IMPACT OF THE PROTON TRANSVERSE STRUCTURE IN QCD PHENOMENOLOGY

Alba Soto-Ontoso[1,2]

+ Javier L. Albacete[1], Harri Niemi[4] and Hannah Petersen[2,3,5]

[1] Departamento de Física Teórica y del Cosmos, Universidad de Granada
[2] Frankfurt Institute for Advanced Studies
[3] Goethe Universität
[4] University of Jyväskylä
[5] GSI

Workshop “Probing quark-gluon matter with jets”

Brookhaven National Lab, 24th July, 2018

Disclaimer

This talk

This workshop

p_T

The main goals of this talk

?

The main goals of this talk

?

Constrain the transverse spatial structure of the proton via elastic scattering data from ISR ($23.4 < \sqrt{s} < 62.5$ GeV) and LHC ($\sqrt{s} = 7$ TeV)

The main goals of this talk

?

Constrain the transverse spatial structure of the proton via elastic scattering data from ISR ($23.4 < \sqrt{s} < 62.5$ GeV) and LHC ($\sqrt{s} = 7$ TeV)

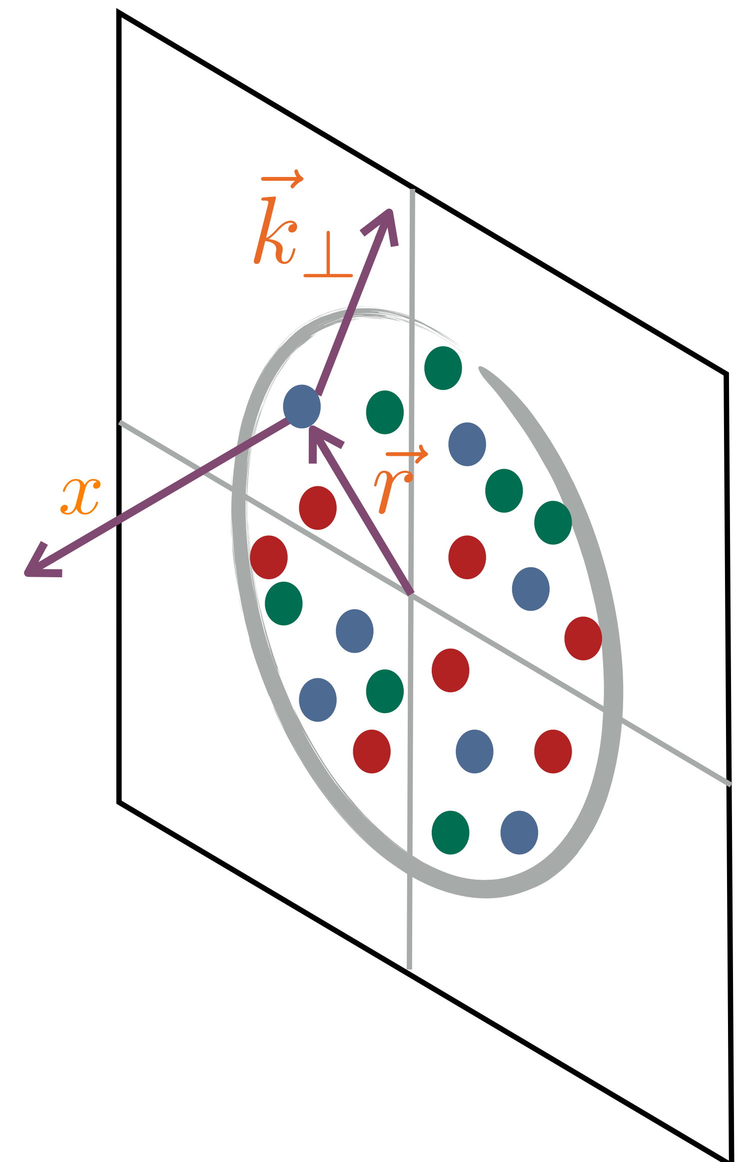
Gauge the impact of a fine-detailed description of the proton geometry on observables relevant to quark gluon plasma (QGP) studies

HADRON STRUCTURE

What do we need?

Goal: fully characterize a parton in a hadron

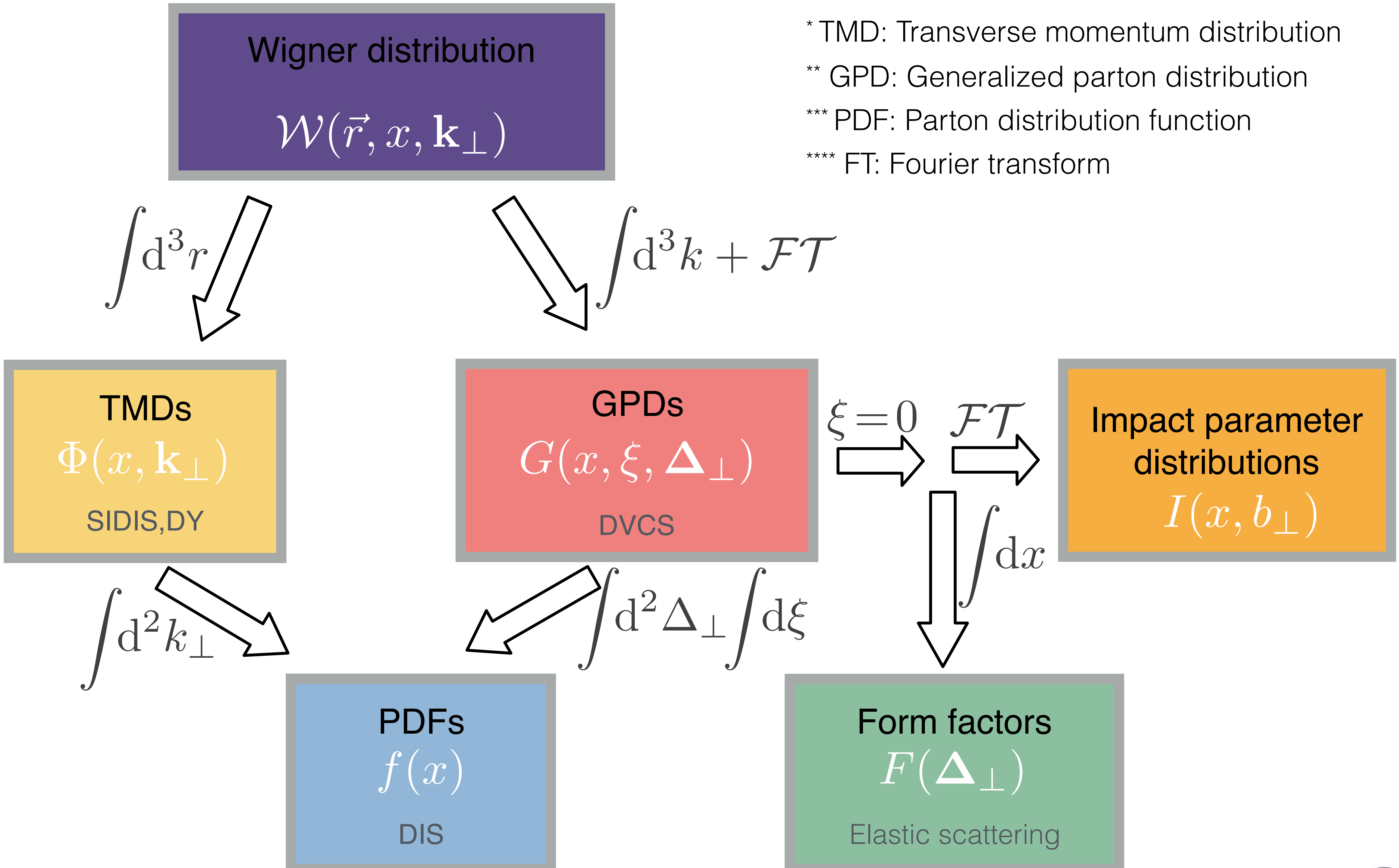
- x : longitudinal momentum fraction (1D)
- $\vec{k}_\perp$: transverse momentum (2D)
- $\vec{r}$: position (2 or 3D)
- Spin



Theoretically, information encoded in Wigner distribution

The big picture

* TMD: Transverse momentum distribution
** GPD: Generalized parton distribution
*** PDF: Parton distribution function
**** FT: Fourier transform



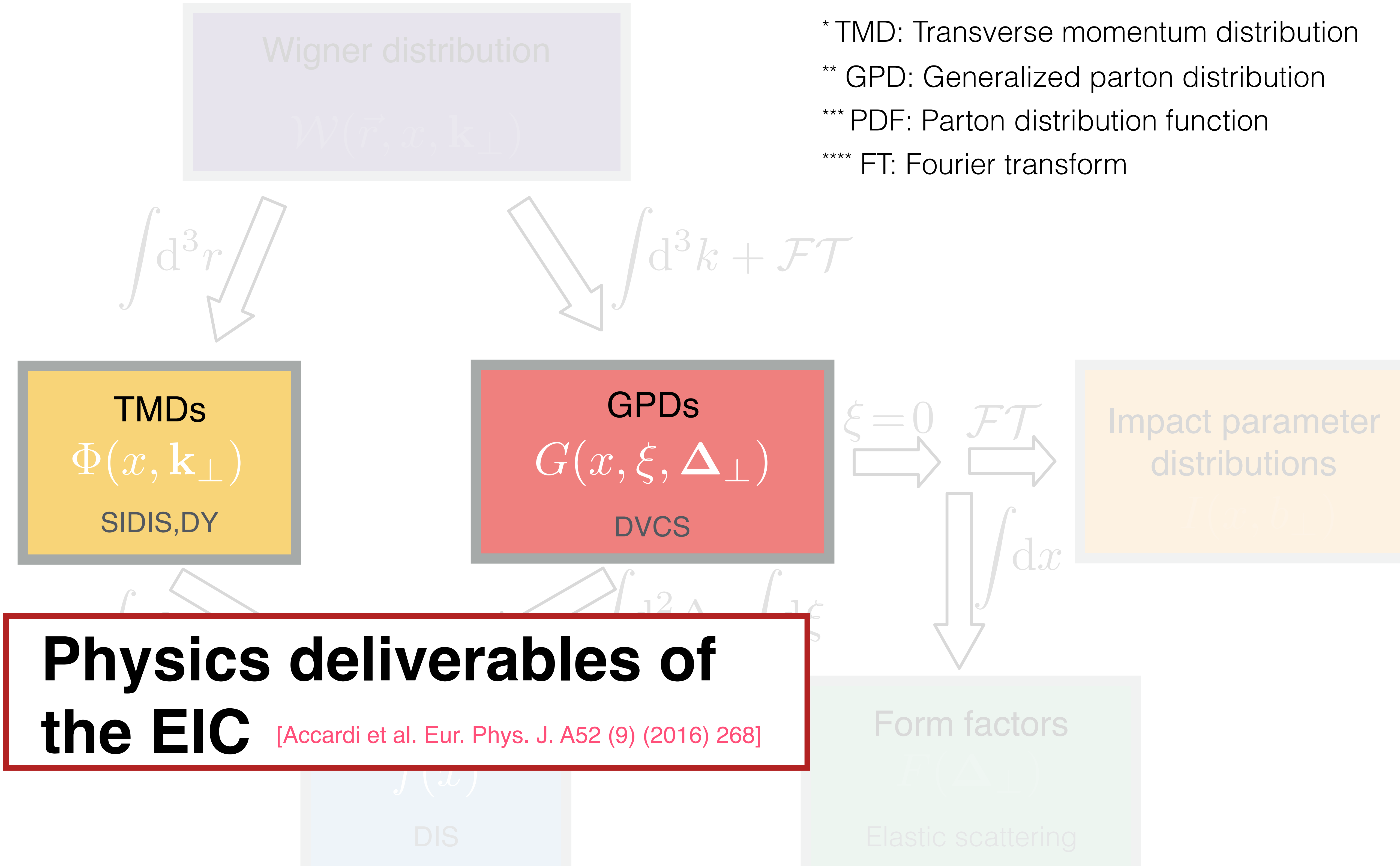
The big picture

[*] TMD: Transverse momentum distribution

[**] GPD: Generalized parton distribution

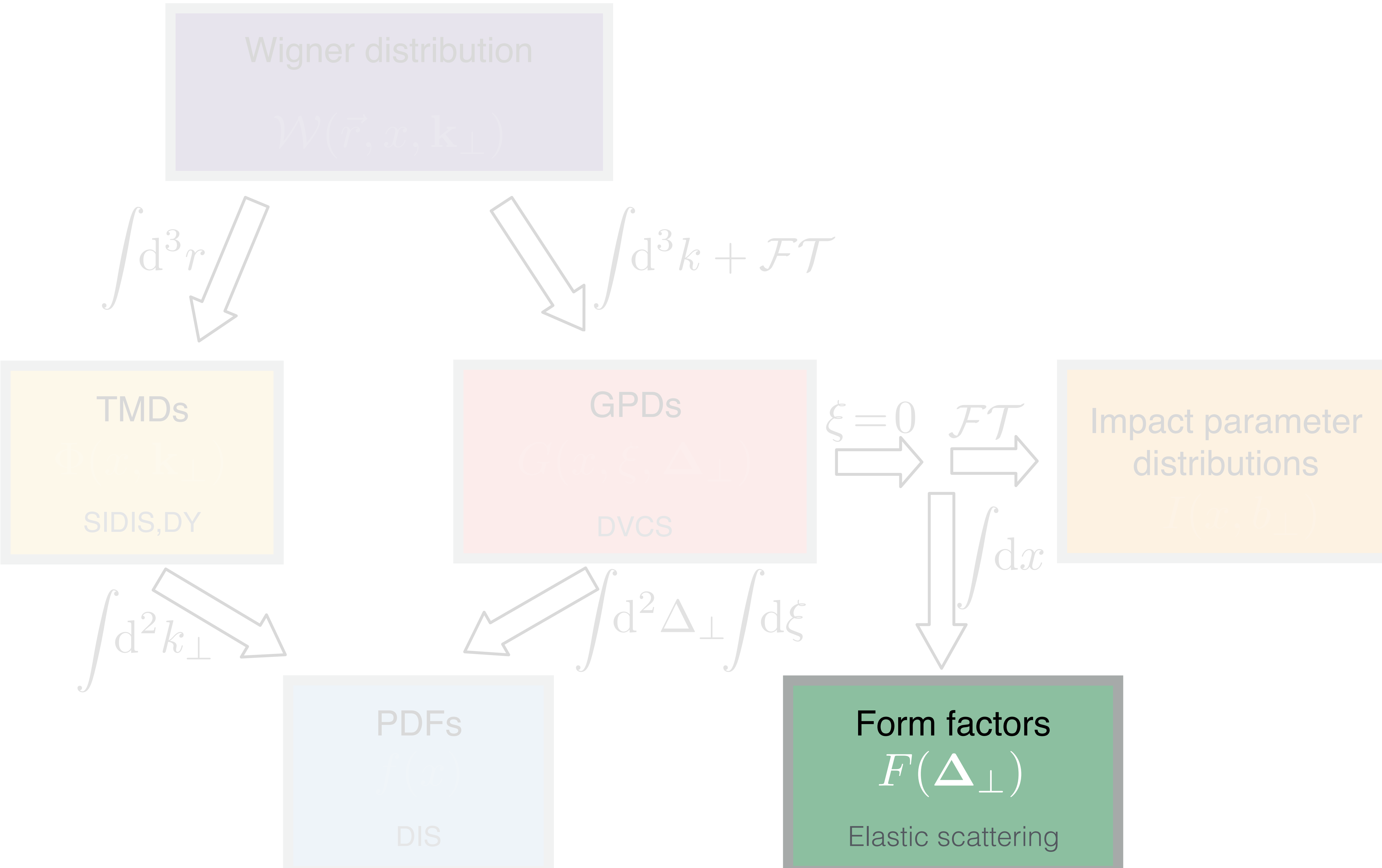
[***] PDF: Parton distribution function

[****] FT: Fourier transform



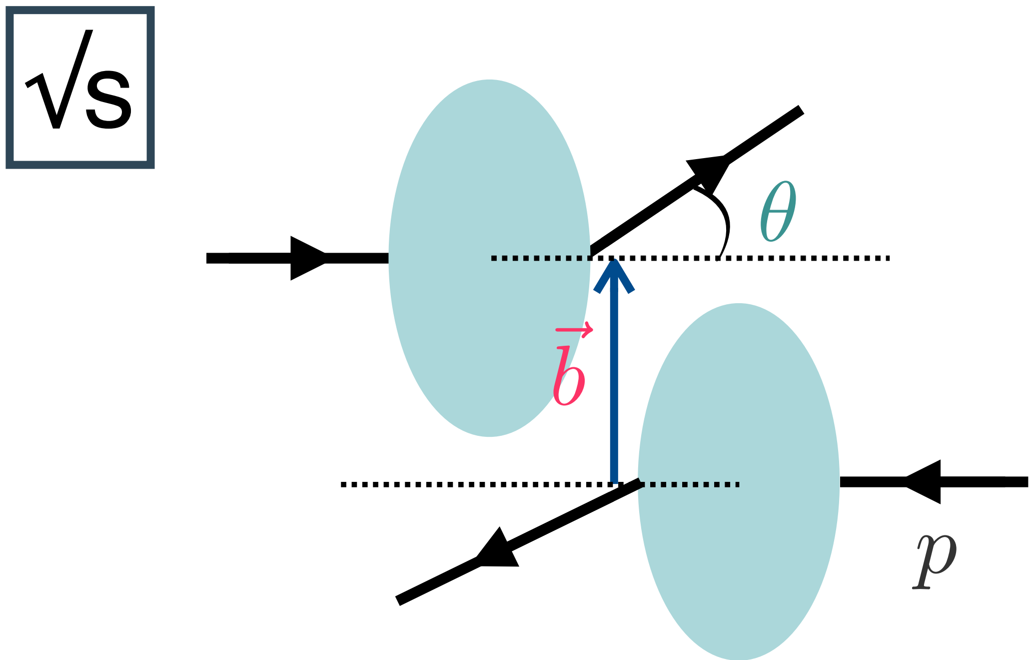
Physics deliverables of the EIC [Accardi et al. Eur. Phys. J. A52 (9) (2016) 268]

The focus of this talk



ELASTIC SCATTERING

Theory



$$\frac{d\sigma_{\rm el}}{dt} = \frac{1}{4\pi}|T_{\rm el}(s,t)|^2$$

with $t = -2p^2(1-\cos\theta)$

$\boxed{T_{\rm el}(s,t)\ \textbf{is the main building block of scattering theory}}$

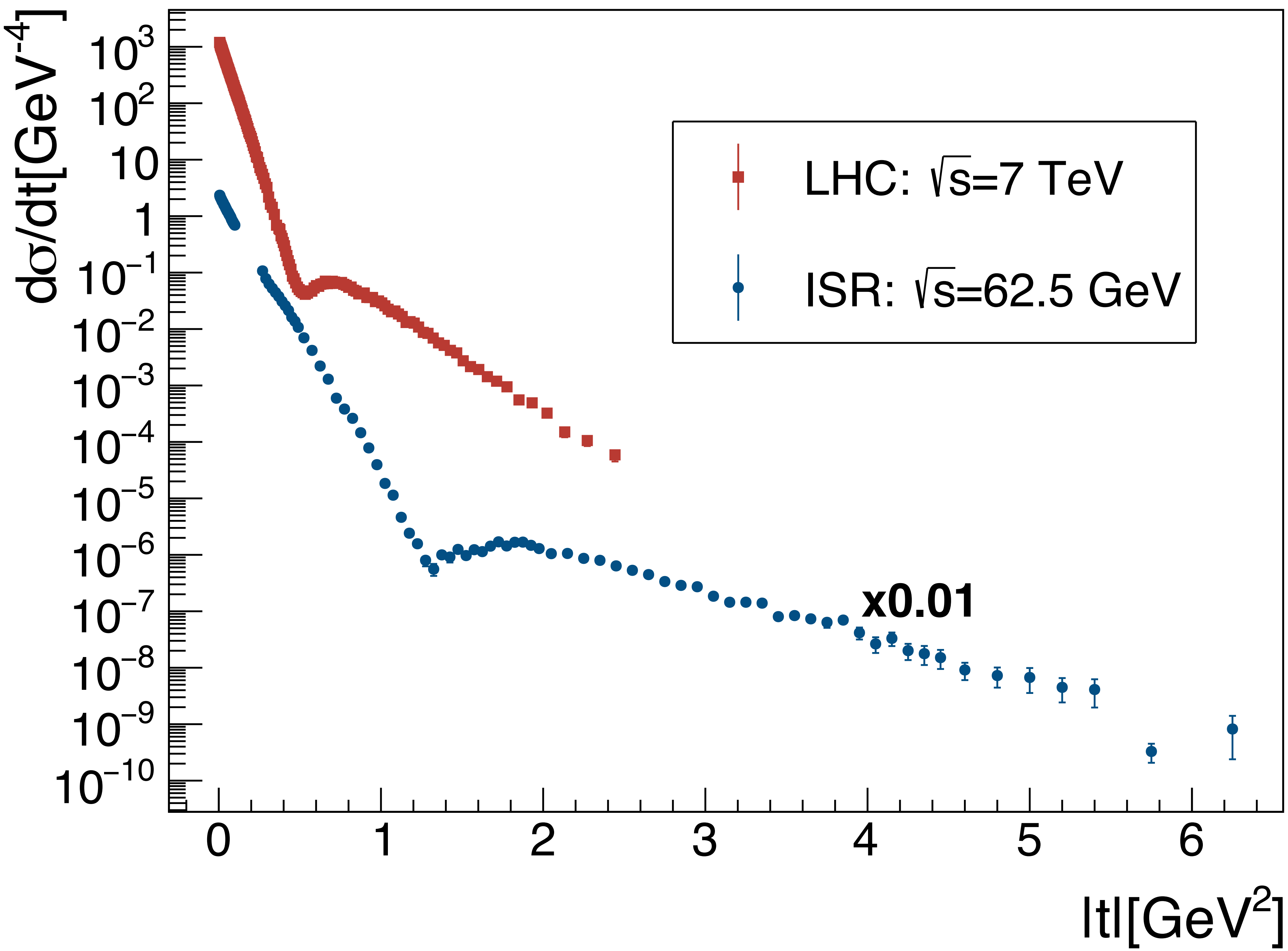
⇨ A detailed map of the interaction region in $\vec{b}$-space

$T_{\rm el}(s,t) \overset{\mathcal{FT}}{\Longrightarrow} \widetilde{T}_{\rm el}(s,b)$ **Scan of the proton at** $b \sim 1/\sqrt{|t|}$

$$\sigma_{\rm tot}(s) = 2{\rm Im}T_{\rm el}(s,0)$$

$$\rho(s,t) = \frac{{\rm Re}T_{\rm el}(s,t)}{{\rm Im}T_{\rm el}(s,t)}$$

Elastic scattering data



Extracting the inelasticity density

The unitarity condition ($\sigma_{\rm tot} = \sigma_{\rm in} + \sigma_{\rm el}$) can be written as

$$0 < \boxed{G_{\rm in}(s,\vec{b}) \equiv \frac{d^2\sigma_{\rm in}}{d^2\vec{b}} = 2{\rm Im}\widetilde{T}_{\rm el}(s,\vec{b}) - |\widetilde{T}_{\rm el}(s,\vec{b})|^2} < 1$$

where $G_{\rm in}(s,\vec{b})$ is the inelasticity density. NOT measurable!

