

Gluon saturation in dijet production at $LH\mu C$

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in collaboration with Piotr Kotko



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High energy, high luminosity *muon-hadron* collider at CERN



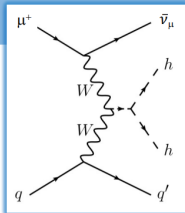
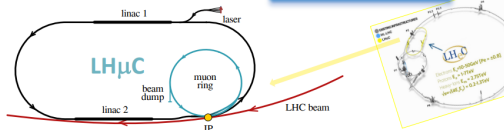
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AGH University of Krakow

AGH

on behalf of HELP4CERN Study Group

DIS 2026



Talk given at the 33rd International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2026) by Krzysztof Piotrkowski

PTEP

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μ LHC: Antimuon Ring and High Luminosity-LHC-Based $\mu^+ p$ Collider

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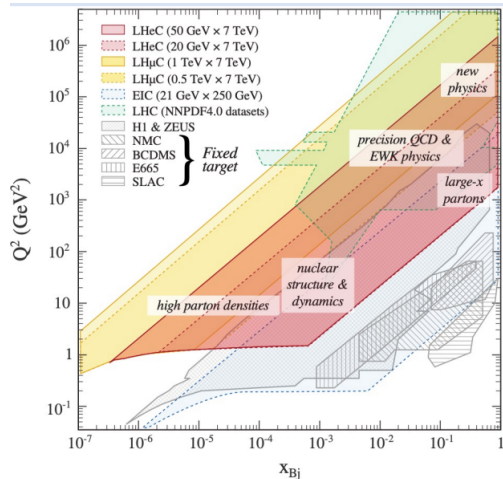
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A conceptual design and a performance evaluation of the High Luminosity-Large Hadron Collider (HL-LHC)-based antimuon-proton collider μ LHC are presented. Leveraging the μ TRISTAN concept based on established Japan Proton Accelerator Research Complex (J-PARC) ultra-cold μ^+ beam technology, μ LHC will give the opportunity to achieve a 5.3-TeV center-of-mass energy, significantly surpassing the Electron Ion Collider (EIC) and Large Hadron-electron Collider (LHeC). Two booster ring options for μ^+ acceleration, namely, a μ TRISTAN-based and a repurposed LHeC Energy Recovery Linac (ERL)-based system, are explored. Achievable luminosities are predicted to exceed $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. The μ LHC offers substantially wider kinematic plane coverage, particularly in small- x and high- Q^2 regions, significantly contributing to QCD basics and Higgs boson properties. Its unique potential for Beyond the Standard Model physics extends to muon-related phenomena like excited muons, color-octet muons, leptoquarks, and contact interactions. A possible detector concept is also outlined. Given the maturity of ultra-cold μ^+ beam technology, μ LHC is highly feasible for earlier realization than the muon collider, positioning it as a critical tool for the future of high-energy physics.

Subject Index B40, C00, G00, G06, H01

Motivation



Research power of LH μ C:

- CM energy $\sqrt{s} = 3.3 \div 7.5\text{TeV}$
- access to (really) small- x
- many studying areas: top, electroweak physics, Higgs physics, BSM
- relatively low costs

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Dijet production at $LH\mu C$

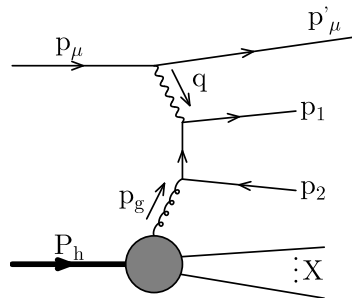
We consider the following process:

$$\mu^+ h \rightarrow j_1 j_2 \mu^+ X$$

The hadron moves with positive rapidity, while anti-muon with negative.

Kinematic:

- $1 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$
- $0.001 < \nu < 0.9$
- $\Delta R^{\text{Berit}}(j_1, j_2) > 1$
- $-4 < y_1, y_2 < 4$ / $-4 < y_1, y_2 < 0$
- $5 \text{ GeV} < p_{T1}^{\text{Berit}}, p_{T2}^{\text{Berit}}$



- The hadron (proton or lead) energy per nucleon $E_h = 2.76 / 7 \text{ TeV}$
- The muon energy $E_\mu = 1 \text{ TeV}$

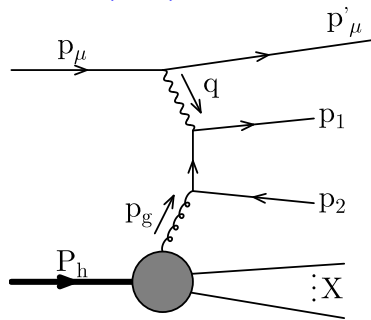
Why dijets in small- x region are interesting?

