Programy finansowane
z Funduszy Strukturalnych

FNP

Forward physics: hard processes and saturation – phenomenology and theory review

Krzysztof Kutak

Instytut Fizyki Jądrowej
im. Henryka Niewodniczańskiego
Polskiej Akademii Nauk

High energy scattering as a probe of new physics

- New dynamical effects in SM
  Color Glass Condensate, Quark Gluon Plasma,
  saturation,..

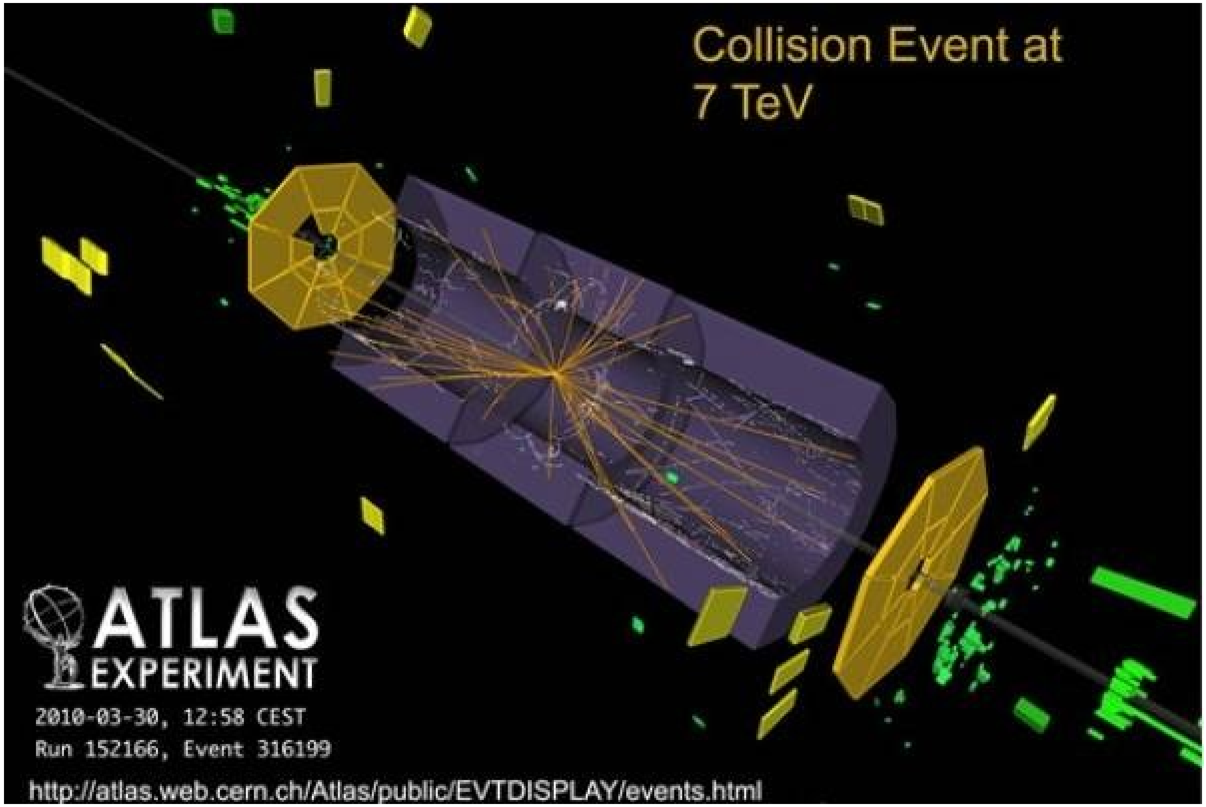
- Hopefully production of new particles not included in SM
  gravitons, SUSY, LED, Higgs

For all this one needs to understand the behavior of QCD cross section at high energies (constraints, uncertainties of pdf sets, NLO calculations)

Forward physics: studies of dynamics of QCD

Historically:

- measrement of total and elastic cross sections
- dominated by soft physics



At the LHC:

- forward processes involve both soft and hard production
- phase space opend for large total energy
- forward high pt production
- central production of high pt

Why forward physics?

- Forward jet production as a multi-scale problem
- Probing small x and large x parton densities
- Small x parton densities have not been tested at large scales

- Summation of high-energy logarithmic corrections recognized to be necessary for reliable QCD predictions

$$\sim \sum_n \alpha_s^n \ln^n s$$

- High pt processes. Large logarithmic corrections are present also in the hard scale

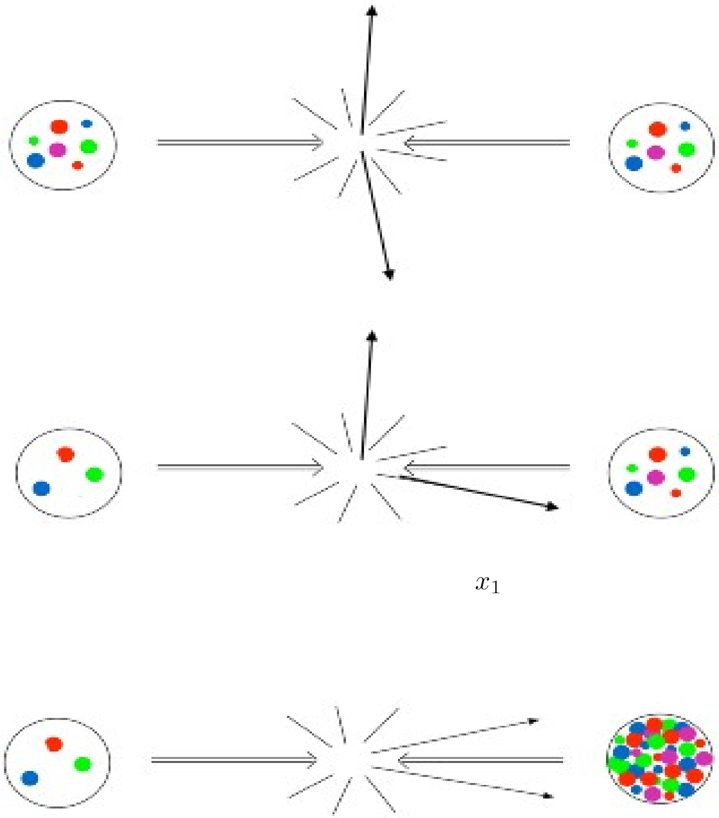
$$\sim \sum_n \alpha_s^n \ln^n p_T/\mu$$

High pt production in the forward region

Final state momenta
and rapidities $p_1\,,p_2\,,y_1\,,y_2$

$$x_1 = \frac{p_1 e^{y_1} + p_2 e^{y_2}}{\sqrt{s}}$$

$$x_2 = \frac{p_1 e^{-y_1} + p_2 e^{-y_2}}{\sqrt{s}}$$



$$x_1 \sim x_2 < 1$$

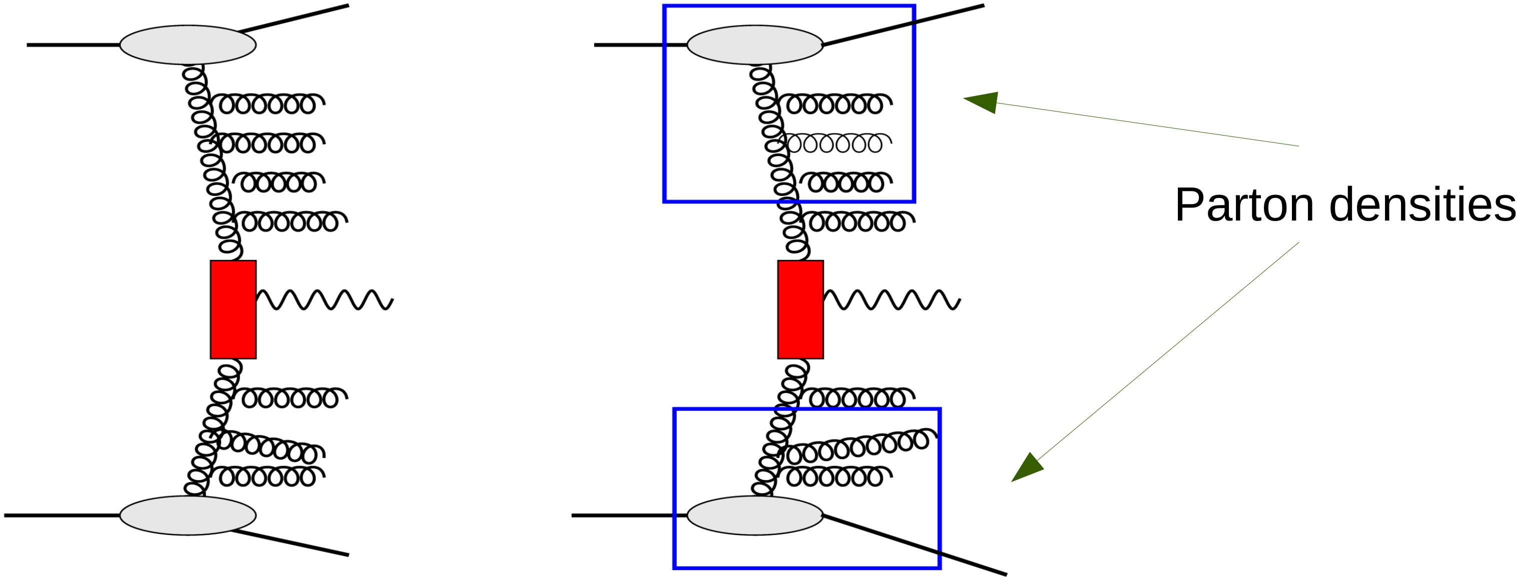
$$x_1 \sim 1\,,\; x_2 < 1$$

$$x_1 \sim 1\,,\; x_2 \ll 1$$

From C. Marquet

pQCD calculations

- Matrix element + factorization theorems – momentum space point of view
  - Factorization theorems allow for decomposition of process ep, pp under some ordering condition into long and short distant parts (ep, pp). Also in AA but after inclusion of geometry factor due to overlap of nuclei, Glauber model.



Parton densities

Matrix element convoluted with resumed contributions of higher orders – Factorization Theorems

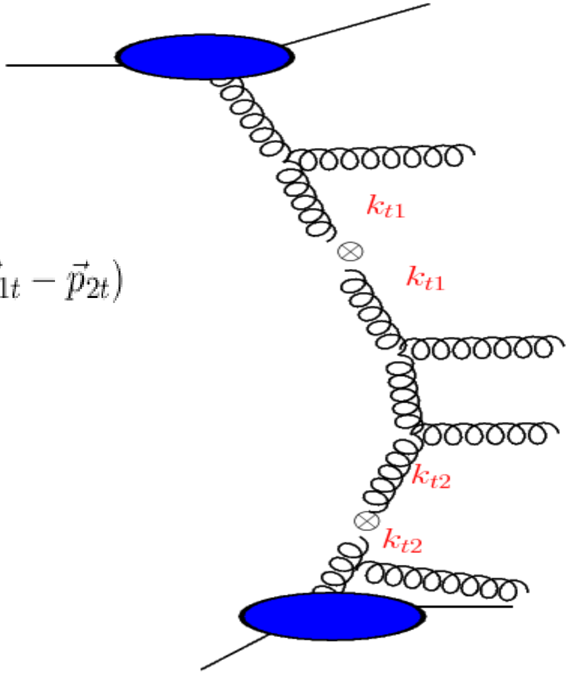
Observable ~ parton density $\otimes$ ME $\otimes$ parton density

Forward physics investigations with production of jets.