Extract $G_{\rm in}(s,\vec{b})$ from $d\sigma_{\rm el}/dt$ data

But…describing $d\sigma_{\rm el}/dt$ is not enough, the phase is needed

$$d\sigma_{\rm el}/dt \propto |\widetilde{T}_{\rm el}(s,\vec{b})|^2 \quad \&\& \text{ e.g } \rho(s,t) = \frac{{\rm Re}T_{\rm el}(s,t)}{{\rm Im}T_{\rm el}(s,t)}$$

Extracting $G_{\mathrm{in}}(s,\vec{b})$ methodology

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

1 Generic (no physical meaning) parametrization of $T_{\mathrm{el}}(s,t)$

$$\mathrm{Im}T_{\mathrm{el}}(s,t) = a_1 e^{b_1 t} + a_2 e^{b_2 t} + a_3 e^{b_3 t}$$

$$\mathrm{Re}T_{\mathrm{el}}(s,t) = c_1 e^{d_1 t}$$

+ phenomenological constraints

$$\sigma_{\mathrm{tot}} = 2\sum_{i=1}^{3} a_i = \begin{cases} 43.32 \pm 0.34 \text{ mb ISR} \\ 98.3^{+2.8}_{-2.7} \text{ mb LHC} \end{cases}$$

$$\rho = c_1 \sum_{i=1}^{3} 1/a_i = \begin{cases} 0.095 \pm 0.018 \text{ ISR} \\ 0.14^{+0.01}_{-0.08} \text{ LHC} \end{cases}$$

[COMPETE Phys. Rev. Lett. 89 (2002) 201801]

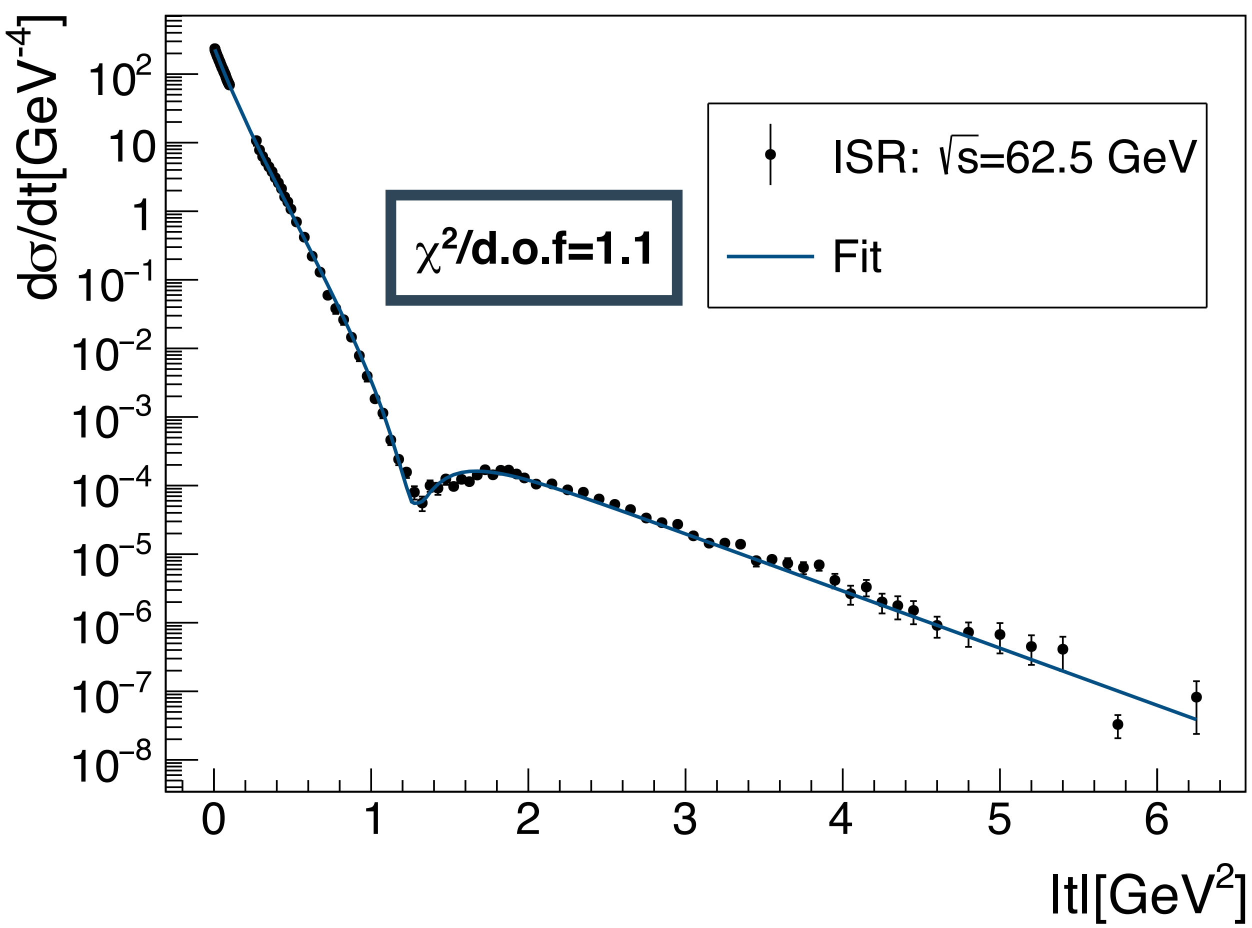
#d.o.f = 6

Extracting $G_{\rm in}(s,\vec{b})$ methodology

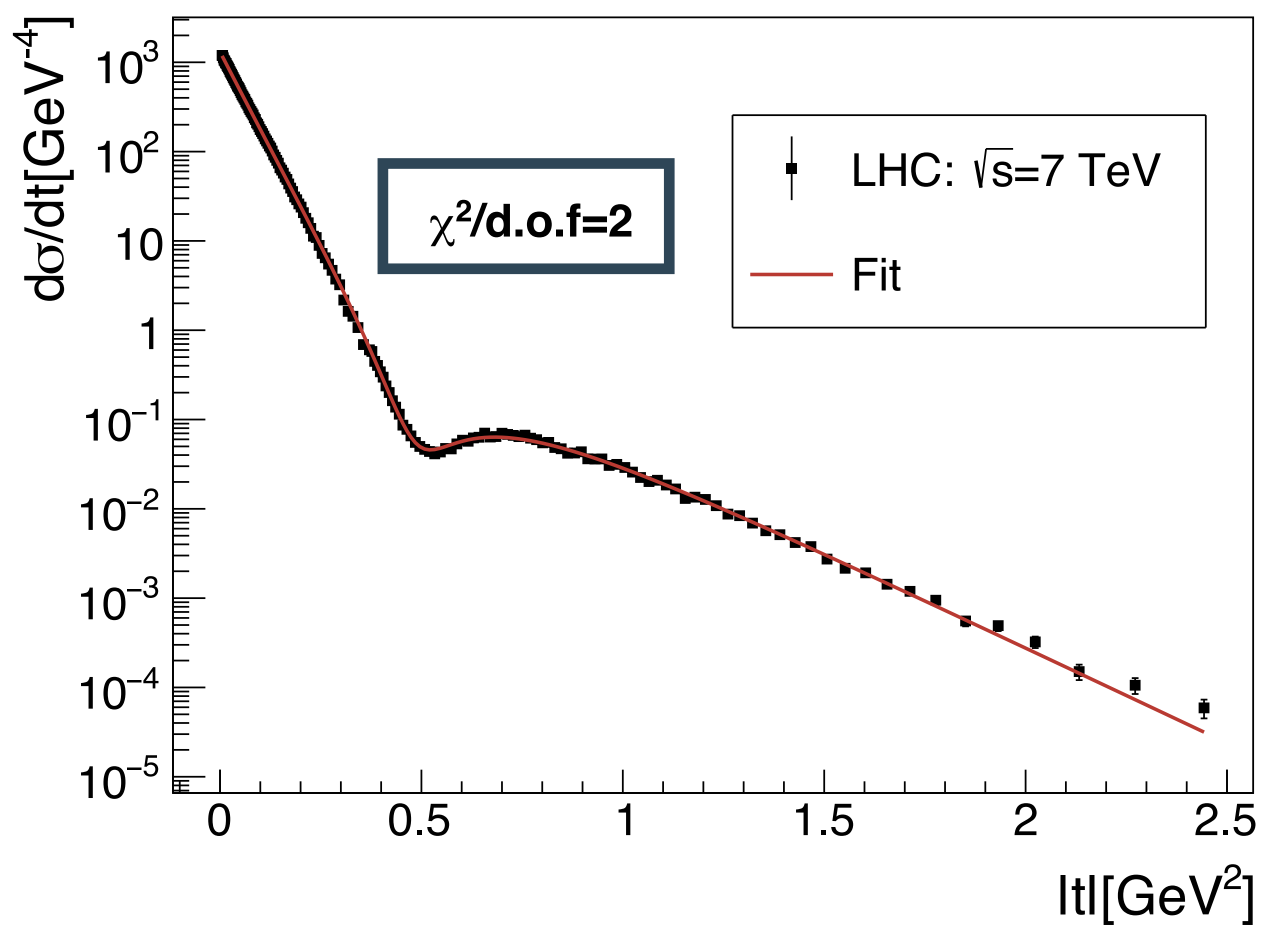
[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

2 Fit the elastic scattering data

ISR



LHC

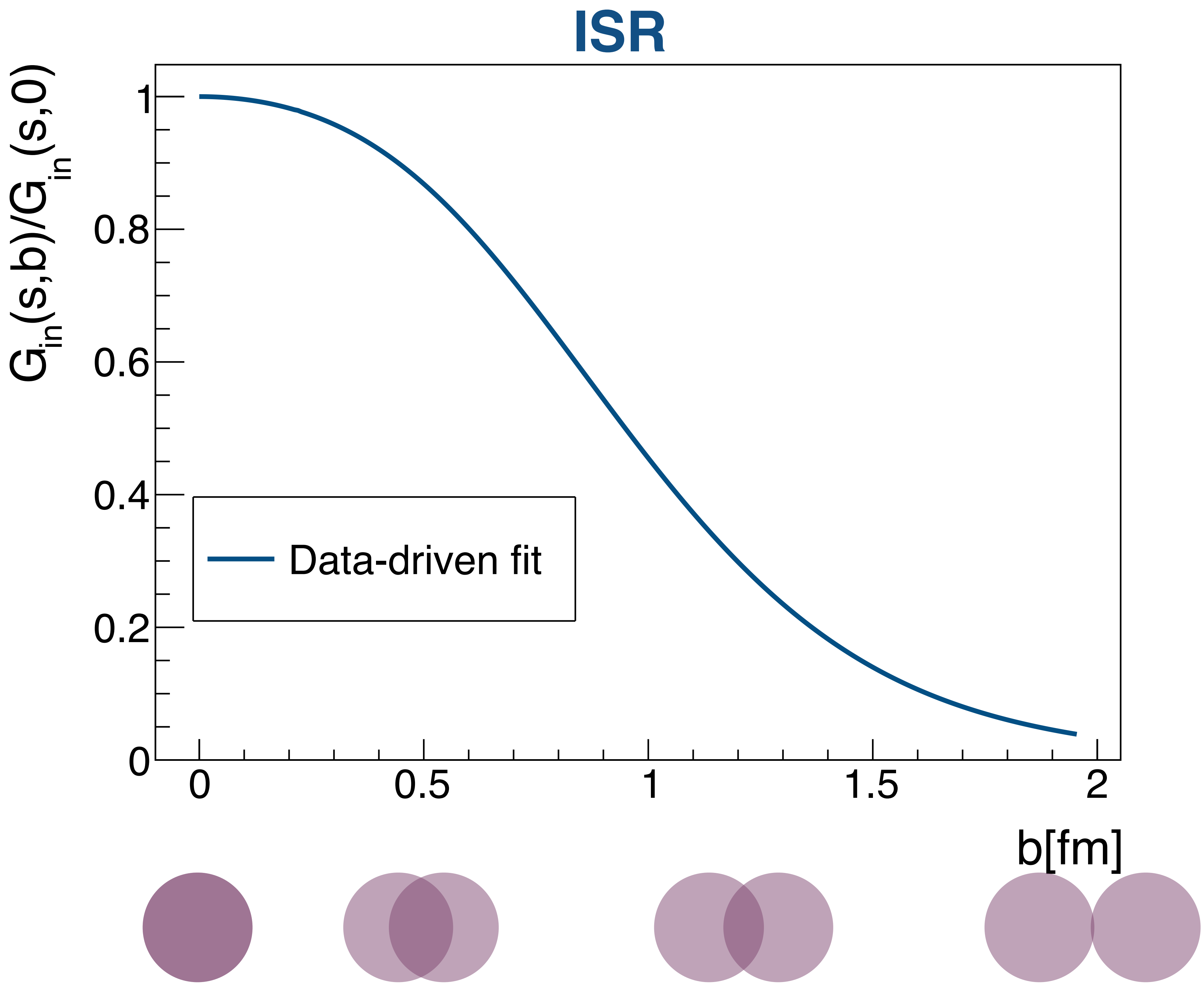


$$T_{\rm el}(s,t) \xrightarrow{\mathcal{FT}} \widetilde{T}_{\rm el}(s,b)$$

Extracting $G_{\rm in}(s,\vec{b})$ methodology

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

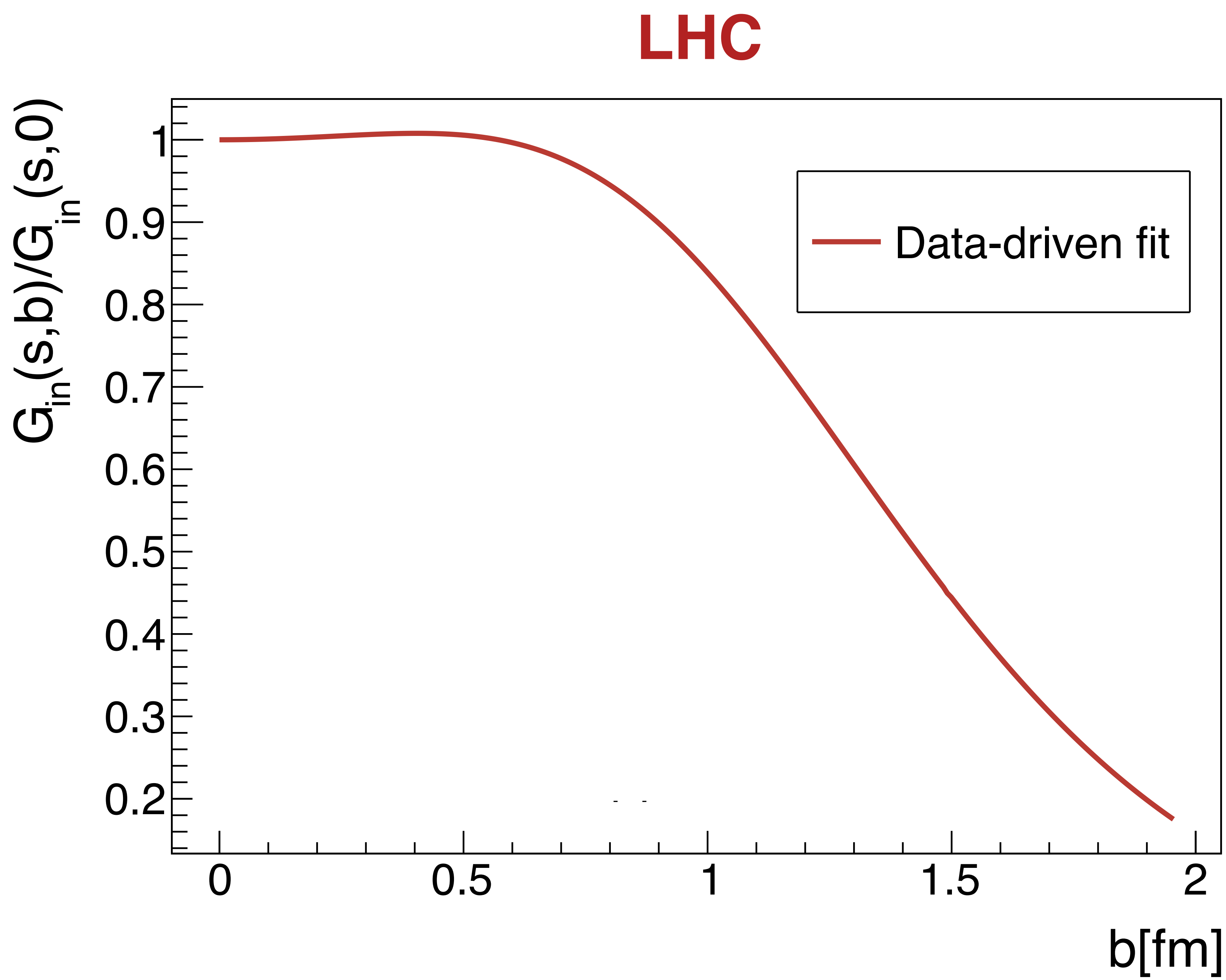
3 Fourier transform to obtain $G_{\rm in}(s,\vec{b}) = 2{\rm Im}\widetilde{T}_{\rm el}(s,\vec{b}) - |\widetilde{T}_{\rm el}(s,\vec{b})|^2$



Extracting $G_{\rm in}(s,\vec{b})$ methodology

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

3 Fourier transform to obtain $G_{\rm in}(s,\vec{b}) = 2{\rm Im}\widetilde{T}_{\rm el}(s,\vec{b}) - |\widetilde{T}_{\rm el}(s,\vec{b})|^2$

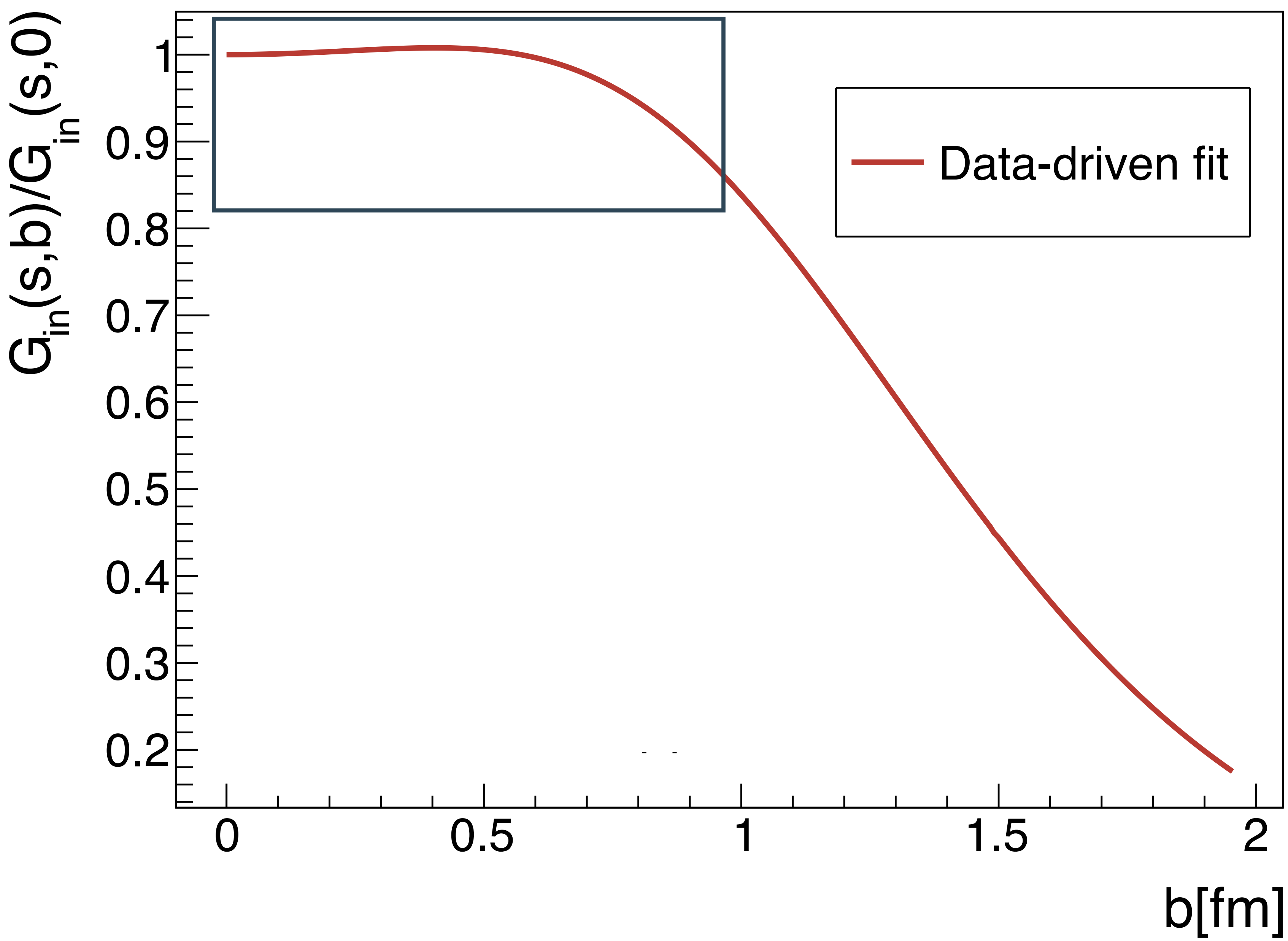


Extracting $G_{\rm in}(s,\vec{b})$ methodology

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

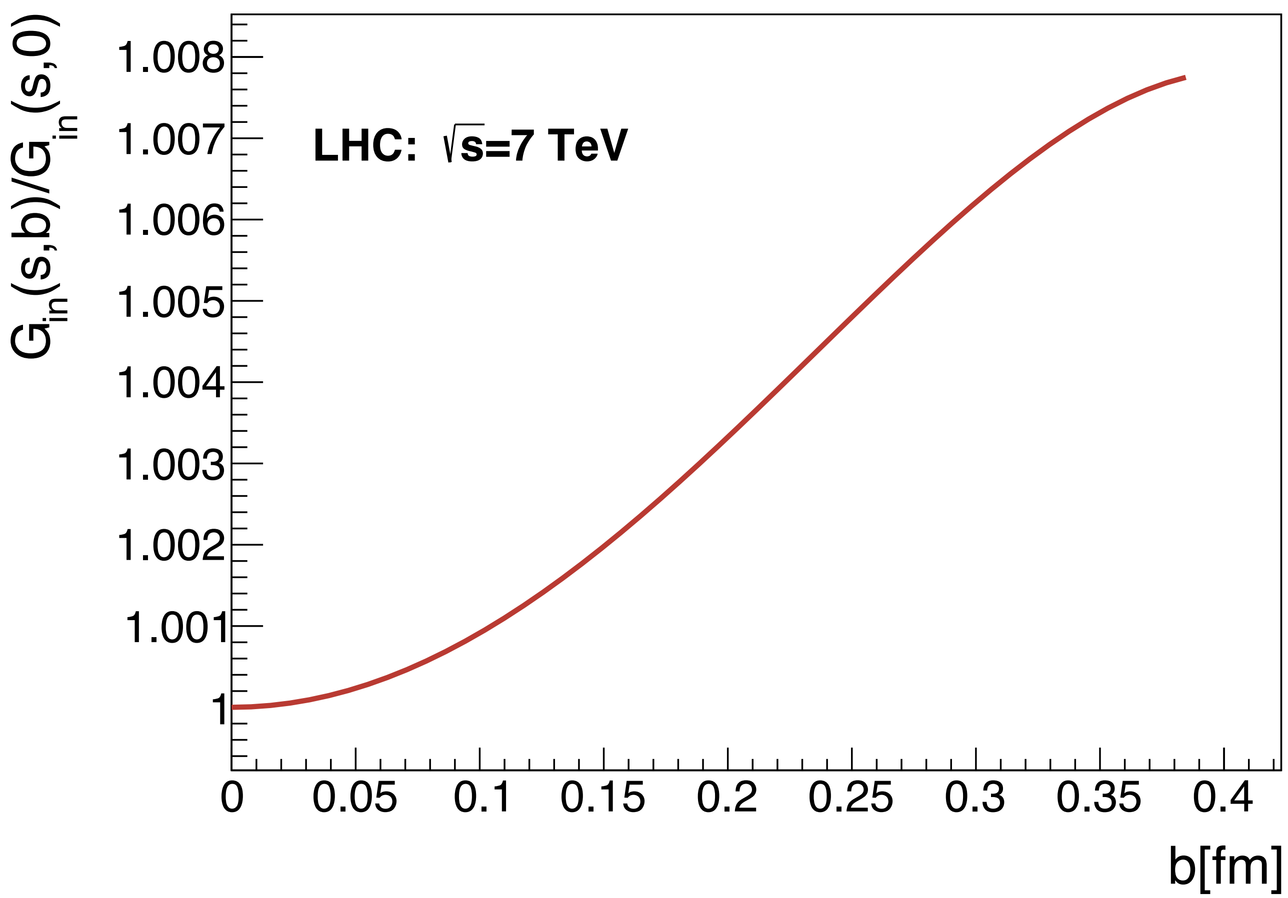
3 Fourier transform to obtain $G_{\rm in}(s,\vec{b}) = 2{\rm Im}\widetilde{T}_{\rm el}(s,\vec{b}) - |\widetilde{T}_{\rm el}(s,\vec{b})|^2$

