Side splash in Ar+KCl collisions at 1.8 GeV/nucl from reaction-plane deblurring

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Equation of State of Dense Matter
at RIBF and FRIB
RIKEN, the Institute of Physical and Chemical Research

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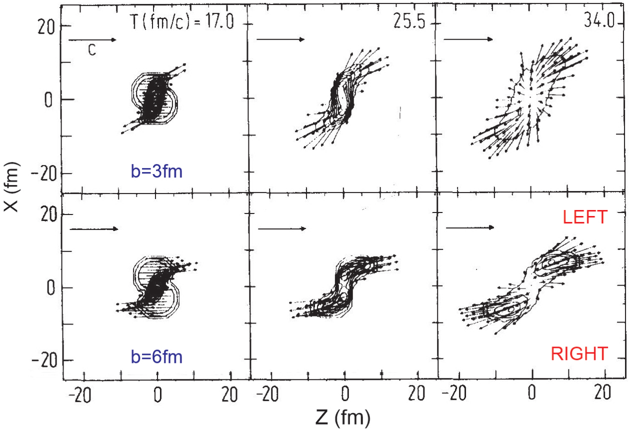
Side Splash in Hydrodynamic Calculations

Matter dispersed in the final stage, but most likely direction of motion away from the beam, e.g., in the calculations by Buchwald for Nb + Nb at 400 MeV/nucl

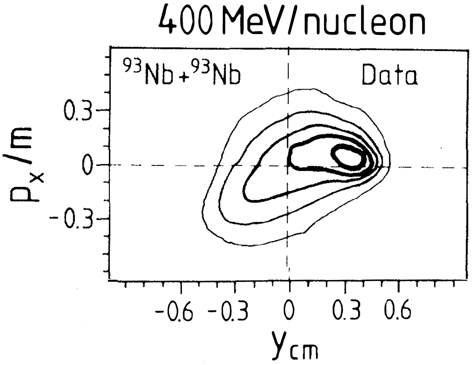
Stöcker&Greiner Phys.Rep. 137(86)277



Can this be seen experimentally??

1984 Claim

Gustafsson *et al.* PRL 18(84)1590 Plastic Ball Group claims to see preferential emission away from the beam axis, in $d^3N_{ch}/dy\, d^2p^{\perp}$ for 400 MeV/nucl Nb + Nb collisions, when determining reaction plane from flow tensor, $\mathbf{S}^{\perp z} = \sum_{\nu} \mathbf{p}_{\nu}^{\perp}\, p^z/2m_{\nu}$



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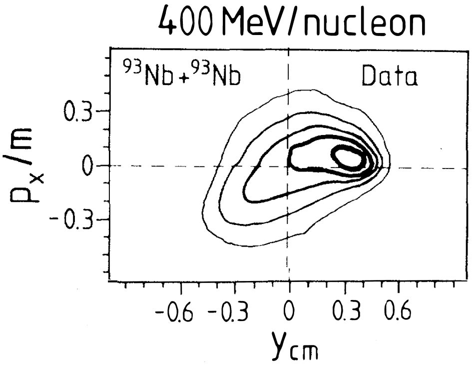

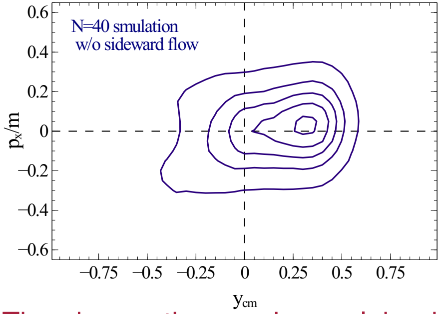

The observation can be explained by particle self-correlation, w/o invoking transverse collective movement

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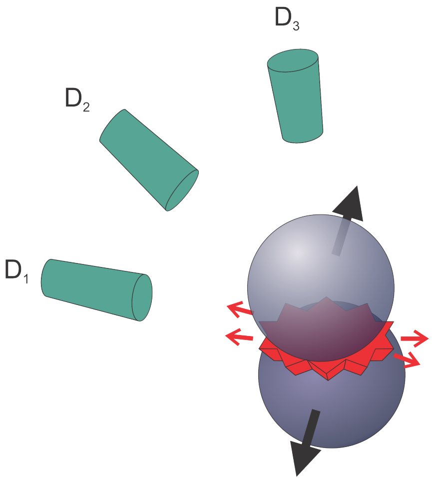
Estimating Reaction-Plane Direction w/o Self-Correlation



