Exploring QCD Phase Structure in Heavy-Ion Collisions

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J-PARC分室活動総括研究会

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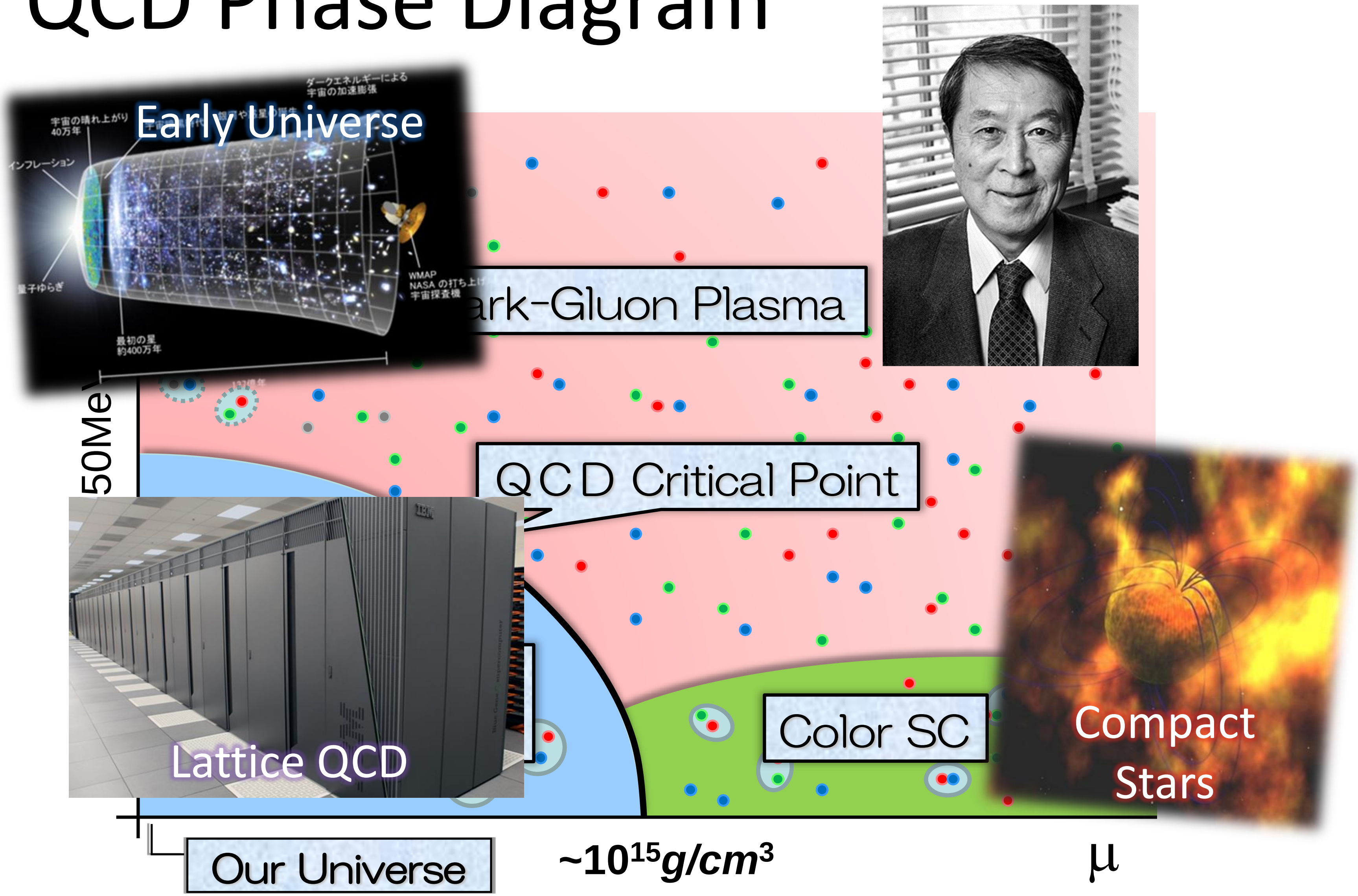
Keywords

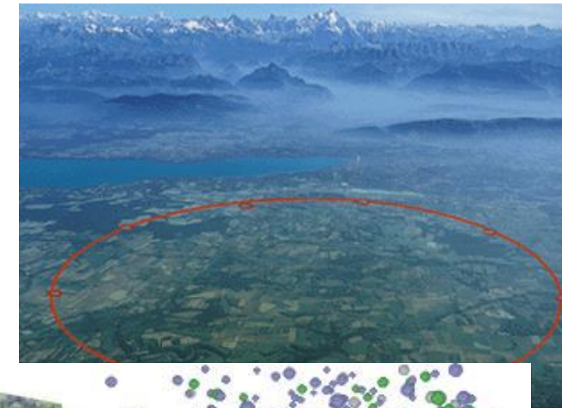
- QCD at nonzero T/μ
  - quark-gluon plasma
  - chiral transition
  - QCD critical point / 1^{st} order phase transition
- Relativistic heavy-ion collisions
  - beam-energy scan
  - J-PARC heavy-ion program
  - Modelling dynamics of low-E collisions

QCD Phase Diagram

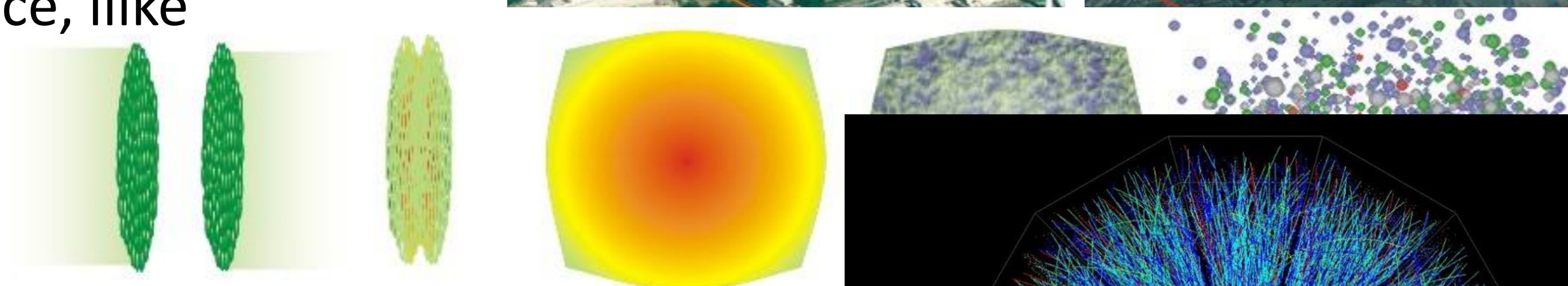


Relativistic Heavy-ion Collisions

Accelerate heavy ions
by accelerators such as,

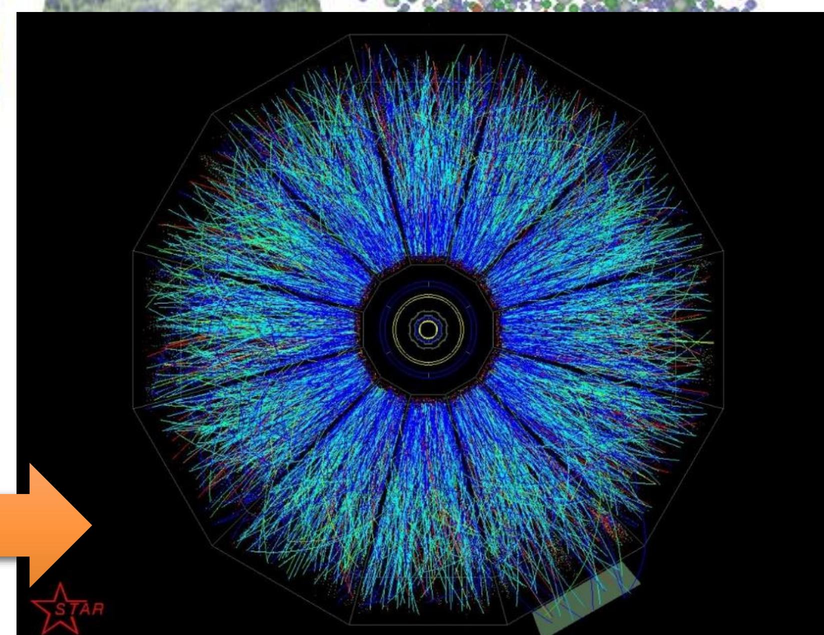


Then, collisions take
place, llike

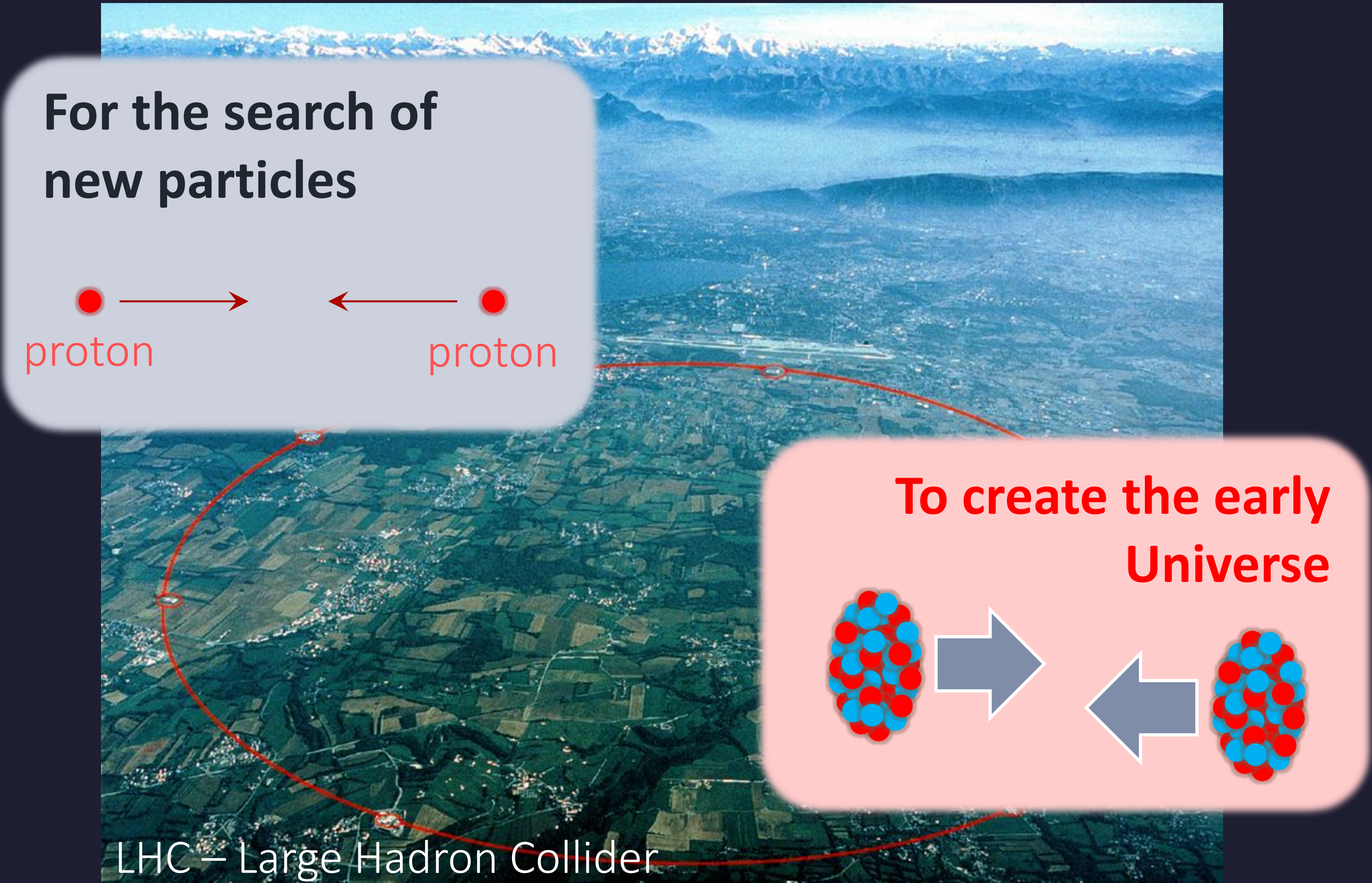


And QGP is formed around here

Many particles are created like this.
We study QGP from this exp. data.



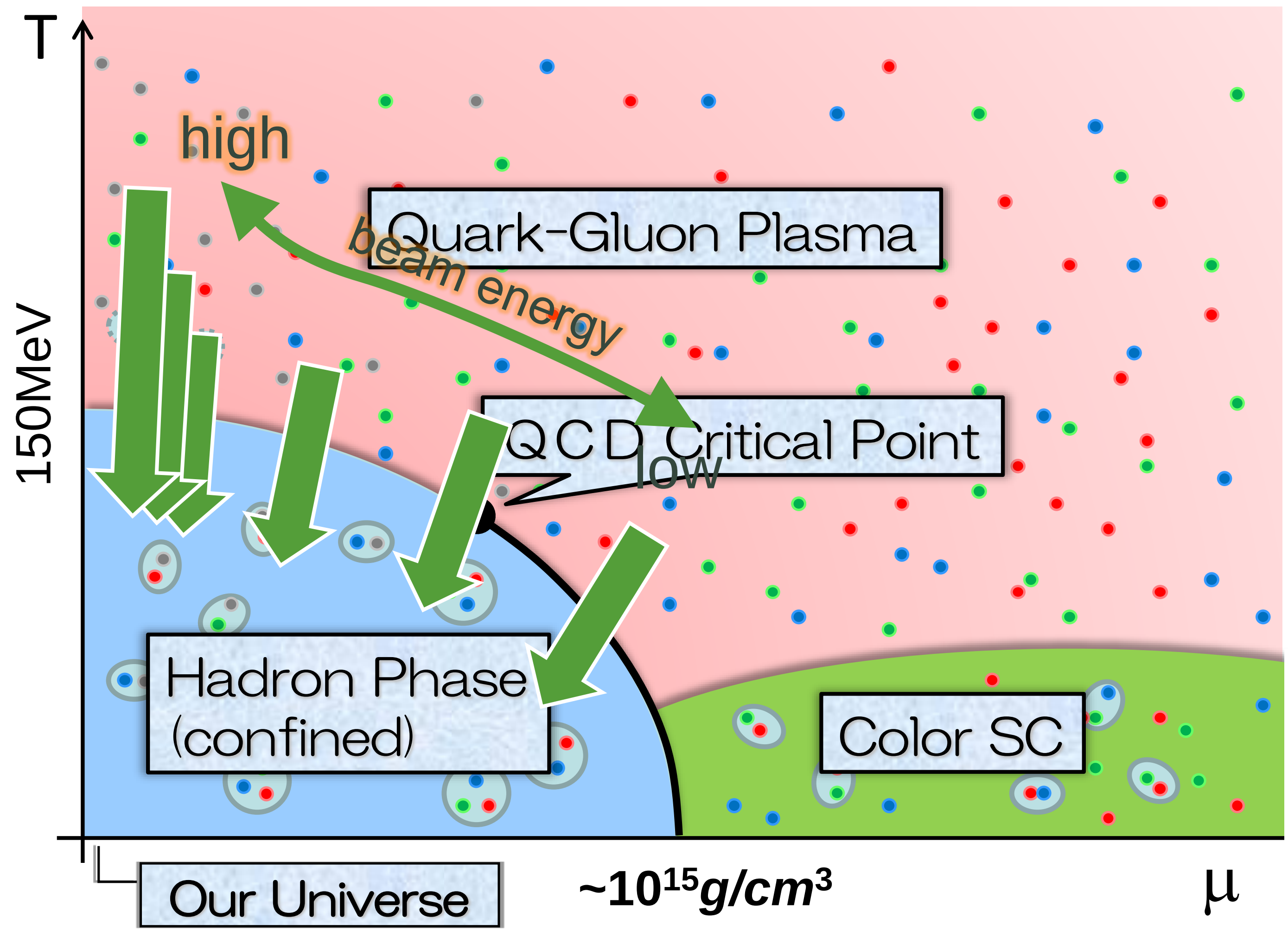
Accelerator Experiments



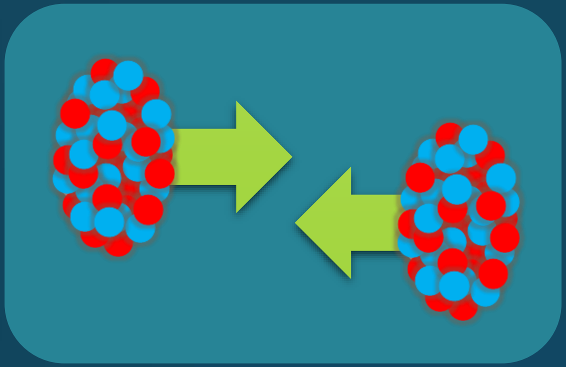
Recent Hot Topics in HIC

- Beam-energy scan
  - search for QCD-CP / 1^{st} transition
- chiral magnetic effect
  - isobaric collisions A=96 ($_{44}$Ruthenium/$_{40}$Zirconium)
- small systems
  - Is QGP formed in pp, pA collisions?

