Z+jet correlations with NLO-matched parton-shower and jet-medium interaction in high-energy nuclear collisions

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Shan-Liang. Zhang, T. Luo, X. N. Wang and B. W. Zhang, arXiv:1804.11041 [nucl-th].

Outline

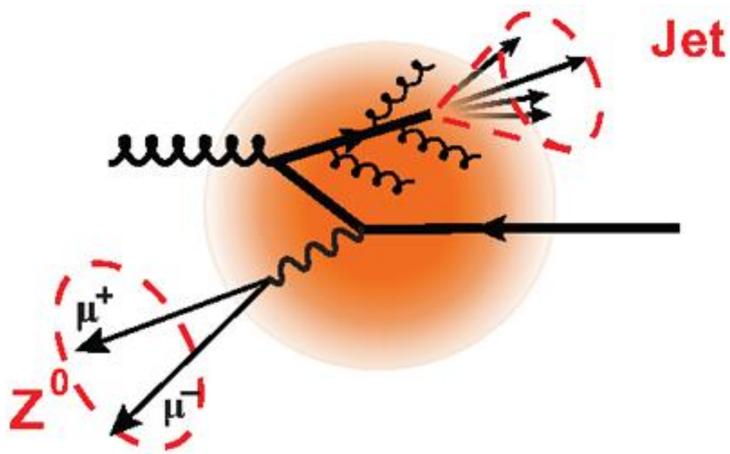
- Introduction
- Jet production within Sherpa
- Jet propagation within a Linear Boltmann Transport (LBT) model
- Numerical results
- Summary

Introduction

- Z+jet: Golden channel to study jet quenching.

  V. Kartvelishvili, R. Kvatadze and R. Shanidze, Phys. Lett. B 356, 589 (1995)

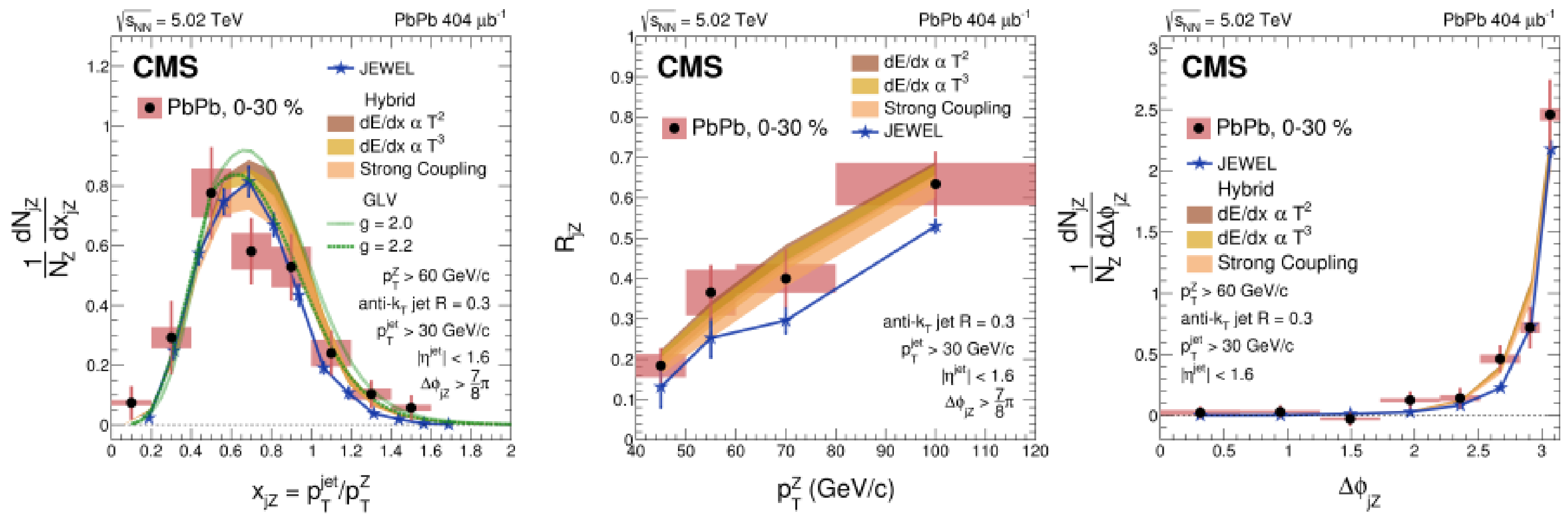
  – High energy parton from hard scattering lose energy due to strong interactions.



