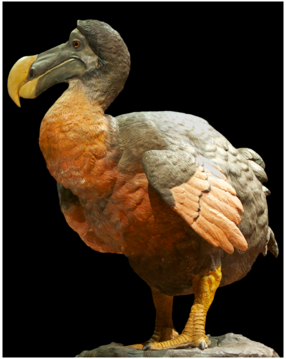
Looking for saturation in UPC vector meson and $c\bar{c}$, $b\bar{b}$ production at the LHC

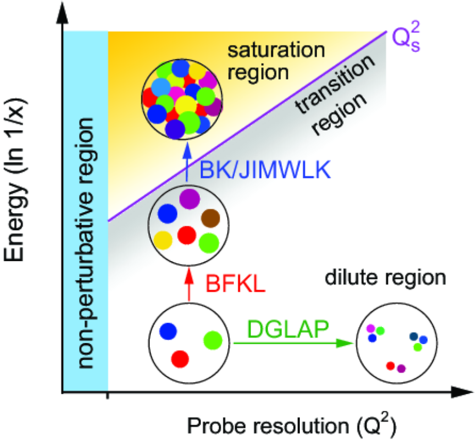
Christophe Royon
University of Kansas, Lawrence, USA
EMMI workshop on saturation

July 6-10 2026, GSI, Germany



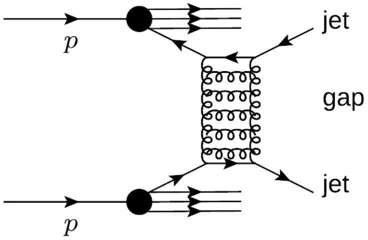
- Vector meson production (J. Penttala, CR, ArXiv 2411.14815; Phys. Lett. B 864 (2025) 139394)
- Have we seen saturation in Pb Pb data at the LHC?
- Charm and beauty production (J. Vierros, J. Penttala, CR)

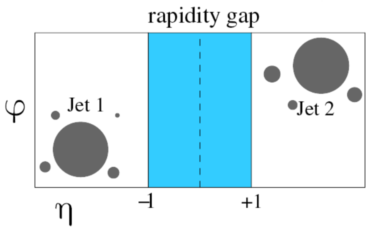
Looking for BFKL resummation /saturation effects



- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2, resums terms in $\alpha_S \log Q^2 \to$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x, resums terms in $\alpha_S \log 1/x \to$ Large parton densities at small x
- Saturation region at very small x
- Important to understand QCD evolution, parton densities

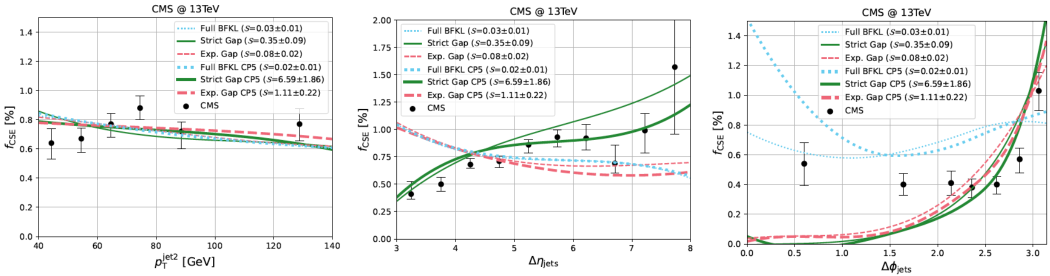
Mueller Tang: Gap between jets at the Tevatron and the LHC





- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA Monte Carlo

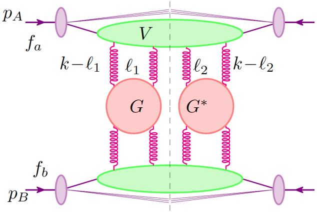
Jet gap jet measurements at the LHC (CMS@13 TeV)



- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Good agreement with theory with "strict" gap definition (C. Baldenegro, P. Gonzalez Duran, M. Klasen, C. Royon, J. Salomon, JHEP 08 (2022) 250)

