New baryonic and mesonic observables from NA61/SHINE

Antoni Marcinek
for the NA49 and NA61/SHINE collaborations

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Polish Academy of Sciences

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Outline

1. ϕ meson production in proton-proton collisions (A.M.)
2. Search for QCD critical point via intermittency analysis (N. Davis, N. Antoniou, F. Diakonos)
3. Electromagnetic effects in pion emission (A. Rybicki, A. Szczurek, M. Kiełbowicz)

ϕ meson production — introduction

$\phi = s\bar{s}$ meson according to PDG 2014

- Mass $m = (1019.461 \pm 0.019)\,\mathrm{MeV}$
- Width $\Gamma = (4.266 \pm 0.031)\,\mathrm{MeV}$
- $\mathcal{BR}(\phi \to K^+K^-) = (48.9 \pm 0.5)\,\%$

Goal of the analysis

- Differential ϕ multiplicities in p+p collisions measured in NA61/SHINE
  - $\rightarrow$ from invariant mass spectra fits in $\phi \to K^+K^-$ decay channel
  - $\rightarrow$ as function of rapidity y and transverse momentum p_T

Motivation

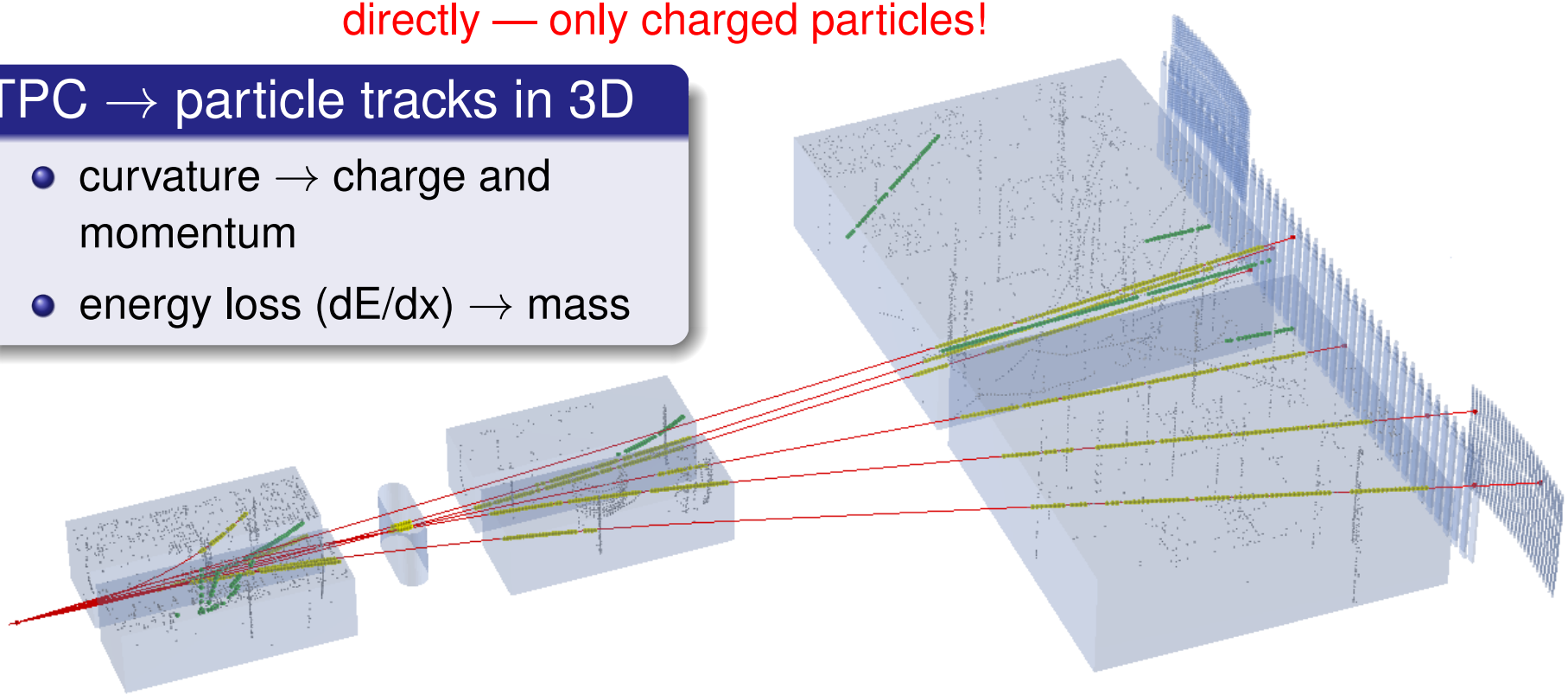
- To constrain hadron production models
  - $\rightarrow$ ϕ interesting due to its hidden strangeness ($s\bar{s}$)
- Reference data for Pb+Pb at the same energies

NA61/SHINE detector

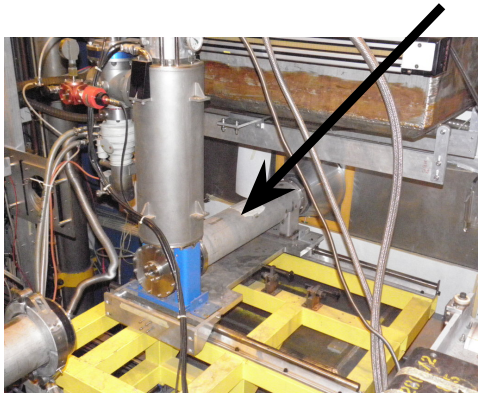
directly — only charged particles!

TPC → particle tracks in 3D

- curvature → charge and momentum
- energy loss (dE/dx) → mass



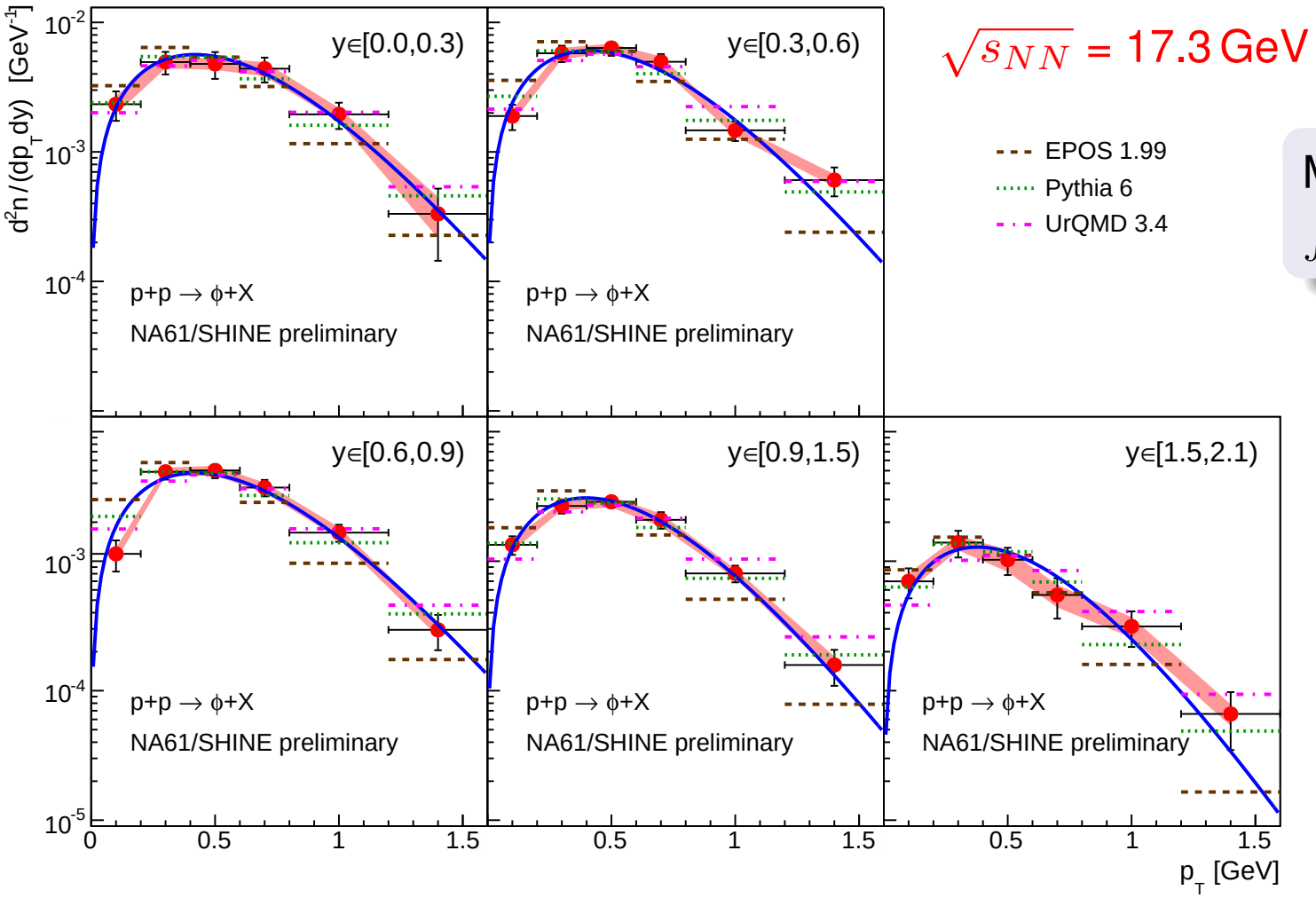
liquid H_2 target



Performance

- total acceptance $\sim 80\,\%$
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4}\,\mathrm{GeV}^{-1}$
- track reconstruction efficiency $> 95\,\%$

Double differential spectra: p+p @ 158 GeV



$\sqrt{s_{NN}}$ = 17.3 GeV

MC normalization: $\int$ model $=$ $\int$ data

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty$ $\rightarrow$ tail $< 1\,\%$

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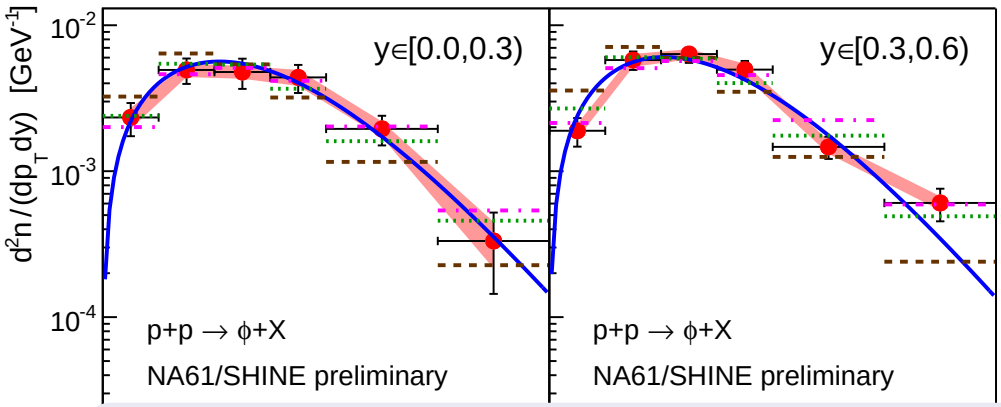
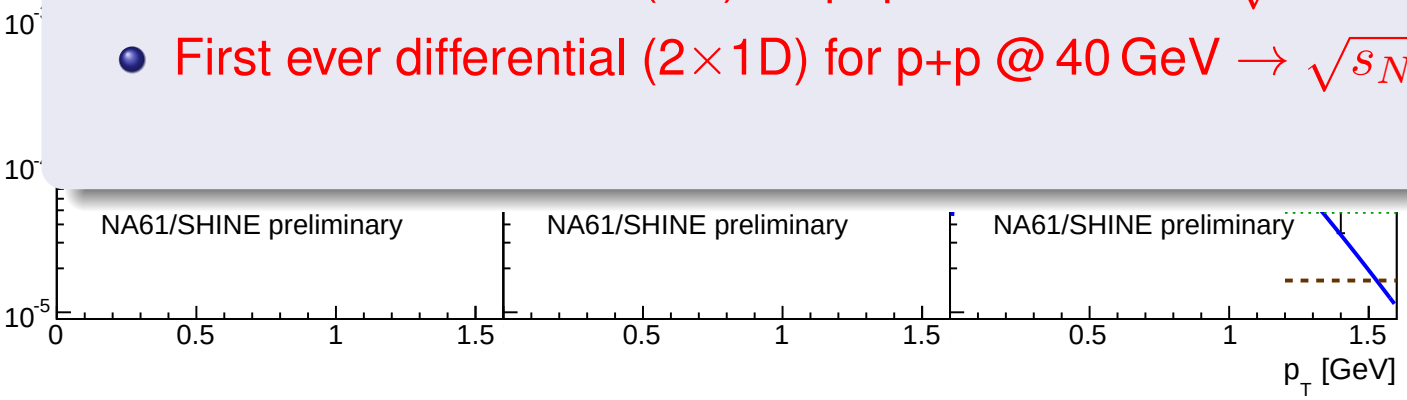


$\sqrt{s_{NN}}$ = 17.3 GeV

EPOS 1.99
Pythia 6
UrQMD 3.4

MC normalization:
$\int$ model $=$ $\int$ data

- First 2D (y vs p_T) ϕ production measurements for p+p @ 158 GeV
- First ever differential (2D) for p+p @ 80 GeV $\rightarrow$ $\sqrt{s_{NN}}$ = 12.3 GeV
- First ever differential (2$\times$1D) for p+p @ 40 GeV $\rightarrow$ $\sqrt{s_{NN}}$ = 8.8 GeV



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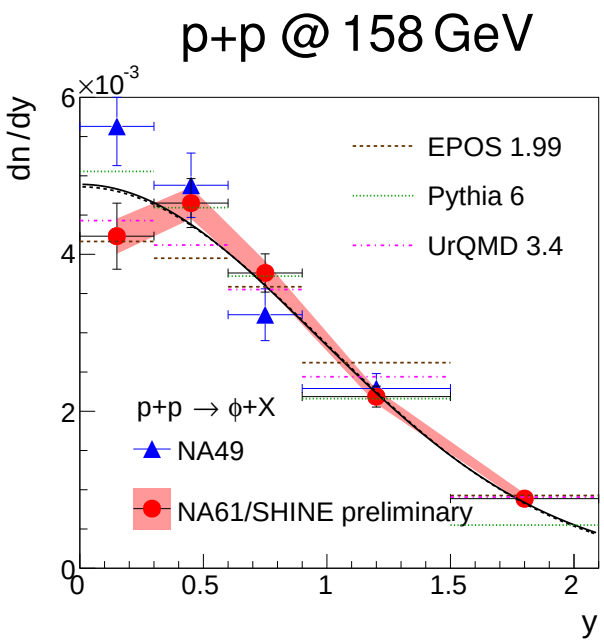
Rapidity



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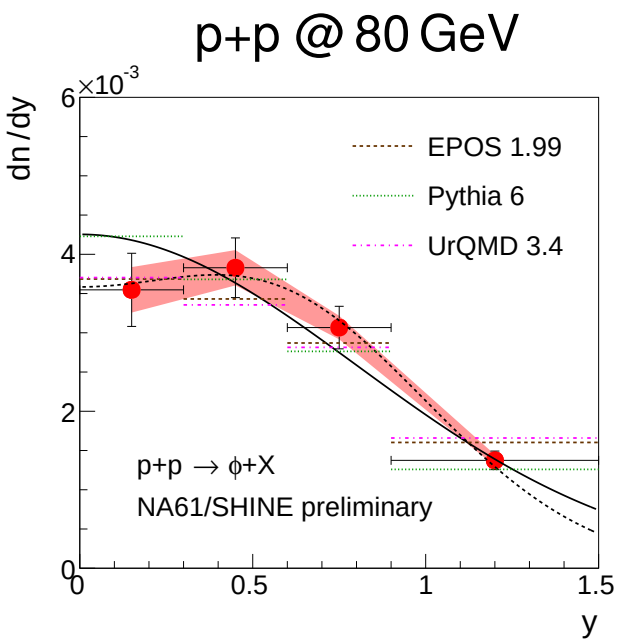
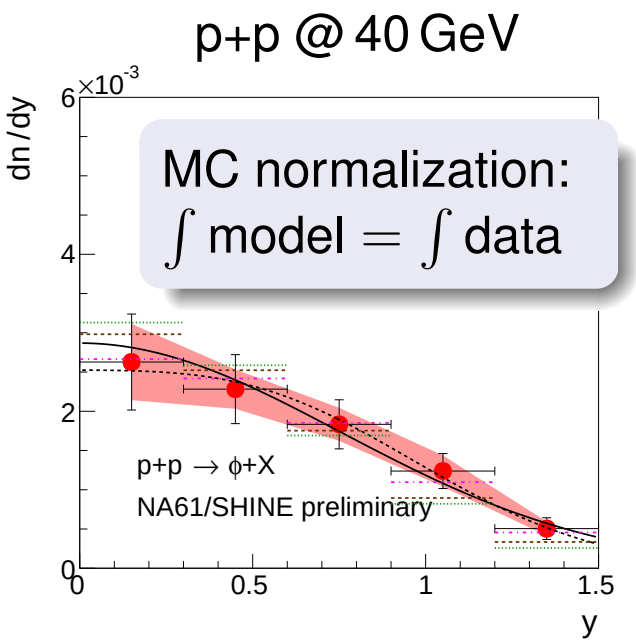