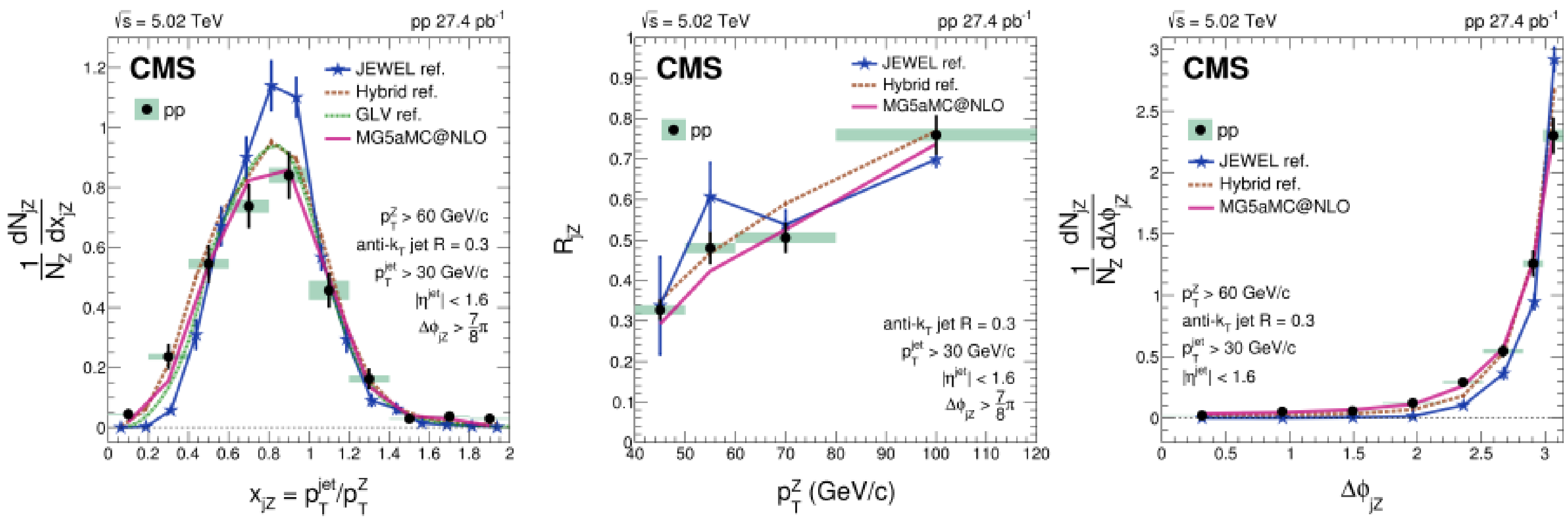
  – Mean-free-path of Z boson is longer than the size of QGP.
  – Z boson will not participate in strong interactions directly.
  – No fragmentation contributions due to large mass (M_Z = 91.18 GeV).
  – Large fraction of quark jets (> 70%).
- Important background to new physics, e.g. tops and Higgs.

Current Status

- Z+jet correlations in Pb+Pb collisions. Phys. Rev. Lett. 119, no. 8, 082301 (2017)



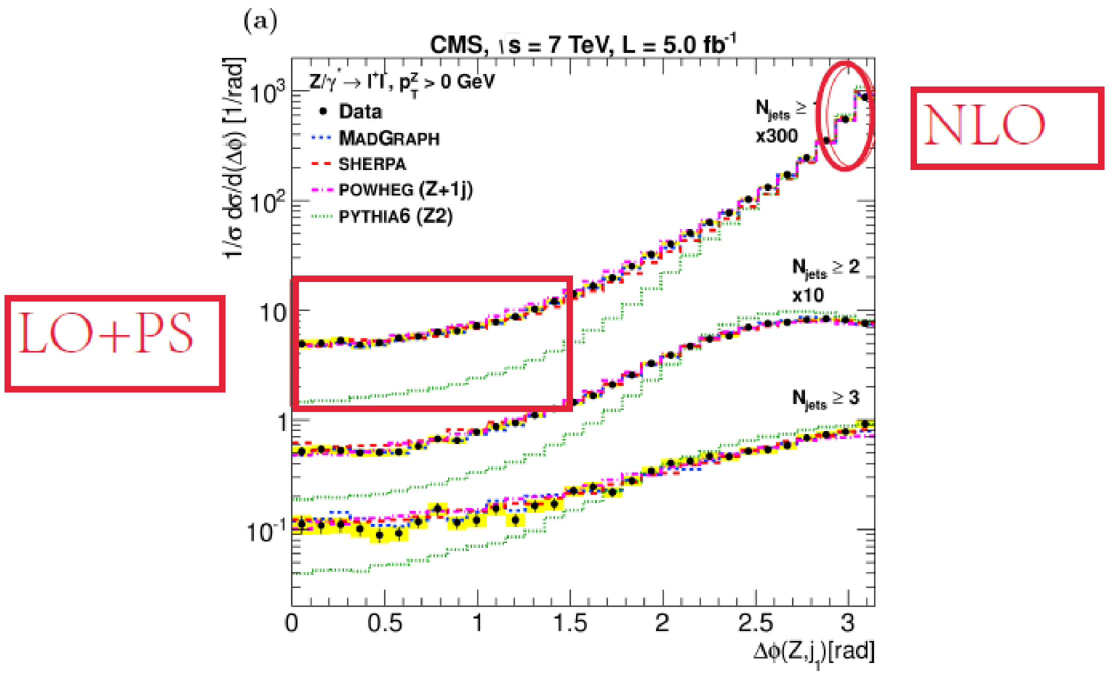
- Z+jet correlations in p+p collisions. CMS-HIN-15-013



Z+jet correlations in pp

- Z+jet azimuthal angle correlations

  S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B **722**, 238 (2013)



  – NLO calculations suffer divergency at $\Delta\phi_{\rm jZ} \approx \pi$.

  – LO+PS calculations underestimate at $\Delta\phi_{\rm jZ} < 2$.

- We adopt NLO+PS and Eloss to study Z+jet correlations.

Sherpa

Sherpa: Simulate of High-Energy Reactions of PArticals in the SM.

Merging schemes are provided to calculate multijets.

T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP **0902**, 007 (2009);
S. Hoeche,F. Krauss,S. Schumann and F. S,JHEP 0905,053(2009);JHEP 1108,123(2011);JHEP 1304,027(2013).

– Low multiplicities: NLO matched to the parton shower.

– High multiplicities: LO merged on the parton shower.

