Forward physics and the glue at small x

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Outline

A short introduction

High energy effective action (canceled)

BFKL & exclusive Vector Mesons

3 parton production in the presence of high gluon densities

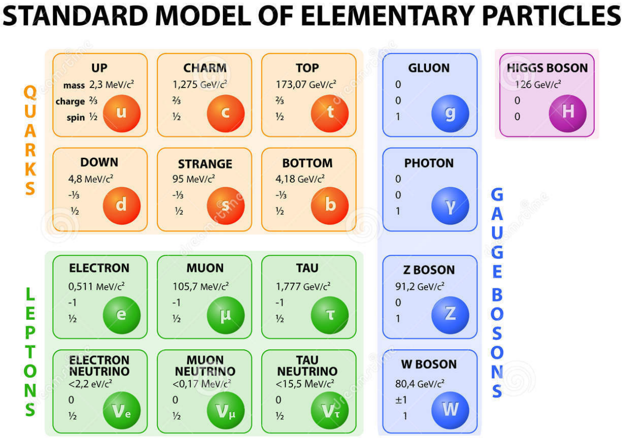
Conclusion

Low x physics .... a small community

- yellow report on LHC forward physics (184 authors) [arXiv:1611.05079]
- typical workshop size: 89 participants (DIFFRACTION 2016, International Workshop on Diffraction in High-Energy Physics), 44 talks in Low x and Diffraction working group at DIS 2017

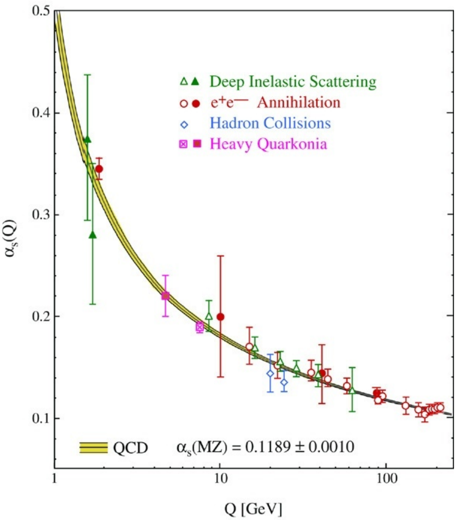
- overlap with various (QCD) communities
  - heavy ion/high multiplicity physics
  - transverse momentum dependence in parton distribution functions
  - physics of a future Electron Ion Collider
  - higher order corrections & precision physics (resummation!)
  - new physics searches in 'strange' hadronic processes

- forward physics in *e.g.* pp: rapidities close to the beam line probe 2nd proton at low x ...



interested in strong interactions, in particular the dynamics of the gluon in the high energy limit

Important QCD property: asymptotic freedeom



strong coupling strong at large distances $\equiv$ low energy scales

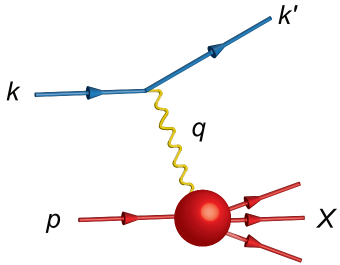
weak at small distances $\equiv$ hard energy scales

$\alpha_s = \alpha_s(Q)$ running coupling

$\Rightarrow$ process with hard scale accessible to perturbative treatment

Hadron structure from Deep Inelastic Scattering (DIS) of electrons on protons

- knowldege of scattering enery + nucleon mass + measure scattered electron ➡ control kinematics



Photon virtuality
$Q^2 = -q^2$

Resolution
$\lambda \sim \frac{1}{Q}$

Bjorken $\boldsymbol{x} = \frac{Q^2}{2p \cdot q}$

Interpretation of observation (MIT-SLAC '67)

