Shear viscosity of the quark-gluon plasma

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(Work in progress with Jean-Yves Ollitrault)

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Viscosity

Question:

What is the shear viscosity of the quark gluon plasma?

Goal

- Determine the best way to extract η/s from data
- Obtain a reliable value and systematically quantify the uncertainty

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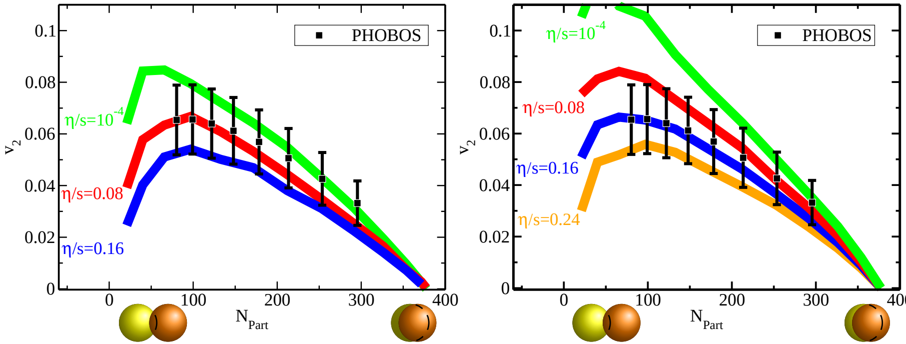
η/s FROM FLOW (HISTORICAL)

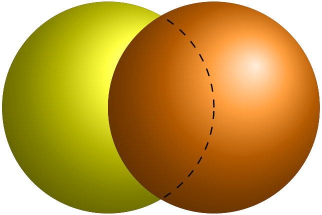
"Glauber" initial conditions "CGC" initial conditions



(ML & Romatschke, Phys.Rev. C78 (2008) 034915)

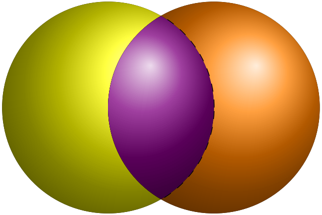
- Best extraction of η/s by comparing viscous hydro to flow data
- Largest uncertainty from unknown initial condition

INITIAL ECCENTRICITY



- Early-time physics is not well known
- Different initial physics $\Longrightarrow$ different eccentricity ε_2

Initial eccentricity



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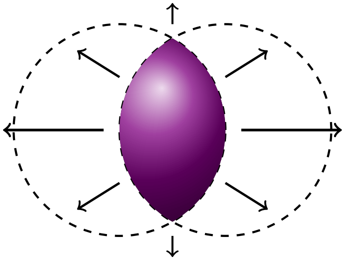

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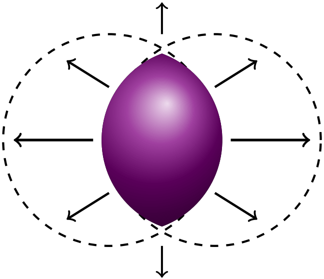

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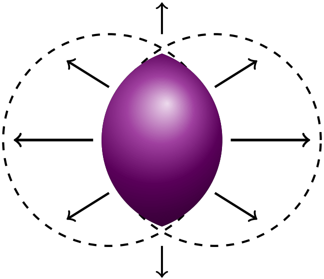

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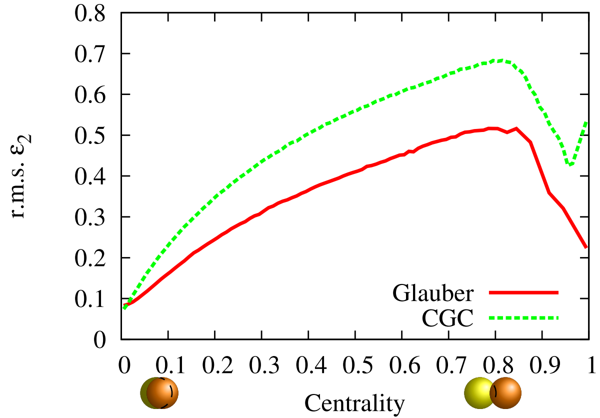