Plane direction f/particle μ estimated with

$$\mathbf{q}_\mu = \frac{1}{N}\sum_{\nu\neq\mu}\omega_\nu\,\mathbf{p}_\nu^\perp \qquad \omega_\nu = \begin{cases} +1, & \text{if } p_\nu^z > 0 \\ -1, & \text{if } p_\nu^z < 0 \end{cases}$$

N - measured particle multiplicity; other ptcles in the event used as reference for μ

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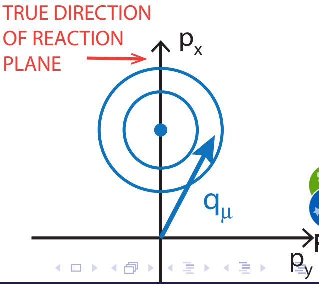
Problem: Reference vector $\mathbf{q}_\mu$ Gaussian fluctuates around true plane direction



Current Solution: Angular Moments of Distributions

Solution: average angular moments (azimuthal Fourier coefficients)

$$v_n = \langle \cos n\phi \rangle$$

ϕ - angle relative to true reaction plane

Voloshin&Zhang ZfPhC70(1996)665

v_n derived from average scalar products/contractions, e.g.,

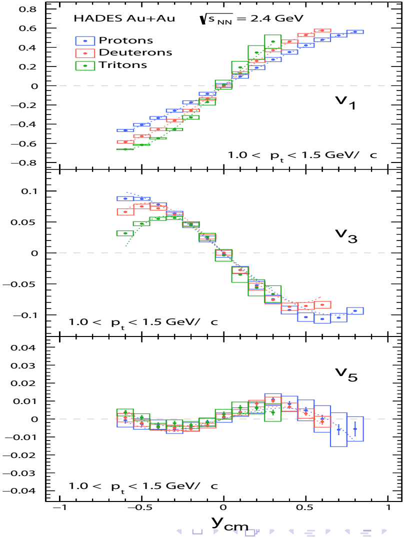
$$\langle \mathbf{p}^{\perp}_{\mu} \cdot \mathbf{q}_{\mu} \rangle \simeq p^{\perp} \langle q^x \rangle \langle \cos \phi \rangle$$

for different $p^{\perp}$, y and ptcle ID

Problem: unclear physics in v_n especially for higher n

$1.23\,\text{GeV/nucl Au} + \text{Au}\ b \simeq 6\,\text{fm}$

HADES PRL125(2020)262301



Paradigm: Triple-Differential Yields from Data

Distributions for *Fixed Direction of Reaction Plane* from Theory and Experiment

no control over plane

What is it?!

Paradigm: Triple-Differential Yields from Data

Distributions for *Fixed Direction of Reaction Plane* from Theory and Experiment

no control over plane

some control, v_n

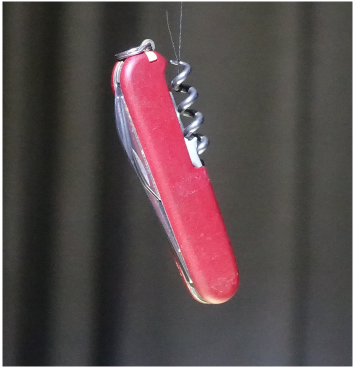
Still not clear what the system is. . .

Paradigm: Triple-Differential Yields from Data

Distributions for *Fixed Direction of Reaction Plane* from Theory and Experiment

no control over plane

some control, v_n



full control, $\frac{d^3N}{dp^3}$

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Claim: You can go from center to right panel through deblurring

Deblurring by Example

Budd, *Crime Fighting Math*, plus.maths.org magazine

Blurred Photo of Moving Car

Deblurred

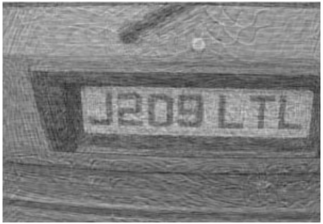
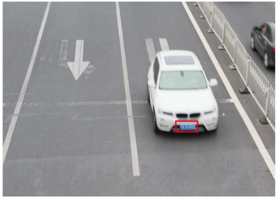


