Probing the proton structure from vector boson production accompanied by heavy jets at LHC

Gennady Lykasov[1]

in collaboration with
Stanley Brodsky[2] , Artem Lipatov[1,3],
Maxim Malyshev[3]

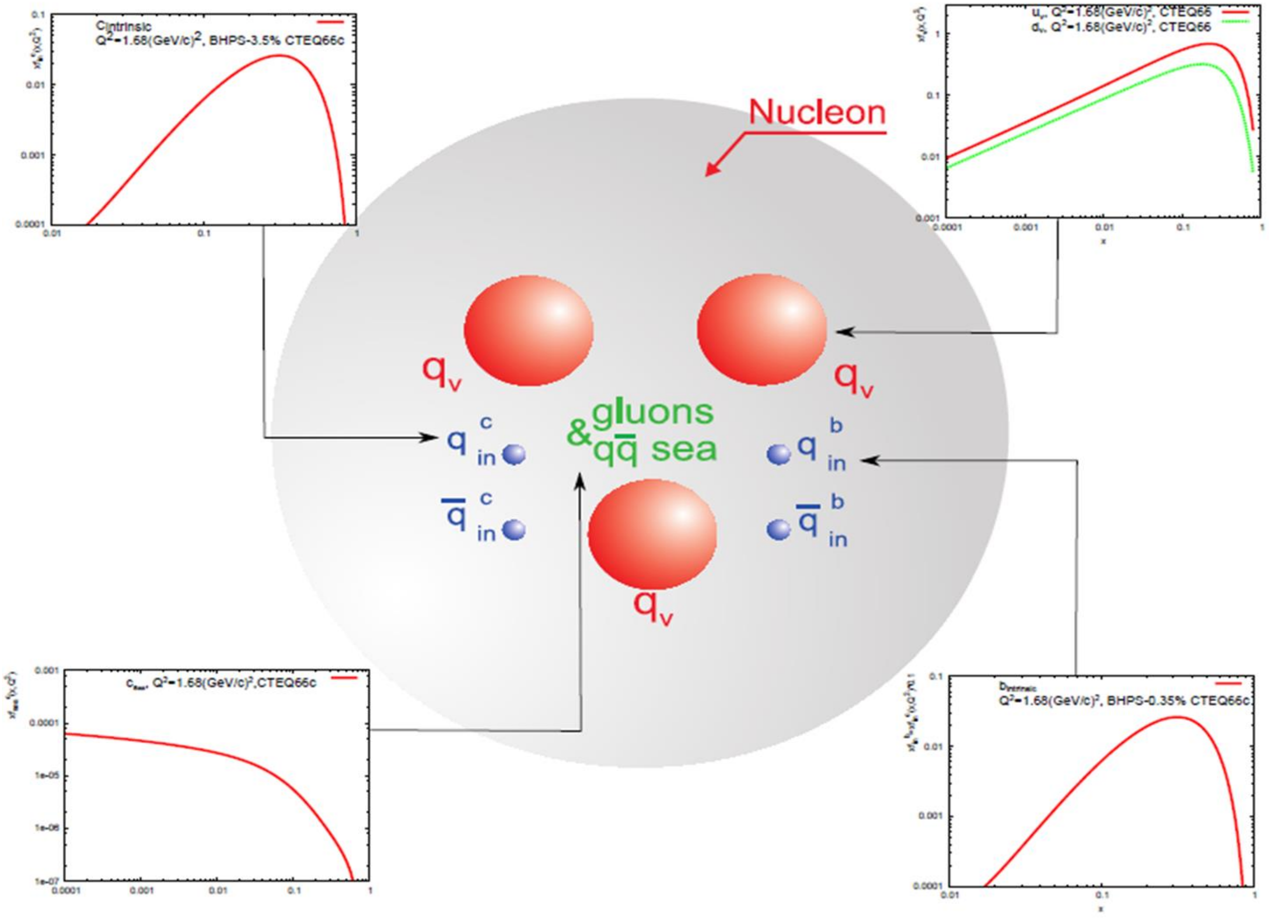
[1]JINR, Dubna,
[2]SLAC, Stanford University,
United States
[3]Moscow State University,
Moscow

OUTLINE

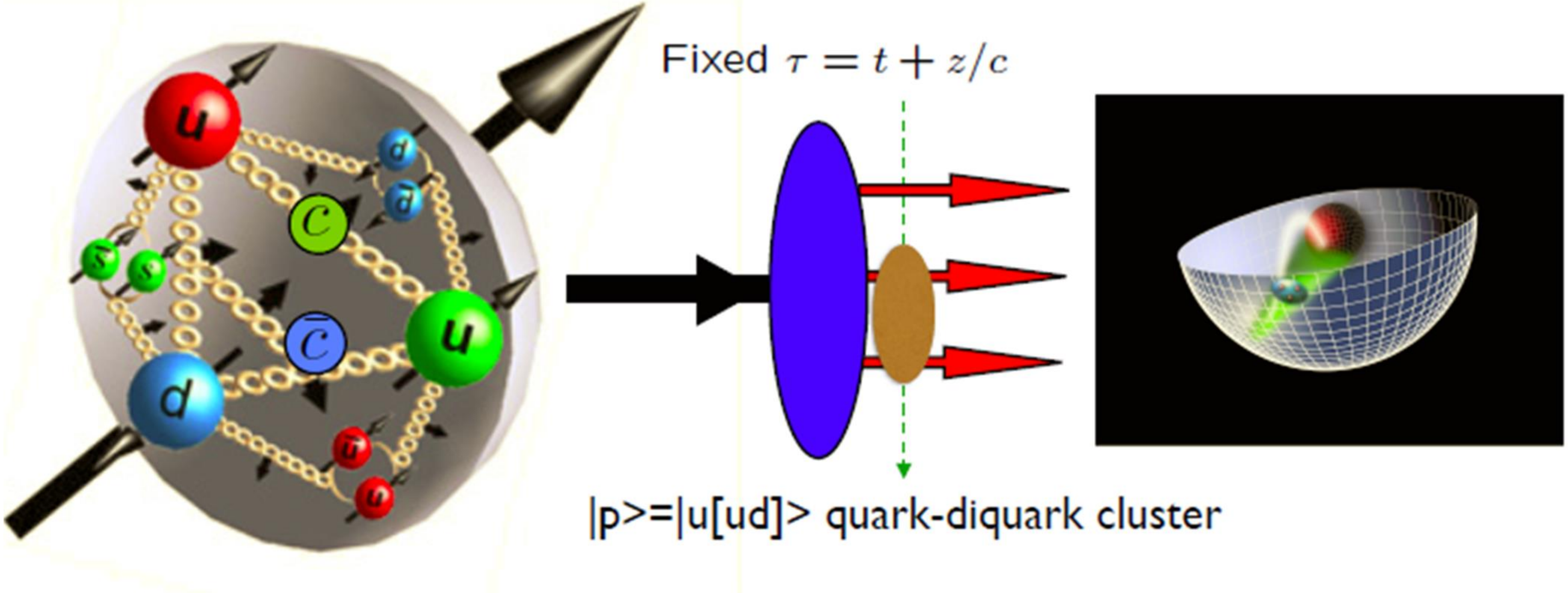
1. Short overview of searching for the IC component in the proton
2. Main goal of our study: search for the IC signal in hard Z-boson production accompanied by c- jet.
3. Extreme kinematics to observe IC signal in p_T-spectrum of Z or c-jet in $p+p \to Z+c+X$ processes.
4. Results and discussion.
5. Summary.

BHPS model: S.J. Brodsky,P. Hoyer, C. Peterson and N.Sakai, Phys.Lett.B9(1980) 451; S.J. Brodsky, S.J. Peterson and N. Sakai, Phys.Rev. D23 (1981) 2745.

Intrinsic $Q\bar{Q}$ in proton



BHPS model: S.J. Brodsky,P. Hoyer, C. Peterson and N.Sakai, Phys.Lett.B9(1980) 451; S.J. Brodsky, S.J. Peterson and N. Sakai, Phys.Rev. D23 (1981) 2745.



