FLOW HARMONIC COEFFICIENTS IN SMALL SYSTEMS AT THE LHC: INITIAL OR FINAL STATE EFFECT?

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based on Phys. Lett. B770 (2017) 149-153, Phys.Rev. C95 (2017) no. 6, 064909, arXiv:19xx.xxxx

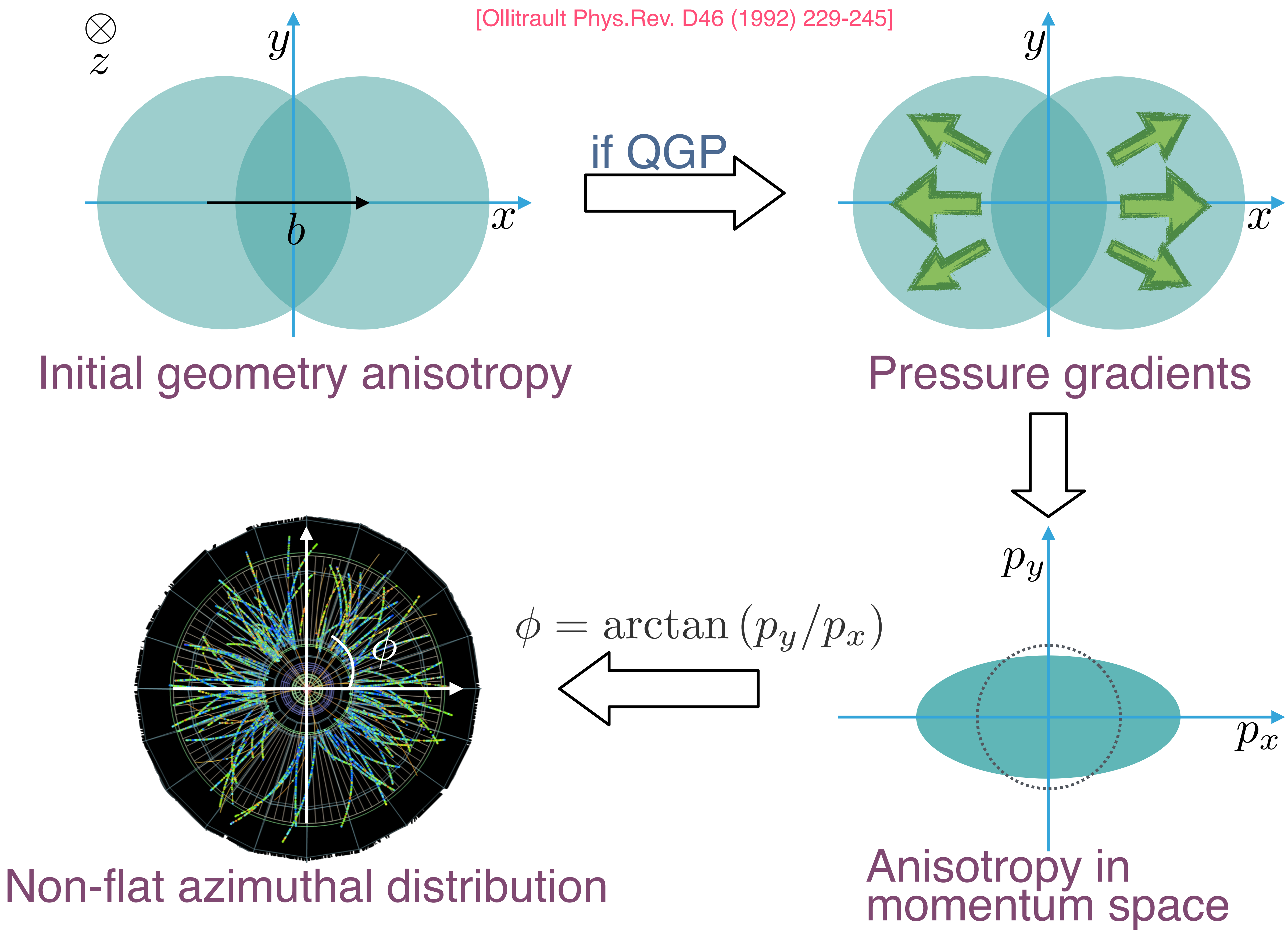
Multiple partonic interactions at the LHC (MPI@LHC)

Perugia, 10th December, 2018

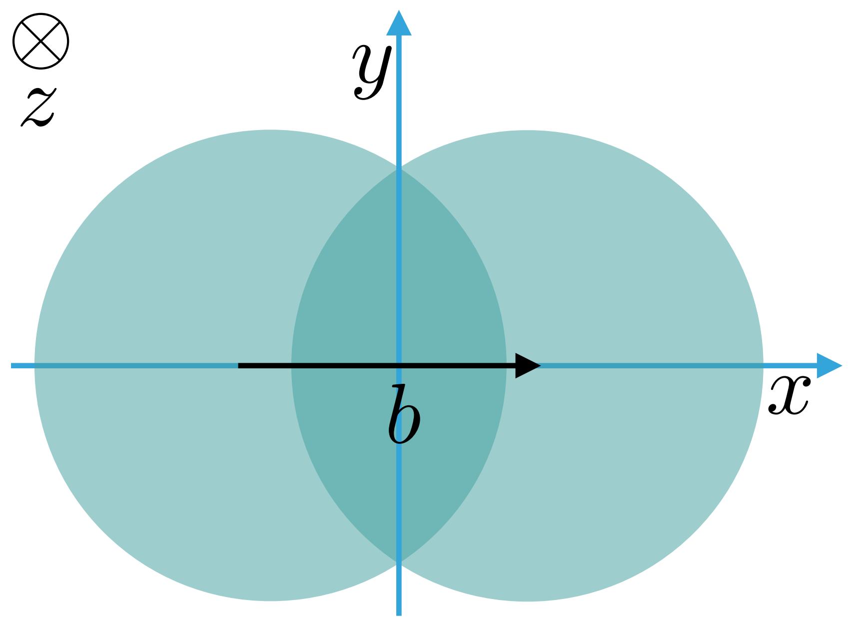
BROOKHAVEN NATIONAL LABORATORY

Center for Frontiers in Nuclear Science

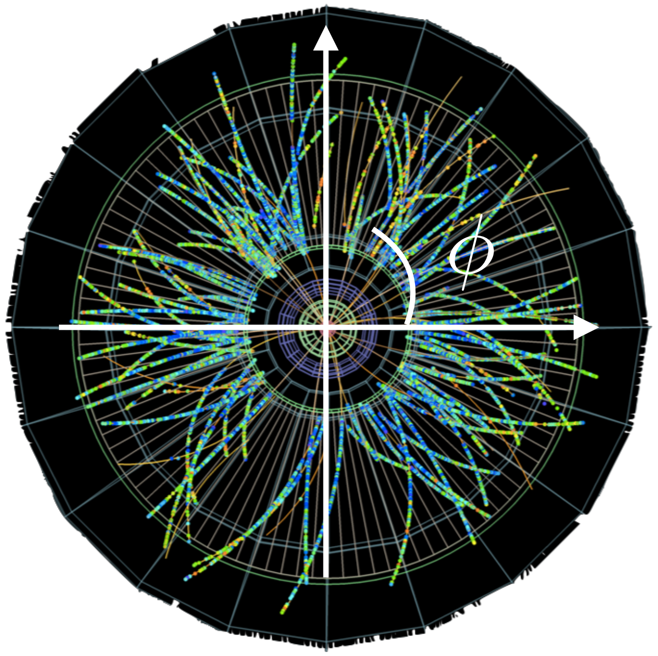
QGP footprints: flow harmonic coefficients



QGP footprints: flow harmonic coefficients



if QGP



Initial geometry anisotropy

Anisotropic azimuthal distribution

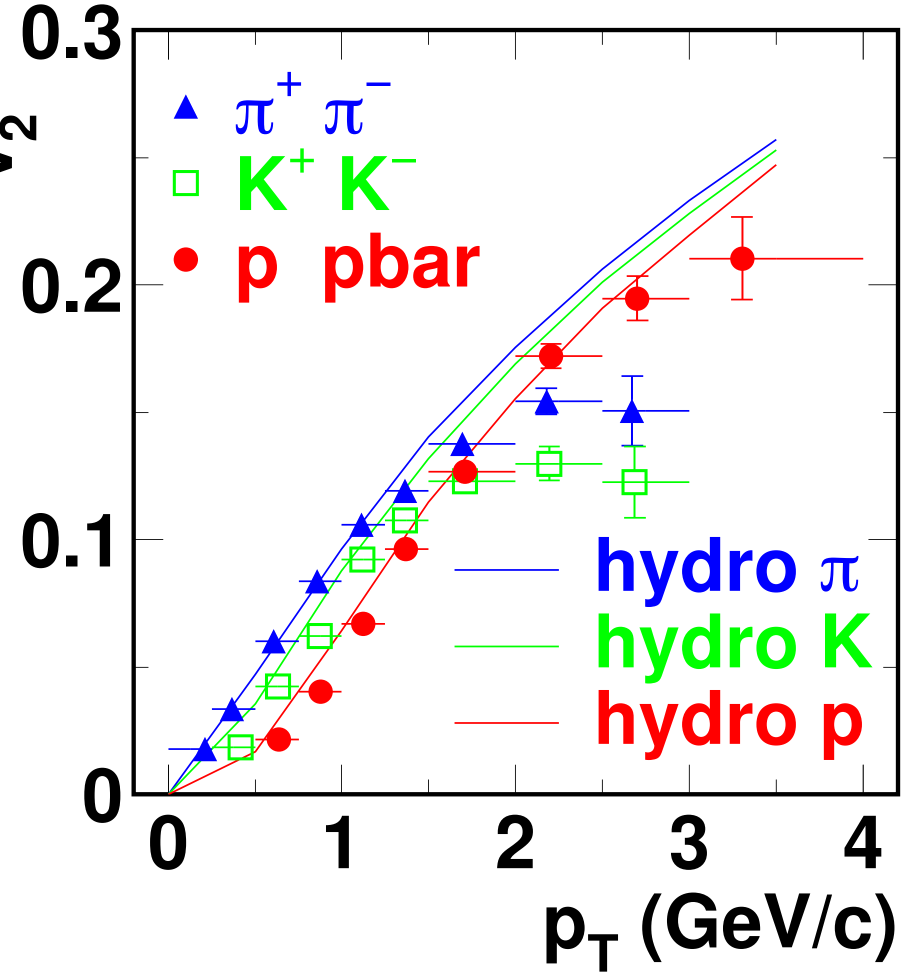
$$E\frac{dN}{d^3p} \propto \frac{dN}{p_{\mathrm{T}}dp_{\mathrm{T}}dy}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_{\mathrm{T}}, y)\cos[n(\phi - \psi_{\mathrm{RP}})]\right]$$

$$v_n = \langle\cos(n[\phi_1 - \phi_2])\rangle = \frac{1}{N(N-1)}\sum_{\substack{i \neq j \\ i,j=1}}^{N} \cos[n(\phi_i - \phi_j)]$$

