Exploring high-multiplicity events in high-energy proton-proton collisions

PRC 106 (2022) 6, 065206 / EPJA 60 (2024) 3, 54 / PRD 109 (2024) 9, 094035

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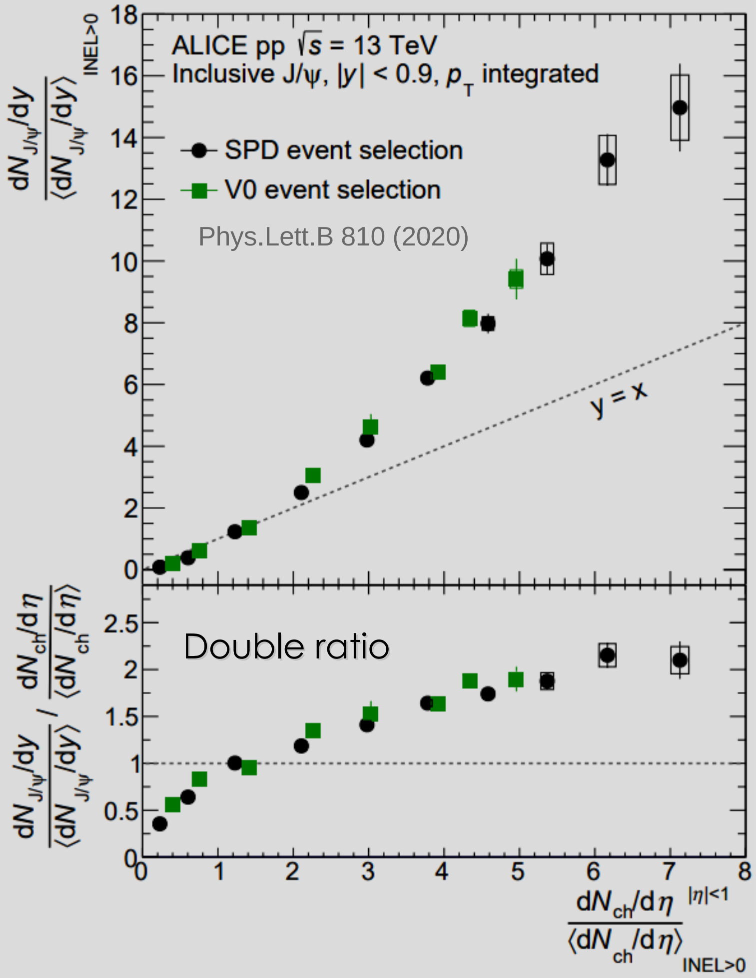
Diffraction and Low-x 2024 8 – 14, Sept, 2024

Particle multiplicities in high-energy pp collisions

Multiplicity: counting of (produced) particles

Recent experimental results: **stronger increase in identified particle multiplicities when compared to the minimum-bias case**

Two questions may be addressed



Particle multiplicities in high-energy pp collisions

1. Comparison with available models: **no unified agreement w.r.t. data**

2. Beyond a quantitative description: **what causes this change in behavior?**

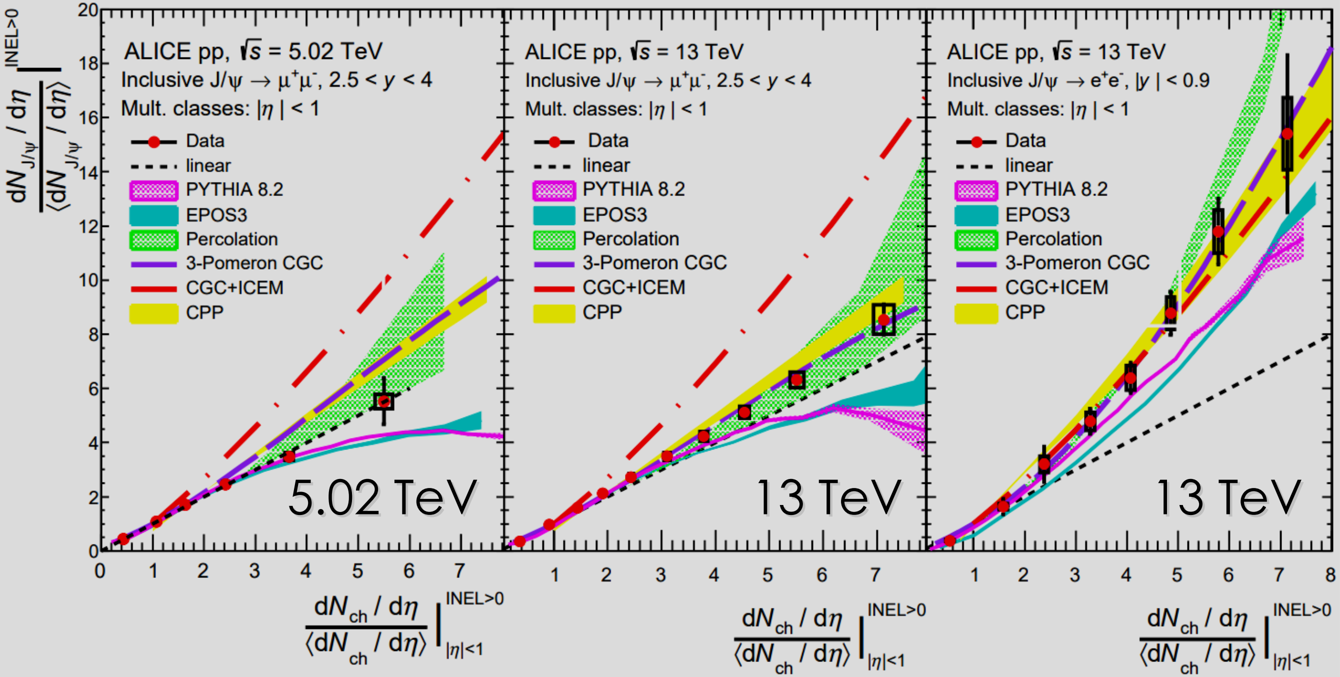
Is it an initial-state effect?

A final-state effect?

A mixture of both?

Data for J/Ψ

JHEP 06 (2022) 015

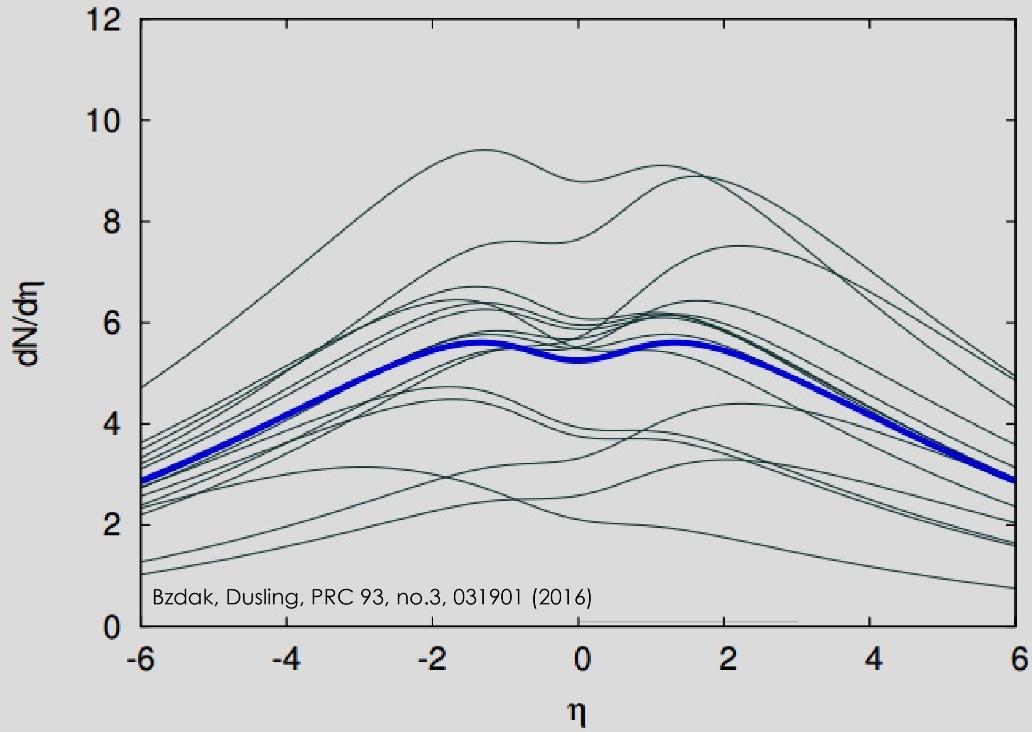


Qualitative scenario of proton-proton collisions

Proton-proton collisions: average result is symmetric, as expected

Event-by-event color charge fluctuations may produce asymmetric collisions

Could be the case for multiplicities larger than average, excluding highest multiplicities



Bzdak, Dusling, PRC 93, no.3, 031901 (2016)