LHC

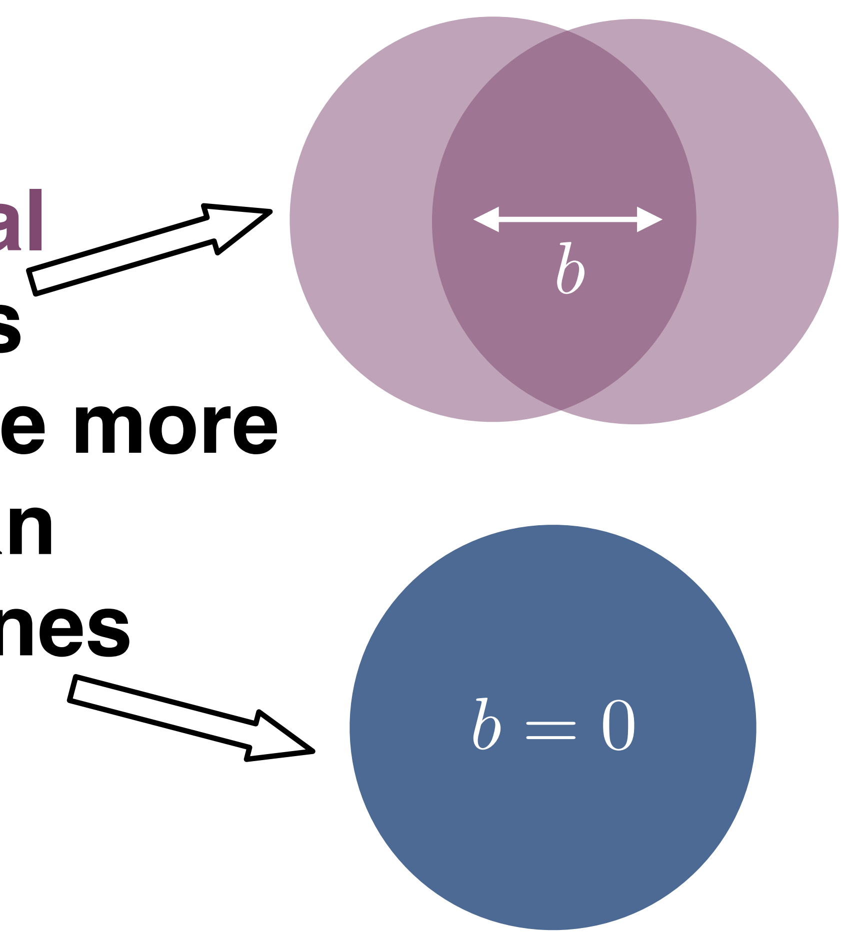


Inelasticity density @LHC

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

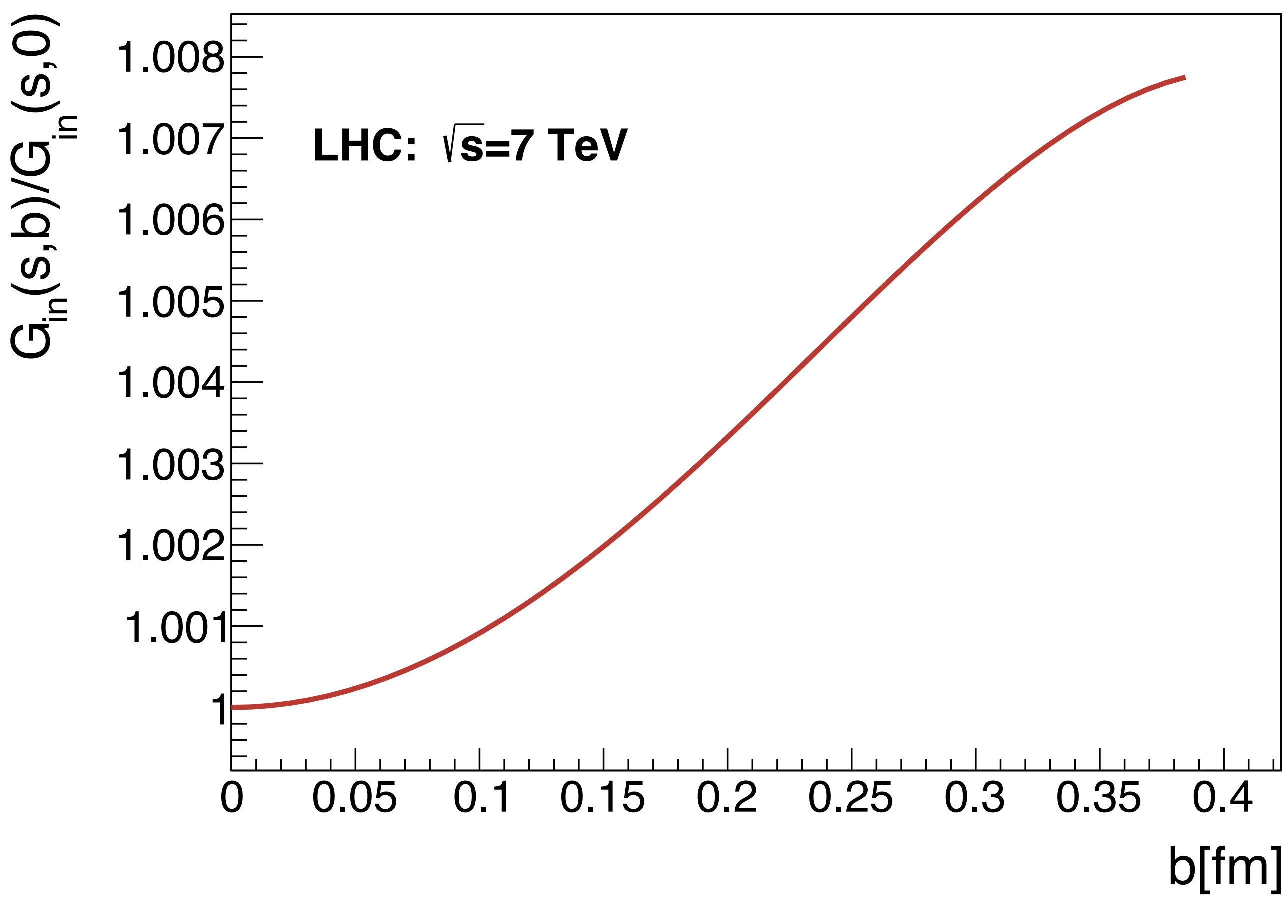


- **STRIKING growing behavior at low impact parameter**
- **Not observed at ISR energy**
- **Peripheral collisions contribute more to $\sigma_{\rm in}$ than central ones**



Inelasticity density @LHC

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]



- **Independent confirmation by**

  [Arriola, Broniowski Phys. Rev. D95 (2017) 07430]
  [Alkin et al., Phys. Rev. D89 (9) (2014) 091501]
  [Dremin Phys. Ints. 44 (2017) 94-98]

HOLLOWNESS EFFECT

- **Found at 13 TeV including error propagation**

  [Alkin et al., arXiv:1807.06471]

The hollowness effect

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

$\Rightarrow$ $\left.\frac{dG_{\text{in}}(s,b)}{db}\right|_{b=0} > 0$ @**LHC** highly non-trivial dynamical feature

$\Rightarrow$ Challenges the standard geometric interpretation

$G_{\text{in}} \propto \rho(b') \otimes \rho(b'-b)$

Maximum always at b=0

Folding/ geometrical models precluded

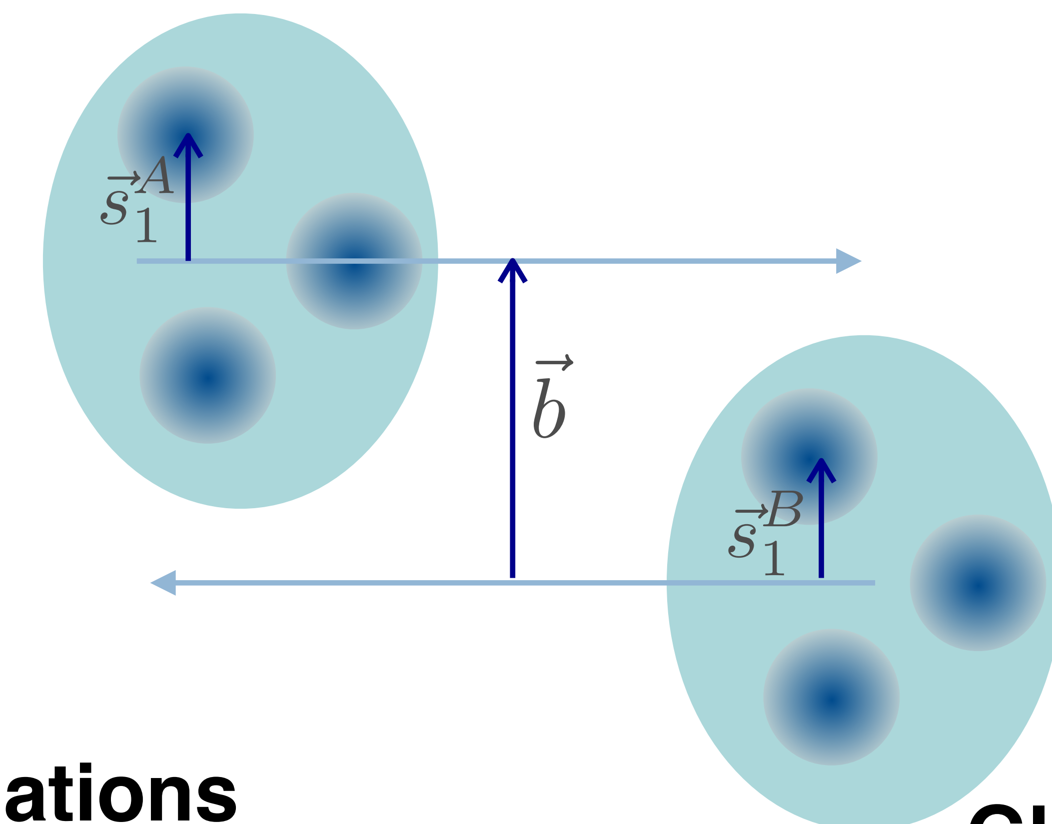
$\Downarrow$

Quantum interference/coherence effects needed to describe the onset of the hollowness effect

Model description

Setup

Gluonic hot-spots as effective d.o.f
characterized by R_{hs} and N_{hs}



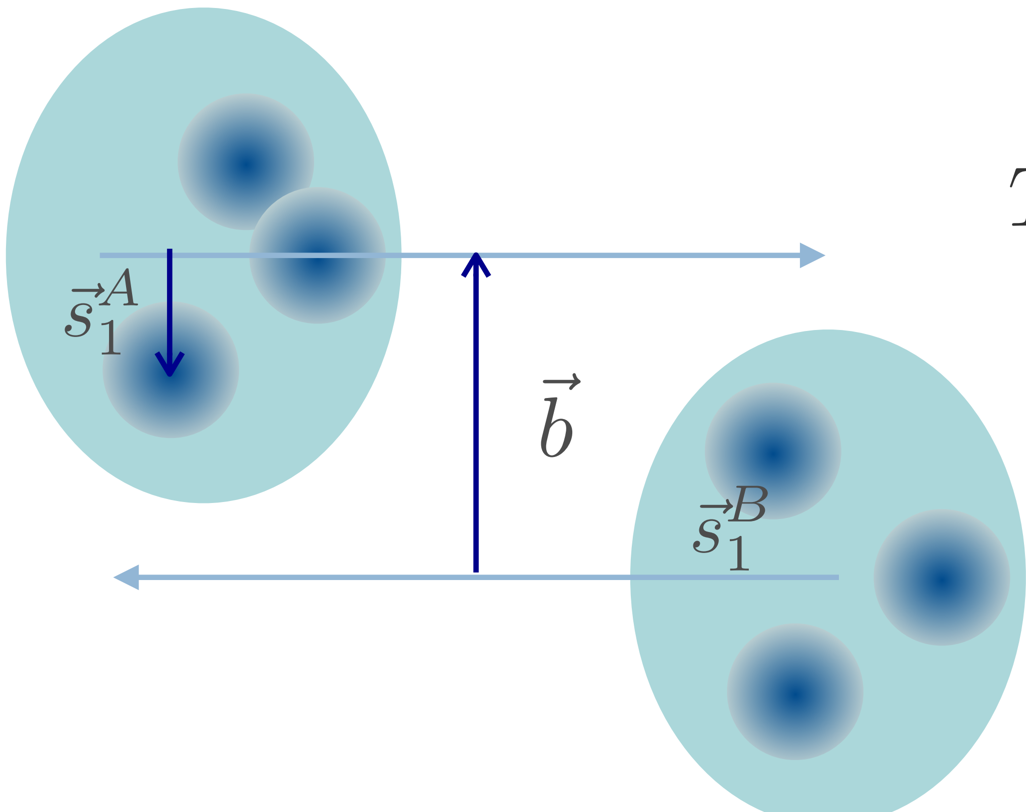
Spatial correlations
in transverse space

Glauber multiple
scattering expansion

Glauber model

[Glauber, Lectures in Theoretical Physics, 1955]

Quantum mechanical scattering theory for composite systems at high energies. Conceived for A+A collisions



$$T_{\mathrm{el}}(\vec{b}) = 1 - \prod_{i=1}^{3}\prod_{j=1}^{3}\left[1 - \Theta(\vec{b} + \vec{s}_i^{\,A} - \vec{s}_j^{\,B})\right]$$

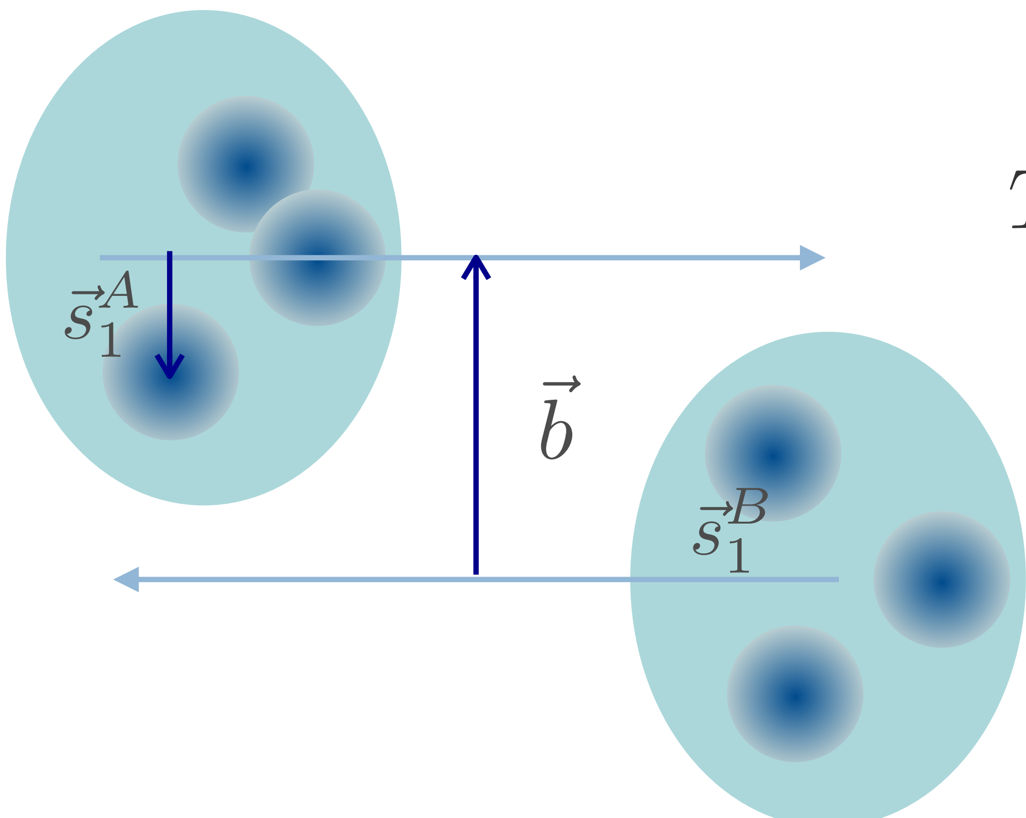
To facilitate analytical calculations

$$\boxed{\Theta(s_{ij}) = \exp\left(-s_{ij}^2/2R_{hs}^2\right)\left(1 - \mathrm{i}\rho_{hs}\right)}$$

Glauber model

[Glauber, Lectures in Theoretical Physics, 1955]

Quantum mechanical scattering theory for composite systems at high energies. Conceived for A+A collisions



$$T_{\rm el}(\vec{b}) = 1 - \prod_{i=1}^{3}\prod_{j=1}^{3}\left[1 - \Theta(\vec{b} + \vec{s}_i^A - \vec{s}_j^B)\right]$$

To facilitate analytical calculations

$$\boxed{\Theta(s_{ij}) = \exp\left(-s_{ij}^2/2R_{hs}^2\right)\left(1 - \mathrm{i}\rho_{hs}\right)}$$

$\Rightarrow$

$$\boxed{\widetilde{T}_{\rm el}(\vec{b}) = \int \prod_{k,l} \mathrm{d}^2 s_k^A \mathrm{d}^2 s_l^B D_A(\{\vec{s}_k^A\}) D_B(\{\vec{s}_l^B\}) T_{\rm el}(\vec{b})}$$

- $D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$: probability distribution for the transverse positions of the hot spots

Spatial distribution of hot spots

$$D(\vec{s}_1,\vec{s}_2,\vec{s}_3) = C \boxed{\prod_{i=1}^{3} e^{-s_i^2/R^2}} \boxed{\delta^{(2)}(\vec{s}_1+\vec{s}_2+\vec{s}_3)} \times \boxed{\prod_{\substack{i<j \\ i,j=1}}^{3} \left(1 - e^{-\mu|\vec{s}_i-\vec{s}_j|^2/R^2}\right)}$$

uncorrelated probability distribution characterized by R (not the proton radius)

fixes the C.o.M of the hot spots system

short range repulsive correlations controlled by $r_c^2 \equiv R^2/\mu$

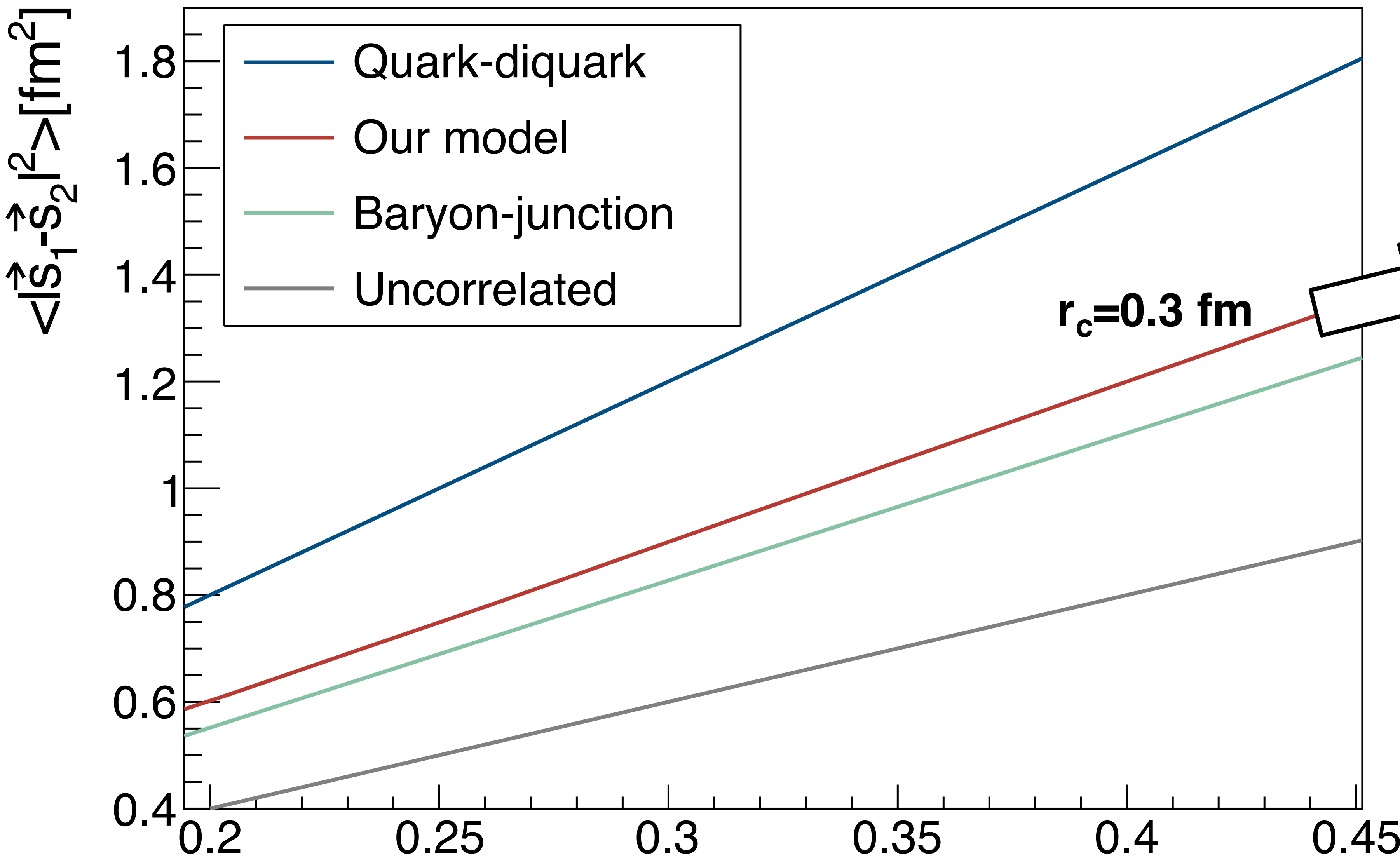
Main novelty

*C: normalization constant

Spatial distribution of hot spots

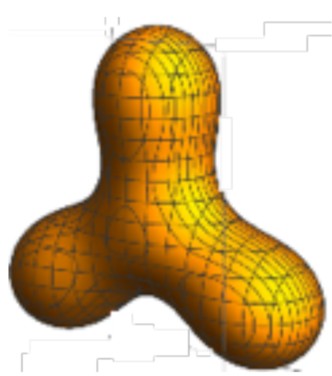
[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

$$\langle X \rangle = \int \mathrm{d}\vec{s}_1 \mathrm{d}\vec{s}_2 \mathrm{d}\vec{s}_3 X D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$$



Interpolates between realistic models of proton substructure

Baryon-junction



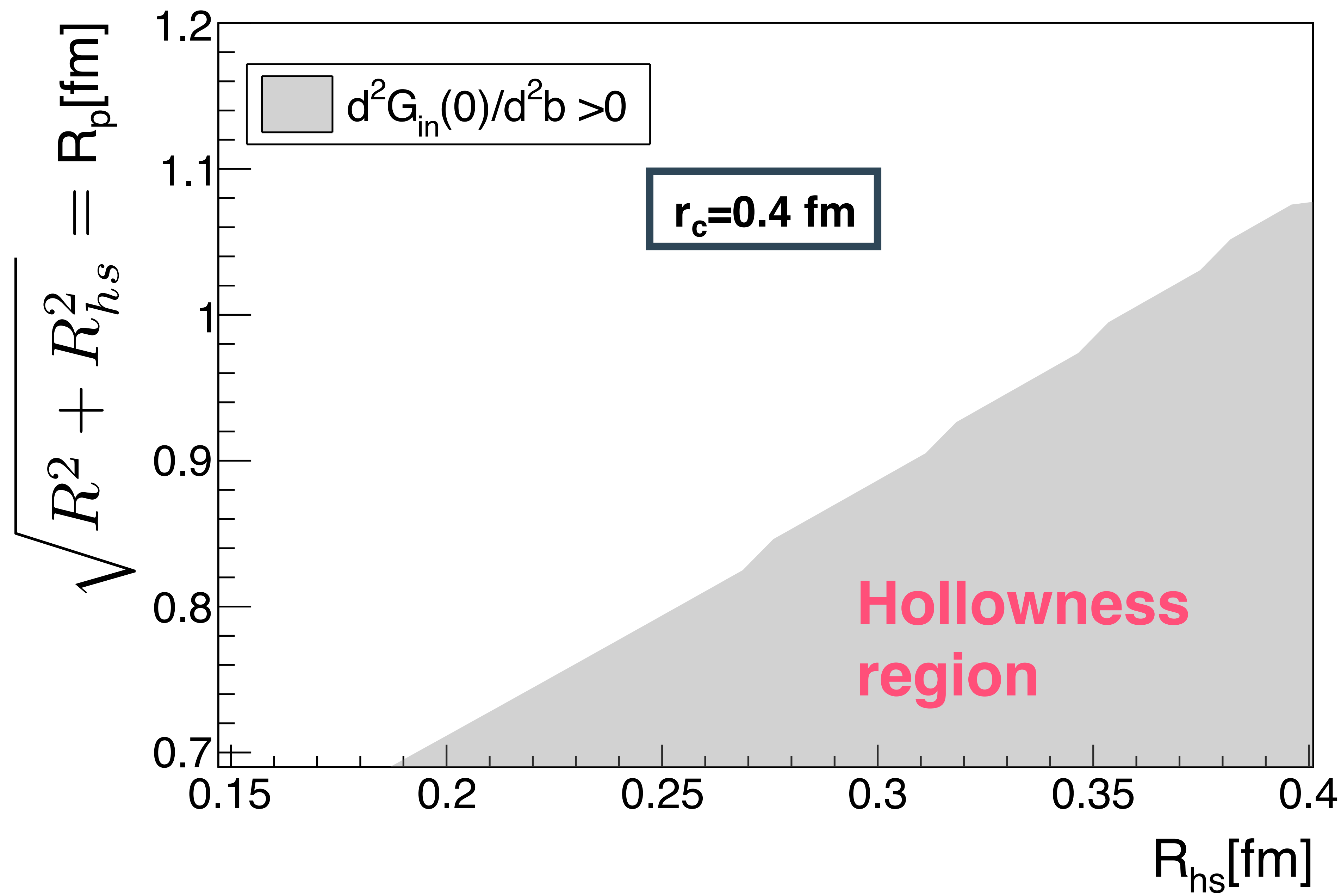
Quark-diquark

[Kubiczek et al. Lith.J.Phys. 55 (2015) 155]

