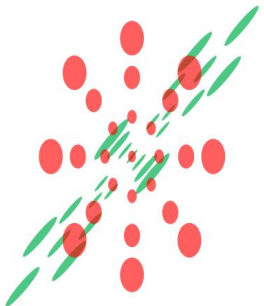
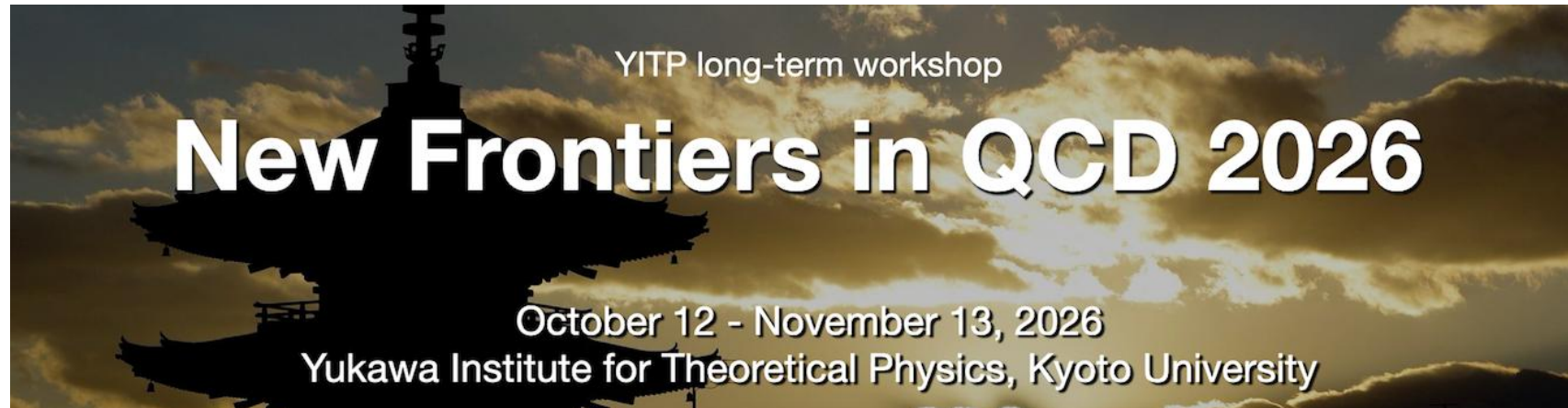


Forward Hadron Production in p - p , p + Pb and d + Au Collisions within the CGC-Based Monte Carlo Model



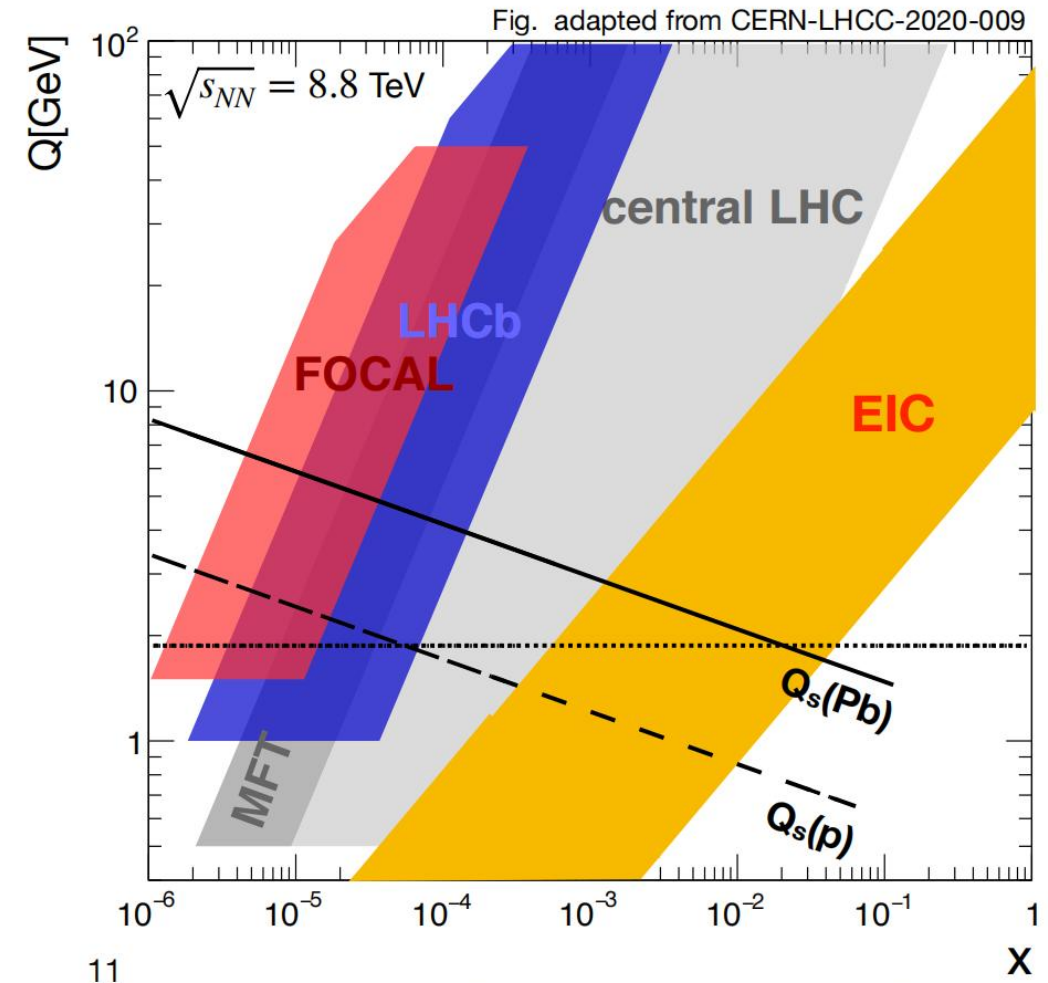
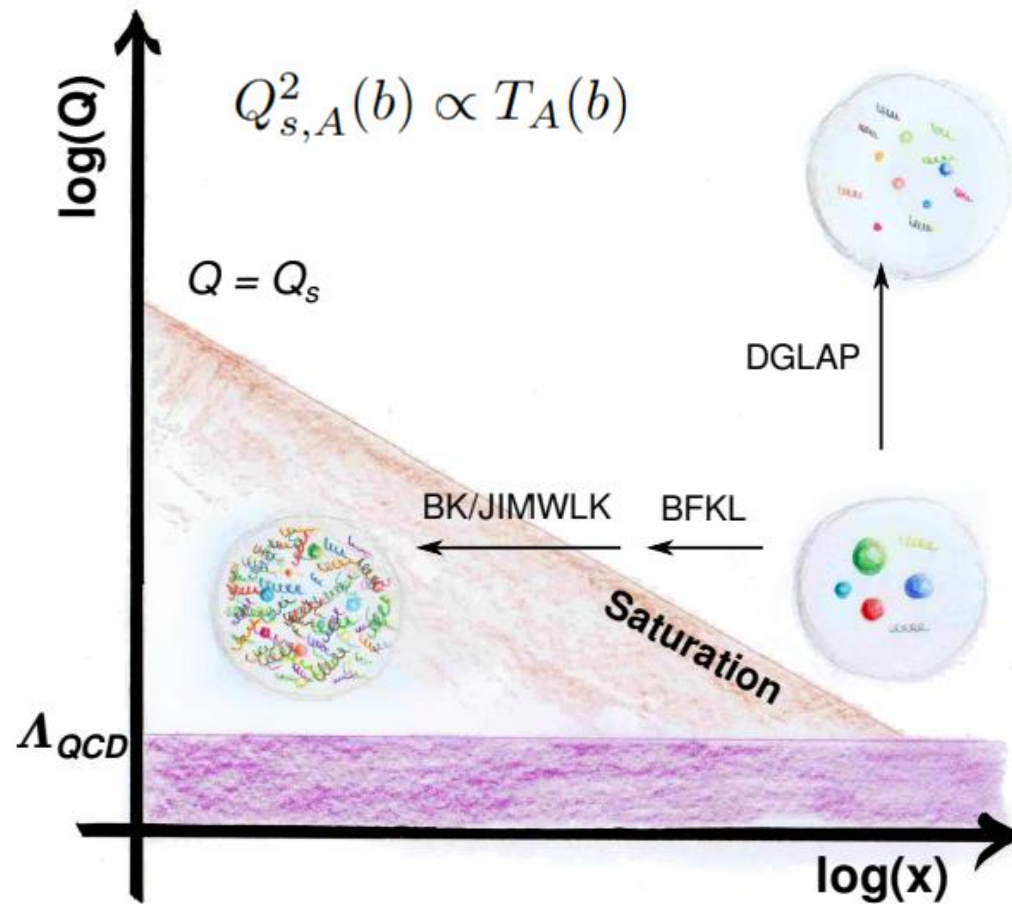
SOPHIA
HADRON
PHYSICS
GROUP

Shujun Zhao, 2026.10.15

Sophia University

In Collaboration with H. Fujii, T. Hirano, K. Itakura, and Y. Nara

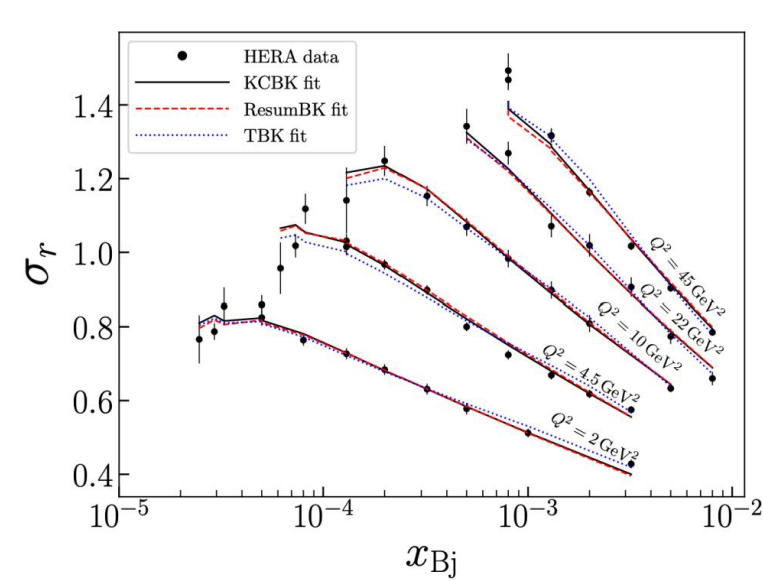
Towards the Small-x Saturation Region



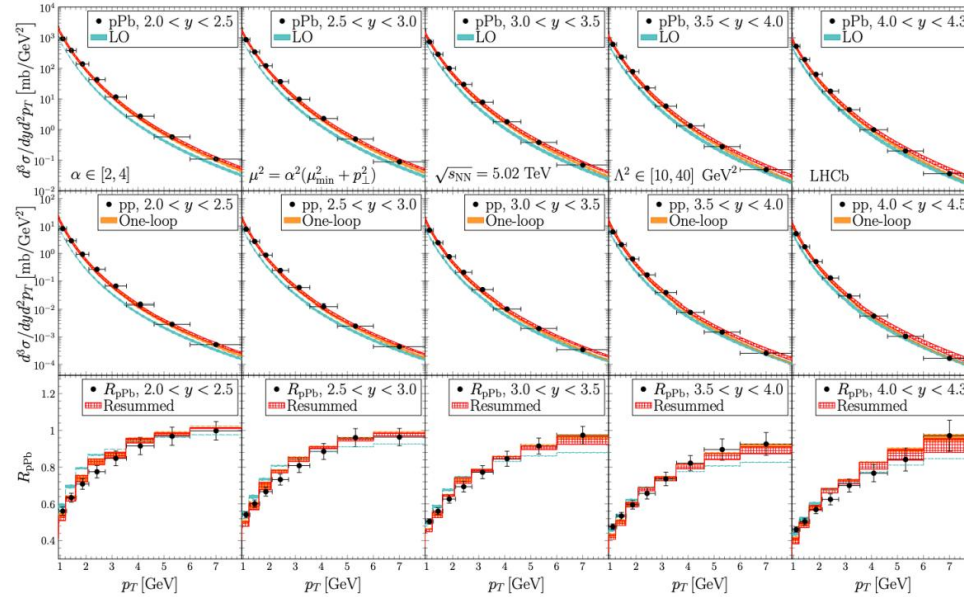
CGC: an effective theory of QCD for small-x region.

Future experiments will enable us to probe the deep saturation regime.

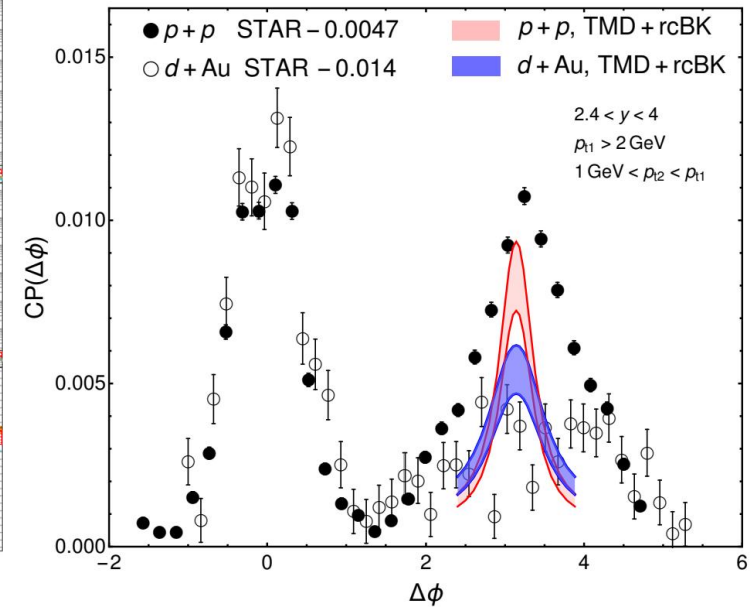
Theoretical Predictions within the CGC Framework



Beuf, Lappi, Hänninen,
Mäntysaari.
PRD 102 (2020) 074028



Shi, Wang, Wei, Xiao.
PRL 128 (2022) 20, 202302



Albacete, Giacalone, Marquet,
Matas. PRD 99 (2019) 1, 014002.

- Extensive theoretical studies have been conducted within the CGC framework.
- However, a realistic event generator is still needed to connect theoretical predictions with experimental observables (MPI, ISR, longitudinal momentum depletion, remnants).

Initial Geometry

For proton: Gaussian shape

$$T_N(\vec{s}) = \frac{1}{2\pi B_{NN}} e^{-\vec{s}^2/(2B_{NN})}, \quad B_{NN} = 0.325 \text{ fm}^2,$$

For deuteron: Hulthén wavefunction

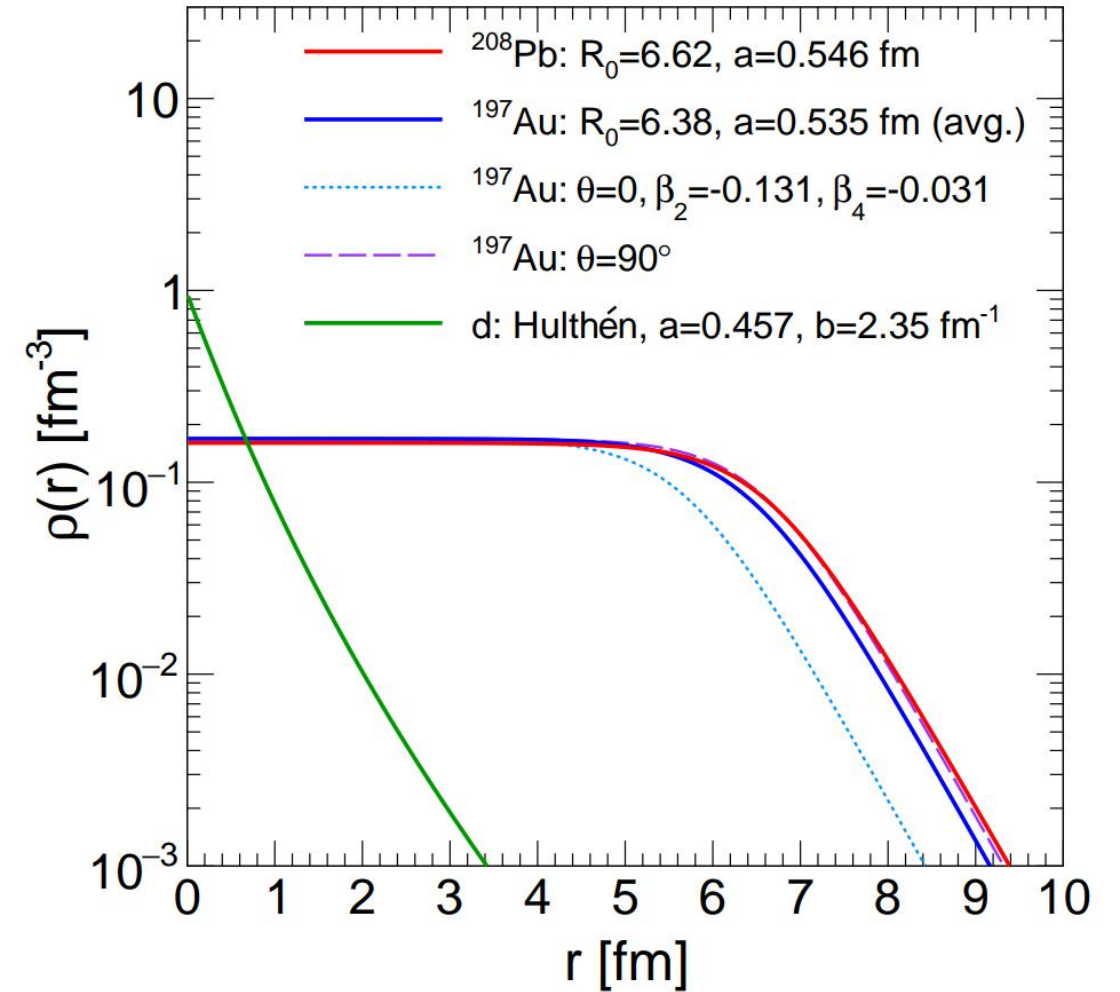
$$\psi(r) \propto \frac{1}{\sqrt{4\pi}} \frac{e^{-ar} - e^{-br}}{r}, \quad a = 0.457 \text{ fm}^{-1}, \quad b = 2.35 \text{ fm}^{-1}$$

For Heavy-ions: Woods-Saxon shape

$$\rho(r, \theta, \phi) = \frac{1}{1 + \exp((r - R(\theta, \phi))/a)},$$

$$R(\theta, \phi) = r_0 \left[1 + \beta_2 (\cos \gamma Y_{20} + \sqrt{2} \sin \gamma \text{Re} Y_{22}) + \beta_3 Y_{30} + \beta_4 Y_{40} \right],$$

Wounded nucleons determined by geometry criteria, with which the local thickness and $Q_{s0,A}^2(b)$ can be constructed.