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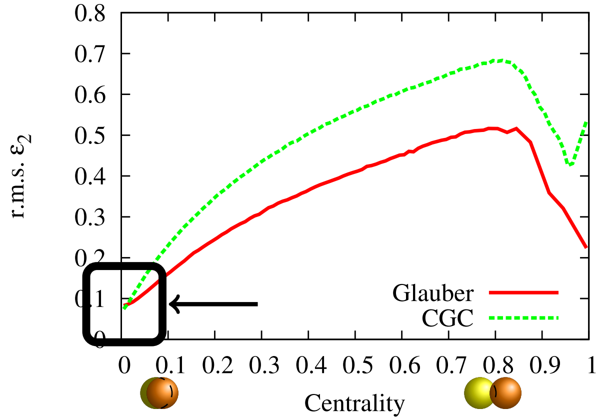

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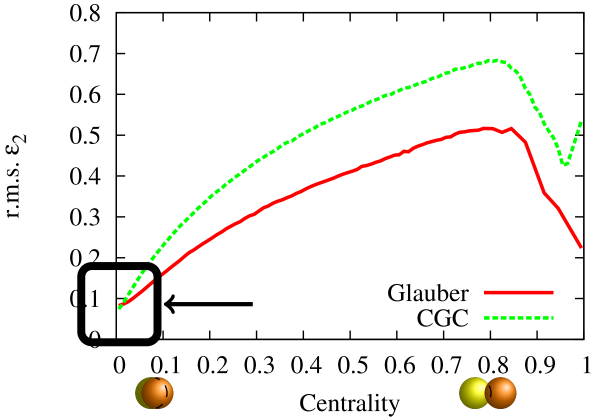

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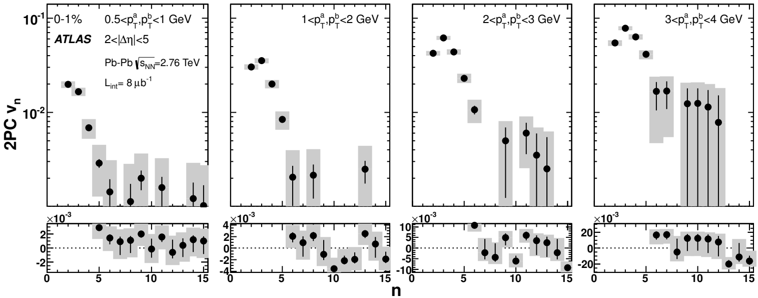
- Central collisions less sensitive to differences in initial physics

Extracting η/s from v_n in central collisions



New measurements of central collisions from ATLAS at LHC

- Extract η/s from p_T-integrated v_n in ultra-central LHC collisions:
- Minimizes uncertainty from initial conditions
- LHC collisions more sensitive to viscosity in QGP phase
- $v_n \propto \varepsilon_n$ in central collisions (even for $n > 3$!) (see F. Gardim, Friday 6D)

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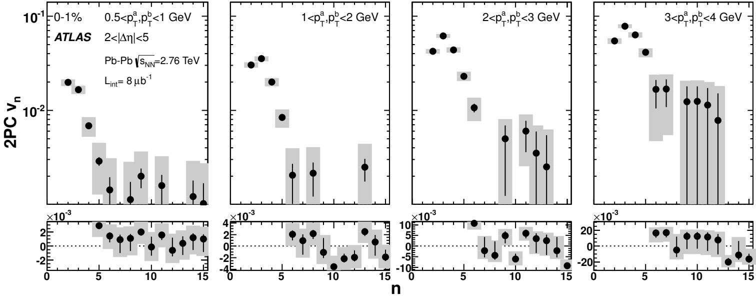

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OUR HYDRO SETUP

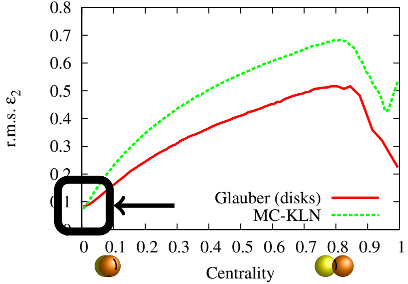
- 2+1d, 2nd order conformally invariant viscous hydro
- Constant η/s
- With or without separate chemical and kinetic freeze out
- Can directly test effects of:
  - As many models for initial conditions as we can get our hands on
  - Thermalization time, initialization of shear tensor, viscous correction to freeze out distribution function, second order transport coefficients, equation of state, chemical freeze-out, etc.
- Not directly tested in this work:
  - Longitudinal dynamics / fluctuations
  - Bulk viscosity
  - Hydro afterburners
  - Full event-by-event analysis