Bjorken: parametrize cross-section in terms of
proton structure functions F_1 **and** F_2 $(F_L = F_2 - 2xF_1)$

$$\frac{d^2\sigma^{eh\to eX}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2\boldsymbol{F}_2(x,Q^2) - y^2\boldsymbol{F}_L(x,Q^2)\right]$$

Feynman [Feynman, August 1968]:

- proton composed of generic point-like free constitutents, called "*partons*" – later identified as quarks & gluons

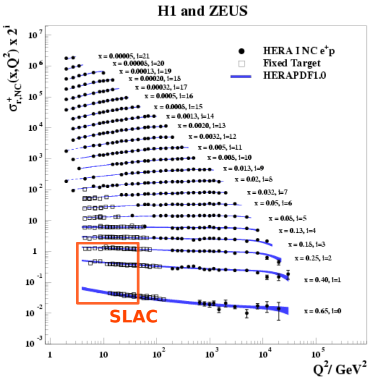
proton structure function

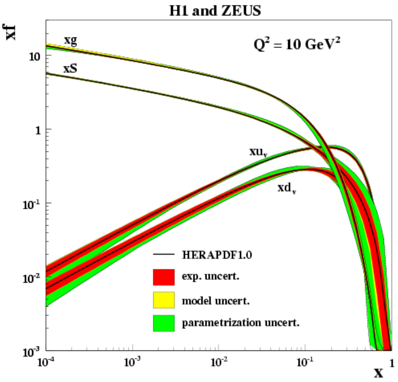
$$F_2(x,Q^2) = \sum_{\text{partons}} e^2_{\text{parton}} \cdot f_{\text{parton}}(x)$$

parton distribution function

$f_{\text{parton}}(x)$ probability to hit a parton with proton momentum fraction x

HERA collider at DESY (also hadron-hadron machines + fixed target)

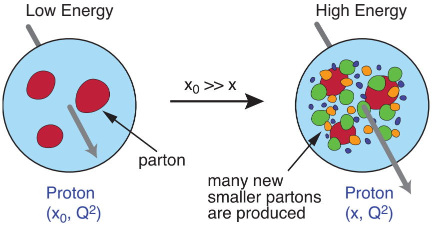




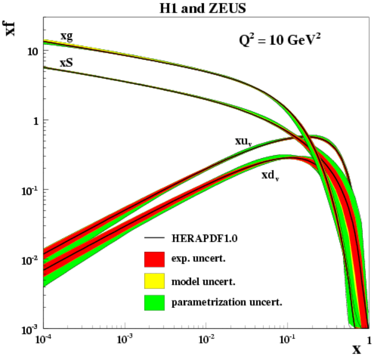
- fit x-dependence of pdf's at intial scale $Q_0^2 \sim 2$ GeV^2
- QCD (DGLAP equation): evolution from Q_0^2 to Q^2

$$\partial_{\ln \mu_f^2} f_k(x, \mu_f) = \sum_{l=q,g} P_{kl} \otimes f_l$$

The proton at high center of mass energies



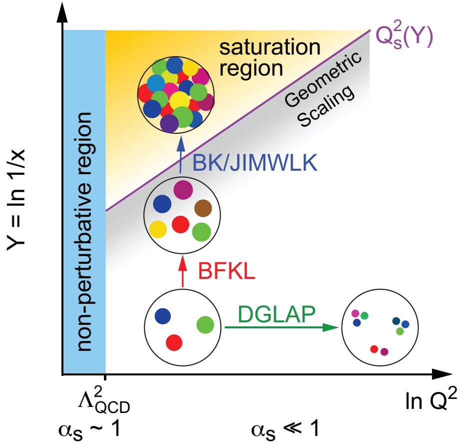
- At small x: proton dominated by gluons (and sea-quarks)
- At small x: Parton fluctuations time dilated on strong interaction times scales ....



- .... long lived gluons radiate further small x gluons
- power-like rise of gluon and sea-quark distribution – probability distribution!

