ACCESSING SATURATION AND SUBNUCLEAR STRUCTURE WITH MULTIPLICITY DEPENDENT J/Ψ PRODUCTION IN p+p AND p+Pb COLLISIONS

29TH INTERNATIONAL CONFERENCE ON ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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KRAKÓW, POLAND

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

BASED ON: F. SALAZAR, B. SCHENKE, A. SOTO-ONTOSO, PHYS.LETT.B 827 (2022) 136952, E-PRINT: 2112.04611

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Brookhaven National Laboratory
QM QUARK MATTER KRAKÓW 2022

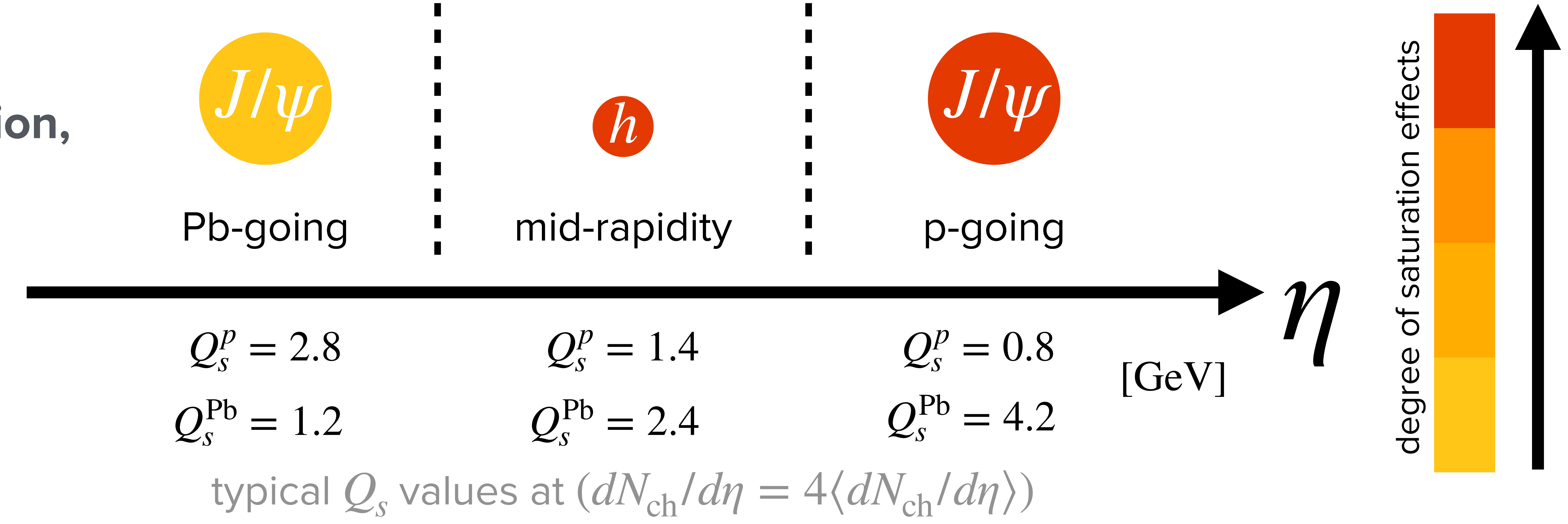
SCANNING SATURATION WITH J/Ψ AND h_c

Study production of J/ψ at different rapidities relative to charged hadrons at midrapidity

Expect varying sensitivity to saturation, depending on probed Q_s and mass:

J/ψ $m_{J/\psi} = 3.1\,\mathrm{GeV}$

h $m_{h_c} \approx 0.5\,\mathrm{GeV}$



Most important physics in $Q_s^2(x, \boldsymbol{R}_\perp) = T_A(\boldsymbol{R}_\perp) S_\perp Q_s^2(x)$. Depends on rapidity ($x$) and transverse space.

Spatial dependence in $T_A(\boldsymbol{R}_\perp)$ includes fluctuations of nucleon positions and nucleon substructure:

3 hot spots locations per nucleon sampled from

$P(\boldsymbol{R}_{\perp,i}) = \frac{1}{2\pi B_{\mathrm{qc}}} e^{-\boldsymbol{R}_{\perp,i}^2/(2B_{qc})}$ and hot spot density distribution $T_q(\boldsymbol{R}_\perp - \boldsymbol{R}_{\perp,i}) = \xi_{Q_s^2} e^{-(\boldsymbol{R}_\perp - \boldsymbol{R}_{\perp,i})^2/(2(\xi_{B_q})B_q)}$

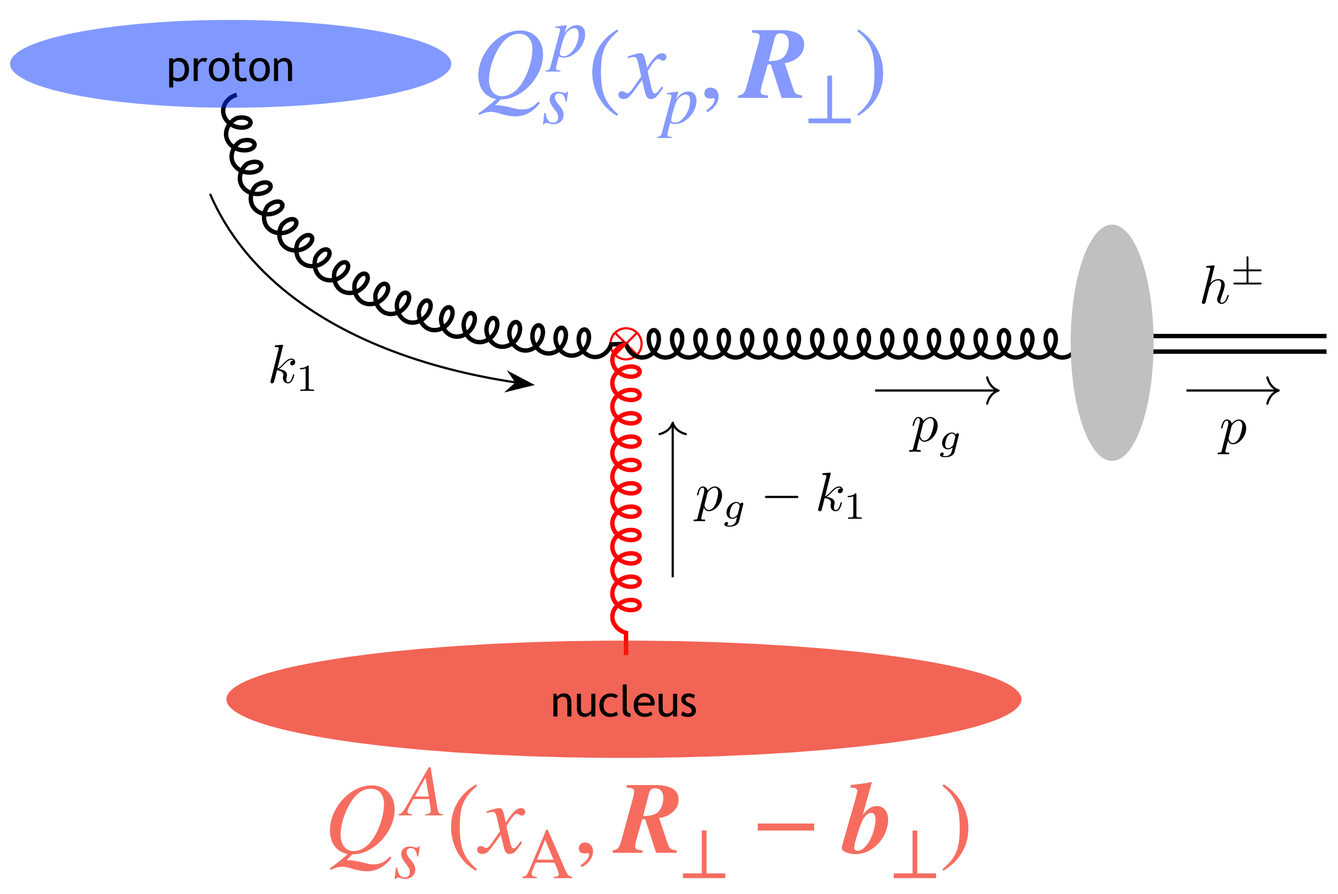
fluctuating normalization

fluctuating size

CHARGED HADRON AND J/Ψ PRODUCTION

Use k_T-factorization for gluon production Y. V. Kovchegov, K. Tuchin, Phys. Rev. D 65, 074026 (2002) J. P. Blaizot, F. Gelis, R. Venugopalan, Nucl. Phys. A743, 13 (2004)

$$\frac{\mathrm{d}N_g(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{p}_{g\perp}\mathrm{d}y_g} = \frac{\alpha_s}{(\sqrt{2}\pi)^6 C_F}\frac{1}{\boldsymbol{p}_{g\perp}^2}\int_{\boldsymbol{k}_{1\perp},\boldsymbol{R}_\perp} \phi^p(x_p;\boldsymbol{k}_{1\perp};\boldsymbol{R}_\perp)\phi^A(x_A;\boldsymbol{p}_{g\perp}-\boldsymbol{k}_{1\perp};\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)$$



