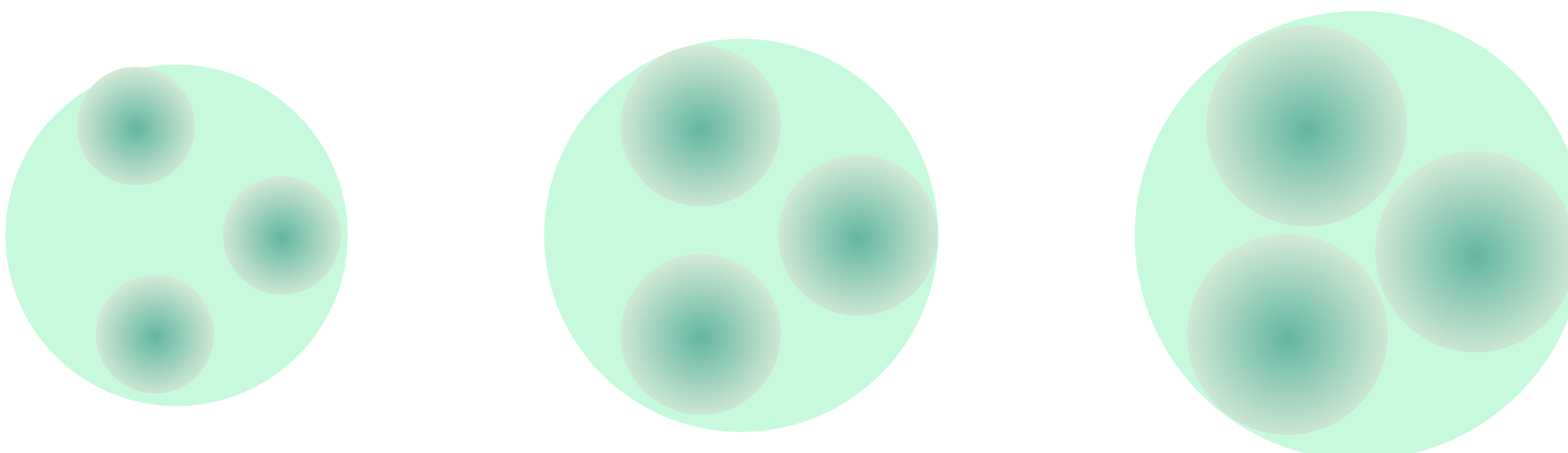
Hot Spots and the Hollowness of Proton-Proton interactions



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to appear (SOON) on arXiv:1605.

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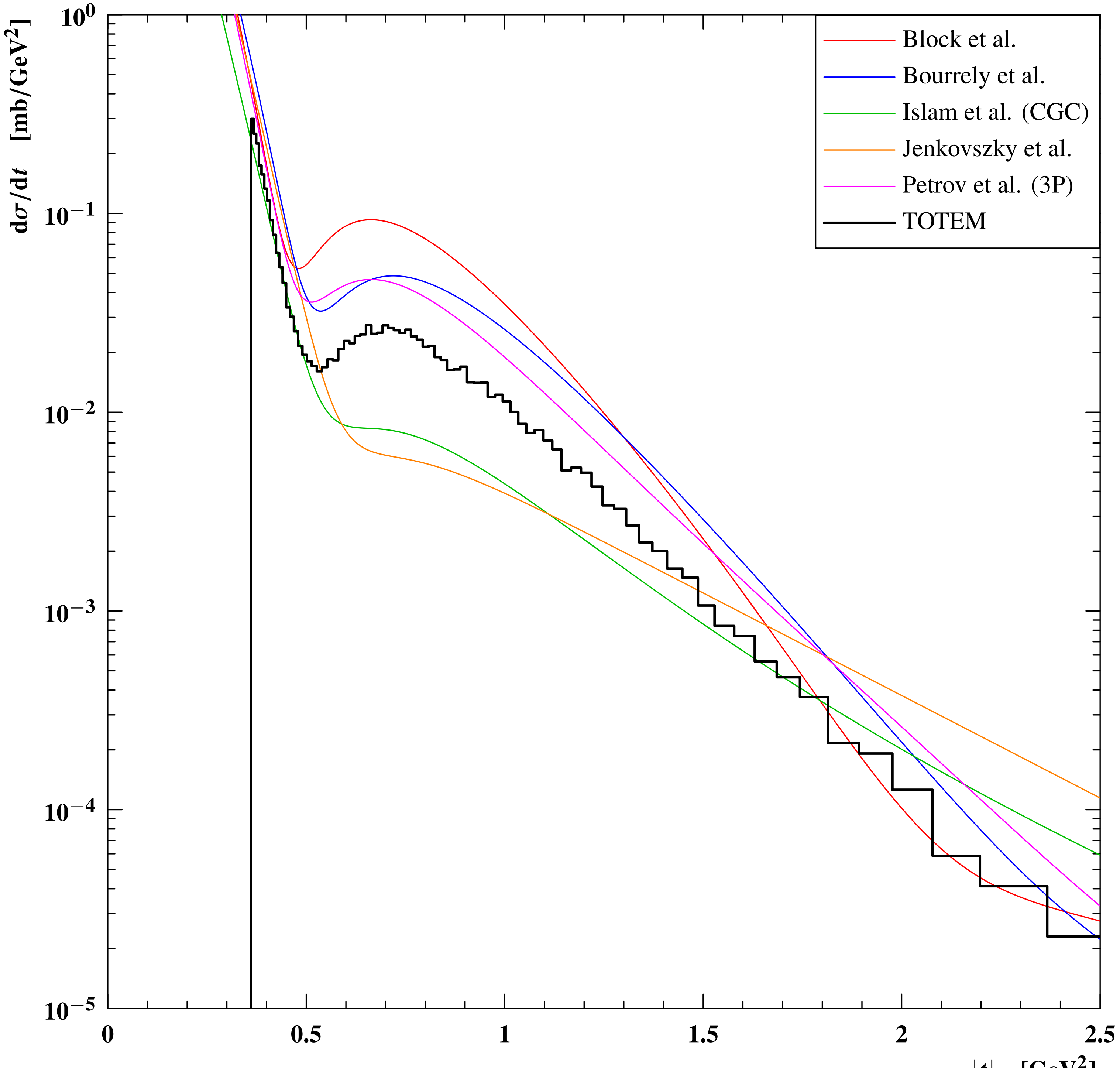
1. Motivation

pp elastic scattering

[TOTEM Collab'11]

- TOTEM data on elastic differential cross section in *pp* collisions at 7 TeV



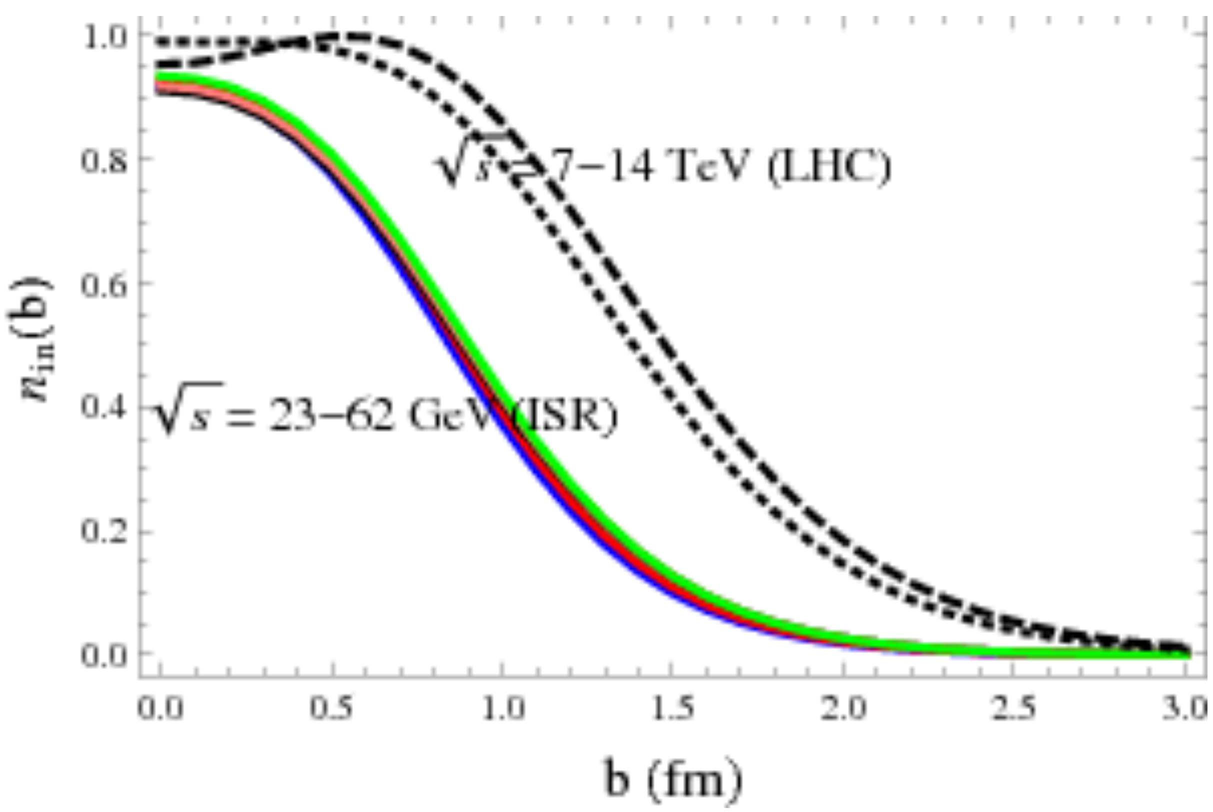
$$\boxed{\frac{d\sigma_{\rm el}}{dt} = \frac{1}{4\pi}|T_{\rm el}(s,t)|^2}$$