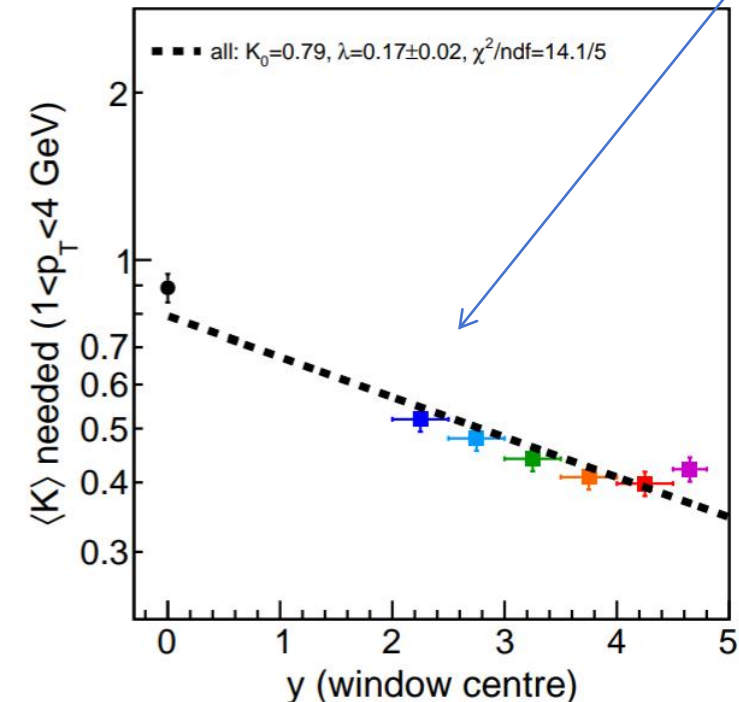
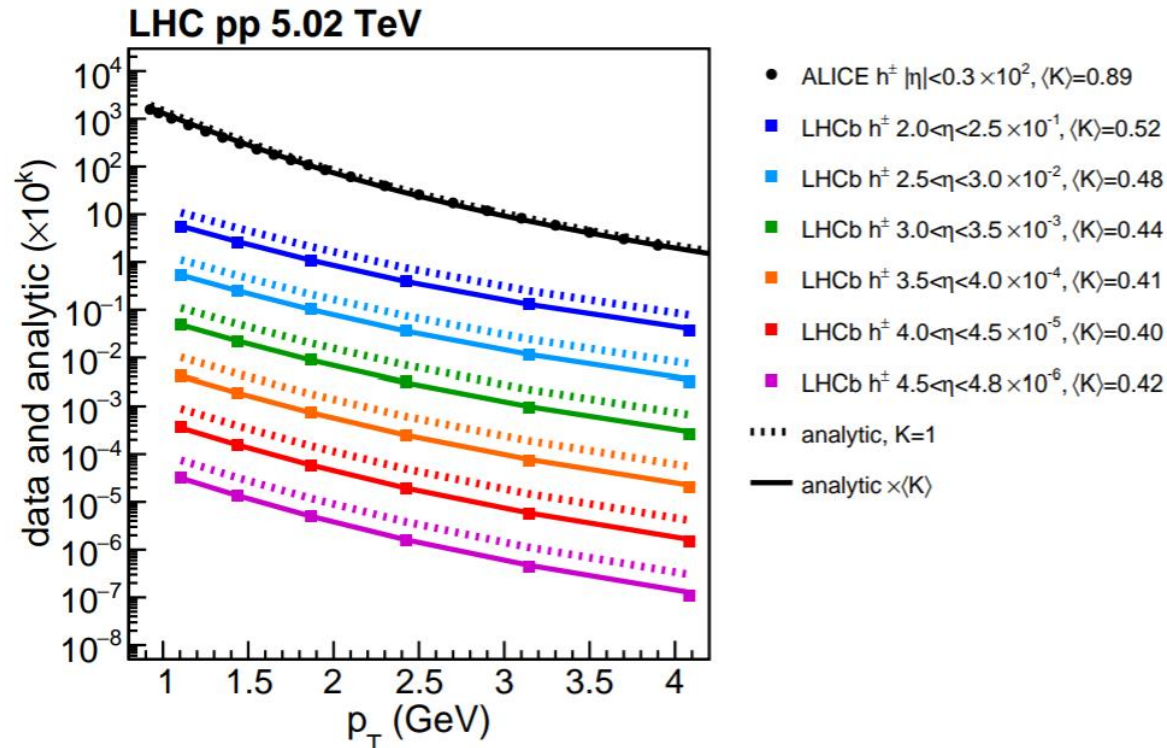
$$|\vec{s}_i - (\vec{s}_j + \vec{b})| < d_{\min} = \sqrt{\sigma_{\text{wound}}/\pi} \quad Q_{s0,A}^2(b) = \begin{cases} (T_A(b)/T_p(0))Q_{s0,p}^2 & A \neq 1 \\ Q_{s0,p}^2 & A = 1 \end{cases}, \quad T_A(b) = \sum_{i=1}^{N_{\text{part},A}} \frac{1}{2\pi B_{NN}} \exp\left(-\frac{|\mathbf{r} - \mathbf{r}_i|^2}{2B}\right)$$

Scattering Kernel, MPI, ISR, FSR

Default channel: LO Hybrid Approach (DHJ formula) with rcBK dipole amplitude evolution.

$$\frac{d\sigma}{dy d^2p_T} = K \frac{\sigma_0}{4\pi^2} \left[xG(x_1, Q^2) N_A(p_T; x_2) + xq(x_1, Q^2) N_F(p_T; x_2) \right], \quad K(y) = K_0 \exp(-\lambda|y|)$$

(Optional one: kT-factorization approach)



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MPI in Forward p+Pb collisions: $N_{\text{coll}} \sim 5-7$, stronger x-depletion than in pp collisions.

MPI–ISR interplay: $x_{\text{used}}^+ = \sum_{i \in \text{MPI}} x_{i,\text{hard}}^+ + \Delta x_{\text{ISR}}^+ \leq 1$

Our approach: Careful MPI sampling + ISR interleaving at the nucleon level
Independent FSR, subject to conservation laws.

Azimuthal Angle Assignment

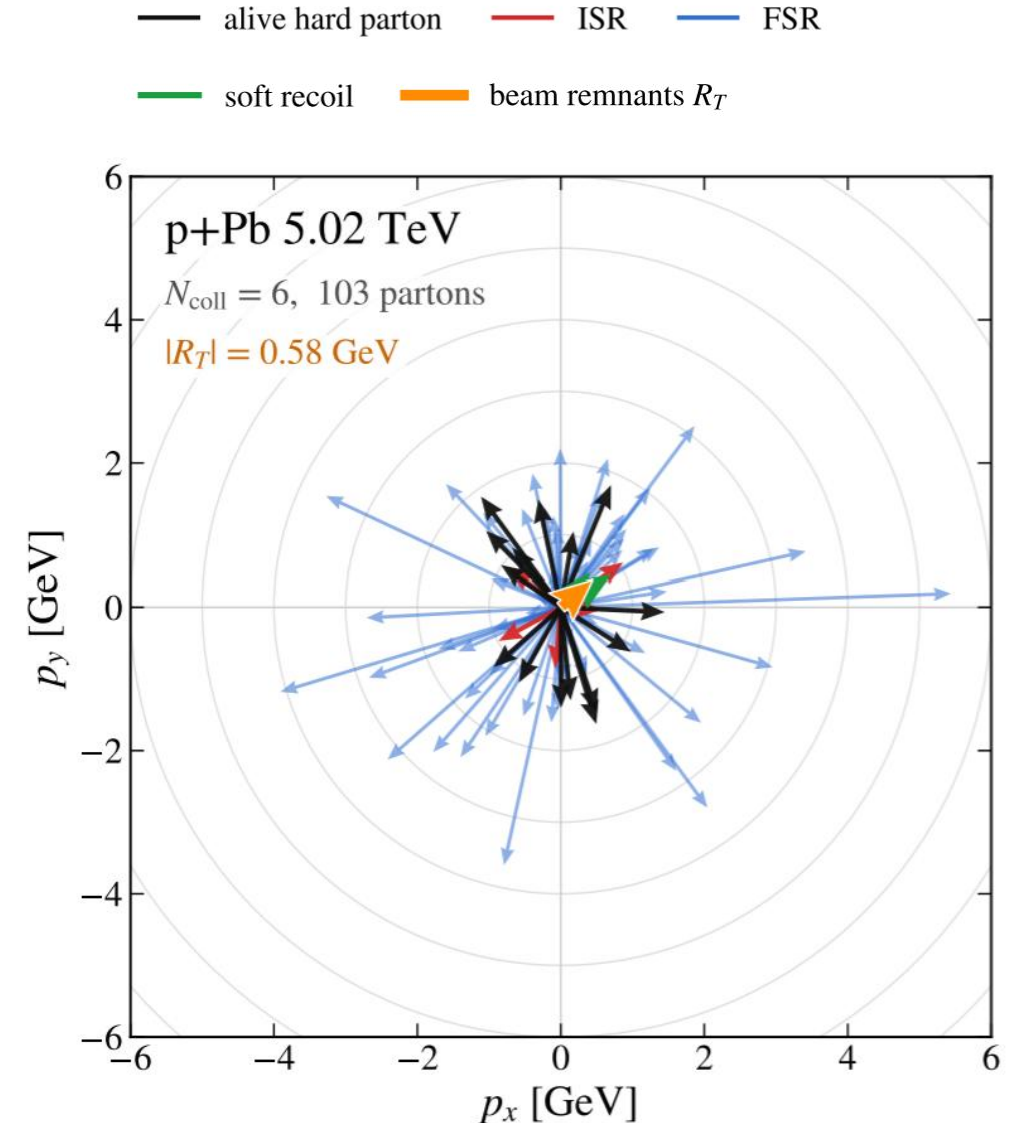
The hybrid framework describes only inclusive processes.

Remnant rapidity: $y_R \sim \ln \left(\frac{R^\pm}{m_T} \right)$

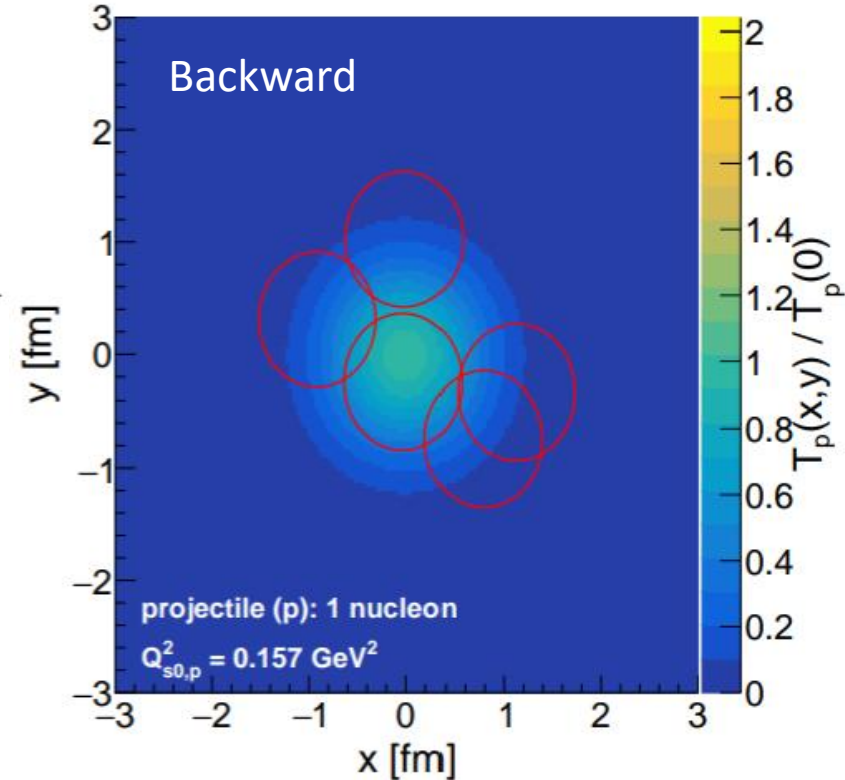
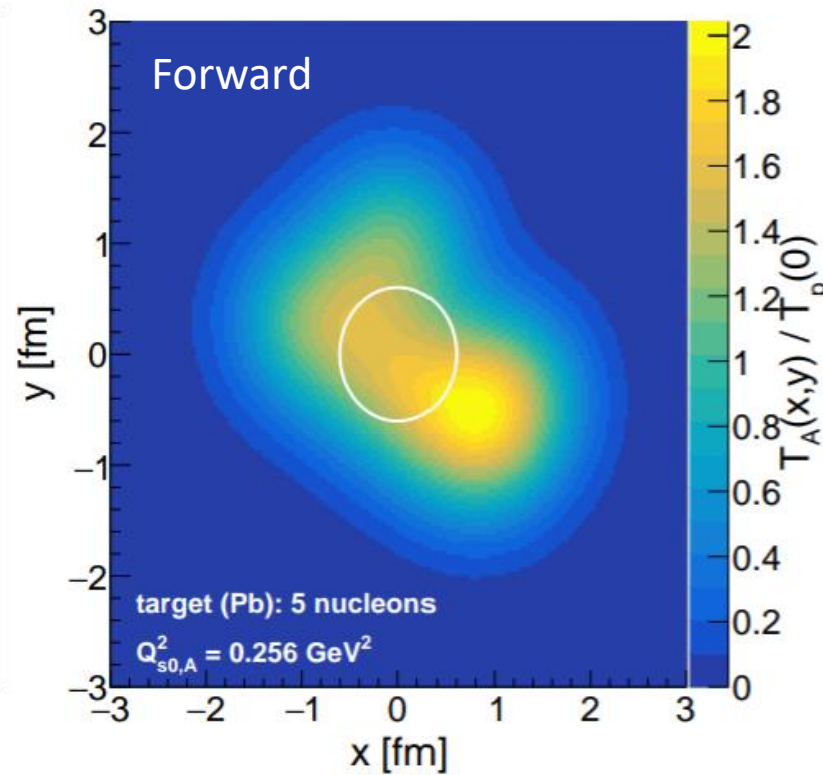
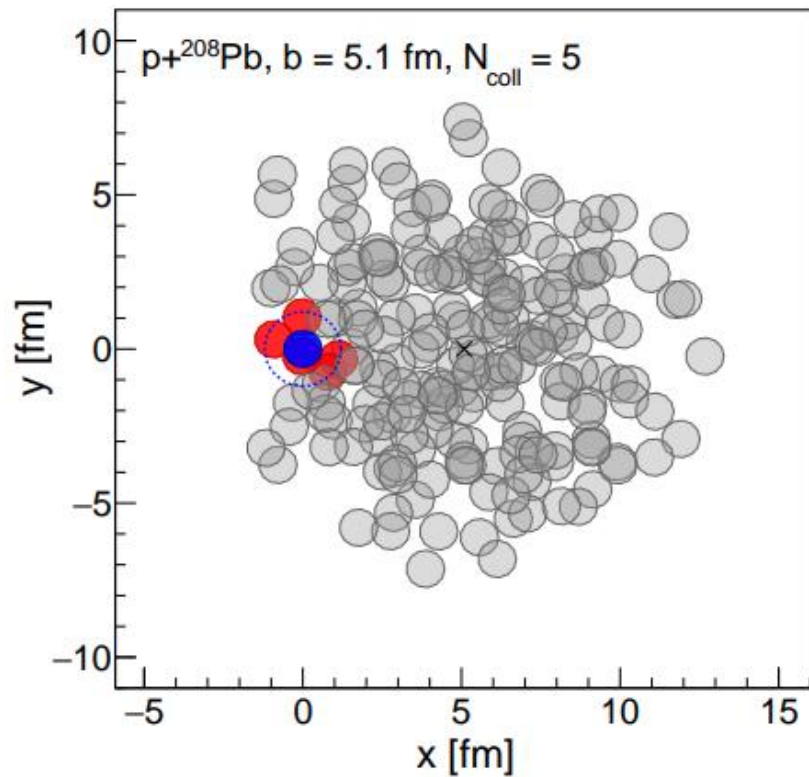
For each scattering, a global SO(2) rotation is applied, with the azimuthal angle ϕ sampled from a von Mises distribution:

$$f(\phi) = \frac{1}{2\pi I_0(\kappa)} \exp [\kappa \cos(\phi - \langle \phi \rangle)],$$

$$R(\kappa) \equiv \min \left(\frac{|\sum_i \mathbf{k}_{T,i}|}{\langle k_T \rangle}, 1.0 \right)$$



From forward to backward production



Basic scattering element: N+CGC type scattering (forward, backward reversed). With interpolation between them.

