Prospects of Investigating Proton Number Fluctuations at SIS18

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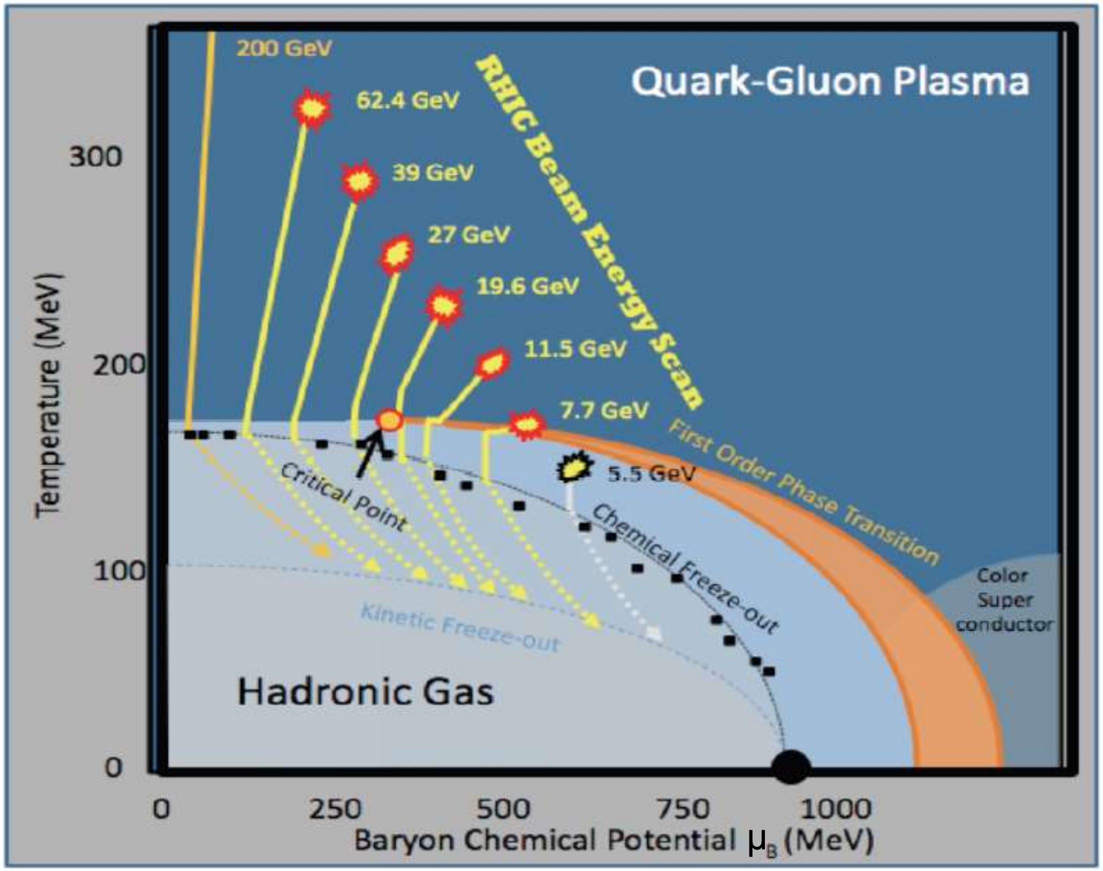
for the HADES collaboration

- Baryon number flucts. in the few-GeV regime
- The HADES experiment at SIS18
- Experimental artifacts
- Outlook: Linking up with the RHIC BES

Is there a CP in the QCD phase diagram?

Lattice QCD calculations: cross-over at low μ_B, 1st-order transition at high μ_B



CP search at RHIC:

Beam energy scan (BES) using Au+Au collisions with $\sqrt{s_{NN}} = 7.7 - 62\ GeV$

Observables sensitive to CP:

- particle nb. flucts.
- particle ratio flucts. (v_{dyn})
- mean pt flucts.

➔ focus on fluctuations of conserved quantities

- net baryon number
- net charge
- net strangeness

Net proton nb. fluctuations: $\delta(\Delta N_p)$

Net number of protons: $\Delta N_p = N_p - N_{\bar{p}}$

- $\delta(\Delta N_p)$ used as estimate of net baryon nb. fluctuations
- justified for $\sqrt{s} \geq 10\ GeV$ Kitazawa & Asakawa, PRC 86, 024904 (2012)
- baryon nb. is conserved quantity ➔ fluctuations in y-p_t bin
- likewise for net charge & net strangeness fluctuations

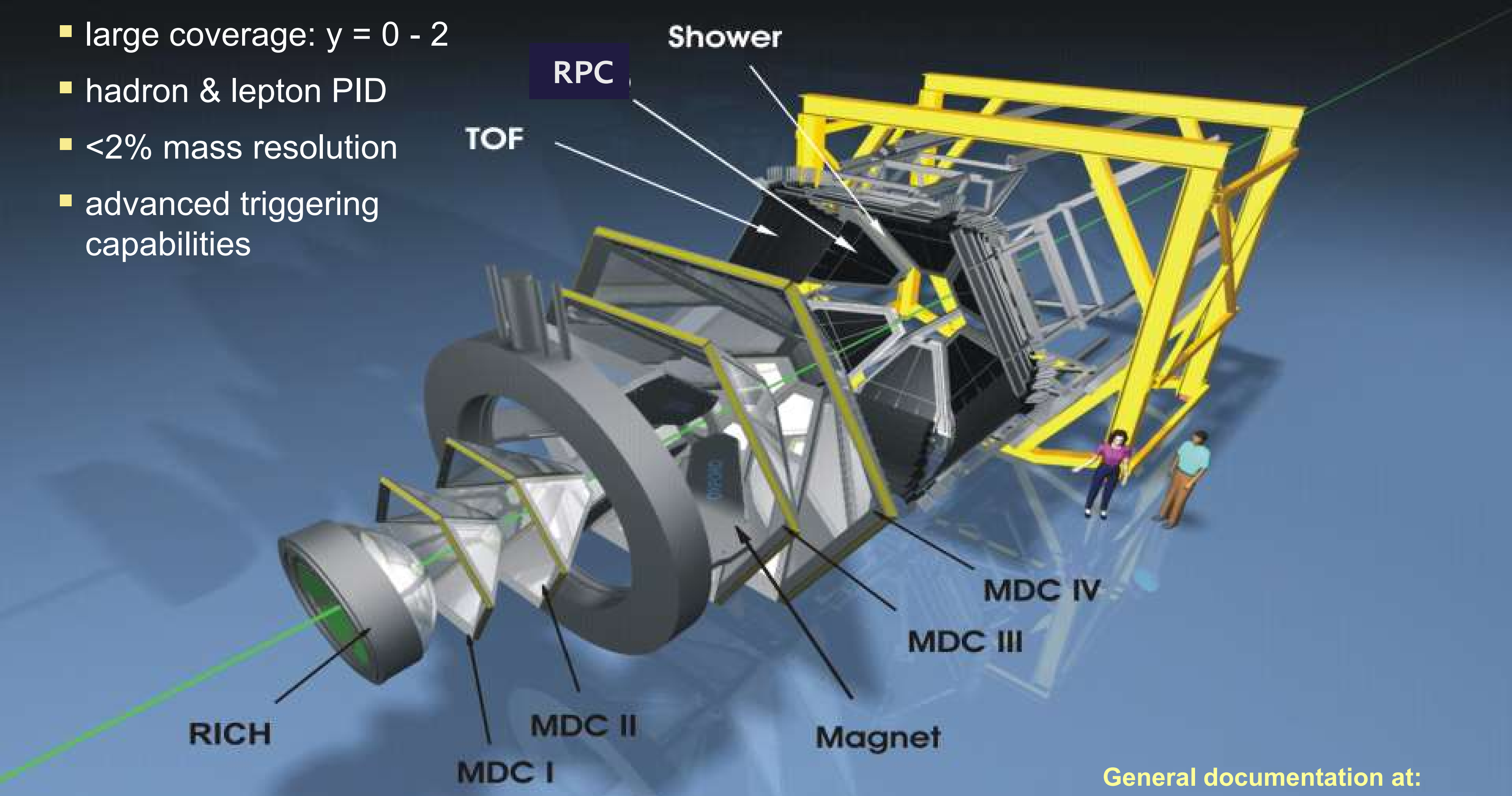
- At **SIS18**: - fixed target expt. ($\sqrt{s} \leq 2.7\ GeV$)
  - what about fragments (d, t, He, etc.) ?
  - what about neutrons ?

➔ Here focus is on proton nb. fluctuations $\boldsymbol{\delta(N_p)}$

The HADES experiment at GSI

High Acceptance DiElectron Spectrometer

- azimuth. symmetry
- large coverage: y = 0 - 2
- hadron & lepton PID
- <2% mass resolution
- advanced triggering capabilities