S.J. Brodsky

with P. Hoyer, N. Sakai, C. Peterson, A. Mueller, J. Collins, S. Ellis, J. Gunion,

INTRINSIC HEAVY QUARK STATES

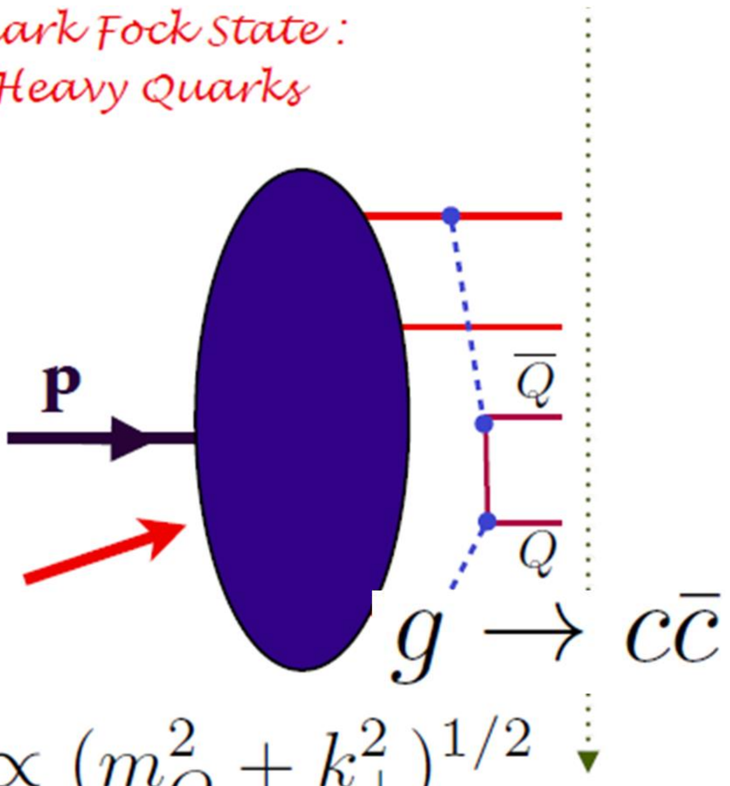
Two types of parton contributions

The extrinsic quarks and gluons are generated on a short time scale in association with a large transverse-momentum reaction.

The intrinsic quarks and gluons exist over a time scale independent of any probe momentum, they are associated with the bound state hadron dynamics.

$$P(x_1,\ldots,x_5)=N_5\,\delta\left(1-\sum_{i=1}^{5}x_i\right)\left[M_p^2-\sum_{i=1}^{5}\frac{m_i^2}{x_i}\right]^{-2}$$

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



$$g \rightarrow c\bar{c}$$

QCD predicts
Intrinsic
Heavy Quarks
at high x!

Minimal off-shellness!

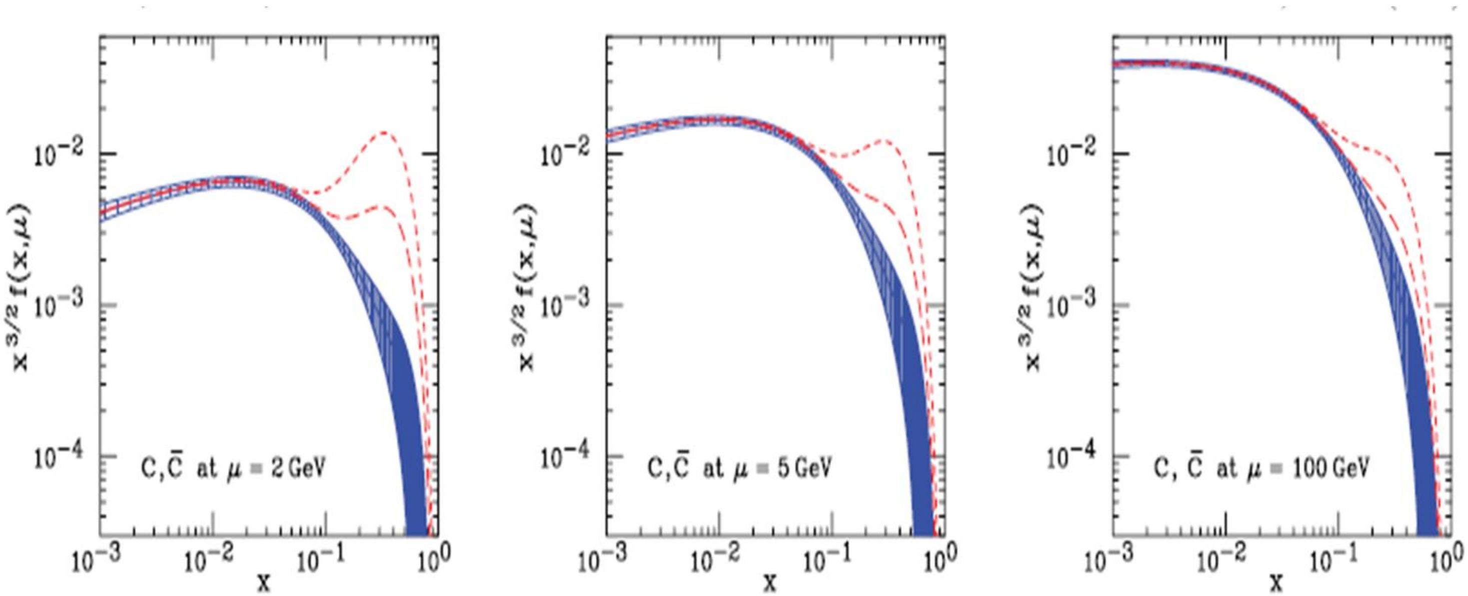
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Lowest order DGLAP extrinsic contribution to c(x) comes from the gluon splitting $g \rightarrow c\bar{c}$, which dominates at low x.

CHARM QUARK DISTRIBUTIONS IN PROTON



Charm quark distributions within the BHPS model. The three panels correspond to the renormalization scales $\mu = 2, 5, 100$ GeV respectively. The long-dashed and the short-dashed curves correspond to $\langle x_{c\bar{c}} \rangle = 0.57\%, 2.\%$ respectively using the PDF CTEQ66c. The solid curve and shaded region show the central value and uncertainty from CTEQ6.5, which contains no ***IC***.

There is an enhancement at x>0.1 due to the IC contribution

Electro-magnetic form factors within the lattice QCD

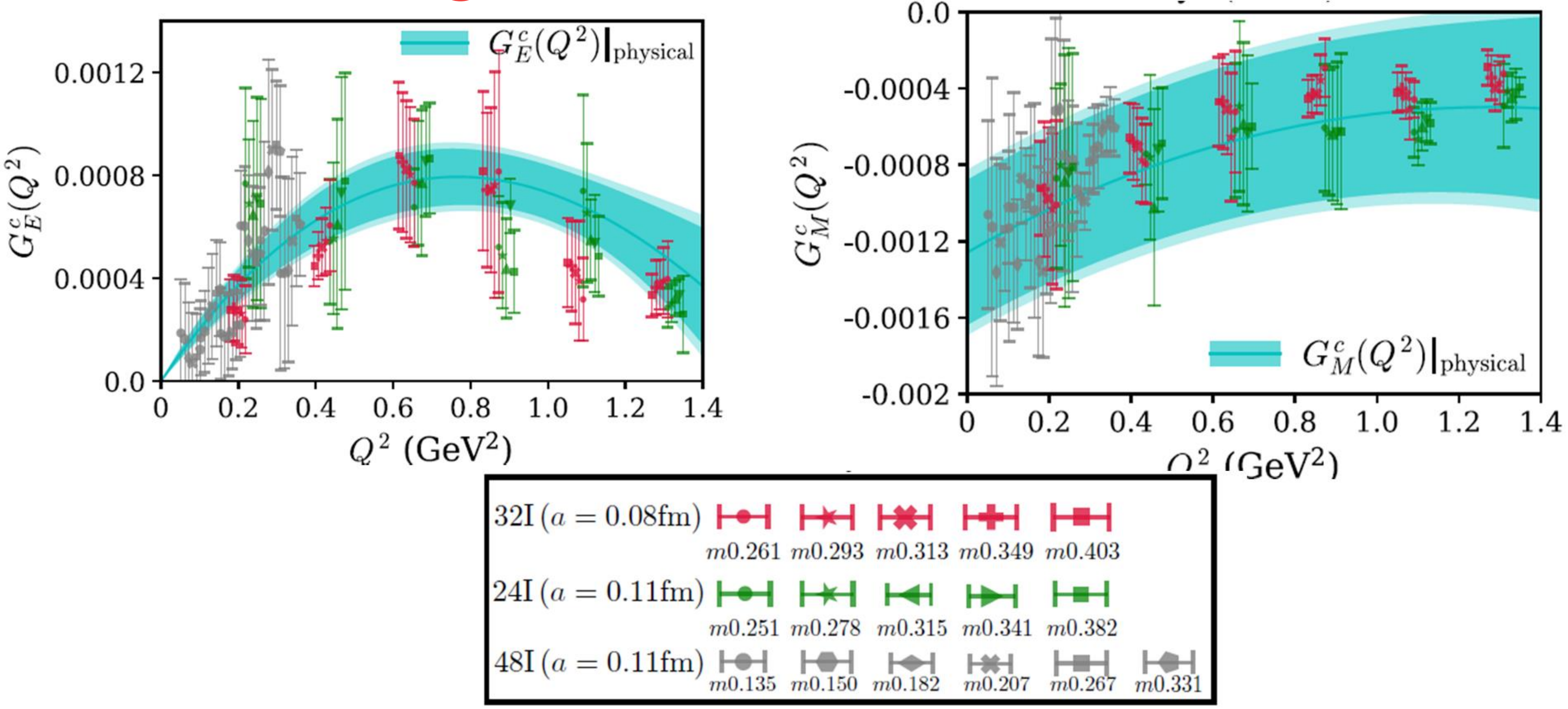


Figure 2: $G^c_{E,M}(Q^2)$ matrix elements obtained from the 48I, 32I, and 24I ensembles. Corresponding legends for different pion masses are included in the lower panel of the figure. The numbers in the legends, such as $m139$, $m251$ represent the data points corresponding to pion mass 139 MeV and 251 MeV, respectively at different Q^2-values. The cyan band indicates $G^c_{E,M}(Q^2)|_{\text{physical}}$. The outer (lighter tinted) cyan margins represent an estimate of systematic uncertainty. Matrix elements at the same Q^2-value but at different pion masses are shown with small offsets for better visibility.

