# Non-statistical higher moments in high-energy pp collisions

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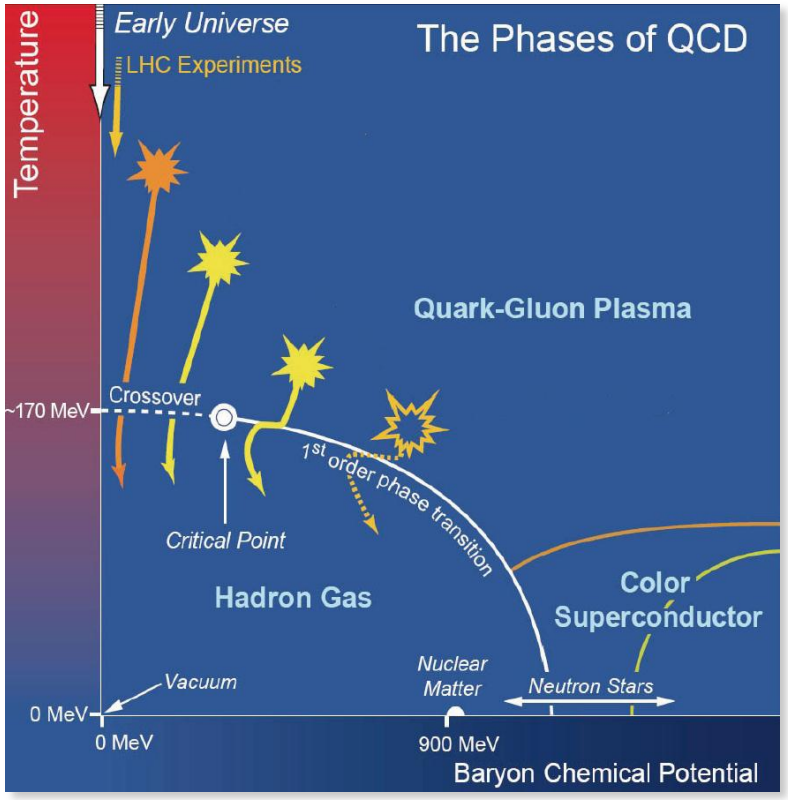
# Outline

- Motivation
- Brief introduction to PACIAE (PYTHIA) models
- PACIAE (PYTHIA) description for charged particle productions
- Preliminary result of higher moments
- Conclusions

# Motivation

One of the major goals of HIC is to explore the QCD phase diagram.




At $\mu_B = 0$, LQCD suggests a crossover at $T_c$~170-190 MeV from HG to QGP. [Y. Aoki et al. PLB 643, 46 (2006); M. Cheng et al. PRD 74, 054507 (2006); S. Gupta et al., Science 332, 1525 (2011)]

At large $\mu_B$ region, the phase transition is of 1st order [S. Ejiri PRD 78, 074507 (2008); E. S. Bowman & J. I. Kapusta, PRC 79, 015202 (2009)]

The point where the 1st phase transition end is the QCD critical point (CP).

Question: Can one find any indication for a possible CP ?

# Observables

## Heavy ion reactions

The increase of non-Gaussian fluctuation and the divergence of correlation length $\xi$ at CP.
[$\xi$~2-3 fm near the CP]
[$\xi$ is related to various moments of the distributions of conserved quantities→ variance $\sigma^2 \sim \xi^2$ ]

[M. Stephanov et al., PRD 60, 114028 (1999); B. Berdnikov & K. Rajagopal, PRD 65, 105017 (2000)]

[V. Koch et al., PRL 95, 182301 (2005); M. Asakawa et al., PRL 85, (2000)]

## Enhanced fluctuations

Multiplicity, Average $p_t$
Particle ratios

[NA49, PRC83, 061902 (2011); NA49, PRC79, 044910 (2009); STAR, PRL103, 092301 (2009)]

## Conserved quantities

Net Strangeness *S*
Net Baryon number *B*
Net Charge *Q*

Measure of non-Gaussian behavior have a sensitivity to CP.

Higher moments more sensitive to the divergence of correlation lengths $\xi$

[M. Stephanov et al., PRL 102, 032301 (2009)]

Cr: C. Blume's talk @ CPOD2011

# Introduction to the moments of conserved quantities

For example, net proton ( $N=N_p-N_{pbar}$ ) in one event

The deviation of N from its mean value can be defined by

$$\delta N = N - \langle N \rangle$$

The various order **cumulants** of event-by-event distributions can be defined as

$C_{1,N} = \langle N \rangle$,
$C_{2,N} = \langle (\delta N)^2 \rangle$,
$C_{3,N} = \langle (\delta N)^3 \rangle$,
$C_{4,N} = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$,

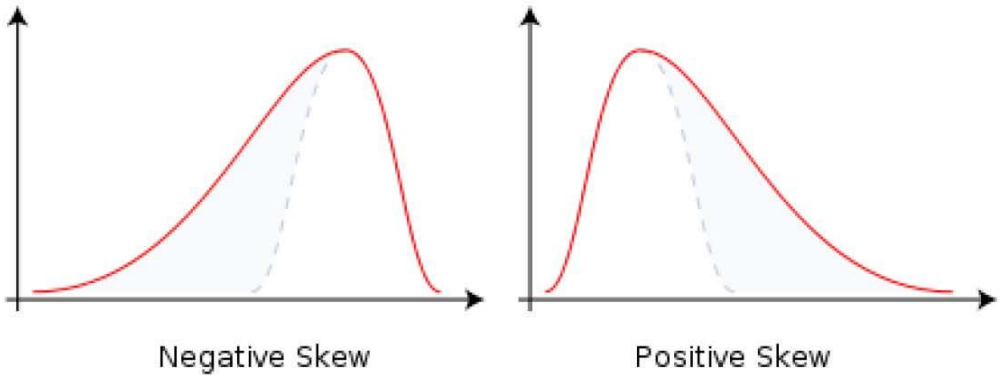
The various order **moments** of event-by-event distributions can be defined as

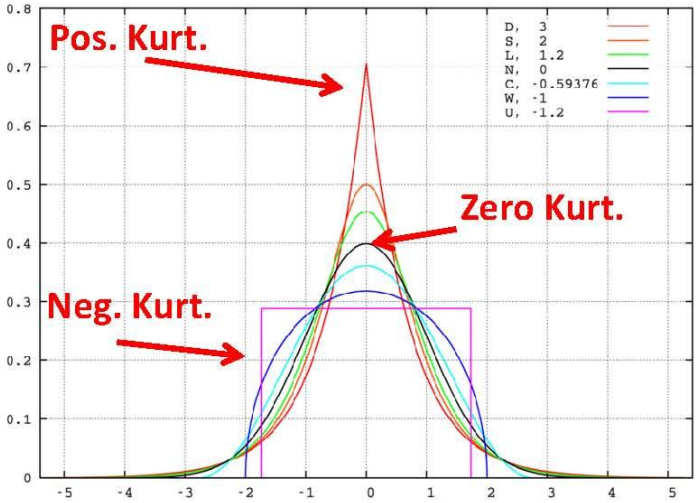
1st $M = C_{1,N} = \langle N \rangle$,
2nd $\sigma^2 = C_{2,N} = \langle (\delta N)^2 \rangle$,
3rd $S = C_{3,N}/(C_{2,N})^{3/2}$
4th $\kappa = C_{4,N}/(C_{2,N})^2$,

Moment products: $S\sigma = C_{3,N}/C_{2,N}$ and $\kappa\sigma^2 = C_{4,N}/C_{2,N}$

# Skewness and Kurtosis : Non-Gaussian measure

**N: Event by Event Multiplicity**




- **For Gaussian distribution, the skewness and kurtosis are equal to zero. Ideal probe of the non-Gaussian fluctuations near critical point.**

Cr: X. Luo's talk @ CPOD2011

# Review of previous exploration

- Higher moments as well as moment products are sensitive to the correlation length and directly connected to the thermodynamic susceptibilities computed in LQCD and HRG [X. Luo, J. Phys. Conf. Ser. 316, 012003 (2011)]

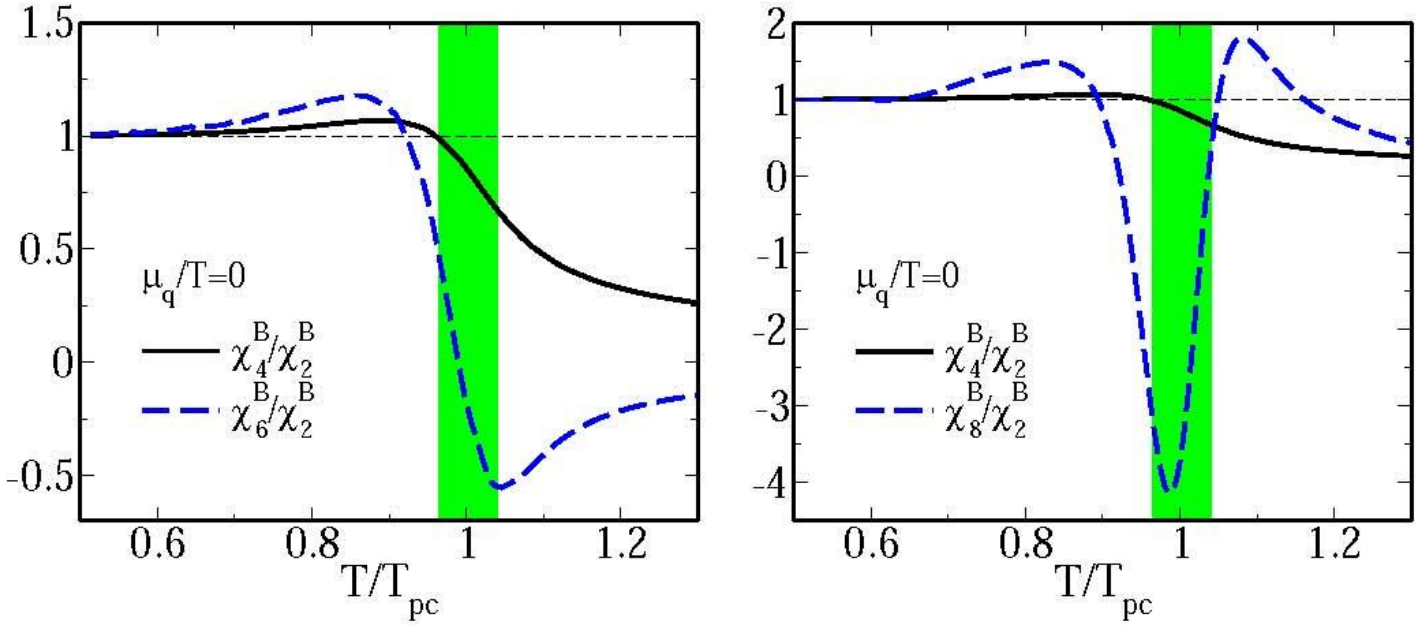
$$\chi^{(2)} = \langle(\delta N)^2\rangle / VT^3$$
$$\chi^{(3)} = \langle(\delta N)^3\rangle / VT^3$$
$$\chi^{(4)} = \langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 / VT^3$$

$$\chi^{(4)}/\chi^{(2)} = C_{4,N}/(C_{2,N}) = \kappa\sigma^2$$
$$\chi^{(3)}/\chi^{(2)} = C_{3,N}/(C_{2,N}) = S\sigma$$

[M. Cheng et al. PRD 79, 074505 (2009); F. Karsch et al, PLB 695, 136 (2011)]

- The relation between LQCD calculated NBN susceptibility and HIC experimental data of NBN moments allows one to find critical T of QCD phase transition [S. Gupta et al., Science 332, 1525 (2011)]

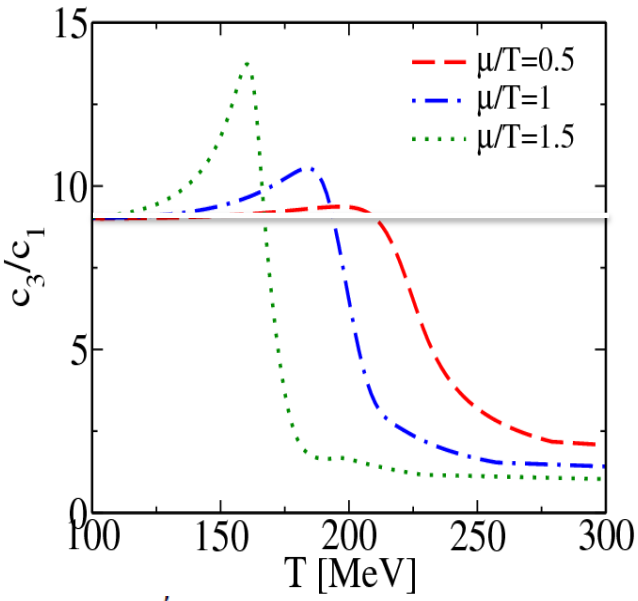
- Third moments of conserved charges as probes of QCD phase structure [M. Asakawa et al., PRL 103, 262301 (2009)]
- Kurtosis is negative when the CP is approached [M. A. Stephanov, PRL 107, 052301 (2011)]
- Fluctuations as probe of the QCD phase transition in heavy ion collisions at LHC and RHIC [B. Friman et al., Eur.Phys.J. C71, 1694 (2011)]