General documentation at:
http://www-hades.gsi.de

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HADES

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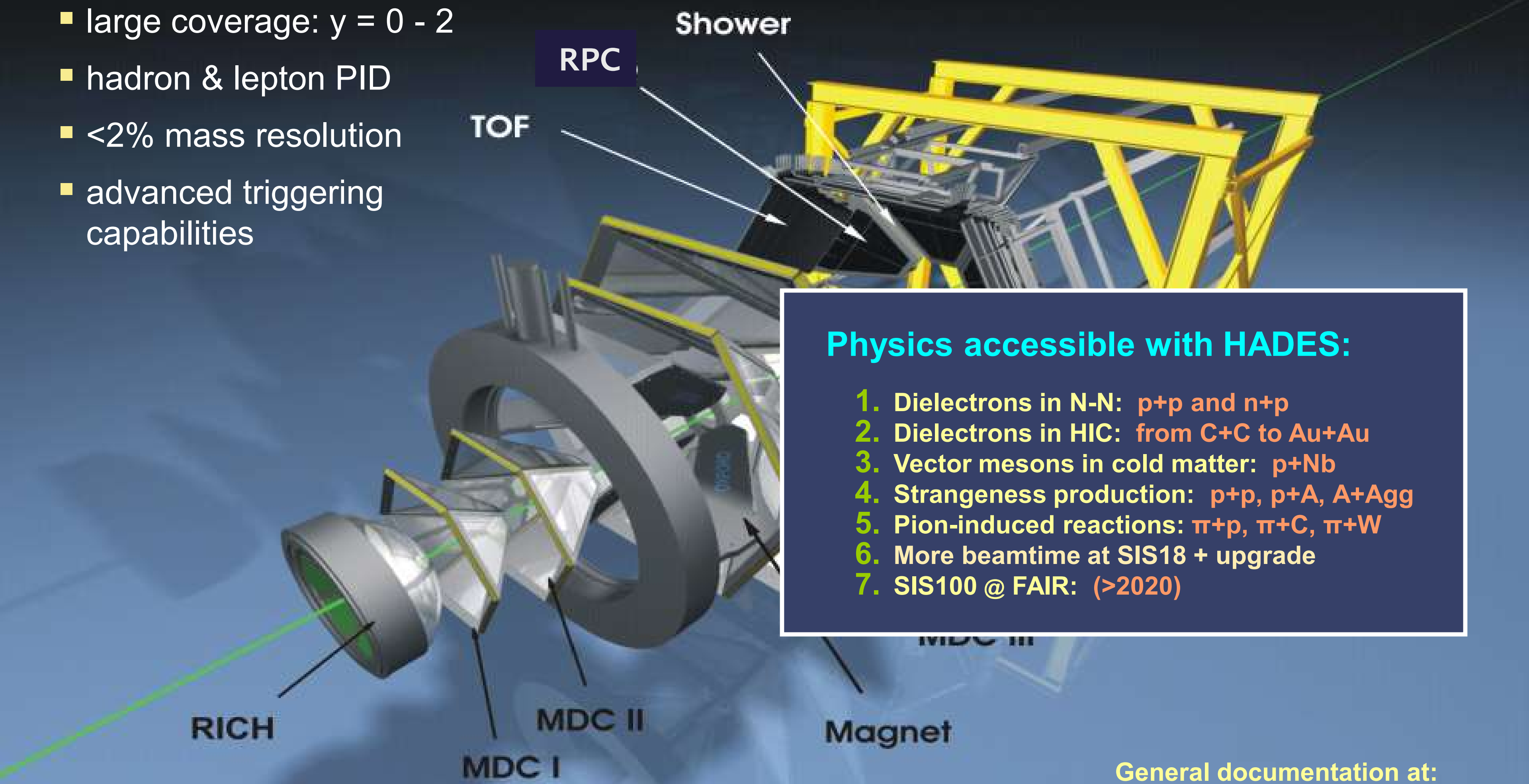
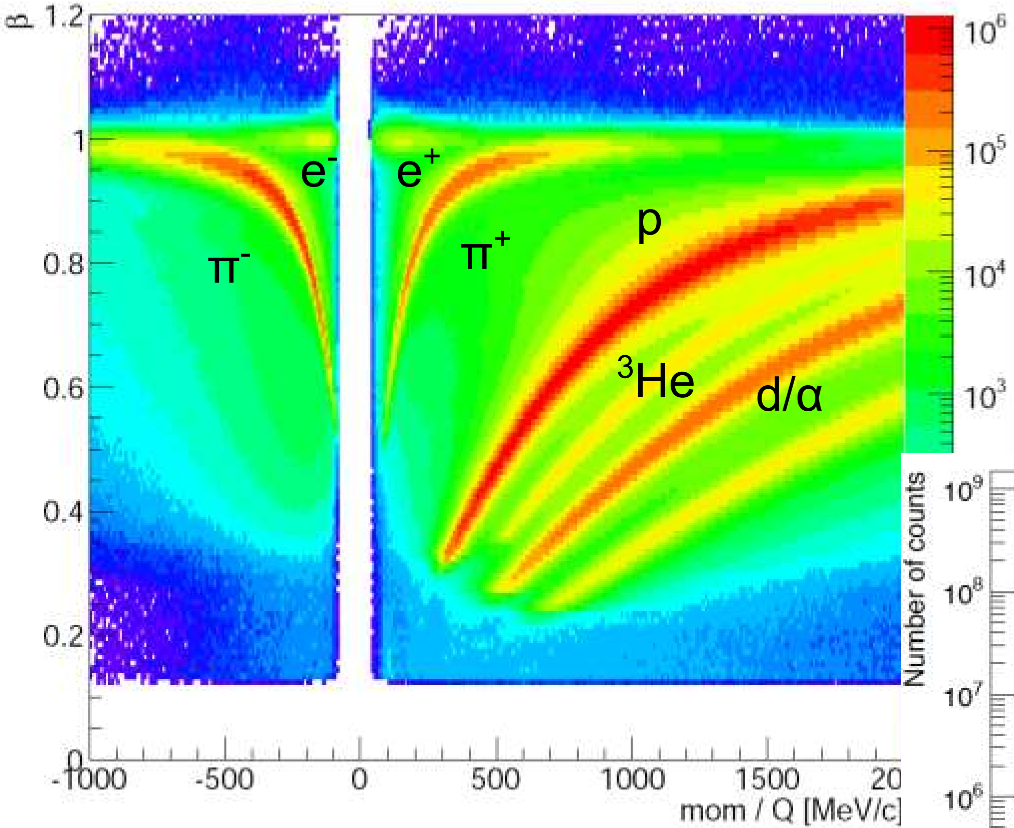


Physics accessible with HADES:

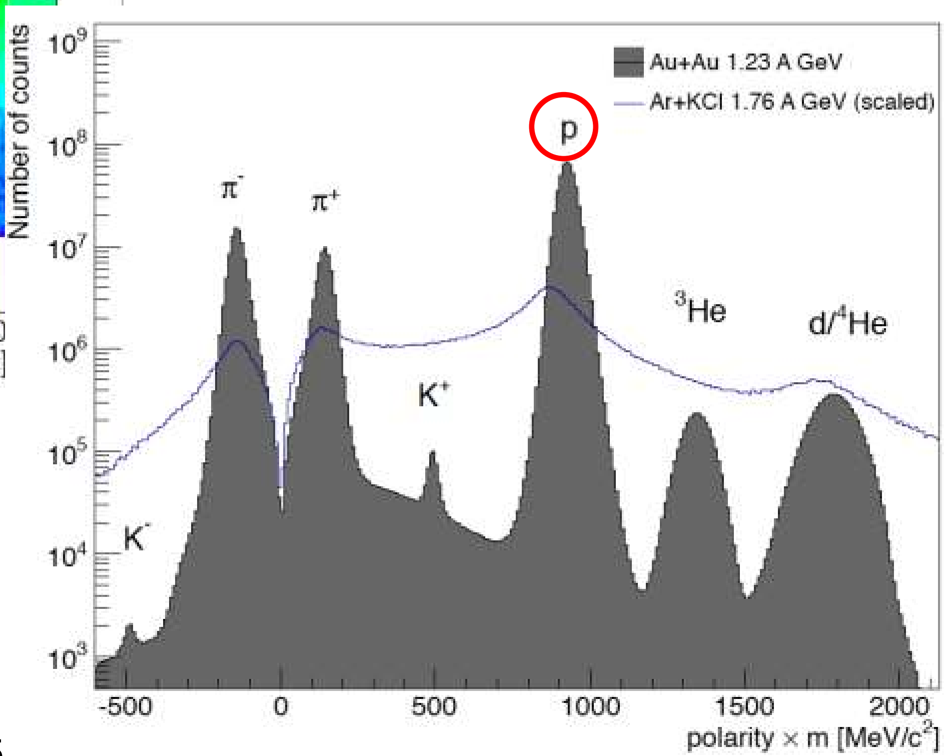
1. **Dielectrons in N-N: p+p and n+p**
2. **Dielectrons in HIC: from C+C to Au+Au**
3. **Vector mesons in cold matter: p+Nb**
4. **Strangeness production: p+p, p+A, A+Agg**
5. **Pion-induced reactions: π+p, π+C, π+W**
6. **More beamtime at SIS18 + upgrade**
7. **SIS100 @ FAIR: (>2020)**