Raza Sabbir Sufian, S. Brodsky, et al., Phys. Lett. B 808 (2020),135633

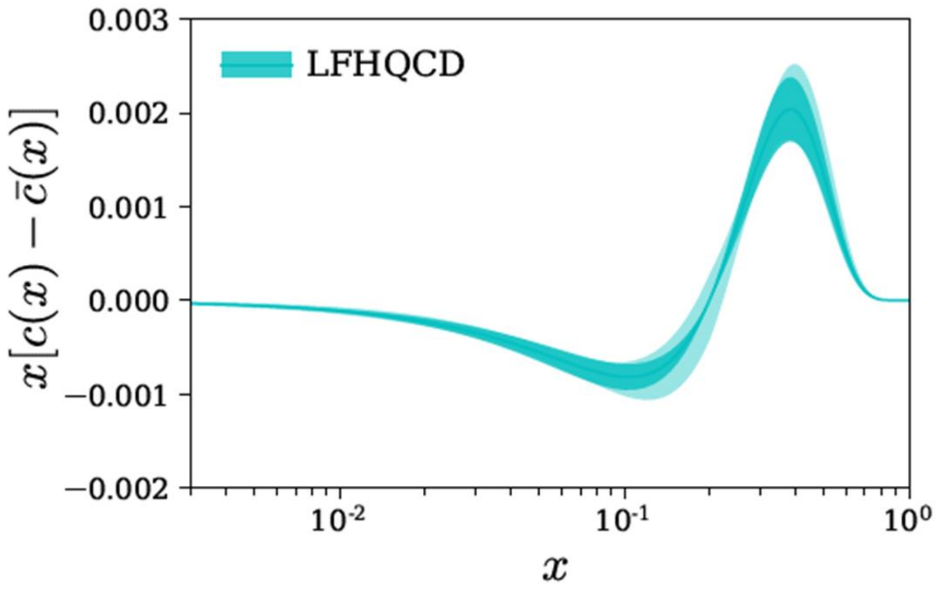


Figure 3: The distribution function $x[c(x) - \bar{c}(x)]$ obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors $G^c_{E,M}(Q^2)$. The outer cyan band indicates an estimate of systematic uncertainty in the $x[c(x) - \bar{c}(x)]$ distribution obtained from a variation of the hadron scale κ_c by 5%. It was taken from Ref. [1].

The nonzero

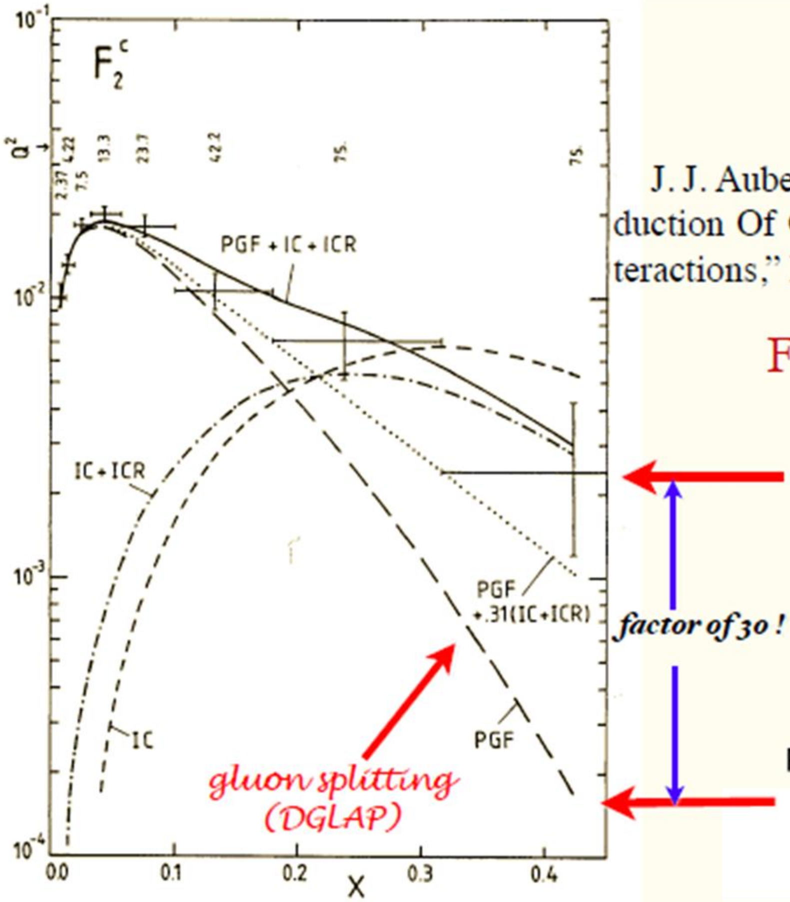
$G^c_E(Q^2)$ indicates the existence of a nonvanishing asymmetric charm-anticharm sea in the nucleon. Performing a nonperturbative analysis based on holographic QCD and the generalized Veneziano model, we study the constraints on the $[c(x) - \bar{c}(x)]$ distribution from the lattice QCD results presented here. Our results provide complementary information and motivation for more detailed studies of physical observables that are sensitive to intrinsic charm and for future global analyses of parton distributions including asymmetric charm-anticharm distribution.

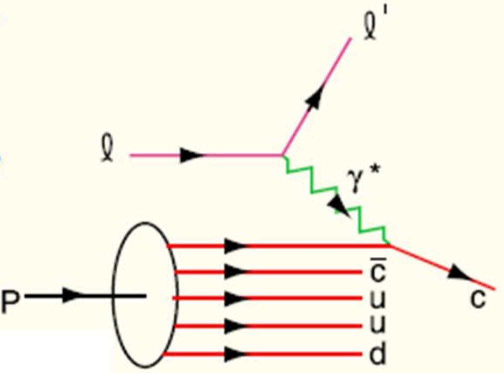
Raza Sabbir Sufian, S. Brodsky, et al., Phys. Lett. B 808 (2020),135633

Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm





DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

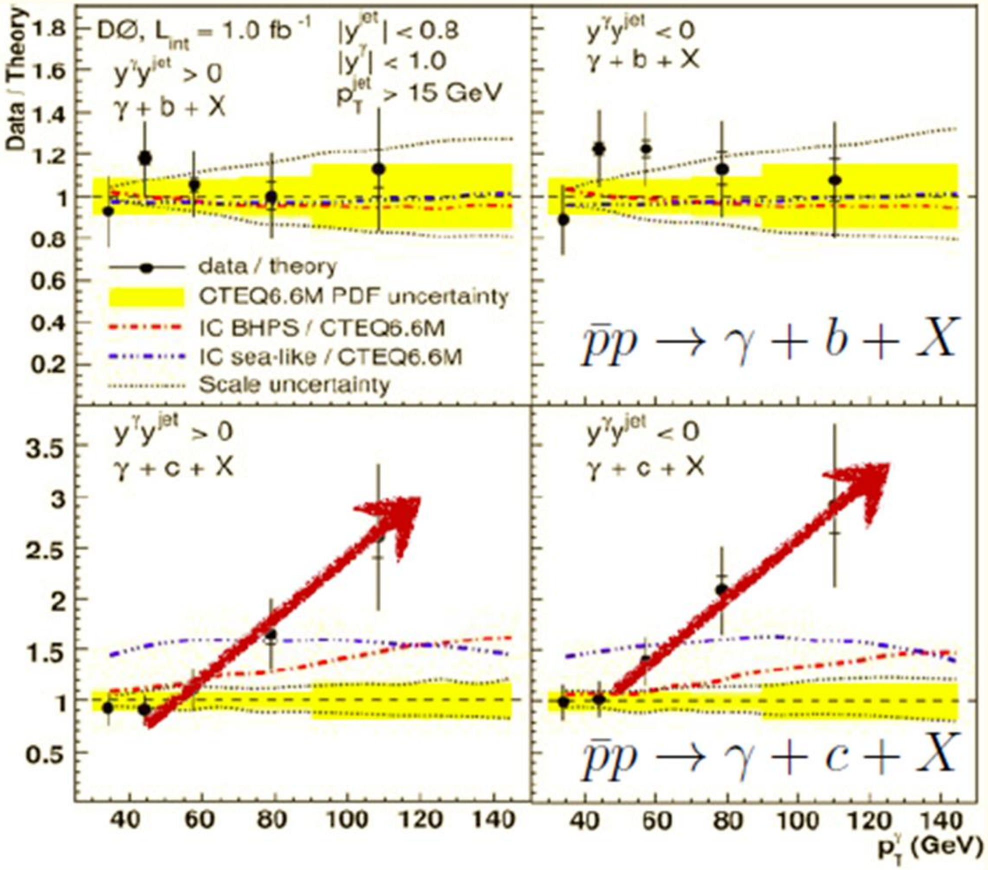
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