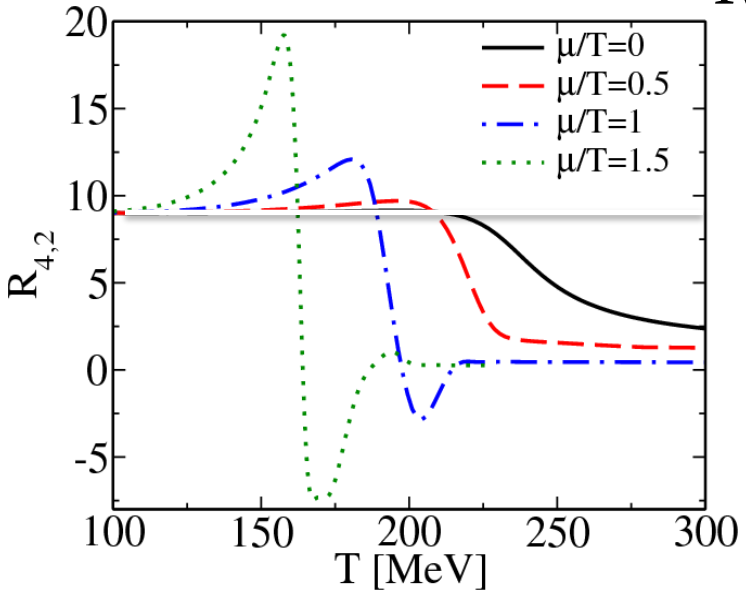


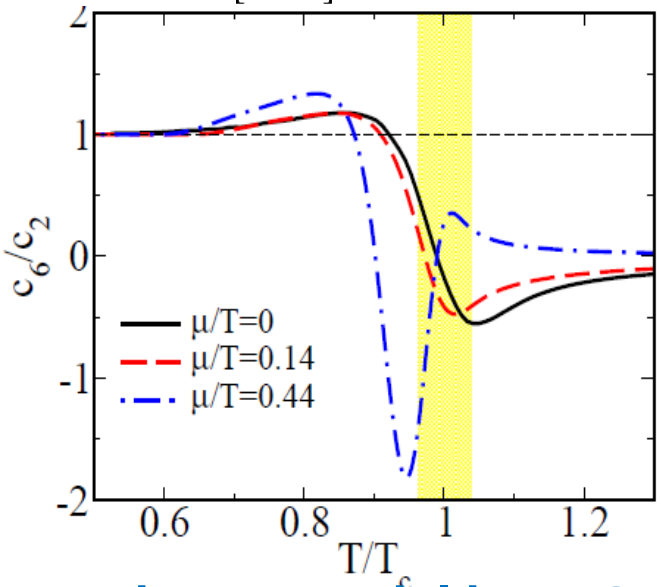
# Deviation of ratio of cumulants (PQM)

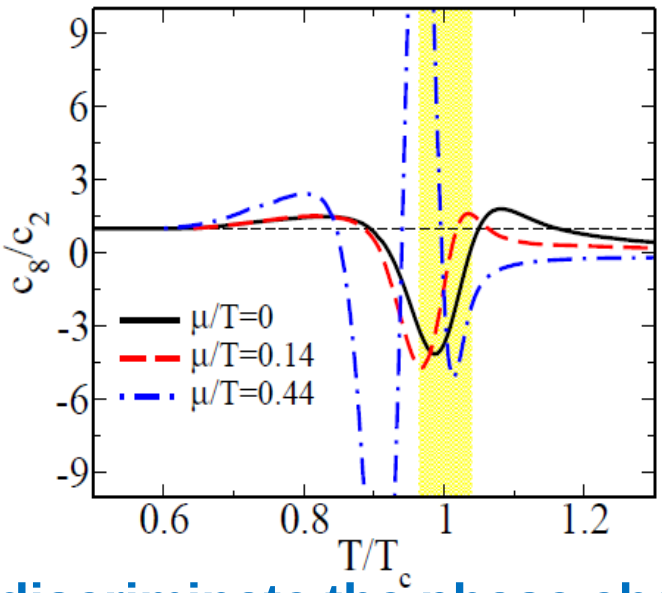
$$R_{4,2} = C_4 / C_2$$

V. Skokov, CPOD2011




**Properties essential in HIC to discriminate the phase change by measuring baryon number fluctuations !**

- At pp and ppbar collisions, there are evidences of crossover from HG to QGP [R. Campanini and G. Ferri, Phys. Lett. B 703 (2011) 237]

**It is expected in this work that the moments of net proton, net baryon and net charge would be one of the tools to reveal the mystery of critical point.**

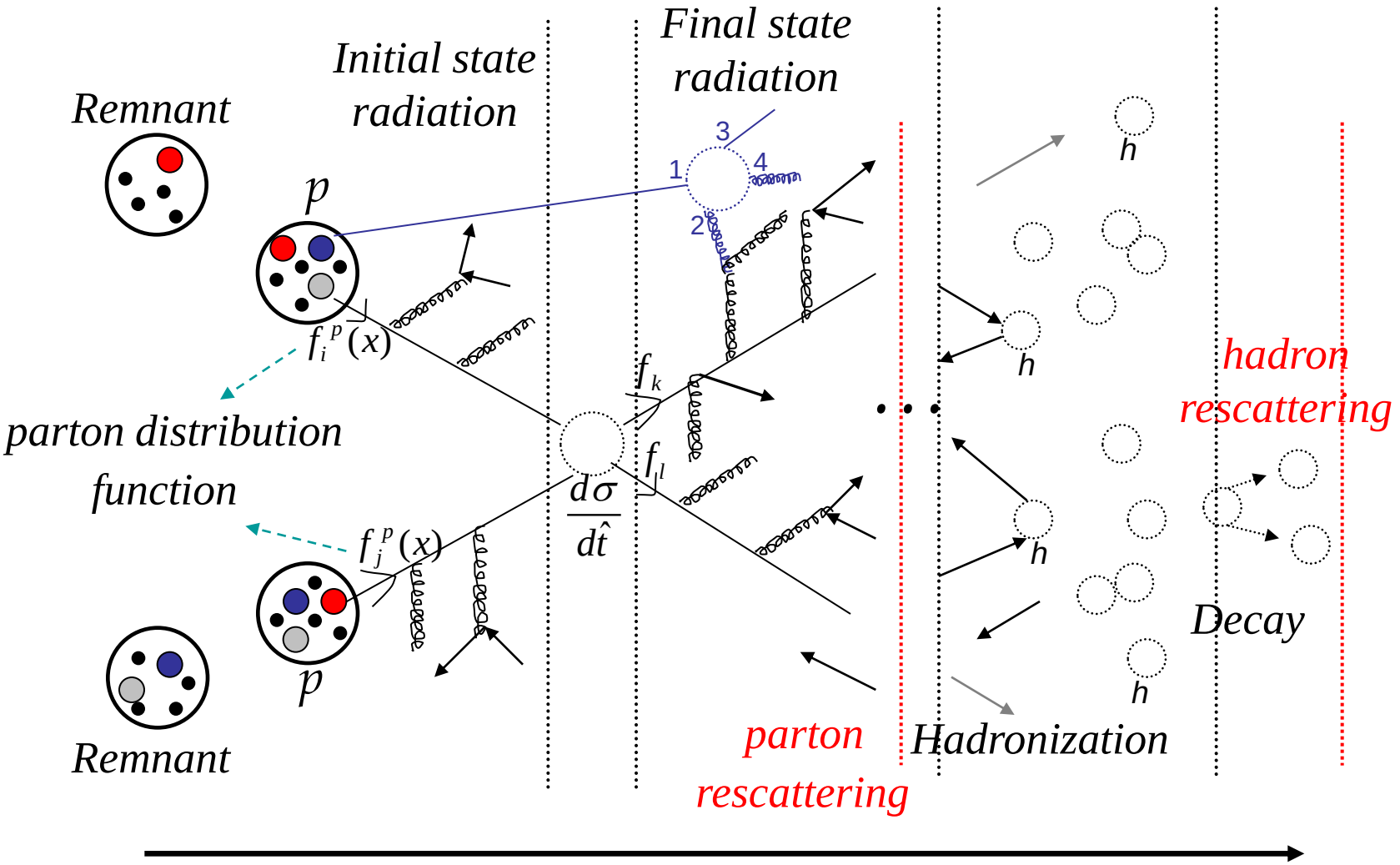
# Brief introduction for PACIAE model

PACIAE, parton and hadron cascade model, is based on PYTHIA model for both p+p and A+A collisions. The model is updated to PACIAE 2.0 based on PYTHIA 6.4.

[B. H. Sa et al., Computer Physics Communications 183, 333 (2012)]

# DYNAMIC SIMULATION (PYTHIA,PACIAE)

## Sketch for pp dynamic simulation



# PACIAE (PYTHIA) description for charged particle production

The ALICE, CMS and ATLAS measurement for p+p at LHC energies are analyzed systemically using the PACIAE and PYTHIA model

# Charged particle multiplicity

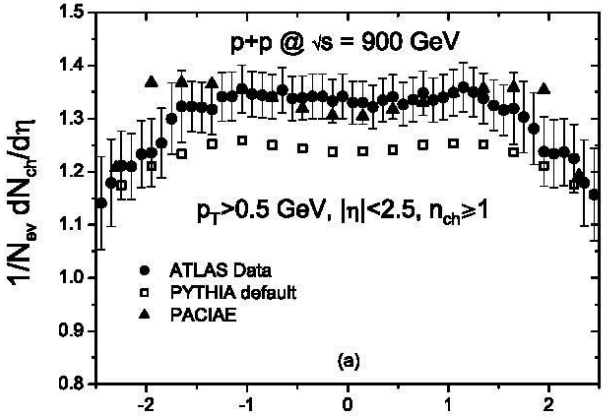
| Energy TeV | ATLAS | PYTHIA | PACIAE |
|---|---|---|---|
| 0.9 | $1.333 \pm 0.003 \pm 0.040$[a] | 1.240 | 1.309 |
| 2.36 | | 1.659 | 1.790 |
| 7 | | 2.371 | 2.768 |

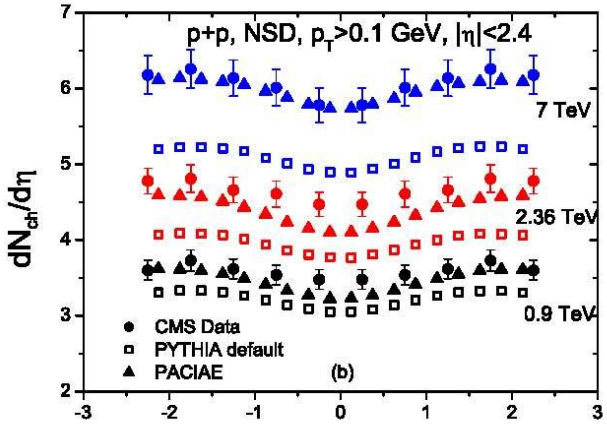
| Energy TeV | CMS | PYTHIA | PACIAE |
|---|---|---|---|
| 0.9 | $3.48 \pm 0.02 \pm 0.13$[b] | 3.07 | 3.25 |
| 2.36 | $4.47 \pm 0.04 \pm 0.16$[b] | 3.80 | 4.12 |
| 7 | $5.78 \pm 0.01 \pm 0.23$[d] | 4.91 | 5.76 |

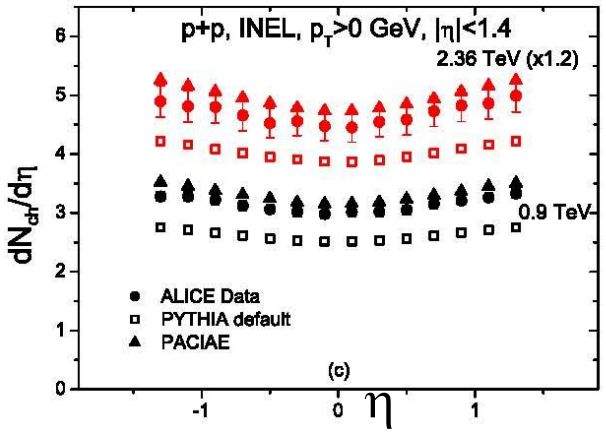
| Energy TeV | ALICE | PYTHIA | PACIAE |
|---|---|---|---|
| 0.9 | $3.81 \pm 0.01 \pm 0.07$[c] | 3.41 | 3.64 |
| 2.36 | $4.70 \pm 0.01 \pm 0.10$[c] | 4.15 | 4.52 |
| 7 | $6.01 \pm 0.01 \pm 0.16$[c] | 5.30 | 6.11 |

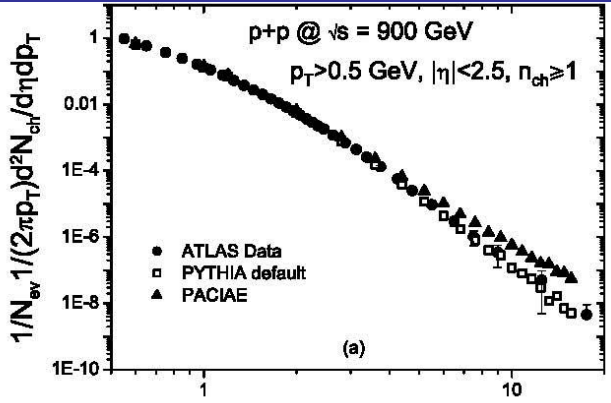
*D.-M. Zhou et al. Physics Letters B 694 (2011) 435–439*

