Exploring femtoscopy as a measurement tool for ultra-peripheral collisions

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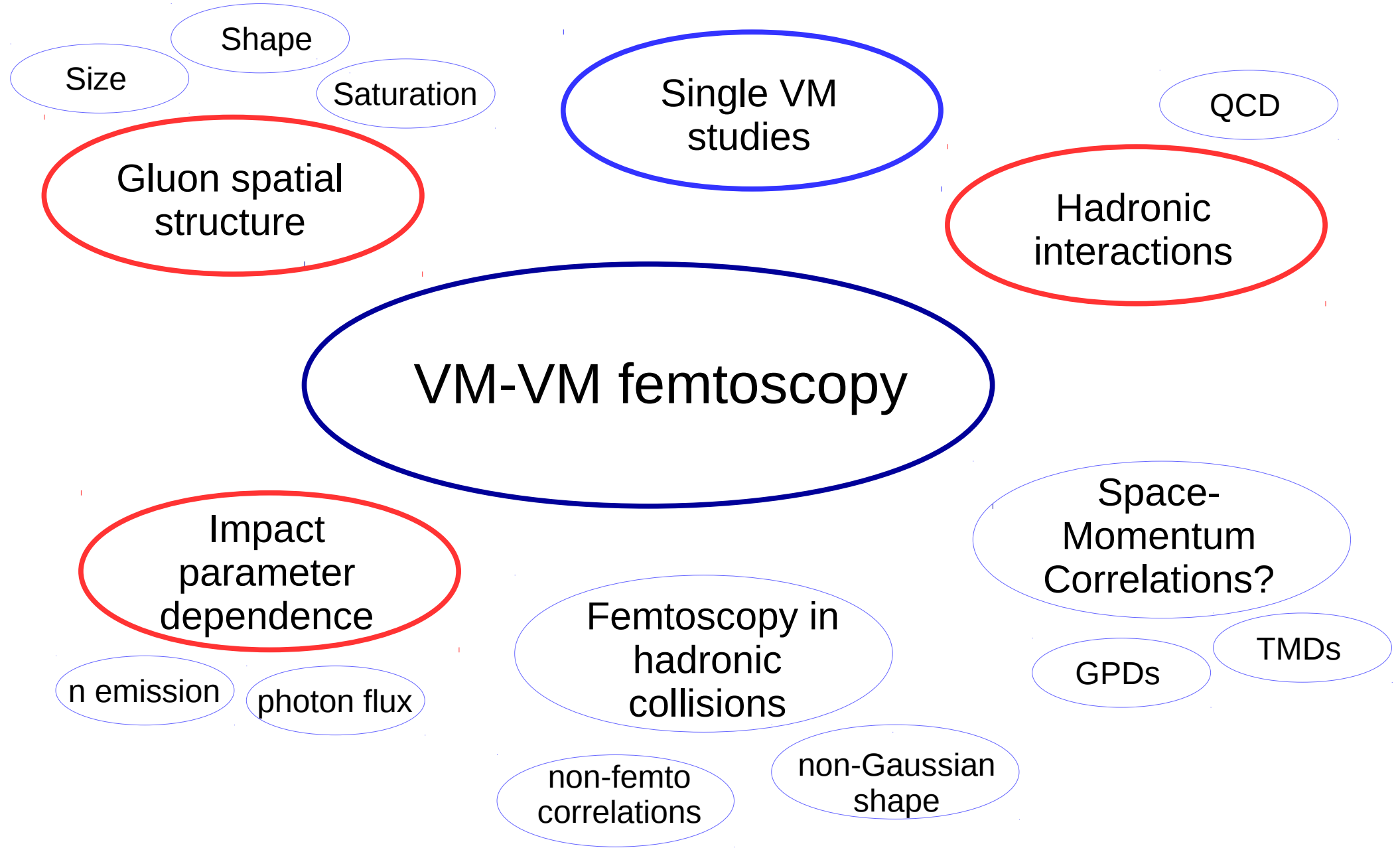
Creighton University

Forward QCD: open questions and future directions
University of Kansas
23-24 May 2022

Topics


Shape
Size
Saturation
Single VM studies
QCD
Gluon spatial structure
Hadronic interactions
VM-VM femtoscopy
Impact parameter dependence
Space-Momentum Correlations?
n emission
photon flux
Femtoscopy in hadronic collisions
TMDs
GPDs
non-femto correlations
non-Gaussian shape

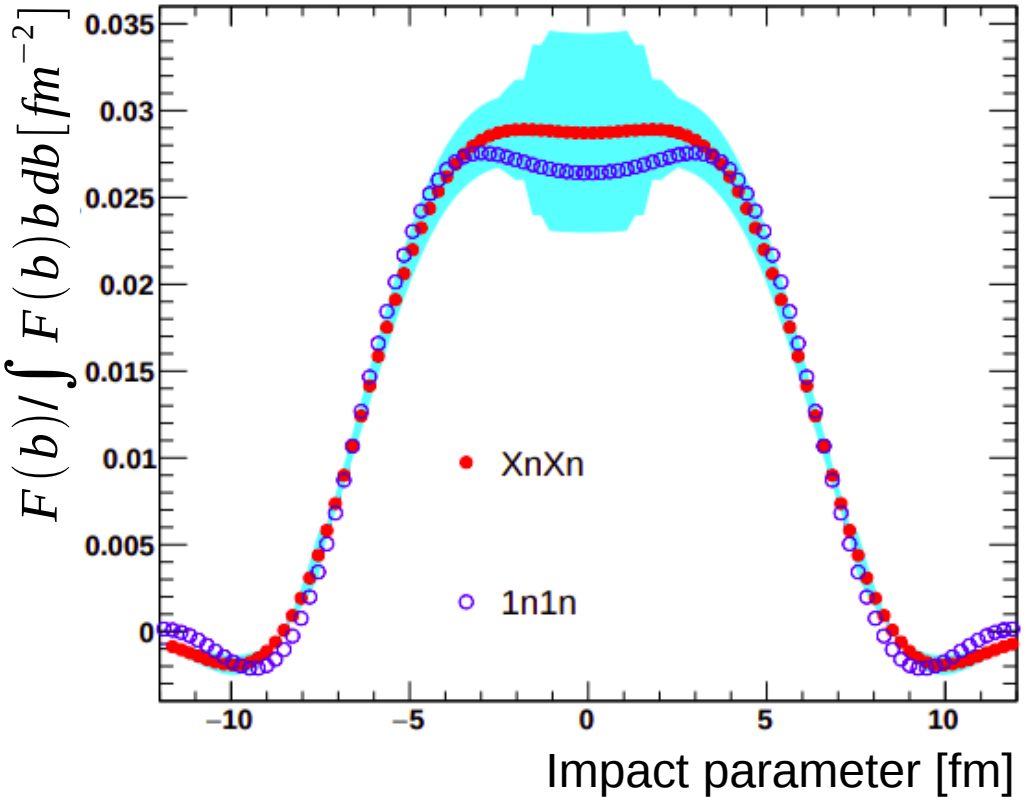
Single Vector Meson Photoproduction

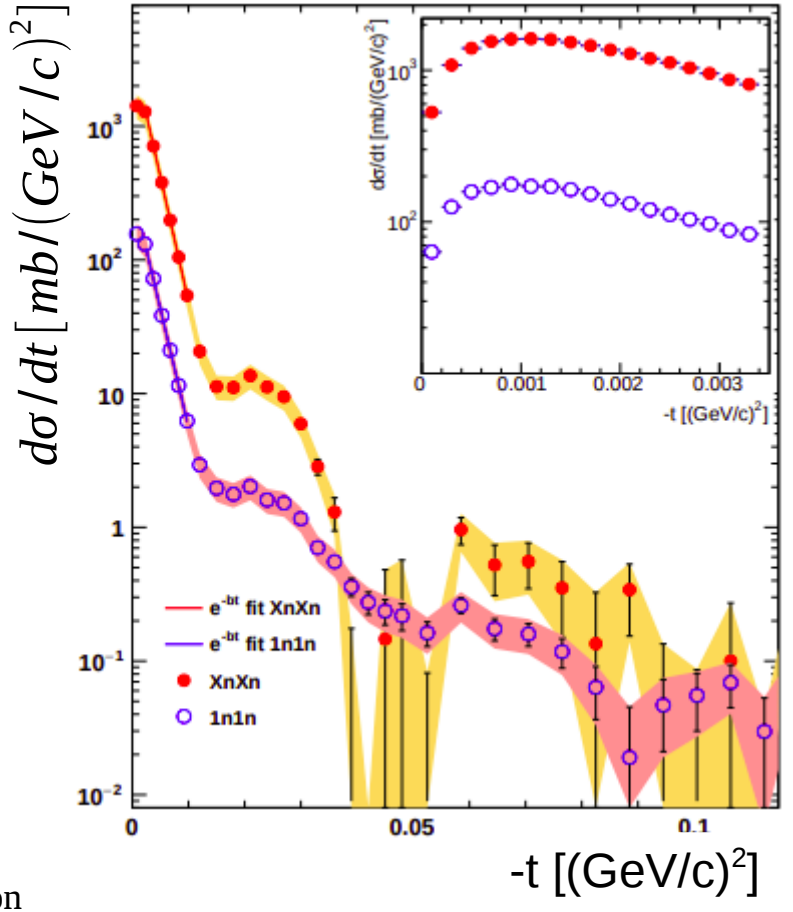
Coordinate space
b=R$_{transverse}$

Fourier transform

Momentum space
t ~ p$_T^2$

$$F(b) \sim \int_0^\infty p_T J_0(b\,p_T) \sqrt{\frac{d\sigma}{dt}}\, dp_T$$





STAR, Phys. Rev. C 96 (2017) 054904

Double Vector Meson Photoproduction

Relative momentum space
$k^* = p_1 - p_2$

Koonin-Pratt equation[††]