A. van Hameren, P. Kotko, K. Kutak, S. Sapeta, E. Żarów, Eur.Phys.J.C 81 (2021) 8, 741

A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, S. Sapeta, Eur.Phys.J.C 83 (2023) 10, 947

We can examine:

- non trivial azimuthal distributions
- sensitivity to gluon number density – Weizsäcker-Williams (WW) TMD gluon distribution F. Dominguez, C. Marquet, B.-W. Xiao, F. Yuan, Phys.Rev.D 83 (2011) 105005
- gluon saturation effects – imbalance between the jet transverse momenta is of the order of the saturation scale



Framework

P. Kotko, K. Kutak, S. Sapeta, A.M. Stasto, M. Strikman, Eur.Phys.J.C 77 (2017) 5, 353

We work in the factorization framework with Weizsäcker-Williams TMD gluon distribution for the process: $\gamma h \rightarrow 2 \text{ jet} + X$

$$d\sigma_{\gamma h \rightarrow 2\text{jet}+X} = \sum_{q,\bar{q}} \int \frac{dx_g}{x_g} \int d^2k_T x_g G_1(x_g, k_T) d\sigma_{\gamma g^* \rightarrow q\bar{q}}(x_g, k_T)$$

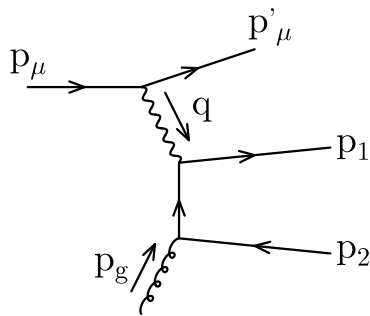
where

$x_g G_1(x_g, k_T)$ - WW TMD

$$x_g = \frac{p_g^+}{P_h^+}$$

Bjorken variable $x_{Bj} = \frac{Q^2}{2P_h \cdot q}$,

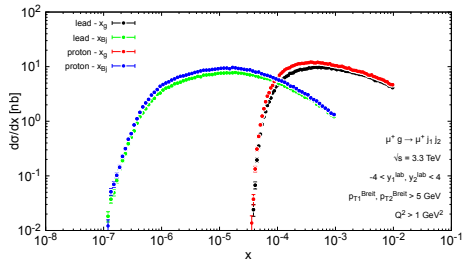
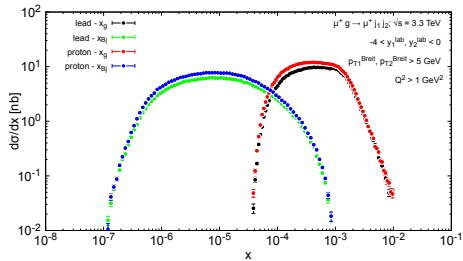
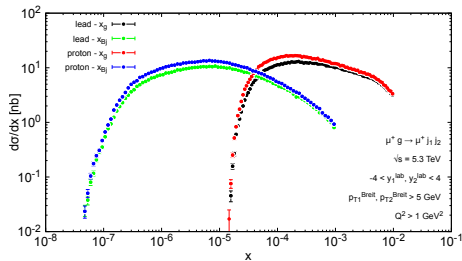
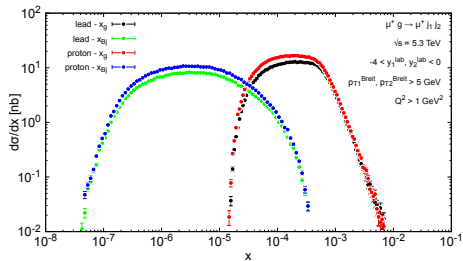
with $Q^2 = -q^2$, and $q = p_\mu - p'_\mu$



- KaTie - event generator [A. van Hameren, Comput.Phys.Commun. 224 \(2018\) 371-380](#)
 - tree-level off-shell matrix elements
 - arbitrary Standard Model processes
 - it uses the RANLUX generator [F. James, Comput.Phys.Commun. 79 \(1994\) 111-114, Comput.Phys.Commun. 97 \(1996\) 357 \(erratum\)](#)