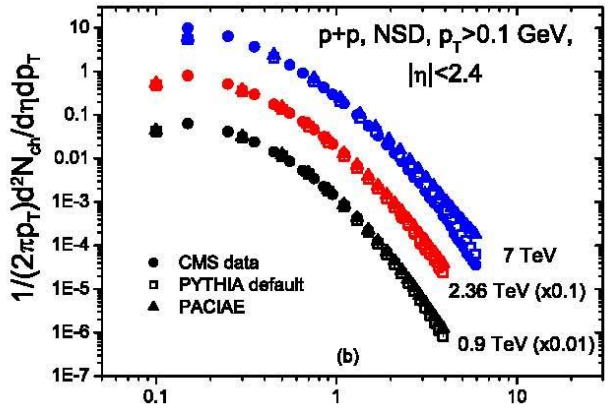
# η and pt distributions

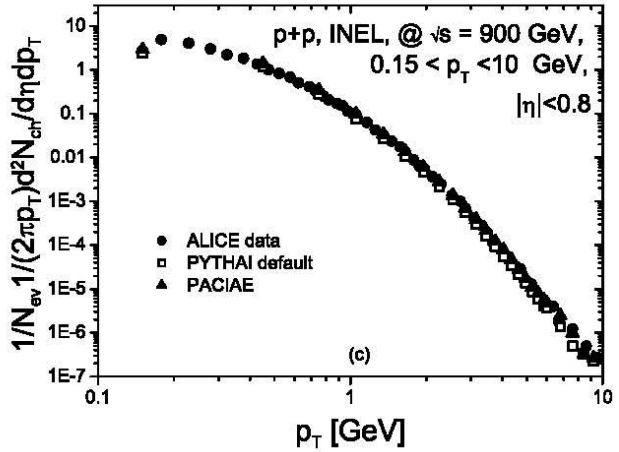


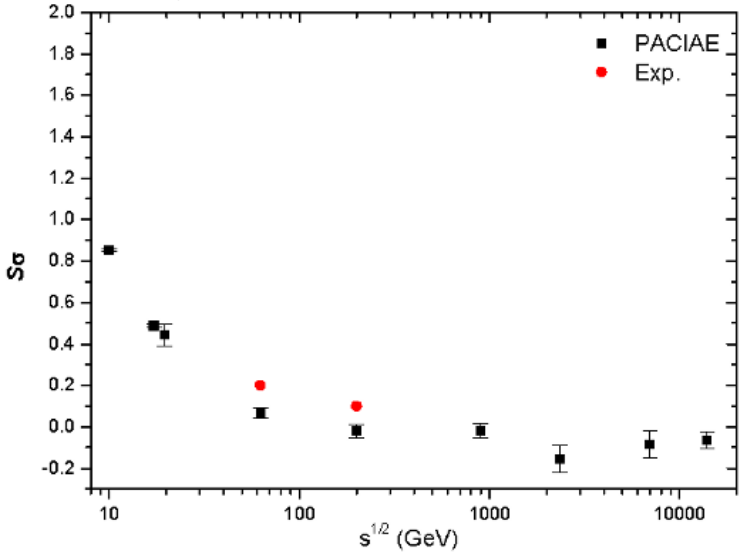




*D.-M. Zhou et al.*

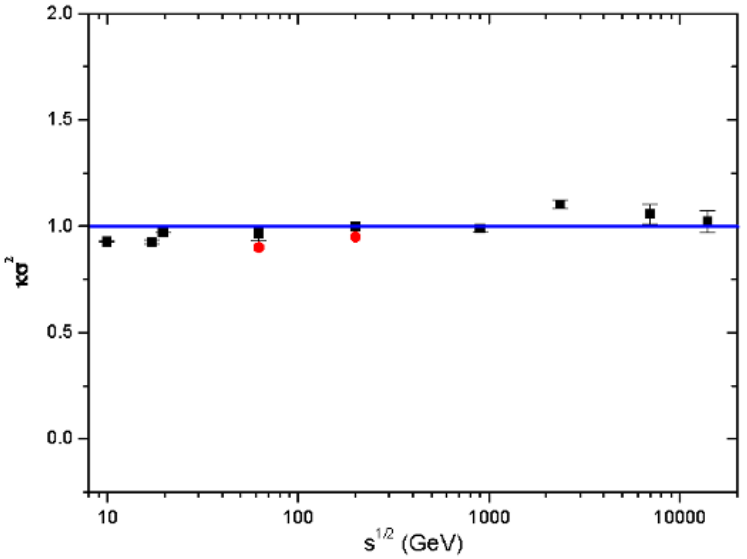
*Physics Letters B 694 (2011) 435–439*

# PACIAE capability in describing net proton moments

p+p@$\sqrt{s}$ = 10, 17.2, 19.6, 62.4, 200, 900 GeV, 2.36, 7 and 14 TeV at 0.4 < pt < 0.8 GeV/c and |y|<0.5; Exp. data are taken from X. Luo, JPCS 316, 012003 (2011)




**$S\sigma$** experiences a weak decrease with energy increasing




$\kappa\sigma^2$ is almost energy independent

*A. Limphirat et al. Cen. Eur. J. Phys. (2012)*

# An idea for subtracting the statistical fluctuation

As the study of phase transition and approaching CP is a matter of dynamics in order to eliminate the finite size effect and limit statistic effect etc.,

one should study $M_D^{(n)} = M_R^{(n)} - M_M^{(n)}$ instead of $M_R^{(n)}$ only

where

$M_R^{(n)}$ : calculated by real events constructed or generated

$M_M^{(n)}$ : calculated by mixed events constructed randomly according to real events, event-by-event, with event multiplicity unchange and without any conservation law at all

# PACIAE preliminary result of higher moments

p+p @ $\sqrt{s}$ = 19.6, 62.4, 200, 500, 900 GeV,

1.2, 1.5, 1.9, 2.36, 7, 14 TeV

In full phase space

and partial phase space (0.4 < $p_t$ < 0.8 GeV/c and |y|<0.5)

- Net proton $(N_p - N_{\bar{p}})$
- Net baryon $(N_B - N_{\bar{B}})$

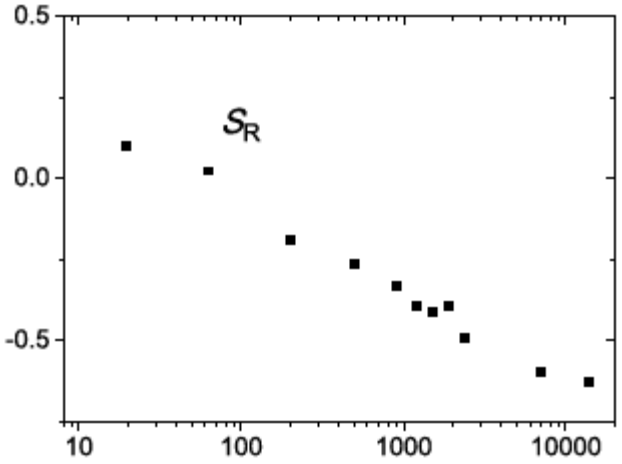
  $B \equiv p, n, \Lambda$
- Net charge $(N_{Ch+} - N_{Ch-})$

