Jet quenching in Z+jet in heavy-ion collisions

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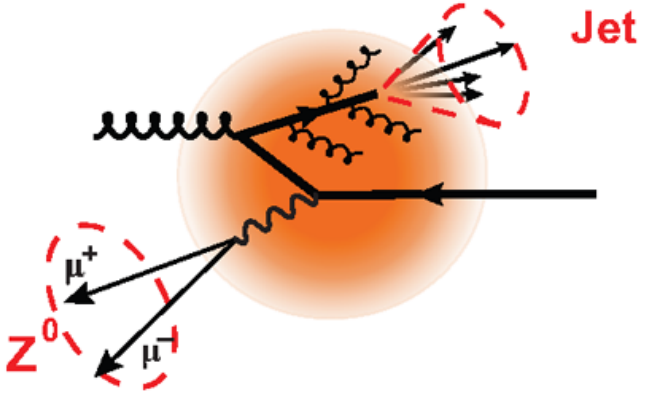
Shan-Liang. Zhang, T. Luo, X. N. Wang and B. W. Zhang, arXiv:1804.11041 [nucl-th].

Motivation

- 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.



  – Z boson will not participate in strong interactions directly.

  – Mean-free-path of Z boson is longer than the size of QGP.

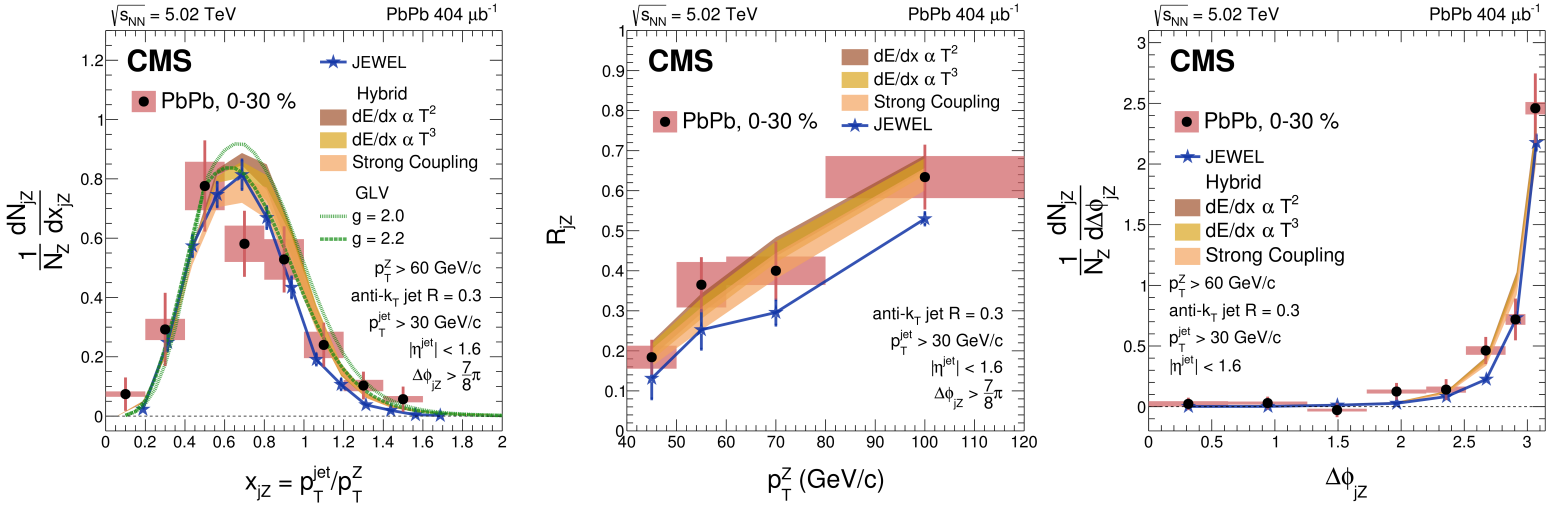
  – No fragmentation contributions due to large mass $(M_Z = 91.18\ GeV)$.

  – Large fraction of quark jets ($> 70\%$).