Relative coordinate space
$r = r_1 - r_2$

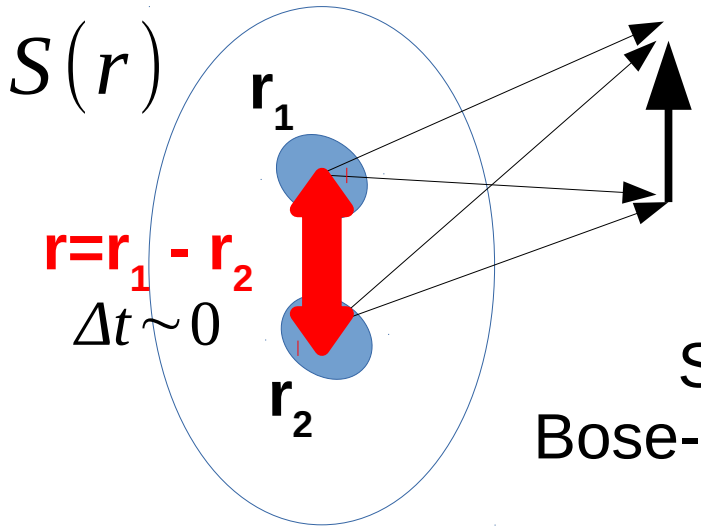
$$C(k^*) = \int S(r)\,|\psi_2(r)|^2\,d^3r$$

Correlation
A(k*)/B(k*)
= same event / mixed event

Geometry
Size, Shape

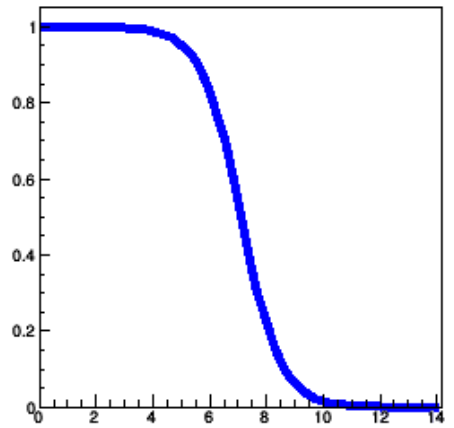
Final State Interaction
Hadronic interaction, V(r)

$$\frac{-h^2}{2m}\frac{d^2u}{dr^2} + \left(V(r) + \frac{h^2}{2m}\frac{l(l+1)}{r^2}\right)u = Eu$$



$k^* = p_1 - p_2$

Δt ~ r ~ k* small
Similar phase space
Bose-Einstein peak at small k*

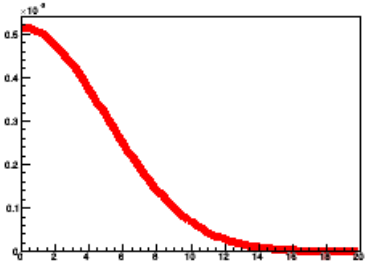


[††]Koonin-Pratt Equation: Phys. Rev. C 42 (1990) 2646, Phys. Lett. B 70 (1977) 43

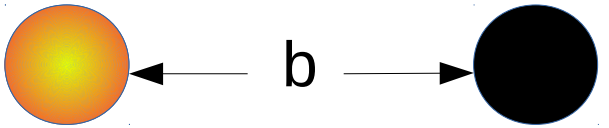
Source distributions

Hadronic collisions
One interaction region

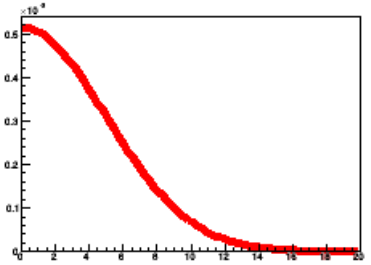
Gaussian source



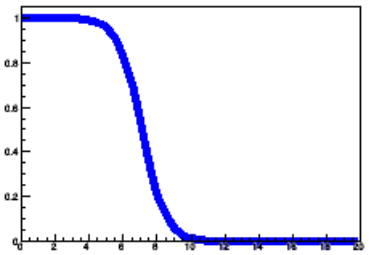
Photoproduction
Two interaction regions



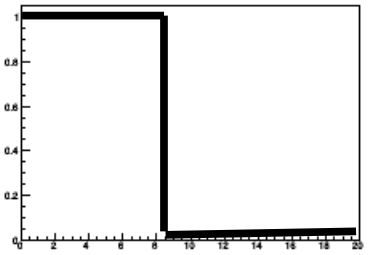
Gaussian

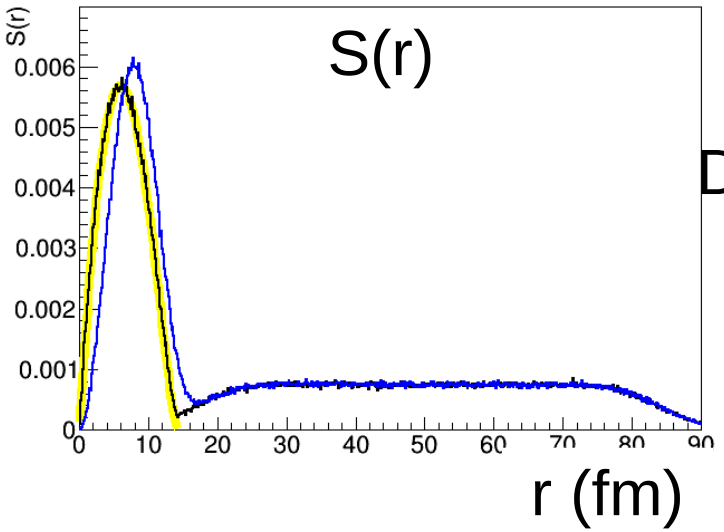


Wood-Saxon



Black Disk





Recipe for a source

Select impact parameter (from a distribution).
Draw two points from chosen gluon distribution.
Select “same source” or “different source”
Add ½ impact parameter.
Subtract position.

S(r) is distribution of distance between points.

Correlation function calculation

Source S(r)

Interaction V(r)

Particle Type

$^{2s+1}L_J$

CATS

Correlation Analysis Tool using the Schrodinger equation

[Eur. Phys. J C 78 (2018) 394]

Solve numerically

Appropriate for small systems

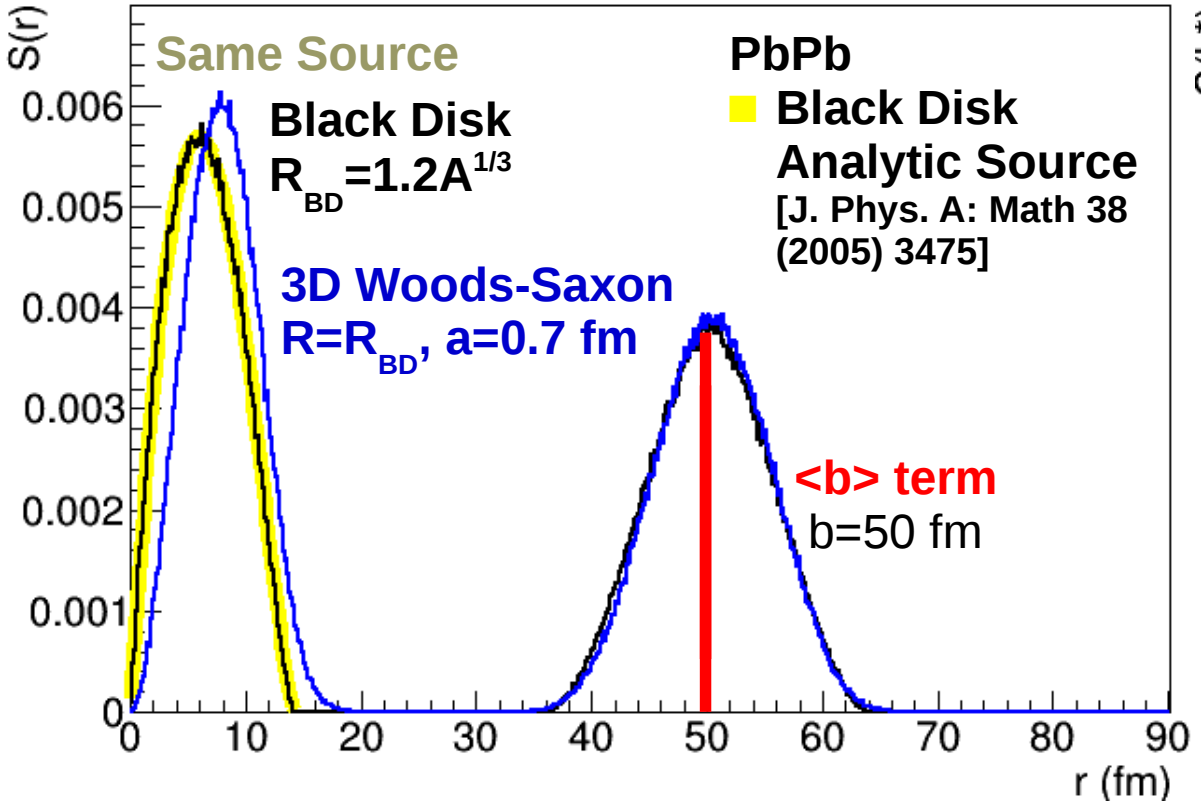
Correlation Function C(k*)