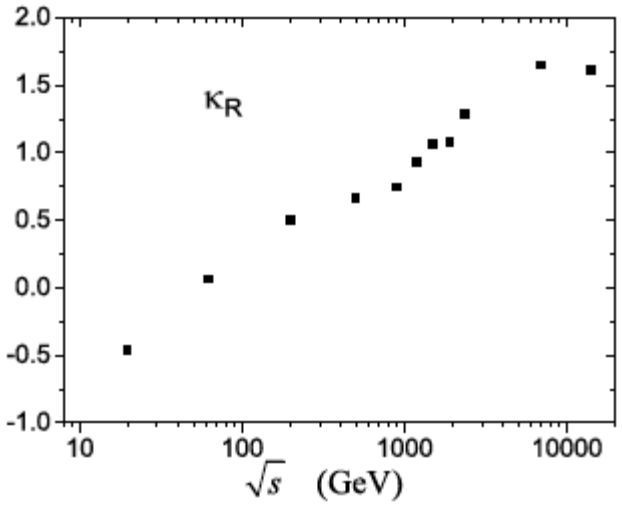
  $Ch^+ \equiv \pi^+, K^+, p$

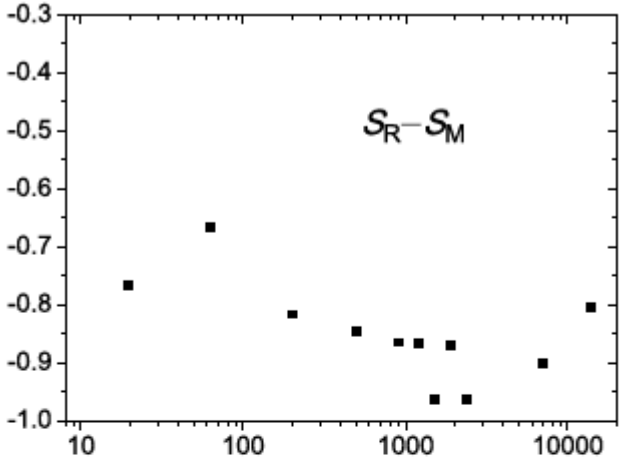
# Net proton in Full phase space

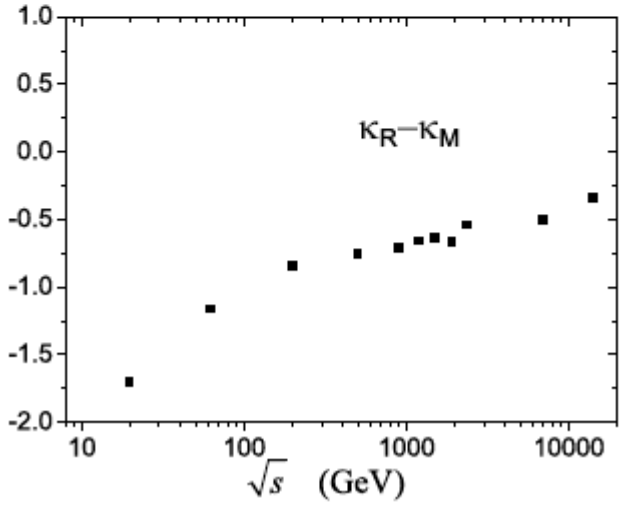
Real

Non-statistical



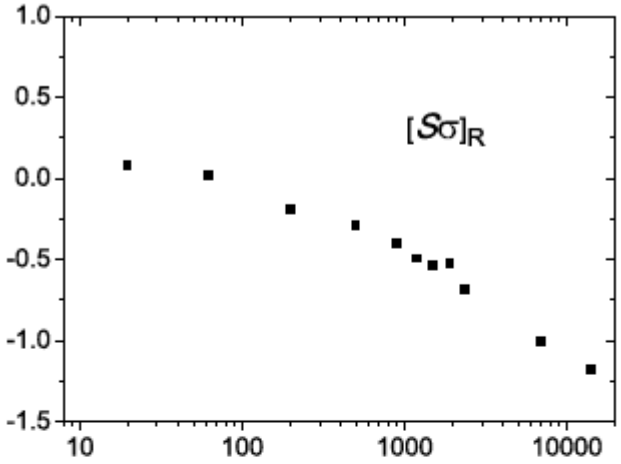



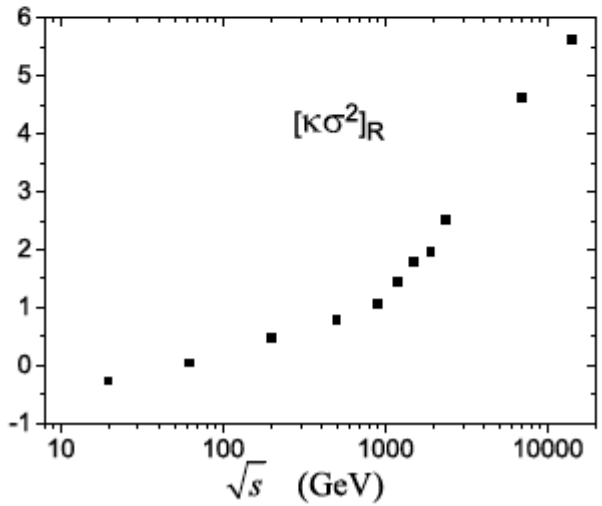



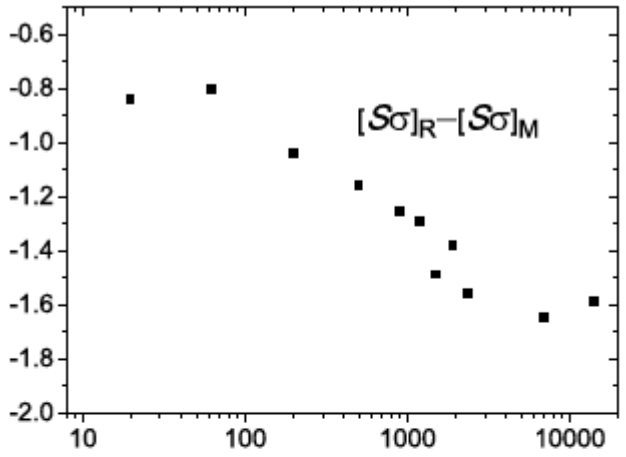
# Net proton in Full phase space

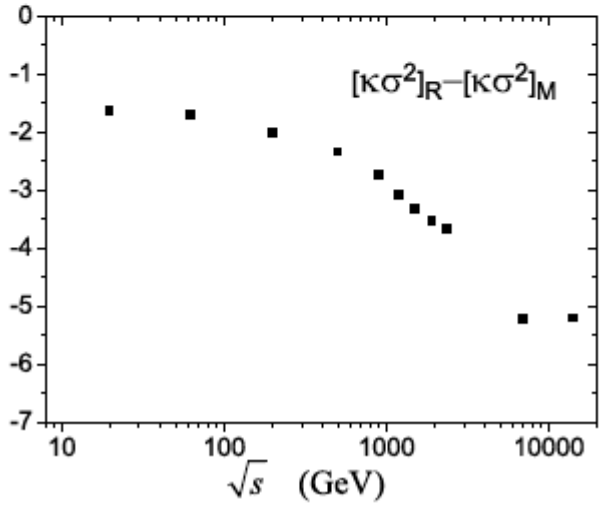
Real

Non-statistical



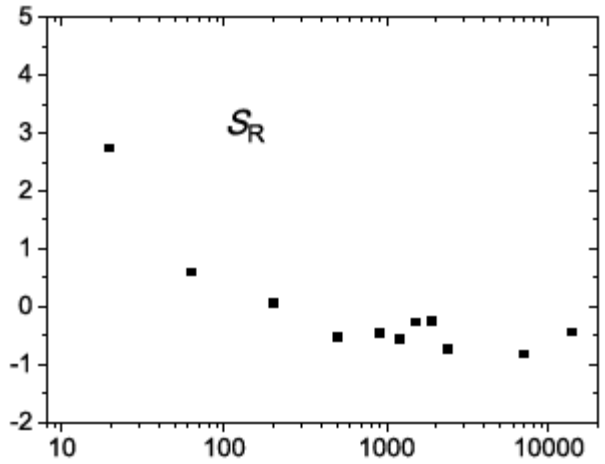



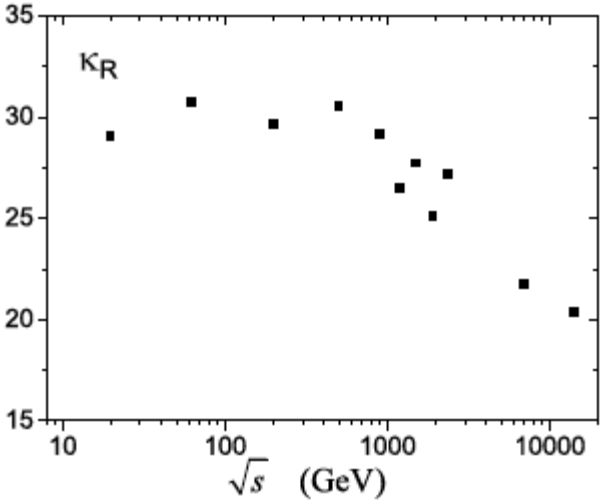



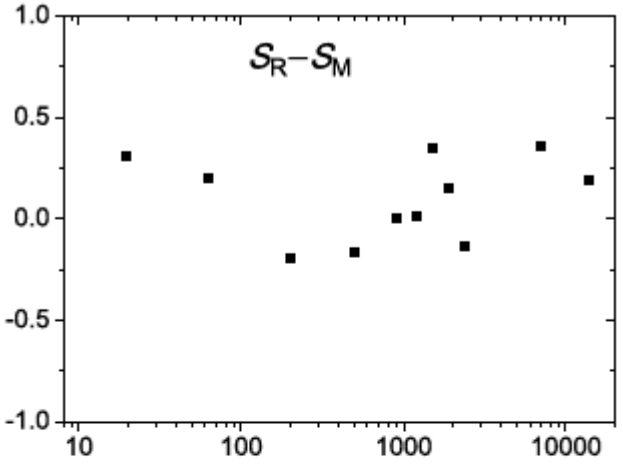
# Net proton in partial phase space

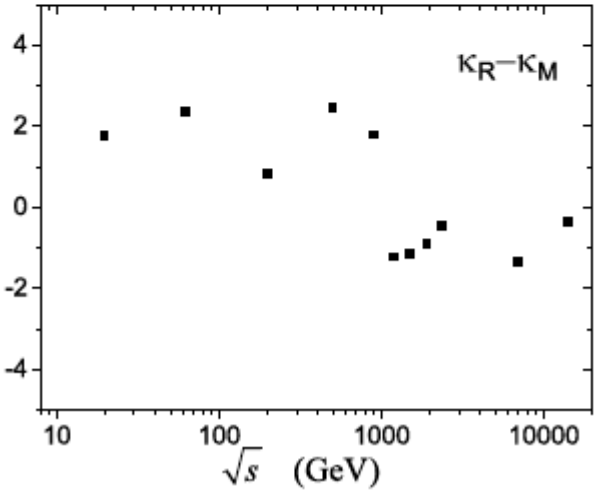
## Real



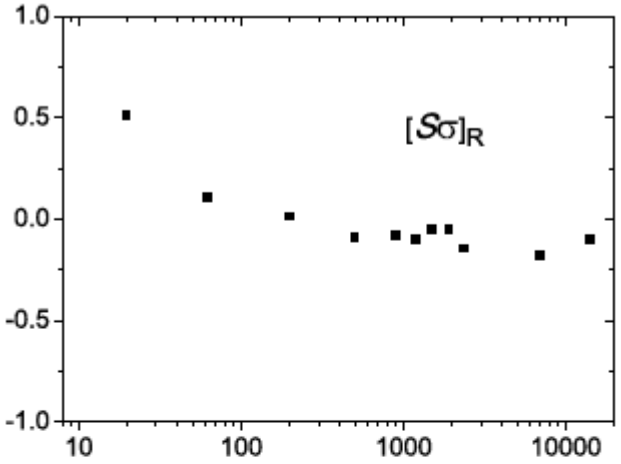

## Non-statistical

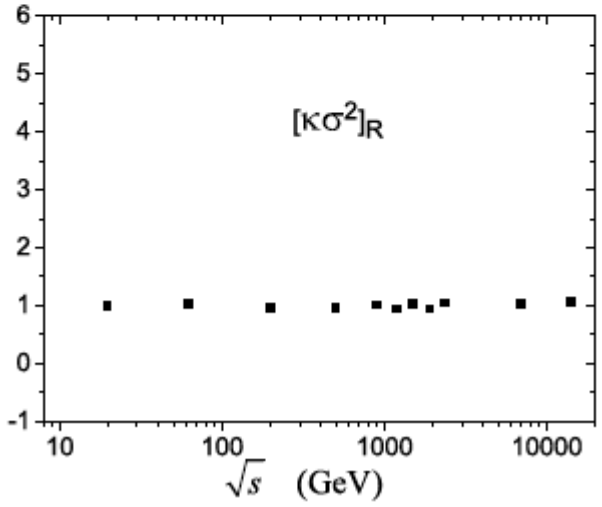


# Net proton in partial phase space

## Real

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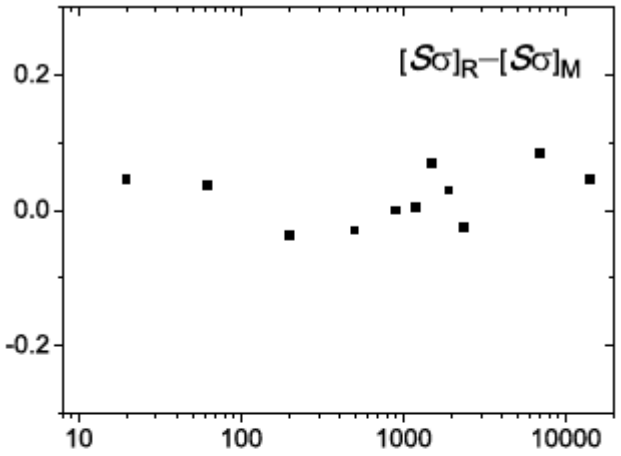
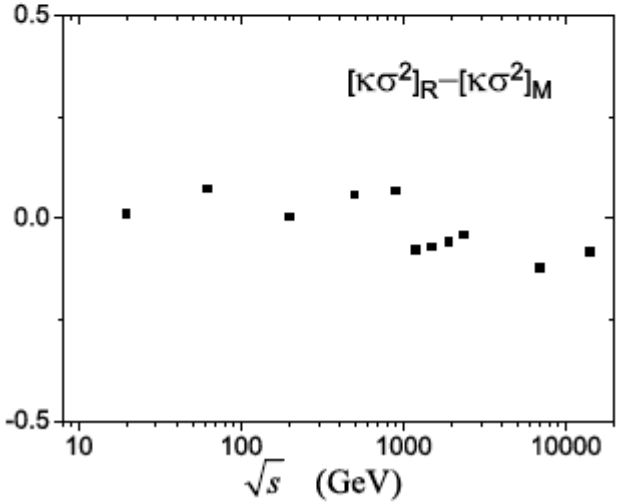
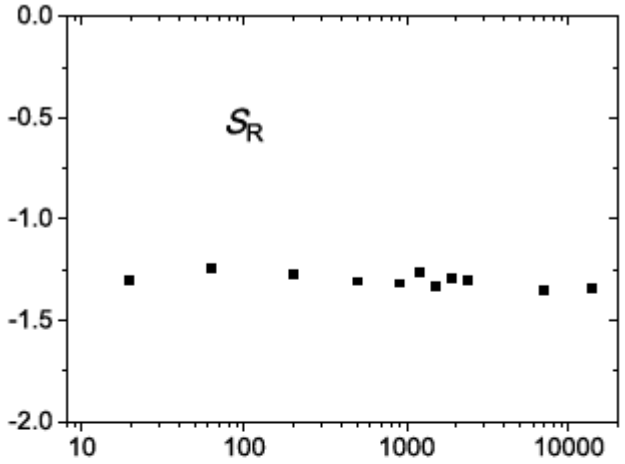
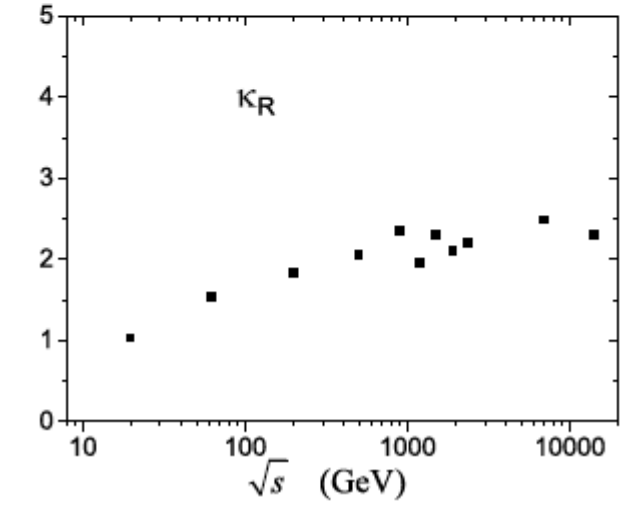