*N: Number of particles in an event

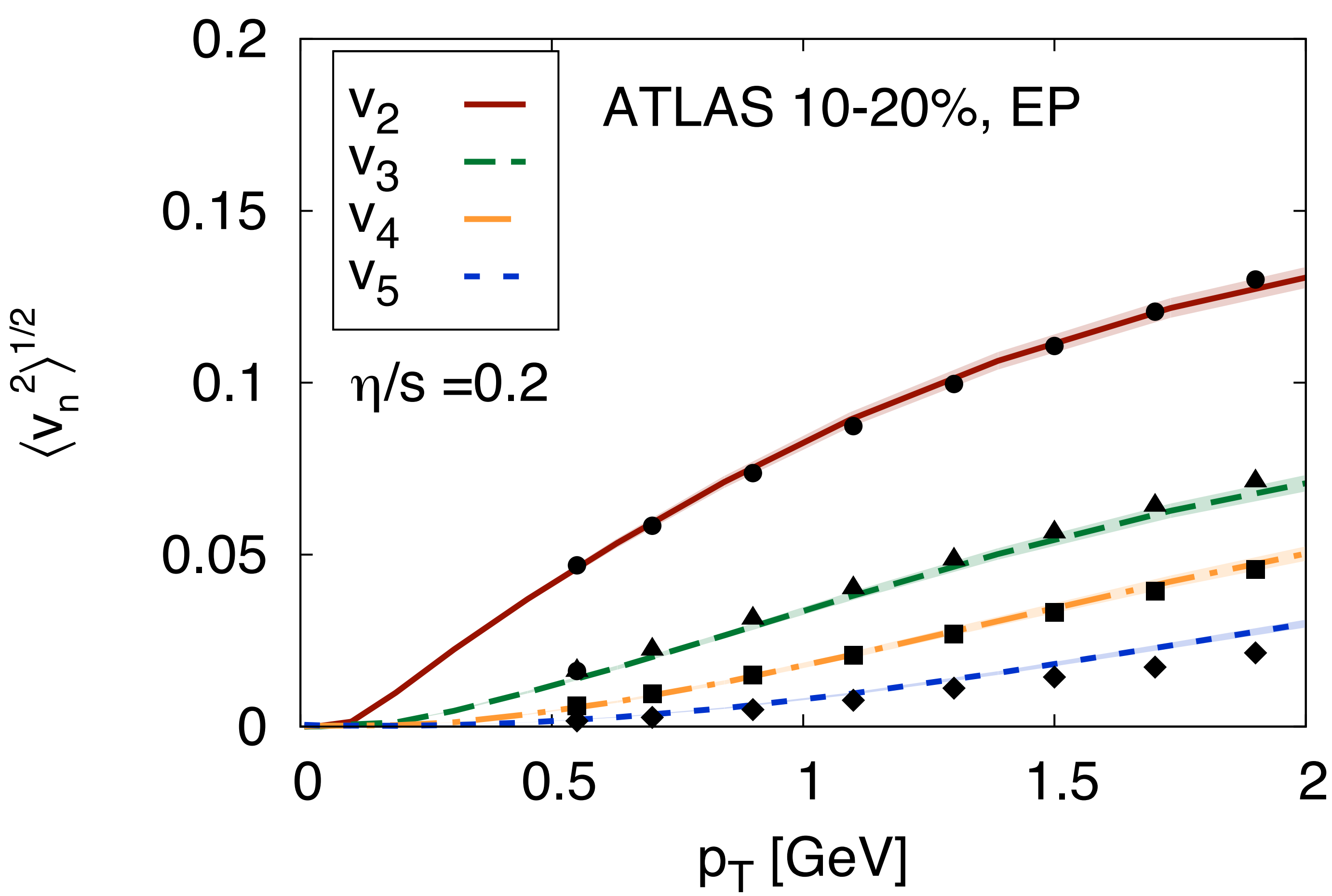
Flow in heavy ion collisions

Au+Au@200 GeV



[Adler et al. Phys.Rev. Lett. 91 (2003) 182301]

Pb+Pb@2.76 TeV



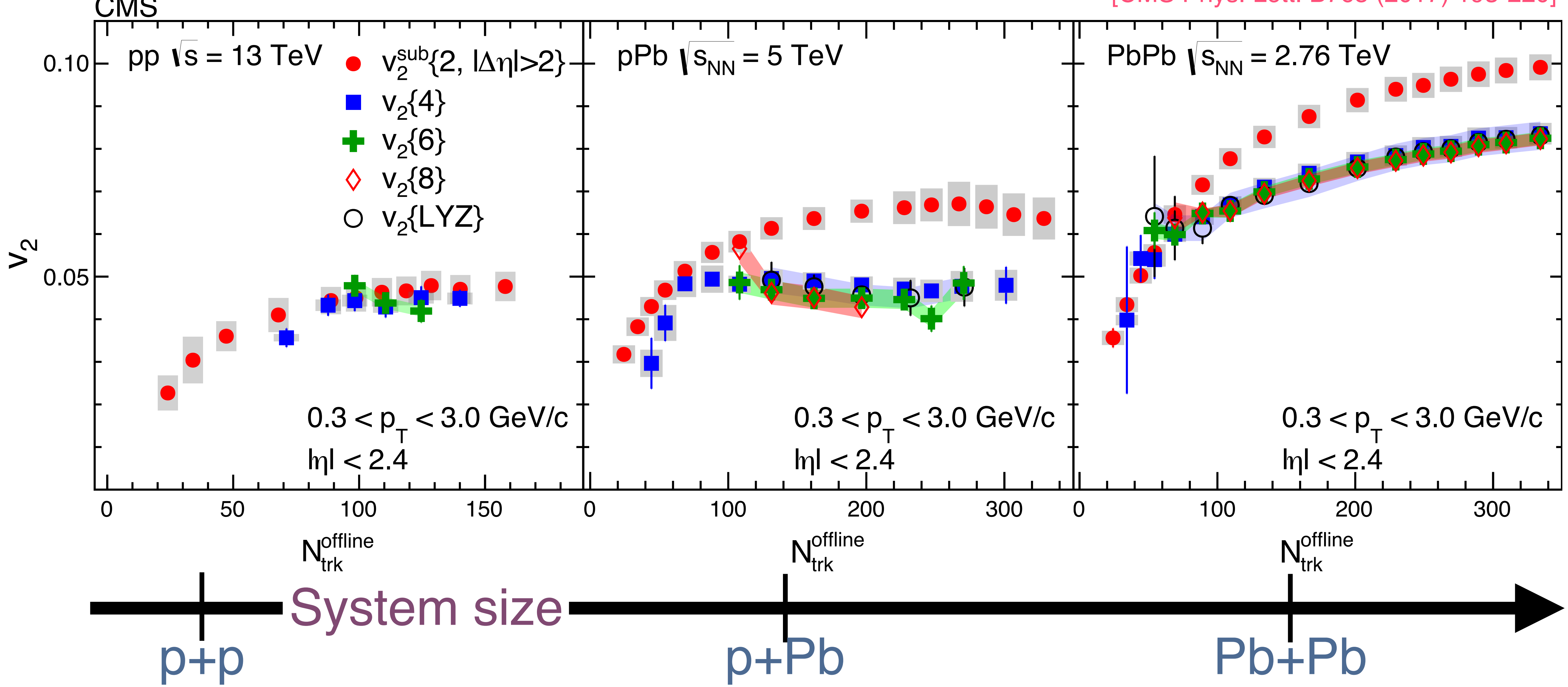
[Gale et al. Phys.Rev. Lett. 110 (2013) 012302]

QGP discovered in ultra relativistic heavy ion collisions*.
Excellent agreement between data and viscous hydro

*+ Jet quenching, quarkonia melting, strangeness enhancement…

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. "The small system puzzle"