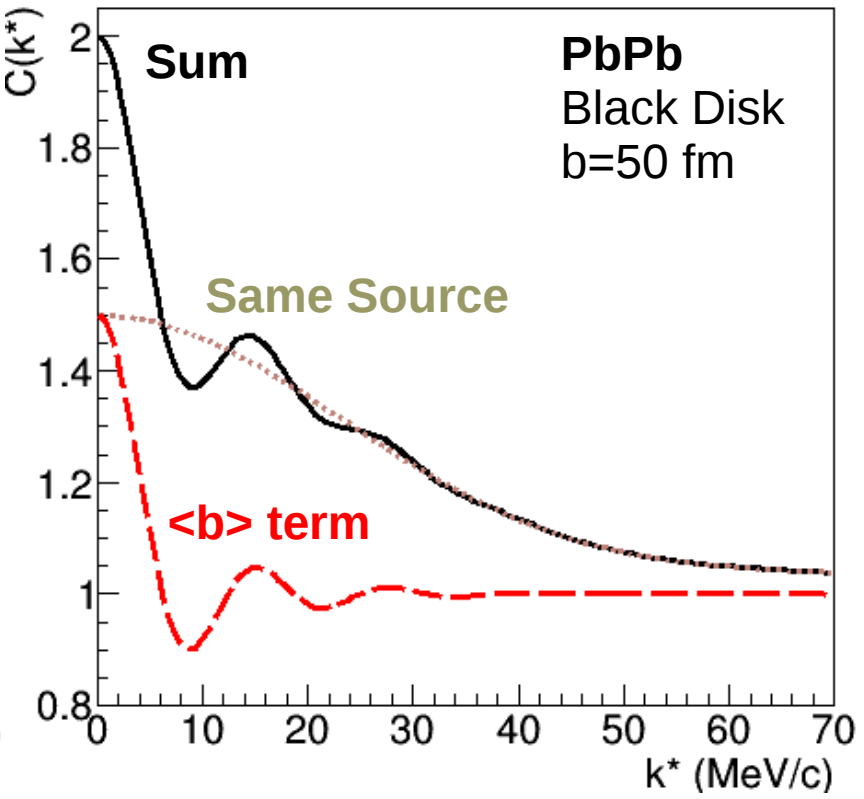
$$C(k^*) = \int S(r) |\psi_2(r)|^2 d^3 r$$

$$S(r) = \alpha S_{SS} + (1-\alpha) S_{\langle b \rangle}$$

$$C(k) = \alpha C_{SS} + (1-\alpha) C_{\langle b \rangle}$$

Source distributions





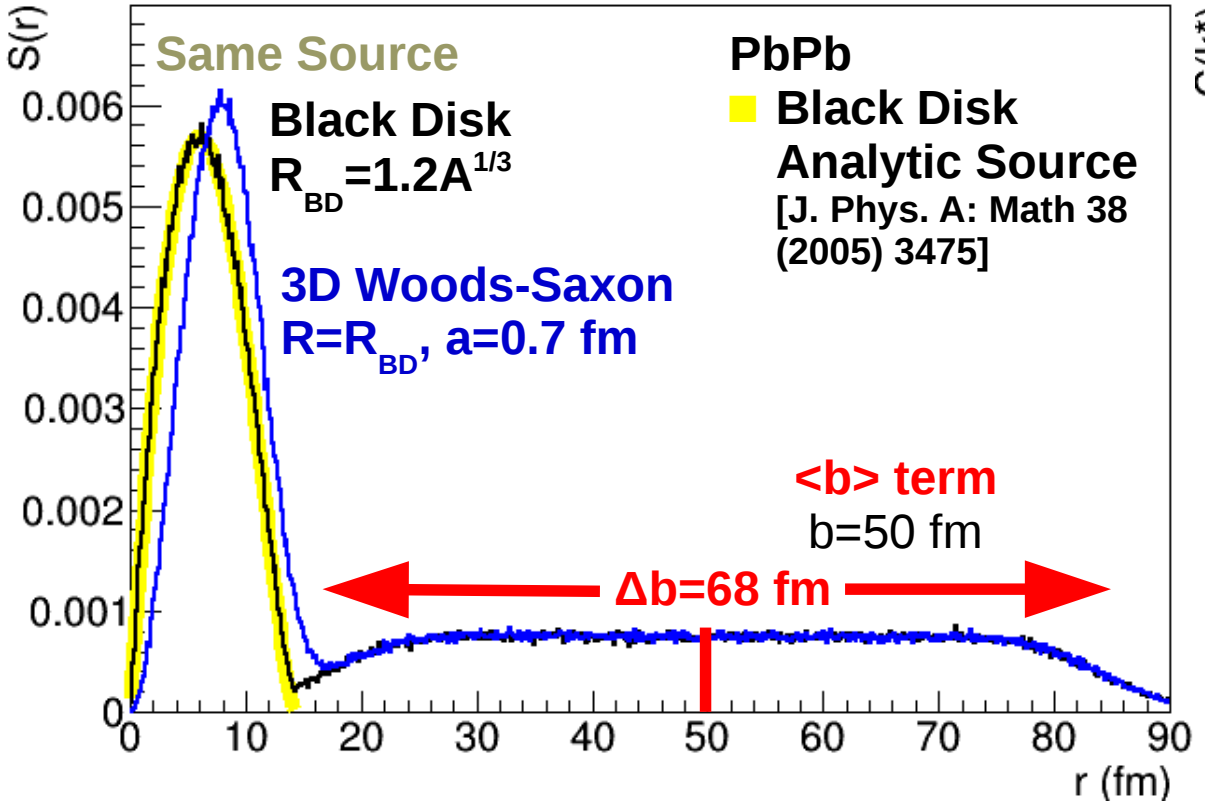
Particles probe same nucleus.

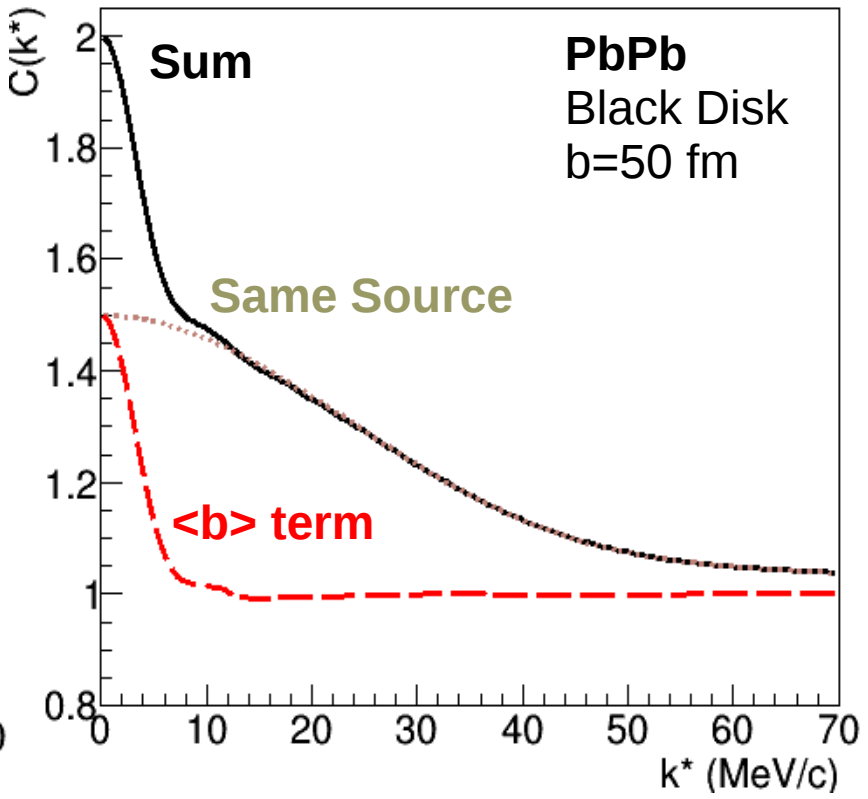
Particles probe different nucleus.

Correlation function from each source contribution add up.

- **pp just has narrower distributions.**
- **pA only has “Same Source” distribution.**

Source distributions





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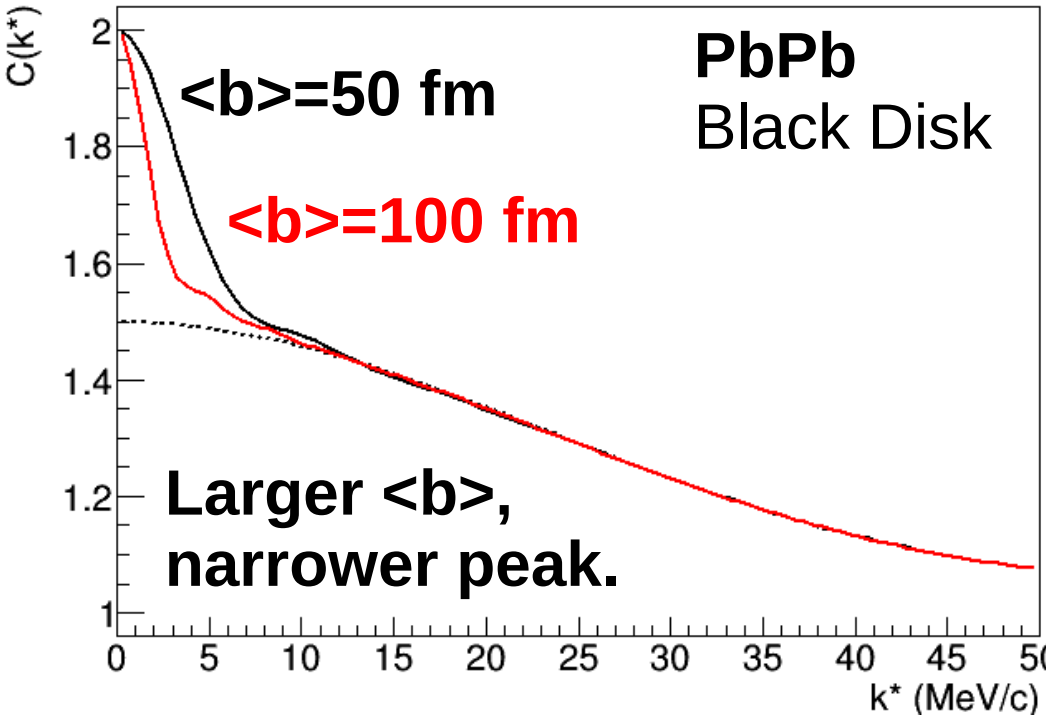
Impact parameter dependence