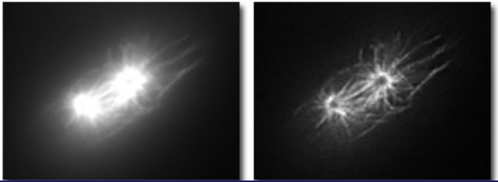
Photo of Parked Car

Fast Moving



Deblurring in Optical Microscopy

Before and After Nearest Neighbor Deconvolution Analysis



Correcting f/Distortions Due to Apparatus or Method

Detector efficiency ϵ, n measured ptcle number, N actual number

$$N \simeq \frac{1}{\epsilon}\, n$$

Typical energy loss in thick target $\overline{\Delta E}$ for detected particle

$$E_{\mathrm{prod}} \simeq E_{\mathrm{det}} + \overline{\Delta E}$$

General problem stated probabilistically, with $P(\zeta|\xi)$ - probability to measure ptcle characteristic to be ζ when it is actually ξ

$$n(\zeta) = \int \mathrm{d}\xi \, P(\zeta|\xi) \, N(\xi)$$

For small distortions, P finite only when ζ little different from ξ. Optical terminology: P - blurring or transfer function.

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Bayesian Deblurring

Distorted $n(\zeta)$ measured, while pristine $N(\xi)$ sought:

$$n(\zeta) = \int \mathrm{d}\xi \, P(\zeta|\xi) \, N(\xi)$$

$P(\zeta|\xi)$ - probability that ptcle with ζ detected while it really has characteristic ξ, understood given the method/apparatus, can be simulated (Geant4) & can depend on N

$Q(\xi|\zeta)$ - unknown complementary probability that ptcle has characteristic ξ while measured at ζ

Bayesian relation: number of times ptcle has characteristic in $\mathrm{d}\xi$ while measured in $\mathrm{d}\zeta$ is

$$P(\zeta|\xi) \, N(\xi) \, \mathrm{d}\xi \, \mathrm{d}\zeta = Q(\xi|\zeta) \, n(\zeta) \, \mathrm{d}\xi \, \mathrm{d}\zeta$$

Hence $$N(\xi) = \frac{\int \mathrm{d}\zeta \, Q(\xi|\zeta) \, n(\zeta)}{\int \mathrm{d}\zeta' \, P(\zeta'|\xi)} \, , \quad Q(\xi|\zeta) = \frac{P(\zeta|\xi) \, N(\xi)}{\int \mathrm{d}\xi' \, P(\zeta|\xi') \, N(\xi')}$$

Richardson-Lucy method solves eqs iteratively till stabilization

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Richardson-Lucy (RL) Method from Astronomy

Iterative method, r - iteration index

$$n^{(r)}(\zeta) = \int d\xi \, P^{(r)}(\zeta|\xi) \, N^{(r)}(\xi)$$

$$A^{(r)}(\xi) = \frac{\int d\zeta \, \frac{n(\zeta)}{n^{(r)}(\zeta)} \, P^{(r)}(\zeta|\xi)}{\int d\zeta' \, P^{(r)}(\zeta'|\xi)}$$

$$N^{(r+1)}(\xi) = A^{(r)}(\xi) \, N^{(r)}(\xi)$$

ξ & ζ are binned (pixelated), n & N are arrays and P transformation (transfer) matrix from the method/apparatus. Deblurring amounts to iterative multiplication of arrays by matrices + matrix reconstruction. Typical start: $N^{(1)}(\xi) = n(\xi)$

Richardson JOSA 62(1972)55 ; Lucy AJ 79(1974)745
D'Agostini NIMPRA362(1995)487
https://en.wikipedia.org/wiki/Richardson-Lucy_deconvolution

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Other methods include Fourier transformation

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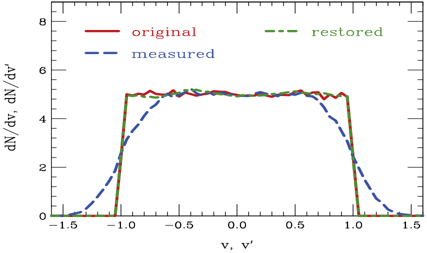
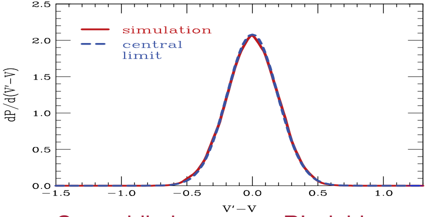
Schematic 1D Model

Proposition: Carry out as good determination of 3D info as you can & refine with deblurring. ~~v_n~~?