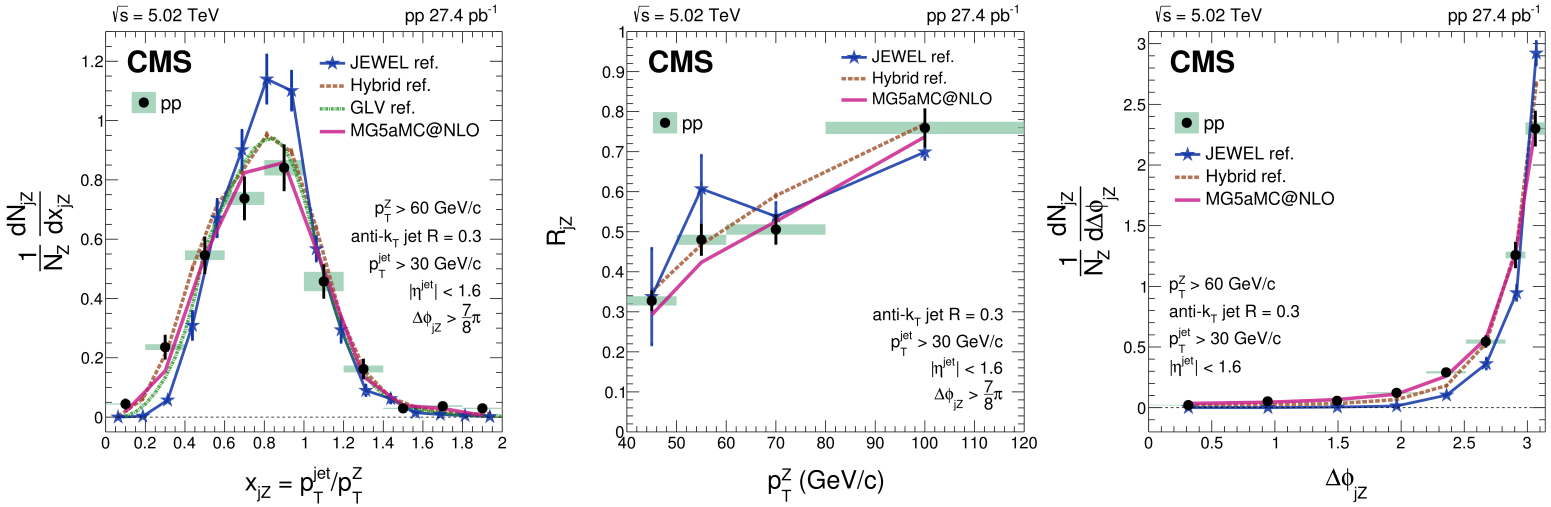
- Important background to new physics, e.g. tops and Higgs.

Current status

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



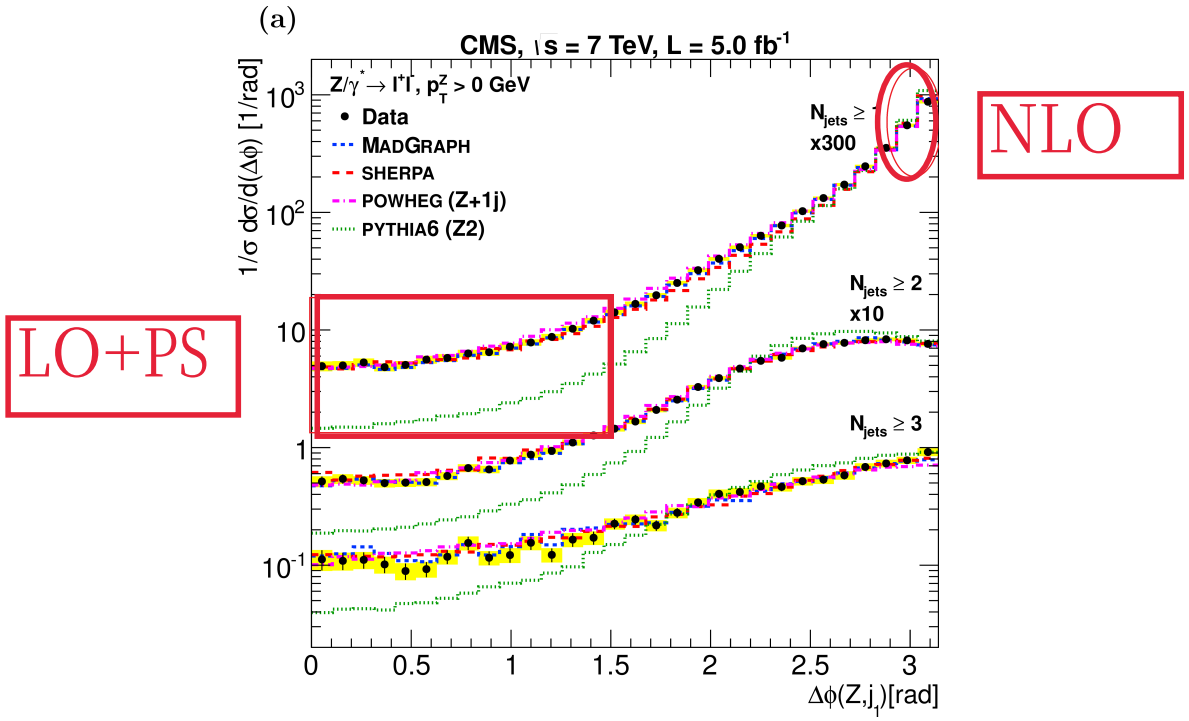
- Z+jet correlations in p+p collisions. CMS-HIN-15-013