Underlying dynamics

CGC See talk by Skokov

Hydrodynamics

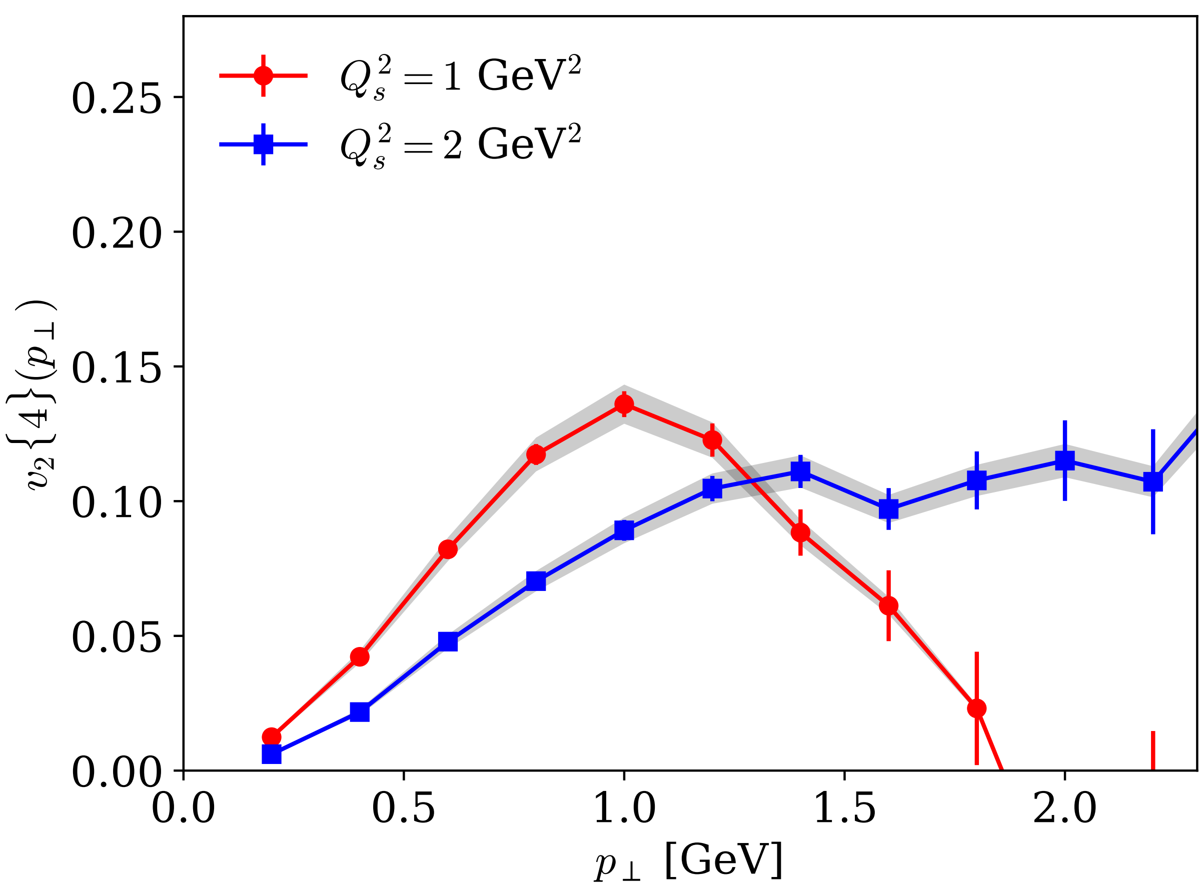
Initial state dynamics; no QGP

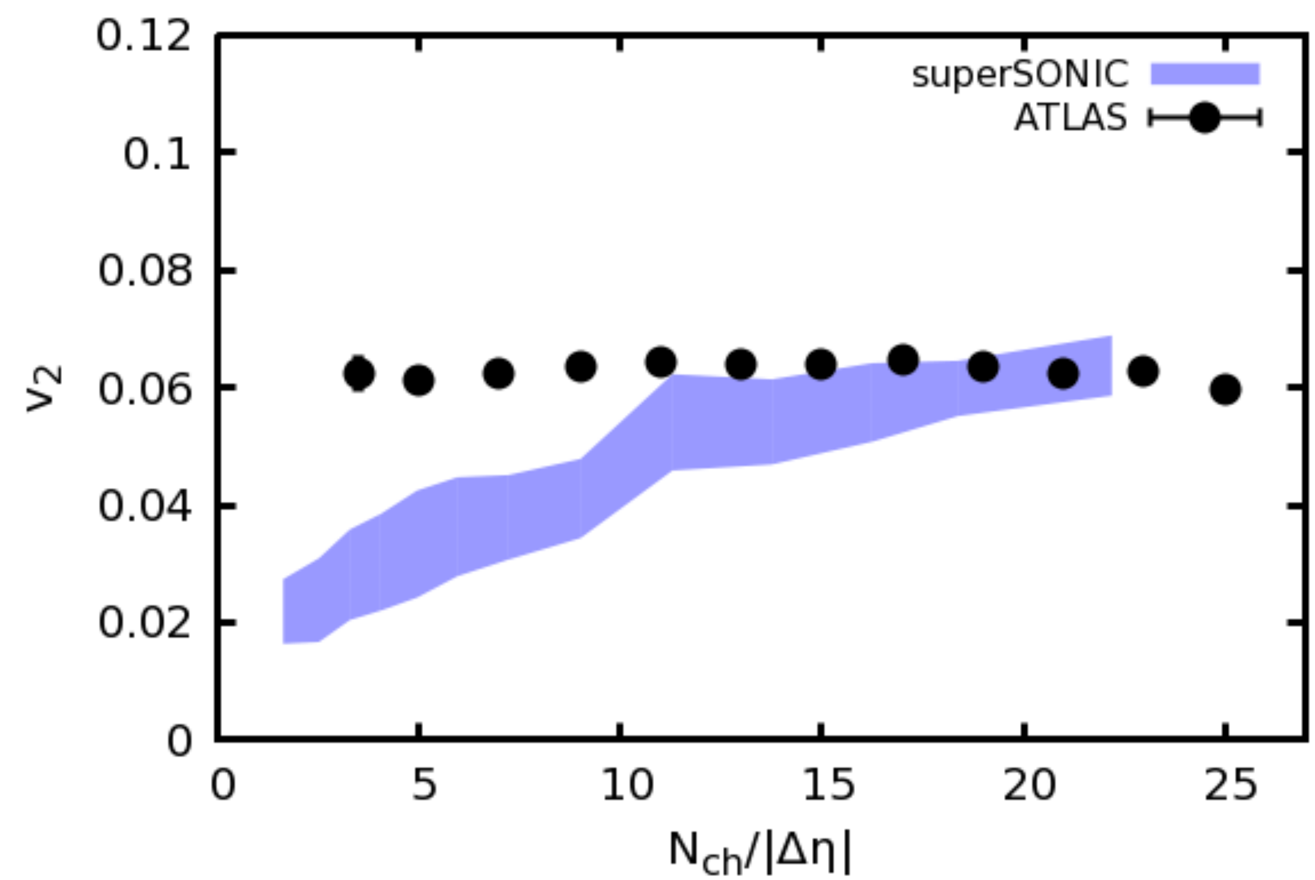
Panta Rhei; QGP as in A+A

$v_2\{4\}$

v_2

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





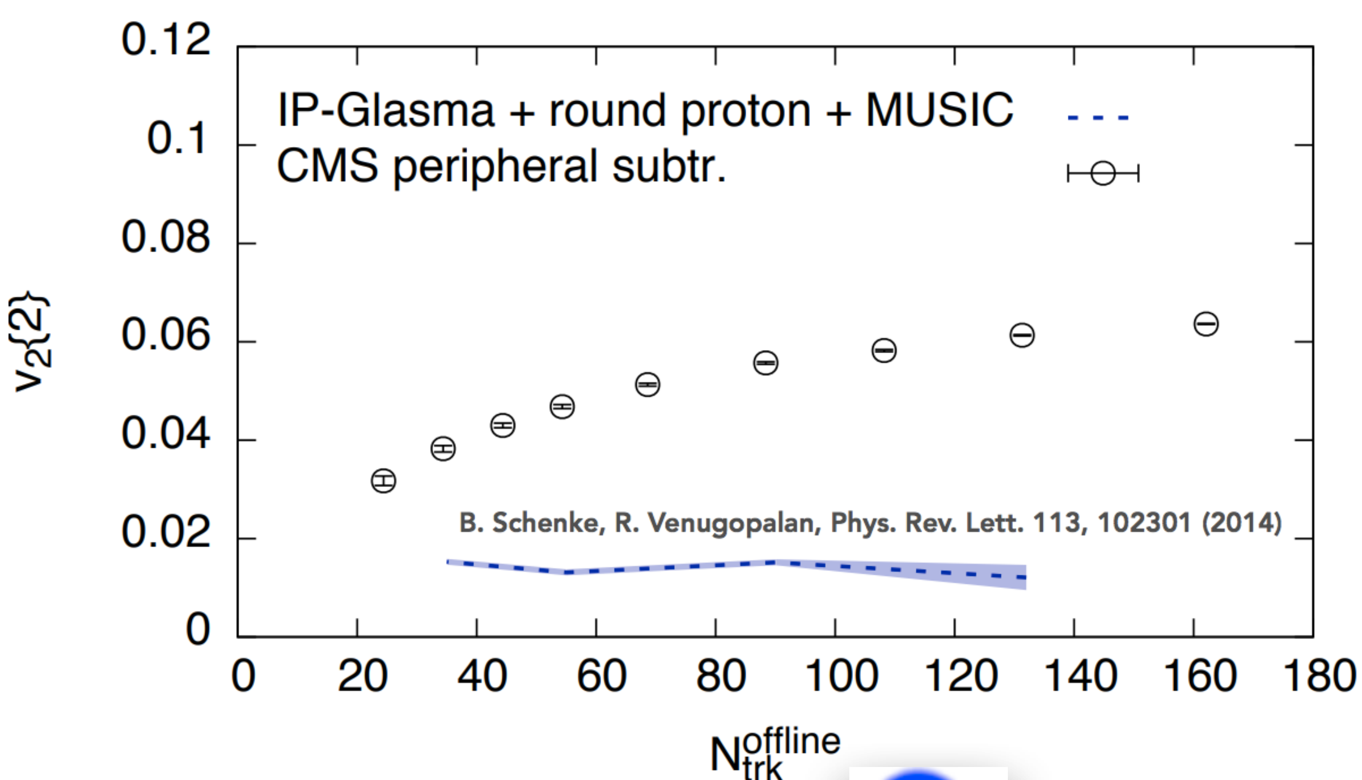
[Weller et al. Phys.Lett. B774 (2017) 351-356]

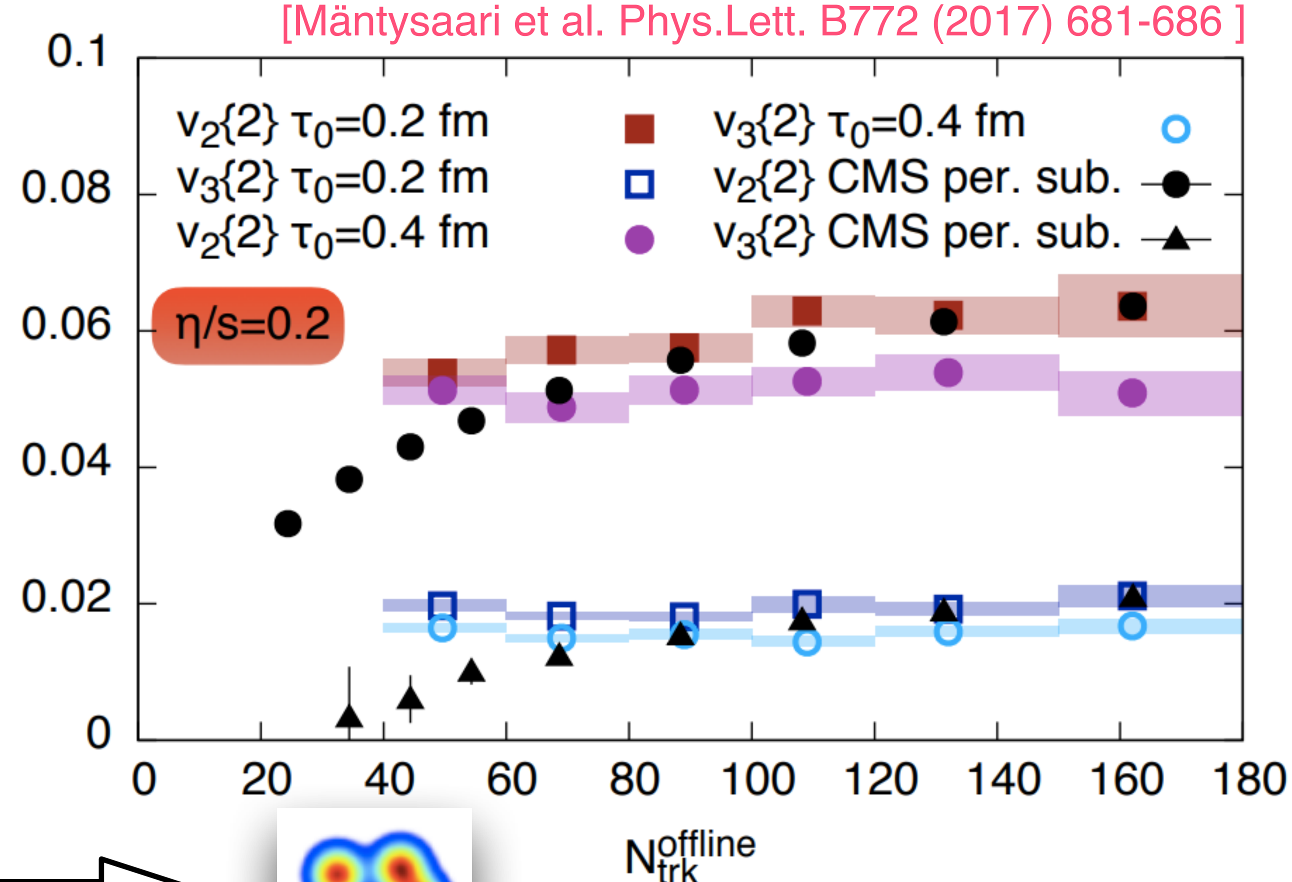
Common input: geometric structure of the proton

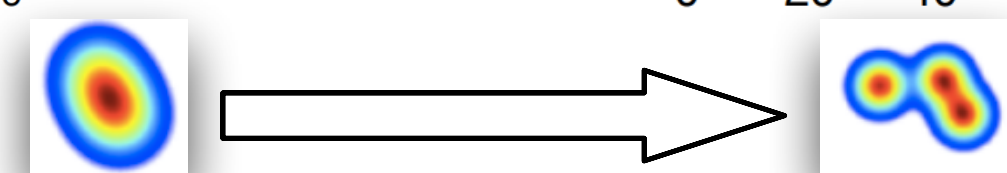
Role of proton geometry in p+A

Initial state dynamics + QGP effects

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





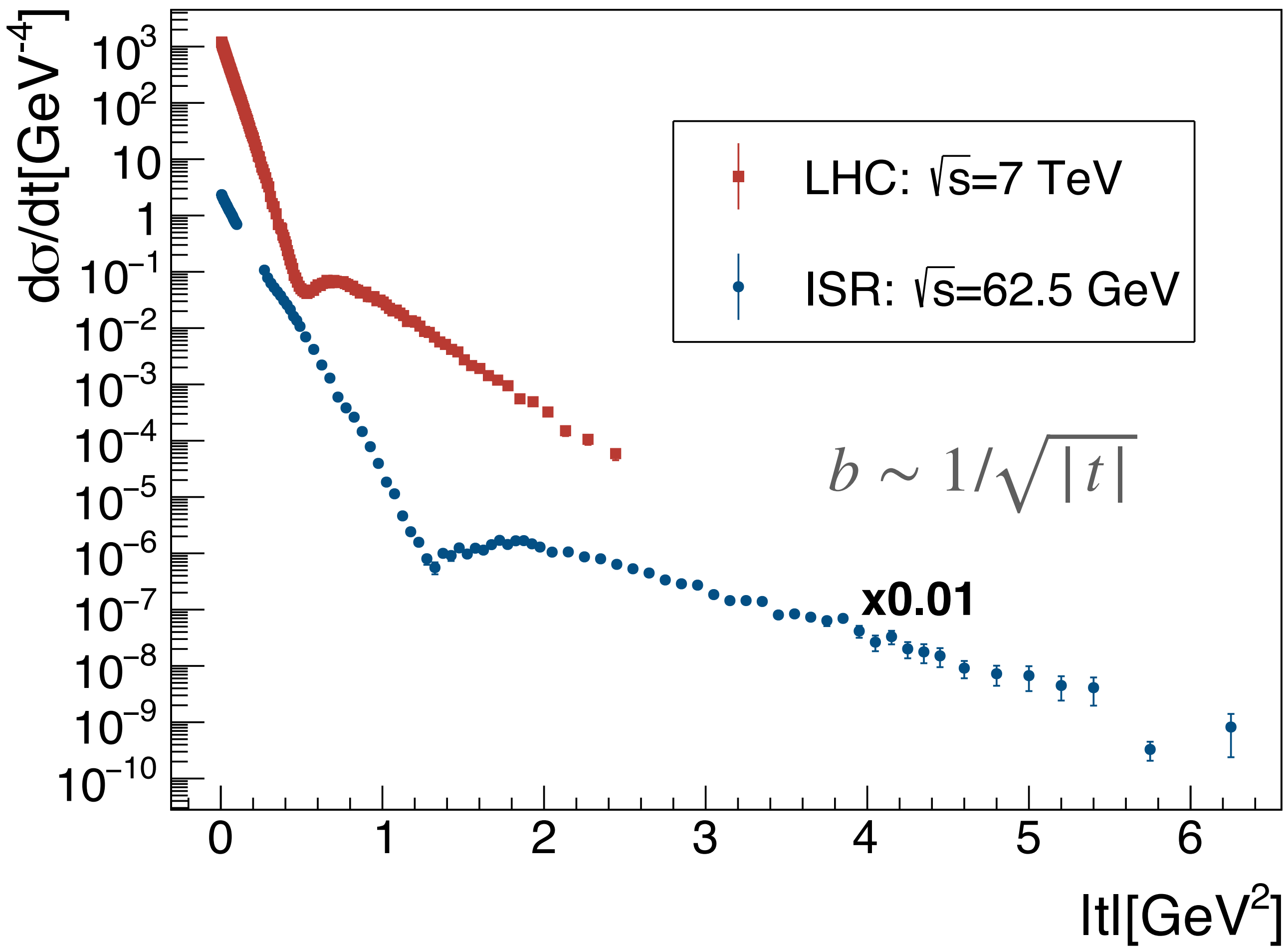


Fluctuating internal d.o.f

Highly precise LHC/RHIC data calls for a fine detailed description of the proton structure. How can it be constrained?