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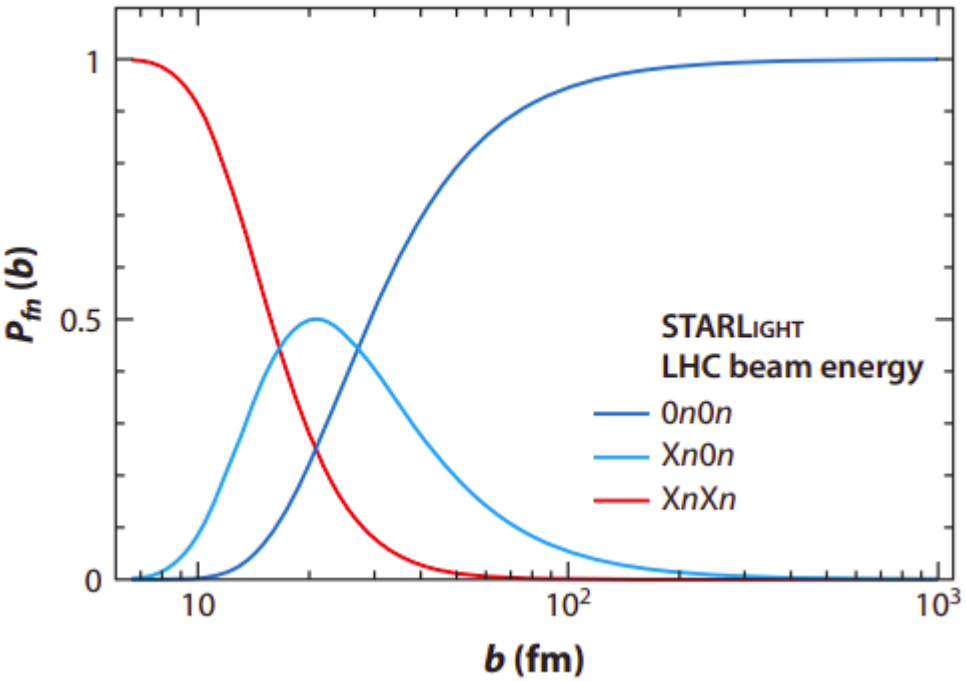


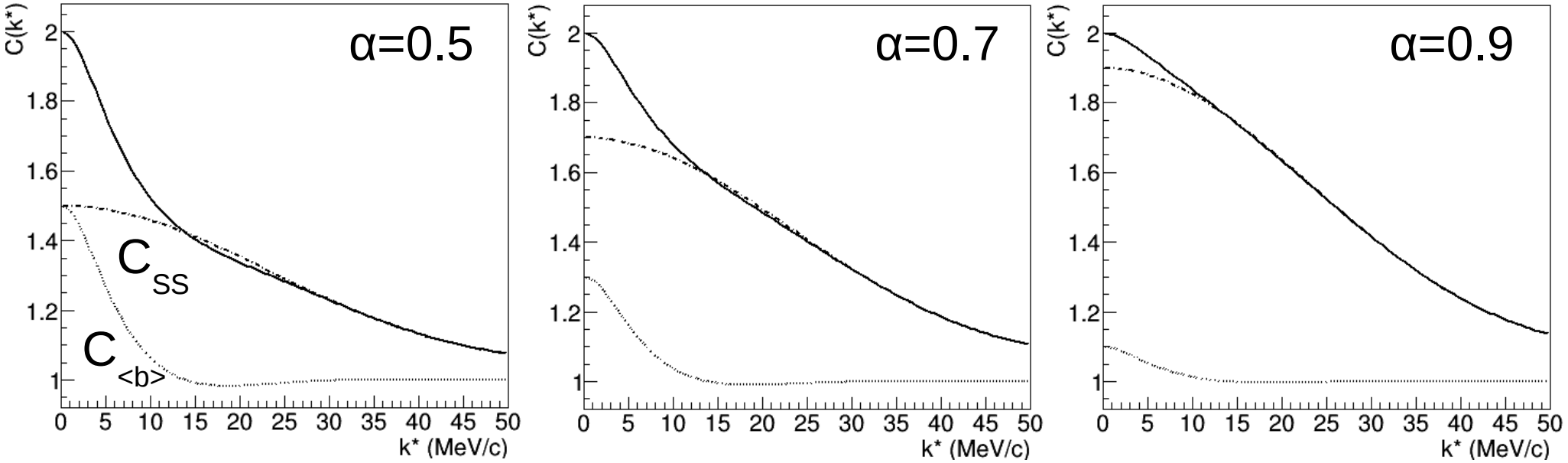
Note: Oscillations may remain for narrow b distribution (XnXn).

Application & Test

- ZDC selections (0n0n, 0nXn, XnXn)→ Different peak widths
- Calibrate two methods
- Constrain fits to extract gluon source parameters.

Rapidity considerations

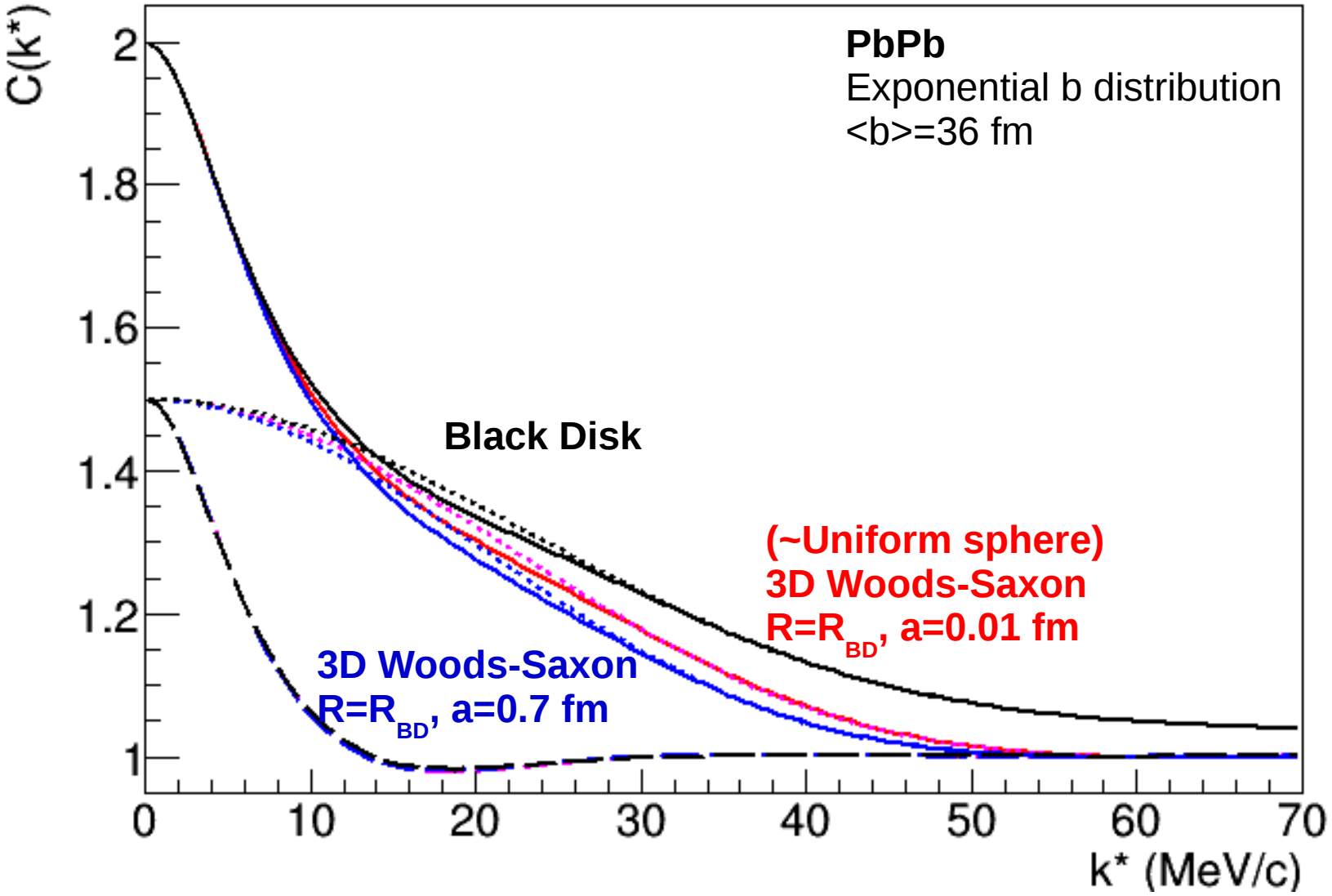
$$C = \alpha C_{SS} + (1-\alpha) C_{\langle b \rangle}$$



- <b> term needs forward & backward VM + similar momentum
- Impact parameter contribution may decrease.
- Study using fit parameter.
- Larger y, smaller x.

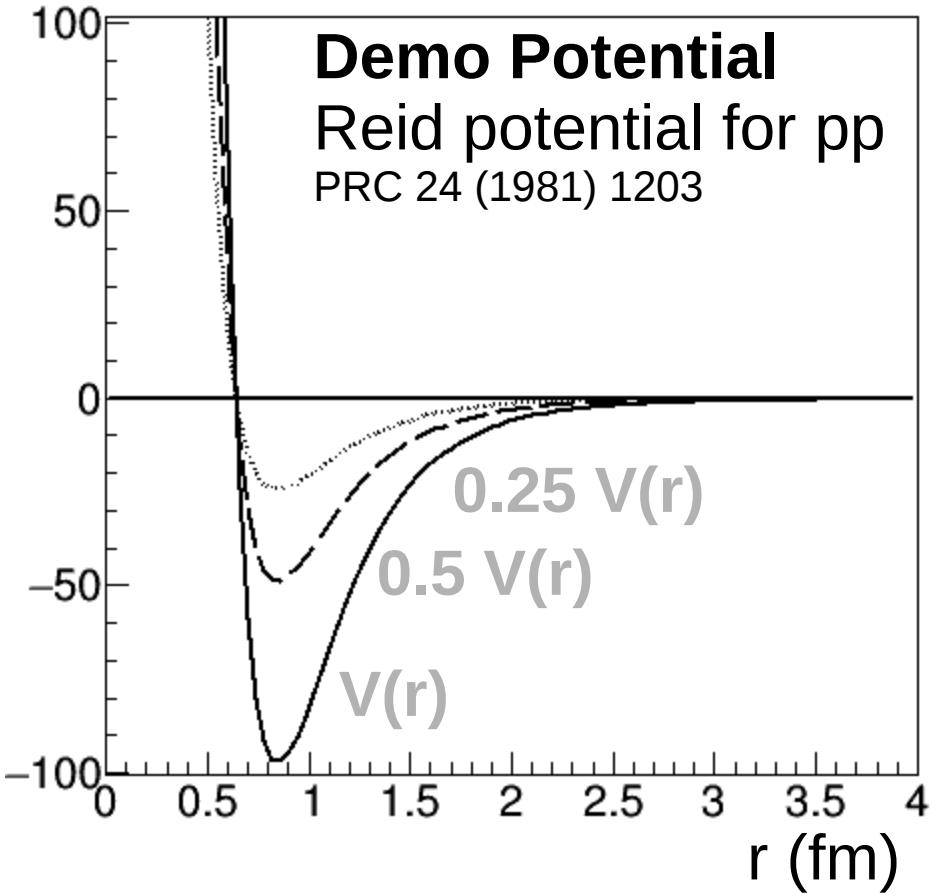
Will future forward detectors allow forward measurement?
What are tracking & PID capabilities?