Unintegrated gluon distributions ϕ^p and ϕ^A (with $A = p, \mathrm{Pb}$) from BK evolution with McLerran-Venugopalan initial conditions + spatial dependence

Hadronize using KKP fragmentation function

$c\bar{c}$-pair production in NRQCD Z.-B. Kang, Y.-Q. Ma, and R. Venugopalan, JHEP 01, 056 (2014)

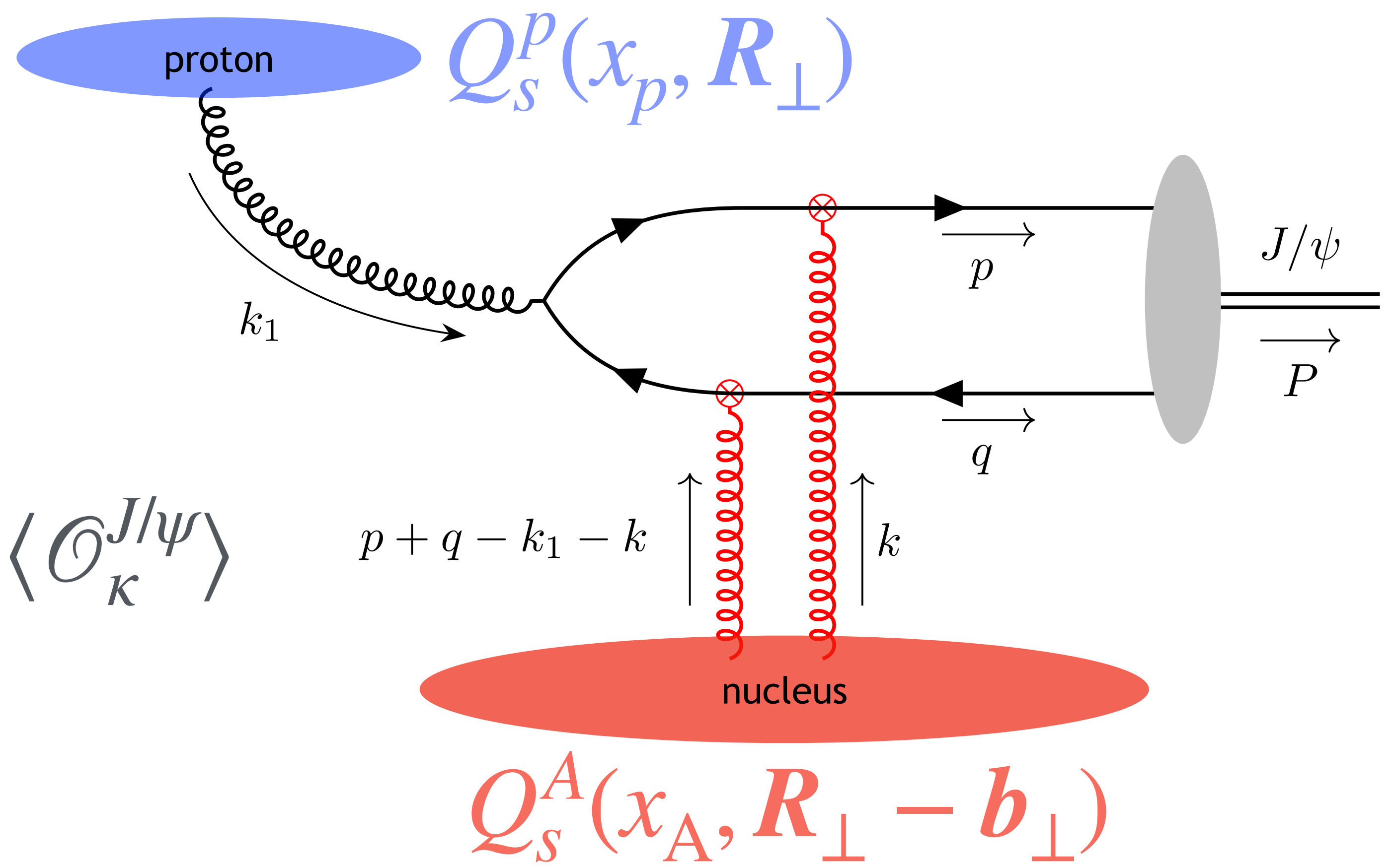
$$\frac{\mathrm{d}N^\kappa_{c\bar{c}}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}Y} = \frac{\alpha_s}{(2\pi)^9(N_c^2-1)}\int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp,\boldsymbol{R}_\perp} \mathscr{H}^\kappa(\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)\frac{\phi^p(x_p,\boldsymbol{k}_{1\perp},\boldsymbol{R}_\perp)}{\boldsymbol{k}_{1\perp}^2}\tilde{\Xi}^\kappa(x_A;\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp;\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)$$

for quantum state κ. The pair momentum is $\boldsymbol{P}_\perp = \boldsymbol{p}_\perp + \boldsymbol{q}_\perp$, $\mathscr{H}^\kappa$ are the hard factors,

and the $\tilde{\Xi}^\kappa$ contain dipole amplitudes (related to ϕ^A)

$$\frac{\mathrm{d}N_{J/\psi}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}Y} = \sum_\kappa \frac{\mathrm{d}N^\kappa_{c\bar{c}}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}Y}\langle\mathcal{O}_\kappa^{J/\psi}\rangle$$

with non-perturbative long distance matrix elements $\langle\mathcal{O}_\kappa^{J/\psi}\rangle$

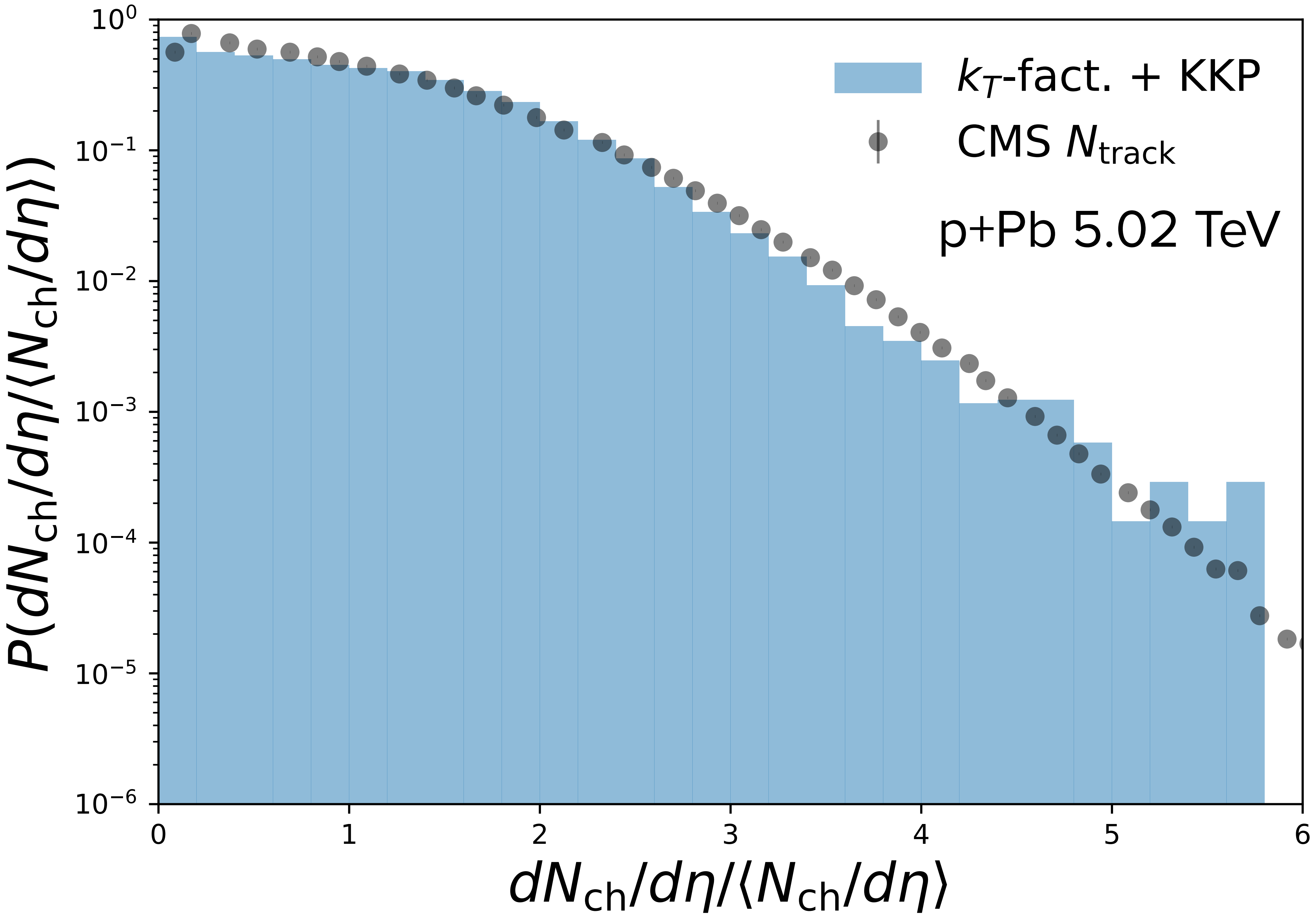


K.-T. Chao, Y.-Q. Ma, H.-S. Shao, K. Wang, Y.-J. Zhang, Phys. Rev. Lett. 108, 242004 (2012)
Y.-Q. Ma, R. Venugopalan, H.-F. Zhang, Phys. Rev. D 92, 071901 (2015)