Matching scheme can be simply formulated as:

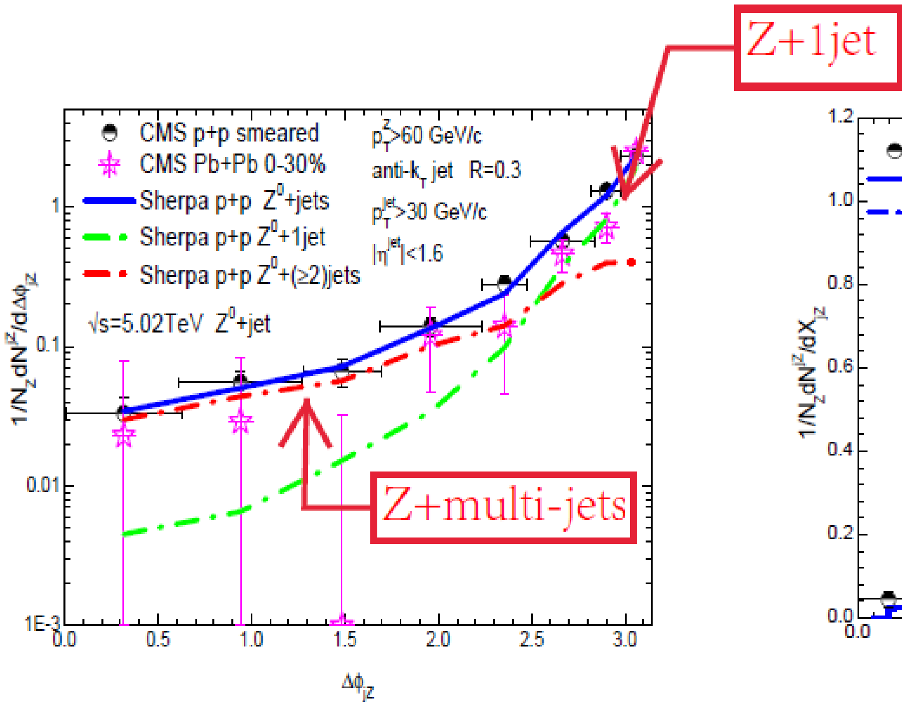
$$\langle O\rangle^{(NloPs)} = \int d\Phi_B \left[B + \tilde{V} + I^S\right](\Phi_B)\widetilde{PS}_B(\mu_Q^2, O) + \int d\Phi_R \left[R - D^S\right](\Phi_R)\widetilde{PS}_R(t_R, O)$$

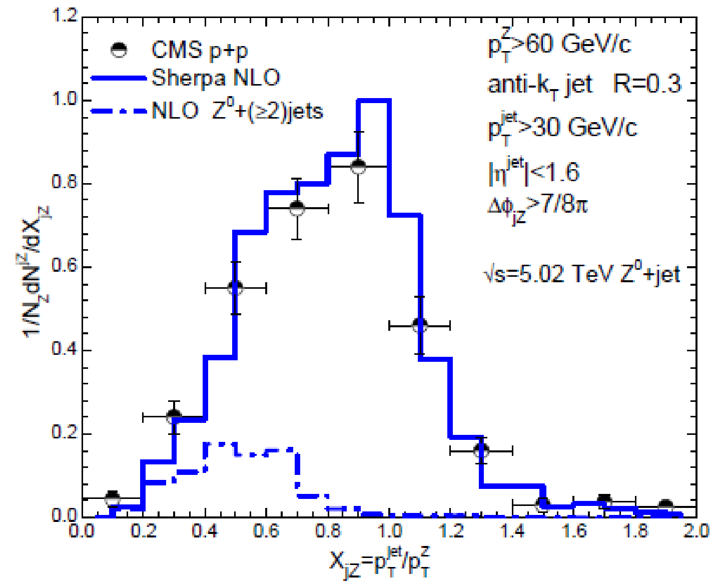
- B, $\tilde{V}$ and R is born, virtual and real terms respectively.
- D ($I^S = \int d\Phi_1 D^{(S)}$) is the (Integrated) subtraction term.
- $\widetilde{PS}$: the parton shower branch.

Sherpa: Gauge boson(γ, Z, W)+jets, b(c) jets, tops, Higgs...

Z+jets in pp collisions with Sherpa

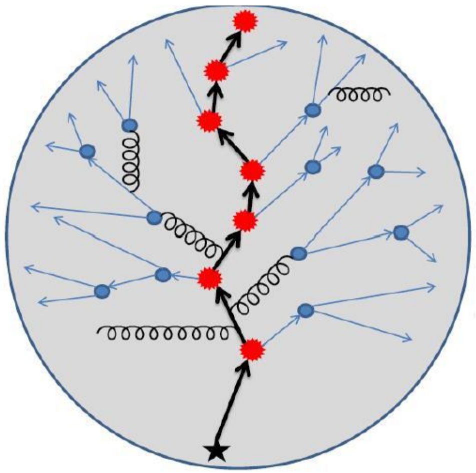
- Z+jet correlations in p+p collisions.
  Loop ME: OpenLoops. F. Cascioli, P. Maierhofer and S. Pozzorini, Phys. Rev. Lett. 108, 111601
  PDF: CETQ14nlo.





- NLO matched PS calculations show excellent agreement with experimental data in p+p collisions.
- Z+1jet dominate $\Delta\phi_{jZ} \approx \pi$, Z+multi-jets dominate $\Delta\phi_{jZ} < 2$ region.

Linear Boltzmann Transport (LBT) model



Linear Boltzmann jet Transport

- Elastic collision + Induced gluon radiation.
- Follow the propagation of recoiled parton.
- Back reaction of the Boltzmann transport.

H. Li, F. L, G. l. Ma, X. N. W and Y. Z, PhysRevLett.106.012301; X. N. Wang and Y. Zhu, PhysRevLett.111.062301; Y. He, T. Luo, X. N. Wang and Y. Zhu, PhysRevC.91.054908.

$$p_1 \cdot \partial f_a(p_1) = -\int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times \frac{1}{2} \sum_{b(c,d)} [f_a(p_1)f_b(p_2) - f_c(p_3)f_d(p_4)] |M_{ab\to cd}|^2 \times S_2(s,t,u)(2\pi)^4 \delta^4(p_1+p_2-p_3-p_4)$$

Elastic Scattering--Complete set of 2-2 scattering processes.

