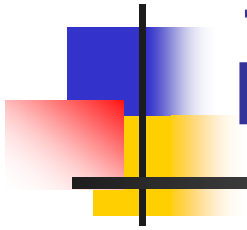
Classical vs Quantum Description of Gravitational Effects in Hadronic Collisions

(or Gravity and Partons)

1st Bogoliubov Readings

Dubna, BLTP JINR, Sept. 22 2010



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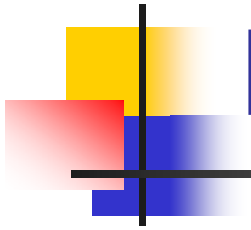
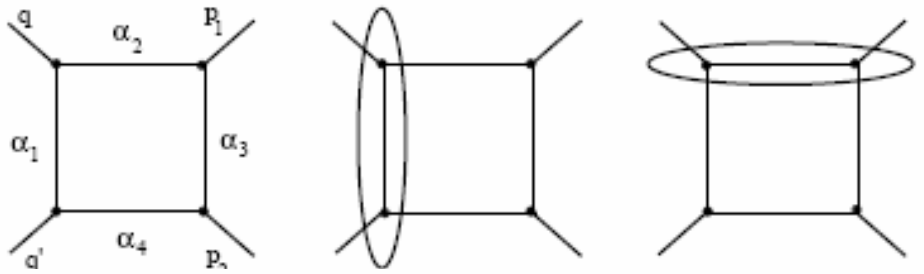


Main Topics

- QCD factorization
- Quantum vs classical picture of BH production
- Classical BH production and partonic transverse momentum
- Suppression of partonic couplings to BH: Hawking radiation vs QCD jets
- Higher twists contributions and BH in heavy ions collisions
- Gravitational form factors and exclusive processes
- Conclusions

QCD factorization

- Hard subprocess (calculable) + soft parton distributions – HADRONIC matrix elements of quark and gluon operators (uncalculable but universal). Simple in alpha representation – (Bogoliubov-Shirkov textbook) - Efremov, Radyushkin…
- Asymptotics – integration over region where some parameters are small (subprocess)
- The rest - distributions
- Do not have physical meaning separately
- Hard scale required



$$\mathcal{A}(s,t,m^2) = -\frac{g^4}{16\pi^2}\int_0^\infty \frac{\prod_{i=1}^4 d\alpha_i}{D^2}\exp\left[-\frac{1}{D}\left(Q^2\alpha_1\alpha_2 + s\alpha_2\alpha_4 + t\alpha_1\alpha_3 + m^2D^2\right)\right],$$

$$D = \alpha_1 + \ldots + \alpha_4.$$

What about extra-dimensional gravity (talk of I. Arefeva), in particular, BH?

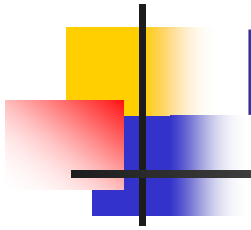
- Usually – collinear parton distributions + classical geometric cross-section (talk of M. Savina)

$$\frac{d\sigma}{dM} = \sum_{A_1 B_1} \int_0^1 dx_1 \frac{2\sqrt{\hat{s}}}{x_1 s} f_a(x_1, \hat{s}) f_B(x_2, \hat{s}) \sigma(M, k)$$

$$\sigma(M) \approx \pi R_H^2 \Theta(M - M_\star) \qquad R_H^{k+1} = \frac{2}{k+1} \left(\frac{1}{M_\star}\right)^{k+1} \frac{M}{M_\star}$$