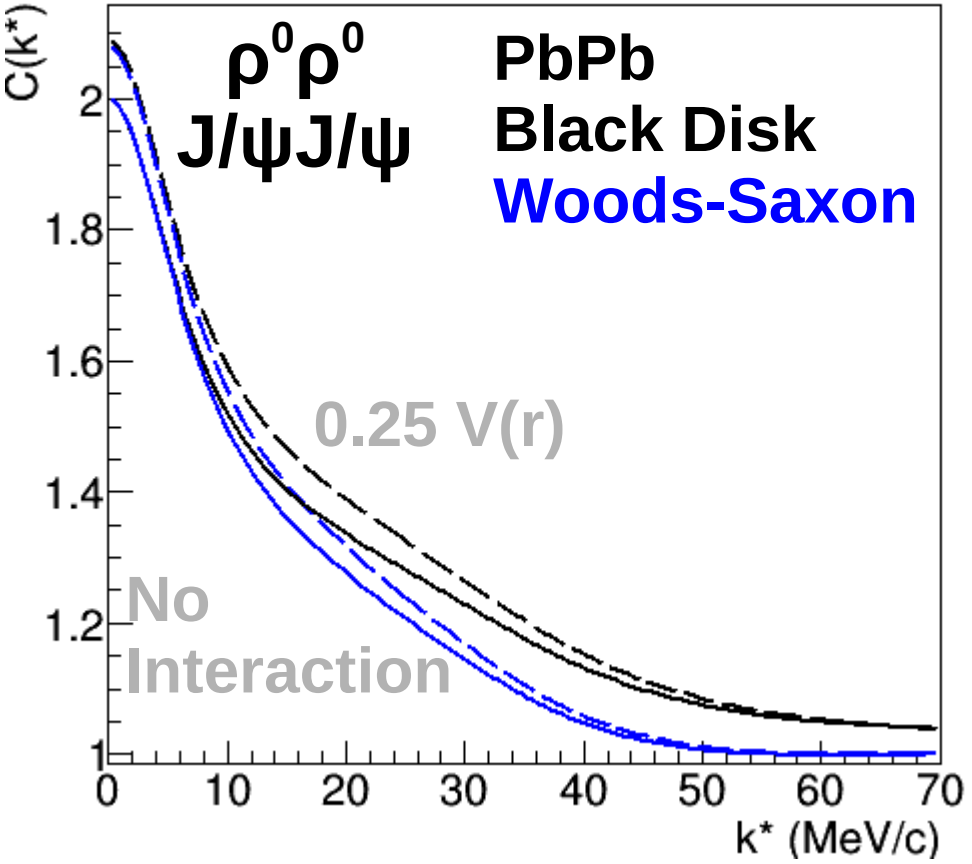
Woods-Saxon vs. Black Disk



- **Distinguishes between expected gluon distributions.**
- **<b> contribution and gluon distribution affect different areas.**

$\rho^0\rho^0$ vs J/ψJ/ψ & hadronic interactions





Demo Potential

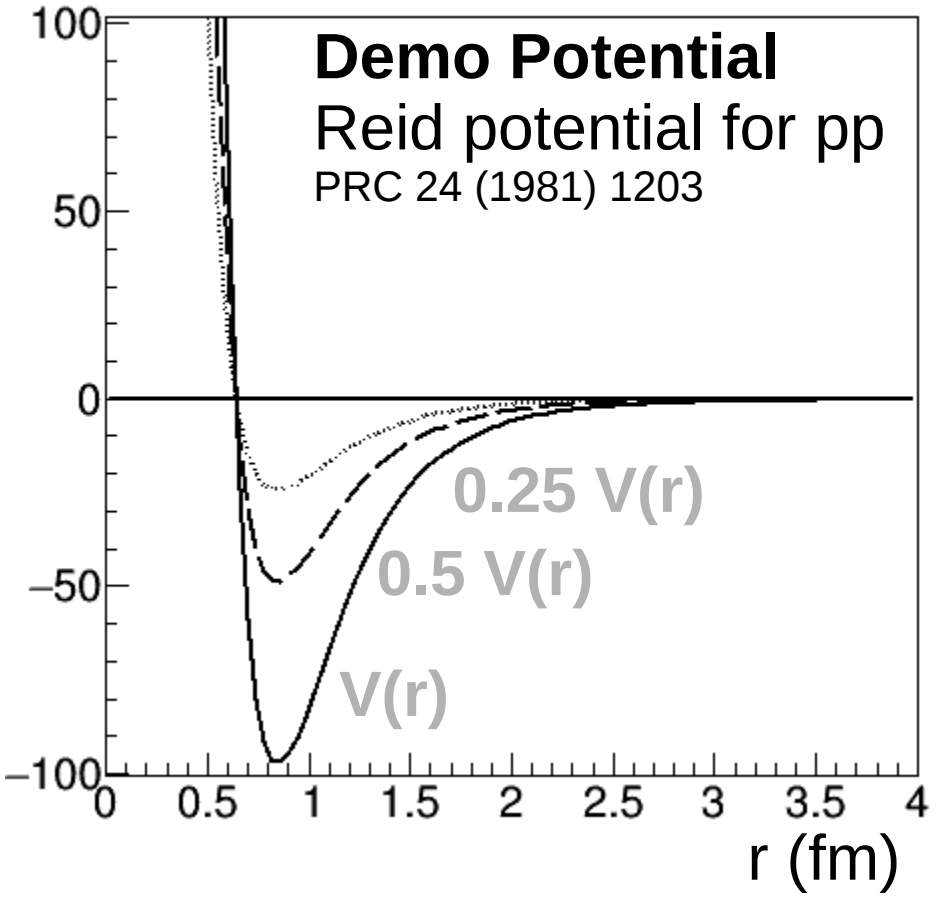
$$V(r) = \frac{-10.463\,e^{-0.7r} - 1650.6\,e^{-2.8r} + 6484.2\,e^{-4.9r}}{0.7\,r}$$

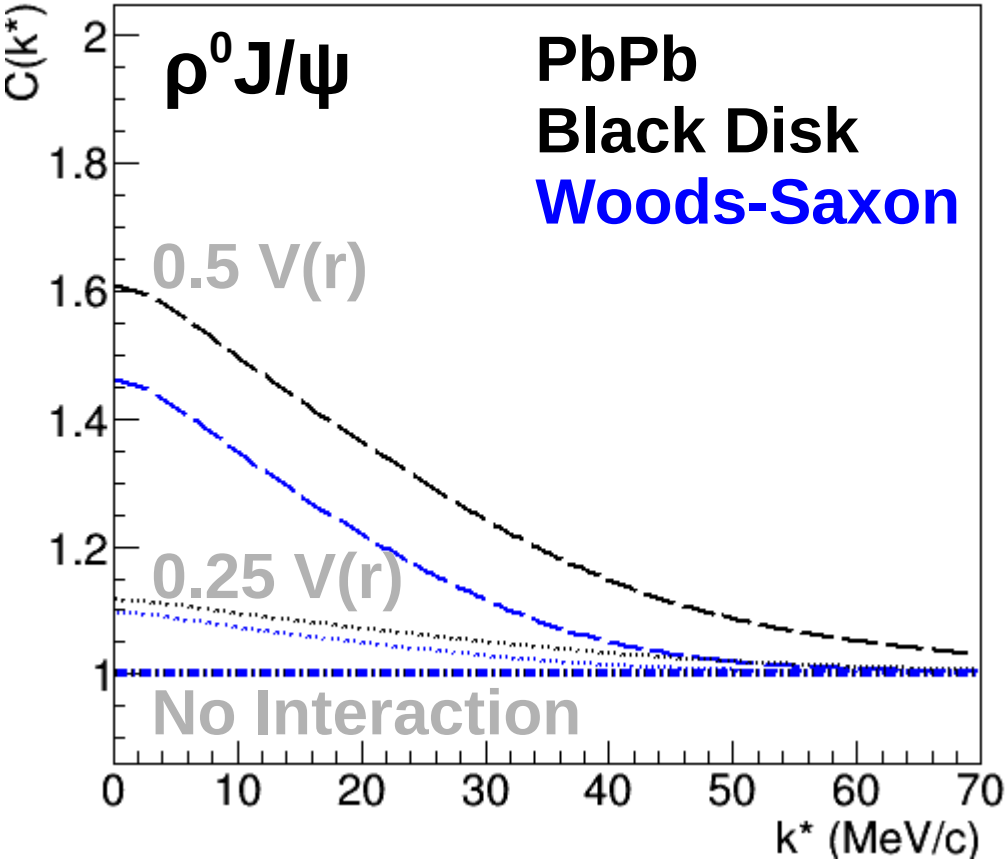
Identical particles ($\rho^0\rho^0$, J/ψJ/ψ):

- ρ^0 and J/ψ different sources?
- $\rho^0\rho^0$ vs J/ψJ/ψ interaction?

Compare pA and AA.

