# Investigating Proton Number Fluctuations with HADES at SIS18

EMMI Fluctuation Workshop - Nov 2015

R. Holzmann (GSI) & M. Szala (Frankfurt)

- Baryon number flucts. in the few-GeV regime
- The HADES experiment at SIS18
- Experimental artifacts

# 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

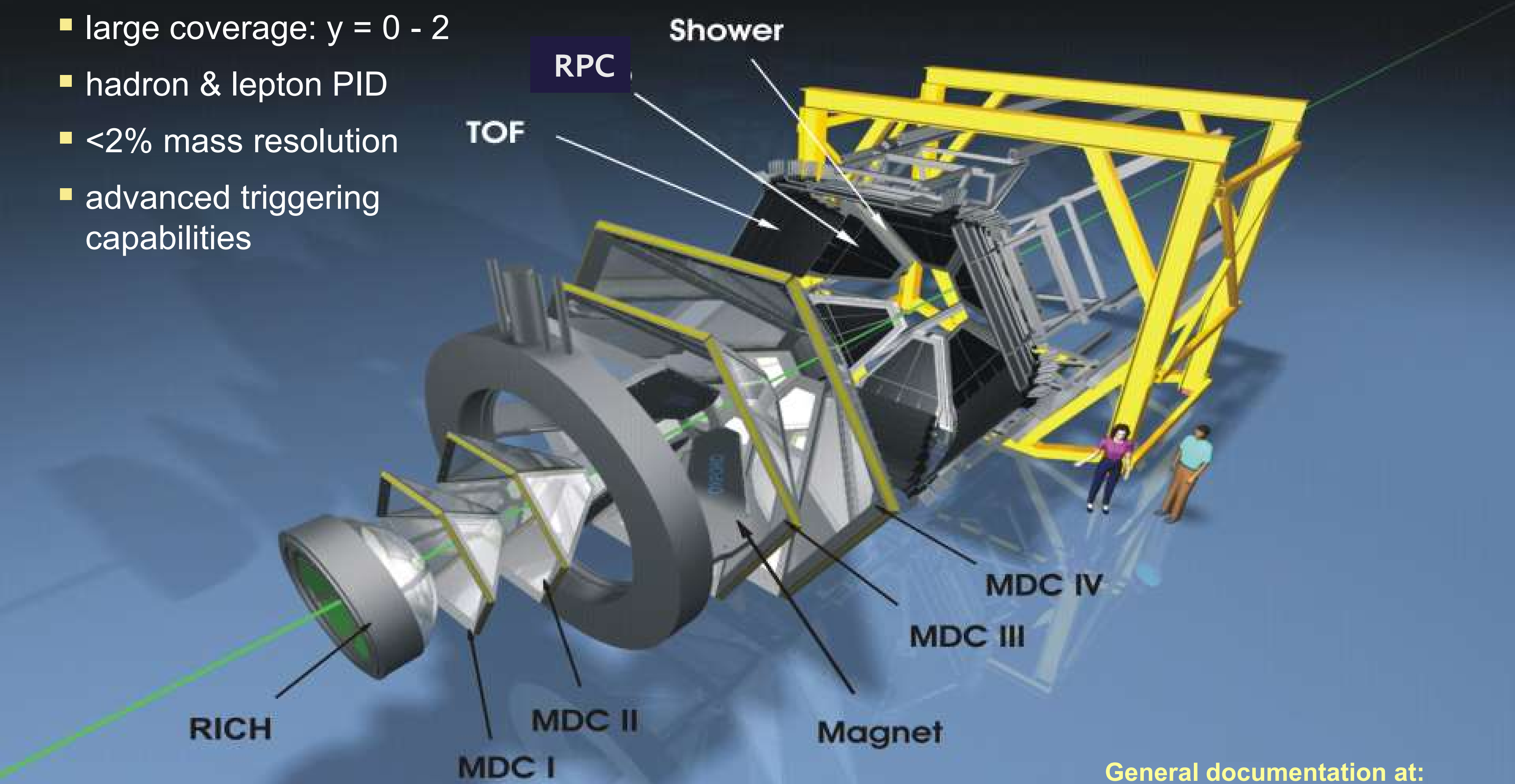
- At **SIS18**: - fixed target expt. ($\sqrt{s} \leq 2.7\ GeV$)
  - what about fragments (d, t, He, etc.) ?
  - what about neutrons ?

➔ 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**

# The HADES experiment at GSI

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- azimuth. symmetry
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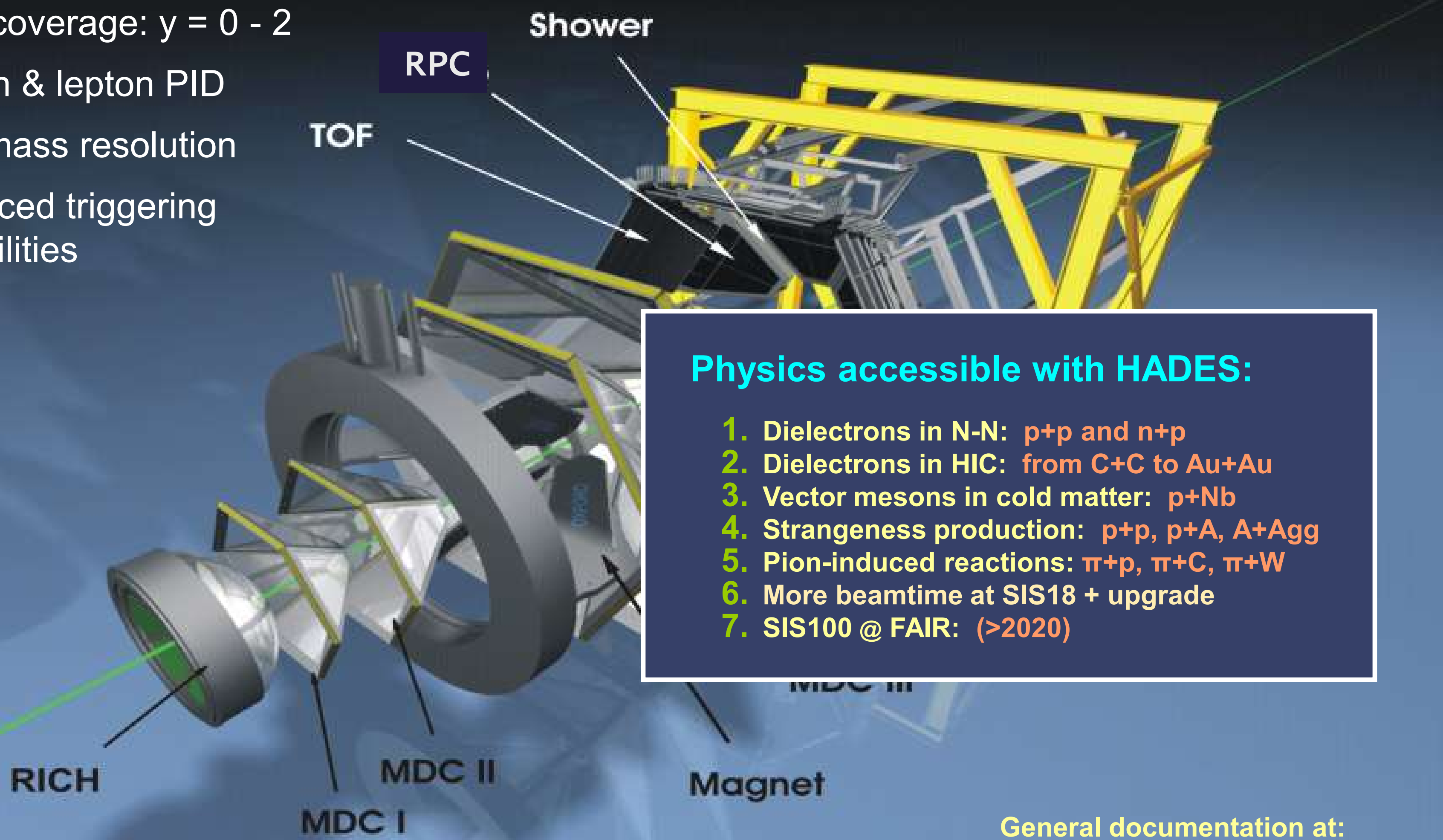