Hollowness effect

- The *hollowness/grayness* effect in *pp* interactions @LHC

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

$$G_{\rm in} = {\rm d}^2\sigma_{\rm inel}/{\rm d}^2 b$$



[Ruiz-Arriola et Al. '15]

Contributes more to $\sigma_{\rm inel}$ than

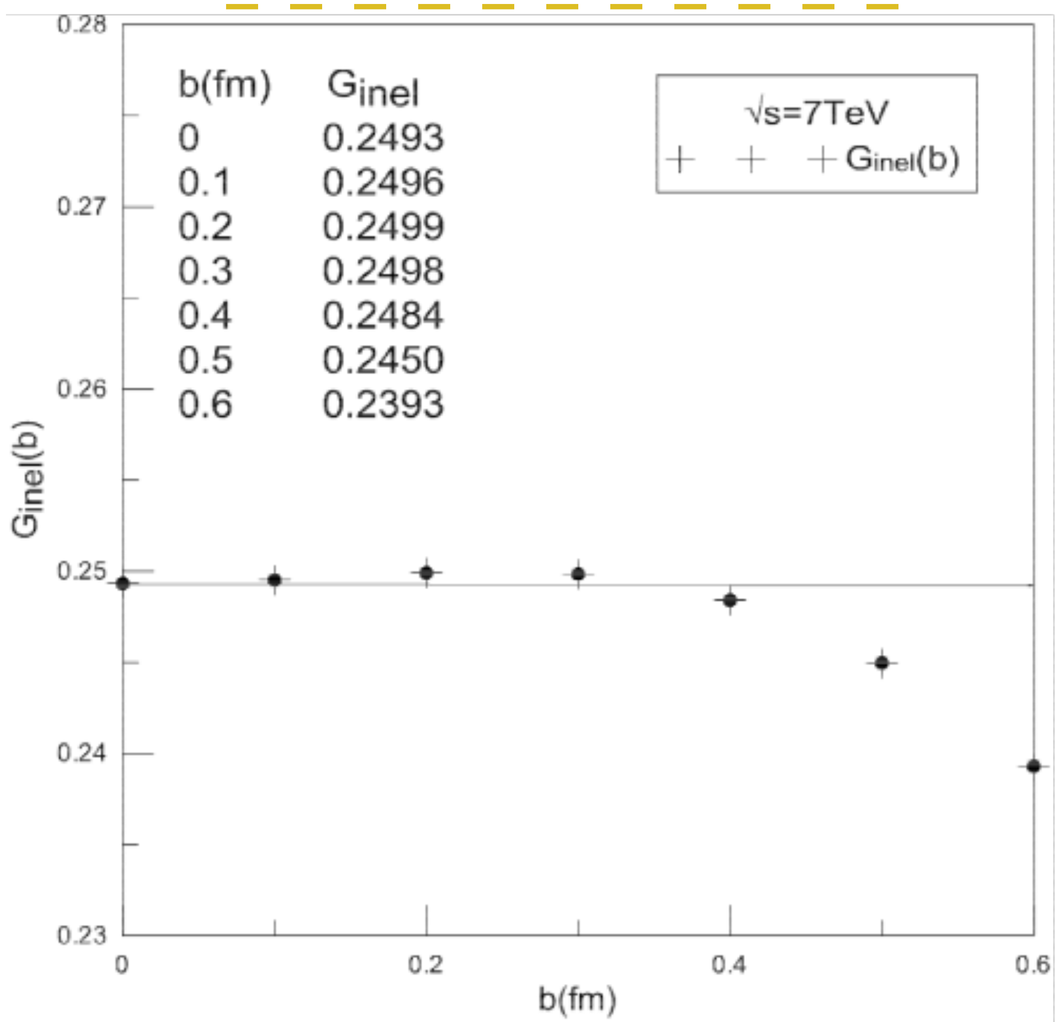
- Not observed @ISR and no dynamical explanation @market

Hollowness effect

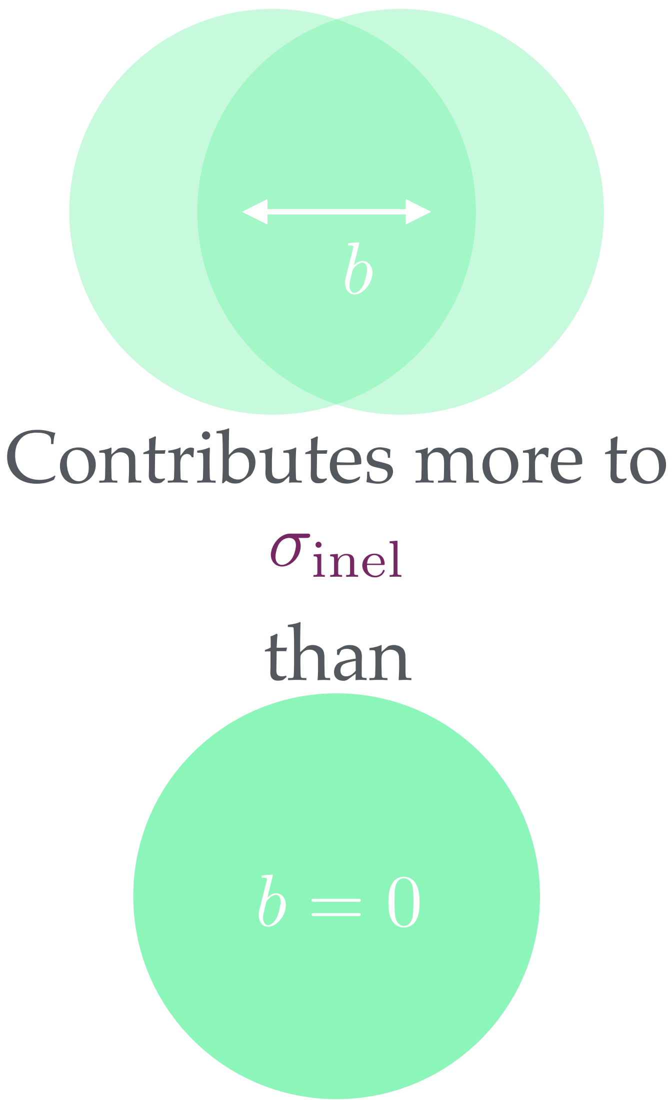
- The *hollowness/grayness* effect in *pp* interactions @LHC

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

$$G_{\rm in} = {\rm d}^2\sigma_{\rm inel}/{\rm d}^2 b$$



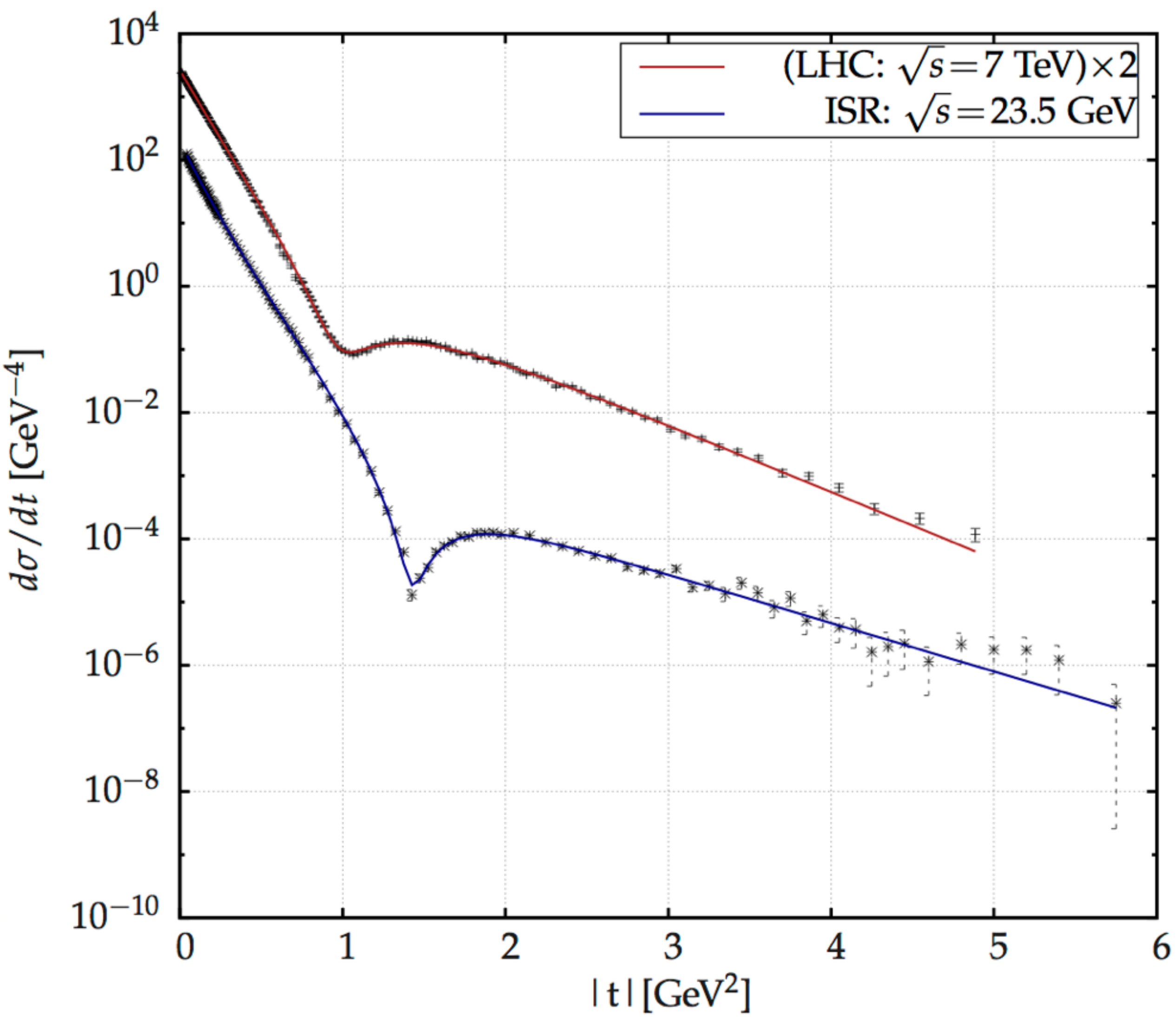
[A.Alkin et Al. '14]