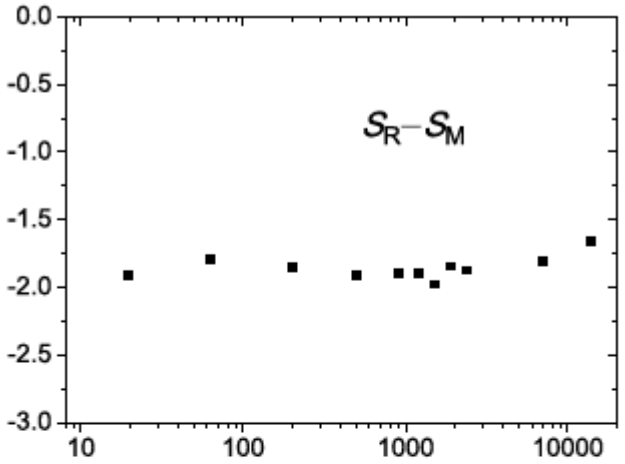
# Net Baryon in full phase space

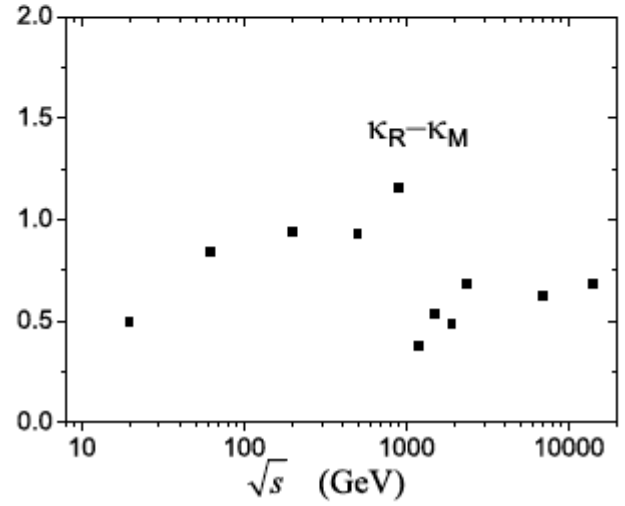
## Real



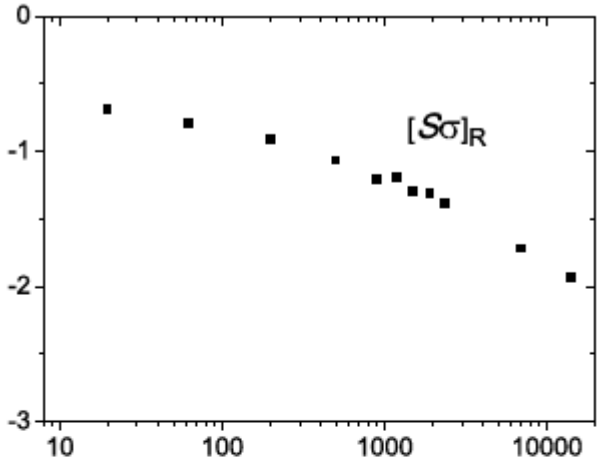

## Non-statistical

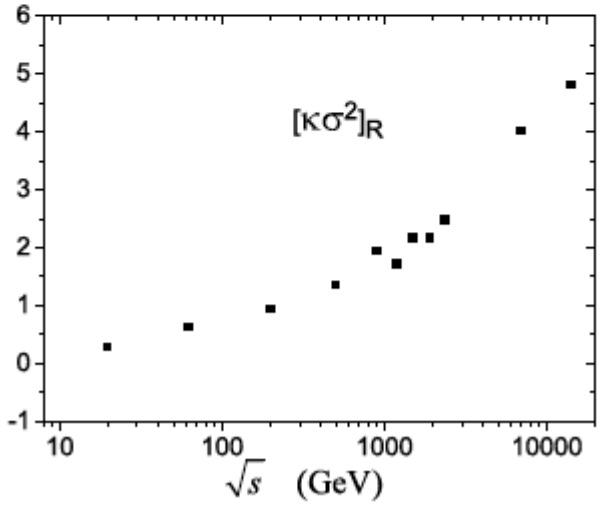


# Net Baryon in full phase space

## Real

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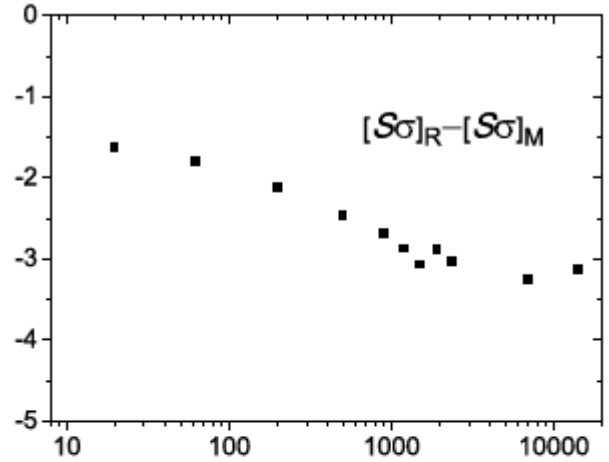
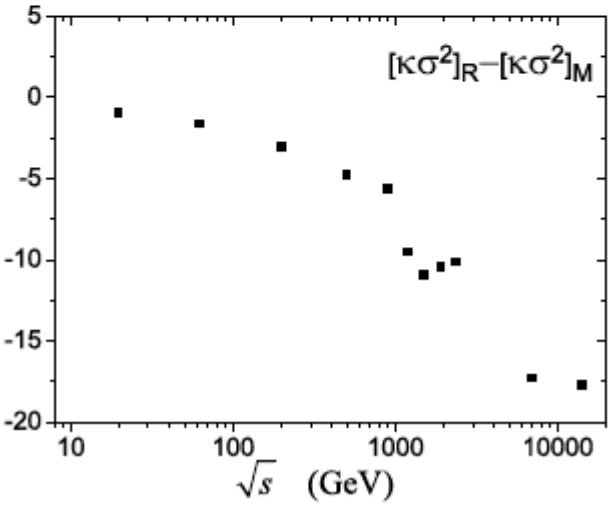
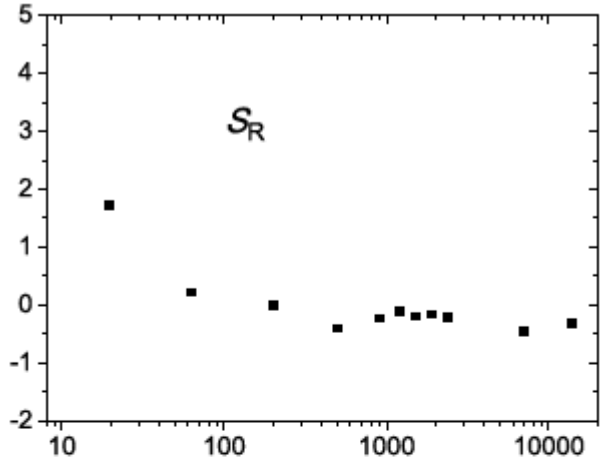
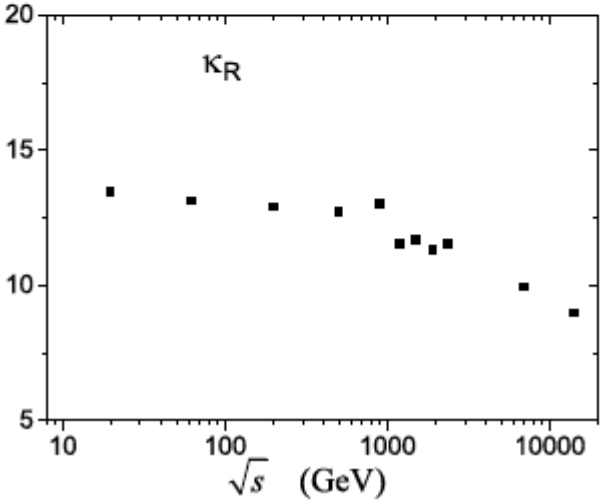


# Net Baryon in partial phase space

## Real

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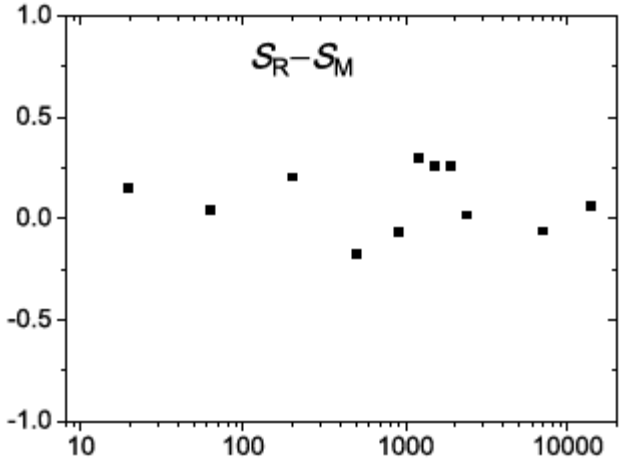
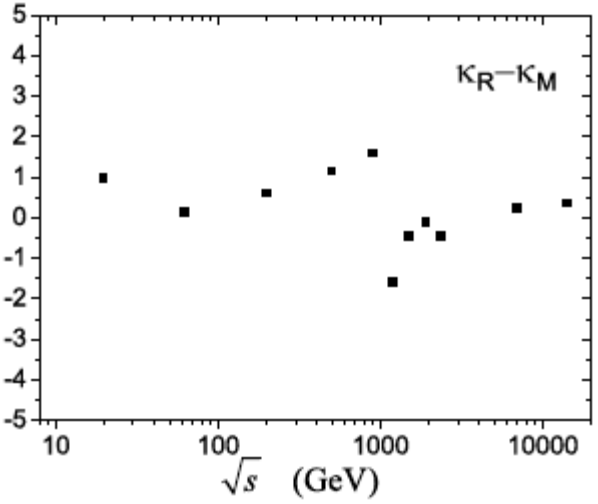
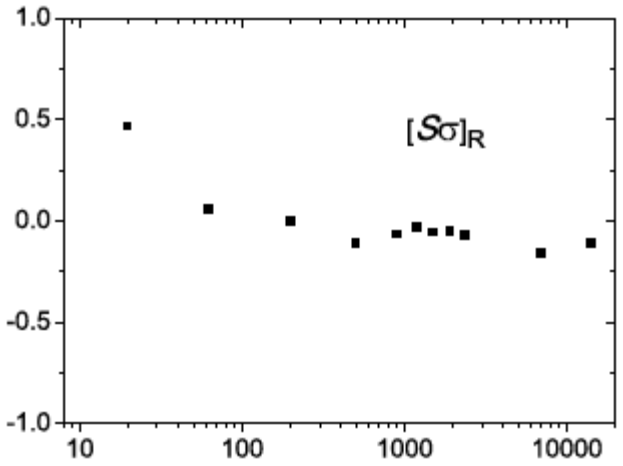
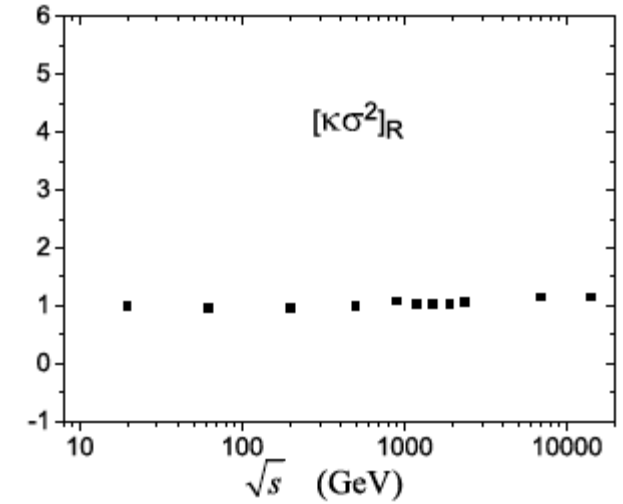


# Net Baryon in partial phase space

## Real

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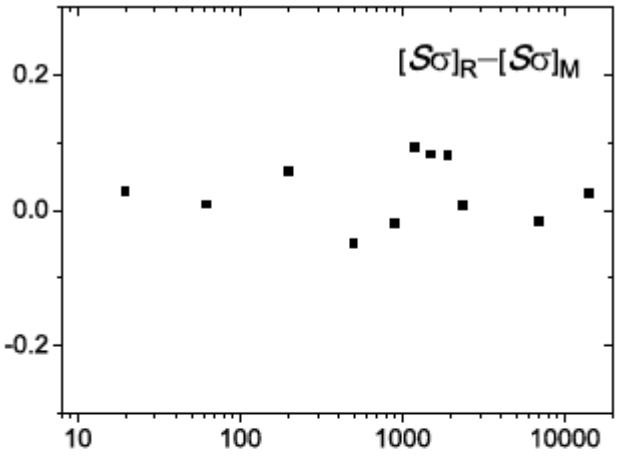
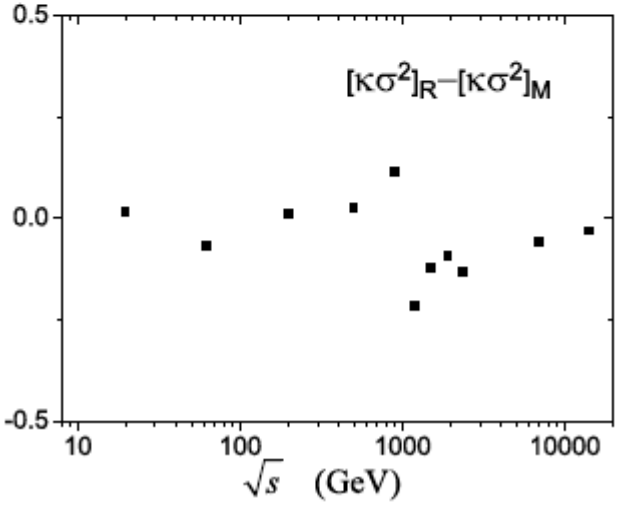
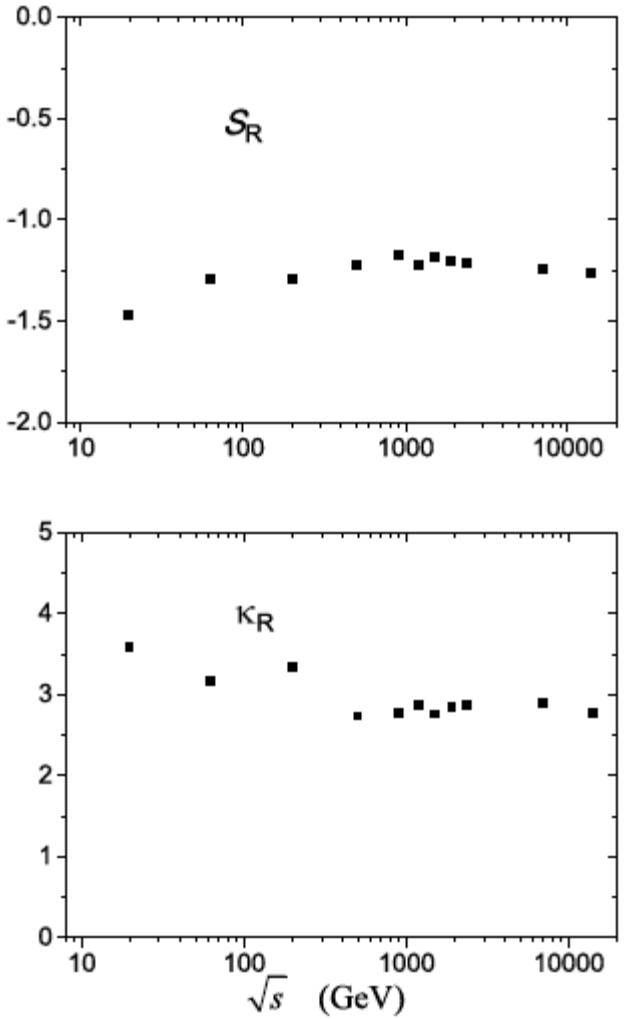