**Physics accessible with HADES:**

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:**
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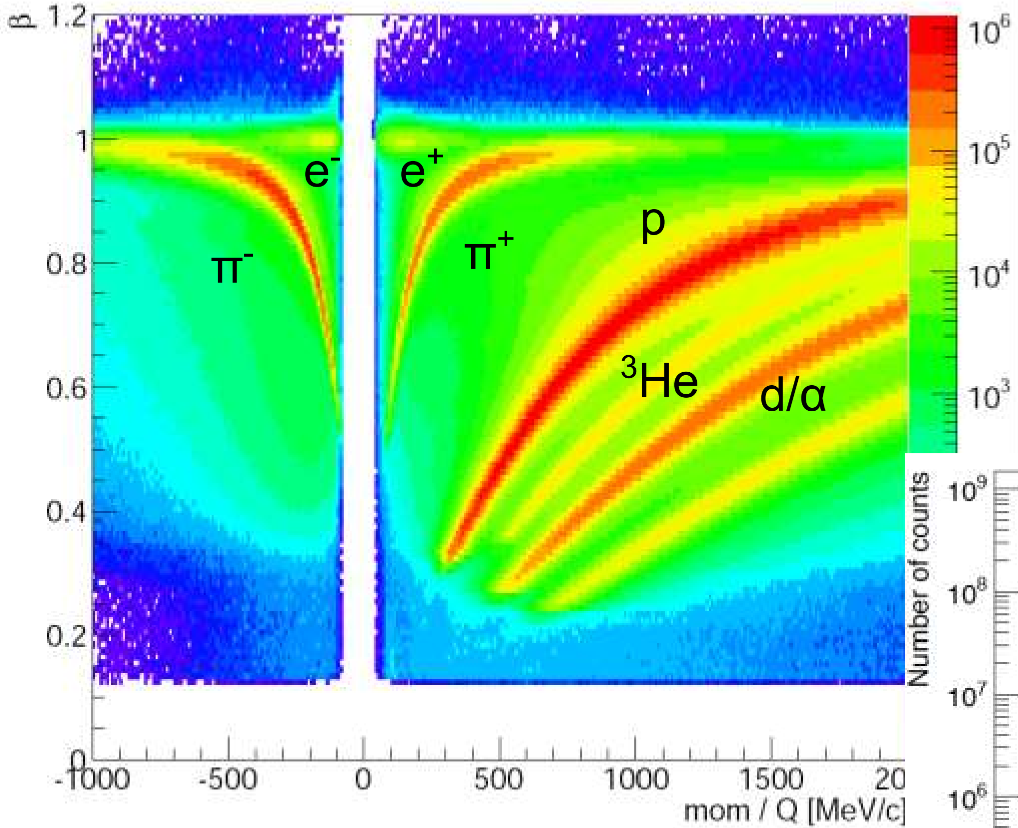
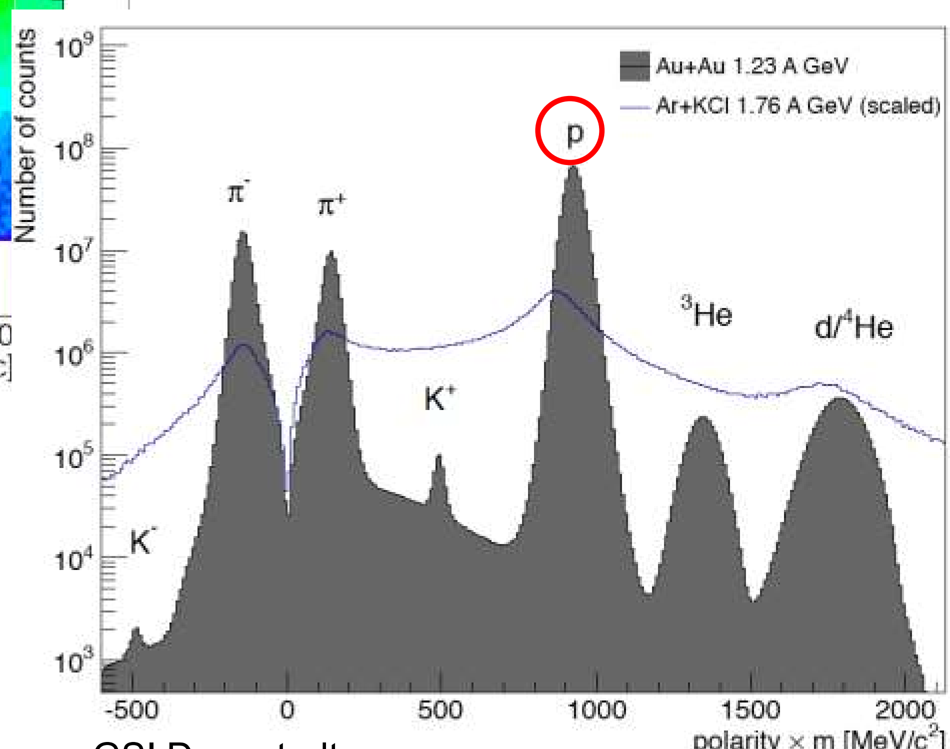
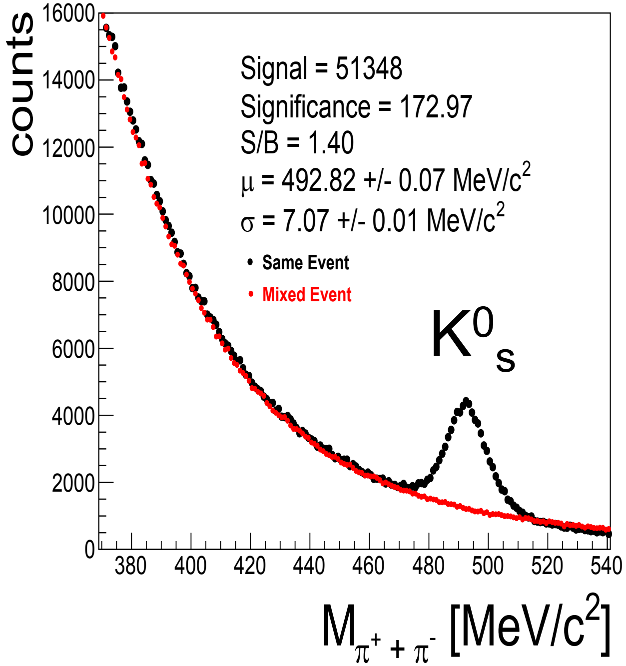
# Performance: particle ID