PRL **102,** 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

D0

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$$p\bar{p} \to \gamma + Q + X$$



$$\bar{p}p \to \gamma + b + X$$

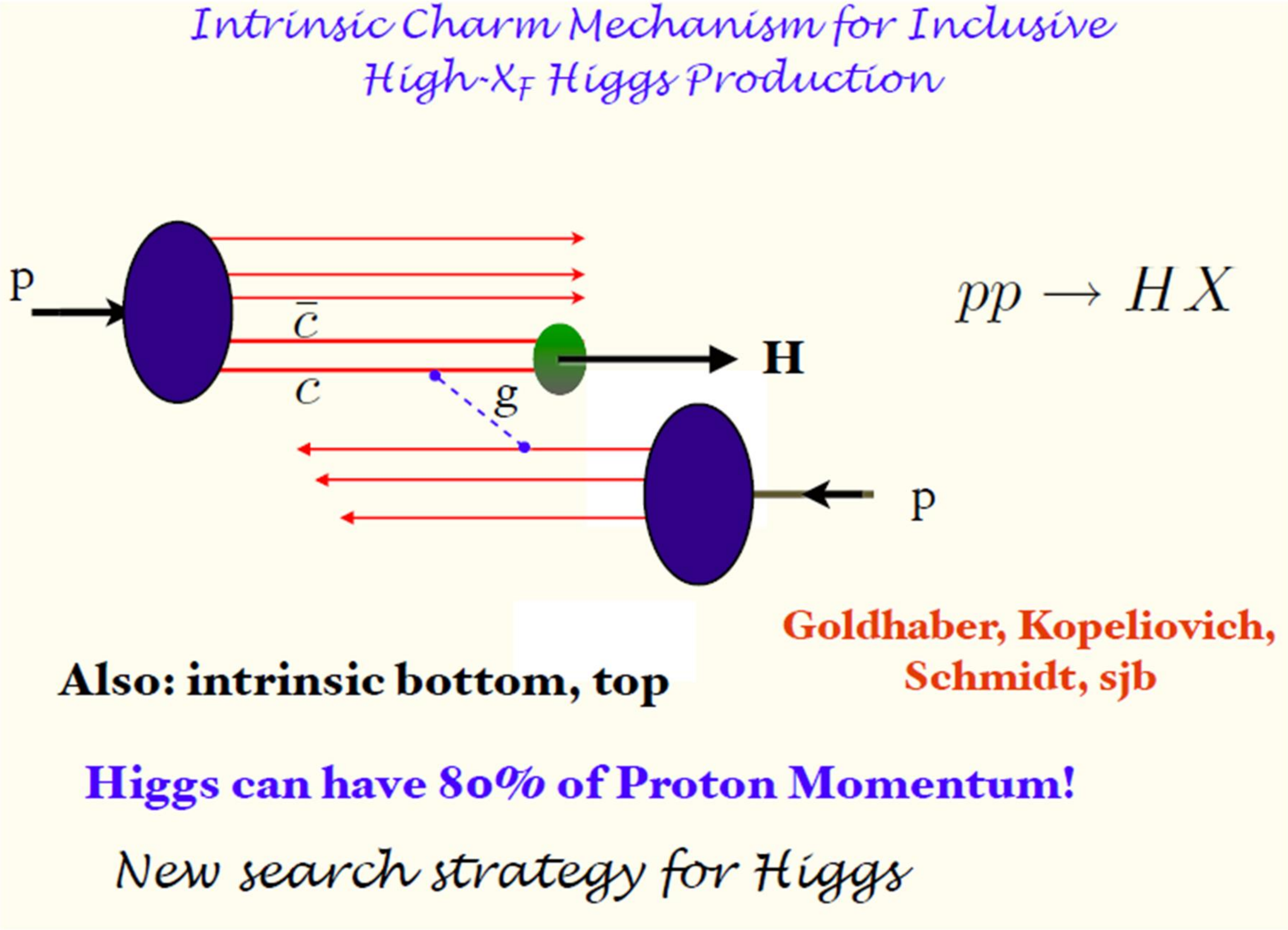
$$\bar{p}p \to \gamma + c + X$$

$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

Consistent with $\frac{m_c^2}{m_b^2}$ relative suppression of intrinsic bottom

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$



Intrinsic Charm Mechanism for Inclusive High-x_F Higgs Production

$pp \rightarrow H X$

Also: intrinsic bottom, top

Goldhaber, Kopeliovich, Schmidt, sjb

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Higgs production is equal from the IC and IB

p+p -> γ+c-jet+X at $s^{1/2}$ = 8 TeV, ATLAS data

the upper limit of the IC probability is about 1.97%

V.A. Bednyakov, S. J. Brodskiy, A.V. Lipatov, G.L., et al., Eur. Phys.J. C 79, 92 (2019)

S.J. Brodsky, G.I. Lykasov, A.V. Lipatov et al. / Progress in Particle and Nuclear Physics 114 (2020) 103802 23

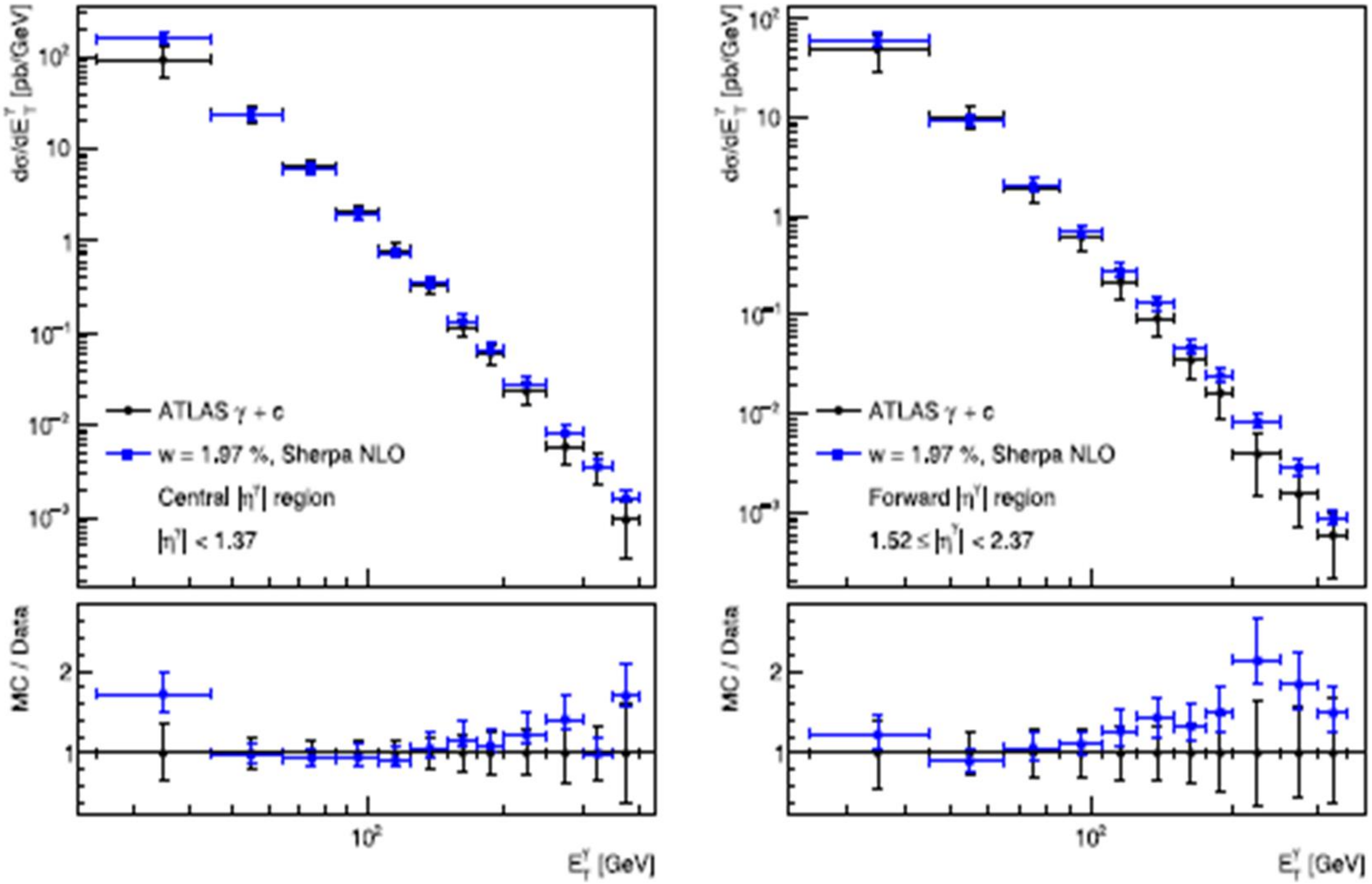
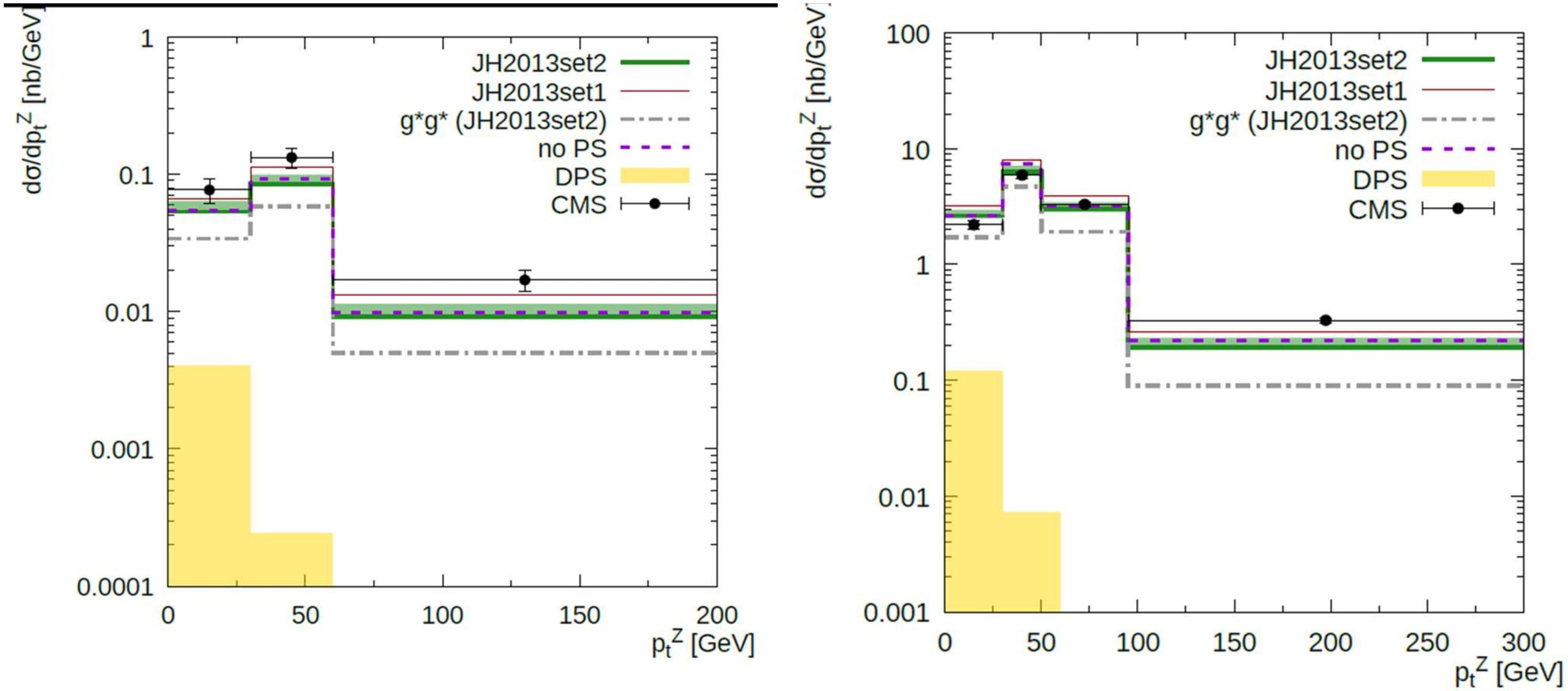