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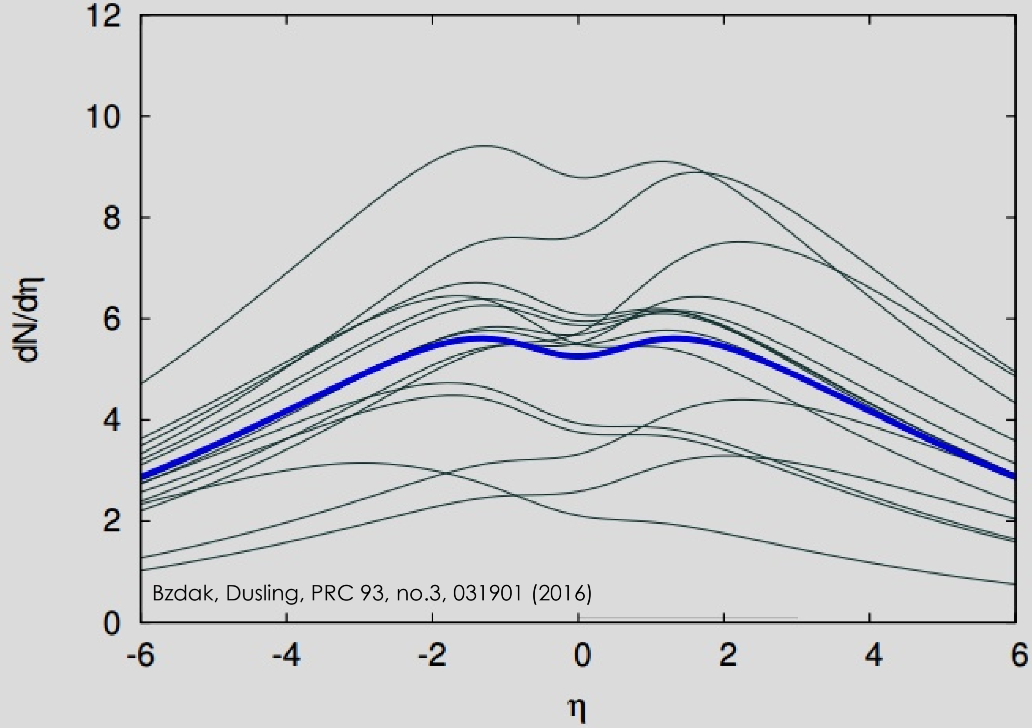
Qualitative scenario of proton-proton collisions

Will make two assumptions:

1. The production mechanism is the same for low and high multiplicities events

2. Final multiplicity proportional to the initial partonic configuration: high multiplicity events have larger Q_s than minimum bias events



Bzdak, Dusling, PRC 93, no.3, 031901 (2016)

Particle production @ CGC EFT

$$\frac{dN_h}{dy\,d^2p_T} = \frac{K}{(2\pi)^2}\int_{x_F}^{1}\frac{dz}{z^2}\Bigg[f_{q/p}(x_1,\mu^2)\,\widetilde{N}_F\left(\frac{p_T}{z},x_2\right)\,D_{h/q}\left(z,\mu_{FF}^2\right) + f_{g/p}(x_1,\mu^2)\,\widetilde{N}_A\left(\frac{p_T}{z},x_2\right)\,D_{h/g}\left(z,\mu_{FF}^2\right)\Bigg]$$

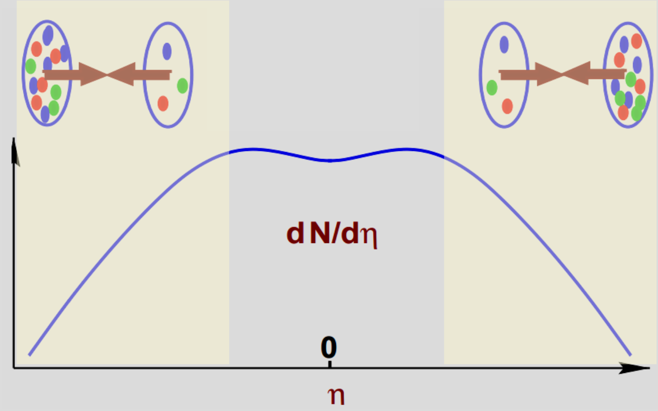
Dipole scattering amplitude

$$\widetilde{N}_{A,F}(x,p_T) = \int d^2r\, e^{i\vec{p_T}\cdot\vec{r}}\,[1 - \boxed{\mathcal{N}_{\mathcal{A},\mathcal{F}}(x,r)]}$$

$$x_{1,2} = (p_T/\sqrt{s})\exp(\pm y)$$

"Hybrid formalism"

(collinear + TMD)



Employed to describe particle production @ RHIC, LHC

Dumitru, Hayashigaki, Jalilian-Marian, NPA 765, 464-482 (2006); Boer, Utermann, Wessels, PRD 77, 054014 (2008;, Betemps, Goncalves, JHEP 09, 019 (2008); Albacete, Marquet, PLB 687, 174-179 (2010); Altinoluk, Kovner, PRD 83, 105004 (2011); Albacete, Dumitru, Fujii, Nara, NPA 897, 1-27 (2013); Chirilli, Xiao, Yuan, PRL 108, 122301 (2012); Kang, Vitev, Xing, PRL 113, 062002 (2014); Altinoluk, Armesto, Beuf, Kovner, Lublinsky, PRD 91, no.9, 094016 (2015); Iancu, Mueller, Triantafyllopoulos, JHEP 12, 041 (2016); Durães, AVG, Goncalves, Navarra, PRC 94, no.2, 024917 (2016); Ducloué et. al, PRD 97, no.5, 054020 (2018); Ducloué, Lappi, Zhu, PRD 95, no.11, 114007 (2017); Carvalho, AVG, Goncalves, Navarra, PRD 96, no.9, 094002 (2017); Liu, Ma, Chao, PRD 100, no.7, 071503 (2019); Iancu, Mulian, JHEP 03, 005 (2021); Shi, Wang, Wei, Xiao, PRL 128, no.20, 202302 (2022)

Particle production @ CGC EFT

Final states: $\mathrm{FS} = \mathrm{K}^0_S \,,\; h^+ + h^-$

$$\sigma(pp \to FS + X) \propto \sum_i f_i(x_1) \otimes \widetilde{N}_F(x_2) \otimes D_{i/h} \;+\; g(x_1) \otimes \widetilde{N}_A(x_2) \otimes D_{g/h}$$

Photon production, $q + g \to q + \gamma$ [QCD "Compton" scattering]

$$\sigma(pp \to \gamma + X) \propto \sum_i f_i(x_1) \otimes \widetilde{N}_F(x_2)$$

No FF!

Collinear + TMD factorization for all processes here

D-meson production, $c + g \to D^0 + X \;+\; \{g + p \to Q\bar{Q}\} \to D^0 + X$

$$\sigma(pp \to D^0 + X) \propto c(x_1) \otimes \widetilde{N}_F(x_2) \otimes D_{c/D} + g(x_1) \otimes k_T^2 \widetilde{N}_A(x_2) \otimes D_{c/D}$$

CGC EFT provides a unified description of these processes!

Specifying the dipole scattering amplitude

$$\frac{\partial \mathcal{N}(r,Y)}{\partial Y} = \int d^2 r_1\, K(r,r_1,r_2)\,[\mathcal{N}(r_1,Y)+\mathcal{N}(r_2,Y)-\mathcal{N}(r,Y)-\mathcal{N}(r_1,Y)\mathcal{N}(r_2,Y)]$$

$$\mathcal{N}_F(r,x) \equiv \mathcal{N}(r,x)$$

Balitsky, Kovchegov: NPB 463 (1996) 99, PRL 81 (1998) 2024, PRD 60 (1999) 014020, PLB 518 (2001) 235, NPB 629 (2002) 290, PRD 60 (1999) 034008, PRD 61 (2000) 074018

Running coupling BK: provides the small-x evolution given an initial condition

$$\mathcal{N}_F(r,x_0) = 1 - exp\left[-\frac{(r^2\, Q^2_{s0,\mathrm{proton}})^{\gamma}}{4}\, ln\left(\frac{1}{\Lambda r}+e\right)\right]$$

MV–like ic

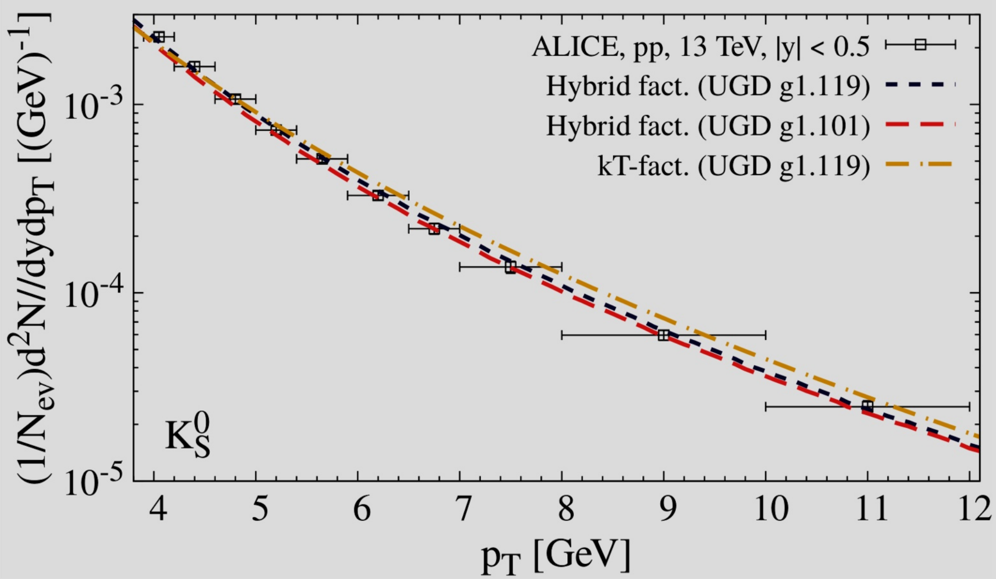
$$\mathcal{N}_F(r,x_0) = 1 - exp\left[-\frac{r^2\, Q^2_{s0,\mathrm{proton}}}{4}\right]$$