$\sqrt{s_{NN}}$ = 12.3 GeV

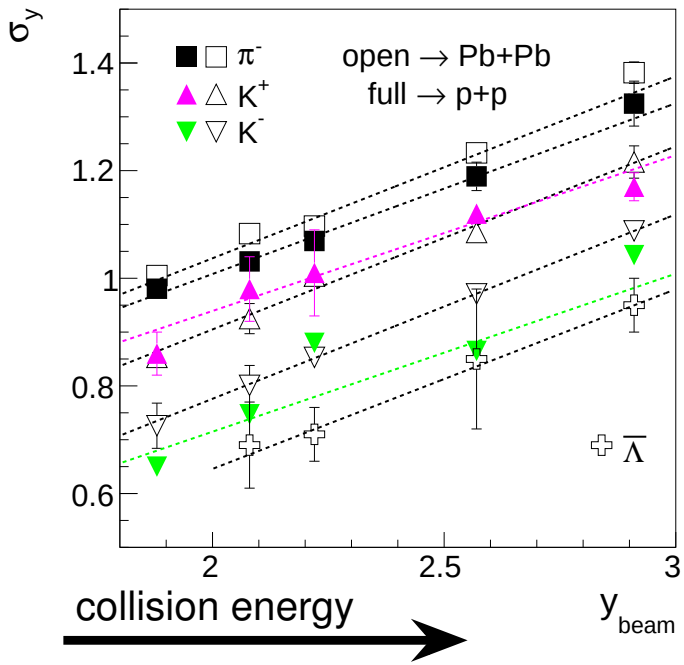


$\sqrt{s_{NN}}$ = 8.8 GeV

- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
- Fit Gaussian $e^{-y^2/2\sigma_y^2}$ $\rightarrow$ extrapolation to $y = \infty \rightarrow$ tails: $3\,\%$ for 158 GeV, $7\,\%$ for 80 GeV, $5\,\%$ for 40 GeV
- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)

Reference data for Pb+Pb: σ_{y} = width of $\mathrm{d}n/\mathrm{dy}$

NA49: PLB 491 (2000), PRC 66 (2002), PRL 93 (2004), PRC 77 (2008), PRC 78 (2008)



Comparison of particles / reactions

- All but ϕ in Pb+Pb:
  σ_{y} proportional to $\mathrm{y}_{\mathrm{beam}}$ with the same rate of increase
- two new ϕ points in p+p emphasize peculiarity of ϕ in Pb+Pb

Coalescence

- Not compatible with production through K^+ K^- coalescence, but p+p closer

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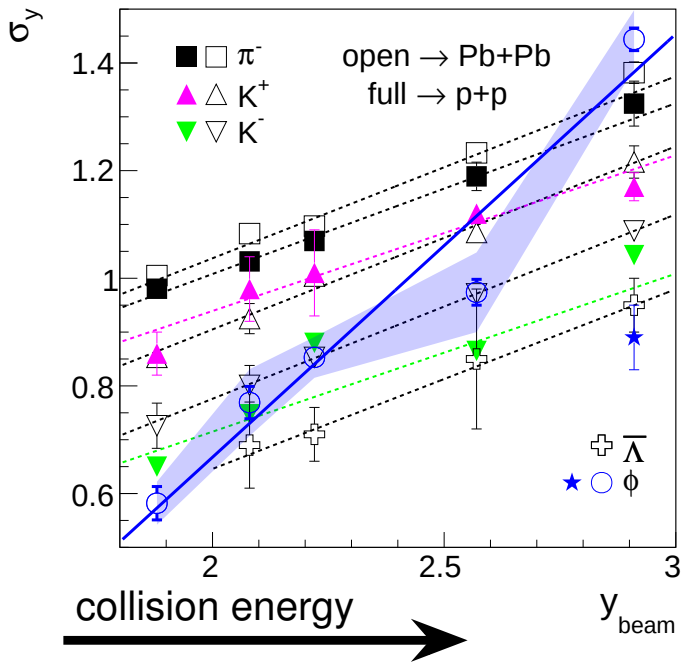

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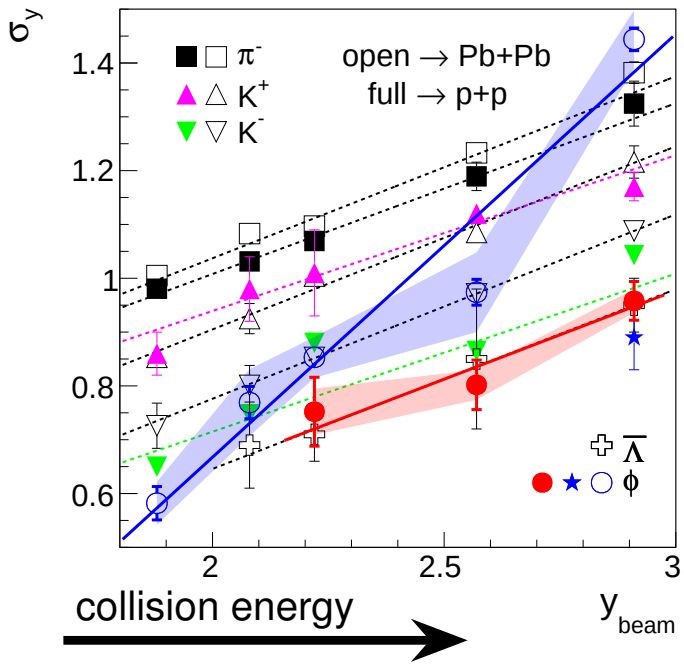

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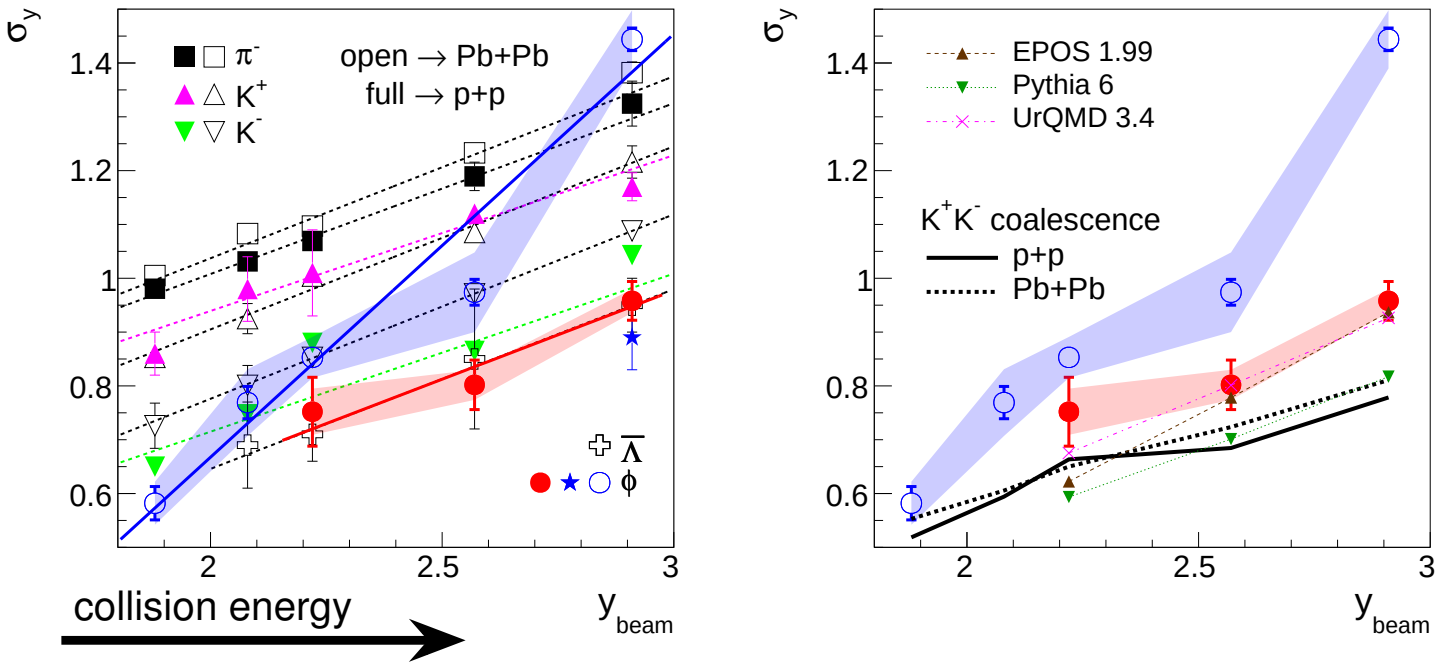

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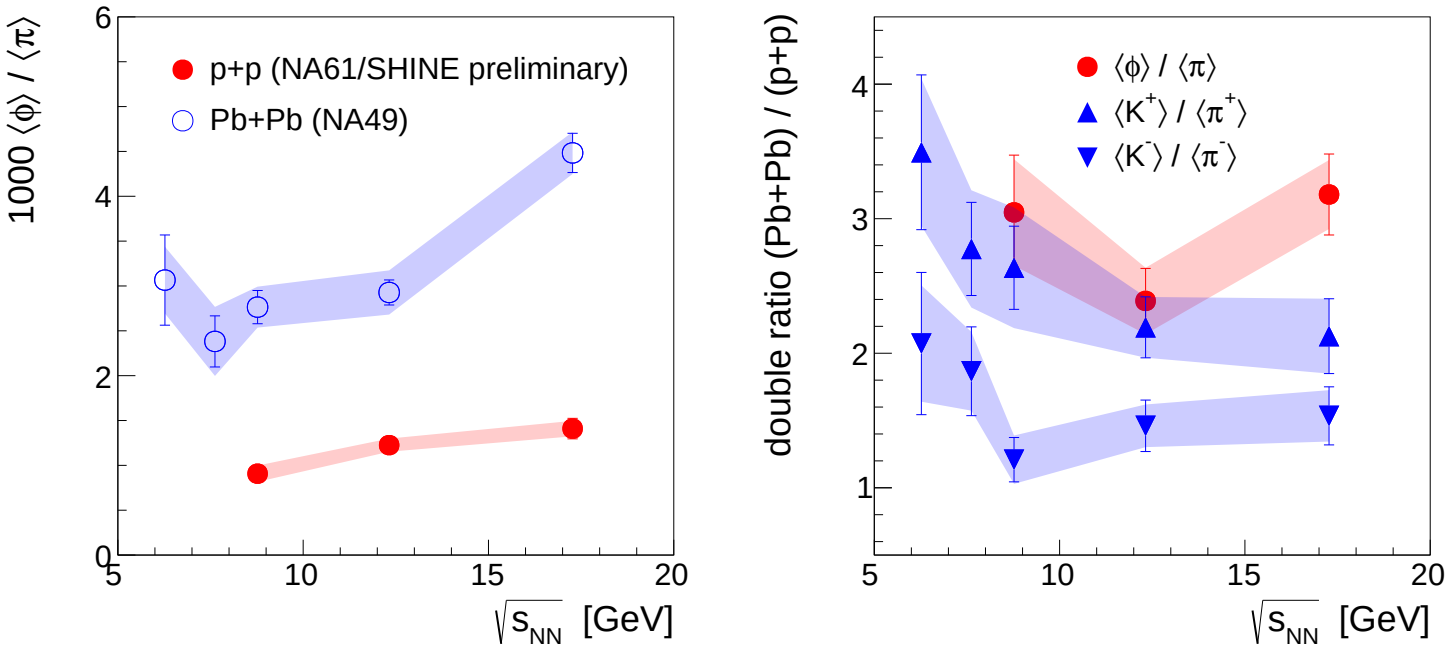
Reference data for Pb+Pb: total yield

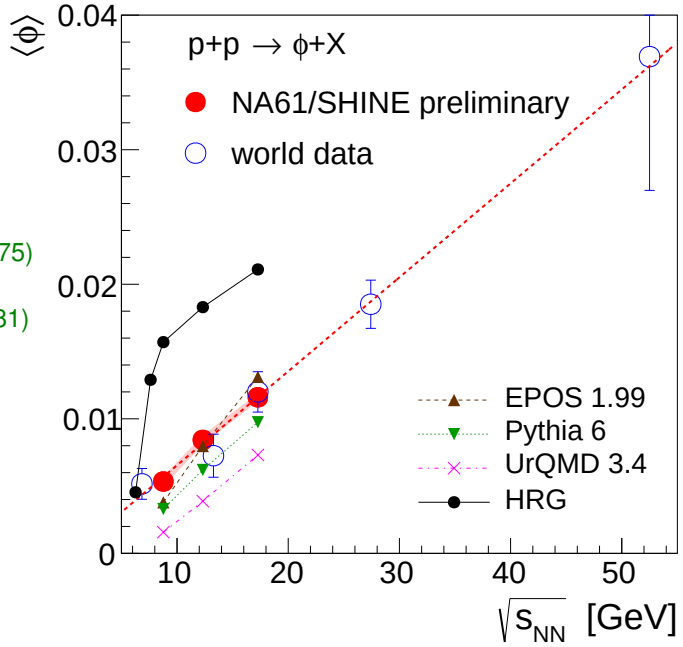
NA49: PRC 66 (2002), PRC 77 (2008), PRC 78 (2008)



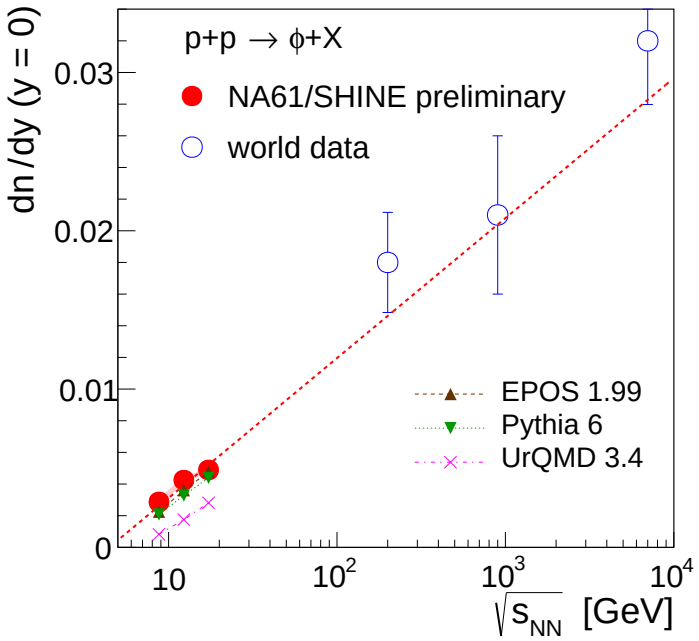
- ϕ/π ratio increases with collision energy
- Production enhancement in Pb+Pb about 3$\times$, independent of energy
- Enhancement systematically larger than for kaons, comparable to K^+
  - $\rightarrow$ for K^- consistent with strangeness enhancement in parton phase (square of K^- enhancement)

Comparison with world data and models

V. Blobel et al., PLB 59 (1975)
ACCMOR, NPB 186 (1981)
D. Drijard et al., ZPC 9 (1981)
LEBC-EHS, ZPC 50 (1991)
NA49, PLB 491 (2000)