RESULTS: FLUCTUATIONS

- **Charged hadron multiplicity distribution**

  Experimental data: CMS Collaboration, Phys.Lett. B718, 795 (2013), https://twiki.cern.ch/twiki/bin/view/CMSPublic/ PhysicsResultsHIN12015



Parameter	Value
N_q	3
B_{qc}	$3\,\mathrm{GeV}^{-2}$
B_q	$1\,\mathrm{GeV}^{-2}$
σ_{B_q}	0.7
$\sigma_{Q_s^2}$	0.1
$S_\perp$	13 mb

Parameter	Value
α_s	0.16
m_{IR}	0.2 GeV
$m_{J/\psi}$	3.1 GeV
m_c	$m_{J/\psi}/2$
m_D	1.87 GeV

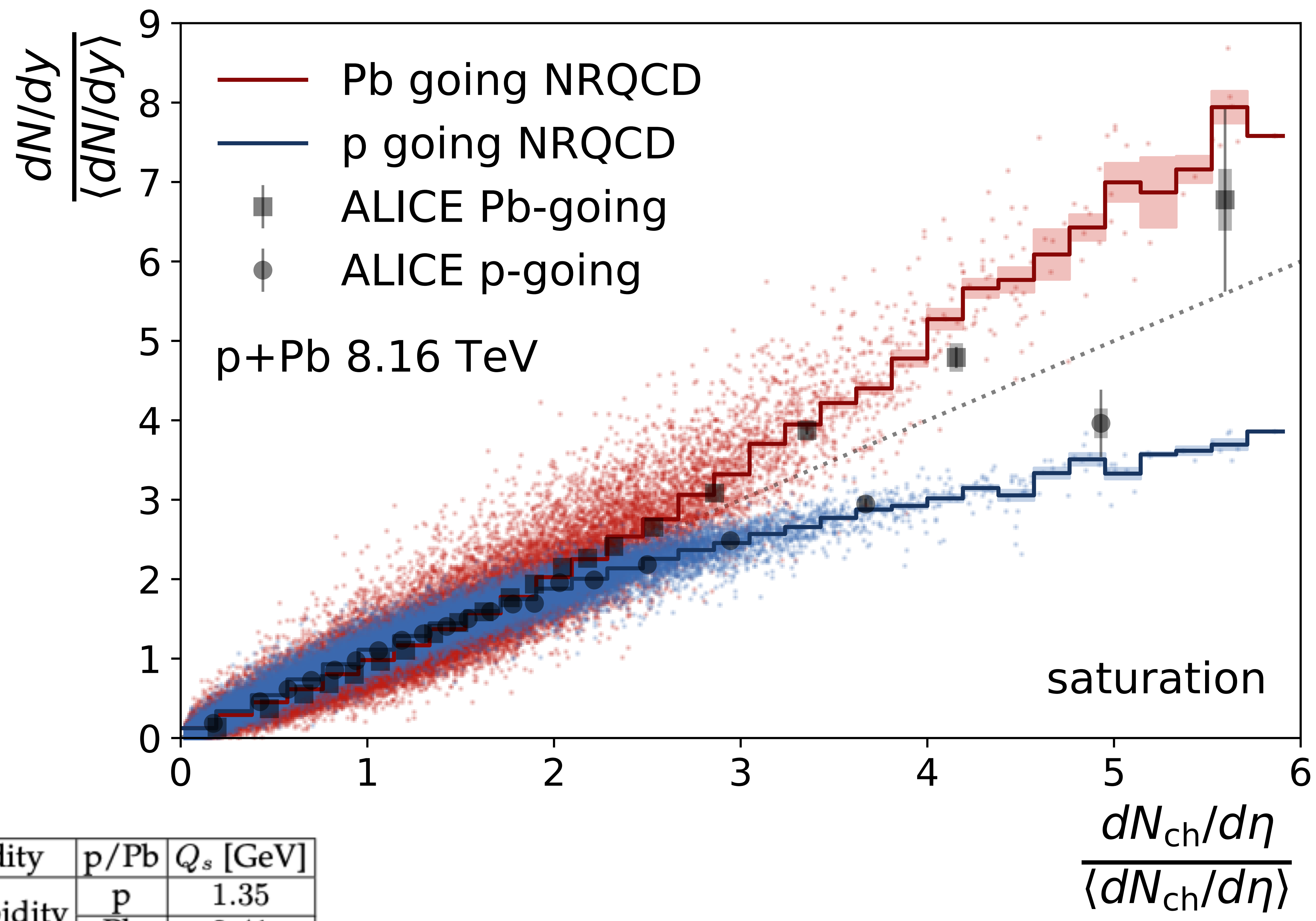
σ_{B_q} and σ_{Q_s}: width parameters in log-normal fluctuations ξ

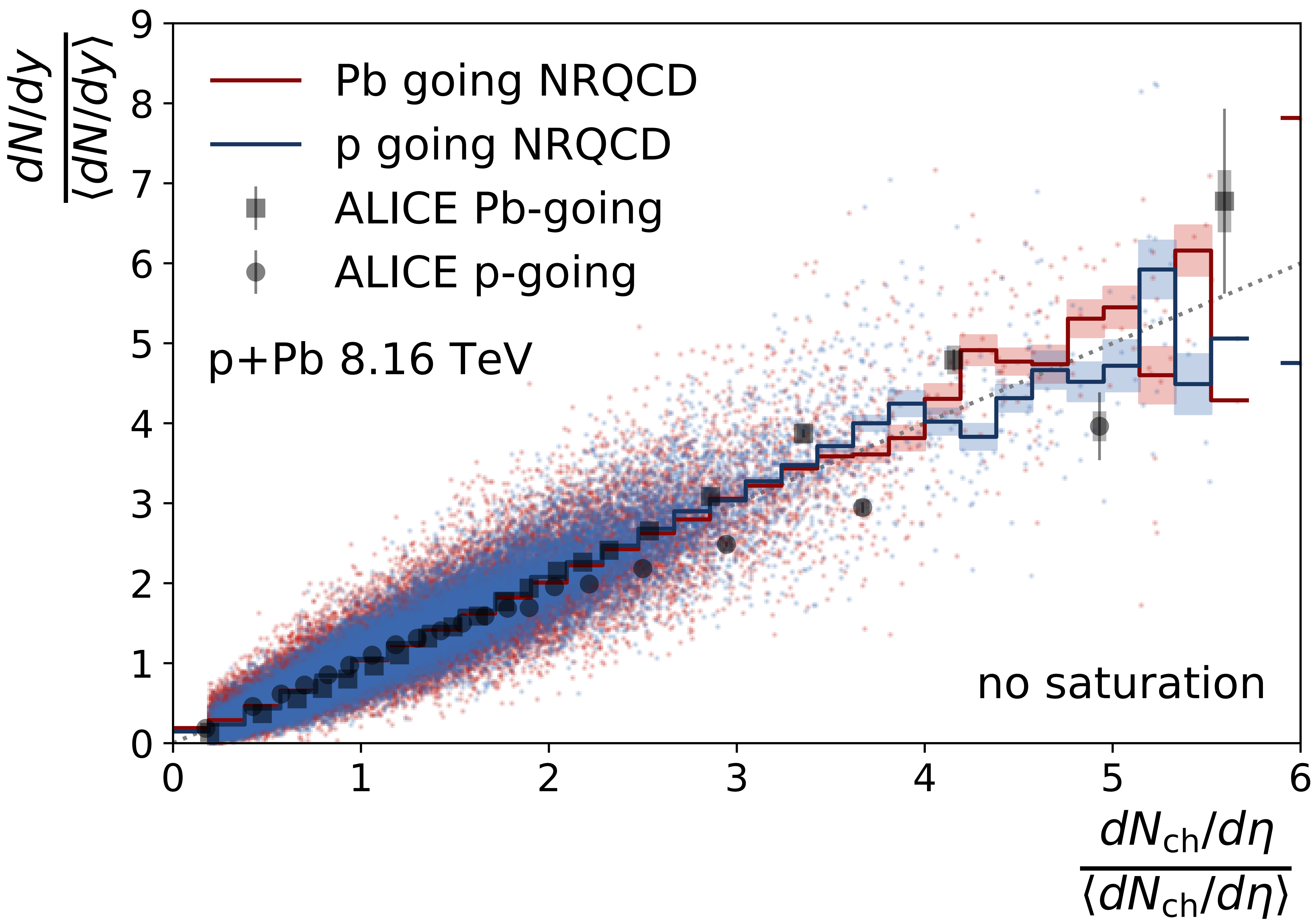
m_{IR}: infrared regulator in the charged hadron calculation