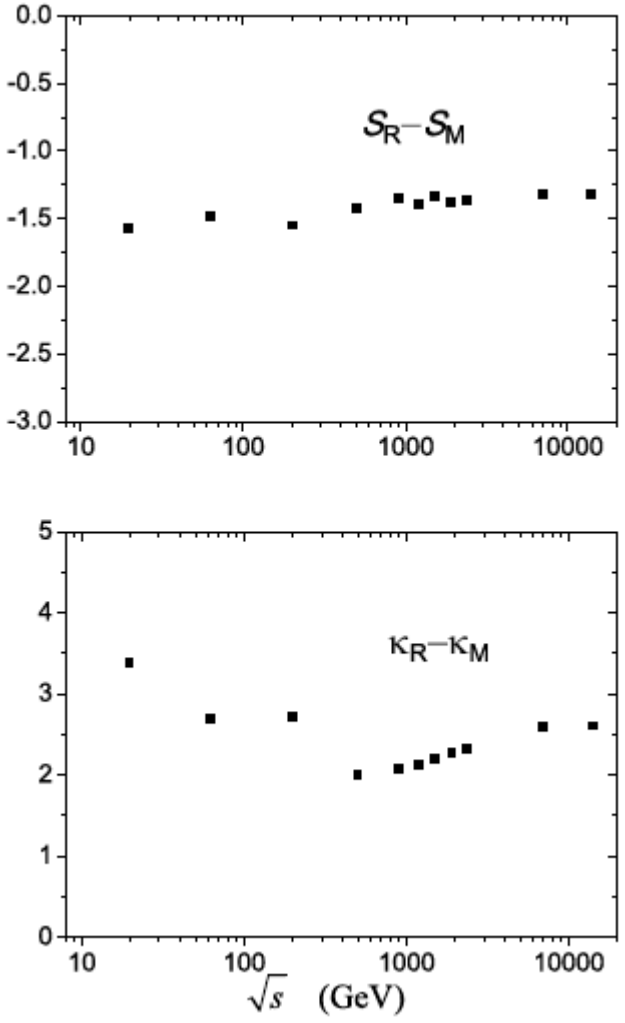



# Net Charge in full phase space

## Real

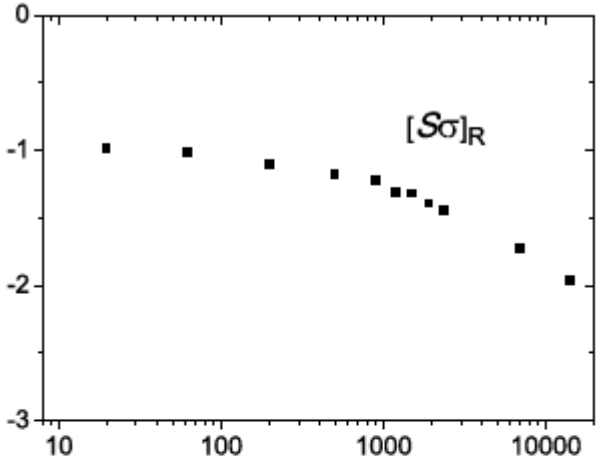


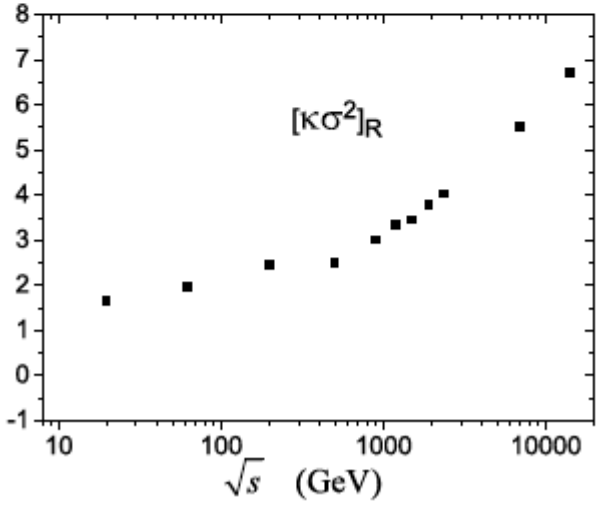

## Non-statistical



# Net Charge in full phase space

## Real

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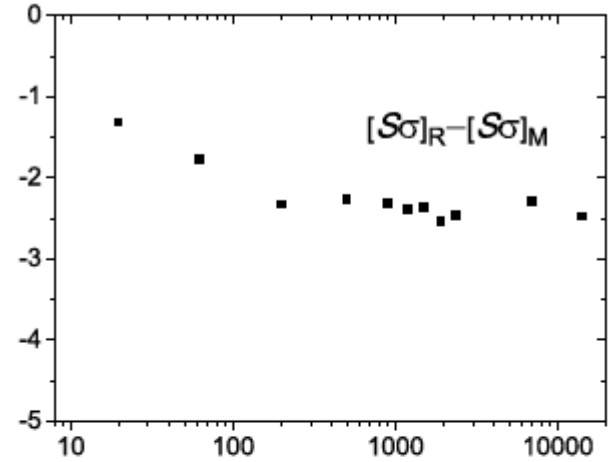
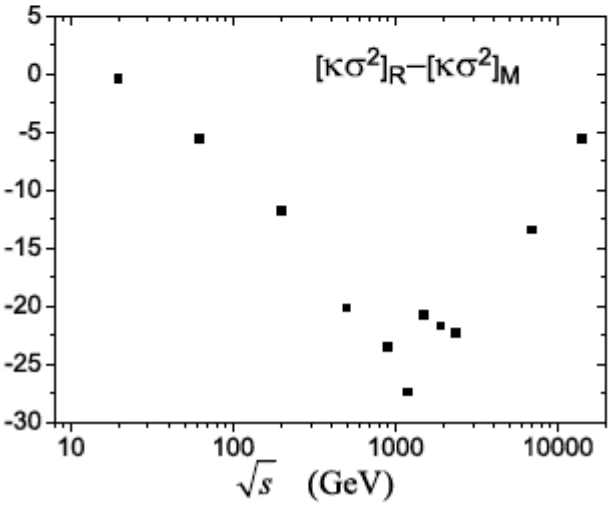
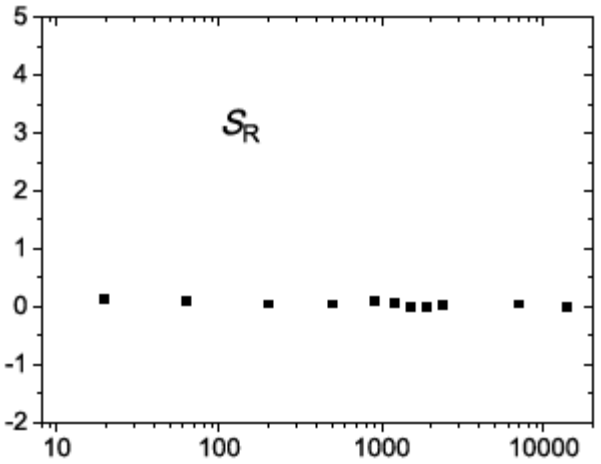
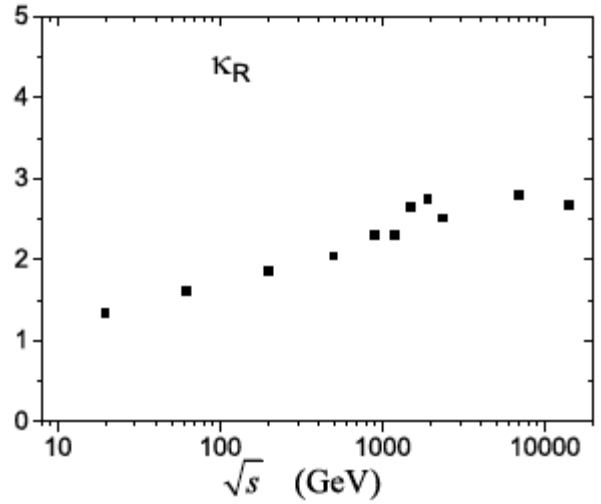