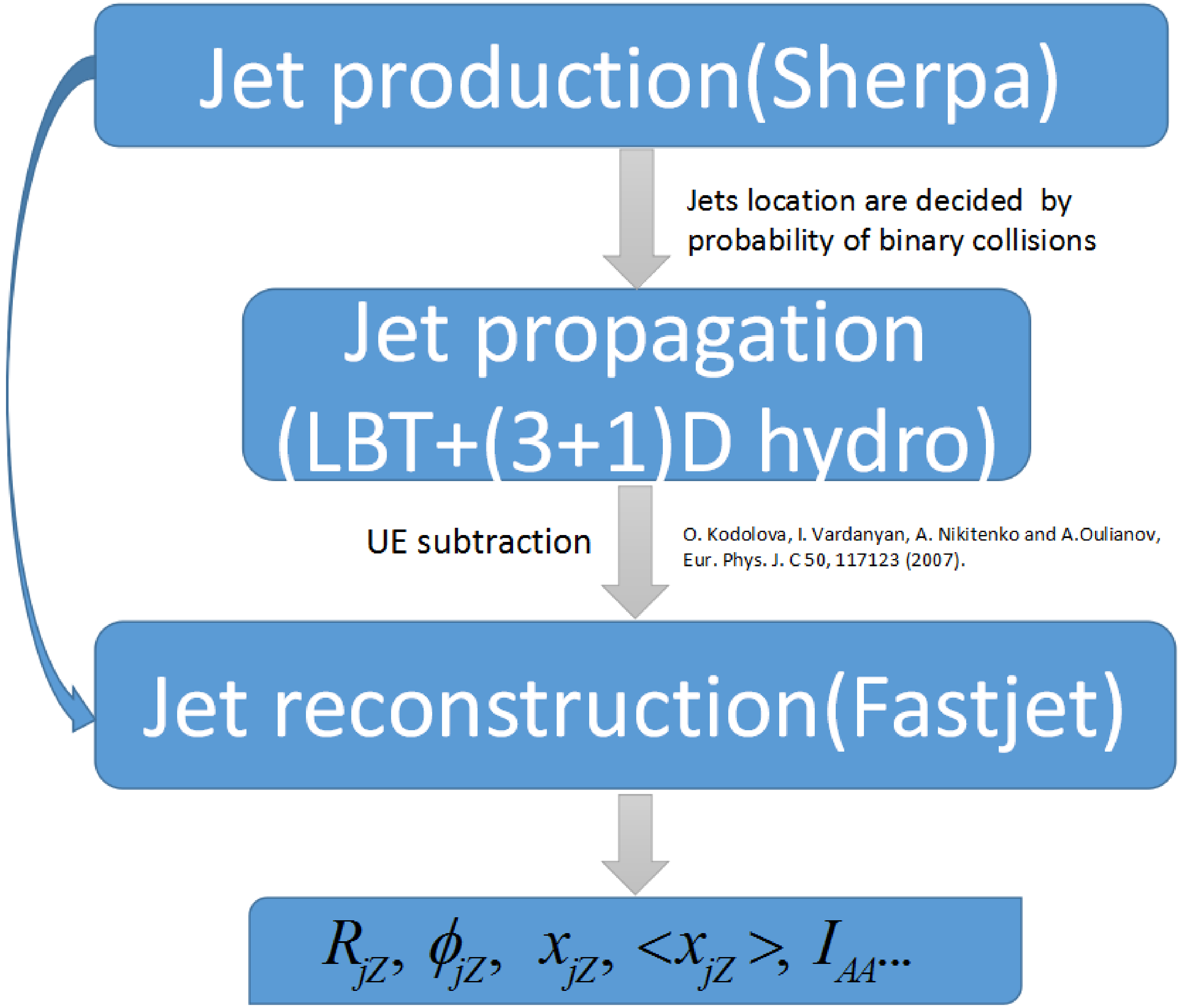
Radiation--Higher Twist: Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004).

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x) k_\perp^4}{\pi (k_\perp^2 + x^2 M^2)^4} \hat{q} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

LBT: γ-jet, single inclusive jets, γ-hadron, light/heavy flavor hadron .

T. Luo, S. Cao, Y. He and X. N. Wang, arXiv:1803.06785;
W. Chen, S. Cao, T. Luo, L. G. Pang and X. N. Wang, Phys. Lett. B 777, 86 (2018);
S. Cao, T. Luo, G. Y. Qin and X. N. Wang, Phys. Rev. C 94, no. 1, 014909 (2016).