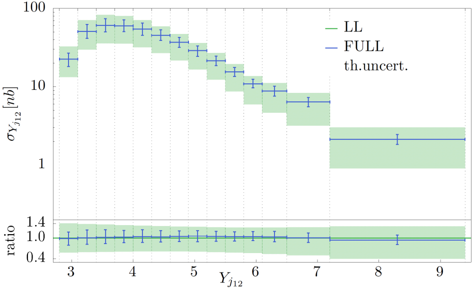
Jet gap jet: Full NLO BFKL calculation including NLO impact factor

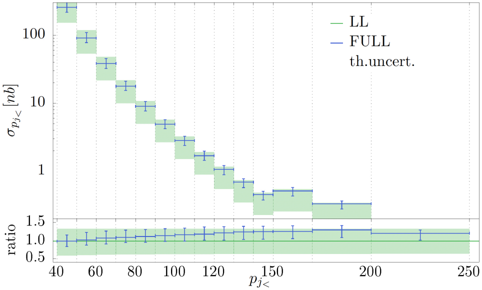
- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)



- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, JHEP 06 (2023) 091

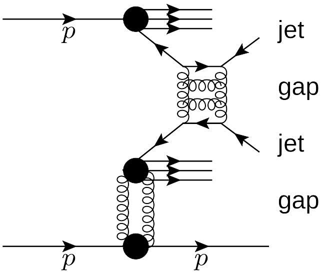
Effect of NLO impact factor on jet gap jet cross section: final results

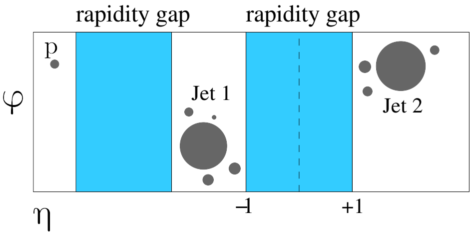




- Higher cross section by 20% at high p_T and small effect on the y dependence
- Total uncertainties are much smaller at NLO: 15-20%

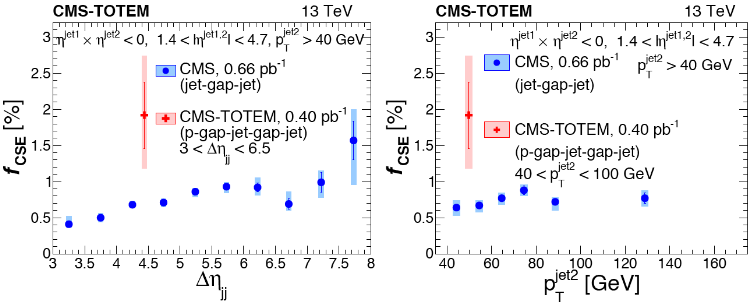
Jet gap jet events in diffraction (CMS/TOTEM)





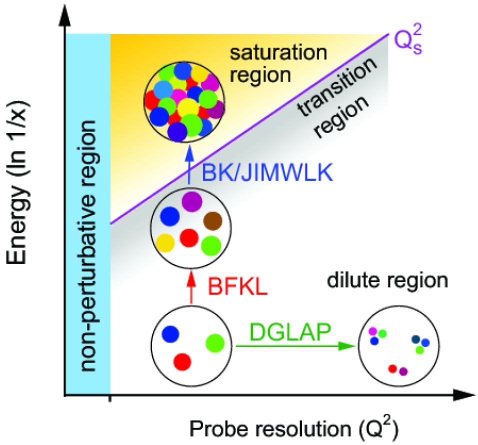
- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

First observation of jet gap jet events in diffraction (CMS/TOTEM)