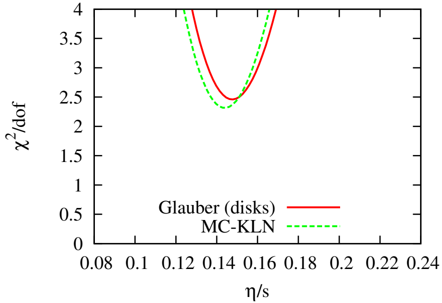
η/s from ultra-central collisions

Procedure

- Calculate integrated v_n/ε_n versus η/s in hydrodynamics
- Calculate r.m.s. ε_n from Monte-Carlo models of initial conditions
  $\implies v_n(\eta/s)$
- Extract best-fit value for η/s from v_2–v_6 in 0–1% central collisions
- Vary all parameters and determine effect on extracted η/s
  $\implies$ uncertainty in η/s
- Estimate uncertainty from other sources
- $\implies$ measurement of η/s with error bar

η/s from ultra-central collisions





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- Range of results quantifies uncertainty

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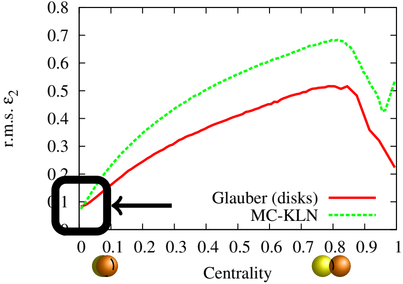

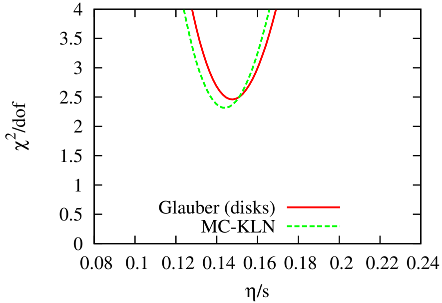

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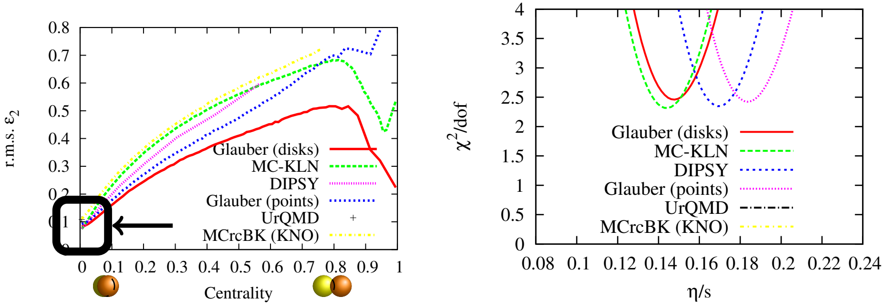

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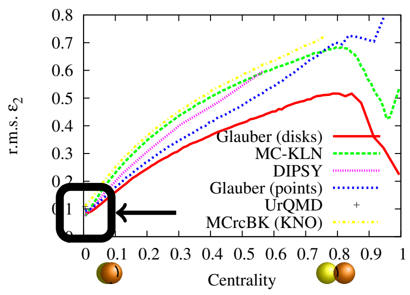
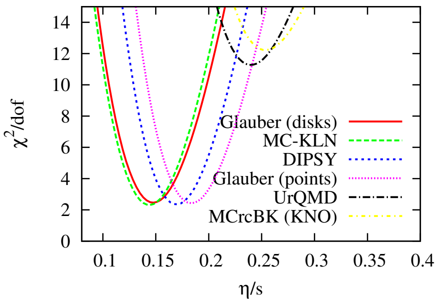
η/s FROM ULTRA-CENTRAL COLLISIONS