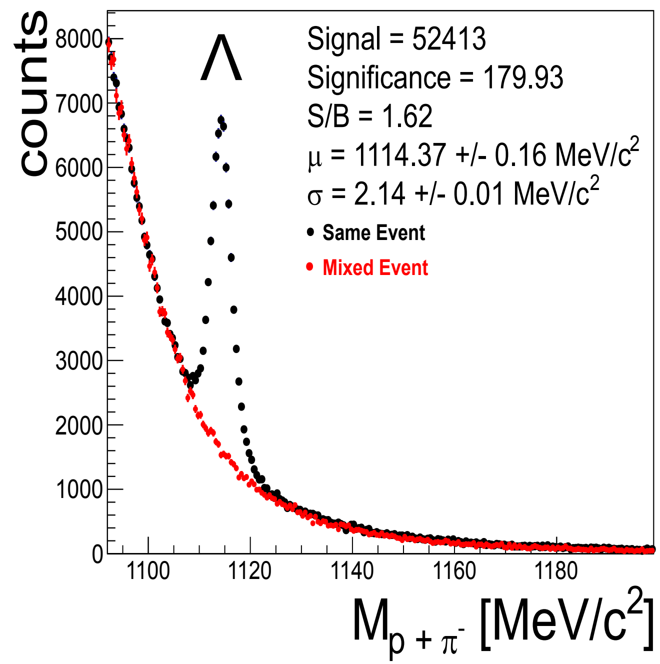



- good pid
- large stat
- good evt vertex

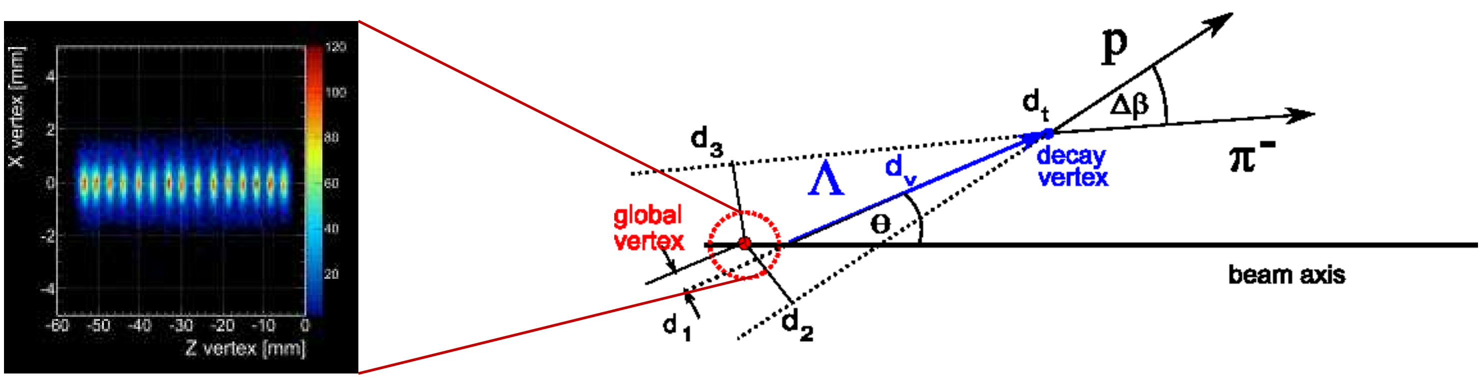


# Performance: weak decays

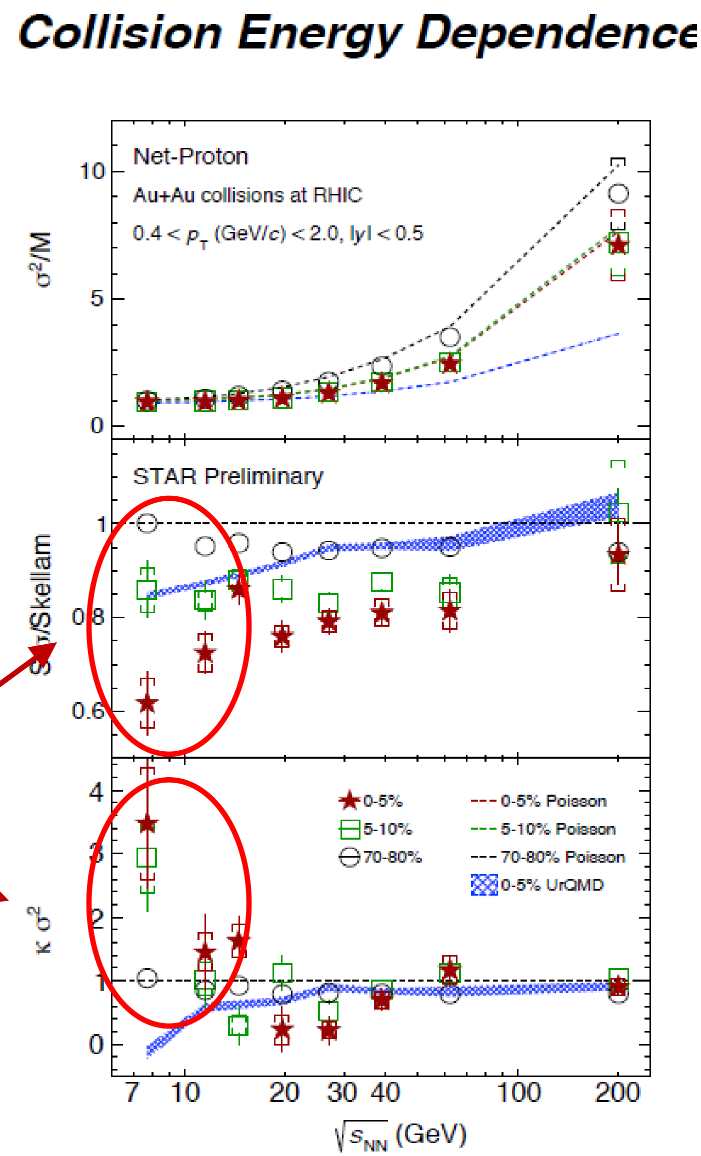



event vertex



# HADES vs. RHIC BES




HADES can add point at $\sqrt{s}$ = 2.4 GeV

Jochen Thäder

# Our sandbox: the Poisson distribution

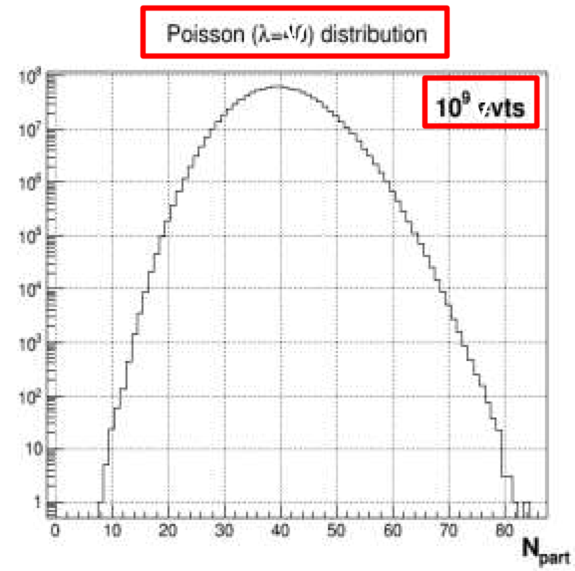
**Reminder:** for Poisson $P(\lambda)$ we have:

- 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

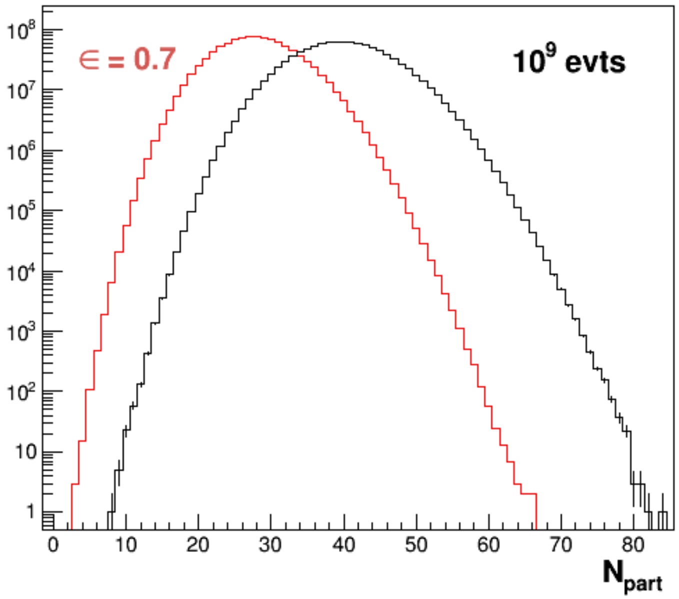
   A. Bzdak & V. Koch, PRC 86 (2012); X. Luo, arXiv:1410.3914