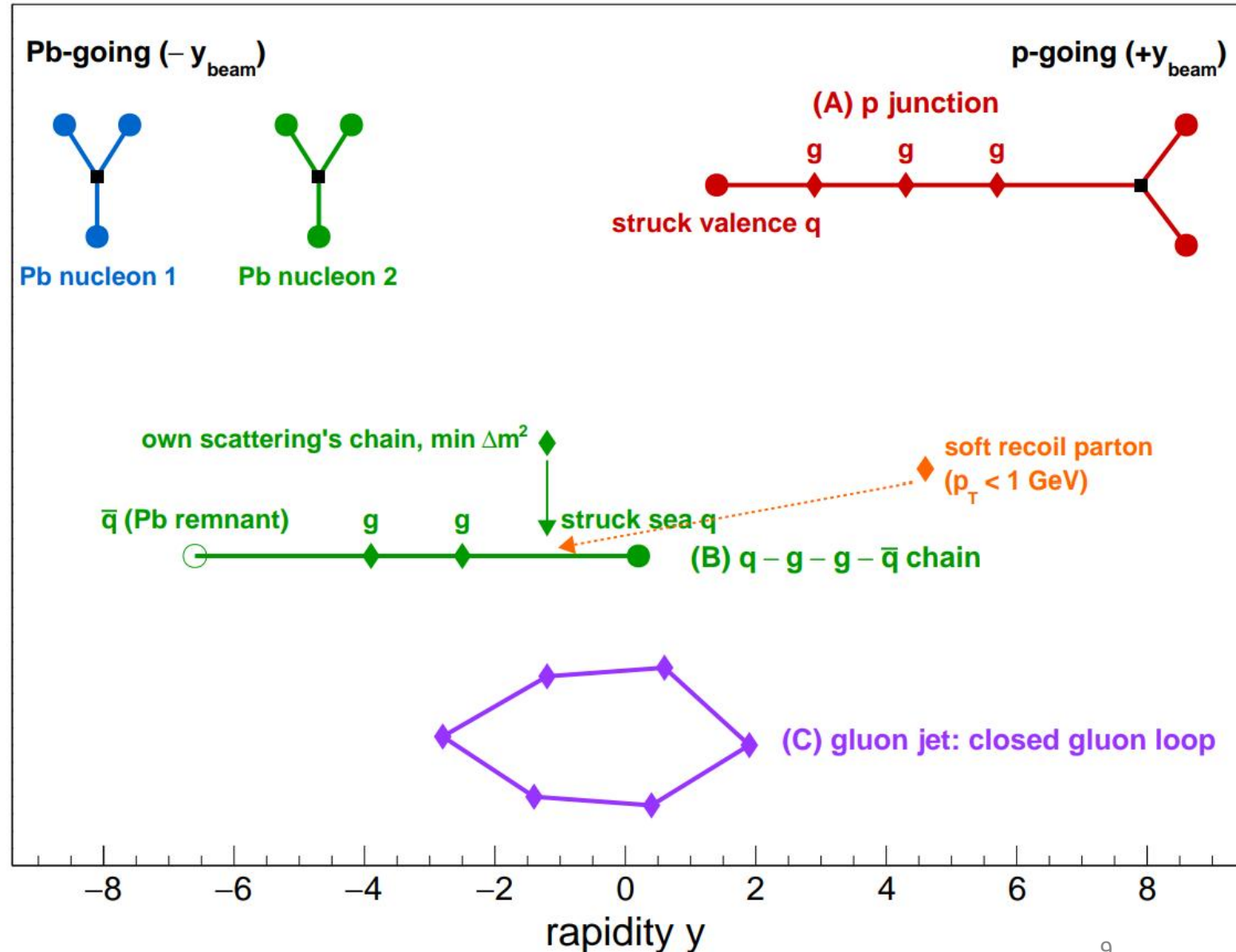
Remnant Splitting and String Connection

- Remnant splitting for each side:

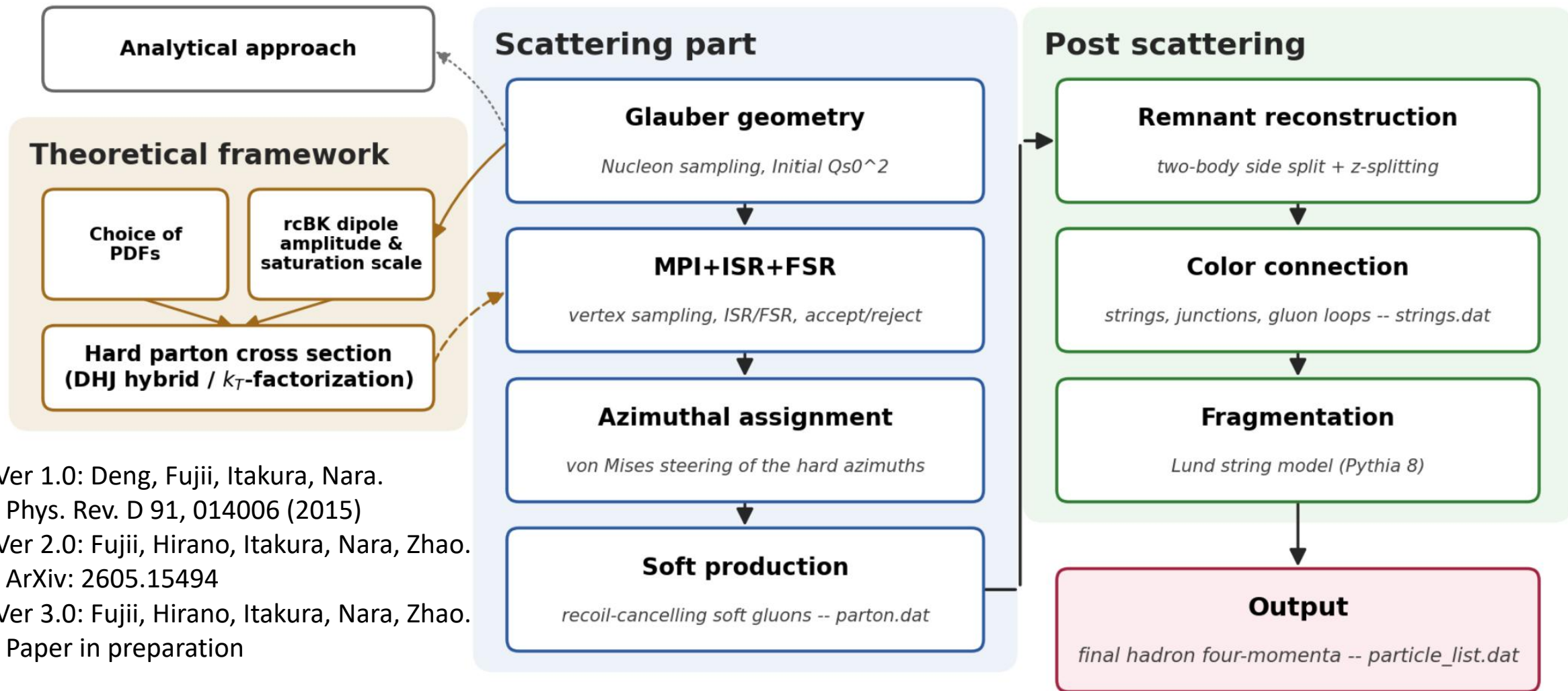
$$k_i^\mu = z_i R_{\text{side}}^\mu, \quad z_i \sim P(z)$$

- String connection:

- Partons are grouped according to their scattering origin.
- String reconnections are performed to minimize the total string length.
- String systems with masses below a specified threshold are merged into heavier systems.



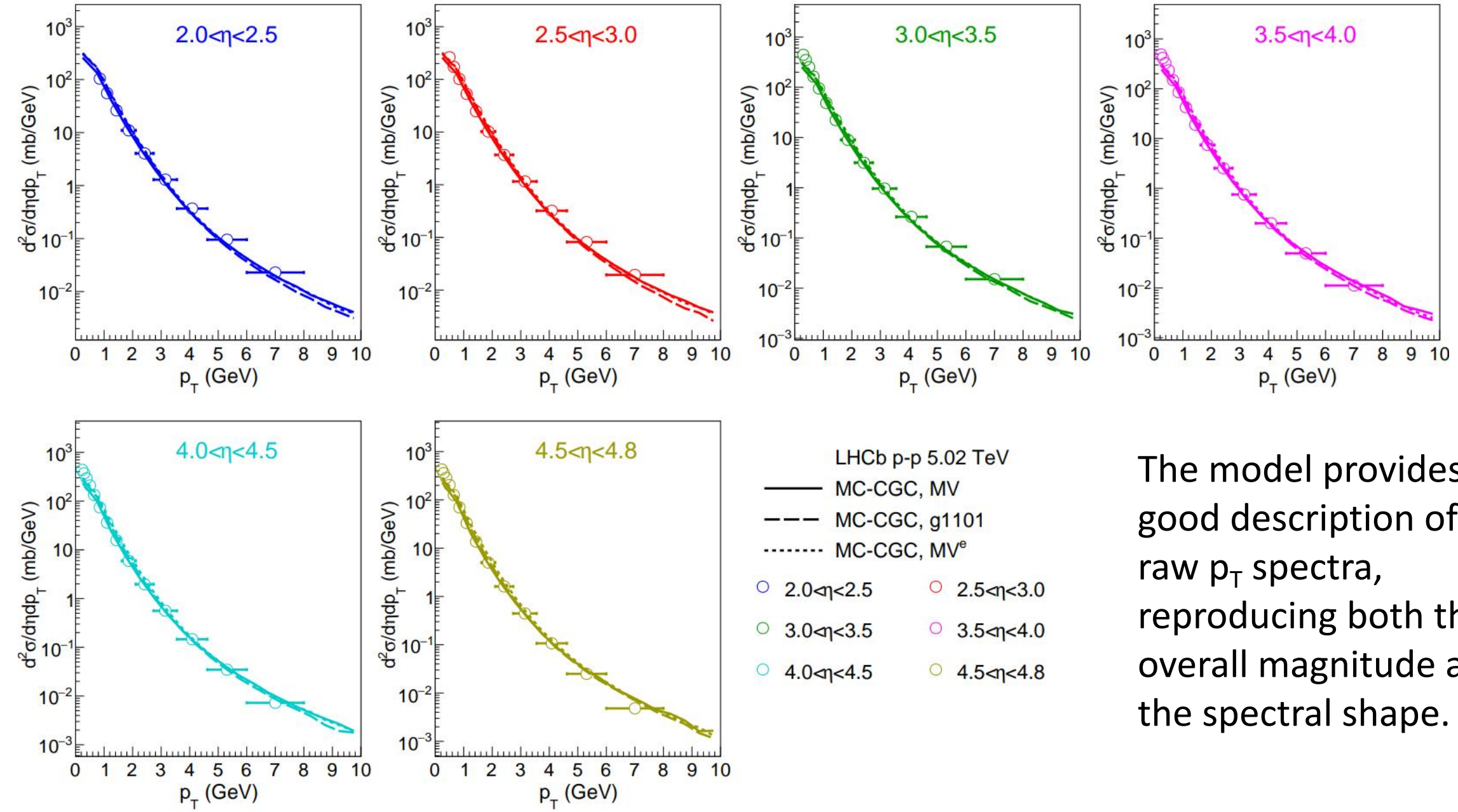
Upgrades of MC-CGC Model: Ver 3.0



- Ver 1.0: Deng, Fujii, Itakura, Nara. Phys. Rev. D 91, 014006 (2015)
- Ver 2.0: Fujii, Hirano, Itakura, Nara, Zhao. ArXiv: 2605.15494
- Ver 3.0: Fujii, Hirano, Itakura, Nara, Zhao. Paper in preparation

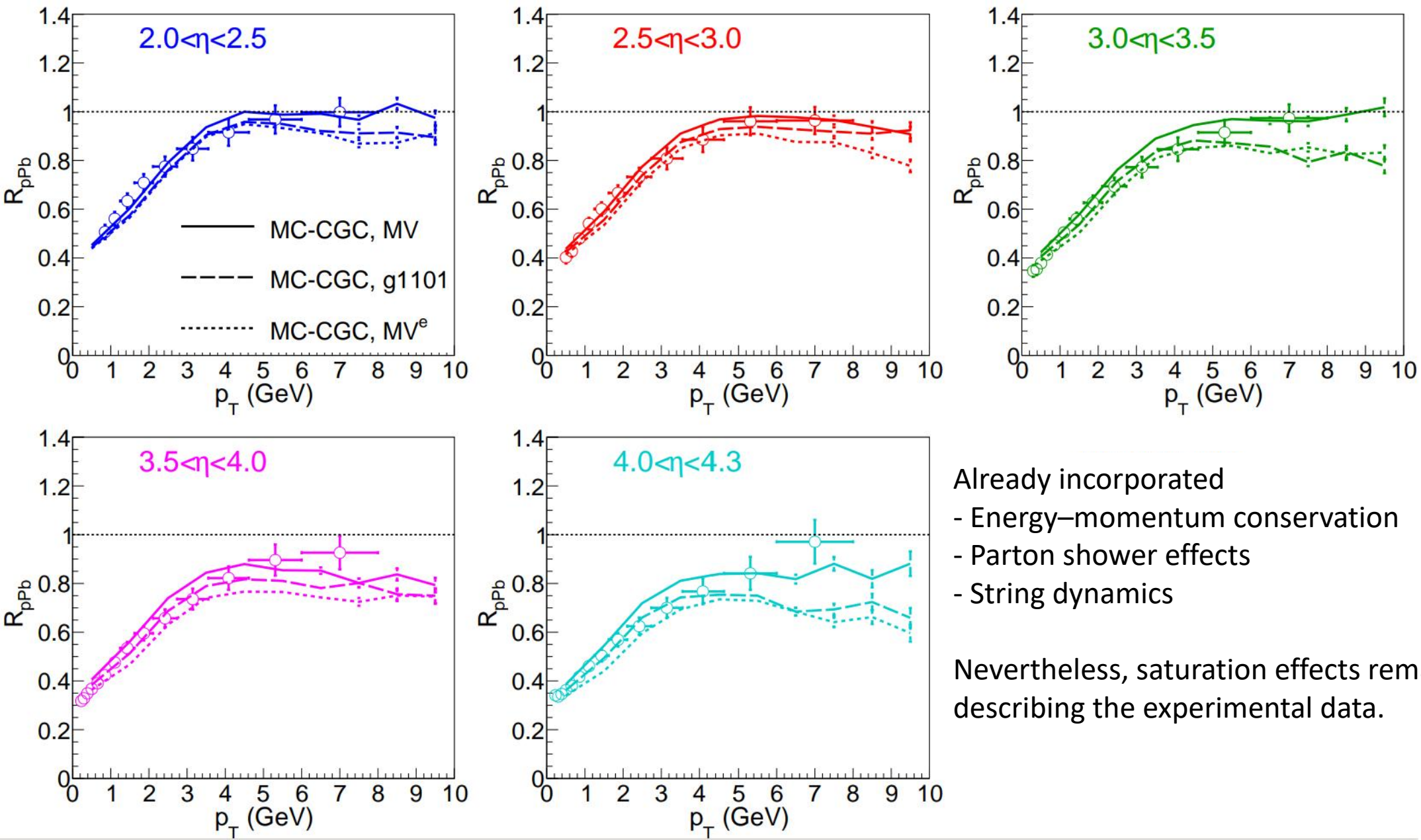
MC-CGC: A Monte-Carlo Event Generator Inspired by CGC Framework

p_T Spectra in pp at 5.02 TeV (Forward Rapidity)



The model provides a good description of the raw p_T spectra, reproducing both the overall magnitude and the spectral shape.

R_{pPb} at 5.02 TeV (Forward Rapidity)

