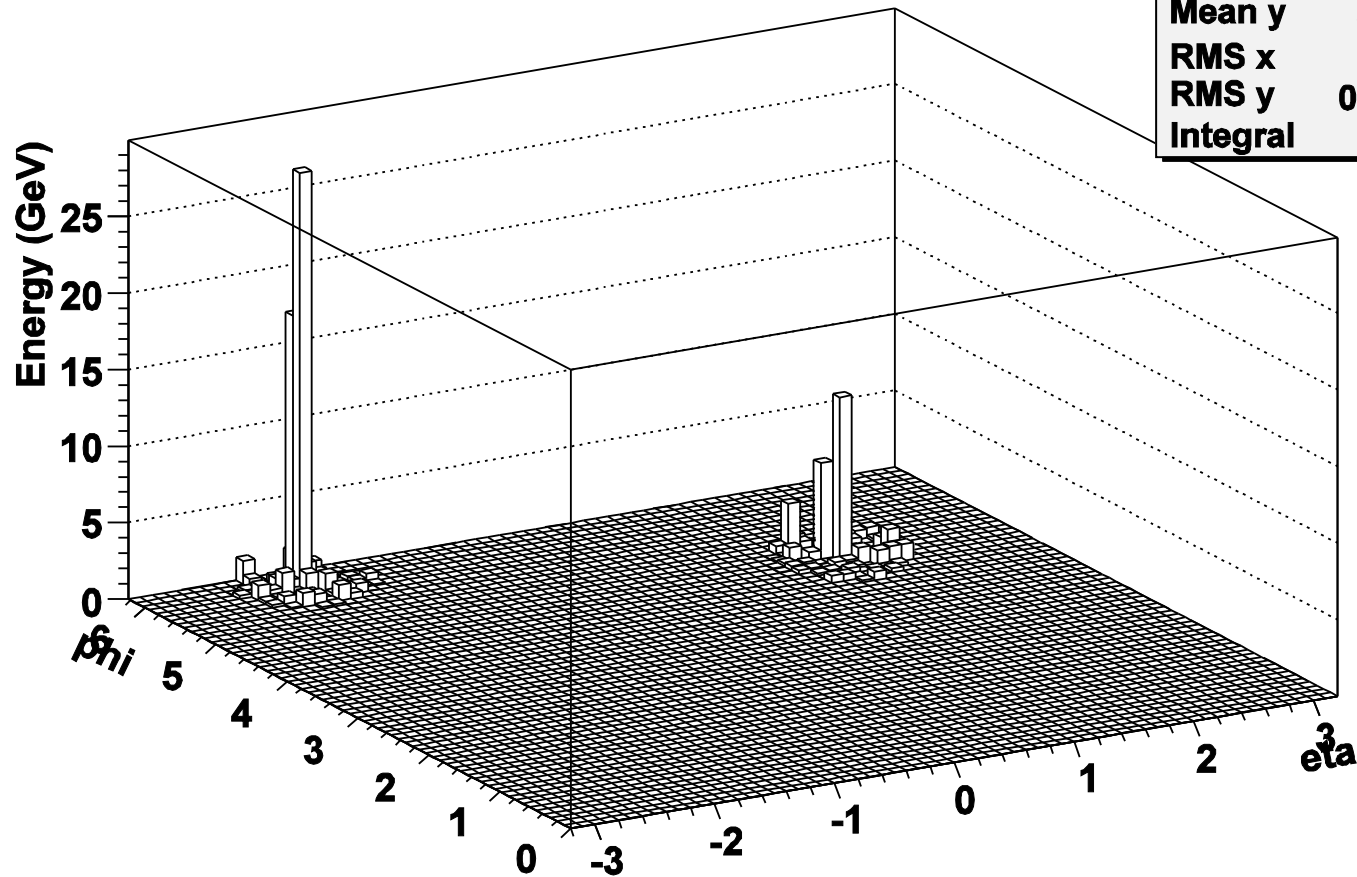
All Towers



Entries	4096
Mean x	-0.02523
Mean y	3.104
RMS x	1.944
RMS y	1.815
Integral	1.416e+04

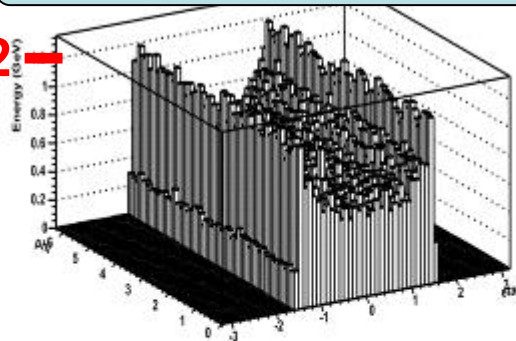
# Merged after "Cell Bkgr Subtraction"