The proton at high energies: saturation

theory considerations:



- effective finite size $1/Q$ of partons at finite Q^2
- at some $x \ll 1$, partons 'overlap' $=$ recominbation effects
- turning it around: system is characterized by *saturation scale* Q_s
- grows with energy $Q_s \sim x^{-\Delta}$, $\Delta > 0$ & can reach in principle perturbative values $Q_s > 1\text{GeV}$

Can attempt description using models, ... ultimate understanding: QCD perturbation theory

requires:

- expansion of perturbative amplitudes in $x \ll 1$
- naïve expansion breaks down due to large logs $\alpha \ln \frac{1}{x} \sim 1$
- + resummation of enhanced terms $\left(\alpha_s(Q^2) \ln \frac{1}{x}\right)^n \sim 1$ to all orders in α_s

→ BFKL equation

LL: [Fadin, Kuraev, Lipatov, PLB 60 (1975) 50]
[Balitsky, Lipatov, SJNP (1978 822)]

NLL: [Fadin, Lipatov; PLB 429 (1998) 127];
[Ciafaloni, Camici; PLB 430 (1998) 349]

+RG: [Salam; hep-ph/9806482], [many others ...],
[MH, Salas, Sabio Vera; 1209.1353]

resummed/collinear improved NLO BFKL kernel

linear vs. non-linear evolution

$$\partial_{\ln 1/x} G(x, \boldsymbol{k}) = K \otimes G$$ BFKL = linear/low density evolution

roughly speaking: powerlike rise $G \sim x^{-\lambda}$ of gluon

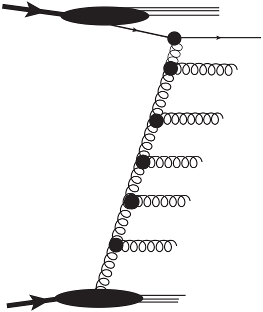
assuming dense gluonic field $A_\mu \sim \frac{1}{g}$: non-linear extension of BFKL

$$\partial_{\ln 1/x} G(x, \boldsymbol{k}) = K \otimes G - G \otimes G$$ BK-JIMWLK = non-linear evolution

[Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovern; 1996-2002], [Balitsky, 1996]; [Kovchegov, 1997]

fixed point at $x = 0$: gluon density constant for $s \to \infty$

Phenomenology at the LHC

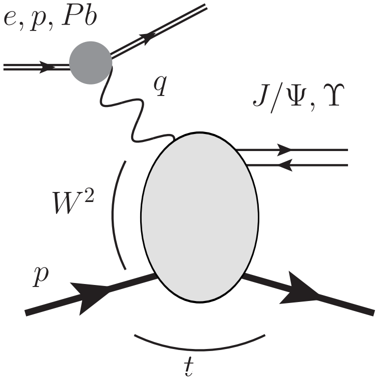


- events close in rapidity to one of the rescattering protons $\equiv$ forward events $\Rightarrow$ probe second proton at low values of $x = \frac{p_t}{\sqrt{s}} e^{-\eta}$,
- want to find:

- evidence for BFKL evolution & fix the region of its applicability
- determine the region where saturation effects become relevant
- needed to arrive at a proper understanding of saturated matter $\rightarrow$ determination of the initial state of heavy ion collisions
- want to understand which picture is correct (low density/DGLAP) or (low density/BFKL) or (high density/JIMWLK/BK)

photo-production of J/Ψ and Υ: explore proton at ultra-small x

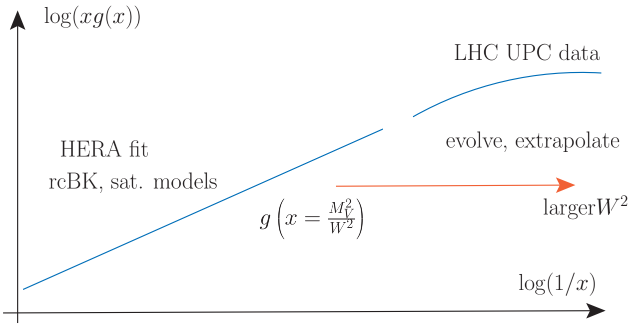
[Bautista, Ferandez-Tellez, MH; 1607.05203]