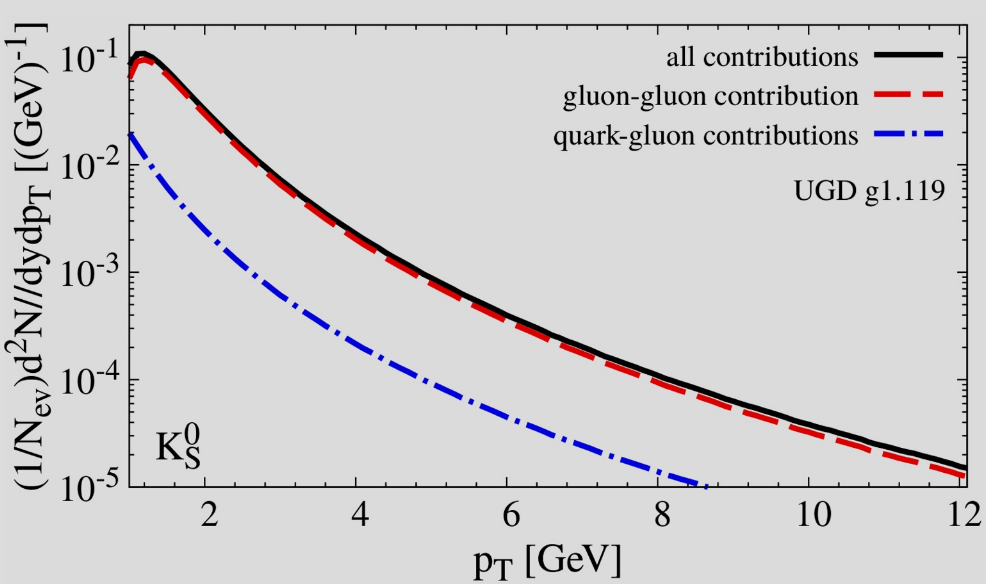
GBW–like ic

Albacete, Armesto, Milhano, Salgado, PRD 80, 034031 (2009)
Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, EPJC 71, 1705 (2011)
Albacete, Dumitru, Fujii, Nara, NPA 897, 1-27 (2013)

Application to selected particles: K_S^0

Lima, AVG, Goncalves, PRC 106 (2022) 6, 065206





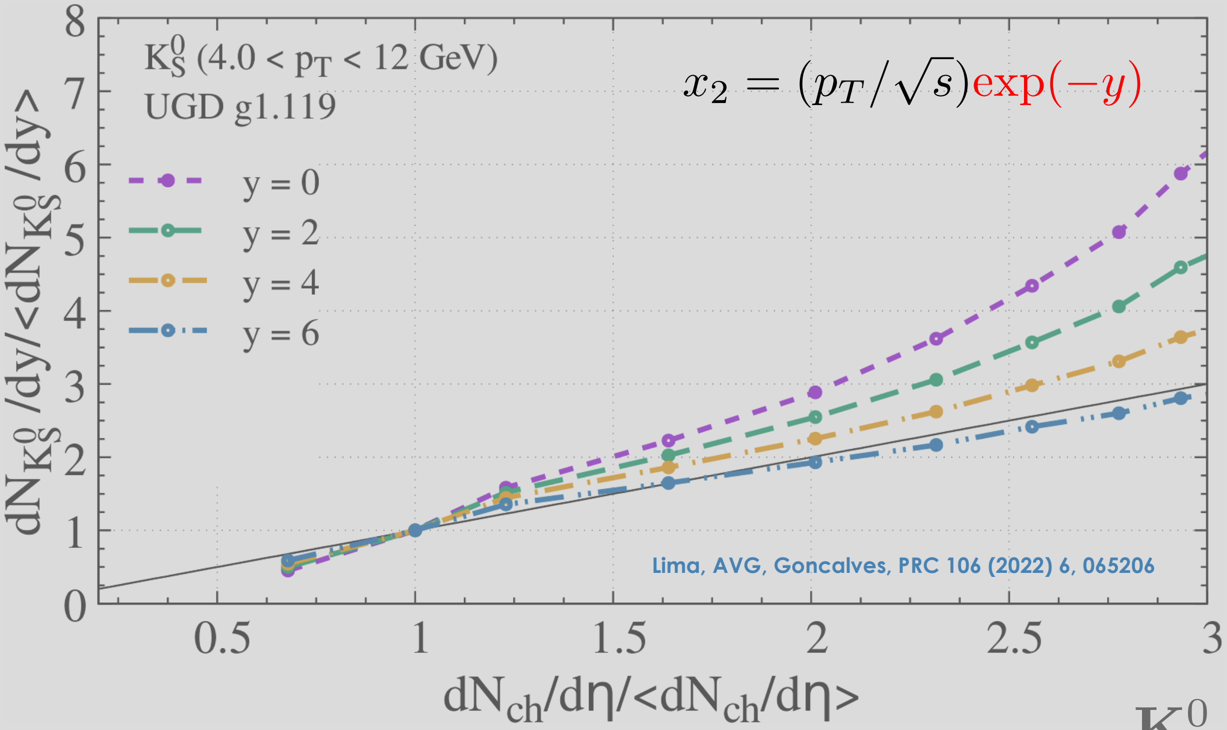
Good description of p_T-spcetra of K_0^S for kt-fact. & hybrid form.

Gluon-initiated interactions are dominant

Quark-initiated channel is sub-dominant

For now on, only results with hybrid formalism for identified final states

Application to selected particles: K_S^0



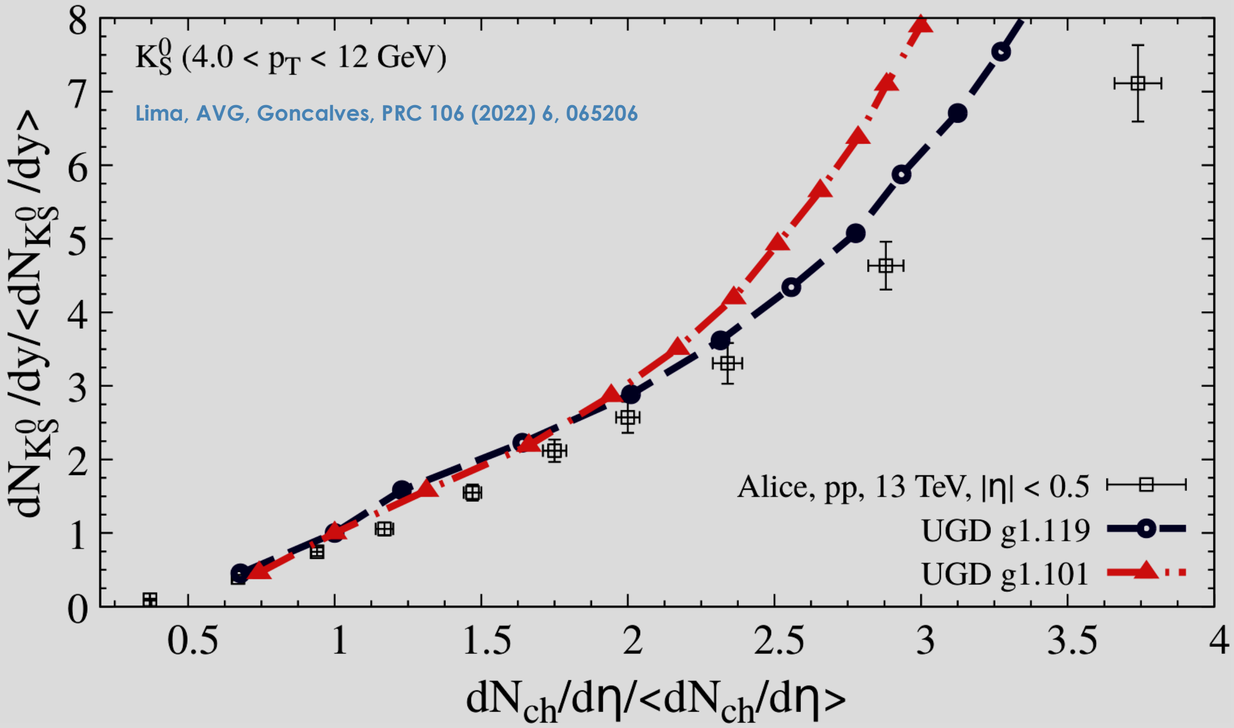
$Q_s(x_2)$ increases: high-p_T kaons are affected in the same way as charged particles

Results depend on p_T cuts as well [backup slides]

K_S^0 : 4 < p_T < 12 GeV

N_{ch} : 0.1 < p_T < 12 GeV, |η| < 0.5

Application to selected particles: K_S^0



Hybrid formalism captures the qualitative behavior seen in data up to: $N_{ch}/\langle N_{ch} \rangle \sim 2.5$

Highest multiplicities not described: missing saturation effects on projectile? Medium modification effects?

Need a way to check what is the reason!