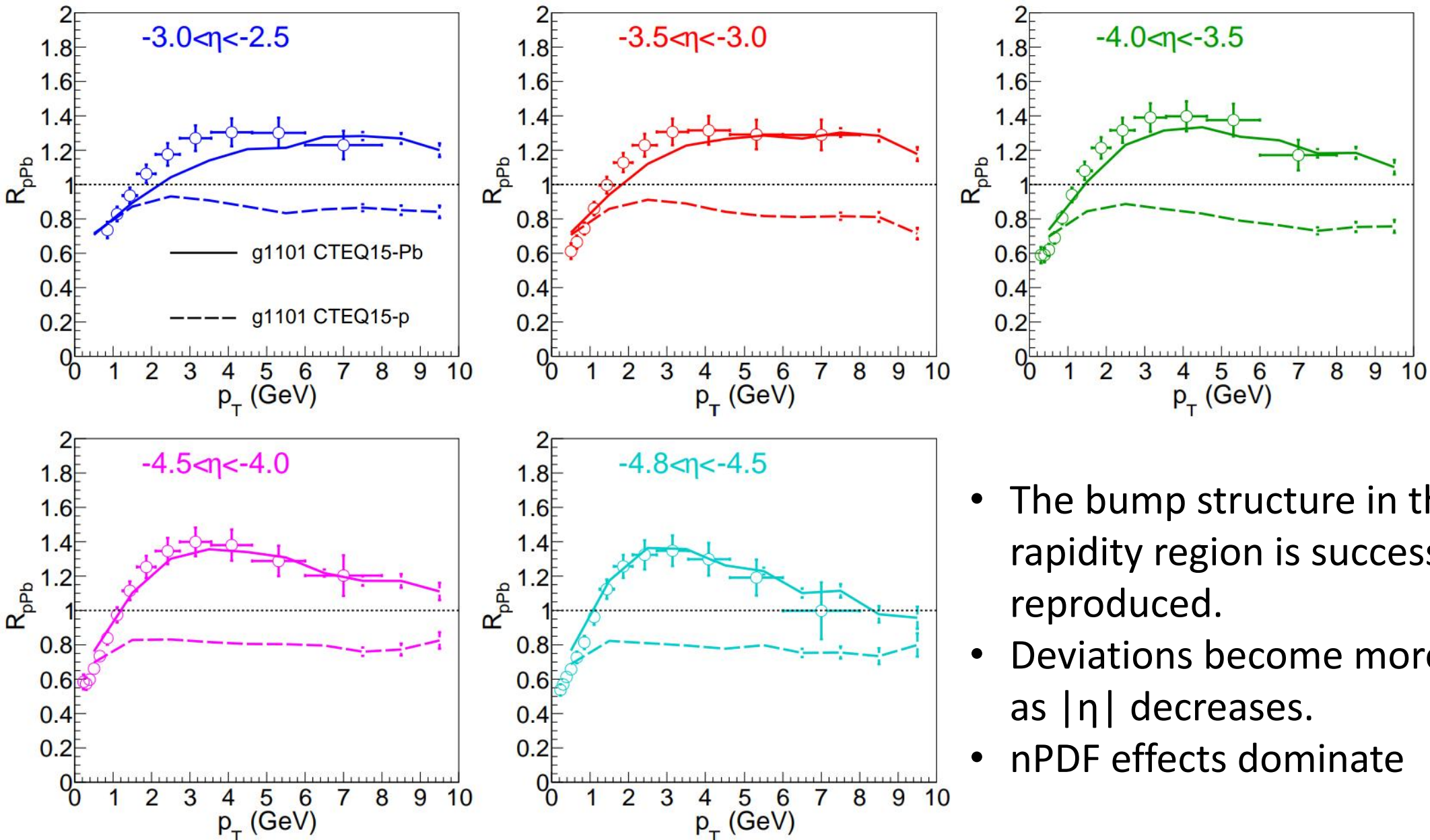


Already incorporated

- Energy-momentum conservation
- Parton shower effects
- String dynamics

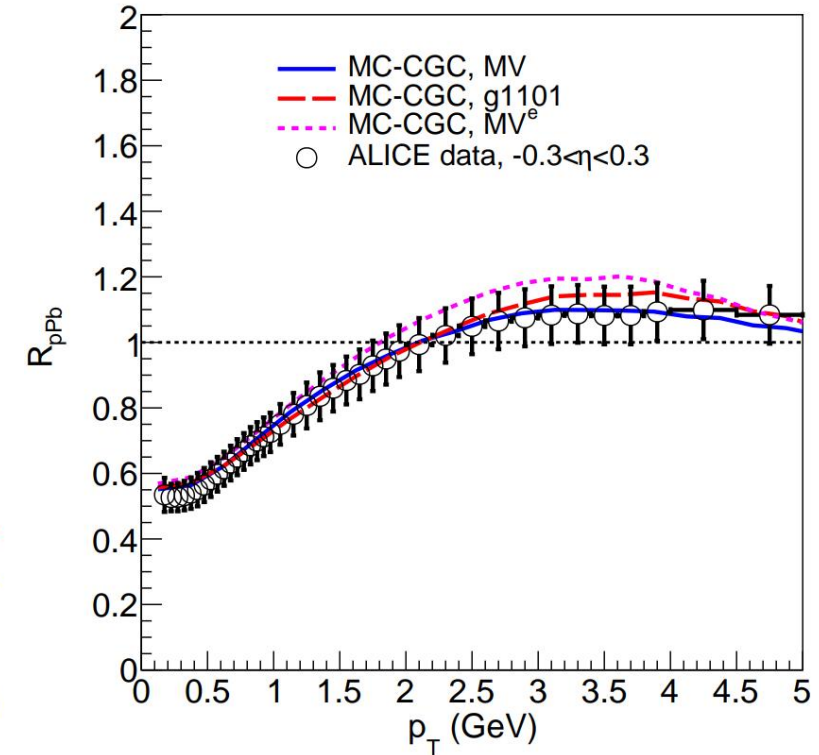
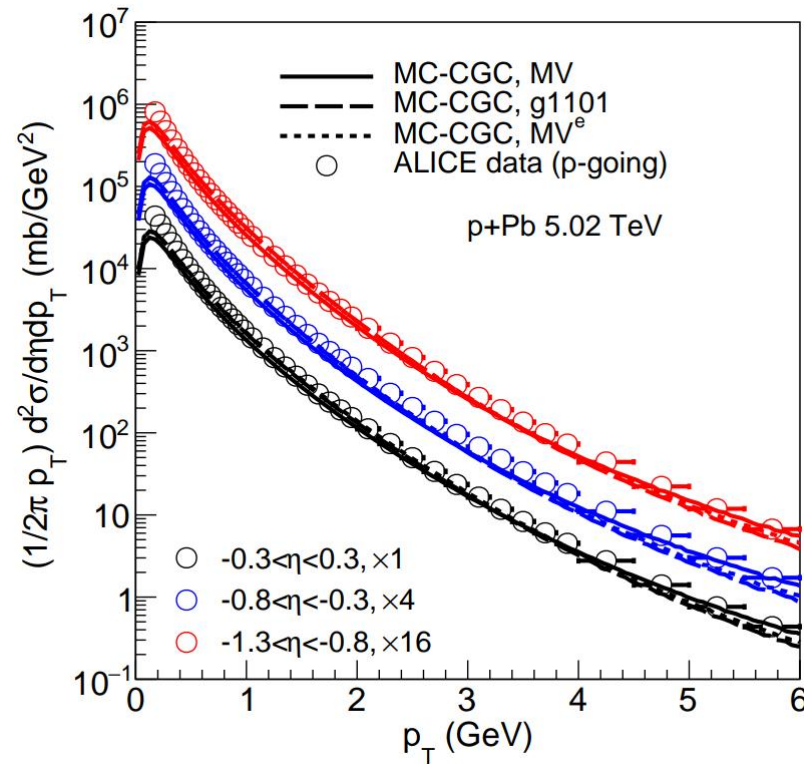
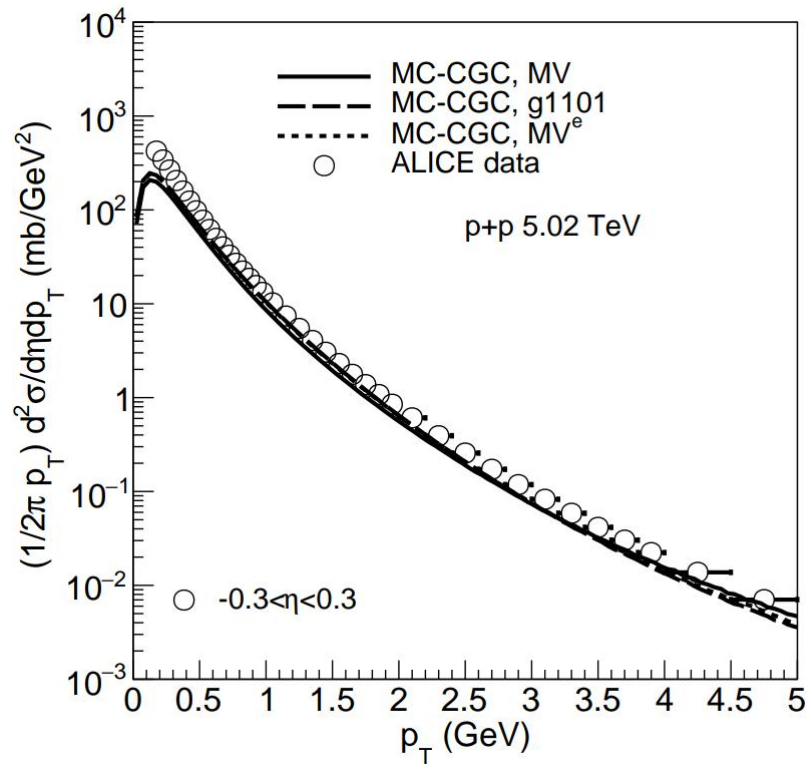
Nevertheless, saturation effects remain essential for describing the experimental data.

R_{pPb} at 5.02 TeV (Backward Rapidity)



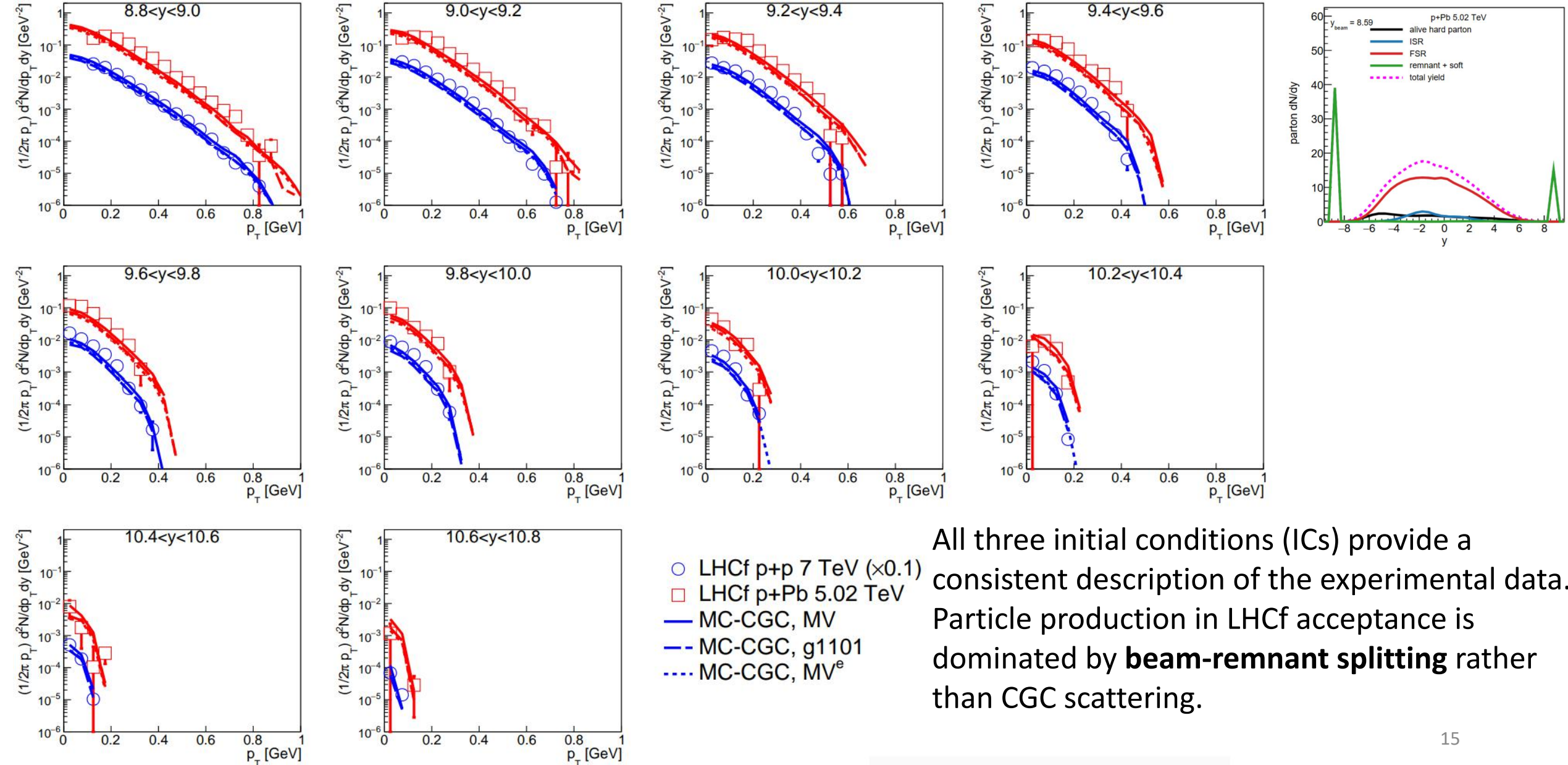
- The bump structure in the backward-rapidity region is successfully reproduced.
- Deviations become more pronounced as $|\eta|$ decreases.
- nPDF effects dominate

Description in pp & pPb at 5.02 TeV (Middle Rapidity)



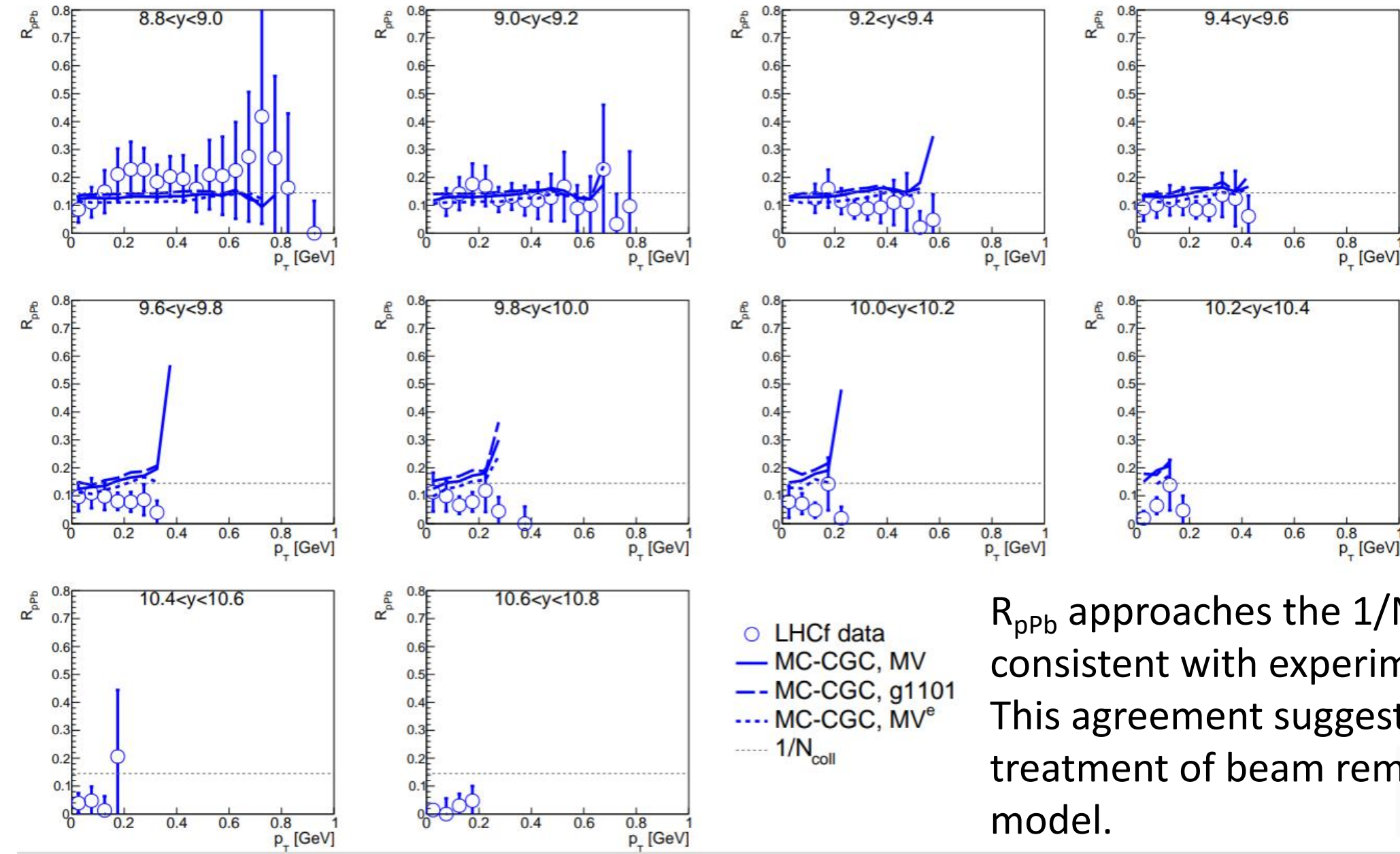
The hybrid approach provides a reasonable description of the p_T spectra even at midrapidity. The required K-factor at midrapidity is approximately 1.5 times that in the forward-rapidity region.

Description in pp & pPb at LHC Energy (Ultra-Forward)



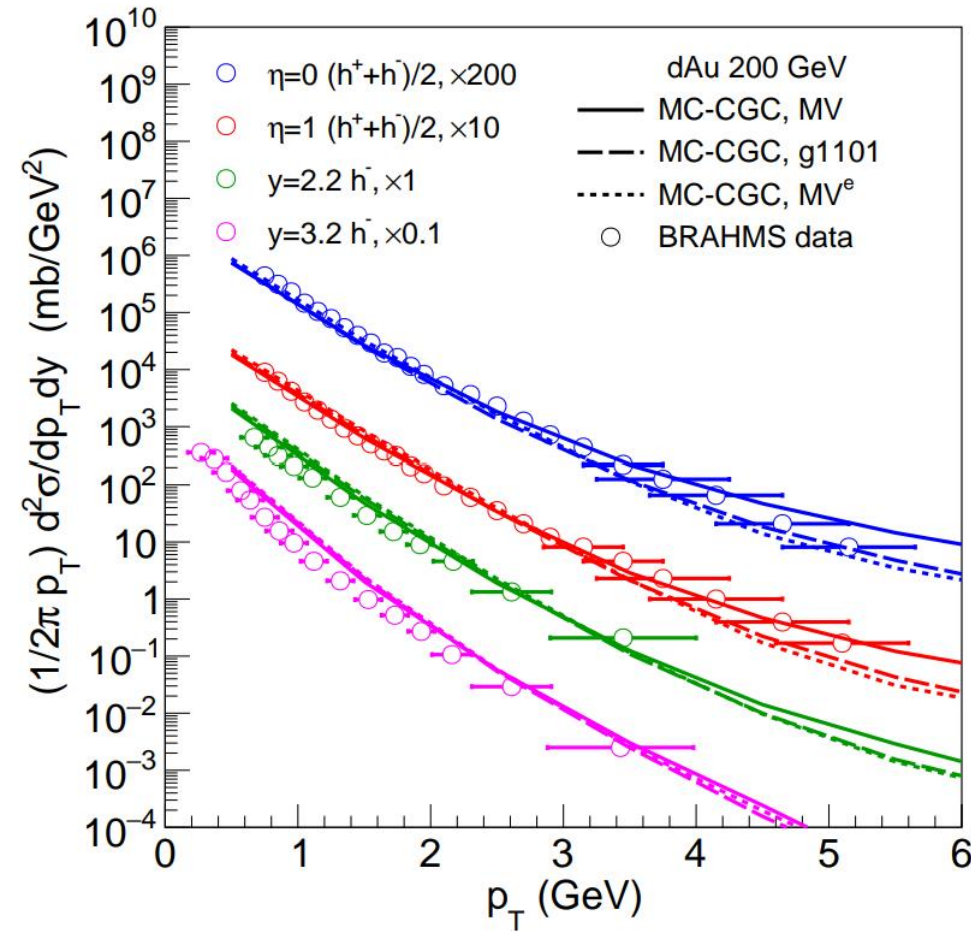
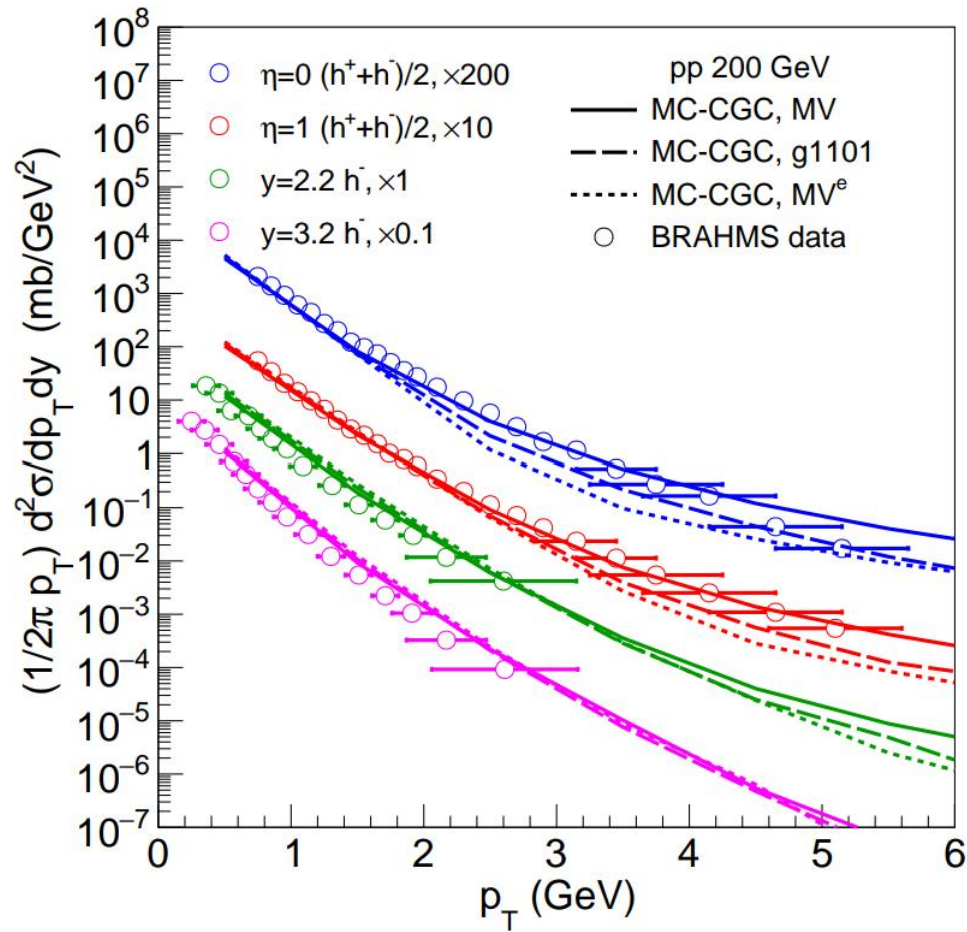
All three initial conditions (ICs) provide a consistent description of the experimental data. Particle production in LHCf acceptance is dominated by **beam-remnant splitting** rather than CGC scattering.