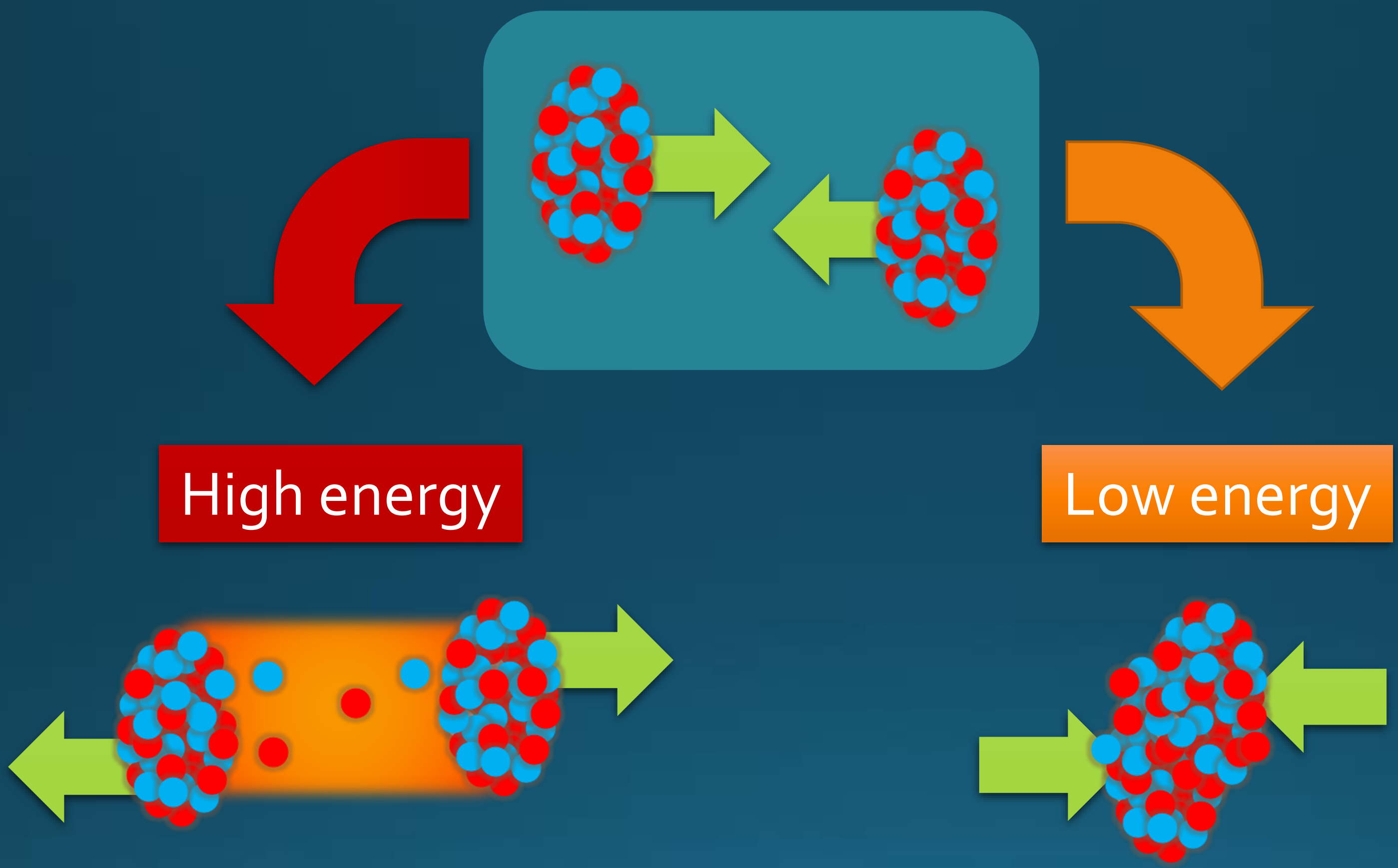
Beam-Energy Scan



Beam-Energy Dependence



Beam-Energy Dependence



Nuclear transparency

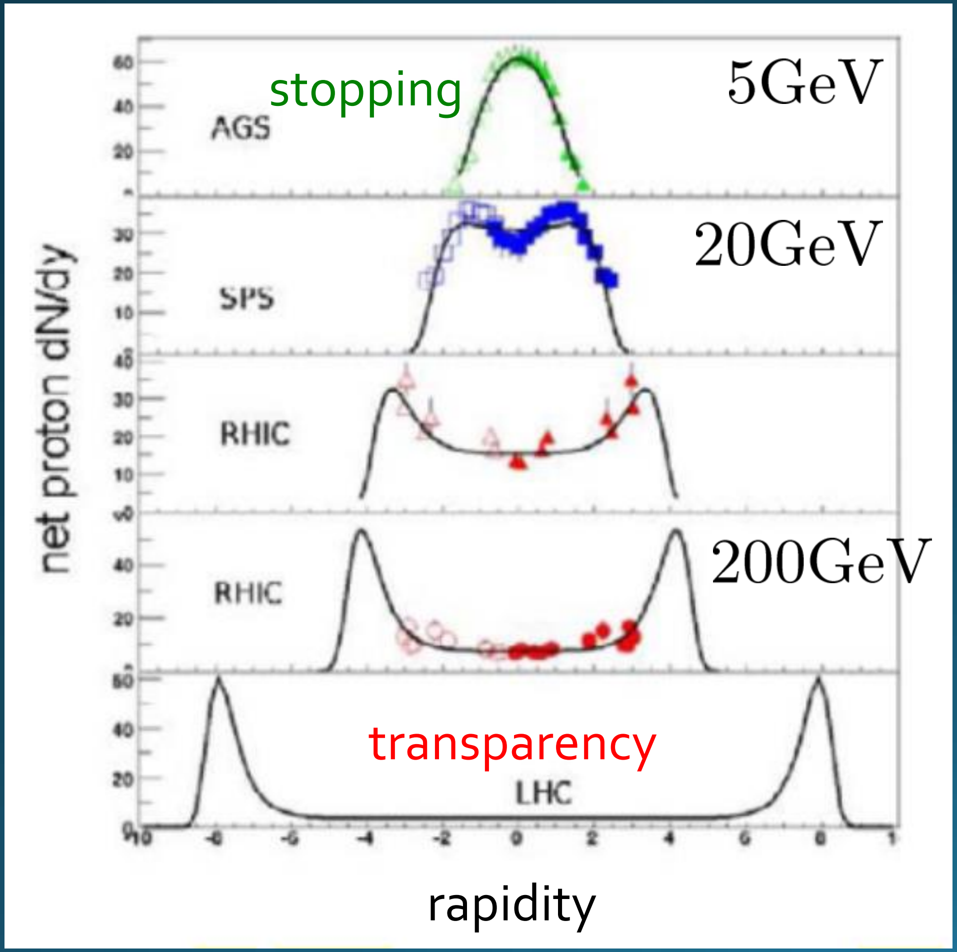
net-baryon #: small

Baryon stopping

net-baryon #: large

Baryon Stopping

rapidity dep. of net-proton #



$\sqrt{s_{NN}} \simeq 4-6\mathrm{GeV}$

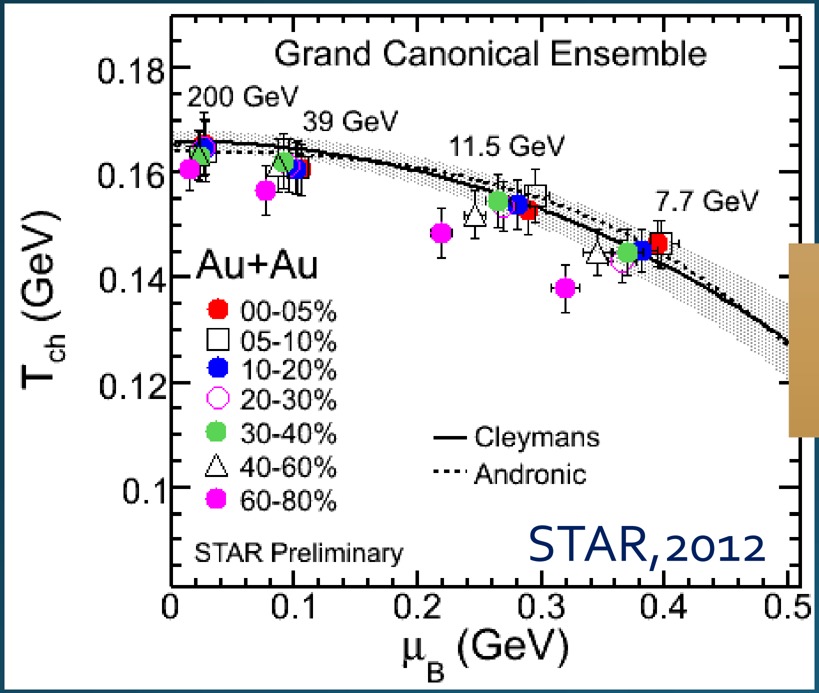
Baryons stop at collision point

$\sqrt{s_{NN}} > 10\mathrm{GeV}$

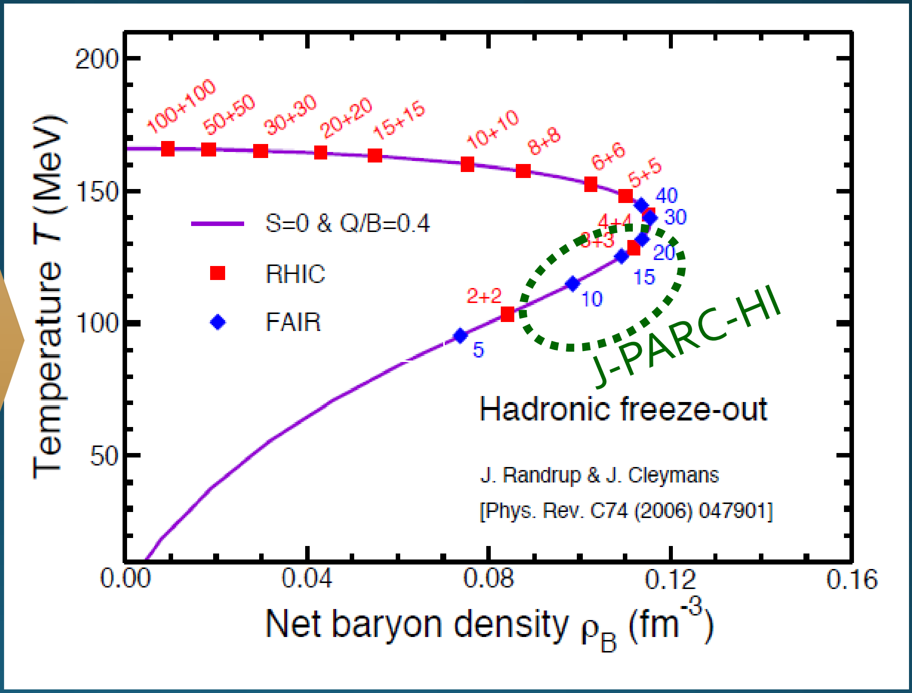
Baryons pass through

Beam-Energy Scan

T, μ from particle yield



Translation to baryon density

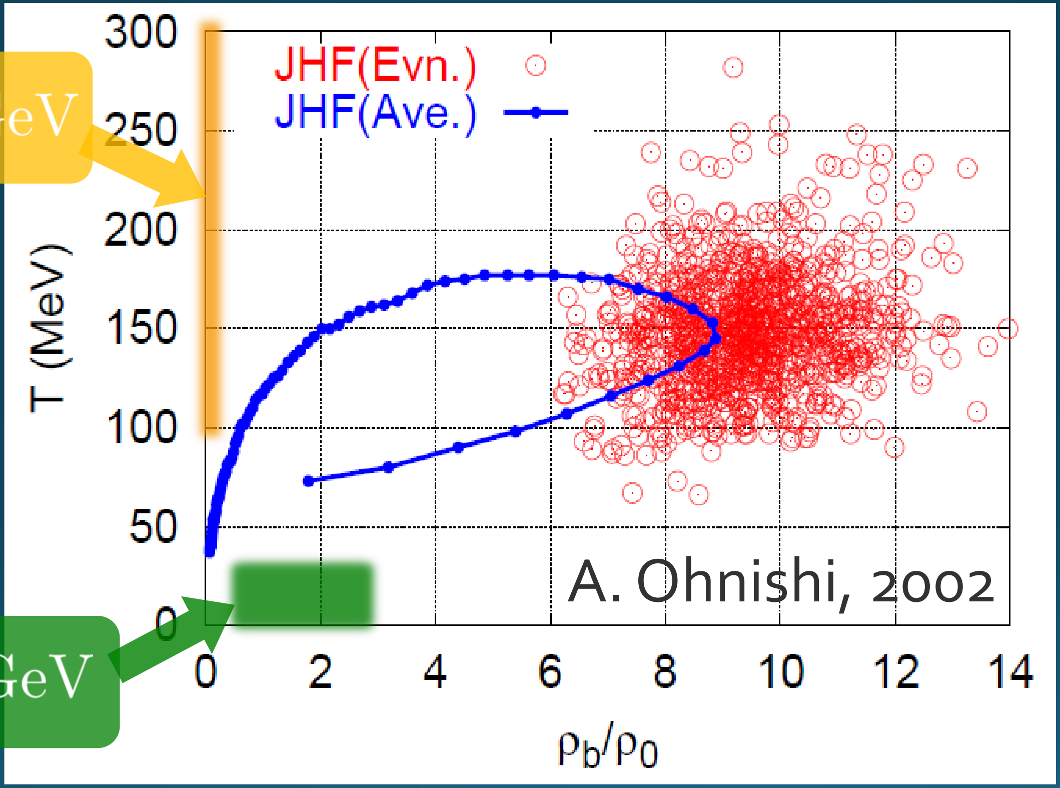


J-PARC energy = highest baryon density

Maximum Density

Time evolution in T-ρ plane by JAM

$\sqrt{s_{\rm NN}} > 100$ GeV

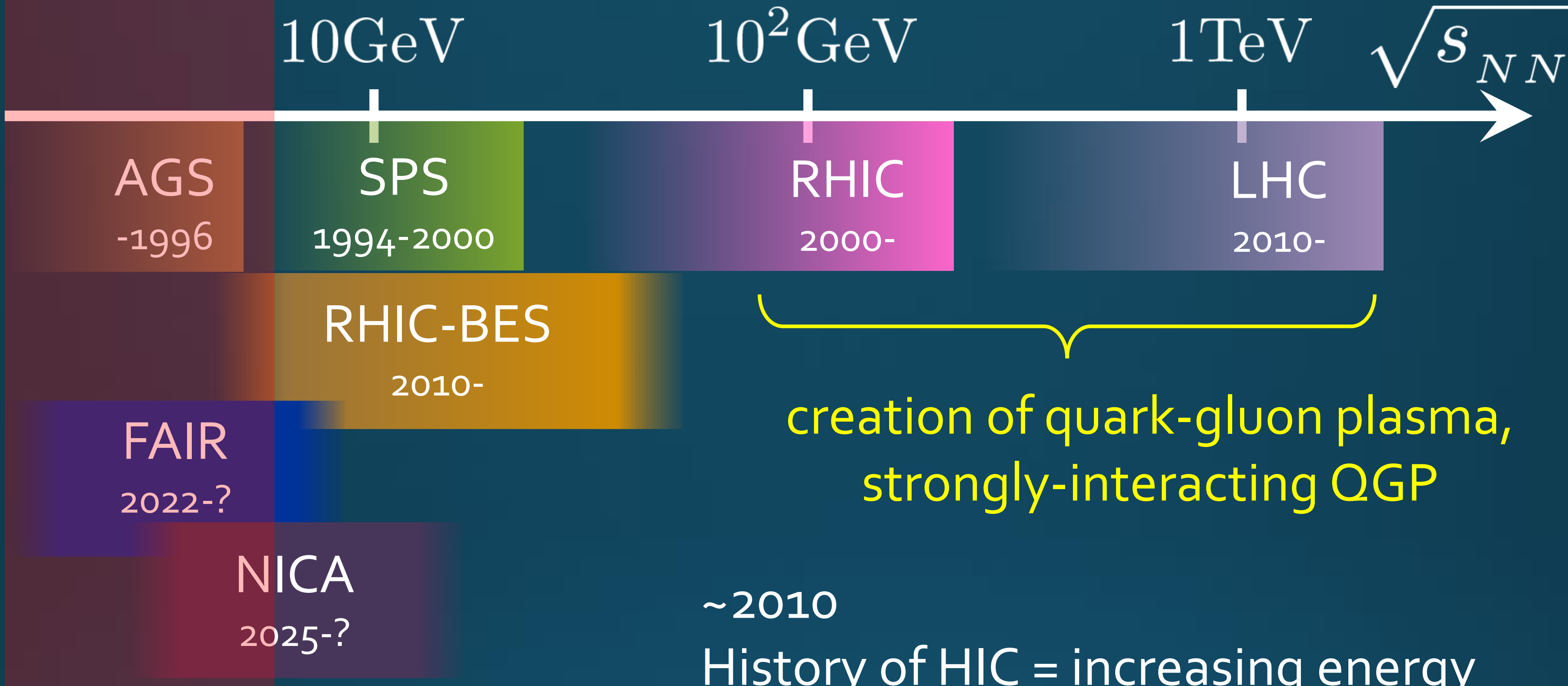


$E/A < 1$ GeV

$E/A = 20\text{GeV}$

$\sqrt{s_{NN}} \simeq 6\text{GeV}$

- ☐ Maximum density 5~10ρ_0 @ J-PARC energy
- ☐ Large event-by-event fluctuations?

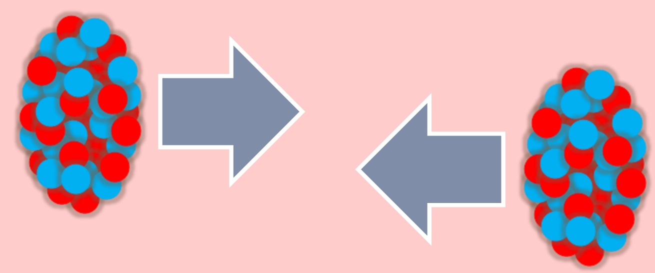


creation of quark-gluon plasma,
strongly-interacting QGP

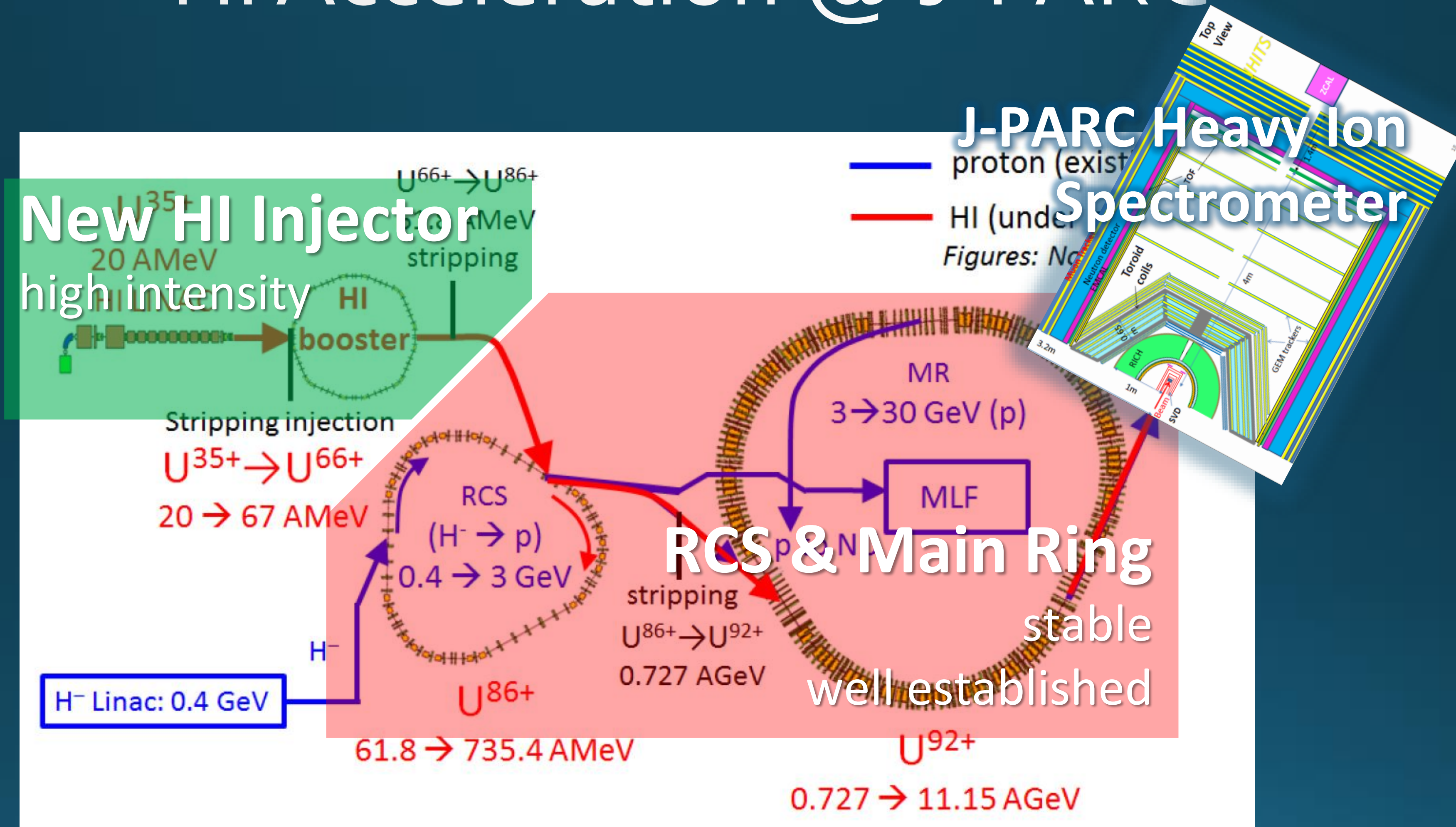
~2010
History of HIC = increasing energy

2010~
Beam-energy scan
Low-energy exp.