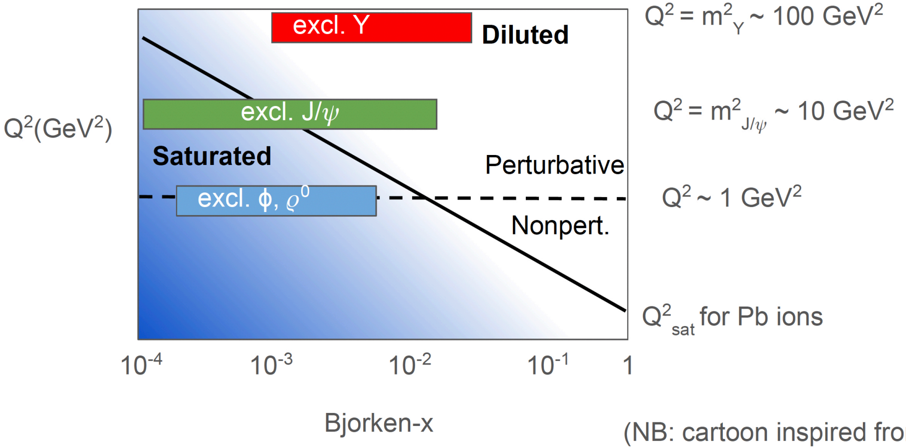
- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

Looking for BFKL resummation /saturation effects



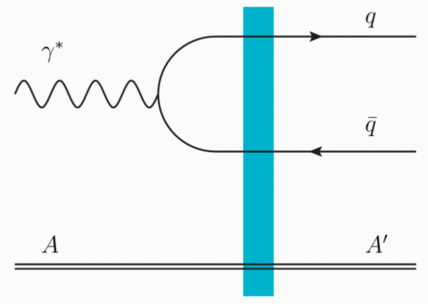
- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2, resums terms in $\alpha_S \log Q^2 \rightarrow$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x, resums terms in $\alpha_S \log 1/x \rightarrow$ Large parton densities at small x
- Saturation region at very small x
- Important to understand QCD evolution, parton densities

Looking for saturation effects: vector meson channel



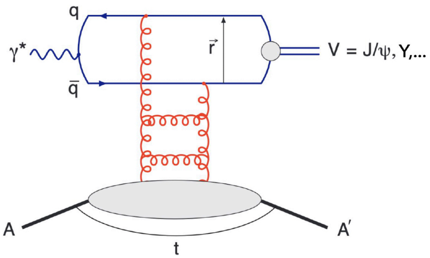
(NB: cartoon inspired from Wei's plot)

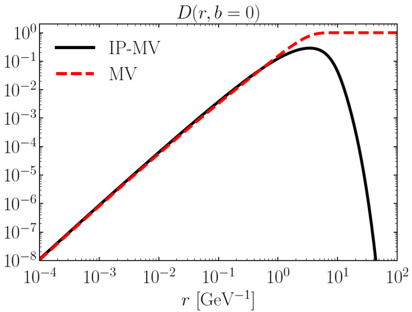
Cross section computation: the case of γPb



- The process can be factorized in two parts: 1. The photon fluctuates into a quark-antiquark pair; 2. The quark-antiquark pair interacts with the target hadron
- The first part is described by the light-cone wave function of the photon, can be computed perturbatively
- The second part of the process is given by the dipole scattering amplitude which is non-perturbative
- However, its energy dependence can be described using perturbative evolution equation (BFKL or BK) and the dipole amplitude must be fitted to measurement data at some initial energy scale

Looking for saturation: vector meson production

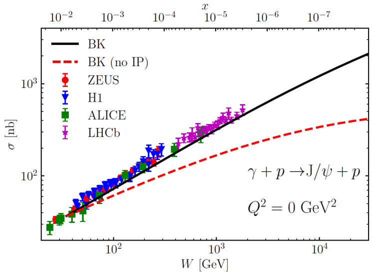


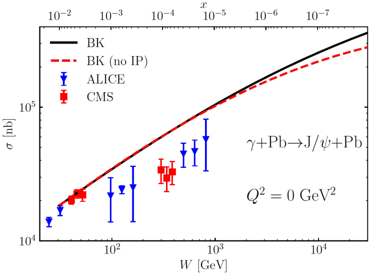


- Compute exclusive vector meson production in γp (HERA, EIC and pPb LHC) and γPb (EIC and Pb Pb LHC) where we probe the gluon density in p or Pb
- Saturation effects are expected to happen in Pb Pb, not in p Pb
- Computation: Factorize the $\gamma \to q\bar{q}$ part from the coupling to the proton: cross section proportional to $(xG)^2$ at LO
- Take into account b impact parameter dependence in dipole amplitude