RESULTS: J/Ψ VS. CHARGED HADRON YIELD

- **Saturation drives the correlation between J/ψ and charged hadrons**

Experimental data: S. Acharya et al. (ALICE), JHEP 09, 162 (2020), arXiv:2004.12673 [nucl-ex].





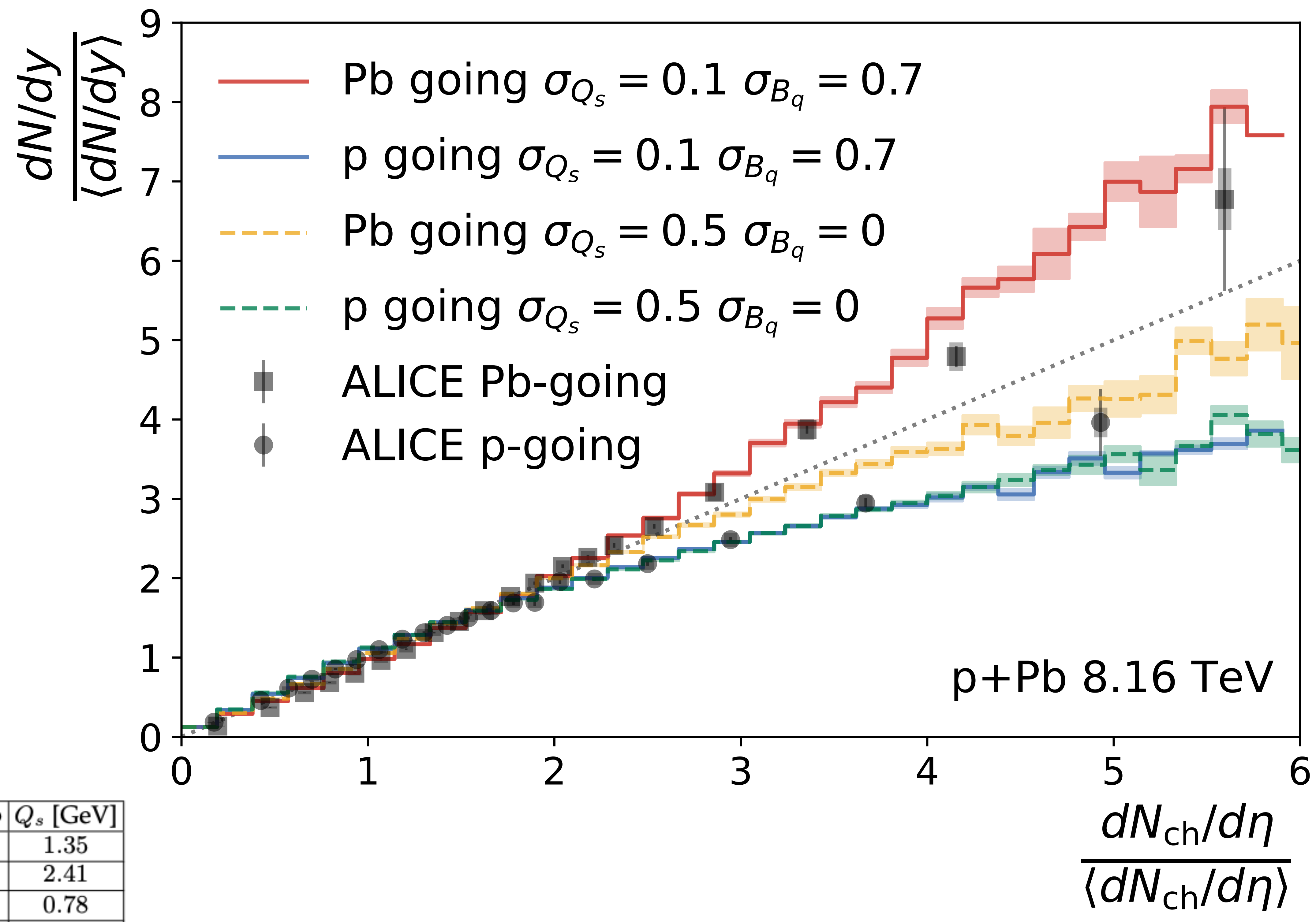
Rapidity	p/Pb	Q_s [GeV]
midrapidity	p	1.35
	Pb	2.41
p-going	p	0.78
	Pb	4.18
Pb-going	p	2.78
	Pb	1.18

$dN_{\rm ch}/d\eta = 4\langle dN_{\rm ch}/d\eta\rangle$

FLUCTUATIONS AFFECT SATURATION AND $\langle p_T \rangle$

Experimental data: ALICE Collaboration, JHEP 09, 162 (2020)

- More normalization fluctuations (less size fluctuations) lead to stronger saturation effects on the J/ψ in the Pb-going direction



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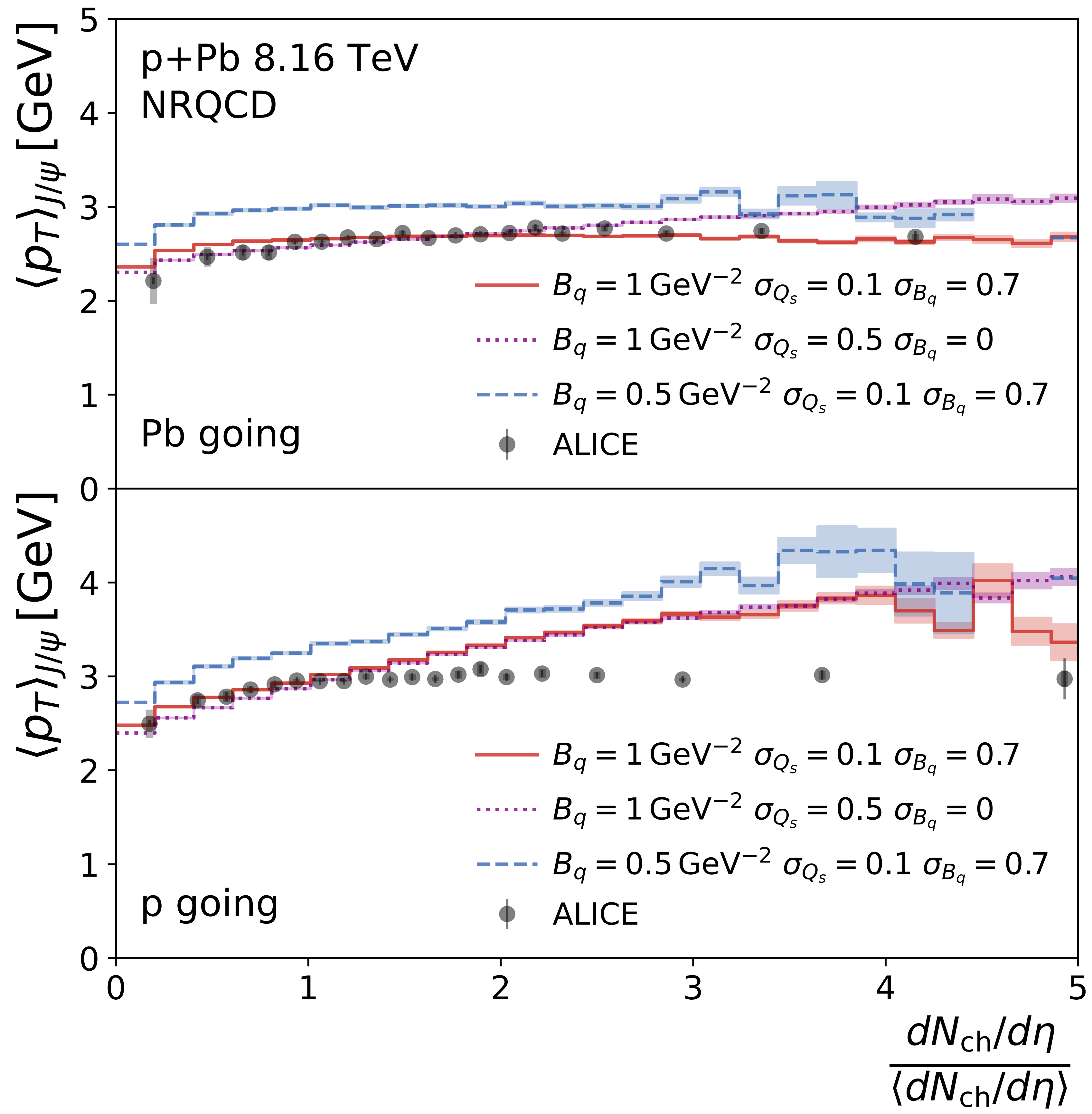
$dN_{ch}/d\eta = 4\langle dN_{ch}/d\eta \rangle$