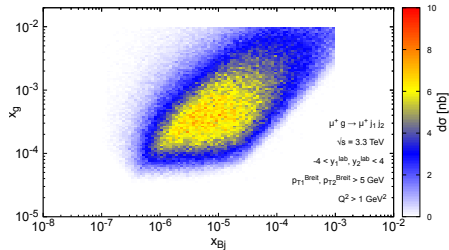
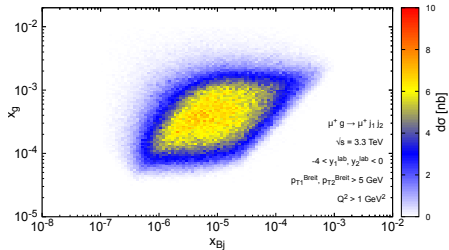
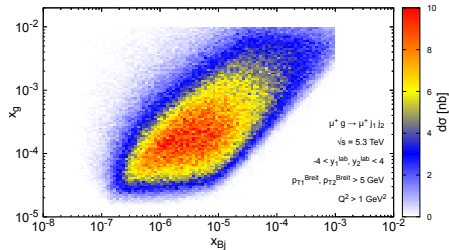
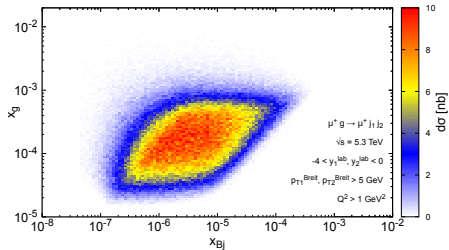
- ITMD-KS-2d-p/Pb set from TMDlib - the Weizsäcker–Williams (WW) TMD gluon distribution. [A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, S. Sapeta, Eur.Phys.J.C 83 \(2023\) 10, 947](#)

x_g and x_{Bj} ranges

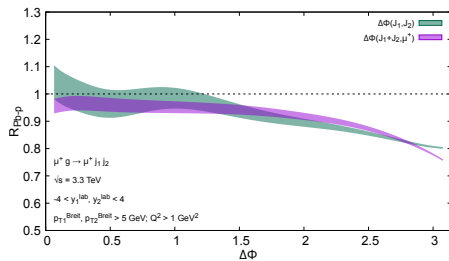
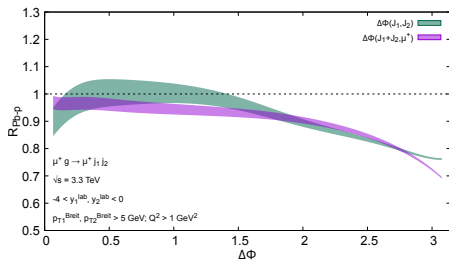
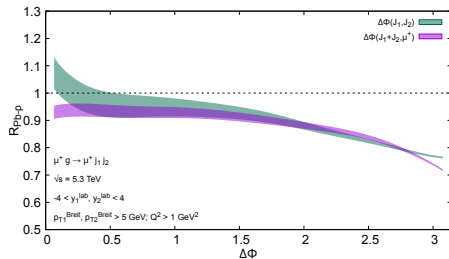
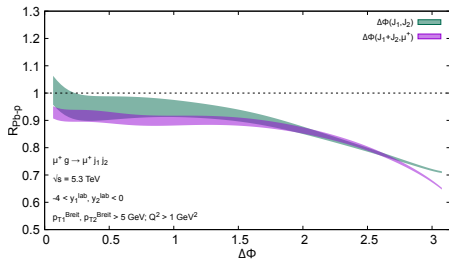


- The ranges for x_{Bj} and x_g are different
- x_{Bj} up to 10^{-7} , x_g up to 10^{-4}