- DY (Higgs) - like formula

- Very large cross-section and counting rates

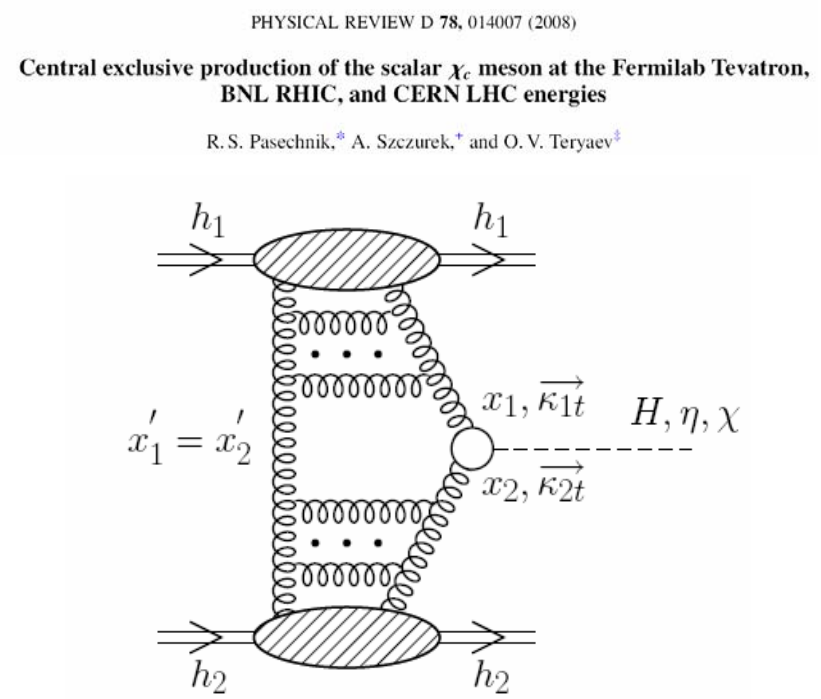


Problems

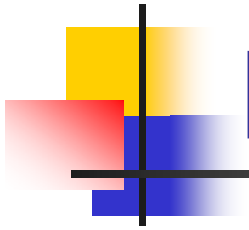
- Intrinsic contradiction (parts of the same QUANTUM amplitude)?
- Hard scale – BH mass – MUST enter the original amplitude to extract parton distributions?
- On-shell collinear partons – plane waves – no bounds in coordinate space?

Experience from "non-exotic" hadronic collisions

- Different types of distributions contribute (quark, GLUON, generalized, unintegrated…)
- Example - Generalized Unintegrated



Classical BH production - can partons be collinear?



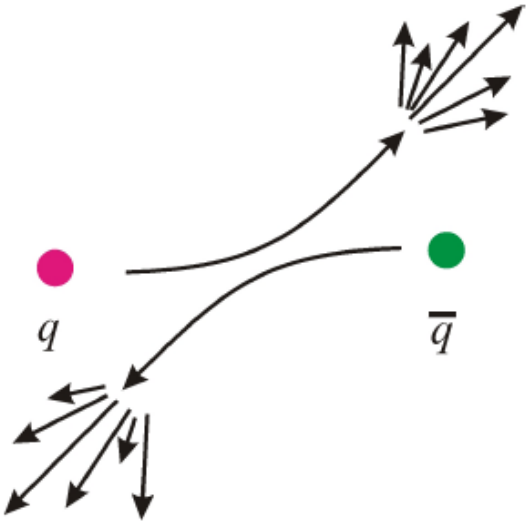
- Bounds in (transverse) coordinate space + uncertainty principle - > transverse momentum (TMD)
- Small-x – UGDF (pertubative gluon emission-BFKL)
- Natural ingredient for BH production
- 2 stages – heavy compact object -> BH
- 1 stage ~ color dipole?! Suppression – small size
- What is shock wave in partonic terms?