RESULTS

[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

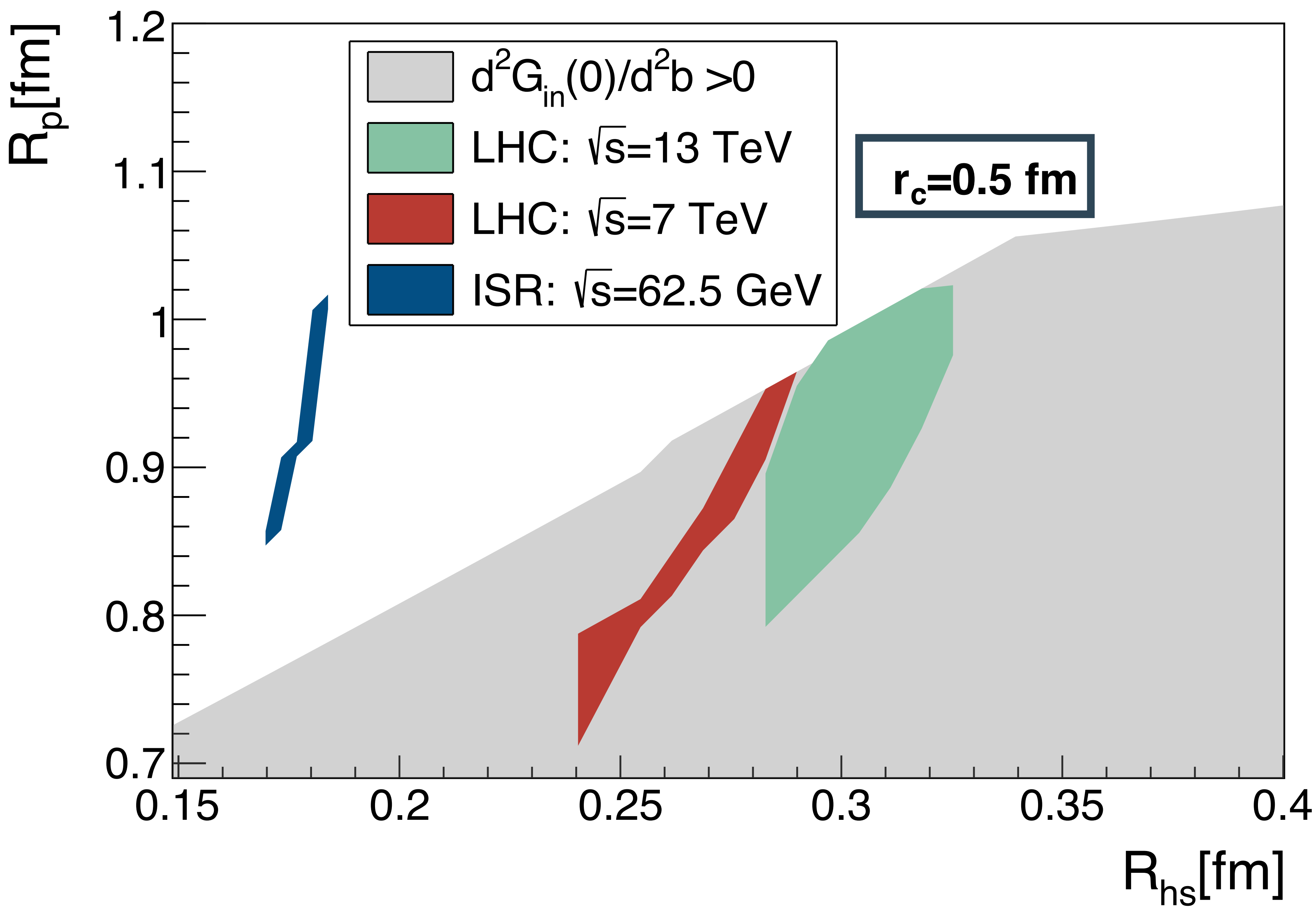
Parameter space: $\{R_{hs}, R_p, r_c, \rho_{hs}\}$



Wide region of the parameter space compatible with the hollowness effect

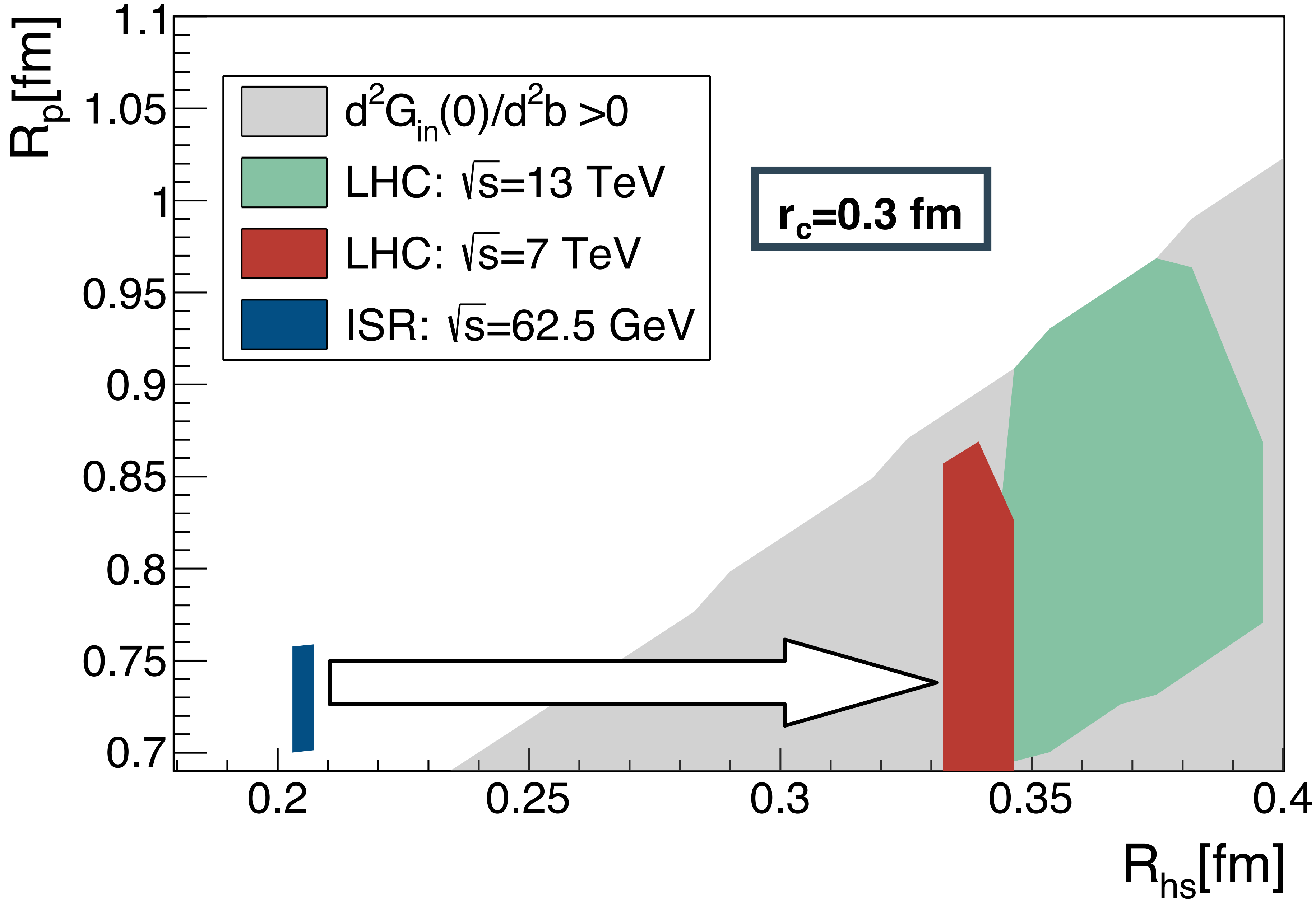
Parameter space: $\{R_{hs}, R_p, r_c, \rho_{hs}\}$

⇨ Reproduce experimental values* of $\sigma_{\rm tot}, \rho$



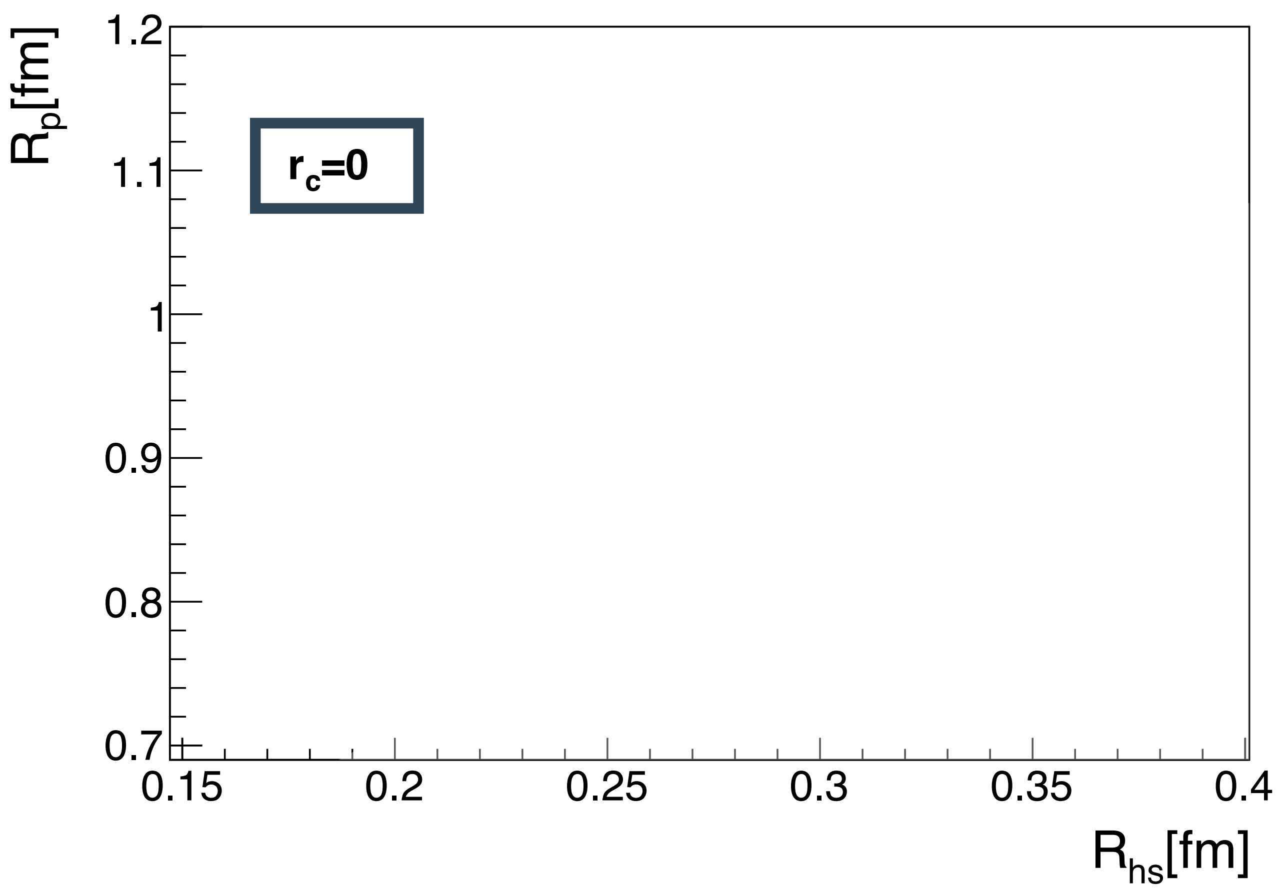
*At 13 TeV no measurement available as of 2016, prediction from COMPETE

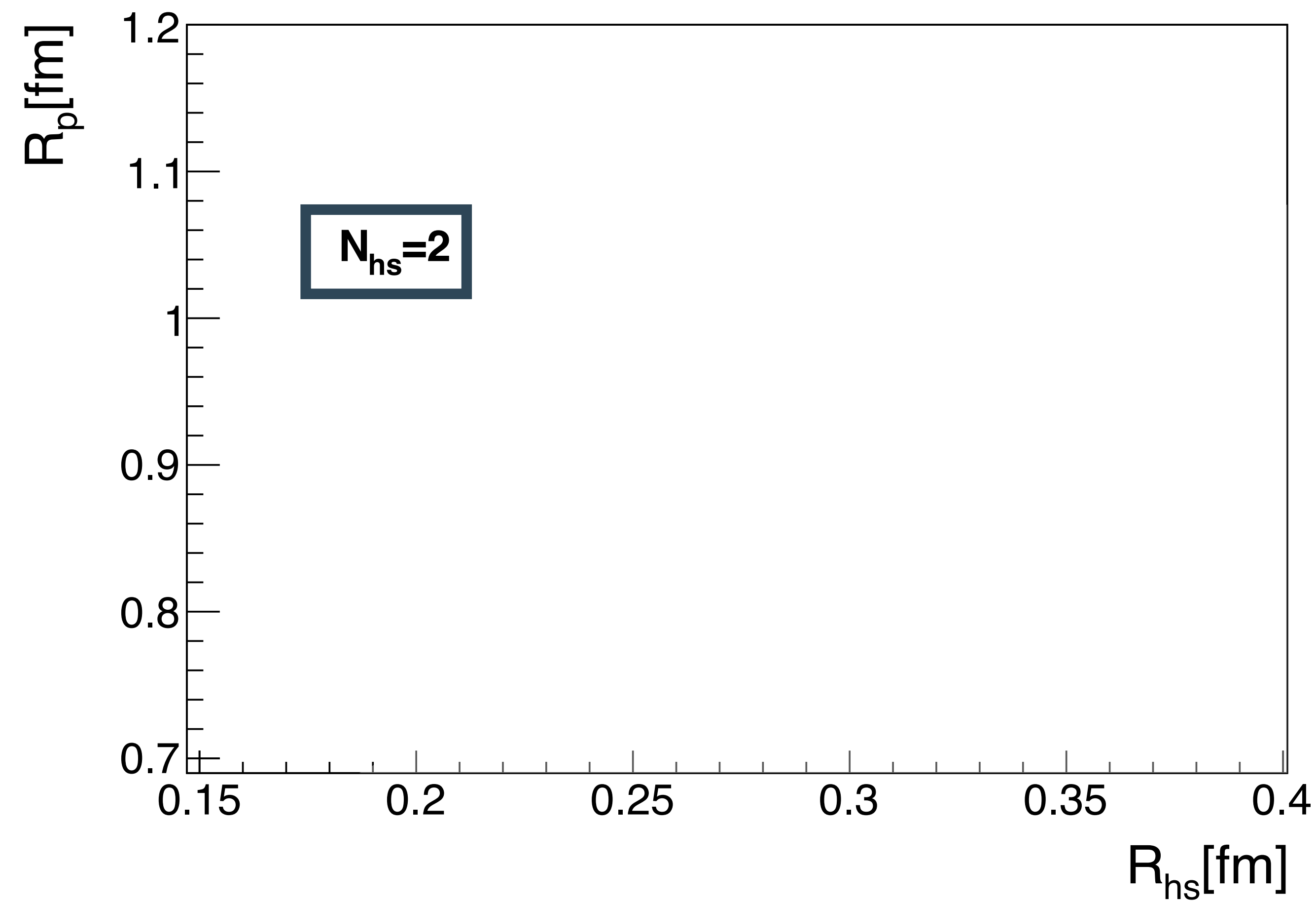
Parameter space: $\{R_{hs}, R_p, r_c, \rho_{hs}\}$



Transverse diffusion of the hot spots with increasing √s

Parameter space: $\{R_{hs}, R_p, r_c, \rho_{hs}\}$





No hollowness effect for r_c=0

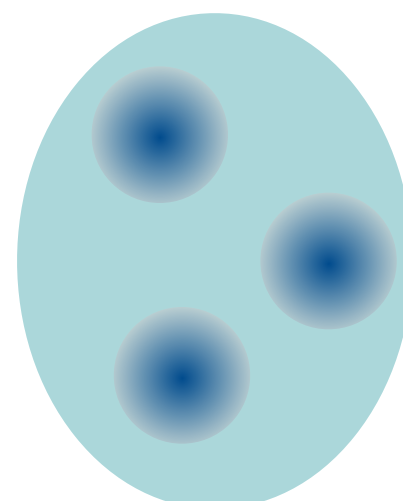
No hollowness effect for N_{hs}=2

Proton transverse structure as a byproduct

Form factors

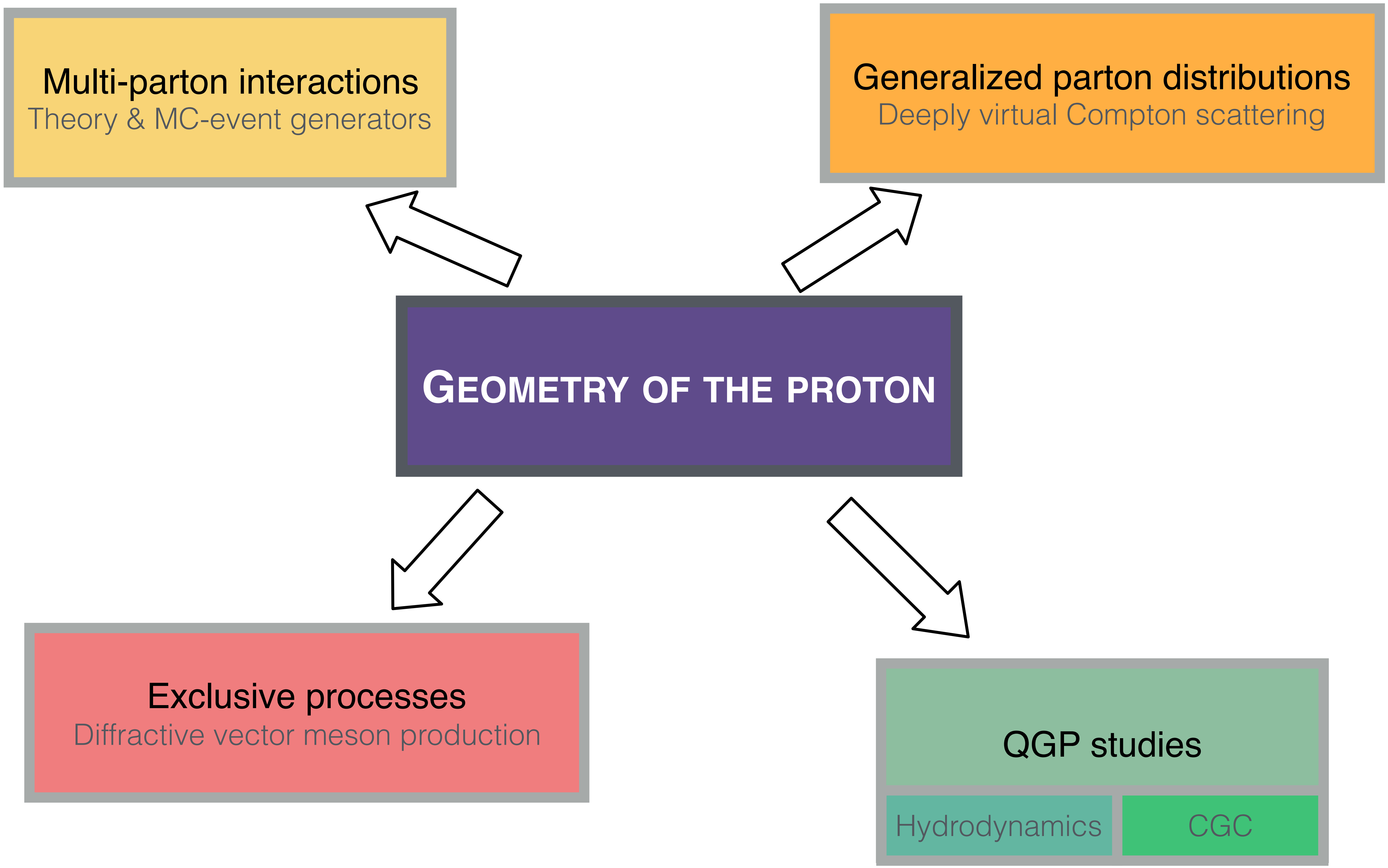
$F(\mathbf{\Delta}_\perp)$

Elastic scattering

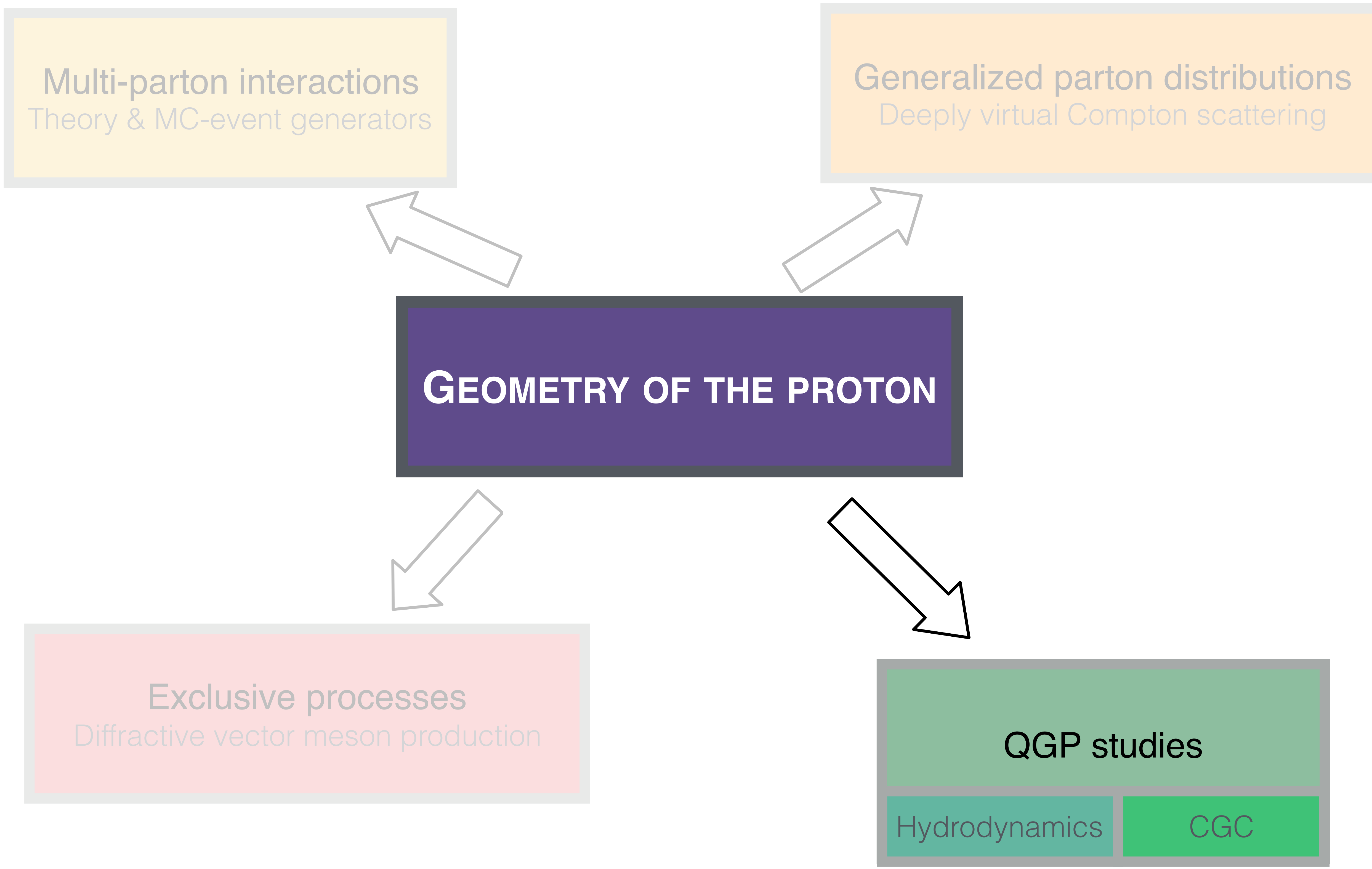


- $N_{hs} > 2$
- $r_c > 0$
- R_{hs} grows with $\sqrt{s}$

QCD phenomenological applications



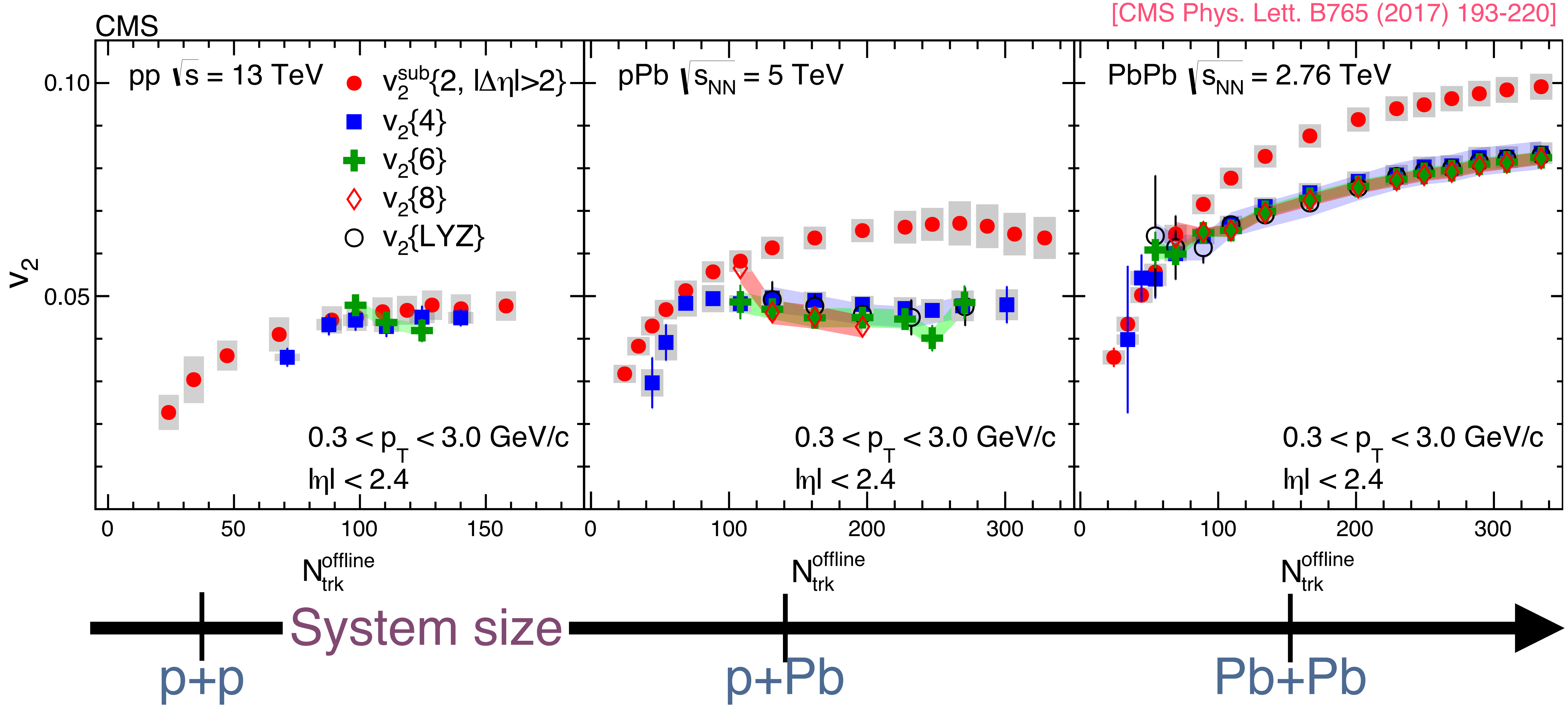
QCD phenomenological applications



The small system puzzle

Flow in all collision systems@LHC

[CMS Phys. Lett. B765 (2017) 193-220]