- Mean p_T driven by mass and Q_s
- Q_s fluctuations and hot spot size matter



BACKUP

MODEL: CHARGED HADRON PRODUCTION

Use k_T-factorization for gluon production

Y. V. Kovchegov, K. Tuchin, Phys. Rev. D 65, 074026 (2002)
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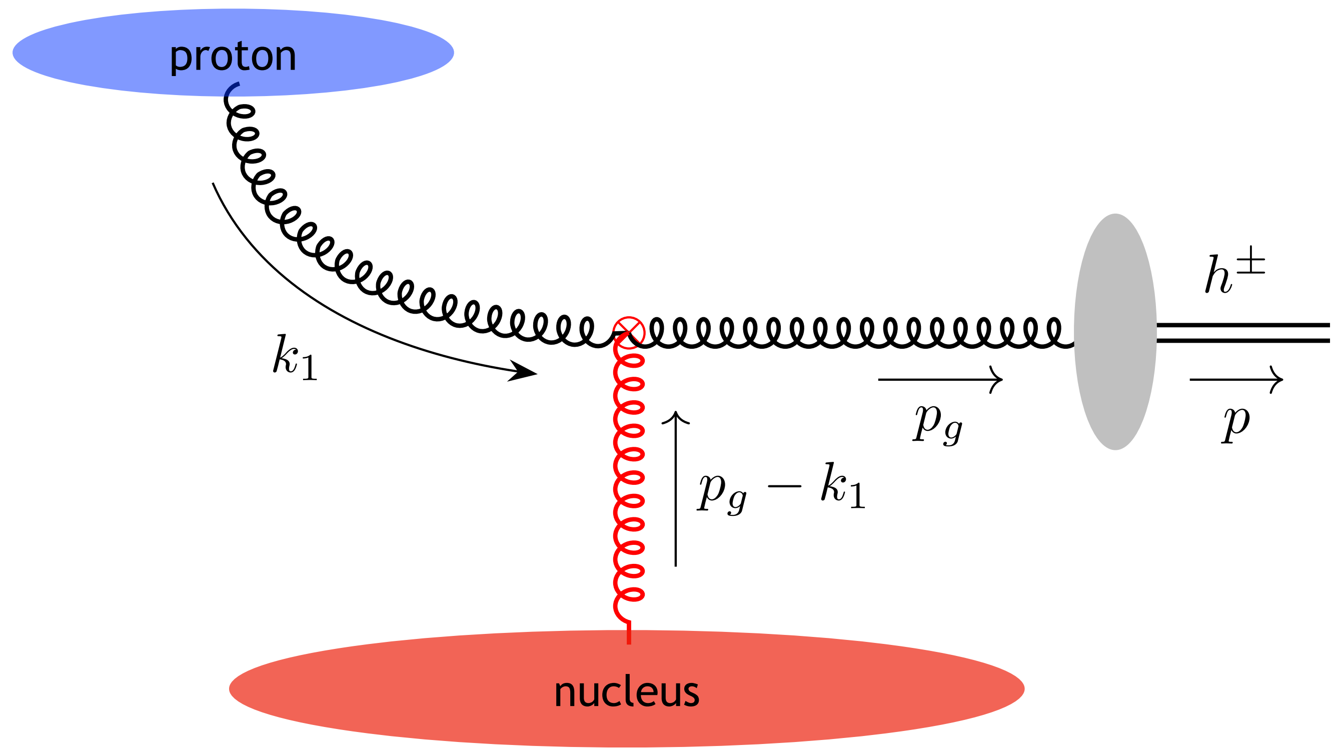


$$\frac{\mathrm{d}N_g(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{p}_{g\perp}\mathrm{d}y_g} = \frac{\alpha_s}{(\sqrt{2}\pi)^6 C_F}\frac{1}{\boldsymbol{p}_{g\perp}^2}\int_{\boldsymbol{k}_{1_\perp},\boldsymbol{R}_\perp} \phi^p(x_p;\boldsymbol{k}_{1_\perp};\boldsymbol{R}_\perp)\phi^A(x_A;\boldsymbol{p}_{g\perp}-\boldsymbol{k}_{1_\perp};\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)$$

Unintegrated gluon distributions ϕ^p and ϕ^A (with $A = p, \mathrm{Pb}$)
from Balitsky-Kovchegov evolution with McLerran-Venugopalan initial conditions

Modified to include spatial dependence with nucleon substructure. 3 hot spots locations sampled from

$$P(\boldsymbol{R}_{\perp,i}) = \frac{1}{2\pi B_{\mathrm{qc}}} e^{-\boldsymbol{R}_{\perp,i}^2/(2B_{qc})}$$ and hot spot density distribution $$T_q(\boldsymbol{R}_\perp - \boldsymbol{R}_{\perp,i}) = \xi_{Q_s^2} e^{-(\boldsymbol{R}_\perp - \boldsymbol{R}_{\perp,i})^2/(2(\xi_{B_q})B_q)}$$

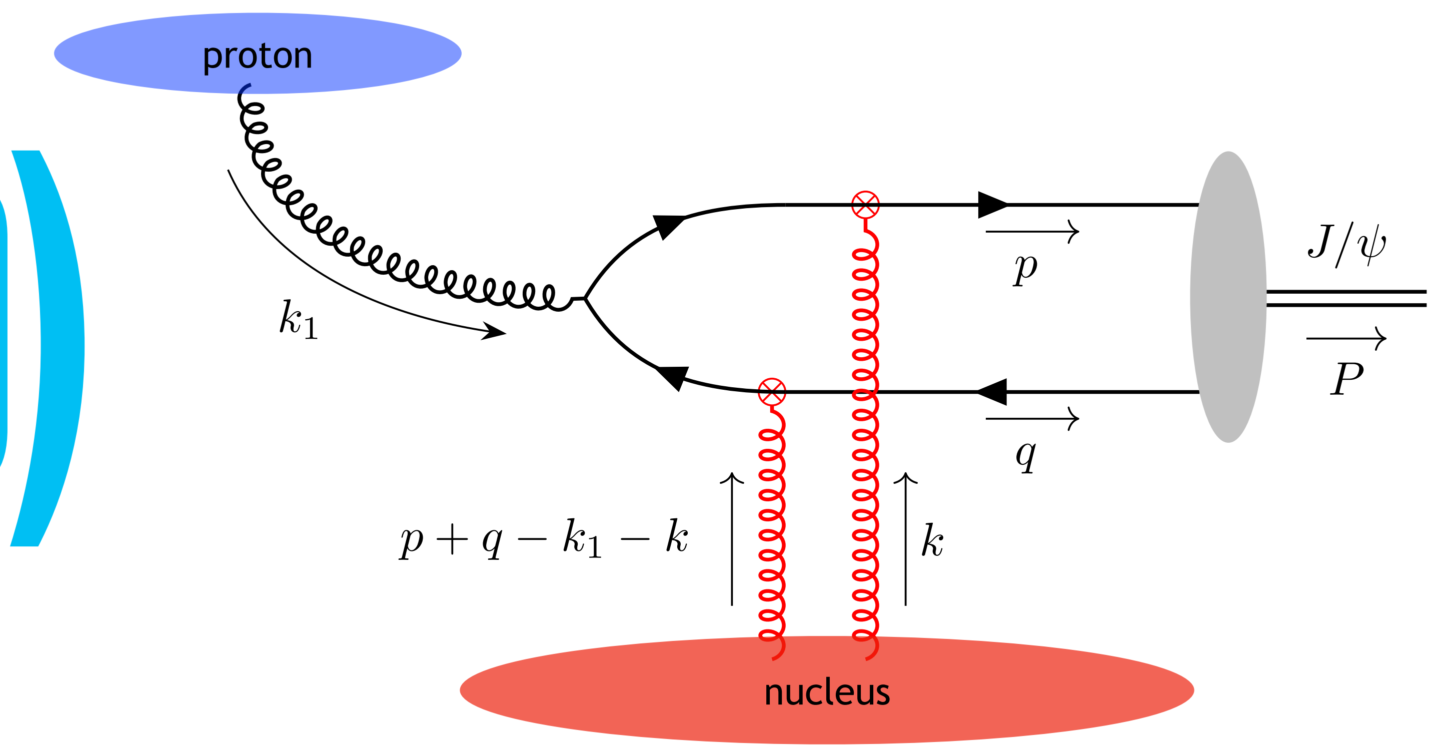
fluctuating normalization

fluctuating size

B_q is given an x dependence motivated by JIMWLK evolution of proton size

Hadronize using KKP fragmentation function $$\frac{\mathrm{d}N_{\mathrm{ch}}(\boldsymbol{b}_\perp)}{\mathrm{d}\eta} = \int_{\boldsymbol{p}_\perp}\int_{z_{\min}}^1 \mathrm{d}z \frac{D_h(z)}{z^2} \mathcal{J}_{y\to\eta} \left.\frac{\mathrm{d}N_g(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{p}_{g\perp}\mathrm{d}y_g}\right|_{\boldsymbol{p}_{g\perp}=\boldsymbol{p}_\perp/z}$$