Heavy-Ion Collisions



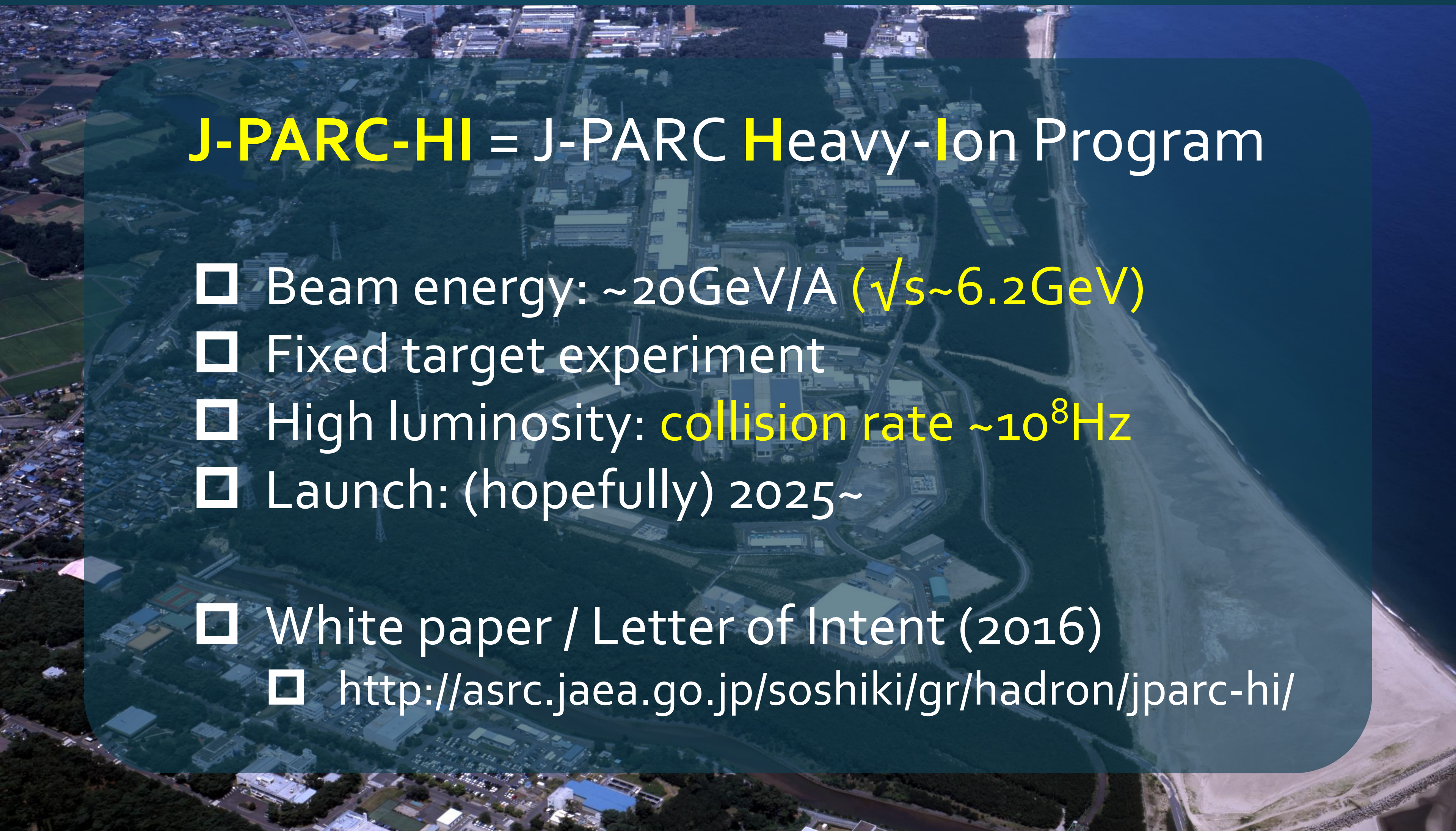
HI Acceleration @ J-PARC



- Use of reliable / high-performance RCS & main ring
- →Reduce cost and time

J-PARC-HI

J-PARC = Japan Proton Accelerator Research Complex

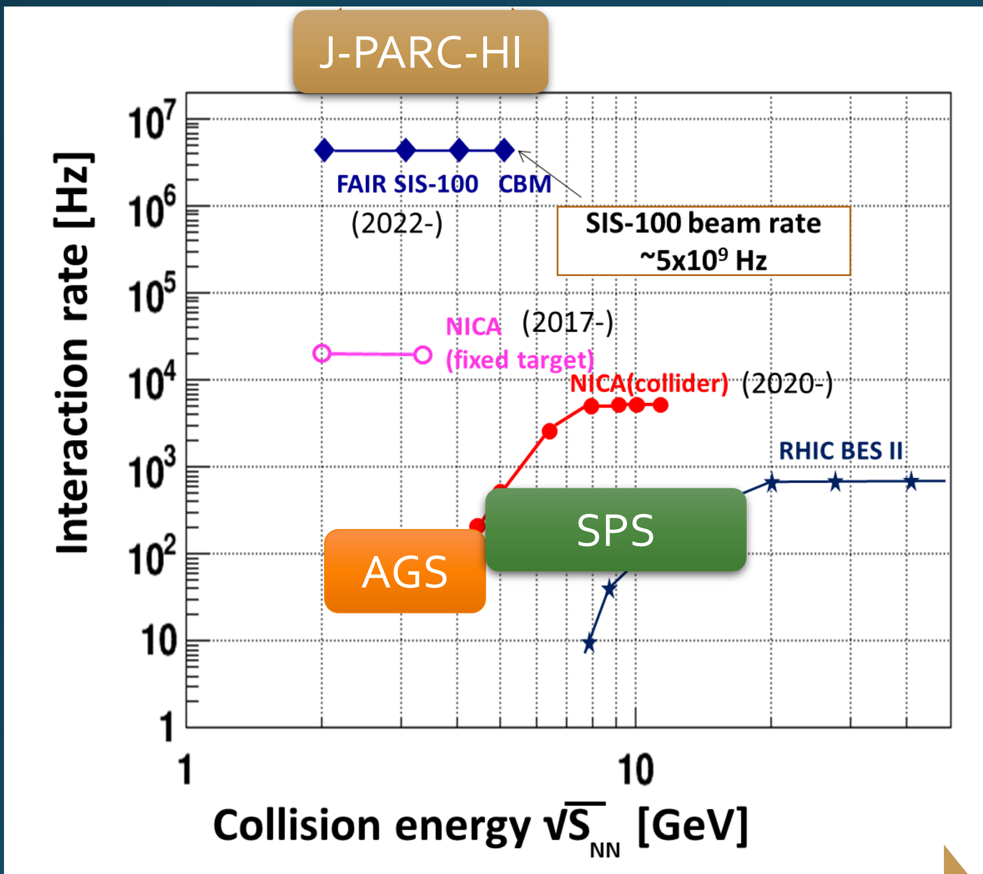


J-PARC-HI = J-PARC **H**eavy-**I**on Program

- Beam energy: ~20GeV/A ($\sqrt{s}$~6.2GeV)
- Fixed target experiment
- High luminosity: collision rate ~10^8Hz
- Launch: (hopefully) 2025~

- White paper / Letter of Intent (2016)
  - http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

Collision Rate



J-PARC-HI:

High-luminosity X Fixed target

→World highest rate～10^8Hz

5-order higher than AGS,SPS

AGS, SPS		J-PARC-HI
1 year	=	5 min.

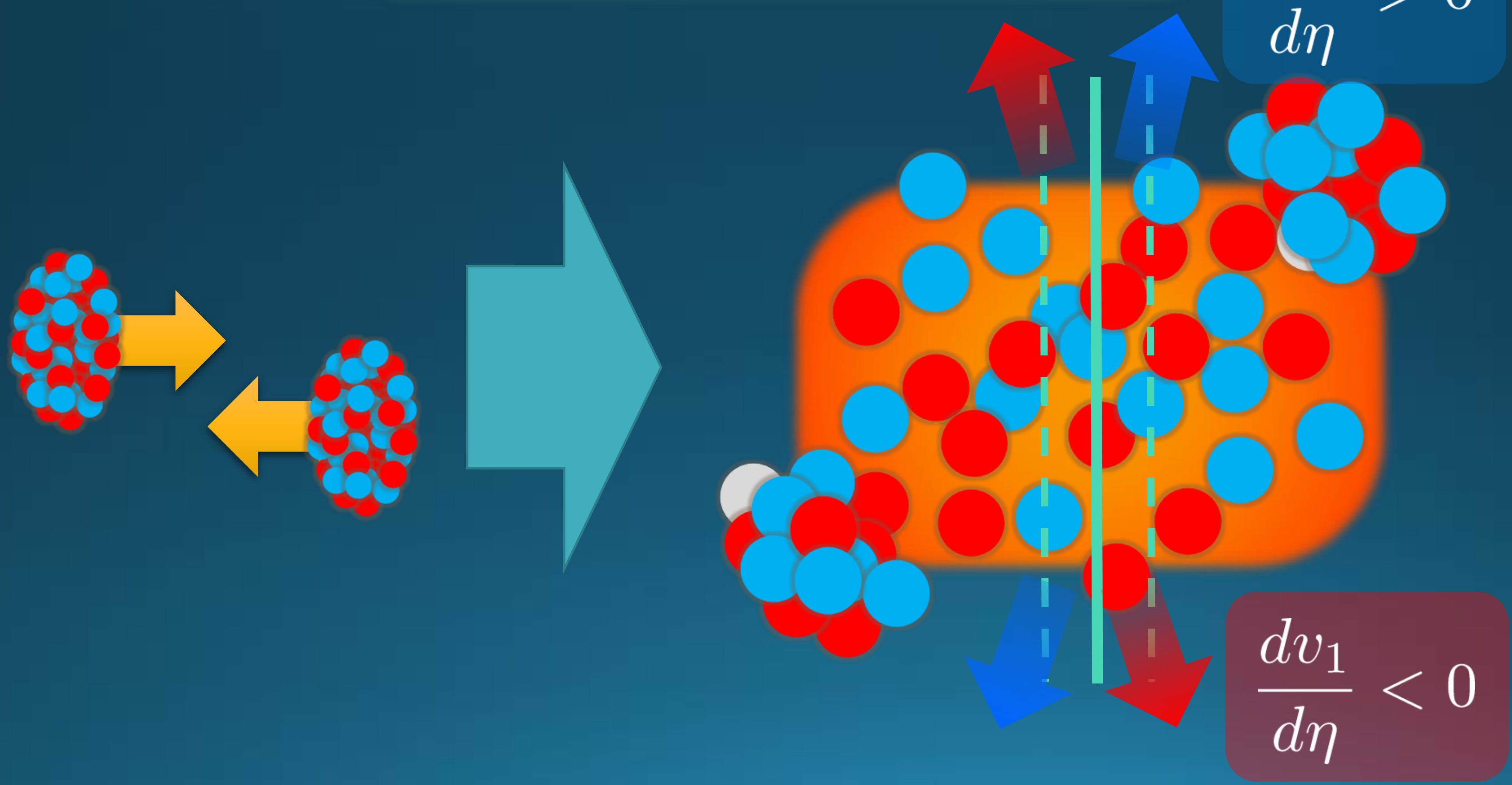
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search of rare events

Observables

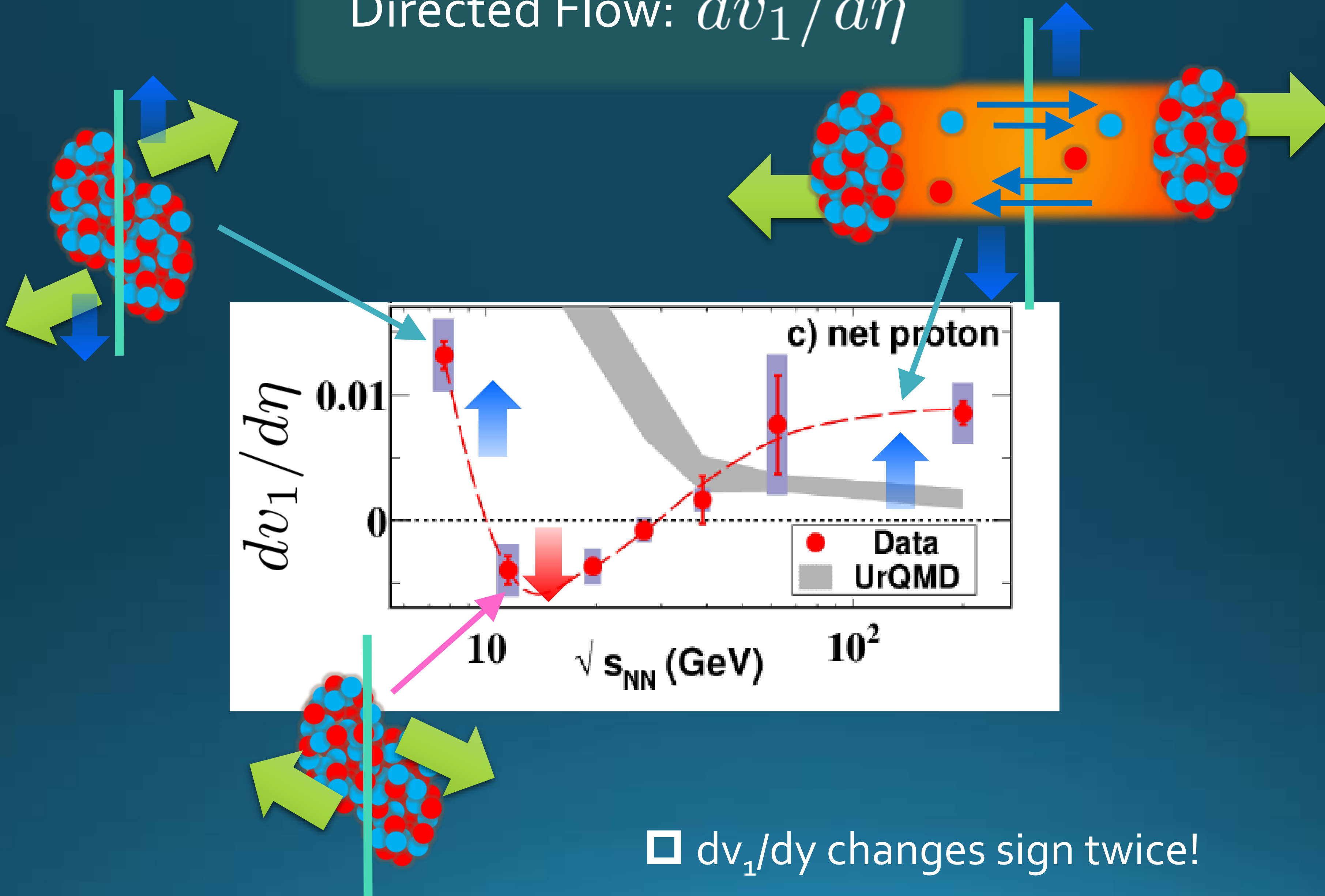
- Directed flow
- Fluctuations
- Elliptic flow
- Higher harmonics
- Strange abundance
- …

Non-trivial Collision Dynamics

Directed Flow: $dv_1/d\eta$

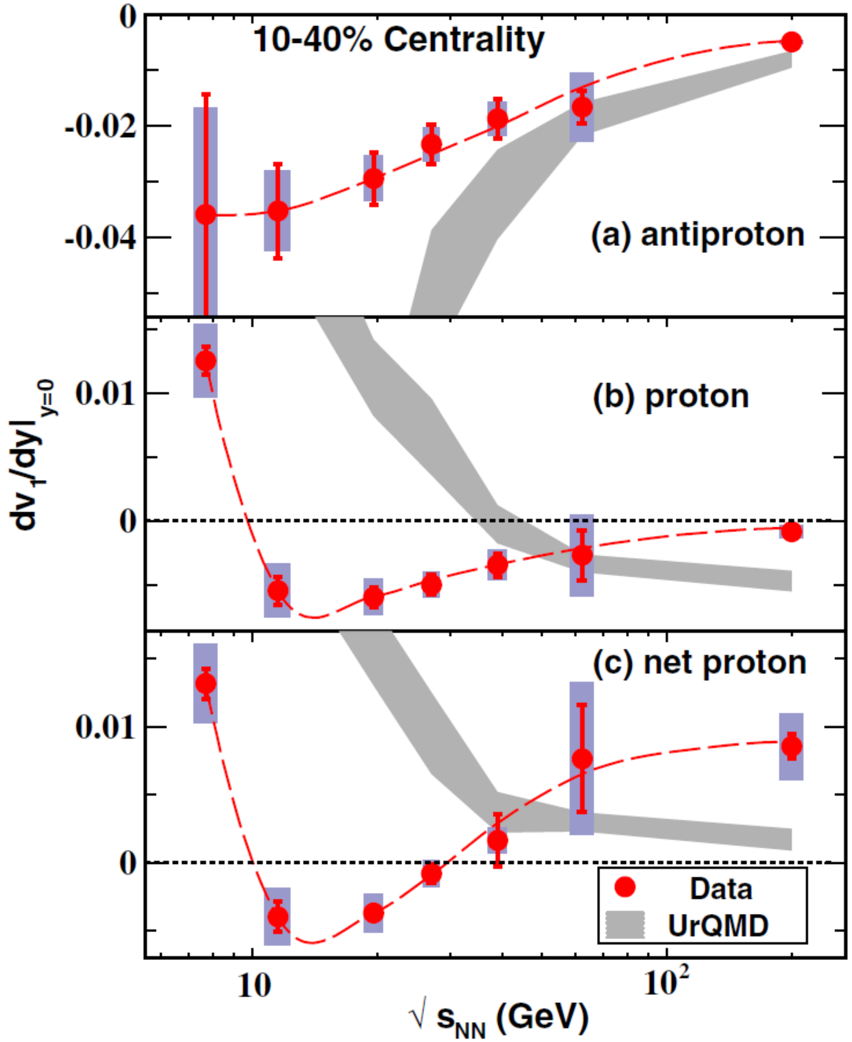


Directed Flow: $dv_1/d\eta$

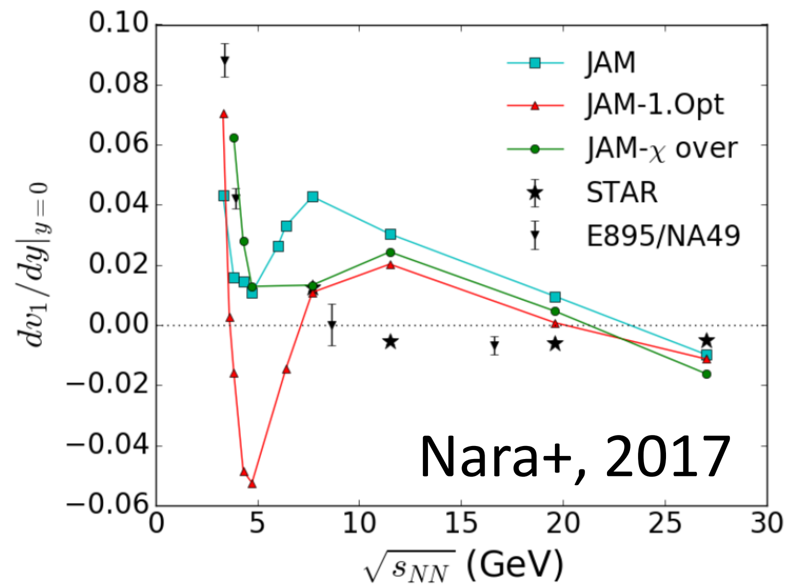


- dv_1/dy changes sign twice!