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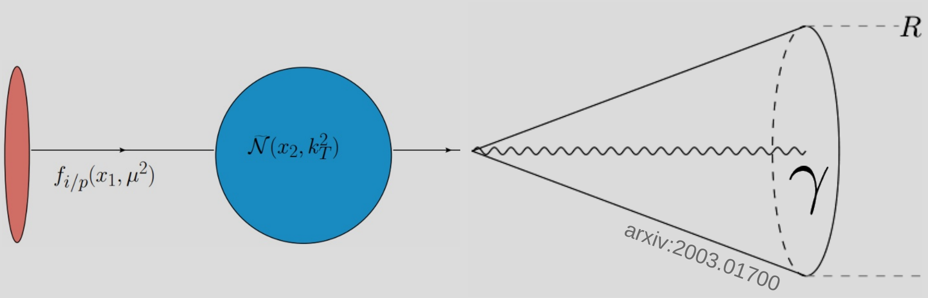
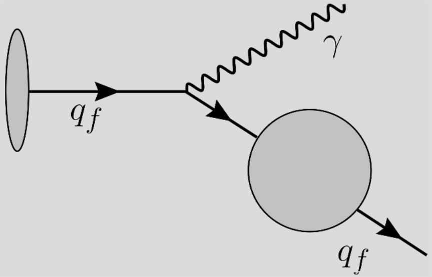
Application to selected particles: isolated photons

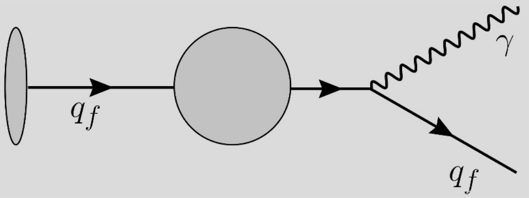


Negligible dependence of isolation radius, will show results for R = 0.1 fm

Not affected by fragmentation processes
(photons from fragmentation suppressed by angular exclusion)



γ – bremsstrahlung off an eikonal parton through the low-x color field



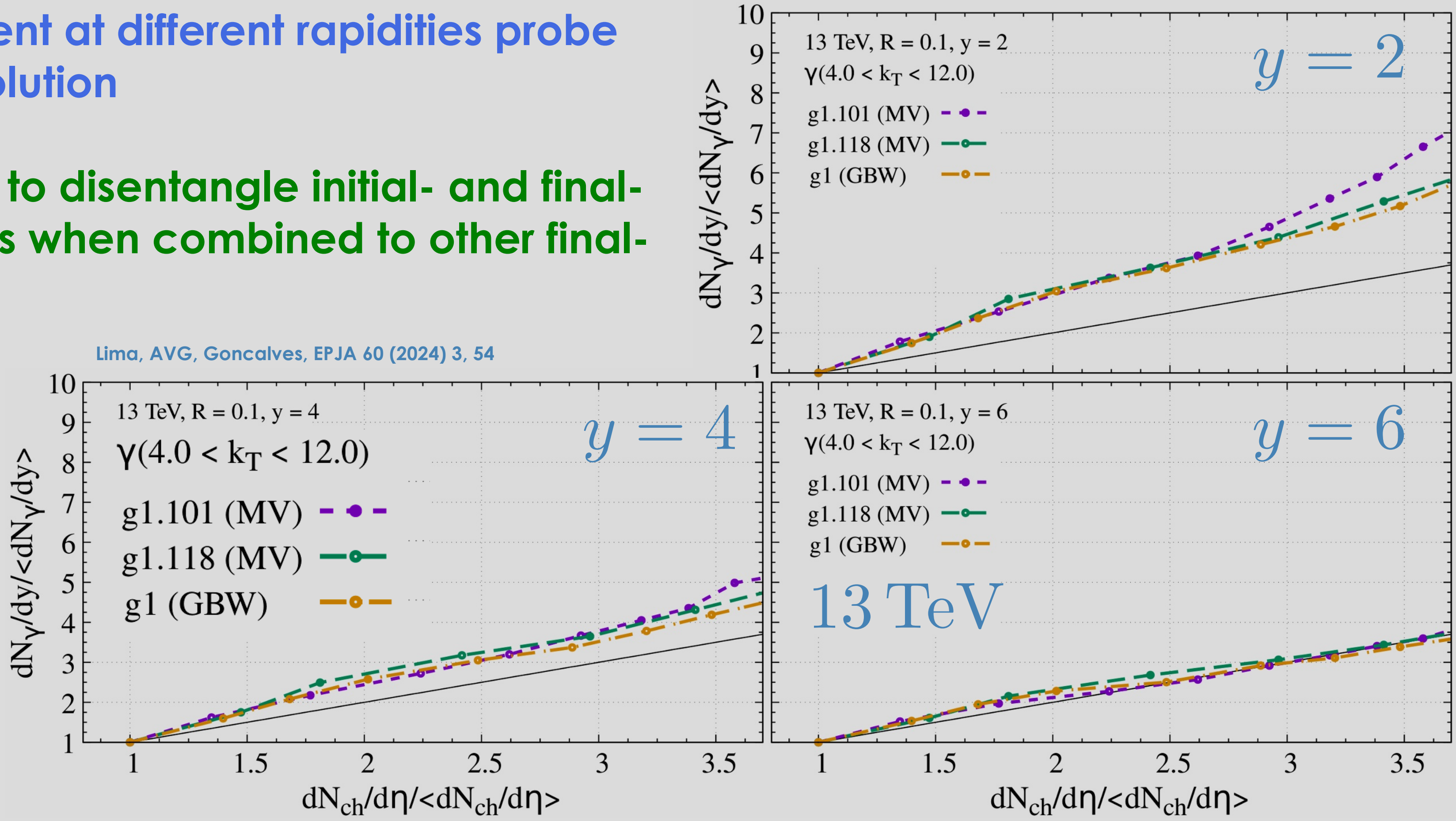
Qualitative description of p_T-spectra [backup slides]

Application to selected particles: isolated photons

Measurement at different rapidities probe small-x evolution

Could help to disentangle initial- and final-state effects when combined to other final-states

Lima, AVG, Goncalves, EPJA 60 (2024) 3, 54



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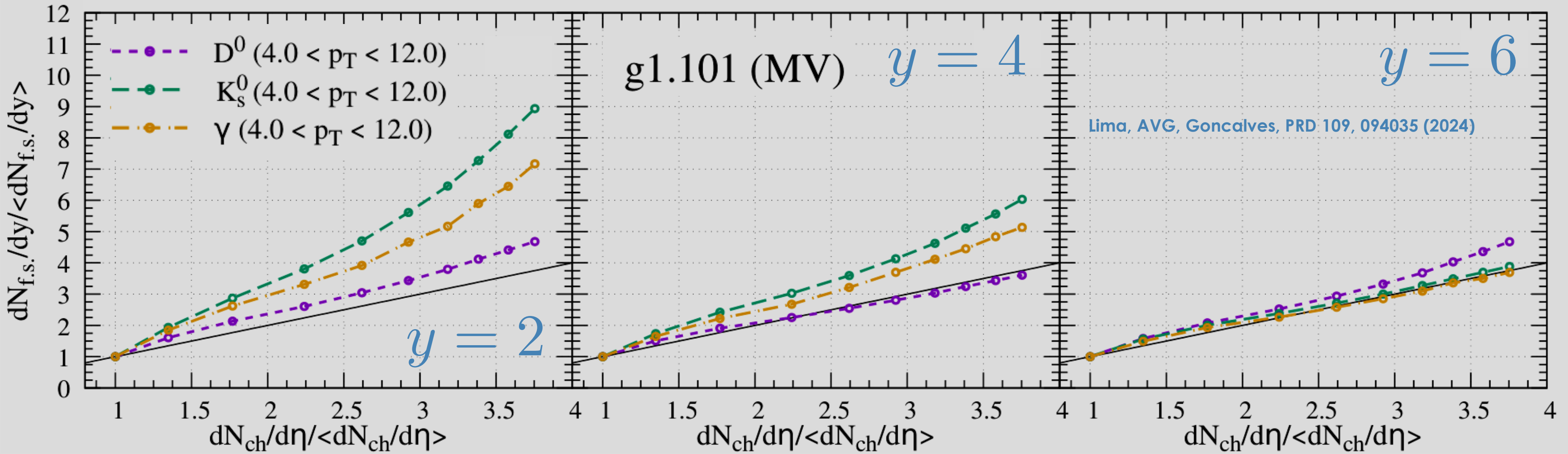
Application to selected particles: D^0 mesons

$$c + g \to D^0 + X \quad + \quad \{g + p \to Q\bar{Q}\} \to D^0 + X$$



Universal, final-state independent curve at (ultra-)forward rapidities If high multiplicity events are mainly a product of initial-state effects

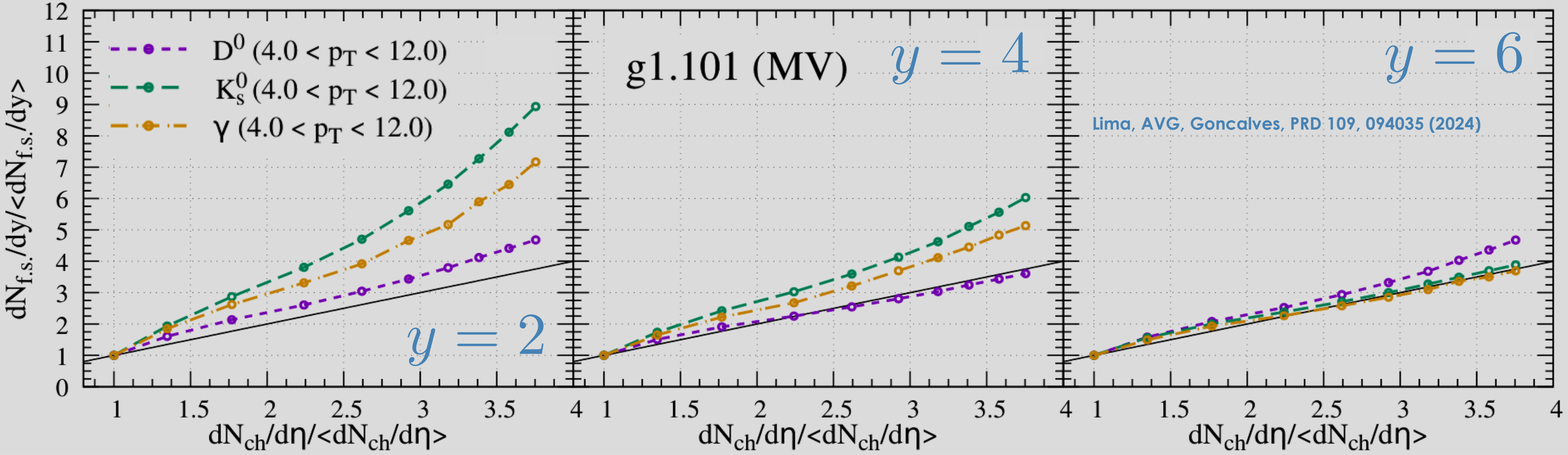
Result will not be universal if final-state effects play a role in such events