STAR: PRC 79 (2009), ALICE: EPJC 71 (2011), EPJC 72 (2012)



p+p world data

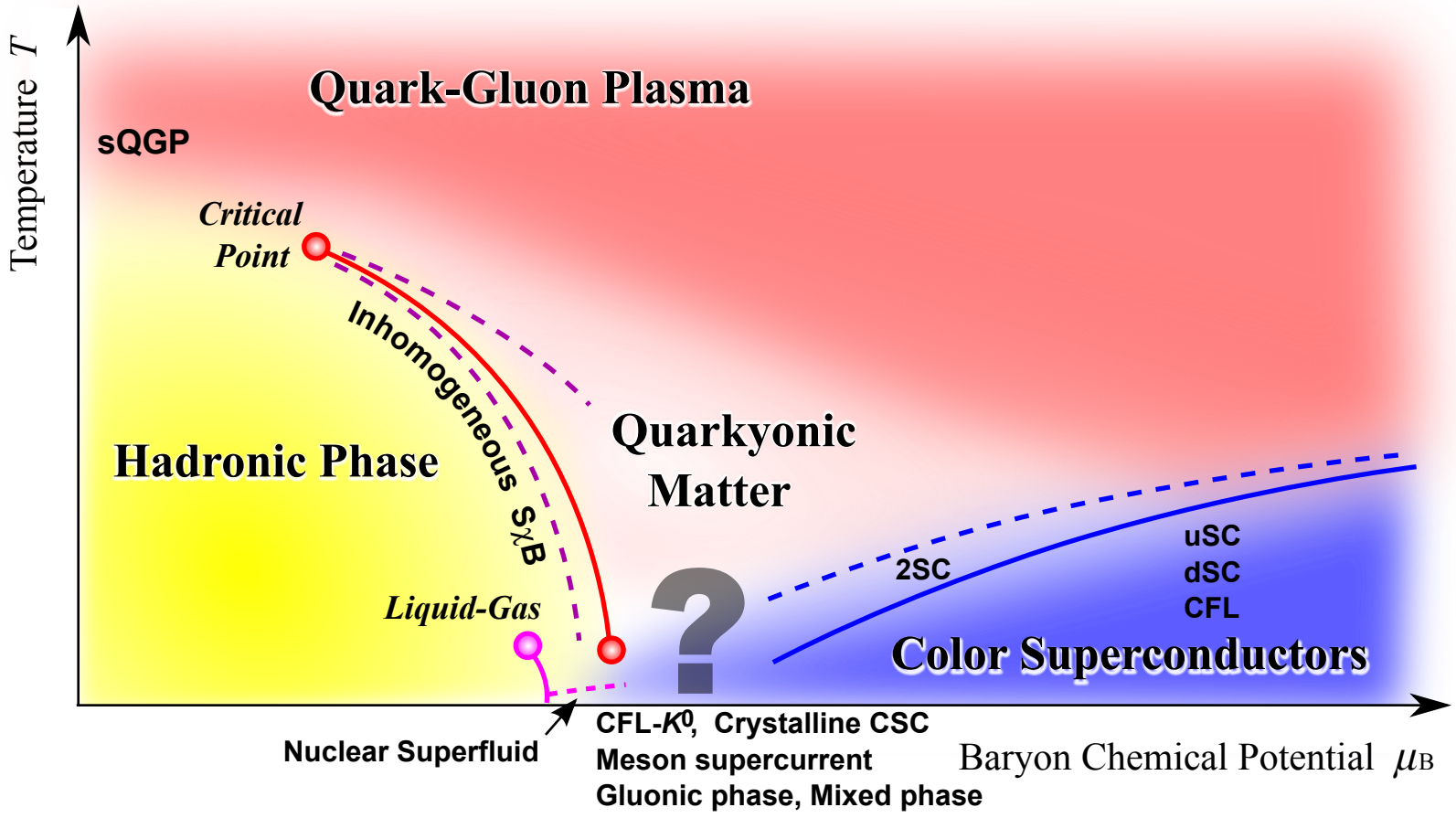
- Results consistent with world data, much more accurate

Models

- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates $\sim 2\times$, HRG (thermal) overestimates $\sim 2\times$
- EPOS rises too fast with $\sqrt{s_{NN}}$

Search for QCD critical point via intermittency analysis

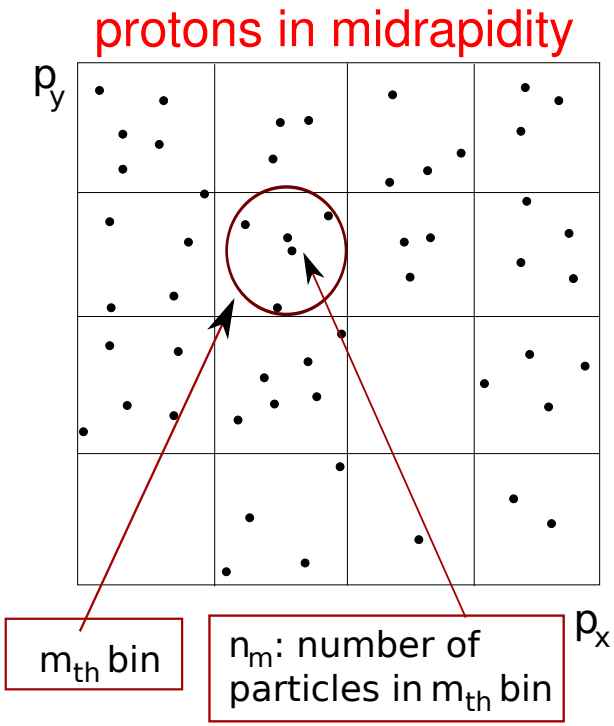
- Objective: Detection / existence of the QCD Critical Point (CP)



K. Fukushima, T. Hatsuda, Rept. Prog. Phys. 74, 014001 (2011)

- Look for observables tailored for the CP; scan phase diagram by varying energy and size of collision system

Intermittency analysis of factorial moments



$$F_2(M) \equiv \frac{\sum_m \langle n_m(n_m-1)\rangle}{\sum_m \langle n_m\rangle^2},$$

where $\langle \ldots \rangle$ denotes averaging over events

- We detect local, power-law fluctuations of baryon density by calculating the scaling of 2nd factorial moments $F_2(M)$ with cell size $\Leftrightarrow$ #cells M in transverse momentum space (intermittency).

  F. K. Diakonos et al., PoS (CPOD2006) 010, Florence

- After subtracting non-critical background moments, the correlator:

$$\Delta F_2^{(e)}(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

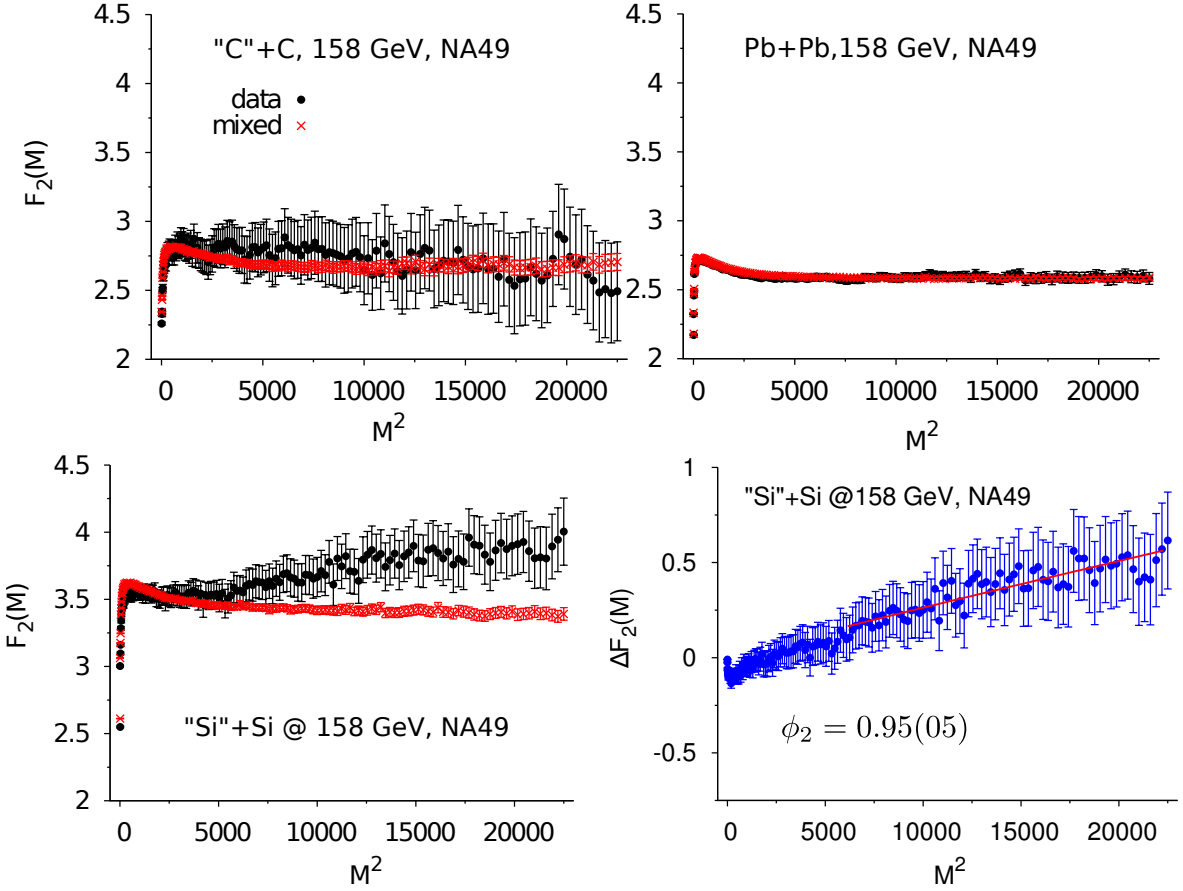
should scale according to a power-law for $M \gg 1$,

$$\Delta F_2(M) \sim \left(M^2\right)^{\varphi_2}, \varphi_{2,cr}^{(B)} = 5/6$$

N. G. Antoniou et al., Phys. Rev. Lett. **97**, 032002 (2006)

Intermittency analysis results – NA49 & NA61/SHINE

- Evidence for intermittency for protons in NA49 “Si”+Si. None detected in NA49 “C”+C and Pb+Pb datasets. T. Anticic et al., Eur. Phys. J. C 75, 587 (2015)



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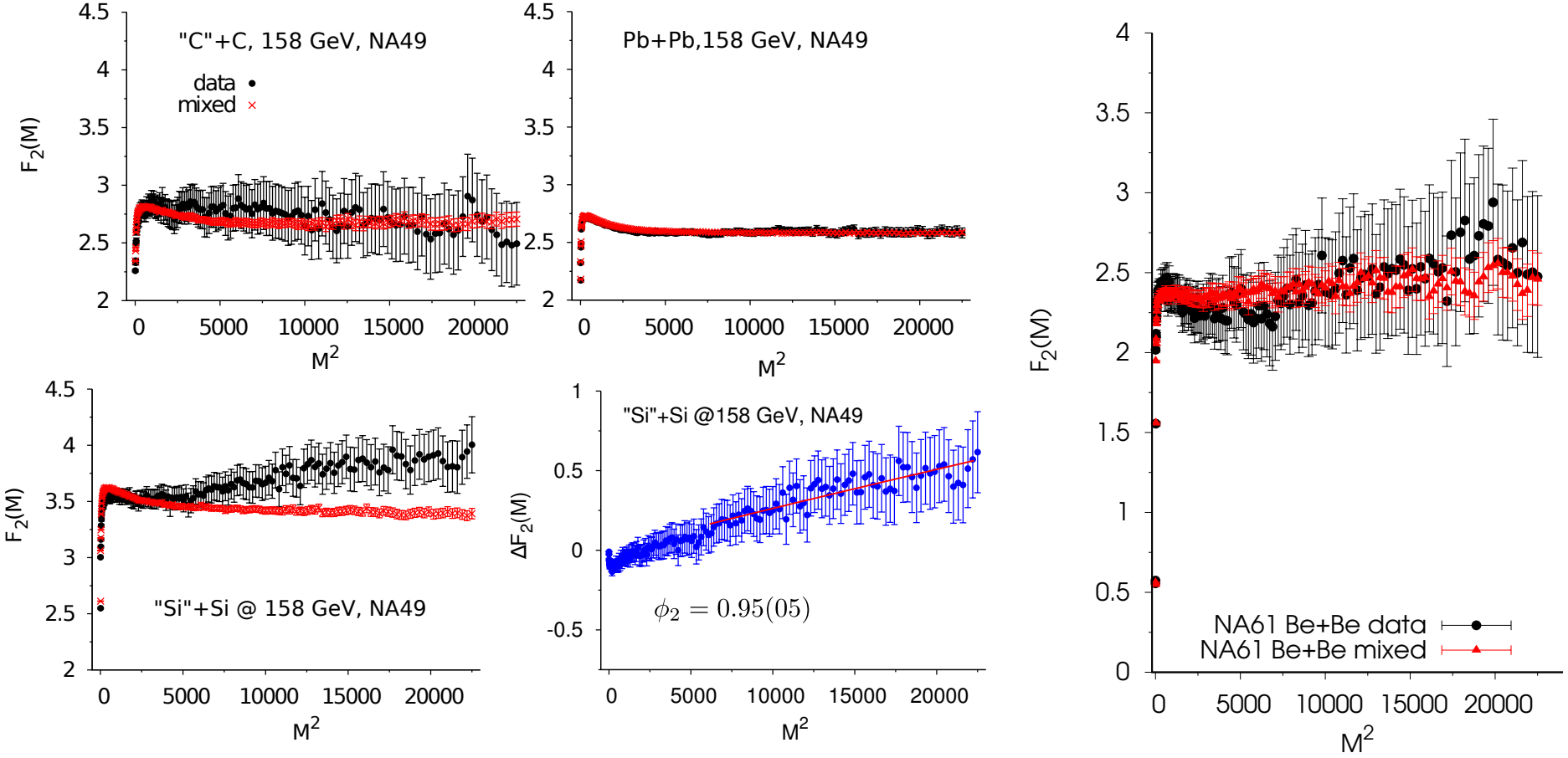
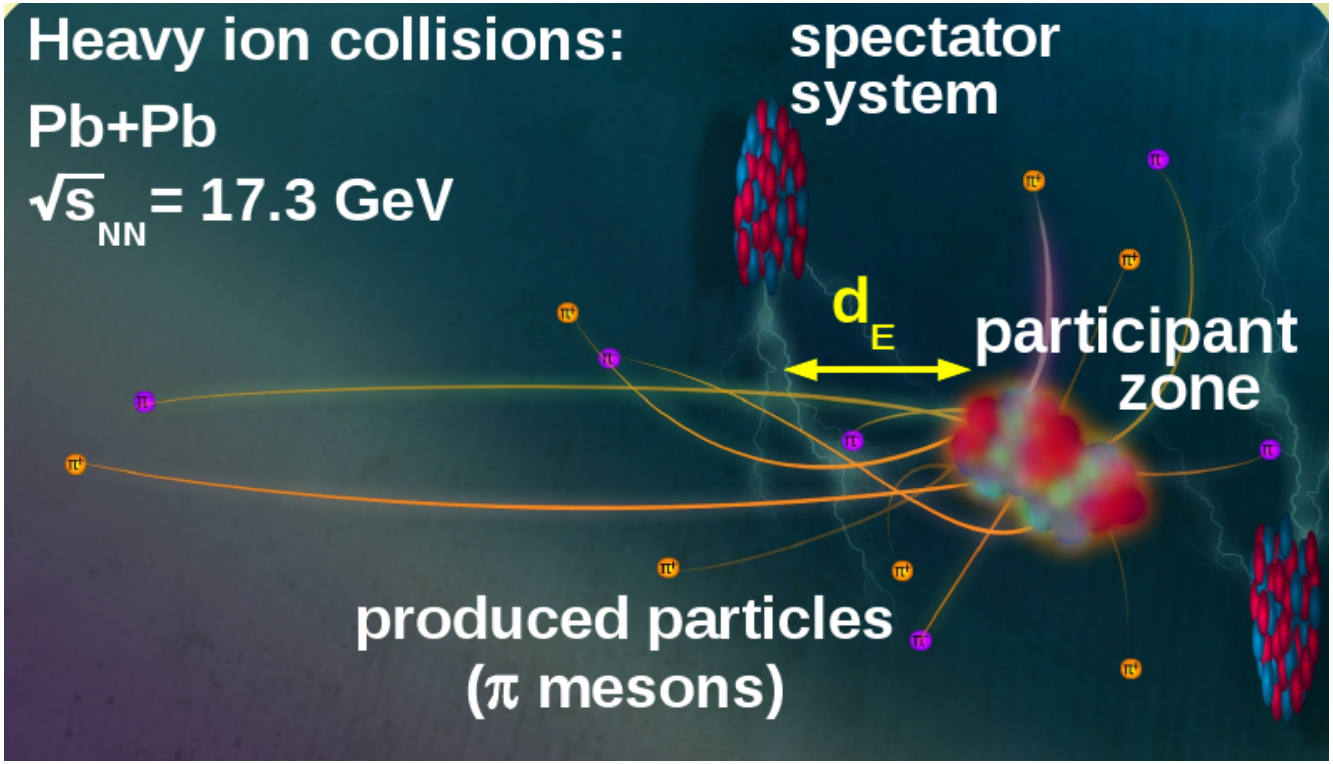


- No indication of intermittency in NA61/SHINE Be+Be @ 150 GeV
- Ar+Sc analysis ongoing