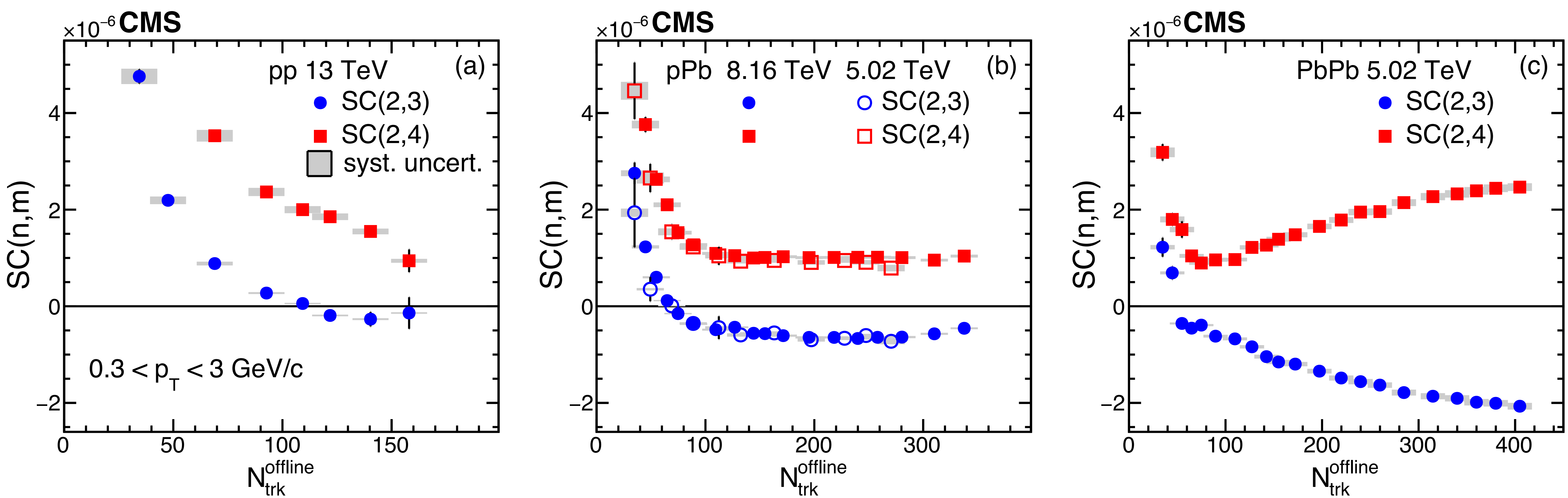


Breaking news from the LHC: non-zero elliptic flow in p+p and p+Pb.

Flow correlations in all collision systems@LHC

$$\mathrm{SC}(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

~Pearson's correlation coefficient
[Bilandzic et al. Phys. Rev. C89 (6) (2014) 064904]



[CMS Phys.Rev.Lett. 120 (2018) no.9, 092301]

System size

p+p p+Pb Pb+Pb

- **SC(2,3)**: initial state fluctuations
- **SC(2,4)**: medium properties

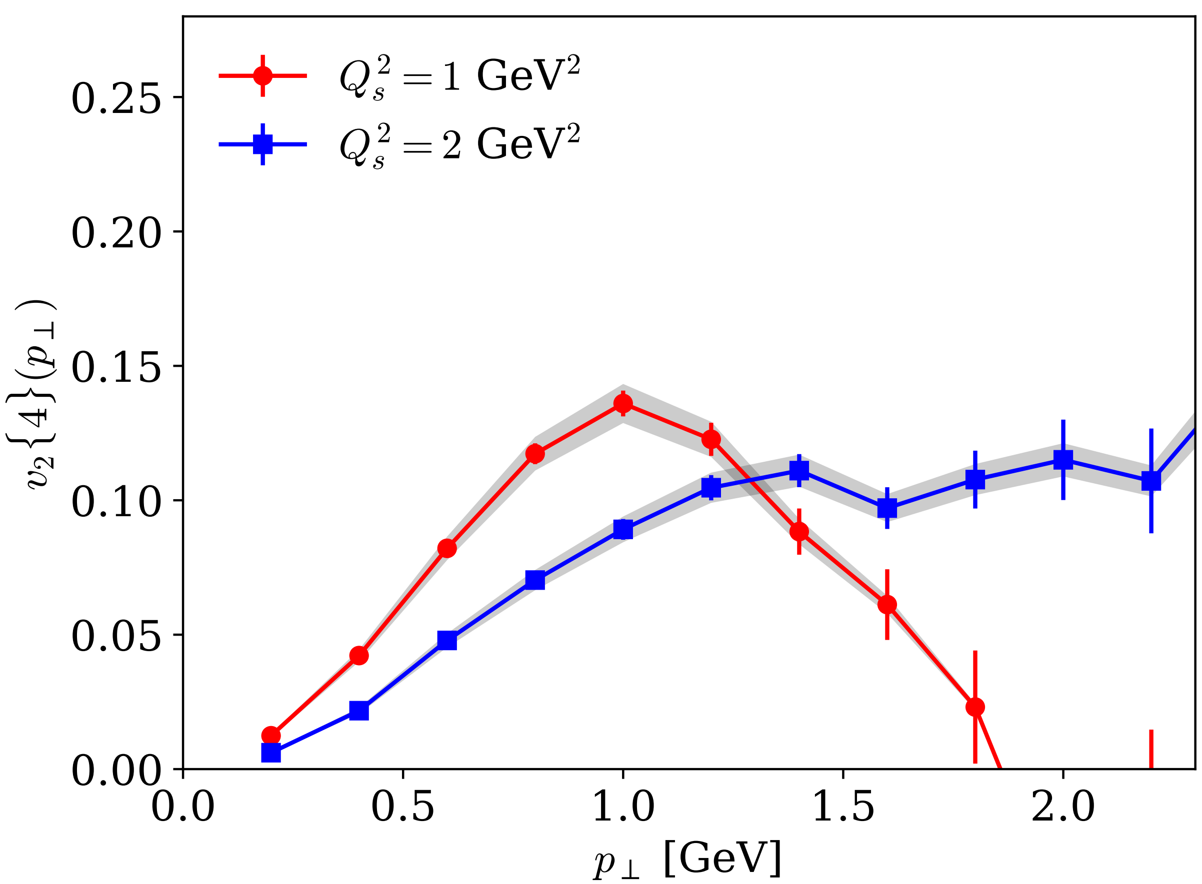
Breaking news from the LHC II: Anti-correlation around the same #tracks ~100

Theory status

CGC

Initial state dynamics; no QGP

$v_2\{4\}$

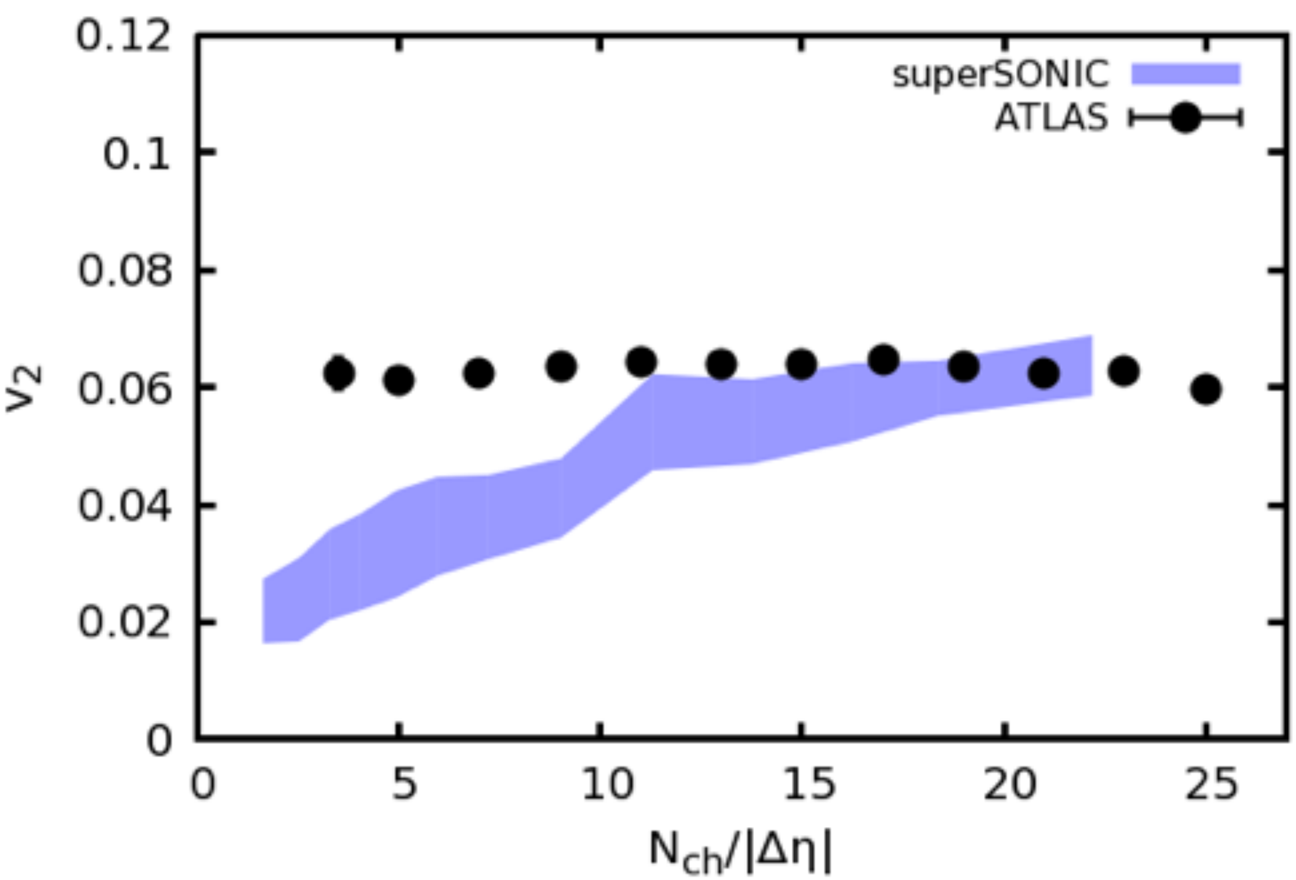


[Dusling et al. Phys.Rev.Lett. 120 (2018) no.4, 042002]

Hydrodynamics

Panta Rhei; QGP as in A+A

v_2

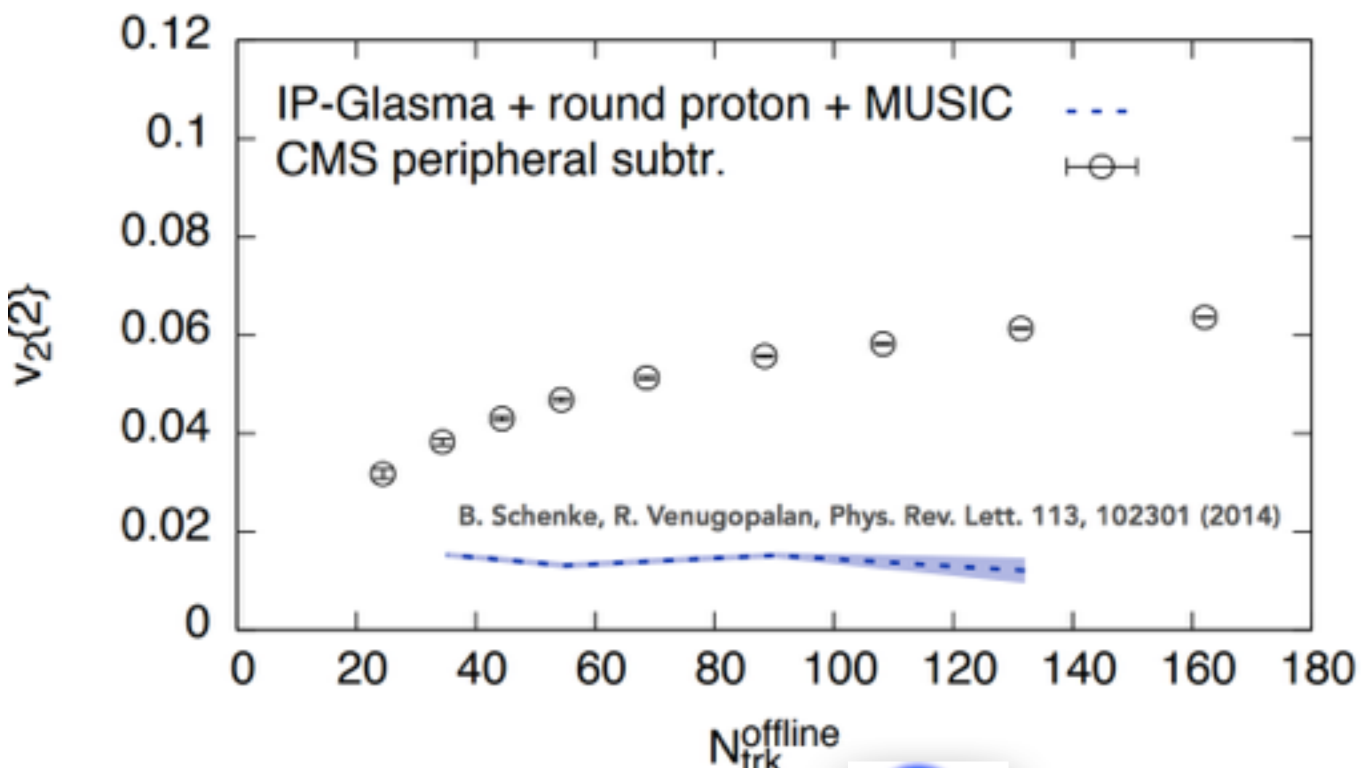


[Weller, Romatschke, Phys.Lett. B774 (2017) 351-356]

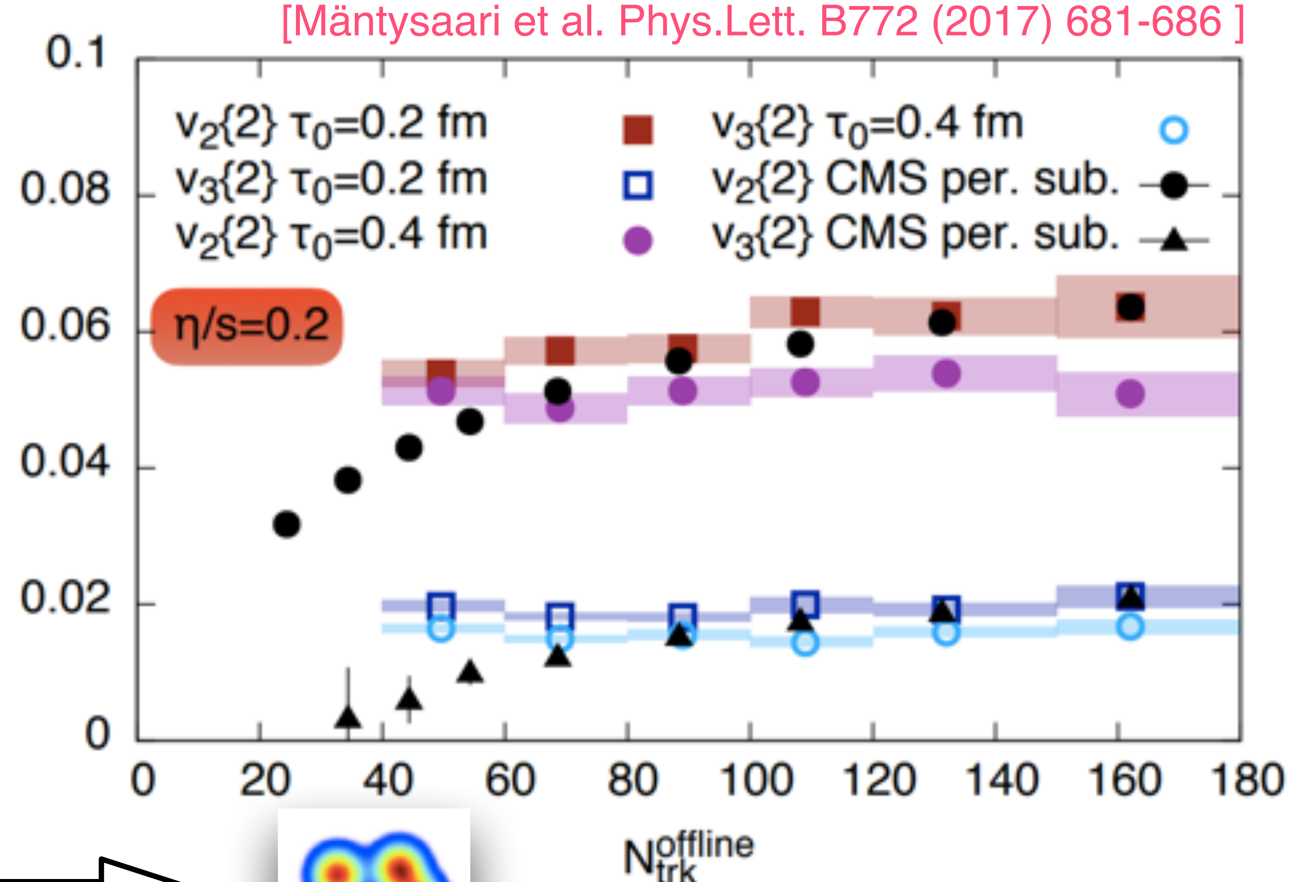
Common input: geometric structure of the proton

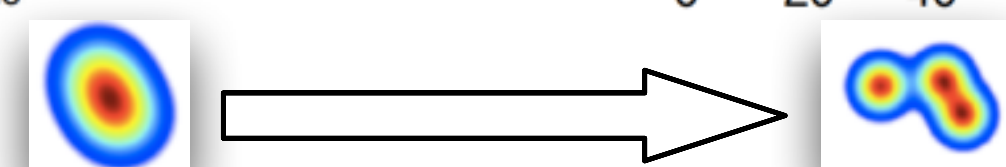
Role of proton geometry in p+A

Initial state dynamics + QGP effects



[Mäntysaari et al. Phys.Lett. B772 (2017) 681-686]





Fluctuating internal d.o.f

Highly precise LHC/RHIC data calls for a fine detailed description of the proton structure. Impact of spatial correlations?

MC-GLAUBER

[Albacete, Petersen, ASO Phys. Rev. C95 (6) (2017) 064909]

Setup

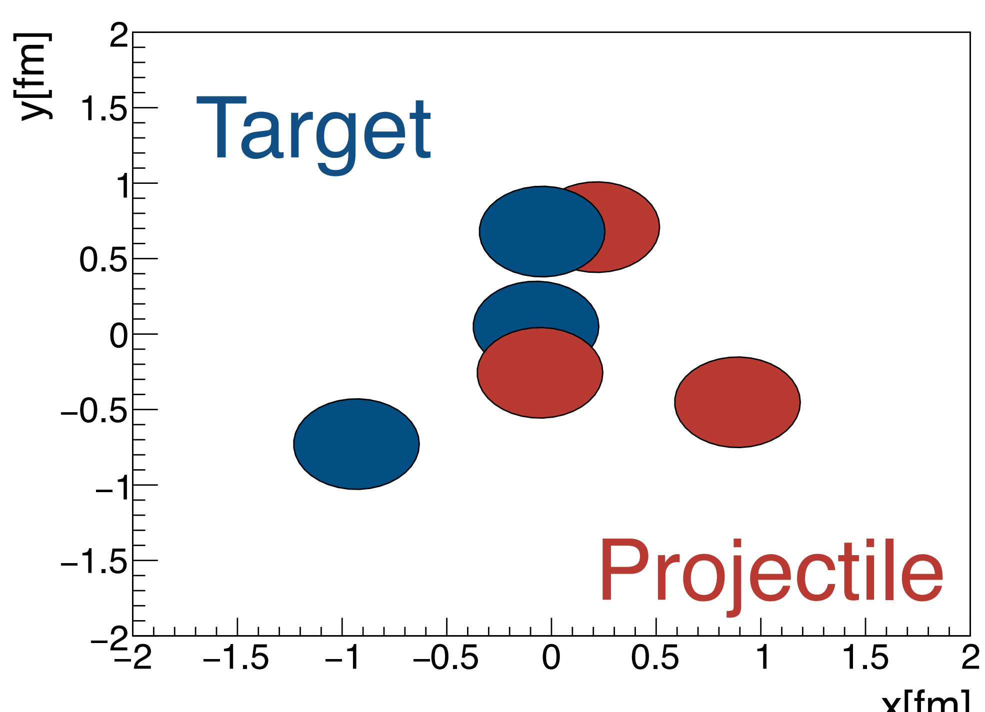
Analytical ⟹ Monte Carlo: event-by-event fluctuations

Similar codes for A+A collisions: [GLISSANDO, Broniowski et al. Comput. Phys. Commun. 180 (2009)] [TGlauberMC, Alver et al. arXiv: 0805.411]

1 Sample impact parameter and hot spots positions

$$dN_{\rm ev}/db \propto b$$

$$D(\vec{s}_1,\vec{s}_2,\vec{s}_3) = C \boxed{\prod_{i=1}^{3} e^{-s_i^2/R^2}} \boxed{\delta^{(2)}(\vec{s}_1+\vec{s}_2+\vec{s}_3)} \times \boxed{\prod_{\substack{i<j\\ i,j=1}}^{3} \left(1-e^{-\mu|\vec{s}_i-\vec{s}_j|^2/R^2}\right)}$$



Setup

1 **Sample impact parameter and hot spots positions**

2 **Collision criterion**: wounded hot spots

$$\mathcal{P}_{\text{in}}(d, R_{hs}) \propto e^{-d^2/R_{hs}^2} \quad \Rightarrow$$

- N_w
- N_{coll}
- (x_w, y_w)