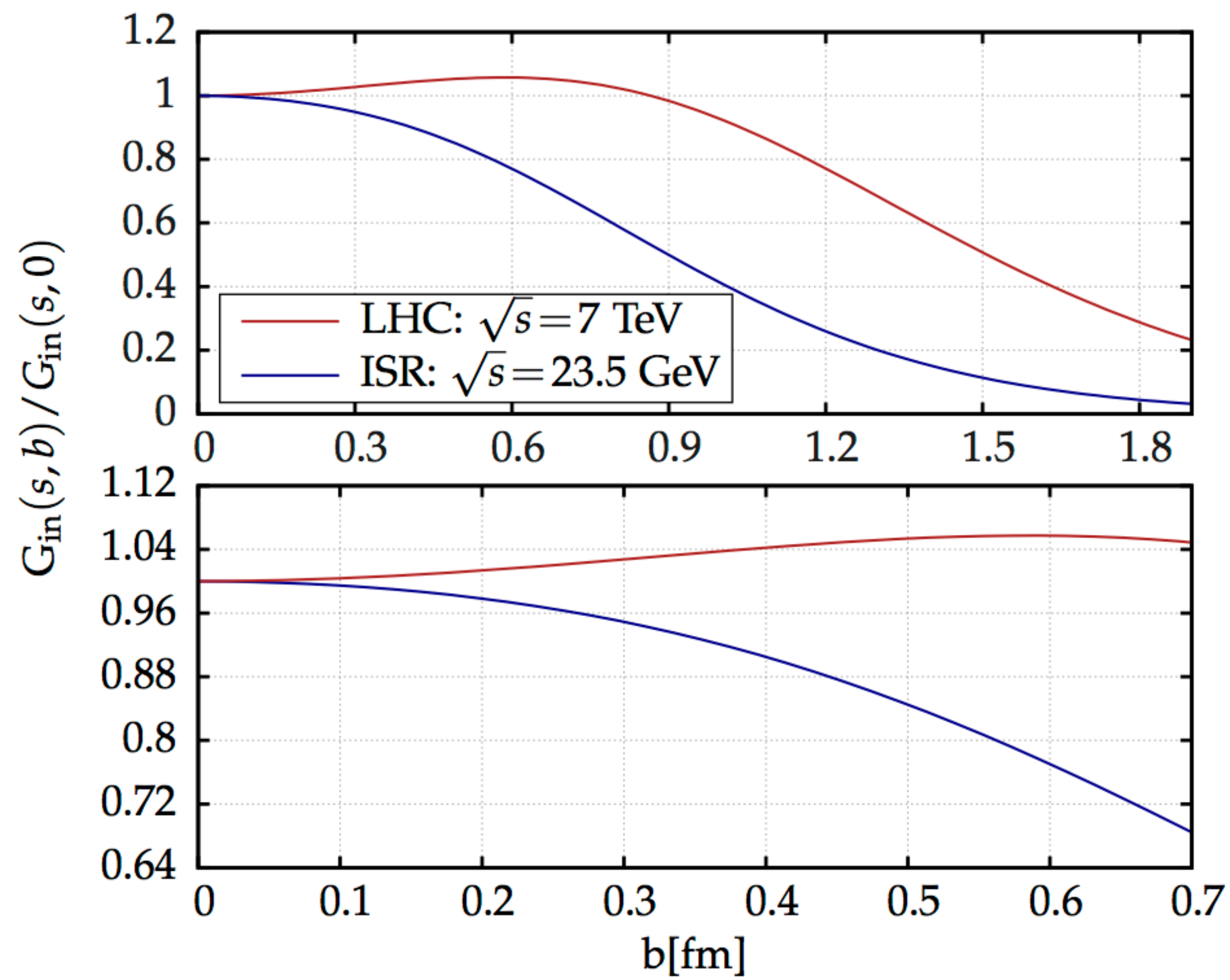


- Not observed @ISR and no dynamical explanation @market

Hollowness effect

- We have performed an independent analysis





- ¡¡The inelasticity density of the collision does not reach a maximum at b=0!!

Problem to solve

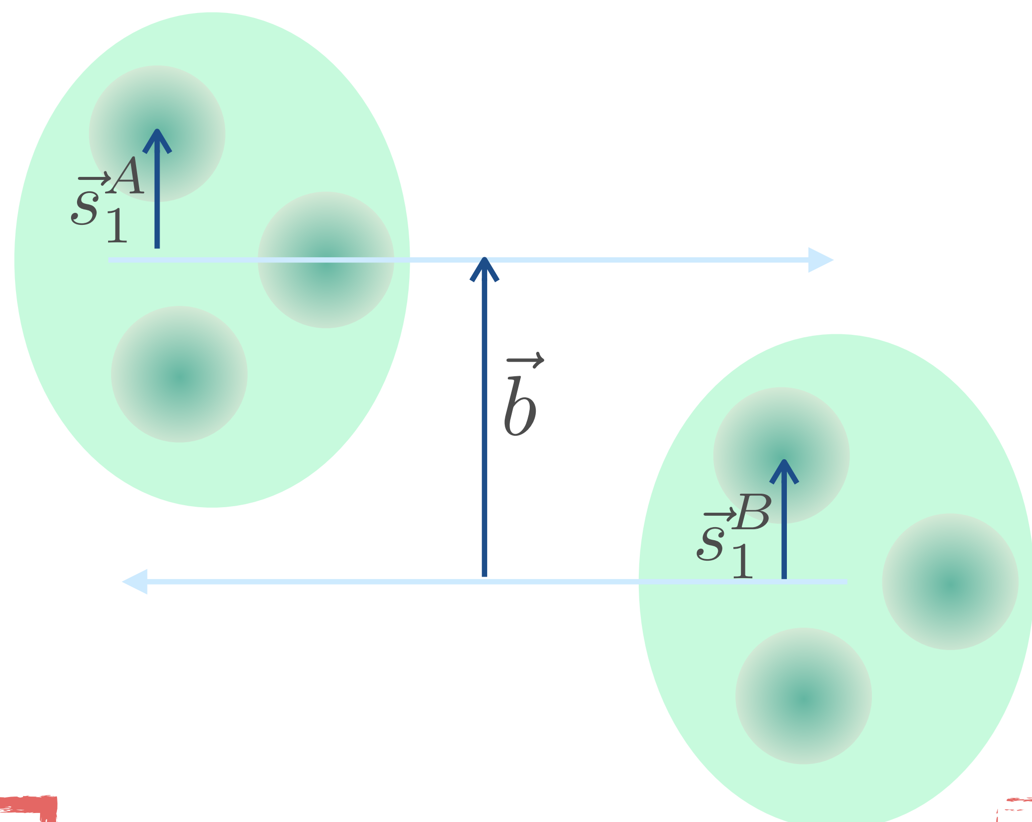
- The inelasticity density exhibits a maximum at b>0: *hollowness* effect
  - Peripheral collisions are more *destructive*.
  - Pure convolution models are precluded.
  - It disappears at ISR energies.
- Constrain the transverse structure of the proton
  - Implications in harmonic flow coefficients.

2. Ingredients

The model

- To construct the elastic scattering amplitude in *pp* collisions

Gluonic hot-spots as effective d.o.f



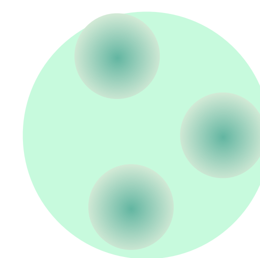
Glauber multiple scattering expansion

Spatial correlations in transverse space

Hot spots

- Assumption: the gluon content of the proton concentrated in small domains

$$\boxed{R_{hs} \ll R_p}$$



- Open debate: they may be radiatively generated from valence quarks in DGLAP or BFKL-like cascades (growth with energy)

Hot spot $\Longrightarrow$ Fock space of the valence partons

/instantons/combination of perturbative and non perturbative physics

[Kopeliovich et Al. '99, Braun et Al. '93, Schafer et Al. '98, Kovner '02, Shuryak'04, Schenke et Al.'15…]

✓Smallness of the correlation length of the gluon field in lattice QCD.

[DiGiacomo et Al. '92]

✓Phenomenological tool [Kopeliovich et Al. '07]

Glauber model

- *pp* interactions as a collision of two systems A and B, each one composed of 3 hot spots

$$\widetilde{T}_{\rm el}(\vec{b}) = \int \prod_{k,l} \mathrm{d}^2 s_k^A \mathrm{d}^2 s_l^B D_A(\{\vec{s}_k^A\}) D_B(\{\vec{s}_l^B\}) \left(1 - \prod_i \prod_j \left[1 - \Theta_{ij}(\vec{b} + \vec{s}_i^A - \vec{s}_j^B)\right]\right)$$

- $\vec{b}$: impact parameter of the collision.

- $\vec{s}_i$: transverse positions the hot spots.

- $D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$: density distribution of hot spots.

- $\Theta_{ij}(\vec{b} + \vec{s}_i^A - \vec{s}_j^B)$: elastic amplitude of the *i*-th and *j*-th hot spot interaction.

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

Spatial correlations

- The general structure that we consider for $D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$

$$D(\{\vec{s}_i\}) = C \left(\prod_{i=1}^{3} d(\vec{s}_i; R) \right) \times f(\vec{s}_1, \vec{s}_2, \vec{s}_3)$$

-C: normalization constant.