Description in pp & pPb at LHC energy (Ultra-forward)



R_{pPb} approaches the $1/N_{coll}$ baseline, consistent with experimental data. This agreement suggests a reasonable treatment of beam remnants in the model.

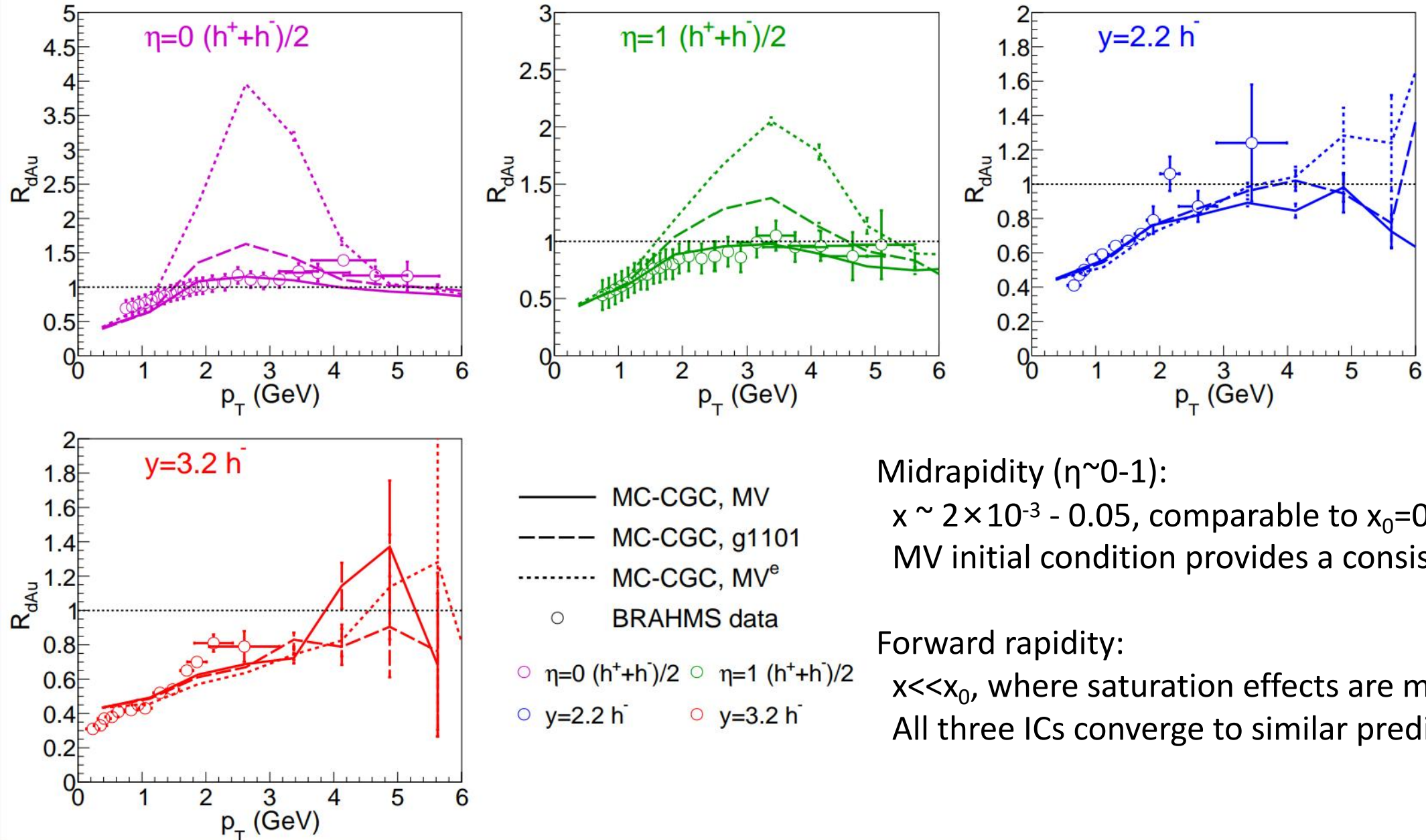
p_T spectra in pp, dAu at 200 GeV (Middle + Forward)



The model provides a good description of the RHIC pp and d+Au p_T spectra using the same parameter sets.

Discrepancies at midrapidity suggest an increased sensitivity to the initial conditions (ICs).

R_{dAu} in pp, dAu at 200 GeV (Middle + Forward)



Summary

- MC-CGC v3.0 has been developed with:
 - A realistic event-by-event particle production event generator
 - Extended collision systems: p, d, O, Ne, Xe, Au, Pb, ...
 - Improved modeling: MPI, ISR, string connections, and beam remnants.

- Simulations at RHIC and the LHC show good agreement with experimental data across Different collision systems, a broad range of collision energies, and wide rapidity coverage.

- Outlook
 - Electromagnetic probes: Photon and dilepton production
 - Multi-particle observables: Dijet correlations
 - New experimental environments: UPCs and the EIC
 - ...

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For proton: Gaussian shape

$$T_N(\vec{s}) = \frac{1}{2\pi B_{NN}} e^{-\vec{s}^2/(2B_{NN})}, \quad B_{NN} = 0.325 \text{ fm}^2,$$

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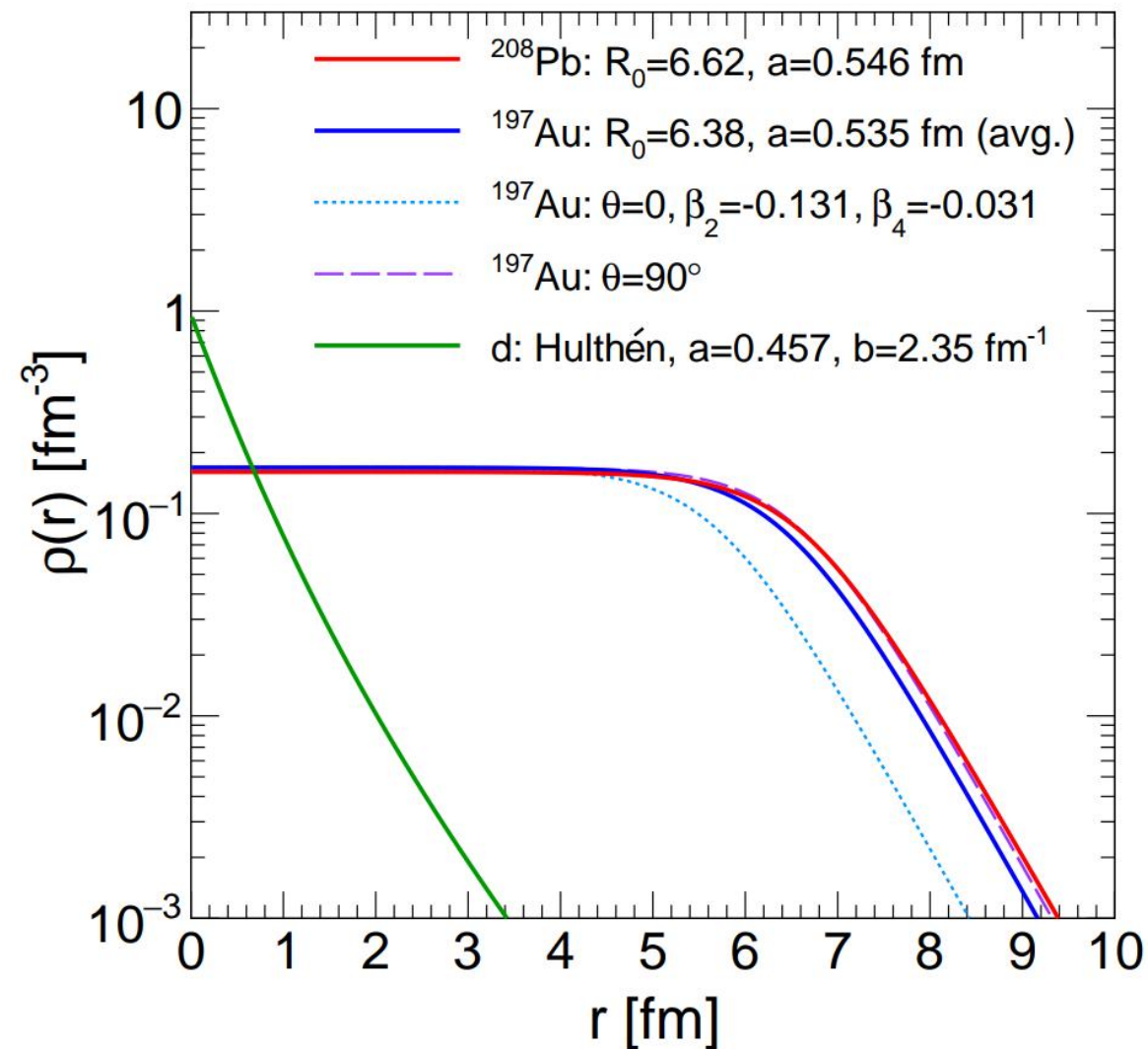
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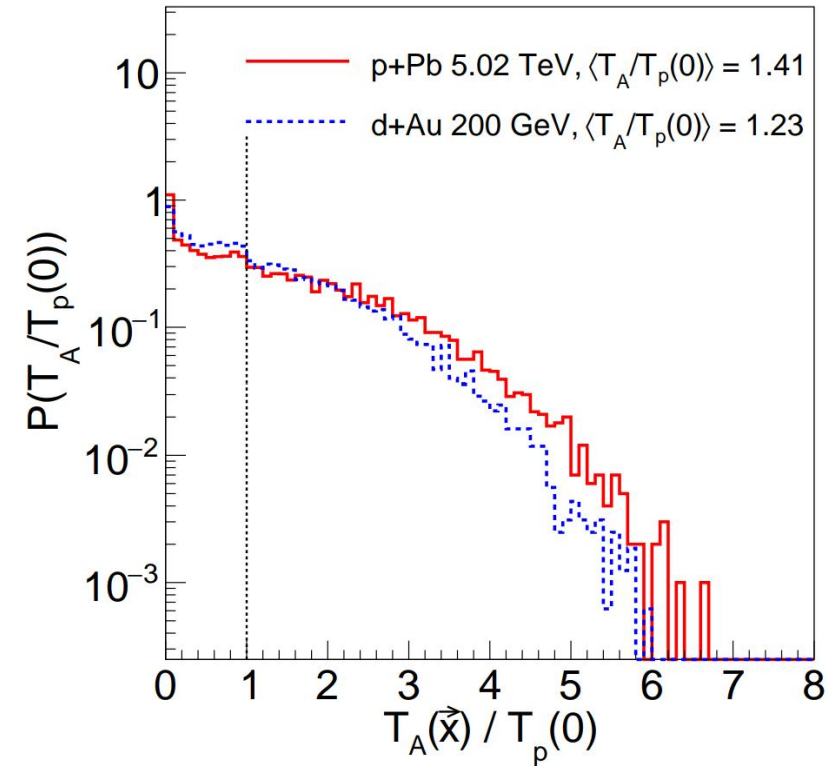
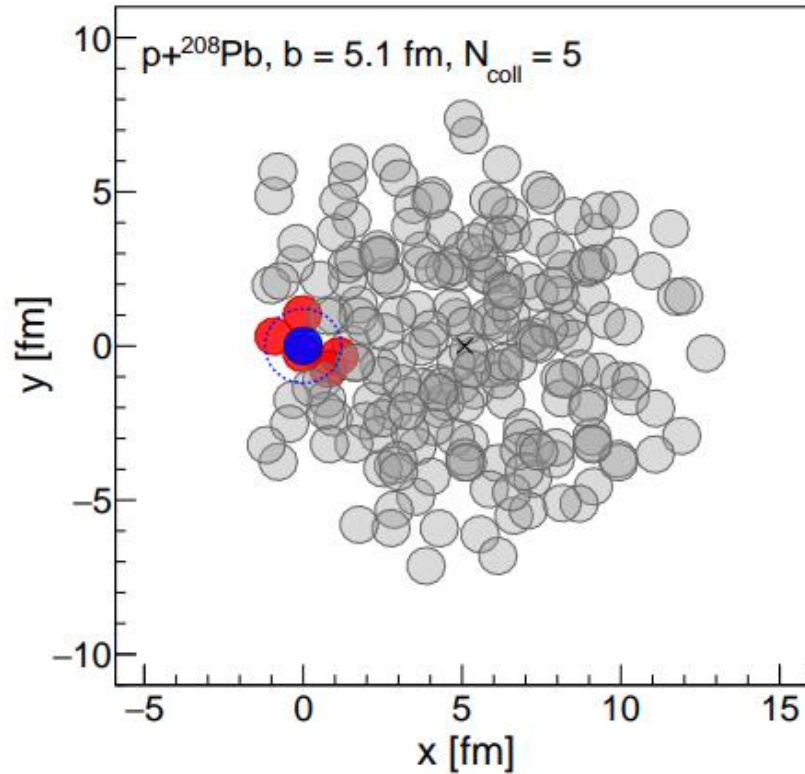
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species	Z	A	r_0 [fm]	a [fm]	β_2	β_3	β_4	γ	nCTEQ15 PDF
p (proton)	1	1	—	—	—	—	—	—	yes (set 7)
d (deuteron)	1	2	Hulthen p - n , not Woods-Saxon						yes (set 8, WZ)
Pb	82	208	6.62	0.546	0	0	0	0	yes (set 5)
Au	79	197	6.38	0.535	-0.131	0	-0.031	0	yes (set 6)
U	92	238	6.81	0.600	0.28	0	0.093	0	no
Xe	54	129	5.36	0.590	0.18	0	-0.003	27°	yes (set 11, A=131)
O	8	16	2.608	0.513	0	0	0	0	yes (set 10, WZ)
Ne	10	20	2.63	0.517	0.7	0	0	0	yes (set 9)



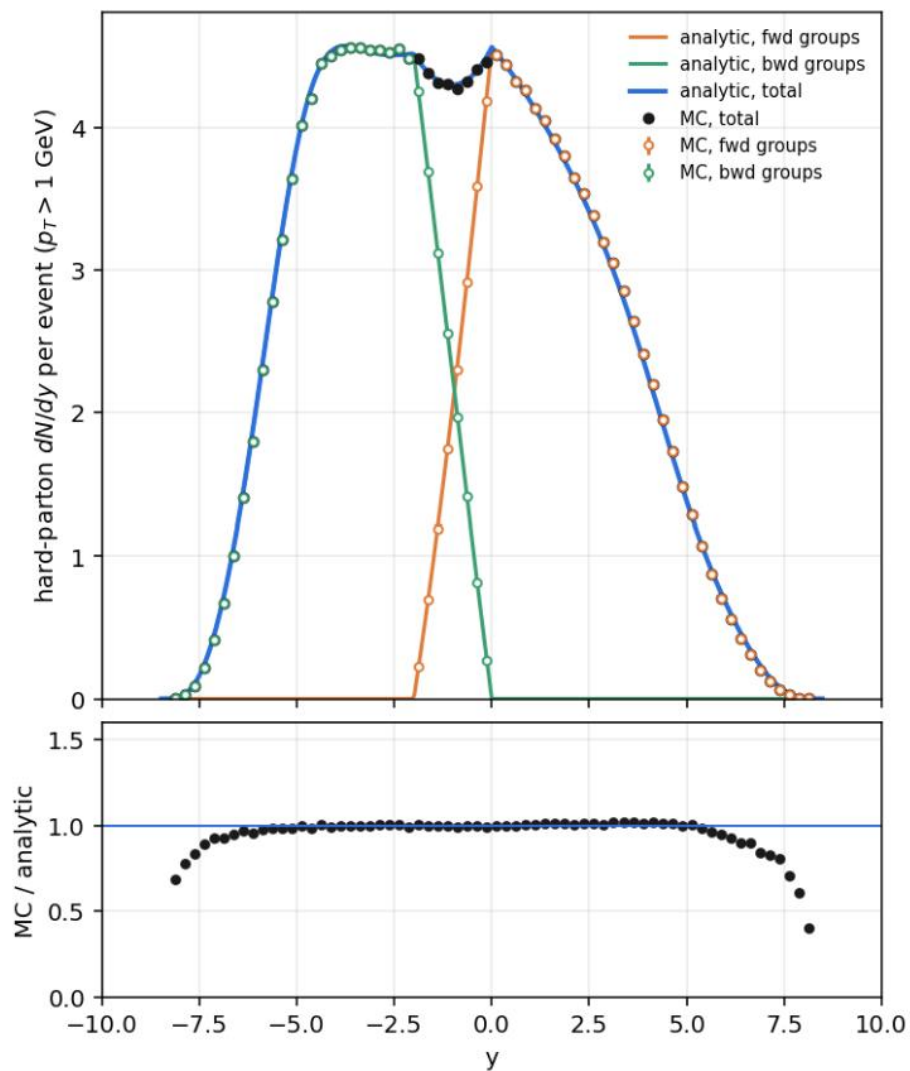
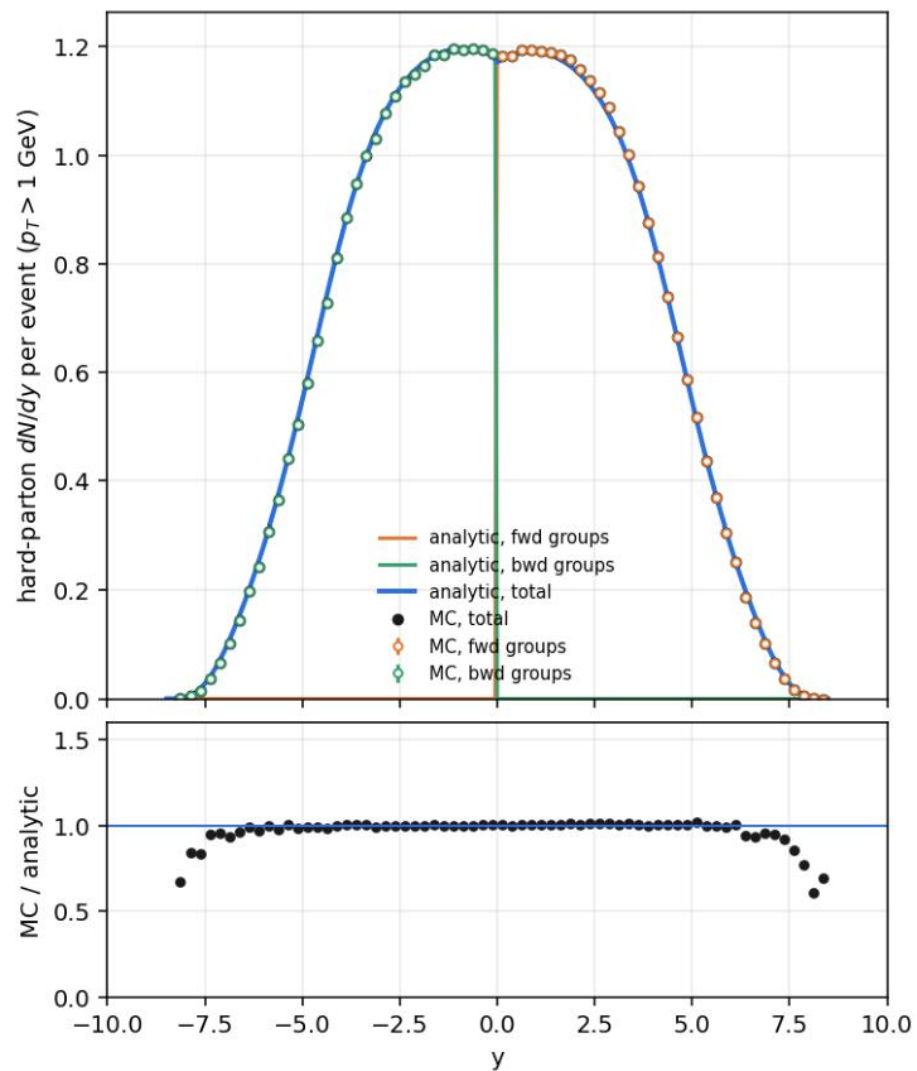
Initial Geometry