Electromagnetic effects in pion emission — introduction

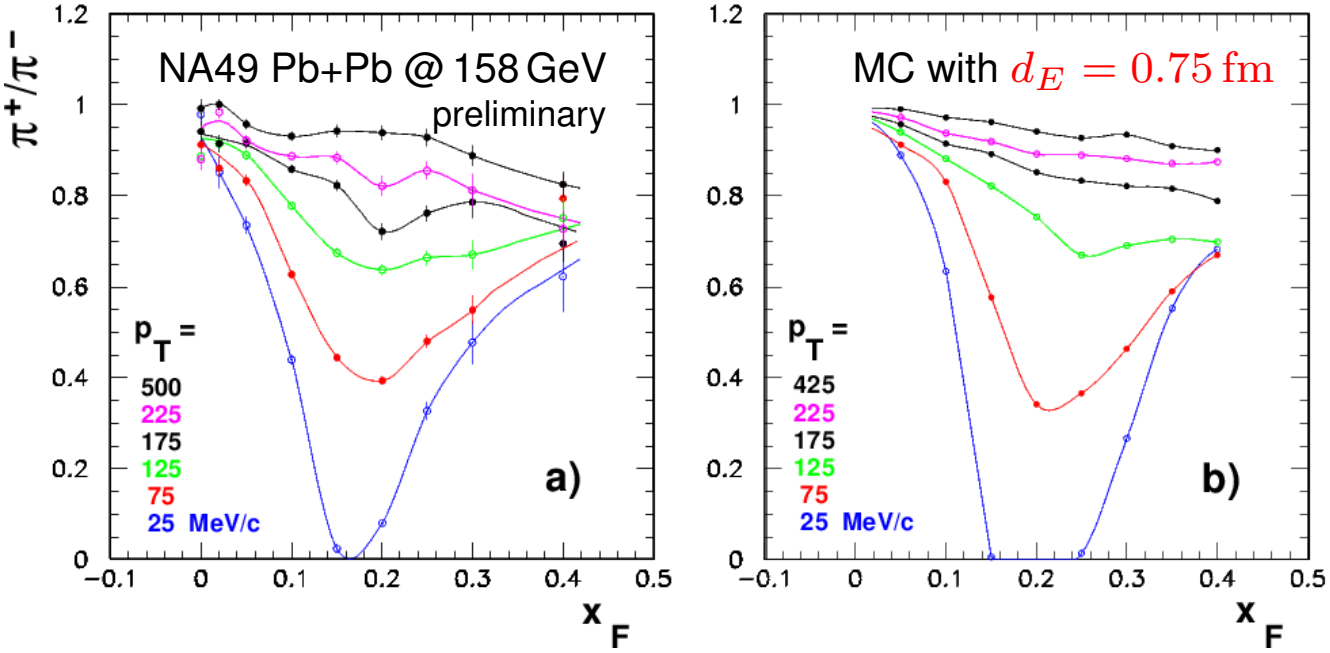


plot by I. Sputowska

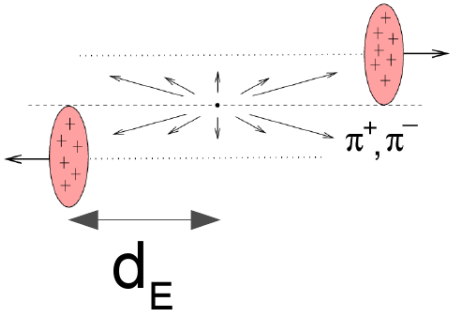
- Charged spectators in non-central collisions generate electromagnetic fields
- These modify the trajectories of final state charged particles
- By studying the resulting charge asymmetries in distributions of produced particles, we obtain information on the distance d_E

Charge asymmetries from EM effects

A. Rybicki, Acta Phys. Polon. **B42**, 867 (2011)



A. Rybicki, A. Szczurek, Phys. Rev. C **75**, 054903 (2007)



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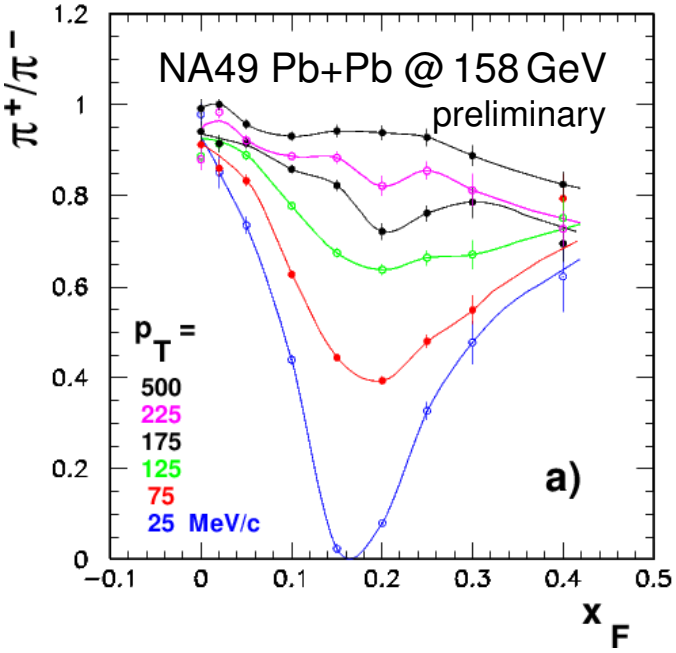

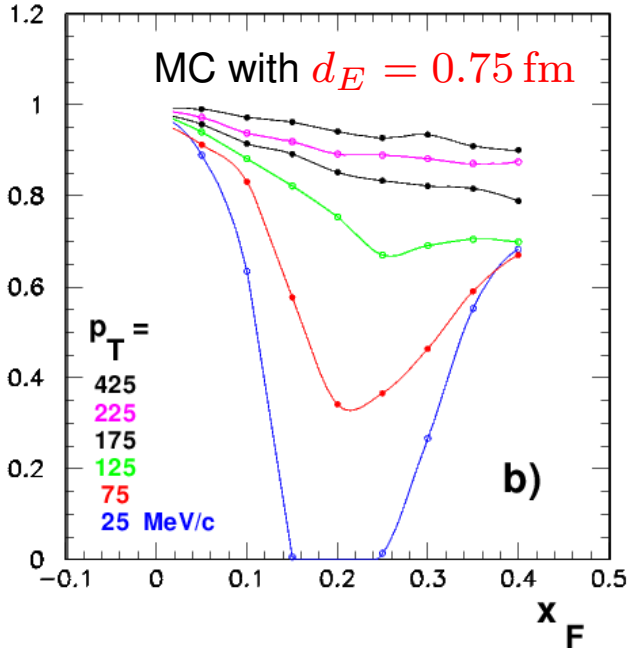

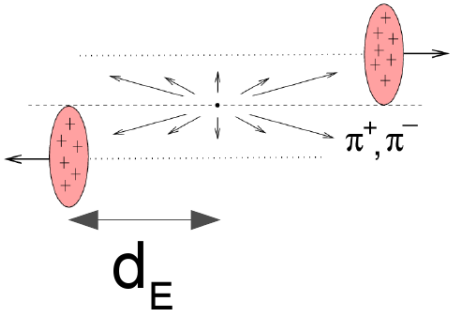

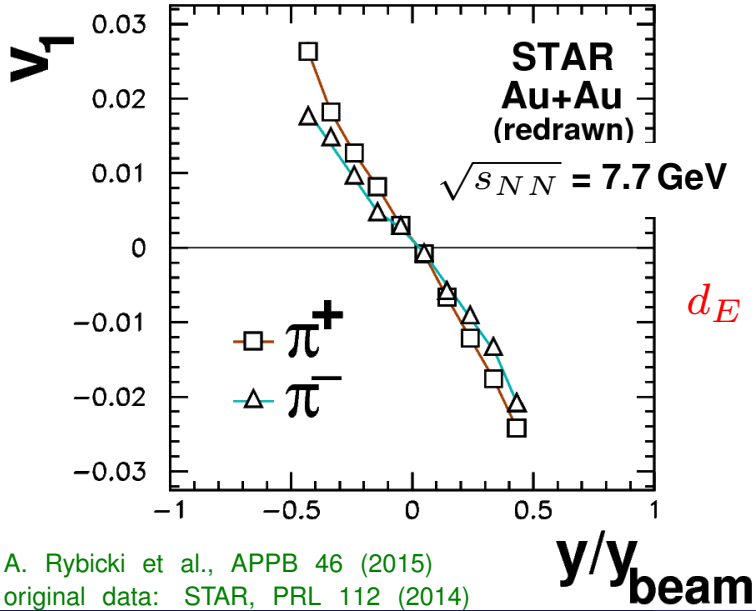

$d_E \approx 3$ fm

A. Rybicki et al., APPB 46 (2015)
original data: STAR, PRL 112 (2014)

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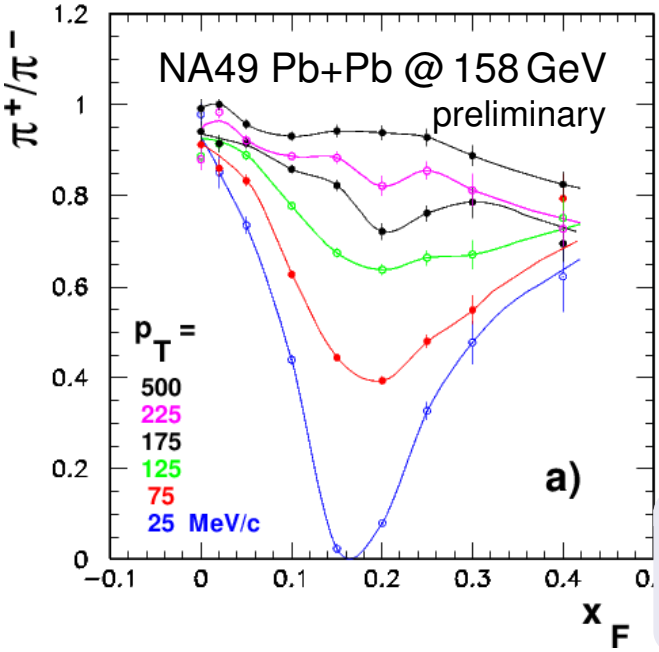

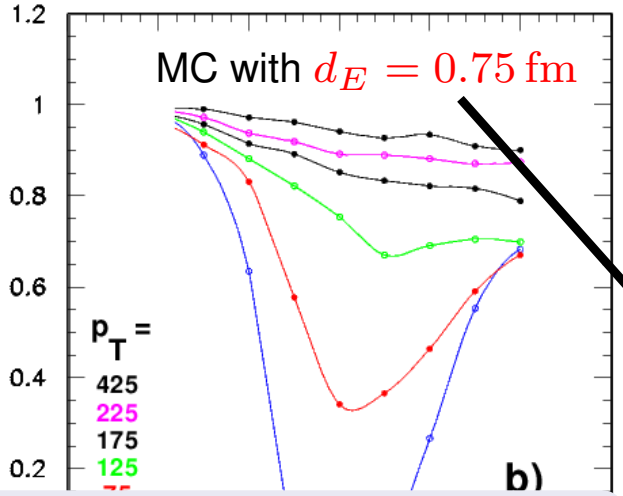

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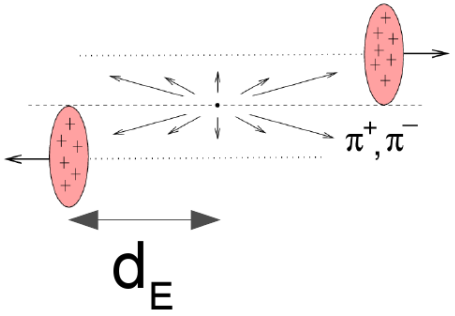
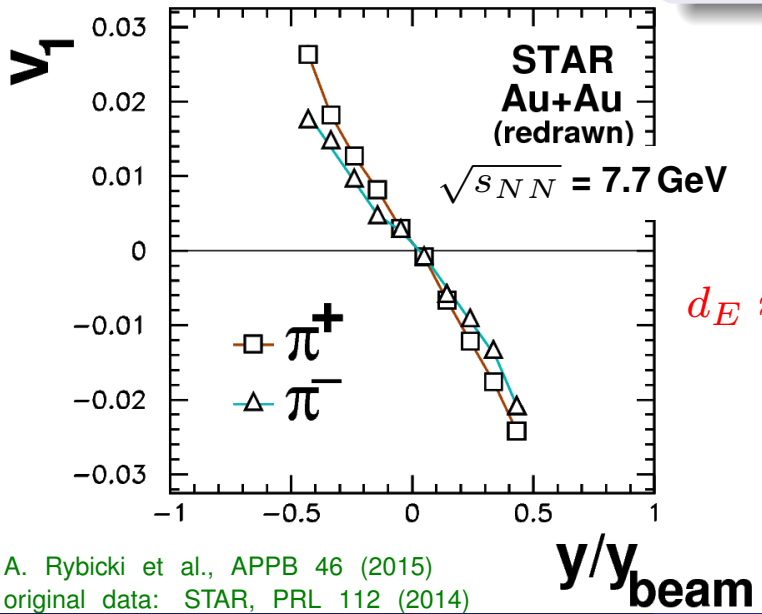


faster pions are produced closer to spectator system!



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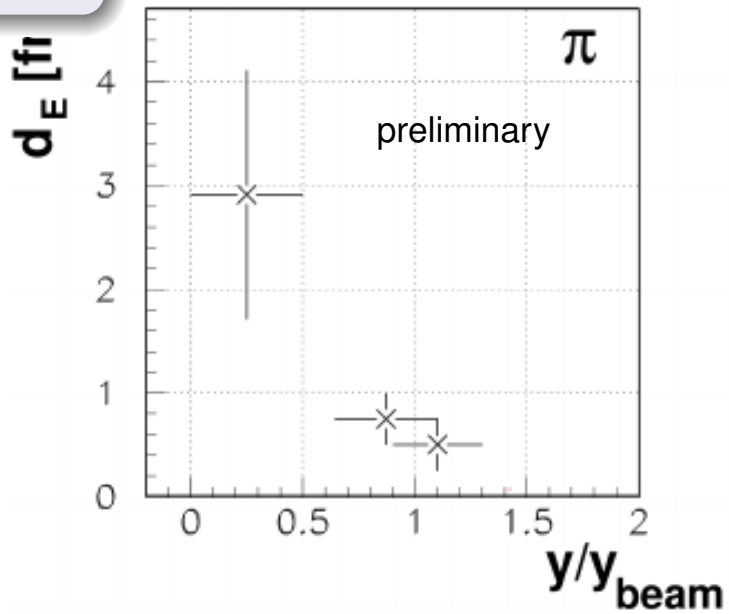
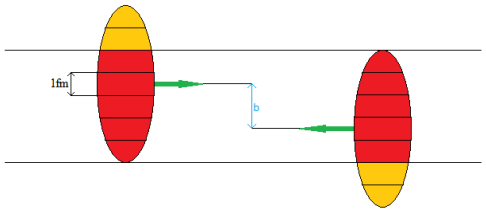


Longitudinal evolution of the system

A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

Bricks collide . . .



local energy-momentum conservation

W. D. Myers, Nucl. Phys. A **296**, 177 (1978)

. . . and form fire streaks

with rapidity from E-p conservation

Each fire streak fragments independently in pions

$$\frac{\mathrm{d}n}{\mathrm{d}y} \sim A \cdot (E_s^* - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

Longitudinal evolution of the system

A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017); data points from: T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)

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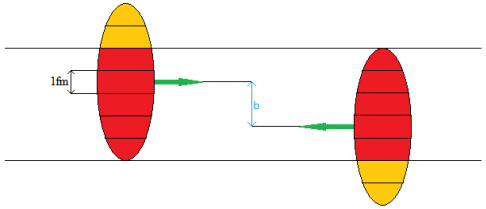

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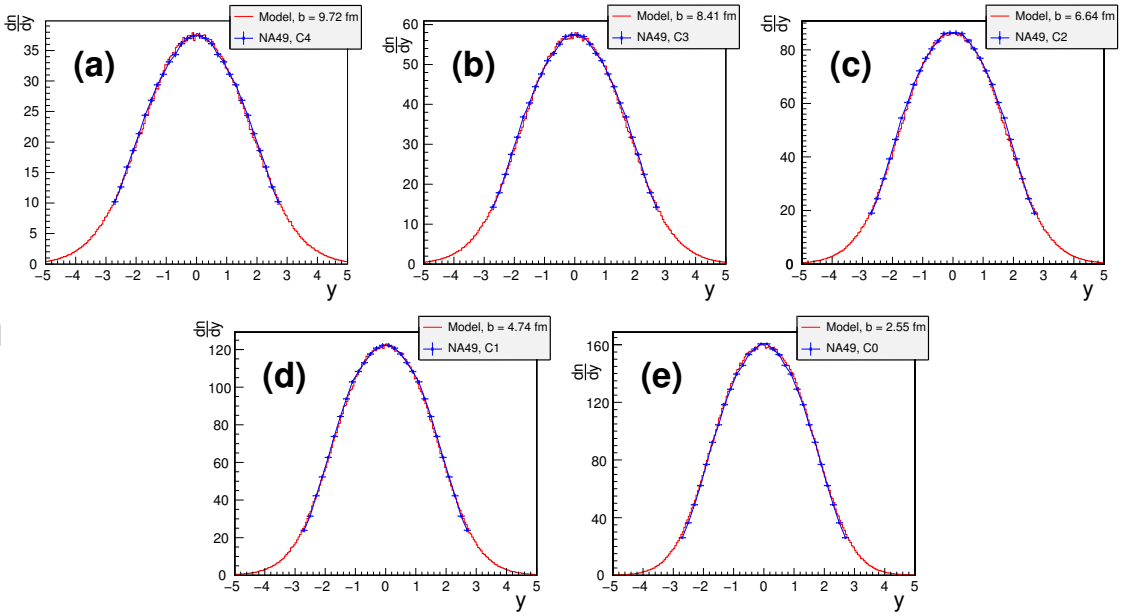
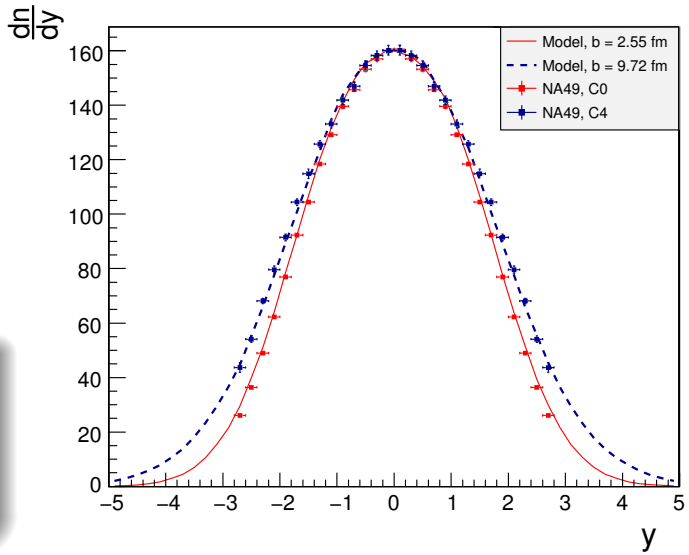