$\rho^0 J/\psi$ & hadronic interactions





Demo Potential

$$V(r) = \frac{-10.463\,e^{-0.7r} - 1650.6\,e^{-2.8r} + 6484.2\,e^{-4.9r}}{0.7\,r}$$

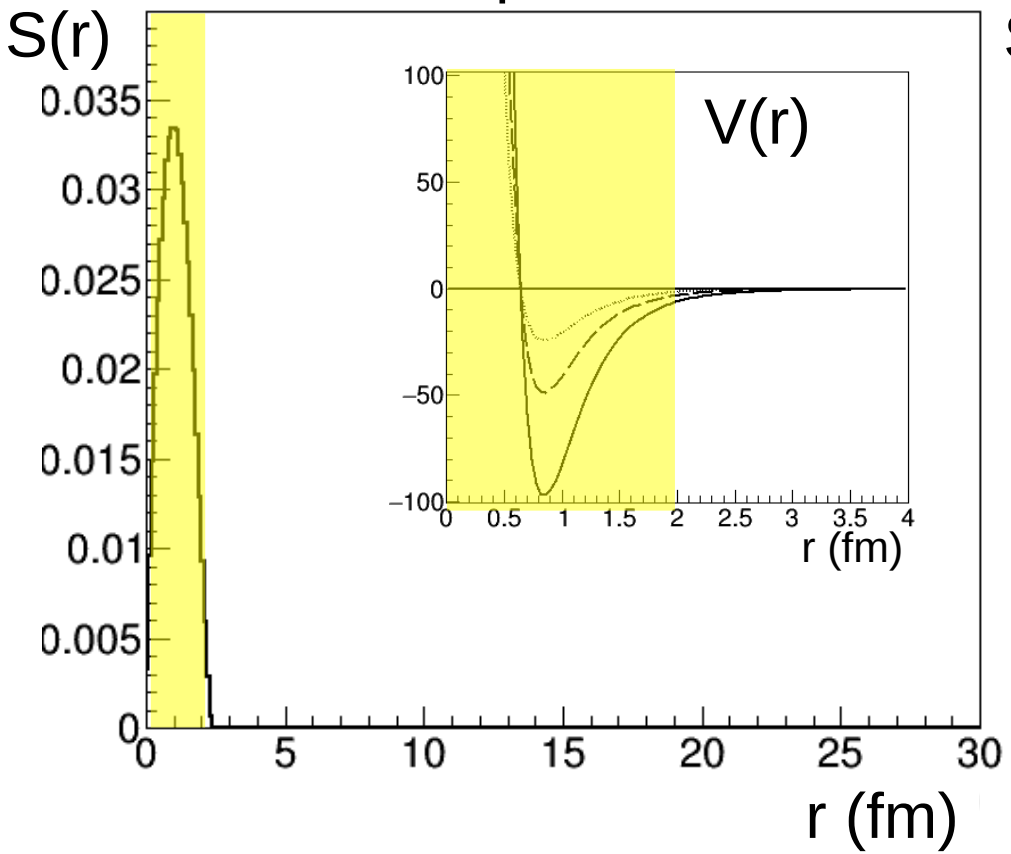
Non-identical mesons ($\rho^0 J/\psi$):

- No Quantum Statistics
- ONLY hadronic interaction

Compare pA and AA.

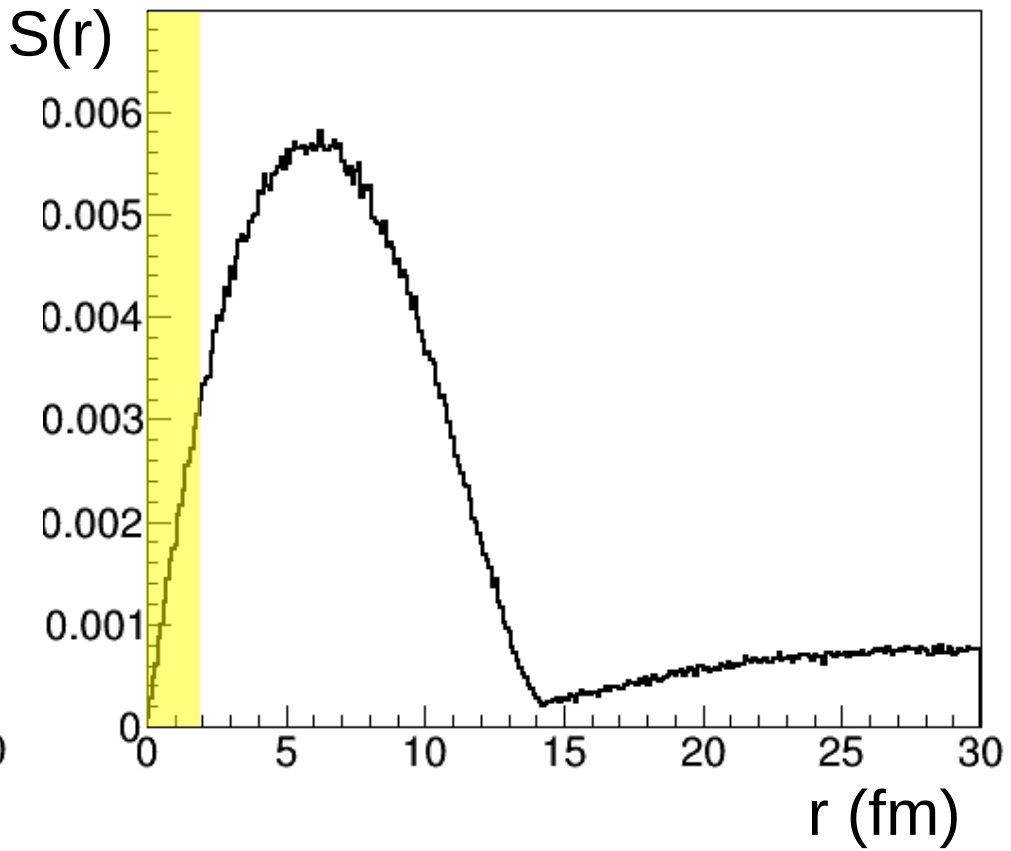
Hadronic interactions

pPb



~100% pairs interact

PbPb



<3.5% (7%) pairs interact

May not be much effect in AA

Hadronic interactions

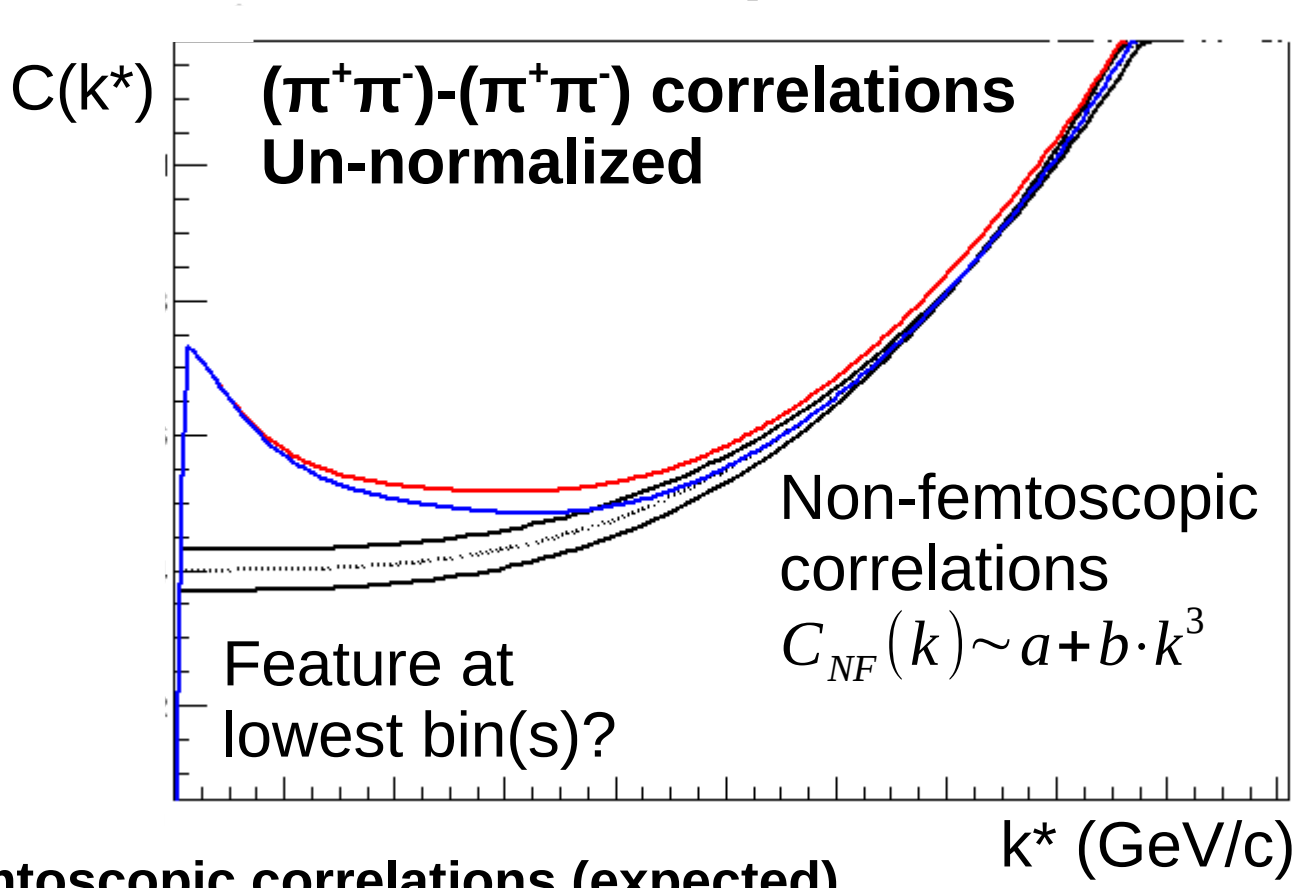
Double VM photoproduction...

- Provides opportunity to study VM-VM interactions
- Hadronic interactions may not be very important in AA

Ideas to try...

- Lednicky formula (but assumes Gaussian source)
- Vary system size
- Vary gluon source shape in pPb.
- Measure in hadronic pp or PbPb collisions?
- Input from theory
- Compare $\rho^0\rho^0$ with $\rho^0 J/\psi$

Non-femtoscopic correlations



Non-femtoscopic correlations (expected)

- Appear in small & low multiplicity systems.
- In hadronic pp, mini-jets and EMCICs (energy-momentum conservation).
- MUST be understood to interpret results. (Combinatorics?)