Final remarks

Studied high-multiplicity p+p collisions for different final states in correlation to charged particles + explored different kinematical regions

Qualitative understanding of kaon production at moderated multiplicities

Possible advances in understanding the mechanism behind high-multiplicity events by simultaneous study of different final states

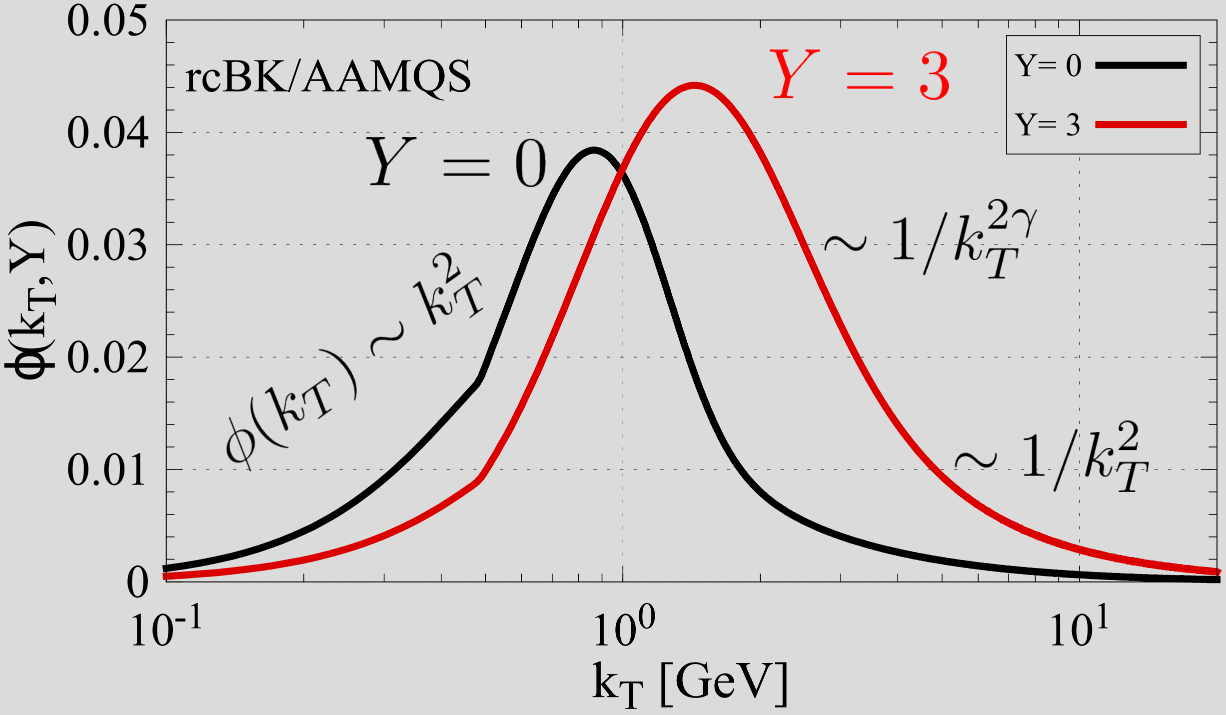


Lima, AVG, Goncalves, PRD 109, 094035 (2024)

Backup slides

Specifying the dipole scattering amplitude

$$\mathcal{N}_F(r, x_0) = 1 - exp\left[- \frac{(r^2\, Q^2_{s0,\mathrm{proton}})^{\gamma}}{4}\, ln\left(\frac{1}{\Lambda r} + e \right) \right]$$

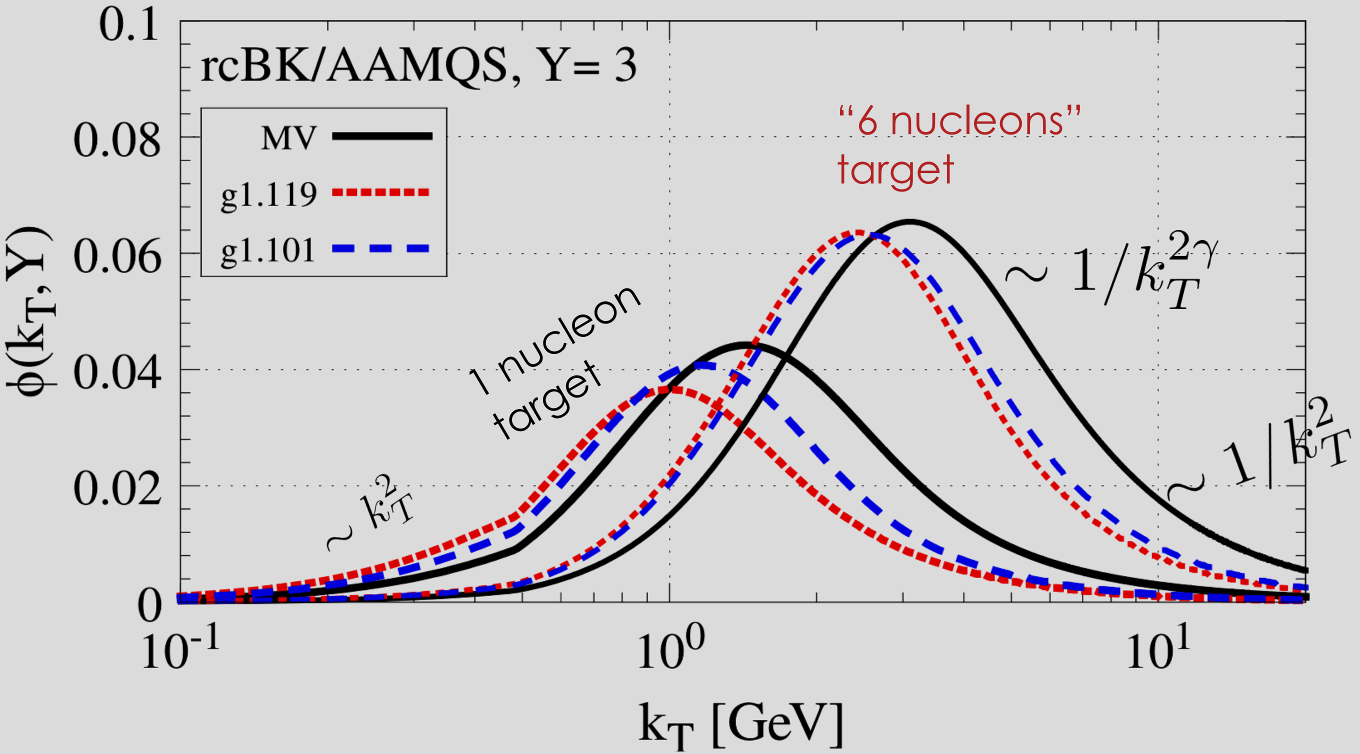


$\gamma = 1$: MV model

$\gamma = 1$ + no log: GBW model

$\gamma > 1$: best fit of HERA data

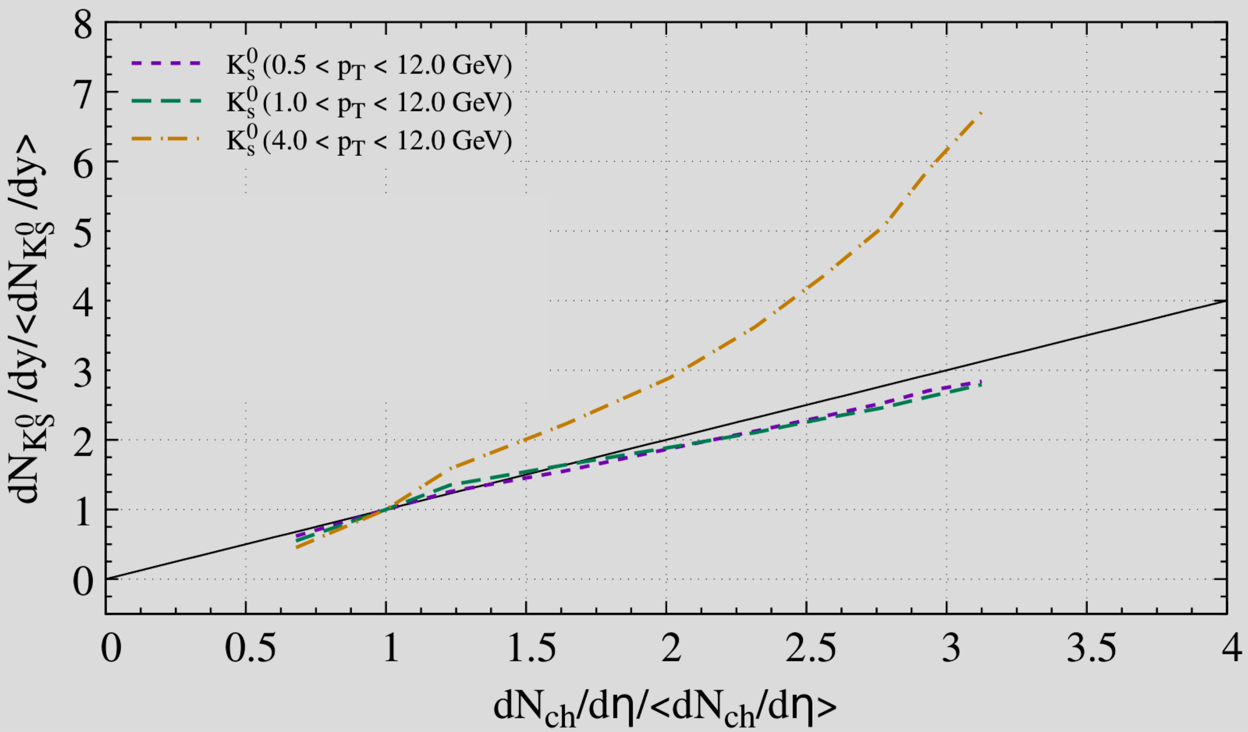
Specifying the dipole scattering amplitude