   ➔ 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
```

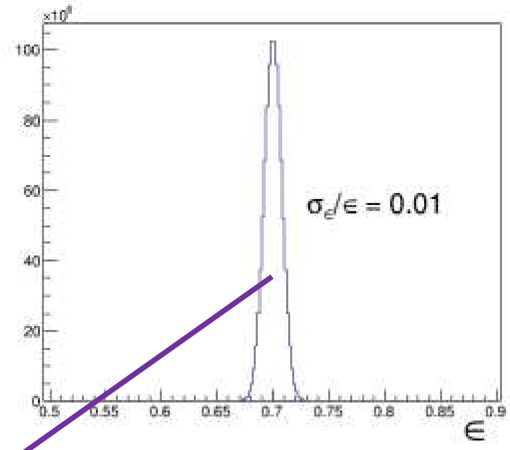
Using the Bzdak-Koch correction procedure:

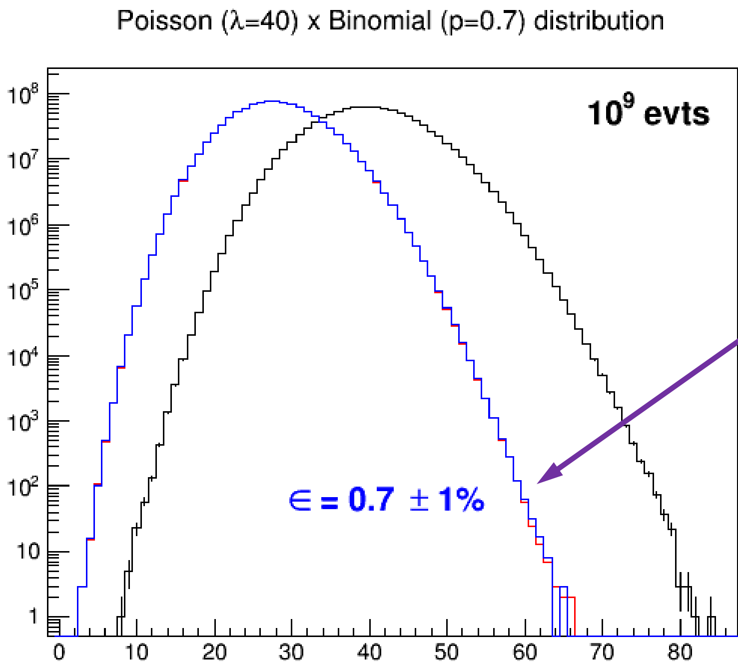
```
Mean      = 40     ± 0.0002
Sigma     = 6.3248 ± 0.0002
Skewness  = 0.1585 ± 0.0001
Kurtosis  = 0.0255 ± 0.0003

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!

# Evt-by-Evt efficiency changes

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



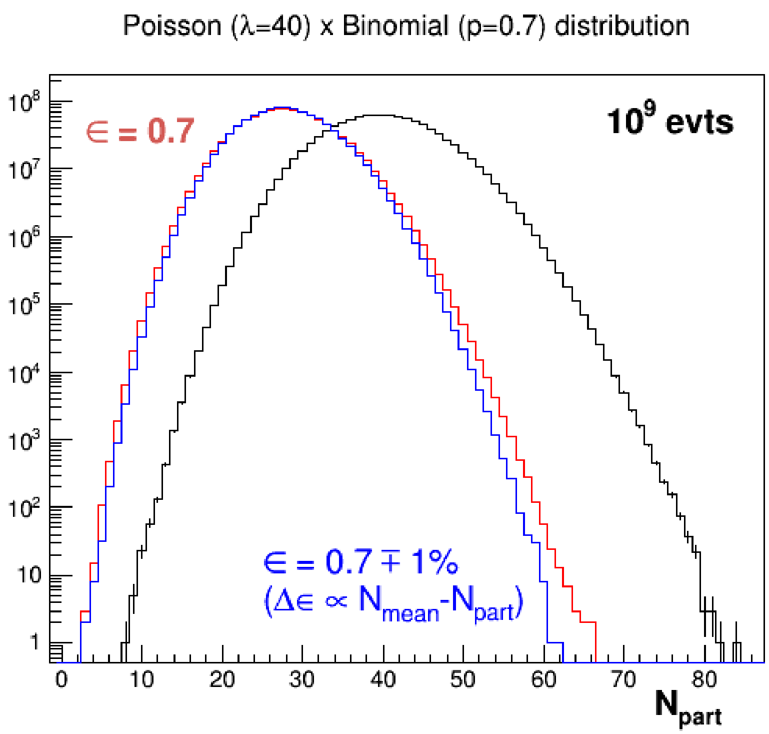




```
Mean     = 40     ± 0.0002
Sigma    = 6.3398 ± 0.0002
Skewness = 0.1592 ± 0.0002
Kurtosis = 0.0258 ± 0.0002

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
```

➔ strong effect !!!

# Realistic simulations: UrQMD + Geant3 + event reconstruction

- UrQMD 1.23 GeV/u Au+Au events
- Geant3 detector simulation
- Full track reconstruction + particle ID
- Proton cumulants + Bzdak-Koch correction
  in $y = y_0 \pm 0.2$ & $p_t = 0.4 - 1.6$ GeV/c bin

➔ compare corrected $c_n$ with UrQMD $c_n$

# Scenario 1: assuming constant efficiencies

UrQMD evts:

Reconstruction corrected with constant mean <ε>:

Centrality:

30-40%

```
Mean     =  6.639 ± 0.002
Sigma    =  2.892 ± 0.002
Skewness =  0.487 ± 0.002
Kurtosis =  0.245 ± 0.006

Omega        =  1.260 ± 0.002
Skew * Sig   =  1.407 ± 0.005
Kurt * Sig2  =  2.051 ± 0.048
```

```
Mean     =  6.702 ± 0.002
Sigma    =  2.842 ± 0.003
Skewness =  0.448 ± 0.004
Kurtosis =  0.190 ± 0.013

Omega        =  1.210 ± 0.002
Skew * Sig   =  1.27 ± 0.01
Kurt * Sig2  =  1.53 ± 0.10
```

➔ wrong !

0 – 5%

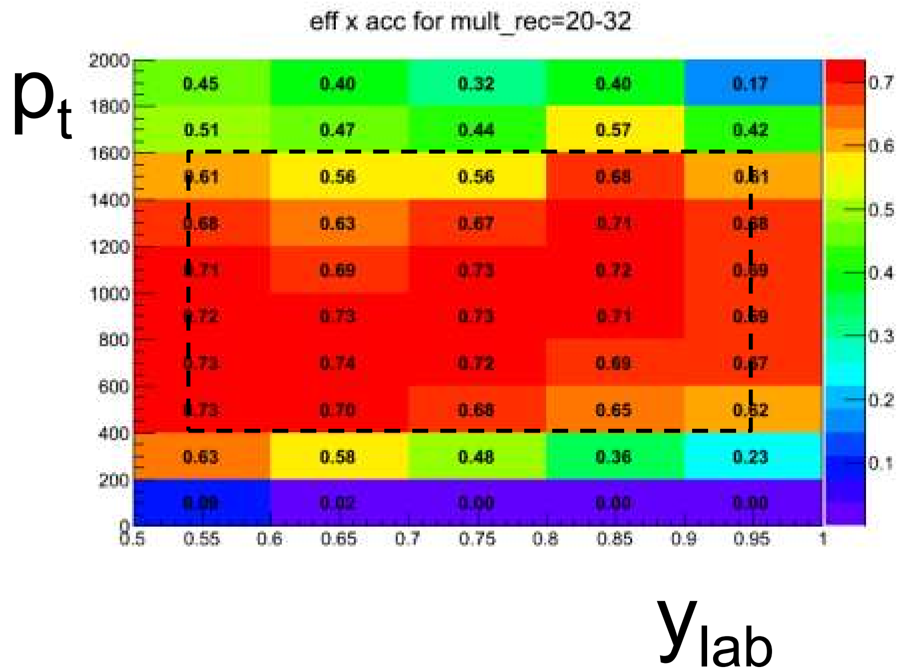
```
Mean     =  32.57 ± 0.01
Sigma    =  5.622 ± 0.005
Skewness =  0.142 ± 0.002
Kurtosis = -0.014 ± 0.006

Omega        =  0.970 ± 0.002
Skew * Sig   =  0.793 ± 0.011
Kurt * Sig2  = -0.45  ± 0.17
```

```
Mean     =  32.86 ± 0.01
Sigma    =  5.163 ± 0.005
Skewness = -0.105 ± 0.004
Kurtosis =  0.65 ± 0.03

Omega        =  0.811 ± 0.002
Skew * Sig   = -0.54  ± 0.02
Kurt * Sig2  = 17.27  ± 0.66
```