- measured at HERA (ep) and LHC (pp, ultra-peripheral pPb)
- charm and bottom mass provide hard scale ➡ pQCD
- exclusive process, but allows to relate to inclusive gluon

reach values down to $x = 4 \times 10^{-6} \to$ (unique ?) opportunity to explore the low x gluon

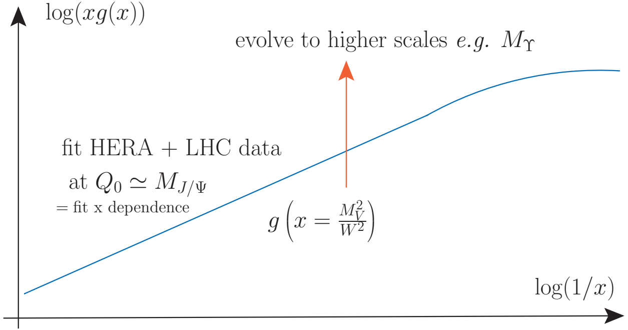
DGLAP vs. saturation (I)



- describes data or not $\to$ re-fit
- if yes: do we really see saturation effects?

i.e. BK type evolution
$$\frac{d}{d\ln 1/x}G(x) = K \otimes G(x) - \underbrace{G \otimes G}_{\text{present, relevant?}}$$

DGLAP vs. saturation (II)

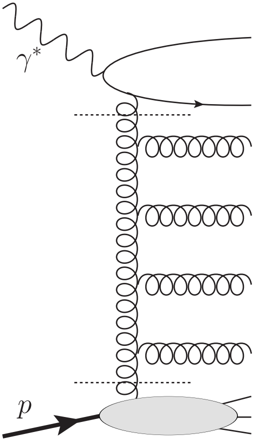


- $J/\Psi \to \Upsilon \simeq$ evolution 2.4 GeV^2 $\to$ 22.4 GeV^2
- high density effects die away in collinear limit
- DGLAP unstable at ultra-small x and small scales ...
- convinced: pdf studies highly valuable $\to$ constrain pdf's at ultra-small x
- useful benchmark for saturation searches (?)

Will argue in the following ...

- a far better dilute (!) benchmark might (?) be given by BFKL evolution ($\rightarrow$ applies for UPCs@LHC, might be different for a future (US-)EIC ... $\rightarrow$ phase space!)
- why? .... BFKL $\equiv$ low x evolution *without* high density/saturation effects
- available up to NLO [Fadin, Lipatov; PLB 429 (1998) 127]; [Ciafaloni, Camici; PLB 430 (1998) 349], resummation schemes for coll. logs exist & to some degree well explored [Salam; hep-ph/9806482], ...
- not only explored in $n = 0$ sector ➡ additional constrains from *e.g.* angular decorrelation studies of jets $\rightarrow$ see talks on Wednesday

The underlying NLO BFKL fit to DIS data



$$F_2(x, Q^2) = \int_0^\infty d\boldsymbol{k}^2 \int_0^\infty \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \Phi_2\left(\frac{\boldsymbol{k}^2}{Q^2}\right) \mathcal{F}^{\text{DIS}}_{\text{BFKL}}(x, \boldsymbol{k}^2, \boldsymbol{q}^2) \Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)$$

virtual photon: quarks mass-less, $n_f = 4$ fixed

proton impact factor: $\Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2}, \delta\right) = \frac{\mathcal{C}}{\pi\Gamma(\delta)}\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)^\delta e^{-\frac{\boldsymbol{q}^2}{Q_0^2}}$