Elastic scattering

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



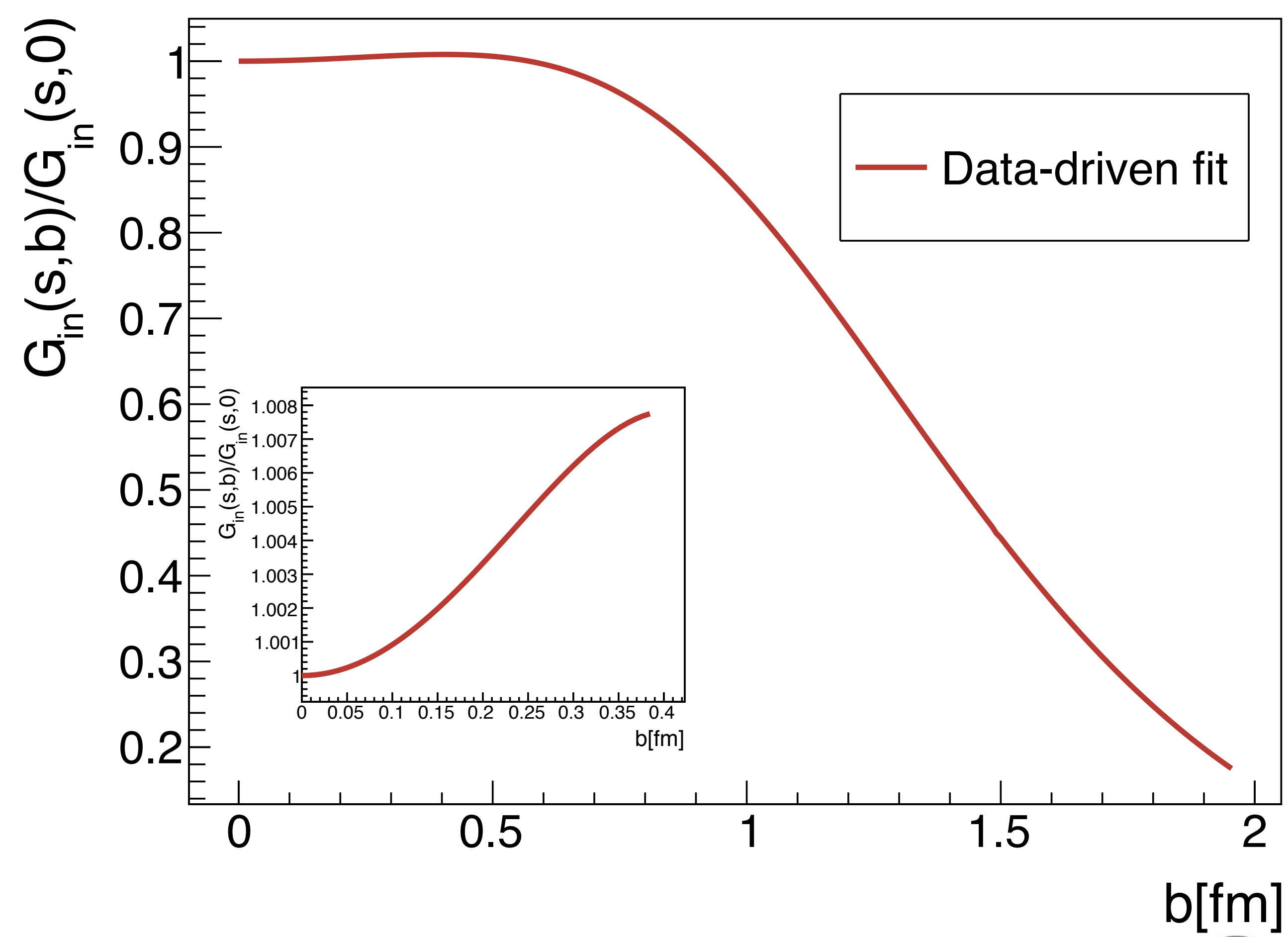
$$\frac{d\sigma_{\rm el}}{dt} \propto |T_{\rm el}(s,t)|^2$$

Unitarity condition +
Fourier Transformation

$$G_{\rm in}(s,b) \equiv \frac{d^2\sigma_{\rm inel}}{d^2b} = 2{\rm Im}T_{\rm el}(s,b) - |T_{\rm el}(s,b)|^2$$

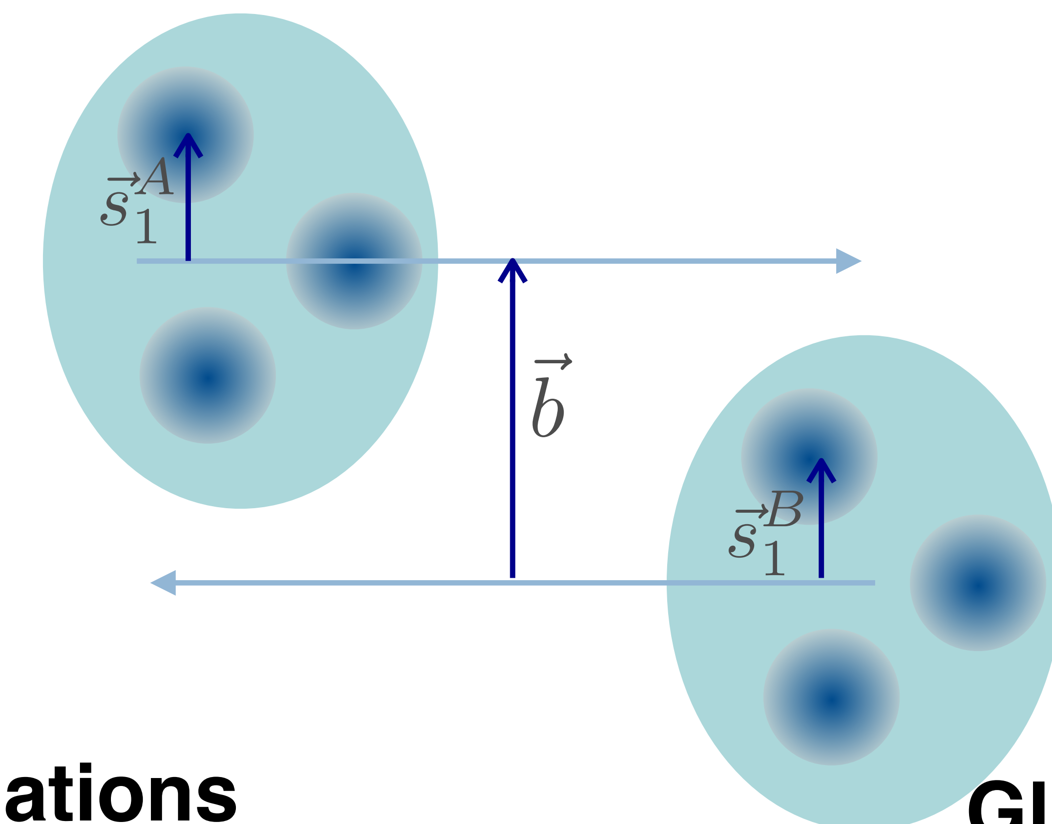
- **STRIKING growing behaviour at low impact parameter**
- **Not observed at ISR energies**
- **Peripheral collisions contribute more to $\sigma_{\rm inel}$ than central ones**

Hollowness effect



Setup

Gluonic hot-spots as effective d.o.f



Spatial correlations in transverse space

Glauber multiple scattering expansion

Spatial distribution of hot spots

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

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

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

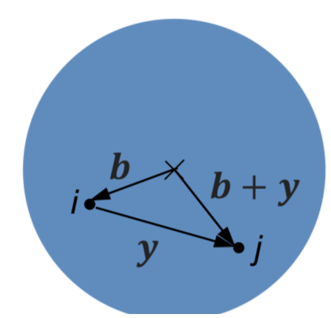
short range repulsive correlations controlled by $r_c^2 \equiv R^2/\mu$

Simplifying assumptions for DPS cross section

If one ignores correlations between partons in the proton:

$$F^{ij}(x_1, x_2, \boldsymbol{y}) = \int d^2\boldsymbol{b}\, D^i(x_1, \boldsymbol{b})\, D^j(x_1, \boldsymbol{b} + \boldsymbol{y})$$

Impact parameter dependent PDFs (FT of GPD)



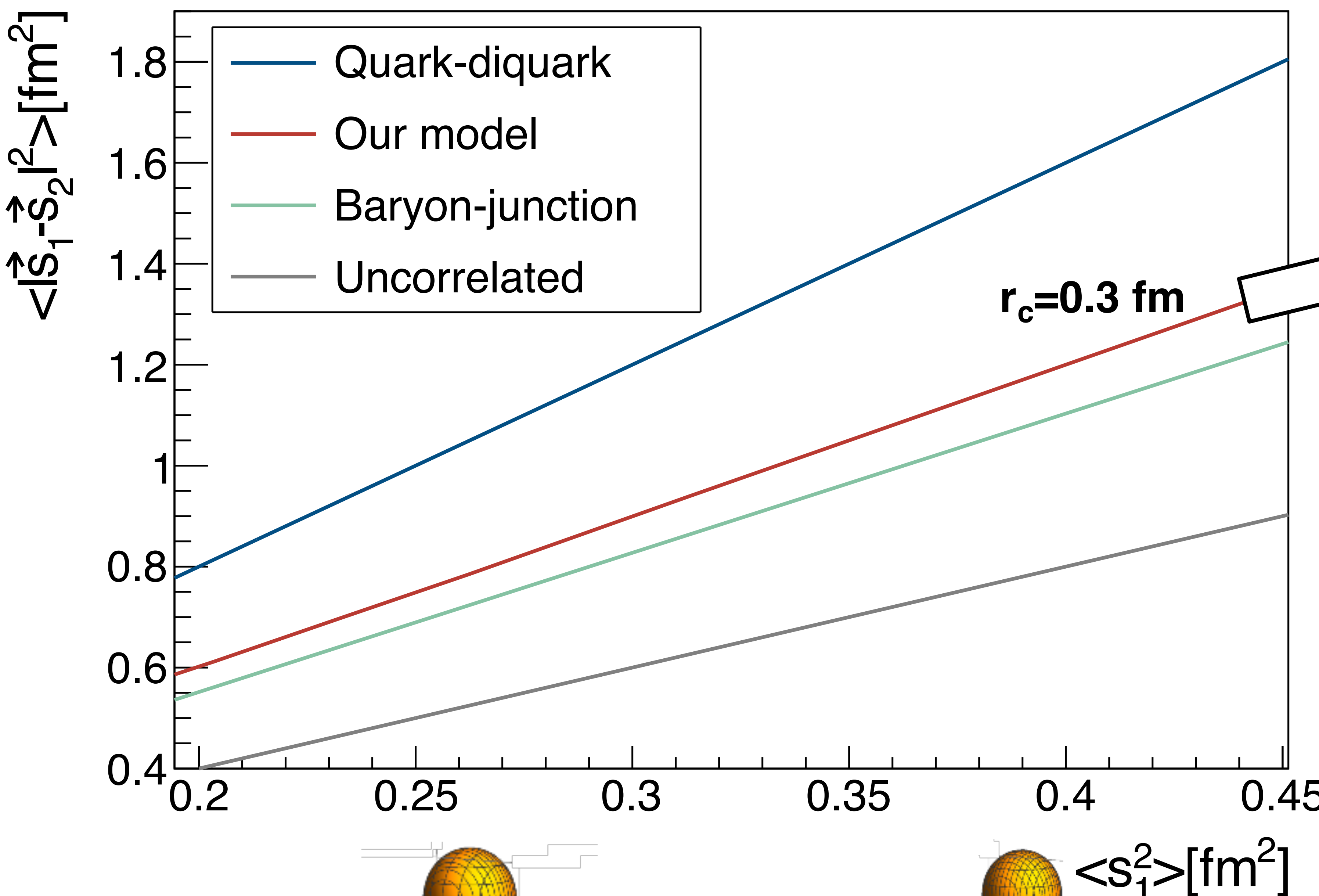
*C: normalization constant

[Talk by Jonathan Gaunt]