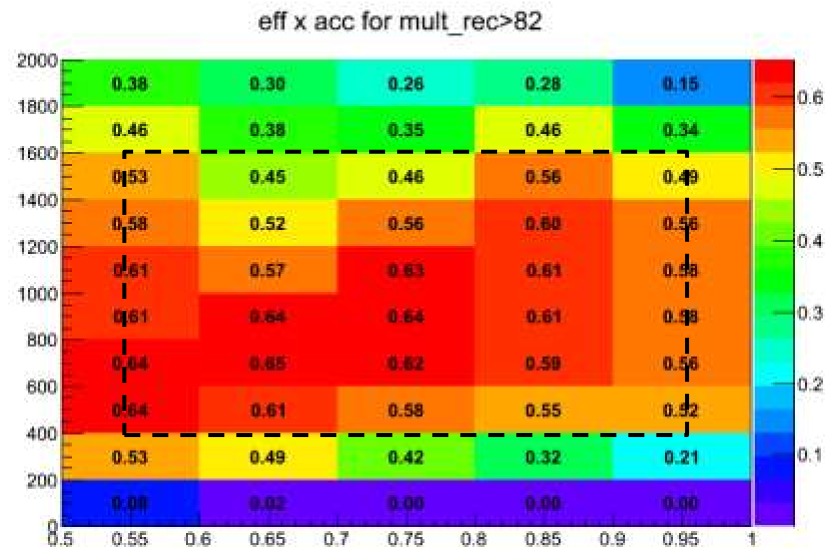
➔ badly wrong !

# Hades proton efficiencies vs. $p_t$, y & centrality

centrality = 30% - 40%

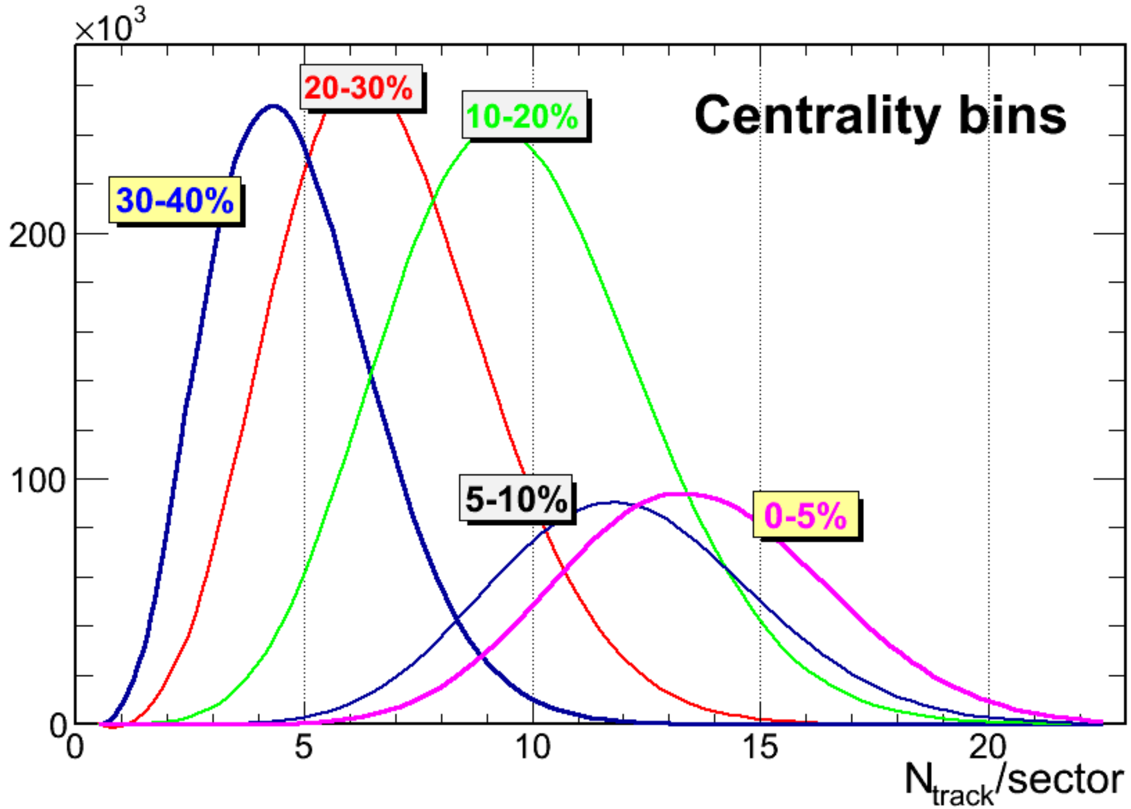



centrality = 0% - 5%



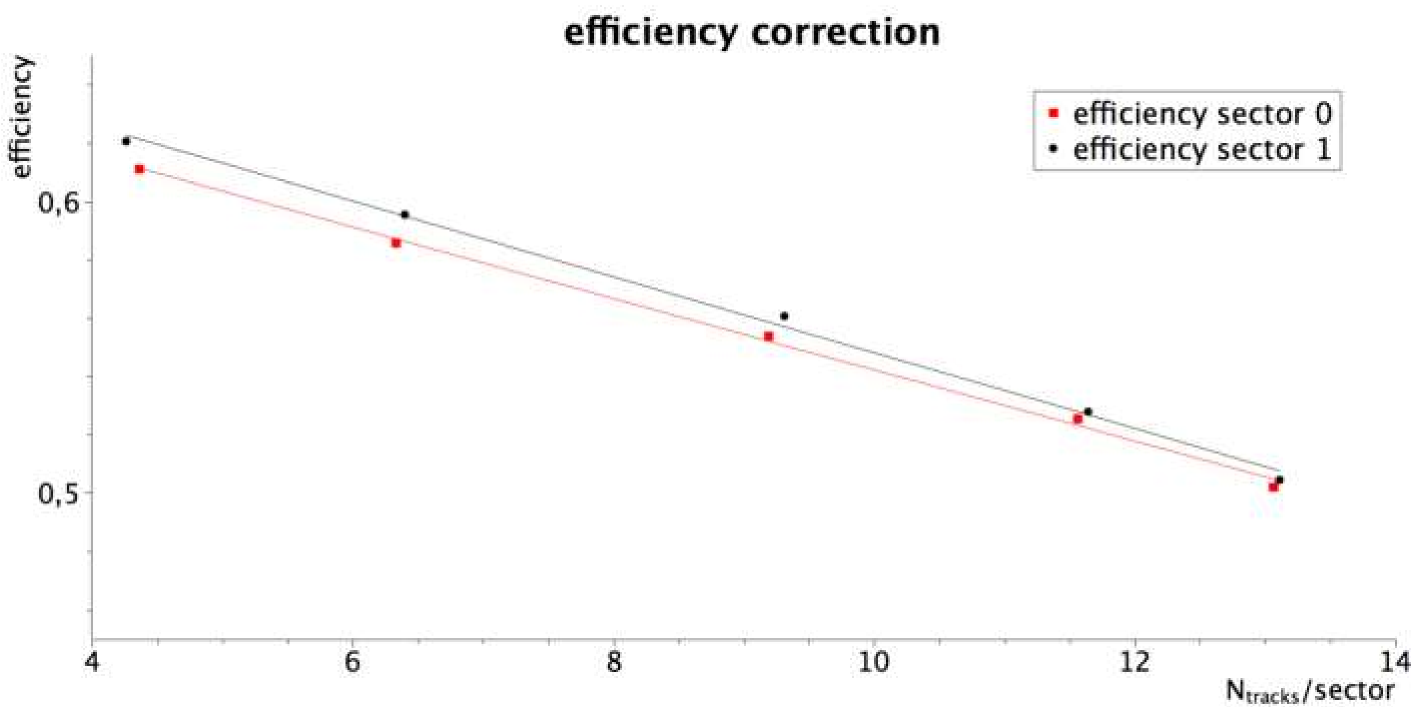
# Centrality selection in Au+Au

UrQMD 1.23 GeV/u Au+Au evts into HADES:




→ large evt-to-evt fluctuations of the detector load, even in a given centrality bin

# HADES proton efficiency vs. $N_{track}$/sector




➔ Efficiency decreases by 10-15% in most central events
➔ Use fitted dependence to correct on evt-by-evt basis ?