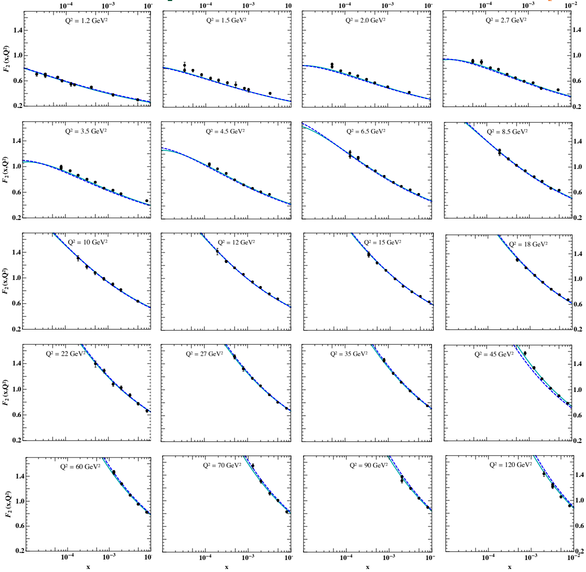
free parameters of proton impact factor from fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]

→ allows for definition of unintegrated gluon density
[Chachamis, Deak, MH, Rodrigo, Sabio Vera; 1507.05778]

$$G(x, \boldsymbol{k}^2, Q_0^2) = \int \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \mathcal{F}^{\text{DIS}}_{\text{BFKL}}(x, \boldsymbol{k}^2, \boldsymbol{q}^2) \Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)$$

	virt. photon impact factor	Q_0/GeV	δ	$\mathcal{C}$	Λ_{QCD}/ GeV
fit 1	leading order (LO)	0.28	8.4	1.50	0.21
fit 2	LO with kinematic improvements	0.28	6.5	2.35	0.21

Good description of cominbed HERA [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]



data: [H1 & ZEUS collab. 0911.0884]

Solve BFKL equation in conjugate (γ) Mellin space

$$G\left(x, \boldsymbol{k}^2, M\right) = \frac{1}{\boldsymbol{k}^2} \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \; \hat{g}\left(x, \frac{M^2}{Q_0^2}, \frac{\overline{M}^2}{M^2}, \gamma\right) \; \left(\frac{\boldsymbol{k}^2}{Q_0^2}\right)^{\gamma}$$

re-introduce two scales: hard scale of process (M) and scale of running coupling ($\overline{M}$)

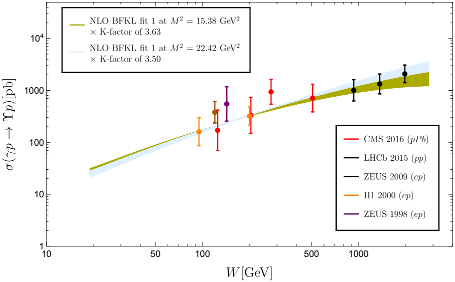
$\hat{g}$: operator in γ space!

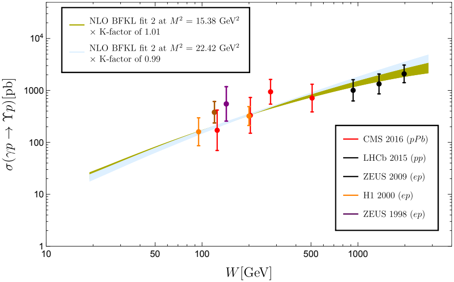
$$\hat{g}\left(x, \frac{M^2}{Q_0^2}, \frac{\overline{M}^2}{M^2}, \gamma\right) = \frac{\mathcal{C}\cdot\Gamma(\delta-\gamma)}{\pi\Gamma(\delta)} \;\cdot\; \left(\frac{1}{x}\right)^{\chi\left(\gamma, \frac{\overline{M}^2}{M^2}\right)} \;\cdot$$
$$\left\{1 + \frac{\bar{\alpha}_s^2 \beta_0 \chi_0(\gamma)}{8N_c} \log\left(\frac{1}{x}\right)\left[-\psi(\delta-\gamma) + \log\frac{M^2}{Q_0^2} - \partial_\gamma\right]\right\},$$