Framework: HEF (High Energy Factorization)

Ciafaloni, Catani, Hautman '94

- Gluon dominates in t channel
- Kinematics precisely enough at LO (parts of NLO DGLAP)
- Sums up large logs of energy



$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,b,c,d} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ab\to cd}|^2} \delta^2(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t})$$

$$\times \, \phi_{a/A}(x_1, k_{1t}^2, \mu^2) \, \phi_{b/B}(x_2, k_{2t}^2, \mu^2) \, \frac{1}{1+\delta_{cd}}$$

- Parton density depends on kt
  - In collinear limit reduces to collinear factorization

Recently matrix elements for forward-central jets have been obtained

CCFM evolution equation - evolution with observer

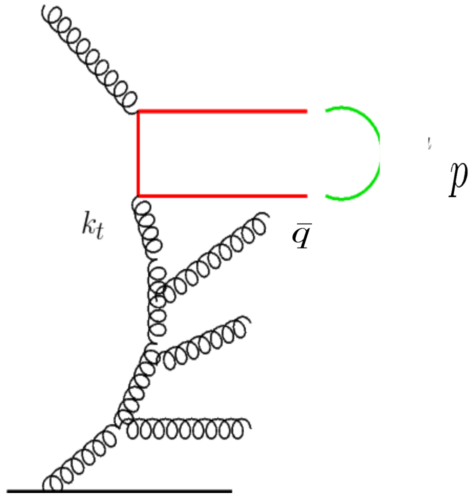
- Linear equation based on strong ordering in angle
- Interpolates between DGLAP and BFKL
- Gluon density is build by constructive interference of gluons
- Sumes up also logs of hard scale

virtual contributions

$$\mathcal{A}(x,k^2,p) = \bar{\alpha}_s \int_x^1 dz \int \frac{\mathrm{d}^2\bar{q}}{\pi\bar{q}^2}\,\theta(p-z\bar{q})\,\Delta_s(p,z\bar{q})\left(\frac{\Delta_{ns}(z,k,q)}{z}+\frac{1}{1-z}\right)\mathcal{A}\left(\frac{x}{z},k',\bar{q}\right)$$

condition on angle

Catani, Fiorani, Marchesini '90



Implemented by H. Jung in Monte Carlo CASCADE

CCFM as phenomenology tool

CASCADE framework Jung et al.

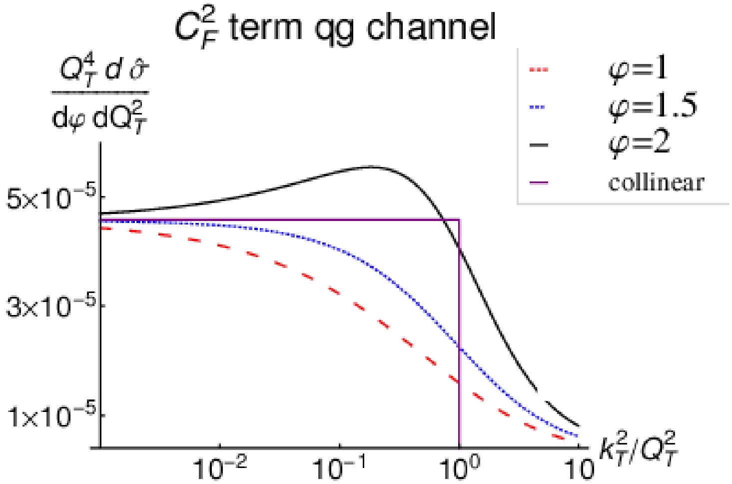
- Initial state parton shower generated according to CCFM equation
- Final state parton shower using PYTHIA
- Matrix elements calculated in High Energy Factorization framework
- Only 3 free parameters
- Extensions towards including other channels

Properties of matrix elements

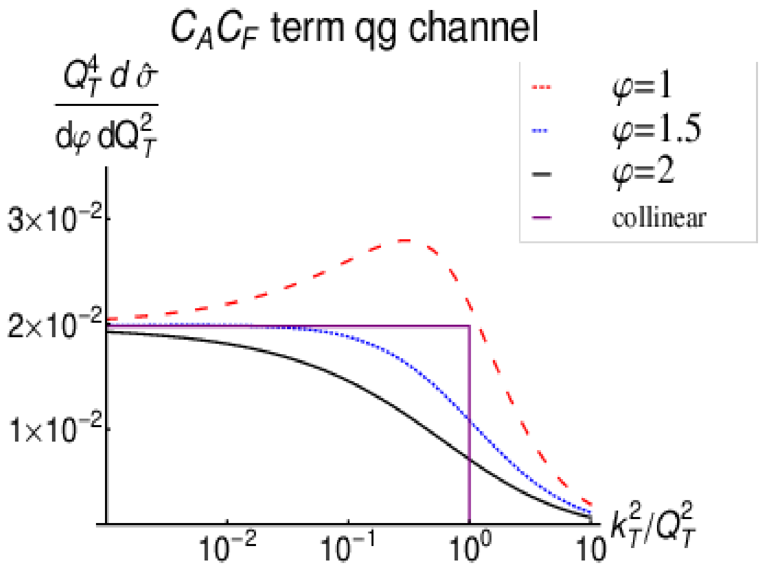
k_T = transversal momentum of incoming gluon = transverse momentum carried away by extra jets

$k_T/Q_T \to 0$ leading order process

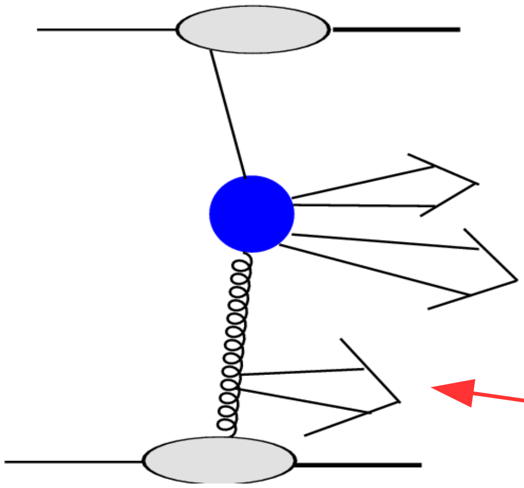
Deak, Hautmann, Jung, Kutak '09



C_F^2 term qg channel



$C_A C_F$ term qg channel



- dynamical cut-off at $k_T \sim Q_T$ set by coherence effects
  - ▷ non-negligible terms from finite k_T tail

Such hard emission is not possible at LO DGAP parton shower. High energy approach allows for it

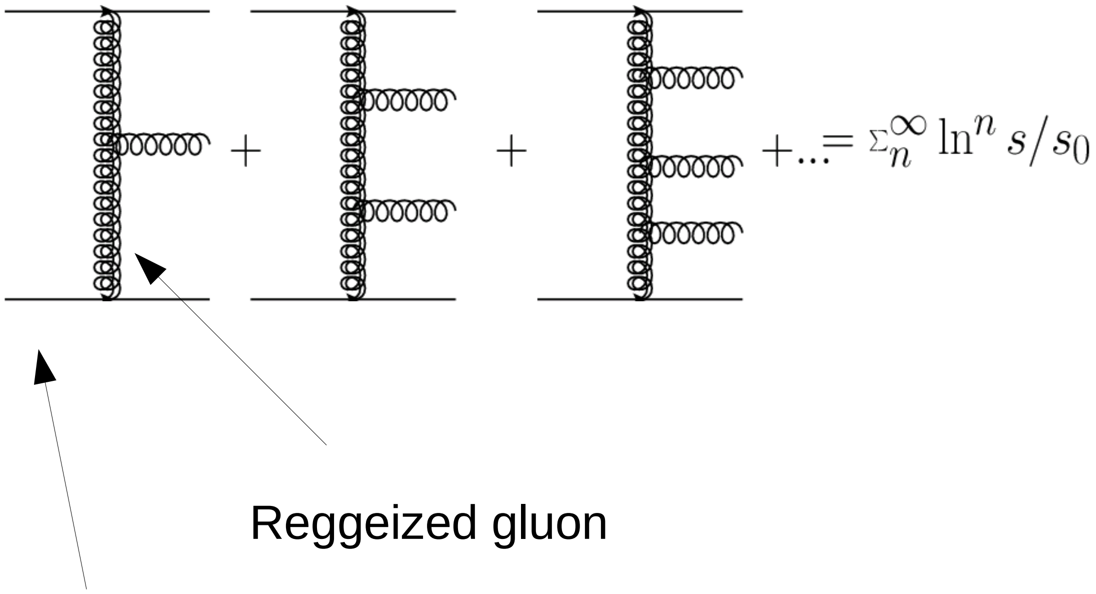
Forward physics investigations with production of jets.

Framework: HEJ (High Energy Jets)

Andersen, Smillie '10

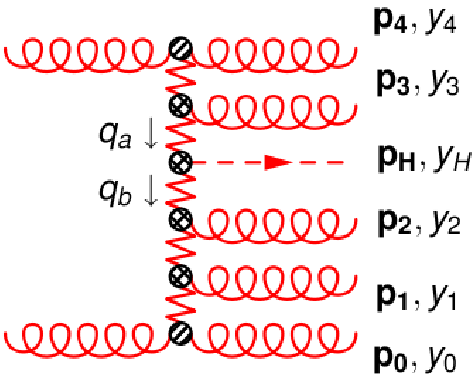
The framework of High Energy Jets (HEJ) an all-order description of processes with more than two hard jets, based on an approximation which captures the hard, emissions. No need for integral equation. Computers fast enough to generate FKL amplitudes.

Inspired by BFKL. Approximations only to partonic amplitudes.
No approximation to phase space



Reggeized gluon

Impact factor



Inside of this amplitude
one can include production of
not gluonic aobervables

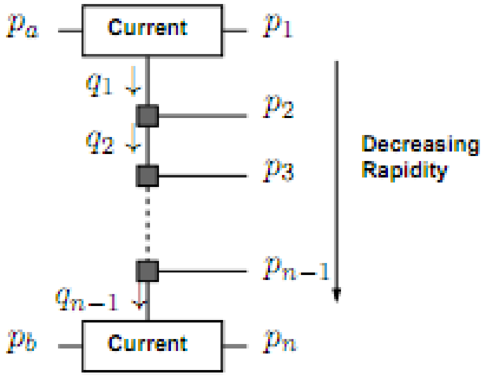
Forward physics investigations with production of jets.

Framework: HEJ (High Energy Jets)

Andersen, Smillie '10

The framework of High Energy Jets (HEJ) an all-order description of processes with more than two hard jets, based on an approximation which captures the hard, emissions. No need for integral equation. Computers fast enough to generate FKL amplitudes.

Inspired by BFKL. Approximations only to partonic amplitudes.
No approximation to phase space



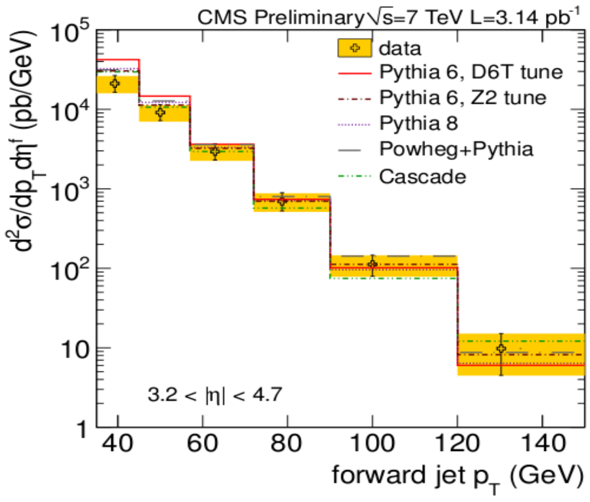
$$
\overline{\left|\mathcal{M}^{t,v}_{\varepsilon\ f_1 f_2\to f_1 g\cdot g f_2}\right|}^2 = \frac{1}{4\ (N_C^2-1)}\ \left\|S_{f_1 f_2\to f_1 f_2}\right\|^2
\cdot \left(g^2\ K_{f_1}\ \frac{1}{t_1}\right) \cdot \left(g^2\ K_{f_2}\ \frac{1}{t_{n-1}}\right)
\cdot \prod_{i=1}^{n-2}\left(\frac{-g^2 C_A}{t_i t_{i+1}}\ V^\mu(q_i,q_{i+1})V_\mu(q_i,q_{i+1})\right)
\cdot \prod_{j=1}^{n-1}\exp\left[2\hat{\alpha}(q_j)(y_{j-1}-y_j)\right],
$$

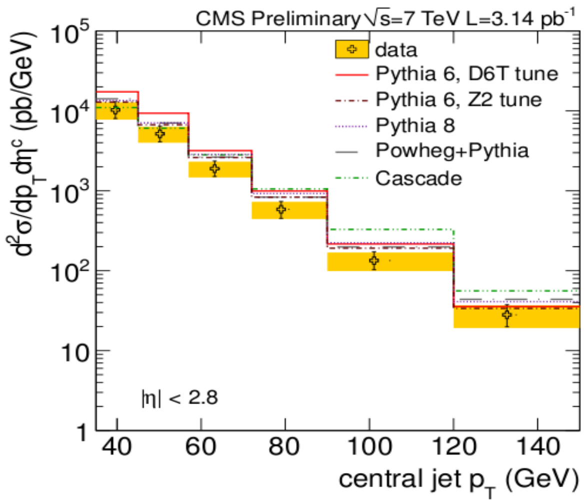
$$
\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2}\ \sum_{n=2}^{\infty}\ \prod_{i=1}^{n}\left(\int_{p_{i\perp}=0}^{p_{i\perp}=\infty}\frac{\mathrm{d}^2\mathbf{p}_{i\perp}}{(2\pi)^3}\ \int\frac{\mathrm{d}y_i}{2}\right)\ \frac{\overline{\left|\mathcal{M}_{\text{HEJ}}^{f_1 f_2\to f_1 g\cdots g f_2}(\{p_i\})\right|}^2}{\hat{s}^2}
\times\ \sum_m \mathcal{O}^e_{mj}(\{p_i\})\ w_{m-\text{jet}}
\times\ x_a f_{A,f_1}(x_a,Q_a)\ x_2 f_{B,f_2}(x_b,Q_b)\ (2\pi)^4\ \delta^2\!\left(\sum_{i=1}^{n}\mathbf{p}_{i\perp}\right)\ \mathcal{O}_{2j}(\{p_i\})
$$