MODEL: J/Ψ PRODUCTION (NRQCD)



$c\bar{c}$-pair production in NRQCD Z.-B. Kang, Y.-Q. Ma, and R. Venugopalan, JHEP 01, 056 (2014)

$$\frac{\mathrm{d}N^{\kappa}_{c\bar{c}}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}Y} = \frac{\alpha_s}{(2\pi)^9(N_c^2-1)}\int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp,\boldsymbol{R}_\perp} \mathscr{H}^{\kappa}(\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)\frac{\phi^p(x_p,\boldsymbol{k}_{1\perp},\boldsymbol{R}_\perp)}{\boldsymbol{k}_{1\perp}^2}\tilde{\Xi}^{\kappa}(x_A;\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp;\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)$$

for quantum state κ. The pair momentum is $\boldsymbol{P}_\perp = \boldsymbol{p}_\perp + \boldsymbol{q}_\perp$, $\mathscr{H}^{\kappa}$ are the hard factors, and $\tilde{\Xi}^{\kappa}$ the Wilson line correlators:

$$\tilde{\Xi}^{[8]}(x;\boldsymbol{l}_\perp,\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp;\boldsymbol{R}_\perp) = (2\pi)^2\delta^{(2)}(\boldsymbol{k}_\perp-\boldsymbol{k}'_\perp)\tilde{\mathscr{S}}^A_{\mathrm{F}}(x;\boldsymbol{k}_\perp;\boldsymbol{R}_\perp)\tilde{\mathscr{S}}^A_{\mathrm{F}}(x;\boldsymbol{l}_\perp-\boldsymbol{k}_\perp;\boldsymbol{R}_\perp) + \mathcal{O}\left(1/N_c\right) \text{ (octet)}$$

$$\tilde{\Xi}^{[1]}(x;\boldsymbol{l}_\perp,\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp;\boldsymbol{R}_\perp) = \tilde{\mathscr{S}}^A_{\mathrm{F}}(x;\boldsymbol{k}_\perp;\boldsymbol{R}_\perp)\tilde{\mathscr{S}}^A_{\mathrm{F}}(x;\boldsymbol{k}'_\perp;\boldsymbol{R}_\perp)\tilde{\mathscr{S}}^A_{\mathrm{F}}(x;\boldsymbol{l}_\perp-\boldsymbol{k}_\perp-\boldsymbol{k}'_\perp,\boldsymbol{R}_\perp) + \mathcal{O}\left(1/N_c\right) \text{ (singlet)}$$

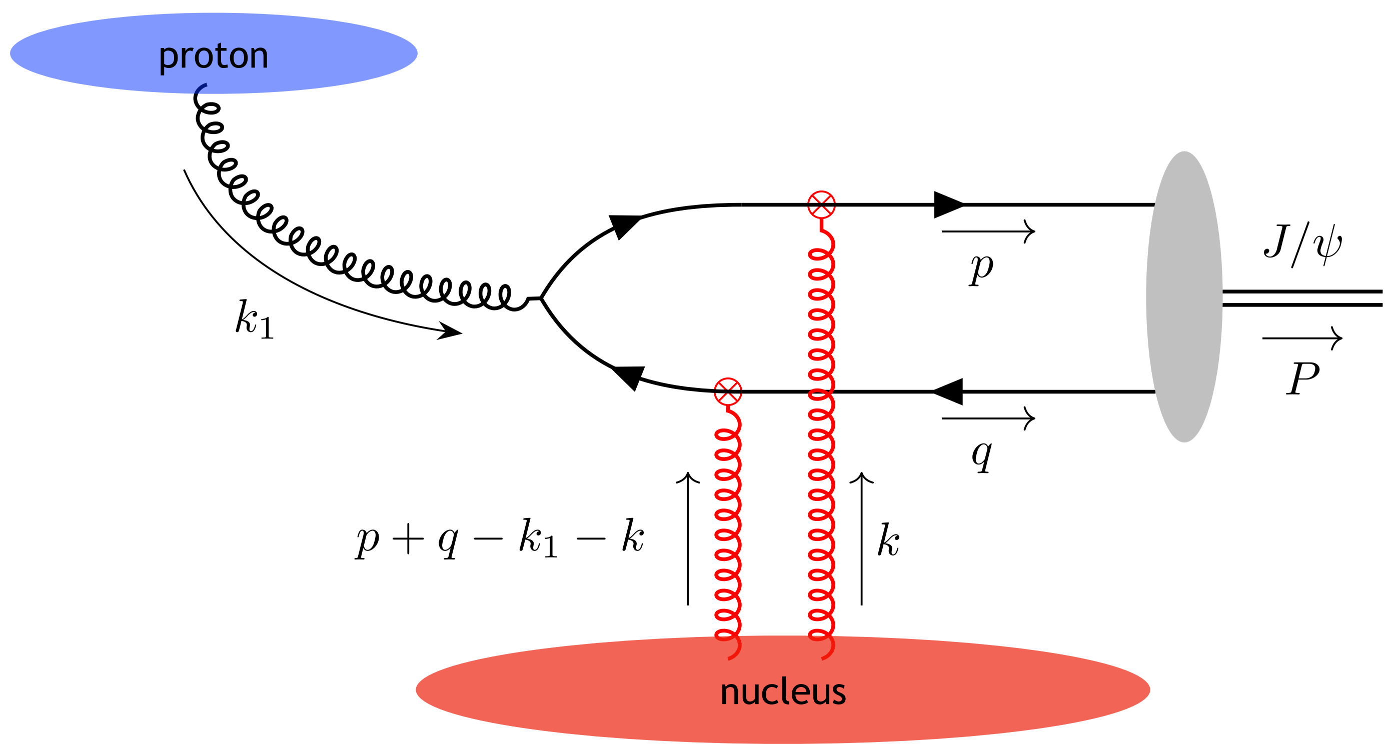
$$\frac{\mathrm{d}N_{J/\psi}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}Y} = \sum_{\kappa}\frac{\mathrm{d}N^{\kappa}_{c\bar{c}}(\boldsymbol{b}_\perp)}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}Y}\langle\mathcal{O}^{J/\psi}_{\kappa}\rangle$$

with non-perturbative long distance matrix elements $\langle\mathcal{O}^{J/\psi}_{\kappa}\rangle$

K.-T. Chao, Y.-Q. Ma, H.-S. Shao, K. Wang, Y.-J. Zhang, Phys. Rev. Lett. 108, 242004 (2012)
Y.-Q. Ma, R. Venugopalan, H.-F. Zhang, Phys. Rev. D 92, 071901 (2015)

Again, spatial dependence in ϕ^p and $\tilde{\mathscr{S}}^A_F$

MODEL: J/Ψ PRODUCTION (ICEM)



$\bar{c}c$-pair production in the Improved Color Evaporation Model (ICEM):

H. Fujii, F. Gelis, and R. Venugopalan, Nucl. Phys. A 780, 146 (2006); H. Fujii, K. Watanabe, Nucl. Phys. A 915, 1 (2013)

$$\frac{dN_{\bar{c}c}(\boldsymbol{b}_\perp)}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_c dy_{\bar{c}}} = \frac{\alpha_s N_c^2}{2(2\pi)^{10}(N_c^2-1)} \int_{\boldsymbol{k}_{1_\perp};\boldsymbol{k}_\perp;\boldsymbol{R}_\perp} \frac{\phi^p(x_p;\boldsymbol{k}_{1_\perp};\boldsymbol{R}_\perp)}{\boldsymbol{k}_{1_\perp}^2} \tilde{\mathcal{S}}_F^A(x_A;\boldsymbol{k}_\perp;\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)\tilde{\mathcal{S}}_F^A(x_A;\boldsymbol{p}_\perp+\boldsymbol{q}_\perp-\boldsymbol{k}_{1_\perp}-\boldsymbol{k}_\perp;\boldsymbol{R}_\perp-\boldsymbol{b}_\perp)\mathcal{H}(\boldsymbol{p}_\perp,\boldsymbol{q}_\perp,\boldsymbol{k}_{1_\perp},\boldsymbol{p}_\perp+\boldsymbol{q}_\perp-\boldsymbol{k}_{1_\perp}-\boldsymbol{k}_\perp) + \mathcal{O}\left(1/N_c\right)$$