High energy evolution

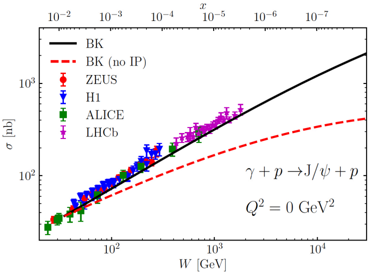
$$\partial_Y D(\mathbf{x}_0,\mathbf{x}_1,Y) = \int \mathrm{d}^2\mathbf{x}_2\, K_{\mathrm{BK}}(\mathbf{x}_0,\mathbf{x}_1,\mathbf{x}_2)\Big[D(\mathbf{x}_0,\mathbf{x}_2,Y) + D(\mathbf{x}_2,\mathbf{x}_1,Y) - D(\mathbf{x}_0,\mathbf{x}_1,Y) - D(\mathbf{x}_0,\mathbf{x}_2,Y)D(\mathbf{x}_2,\mathbf{x}_1,Y)\Big]$$

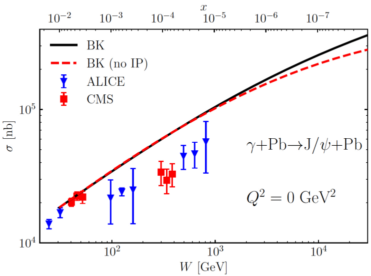




- Use Balitsky Kovchegov (BK) equation to describe the dipole evolution (so including saturation effects)

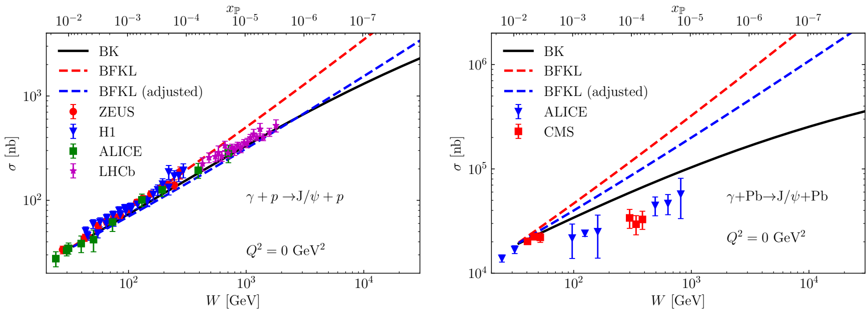
High energy evolution



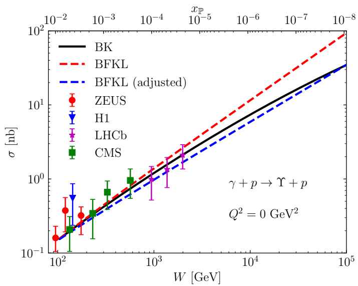


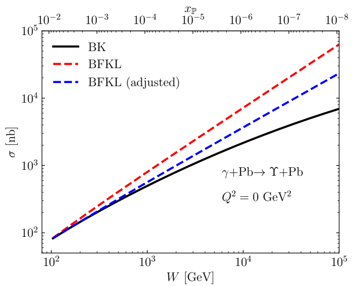
- Huge difference between taking into account b impact parameter dependence or not for γp (H. Mäntysaari, J. Penttala, F. Salazar, B. Schenke, Phys. Rev. D 111 (2025))
- Much smaller differences for γPb: nucleus much larger than proton and neglecting impact parameter dependence is more justified
- Possibility to determine effects of saturation by neglecting the gluon recombination term in BK: equivalent of linear BFKL equation

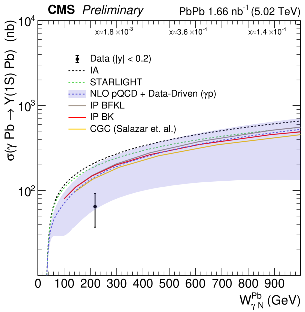
Looking for saturation: J/Ψ vector meson production