Dip at very low k* (unanticipated, not surprising)

- Two-slit interference, binning/momentum resolution, track splitting/merging, parity effects, P- or D-state, V(r)?

Statistics estimate

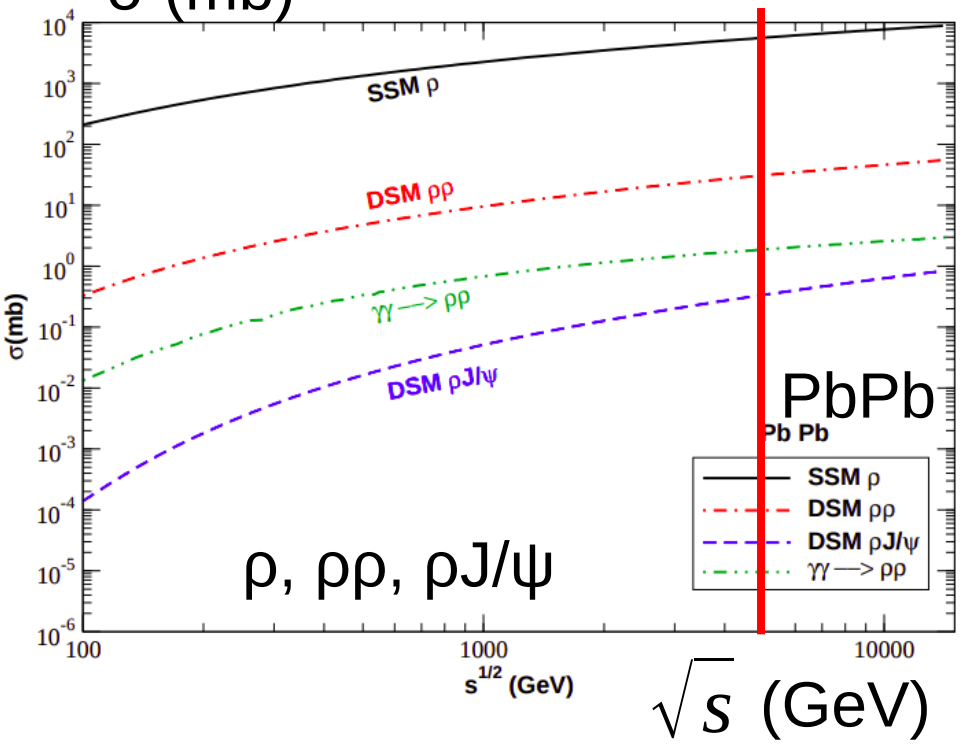
Z. Citron, et. al. Arxiv: 1812.06772

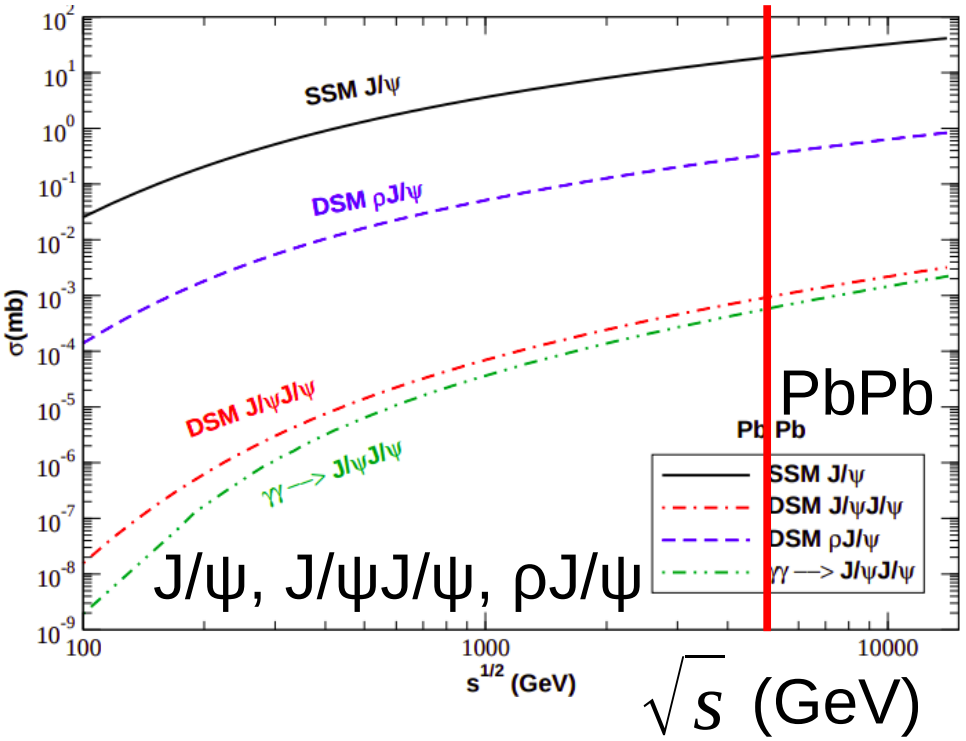
Condition	Tot.	Central 1 Narrow	Central 2 Wide	Forward 1 Narrow	Forward 2 Wide
Rapidity	-	$\|y\| < 0.9$	$\|y\| < 2.4$	$2.5 < y < 4.0$	$2 < y < 5$
e/π/μ pseudorapidity	-	$\|\eta\| < 0.9$	$\|\eta\| < 2.4$	$2.5 < \eta < 4.0$	$2 < \eta < 5$

		PbPb			
Meson	σ All Total	Central 1 Total	Central 2 Total	Forward 1 Total l	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b 68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb 9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b 2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb 14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb 400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb 26 K	2.8 K	14 K	880	2.0 K

Statistics estimate

Eur. Phys. J. C 76 (2016) 7, 388





Back of envelope calculation...

- N_v from previous slide.
- Cross sections estimates at 5. TeV.

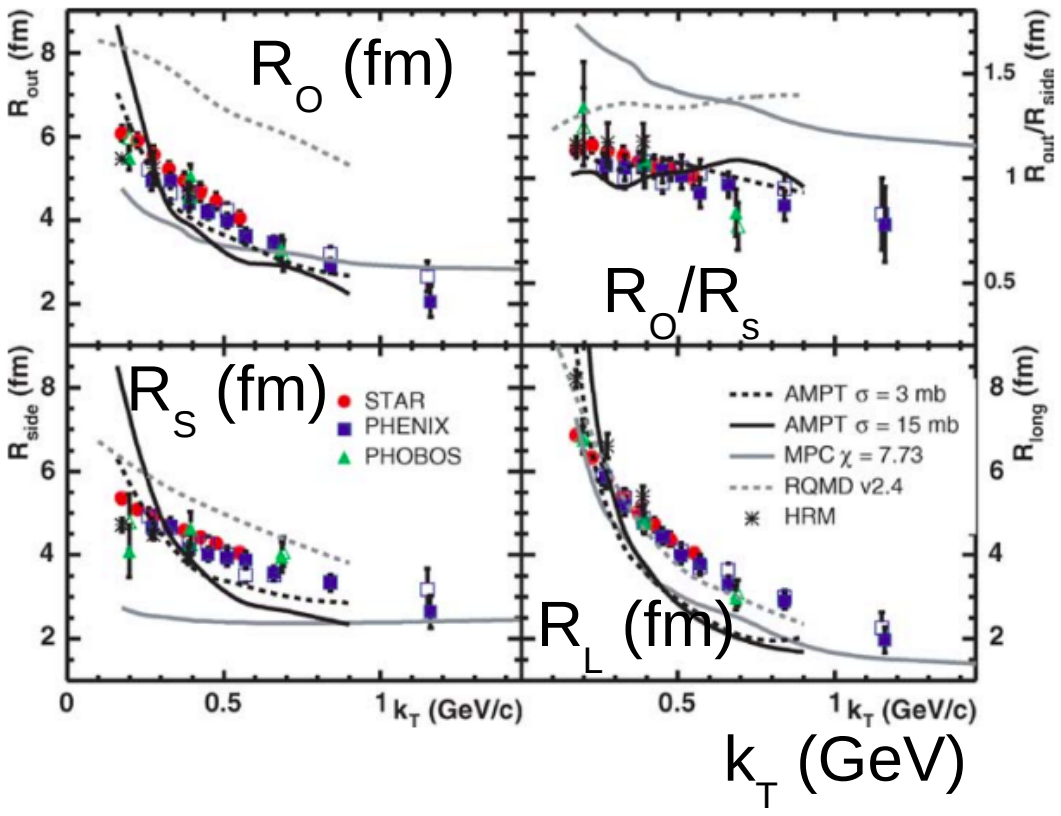
$$\frac{\sigma_{VV}}{\sigma_V} = \frac{N_{VV}}{N_V}$$

Mesons	Estimated
ρρ	25 M (9.2 M)
ρJ/ψ	17 K - 330 K (34 M)
J/ψJ/ψ	50

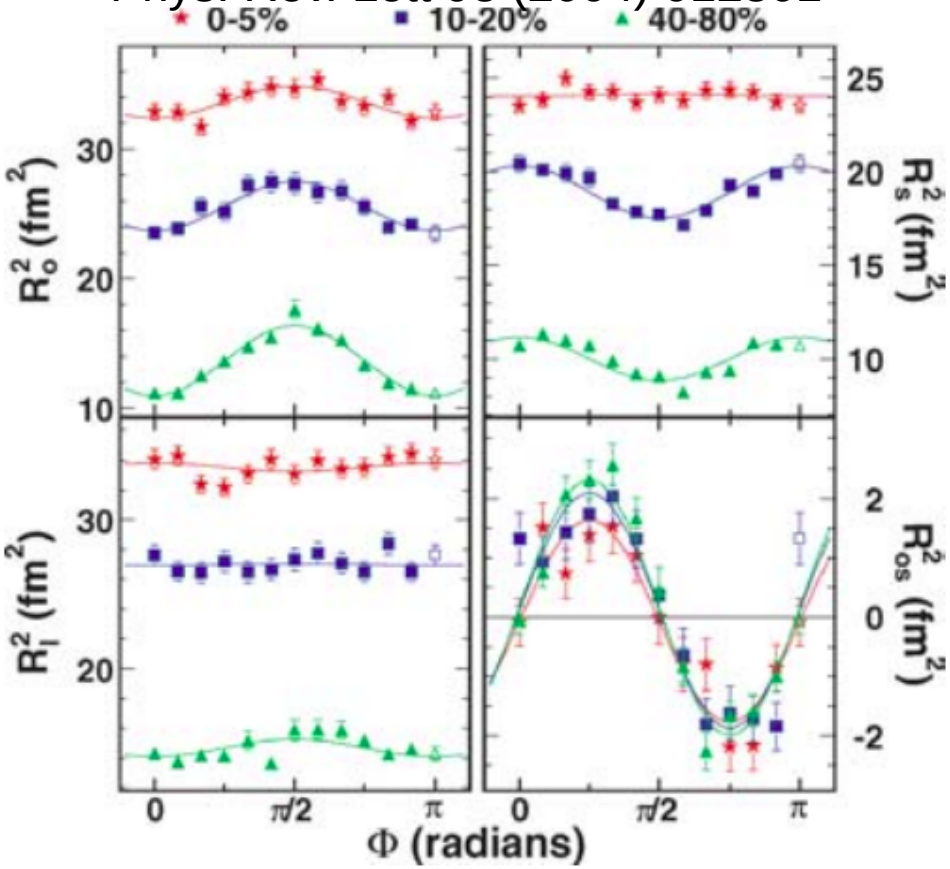
*Don't take too seriously! Very rough estimate.