Quantum description

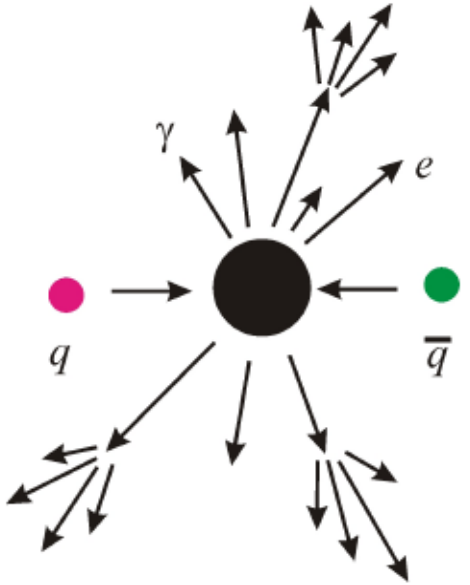
- Naturally required by DY type formula
- Def: BH -> Quantum state with definite mass + Hawking decay mode - $|M, T\rangle$
- Decay - still not developed for extra-dimensional BH
- One of the main experimental signals

Final state of the SM process vs typical BH decay spectra

SM



BH decay



Pictures by Sabine Hossenfelder

Multi-jet and hard leptons events, spherical, typical temperature about 200 GeV

BH production subprocess

- Another non-perturbative ingredient
- QCD factorization –starts with analysis of diagrams asymptotics
- At the end of the day - no diagrams at all
- Practically similar situation – when perturbative corrections to subprocess amplitudes are large

BH a la heavy meson

- Meson: Coupling to gluons related to decay width

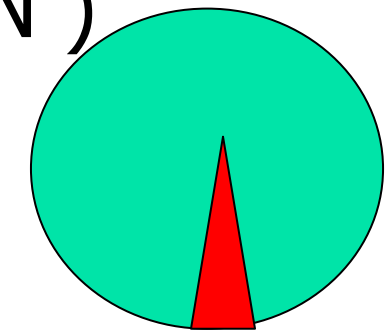
$$A^2 = K\frac{64\pi\Gamma(\chi_{c0} \to gg)}{(N_c^2-1)M^3}, \qquad \text{NLO} \quad \to \quad K = 1.5$$

- Up to normalization – also for BH

- What is BH decay width to 2 gluons ->
- 2 jets (q-h duality)?!

What is the overlap of thermalaized and 2jets events?

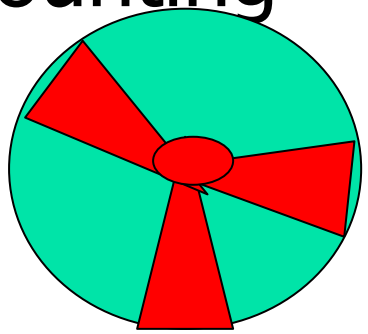
- Probabilistic reasoning : $|\langle 2j|T\rangle|^2 \sim \beta \sim \exp(-N)$



β - Exponential suppression of BH production (cf M.B. Voloshine – from semiclassical arguments)

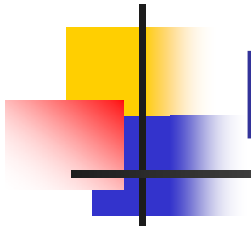
Other mechanisms

- Extra gluons – higher twists <p|GG..G|p> - power suppression – but not exponential – multijet decays
- Small x – no twist counting - Colour Glass Condensate



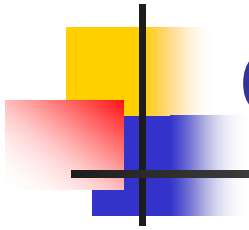
- Heavy Ions collisions

Relations to fundamental problems of BH?



- Suppression – related to information loss ?
- Unitarity + loss = suppression of coupling to non-thermal states
- Classical formula - irreversibility
- Coupling <-> decay width
  |<BH|2j>|=|<2j|BH>| - T(+P=C) invariance
- Virtual space-like (t-channel) gluons – crossing invariabce
- Relation of Gravity (Hawking radiation) and QCD (jet fragmentation)

Partons in exclusive graviton exchanges



- Graviton exchanges - eikonal scattering (talk of O. Selyugin)
- How (extra dimensional) gravity couples to quarks (current or constituent mass?)?
- Naively – to free quarks
- In reality – matrix element of Energy-momentum tensor (like that of current in photon exchange)