General documentation at:
http://www-hades.gsi.de

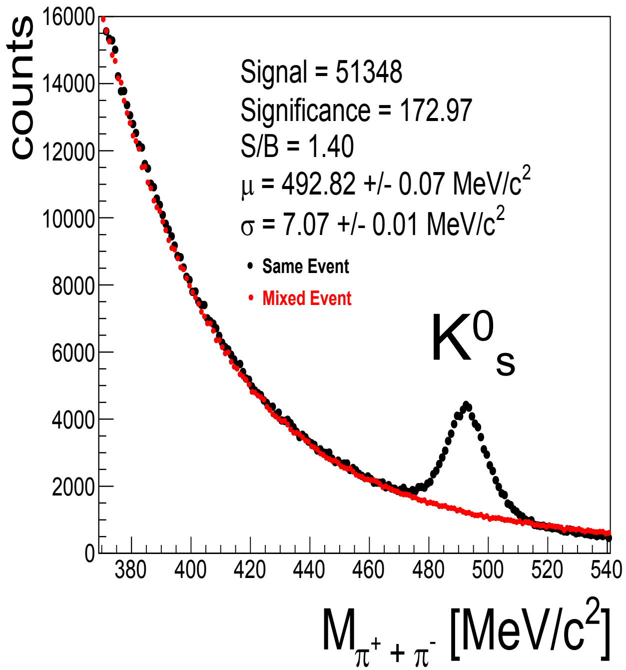
Performance: particle ID

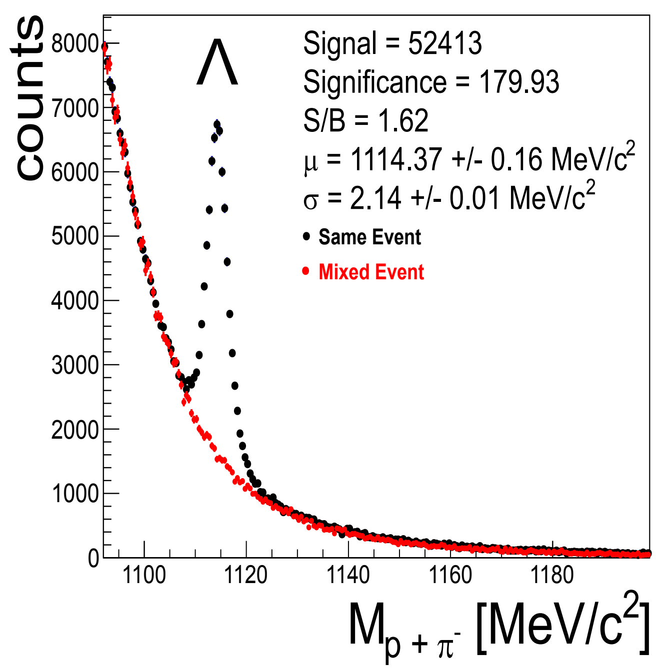


- good pid
- large stat
- good evt vertex

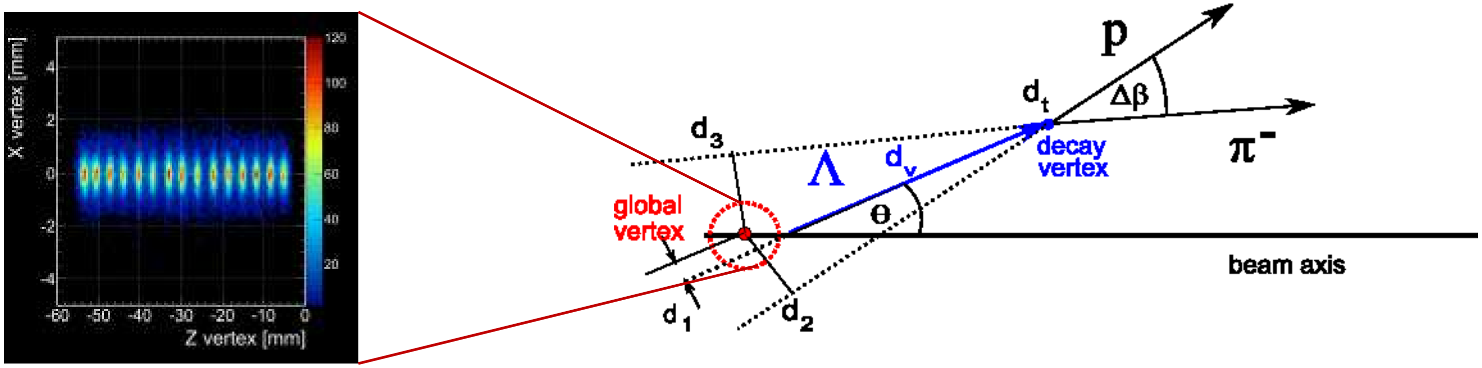


Performance: weak decays





event vertex



Determining the event plane

HADES

1.) P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985)

Use transverse momentum vectors to approximate event-wise the reaction plane:

$$\mathbf{Q_1} = \sum_{j=1}^{N} w_j \mathbf{u}_j$$

weight:
>0 at forward y
<0 at backward y

2.) S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996)

Azimuthally anisotropic emission pattern described by Fourier expansion:

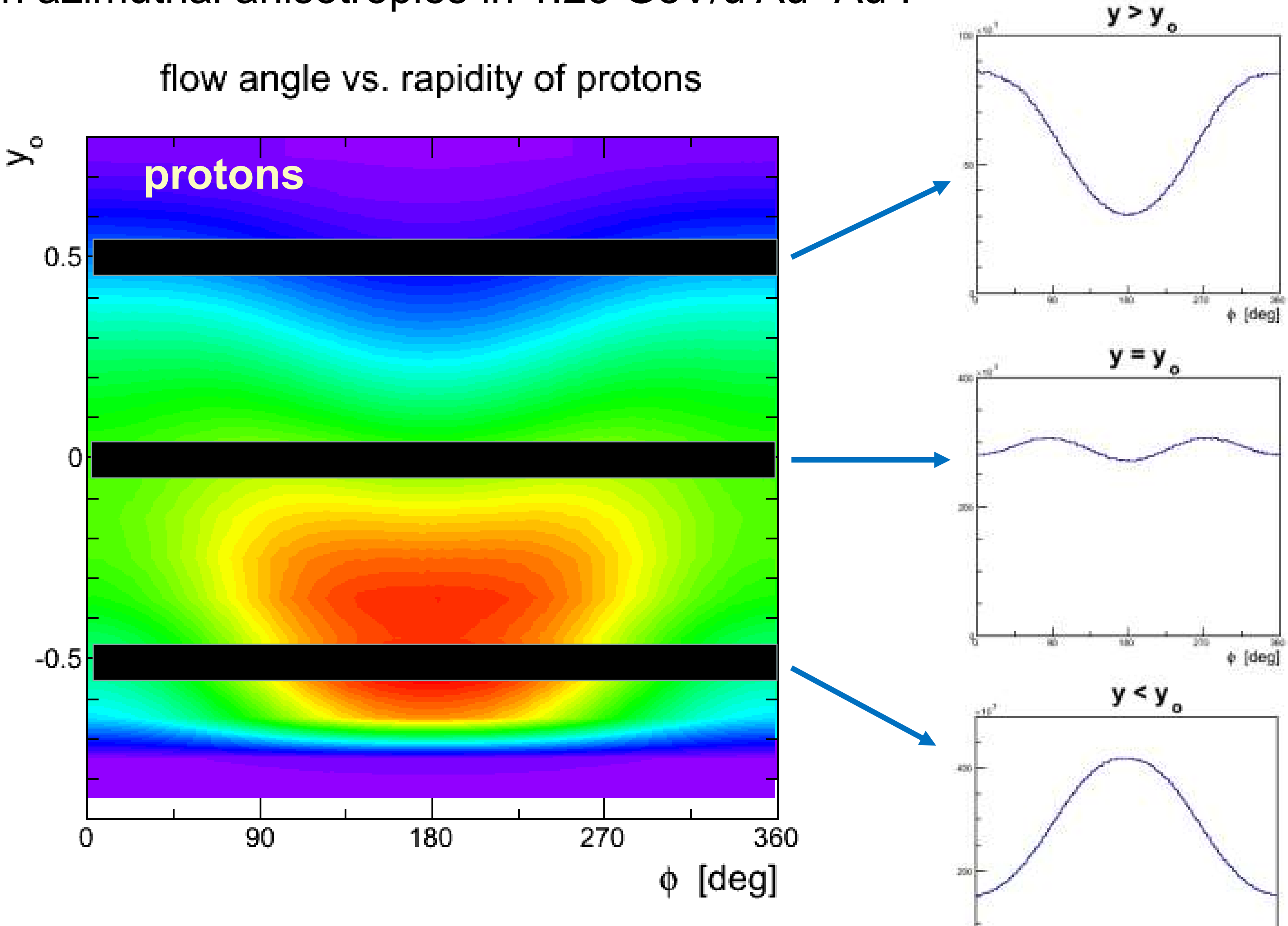
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_R\right)\right]\right)$$

Where Ψ_R is determined event-by-event from ALL tracks or

➔ use Forward Wall hits to determine EP 🡐

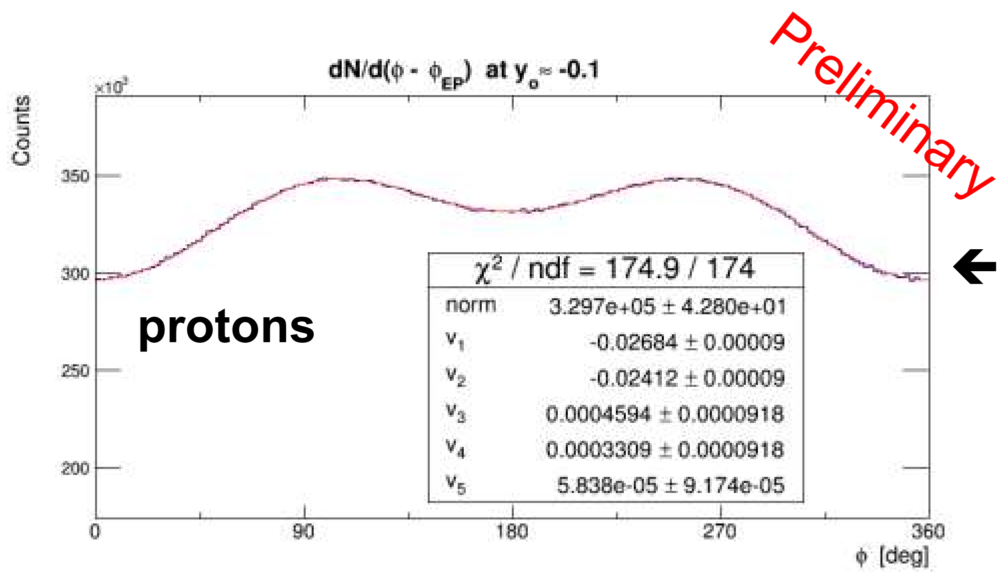
A taste of HADES data: proton flow

Proton azimuthal anisotropies in 1.23 GeV/u Au+Au :