Fig. 18. The E_T^γ spectrum of $\gamma + c$-jet from the SHERPA NLO sample compared with the ATLAS measurement in two $|\eta^\gamma|$ regions. Both panels show the simulated spectrum at the upper limit IC contribution $w_{ul} = 1.97\%$ at 68% CL.

p+p -> Z+c-jet+X at $s^{1/2}$ = 8 TeV & 13 TeV
CMS data

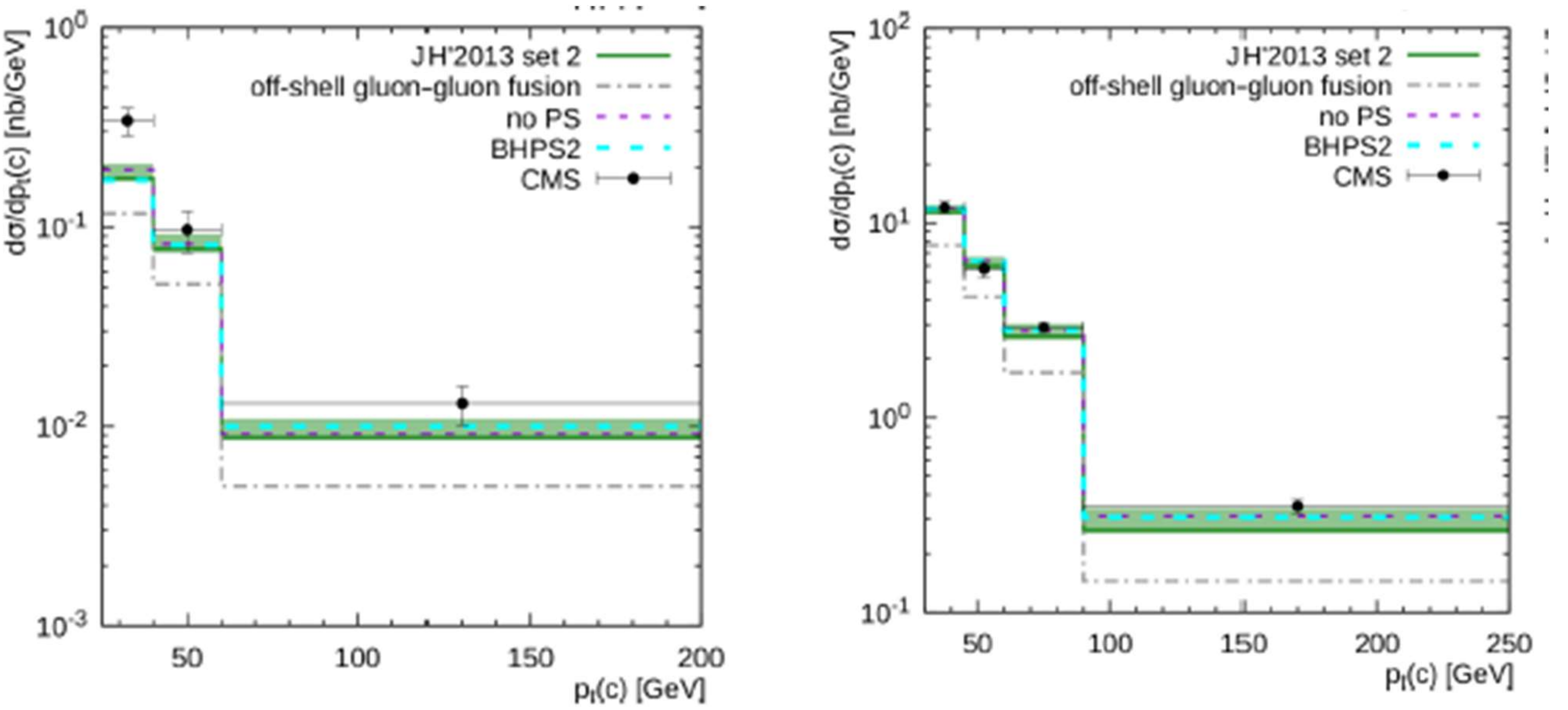


Left: the Z-boson distribution as a function of its transverse momentum p_t^Z at $s^{1/2}$ =8 TeV and different TMD gluon density functions; PS means the parton shower;

DPS is the double parton scattering.

Right: the same as at left but at $s^{1/2}$ = 13TeV.

p+p -> Z+c-jet+X at $s^{1/2}$ = 8 TeV & 13 TeV
CMS data



Left: the c-jet distribution as a function of its transverse momentum p_t^c at $s^{1/2}$ =8 TeV ; PS means the parton shower; BHPS2 corresponds to the IC probability about 3,5%

Right: the same as at left but at $s^{1/2}$ = 13TeV.