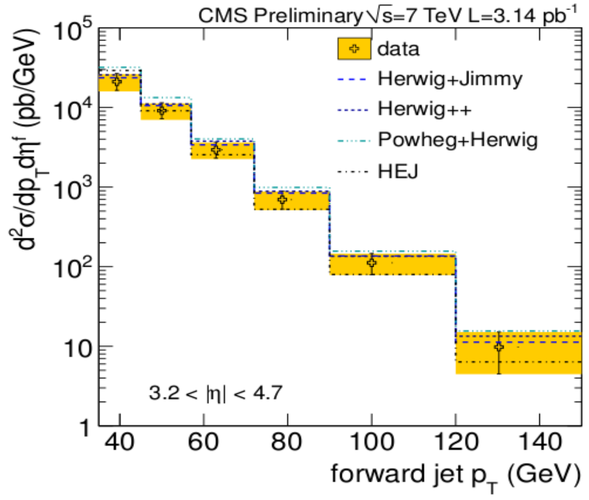
Lipatov vertices

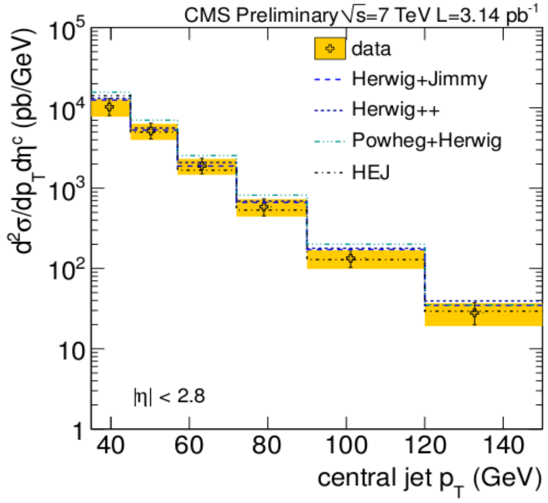
virtual contributios

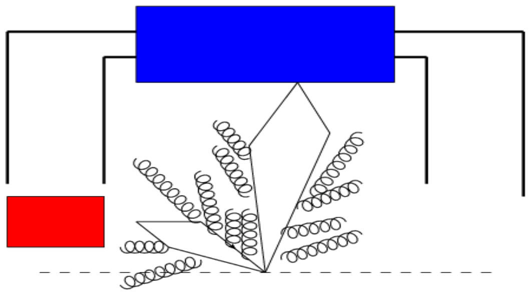
Forward central – jet production











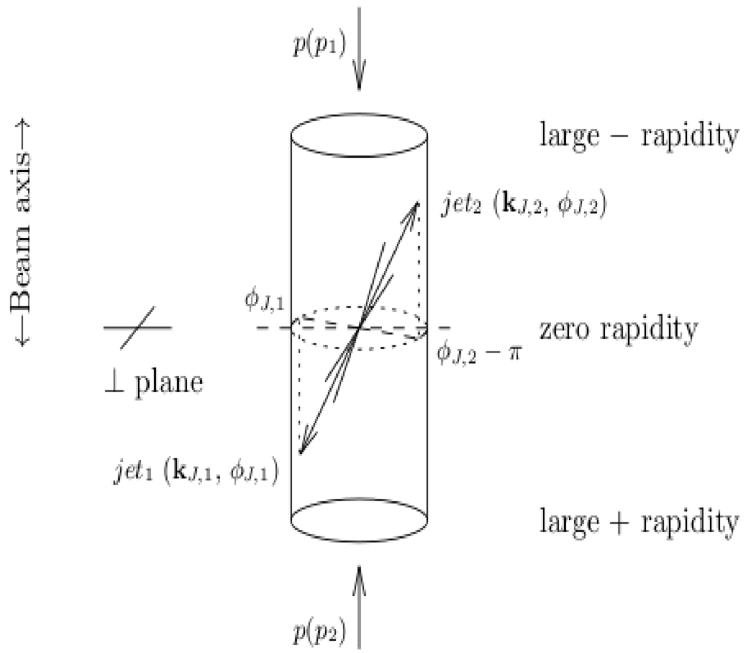
Why differences?

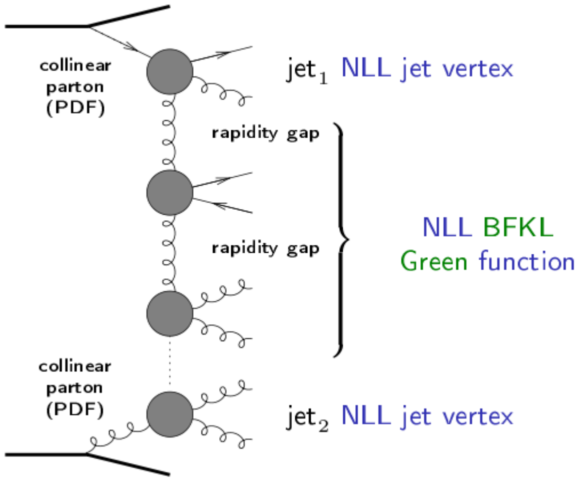
- HEJ and CASCADE based on unordered in kt emissions but use different parton densities
- Herwig and PYTHIA use collinear parton densities but differ in approximations in ME and ordering conditions in shower.

Forward physics investigations with production of jets.

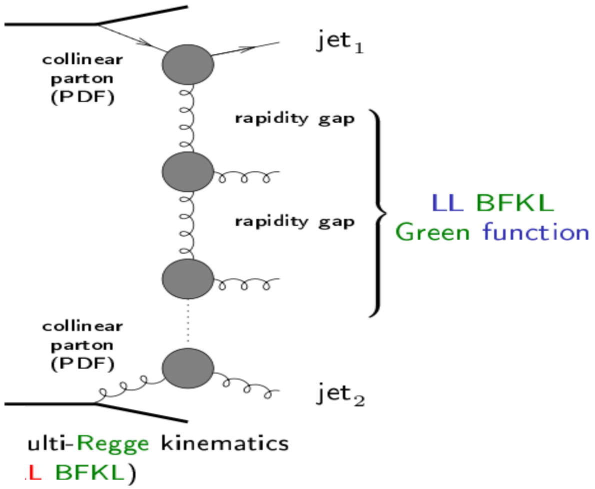
Szymanski, Wallon '09

Towards NLO calculations of Mueller-Navalet jets





Quasi Multi-Regge kinematics (here for NLL BFKL)



$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_{J,1}|\,\mathrm{d}|\mathbf{k}_{J,2}|\,\mathrm{d}y_{J,1}\,\mathrm{d}y_{J,2}} = \sum_{\mathrm{a,b}} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_{\mathrm{a}}(x_1) f_{\mathrm{b}}(x_2) \frac{\mathrm{d}\hat{\sigma}_{\mathrm{ab}}}{\mathrm{d}|\mathbf{k}_{J,1}|\,\mathrm{d}|\mathbf{k}_{J,2}|\,\mathrm{d}y_{J,1}\,\mathrm{d}y_{J,2}}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_{J,1}|\,\mathrm{d}|\mathbf{k}_{J,2}|\,\mathrm{d}y_{J,1}\,\mathrm{d}y_{J,2}} =$$

$$= \int \mathrm{d}\phi_{J,1}\,\mathrm{d}\phi_{J,2} \int \mathrm{d}^2\mathbf{k}_1\,\mathrm{d}^2\mathbf{k}_2\, \Phi(\mathbf{k}_{J,1}, x_{J,1}, -\mathbf{k}_1) G(\mathbf{k}_1, \mathbf{k}_2, \hat{s}) \Phi(\mathbf{k}_{J,2}, x_{J,2}, \mathbf{k}_2)$$

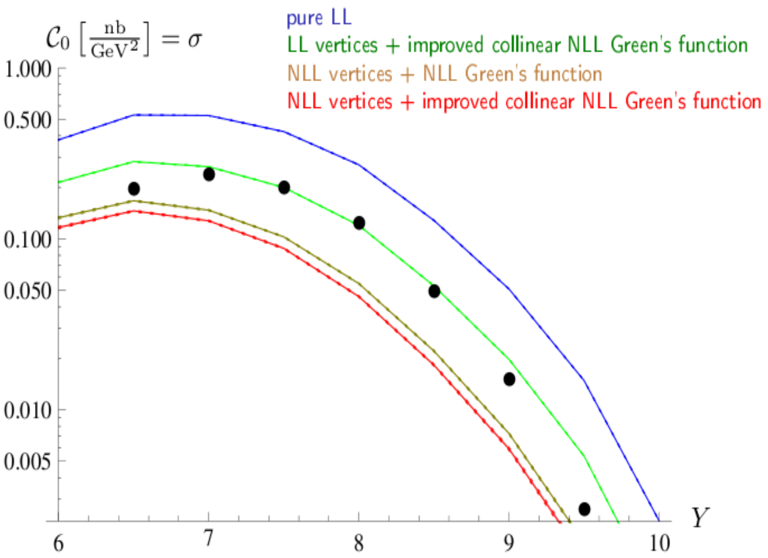
Forward physics investigations with production of jets.

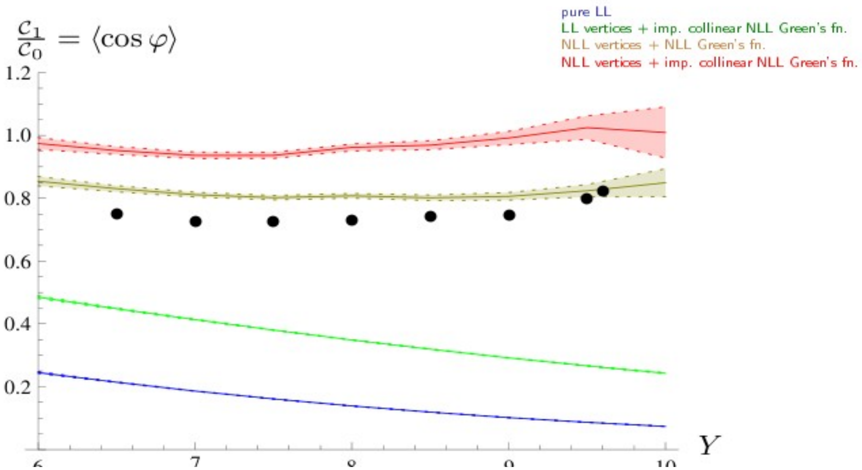
$$\frac{d\hat{\sigma}\left(\alpha_s, \mathrm{Y}, p^2\right)}{d\phi} = \frac{\pi^3\bar{\alpha}_s^2}{2p^2}\frac{1}{2\pi}\sum_{n=-\infty}^{\infty} e^{in\phi}\mathcal{C}_n\left(\mathrm{Y}\right)$$

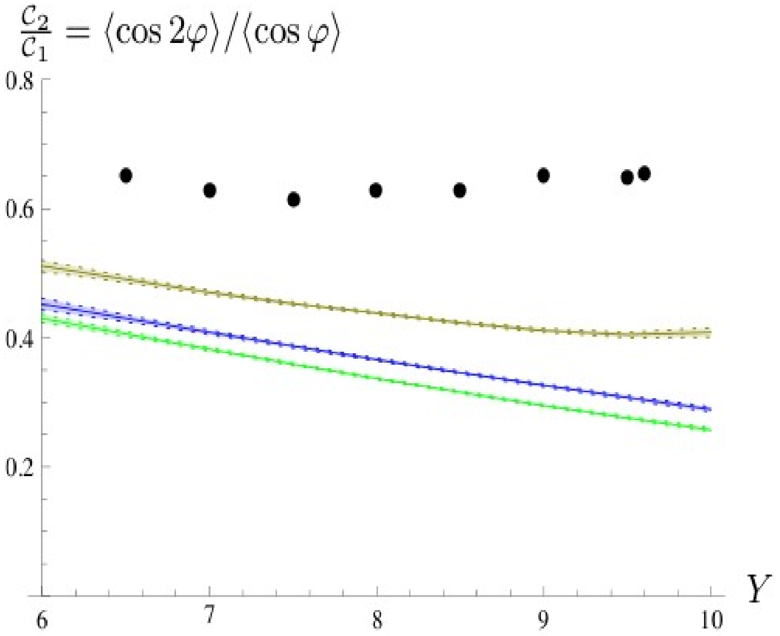
The higher n the more BFKL angenvalues contribute

$$\langle\cos(m\varphi)\rangle \equiv \langle\cos\left(m(\phi_{J,1}-\phi_{J,2}-\pi)\right)\rangle = \frac{\mathcal{C}_m}{\mathcal{C}_0}.$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_{J,1}|\,\mathrm{d}|\mathbf{k}_{J,2}|\,\mathrm{d}y_{J,1}\,\mathrm{d}y_{J,2}} = \mathcal{C}_0$$