π^- in NA49 Pb+Pb @ 158 GeV



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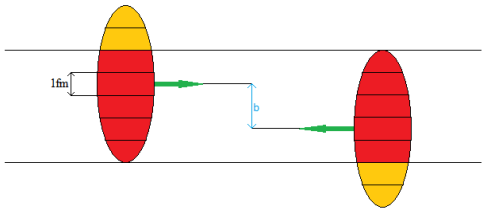

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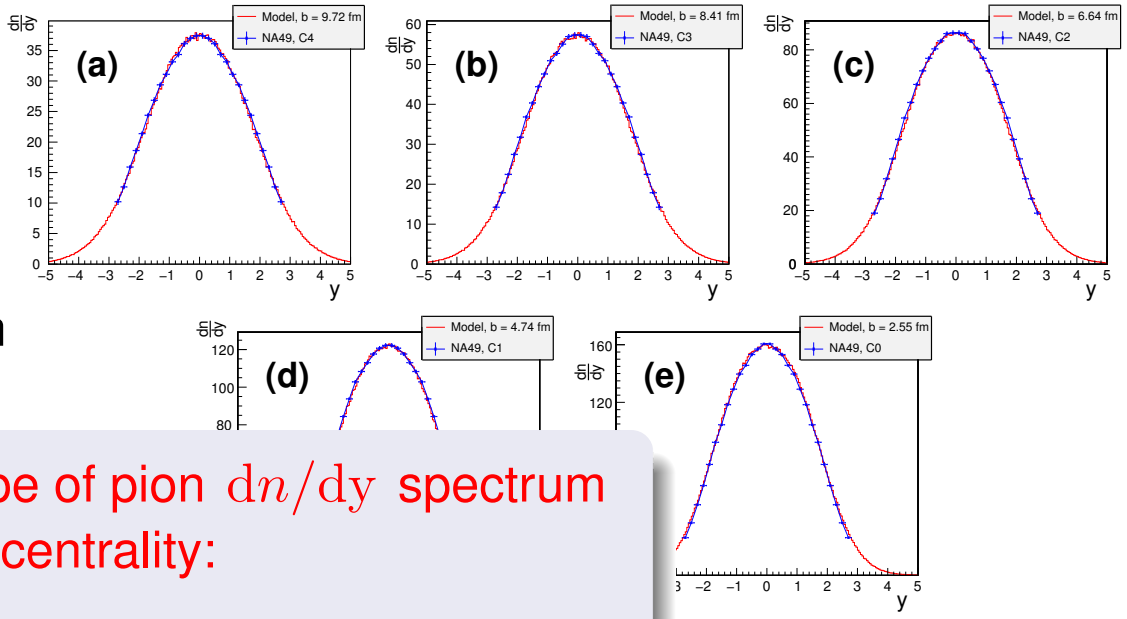

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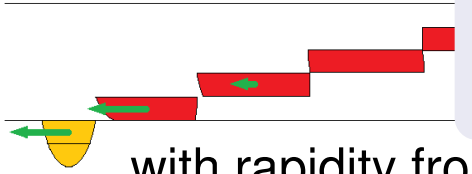
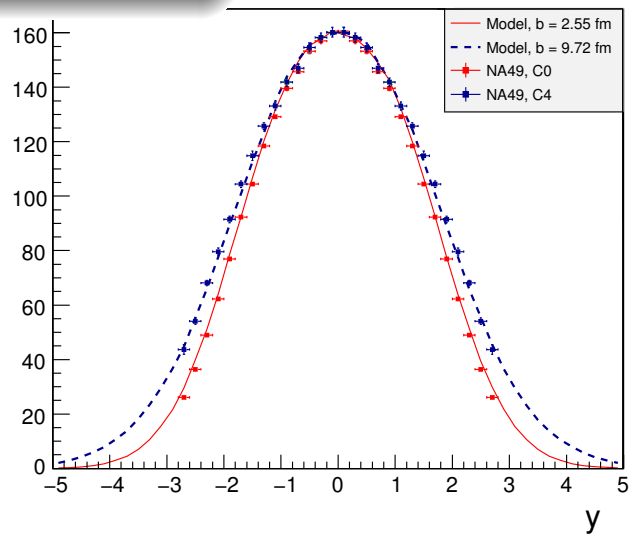


with rapidity from E-p conservation

yield and shape of pion $\mathrm{d}n/\mathrm{dy}$ spectrum as function of centrality:

only from local E-p conservation!

Pb+Pb @ 158 GeV



Each fire streak fragments independently in pions

$$\frac{\mathrm{d}n}{\mathrm{dy}} \sim A \cdot (E_{\mathrm{s}}^{*} - m_{\mathrm{s}}) \cdot \exp\left(- \frac{\left[(\mathrm{y} - \mathrm{y_s})^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_{\mathrm{y}}^{n}} \right)$$

Summary

ϕ meson production in p+p collision

- Differential (y and p_T) multiplicities at beam energies 40 GeV, 80 GeV, 158 GeV
- Non-trivial system size dependence of width of rapidity distribution (σ_{y}), contrasting with that of other mesons
- Failure of microscopic and thermal models properties

Critical Point via intermittency analysis

- Evidence for intermittency in NA49 Si+Si @ 158 GeV
- None detected in NA49 C+C, Pb+Pb @ 158 GeV, nor NA61/SHINE Be+Be @ 150 GeV

EM effects in pion emission

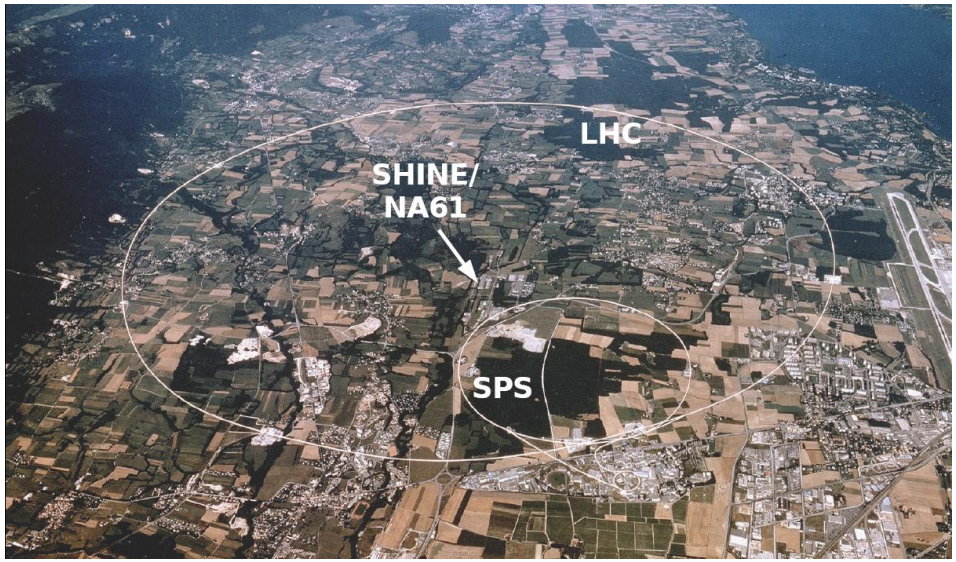
- Bring information on space-time position of pion formation zone, which is much closer to spectator for faster pions than for slower ones
- On that basis, longitudinal evolution of the system at SPS energies may be interpreted as pure consequence of energy-momentum conservation

Acknowledgements

- This work was supported by the National Science Centre, Poland (grant numbers: 2014/14/E/ST2/00018, 2015/18/M/ST2/00125)
- and the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund

BACKUP

NA61/SHINE experiment

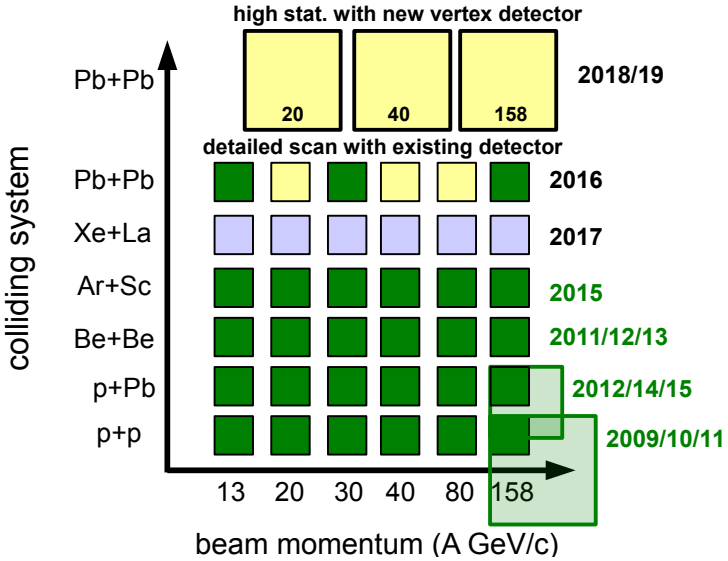


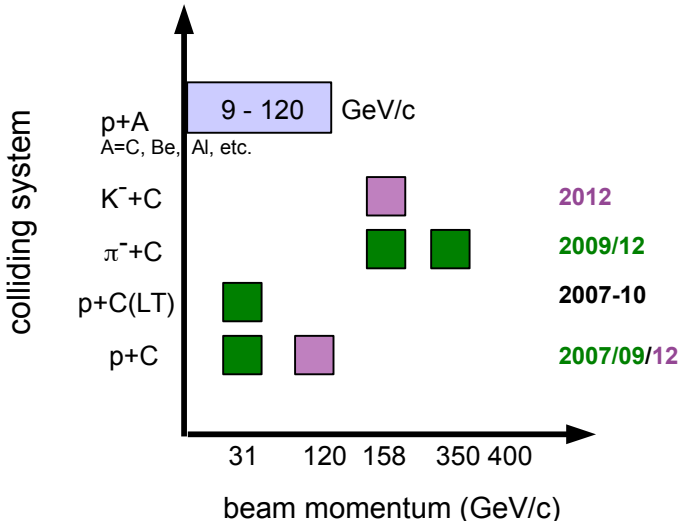
General info

- Fixed target experiment in the North (experimental) Area of CERN SPS
- Successor of NA49
- Beams
  - hadrons (secondary)
  - ions (secondary and primary)
- $\sim$150 physicists
- Physics active since 2009

Physics programme

SHINE = SPS Heavy Ion and Neutrino Experiment





Heavy ion physics

- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
- ⋆ EM interactions with spectators

Cosmic rays and neutrinos

- precision measurements of spectra
- cosmic rays: Pierre Auger Observatory, KASCADE
- neutrinos: T2K, Minerνa, MINOS, NOνA, LBNE

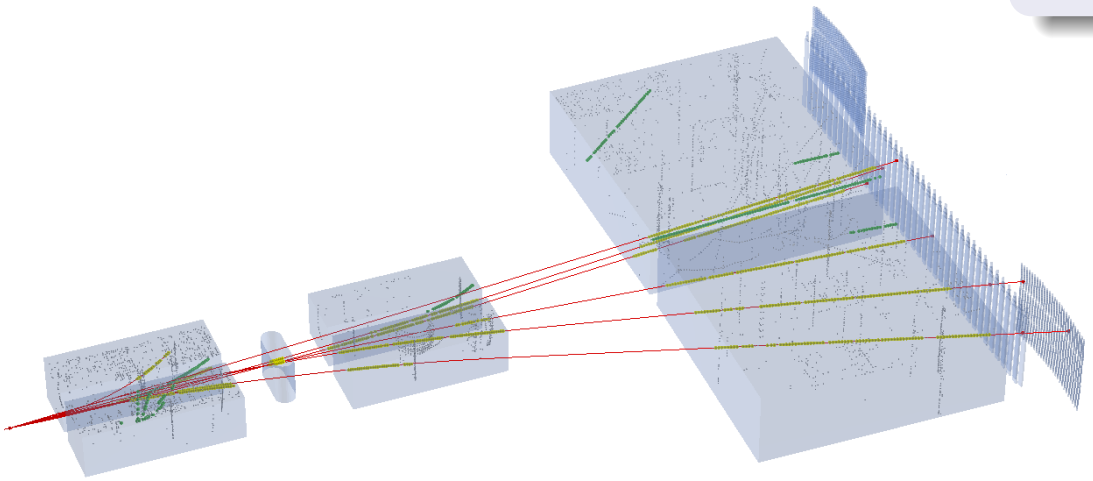
Data selection

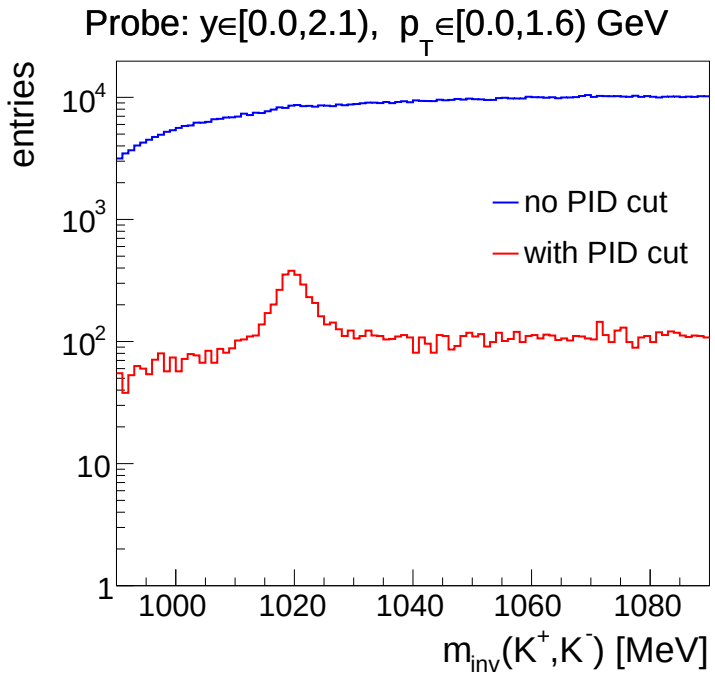
Events

- inelastic
- in the target
- with well measured main vertex

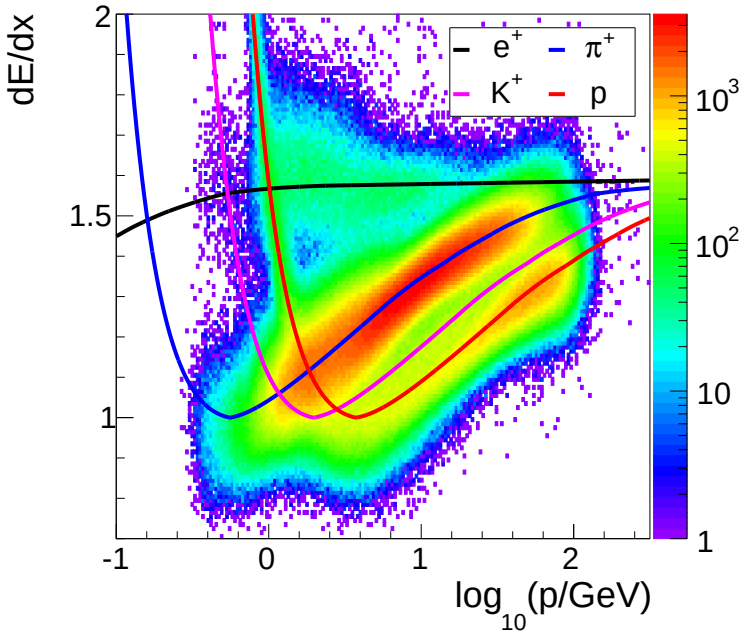
TPC tracks

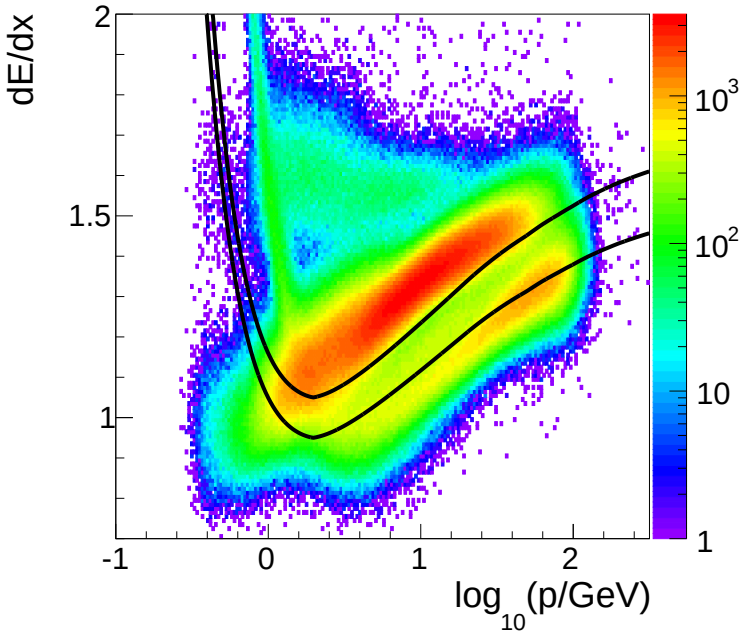
- from main vertex
- well reconstructed
- number of points in TPCs $\rightarrow$ accurate dE/dx and momentum
- with dE/dx corresponding to kaons (PID cut)