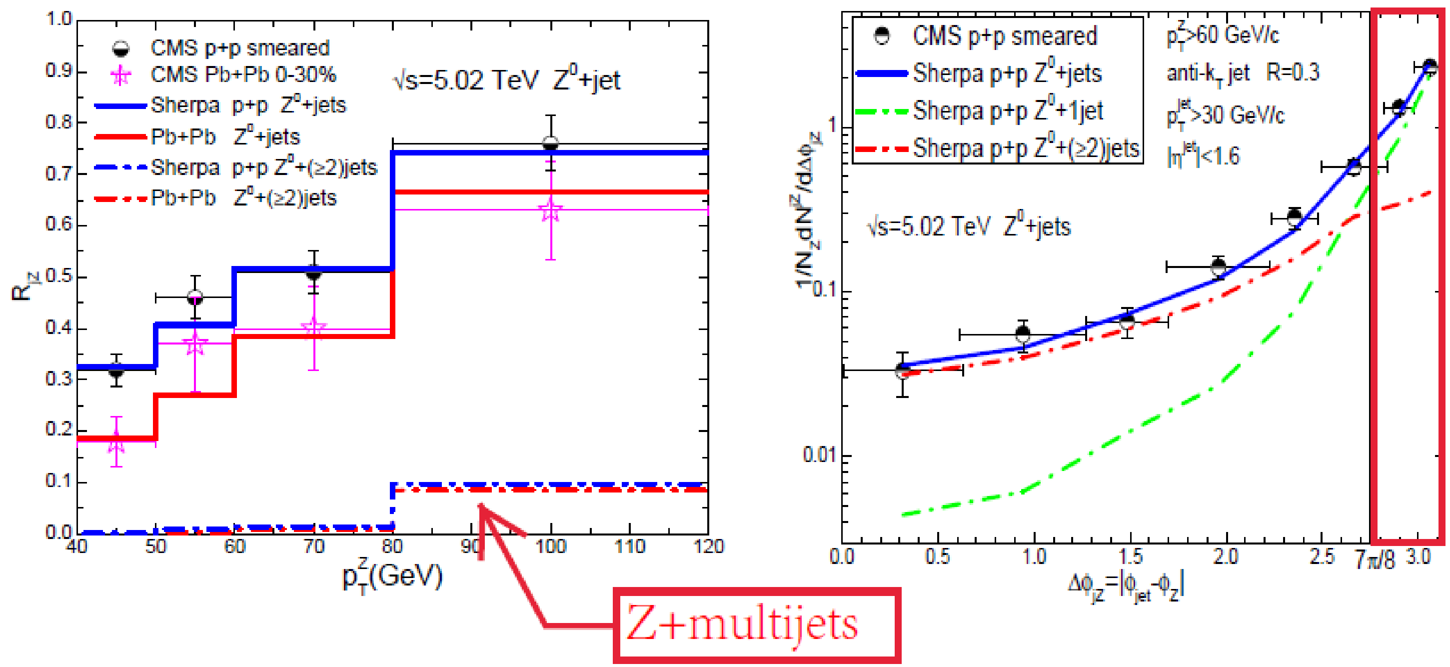
Framework



Jet production(Sherpa)
Jets location are decided by probability of binary collisions
Jet propagation (LBT+(3+1)D hydro)
UE subtraction
O. Kodolova, I. Vardanyan, A. Nikitenko and A.Oulianov, Eur. Phys. J. C 50, 117123 (2007).
Jet reconstruction(Fastjet)
R_{jZ}, ϕ_{jZ}, x_{jZ}, $<x_{jZ}>$, I_{AA}...

Z+jet ratio and multi-jets contributions

- Fix the parameter α_s via the comparison with the $R_{jz} = N_{jz} / N_z$.



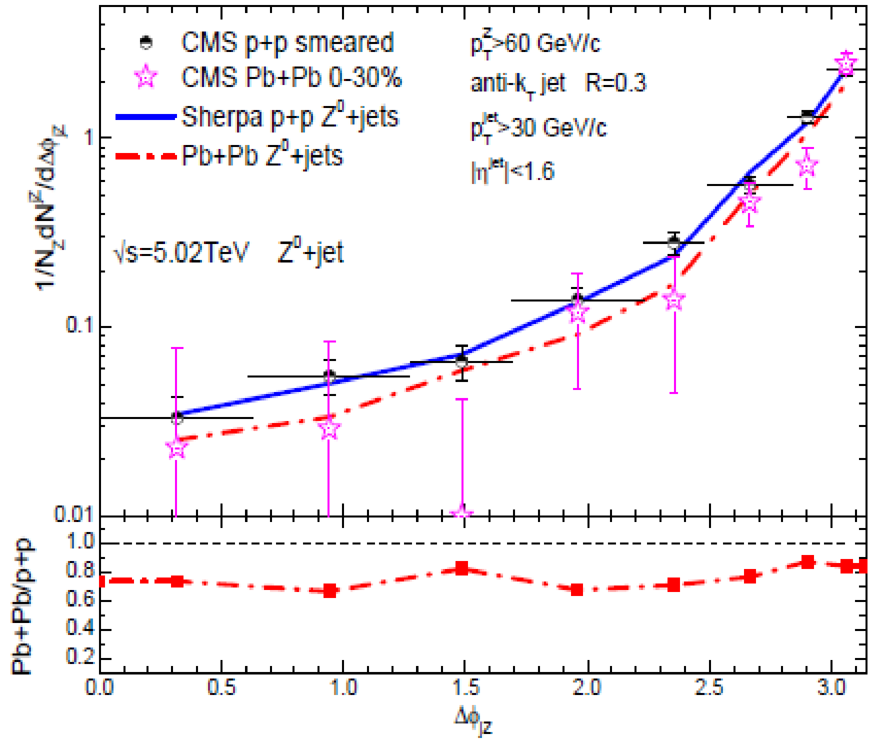
R_{jz} is overall suppressed.

- Large fraction of jets lose energy and fall below 30 GeV threshold.
- α_s= 0.20 is fixed to best describe experimental data in Pb+Pb collisions.

Multi-jets have small contributions to R_{jz}, p_T^Z> 80 GeV : 15%.

Z+jet azimuthal angle correlations

- Suppression of azimuthal angle correlations $\Delta\phi_{jz} = |\phi_j - \phi_z|$



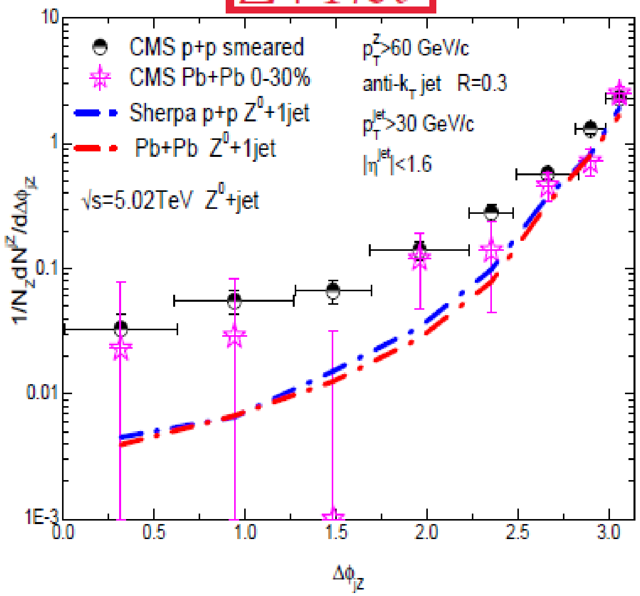
$\Delta\phi_{jz}$ is moderately suppressed in Pb+Pb collisions, almost a constant.