The correlation between x_g and x_{Bj}



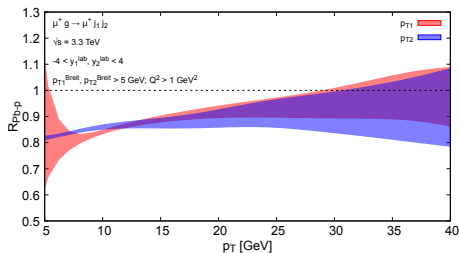
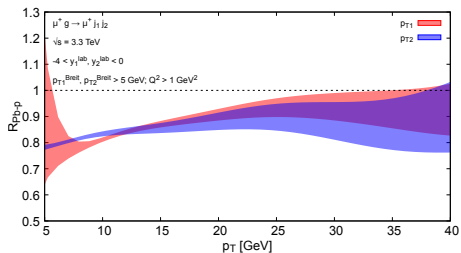
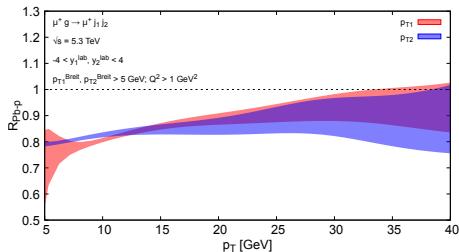
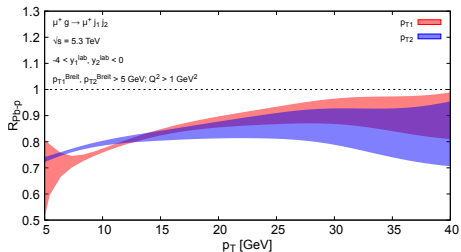
Nuclear modification ratio $R(\Delta\phi)$



$$R = \frac{d\sigma_{\mu Pb}}{Ad\sigma_{\mu p}}$$

We observe the suppression for back-to-back jets up to 20÷30 %

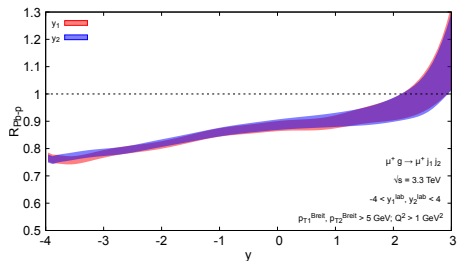
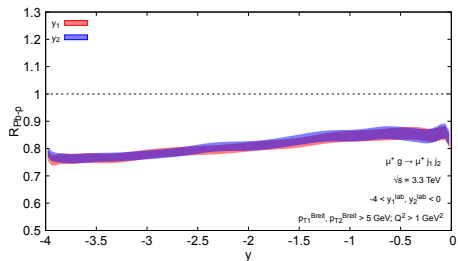
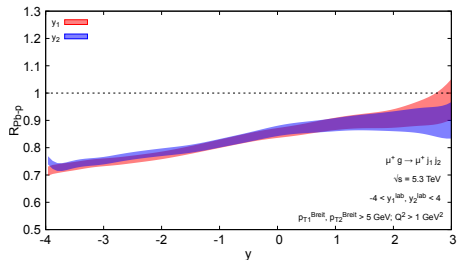
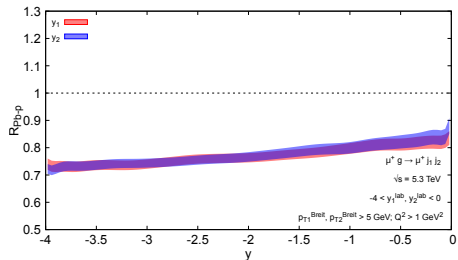
Nuclear modification ratio $R(p_T)$



$$R = \frac{d\sigma_{\mu P b}}{A d\sigma_{\mu p}}$$

We observe the suppression for low p_T of jets up to 20÷25 %

Nuclear modification ratio $R(y)$



$$R = \frac{d\sigma_{\mu Pb}}{Ad\sigma_{\mu p}}$$

We observe the suppression for forward jets up to 20÷30 %

Conclusions:

- Small-x: up to 10^{-4} for x_g and up to 10^{-7} for x_{Bj}
- Application of the saturation framework requires hemispherical rapidity cuts
- We observe the nuclear suppression for forward, low p_T and back-to-back (in azimuthal angle) jets up to 20÷30 %