First 1D deblurring test. Projectile at unknown velocity V deexcites emitting $N = 10$ ptcles distributed with box-like $\mathrm{d}N/\mathrm{d}v$ in projectile cm. Task: Measuring ptcles in lab, determine $\mathrm{d}N/\mathrm{d}v$. Cm velocity V' estimated from remaining ptcles, so V' & $\mathrm{d}N/\mathrm{d}v'$ smeared:

$$\frac{\mathrm{d}N}{\mathrm{d}v'} = \int \mathrm{d}V' \, \frac{\mathrm{d}P}{\mathrm{d}V'} \, \frac{\mathrm{d}N}{\mathrm{d}v}$$





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→Central-limit smear + RL deblur

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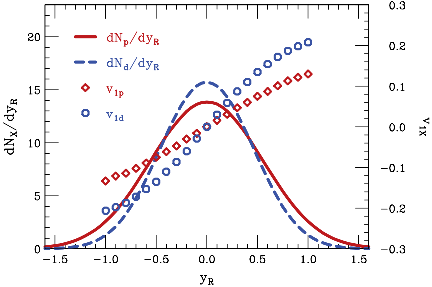
3D Model for Collisions

Customary thermal model with flow, N, d, t, ^{3}He, ^{4}He. $\langle Z_{Tot} \rangle = 50$
Rapidity dstr, temperature & flow typical for semicentral collisions at 300 MeV/nucl

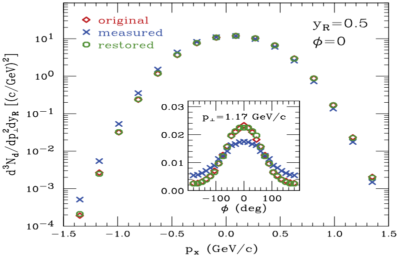


$$\frac{dN}{d\phi'} = \int d\Phi' \, \frac{dP}{d\Phi'} \, \frac{dN}{d\phi}$$

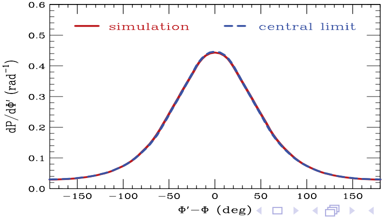
$$\phi' + \Phi' = \phi + \Phi$$

RL deblur + central-limit
Strong anisotropies restored!

Triple differential spectrum in reaction plane:



Uncertainty in reaction plane:



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Ar + KCl @ 1.8 GeV/nucl

Ströbele PRC 27(83)1349

495 events from Streamer Chamber, $b \lesssim 2.4\,\mathrm{fm}$

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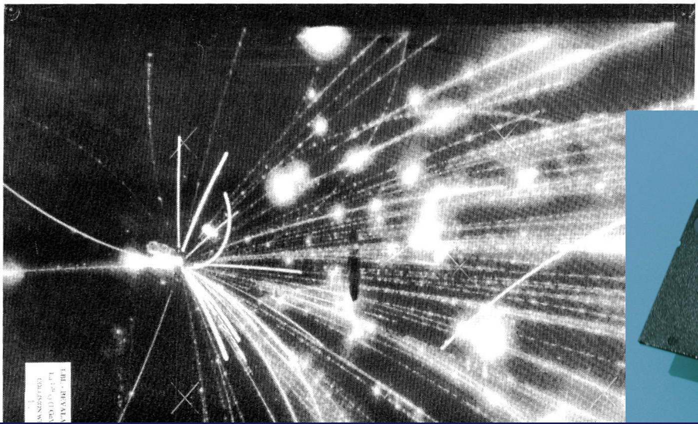