-$d(\vec{s}_i; R)$: uncorrelated probability distribution for a single hot spot.

$$d(\vec{s}_i; R) = \exp\left(-s_i^2/R^2\right)$$

-$f(\vec{s}_1, \vec{s}_2, \vec{s}_3)$: correlation structure.

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

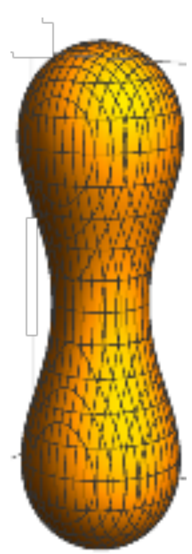
Spatial correlations

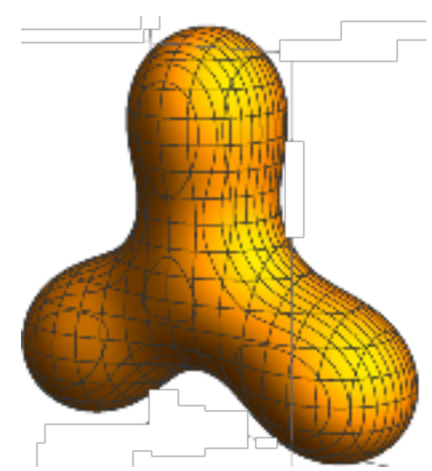
$$f(\vec{s}_1,\vec{s}_2,\vec{s}_3)= \delta^{(2)}(\vec{s}_1+\vec{s}_2+\vec{s}_3)\prod_{\substack{i<j\\ i,j=1}}^{3}\left(1-e^{-\mu|\vec{s}_i-\vec{s}_j|^2/R^2}\right)$$

- $\delta^{(2)}(\vec{s}_1+\vec{s}_2+\vec{s}_3)$: fixes the center of mass of the hot spots system.
- $\prod_{\substack{i<j\\ i,j=1}}^{3}\left(1-e^{-\mu|\vec{s}_i-\vec{s}_j|^2/R^2}\right)$: repulsive short-range correlations controlled by

$$r_c^2 \propto R^2/\mu$$

- Similar correlation structure than 3D models (when projected)

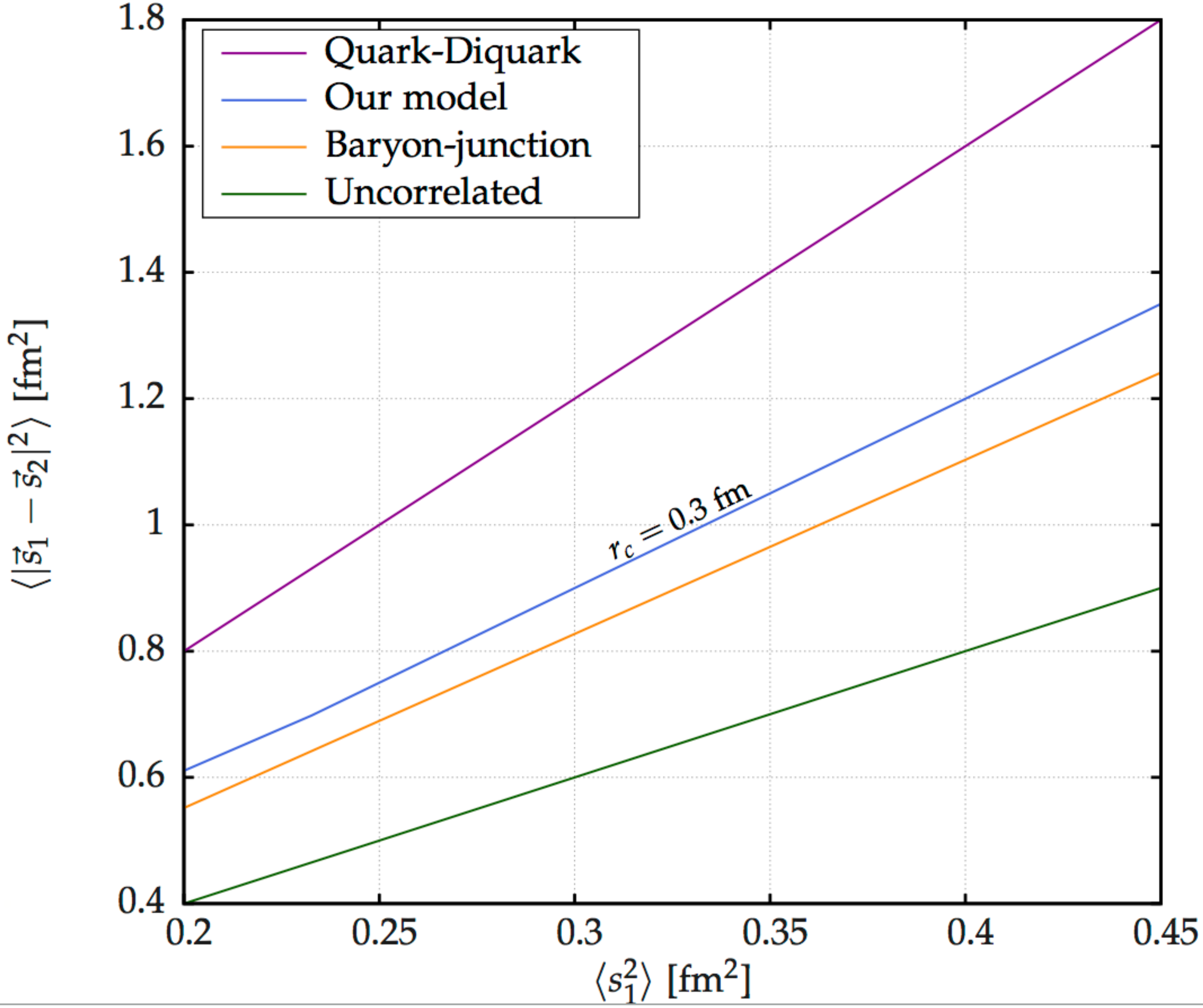
Quark-Diquark: 

Baryon junction: 

[Kubiczek et Al. '15]

Spatial correlations

- Averaged hot spot-hot spot transverse distance for different $D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$



Conventions

- $\dfrac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t} = \dfrac{1}{4\pi}|T_{\mathrm{el}}(s,t)|^2$
- $T_{\mathrm{el}}(s,t) = \int \mathrm{d}^2 b\ \widetilde{T}_{\mathrm{el}}(s,\vec{b})e^{-\mathrm{i}\vec{q}\cdot\vec{b}}$
- $\sigma_{\mathrm{el}} = \int \mathrm{d}^2 b\ |\widetilde{T}_{\mathrm{el}}(s,\vec{b})|^2$
- $\sigma_{\mathrm{tot}} = 2\mathrm{Im}T_{\mathrm{el}}(s,0) = 2\int \mathrm{d}^2 b\ \mathrm{Im}\widetilde{T}_{\mathrm{el}}(s,\vec{b})$
- $\sigma_{\mathrm{in}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} = \int \mathrm{d}^2 b\ 2\mathrm{Im}\widetilde{T}_{\mathrm{el}}(s,\vec{b}) - |\widetilde{T}_{\mathrm{el}}(s,\vec{b})|^2$
- $\rho = \dfrac{\mathrm{Re}T_{\mathrm{el}}(s,0)}{\mathrm{Im}T_{\mathrm{el}}(s,0)}$
- $\boxed{G_{\mathrm{in}}(s,\vec{b}) = 2\mathrm{Im}\widetilde{T}_{\mathrm{el}}(s,\vec{b}) - |\widetilde{T}_{\mathrm{el}}(s,\vec{b})|^2}$

3. Results

R_p vs R_{hs} Conditions

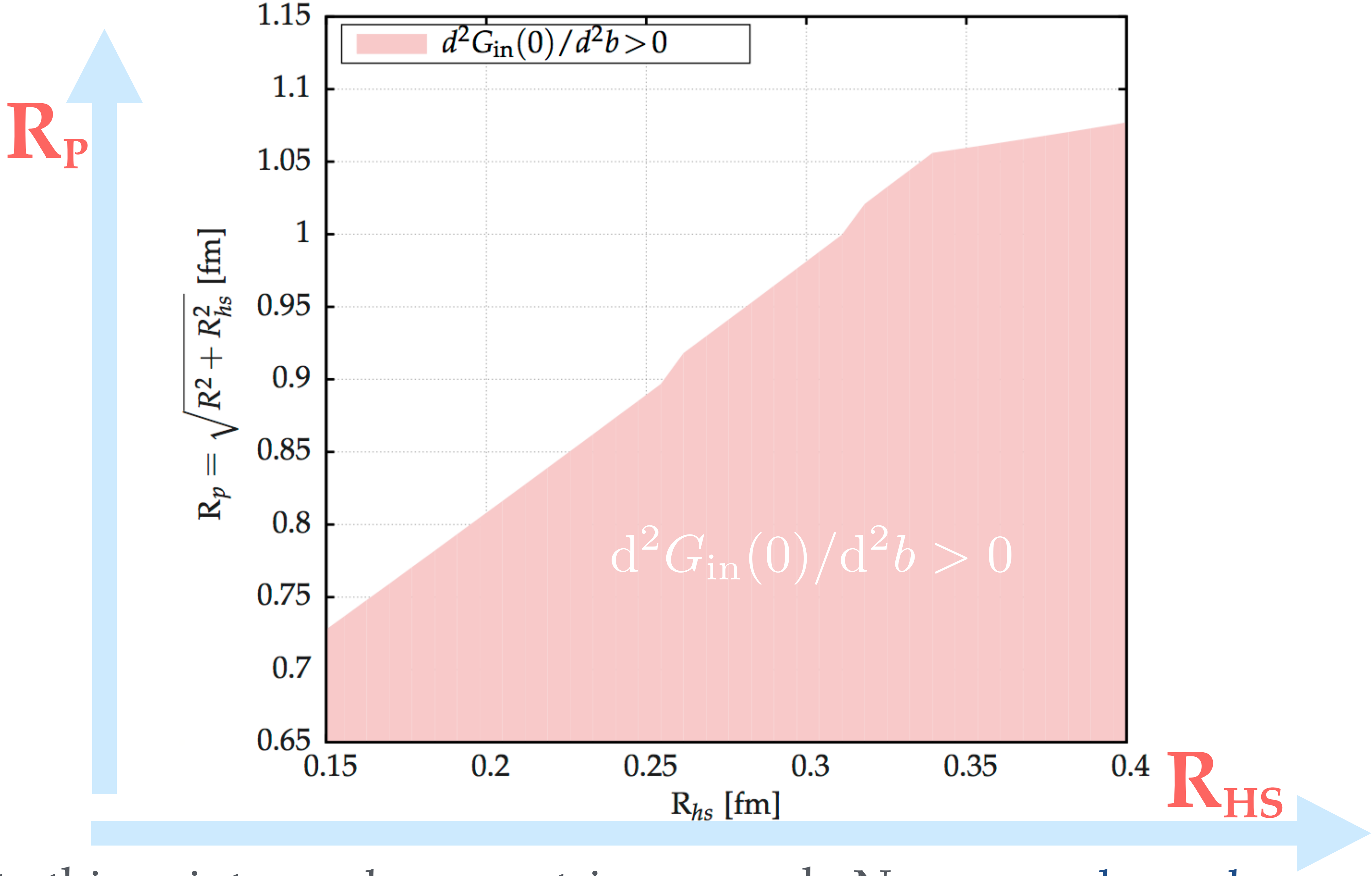
- We scan the parameter space with the conditions