3 **Entropy deposition**

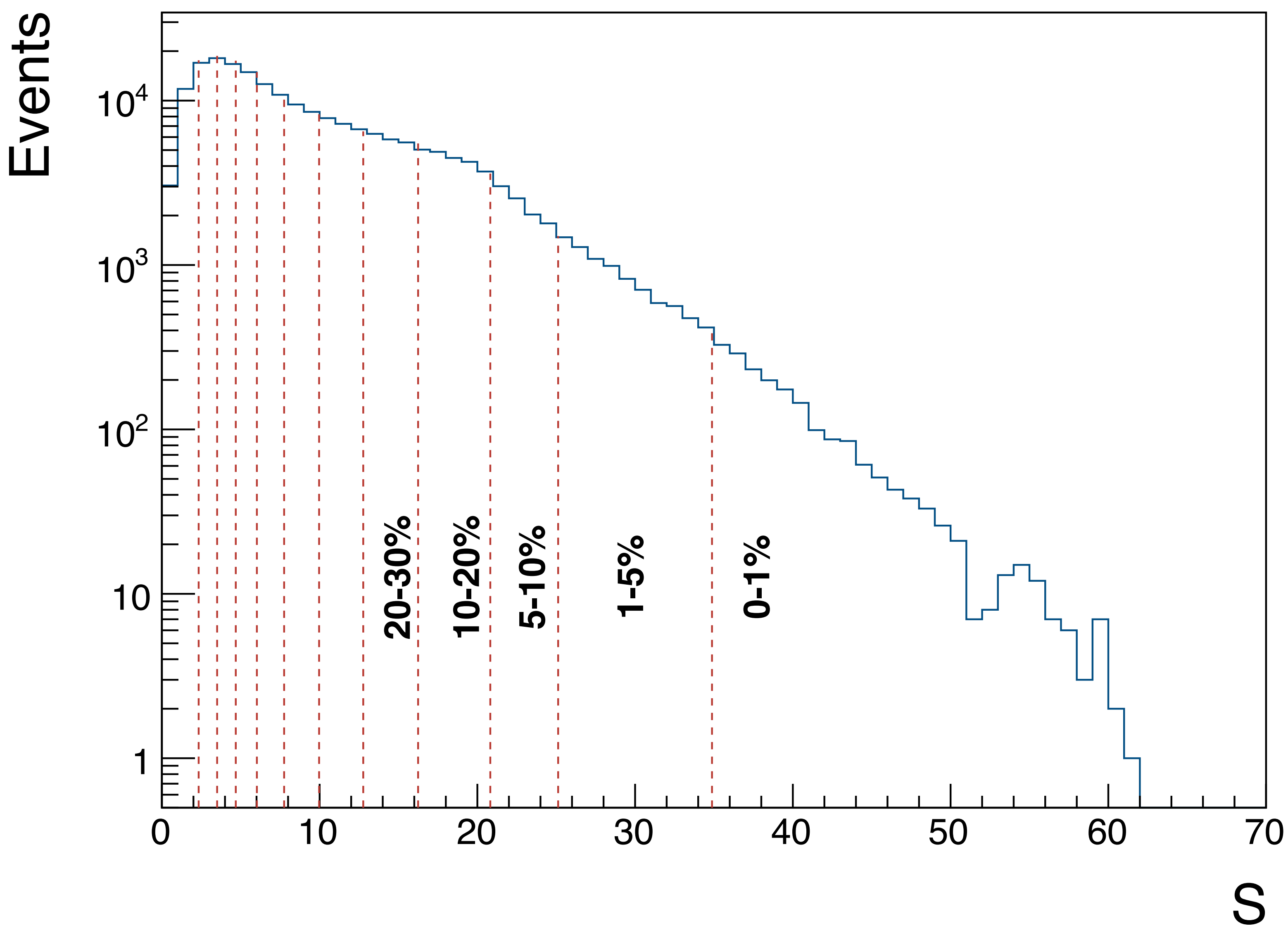
$$s(x,y) = s_0 \frac{1}{\pi R_{hs}^2} \exp\left(-\frac{(x-x_w)^2 + (y-y_w)^2}{R_{hs}^2}\right)$$

s_0: fluctuates independently for each wounded hotspot

$$\mathcal{P}(s_0) \propto \mathcal{P}(N_{\text{ch}})$$

Setup

5 Centrality classes (the X-axis)



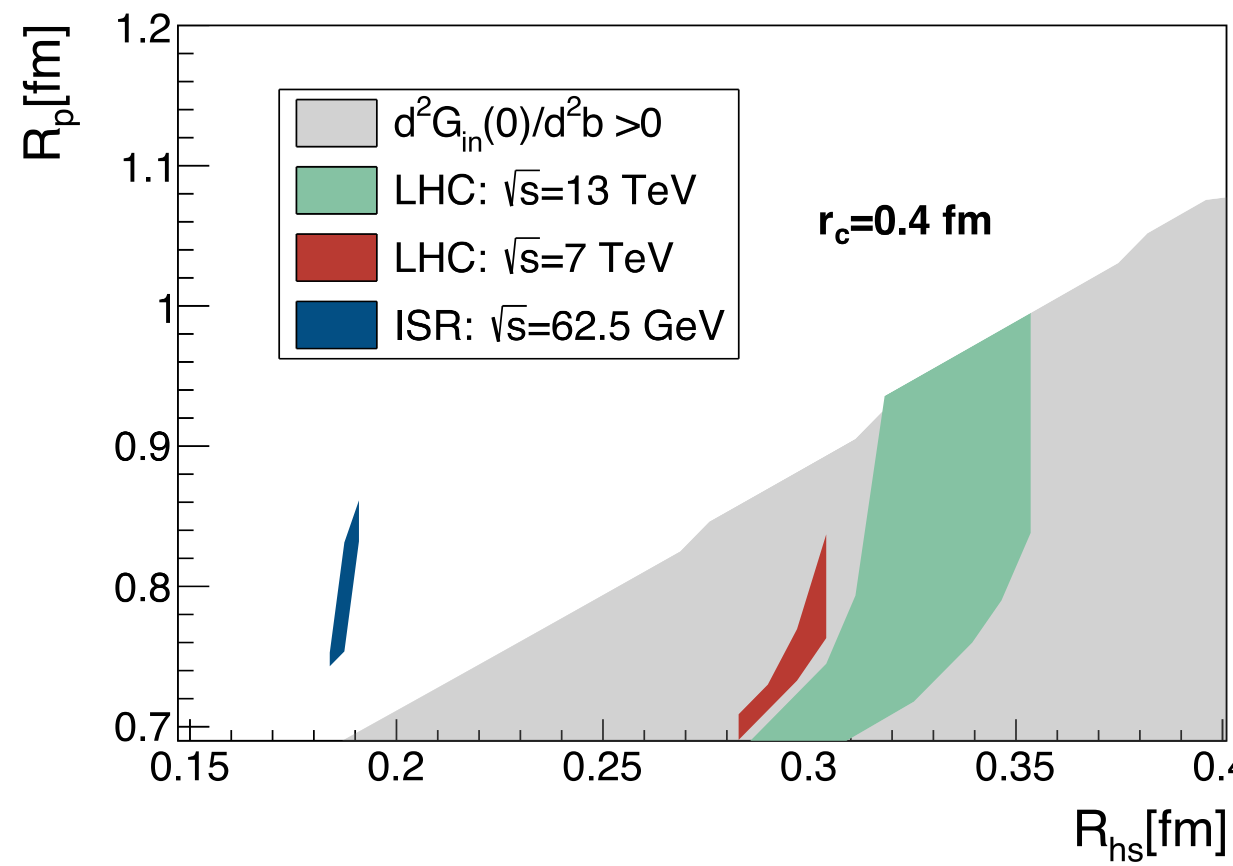
$$S = \sum_{i=2}^{N_w} s_0^i$$

More central == more effective producing entropy

Parameters

⇨ Correlated (r_c=0.4)

Representative values of the hollowness-study phase space reproducing $\sigma_{\rm tot}, \rho$



⇨ Uncorrelated

Problem: Not enough to set $\mu \to \infty$, swelling effects

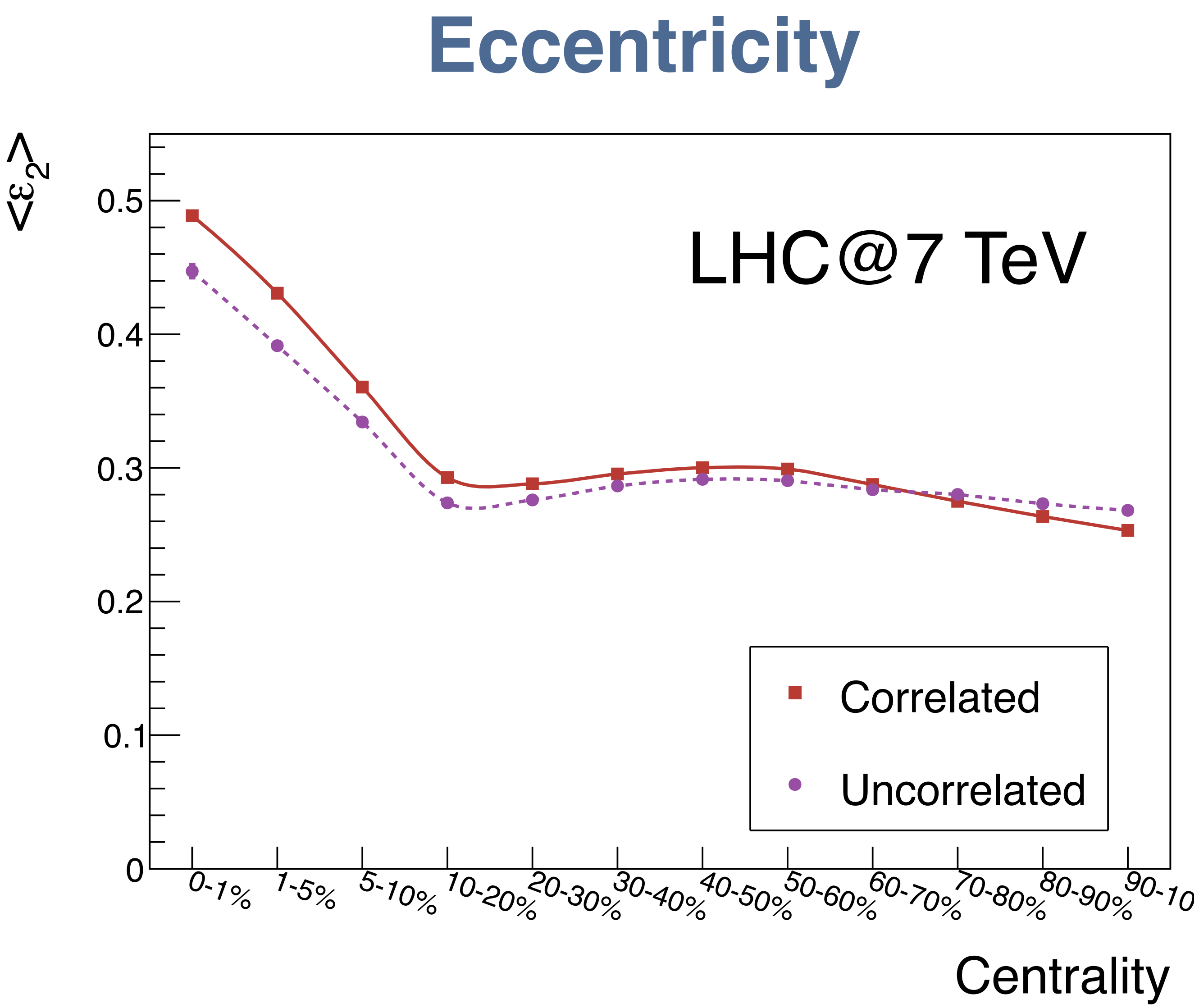
Solution: R_{hs} as in the correlated case and choose R to have identical proton size in both cases

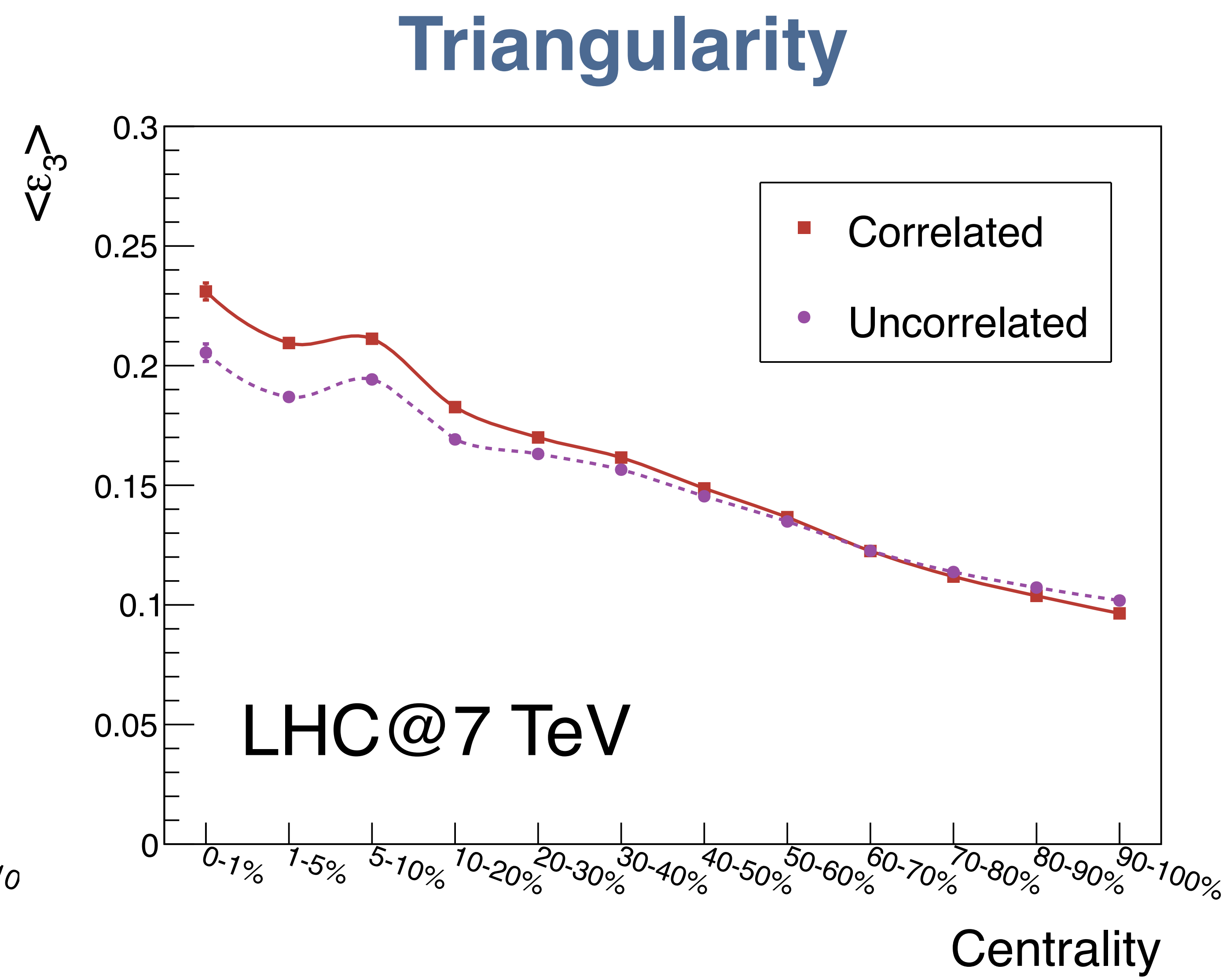
$$\langle s_1 \rangle = \int s_1 \mathrm{d}\vec{s}_1 \mathrm{d}\vec{s}_2 \mathrm{d}\vec{s}_3 D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$$

SPATIAL ECCENTRICITY MOMENTS

[Albacete, Petersen, ASO Phys. Rev. C95 (6) (2017) 064909]

Eccentricity & triangularity





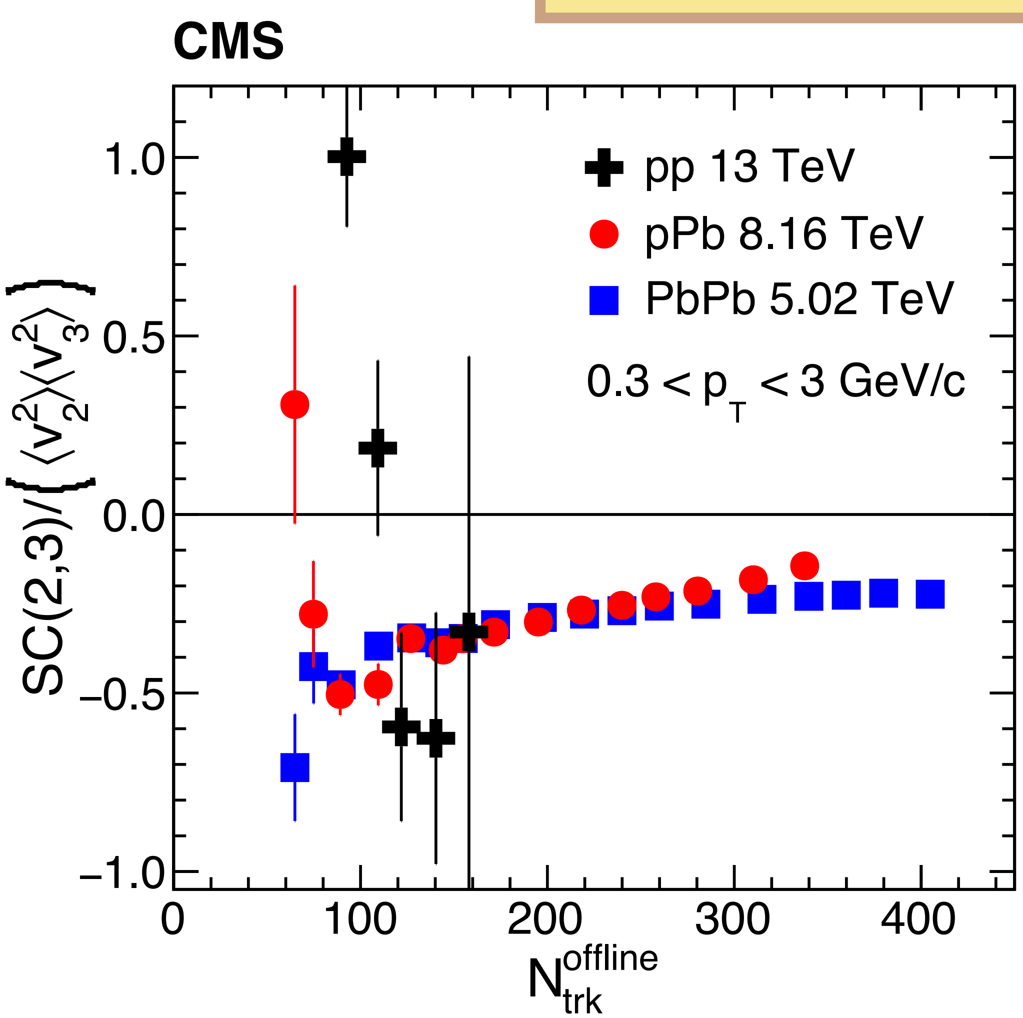
Repulsive correlations make $\varepsilon_{2,3}$ increase in ultra-central collisions

SYMMETRIC CUMULANTS

[Albacete, Petersen, ASO Phys. Lett. B778 (6) (2018) 128-136]

Definition

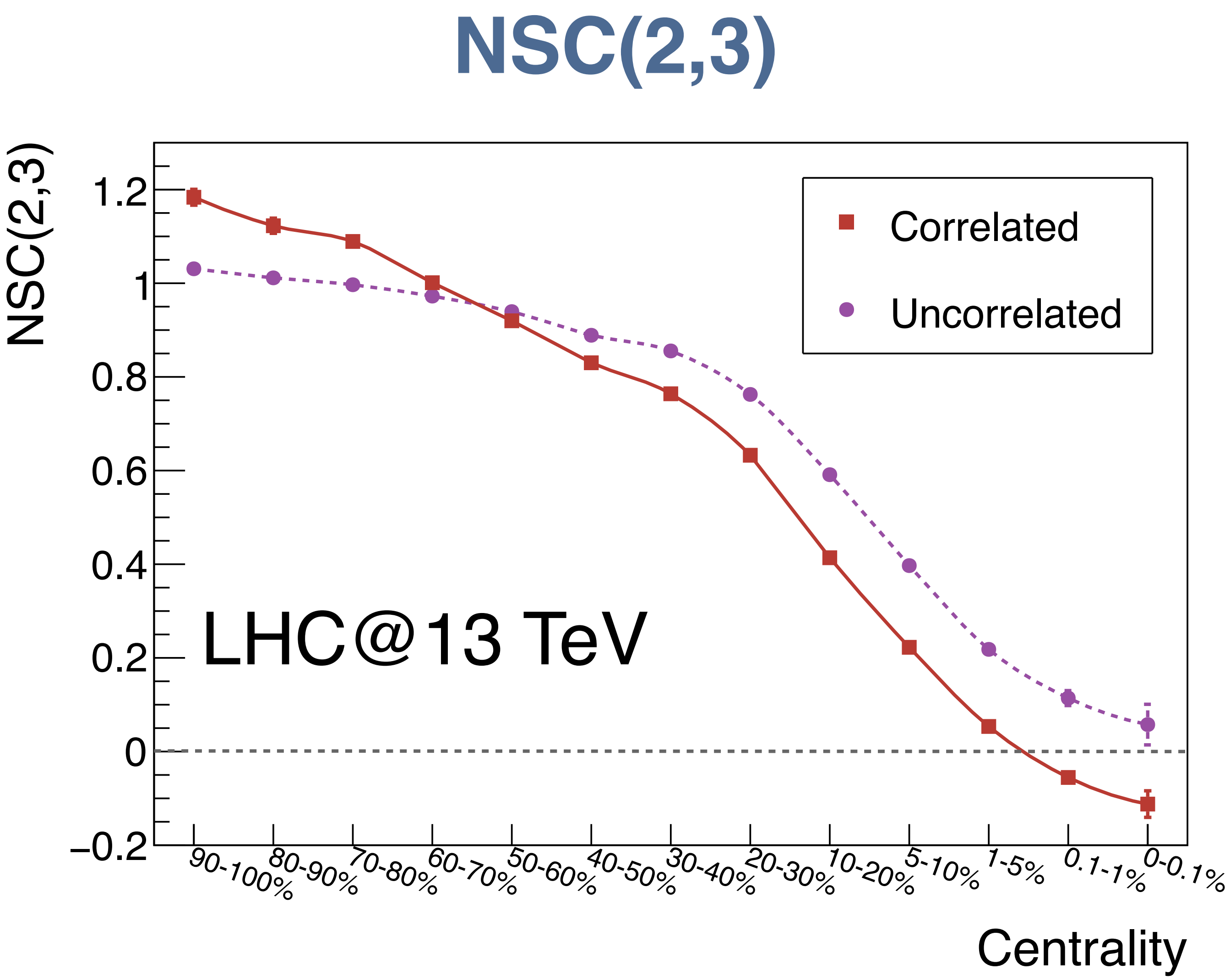
$$\mathrm{NSC(n,m)} = \frac{\langle \varepsilon_n^2 \varepsilon_m^2 \rangle - \langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle}{\langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle}$$

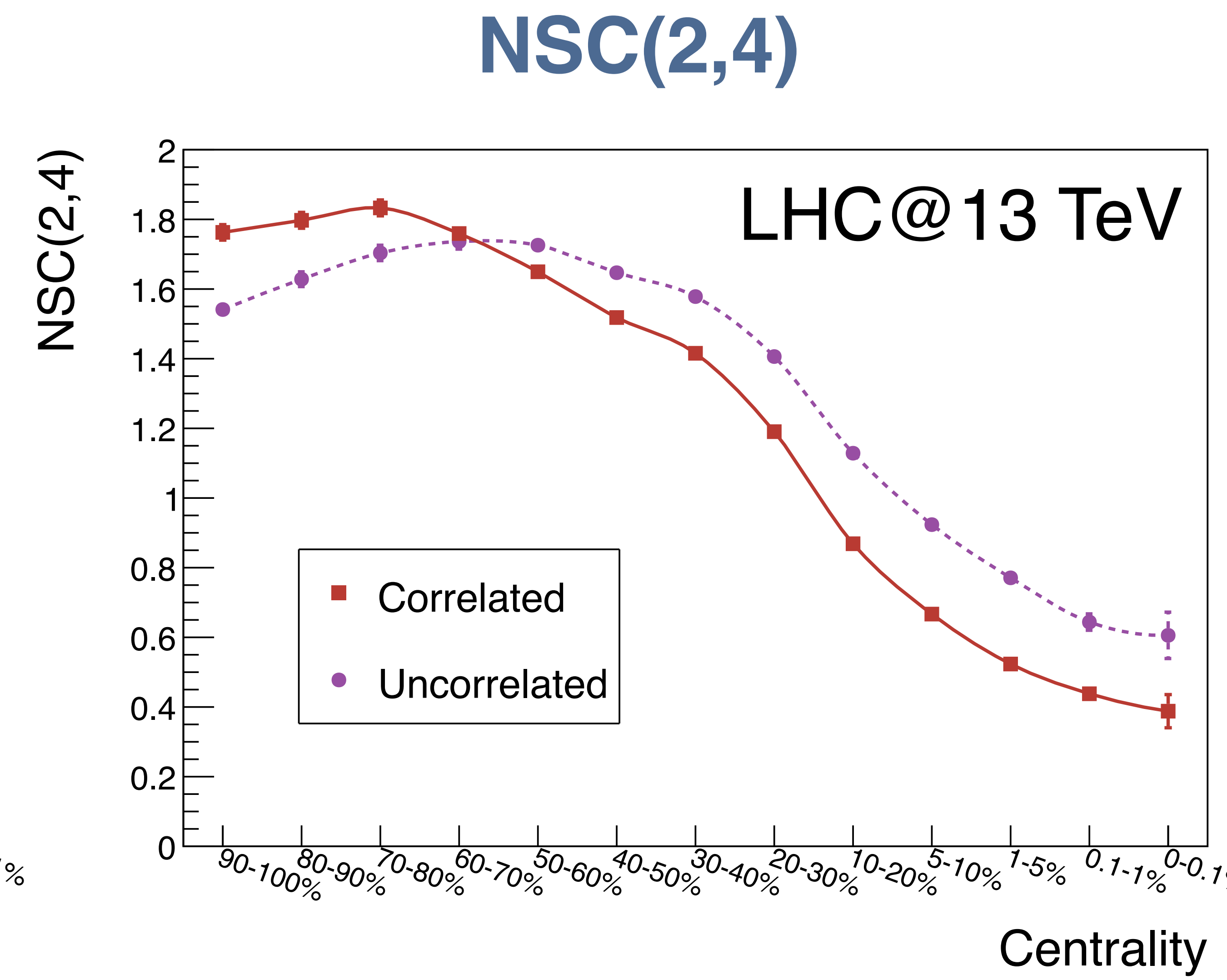


Note: data in terms of flow, our results at the eccentricity level. Not an apples-to-apples comparison