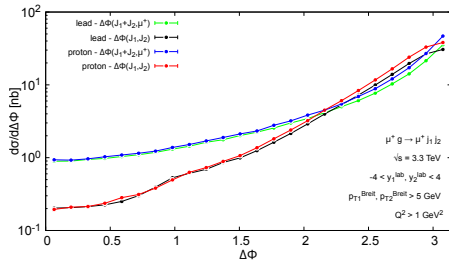
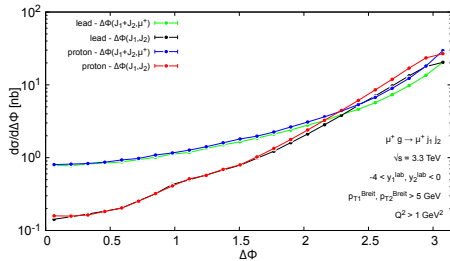
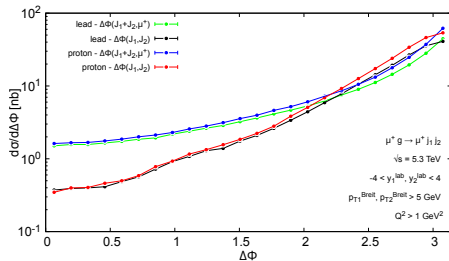
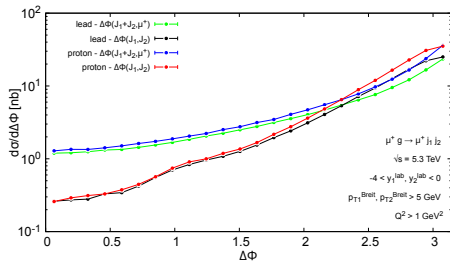
Future plans:

- Complete energy sets ($E_\mu = 0.5 / 2 \text{ TeV}$)
- Trijet production at $\text{LH}\mu\text{C}$

Thank you for listening!

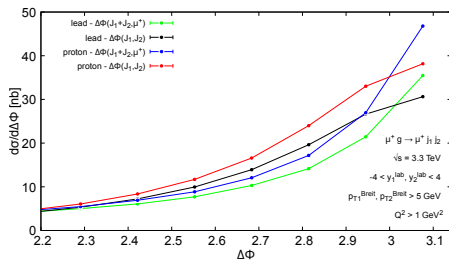
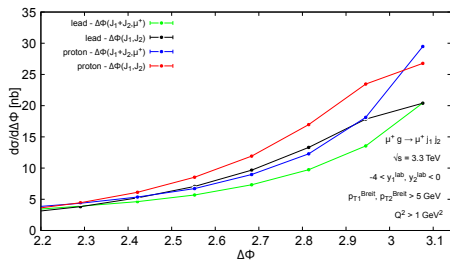
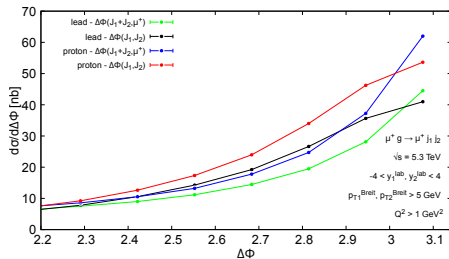
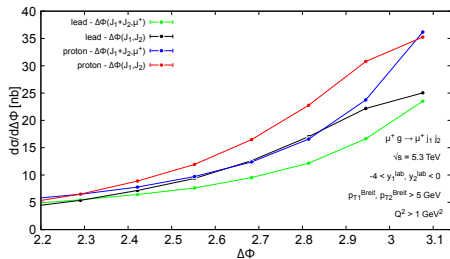
Back-up

Azimutal distributions



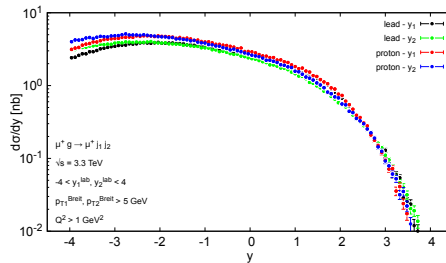
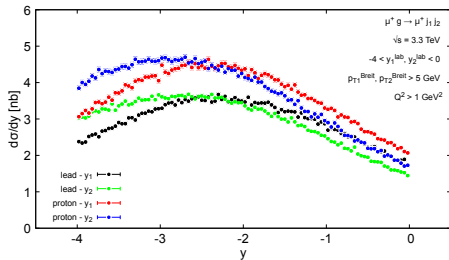
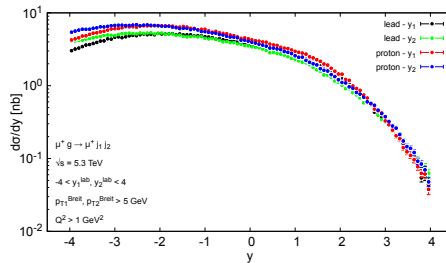
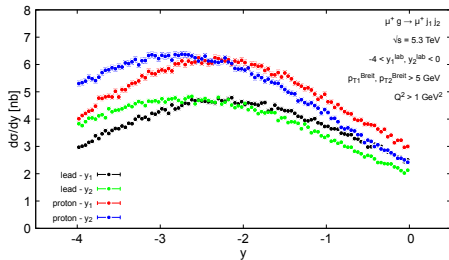
- We observe the suppression for back-to-back jets