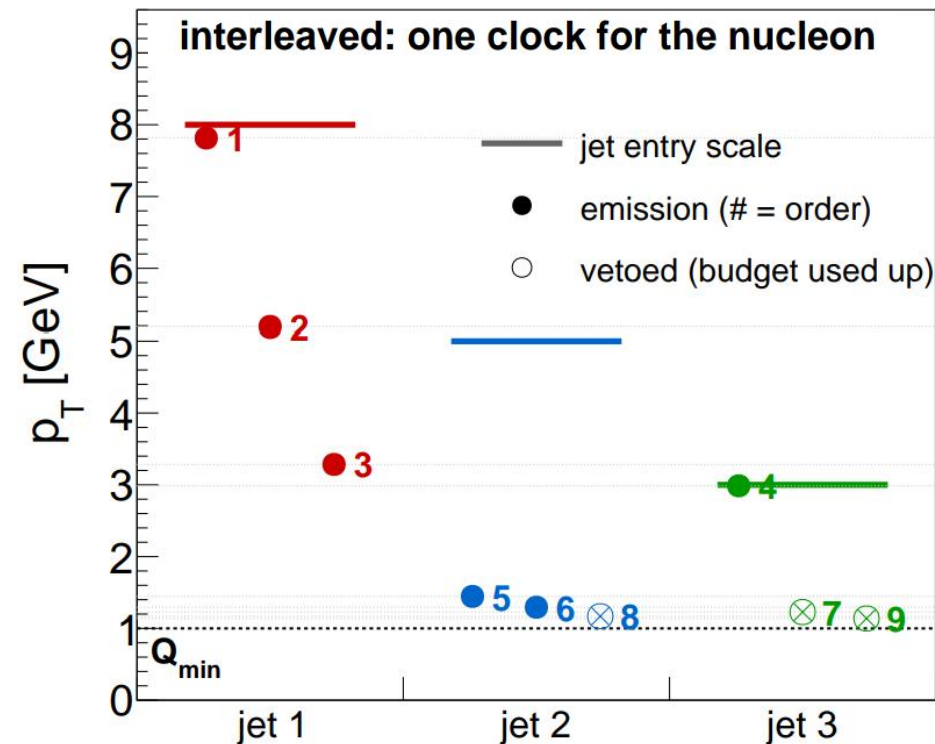
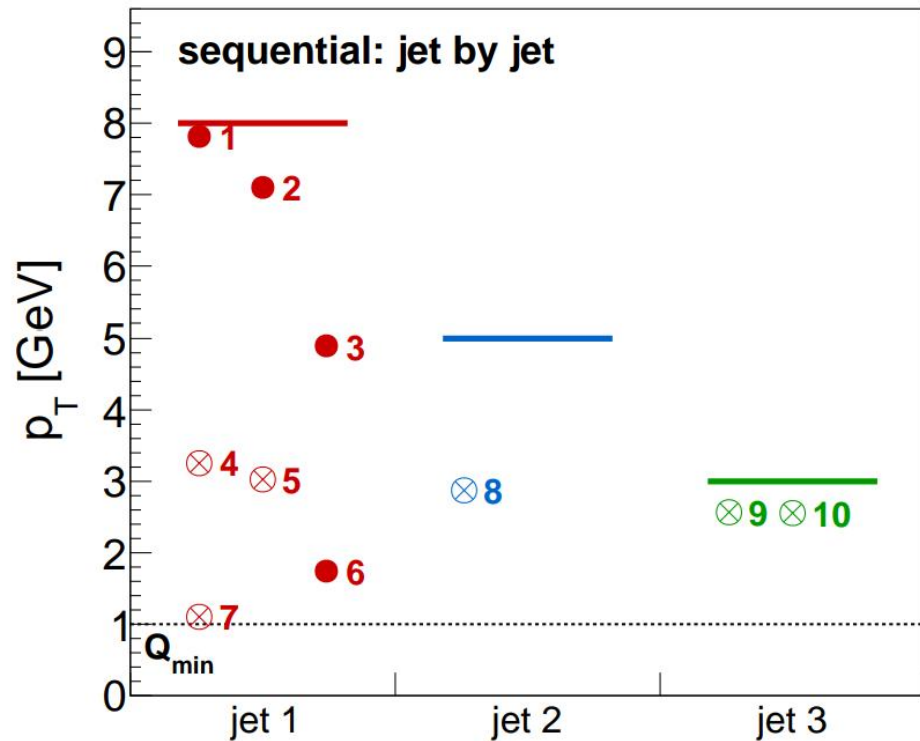
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MPI, ISR, FSR



MPI, ISR, FSR

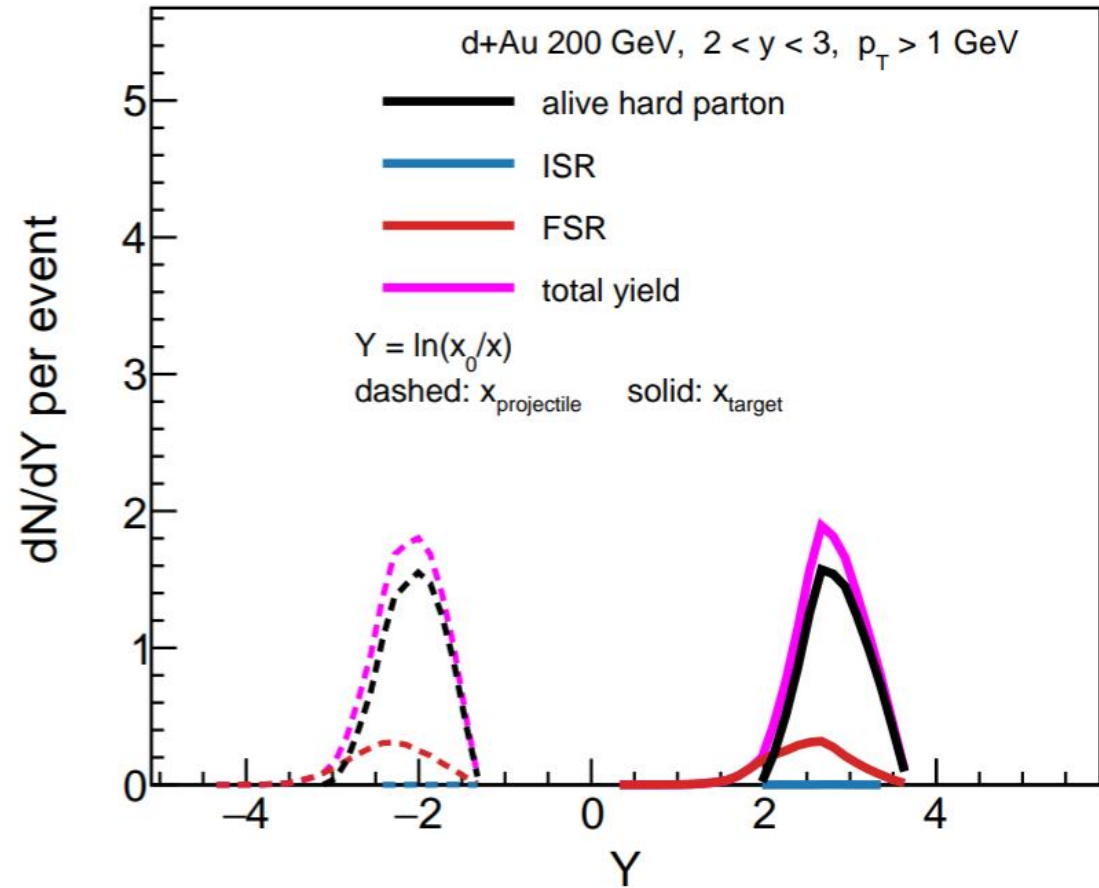
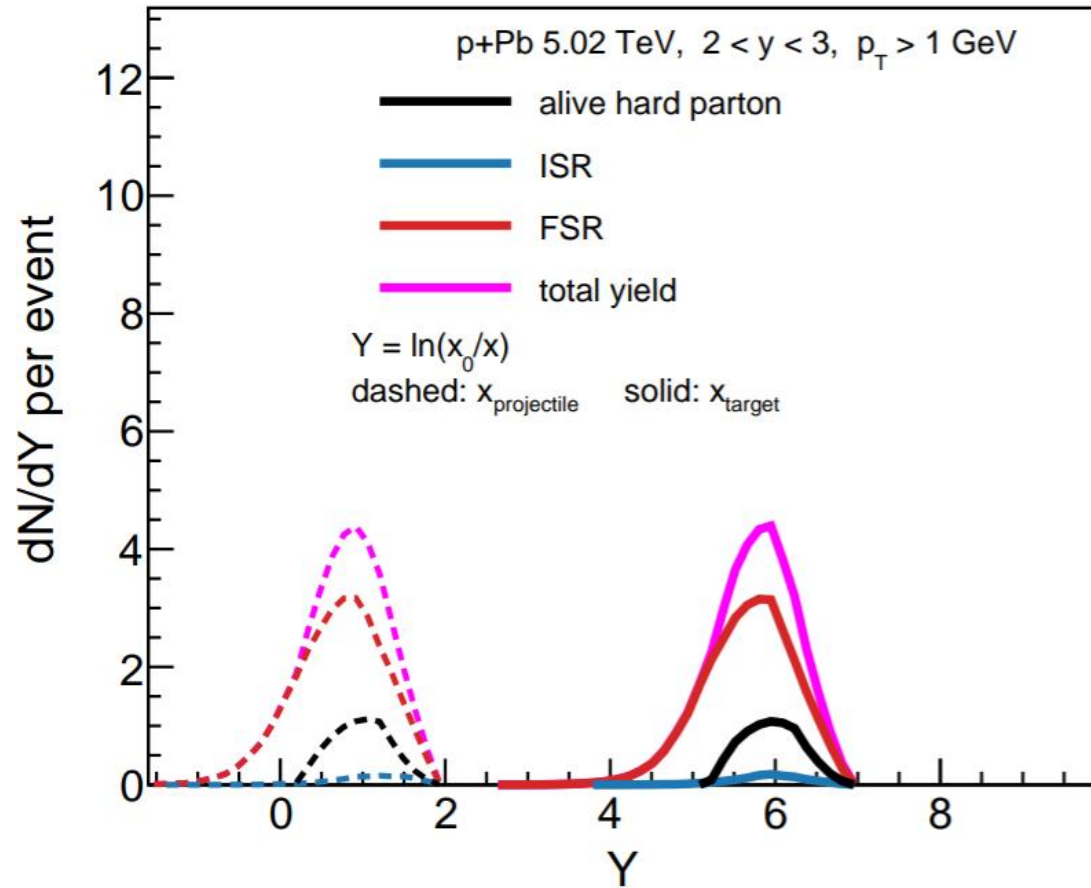


MPI in Forward p+Pb collisions: $N_{\text{coll}} \sim 5-7$, stronger x-depletion than in pp collisions.

MPI–ISR interplay:
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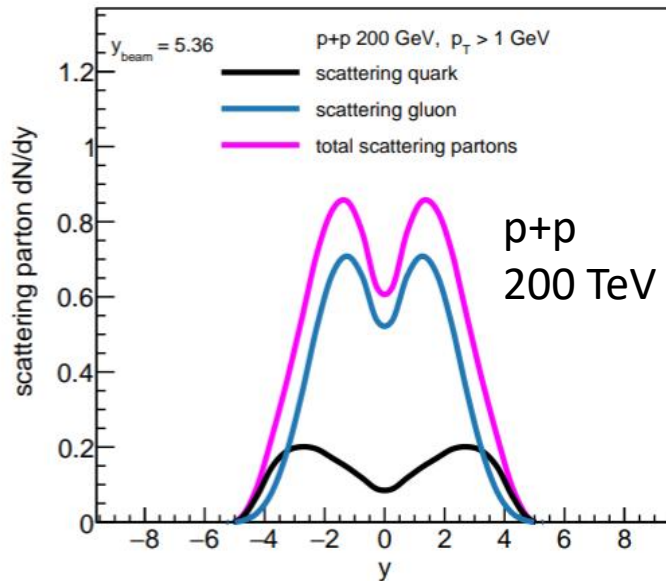
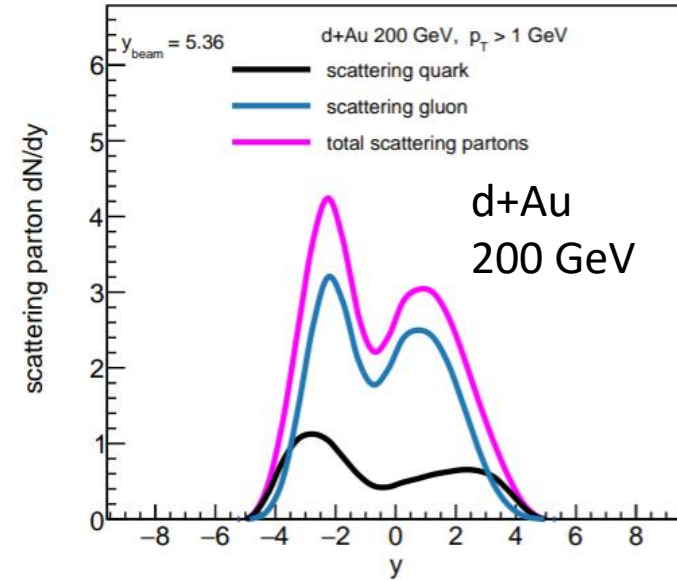
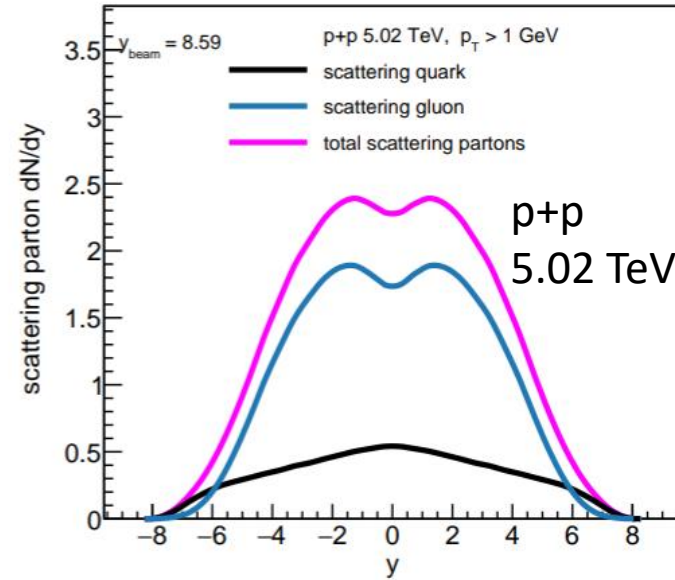
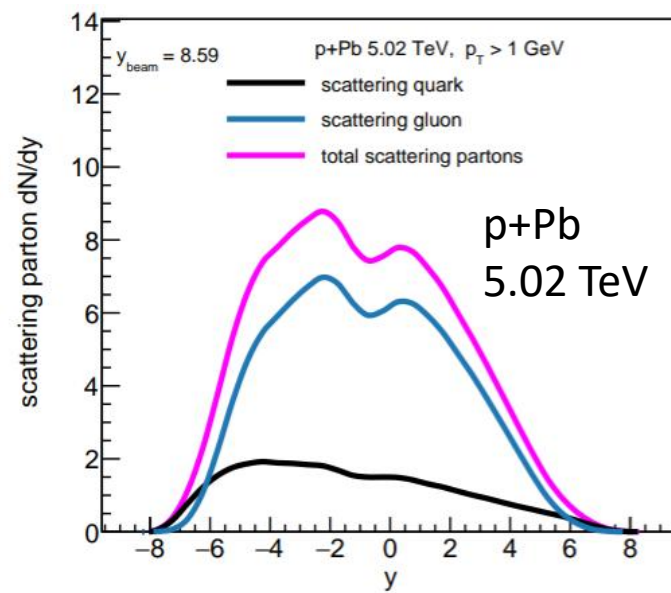
Parton Distribution



In LHC energy: FSR parton dominate the distribution.