  - Maximum of the elastic amplitude: $$\frac{d^2\widetilde{T}(s,0)}{d^2b} < 0$$

  - Maximum of the inelastic density: $$\frac{d^2G_{\text{in}}(s,0)}{d^2b} > 0$$

R_p vs R_{hs}

- For $r_c = 0.5$ fm and $\rho_{hs} = 0.1$,



- Up to this point, purely geometric approach. No energy dependence.

R_p vs R_{hs} Conditions

- To be compatible with the phenomenology

  - Maximum of the elastic amplitude: $$\frac{d^2\widetilde{T}(s,0)}{d^2b} < 0$$

  - Maximum of the inelastic density: $$\left.\frac{d^2G_{\text{in}}(s,0)}{d^2b} > 0\right|_{\text{LHC}}$$ $$\left.\frac{d^2G_{\text{in}}(s,0)}{d^2b} < 0\right|_{\text{ISR}}$$

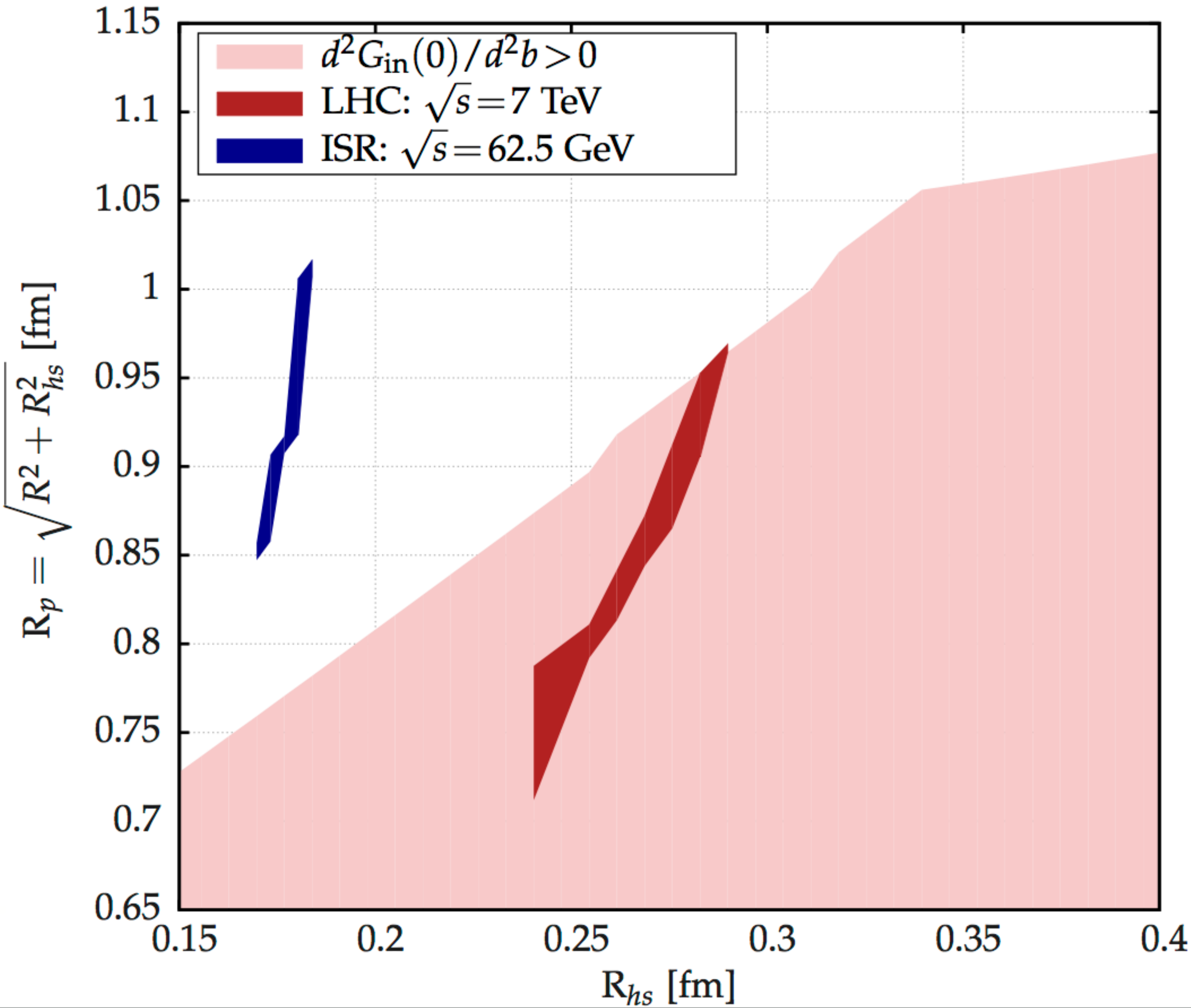
  - Phenomenological constraints:

    - LHC, 7 TeV: $\sigma_{\text{tot}} = 9,83 \pm 0.28\ [\text{fm}^2]\quad \rho = 0.14^{+0.01}_{-0.08}$

    - ISR, 62.5 GeV: $\sigma_{\text{tot}} = 4,332 \pm 0.023\ [\text{fm}^2]\quad \rho = 0.095 \pm 0.018$