resummed NLO BFKL eigenvalue with optimal scale setting ($\rightarrow$ modifies $\chi_1(\gamma)$):

$$\chi\left(\gamma, \frac{\overline{M}^2}{M^2}\right) = \bar{\alpha}_s\chi_0(\gamma) + \bar{\alpha}_s^2\tilde{\chi}_1(\gamma) - \frac{1}{2}\bar{\alpha}_s^2\chi_0'(\gamma)\chi_0(\gamma)$$
$$+ \chi_{RG}(\bar{\alpha}_s, \gamma, \tilde{a}, \tilde{b}) - \frac{\bar{\alpha}_s^2\beta_0}{8N_c}\chi_0(\gamma)\log\frac{\overline{M}^2}{M^2}.$$

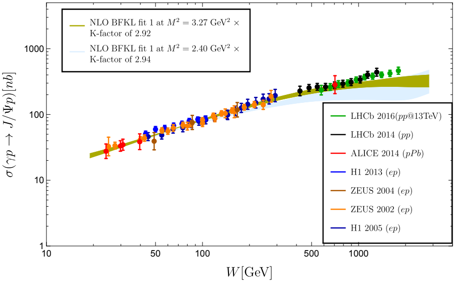
comparison to data: Υ production

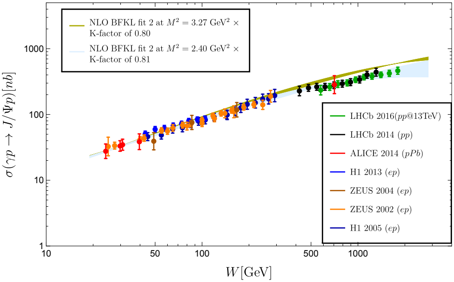




- provide study for two hard scales:
  photoproduction scale: $M_{\text{pp}} = M_V/2$
  impact factor motivated: $M_{\text{if}}^2 = 8\mathcal{R}_V^{-2}$
- fix normalization by low energy H1 data point $\to$ K-factor; no further adjustments

comparison to data: J/Ψ production





- NEW (wrt. [Bautista, Fernando Tellez, MH; 1607.05203]): 13 TeV LHCb data
- fix normalization by low energy ALICE data point → K-factor
  believe: related to HERA fit (massless, $n_f = 4$, $(\mathcal{C}_1/\mathcal{C}_2)^2 = 2.45$)
- often included (not here): GPD motivated factor ("$x' \neq x$"); known for collinear [Shuvaev, Golec-Biernat, Martin, Ryskin, hep-ph/9902410]
  ➡ to be calculated for k_T factorized BFKL impact factor
  $\sim$ kinematic improvements for $\gamma \to V$

Concluding remarks for Vector mesons

BFKL fits [MH, Salas, Sabio Vera; 1301.5283] somehow approach its limits, but so far works very well $\rightarrow$ keep in mind: *most simple combination of existing NLO BFKL fit & existing VM impact factor*

first suggestion: no need for saturation effects, linear NLO evolution sufficient

why so hard to manifest saturation? .... two possible reasons:

a) BFKL simply appropiate framework,... saturation effects not (yet) present

b) observable $\sim \mathcal{N}^{\text{dipole}} \Leftrightarrow G_{\text{ugd}}^{\text{BFKL}} \Rightarrow$ high density effects (if at all present) only through evolution

➡ but evolve not even an order of magnitude w.r.t. HERA data;

A possible way out ...