Spatial distribution of hot spots

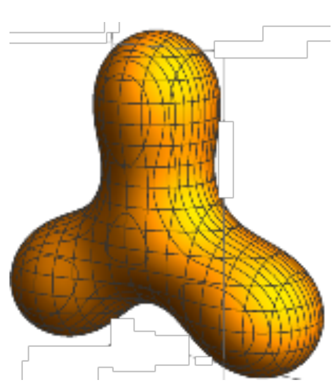
[Albacete, ASO Phys. Lett. B770 (2017) 149-153]

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

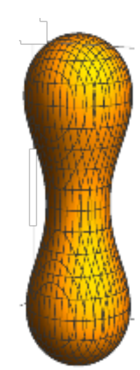


Interpolates between realistic models of proton substructure

Baryon-junction

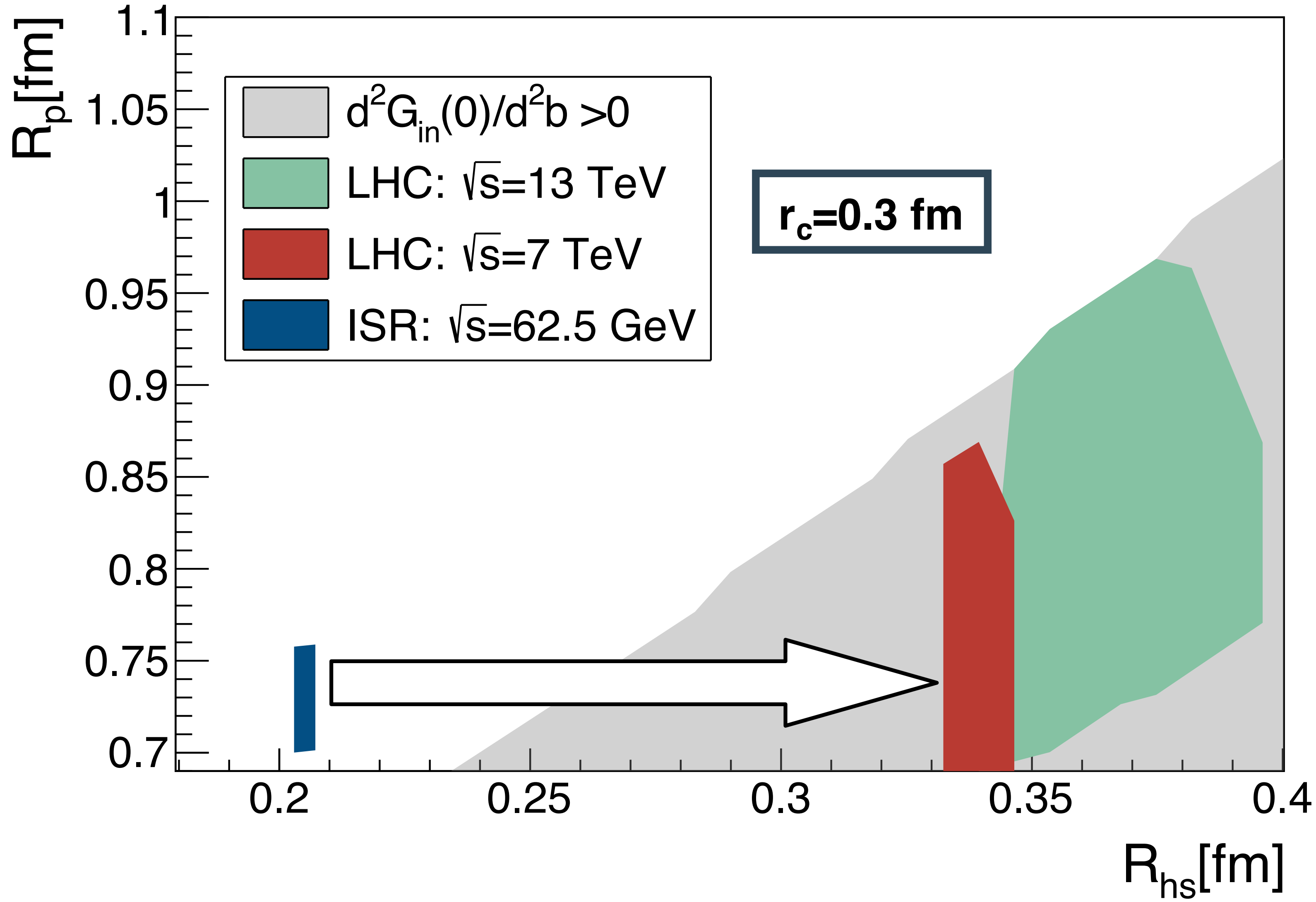


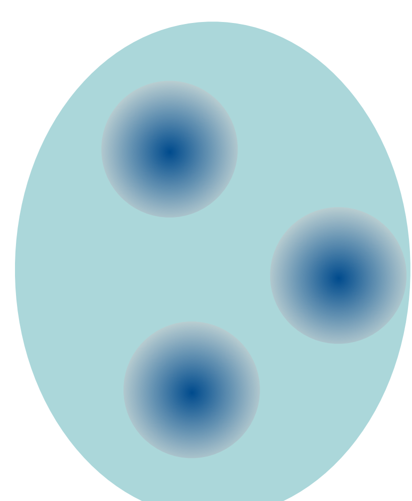
Quark-diquark



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

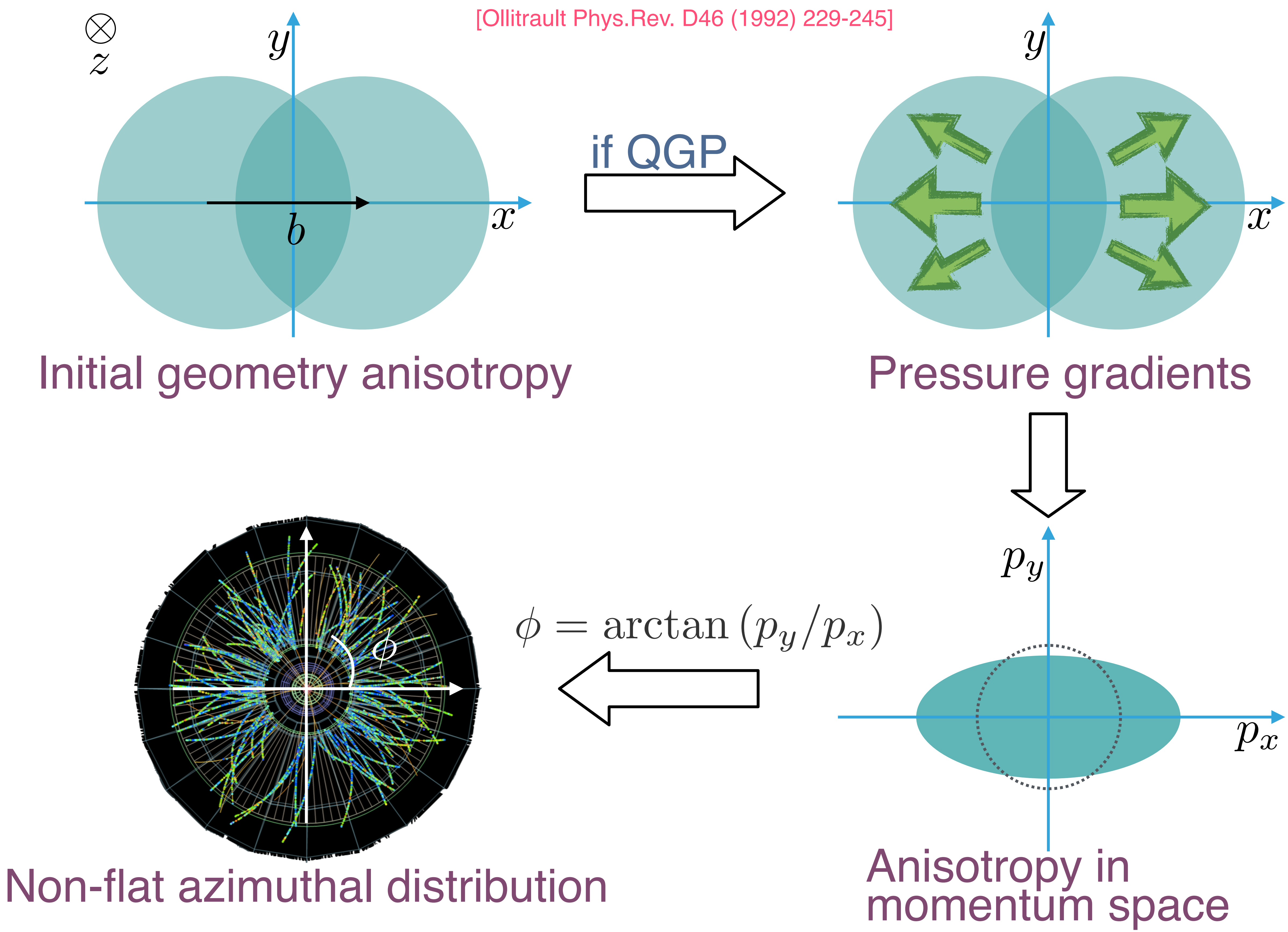
Proton transverse structure as a byproduct





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

Test case: hydro responsible for v_n's in p+p



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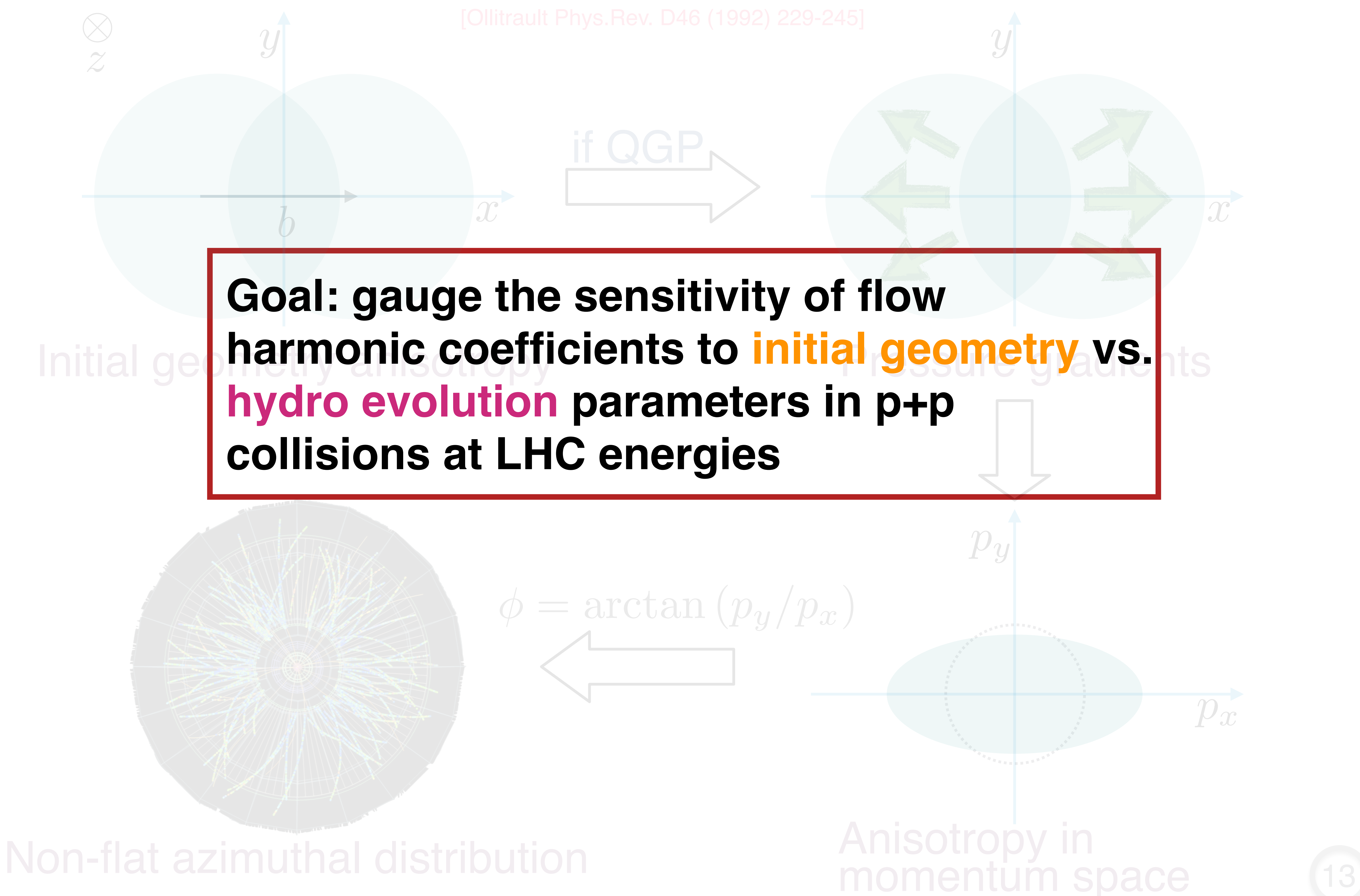