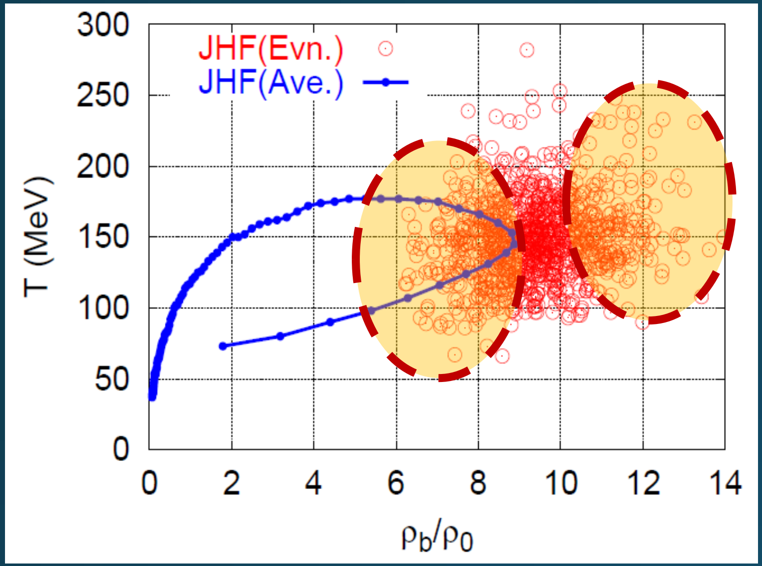
dv_1/dy: Signal of 1st Phase Tr.?



Negative v_1
= signal of softening
≅1st order transition??

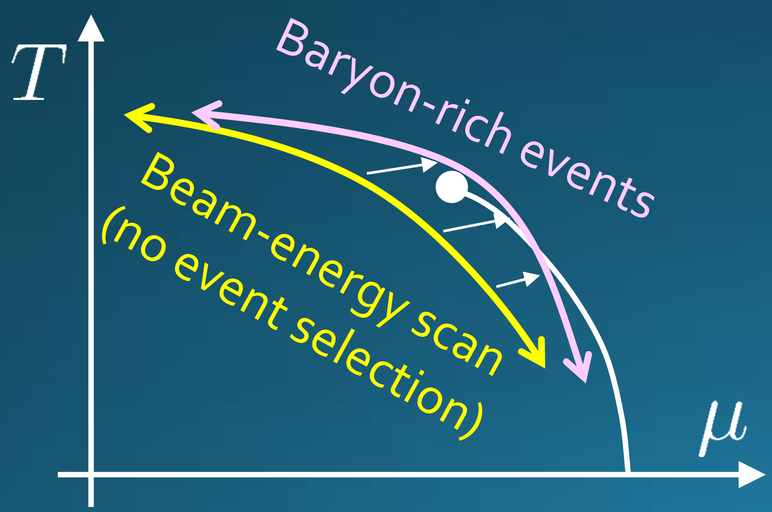


Maximum Density Scan?

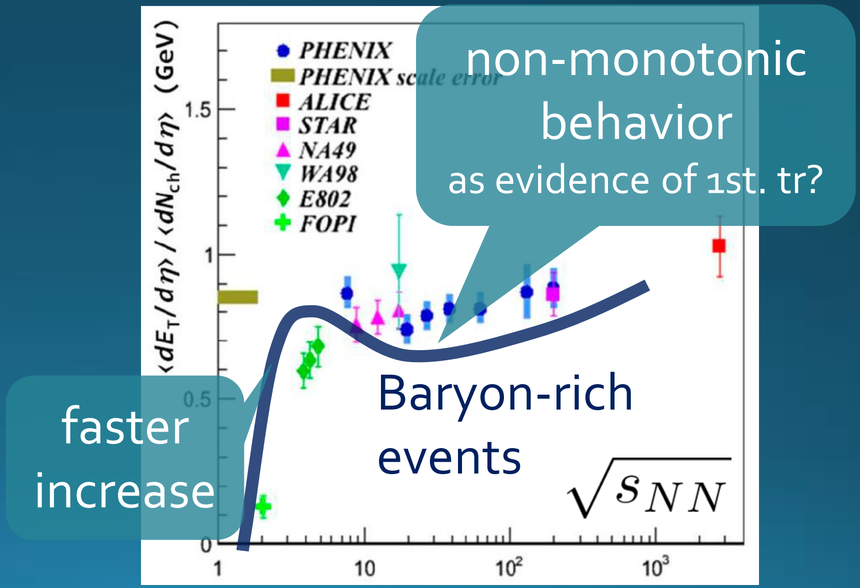


Large event-by-event fluctuations even after fixed centrality / collision energy

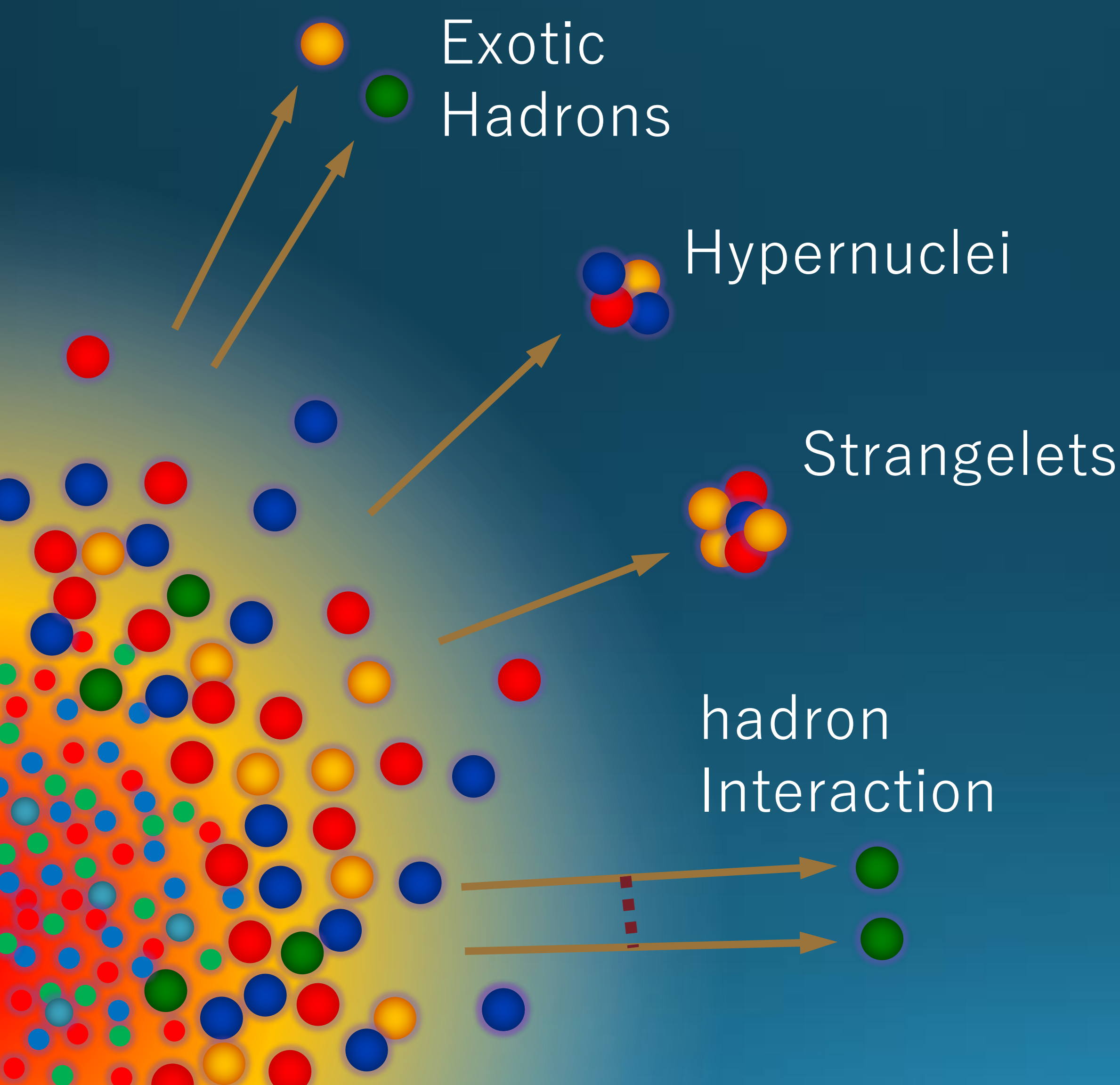
If we can select events, "maximum density" dependence can be studied experimentally.



average transverse energy



Search of Rare Events



- High density
- High luminosity
- High strange yield

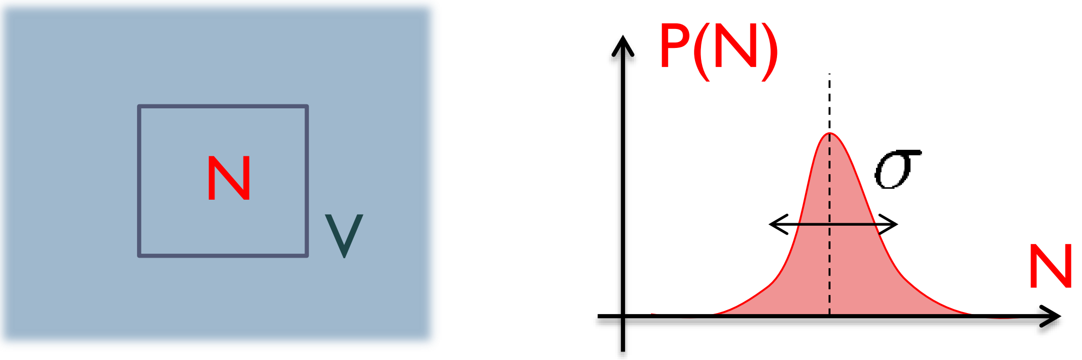
Rare-event Factory

- creation
- properties
- interaction

Fluctuations

Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.



Thermal Fluctuations

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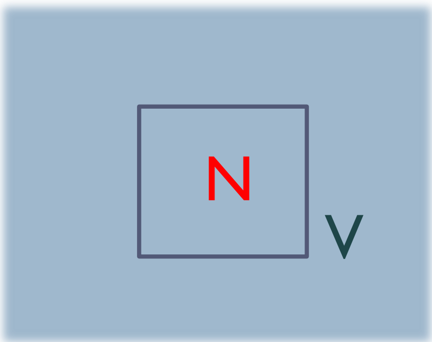
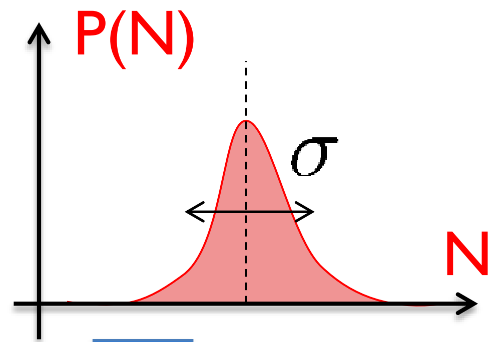




- Variance: $\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$
- Skewness: $S = \dfrac{\langle \delta N^3 \rangle}{\sigma^3}$
- Kurtosis: $\kappa = \dfrac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$

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

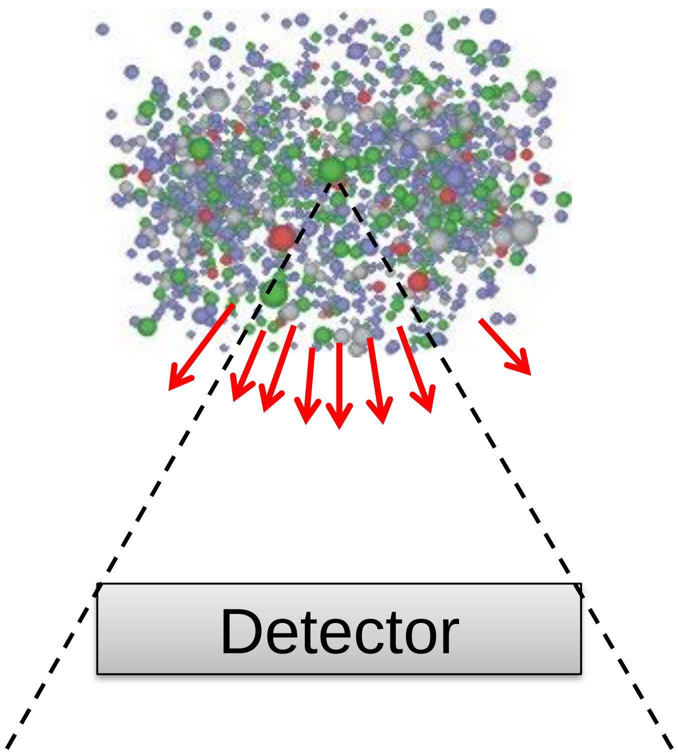
Non-Gaussianity

Review:
Asakawa, MK, PPNP**90** ('16)

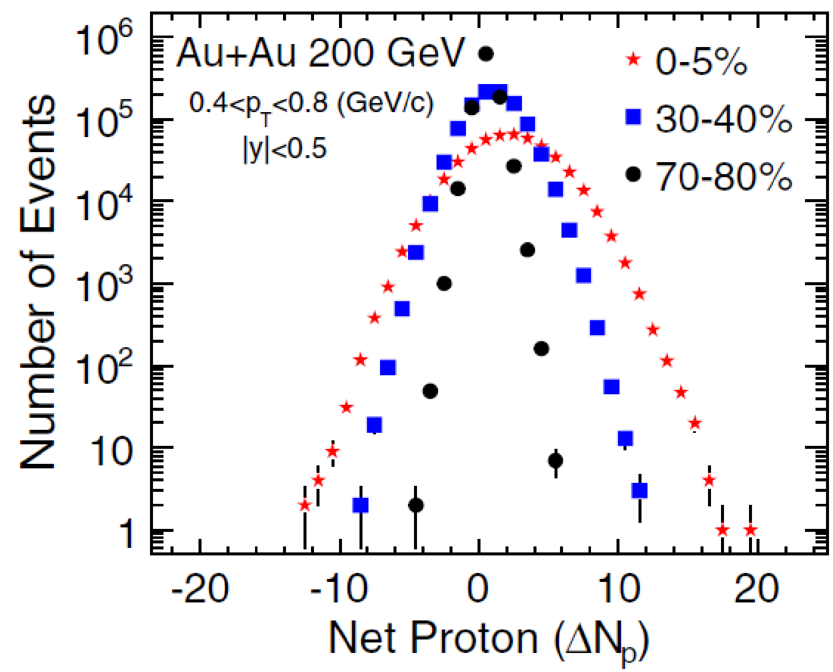
Event-by-Event Fluctuations

Review: Asakawa, MK, PPNP **90** (2016)

Fluctuations can be measured by e-by-e analysis in experiments.



STAR, PRL**105** (2010)



Cumulants

$$\langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c$$

A Coin Game

① Bet 500YEN
② You get head coins of

A. 20 x 50YEN

B. 10 x 100YEN

Same expectation value.