As of today, no theoretical description in the literature of the SC(n,m) negative sign. Not even at the eccentricity level

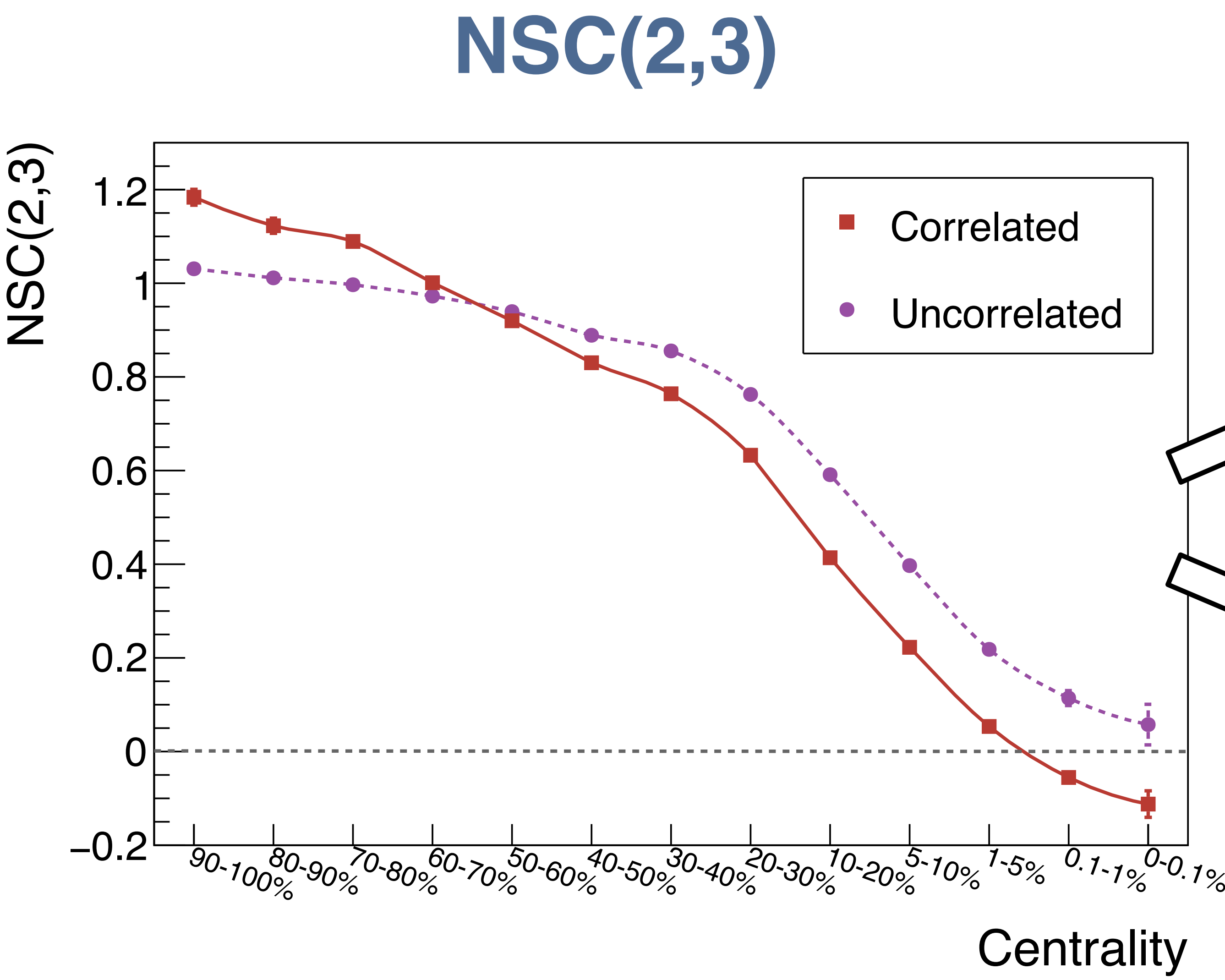
Symmetric cumulants





Repulsive correlations make NSC(n,m) increase in peripheral and decrease in ultra-central collisions

Negative sign of NSC(2,3)

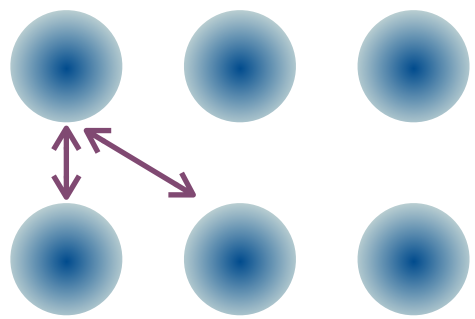


Why do the repulsive correlations push NSC(2,3) to negative values?

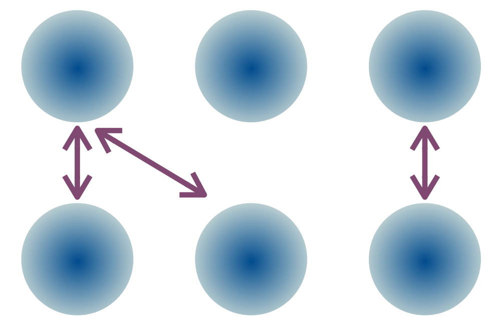
Is the negative sign a unique feature of the correlated scenario?

Interpretation of NSC(2,3)<0

We define interaction topologies characterized by (N_w, N_{coll})

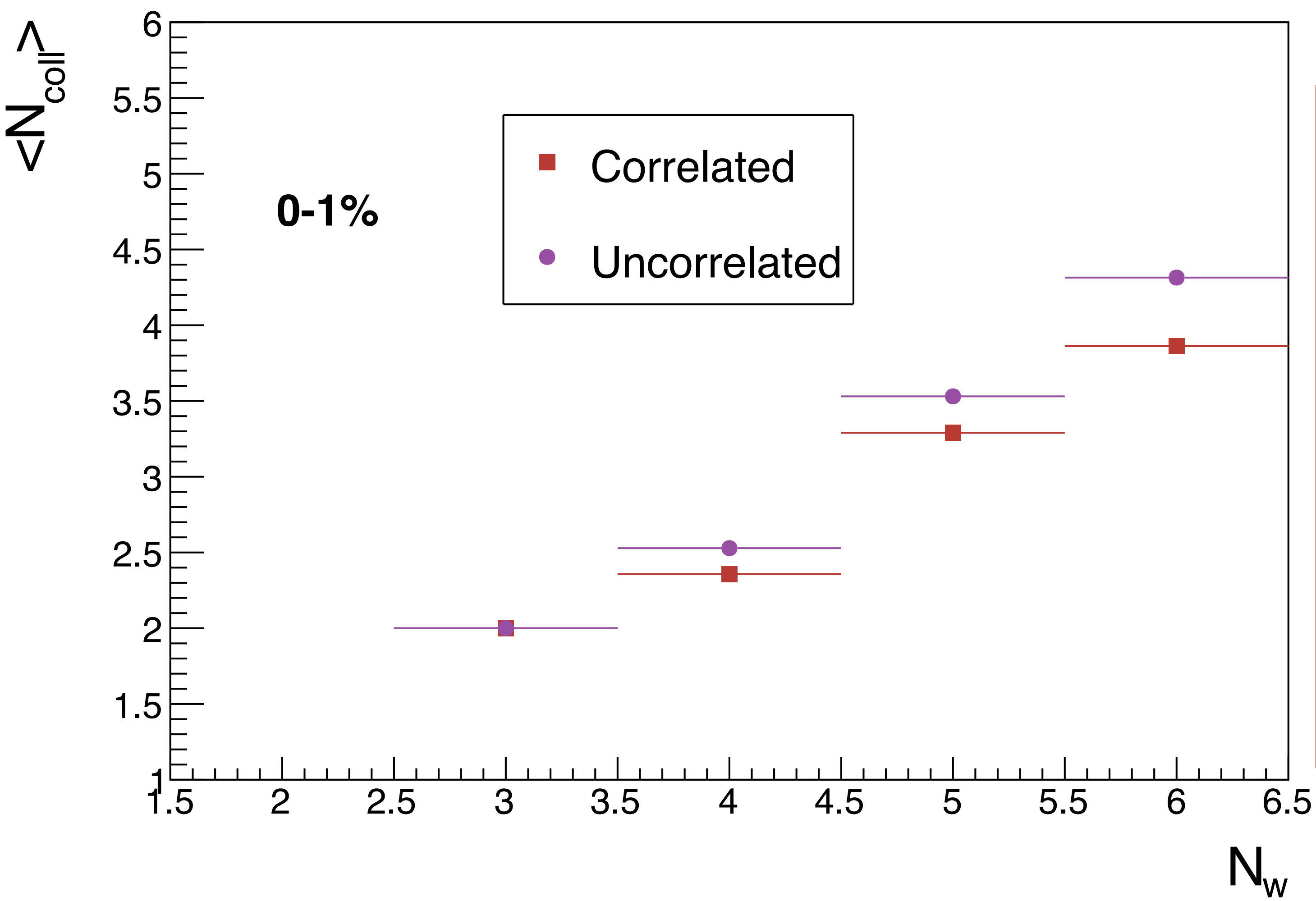


= (3,2)

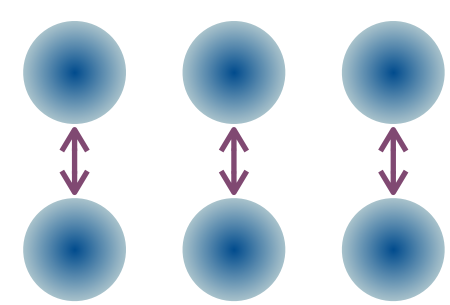


= (5,3)

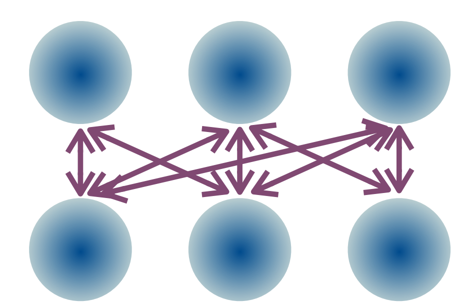
where, for N_{hs}=3, $N_w \in [2,6]$ and $N_{coll} \in [1,9]$



Correlations enhance the probability of having a small N_{coll}

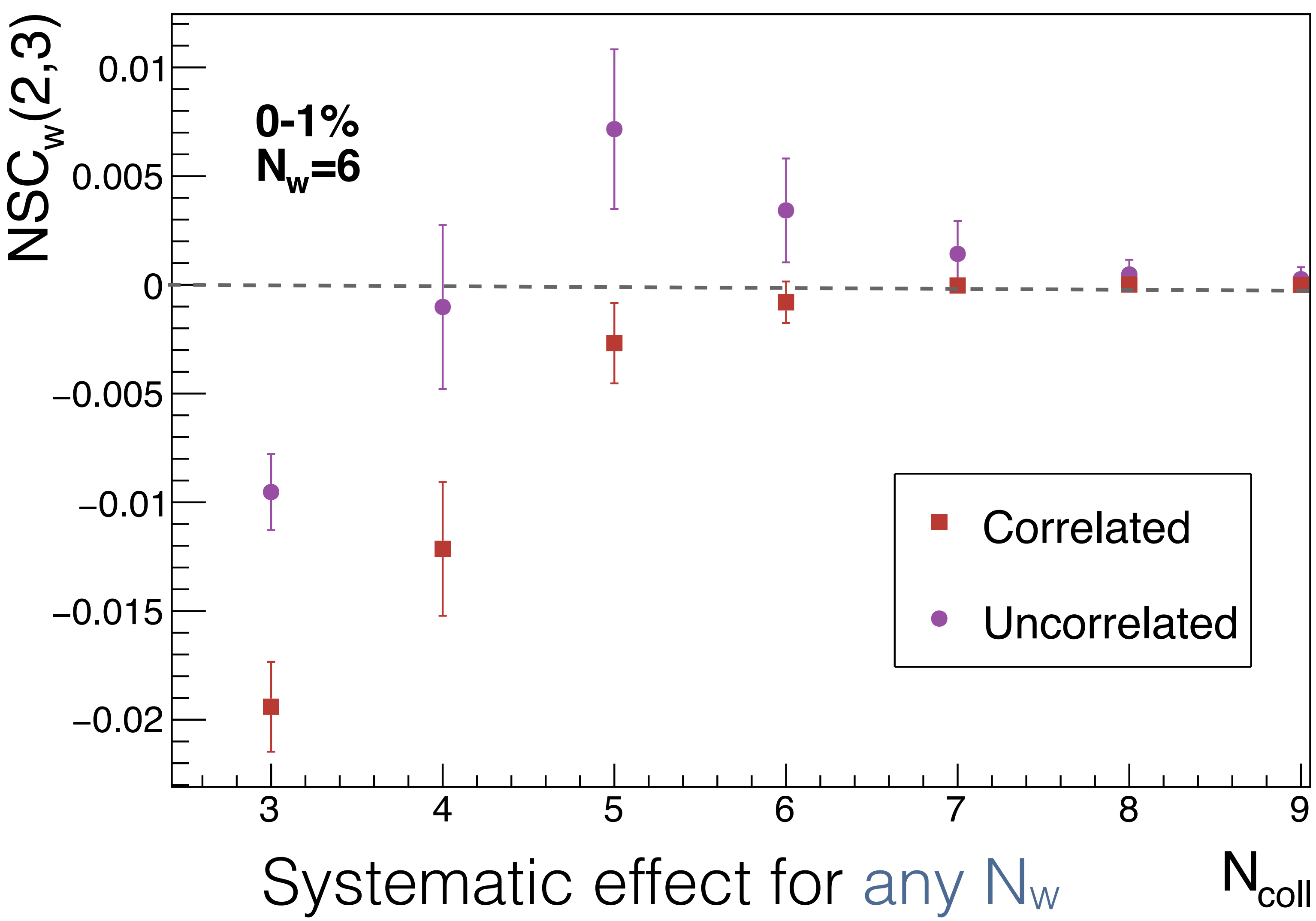


correlated



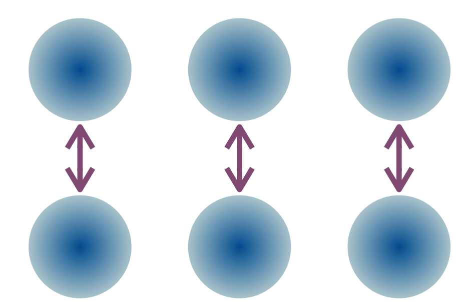
uncorrelated

Interpretation of NSC(2,3)<0



Systematic effect for any N_w

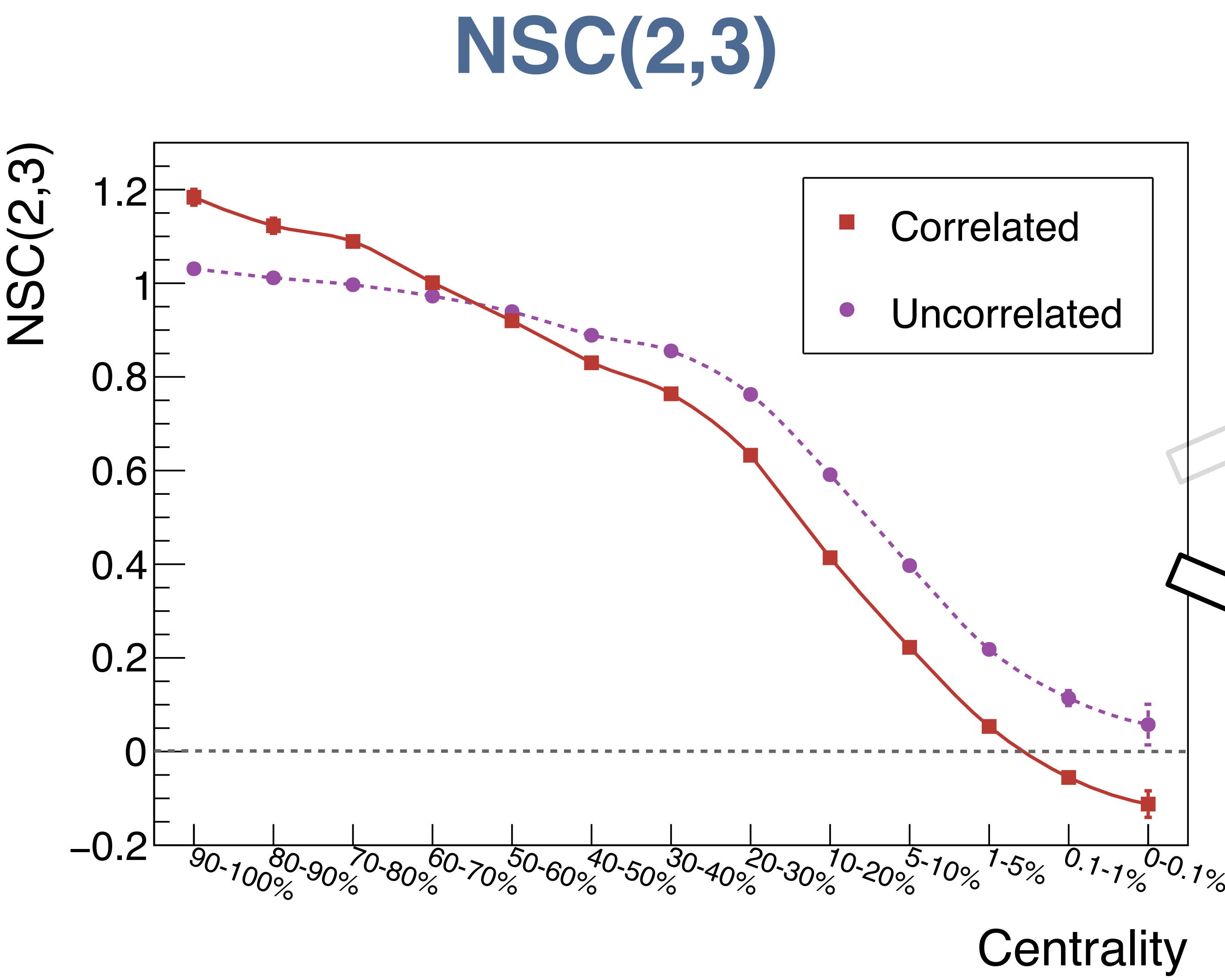
Configurations with large N_w and small N_{coll} responsible for making NSC(2,3)<0



Correlations modify/ enhance the weight of these interaction topologies in the MC

*$NSC_w(n,m)$==weighted by the probability of occurrence in the Monte Carlo

Negative sign of NSC(2,3)

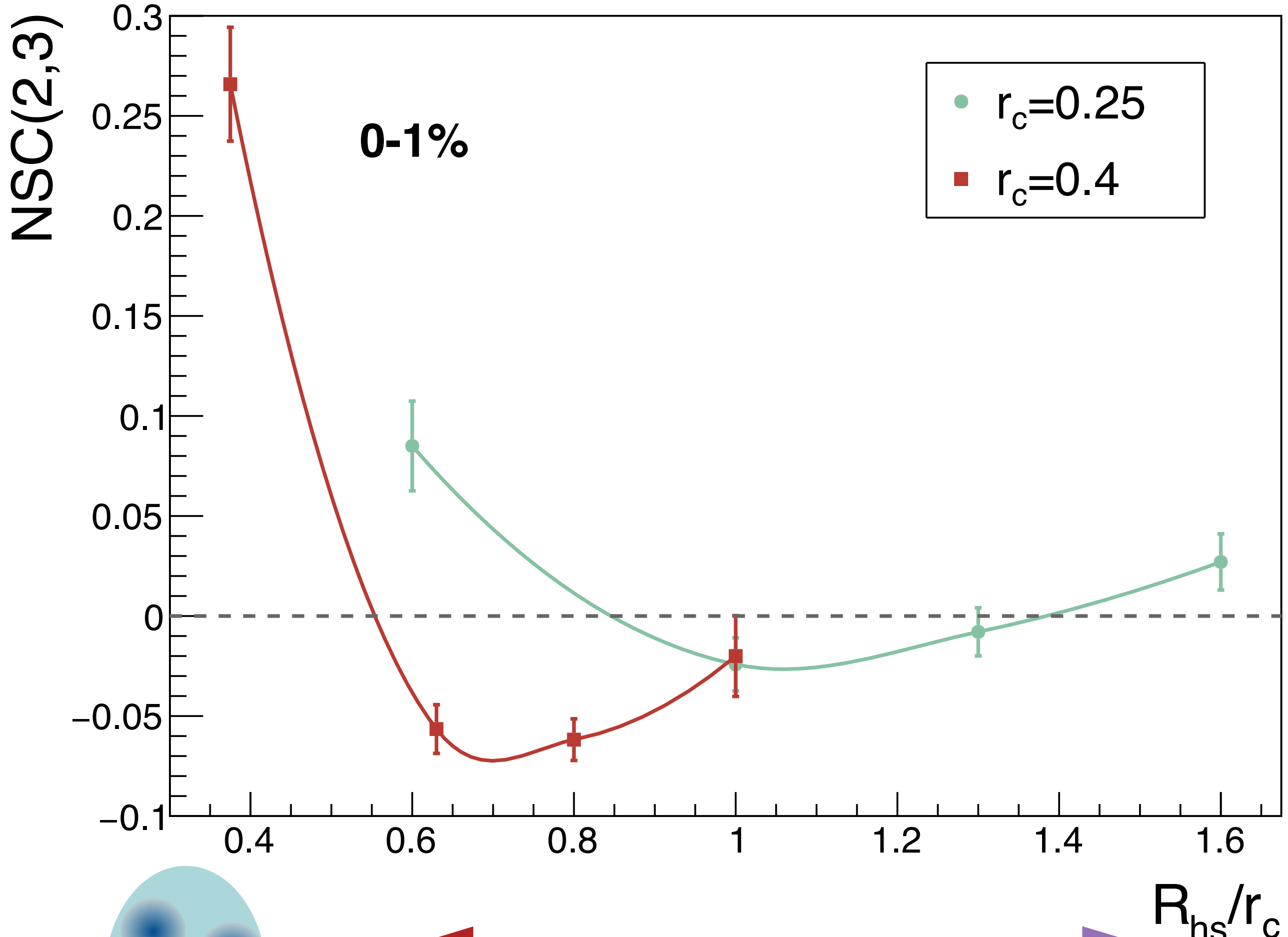


Why do the repulsive correlations push NSC(2,3) to negative values?