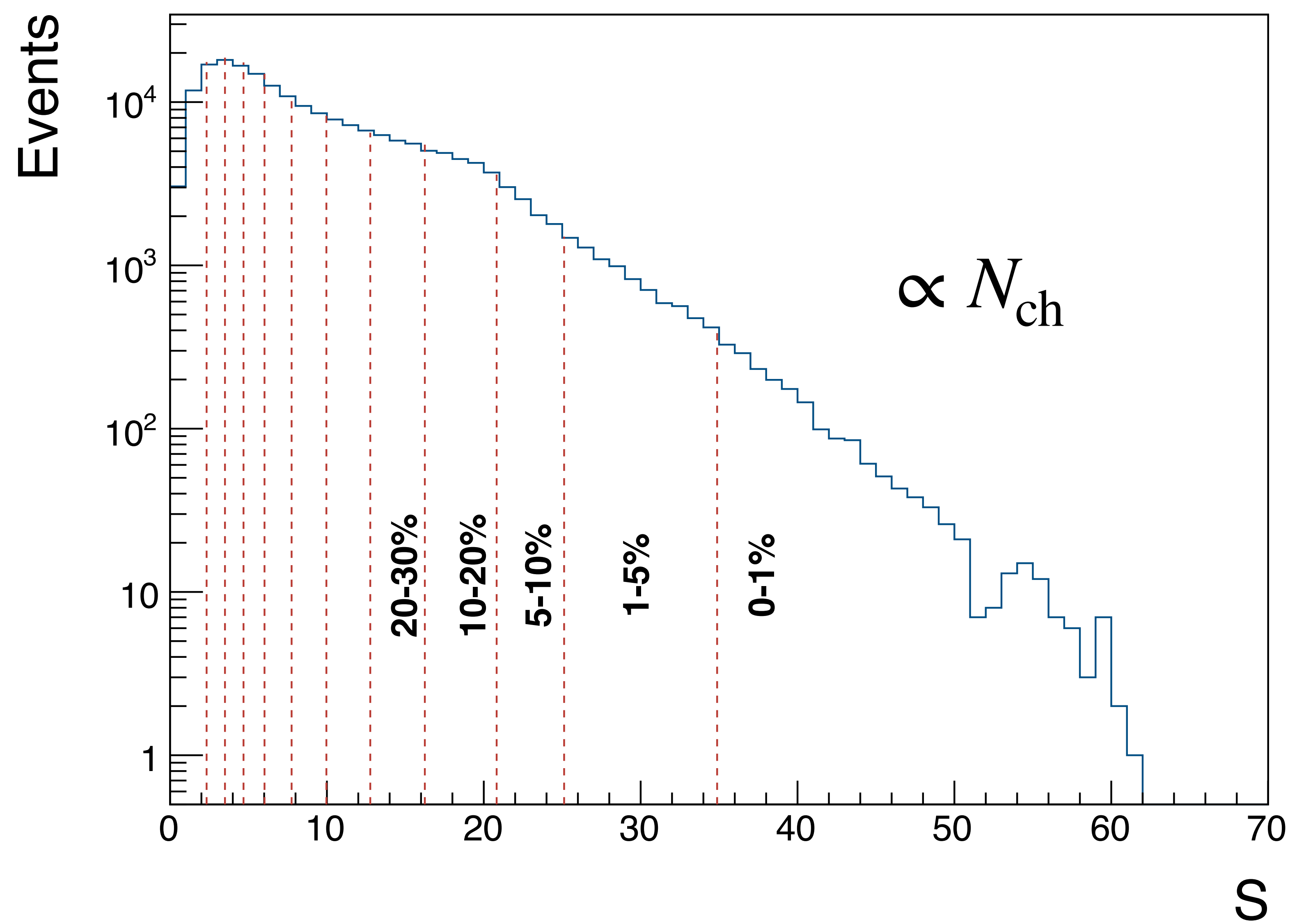
Goal: gauge the sensitivity of flow harmonic coefficients to initial geometry vs. hydro evolution parameters in p+p collisions at LHC energies

Initial geometry anisotropy: MC Glauber

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

Analytical ⇨ Monte Carlo: event-by-event fluctuations

- Sampling hot spot positions (correlated/ uncorrelated)
- Geometric collision criterion
- Each wounded hot spot deposits entropy in the transverse plane



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

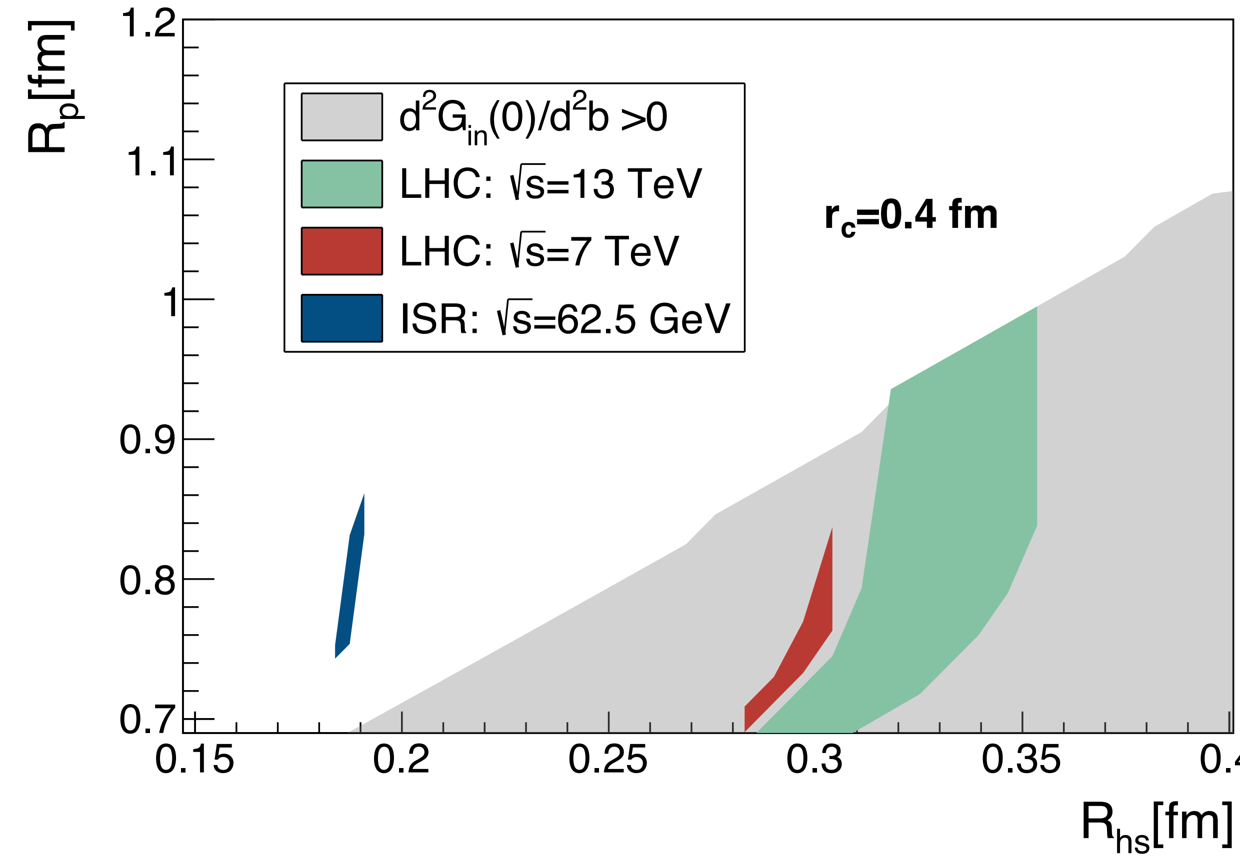
⇨ **Input for hydro**

MC Glauber: parameters

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

⇨ **Correlated (r_c=0.4)**

Representative values of the hollowness-study phase space reproducing



⇨ **Uncorrelated**

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

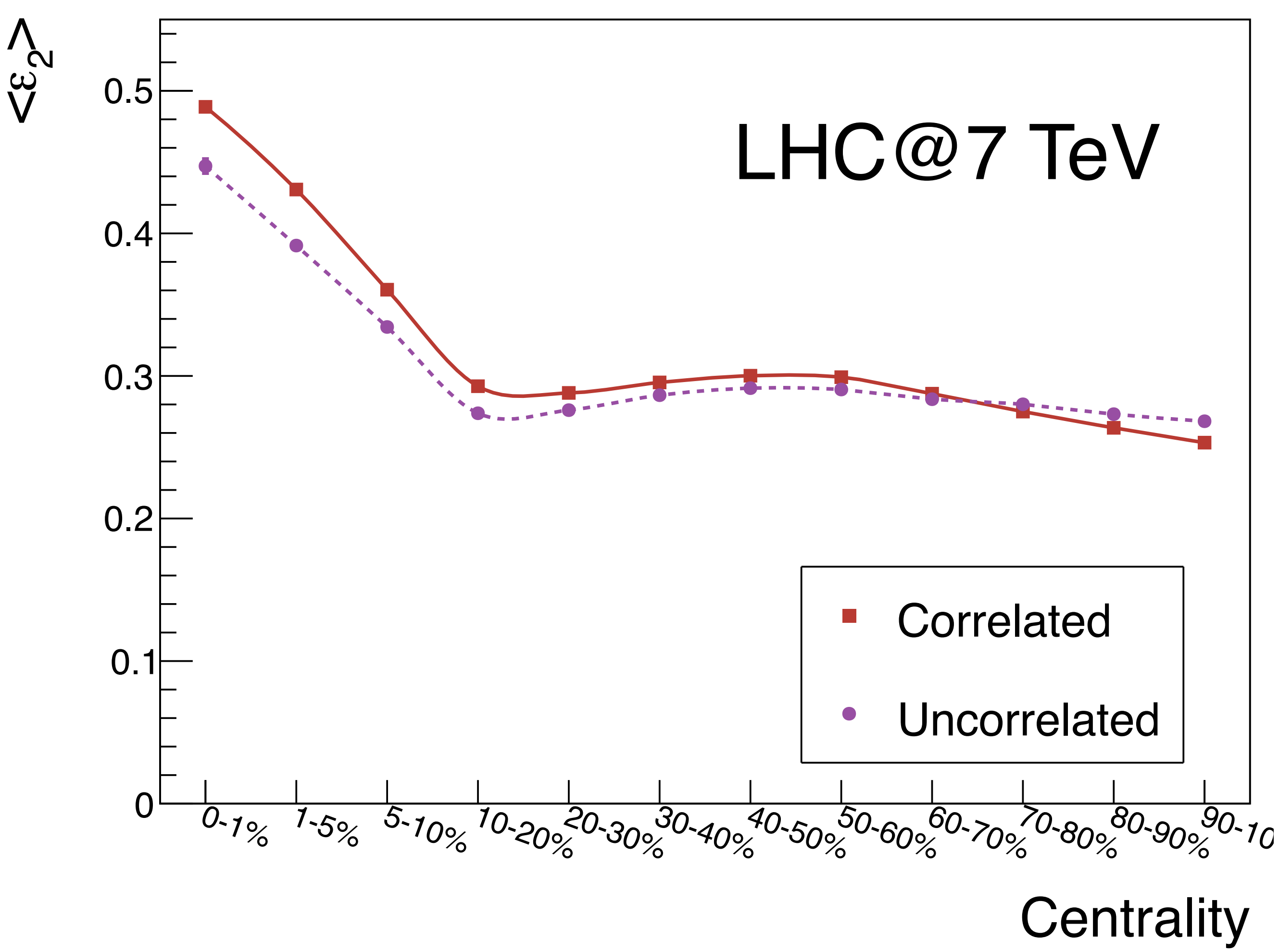
Solution: R_{hs} as in the correlated case and choose R to have identical proton size in both cases

$$\langle s_1 \rangle = \int s_1 \mathrm{d}\vec{s_1}\mathrm{d}\vec{s_2}\mathrm{d}\vec{s_3} D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$$