A Coin Game

① Bet 500YEN
② You get head coins of

A. 20 x 50YEN

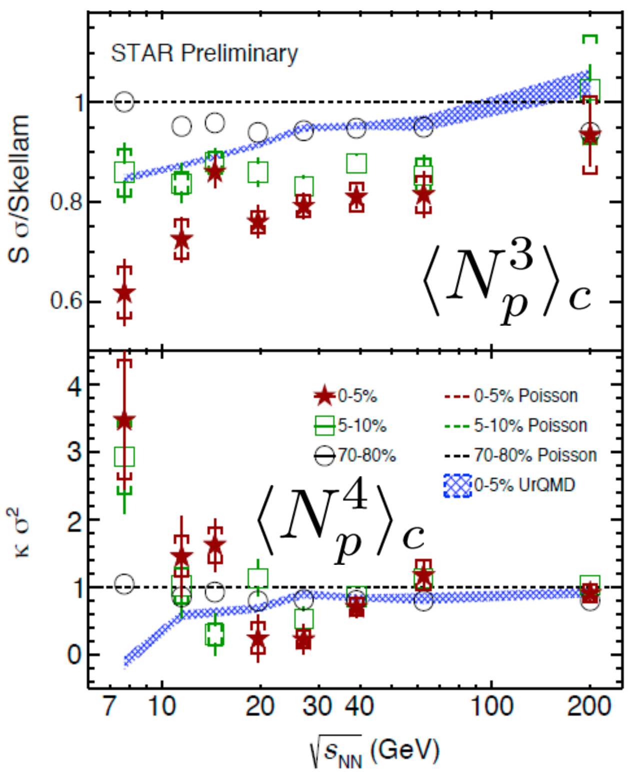
B. 10 x 100YEN

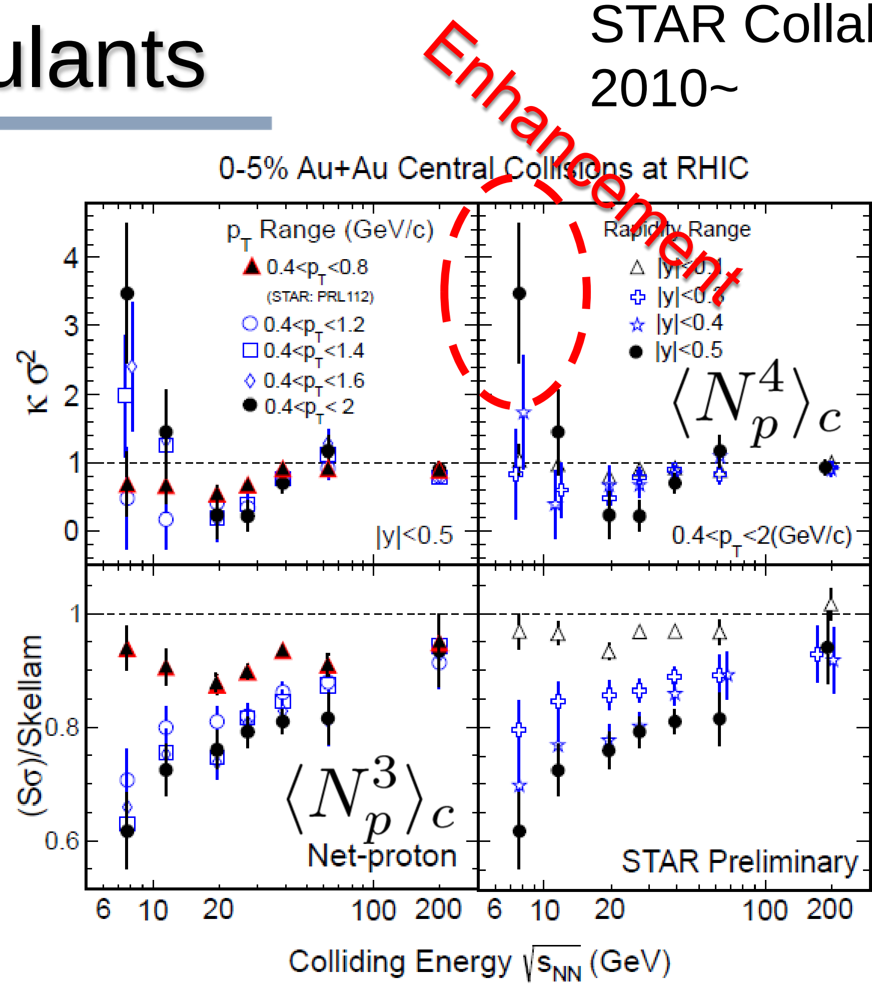
C. 1 x 1000YEN

Same expectation value.
But, different fluctuation.

Higher-Order Cumulants

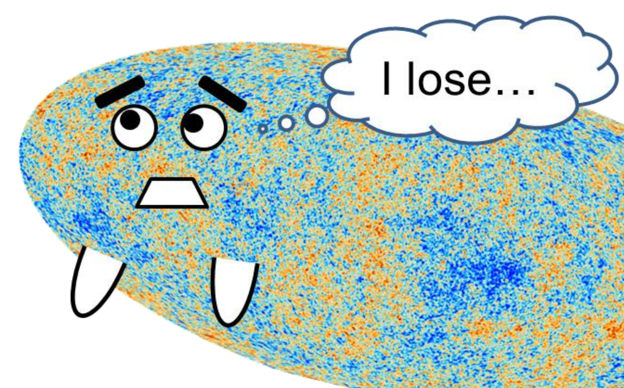
STAR Collab.
2010~





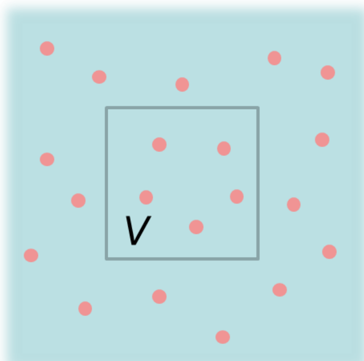
Non-zero **non**-Gaussian cumulants have been established!

Have we measured critical fluctuations?



Fluctuations: Theory vs Experiment

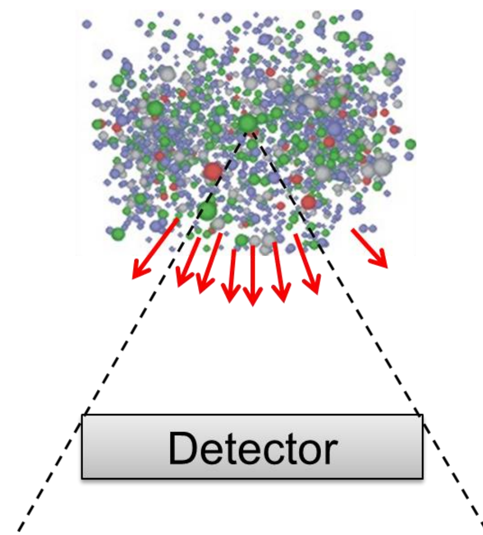
Theoretical analyses
based on statistical mechanics



lattice, critical point,
effective models, …

Fluctuation in a spatial volume

Experiments



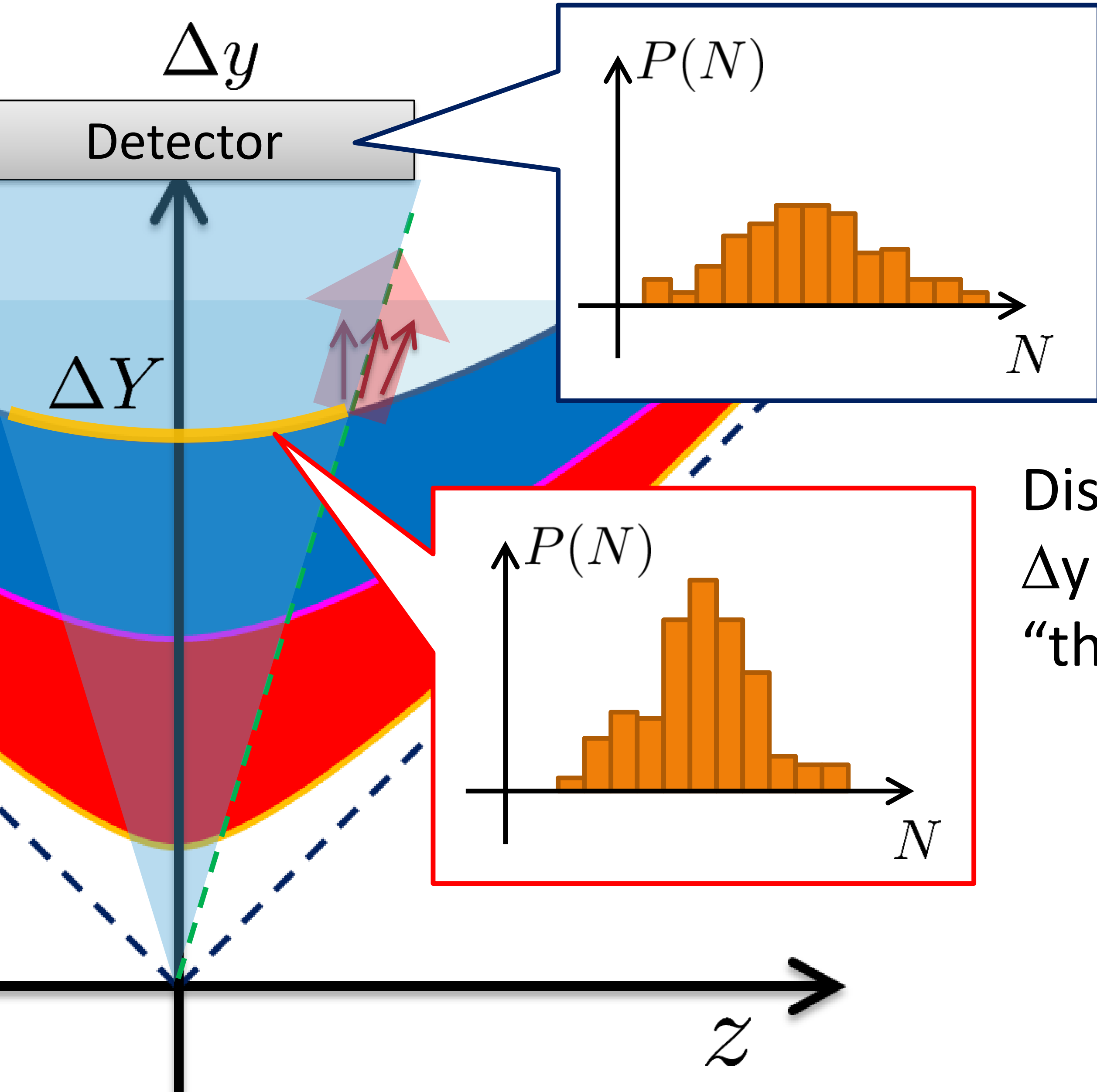
Fluctuations in a momentum space

discrepancy in phase spaces

Asakawa, Heinz, Muller, 2000; Jeon, Koch, 2000; Shuryak, Stephanov, 2001

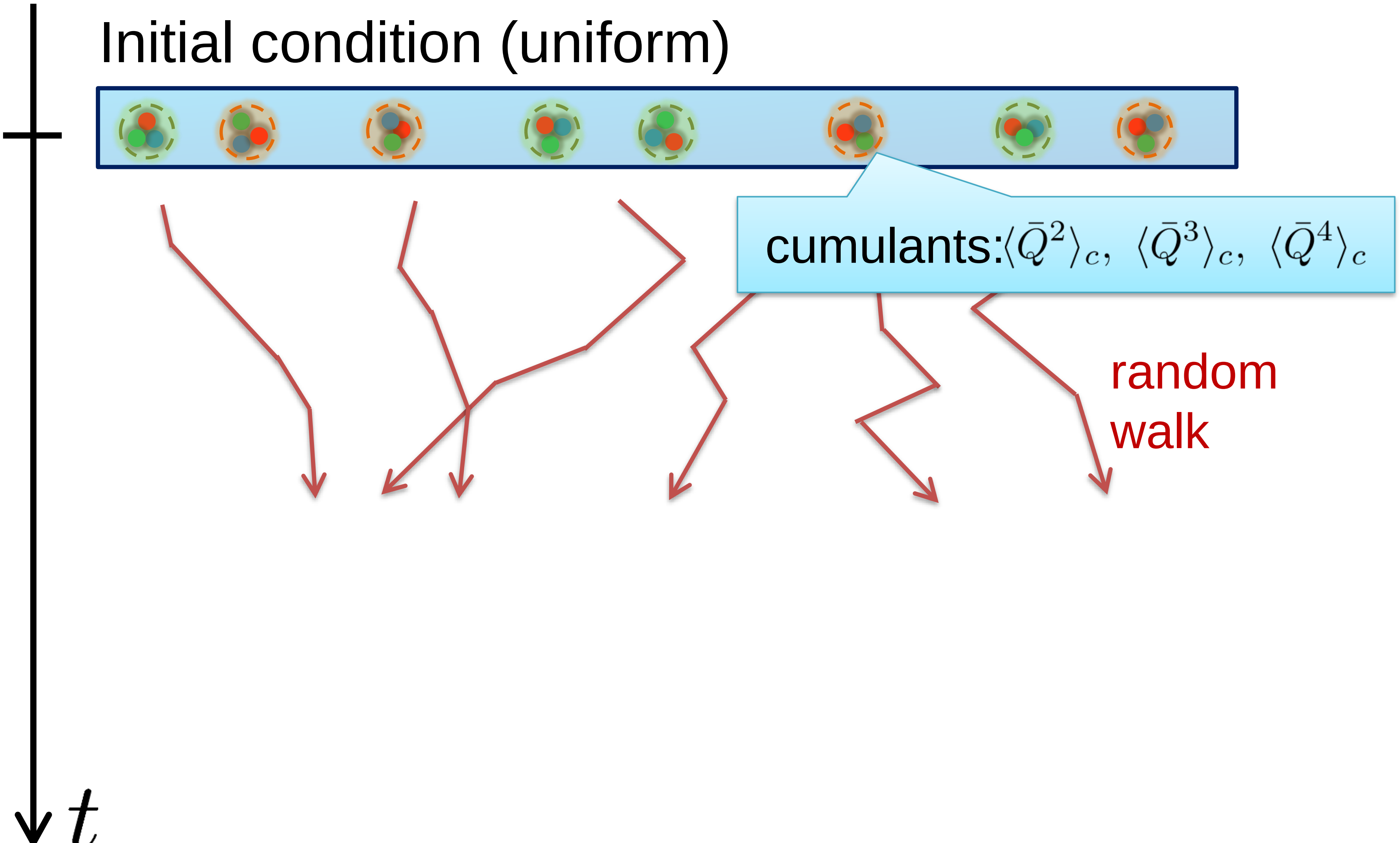
Thermal Blurring

Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000



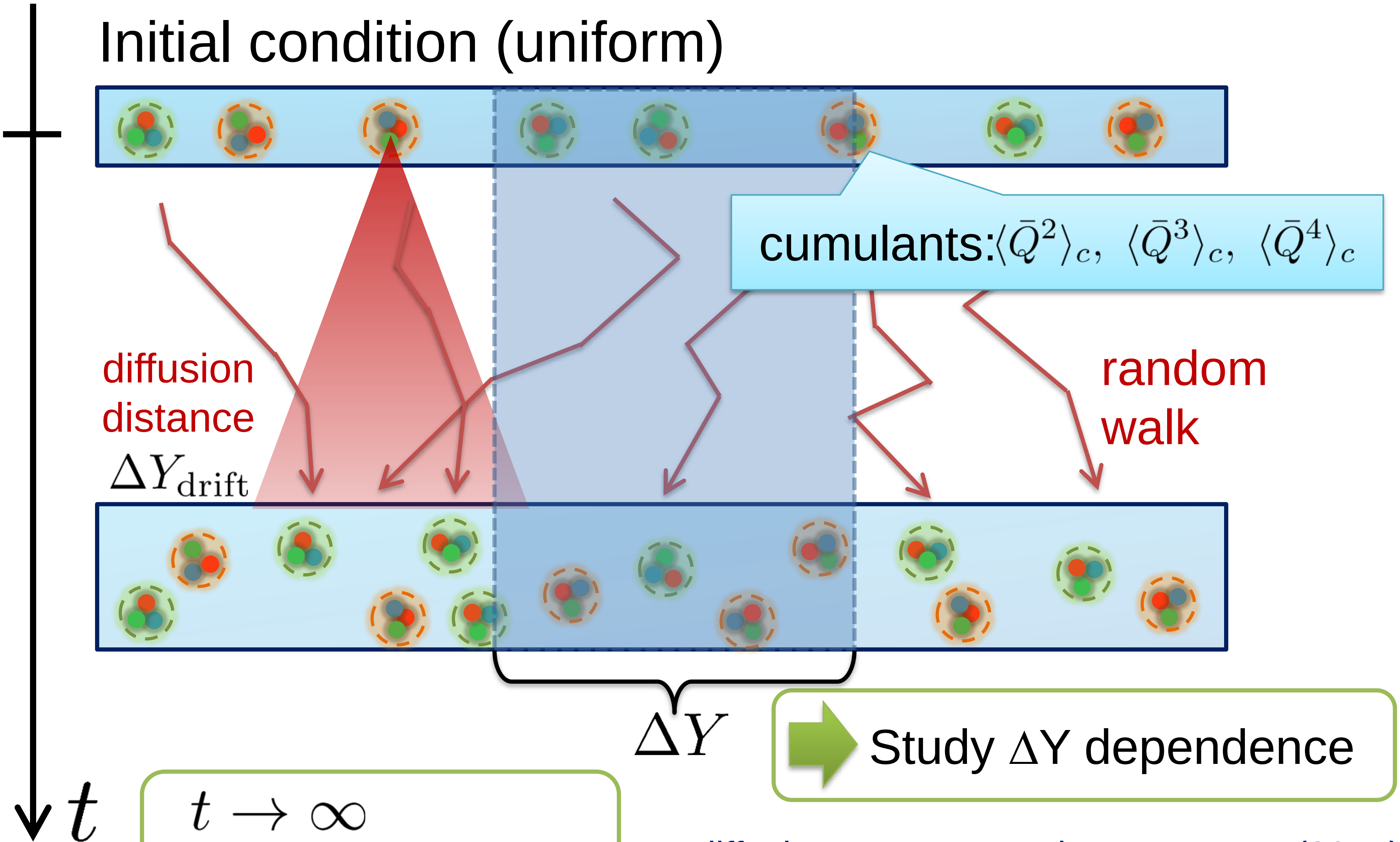
Distributions in ΔY and Δy are different due to "thermal blurring".