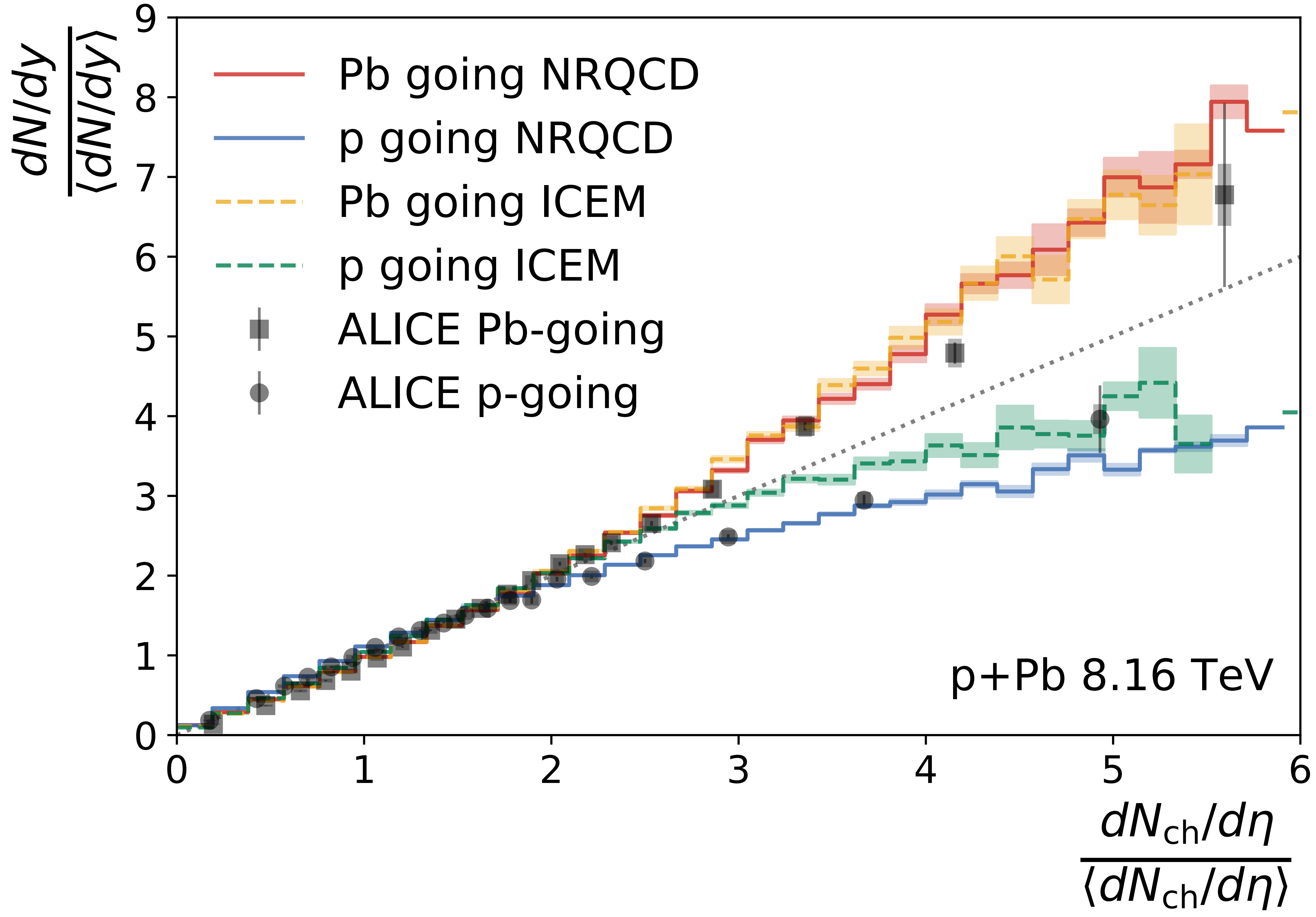
with the Wilson line correlator $\tilde{\mathcal{S}}_F^A$ in the fundamental representation (with $A = p, \mathrm{Pb}$)

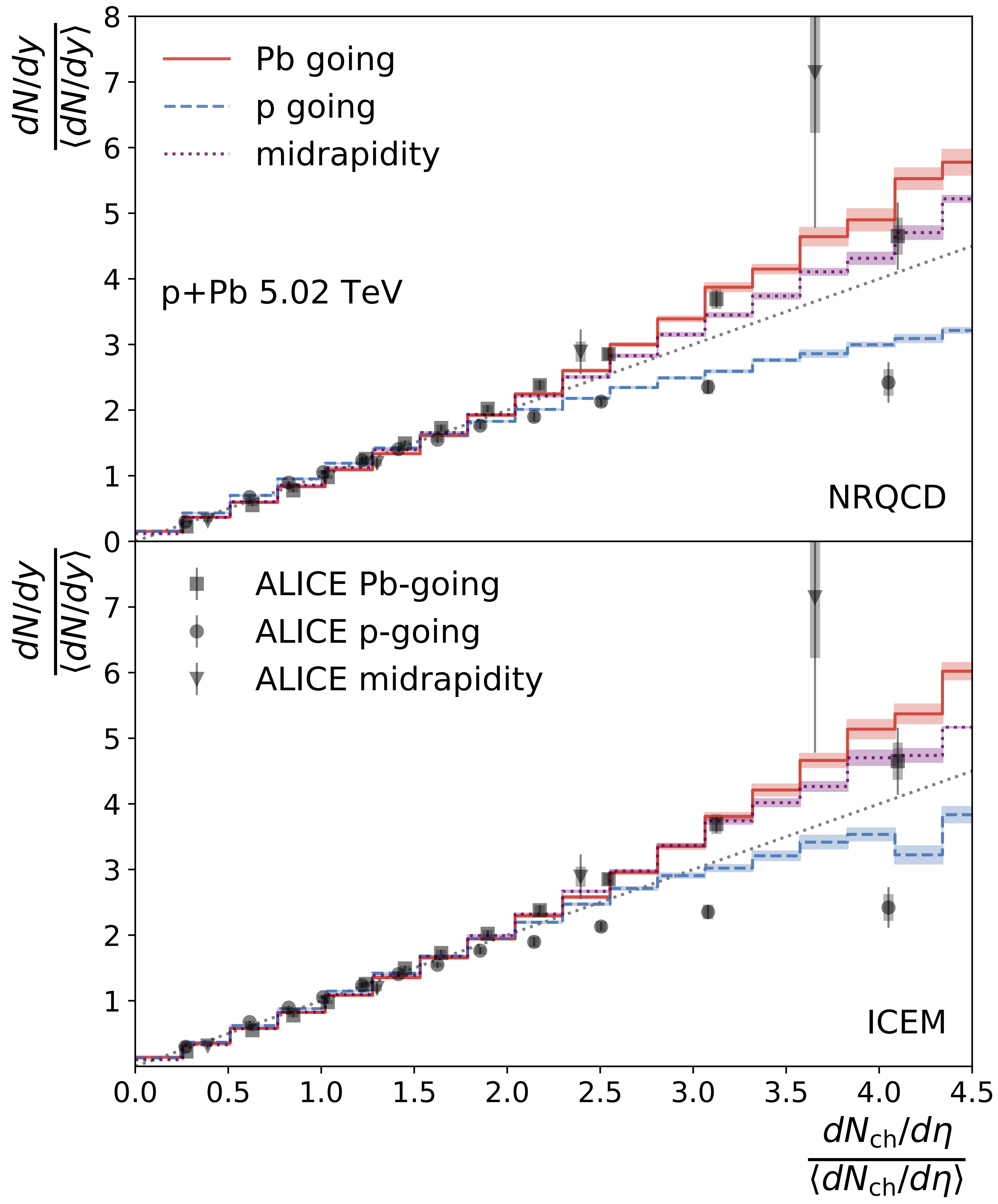
Production of J/ψ is then given by

$$\frac{dN_{J/\psi}(\boldsymbol{b}_\perp)}{d^2\boldsymbol{P}_\perp dY} = F\int_{m_{J/\psi}^2}^{4m_D^2} dM^2 \frac{M^2}{m_{J/\psi}^2} \frac{dN_{c\bar{c}}(\boldsymbol{b}_\perp)}{dM^2 d^2\boldsymbol{P}_\perp dY}, \text{ where } \frac{dN_{c\bar{c}}(\boldsymbol{b}_\perp)}{dM^2 d^2\boldsymbol{P}_\perp dY} = \int_0^{\sqrt{\frac{M^2}{4}-m_c^2}} d\tilde{q} \int_0^{2\pi} d\phi\, \mathcal{J} \frac{dN_{c\bar{c}}(\boldsymbol{b}_\perp)}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q}$$

where $\tilde{q}$ and ϕ are the relative transverse momentum and angle between the c and the $\bar{c}$ in the rest frame of the pair.