Higher than average multiplicity events from collisions where (at least one of the) protons have larger Q_s

Larger Q_s: UGD peak is shifted to the right

Application to selected particles: K_S^0



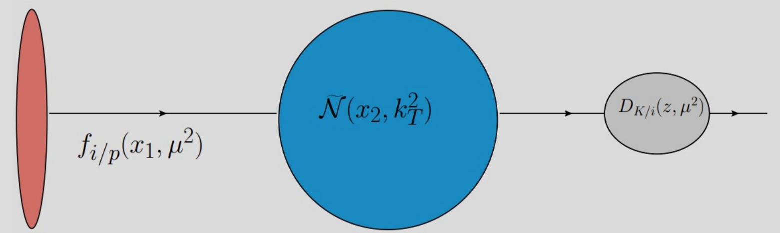
Dependence with p_T cuts

Ch. particles always in $0.1 < p_T < 12$ GeV

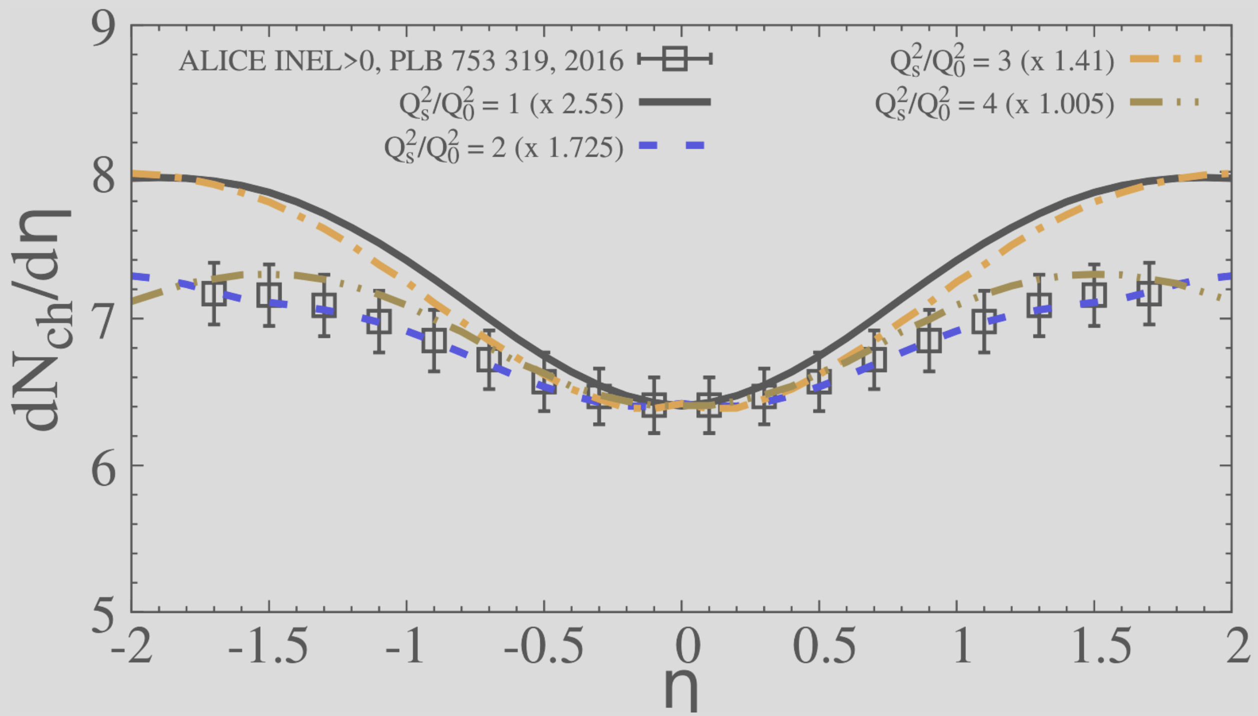
Including low-p_T particles favors saturation effects

Larger pt ranges require larger Qs(x) to be affected in same way as charged particles

Describing the charged paricle multiplicity



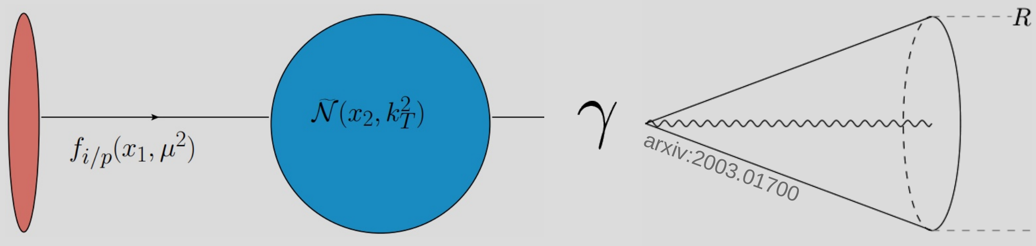
$$h^+ + h^-$$



Best description is provided when assuming a slightly larger saturation scale for the proton

Ratios do not depend on K-factor!

Isolated photons in the hybrid formalism



$$\frac{dN^{pp\to\gamma X}}{d^2\mathbf{k}_T dy} = \sum_q \frac{e_q^2\alpha_{em}}{\pi(2\pi)^3}\int d^2\mathbf{l}_T\int_{x_{min}} dx_p z^2[1+(1-z)^2]\frac{q(x_p,\mu^2)}{\mathbf{k}_T^2}$$

$$\times \quad \frac{(\mathbf{k}_T+\mathbf{l}_T)^2}{[z\mathbf{l}_T-(1-z)\mathbf{k}_T]^2}\int d^2\boldsymbol{b}S(\mathbf{k}_T+\mathbf{l}_T,\boldsymbol{b},x_g)\ \theta[\sqrt{(y-y_q)^2+\boxed{\Delta\phi}}-R]$$

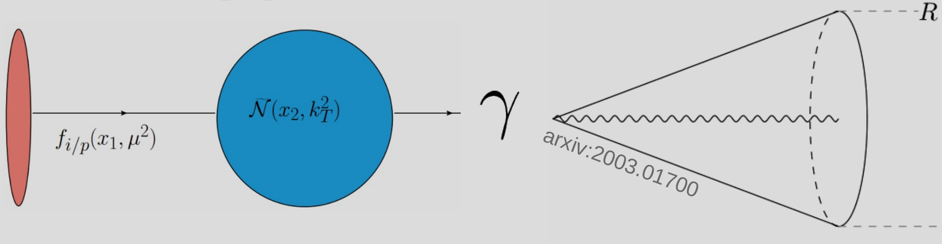
Ducloue, Lappi, Mantysaari, PRD 97(5), 054023 (2018)

$$S = 1-\mathcal{N}$$

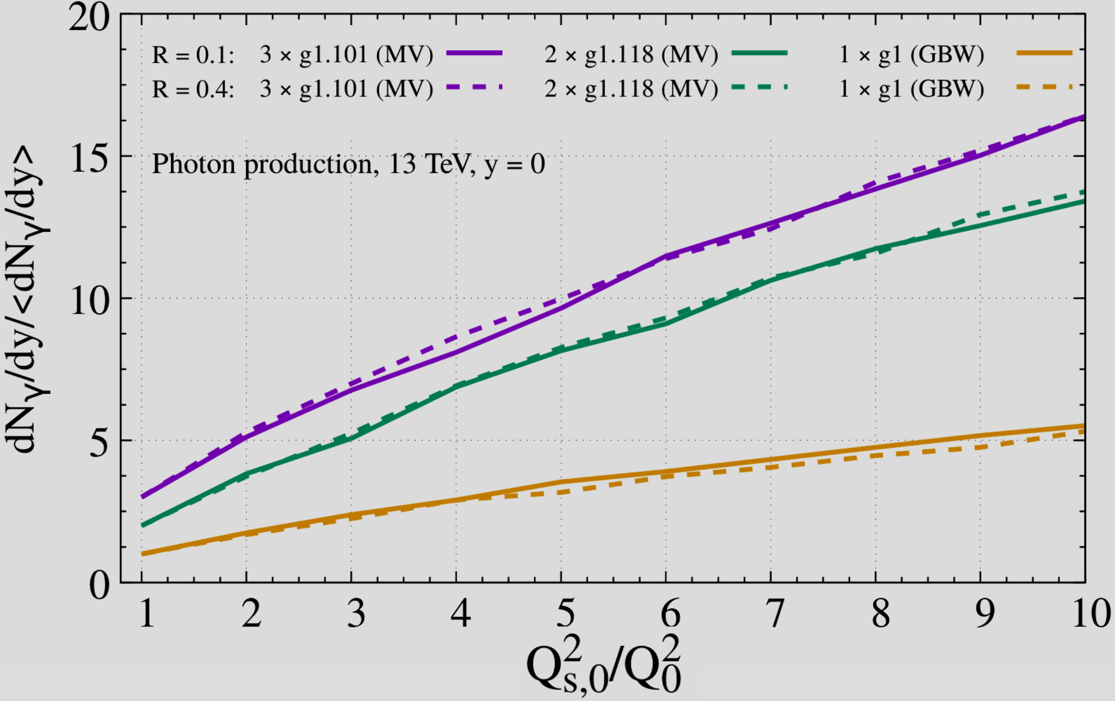
azimuthal angle between the scattering quark and the photon

$$x_g = \frac{|\mathbf{k}_T|e^{-y}+|\mathbf{l}_T|e^{-y_q}}{\sqrt{s}}, \qquad y_q = \log\left(\frac{-e^y|\mathbf{k}_T|+x_p\sqrt{s}}{|\mathbf{l}_T|}\right), \qquad z = \frac{|\mathbf{k}_T|}{x_p\sqrt{s}e^y}$$