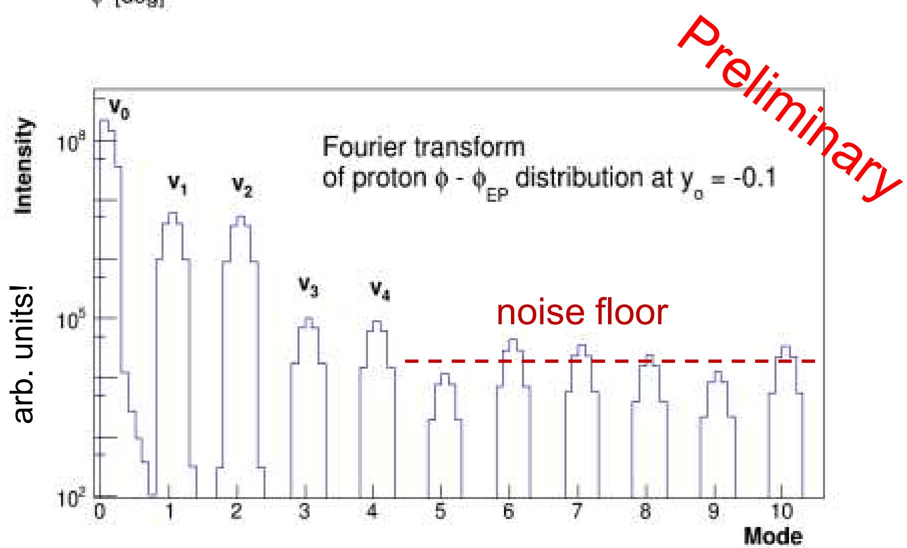
$$\phi = \phi_p - \phi_{FW}$$

Fourier analysis of $dN/d\phi$



← Fit delivers v_n and stat errors up to v_4

Alternatively, a Fourier transform gives the full mode spectrum →



Our sandbox: the Poisson distribution

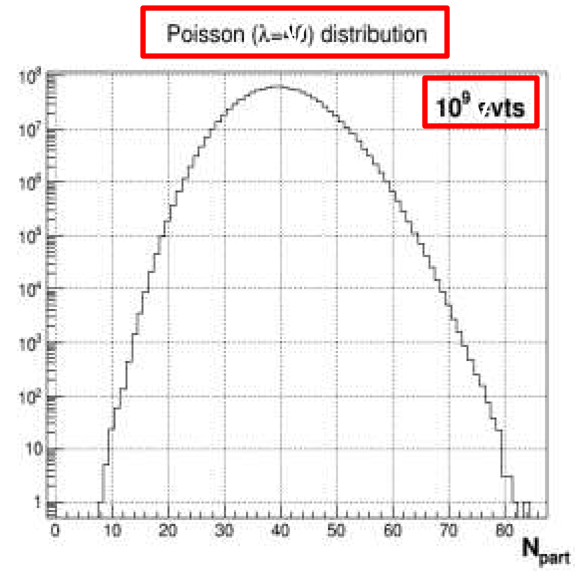
Reminder: for Poisson $P(\lambda)$ we have:

- mean $\mu = \lambda$
- width $\sigma = \sqrt{\lambda}$
- skewness $\mathbf{Sk} = \frac{1}{\sqrt{\lambda}}$
- kurtosis $\kappa = 1/\lambda$

More generally: all cumulants $c_n = \lambda$

It follows that $\frac{c_n}{c_2} = 1$, in particular:

→ $\omega = \frac{\sigma^2}{\mu} = 1, \quad \mathbf{Sk} \times \sigma = 1, \quad \kappa \times \sigma^2 = 1$




```
Mean      = 40     ± 0.0002
Sigma     = 6.3245 ± 0.0002
Skewness  = 0.1580 ± 0.0002
Kurtosis  = 0.0251 ± 0.0002

Omega        = 1.00000 ± 0.00004
Skew * Sig   = 0.9991  ± 0.0005
Kurt * Sig2  = 1.003   ± 0.007
c5/c2        = 0.99    ± 0.11
```

ok!

Data need efficiency corrections

Efficiency = acc x det. eff x rec. eff

1. Correct measured distributions (bayesian unfolding)

   Garg et al., J. Phys. G: Nucl. Part. Phys. 40 (2013)

2. Correct the moments

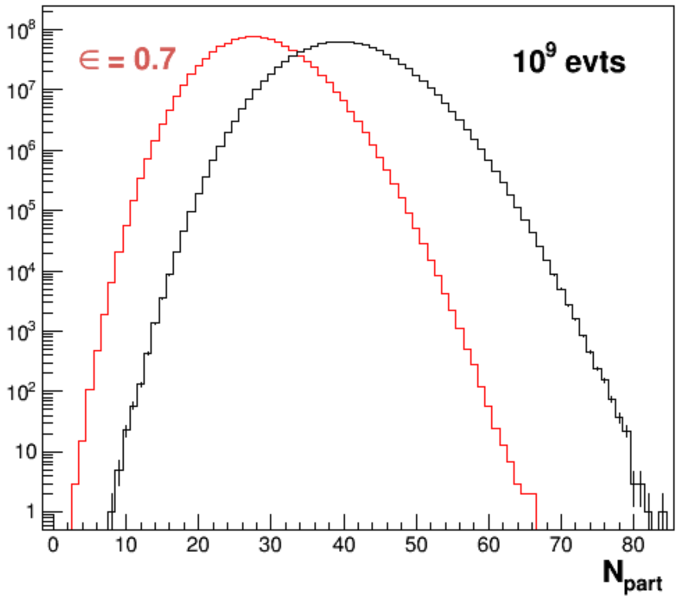
   Bzdak & Koch, PRC 86 (2012); Xiaofeng, arXiv:1410.3914

   ➔ used by STAR

Experimental bias: Efficiency

With efficiency = **0.7**

Poisson (λ=40) x Binomial (p=0.7) distribution



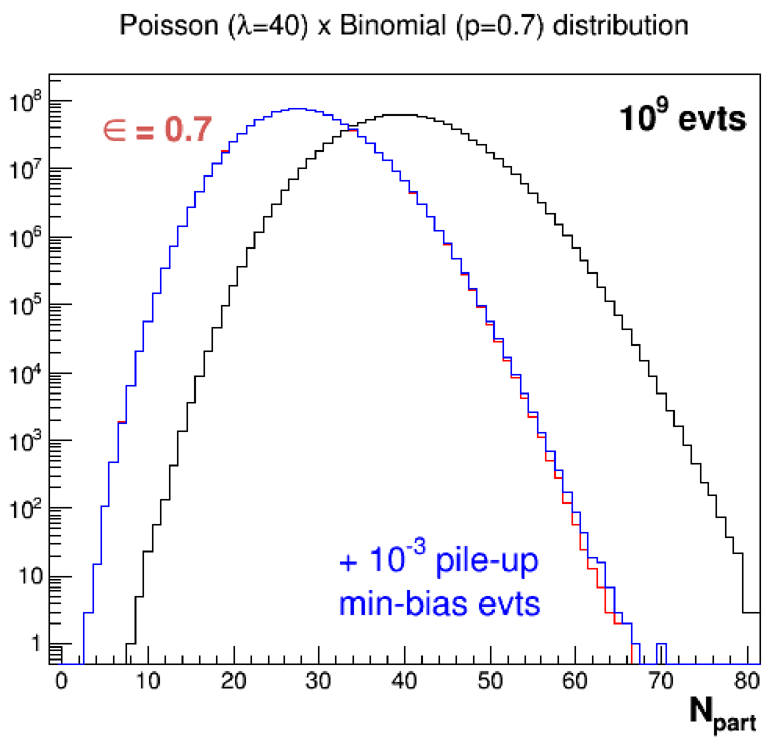

```
Mean     = 28     ± 0.0002
Sigma    = 5.2915 ± 0.0001
Skewness = 0.1889 ± 0.0001
Kurtosis = 0.0358 ± 0.0002

Omega        = 0.99998 ± 0.00004
Skew * Sig   = 0.9993  ± 0.0004
Kurt * Sig2  = 1.002   ± 0.005
c5/c2        = 1.08    ± 0.07
```

Using the Bzdak-Koch correction procedure:

```
Mean     = 40     ± 0.0002
Sigma    = 6.3248 ± 0.0002
Skewness = 0.1585 ± 0.0001
Kurtosis = 0.0255 ± 0.0003

Omega        = 1.00009 ± 0.00006
Skew * Sig   = 1.0022  ± 0.0008
Kurt * Sig2  = 1.019   ± 0.014
c5/c2        = 1.05    ± 0.25
```

ok, but errors increase!

Experimental bias: Event pile-up



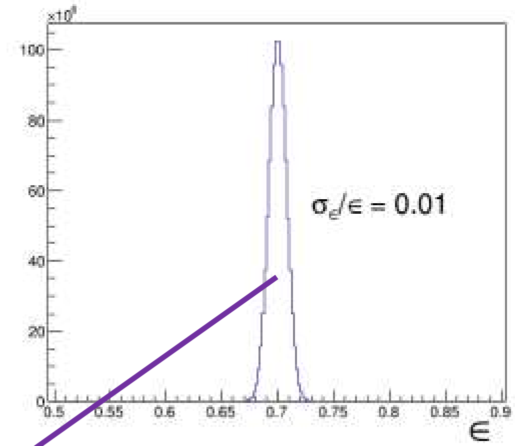
central event is overlayed with random i.e. min-bias event at 10^{-3} level:

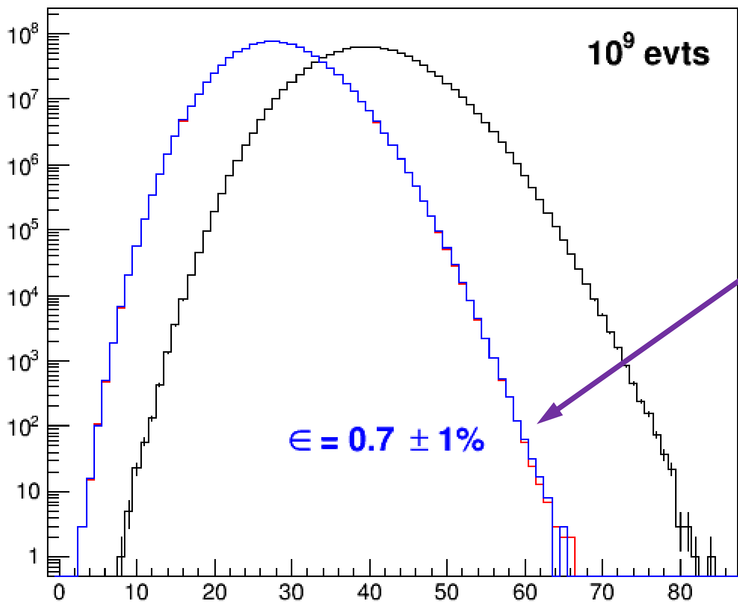
```
Mean     = 40.01  ± 0.0002
Sigma    = 6.3332 ± 0.0002
Skewness = 0.1627 ± 0.0002
Kurtosis = 0.0358 ± 0.0004

Omega        = 1.00249 ± 0.00006
Skew * Sig   = 1.0303  ± 0.0009
Kurt * Sig2  = 1.435   ± 0.014
c5/c2        = 6.51    ± 0.26
```

higher cumulants are affected!