(Non-Interacting) Brownian Particle Model



diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)

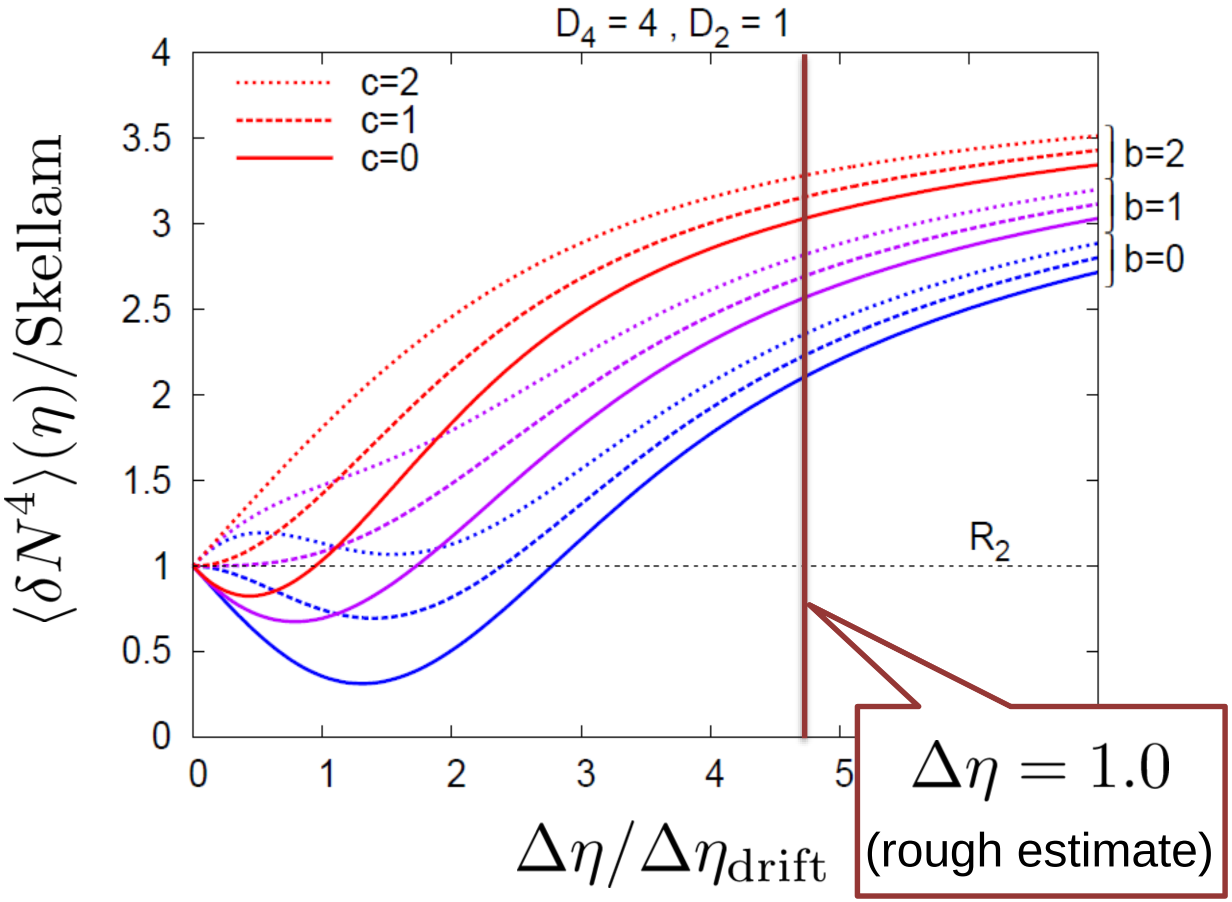
(Non-Interacting) Brownian Particle Model



diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)

4^{th} order : w/ Critical Fluctuation

MK+ (2014)
MK (2015)



Initial Condition

$$D_4 = \frac{\langle Q^4_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 4$$

$$b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{net})} \rangle}$$

$$c = \frac{\langle Q^2_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

$$D_2 = \frac{\langle Q^2_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 1$$

- Higher order cumulants can behave non-monotonically.

Rapidity Window Dep.

4th-order cumulant

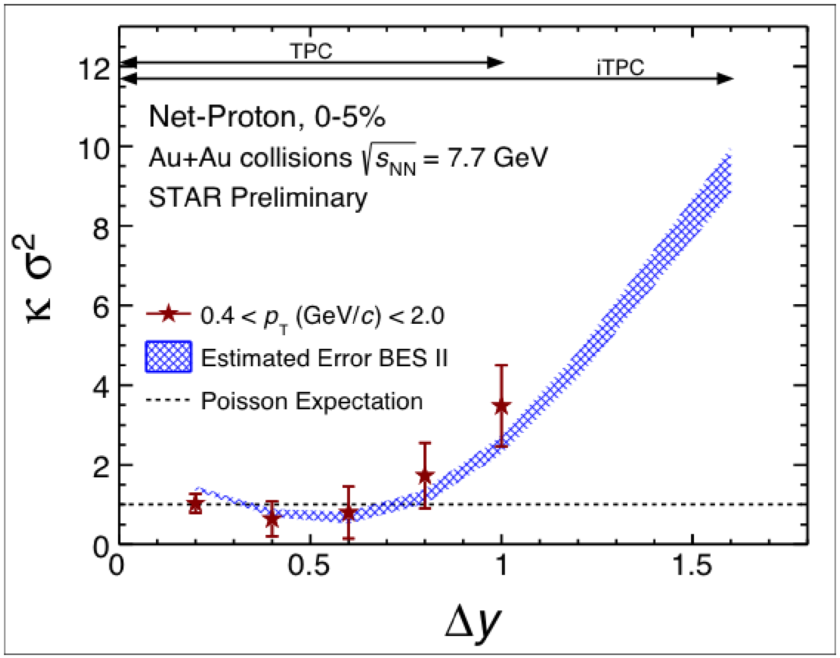
MK+, 2014
MK, 2015

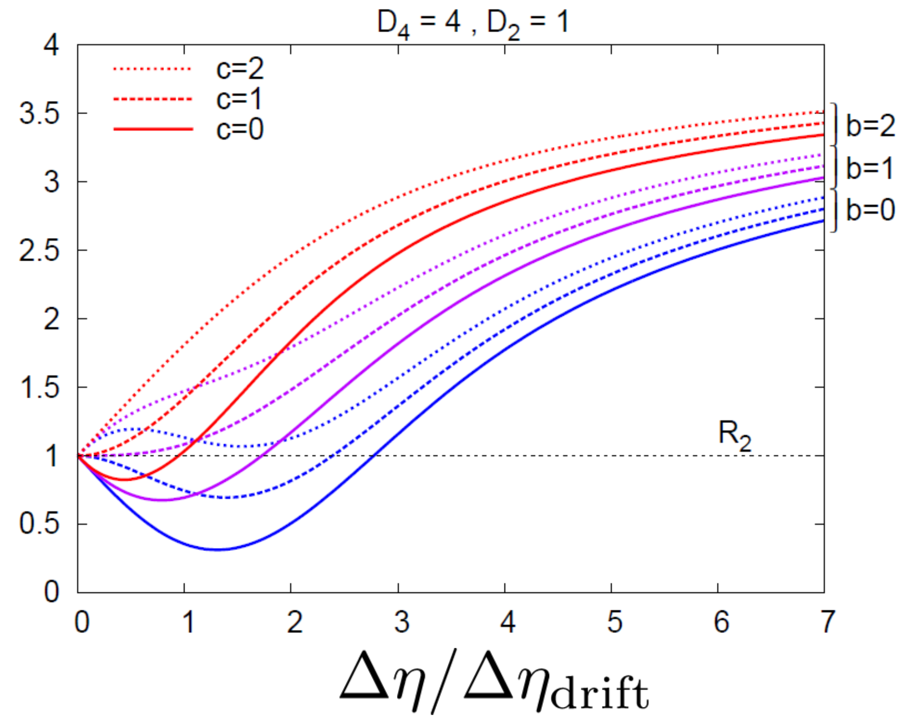
Initial Conditions

$$D_4 = \frac{\langle Q^4_{(\text{net})} \rangle_c}{\langle Q_{(\text{tot})} \rangle} \qquad b = \frac{\langle Q^2_{(\text{net})} Q_{(\text{tot})} \rangle_c}{\langle Q_{(\text{net})} \rangle}$$

$$D_2 = \frac{\langle Q^2_{(\text{net})} \rangle_c}{\langle Q_{(\text{tot})} \rangle} \qquad c = \frac{\langle Q^2_{(\text{tot})} \rangle_c}{\langle Q_{(\text{tot})} \rangle}$$

STAR Collab. (X. Luo, CPOD2014)

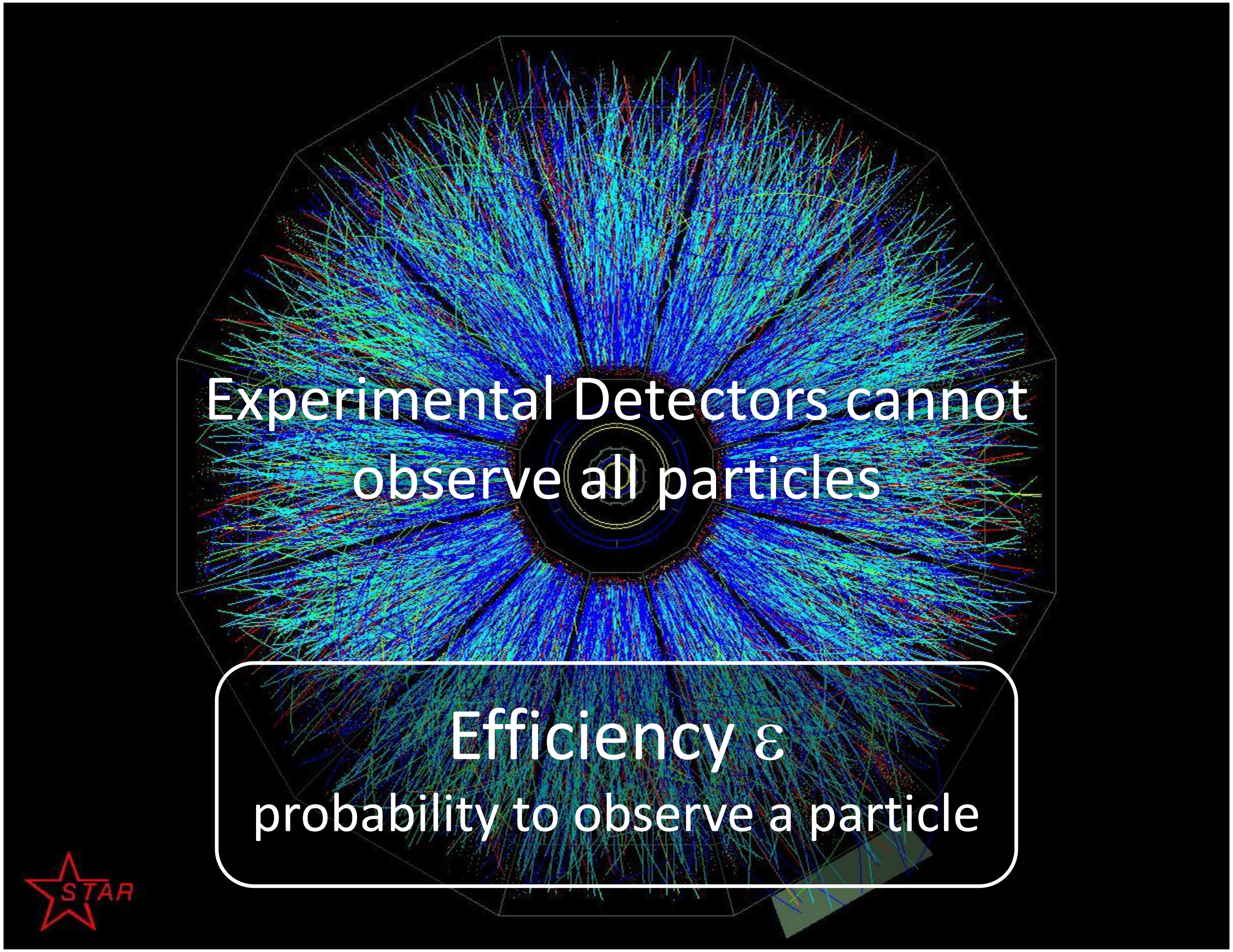




- Different initial conditions give rise to different characteristic Δη dependence. → Study initial condition
- Non-monotonic behaviors can appear in Δη dependence.

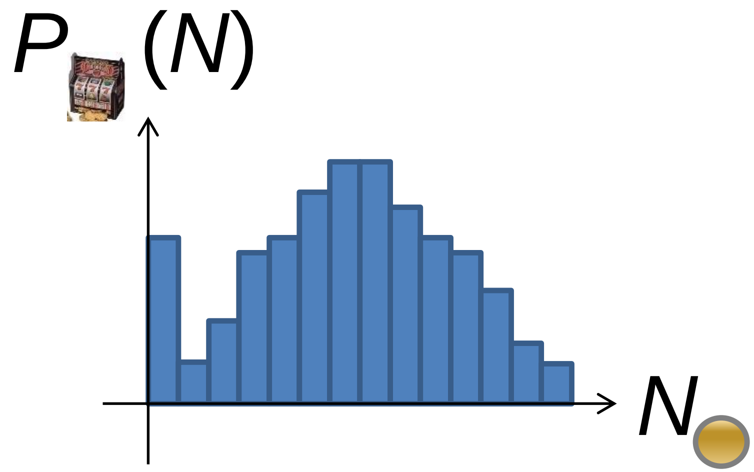
Finite volume effects: Sakaida+, PRC90 (2015)

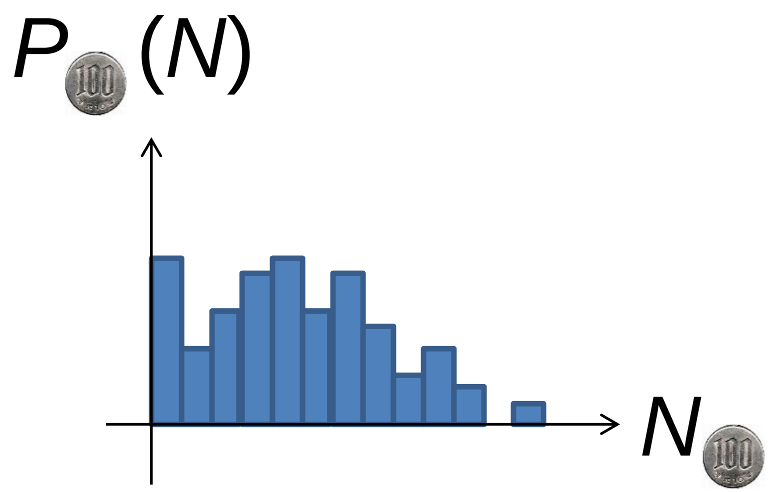
Efficiency Correction



Efficiency correction is indispensable in experimental analyses!

Slot Machine Analogy

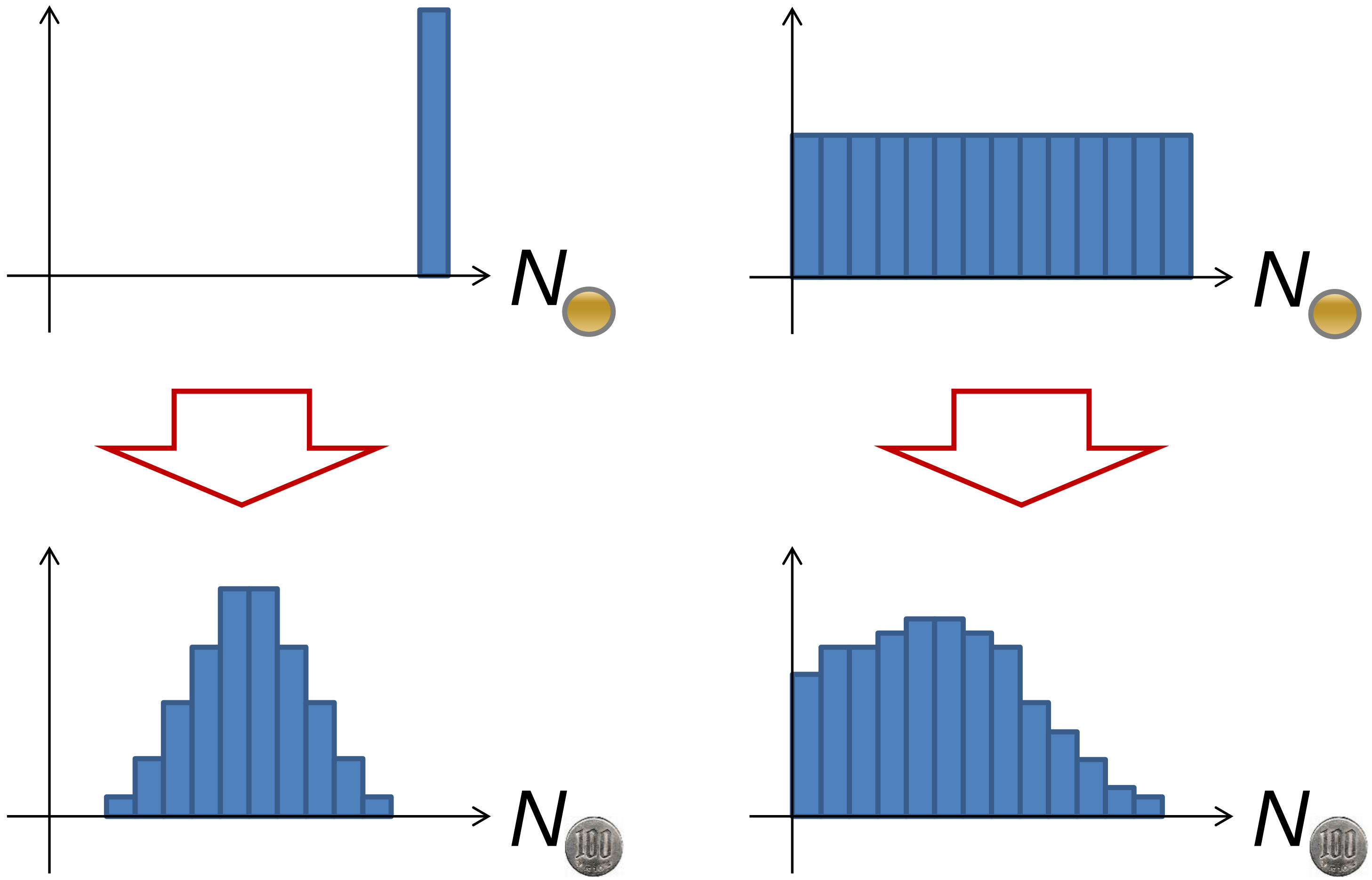




Slot Machine Analogy

Fixed # of coins

Constant probabilities



The Binomial Model

MK, Asakawa, 2012; 2012
Bzdak, Koch, 2012

When efficiency for individual particles are **independent**

$$P_{\text{obs}}(n) = \sum_N B_p(n;N)P(N)$$

dist. func. of **observed** particle #

binmial dist. func.

dist. func. of **original** particle #

The cumulants connected with each other

$$\langle n^m \rangle_c \Longleftrightarrow \langle N^m \rangle_c$$

Caveat: Effects of nonvanishing correlations: Holtzman+ 2016

$$\langle n^m \rangle_c \Longleftrightarrow \langle N^m \rangle_c$$

$$\langle N^m \rangle_c \Rightarrow \langle n^m \rangle_c$$

$$\begin{aligned}
\langle n \rangle &= \xi_1 \langle N \rangle, \\
\langle n^2 \rangle_c &= \xi_1^2 \langle N^2 \rangle_c + \xi_2 \langle N \rangle, \\
\langle n^3 \rangle_c &= \xi_1^3 \langle N^3 \rangle_c + 3\xi_1\xi_2 \langle N^2 \rangle_c + \xi_3 \langle N \rangle, \\
\langle n^4 \rangle_c &= \xi_1^4 \langle N^4 \rangle_c + 6\xi_1^2\xi_2 \langle N^3 \rangle_c + (3\xi_2^2 + 4\xi_1\xi_3) \langle N^2 \rangle_c + \xi_4 \langle N \rangle,
\end{aligned}$$

$$\langle n^m \rangle_c \Rightarrow \langle N^m \rangle_c$$

$$\begin{aligned}
\langle N \rangle &= \xi_1^{-1} \langle n \rangle, \\
\langle N^2 \rangle_c &= \xi_1^{-2} \langle n^2 \rangle_c - \xi_2\xi_1^{-3} \langle n \rangle, \\
\langle N^3 \rangle_c &= \xi_1^{-3} \langle n^3 \rangle_c - 3\xi_2\xi_1^{-4} \langle n^2 \rangle_c + (3\xi_2^2\xi_1^{-5} - \xi_3\xi_1^{-4}) \langle n \rangle, \\
\langle N^4 \rangle_c &= \xi_1^{-4} \langle n^4 \rangle_c - 6\xi_2\xi_1^{-5} \langle n^3 \rangle_c + (15\xi_2^2\xi_1^{-6} - 4\xi_3\xi_1^{-5}) \langle n^2 \rangle_c \\
&\quad - (15\xi_2^3\xi_1^{-7} - 10\xi_2\xi_3\xi_1^{-6} + \xi_4\xi_1^{-5}) \langle n \rangle,
\end{aligned}$$