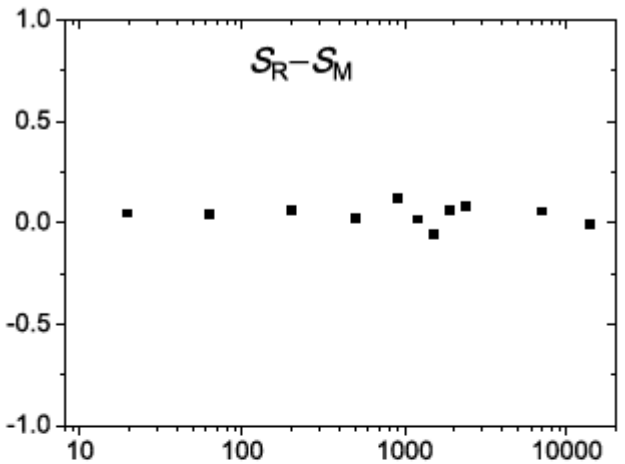
# Net Charge in partial phase space

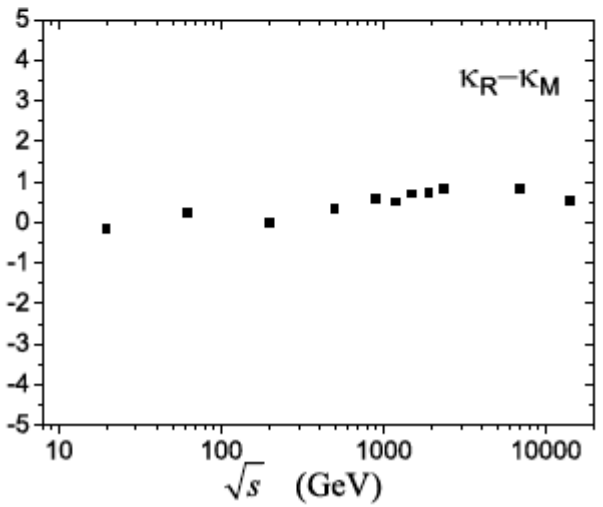
## Real



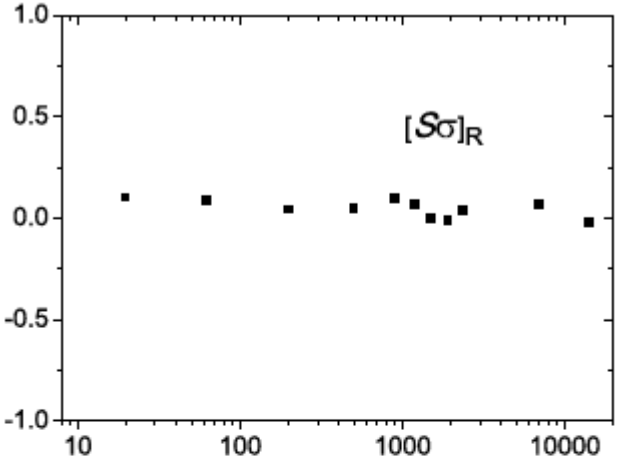

## Non-statistical

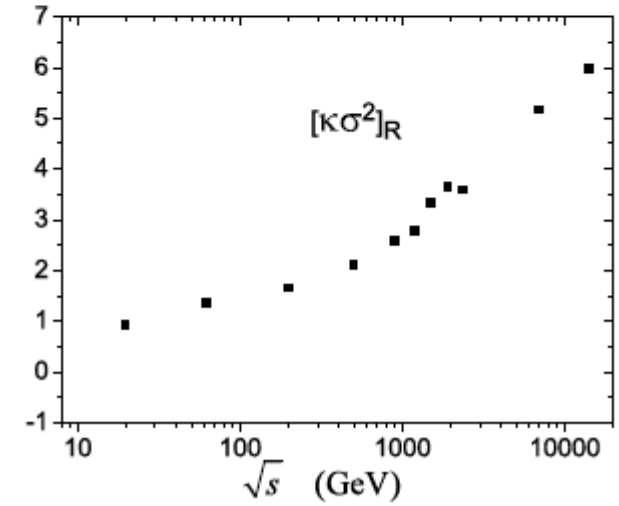


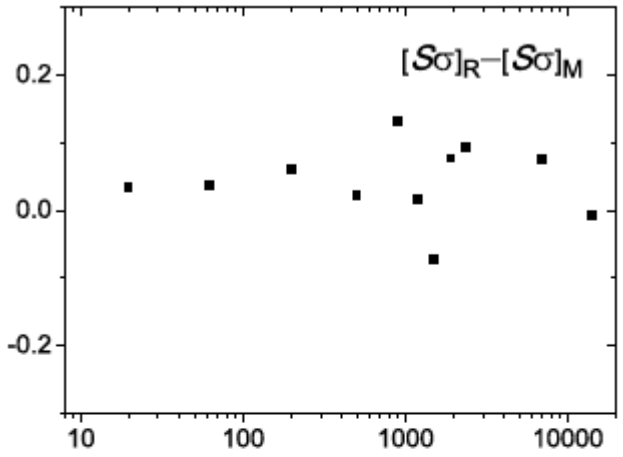
# Net Charge in partial phase space

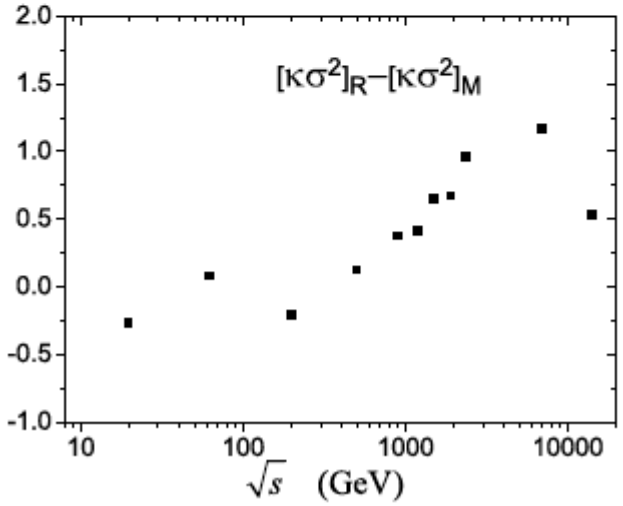
## Real



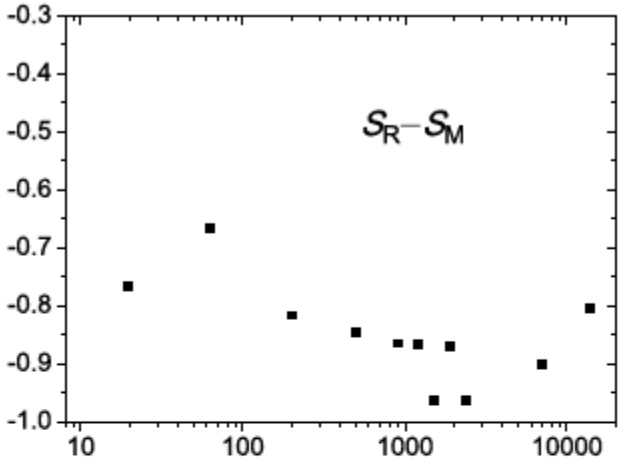

## Non-statistical

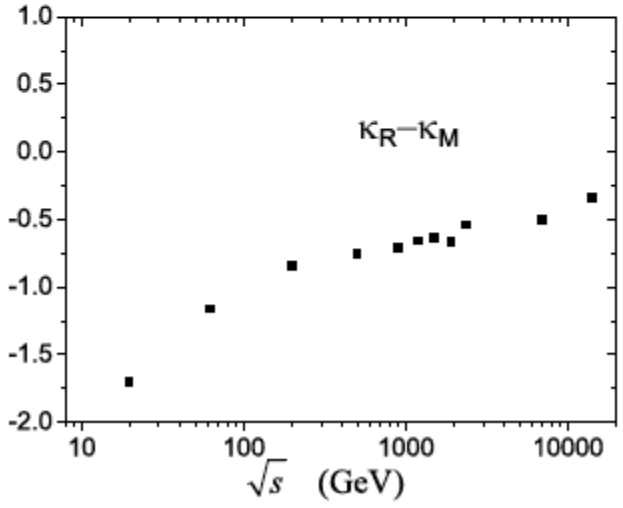


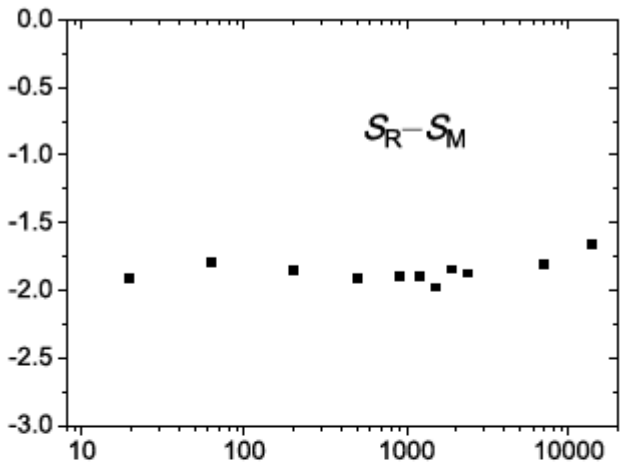
# All Non-statistical higher moments in full phase space

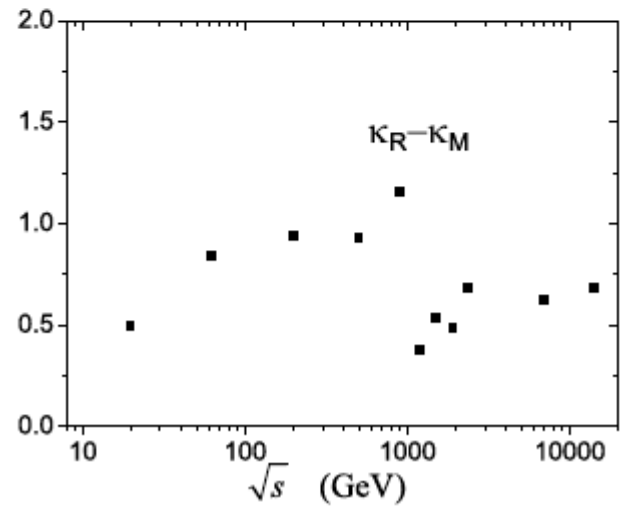
## Net proton



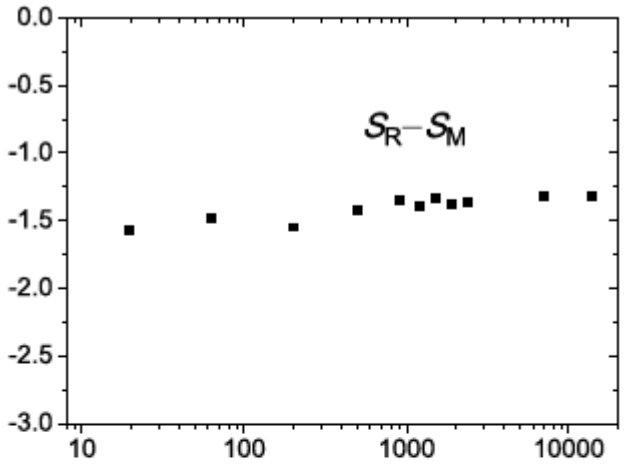



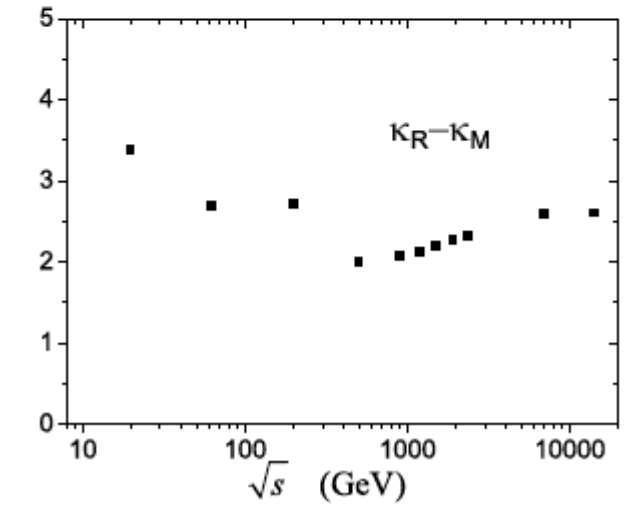

## Net baryon




## Net charge



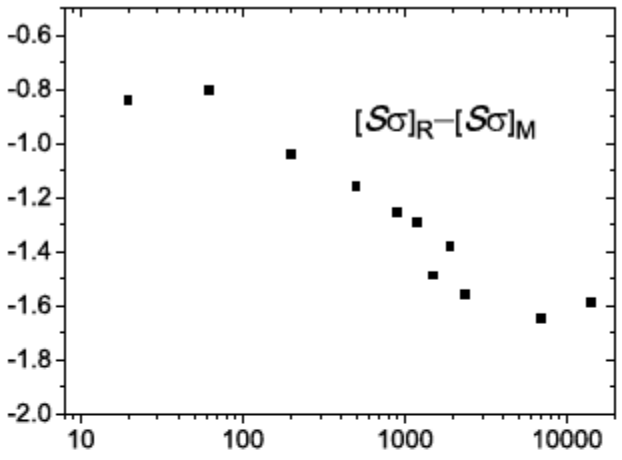



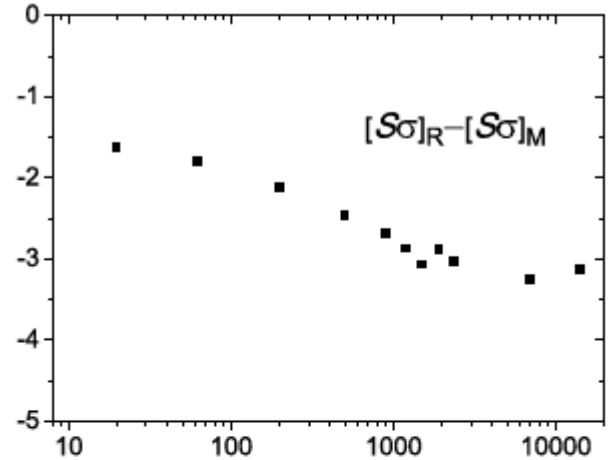
# All Non-statistical higher moments in full phase space