Kaon candidate selection — PID cut

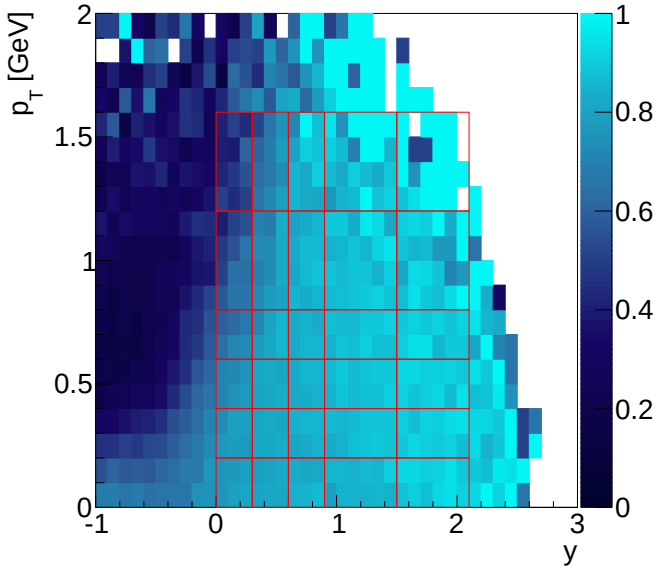


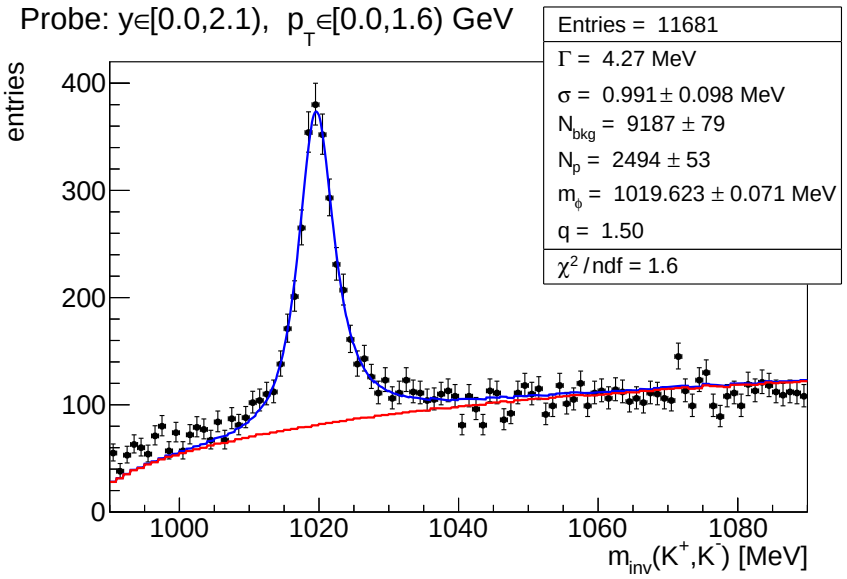


- Selection done with dE/dx
- Accept tracks in $\pm 5\,\%$ band around kaon Bethe-Bloch curve (area between black curves in right picture)
- Losses due to efficiency of this selection corrected with tag-and-probe method

Signal extraction

phase space binning, invariant mass spectrum





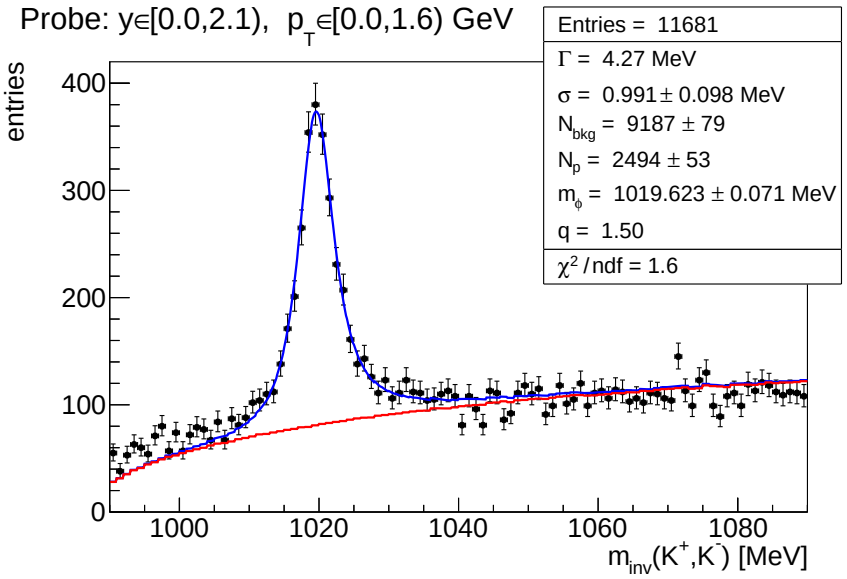
Signal extraction

phase space binning, invariant mass spectrum

Signal

Convolution of:

- relativistic Breit-Wigner $f_{\text{relBW}}(m_{\text{inv}}; m_\phi, \Gamma)$ resonance shape
- q-Gaussian $f_{\text{qG}}(m_{\text{inv}}; \sigma, q)$ broadening due to detector resolution



Background

Obtained with the event mixing method:

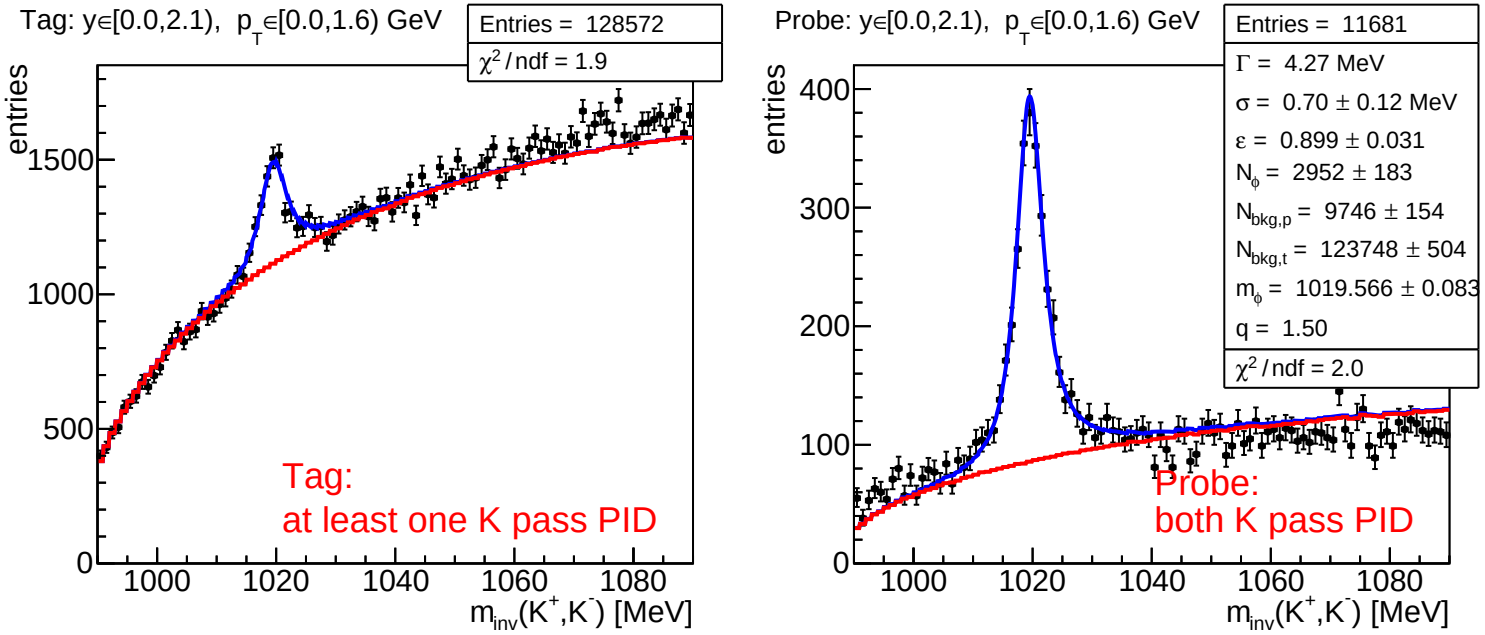
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create ϕ candidates in the mixed events spectrum

Fitting function

$$f(m_{\text{inv}}) = N_{\text{p}} \cdot (f_{\text{relBW}} * f_{\text{qG}})(m_{\text{inv}}; m_\phi, \Gamma, \sigma, q) + N_{\text{bkg}} \cdot B(m_{\text{inv}})$$

Signal extraction

tag-and-probe method → ATLAS, LHCb



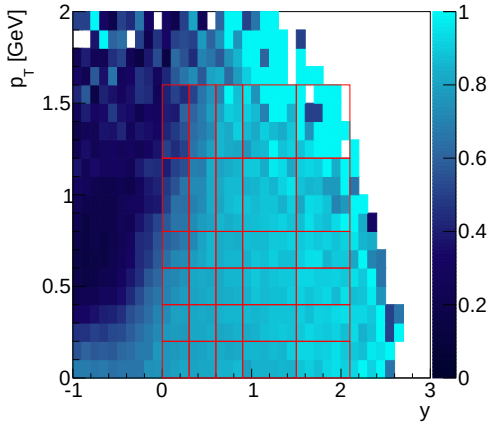
- Goal: to remove bias of N_ϕ due to PID cut efficiency ε
- Simultaneous fit of 2 spectra:
  - tag — at least one track in the pair passes PID cut

$$N_{\mathrm{t}} = N_\phi \varepsilon (2 - \varepsilon)$$

  - probe — both tracks pass PID cut

$$N_{\mathrm{p}} = N_\phi \varepsilon^2$$

Normalization and corrections



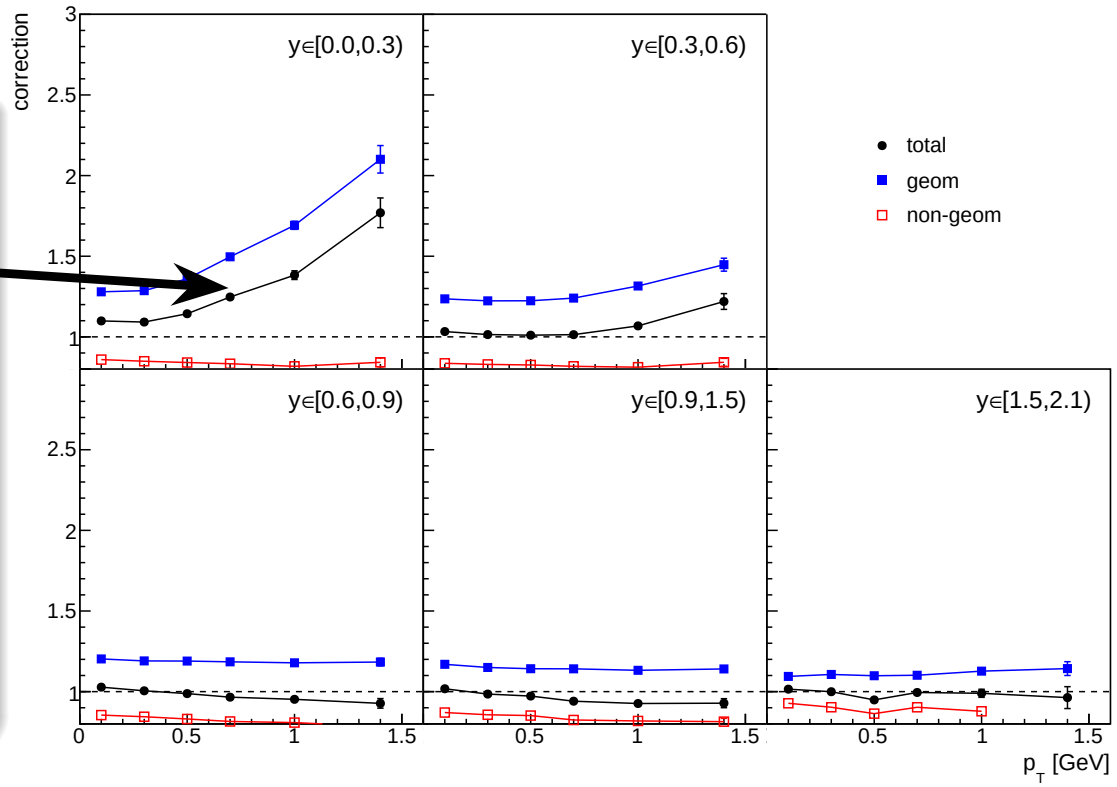
$$\frac{\mathrm{d}^2 n}{\mathrm{d}p_T\,\mathrm{d}y} = \frac{N_\phi}{N_{\text{ev}}\,\Delta p_T\,\Delta y} \times \frac{c_\infty \cdot c_{\text{bkg}} \cdot c_{\text{MC}}}{\mathcal{BR}(\phi \to K^+K^-)}$$

- $c_\infty \sim 1.06$ — extrapolation of the resonance curve
- $c_{\text{bkg}} = 1.05$ — unaccounted-for effects in the background description by event mixing

Monte Carlo correction

$$c_{\text{MC}} = \frac{N_\phi^{\text{gen}}}{N_{\text{ev}}^{\text{gen}}} \Big/ \frac{N_\phi^{\text{sel}}}{N_{\text{ev}}^{\text{sel}}}$$

- registration efficiency
- trigger bias
- losses due to vertex cuts
- reconstruction efficiency



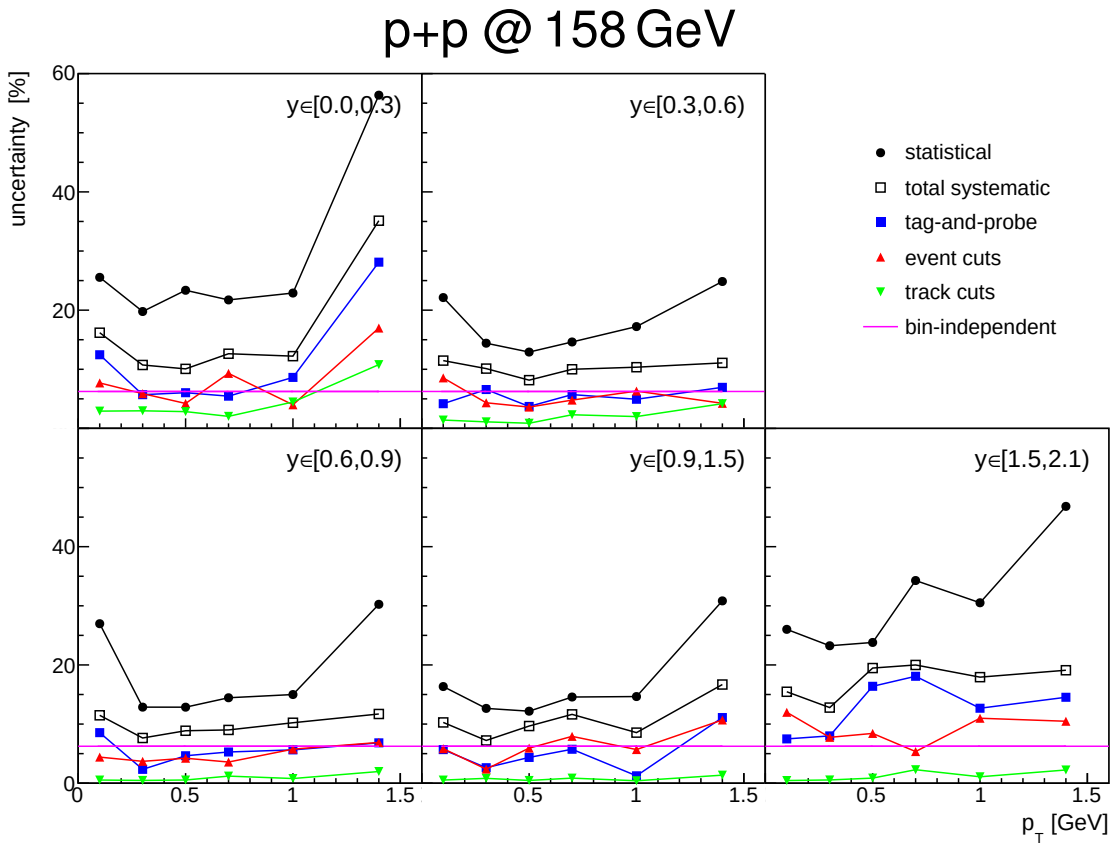
Uncertainties

Statistical

MINUIT/HESSE (symmetric)