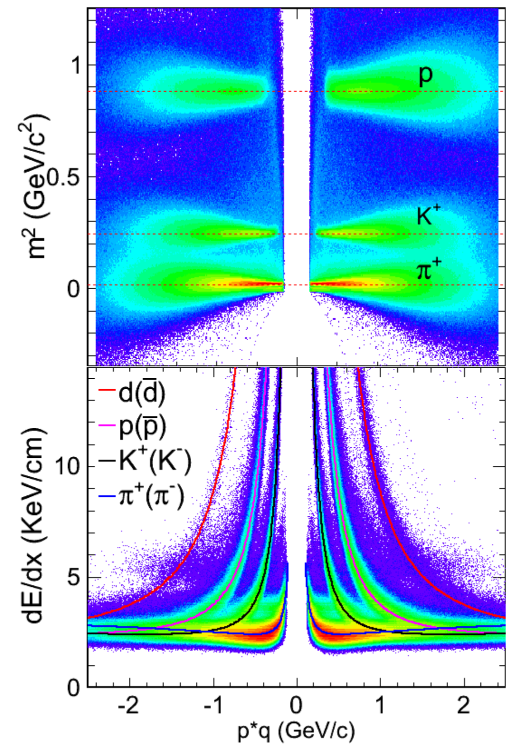
Another formula using factorial moments: Bzdak, Koch, 2012

Multi-efficiency Problem

- efficiency for proton ≠ anti-proton
- efficiency has p_T dependence

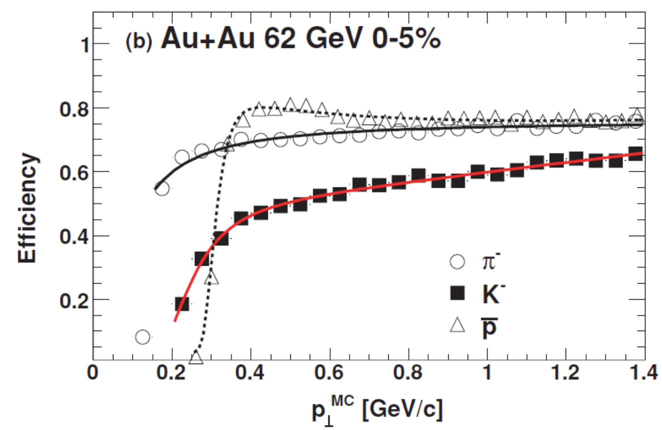
STAR, net proton

$$\begin{cases} p_T < 0.8\mathrm{GeV} & \text{TPC } \varepsilon\sim 80\% \\ p_T > 0.8\mathrm{GeV} & \text{TPC+TOF } \varepsilon\sim 50\% \end{cases}$$



- Multi-variable efficiency correction

A method was proposed, but too large numerical costs



Luo, 2014
Bzdak, Koch, 2015

New Formula for Efficiency Correction

MK, PRC,2016

$$\langle Q\rangle_c = \langle\langle q_{(1)}\rangle\rangle_c,$$
$$\langle Q^2\rangle_c = \langle\langle q_{(1)}^2\rangle\rangle_c - \langle\langle q_{(2)}\rangle\rangle_c,$$
$$\langle Q^3\rangle_c = \langle\langle q_{(1)}^3\rangle\rangle_c - 3\langle\langle q_{(2)}q_{(1)}\rangle\rangle_c + \langle\langle 3q_{(2,1|2)} - q_{(3)}\rangle\rangle_c,$$
$$\begin{aligned}\langle Q^4\rangle_c = &\langle\langle q_{(1)}^4\rangle\rangle_c - 6\langle\langle q_{(2)}q_{(1)}^2\rangle\rangle_c + 12\langle\langle q_{(2,1|2)}q_{(1)}\rangle\rangle_c \\ &+ 6\langle\langle q_{(1,1|2)}q_{(2)}\rangle\rangle_c - 4\langle\langle q_{(3)}q_{(1)}\rangle\rangle_c - 3\langle\langle q_{(2)}^2\rangle\rangle_c \\ &+ \langle\langle -18q_{(2,1,1|2,2)} + 6q_{(2,1,1|3)} + 4q_{(3,1|2)} \\ &+ 3q_{(2,2|2)} - q_{(4)}\rangle\rangle_c,\end{aligned}$$

$$Q = \sum_{i=1}^{M} a_i N_i$$

linear combination of original particle numbers

$$q_{(\cdots)} = \sum_{i=1}^{M} c_{(\cdots)}^{(i)} n_i$$

linear combination of observed particle numbers

Numerical Cost

For nth order and M variables

- F-moment method $\sim \mathcal{O}(M^n)$
- Our method $\sim \mathcal{O}(M)$

for $M \to \infty$

Drastic reduction of numerical cost : private communication with T. Nonaka

検出効率補正への応用

キュムラント検出効率補正小史

- **最初の提案**
  MK, Asakawa ('12), Bzdak, Koch ('12)
  ➡ 2粒子種しか扱ってない

- **Fモーメントを使った方法**
  Bzdak, Koch ('15), Luo ('15)
  ➡ 数値解析重すぎ

- **キュムラント展開を使った方法**
  MK ('16)
  ➡ 手計算複雑すぎ

- **新しい提案**：Fキュムラントを使った方法
  T. Nonaka, MK, Esumi, 1702.07106

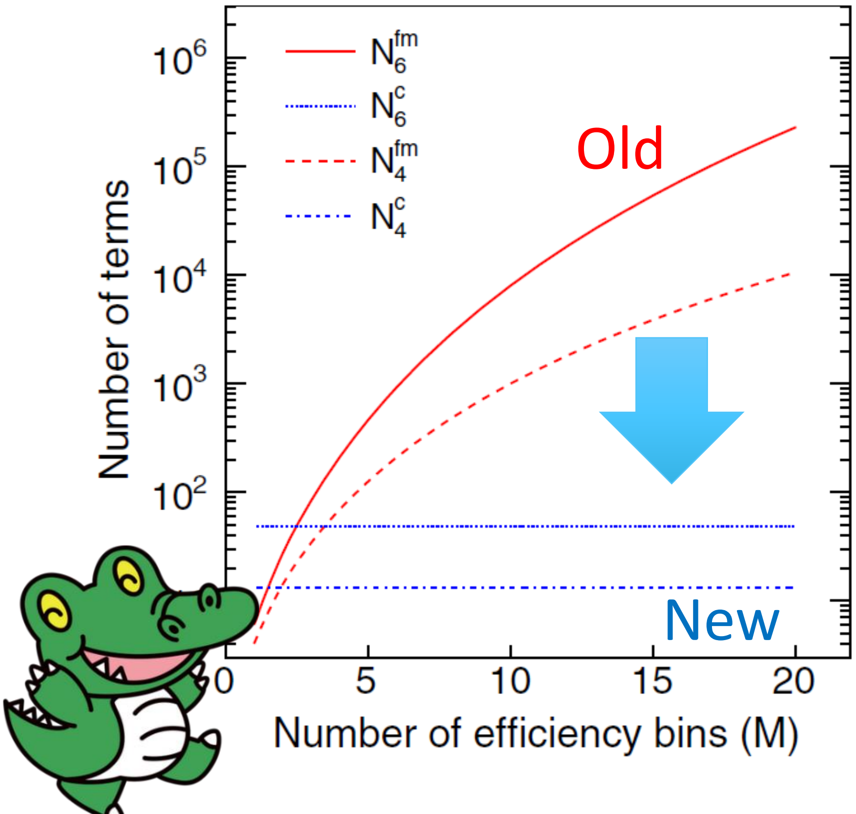
➡ **手計算シンプル、かつ低数値コスト**

大阪大学公式キャラクター
「ワニ博士」

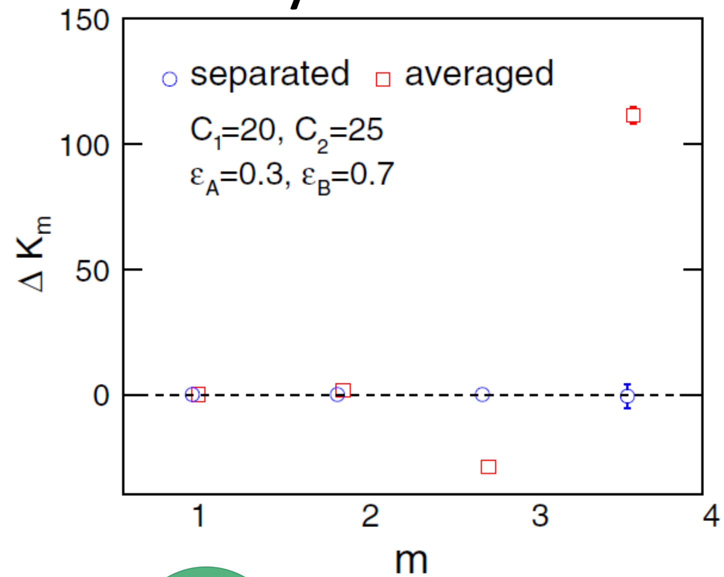
More Efficient Formulas

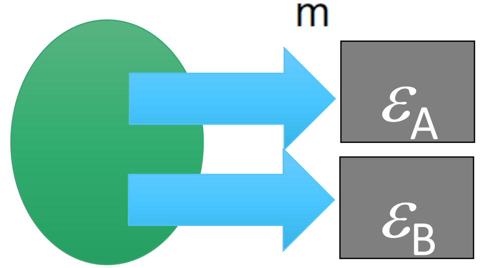
Nonaka, Esumi, MK, 2017

Numerical Cost



A Toy Model Test





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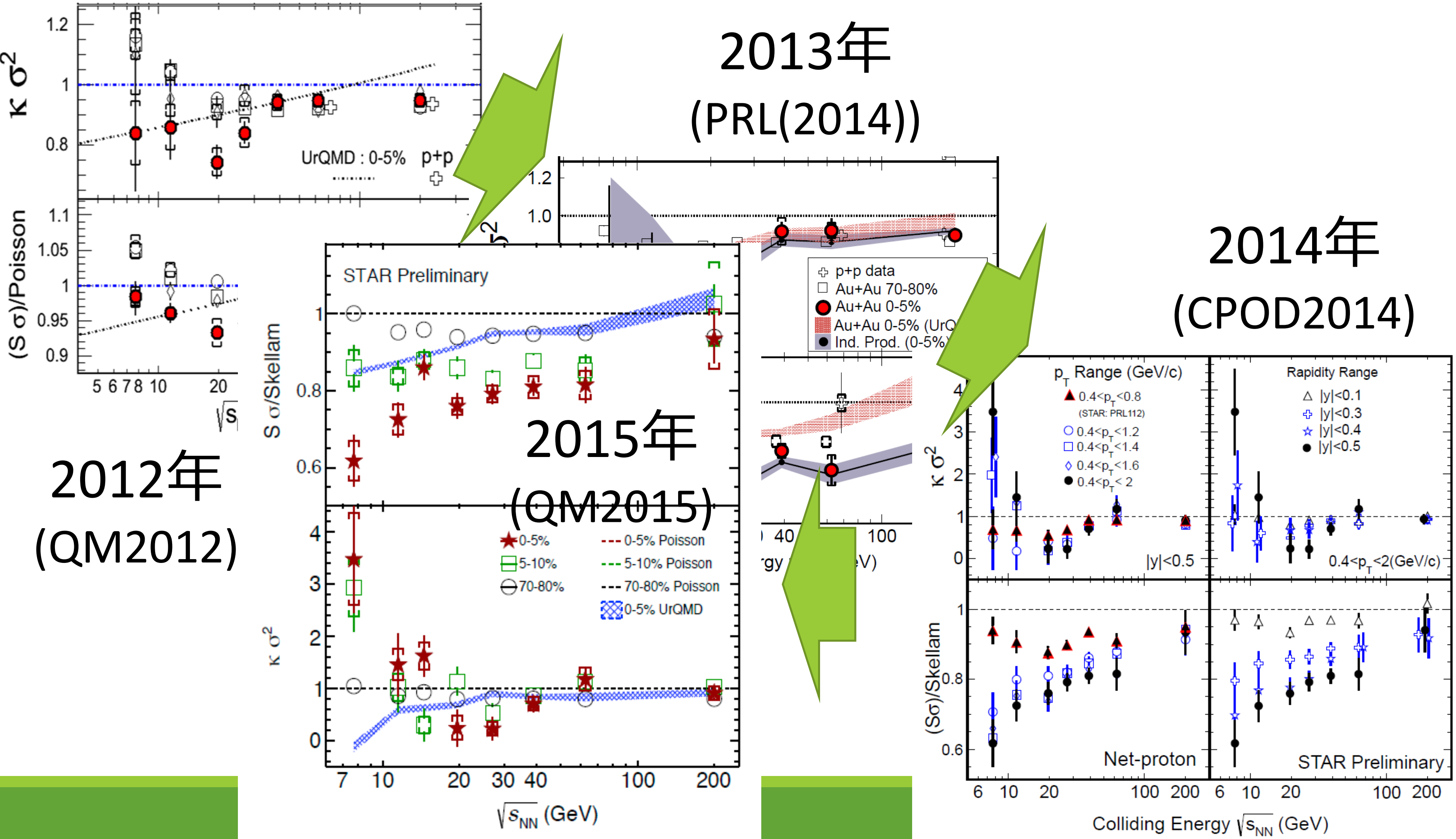
4th Order Cumulant: History



2012年
(QM2012)

2013年
(PRL(2014))

2014年
(CPOD2014)

2015年
(QM2015)

Proton v.s. Baryon Number Cumulants

MK, Asakawa, 2012; 2012

Experiments

proton number cumulants

$$\langle N_p^n \rangle_c$$

Many theories

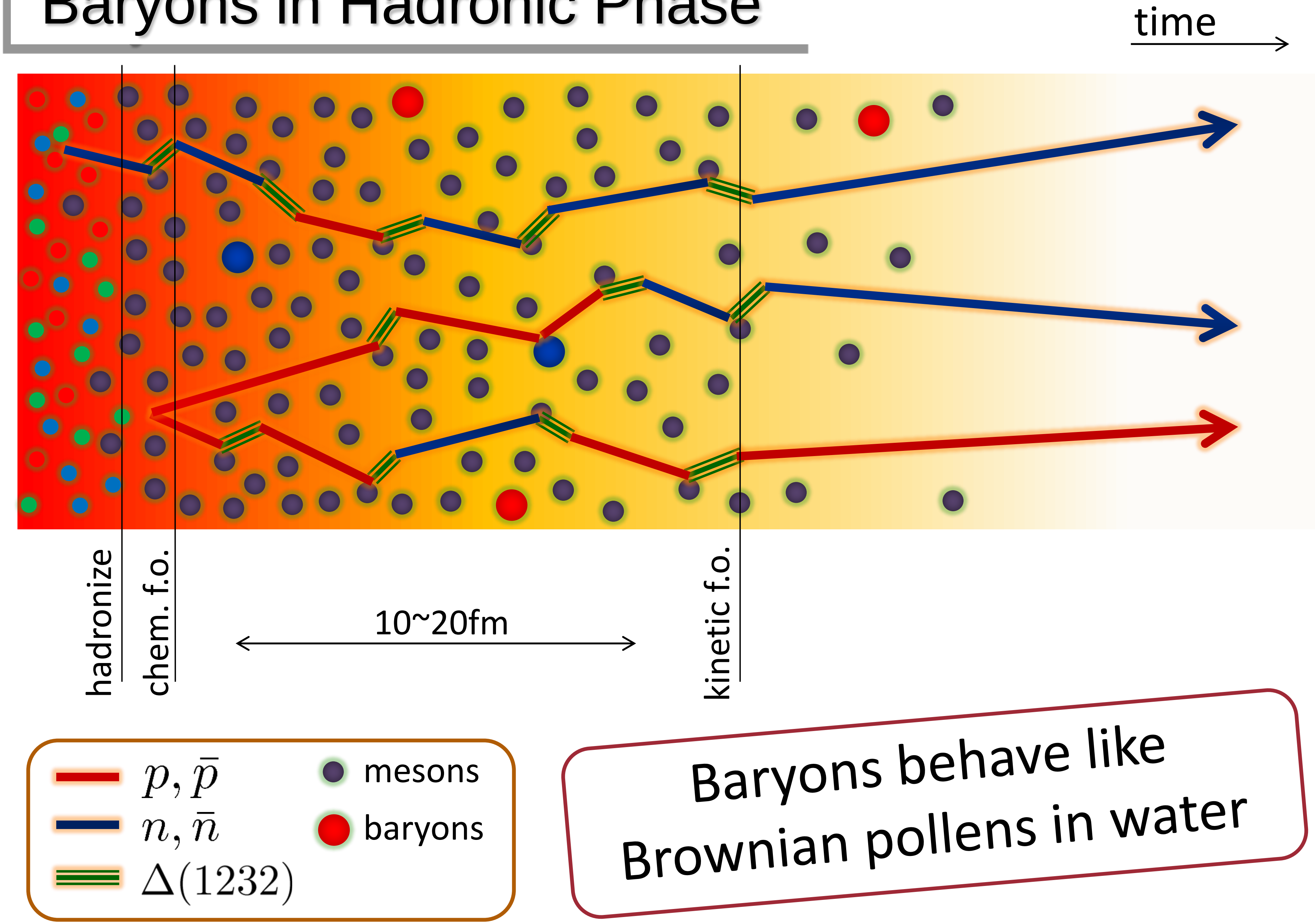
baryon number cumulants

$$\langle N_B^n \rangle_c$$

measurement with 50% efficiency loss

- The difference would be large.
- Reconstruction of $\langle N_B^n \rangle_c$ is possible using the binomial model.
- The use of binomial model is justified by "isospin randomization."