Possibilities with ρρ?

Ann. Rev. Nucl. Part. Sci. 55 (2005) 357



Phys. Rev. Lett 93 (2004) 012301



- 2D or 3D structure.
- Momentum
- Rapidity

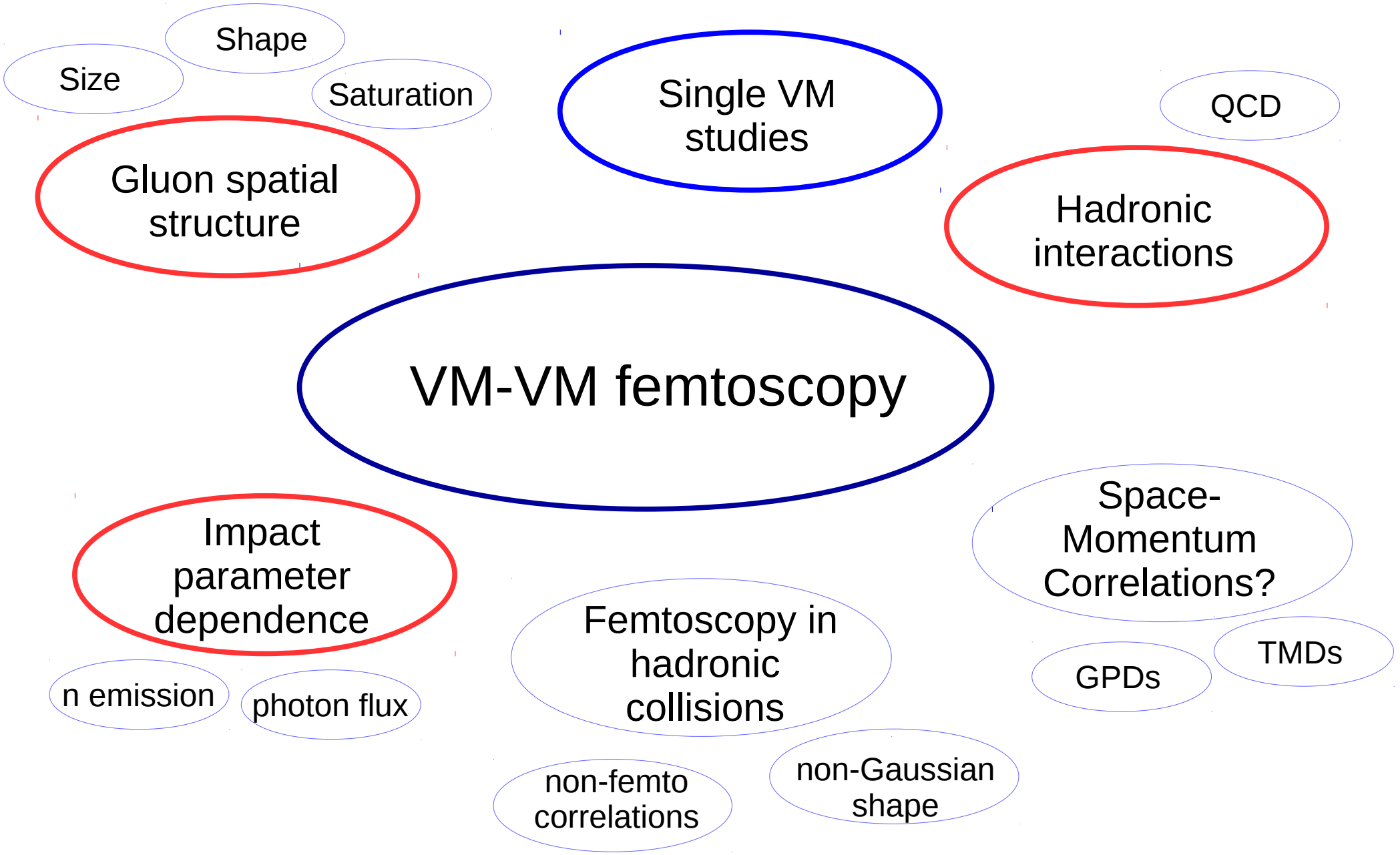
- Relative to impact parameter
- Polarization effects
- VM-VM & ππ correlations

- Two-slit interference effects?

Summary

- **New application of femtoscopy.**
- **May be way to probe gluon structure.**
- **Correlations sensitive to**
  - impact parameter
  - gluon spatial distributions
  - hadronic interactions
- **Decouple effects by comparing**
  - different particles
  - collision systems
  - complementary studies
  - theory input.
- **Needs further development but looks promising!**

Topics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n emission
photon flux
non-femto correlations
non-Gaussian shape

Backup

Other topics...

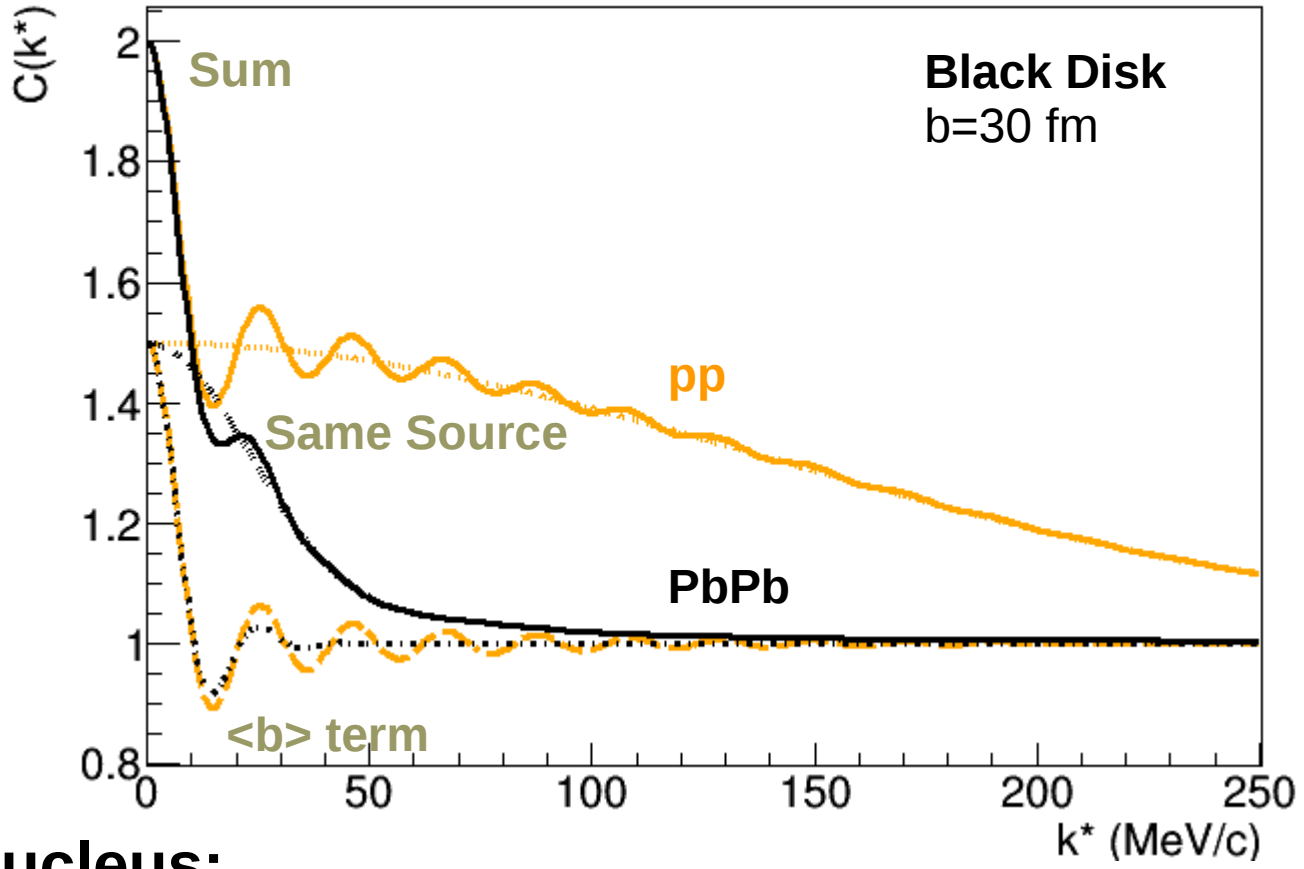
Coherent vs Incoherent

- Looking at difference in interaction points, fluctuations may average out.
- Incoherent may also probe gluon distribution.

Quantum Correlations

- Do Two-slit interference affect two-particle correlations too?

pp, AA and pA



Proton-Nucleus:

- Only proton gluon distribution contributes

Proton-Proton:

- All observations similar to PbPb.
- pp has wider “Same Source” contribution.
- <b> term largely independent of source size & shape.