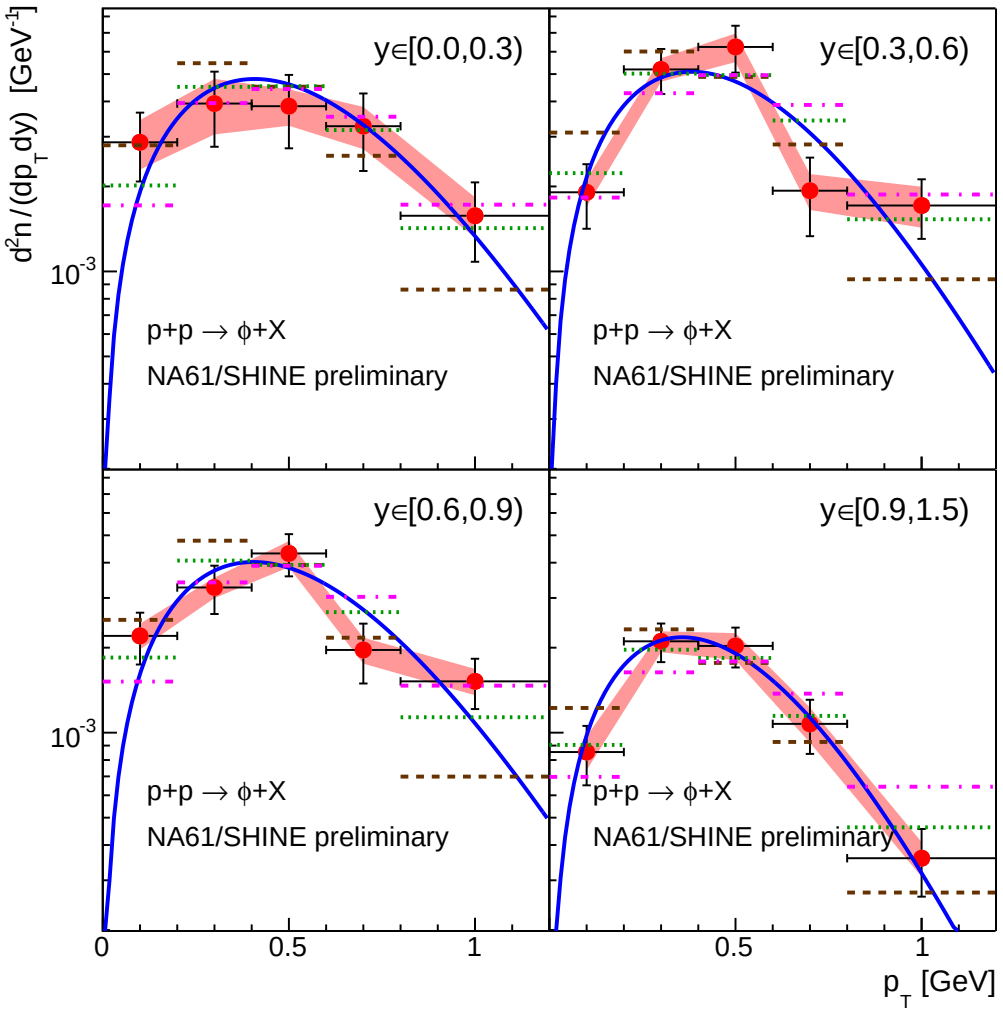
Systematic bin-independent

Source	value [%]
$\mathcal{BR}(\phi \to K^+K^-)$	1
fitting constraints	2
resonance theory	3
background	5
Total (quadratic)	6



- Total systematic uncertainty $= \sqrt{\sum \sigma_i^2}$
- For p+p @ 40 GeV additional bin-independent 3 % due to c_{MC} averaging
- Statistical uncertainty dominates

Double differential spectra: p+p @ 80 GeV



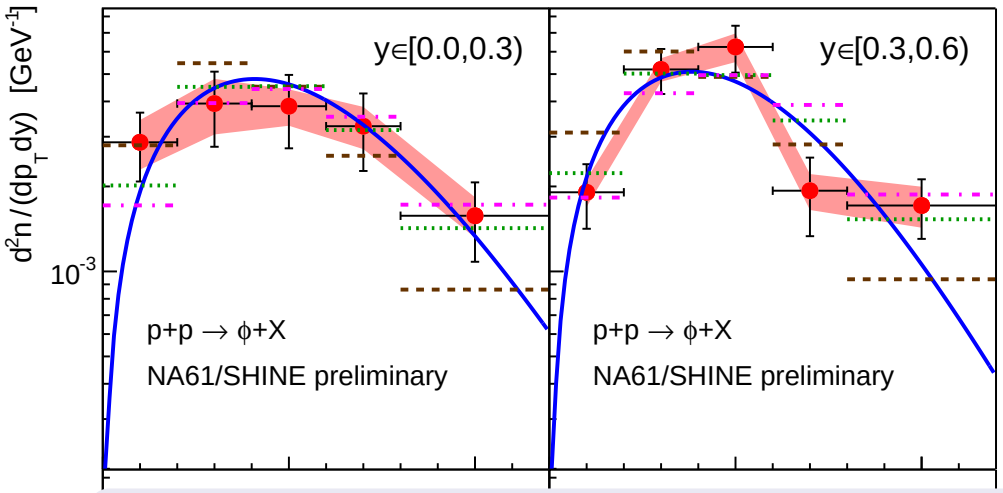
$\sqrt{s_{NN}}$ = 12.3 GeV

- EPOS 1.99
- Pythia 6
- UrQMD 3.4

MC normalization:
$\int$ model $=$ $\int$ data

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty$ $\rightarrow$ tail $< 4\,\%$

Double differential spectra: p+p @ 80 GeV



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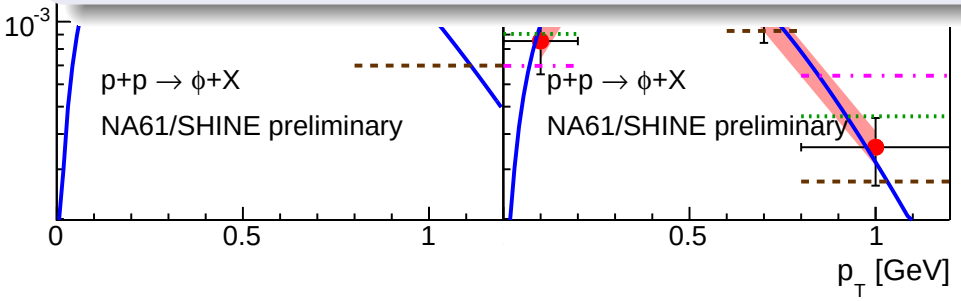
- First ϕ production measurements for p+p @ 80 GeV



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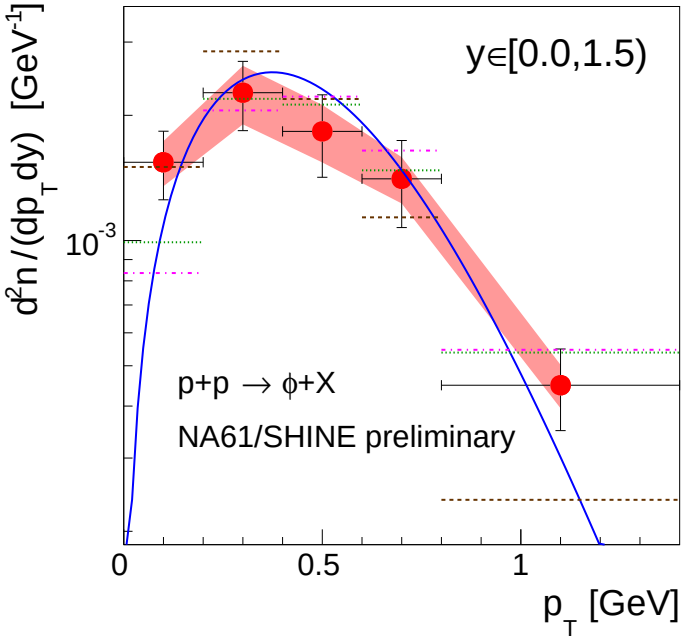
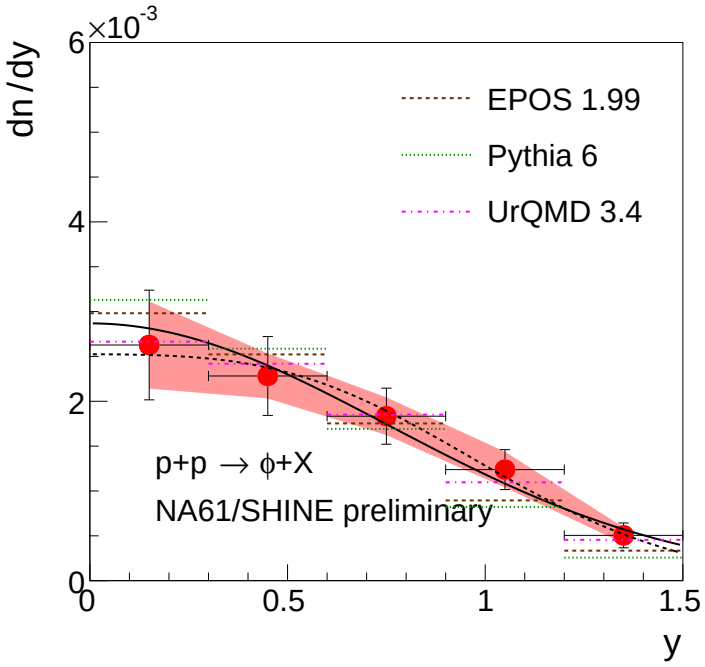
- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty$ $\rightarrow$ tail $< 4\,\%$

Single differential spectra: p+p @ 40 GeV





$\sqrt{s_{NN}}$ = 8.8 GeV

MC normalization:
$\int$ model $=$ $\int$ data

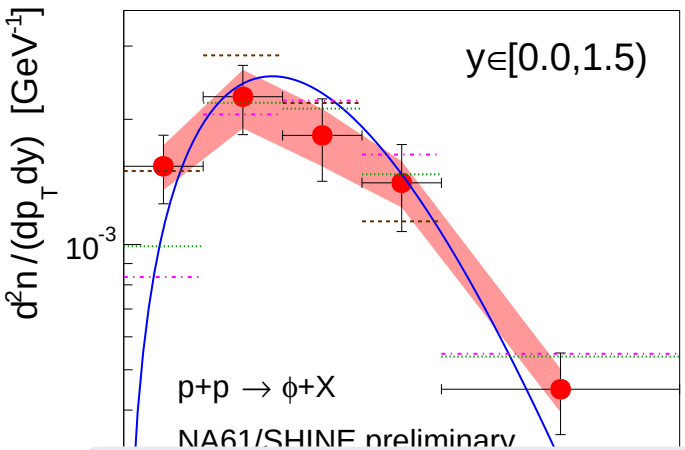
p_T

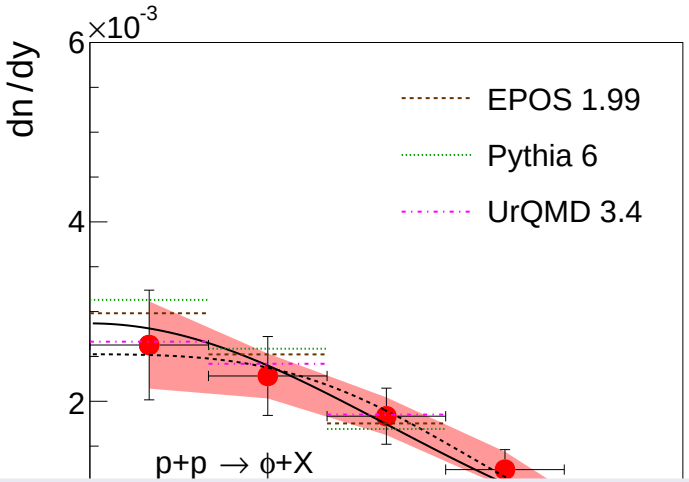
- Pythia agrees best, UrQMD similar, EPOS spectrum too short tail
- extrapolation tail $< 1\,\%$

y

- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail $5\,\%$

Single differential spectra: p+p @ 40 GeV





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MC normalization:
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y

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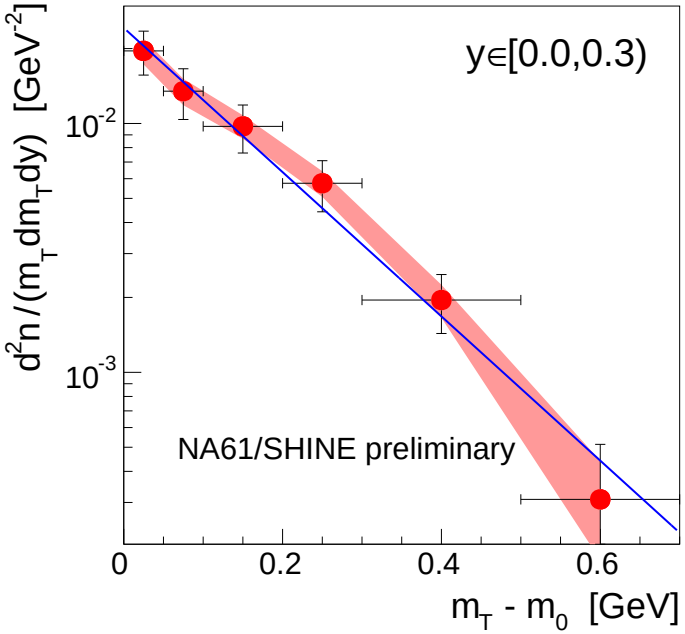
- extrapolation tail $5\,\%$

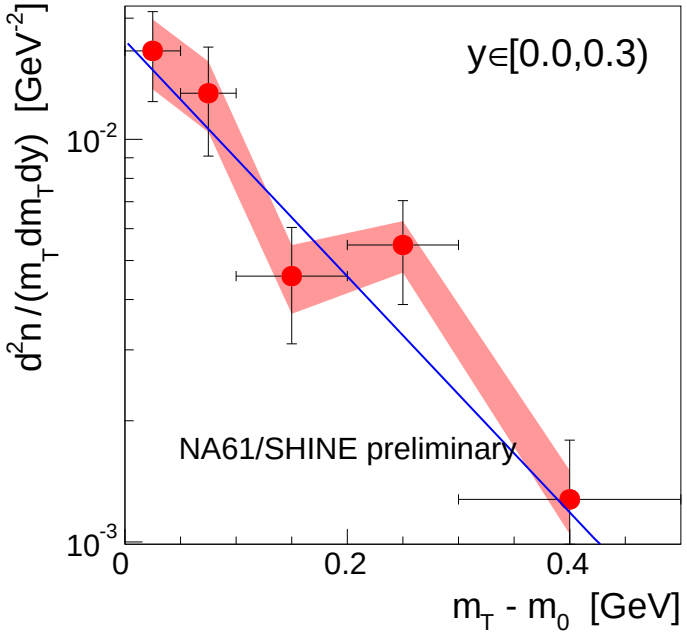
Transverse mass spectra at midrapidity

p+p @ 158 GeV



$\sqrt{s_{NN}}$ = 17.3 GeV

p+p @ 80 GeV



$\sqrt{s_{NN}}$ = 12.3 GeV

Thermal fit results

p_{beam} [GeV]	T_ϕ [MeV]	T_{π^-} [MeV]
158	$150 \pm 14 \pm 8$	$159.3 \pm 1.3 \pm 2.6$
80	$148 \pm 30 \pm 17$	$159.9 \pm 1.5 \pm 4.1$

Observing power-law fluctuations

Experimental observation of local, power-law distributed fluctuations

$\Downarrow$

Intermittency in transverse momentum space (net protons at mid-rapidity)

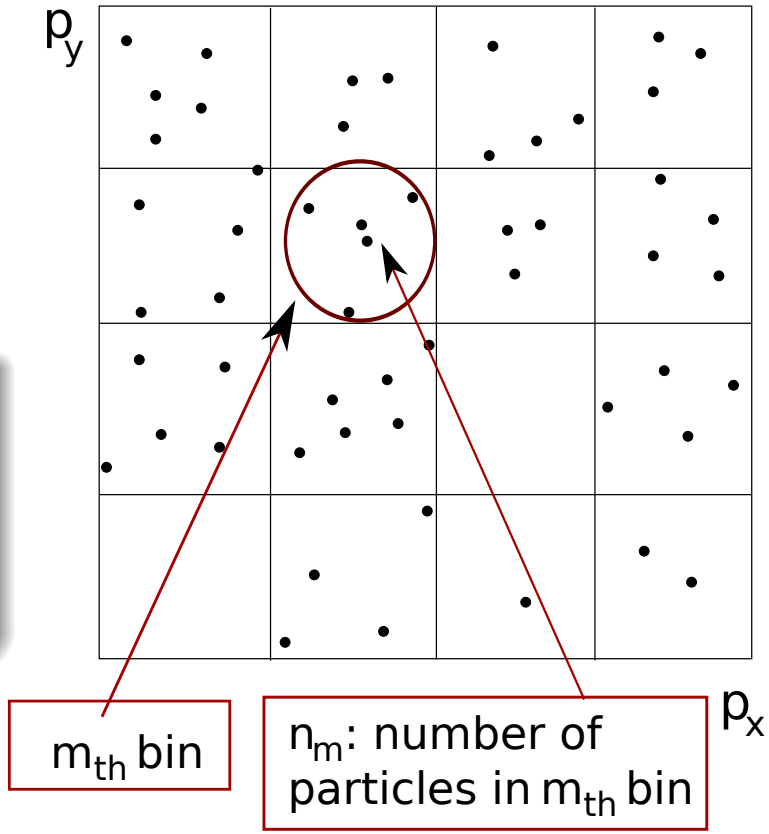
(Critical opalescence in ion collisions)

F. K. Diakonos et al., PoS (CPOD2006) 010, Florence

- Transverse momentum space is partitioned into M^2 cells
- Calculate second factorial moments $F_2(M)$ as a function of cell size $\Leftrightarrow$ number of cells M:

$$F_2(M) \equiv \frac{\sum_m \langle n_m(n_m-1)\rangle}{\sum_m \langle n_m\rangle^2},$$

where $\langle \ldots \rangle$ denotes averaging over events.