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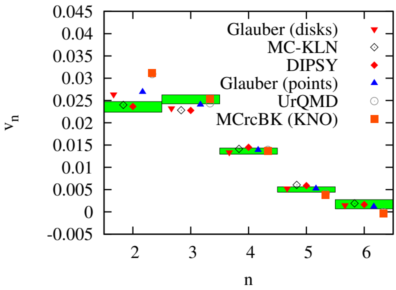

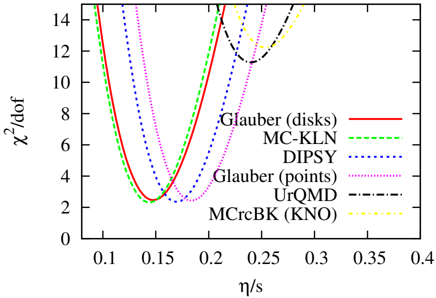

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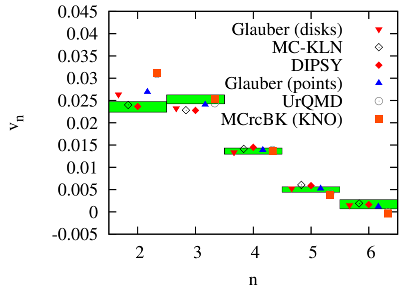
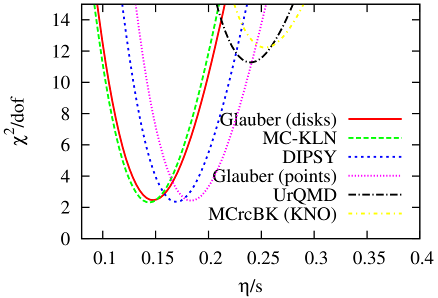
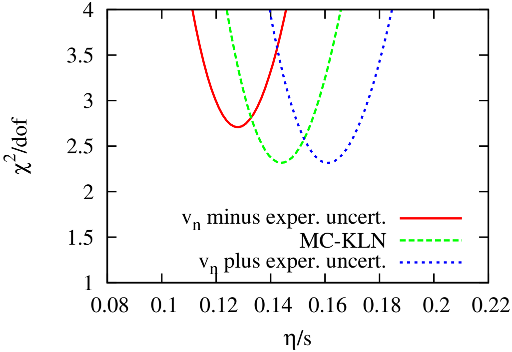




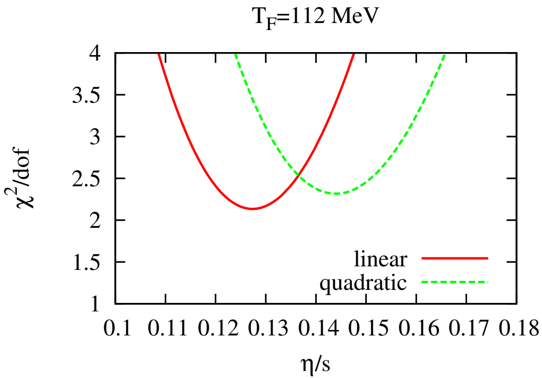
- A simultaneous fit of v_2–v_6 gives a preferred extracted η/s for each initial condition
- Range of results quantifies uncertainty
- Uncertainty due to initial ε_n: $\sim \pm 0.05$

Experimental uncertainty



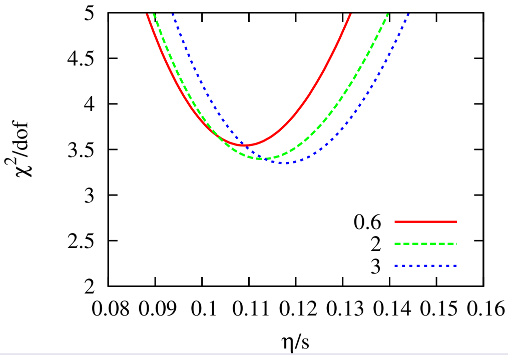
- Systematic (plus statistical) experimental error: $\delta v_2/v_2 \simeq 5\%$, $\delta v_3/v_3 \simeq 4\%$, $\delta v_4/v_4 \simeq 5\%$, $\delta v_5/v_5 \simeq 12\%$, $\delta v_6/v_6 \simeq 61\%$
- Uncertainty due to experimental error: $\sim \pm\, 0.02$