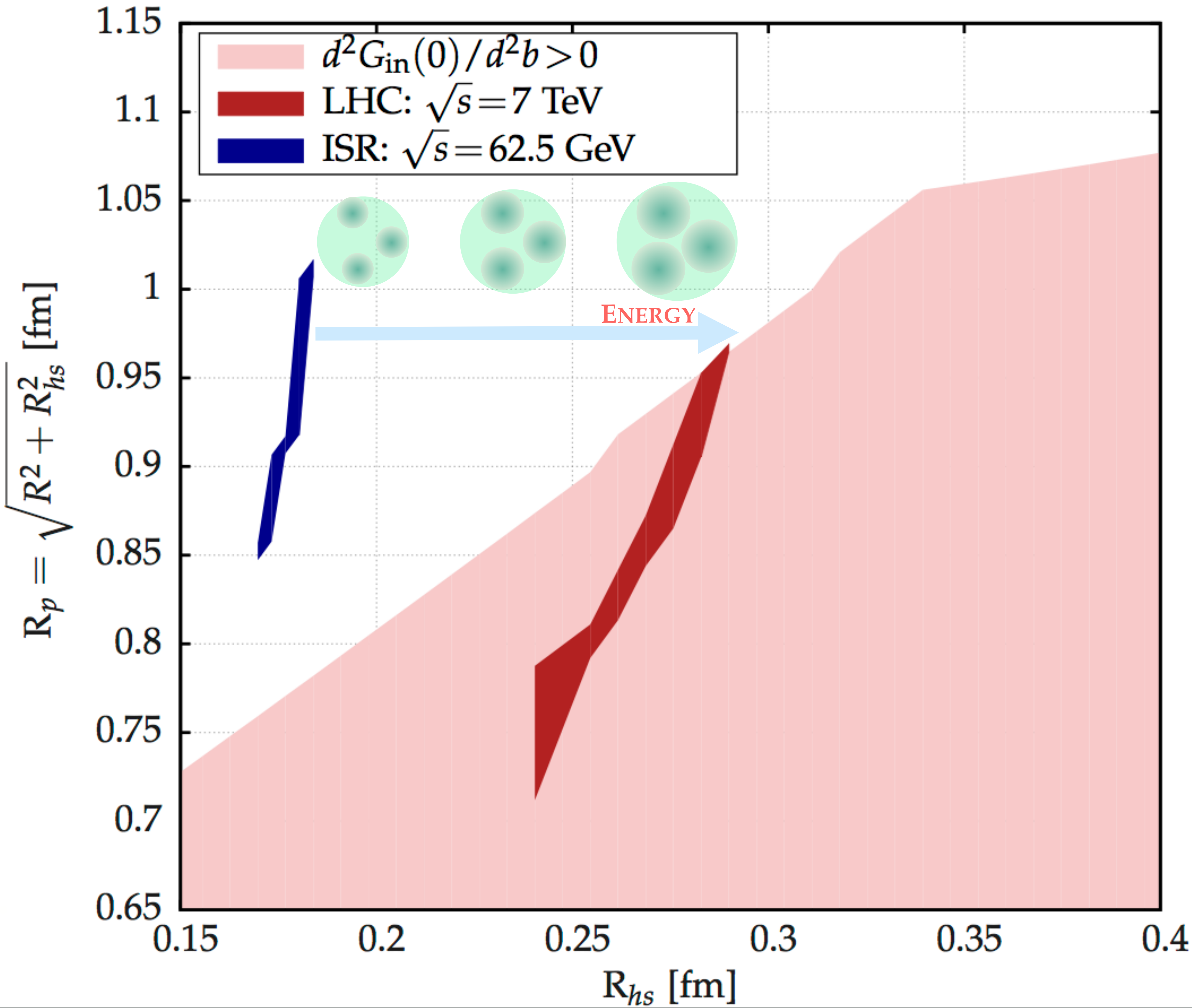
R_p vs R_{hs}

r_c=0.5 fm



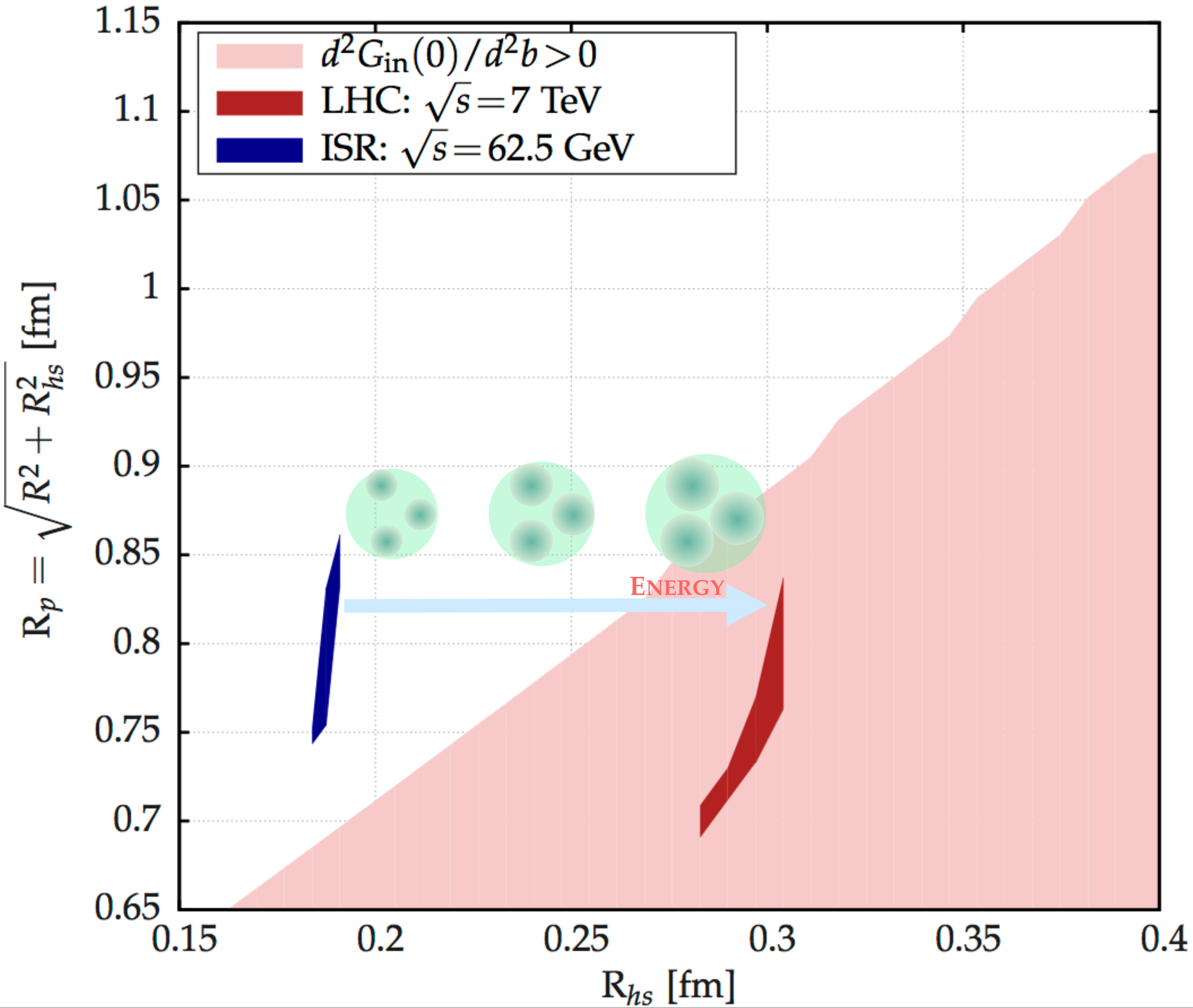
R_p vs R_{hs}

r_c=0.5 fm

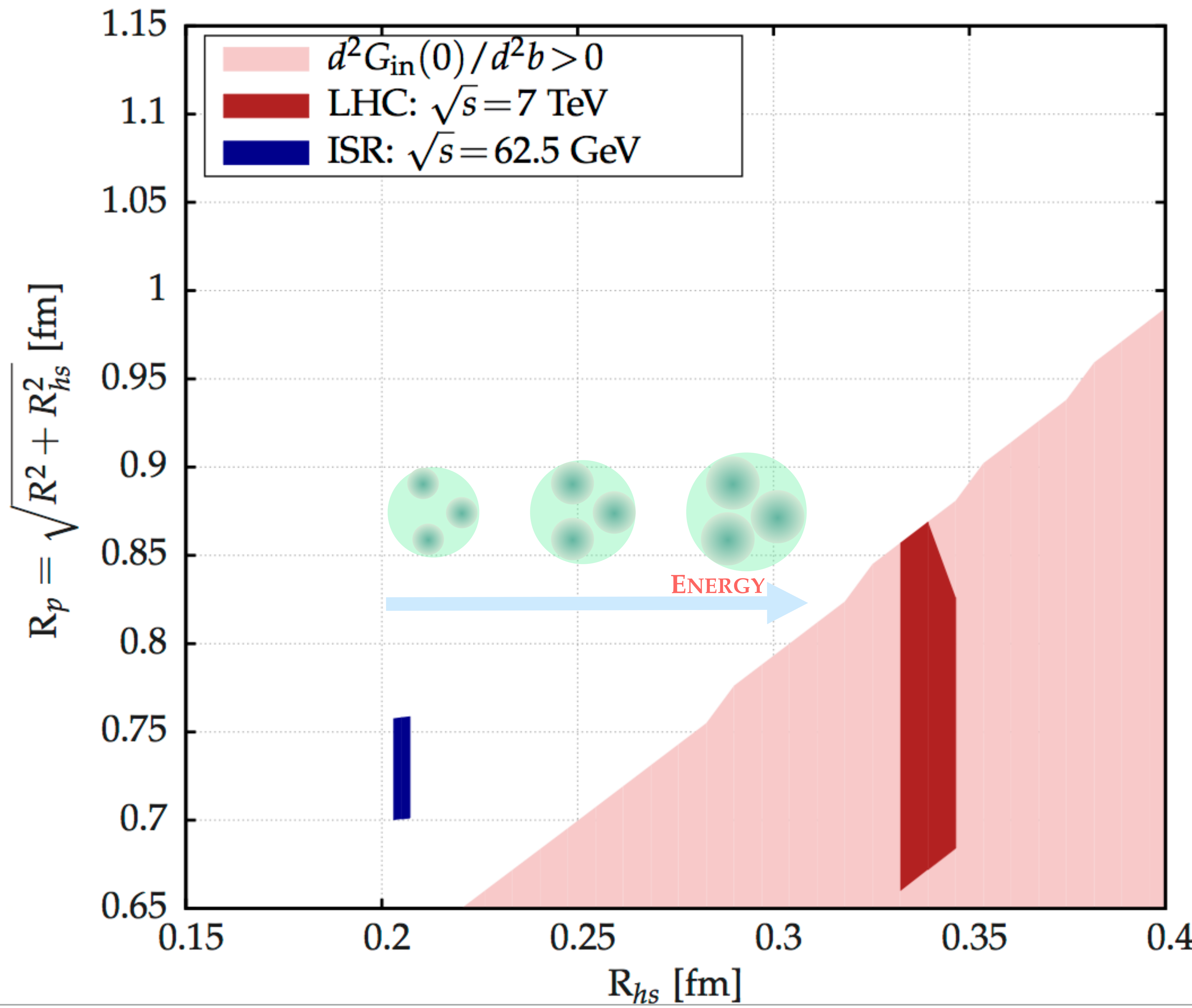


R_p vs R_{hs}

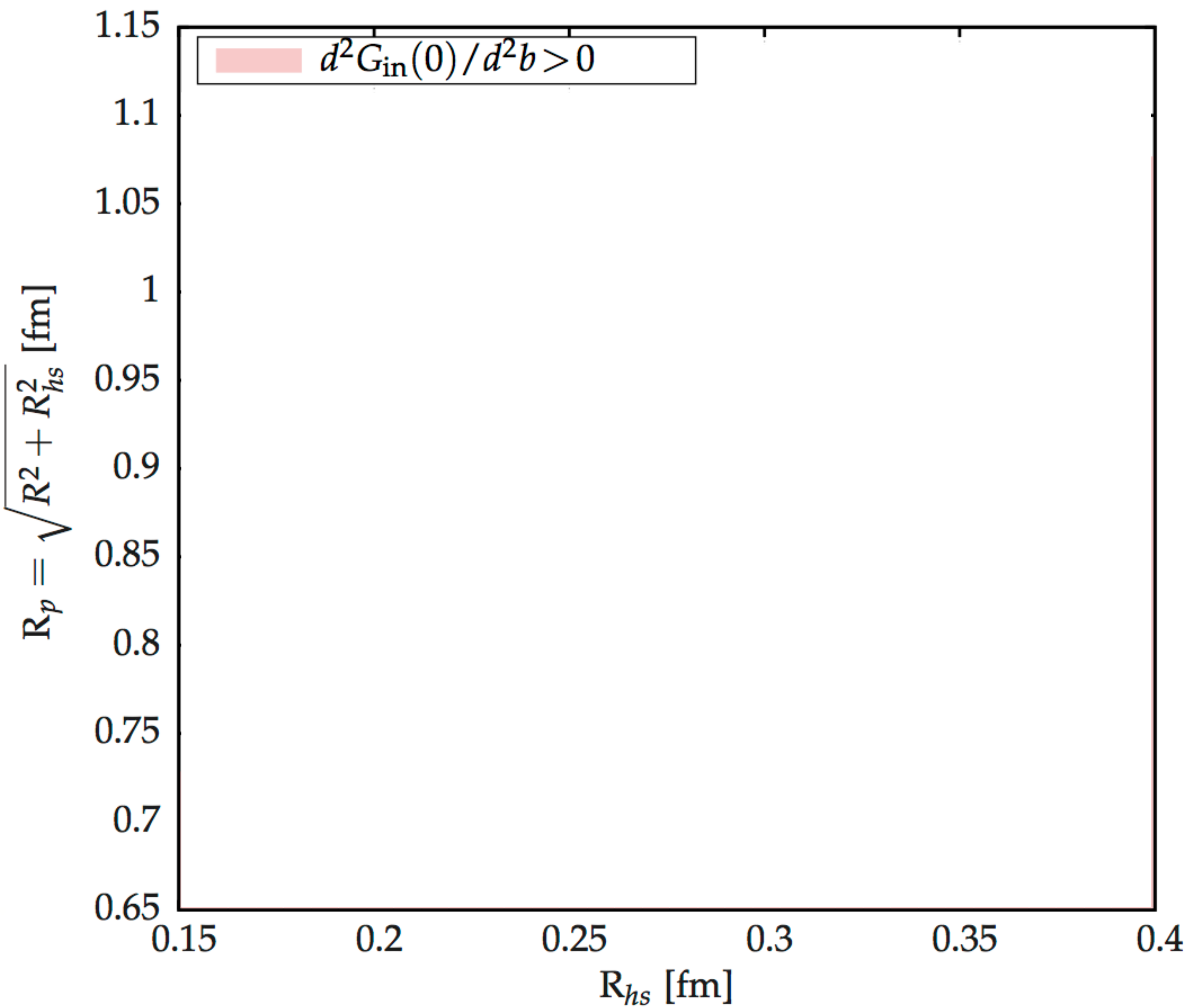
r_c=0.4 fm



R_p vs R_{hs} **r_c=0.3 fm**