Evt-by-Evt efficiency changes (I)

<u>Scenario 1:</u> Apply random changes of ε in event generator, but correct with mean <ε> = 0.7



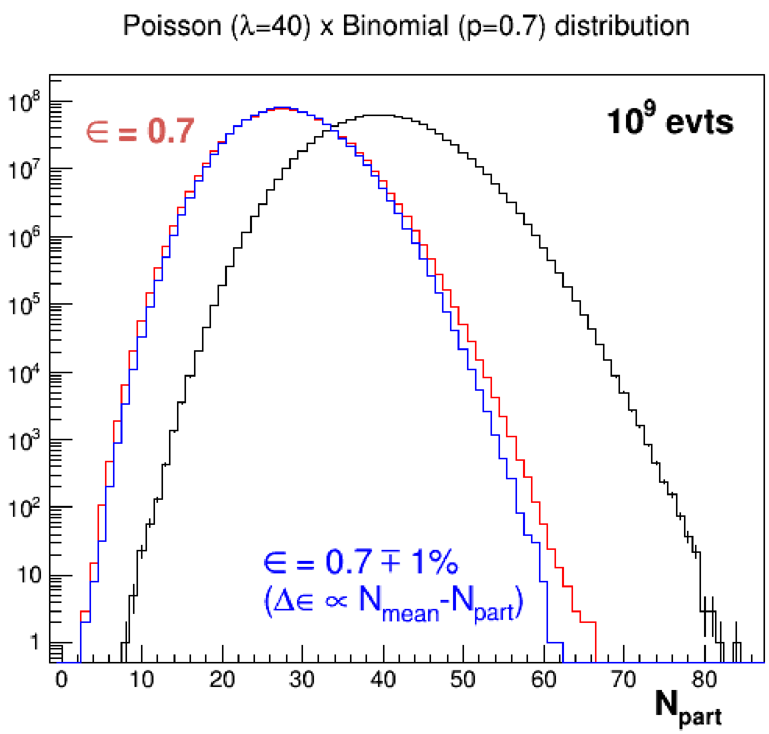



```
Mean     = 40     ± 0.0002
Sigma    = 6.3398 ± 0.0002
Skewness = 0.1592 ± 0.0002
Kurtosis = 0.0258 ± 0.0002

Omega       = 1.0050 ± 0.00006
Skew * Sig  = 1.0091 ± 0.0008
Kurt * Sig2 = 1.036  ± 0.014
c5/c2       = 0.93   ± 0.25
```

slight broadening!

Evt-by-Evt efficiency changes (II)

Scenario 2: Correlated changes of ε with track density: ±1% variation correct with mean <ε>

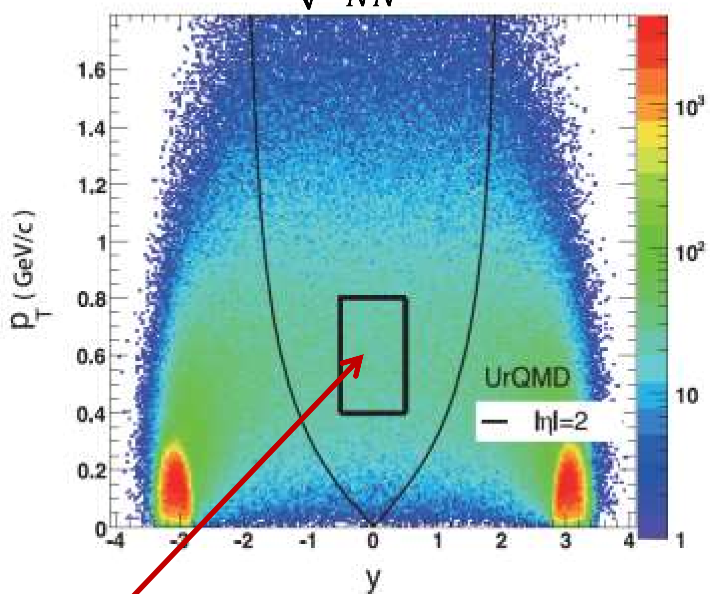



```
Mean      = 39.93   ± 0.0002
Sigma     = 5.8742  ± 0.0002
Skewness  = 0.1223  ± 0.0002
Kurtosis  = 0.0082  ± 0.0004

Omega        = 0.86424 ± 0.00006
Skew * Sig   = 0.7185  ± 0.0008
Kurt * Sig2  = 0.283   ± 0.012
c5/c2        = -0.08   ± 0.21
```

➔ All hell breaks loose !!!

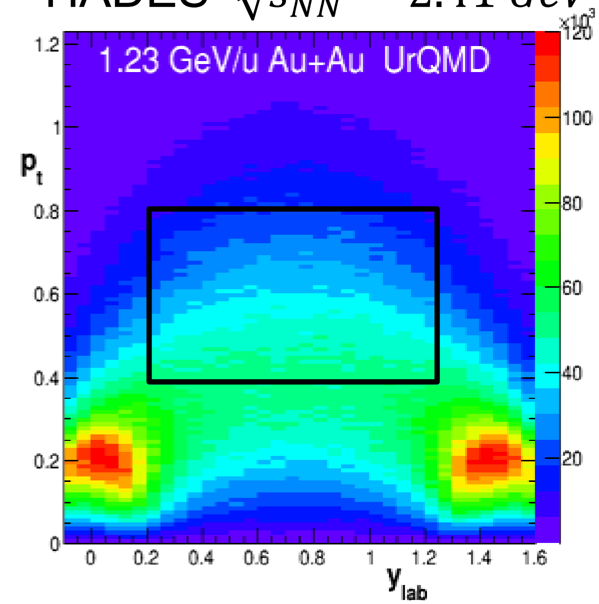
Which phase-space bite to use?

STAR $\sqrt{s_{NN}} = 19.6\ GeV$



rapidity gap = 6 units!

HADES $\sqrt{s_{NN}} = 2.41\ GeV$



rapidity gap = 1.5 units!

STAR phase space bin: $y = y_o \pm 0.5$

$p_t = 0.4 - 0.8\ GeV/c$

$(p_t = 0.4 - 2.0\ GeV/c)$

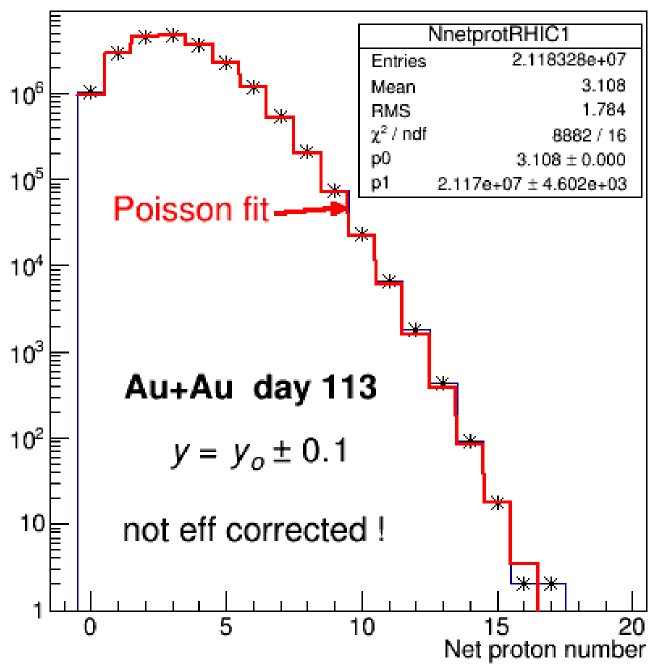
➔ Need to reduce the y bite:

$\pm 0.5 \ \rightarrow\ \leq \pm 0.25$

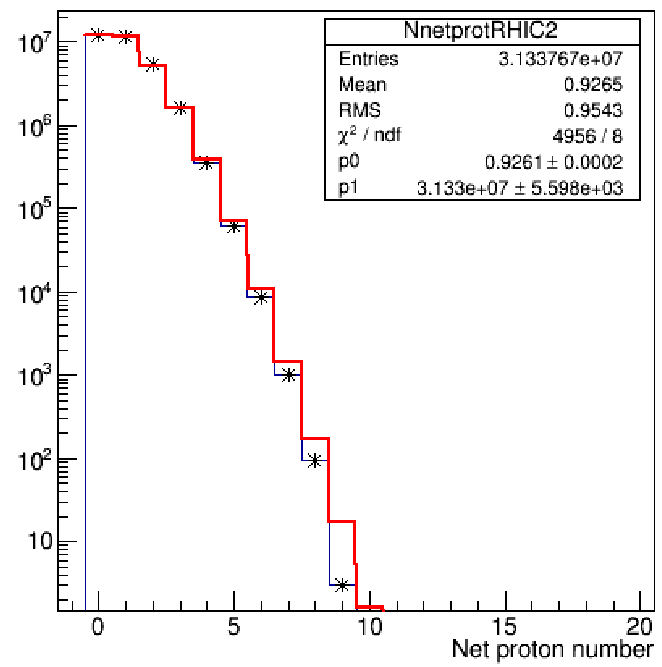
A look at HADES data: Au+Au 1.23 GeV/u

2 different centrality cuts, $y = y_o \pm 0.1,\ p_t = 0.4 - 0.8\ GeV/c$

net proton number (RHIC cuts, 0%-5% central)