# 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)

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

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

➔ correct evt-by-evt
(assuming binomial !)

# Scenario 2: efficiency depends on $N_{track}$

Centrality:

**30-40%**

| | UrQMD evts: | Reconstruction corrected with mean <ε>: |
|---|---|---|
| Mean | 6.639 ± 0.002 | 6.714 ± 0.003 |
| Sigma | 2.892 ± 0.002 | 2.935 ± 0.003 |
| Skewness | 0.487 ± 0.002 | 0.491 ± 0.003 |
| Kurtosis | 0.245 ± 0.006 | 0.252 ± 0.012 |
| Omega | 1.260 ± 0.001 | 1.283 ± 0.002 |
| Skew * Sig | 1.407 ± 0.005 | 1.440 ± 0.009 |
| Kurt * Sig2 | 2.051 ± 0.048 | 2.17 ± 0.10 |

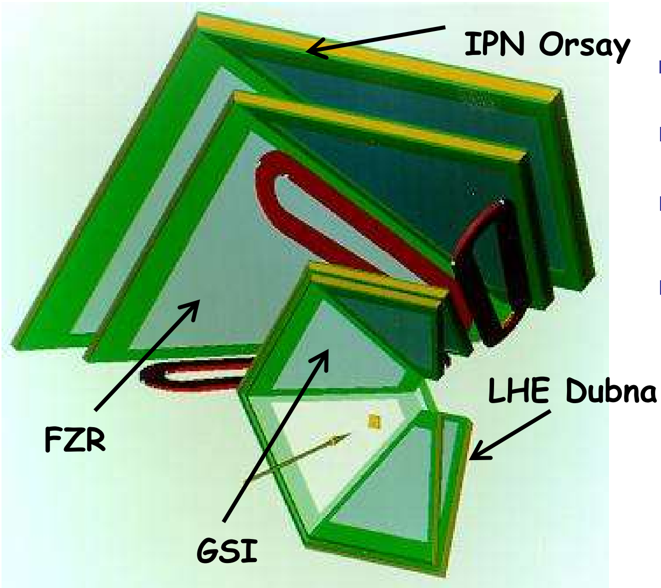
→ ok !

**0 – 5%**

| | UrQMD evts: | Reconstruction corrected with mean <ε>: |
|---|---|---|
| Mean | 32.57 ± 0.01 | 32.53 ± 0.01 |
| Sigma | 5.622 ± 0.005 | 5.743 ± 0.009 |
| Skewness | 0.142 ± 0.002 | -0.004 ± 0.007 |
| Kurtosis | -0.014 ± 0.006 | 0.390 ± 0.026 |
| Omega | 0.970 ± 0.002 | 1.014 ± 0.003 |
| Skew * Sig | 0.793 ± 0.011 | -0.022 ± 0.043 |
| Kurt * Sig2 | -0.45 ± 0.17 | 12.86 ± 0.86 |

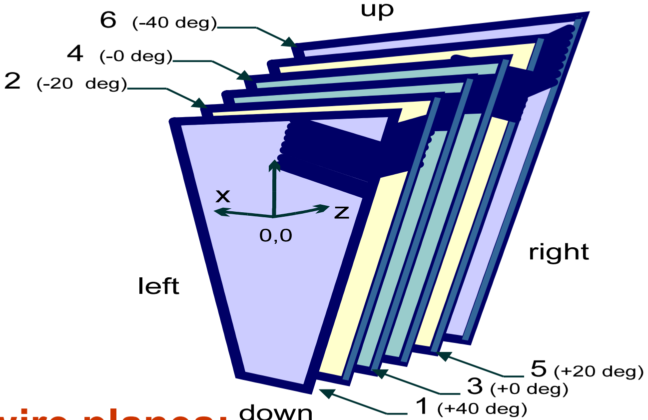
→ still off, but better !

# Tracking: the Multiwire Drift Chambers (MDC)




- 4 MDC/sector
- total 33 $m^2$ area, 27000 cells
- $\Delta y<0.1$ mm resolution
- Ar-i$C_4H_{10}$ [60-40] gas

  and low-Z material

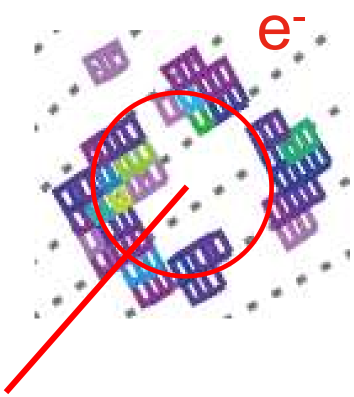




**wire planes:**
**40°,-20°,0°,0°,20°,-40°**

| Layer | Width/m | Height | Area[m^2] |
|---|---|---|---|
| I | 76,7 | 75,5 | 0,34 |
| II | 90,5 | 88,3 | 0,49 |
| III | 180,5 | 178,0 | 1,88 |
| IV | 222,4 | 219,9 | 2,83 |

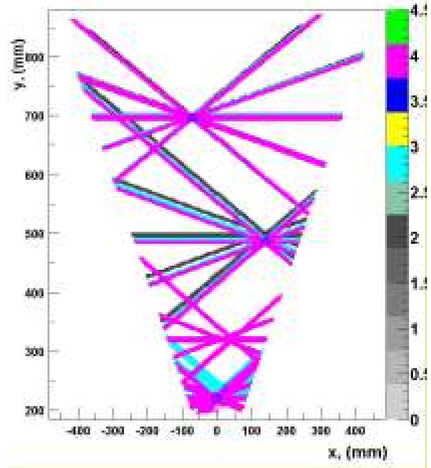
# Electron/positron identification

**RICH pattern**




+

**MDC hit finder & hit/track matching**

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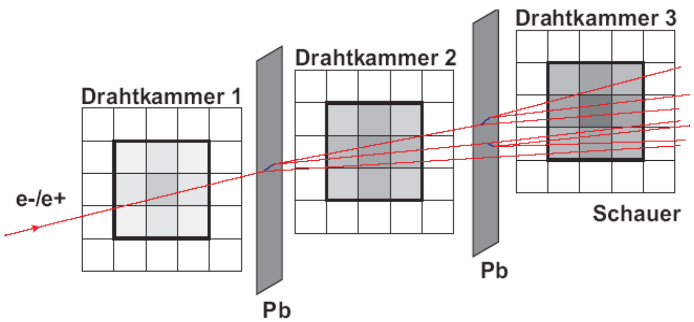
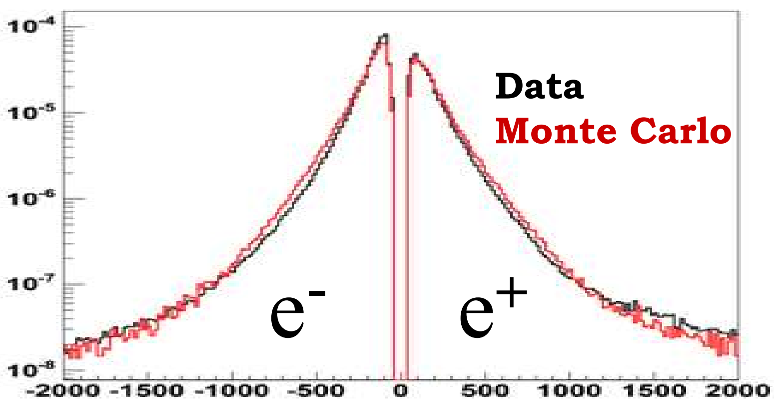
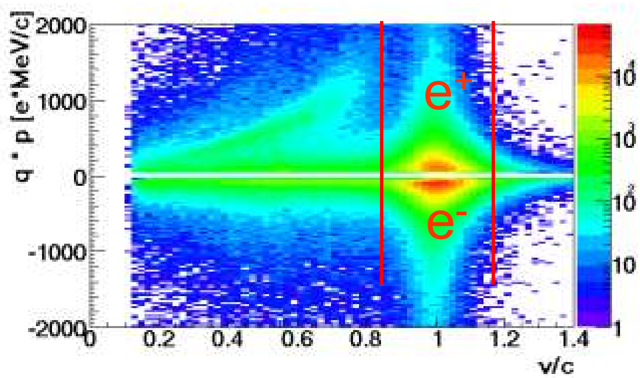
**Pre-Shower condition**