Subtracting the background from factorial moments

- Experimental data is noisy $\Rightarrow$ a background of uncorrelated/non-critical pairs must be subtracted at the level of factorial moments.
- Intermittency will be revealed at the level of subtracted moments $\Delta F_2(M)$.

Partitioning of pairs into critical/background

$$\langle n(n-1)\rangle = \underbrace{\langle n_c(n_c-1)\rangle}_{\text{critical}} + \underbrace{\langle n_b(n_b-1)\rangle}_{\text{background}} + \underbrace{2\,\langle n_b n_c\rangle}_{\text{mixed term}}$$

$$\underbrace{\Delta F_2(M)}_{\text{correlator}} = \underbrace{F_2^{(d)}(M)}_{\text{data}} - \lambda(M)^2\,\underbrace{F_2^{(b)}(M)}_{\text{background}} - 2\,\underbrace{\lambda(M)}_{\text{ratio } \frac{<n>_b}{<n>_d}}\,(1-\lambda(M))f_{bc}$$

- The mixed term can be neglected for dominant background (non-trivial! Justified by CMC simulations)

Scaling of factorial moments – Subtracting mixed events

For $\lambda \lesssim 1$ (background domination), $\Delta F_2(M)$ can be approximated by:

$$\Delta F_2^{(e)}(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

For a critical system, ΔF_2 scales with cell size (number of cells, M) as:

$$\Delta F_2(M) \sim \left(M^2\right)^{\varphi_2}$$

where φ_2 is the intermittency index.

Theoretical predictions for φ_2

universality class, effective actions

$$\varphi_{2,cr}^{(\sigma)} = \frac{2}{3}\ (0.66\ldots)$$

sigmas (neutral isoscalar dipions)

N. G. Antoniou et al., Nucl. Phys. A **693**, 799 (2001)

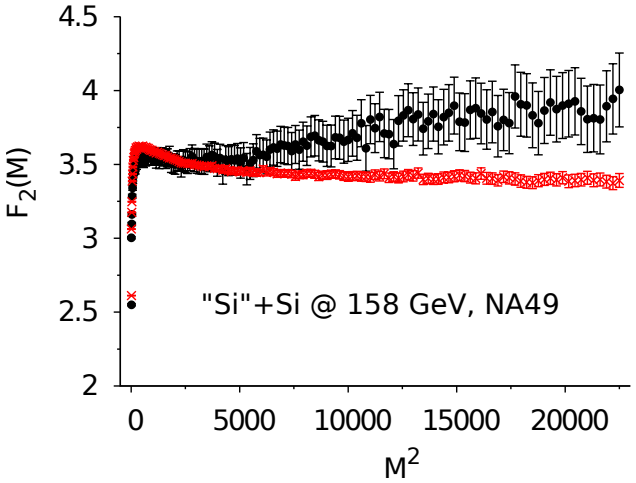
$$\varphi_{2,cr}^{(p)} = \frac{5}{6}\ (0.833\ldots)$$

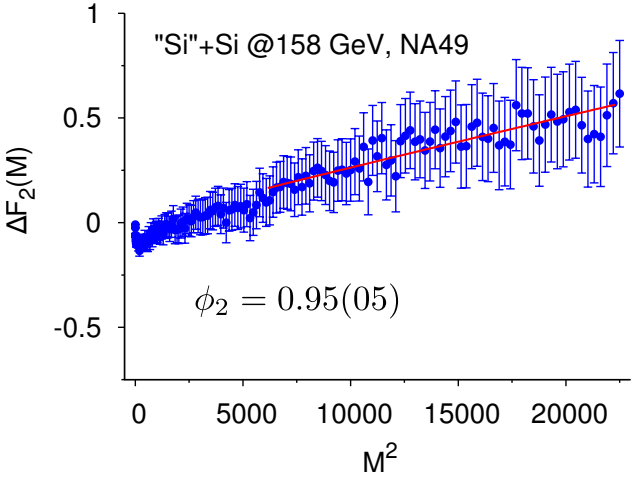
net baryons (protons)

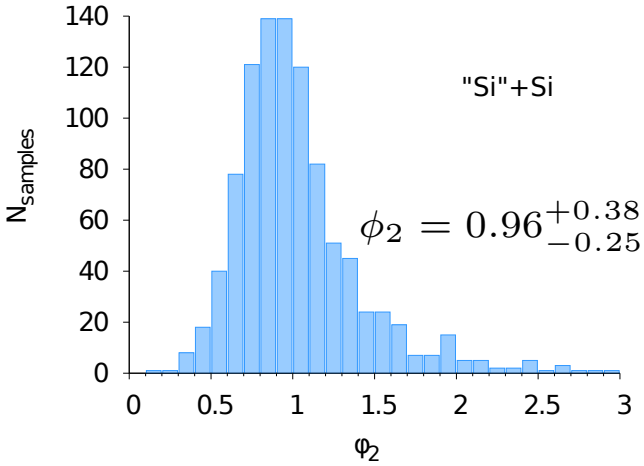
N. G. Antoniou et al., Phys. Rev. Lett. **97**, 032002 (2006)

Intermittency analysis results – NA49 “Si”+Si

- Evidence for intermittency in “Si”+Si – but large statistical errors.
- No intermittency detected in the “C”+C, Pb+Pb datasets.
- Fit with $\Delta F_2^{(e)}(M\ ;\ \mathcal{C}, \phi_2) = e^{\mathcal{C}} \cdot \left(M^2\right)^{\phi_2}$, for $M^2 \geq 6000$







- Bootstrap distribution of ϕ_2 values is highly asymmetric due to closeness of $F_2^{(d)}(M)$ to $F_2^{(m)}(M)$.
- The spread is partly artificial due to pathological fits (negative $\Delta F_2(M)$ values in some bootstrap samples)

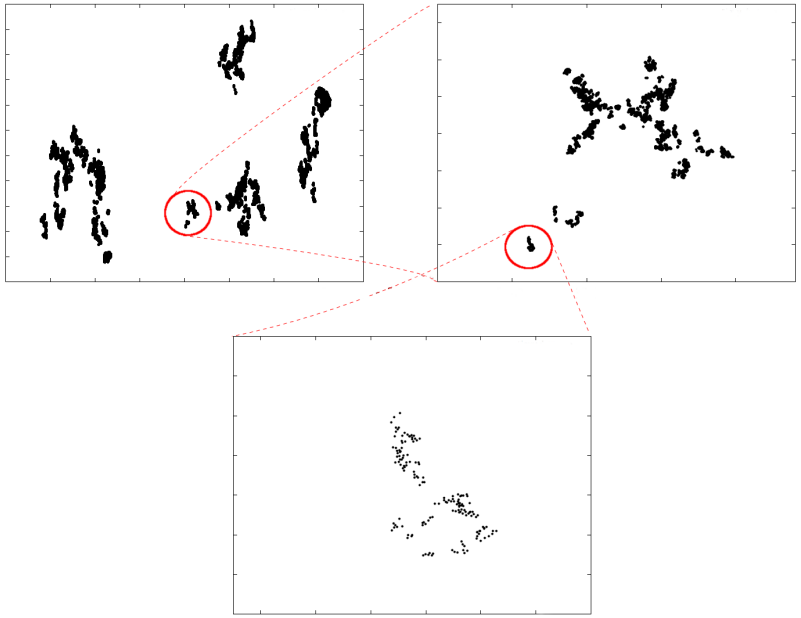
Simulating a system of critical baryons

- Simplified version of CMC code:

  Antoniou et al., Phys. Rev. Lett. 97, 032002 (2006)

  - Only protons produced
  - One cluster per event, produced by random Lévy walk: $\tilde{d}_F^{(B,2)} = 1/3 \Rightarrow \phi_2 = 5/6$
  - Lower / upper bounds of Lévy walks $p_{\text{min,max}}$ plugged in.
  - Cluster center exponential in p_T, slope adjusted by T_c parameter.
  - Poissonian proton multiplicity distribution.

Lévy walk example

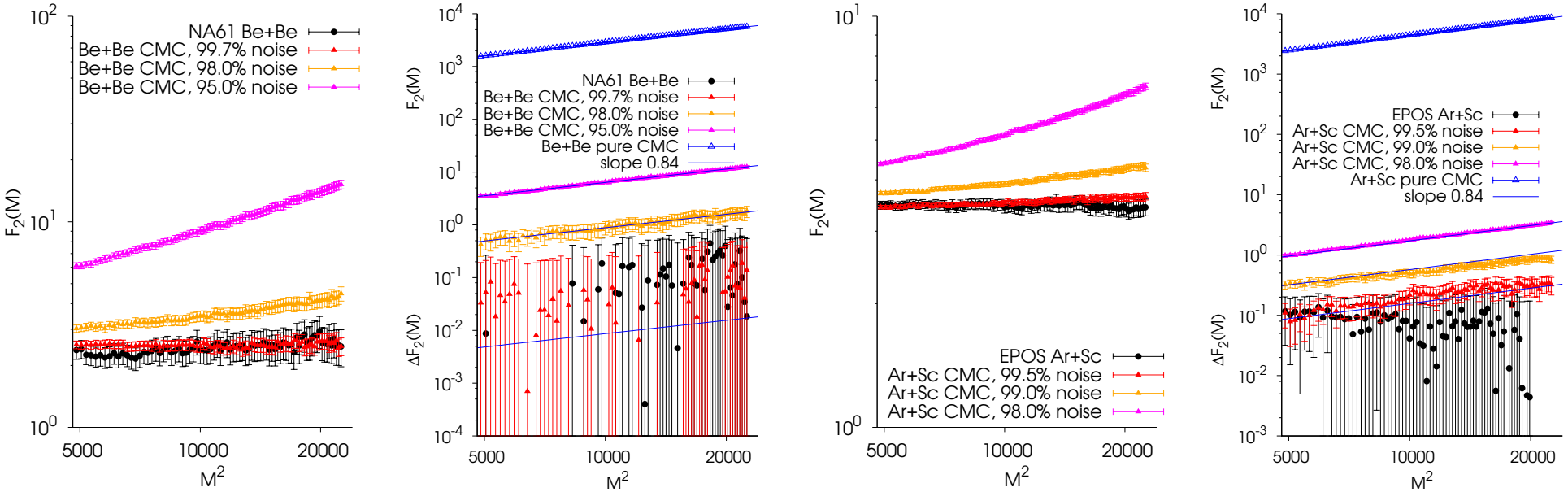


Input parameters

Parameter	p_{min} [MeV]	p_{max} [MeV]	λ_{Poisson}	T_c [MeV]
Value	$0.1 \rightarrow 1$	$800 \rightarrow 1200$	$\langle p \rangle$	163

Critical Monte Carlo + background simulation of data

- Mixing CMC with random proton tracks (noise) allows us to estimate the fraction of critical protons in the analysed data sets.
- $F_2(M)$ levels of noisy CMC & data should match.



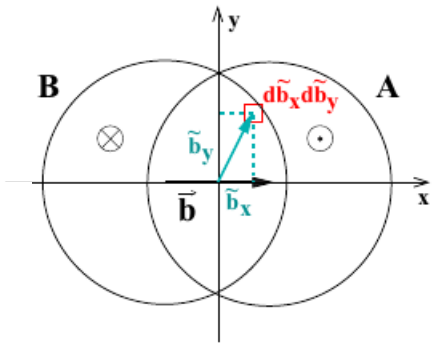
- A critical component as low as 0.5% can be detectable through intermittency, provided a relatively high statistics and proton multiplicity at midrapidity!

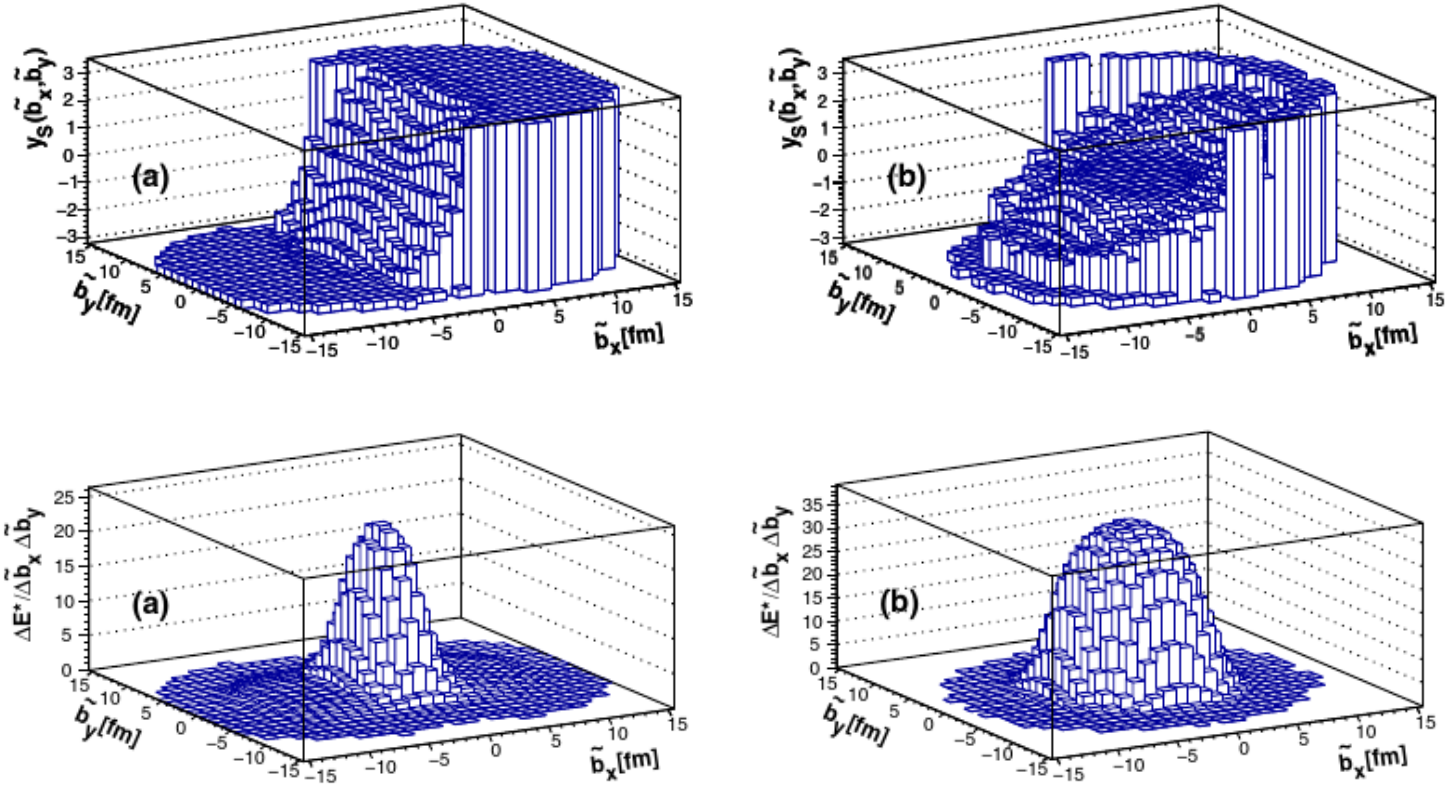
Fire streaks' parameters

A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

Pb+Pb @ 158 GeV $\rightarrow \sqrt{s_{NN}}$ = 17.3 GeV, $y_{\text{beam}} = 2.9$

peripheral $b = 9.72\,\text{fm}$ central $b = 2.55\,\text{fm}$





- Very narrow (if any) 'stopped' region in non-central collisions
- ΔE^* is the streak's energy in its own c.m.s. frame
- In peripheral collisions 2 spectator regions visible (with $\Delta E^* = m$)
- Central collisions: broader 'hot' region, with higher excitation energies