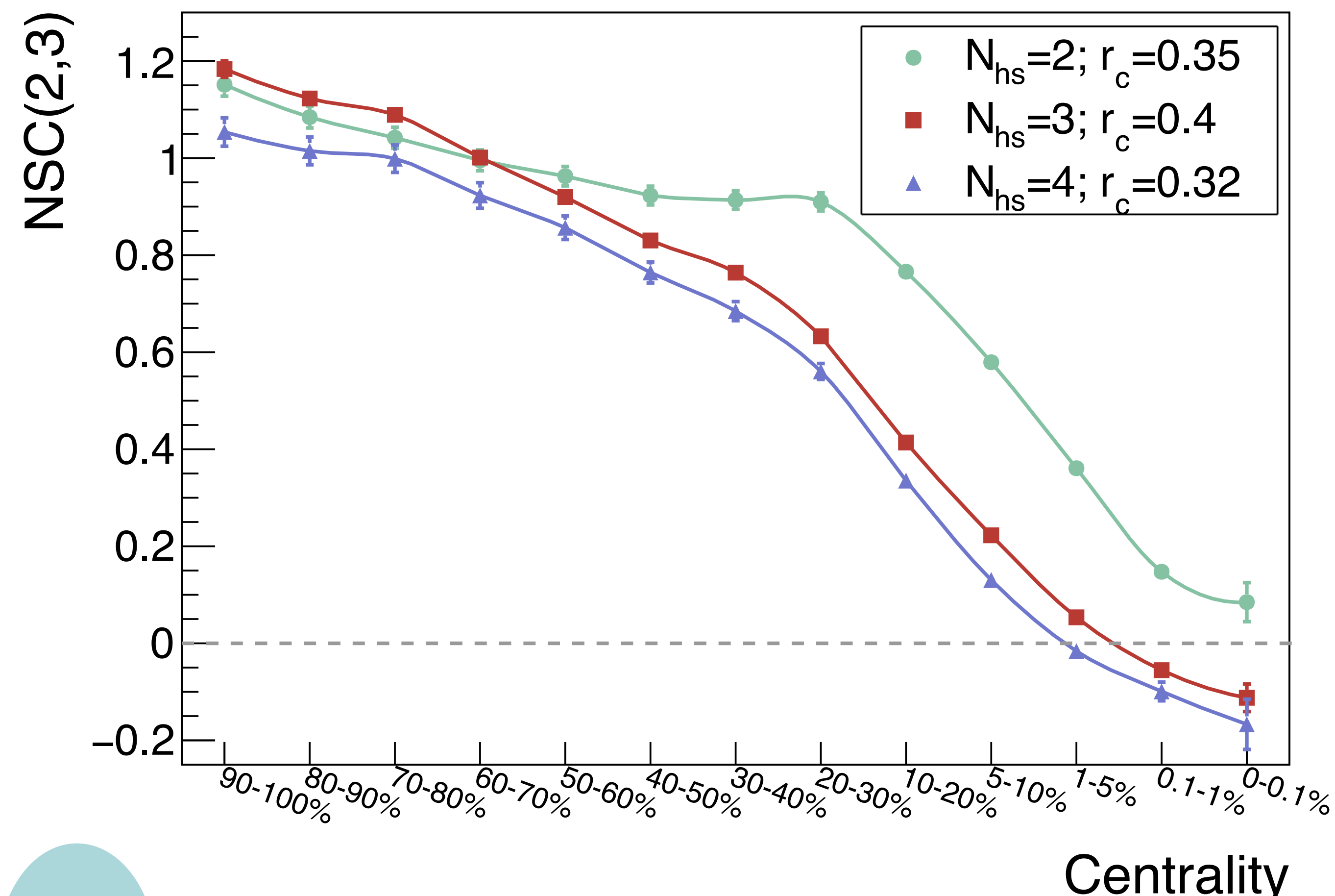
Is the negative sign a unique feature of the correlated scenario?

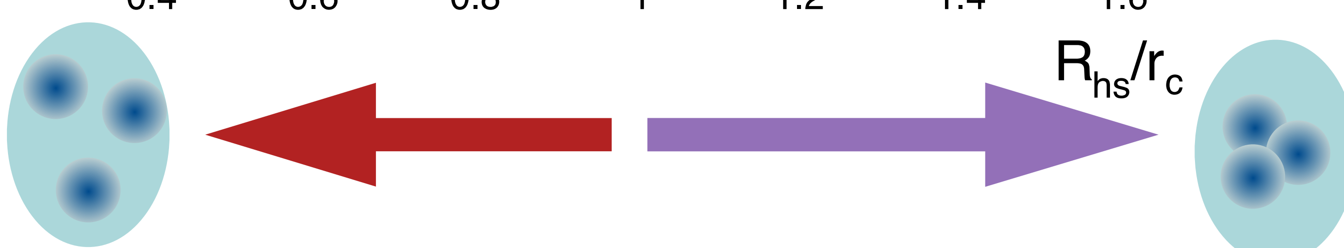
Scan parameter space: correlated scenario

Sensitivity to R_{hs}/r_c



Sensitivity to N_{hs}





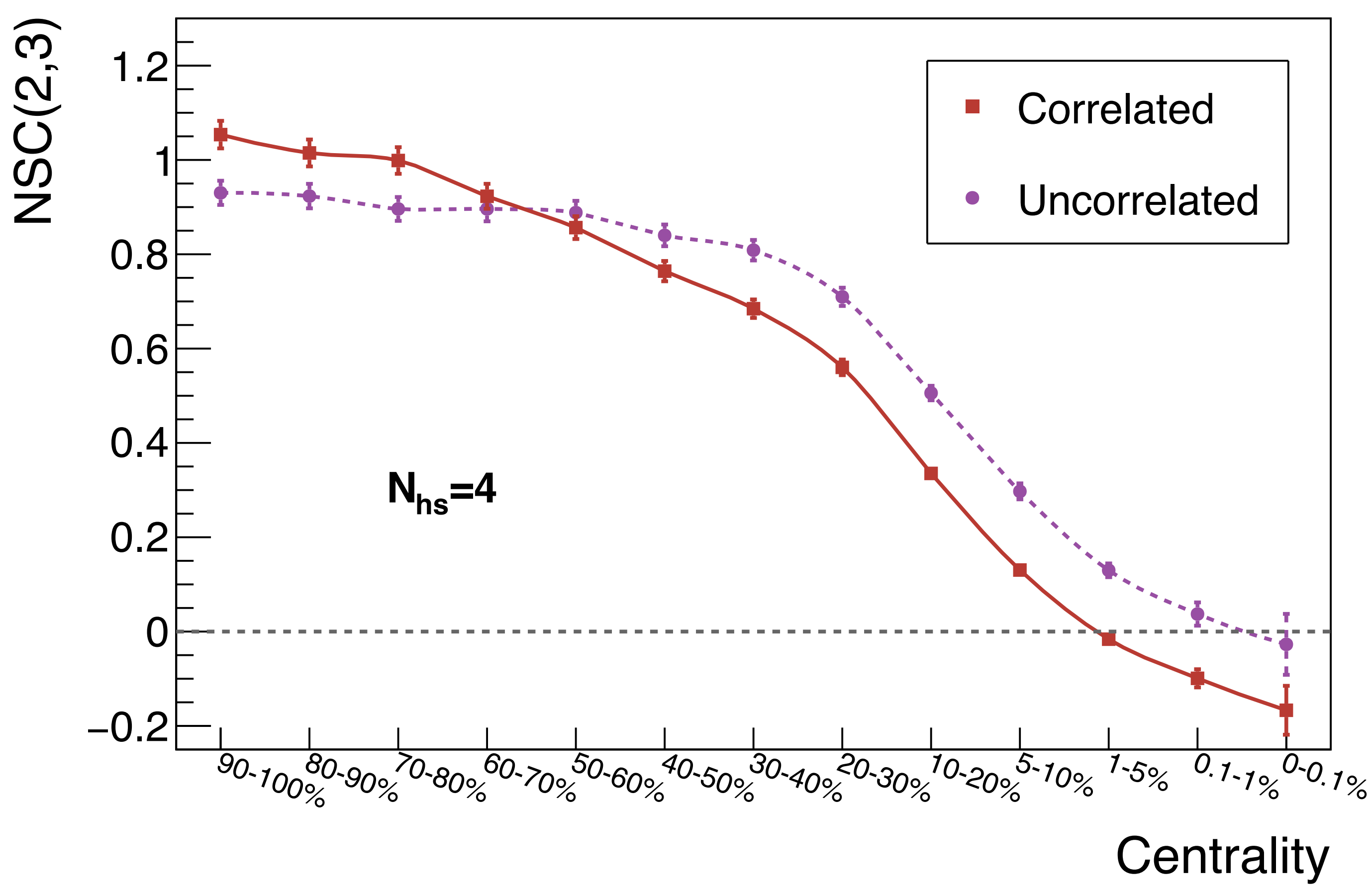
Proton's size fixed in all cases

Our study favors values of $0.6 < R_{hs}/r_c < 1.3$

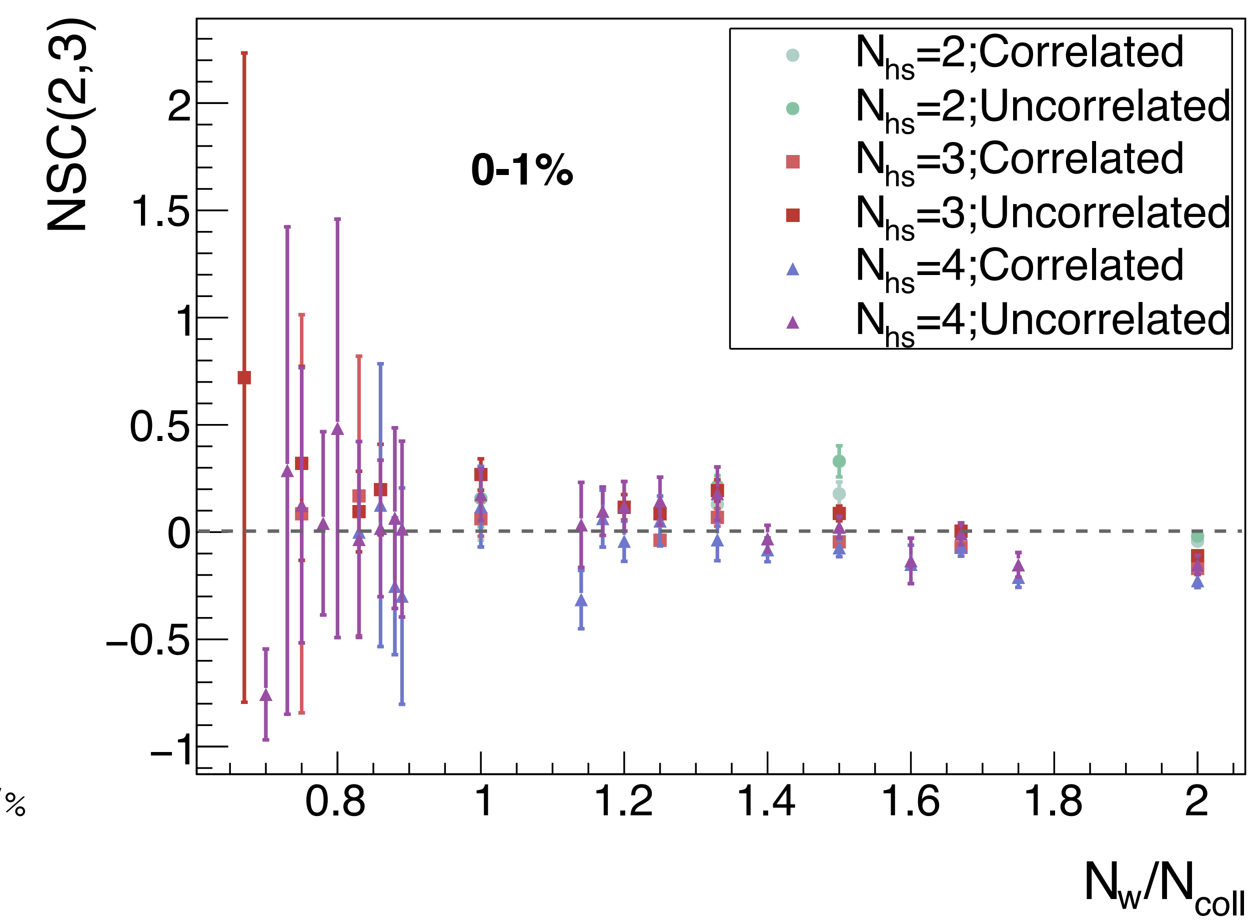
Onset of anti-correlation when $N_{hs} > 2$

Scan parameter space: corr vs unc

N_{hs}=4



Sensitivity to N_w/N_{coll}



NSC(2,3) compatible with being negative in the uncorrelated case

Indications of universality in NSC(2,3) as a function of N_w/N_{coll}

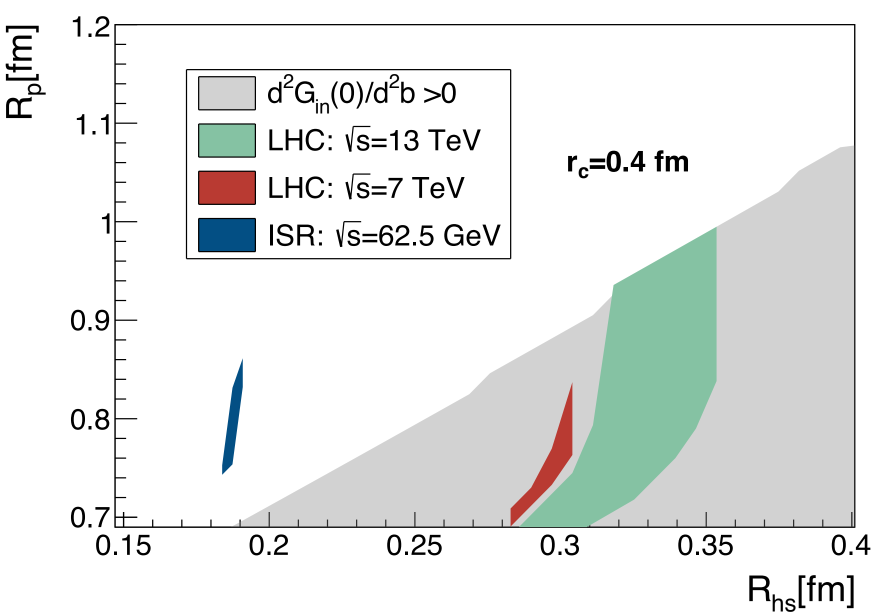
CONCLUSIONS

Highlights

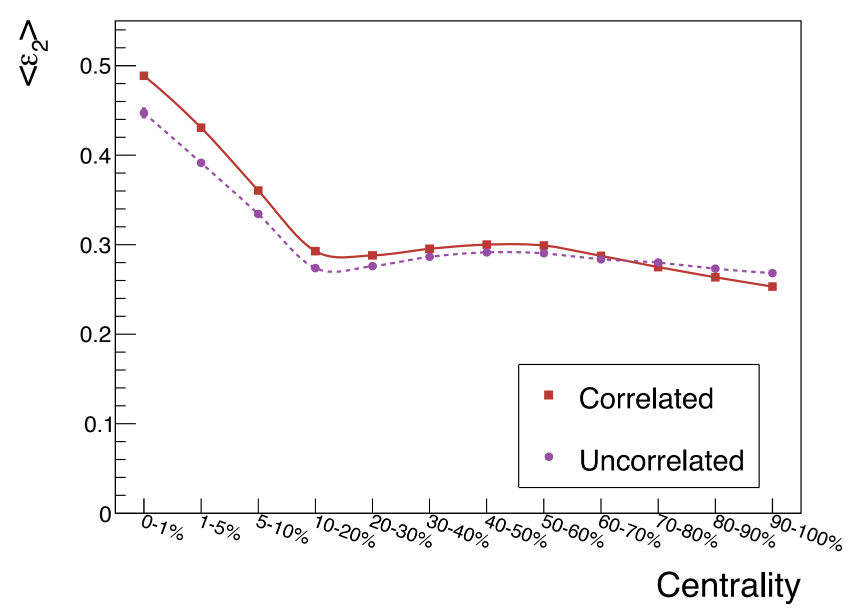
Characterization of the transverse distribution of proton constituents in coordinate space and their fluctuations

Main focus on the impact of spatial correlations in QCD phenomenology

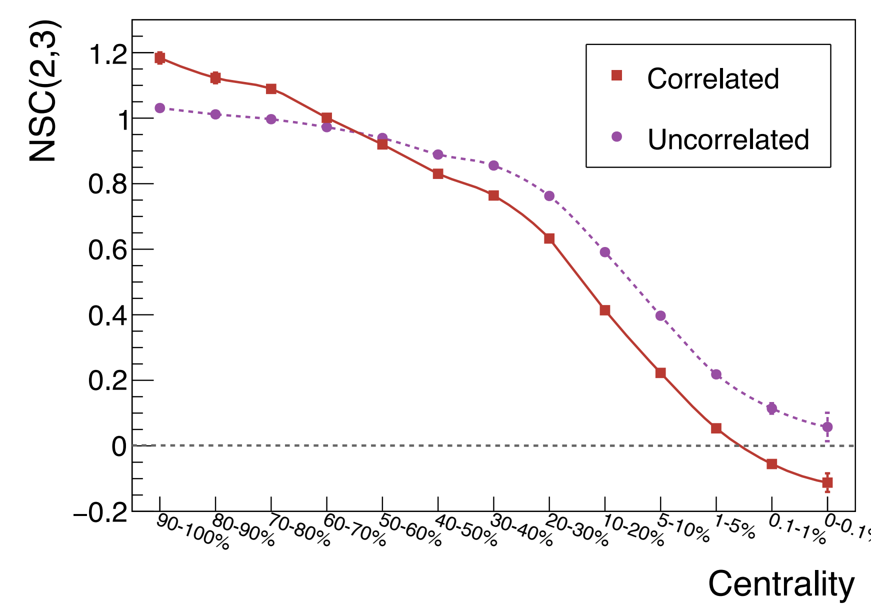
Hollowness effect



Eccentricities



Symmetric cumulants

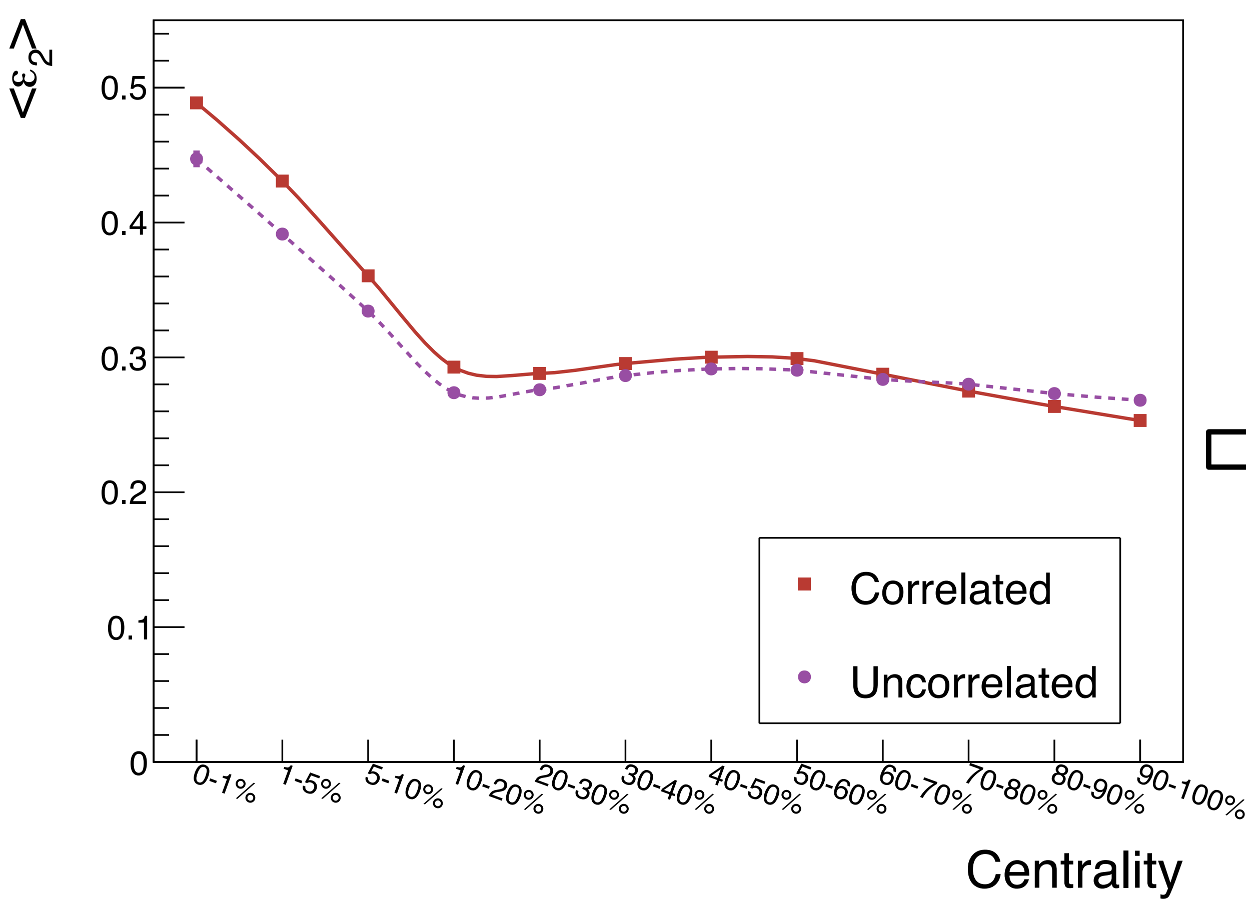


Outlook

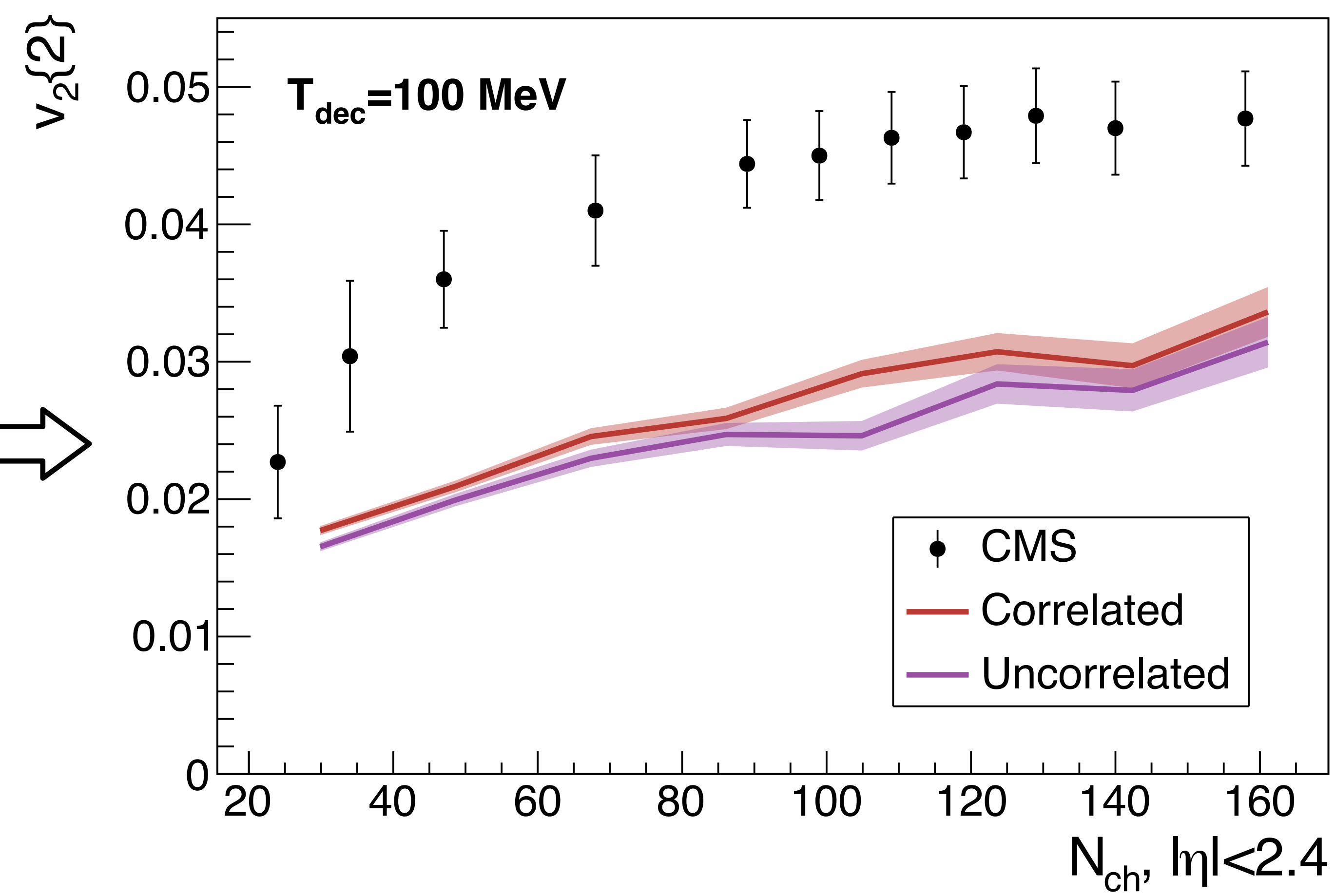
[Albacete, Niemi, Petersen, ASO in preparation]

Perform hydrodynamic evolution of our initial state profiles

Eccentricity



Elliptic flow



Repulsive correlations in the initial geometry seem to affect the elliptic flow. No fine tuning. More statistics (and work) needed!!

Extra slides

Hydrodynamical setup

Initialized event by event with:

$$s(x, y, \tau = 0.2 \text{ fm})$$
$$\pi^{\mu\nu} = 0$$
$$v_{\mathrm{T}} = 0$$

Equation of state: s95p-PCE-v1

[Huovinen, Petreczky Nucl.Phys. A 837 (2010) 26]

$$T_{\mathrm{dec}} = 100 \text{ MeV}$$
$$T_{\mathrm{chem}} = 175 \text{ MeV}$$

Resonance decays after freeze-out included

2+1D viscous hydro

Transport coefficients: neglect bulk viscosity and heat conductivity. Shear viscosity à la EKRT.

[Niemi et Al., Phys.Rev. C93 (2016) no.2, 024907]
[Eskola et Al., Phys.Rev. C93 (2016) no.1, 014912]