p+p -> Z+c/b-jet+X at $s^{1/2}$ = 13 TeV
CMS data

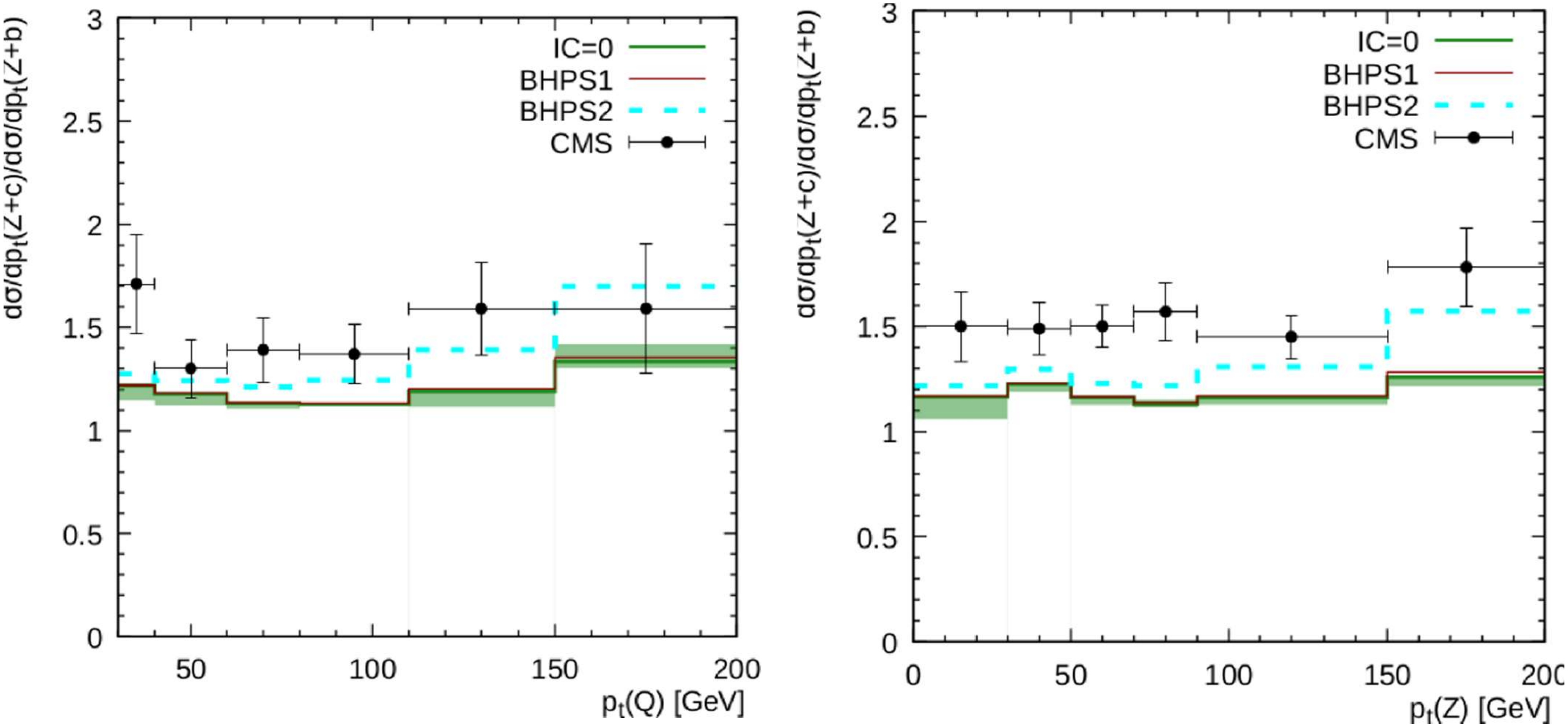
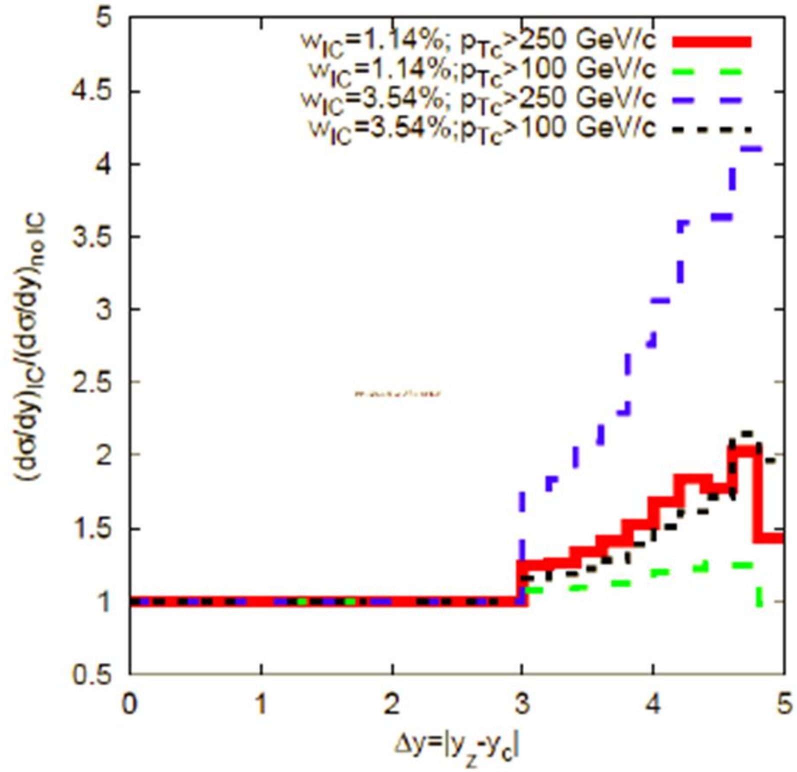
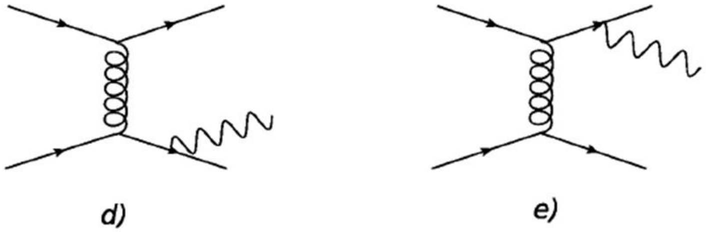


Figure 4: The relative production rate $\sigma(Z+c)/\sigma(Z+b)$ as functions of heavy jet (left panel) and Z boson (right panel) transverse momenta calculated at $\sqrt{s} = 13$ TeV for different IC scenarios with PEGASUS. The experimental data are from CMS [7].

PP→Z+c+X at $s^{1/2}$ = 13 TeV

We suggest the following kinematics: 1.5 < y_c < 2.5 and -2.5 < y_Z < -1.5, i.e., c-jet is produced forward and Z-boson is emitted backward.





The flavour excitation graphs result in a sizable contribution to dσ/dy at large Δy.

The ratio of the rapidity distribution with IC contribution to PDF to the one without IC as a function of $\Delta y = |y_Z - yc|$ at different p_t cuts and IC probabilities w=1.14% (BHPS1) and w=3.54% (BHPS2).

p+p -> Z+c-jet+X at $s^{1/2}$ = 13 TeV

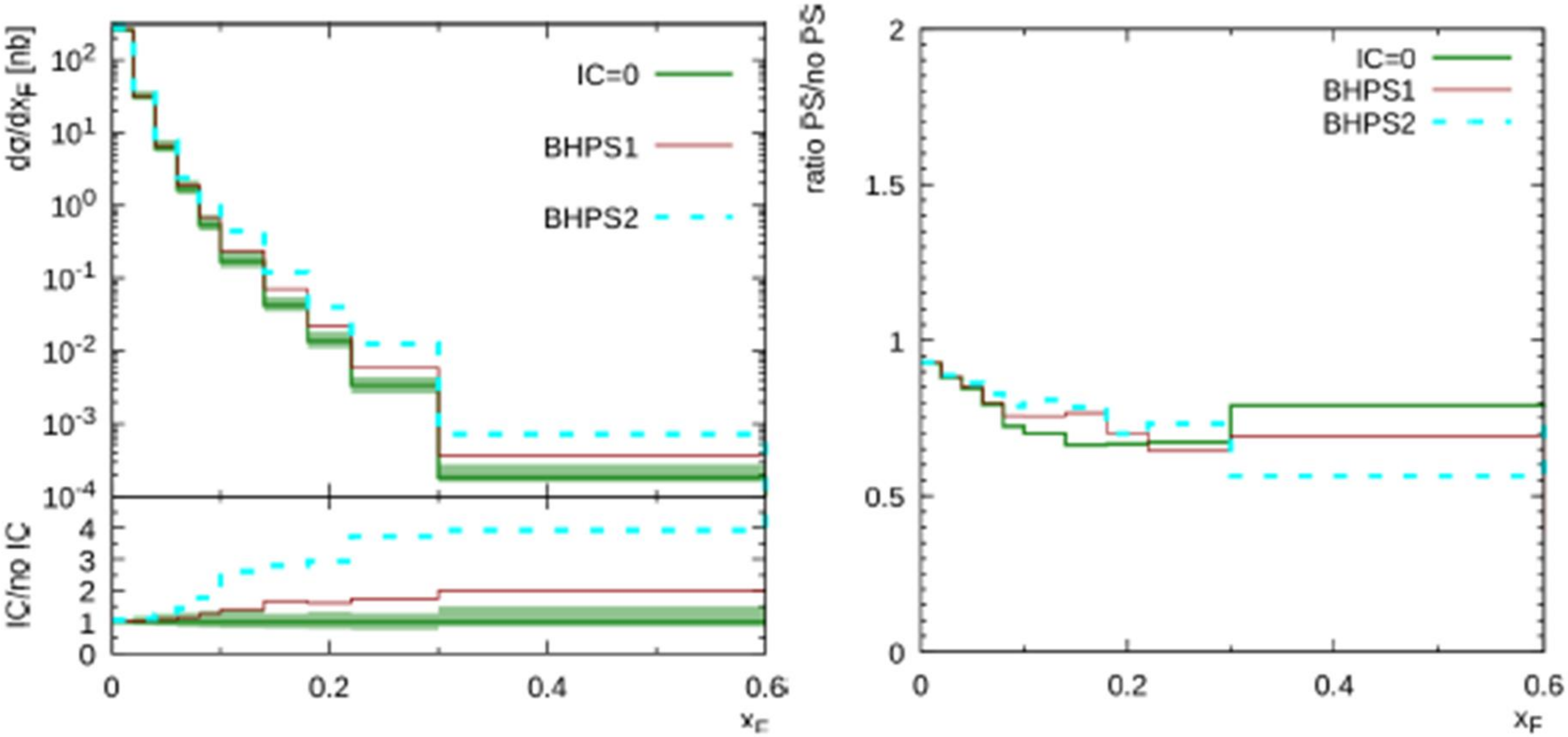


Figure 5: The differential cross sections of associated $Z + c$ production in pp collisions at $\sqrt{s} = 13$ TeV for different intrinsic charm parametrization and their ratios to the zero IC scenario calculated using PEGASUS tool as a function of Feynman variable x_F (left). Right: The ratio of the cross sections calculated with and without PS for the different parametrizations.