observables with higher order correlators of Wilson lines

$\rightarrow$ inclusive observables (no gap) + resolved final sates

(*e.g.* inclusive di- & tri-hadrons/jets)

$$\mathcal{N} \sim 1 - \frac{1}{N_c}\text{tr}\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y}))\right] \qquad \leftrightarrow \qquad G^{\text{BFKL}}(x, \boldsymbol{k})$$

$$\mathcal{Q}^{(4)} \sim 1 - \frac{1}{N_c}\text{tr}\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y})V(\boldsymbol{y}')V^\dagger(\boldsymbol{x}')\right] \quad \leftrightarrow \quad G + \#G^2 + \#G^4 + \dots$$

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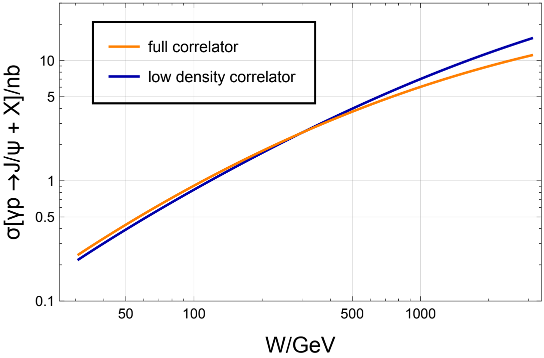
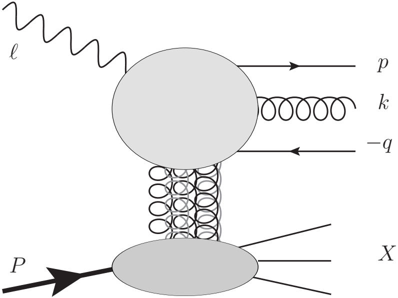


prelim. study using bCGC model

... work in progress, no conclusion to be drawn yet

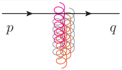
A new process: 3 particle production at high densities [Ayala, MH, Jalilian-Marian, Tejeda-Yeomans; 1604.08526, 1701.07143]



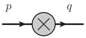
- assumption: high gluon densities exists $\Rightarrow$ higher order correlators $\equiv$ new dynamics w.r.t. BFKL
- access to $\mathcal{Q}^{(4)} \sim 1 - \frac{1}{N_c}\text{tr}\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y})V(\boldsymbol{y}')V^\dagger(\boldsymbol{x}')\right] \leftrightarrow$ $G + \#G^2 + \#G^4 + \ldots$ and more complicated stuff
- experimental difficult observable: relate to more inclusive quantity (energy loss etc.)

Theory: Propagators in background field

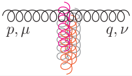
use light-cone gauge, with $k^- = n^- \cdot k$, $(n^-)^2 = 0$, $n^- \sim$ target momentum



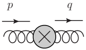
$$= (2\pi)^d \delta^{(d)}(p-q)\tilde{S}_F^{(0)}(p) + \tilde{S}_F^{(0)}(p)$$



$$\tilde{S}_F^{(0)}(q)$$



$$= (2\pi)^d \delta^{(d)}(p-q)\tilde{G}_{\mu\nu}^{(0)}(p) + \tilde{G}_{\mu\alpha}^{(0)}(p)$$



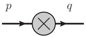
$$\tilde{G}_{\alpha\nu}^{(0)}(q)$$

$$\tilde{S}_F^{(0)}(p) = \frac{i\not{p} + m}{p^2 - m^2 + i0} \qquad \tilde{G}_{\mu\nu}^{(0)}(p) = \frac{i d_{\mu\nu}(p)}{p^2 + i0}$$

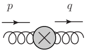
$$d_{\mu\nu}(p) = -g_{\mu\nu} + \frac{n_\mu^- p_\nu + p_\mu n_\nu^-}{n^- \cdot p}$$

[Balitsky, Belitsky; NPB 629 (2002) 290], [Ayala, Jalilian-Marian, McLerran, Venugopalan, PRD 52 (1995) 2935-2943], ...