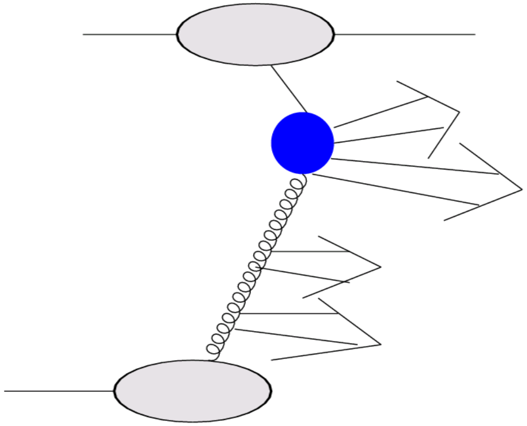




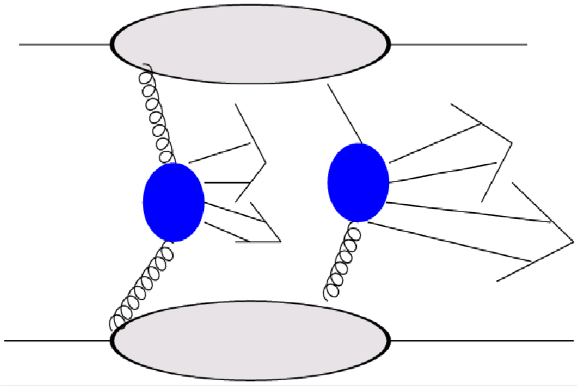
Is something missing?
Opened BFKL phase space but smaller cross section....
Position of jets not specified. Only collinear parton densities

Cross section as a function of the azimuthal difference for different rapidities

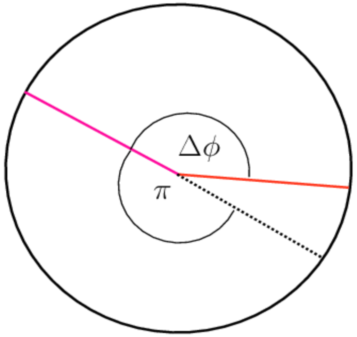
Deak,Jung,Hautmann, Kutak '10

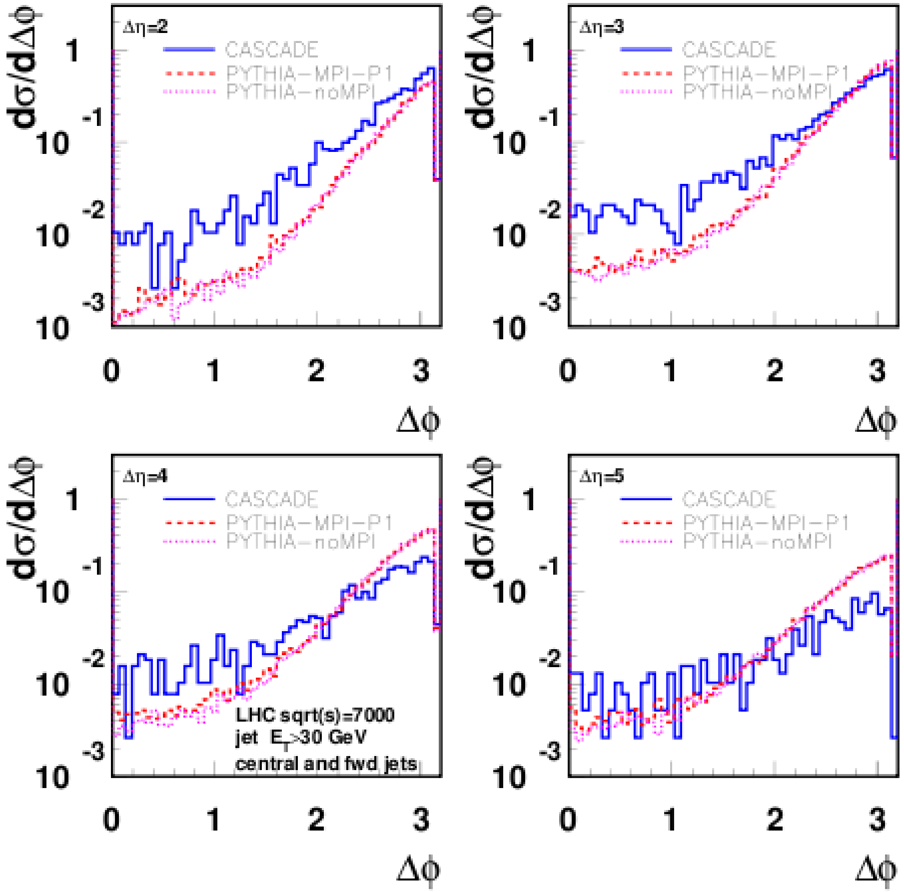


Single chain



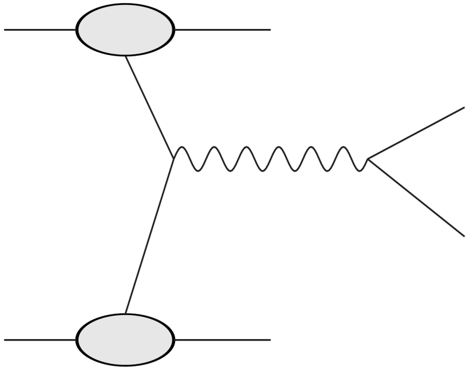
Multiple interactions



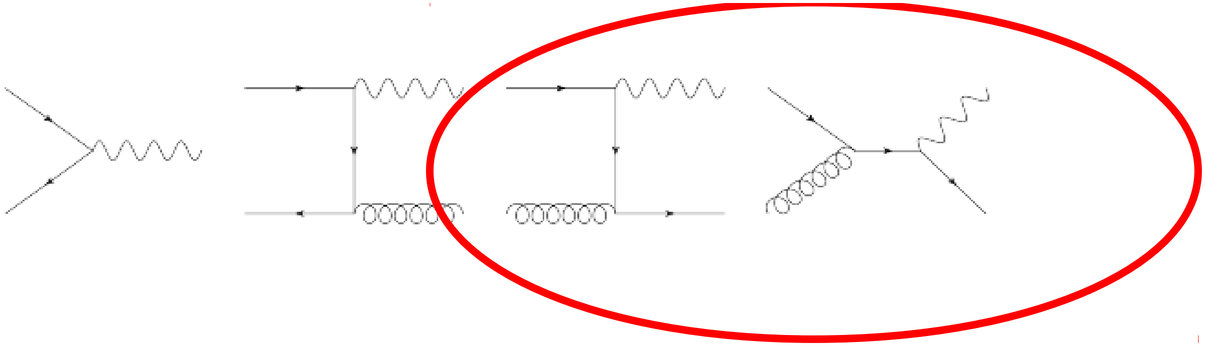


- Observable which measures jet activity in the parton shower
  - Noticeable differences between different approaches
    - More hard emissions in CASCADE therefore larger decorelations

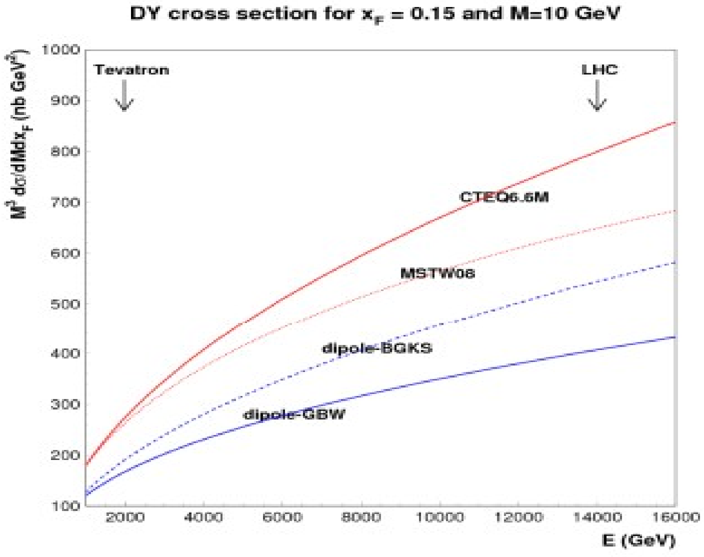
Forward physics investigations with production of Drell-Yan pairs



$$\sigma(\tau_h,Q^2)=\sigma_0(Q^2)\sum_{a,b=q_i,\bar{q}_j,g}\int_\rho^1\frac{dx_1}{x_1}\int_\rho^1\frac{dx_2}{x_2}D_{ab}\left(\frac{\tau_h}{x_1x_2};\alpha_s(Q^2)\right)F_a(x_1,Q^2)F_b(x_2,Q^2)$$



- process which probes quark densities probes gluon density at very small x
- interesting also because of limits coming from unitarity



$$x_2=\frac{M^2}{s\,x_1}\ll 1$$ enhanced

Golec-Biernat, Lewandowska, Stasto

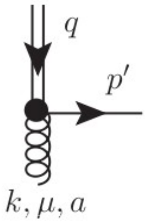
Forward physics investigations with production of Drell-Yan pairs.

Towards Monte Carlo with unintegrated quark densities

Hentschinski, Jung Hautman '11

- Off shell quarks Lipatov, Fadin '01
- At high energies effective degrees of freedom in high energy process with quark exchange in t channel
  - Here applied to $qg^* \longrightarrow Zq$

Effective vertex



$$= igt^a \left(\gamma^\mu - \not{q} \frac{(n^+)^\mu}{k^+} \right)$$

$$P_{qg}^{\mathsf{CH}}\left(z, \boldsymbol{k}^2, \boldsymbol{q}^2\right) = T_R \left(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(1-z)\boldsymbol{k}^2} \right)^2 \left[P_{qg}(z) + 4z^2(1-z)^2 \frac{\boldsymbol{k}^2}{\boldsymbol{q}^2} \right]$$

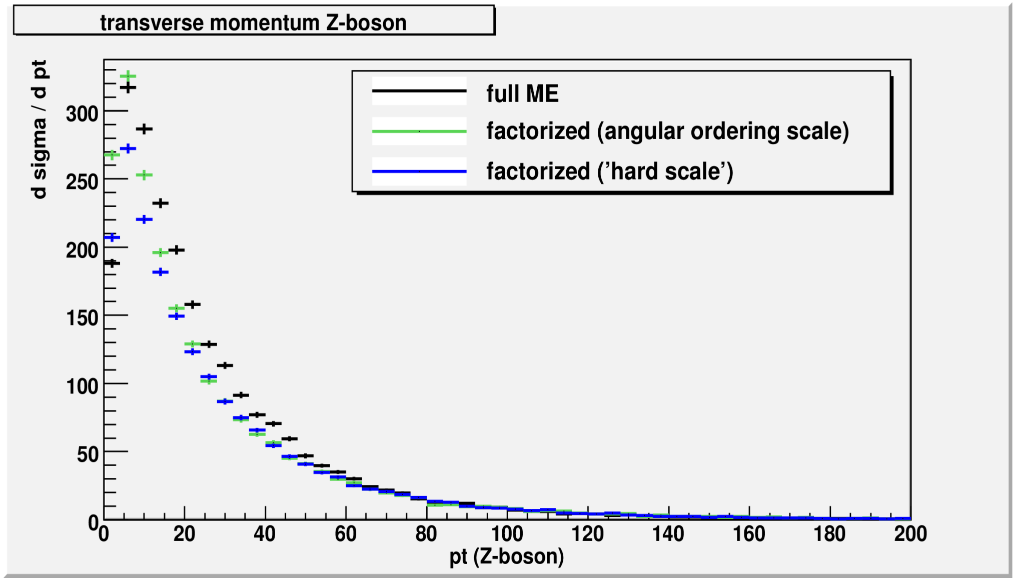
Forward physics investigations with production of Drell-Yan pairs.