Application to selected particles: isolated photons



Lima, AVG, Goncalves, arXiv:2302.13720

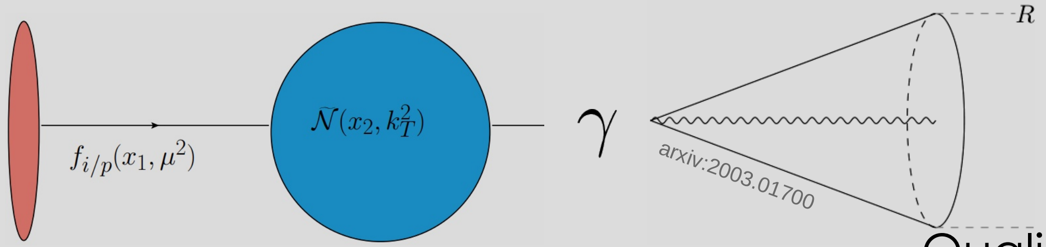


Negligible dependence of isolation radius

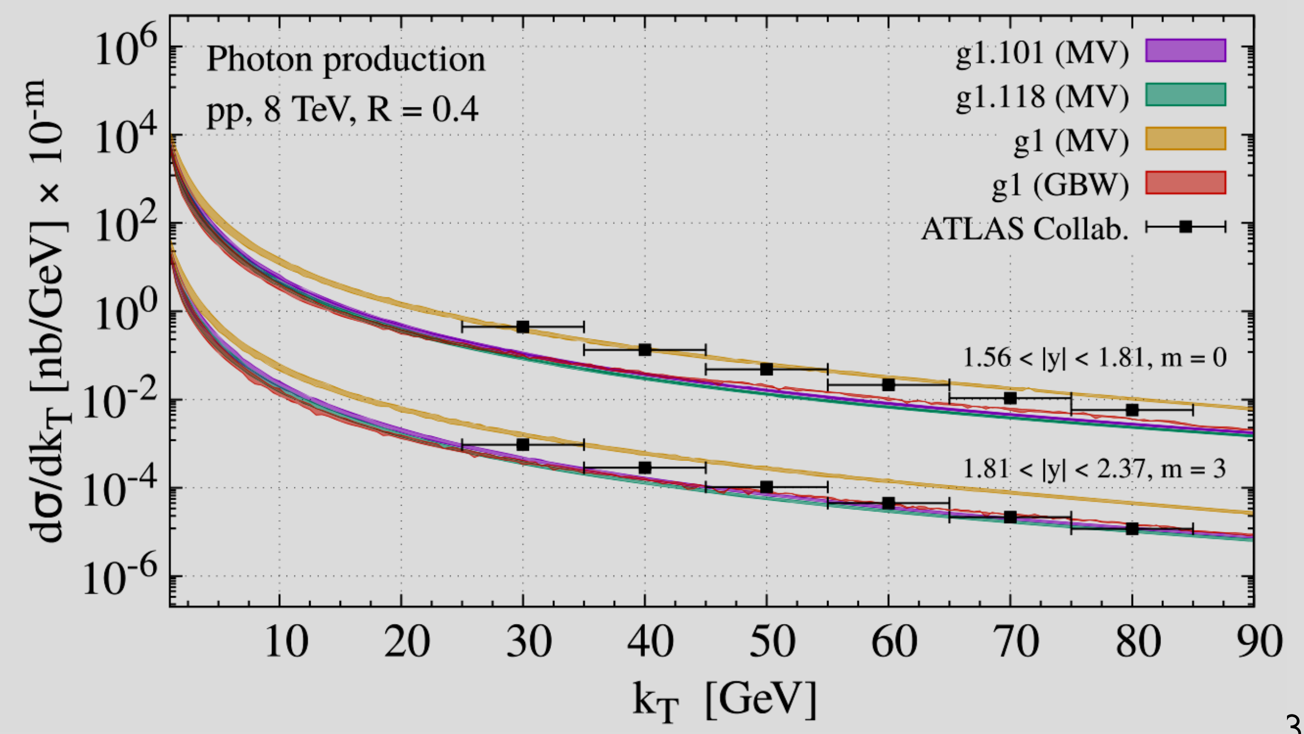
Similar dependence on p_T cuts (as seen in previous plots)

Can check the correlation to charged particles and different kinematical regions

Application to selected particles: isolated photons



Qualitative description of p_T-spectra



Application to selected particles: isolated photons

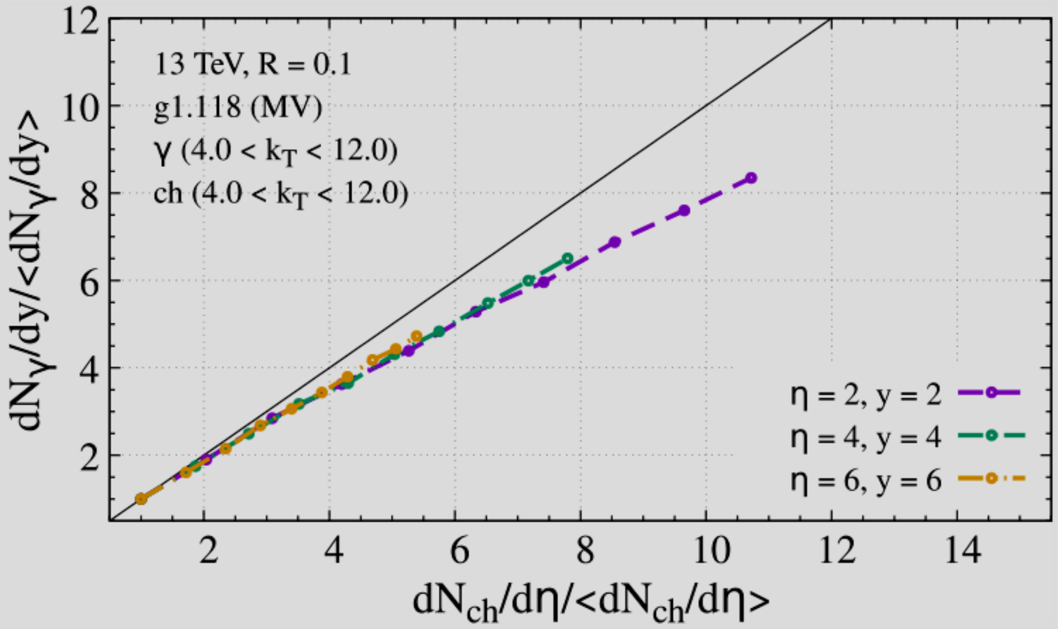


Fig. 6 Correlation between the normalized isolated photon and charged particles yields in *pp* collisions at $\sqrt{s} = 13$ TeV, derived that the distinct yields are integrated over the same transverse momentum range and are estimated at the same rapidity

Ch. particles and photons have similar Qs dependence for same kinematical range

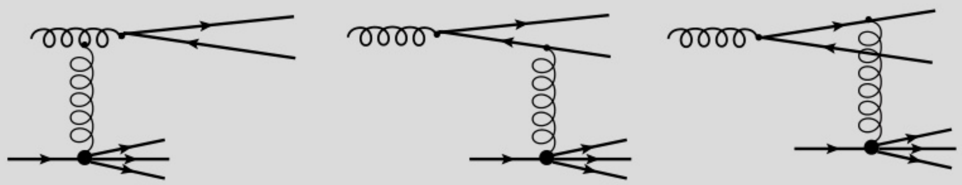
Ch. particles has faster increase compared to photons

Application to selected particles: D⁰ mesons

Goncalves, **Kopeliovich**, Nemchik, Pasechnik, Potashnikova, PRD 96, 014010

$$\left.\frac{d\sigma_{pp\to D^0X}}{dy\,d^2p_T}\right|_{G.I.} = \int_{z_{\min}}^{1}\frac{dz}{z^2}\,x_1 g(x_1,Q^2) \times \int_{\alpha_{\min}}^{1} d\alpha\,\frac{d^3\sigma_{gp\to c\bar{c}X}}{d\alpha\,d^2q_T}\,D_{c/D}(z,\mu^2),$$

$$z_{\min} = \frac{\sqrt{m_D^2+p_T^2}}{\sqrt{s}}\,e^{y} \qquad \alpha_{\min} = \frac{z_{\min}}{z}\sqrt{\frac{m_c^2z^2+p_T^2}{m_D^2+p_T^2}}.$$



interaction of a colorless three-body system gQQbar
scattering off the color background field of the target proton

$$\frac{d^3\sigma_{gp\to c\bar{c}X}}{d\alpha\,d^2q_T} = \frac{1}{6\pi}\int\frac{d^2\kappa_T}{\kappa_T^4}\,\alpha_s\mathcal{K}_{\rm dip}(x_2,\kappa_T^2)\left\{\left[\frac{9}{8}\mathcal{H}_0(\alpha,\bar{\alpha},\vec{q}_T) - \frac{9}{4}\mathcal{H}_1(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T) + \mathcal{H}_2(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T) + \frac{1}{8}\mathcal{H}_3(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T)\right] + [\alpha\leftrightarrow\bar{\alpha}]\right\},$$

$$\mathcal{H}_0(\alpha,\bar{\alpha},\vec{q}_T) = \frac{m_c^2+(\alpha^2+\bar{\alpha}^2)q_T^2}{(q_T^2+m_c^2)^2},$$

