GLUONIC HOT SPOTS AND SPATIAL CORRELATIONS INSIDE THE PROTON

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based on arXiv: 1605.09176, 1612.06274(v2) [hep-ph]

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In principle, p+p too dilute to produce a fluid-like state.

**HOWEVER**

Suggestive signals of collective behavior in high multiplicity events

Non-vanishing triangular flow, the ridge...

Motivation
**Quark-gluon-plasma in p+p?**

- **Intense theoretical interest on the initial geometry in p+p interactions**

Models @market assume **UNCORRELATED** subnucleonic components
Motivation

 Observable: elastic differential cross section in p+p collisions

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

p+p elastic scattering

[TOTEM Collab '11]
[Amaldi et Al. '80]
**Motivation**

**p+p elastic scattering**

[Alkin et Al.'14, Arriola&Broniowski’16, Dremin’16, Troshin et Al.’16...]

- Unexpected properties can be extracted from the data

\[
G_{in}(s, \bar{b}) = 2 \text{Im} \tilde{T}_{el}(s, \bar{b}) - |\tilde{T}_{el}(s, \bar{b})|^2
\]

\[
G_{in} = d^2\sigma_{inel}/d^2b
\]

\[G_{in}(s,b)/G_{in}(s,0)\]

- ISR: \(\sqrt{s} = 62.5\) GeV
- LHC: \(\sqrt{s} = 7\) TeV

\(b\) contributes more to \(\sigma_{inel}\) than \(b = 0\)
The hollowness effect

- Toroid like interaction region at high energies?
- Critical regime at the LHC?
- Disclaimer: Present data compatible with NO hollowness effect within error bars. [Dremin '16,'17]
- Flattening of $G_{in}(2D)$ indicates a hollow in 3D [Arriola&Broniowski '16,'17]

- It precludes UNCORRELATED proton structures.
The hollowness effect

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QCD CHALLENGE

Integrate

It precludes UNCORRELATED proton structures.
Ingredients
A novel initial state geometry for $p+p$ interactions based on:

Gluonic hot-spots as effective d.o.f

Spatial correlations in transverse space

Glauber multiple scattering expansion

[Similar to A. Bialas et Al. '70s]
A novel initial state geometry for p+p interactions based on:

Gluonic hot-spots as effective d.o.f

Spatial correlations in transverse space

Glauber multiple scattering expansion

Fock space of valence partons

[Similar to A. Bialas et Al. '70s]
The model

➡ A novel initial state geometry for p+p interactions based on:

- Glauber multiple scattering expansion
- Spatial correlations in transverse space
- Gluonic hot-spots as effective d.o.f

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

[Similar to A. Bialas et Al. '70s]
The model

A novel initial state geometry for p+p interactions based on:

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Spatial correlations in transverse space

Glauber multiple scattering expansion

Gluonic hot-spots as effective d.o.f

$D(\vec{s}_1, \vec{s}_2, \vec{s}_3) \propto \prod_{i=1}^{3} e^{-s_i^2 / R^2}$

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

Ingredients
Results
Hollowness effect

\[ R_p = (R^2 + R_{hs}^2)^{1/2} \text{[fm]} \]

- It works for \( N_{hs} \geq 3 \)
- In the absence of non-trivial correlations, no hollowness effect.
- Transverse diffusion of \( R_{hs} \) as the main dynamical mechanism for:
  - Onset hollowness effect
  - Growth of \( \sigma_{tot} \) with \( \sqrt{s} \)
Influence of spatial correlations between proton constituents on the initial conditions of P+P collisions???
MC Implementation
Monte-Carlo implementation (ROOT/C++) needed for event-by-event fluctuations.

For each pp event we follow several steps:

★ Impact parameter of the collision $dN_{ev}/db \propto b$

★ Transverse positions of the hot spots inside the proton $D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$

★ Probability of two hot spots to collide

$$G_{in}(d) = 2e^{-d^2/R_{hs}^2} - (1 + \rho_{hs}^2)e^{-d^2/R_{hs}^2}$$

Wounded hot spot == suffered at least one collision

★ Rotate to the participant plane [to appear in 1612.06274(v2)]
Before

After

MC Glauber

[Albacete, Petersen & ASO’17]
Quantitative measurement of the initial anisotropy of the geometry

\[ \epsilon_n = \sqrt{ \frac{\left\langle \sum_{i=1}^{N_w} r_i^n \cos(n\phi_i) \right\rangle^2 + \left\langle \sum_{i=1}^{N_w} r_i^n \sin(n\phi_i) \right\rangle^2}{\left\langle \sum_{i=1}^{N_w} r_i^n \right\rangle} } \]

\[ s(x, y) = \frac{1}{\pi R_{hs}^2} \sum_{i}^{N_P} s_0^i e^{-\left((x-x_i)^2+(y-y_i)^2\right)/R_{hs}^2} \]

where \( s_0 \) fluctuates independently for each participant assuming \( \mathcal{P}(s_0) \propto \mathcal{P}(N_{ch}) \)

\[ \star(r_i, \Phi_i) : \text{wounded hot spots positions after rotation } \Psi_{pp}. \]

\[ \star<...>: \text{average over events weighted by } \int dx \int dy s(x, y) \]
Spatial eccentricities

Reduction of initial eccentricities after inclusion of correlations between subnucleonic d.o.f.

[$\text{Albacete, Petersen & ASO'17}$]
Take home message

➡ New and intriguing feature of hadronic interactions: hollowness effect.

➡ Correlations between hot spots & transverse growth of $R_{hs}$ essential.

➡ Monte-Carlo implementation to obtain event-by-event eccentricities.

★ Eccentricities reduced after inclusion of correlations.

Outlook

➡ Improvements of the model:

★ Fluctuating number of hot spots.
★ Extension to p+A and AA collisions.
★ Coherent description of particle production (à la CGC).

➡ Our to do list:

★ Symmetric cumulants.
★ Hydrodynamic evolution.
★ Implications in Multi Parton Interactions $\sigma_{eff}$
★ Hard-soft correlations.

See talks by Maciula, Staszevski