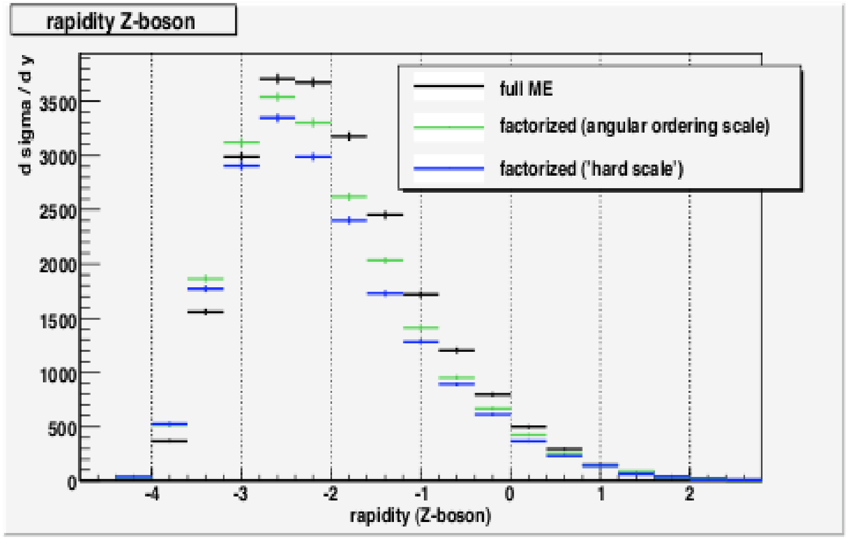
Towards Monte Carlo with unintegrated quark densities

Suplement CCFM evolution equation by gluon-quark splitting at the last step

$$P_{qg}^{\mathrm{CH}}\left(z,\boldsymbol{k}^2,\boldsymbol{q}^2\right) = T_R\left(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(1-z)\boldsymbol{k}^2}\right)^2\left[P_{qg}(z) + 4z^2(1-z)^2\frac{\boldsymbol{k}^2}{\boldsymbol{q}^2}\right]$$

Z production with quark jet





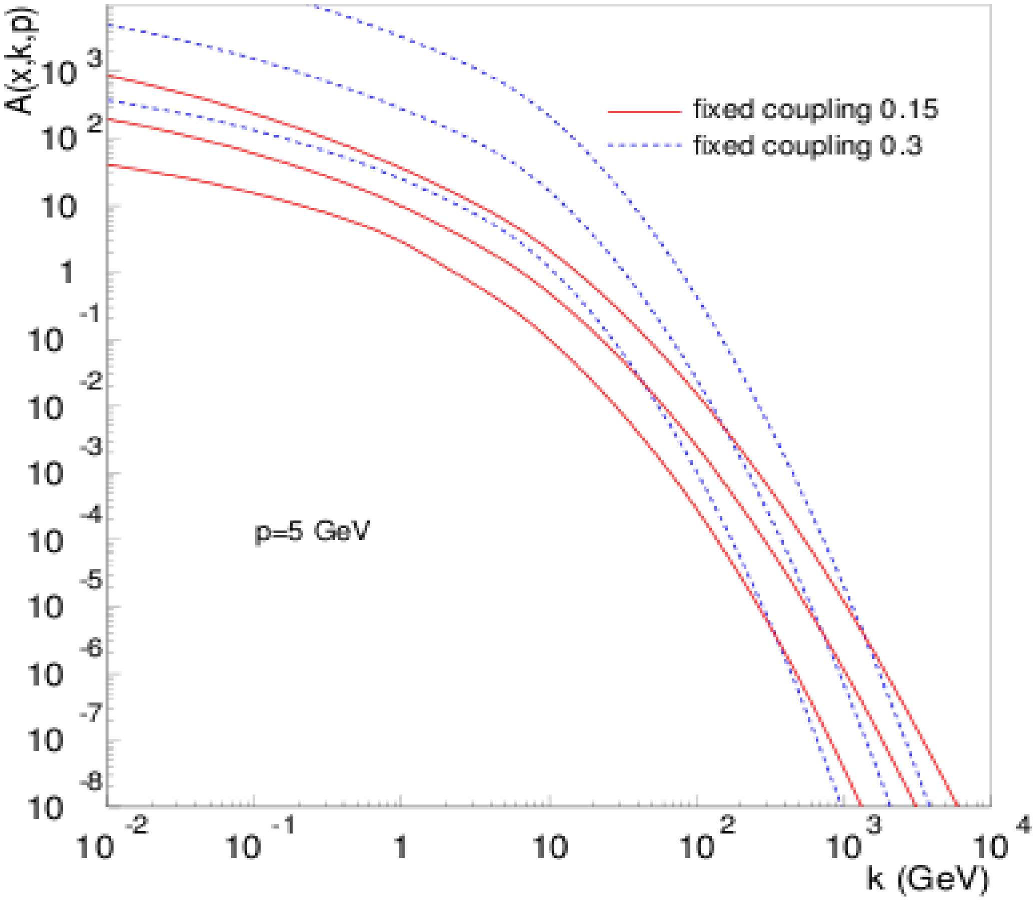
Forward physics and saturation

- At forward rapidity, target might be a dense eventually saturated system. However, probably not in proton-proton

- Indications of a rapid evolution of the wave BRAHMS data on d-AU collisions, and the disappearance of the Cronin peak at increasing rapidity.

- Existence of the Cronin peak and its disappearance with increasing rapidity indications of CGC.

Towards dense partonic system and eventual saturation



From Avsar, Stasto '10

$$\sigma_{\rm tot} \overset{E\to\infty}{\leq} \ln^2 E$$

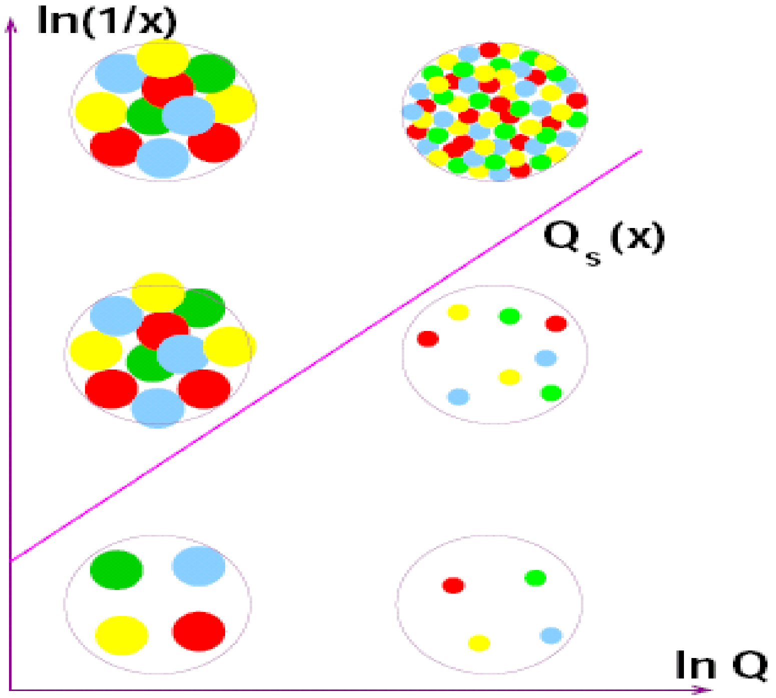
BFKL and CCFM are linear and predict strong growth of number of gluons. The growth has to be stopped.

High energy factorization and saturation

Saturation – state where number of gluons stops growing due to high ocupation number

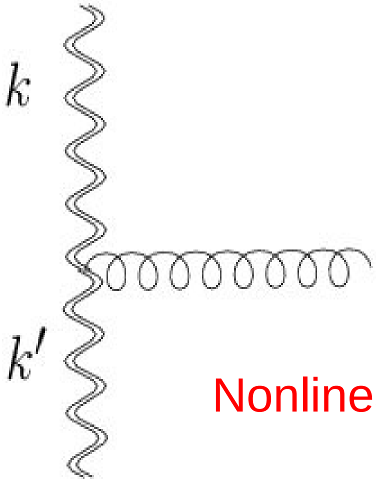
Cross sections change their behaviour from power like to logarithmic like.

Gribov, Levin, Ryskin '83

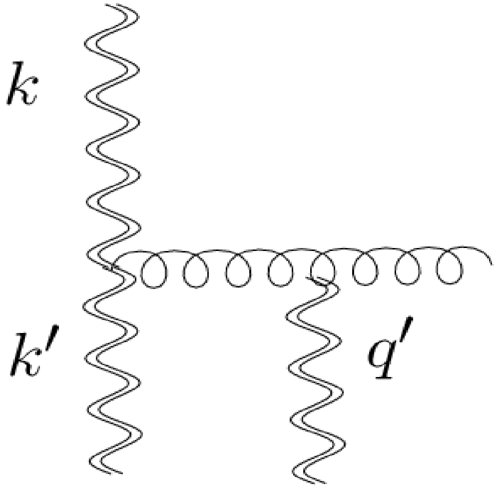


On microscopic level it means that gluon apart from

splitting



recombination

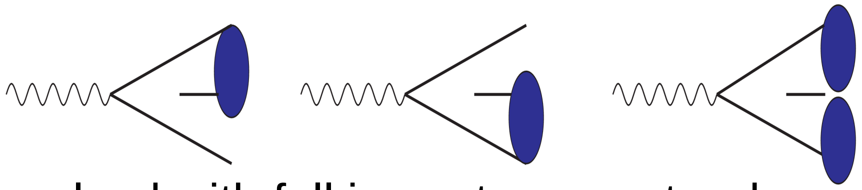


Nonlinear evolution equation BK

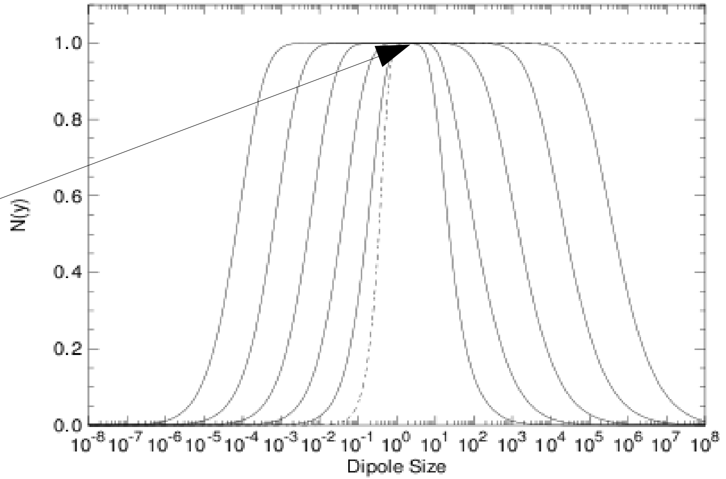
Balitsky, Kovchegov

Simple evolution equation with nonlinearities

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2\underline{r}_1 \; K(\underline{r},\underline{r}_1,\underline{r}_2)\,[\mathcal{N}(r_1,x)+\mathcal{N}(r_2,x)-\mathcal{N}(r,x)-\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

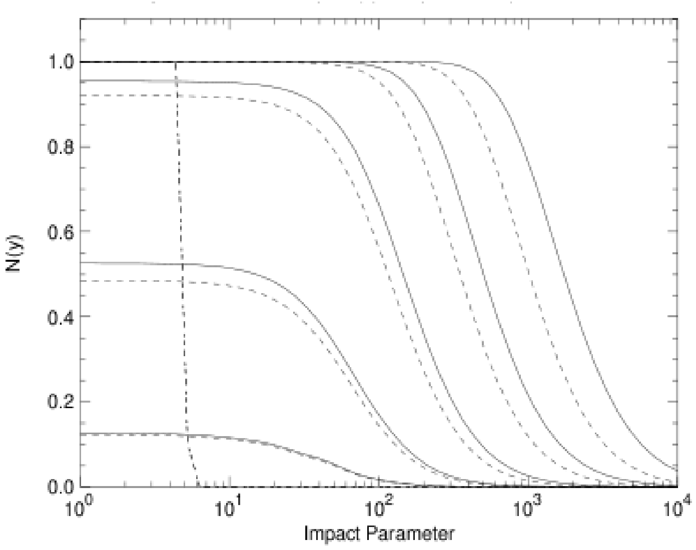


Recently solved with full impact parameter dependence

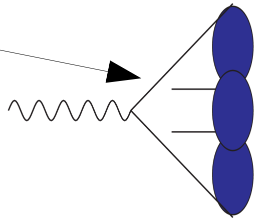


Nonlinear term allows for saturation

Gluon density obtained from:



BK is at present known up to NLO
where such transitions are possible

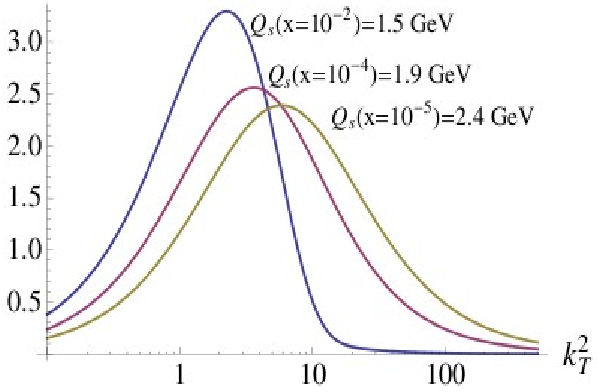


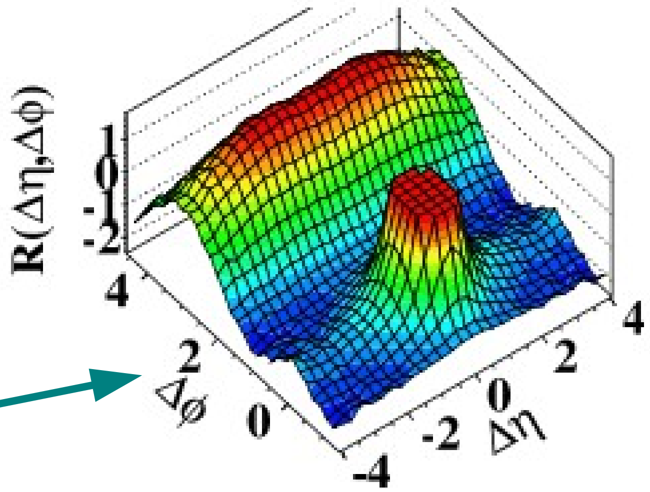
Unintegrated gluon density in saturated region

Possible determination of shape of gluon?
Finally with LHC we can probe gluon

Ridge observed at CMS in 2010

Dumitru, Venugopalan, Gellis McLerran, Lapp '10i





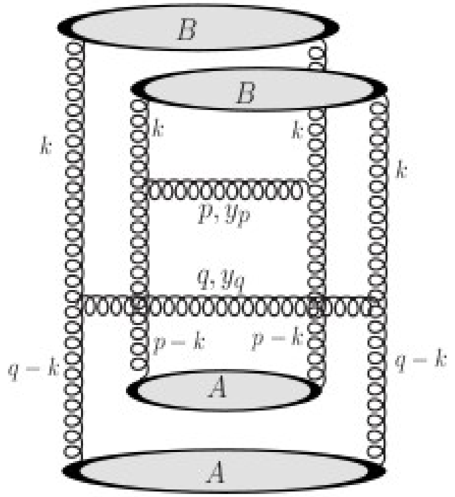
The maximum of glue essential for

$$\varphi(k,x,b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3}\int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\,\nabla^2_{\mathbf{r}}\mathcal{N}_G(r, Y=\ln(x_0/x), b)$$

$$\mathcal{N}_G(r,x) = 2\mathcal{N}(r,x) - \mathcal{N}^2(r,x)$$

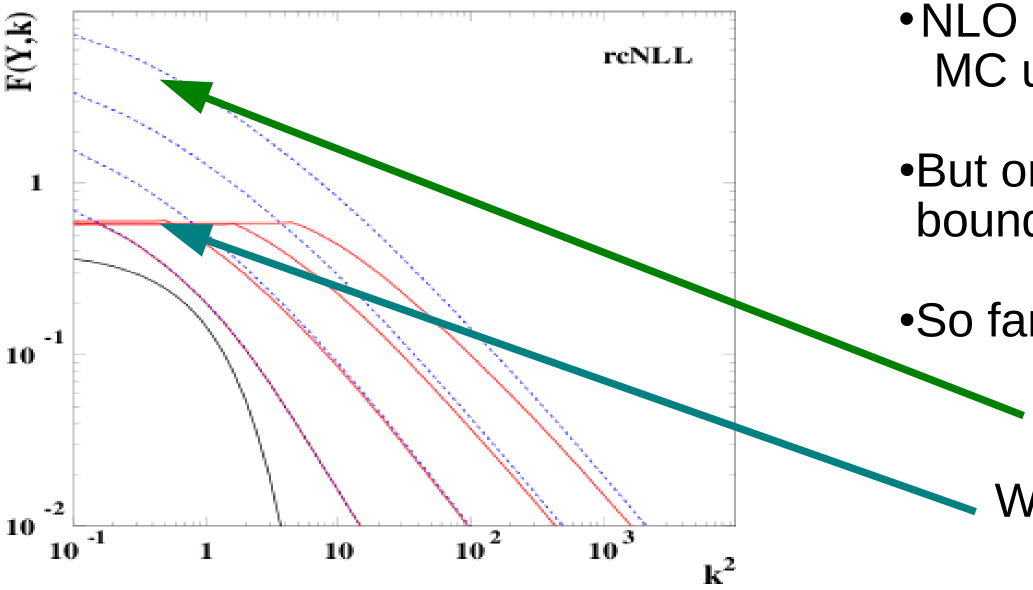
$$|\mathbf{p}_\perp - \mathbf{k}_\perp| \sim Q_s$$

$$|\mathbf{q}_\perp - \mathbf{k}_\perp| \sim Q_s$$



But at least 10 more possible
explanations: Levin, Razaian; Pierog,..

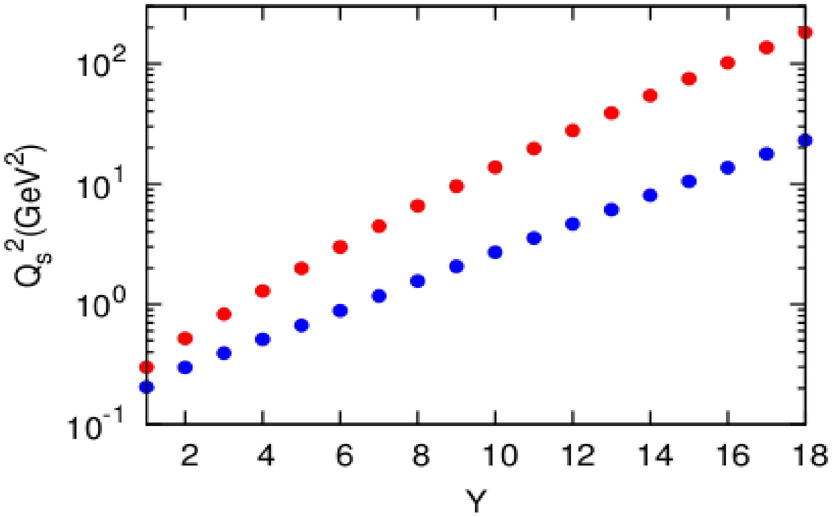
Unitarity corrections via boundary conditions in NLOBFKL



- NLO BK might be difficult for eventual MC usage
- But one can use the absorptive boundary method.
- So far non MC implementations

BFKL

With absorptive boundary

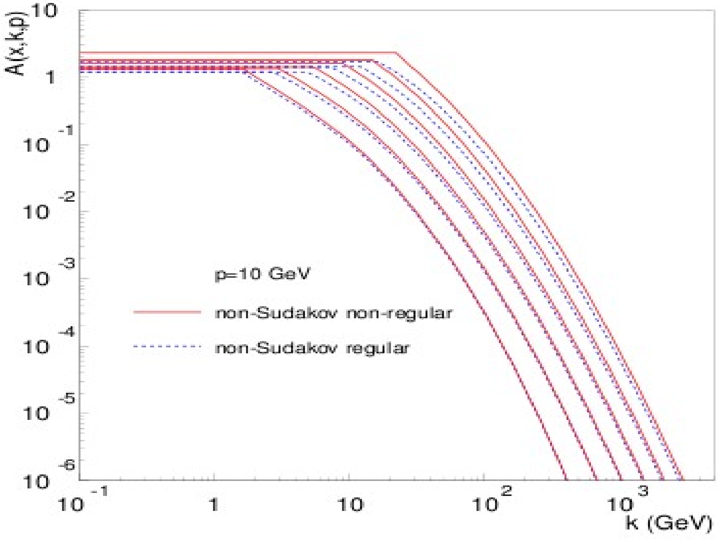


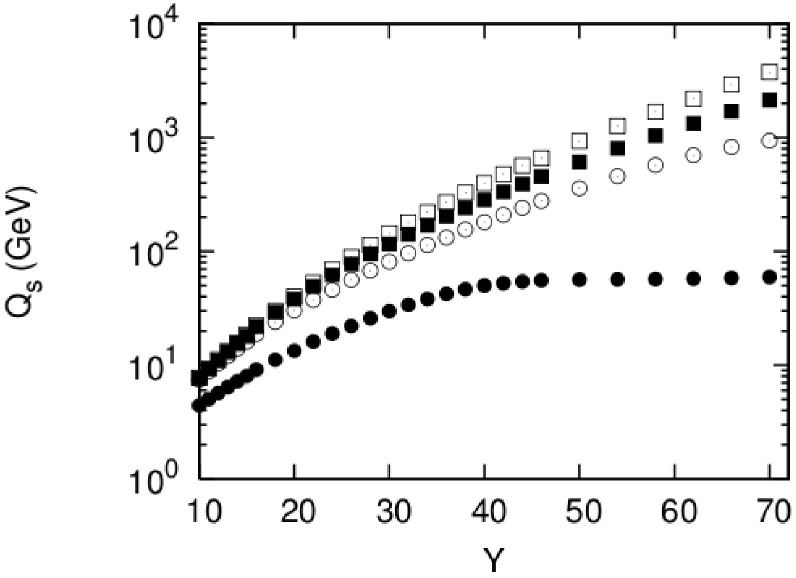
Define such condition for combination of Y and k that F(Y,Qs)~1 where Qs=Qs(Y,k). F(Y,k<Qs) is set to constant

LO accuracy and NLO

Mueller, Triantafulopulous '03
Avsar, Stasto '10

Unitarity corrections via boundary conditions in CCFM





In CCFM there is an issue of different forms of non-Sudakov form factor – virtual contribution relevant at small kt. Saturation makes this region not to contribute.

Saturation scale saturates itself because of limited phase space due to existence of hard scale

From Avsar, Stasto

Kutak, Jung '09
Avsar, Iancu '09
Avsar, Stasto 10

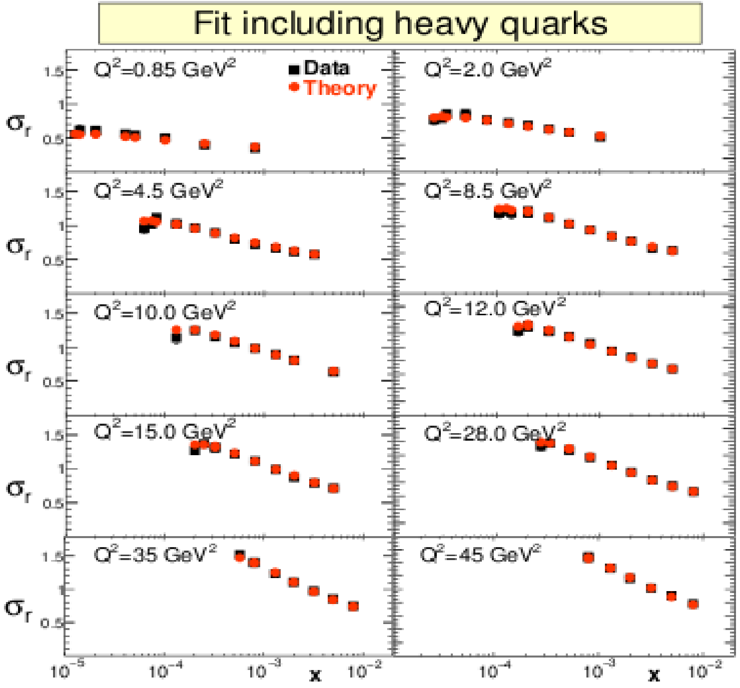
Balitsky-Kovchegov equation as a phenomenology tool

Framework of AAMQS J. Albacete, Armesto,Quiroga,Milhano, Salgado '09

- Running coupling constant – Balitsky's prescription
- Solution in coordinate space
- Fit with heavy and light quarks
- Translational approximation for target's shape
- Initial conditions – MV, GBW
- Fit to latest H1, ZEUS combined data, light and heavy flavors
- Limited to not too large kt as BFKL