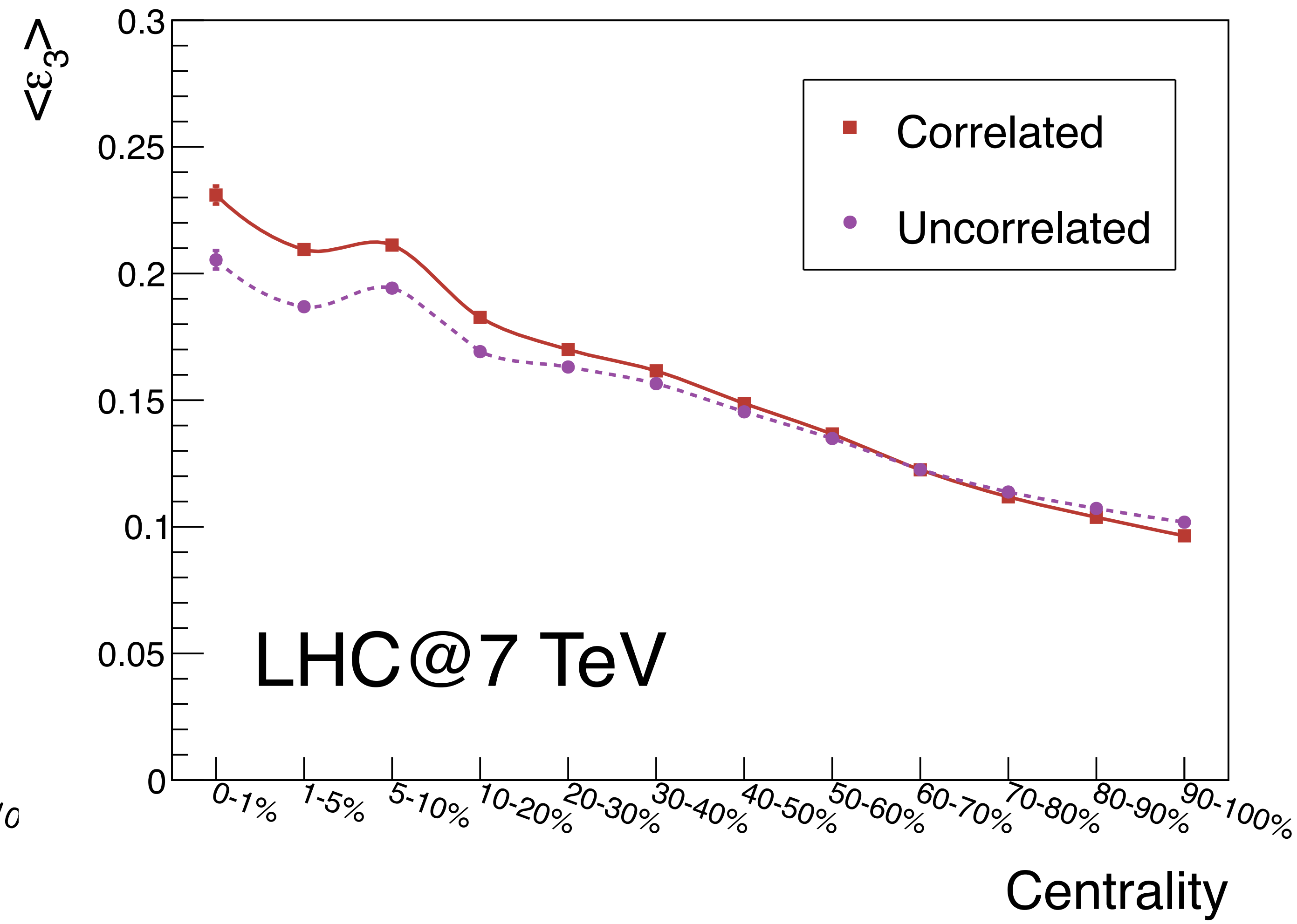
Eccentricity & triangularity

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

Eccentricity



Triangularity



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

2+1D viscous hydrodynamic evolution

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

- Initialized event-by-event with

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

- Equation of state: s95p-PCE-v1

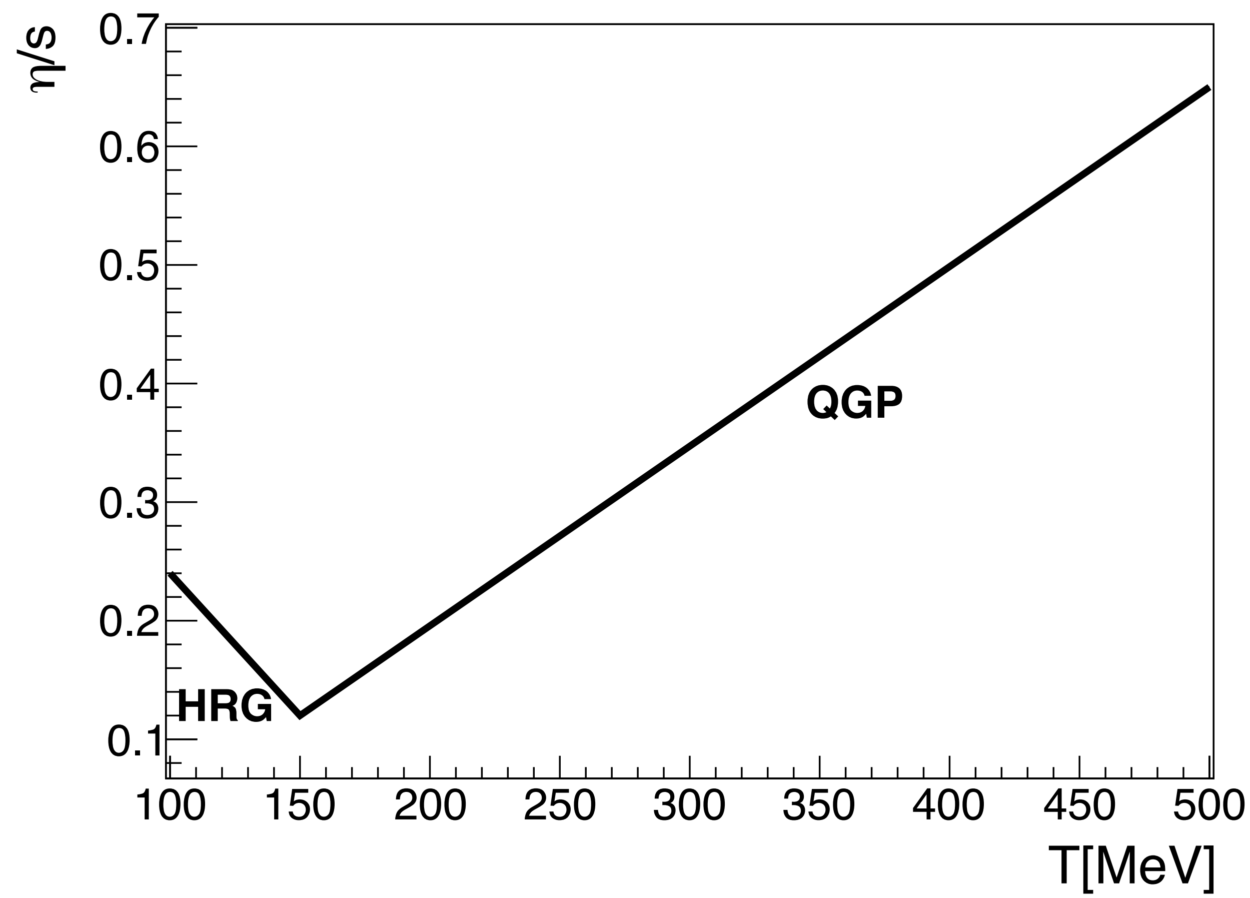
$$T_{\mathrm{dec}} = 100 \text{ MeV} \quad T_{\mathrm{chem}} = 175 \text{ MeV}$$

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

- Resonance decays after freeze out included

- **Transport coefficients:** neglect bulk viscosity and heat conductivity. Shear viscosity à la ERKT

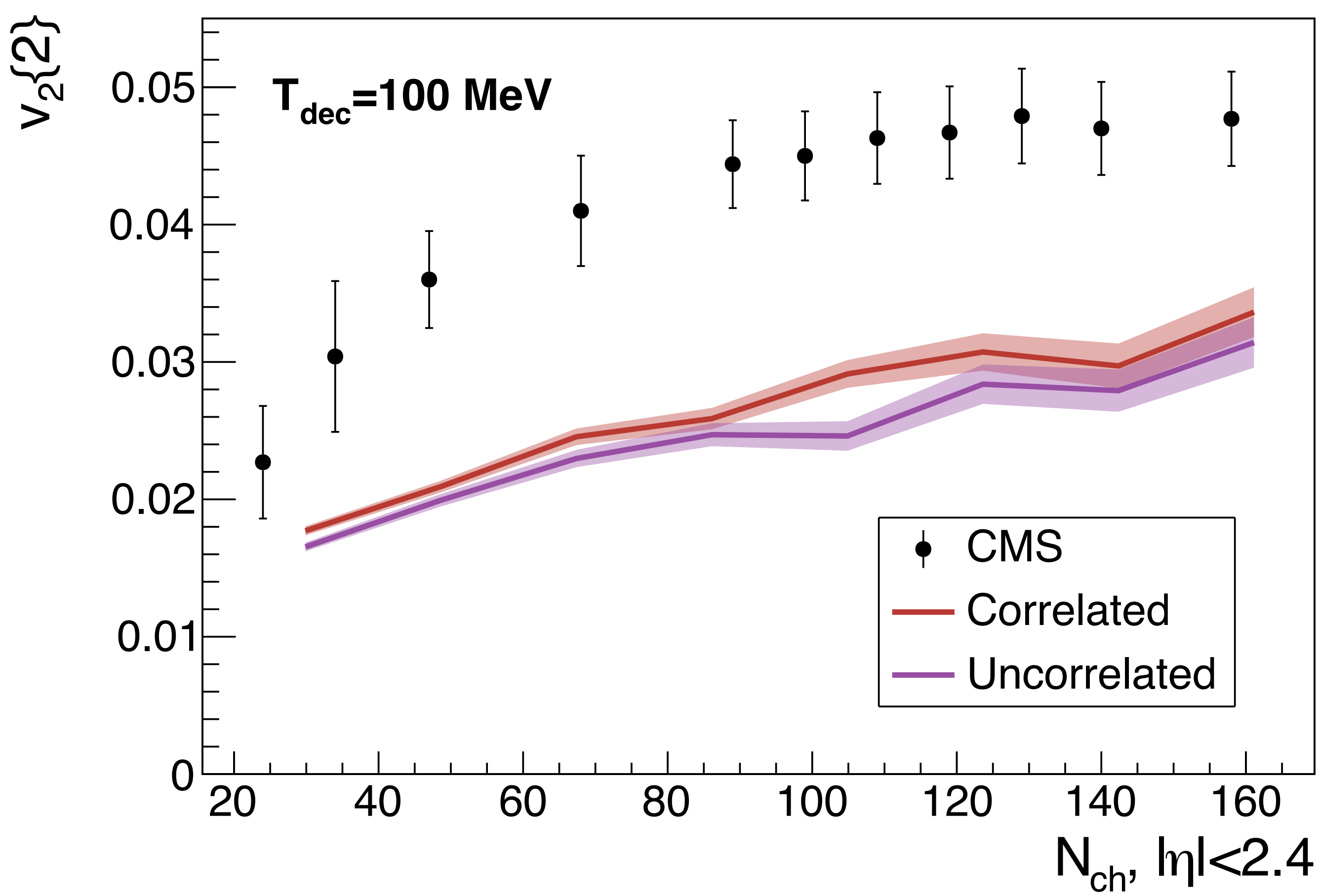
[Niemi et al., Phys.Rev. C93 (2016) no.2, 024907]
[Eskola et al., Phys.Rev. C93 (2016) no.1, 014912]