All Towers

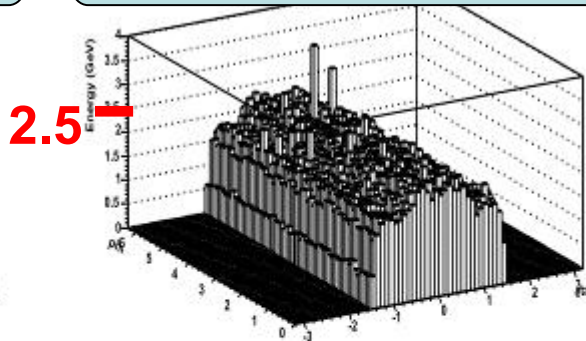


Entries	4096
Mean x	-0.4971
Mean y	5.365
RMS x	1.844
RMS y	0.6778
Integral	121.7

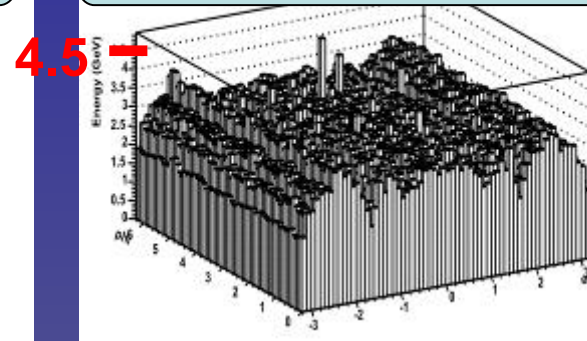
Presampler



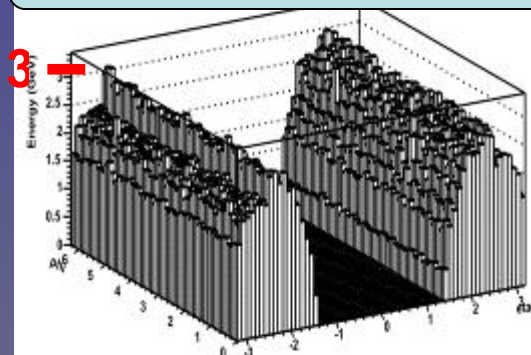
Barrel em.



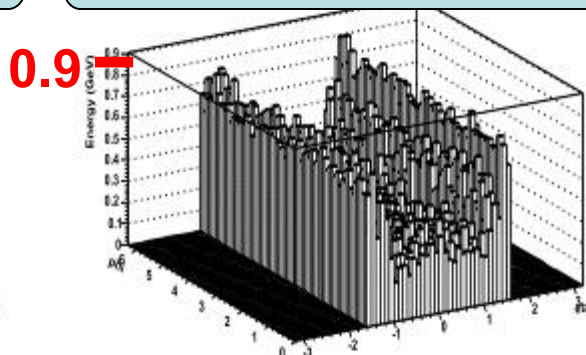
The whole calorimeter



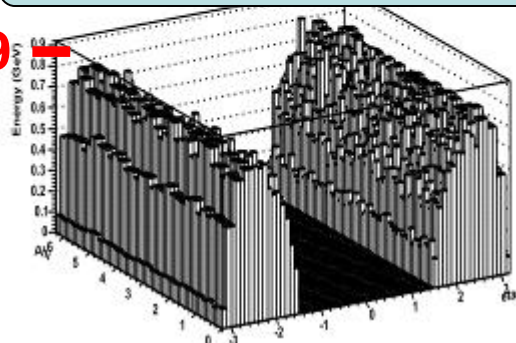
End-cap em.



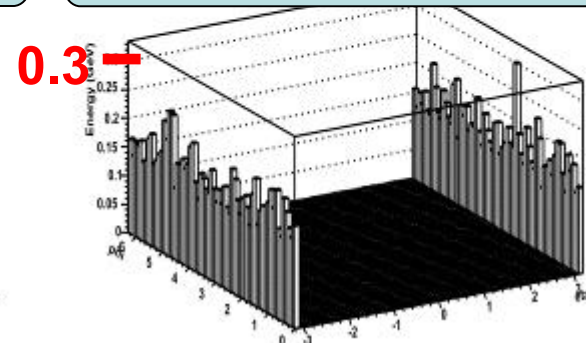
Tilecal



LAr end-cap



Forward calorimeter

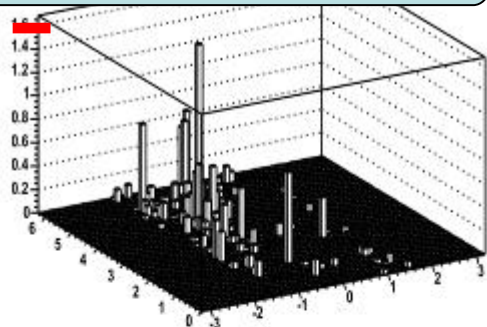


**Average Hijing background  
(around 3 GeV)**

**Population  
of different  
layers  
(100 events)**

Presampler

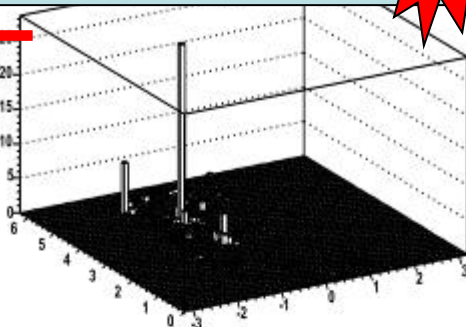
1.6



Barrel em.