**Momentum * charge [MeV/C]**

**velocity vs. momentum**



# Scenario 3: eff = eff($N_{track}$ ,$N_{wire}$/$N_{track}$)

| Centrality: | UrQMD evts: | Reconstruction corrected with mean <ε>: |
|---|---|---|
| 30-40% | Mean = 6.639 ± 0.002 | Mean = 6.967 ± 0.003 |
| | Sigma = 2.892 ± 0.002 | Sigma = 2.966 ± 0.003 |
| | Skewness = 0.487 ± 0.002 | Skewness = 0.478 ± 0.004 |
| | Kurtosis = 0.245 ± 0.006 | Kurtosis = 0.244 ± 0.017 |
| | Omega = 1.260 ± 0.001 | Omega = 1.263 ± 0.003 |
| | Skew * Sig = 1.407 ± 0.005 | Skew * Sig = 1.412 ± 0.011 |
| | Kurt * Sig2 = 2.051 ± 0.048 | Kurt * Sig2 = 2.15 ± 0.15 |
| | | ➔ ok ! |
| 0 – 5% | Mean = 32.57 ± 0.01 | Mean = 33.57 ± 0.01 |
| | Sigma = 5.622 ± 0.005 | Sigma = 5.840 ± 0.010 |
| | Skewness = 0.142 ± 0.002 | Skewness = 0.056 ± 0.010 |
| | Kurtosis = -0.014 ± 0.006 | Kurtosis = 0.230 ± 0.029 |
| | Omega = 0.970 ± 0.002 | Omega = 1.016 ± 0.003 |
| | Skew * Sig = 0.793 ± 0.011 | Skew * Sig = 0.328 ± 0.060 |
| | Kurt * Sig2 = -0.45 ± 0.17 | Kurt * Sig2 = 7.83 ± 1.00 |
| | | ➔ even better ! |

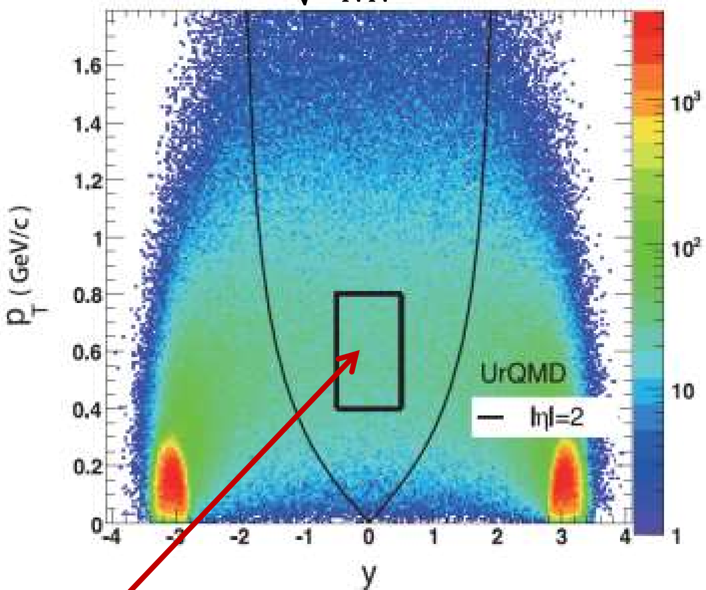
# Things we are still investigating ...

- 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
  ➔ strong detector dependence
  ➔ check independence assumption
- Analyze Au+Au data
- Role of fragments (d,t,He) ➔ do they modify $\delta(\Delta N_p)$ ?

# Back up slides

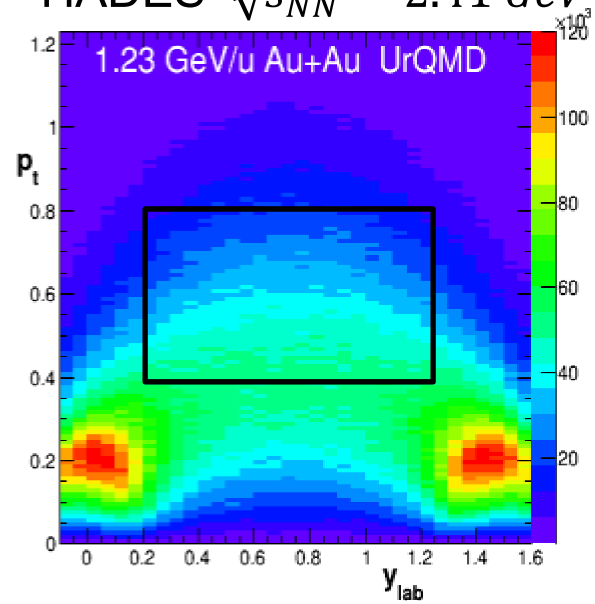
# Which phase-space bite to use?

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:

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

# Towards higher-order cumulants?

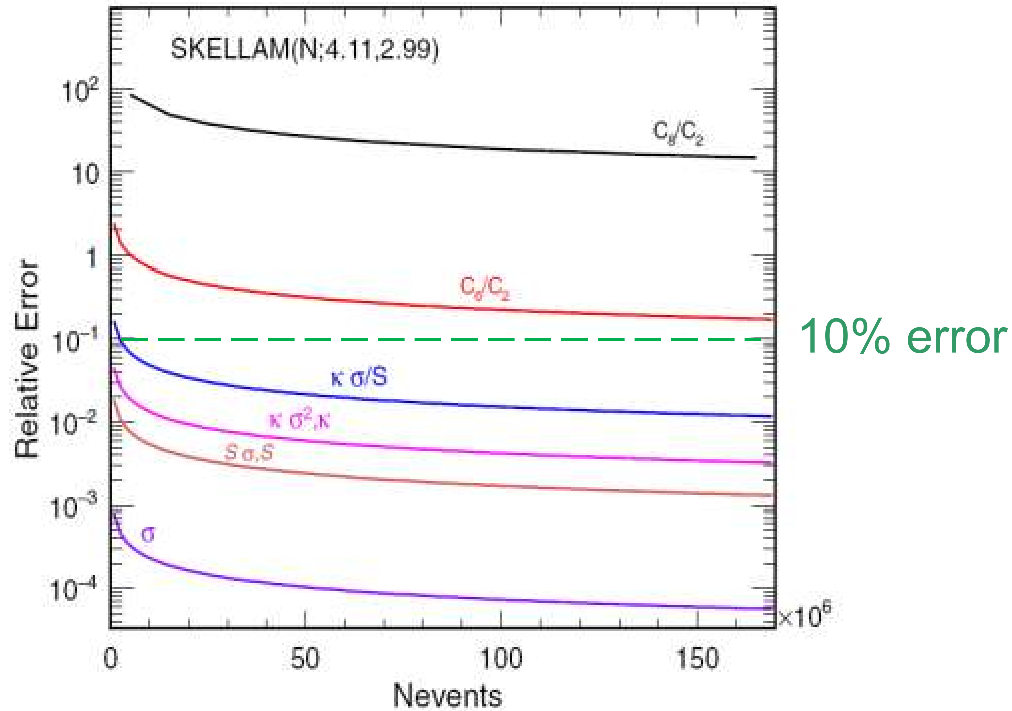
Sensitivity to critical fluctuations is expected to increase with order, but same is true for stat. flucs., etc.