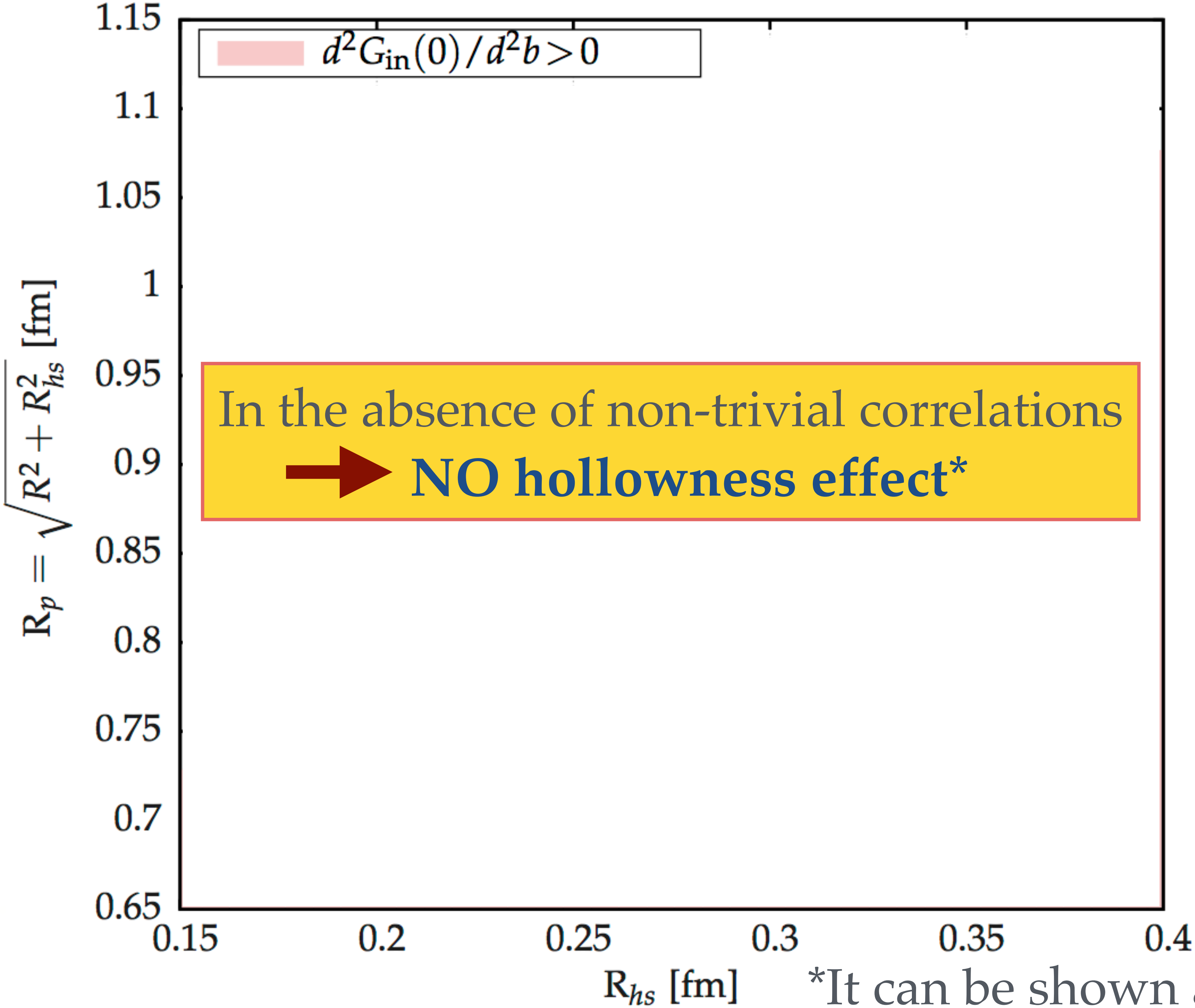


R_p vs R_{hs} r_c=0 fm



R_p vs R_{hs}

r_c=0 fm



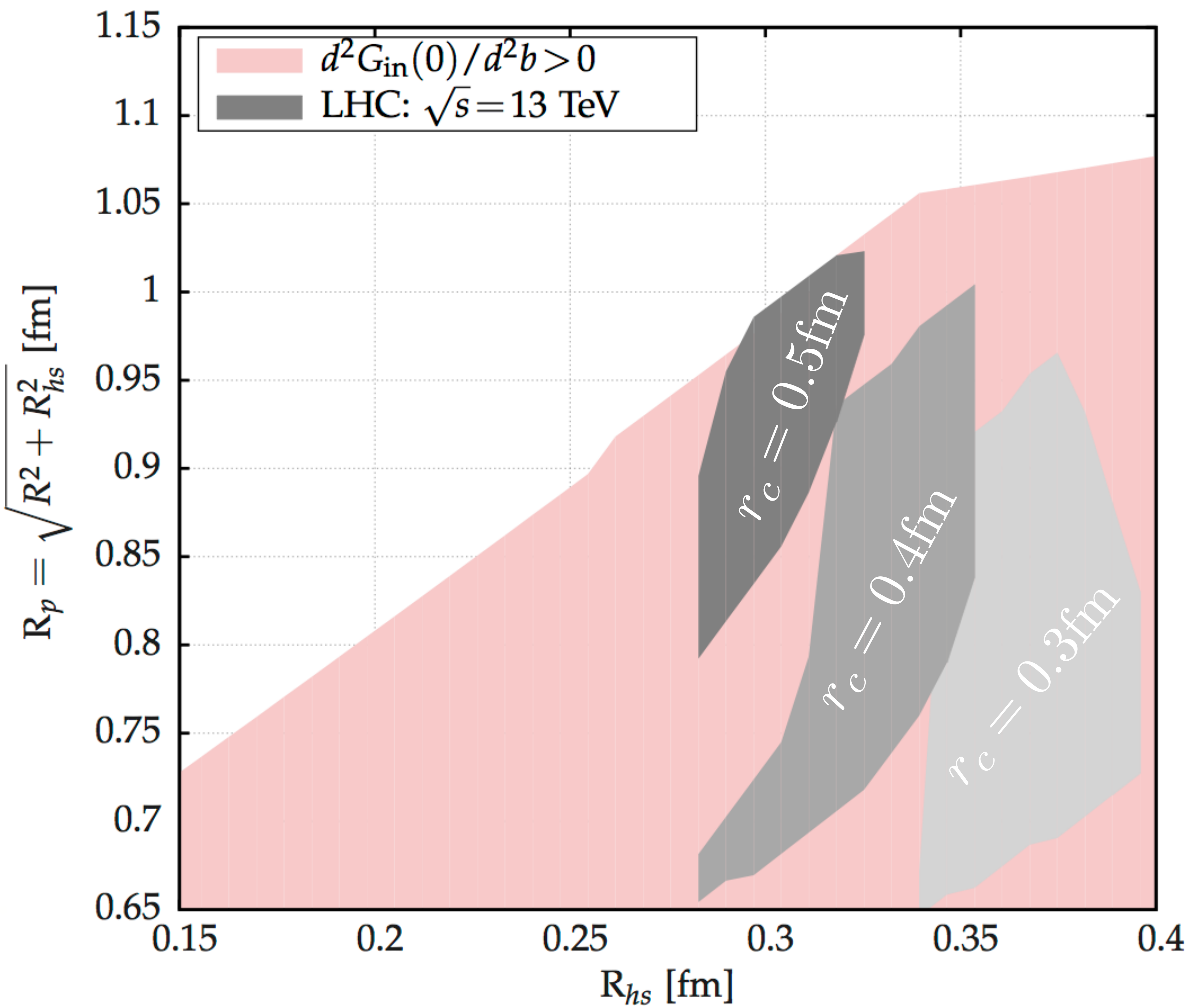
In the absence of non-trivial correlations

→ **NO hollowness effect***

*It can be shown analytically

R_p vs R_{hs} | What about LHC @ 13 TeV?