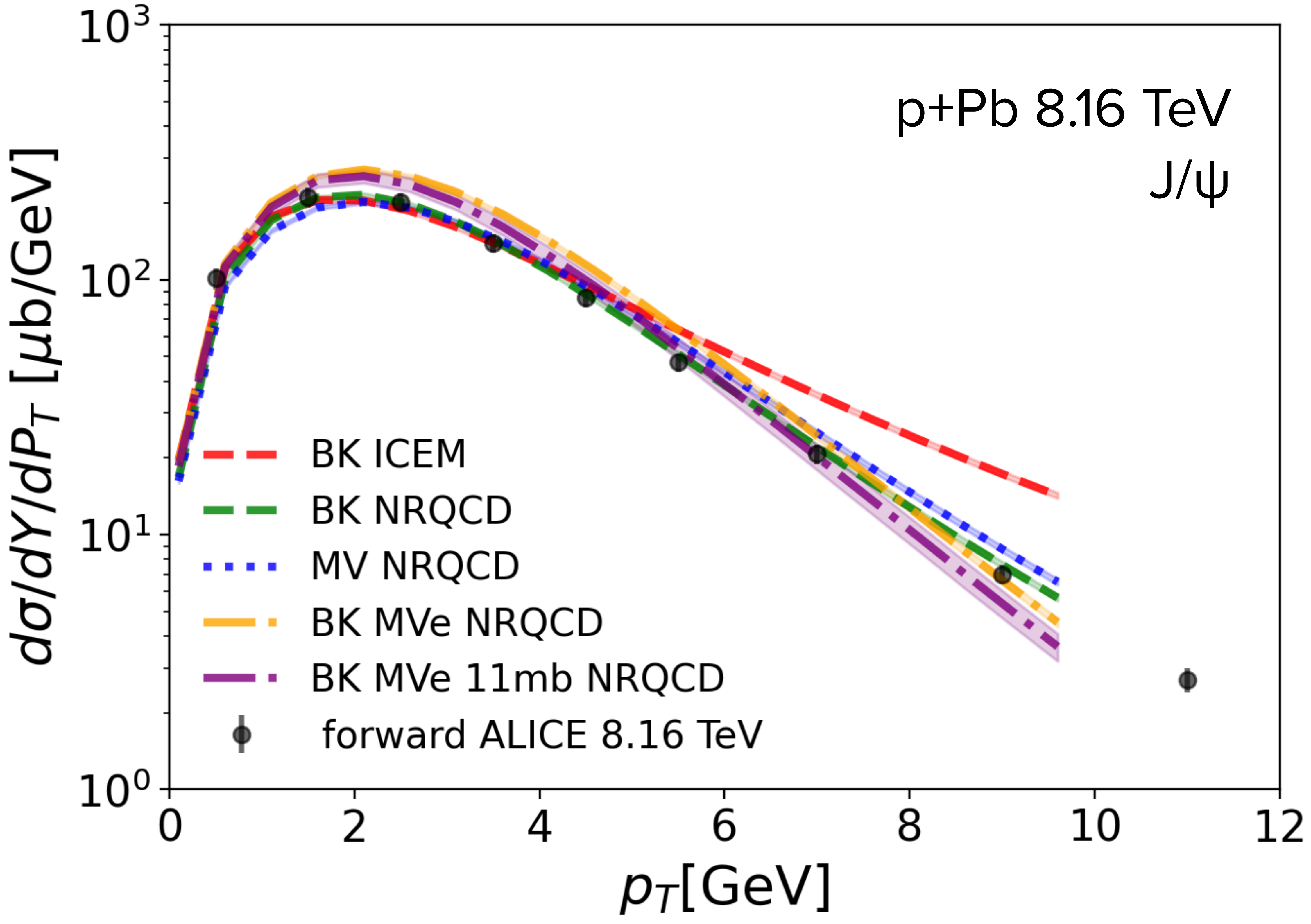
NRQCD VS ICEM

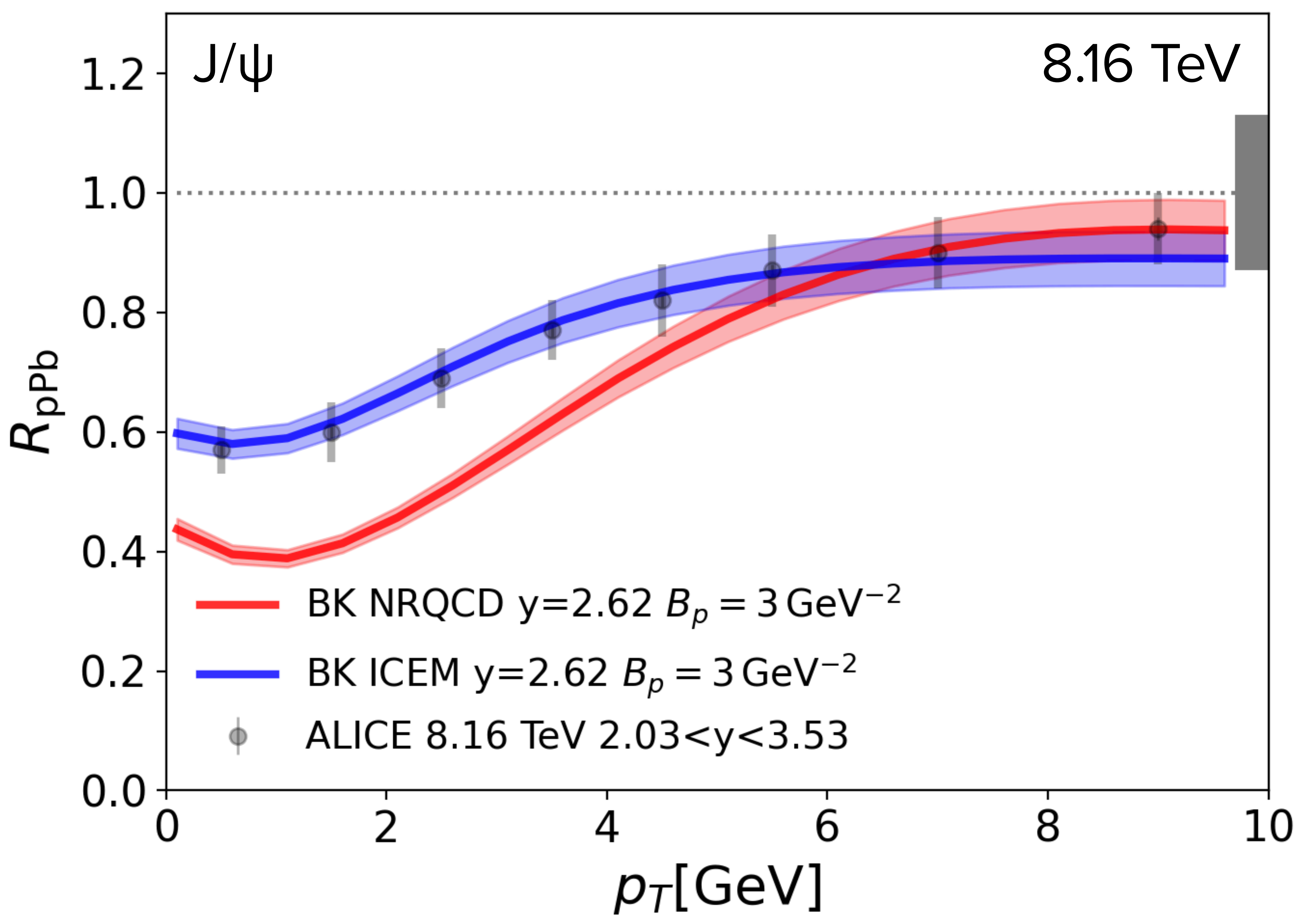




Experimental data: ALICE Collaboration, JHEP 09, 162 (2020); Phys. Lett. B 776, 91 (2018)

J/ψ SPECTRA AND R_{pPb}





Experimental data: ALICE Collaboration, JHEP 07 (2018) 160

Q_s VS. MULTIPLICITY