Gravitational Formfactors

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M\Big]u(p)$$

- Conservation laws (Kobzarev,Zakharov)- zero Anomalous Gravitomagnetic Moment : (g=2)

$$\mu_G = J$$

$$P_{q,g} = A_{q,g}(0) \qquad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \qquad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

$$M = \langle P'|J^{\mu}_{q}|P\rangle A_{\mu}(q) \qquad M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J^{\mu}_{q}|P\rangle = 2e_{q}P^{\mu} \qquad \sum_{q,G}\langle P|T^{\mu\nu}_{i}|P\rangle = 2P^{\mu}P^{\nu}$$

$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P|J^{\mu}_{q}|P\rangle A_{\mu} = 2e_{q}M\,\phi(q) \qquad M_0 = \frac{1}{2}\sum_{q,G}\langle P|T^{\mu\nu}_{i}|P\rangle h_{\mu\nu} = 2M\cdot M\phi(q)$$

- Mass as charge – equivalence principle

Equivalence principle

- Newtonian – "Falling elevator" – well known and checked
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun) – not checked on purpose but in fact checked in atomic spins experiments at % level (Silenko,OT'07)
- Anomalous gravitomagnetic moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way (Necessary for Mach's principle)
- No spin-flip by rotation
- Dirac equation with spin - talks of A. Silenko, V. Neznamov

Gravitomagnetism

- Gravitomagnetic field – action on spin – ½ from $M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

$\vec{H}_J = \frac{1}{2} rot\vec{g};\ \vec{g}_i \equiv g_{0i}$ spin dragging twice smaller than EM

- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00} = 2\phi(x)$ Larmor frequency same as EM $\vec{H}_L = rot\vec{g}$
- Orbital and Spin momenta dragging – the same - Equivalence principle $\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L$

Equivalence principle for moving particles

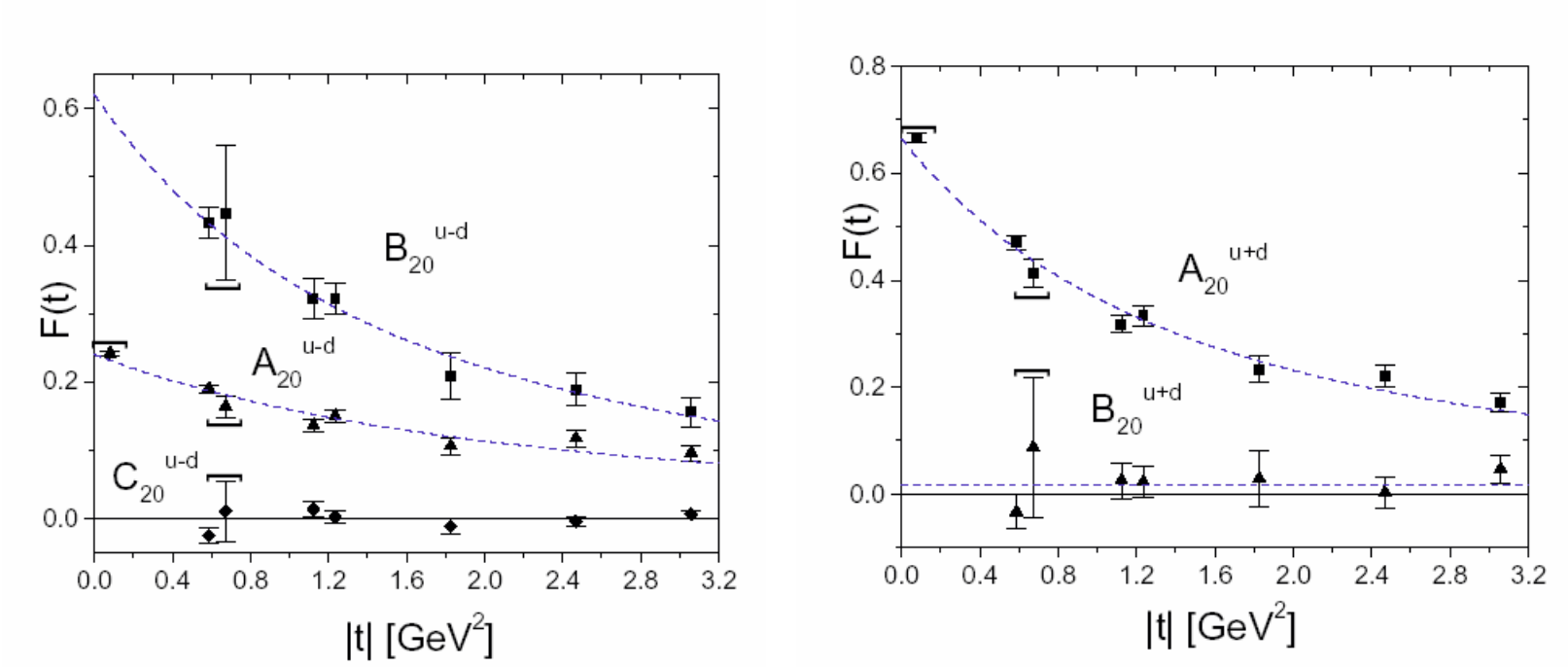
- Compare gravity and acceleration: gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER

$$\mathcal{M}_g = (\epsilon^2 + p^2)h_{00}(q), \qquad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$

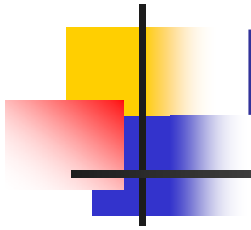
- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solutions of Dirac equation (Obukhov, Silenko, O.T.)

Generalization of Equivalence principle

- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)



Extended Equivalence Principle=Exact EquiPartition

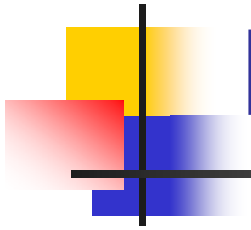


- In pQCD – violated
- Reason – in the case of EEP- no smooth transition for zero fermion mass limit (Milton, 73)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Supported by smallness of E (isoscalar AMM)

Vector mesons and EEP

- J=1/2 -> J=1. QCD SR calculation of Rho's AMM gives g close to 2.

- Maybe because of similarity of moments
- g-2=<E(x)>; B=<xE(x)>
- Directly for charged Rho (combinations like p+n for nucleons unnecessary!). Not reduced to non-extended EP: Gluons momentum fraction sizable. Direct calculation of AGM are in progress.



EEP and AdS/QCD

- Recent development – calculation of Rho formfactors in Holographic QCD (Grigoryan, Radyushkin)
- Provides g=2 identically! (Like for BH!- B. Carter)
- Experimental test at time –like region possible

Another (new!) manifestation of post-Newtonian (E)EP for spin 1 hadrons

- Tensor polarization - coupling of EMT to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$\langle P,S|\bar{\psi}(0)\gamma^{\nu}D^{\nu_1}...D^{\nu_n}\psi(0)|P,S\rangle_{\mu^2} = i^{-n}M^2S^{\nu\nu_1}P^{\nu_2}...P\nu_n\int_0^1 C_q^T(x)x^n dx$$

$$\sum_q \langle P,S|T_i^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}(1-\delta(\mu^2)) + 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