- Z-jet angle correlations is modified by jet-medium interactions?
- Reduction of jet yields above 30 GeV threshold?

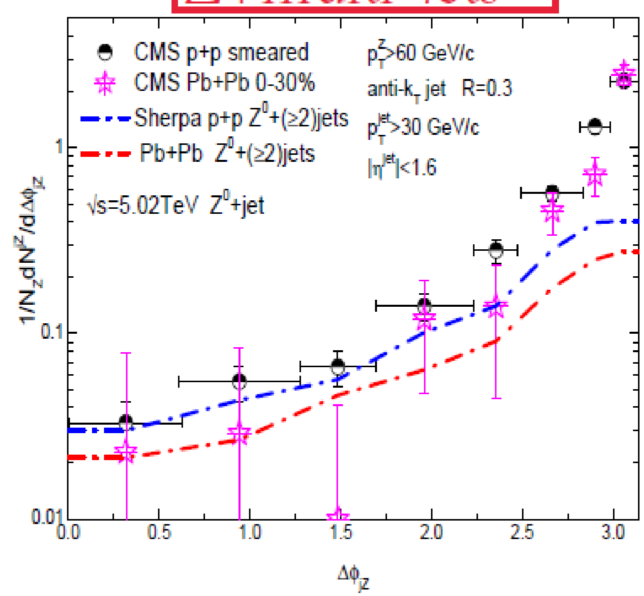
The modification of angle correlations due to multi-jets

- Z+1jet and Z+multi-jets contributions to $\Delta\phi_{jz} = |\phi_{jet} - \phi_z|$.

Z+1jet



Z+multi-jets

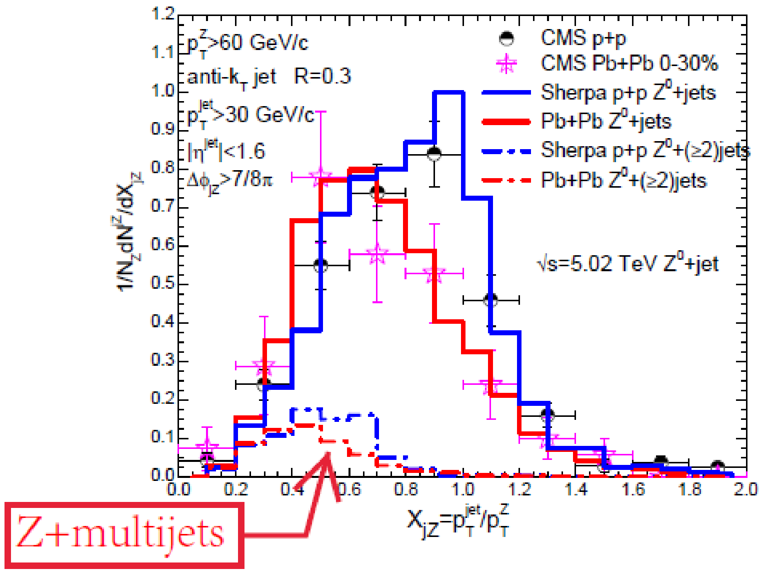


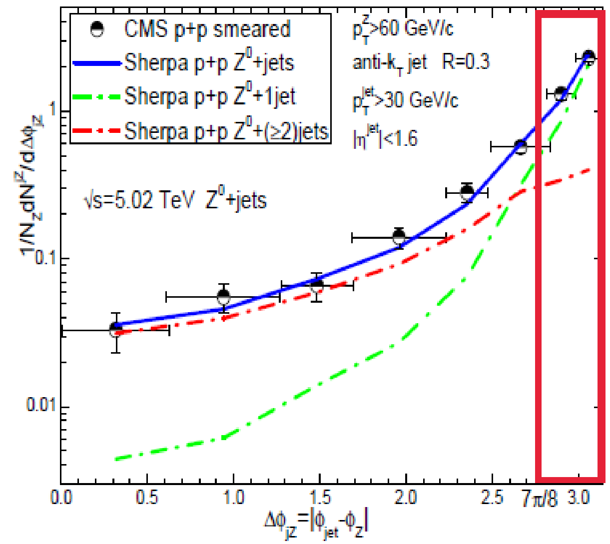
$\Delta\phi_{jz}$ is moderately suppressed in Pb+Pb collisions, almost a constant.
- The suppression of Z+1 jet angle correlations is mild.
- Z+multi-jets angle correlations is considerably suppressed.

Suppression of multi-jets lead to the modification of Z+jet angle correlations.