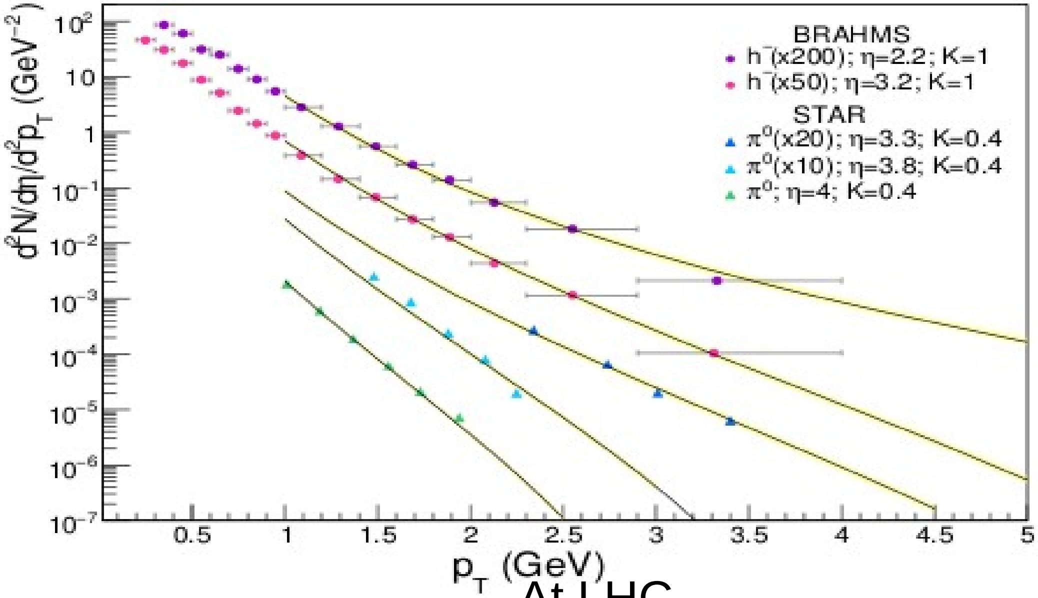
BK applied to e-p , and p-p

Albacete, Marquet '10

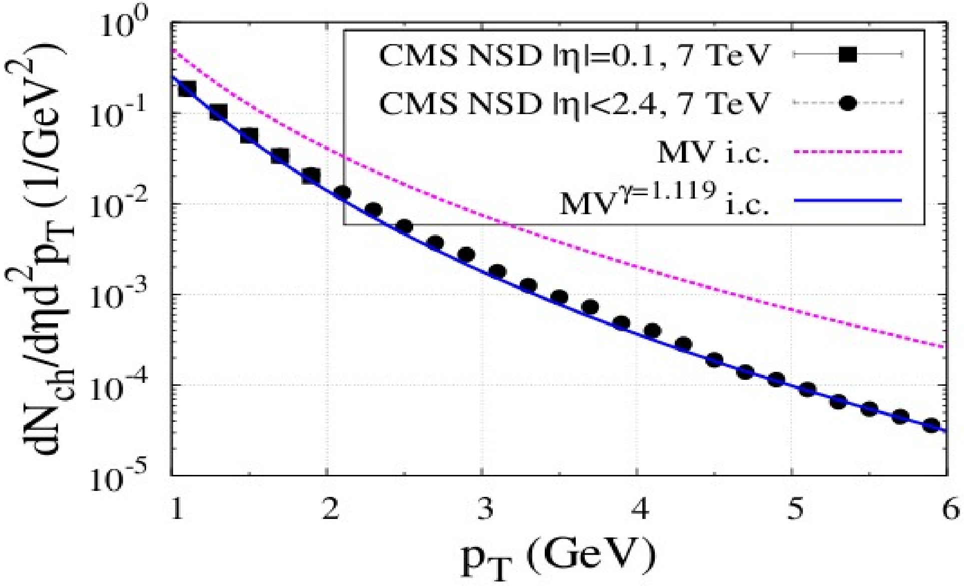


Very good description of inclusive processes

At RHIC



At LHC



Forward physics way to constrain gluon both at large and small pt

Kutak, Sapeta in preparation

KMS

- BFKL + nonsingular pieces of splitting function + kinematical constraint + quarks

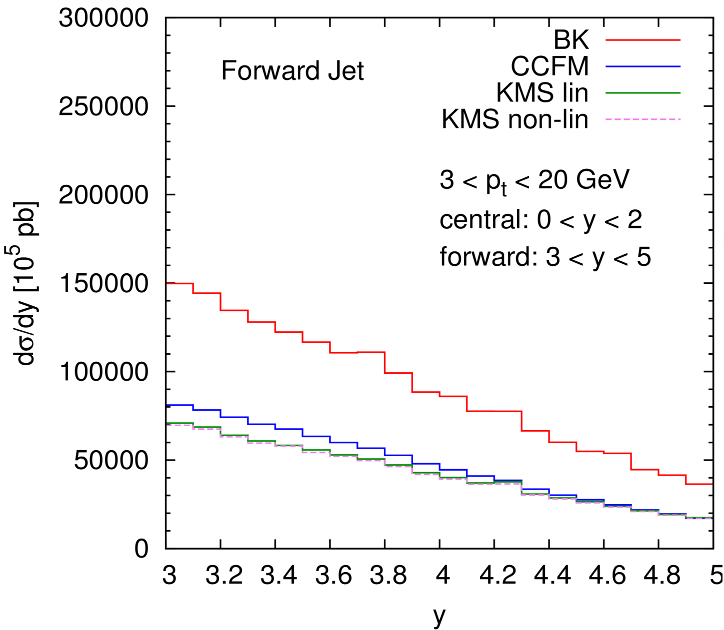
Martin, Kwiecinski, Stast '97

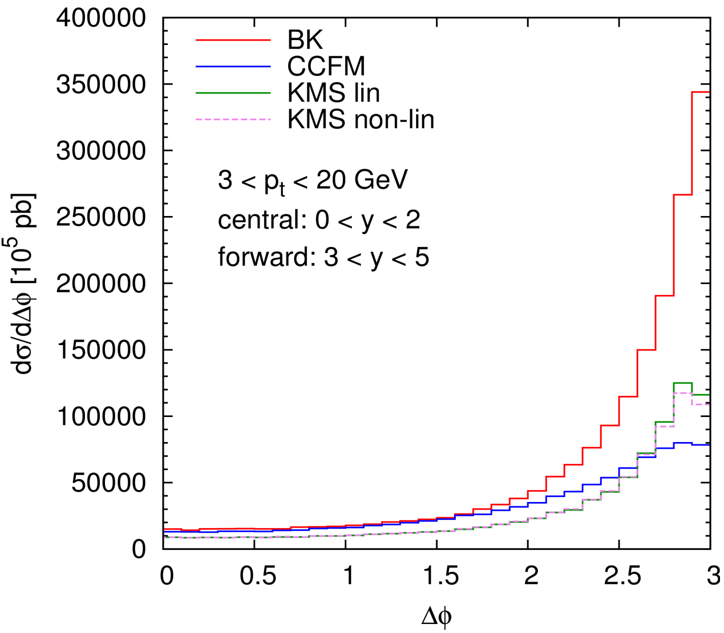
KKS

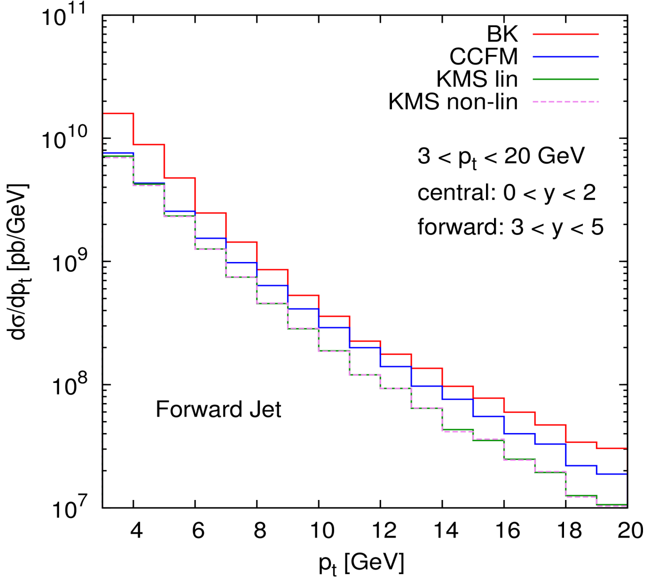
- BK + nonsingular pieces of splitting function + kinematical constraint + quarks

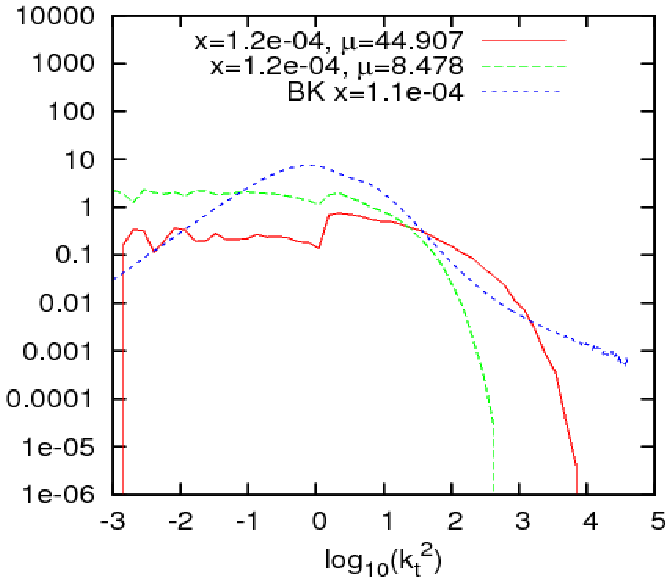
Kutak,Kwiecinski, Stast '03

Importace of other NLO corrections.



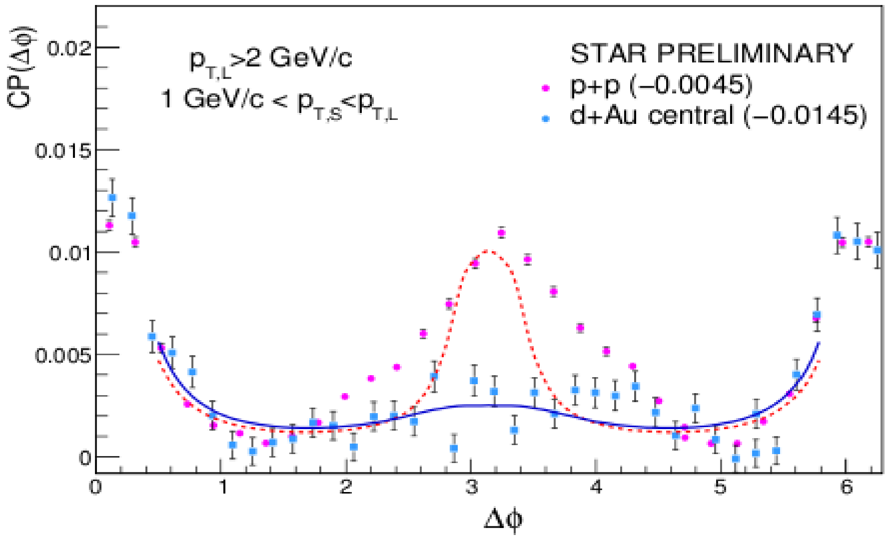






Saturation and production of forward dijets in d-Au at RHIC

Features: studies allow for direct studies of
saturation effects of the correlation function.
In d-Au no smearing due to collecive flow as in A A



$$CP(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}$$

$$N_{pair}(\Delta\phi) = \int_{y_i,|p_{i\perp}|} \frac{dN^{pA\to h_1h_2X}}{d^3p_1d^3p_2}$$

$$N_{trig} = \int_{y,\ p_\perp} \frac{dN^{pA\to hX}}{d^3p}$$

Albacete, Marquet

- Marquet, Albacete

$$\frac{dN^{qA\to qgX}}{d^3kd^3q} = \frac{\alpha_S C_F}{4\pi^2}\,\delta(xP^+-k^+-q^+)\,F(\tilde{x}_A,\Delta)\sum_{\lambda\alpha\beta}\left|I^\lambda_{\alpha\beta}(z,k_\perp-\Delta;\tilde{x}_A)-\psi^\lambda_{\alpha\beta}(z,k_\perp-z\Delta)\right|^2$$

Genarlizes kt factorization

- Tuchin

$$\varphi(x,q^2) = \frac{1}{2\pi^2}\frac{S_\perp C_F}{\alpha_s}\left(1-e^{-Q_s^2/q^2}\right)(1-x)^4$$

KLN approach. Model for gluon
density. Gluon does not vanish at small kt.