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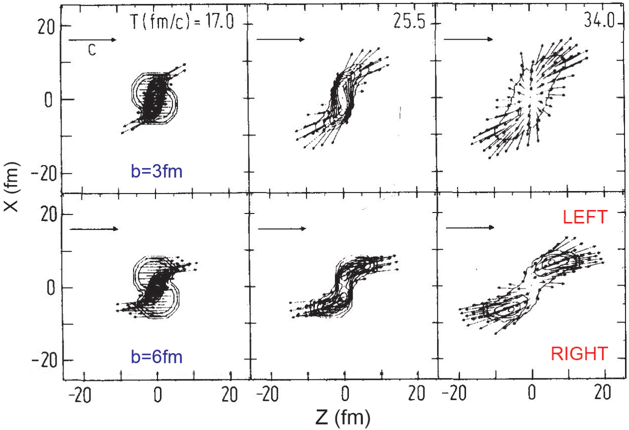
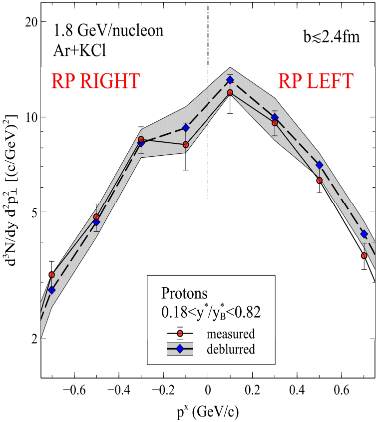


Can this be seen experimentally??

Side-Splash in Ar + KCl 1.8 GeV/nucl?

protons



Particles in the forward hemisphere, $y^* \sim 0.5 y_B^*$

Side-Splash in Ar + KCl 1.8 GeV/nucl?

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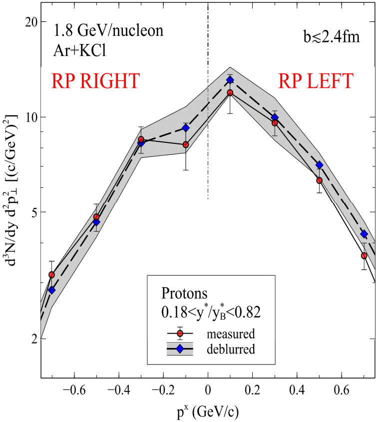
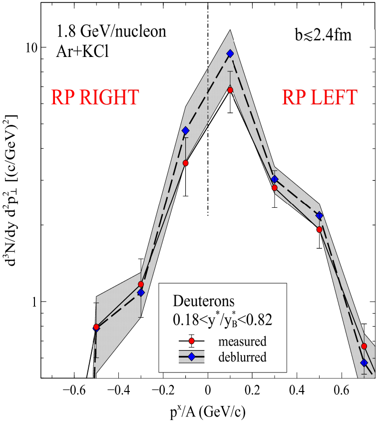


deuterons



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Side-Splash in Ar + KCl 1.8 GeV/nucl

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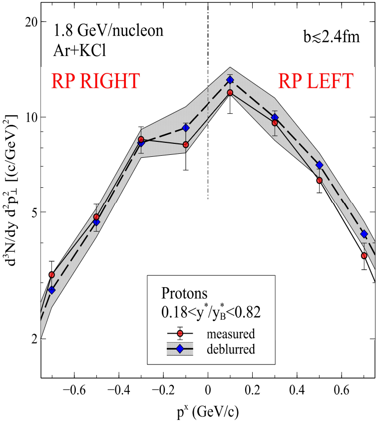

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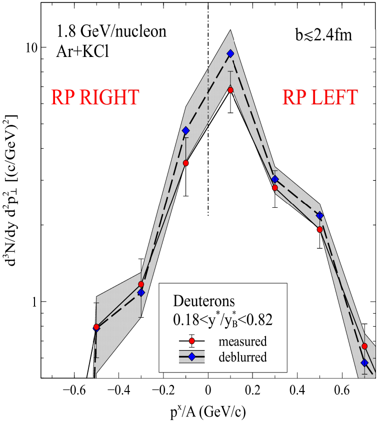
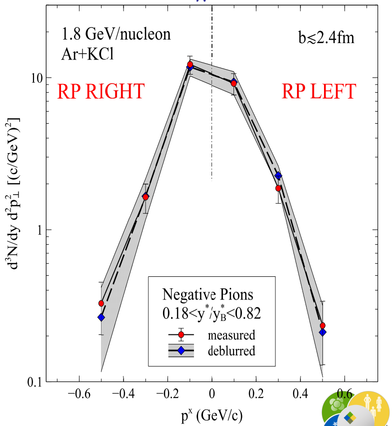