Viscous correction to distribution function δf



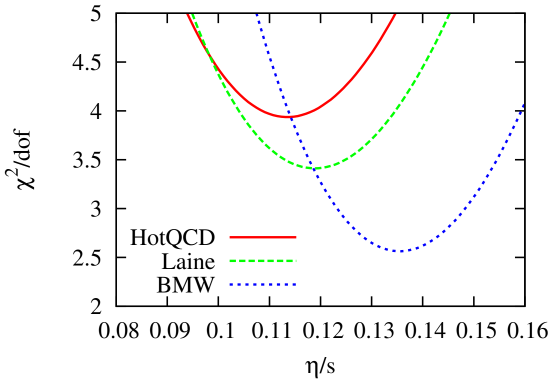
- From fluid d.o.f. to particles: $f(p,x) = f_{equil} + \delta f$
- Uncertainty due to momentum dependence of δf: ± 0.015

SECOND ORDER TRANSPIRE COEFFICIENTS: τ_Π



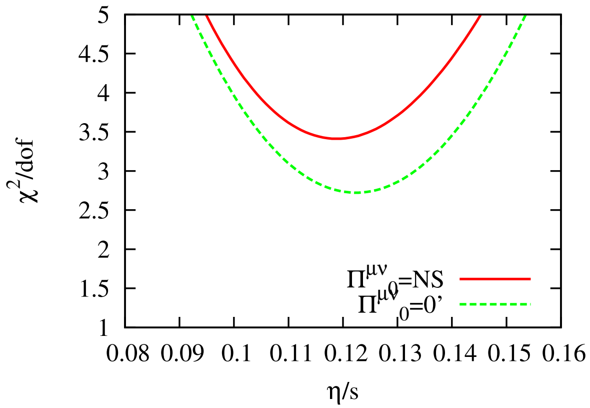
- $$\tau_\Pi = 2\frac{\eta}{sT} \times C$$
- Israel-Stewart: $C = 3$
- SYM: $C = 2 - log(2) \simeq 1.3$
- Uncertainty due to 2nd order transport coeff.: $\pm$ 0.005

Equation of State



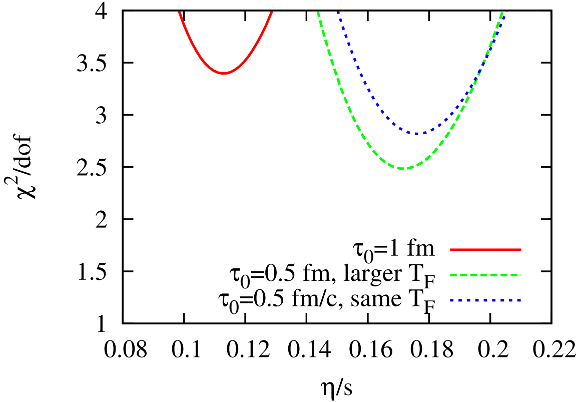
- Uncertainty due to equation of state: ± 0.01

$\Pi^{\mu\nu}$ INITIALIZATION



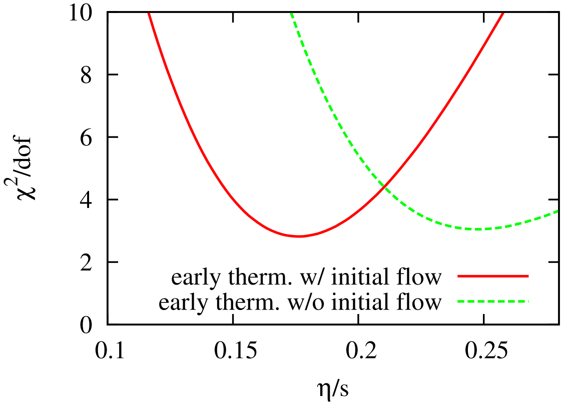
- Uncertainty due to initialization of shear tensor: $< \pm\, 0.005$

Thermalization time τ_0



- Uncertainty from τ_0 $\pm$ 0.03

Initial flow



- Uncertainty from initial flow $\pm$ 0.04

Systematic Uncertainty for η/s

(Preliminary!)