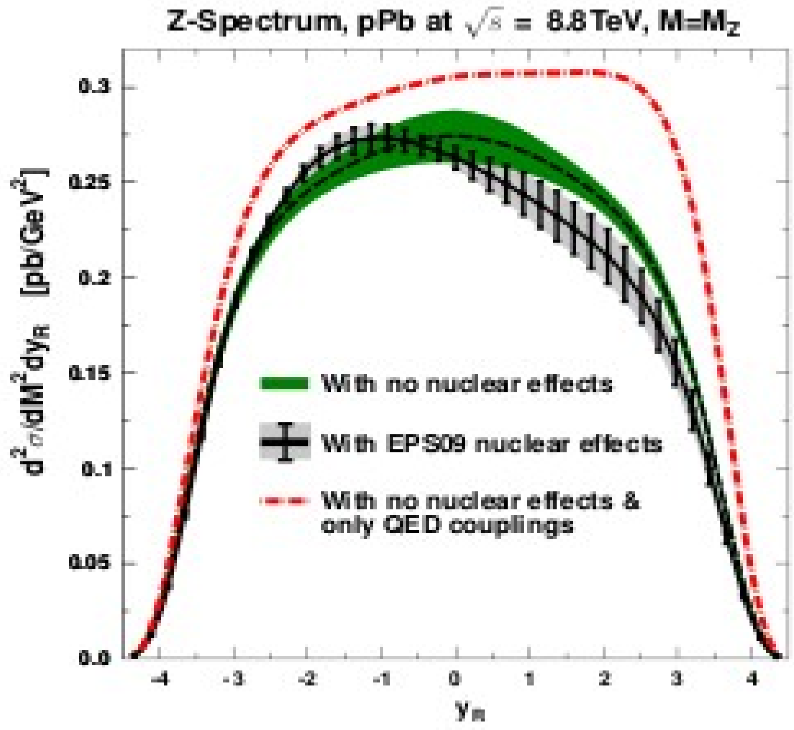
Towards p-Pb at LHC

•Studies of nuclear parton distribution functions (Kumano, Nagai '07; Salgago, Eskola Paukkunen).

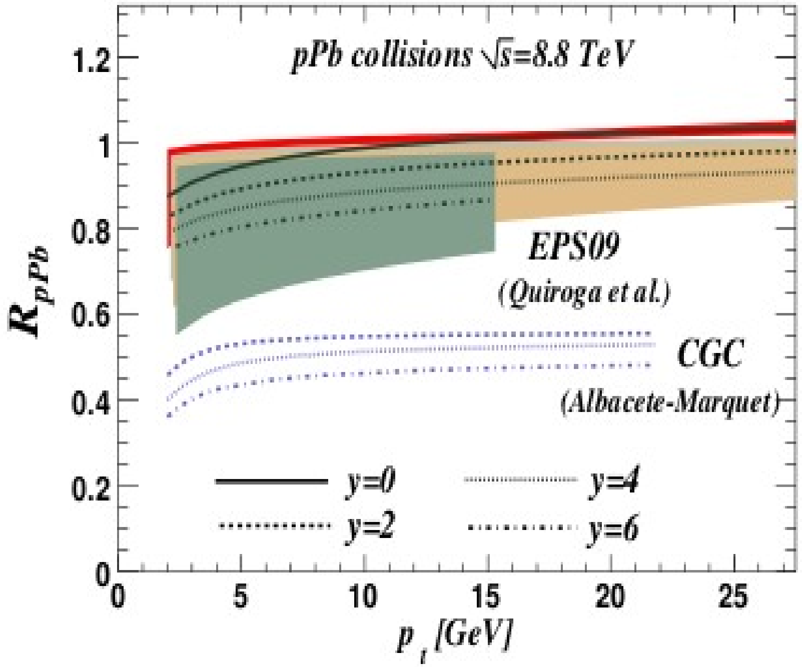
- Check of validity of collinear factorization. Izospin corrections negligible in Z/W production Pb-Pb. Hot QCD effects which wash-out most of information

•J/psi suppression,

• Jet quenching

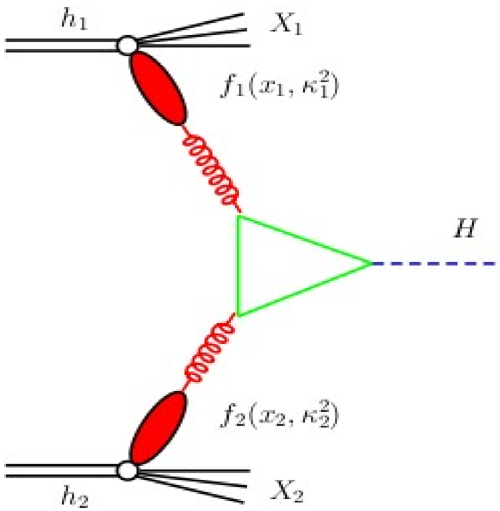


Distribution of di-muon pairs



Nuclear modification factor

Update on diffractive Higgs production

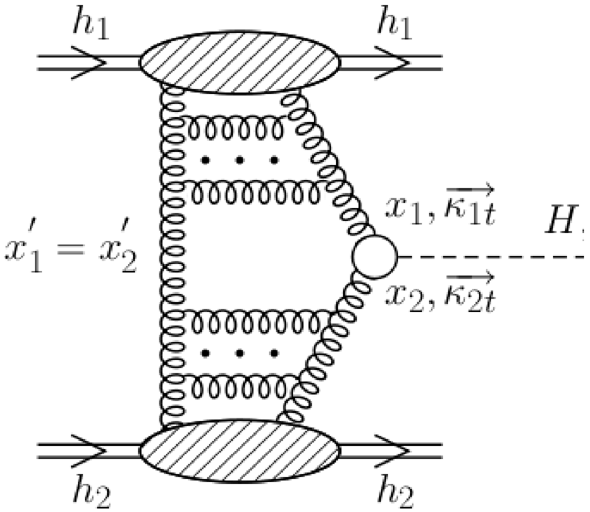


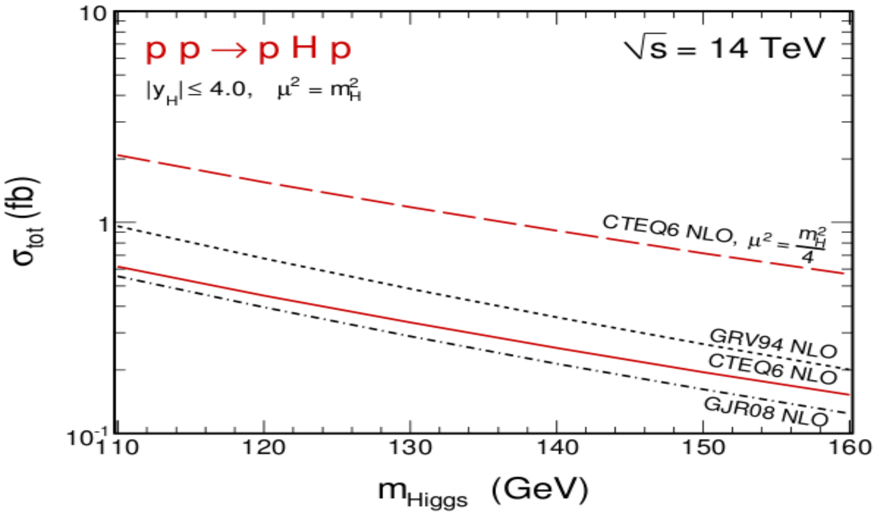
Standard search for Higgs boson in inclusive processes. X means a complicated final state with many mesons

- The dominant mechanism is gluon-gluon fusion
- Several decay channels of interest

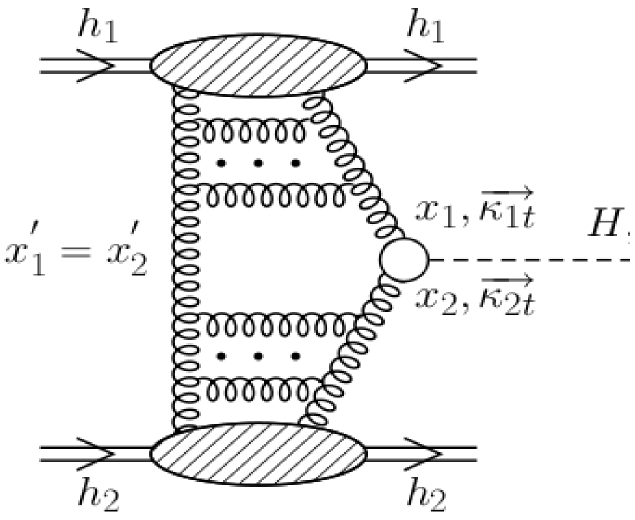
Exclusive reaction

- Search for Higgs primary task for LHC
- Diffractive production of the Higgs boson an alternative to inclusive production
- Drawback low rate ~0.4 fb

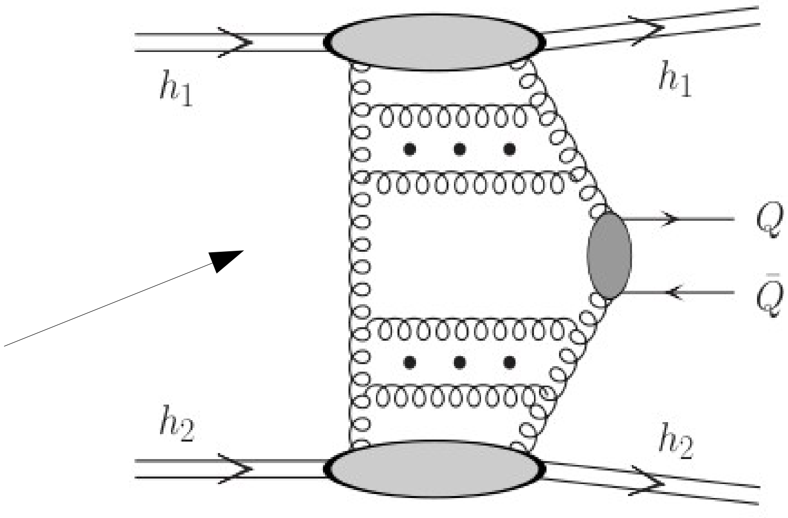




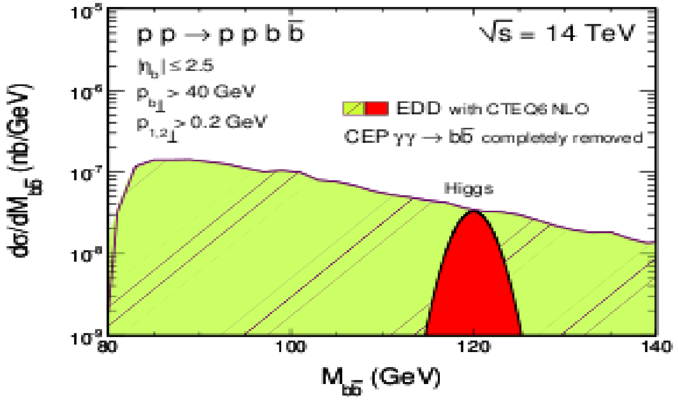
Update on diffractive Higgs production



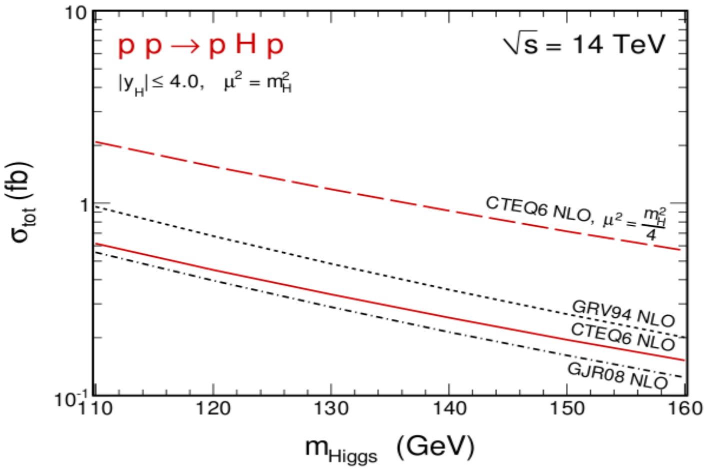
background



Both calculated in high energy factorization approach with off shell gluons.
No approximation to ggttH vertex



Large background



Maciula, Pasechnik, Szczurek '10

Conclusions

- LHC opens phase space for large center-of -mass energies and for presence of multi-scales
- Already we have interesting results from LHC
- We have tools to ask and try to answer for questions
- Many, new challenging issues ahead