- BFKL and BK CGC predictions taking into account b-dependence (J. Penttala, C. R.)
- J/Ψ production in pPb: small differences between BK and BFKL, BK slightly favored
- Large differences between BK and BFKL in PbPb collisions

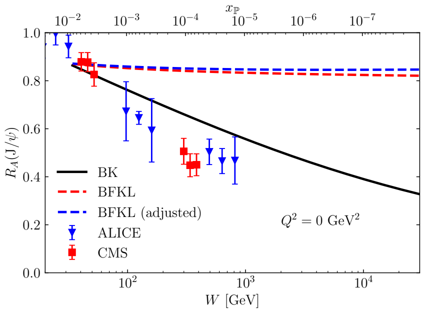


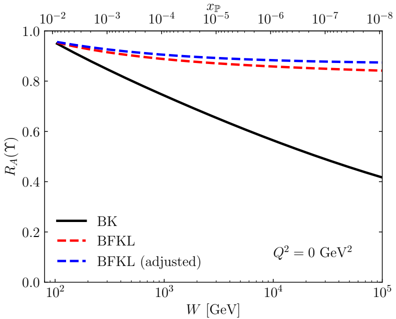




- Υ vector meson production: smaller differences between BFKL and BK in pPb or PbPb collisions
- Looking for additional observables: charm, etc

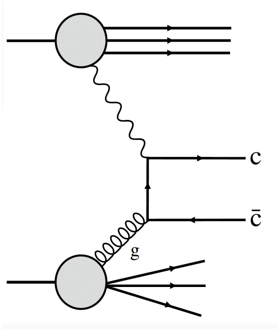
Looking for saturation: J/Ψ and Υ nuclear suppression factor





- Large nuclear suppression factor for J/Ψ in PbPb collisions
- Have we seen saturation in Pb Pb?
- Importance to have precise measurements of pp interactions as a reference at the same $\sqrt{s}$

J/Ψ, Υ, c and b productions: observables for saturation

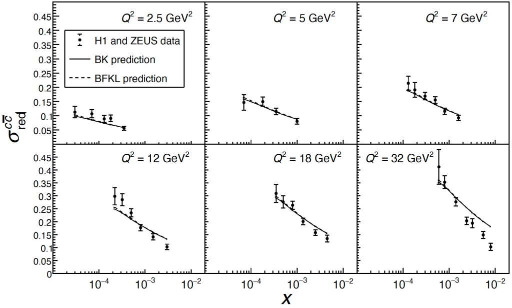


- What do we need to see saturation at the LHC?
- γPb c, b, J/Ψ are ideal probes for low-x physics

$$x = \frac{m_{c\bar{c}}}{\sqrt{s_{NN}}} \exp(-y_c)$$

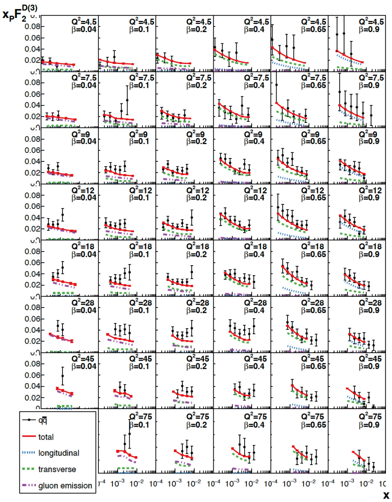
- We can reach low x values of 10^{-4} or smaller
- We need a low scale (to be below Q_S), and this is why c or b where one can go to very low p_T or J/Ψ (low mass vector mesons) are ideal while still being in the perturbative region
- $d\sigma/dW$ is the best observable while $d\sigma/dy$ presents the difficulties to mix up low and high x