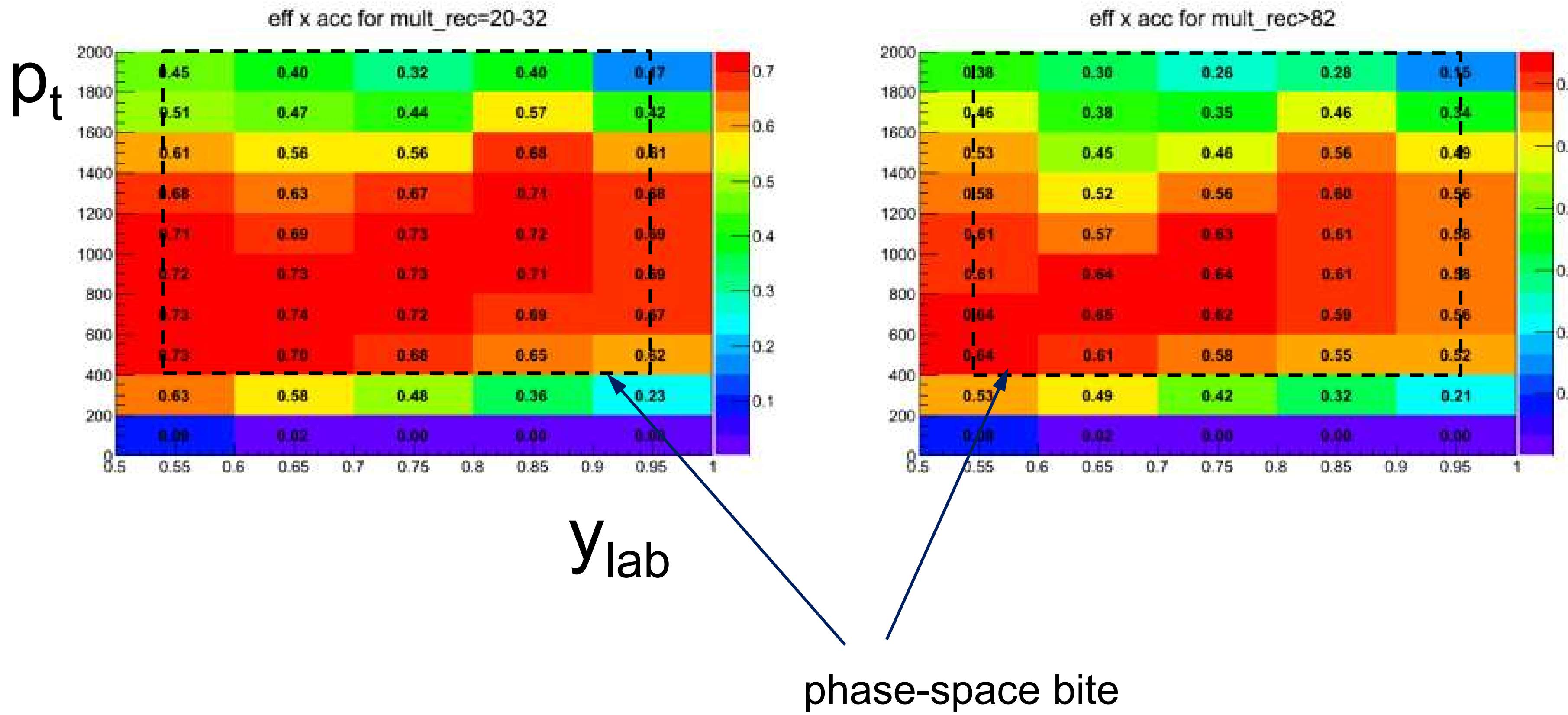
net proton number (RHIC cuts, 30%-40% central)



➔ Data look Poisson-like, but not quite ...

Hades proton efficiencies

centrality = 30% - 40% centrality = 0% - 5%



Things we are still investigating ...

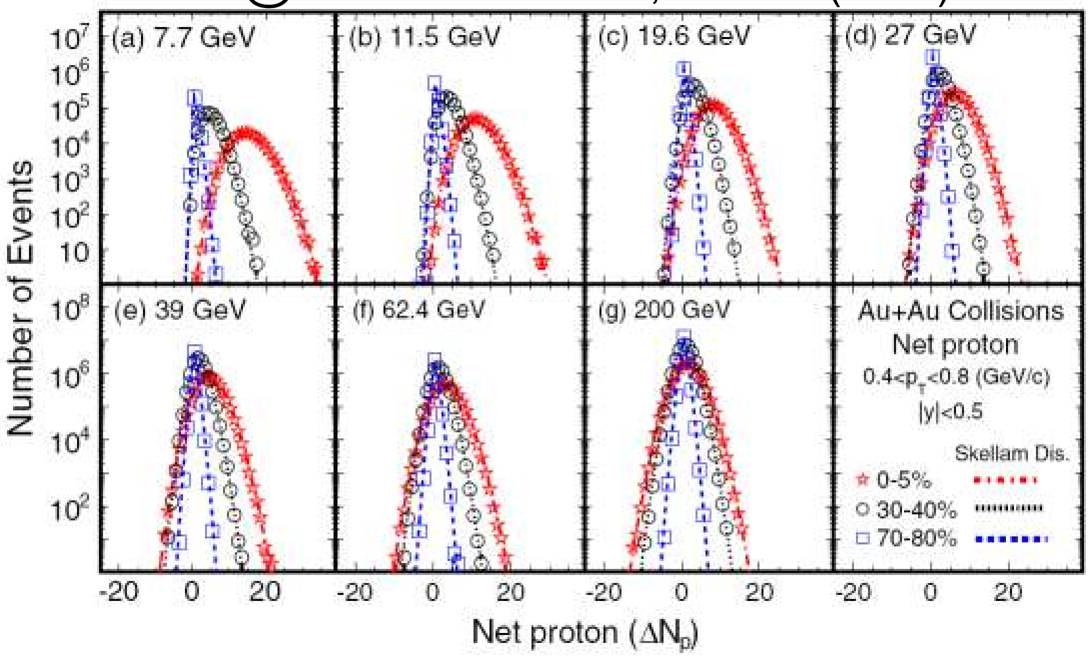
- Centrality selection: META vs. FW ➔ avoid autocorrelation
- Centrality bin width correction ➔ remove volume fluctuations
- Event pile-up ➔ avoid/remove contamination
- Track density dependence of efficiency correction
  ➔ is unfolding a better approach ?
- Role of fragments (d,t,He) ➔ do they modify $\delta(\Delta N_p)$?

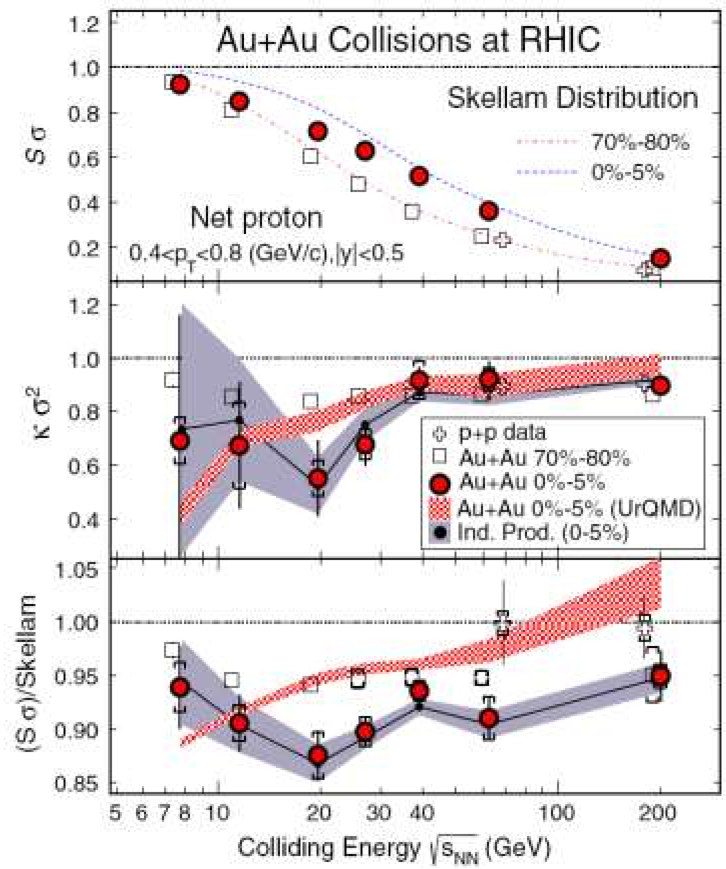
The ultimate goal is of course ...