Daniel Craik
on behalf of the LHCb collaboration

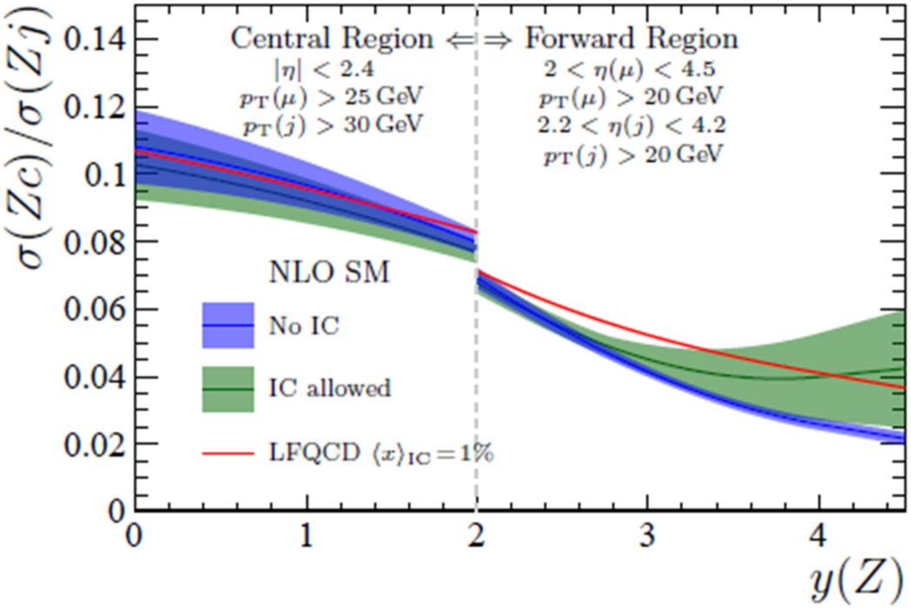
Massachusetts Institute of Technology

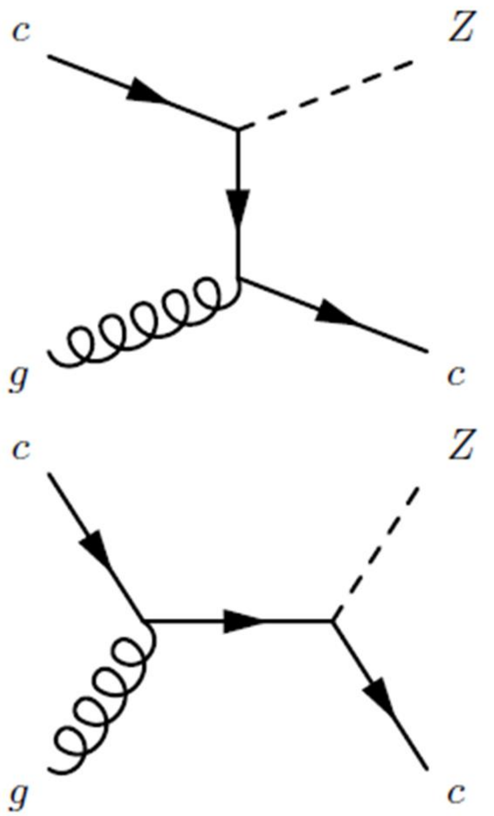
4th August, 2021

Intrinsic charm: $Z + c$

LHCb-PAPER-2021-029 NEW!

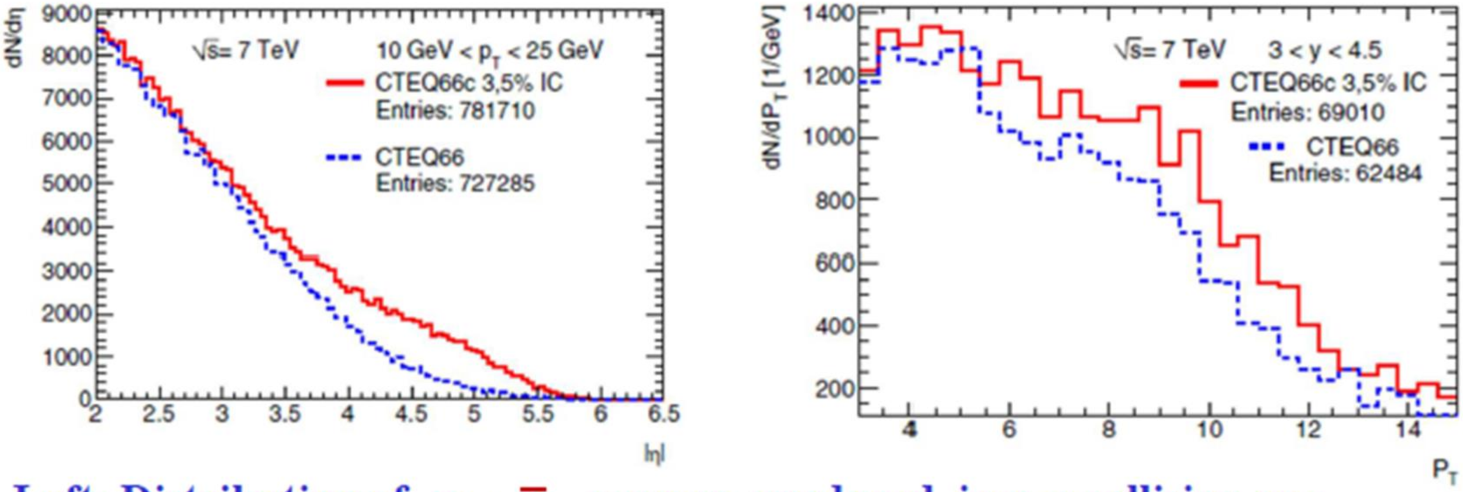
- Study production of c-jets in association with a Z
- Forward region sensitive to high-x, high-Q^2 charm content of the proton





Our predictions for LHCb on the inclusive production of D-mesons at p-p collision published in G.I. Lykasov, et al., EPL,99 92012) 21002, arXiv:1205.1131.

One can see an enhancement in these observables due to the IC contribution



Left: Distribution of $D_0 + \overline{D}_0$ mesons produced in p-p collision as a function of the pseudo-rapidity |η| including the IC component with probability w=3.5% (red histogram) . The blue histogram corresponds the PDF of type CTEQ66 without the IC.

Right : Transverse momentum distribution of these mesons. Notations are the same as in the left plot.

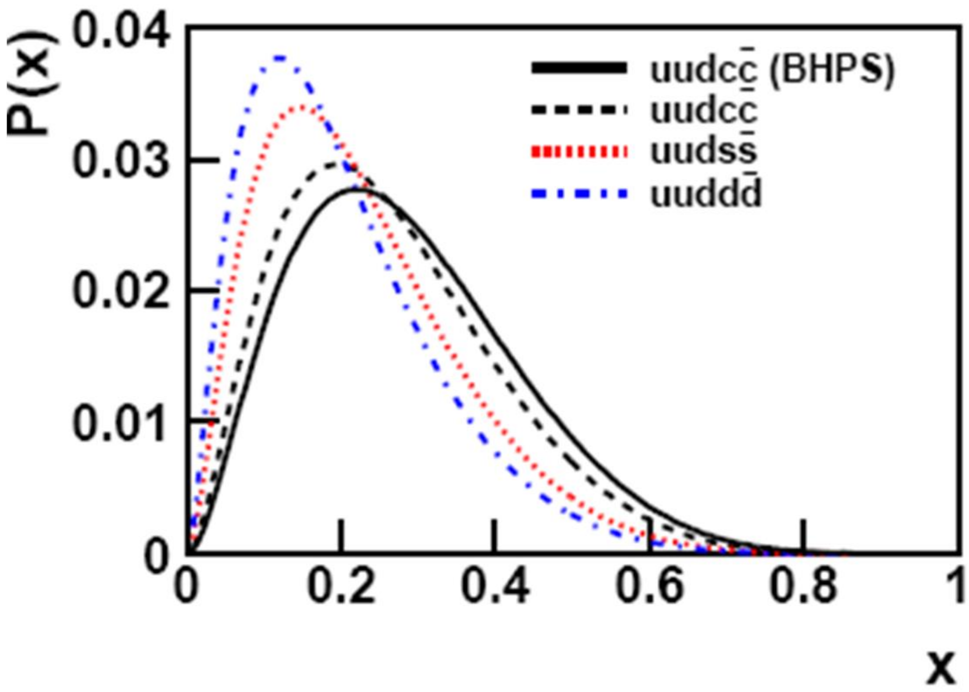
Next prediction for the LHCb: the measurement of the asymmetry $[\sigma(pp\to D^+ X) - \sigma(pp\to D^- X)]/[\sigma(pp\to D^+ X) + \sigma(pp\to D^- X)]$ as a function of p_T or y. It can give us an information on the charm-anticharm asymmetry by inclusion of the IC component in the proton PDF.