Charm production at HERA in γp interactions



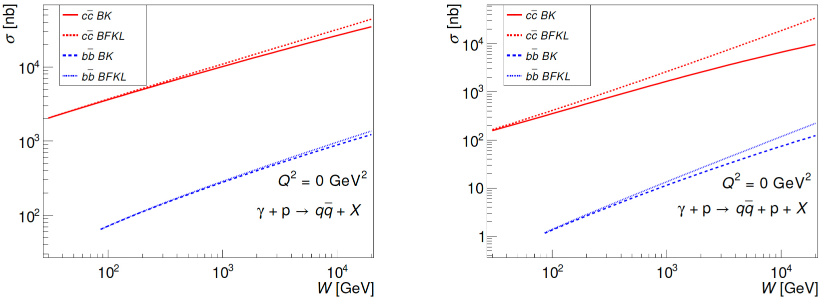
- Comparison between $F_2^{c\bar{c}}$ as measured at HERA with our parameter-free model (parameters of dipole densities at the starting scale fitted to vector meson data measurements at HERA)
- Leads to a fair description of data at low x, Q^2

Comparison with F_2^D measurements at HERA



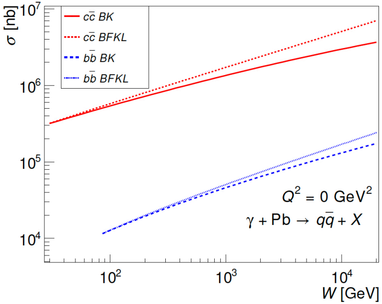
- Comparison between F_2^D measurements at HERA and our parameter free predictions (parameters of dipole densities at the starting scale fitted to vector meson data measurements at HERA)
- Leads to a fair description of data
- $q\bar{q}g$ term taken from Cyrille Marquet et al., https://arxiv.org/abs/0706.2682

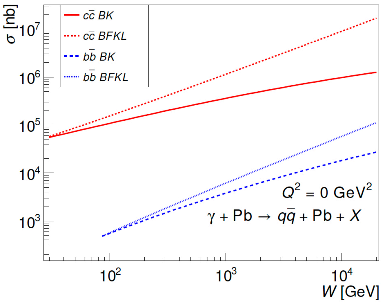
$c\bar{c}$ and $b\bar{b}$ productions: pPb interactions



- Left: inclusive $c\bar{c}$ and $b\bar{b}$ production; Right: diffractive production
- As expected, small effect of saturation in p Pb
- Work done in collaboration with Jarno Vierros, Jani Penttala, CR

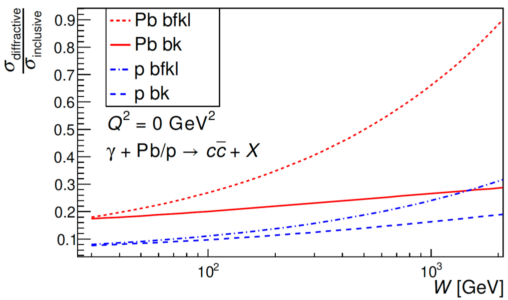
$c\bar{c}$ and $b\bar{b}$ productions: $PbPb$ interactions

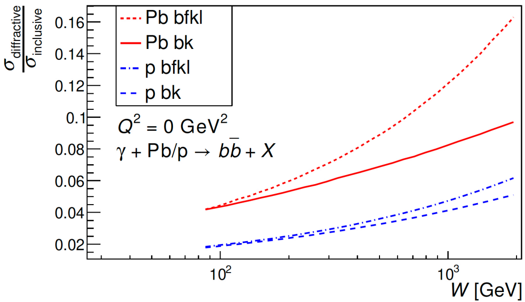




- Left: inclusive $c\bar{c}$ and $b\bar{b}$ production; Right: diffractive production
- As expected, large effect of saturation in p Pb, especially for diffractive component
- Large diffractive component predicted: about 10 to 20% of cross section

$c\bar{c}$ and $b\bar{b}$ productions: diffractive contributions





- Compute the ration of diffractive to total $c\bar{c}$ and $b\bar{b}$ productions when p, Pb is intact in pPb and $PbPb$ collisions
- Large diffractive component predicted: about 10 to 20% of cross section for $PbPb$ interactions

Conclusion

- Saturation at the LHC: use dedicated observables allowing to access low mass, low x such as vector meson (J/Ψ), c and b production
- **Have we seen already saturation at the LHC in J/Ψ production?**
- Predictions concerning c and b quark production using CGC framework to be compared with CMS recent measurement