Ultimate goal: Compare with RHIC data

7 c.m. energies, 3 centrality selections, within a defined y-p_t bin:

STAR @ RHIC   PRL 112, 032302 (2014)

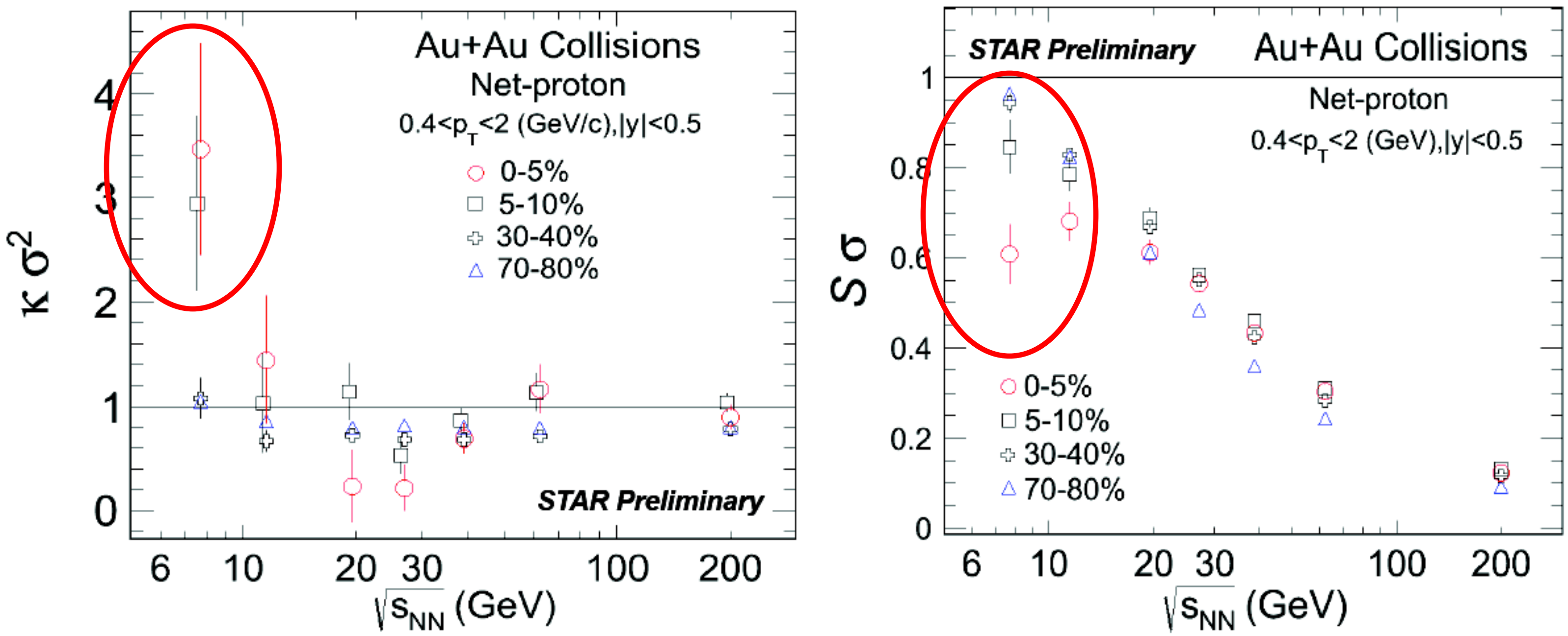




New STAR analysis

Xiaofeng Luo (罗晓峰)

Energy Dependence of Cumulants Ratios

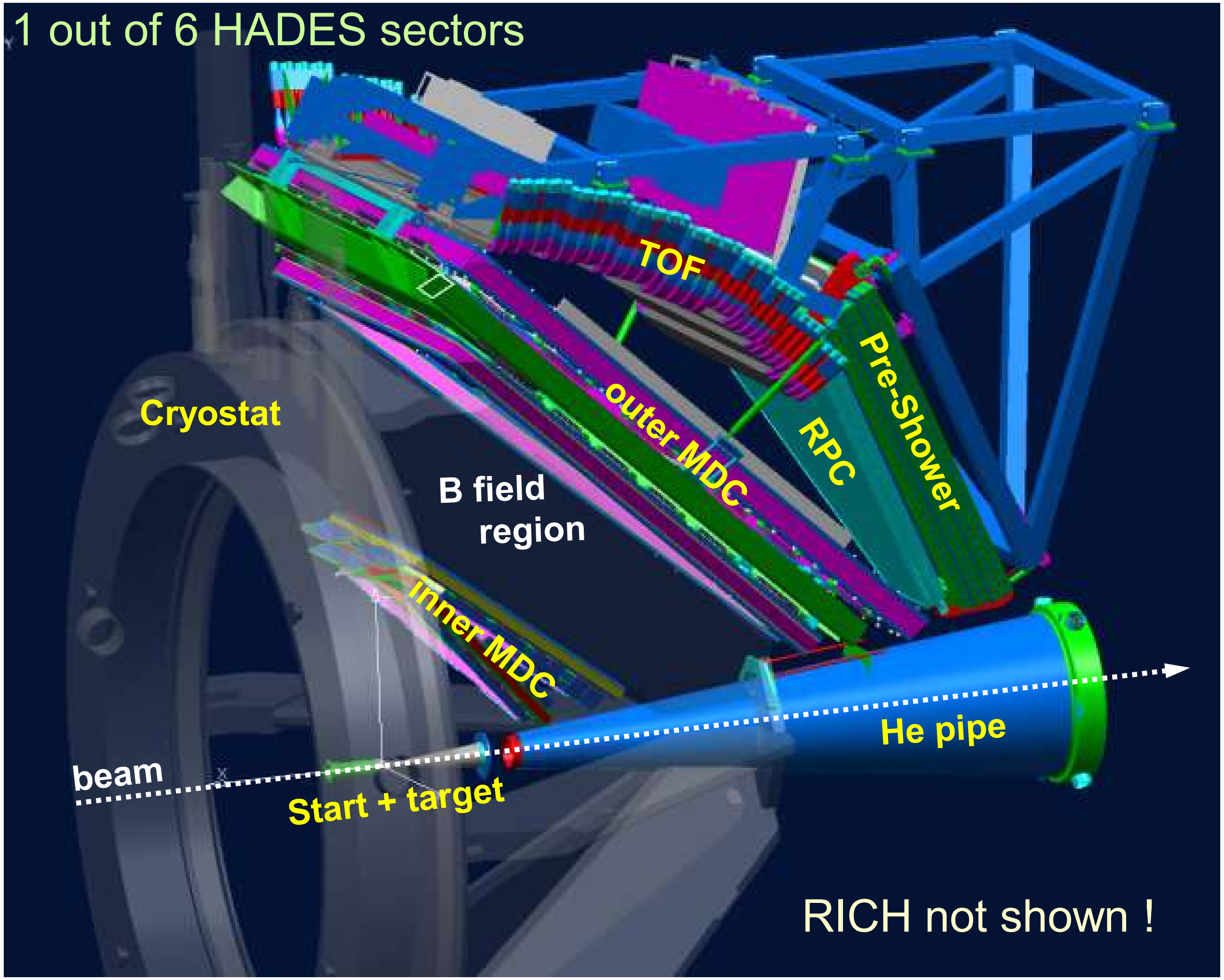


$$\kappa\sigma^2 = \frac{C_4}{C_2}, \qquad S\sigma = \frac{C_3}{C_2}$$

Error bars are statistical only. Systematic errors estimation underway.
Dominant contributors: a) efficiency corrections b) PID.

Back up slides

Technical layout of HADES



HADES + FW

inner MDC

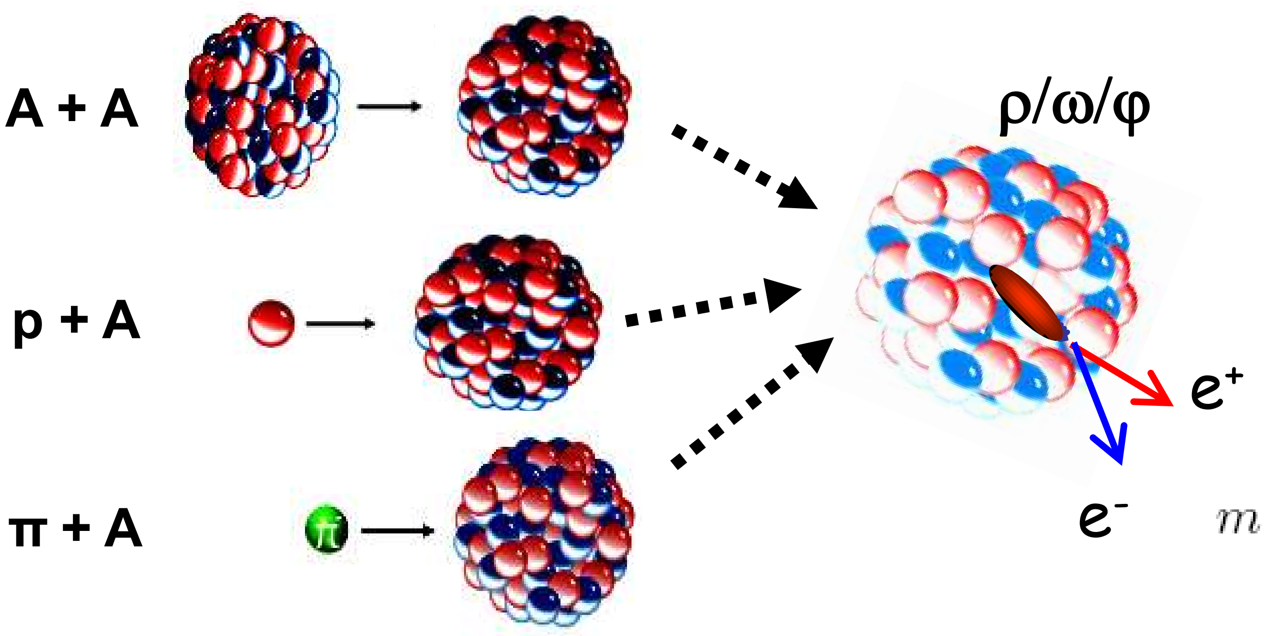
RICH readout

HADES at the future FAIR facility

SIS100 (>2020):

p+A up to 15 GeV
A+A up to 8 GeV/u

Vector mesons in the medium



Recipe:

1. produce VM
2. let decay in medium
3. detect products
4. reconstruct VM mass

$$m(\rho, T, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

Meson	Mass [MeV/c²]	Γ [MeV/c²]	cτ [fm/c]	BR (VM→e+e-)	BR (VM → hadrons)
ρ^0	770	150	1.3	4.4×10^{-5}	$\pi^+ \pi^-$ (~100%)
ω	782	8.4	23.4	7.1×10^{-5}	$\pi^0\gamma \rightarrow 3\gamma$ (9%)
φ	1020	4.4	44.4	3.1×10^{-5}	K^+K^- (50%)

No FSI ! **FSI !**

Physics we are after with HADES

In very general terms:

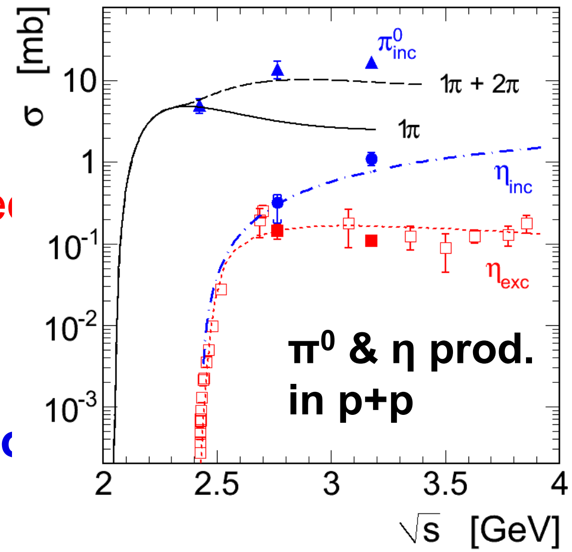
Medium modifications of hadrons (e.g. vector mesons)
- chiral symmetry restoration vs. hadronic effects
  - enhanced dilepton yields → emissivity of hot & dense hadronic matter
  - in-medium spectral functions

➢ **systematic dilepton spectroscopy in A+A, p+A & π+A** ($n/n_0 \approx$ 1-3)

- Hadron production & spectroscopy
  - meson and baryon production
    - coupling of ρ and ω to N*
    - σ_{pn} vs. σ_{pp}
    - strangeness production (ϕ, K, Σ, Λ, Ξ)
    - form factors of ω, ϕ, Δ, Σ^0 and Λ

  } → neede

➢ **systematic dilepton (and hadron) spectrosc**
(n/n_0 = 0)



Characterizing a distribution by its moments

(or alternatively by its cumulants)

A distribution f(x) is fully characterized by its (central) moments:

$$\mu_n = \mathrm{E}\left[(X - \mathrm{E}[X])^n\right] = \int_{-\infty}^{+\infty} (x-\mu)^n f(x)\,dx.$$

n=0, 1, 2, 3, 4, ...,∞

- n=0: normalization = μ_0
- n=1: mean = μ_1
- n=2: variance = μ_2 (or $\sigma = \sqrt{\mu_2}$) measures width
- n=3: skewness = $\frac{\mu_3}{\sigma^3}$ measures asymmetry
- n=4: kurtosis = $\frac{\mu_4}{\sigma^4}$ - 3 measures pointedness/flatness
- n>4: ...

A few common examples

	Mean	Variance	Skewness	Kurtosis
Gauss	μ	σ^2	0	0
Binomial	np	$np(1-p)$	$\frac{1-2p}{\sqrt{np(1-p)}}$	$\frac{1-6p(1-p)}{np(1-p)}$
Poisson	μ	μ	$\mu^{-1/2}$	μ^{-1}
Skellam	$\mu_1 - \mu_2$	$\mu_1 + \mu_2$	$\frac{\mu_1-\mu_2}{(\mu_1+\mu_2)^{3/2}}$	$\frac{1}{\mu_1+\mu_2}$

For easier comparison with Skellam (and to reduce the so-called volume effect), one often computes:

$Sk * \sigma = \frac{\mu_1-\mu_2}{\mu_1+\mu_2}$ and $\kappa * \sigma^2 = 1$

At low beam energies, $\mu_2 = N_{\bar{p}} = 0$ and $\boldsymbol{Sk * \sigma = \kappa * \sigma^2 = 1}$!

Generalized efficiency corrections

Efficiency depends on particle, centrality, pt & y…

➔ need to correct differentially !

Can be done by using the „factorial moments“:

Bzdak & Koch, Phys. Rev. C 86 (2012)
Xiaofeng Liu, arXiv:1410.3914

(1)

$$F_{i,k}(N_p, N_{\bar{p}}) = \left\langle \frac{N_p!}{(N_p - i)!} \frac{N_{\bar{p}}!}{(N_{\bar{p}} - k)!} \right\rangle = \sum_{N_p = i}^{\infty} \sum_{N_{\bar{p}} = k}^{\infty} P(N_p, N_{\bar{p}}) \frac{N_p!}{(N_p - i)!} \frac{N_{\bar{p}}!}{(N_{\bar{p}} - k)!}$$

$$f_{i,k}(n_p, n_{\bar{p}}) = \left\langle \frac{n_p!}{(n_p - i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}} - k)!} \right\rangle = \sum_{n_p = i}^{\infty} \sum_{n_{\bar{p}} = k}^{\infty} p(n_p, n_{\bar{p}}) \frac{n_p!}{(n_p - i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}} - k)!}$$

$$F_{i,k}(N_p, N_{\bar{p}}) = \frac{f_{i,k}(n_p, n_{\bar{p}})}{(\varepsilon_p)^i (\varepsilon_{\bar{p}})^k}$$

(2)

$$\begin{aligned} A_{i,k}(x_1, \ldots, x_i; \bar{x}_1, \ldots, \bar{x}_k) &= \langle N(x_1)[N(x_2) - \delta_{x_1,x_2}] \ldots [N(x_i) - \delta_{x_1,x_i} - \ldots - \delta_{x_{i-1},x_i}] \\ &\quad \bar{N}(\bar{x}_1)[\bar{N}(\bar{x}_2) - \delta_{\bar{x}_1,\bar{x}_2}] \ldots [\bar{N}(\bar{x}_k) - \delta_{\bar{x}_1,\bar{x}_k} - \ldots - \delta_{\bar{x}_{k-1},\bar{x}_k}] \rangle \\ a_{i,k}(x_1, \ldots, x_i; \bar{x}_1, \ldots, \bar{x}_k) &= \langle n(x_1)[n(x_2) - \delta_{x_1,x_2}] \ldots [n(x_i) - \delta_{x_1,x_i} - \ldots - \delta_{x_{i-1},x_i}] \\ &\quad \bar{n}(\bar{x}_1)[\bar{n}(\bar{x}_2) - \delta_{\bar{x}_1,\bar{x}_2}] \ldots [\bar{n}(\bar{x}_k) - \delta_{\bar{x}_1,\bar{x}_k} - \ldots - \delta_{\bar{x}_{k-1},\bar{x}_k}] \rangle . \end{aligned}$$

„local factorial moments“

(3)

$$\begin{aligned} F_{i,k} &= \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} A_{i,k}(x_1, \ldots, x_i; \bar{x}_1, \ldots, \bar{x}_k) \\ f_{i,k} &= \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} a_{i,k}(x_1, \ldots, x_i; \bar{x}_1, \ldots, \bar{x}_k) \end{aligned}$$

$$F_{i,k} = \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} \frac{a_{i,k}(x_1, \ldots, x_i; \bar{x}_1, \ldots, \bar{x}_k)}{\epsilon(x_1) \ldots \epsilon(x_i) \bar{\epsilon}(\bar{x}_1) \ldots \bar{\epsilon}(\bar{x}_k)}$$

Towards higher-order cumulants?

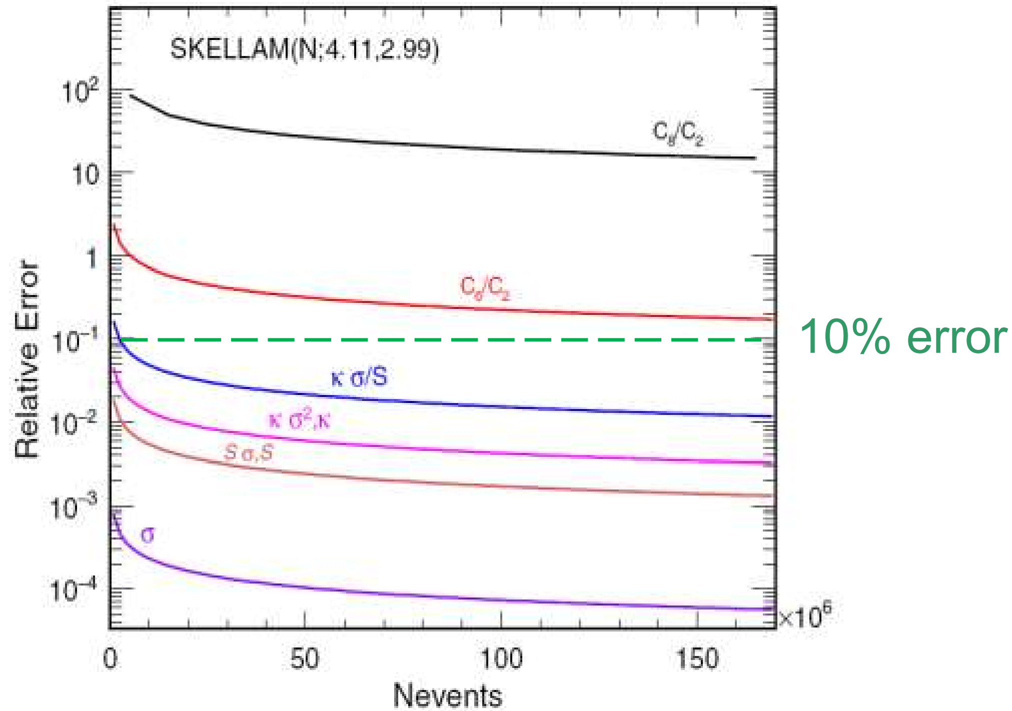
Sensitivity to critical fluctuations is expected to increase with order, but same is true for stat. flucs., etc.

$$\text{error}(\hat{S}\hat{\sigma}) \propto \frac{\sigma}{\sqrt{n}}$$

$$\text{error}(\hat{\kappa}\hat{\sigma}^2) \propto \frac{\sigma^2}{\sqrt{n}}$$

$$\text{error}\left(\frac{\hat{C}_6}{\hat{C}_2}\right) \propto \frac{\sigma^4}{\sqrt{n}}$$

$$\text{error}\left(\frac{\hat{C}_8}{\hat{C}_2}\right) \propto \frac{\sigma^6}{\sqrt{n}}$$



➔ <10% stat. error needs **≈10⁹** evts for 6th order, and **≈10¹³** for 8th order !

(Note: corrections for limited eff & acc will further increase the error)