Z+jet asymmetry and multi-jets contributions

- Shift of momentum imbalance $x_{jz} = p_T^{jet}/p_T^{Z}$





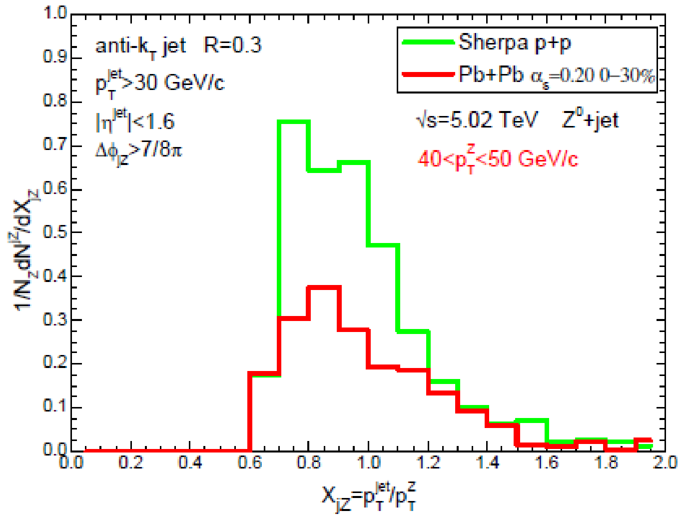
x_{jz} is shifted to smaller value.

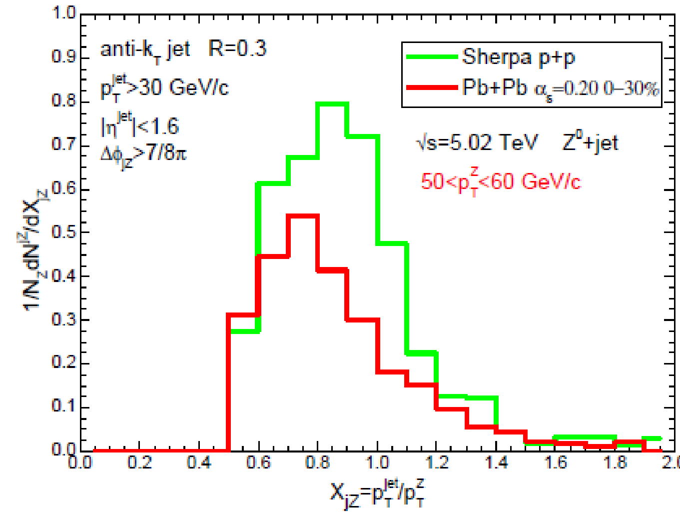
- Transverse momentum of Z boson is unattenuated.
- Jet transverse momentum is modified by medium.

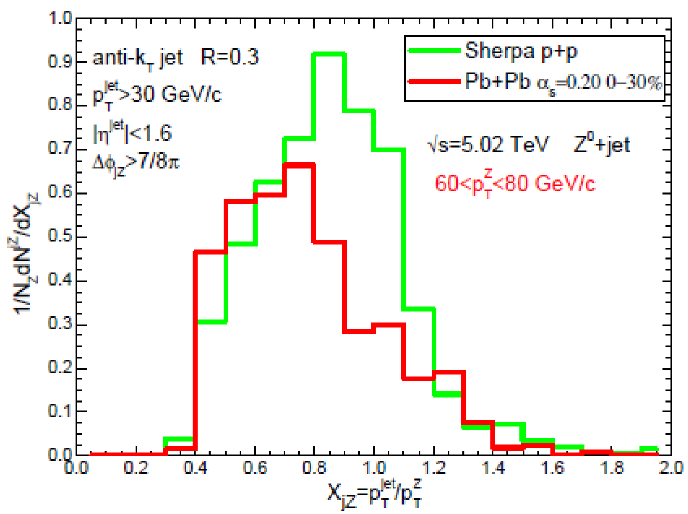
Multi-jets have almost 50% contributions to x_{jz} < 0.5 region.

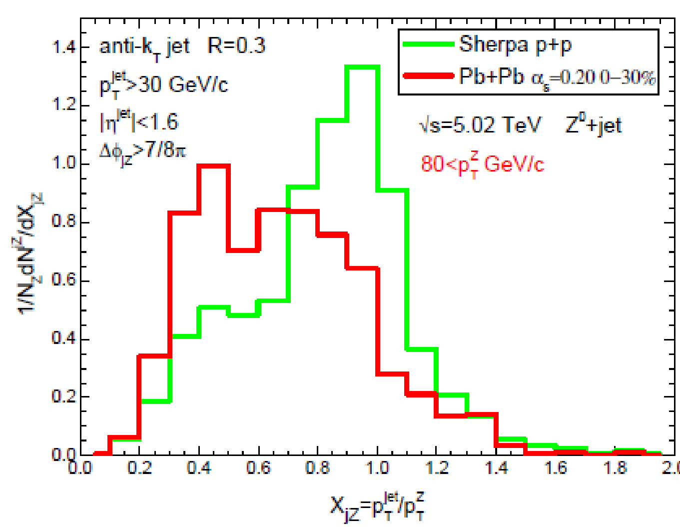
Z+jet asymmetry

- Shift of momentum asymmetry $x_{jZ} = p_T^{jet}/p_T^{Z}$ in different p_T^Z bins.