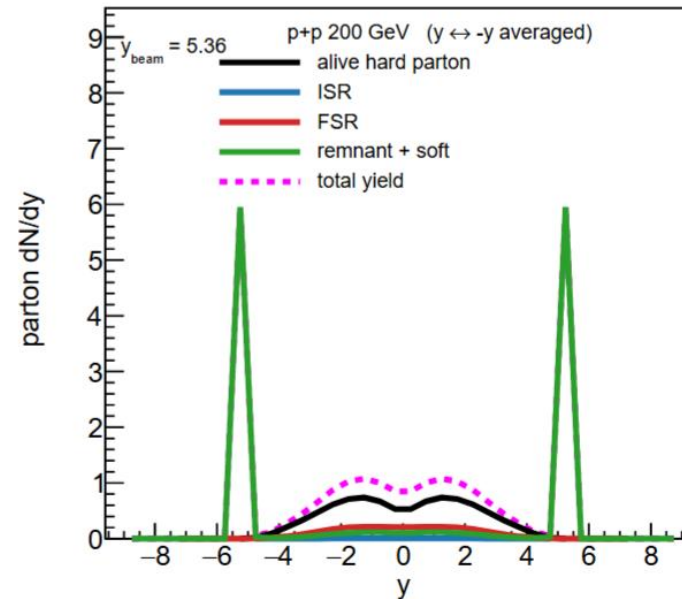
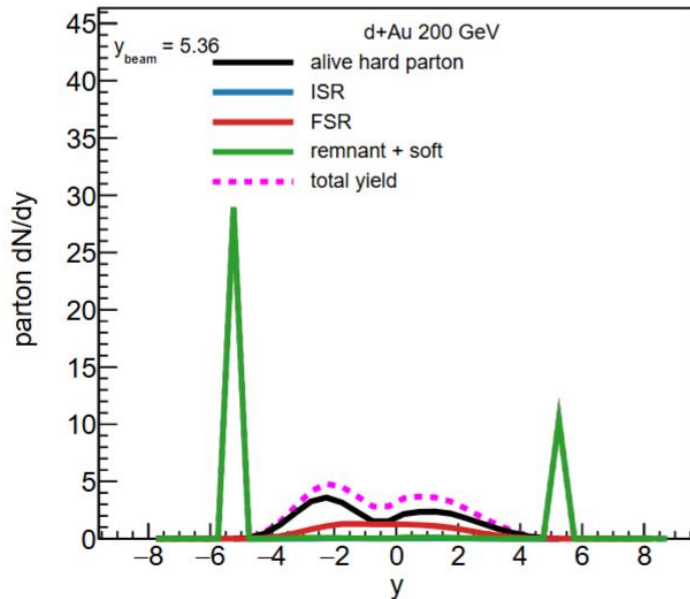
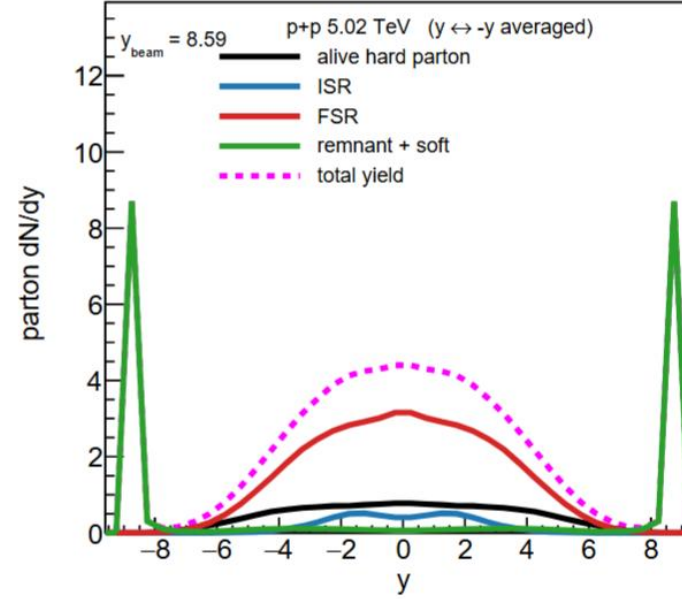
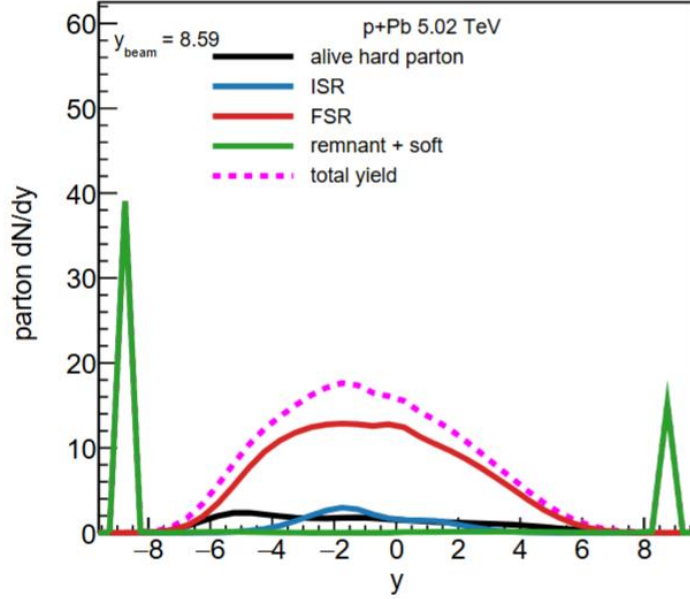
In RHIC energy: With $Q_{\text{min,FSR}}=1.0$ GeV, FSR hardly happen, most partons do not radiate.
ISR suppressed due to more MPI happen in forward region.

Parton Distribution

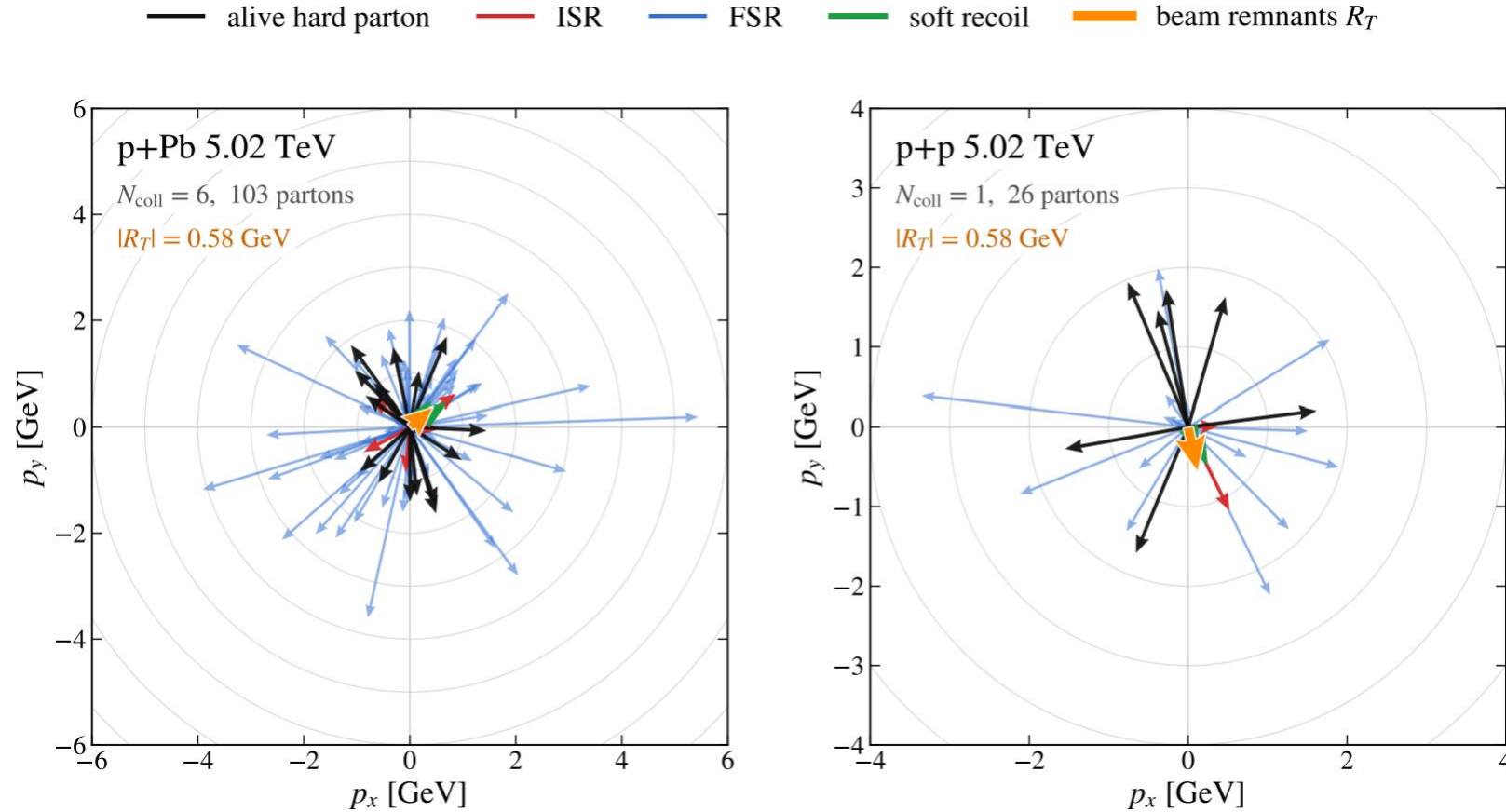


Gluon dominate the mid- to semi-forward/backward rapidity yield.
quark channel becomes important in more forward/backward region, and quark-remnant interaction should be treated more carefully.

Backup: Full parton level distribution



Azimuthal Angle Assignment

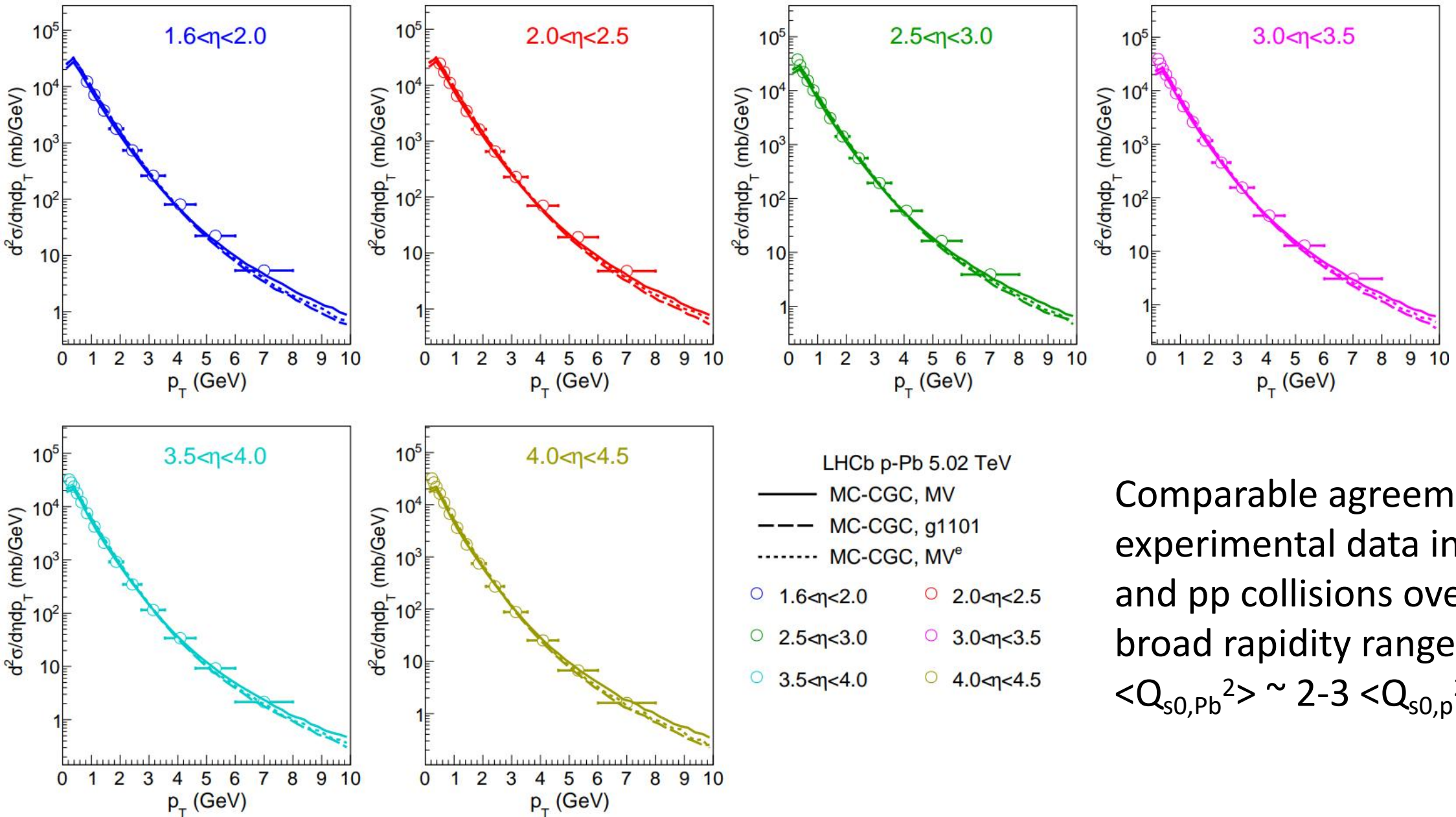


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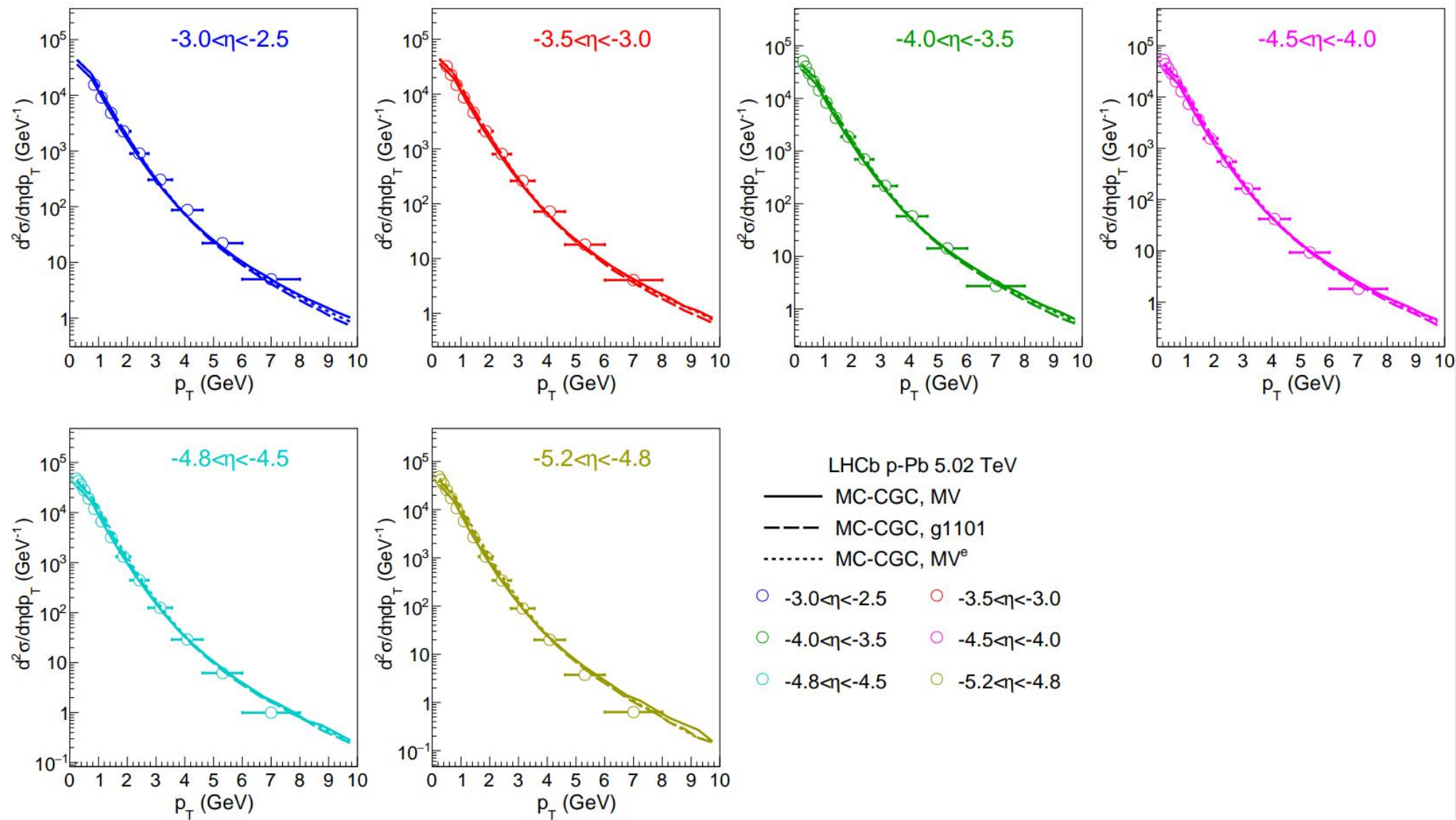
p_T Spectra in pPb at 5.02 TeV (Forward Rapidity)



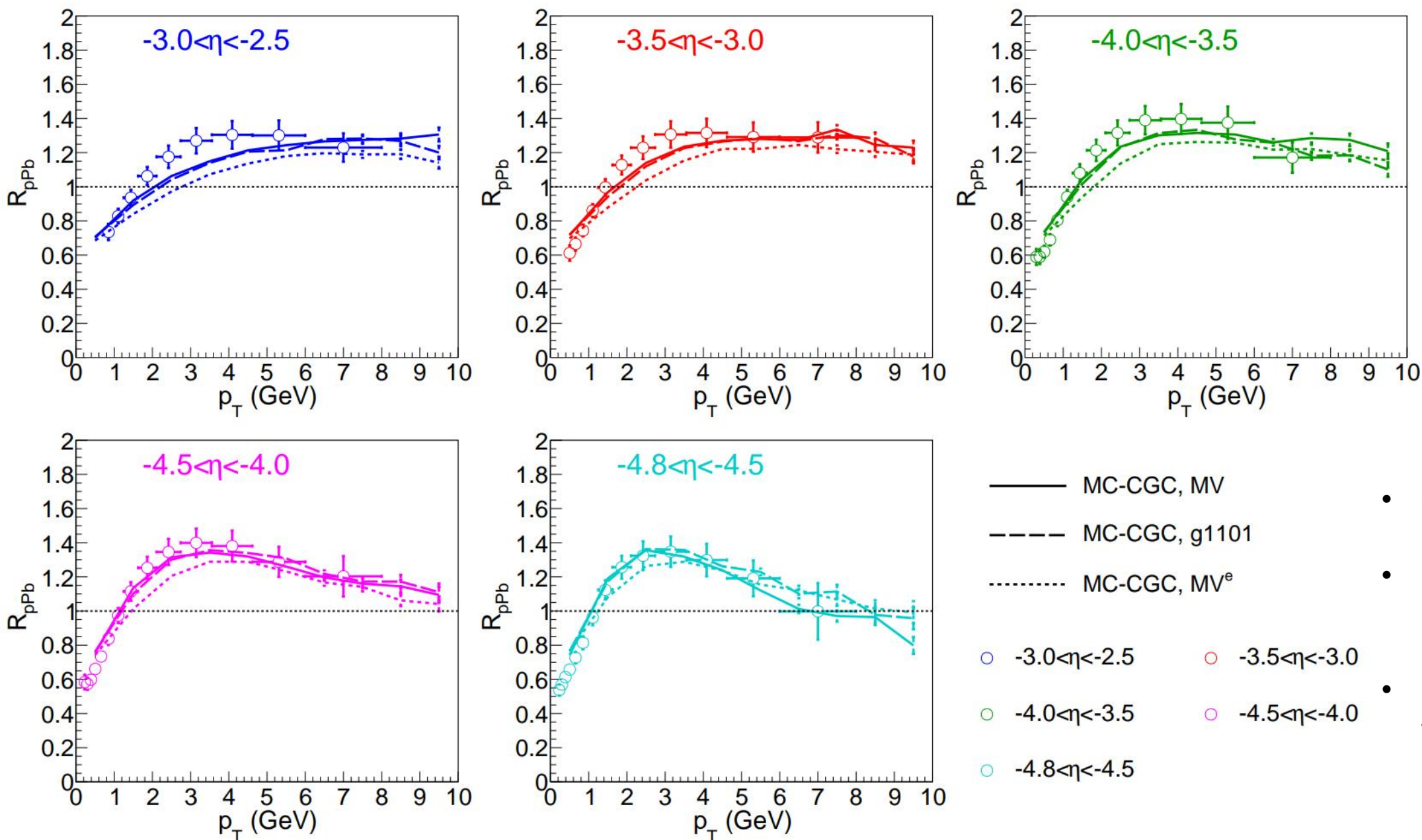
Comparable agreement with experimental data in p+Pb and pp collisions over a broad rapidity range.