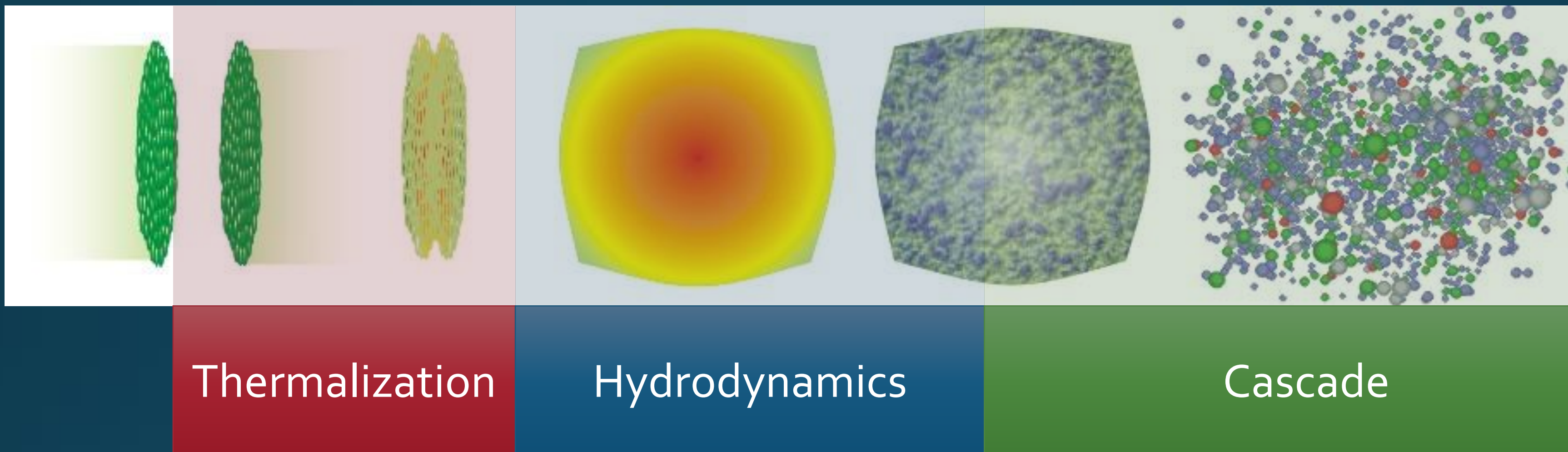
Baryons in Hadronic Phase



Baryons behave like Brownian pollens in water

Constructing Dynamical Model for Low-E Collisions

Theoretical Challenges



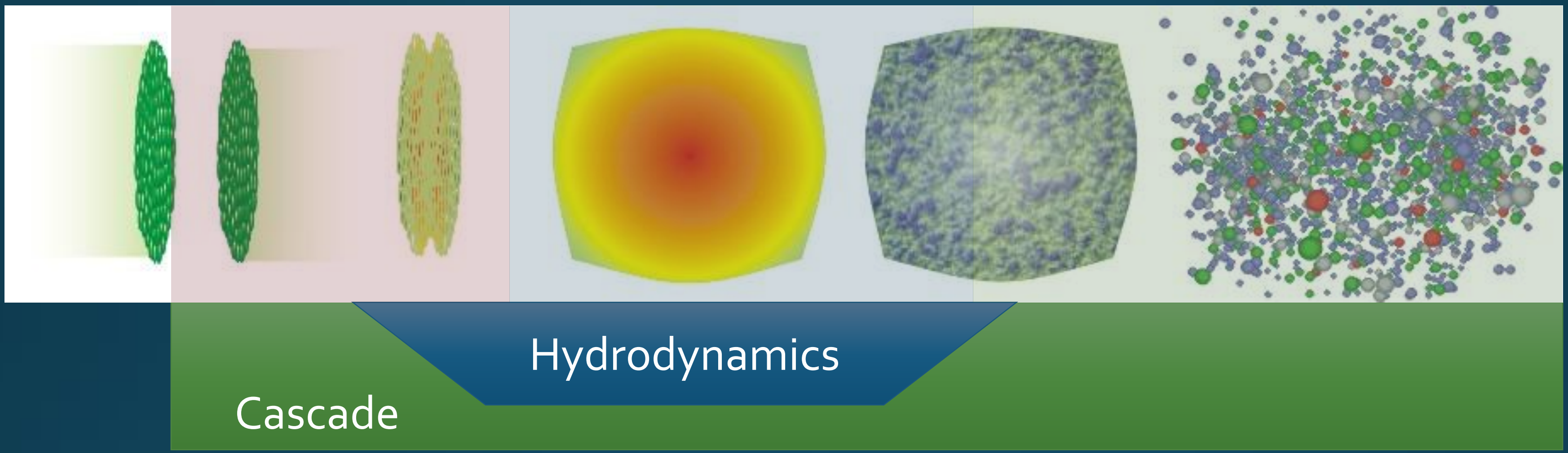
RHIC / LHC

- hydro. for QGP
- early thermalization
- (boost invariance)

Low-E Collisions

- Initial condition?
- Thresholod of QGP formation
- “Integrated” approach
  - Hydro x Cascade

Theoretical Challenges



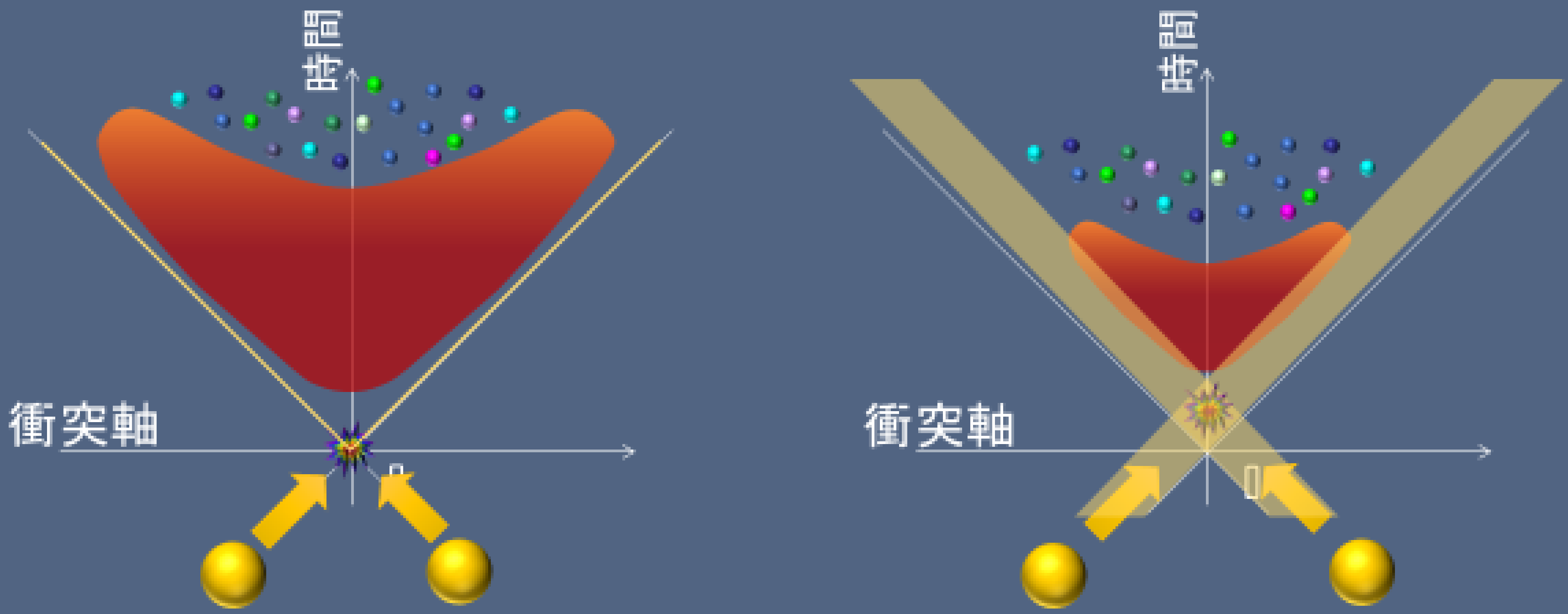
RHIC / LHC

- ☐ hydro. for QGP
- ☐ early thermalization
- ☐ (boost invariance)

Low-E Collisions

- ☐ Initial condition?
- ☐ Thresholod of QGP formation
- ☐ "Integrated" approach
  - Hydro x Cascade

オーバーラップ時間の影響

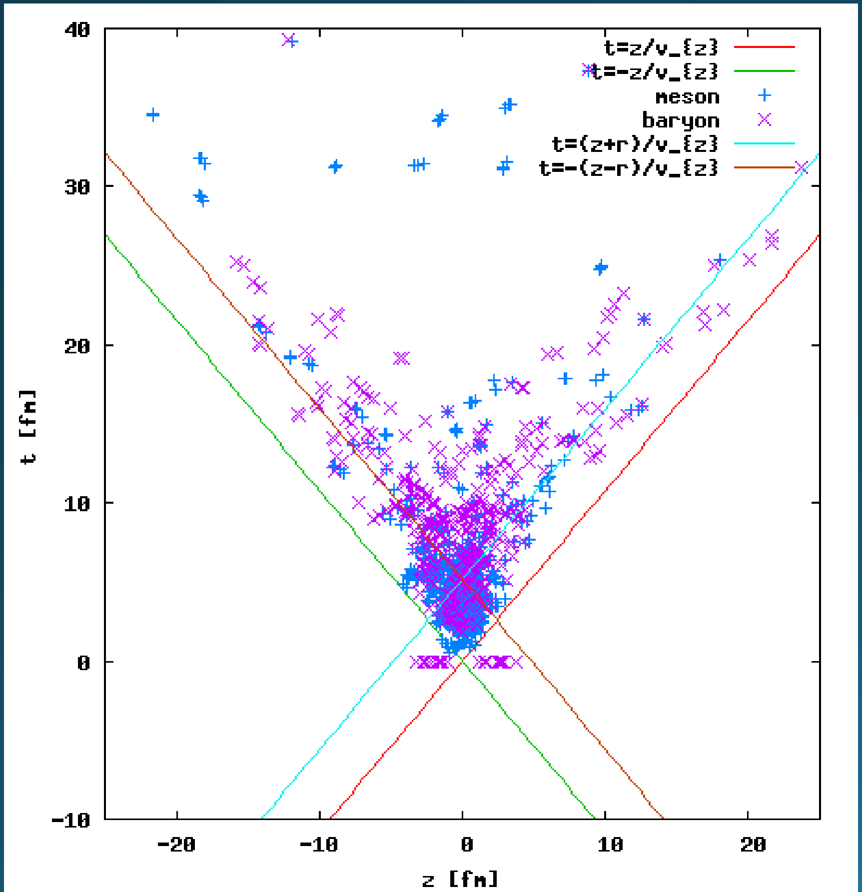


超高エネルギー重イオン衝突　　"高"エネルギー重イオン衝突

Slide from T. Hirano, 2017/9/10, informal meeting

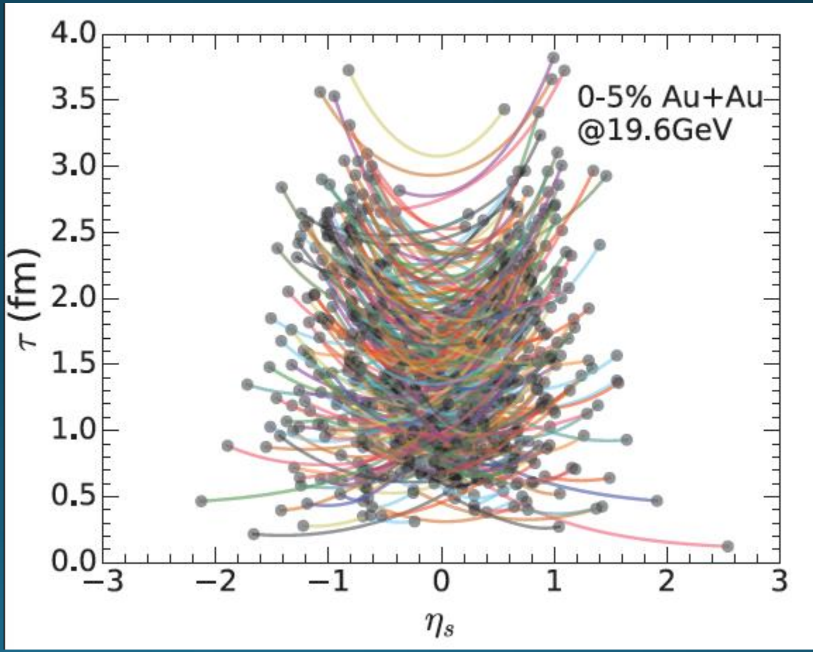
How to Create Initial Condition

Last collision point of hadrons (without BM/MM interaction)

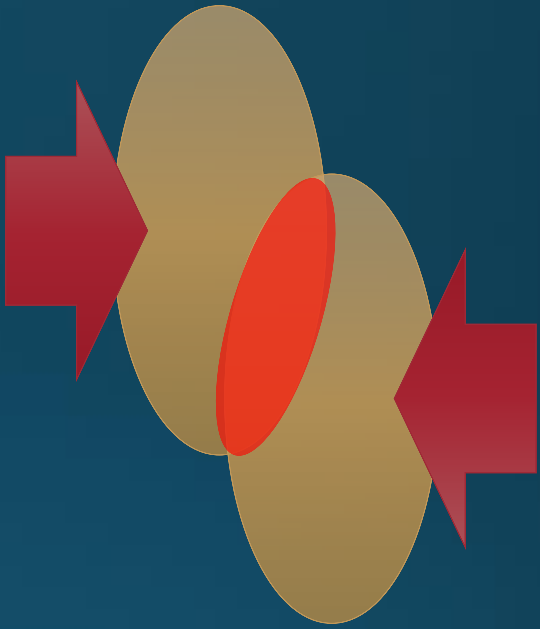


A dynamical initialization

Shen, Shenke, 1711.10544

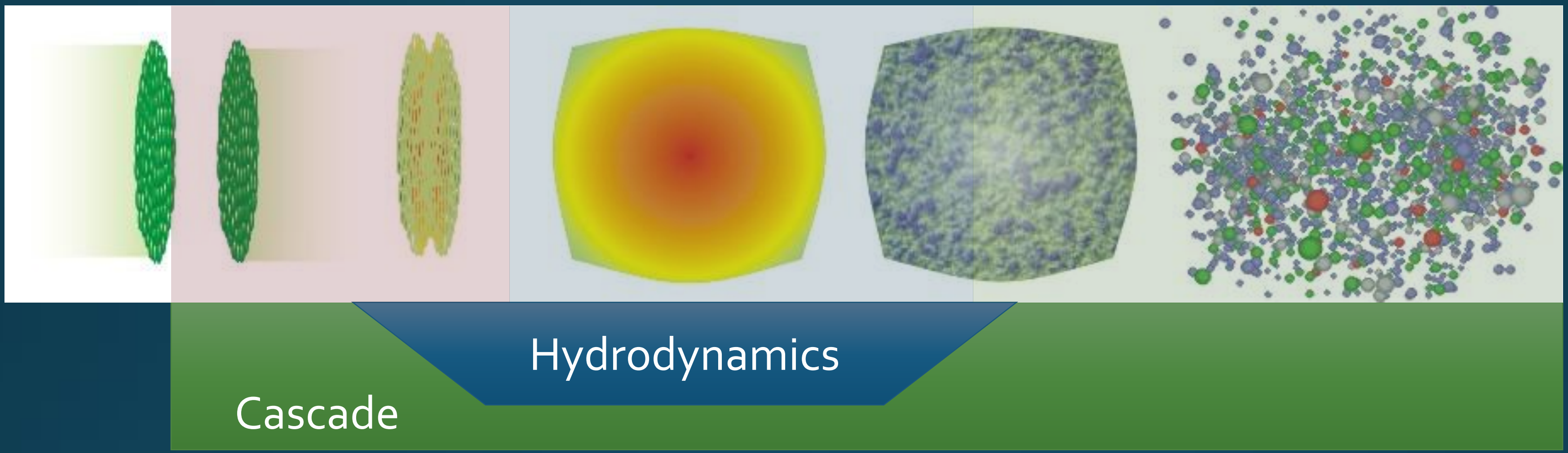


Modelling Low-E Collisions



- Controlling EOS by changing interaction in cascade
  JAM/ Nara, Ohnishi, Stoecker, 2016-
- cascade + hydro + cascade
  UrQMD/ Petersen; Steinheimer
  Karpenko+, 2016-
- 3-fluid dynamics
  THESEUS/ Blaschke, Ivanov, +, 2016
- PHSD + chiral restoration Cassing+, 2016; Palmese+, 2016
- Dynamical Initialization Shen, Shenke, Monnai, Heinz, 2017-
- Chiral fluid Dumitru+; Nahrgang+, 2014-; Song+, 2016-

Project for An Integrated Model



JAM+hydro(Nagoya) + realistic EoS(QCD-CP??)

discussion by
Akamatsu, Asakawa, Hirano, Kitazawa, Morita, Nara, Nonaka, Ohnishi
from 2016 Summer

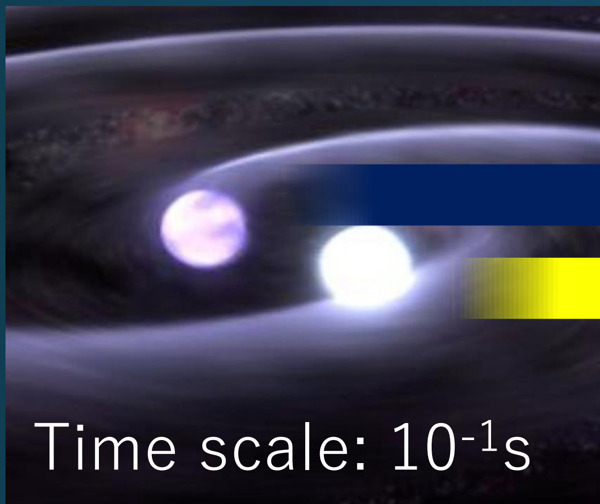
今年度の活動

- 2017/9/10
  - インフォーマルミーティング「動的模型開発」「J-PARC-HI」@KEK東海キャンパス
- 2017/9/11
  - 研究会「J-PARCエネルギー領域重イオン衝突実験のダイナミクス」@KEK東海キャンパス
- 2017/12/15
  - J-PARC-HIインフォーマルミーティング@茨城量子ビーム研究セ

Summary

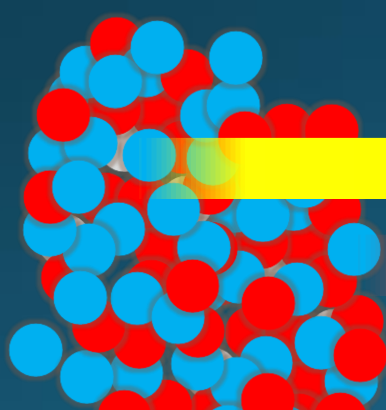
- BES is one of the hot topics in HIC.
- J-PARC-HI will play an important role in exploring QCD phase structure.
- Searches for QCD-CP / 1st tr. are ongoing.
- Fluctuations are important observables.
- Description of low-E collisions is a theoretically-challenging subject.

Lepton & Photon: Hierarchical Observation



gravitational wave

photons



EM probes

hadronic observables

time scale: 10^{-22}s

di-lepton yield