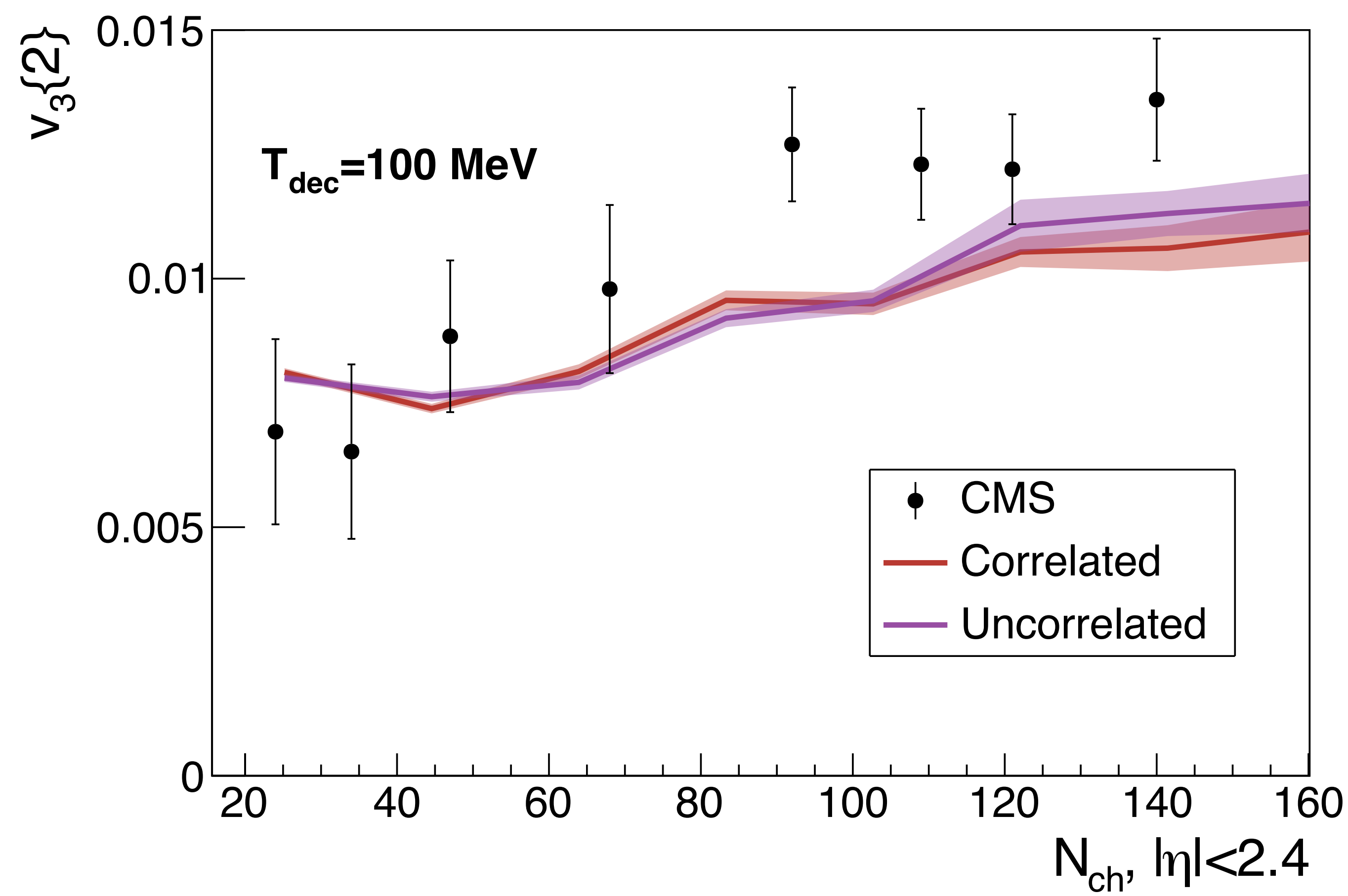
Impact of spatial correlations in v_n's

[Albacete, Petersen, Niemi, ASO in preparation]

Elliptic flow



Triangular flow

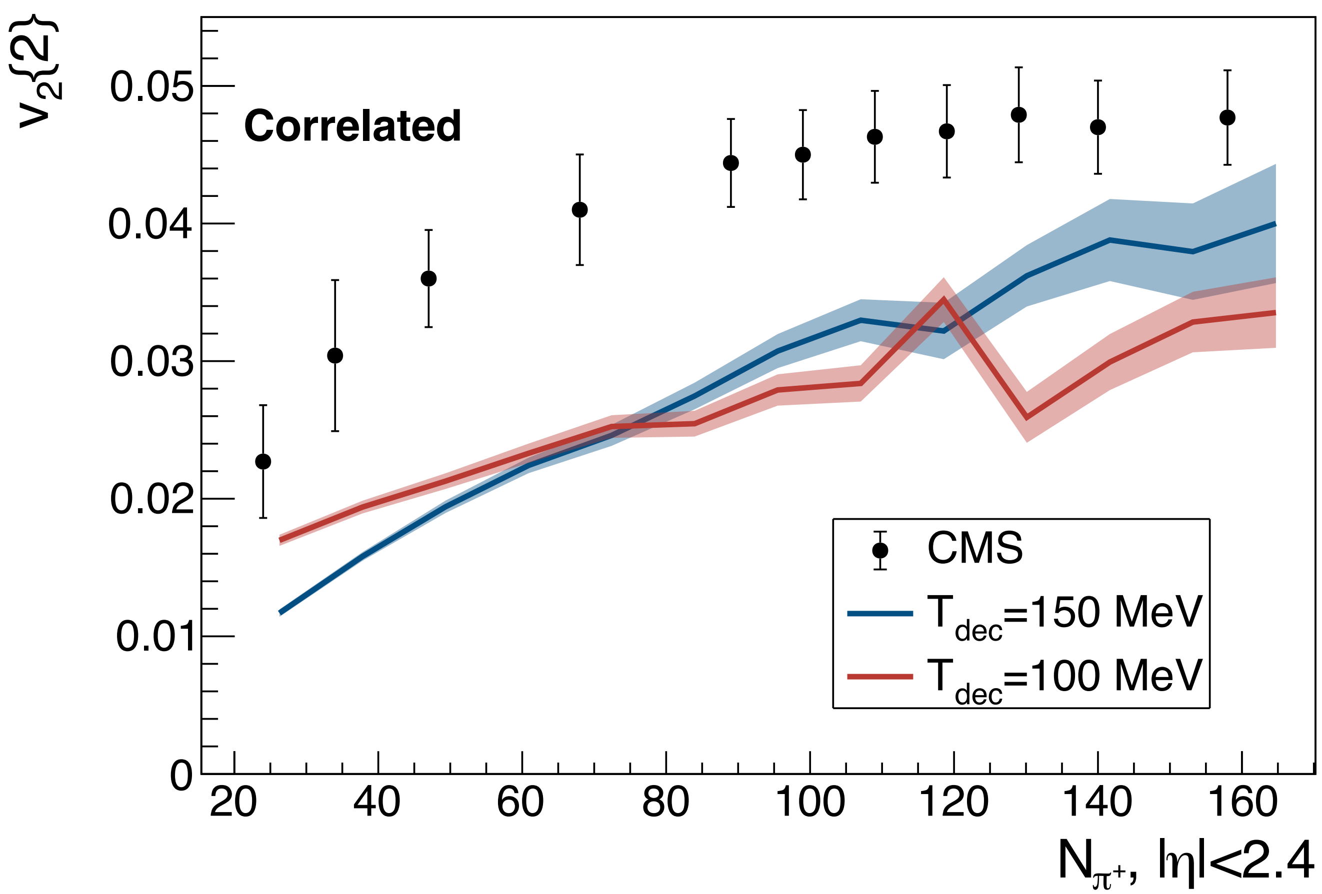


Repulsive correlations in the initial geometry seem to affect the elliptic flow. No fine tuning. More statistics (and work) needed!!

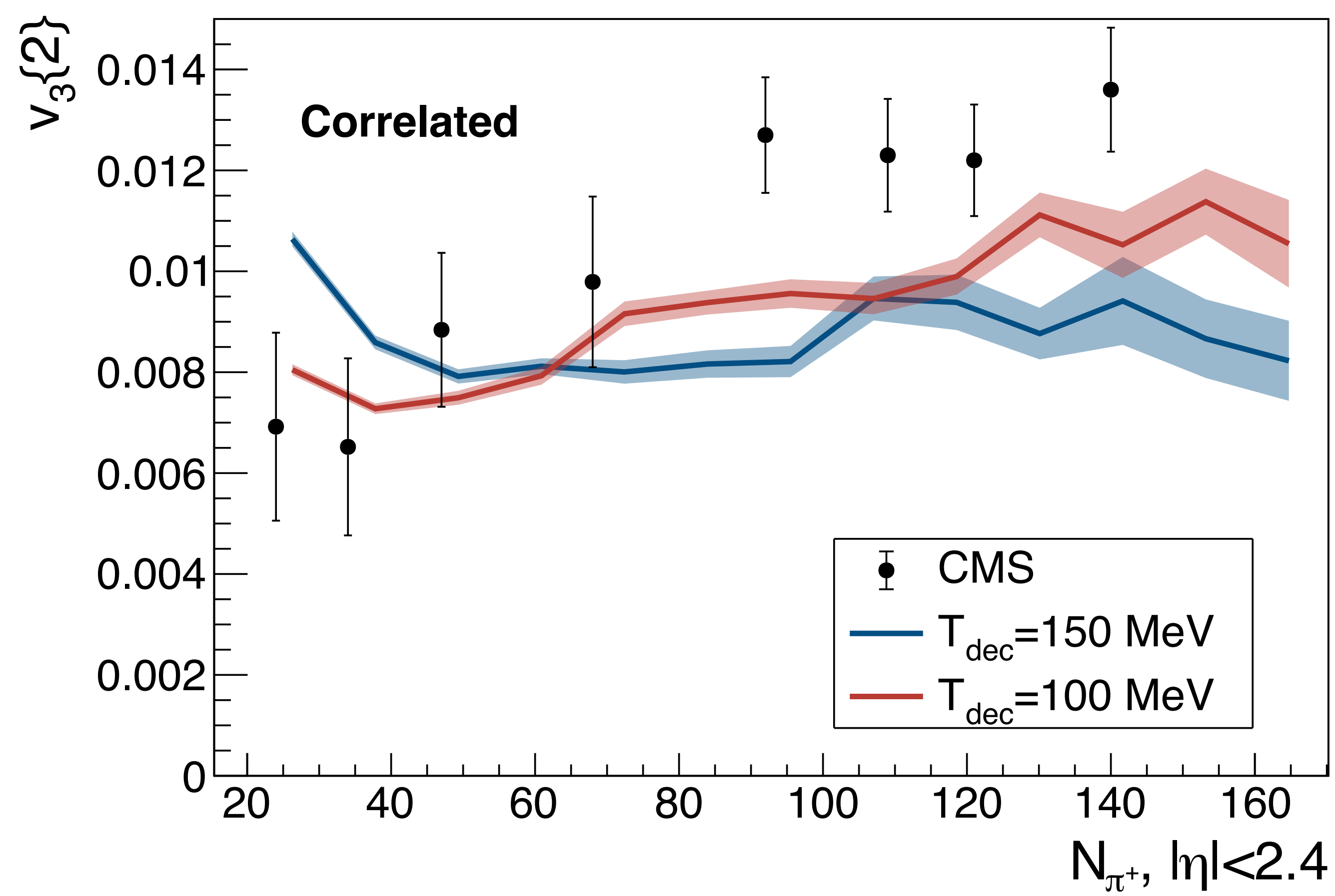
Impact of T_{dec} in v_n's

[Albacete, Petersen, Niemi, ASO in preparation]

Elliptic flow



Triangular flow



Large sensitivity to non-measurable parameters of the hydro evolution observed in the flow coefficients

Flow harmonic coefficients in small systems at the LHC: Initial or Final state effect?

⇨ **Hard to tell!**

⇨ **Deep and quantitative understanding of details in both paradigms needed before extracting strong conclusions from the experimental data**

Hydro side: [Albacete, Petersen, Niemi, ASO in preparation] (and others)

CGC side: See talk by Skokov

⇨ **Constraining power for the proton structure. Interesting to the MPI community!**