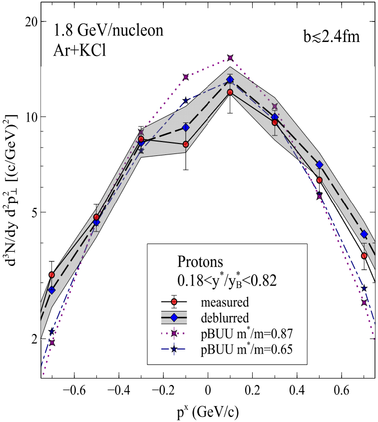
π^-



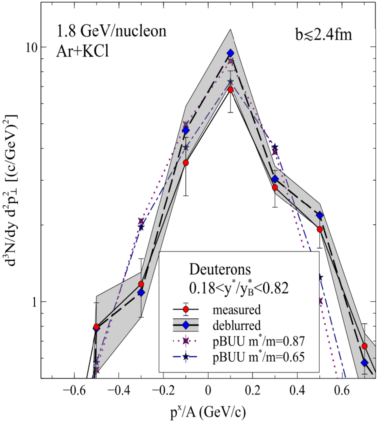
Particles in the forward hemisphere, $y^* \sim 0.5 y^*_B$

Side-Splash: Experiment vs Theory

protons



deuterons



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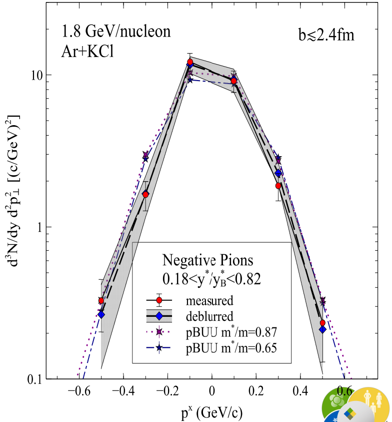

Calculations in pBUU: sensitivity to mean-field *p*-dependence in Ar+KCl

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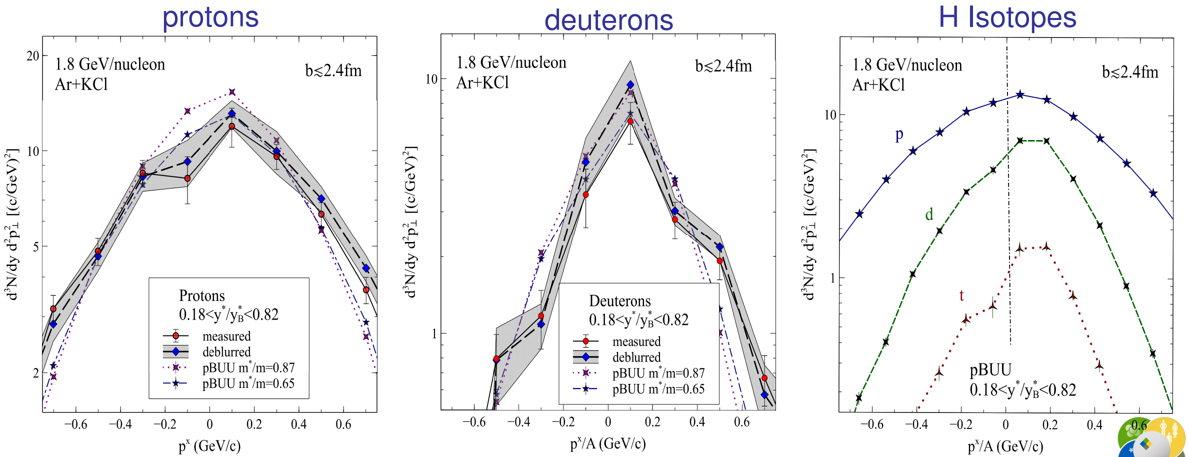
Side-Splash: Experiment & Theory



Transverse boost $v^x \sim 0.1\, c$

Conclusions

- Reaction-plane fluctuations made us concentrate on azimuthal moments w/unclear physics content for higher orders
- Deblurring, common in optics, can enable accessing of 3-differential distributions associated w/true reaction plane
- Side splash in Ar + KCl collisions at 1.8 GeV/nucl with $v^x \sim 0.1\, c$, visible with just $\sim$ 500 collision events, is just an example of what may be achieved!
- Other nuclear problems where deblurring started producing results: $^{26}\text{O} \rightarrow ^{24}\text{O} + n + n$ decay, source-imaging from 2-particle correlations in heavy-ion collisions

PD&Kurata-Nishimura PRC105(2022)034608; Nzabahimana arXiv:2210.00157

Berkowitz Physics 15(2022)s26
https://www.energy.gov/science/np/articles/deblurring-can-reveal-3d-features-heavy-ion-collisions

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