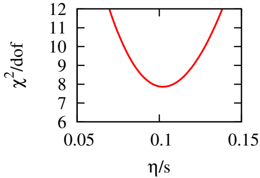
• Experimental uncertainties	± 0.020
• Initial eccentricity	± 0.050
• Thermalization time	± 0.030
• Initialization of shear tensor	± 0.005
• Initial flow	± 0.040
• Equation of State	± 0.015
• Second-order transport coeff.	± 0.005
• Viscous correction to f.o. distribution	± 0.015
• Chemical freeze out	± 0.015

(Preliminary!)

Bounds: Hydro run with largest (smallest) η/s

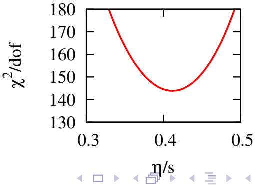
Lower Bound:

- Data + uncert.
- MC-KLN I.C.s
- $\tau_0 = 1$ fm
- $u_0^i = 0$
- $\Pi_0^{\mu\nu} = 0$
- BMW EOS
- $\tau_\pi = \frac{6\eta}{sT}$
- $\delta f \propto p$



Upper Bound:

- Data − uncert.
- MCrcBK (w NB)
- $\tau_0 = 0.5$ fm
- $u_0^i = \frac{-\tau}{2}\partial^i \ln s$
- $\Pi_0^{\mu\nu}$ = Nav. St.
- s95p-PCE165
- $\tau_\pi = \frac{2.6\eta}{sT}$
- $\delta f \propto p^2$



Other uncertainty

Next step: estimate uncertainty from other sources and add to error band

- Bulk Viscosity $\sim \pm 0.010$
- $v_n/\varepsilon_n =$ constant $\sim \pm 0.010$
- Deviation from boost-invariance / longitudinal fluct. $\sim \pm 0.005$
- Freezing out with (PCE +) Cooper-Frye $\sim \pm 0.010$

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Final Result:

$$0.07 \leq \eta/s \leq 0.43$$

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$v_n/\varepsilon_n =$ constant	$\sim \pm 0.010$
Thermalization time	± 0.030
Initialization of shear tensor	± 0.005
Initial flow	± 0.050
Equation of State	± 0.015
Second-order transport coeff.	± 0.005
Bulk Viscosity	$\sim \pm 0.010$
Deviation from boost-invariance / longitudinal fluct.	$\sim \pm 0.005$
Viscous correction to f.o. distribution	± 0.015
Other aspects of freeze out	$\sim \pm 0.025$

(Preliminary!)

Summary

- Flow in central heavy-ion collisions are less sensitive to early-time dynamics
- $\Longrightarrow$ Focusing on ultra-central collisions reduces systematic uncertainty in viscosity extraction
- First extraction of η/s with comprehensive study of systematics, reliable error bar:
- $0.07 \leq \eta/s \leq 0.43$ (preliminary!!)
- Largest *single* source of uncertainty still initial conditions
- Many less significant sources of error are more important in aggregate; almost all have clear potential for improvement

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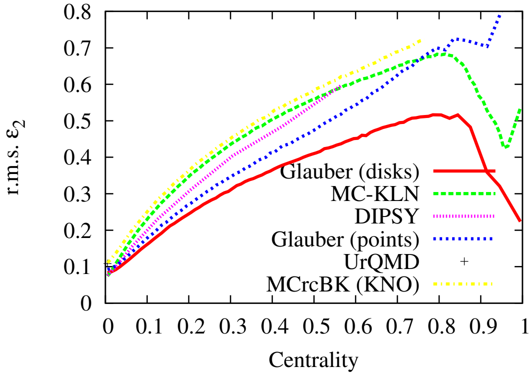
Extra Slides