SUMMARY

1. The lattice QCD calculation shows that the charm quark contribution to the electric form factor of proton doesn’t vanish. It leads to the non vanishing asymmetry c(x)-\bar{c (x)}, which can indicate the IC existence in nucleon.
2. We illustrate that the back-to back production of c-jet and Z-boson in pp results in a sizable enhancement in p_t – spectra, about 200%-300% , when the IC component in PDF is taken into account.
3. We predict the big enhancement in the x_F -spectrum of c-jet produced in p+p -> Z+c+X about 40%-100% at $x_F > 0.1$, when the IC component in PDF is included.
4. The inclusive spectrum of D-mesons produced in p-p collisions at the LHC energy as a function of the pseudo-rapidity $|\eta|$ or transverse momentum p_T can have an enhancement at $3.5<|\eta|<5$ and $10 < p_T <25$ GeV/c, if the IC contribution is included.
5. The measurement of $(\sigma(D^+) - \sigma(D^-))/ (\sigma(D^+) +\sigma(D^-))$ as a function of x_F is very promising for the search of the charm-anticharm quarks asymmetry, which could be very good confirmation of the existence of the IC component in nucleon.

THANK YOU VERY MUCH FOR YOUR ATTENTION !

BACK UP



The x-distribution of the intrinsic **Q** calculated within the BHPS model. **There is an enhancement at x > 0.1**
Jen-Chieh Peng & We-Chen Chang, hep-ph/1207.2193.

INTRINSIC HEAVY QUARK DISTRIBUTION IN PROTON

Integrating $P(x_1,\ldots,x_5)$ over $dx_1\ldots dx_4$ and neglecting of all quark masses except the charm quark mass, we get

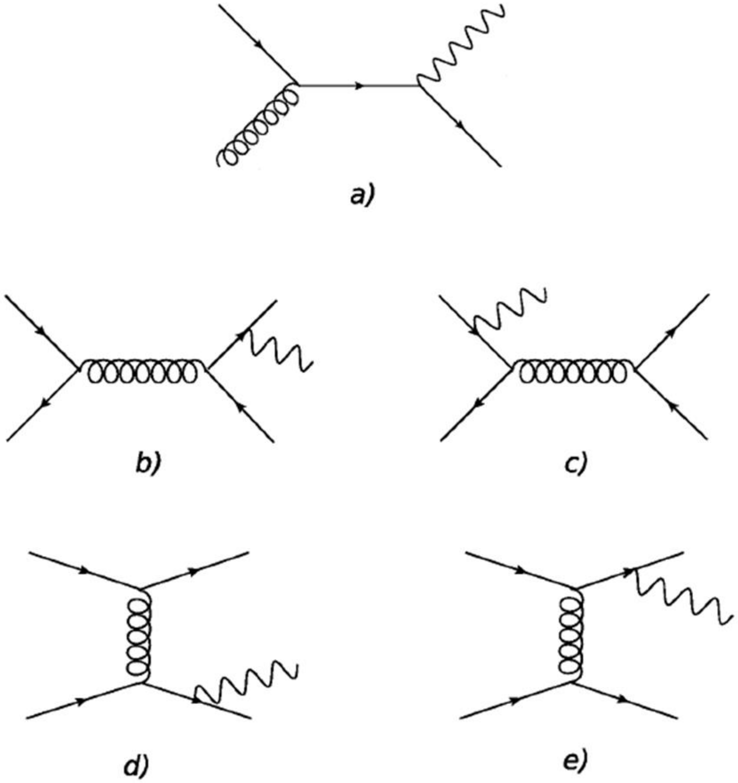
$$P(x_5) = \frac{1}{2}\overline{N}_5 x_5^2 \left[\frac{1}{3}(1 - x_5)(1 + 10x_5 + x_5^2) + 2x_5(1 + x_5)\ln(1 x_5)\right]$$

Where $\overline{N}_5 = N_5 / m_{4,5}^4$ N_5 is the normalization constant . Here $m_4 = m_5 = m_c = m_{\bar{c}}$ is the bar mass of the charmed quark. W_{IQ} determines some probability to find the Fock state |uudQQ > in the proton.

One can see qualitatively that $P(x_5)$ vanishes at $x_5 \to 0$ and $x_5 \to 1$ and has an enhancement at $0 < x_5 < 1$

$$xc(x,\mu_0^2) = xc_{\rm ext}(x,\mu_0^2) + xc_{\rm int}(x,\mu_0^2).$$

S.J.Brodsky, V.A.Bednyakov, G.L., J.Smiesko, S.Tokar, Progr.Part.Phys. 93, 108 (2017)



The $\mathcal{O}(\alpha\alpha_s)$ (a) and $\mathcal{O}(\alpha\alpha_s^2)$ (b) – (e) contributions to the $\gamma(Z) + Q$ production.

a)QCD compton; b),c) QQ annihilaton; d),e) flavour excitation

S.J.Brodsky, V.A.Bednyakov, G.L., J.Smiesko, S.Tokar, Progr.Part.Phys. v.93, 108 (2017)

S.J.Brodsky, G.L., A.V.Lipatov, J.Smiesko, Progr.Part.Phys. v.114, 103802 (2020)

PHOTON (DI-LEPTON) AND c(b)-JETS PRODUCTION IN P-P

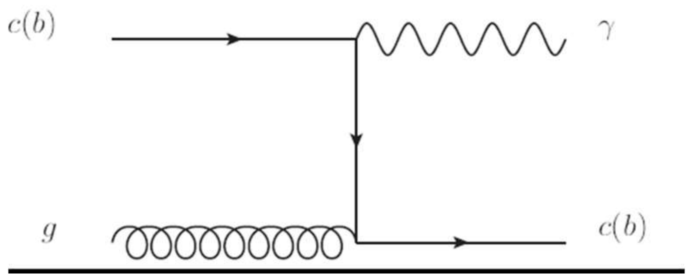


Fig.a. Feynman diagram for the process $c(b)+g \to \gamma + c(b)$

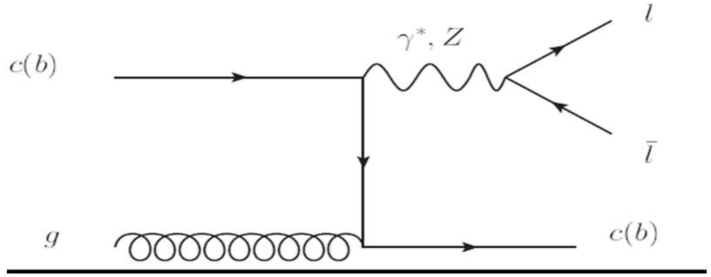


Fig.b. Feynman graph for the process $c(b)+g \to \gamma / Z^0 + c(b)$

$$x_F = \frac{2p_T}{s^{1/2}} sh(\eta); p_{T\gamma} = -\ p_{Tc}.$$

$$x_{c(b)} = \frac{m^2_{l^+l^-}}{x_g s} + x^f_{c(b)}$$

To observe the IC

for Fig.a

$$x_c \geq x_F > 0.1$$

for Fig.b

$$x_{c(b)} = \frac{m^2_{l^+l^-}}{x_g s} + x^f_{c(b)} 0.1$$

.J.BrodskSy, V.A.Bednyakov, G.L., J.Smiesko, S.Tokar, Progr.Part.Phys. 93, 108 (2017)

PRODUCTION OF HEAVY FLAVOURS IN HARD P-P COLLISIONS

$$E\frac{d\sigma}{d^3p} = \sum_{i,j}\int d^2k_{iT}\int d^2k_{jT}\int_{x_i^{\min}}^{1} dx_i\int_{x_j^{\min}}^{1} dx_j\, f_i(x_i,k_{iT})f_j(x_j,k_{jT})\frac{d\sigma_{ij}(\hat{s},\hat{t})}{d\hat{t}}\frac{D^h_{i,j}(z_h)}{\pi z_h}$$

$$x_i^{\min} = \frac{x_T\cot(\frac{\theta}{2})}{2 - x_T\tan(\frac{\theta}{2})} \qquad x_F \equiv \frac{2p_z}{\sqrt{s}} = \frac{2p_T}{\sqrt{s}}\frac{1}{\tan\theta} = \frac{2p_T}{\sqrt{s}}\sinh(\eta)$$

$$x_i^{min} = \frac{x_R + x_F}{2 - (x_R - x_F)} \qquad x_R = 2p/\sqrt{s}$$

One can see that $x_i \geq x_F$ If $x_F > 0.1$ then, $x_i > 0.1$ and the conventional sea heavy quark (extrinsic) contributions are suppressed in comparison to the intrinsic ones.

x_F is related to p_T and η . So, at certain values of these variables, in fact, there is no conventional sea heavy quark (extrinsic) contribution. And we can study the IQ contributions in hard processes at the certain kinematical region.