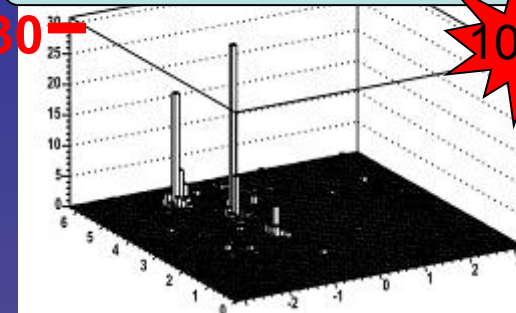
50%

25



The whole calorimeter

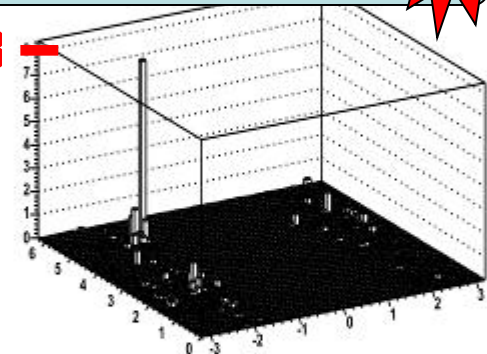
30



Endcap em.

30%

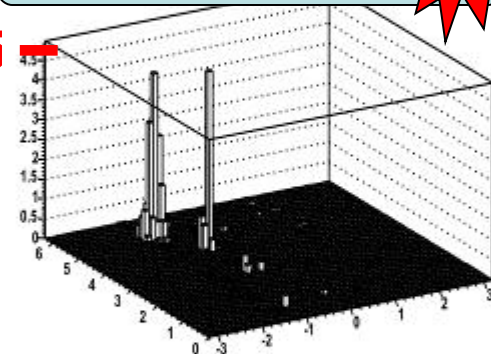
8



Tilecal

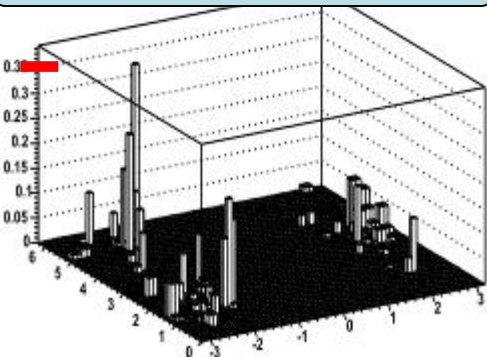
15%

5



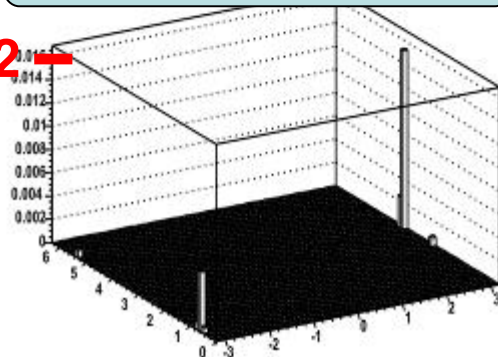
LAr end-cap

0.4



Forward calorimeter

0.02



Pythia  $pp$ -jets

Population of different layers (an example)

process:  
 $qq \rightarrow WH(120) \rightarrow \mu \nu_\mu uu$

# Heavy Ions at the ATLAS detector, few numbers

	RHIC		LHC	
	<i>p-p</i>	<i>Au-Au</i>	<i>p-p</i>	<i>Pb-Pb</i>
Top Energy (TeV/nucleon)	0.1	0.25	7	2.76
Average luminosity (cm <sup>2</sup> s <sup>-1</sup> )	10 <sup>31</sup>	10 <sup>26</sup>	10 <sup>34</sup>	10 <sup>27</sup>
$\langle dN_{ch}/d\eta \rangle$		≈600	200	≥3200

## Calorimeter

	$E_T/\text{GeV}$
Presampler	0.69
Barrel em. calorimeter	1.87
End-cap em. calorimeter	2.14
Tilecal	0.37
LAr end-cap	0.57
Forward calorimeter	0.17
The whole calorimeter	2.91

Pixels	2%
SCT	20%
TRT	---

## Inner detector

$$D_{AA} = \int_{p_t^{\min}}^{p_{t,1}} dp_{t,2} \int_{\Delta\phi > \Delta\phi^{\min}} d\Delta\phi \frac{d^3\sigma_{AA}^{h_1 h_2} / dp_{t,1} dp_{t,2} d\Delta\phi}{d\sigma_{AA}^{h_1} / dp_{t,1}}$$

$$D_q^h(z) = f_q^h(z) + \int_z^1 \frac{dz'}{z'} \sum_{q'} f_q^{q\bar{q}'}(1-z') D_{q'}^h\left(\frac{z}{z'}\right)$$