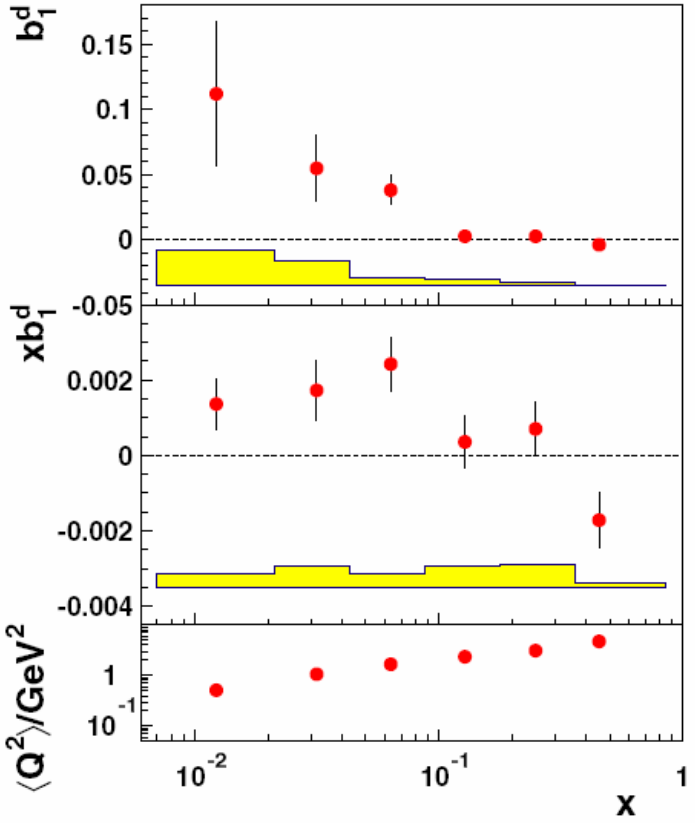
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}\delta(\mu^2) - 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

$$\sum_q \int_0^1 C_i^T(x)xdx = \delta_1(\mu^2)$$ =0 for EEP

HERMES – data on tensor spin structure function

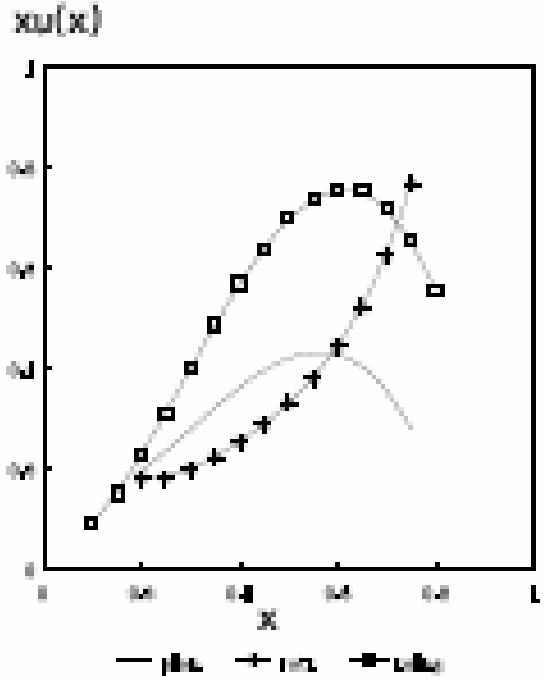
PRL **95,** 242001 (2005)

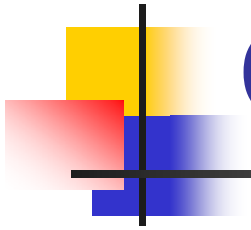
- Isoscalar target – proportional to the sum of u and d quarks – combination required by EEP
- Second moments – compatible to zero better than the first one (collective glue << sea)



What about vector mesons – sum rules (A. Oganesian, **Phys.Atom.Nucl.71:1439-1444,2008**)

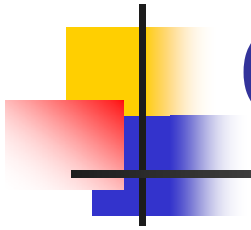
- Very different for longitudinal and transverse rho
- Reason – smallness of tensor polarization dependent part?





CONCLUSIONS

- QCD factorization – naïve BH production picture questioned
- Parton transverse momentum essential – more involved NP objects (TMDs, UGDFs)
- Suppression of BH due to large transverse momentum = small size "dipole" production (Classical) or small (exponentially suppressed) coupling to partons (Quantum)
- Related to fundamental issues of BH physics
- Other empirical QCD/Gravity relations
- BH may be better produced in heavy ions collisions



Outlook

- BH in color-dipole picture
- Calculation of jets-thermal overlap (MC simulations?)
- Multi gluon production at heavy ions collisions