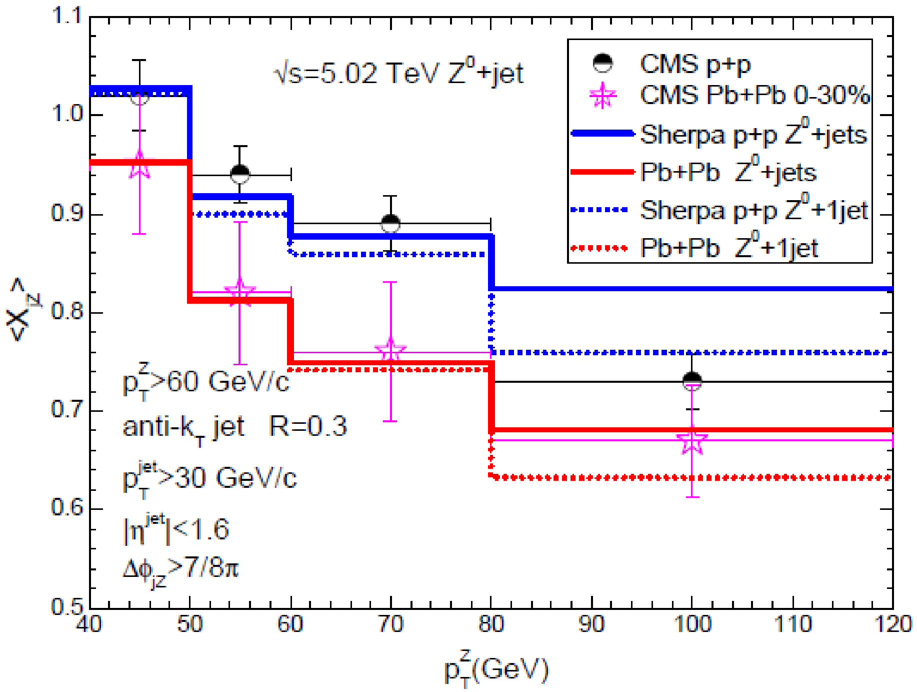






Mean value of momentum imbalance

- Reduction of mean value of momentum imbalance.



$\langle x_{jz}\rangle$ is smaller in Pb+Pb.

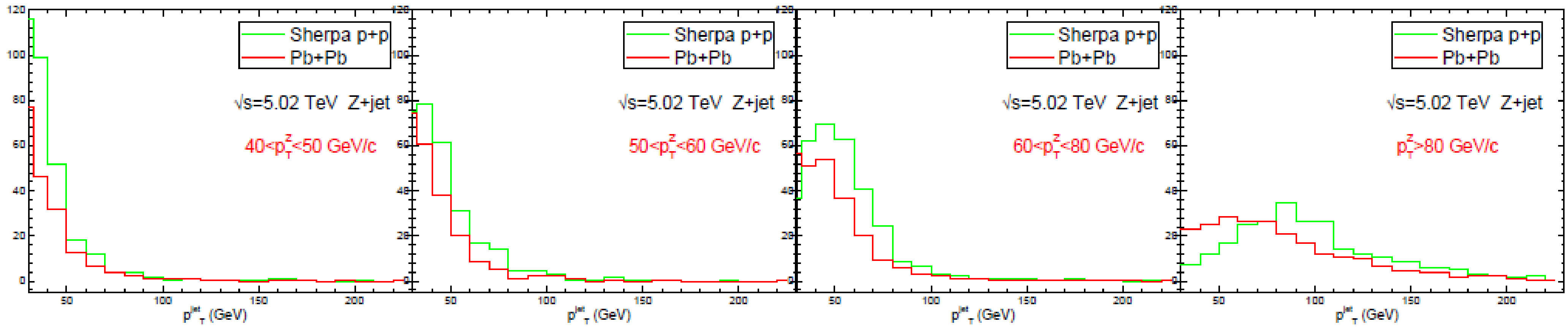
p_T^Z >60 GeV: $\langle x_{jz}\rangle$ is lowered by 15%.

$$\Delta\langle x_j z\rangle = \langle x_{jz}\rangle_{pp} - \langle x_{jz}\rangle_{PbPb}$$

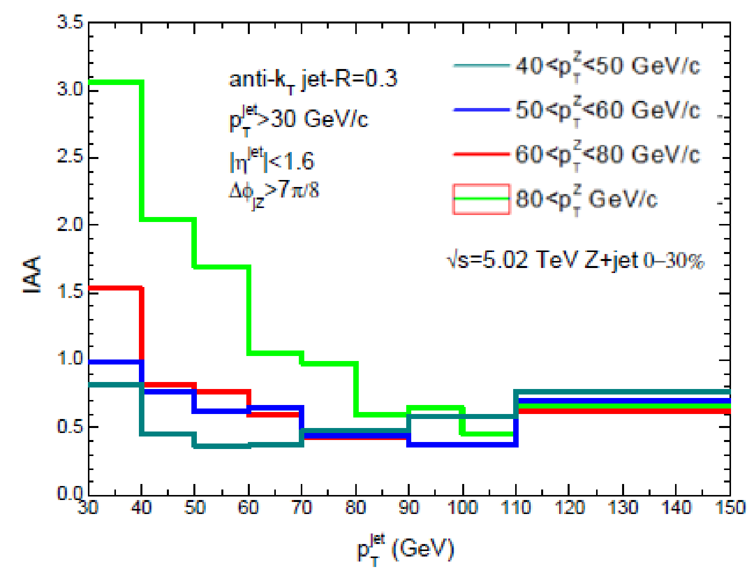
p_T^Z (GeV)	40-50	50-60	60-80	>80
CMS	0.07 ±0.106	0.12±0.148	0.13±0.158	0.06±0.088
$\Delta\langle x_j z\rangle$	0.075	0.106	0.129	0.143

Tagged jet p_T^{jet} spectrums

- Shift of p_T^{jet} spectrum in different p_T^Z bins.



$$I_{AA} = \frac{dN^{Pb+Pb}}{dp_T^{\text{jet}}} \Big/ \frac{dN^{p+p}}{dp_T^{\text{jet}}}$$



p_T^{jet} spectrums are shifted to lower value.

The largest suppression is near $p_T^{jet} \approx p_T^Z$.

Summary

Z+jet correlation in Pb+Pb at the LHC is studied by combining NLO+PS in Sherpa for initial Z+jet production and LBT for jet propagation in the expanding QGP from 3+1D hydrodynamics.

- R_{jz} is smaller in Pb+Pb.

  Large fraction of jets lose energy and fall below 30 GeV threshold.
- $\Delta\phi_{jz}$ is moderately suppressed in Pb+Pb collisions.

  Suppression of multijets lead to the modification of Z+jet angle correlations.
- x_{jz} is shifted to smaller value.
- $\langle x_{jz} \rangle$ is smaller in Pb+Pb.

  NLO+PS LBT describe precisely Z+jet asymmetry