ε_n FROM A FEW MODELS



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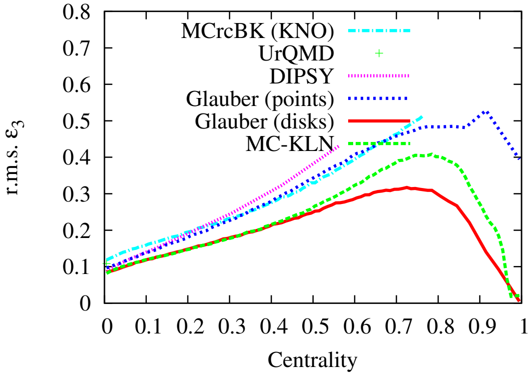

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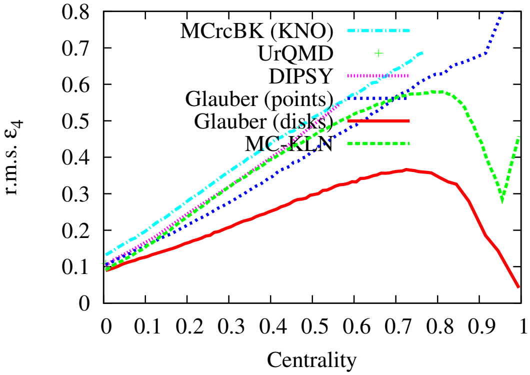

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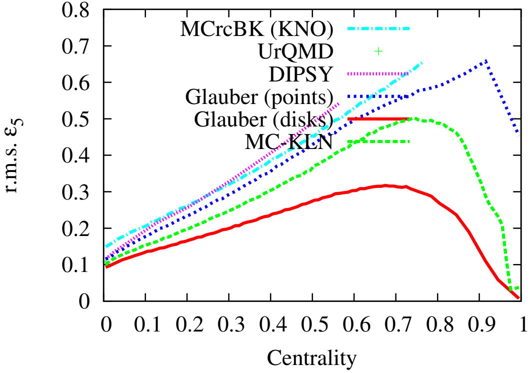
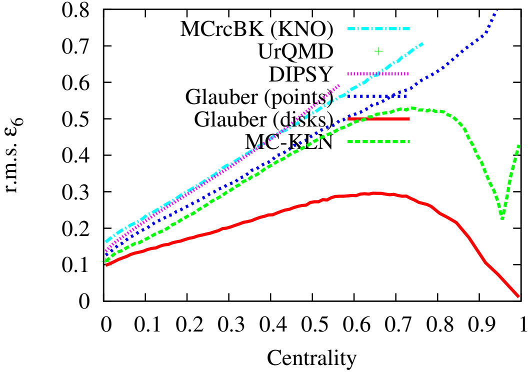
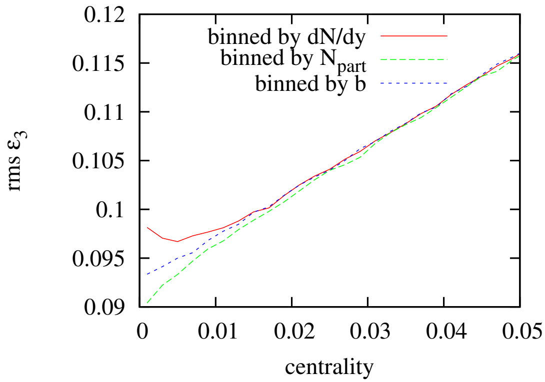


ε_n from a few models

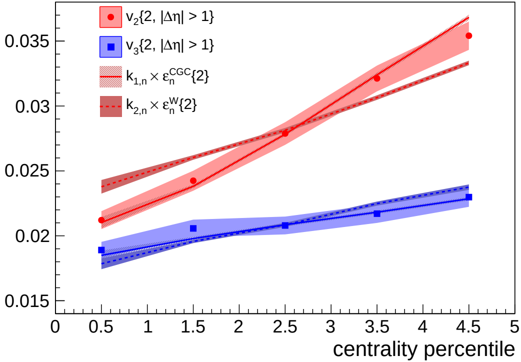


SELECTING CENTRALITY (EXAMPLE FROM PHOBOS GLAUBER)



- Correct binning in centrality is important for very central collisions

CENTRALITY DEPENDENCE OF ε_n (ALICE ARXIV:1105.3865)



- Centrality dependence of $v_2 \implies$ centrality dependence of ε_2 $\implies$ intrinsic eccentricity

EXTRA SLIDES