interaction with the background field:



$$= 2\pi\delta(p^- - q^-)\not{n}^- \int d^{d-2}\boldsymbol{z}\, e^{-i\boldsymbol{z}\cdot(\boldsymbol{p}-\boldsymbol{q})} \cdot \left\{\theta(p^-)[V(\boldsymbol{z}) - 1] - \theta(-p^-)[V^\dagger(\boldsymbol{z}) - 1]\right\}$$



$$= -2\pi\delta(p^- - q^-)2p^- \int d^{d-2}\boldsymbol{z}\, e^{-i\boldsymbol{z}\cdot(\boldsymbol{p}-\boldsymbol{q})} \cdot \left\{\theta(p^-)[U(\boldsymbol{z}) - 1] - \theta(-p^-)[U^\dagger(\boldsymbol{z}) - 1]\right\}$$

$$V(\boldsymbol{z}) \equiv V_{ij}(\boldsymbol{z}) \equiv \mathrm{P}\exp ig \int_{-\infty}^{\infty} dx^- A^{+,c}(x^-, \boldsymbol{z}) t^c$$

$$U(\boldsymbol{z}) \equiv U^{ab}(\boldsymbol{z}) \equiv \mathrm{P}\exp ig \int_{-\infty}^{\infty} dx^- A^{+,c}(x^-, \boldsymbol{z}) T^c$$

strong background field resummed into path ordered exponentials (Wilson lines)

Two-fold interest: phenomenology & further development of theory

- spinor helicity formalism $\equiv$ expand elements of amplitudes (propagators, spinors, polarization vectors, ...) in terms of mass-less spinors with helicity $\lambda = \pm$

$$|k_i^\pm\rangle \equiv \frac{1 \pm \gamma_5}{2} u(k_i), \qquad \epsilon_\mu^\pm(k,n) = \pm \frac{\langle n^\mp|\gamma^\mu|k^\mp\rangle}{\sqrt{2}\langle n^\mp|k^\pm\rangle}$$

- important relations $\langle i^\pm|j^\pm\rangle = 0$ and $\langle i^\pm|i^\mp\rangle = 0$
- successfully employed in multi-loop & leg calculations

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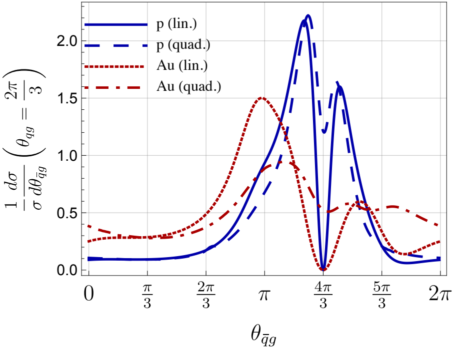
- important relations $\langle i^\pm | j^\pm \rangle = 0$ and $\langle i^\pm | i^\mp \rangle = 0$
- successfully employed in multi-loop & leg calculations
- QCD in the high-energy limit: helicity conserved during interaction with high-energy gluon + use of axial gauge $A \cdot n = 0$
- expansion in spinors reflects these symmetries in a (perfect?) way $\rightarrow$ very compact expressions at amplitude level **[Ayala, MH, Jalilian-Marian, Tejeda-Yeomans; arXiv:1701.07143]**

First phenomenology on partonic level: angular decorrelation

- here: density effects through large nucleus (Au)
- fix one (transverse) angle at $\theta_{qg} = \frac{2\pi}{3}$, vary θ_{qg}



- no p_T from the nucleus/proton $Q_S \to 0$ $\Rightarrow$ Merceces-Benz-star configuration dominant

- higher correlators: Gaussian-approximation expanded to quadratic order in 2-point correlator (model)

Conclusions

- low x/forward physics: QFT under extreme conditions
- need to resum high energy logarithms and possibly high density effects
- leading order description often insufficient for precise quantitative understanding $\Rightarrow$ higher order corrections
- require the development of new calculational techniques
- at the same time need to identify discriminative observables
- lots to be done, but exciting times!