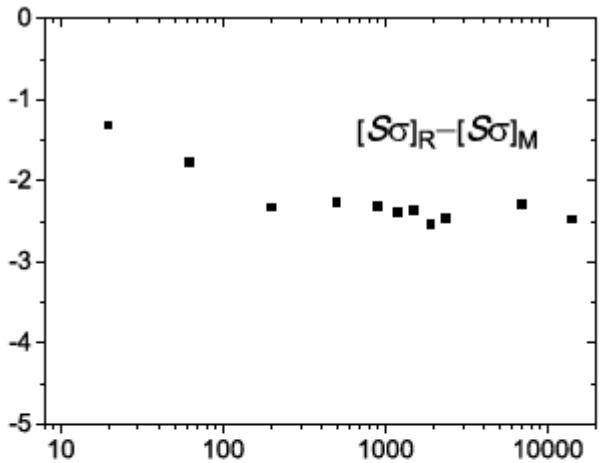
Net proton

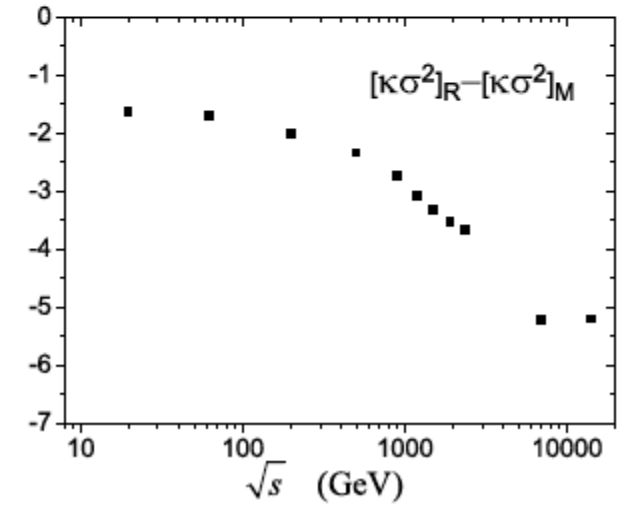
Net baryon

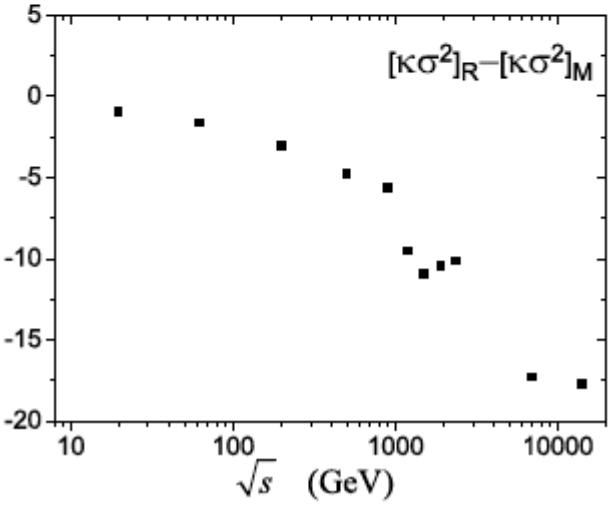
Net charge

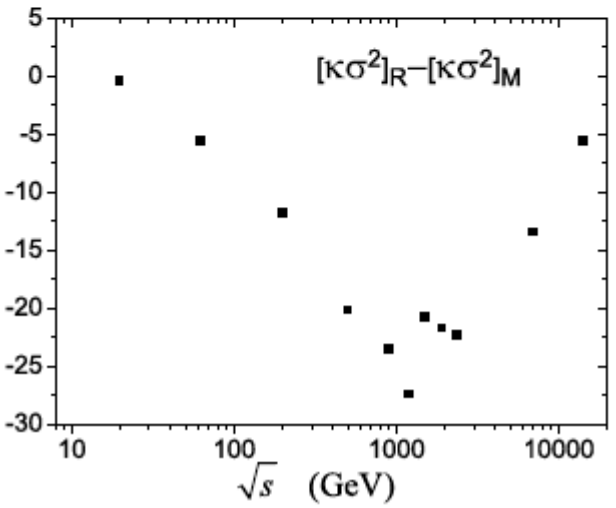


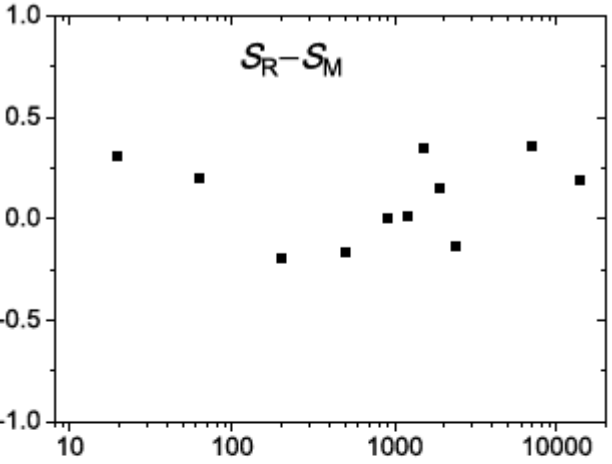



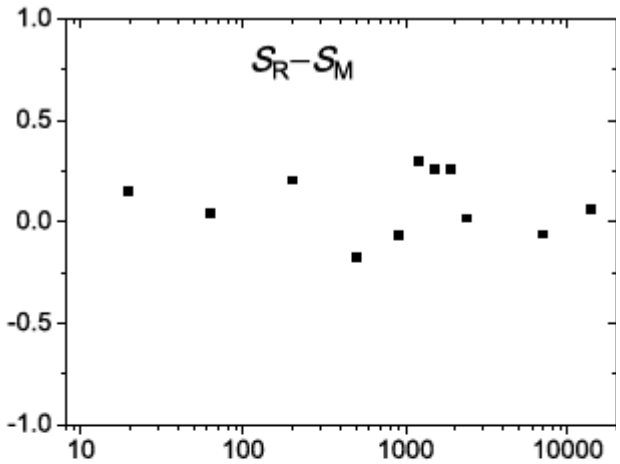
# All Non-statistical higher moments in partial phase space

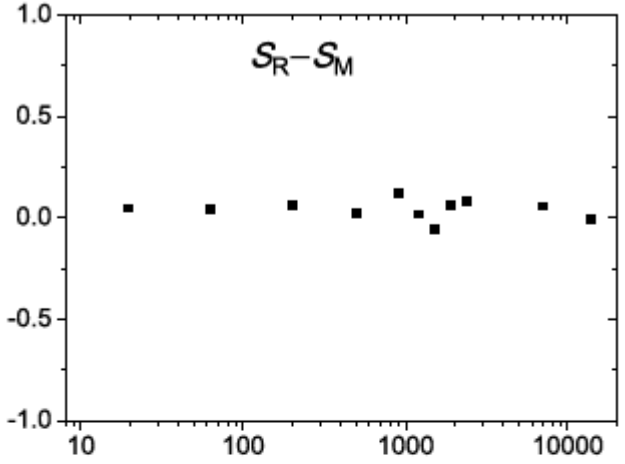
Net proton

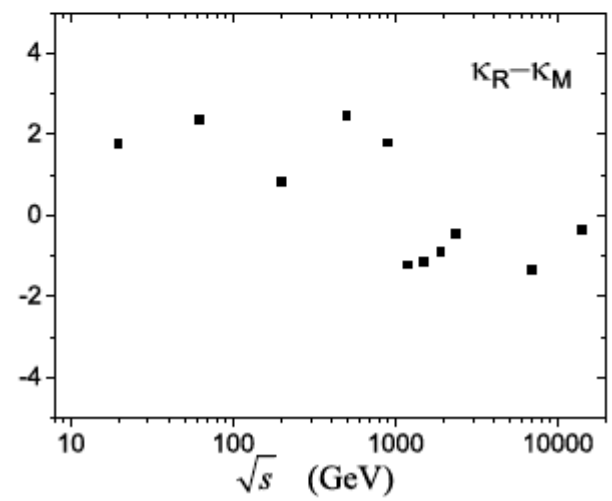
Net baryon

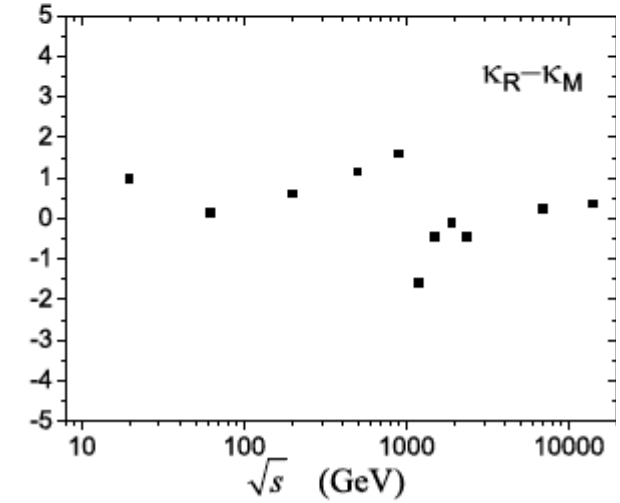
Net charge

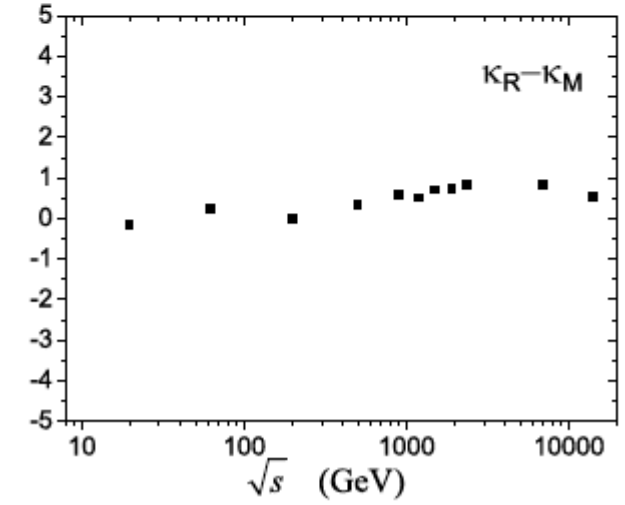


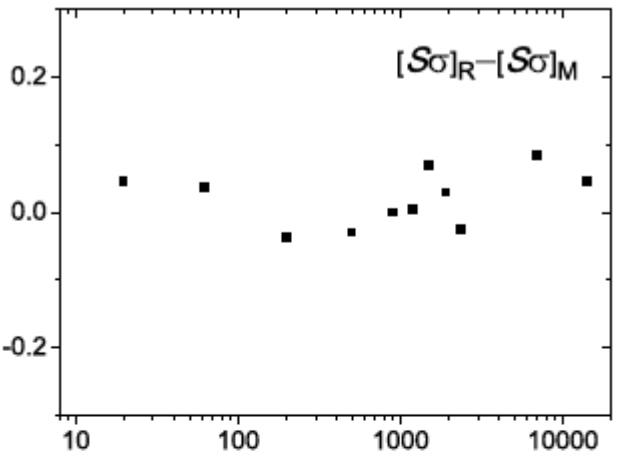



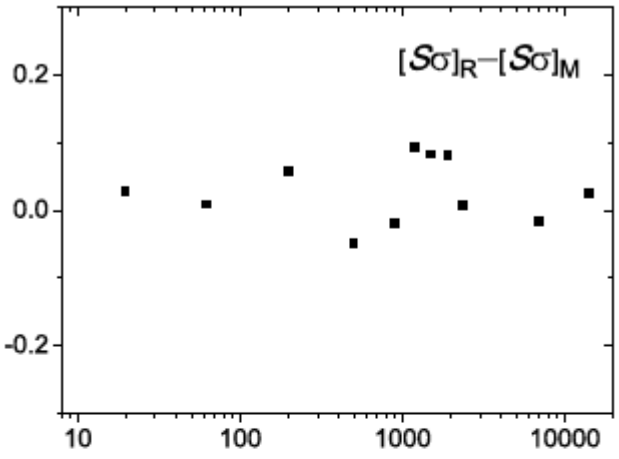
# All Non-statistical higher moments in partial phase space

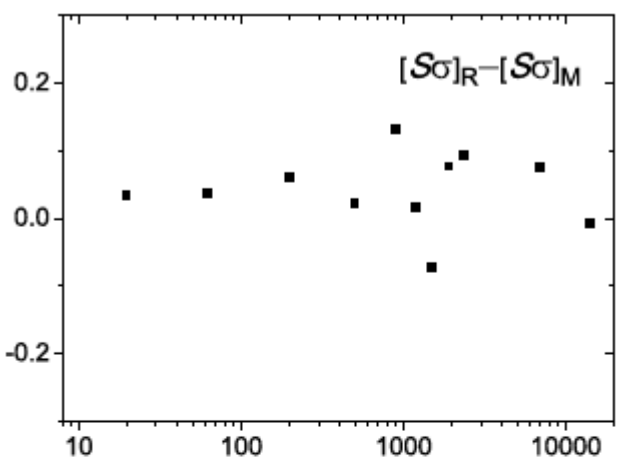
Net proton

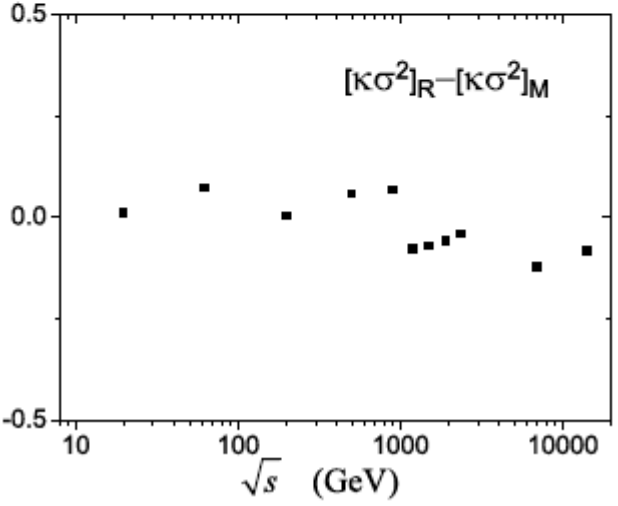
Net baryon

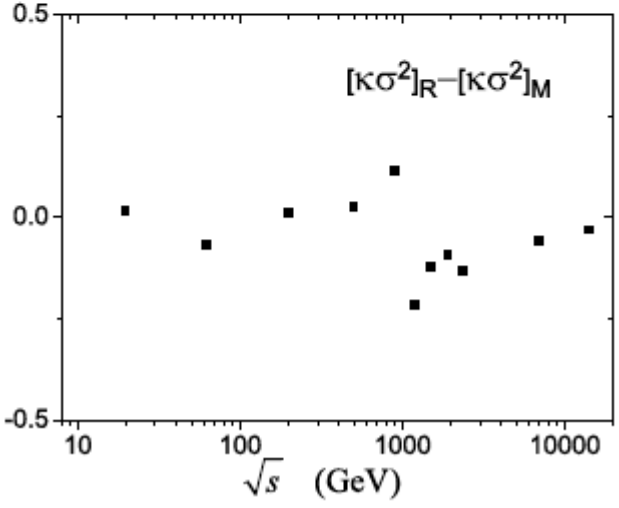
Net charge

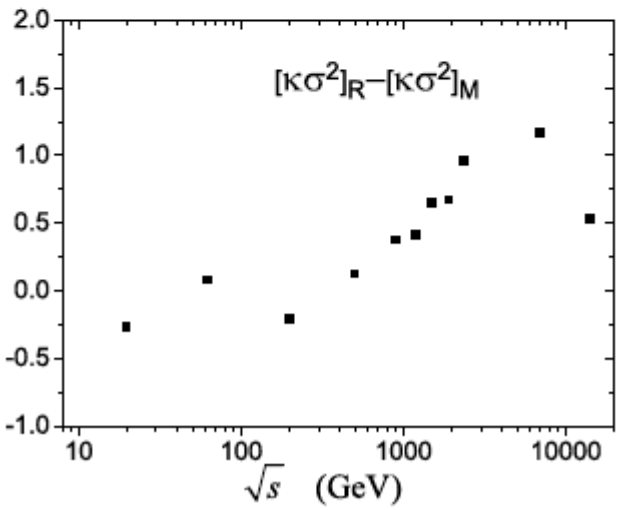


# Conclusion

- For the study of approaching CP, one should study $M_D^{(n)} = M_R^{(n)} - M_M^{(n)}$ instead of $M_R^{(n)}$ itself
- Behavior of moments in partial phase space are different from full phase space
- Found only in partial phase space, Kurtosis and/or Skewness changing sign.
- Note that this is the preliminary result. Need to be improved!!!

# Acknowledgement

We would like to thank:

- ThEP
- TRF-CHE-SUT
- NSFC
- CHE (China)