- LHC, 13 TeV: $\sigma_{\rm tot} = 11,15\pm1[\text{fm}^2]$ $\rho = 0.14^{+0.01}_{-0.08}$
  [COMPETE Collab. '02]



4. Conclusions

Take home message

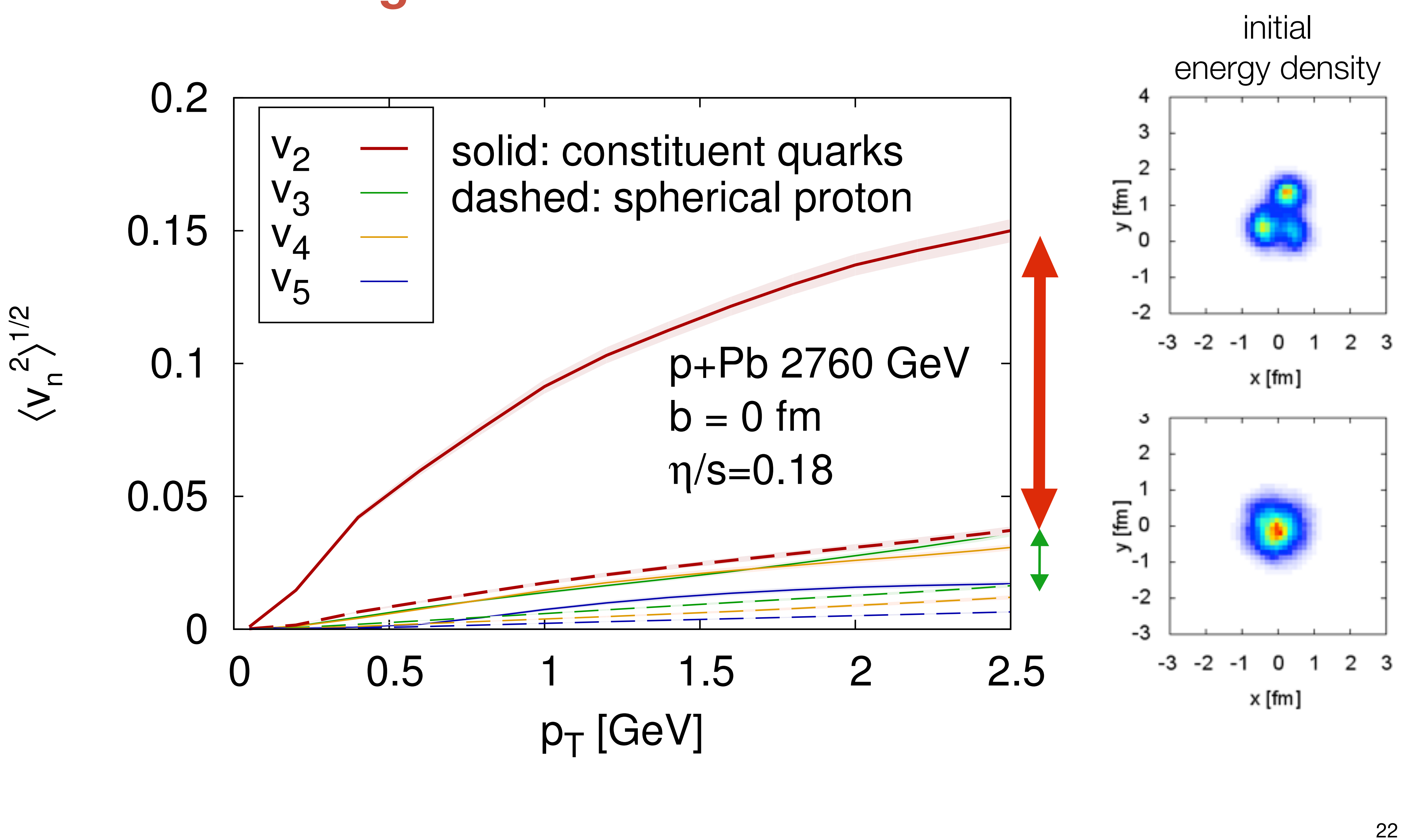
- New and intriguing feature of hadronic interactions: *hollowness* effect.
- We propose a dynamical explanation based on:
  - Hot spots as the effective degrees of freedom.
  - Non-trivial correlations between the transverse positions of the hot spots.
  - Scattering amplitude from a Glauber-like multiple scattering series.
- Diffusion/growth of the hot spots in the transverse plane with increasing collision energy is the key mechanism to explain the *hollowness* effect.
- Future work: impact of this new effect in other observables in *pp* and heavy ion collisions: flow harmonics, multiplicities…

Take home message

[Schenke'15]

Round vs. structured proton: IP-Glasma + MUSIC

It makes a huge difference!



Back up

pp elastic scattering

- Our approach starts from a generic parametrization

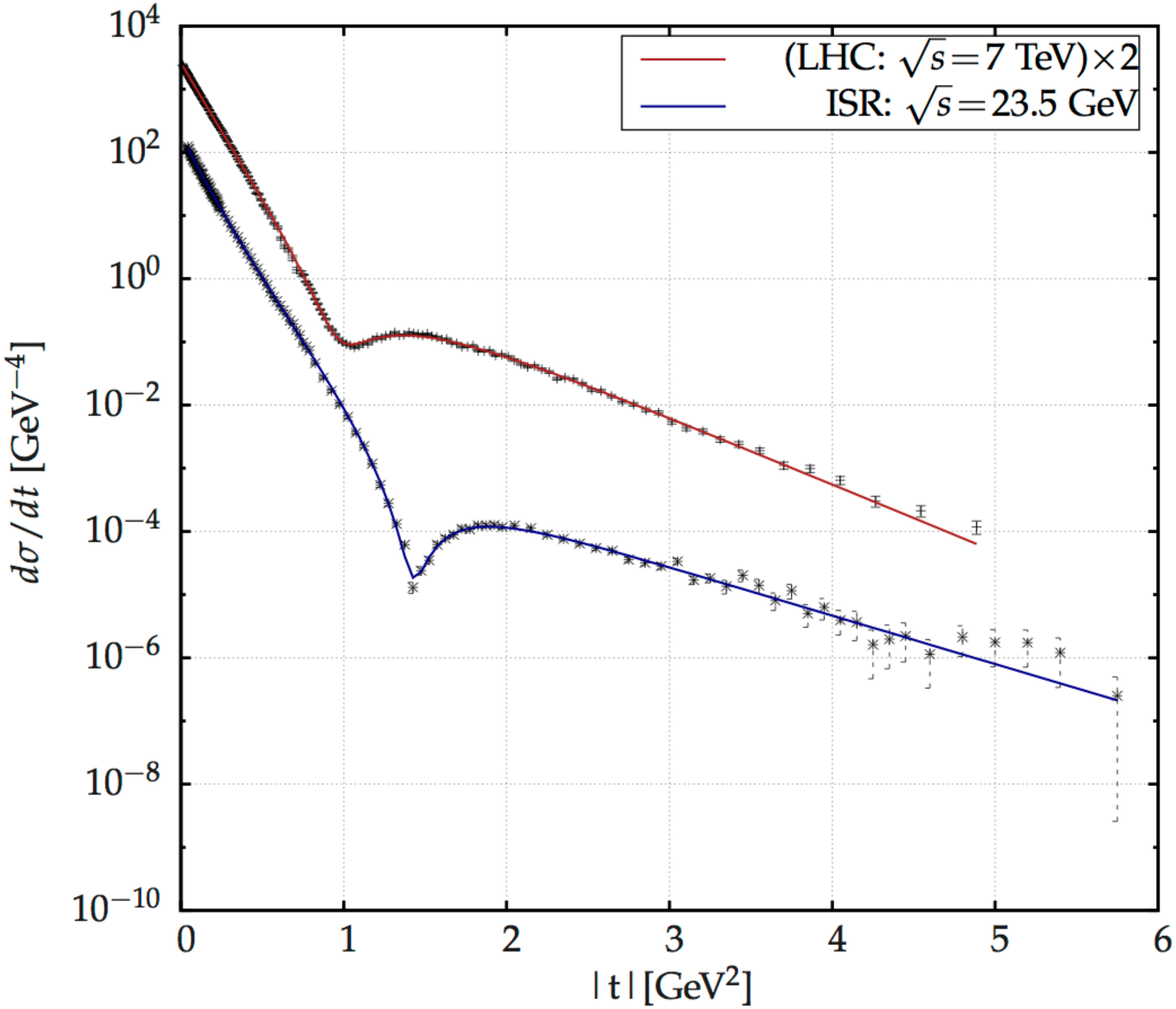
$$\mathrm{Im}T_{el}(s,t) = a_1 e^{b_1 t} + a_2 e^{b_2 t} + a_3 e^{b_3 t}$$
$$\mathrm{Re}T_{el}(s,t) = c_1 e^{d_1 t}$$

- Fit parameters are subject to two phenomenological constraints

$$\sigma_{\mathrm{tot}} = 2\sum_i a_i$$
$$\rho = \sum_i c_i / a_i$$

- Minimal number of parameters to reduce correlations

pp elastic scattering



$\chi^2/\mathrm{d.o.f} \sim 1.1-2$