Azimutal distributions

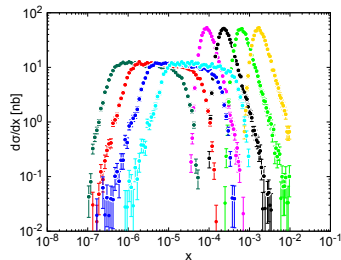
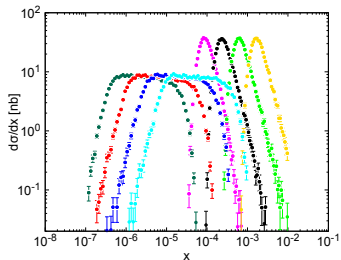
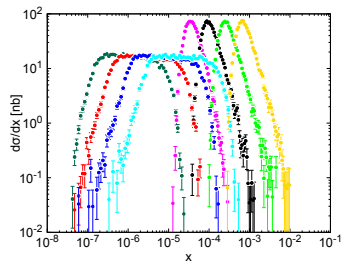
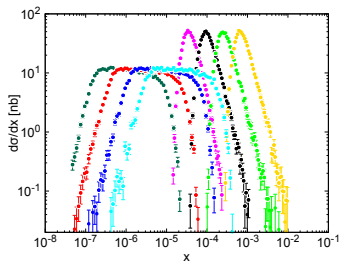


- We observe the suppression for back-to-back jets

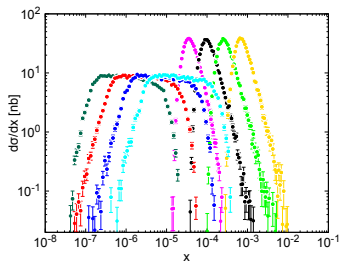
Rapidity distributions



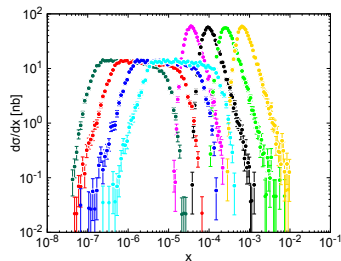
x_g and x_{Bj} distributions for proton



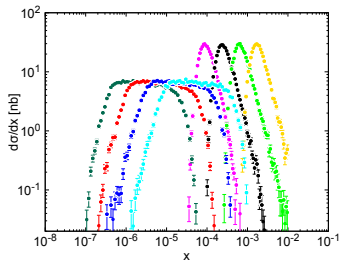
x_g and x_{Bj} distributions for lead



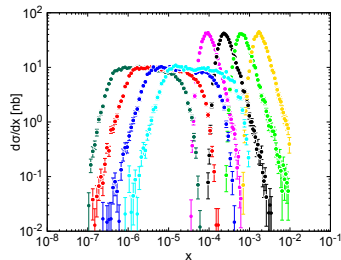
$x_g, -4 < y_1, y_2 < -3$
 $x_{Bj}, -4 < y_1, y_2 < -3$
 $x_g, -3 < y_1, y_2 < -2$
 $x_{Bj}, -3 < y_1, y_2 < -2$
 $x_g, -2 < y_1, y_2 < -1$
 $x_{Bj}, -2 < y_1, y_2 < -1$
 $x_g, -1 < y_1, y_2 < 0$
 $x_{Bj}, -1 < y_1, y_2 < 0$
 $\mu^+ g \rightarrow \mu^+ j_1 j_2$
 $\sqrt{s} = 5.3 \text{ TeV}$
 $-4 < y_1^{lab}, y_2^{lab} < 0$
 $p_{T1}^{Breit}, p_{T2}^{Breit} > 5 \text{ GeV}$
 $Q^2 > 1 \text{ GeV}^2$



$x_g, -4 < y_1, y_2 < -3$
 $x_{Bj}, -4 < y_1, y_2 < -3$
 $x_g, -3 < y_1, y_2 < -2$
 $x_{Bj}, -3 < y_1, y_2 < -2$
 $x_g, -2 < y_1, y_2 < -1$
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$x_g, -4 < y_1, y_2 < -3$
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 $x_g, -3 < y_1, y_2 < -2$
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