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

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

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

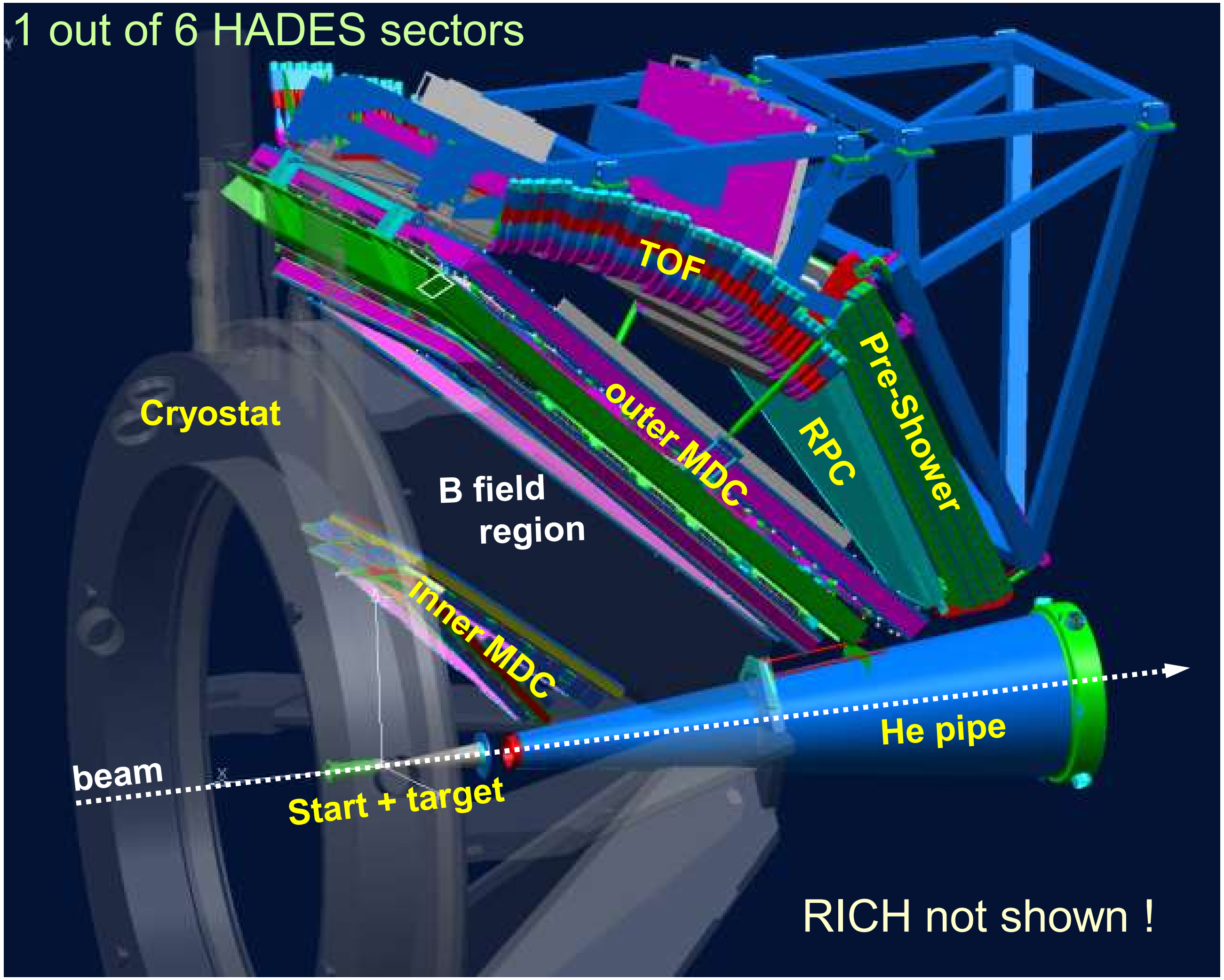
$$\mathrm{error}\left(\frac{\hat{C}_8}{\hat{C}_2}\right) \propto \frac{\sigma^6}{\sqrt{n}}$$




➔ **<10%** stat. error needs **≈$10^9$** evts for $6^{th}$ order, and **≈$10^{13}$** for $8^{th}$ order !

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

# Technical layout of HADES



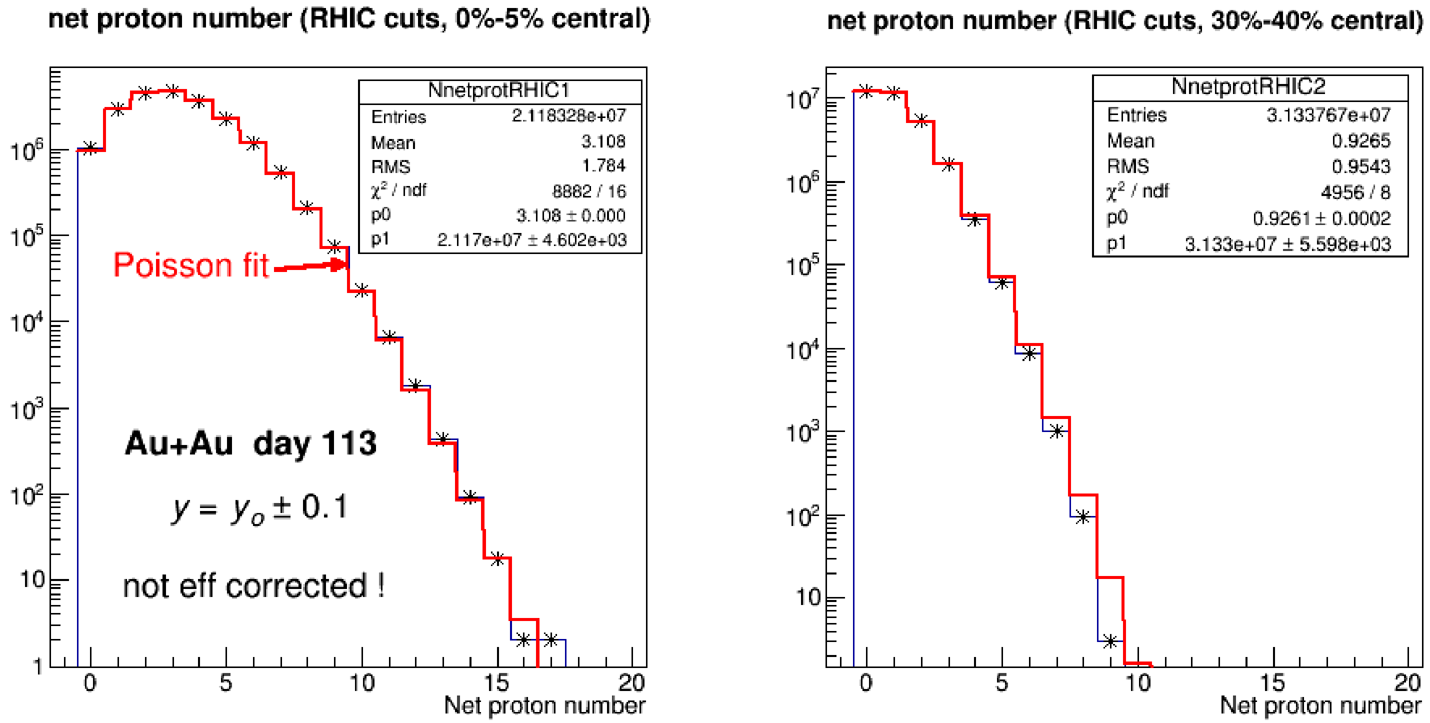

HADES + FW

inner MDC

RICH readout

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

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




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

# 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 = $\mu_0$
- n=1: mean = $\mu_1$
- n=2: variance = $\mu_2$ ( 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 | $\sigma^2$ | 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 | $\mu^{-1/2}$ | $\mu^{-1}$ |
| 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:

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

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

# Ultimate goal:  Compare with STAR data

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

STAR @ RHIC     PRL 112, 032302 (2014)