$\langle Q_{s0,Pb}^2 \rangle \sim 2-3 \langle Q_{s0,p}^2 \rangle$

Backup: backward raw production

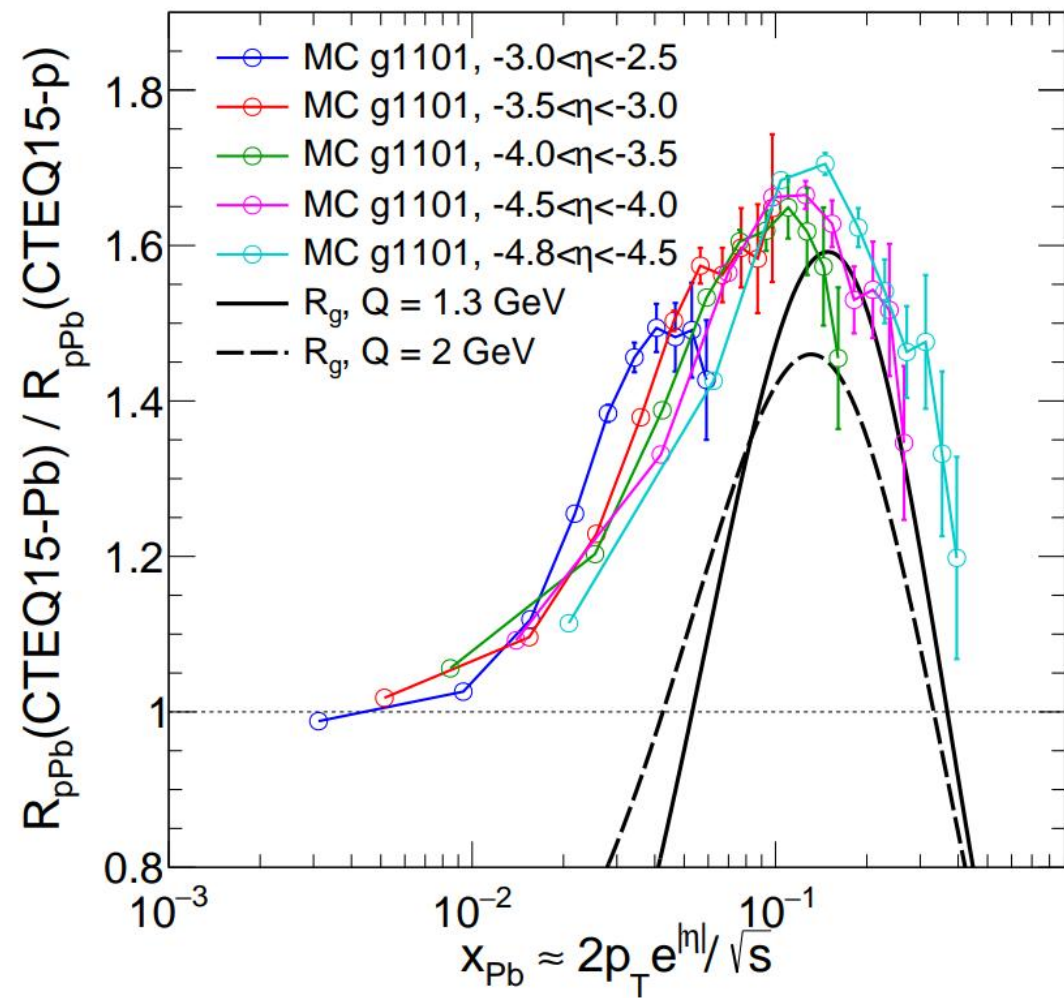
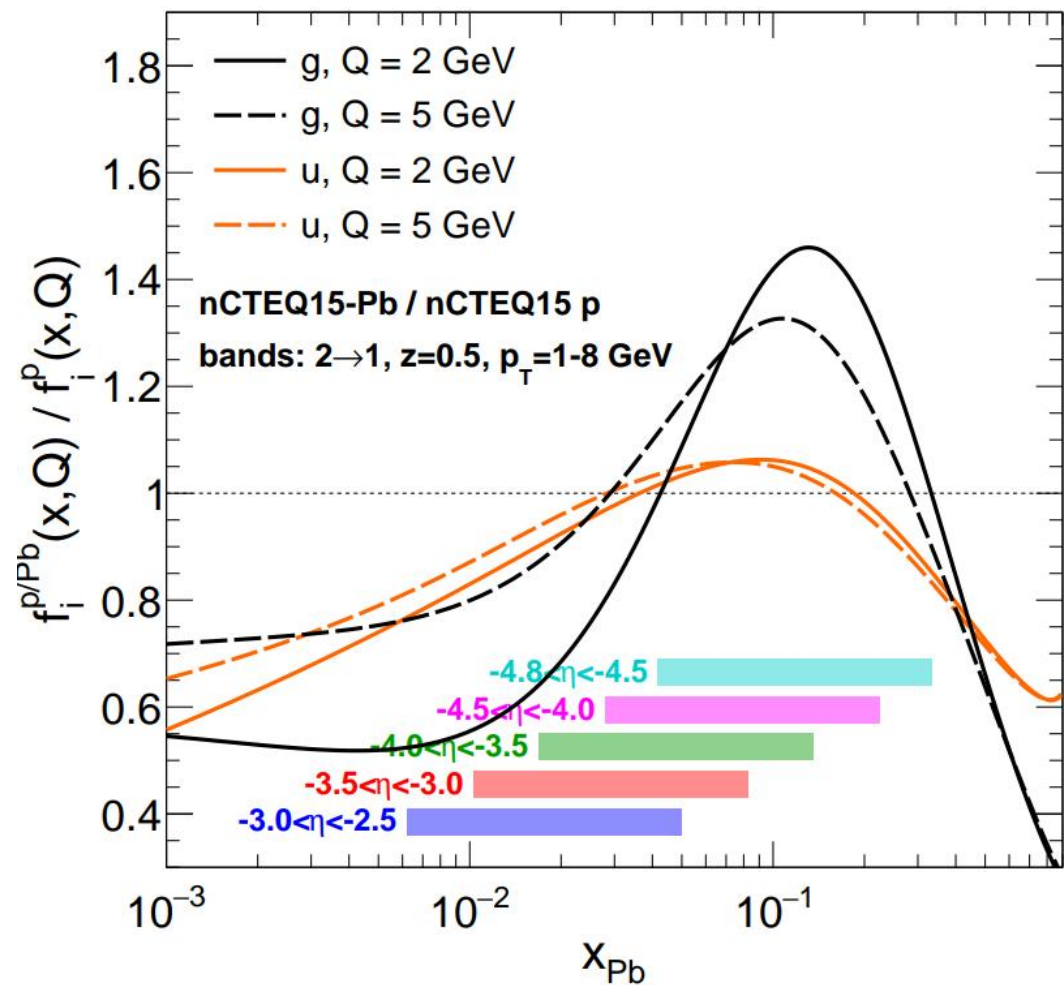


R_{pPb} at 5.02 TeV (Backward)



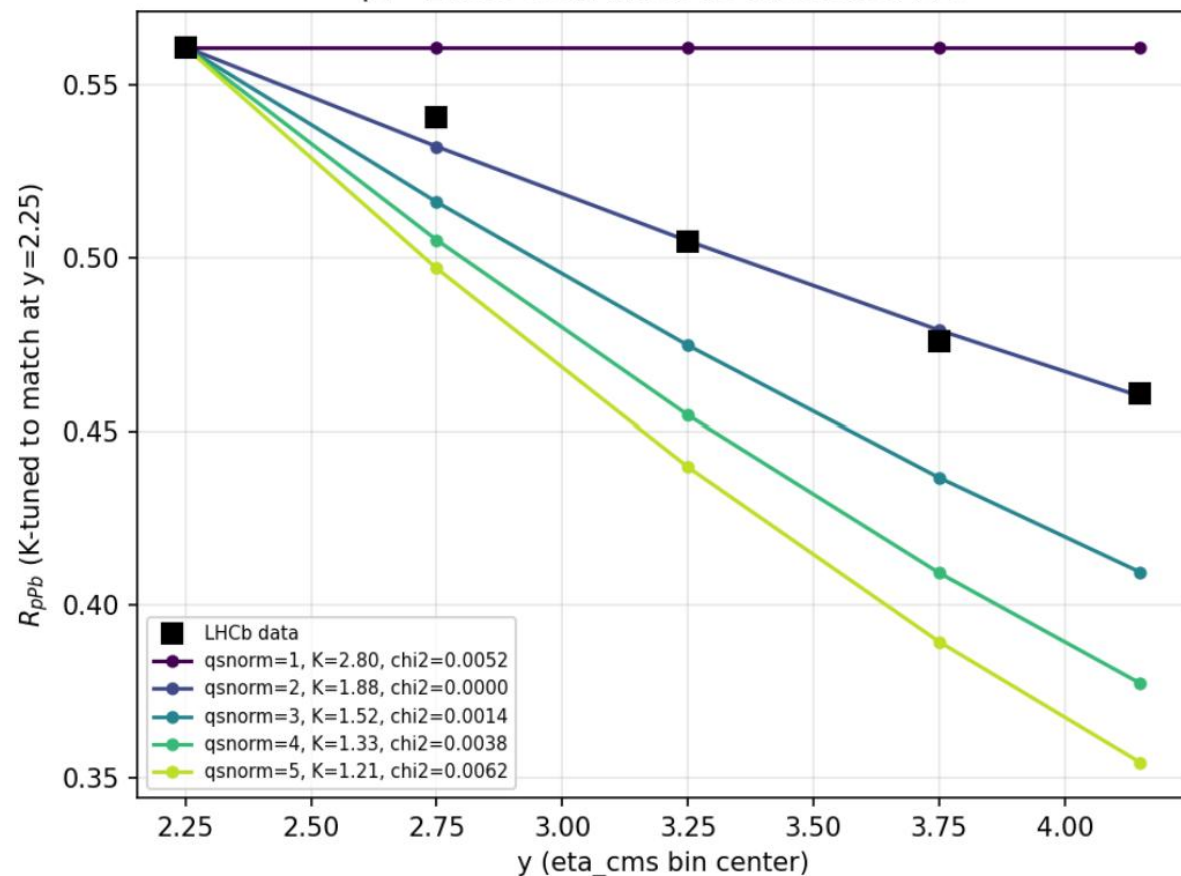
- Coroin peak can be produced.
- Precise description in $-4.8 < \eta < -4.0$ region.
- Lack of description when $|\eta|$ reduce.

PDFs ratio in backward region

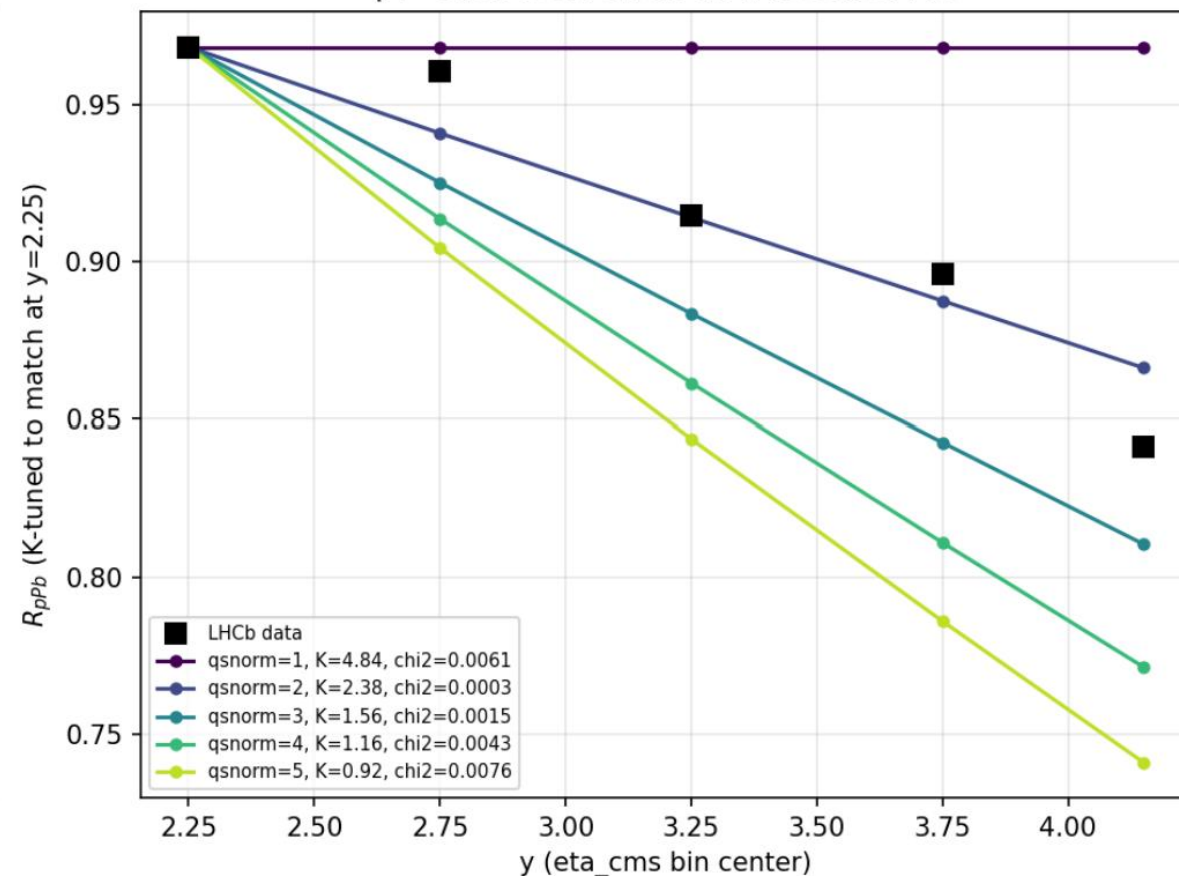


Backup: Analytical baseline

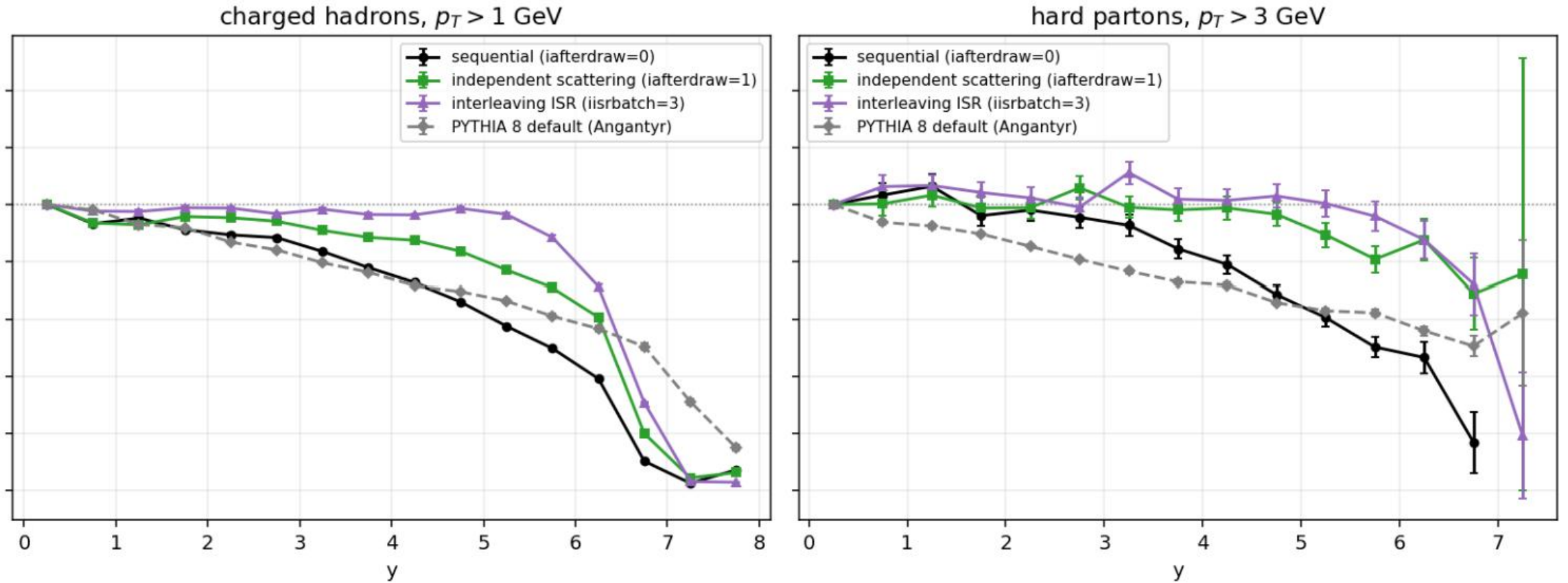
pT=1.105 GeV: LHCb vs K-rescaled MC



pT=5.31 GeV: LHCb vs K-rescaled MC



pPb / pp (y): Comparison



With higher p_T cut, Interleaving provide nearly flat baseline in FoCal acceptance.
Further improvement may possible -- pre-draw residual x-depletion