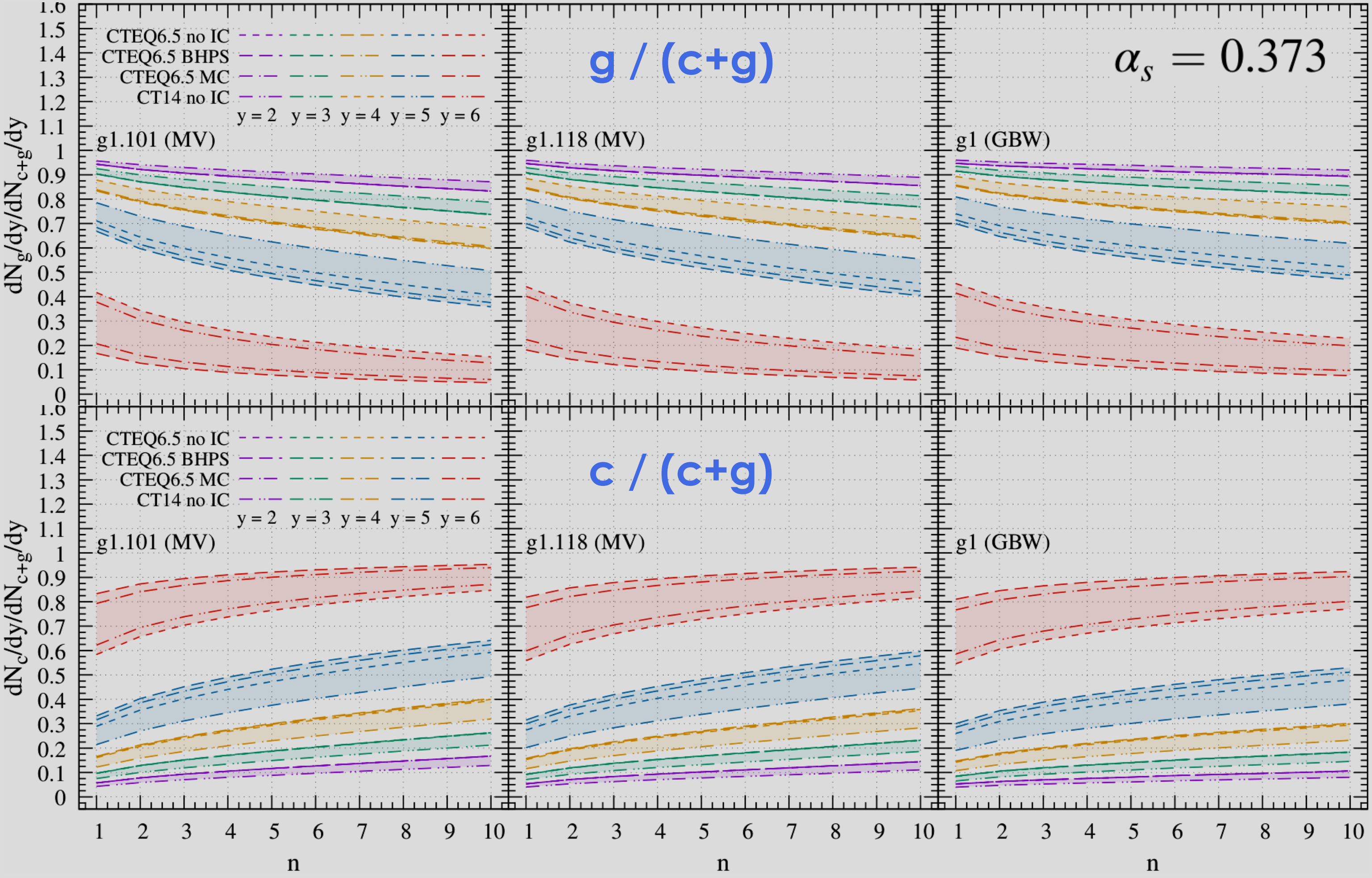
$$\mathcal{H}_1(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T) = \frac{m_c^2+(\alpha^2+\bar{\alpha}^2)\vec{q}_T\cdot(\vec{q}_T-\alpha\vec{\kappa}_T)}{[(\vec{q}_T-\alpha\vec{\kappa}_T)^2+m_c^2](q_T^2+m_c^2)},$$

$$\mathcal{H}_2(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T) = \frac{m_c^2+(\alpha^2+\bar{\alpha}^2)(\vec{q}_T-\alpha\vec{\kappa}_T)^2}{[(\vec{q}_T-\alpha\vec{\kappa}_T)^2+m_c^2]^2},$$

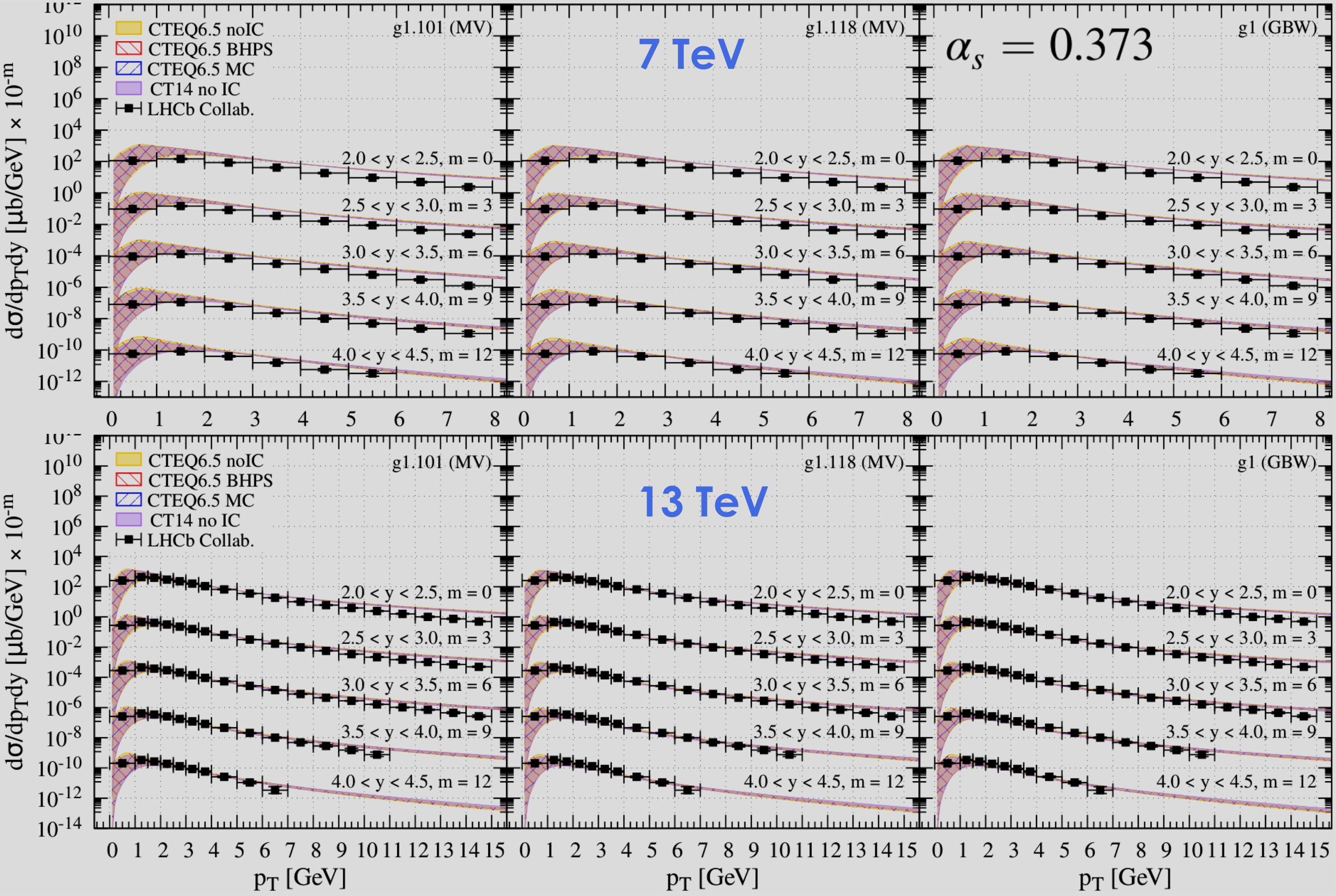
$$\mathcal{H}_3(\alpha,\bar{\alpha},\vec{q}_T,\vec{\kappa}_T) = \frac{m_c^2+(\alpha^2+\bar{\alpha}^2)(\vec{q}_T+\alpha\vec{\kappa}_T)\cdot(\vec{q}_T-\bar{\alpha}\vec{\kappa}_T)}{[(\vec{q}_T+\alpha\vec{\kappa}_T)^2+m_c^2][(\vec{q}_T-\bar{\alpha}\vec{\kappa}_T)^2+m_c^2]}$$

$$x_{1,2} = \frac{M_{Q\bar{Q}}}{\sqrt{s}}\,e^{\pm y} \qquad M_{Q\bar{Q}} \simeq 2\sqrt{m_Q^2+p_T^2}.$$

Application to selected particles: D^0 mesons



Application to selected particles: D^0 mesons



Application to selected particles: D^0 mesons