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 $\Delta\phi_{jZ} \sim \pi$. NLO ✗

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

- 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:

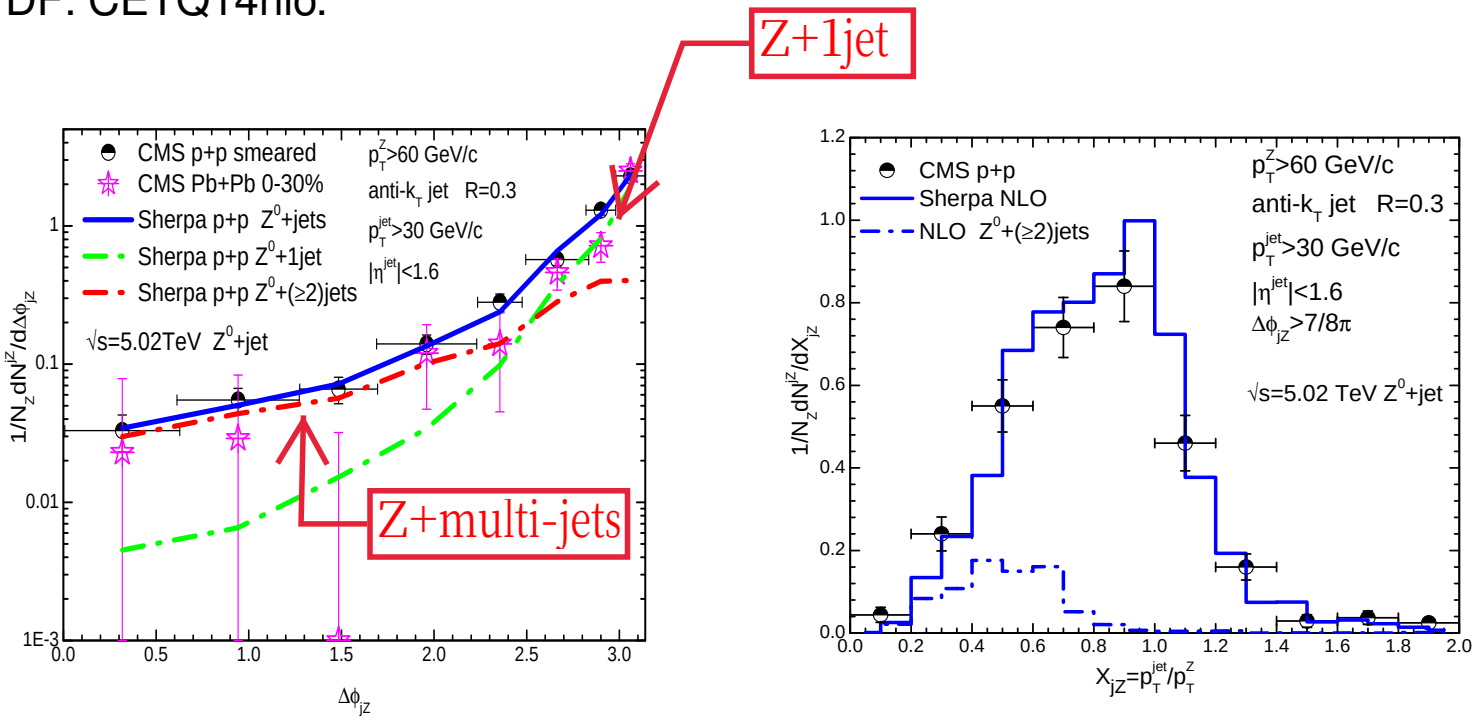
$$\langle O\rangle^{(NloPs)} = \int d\Phi_B \left[B + \widetilde{V} + I^S\right](\Phi_B)\widetilde{PS}_B(\mu_Q^2, O) + \int d\Phi_R \left[R - D^S\right](\Phi_R)\widetilde{PS}_R(t_R, O)$$

- B, $\widetilde{V}$ 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...

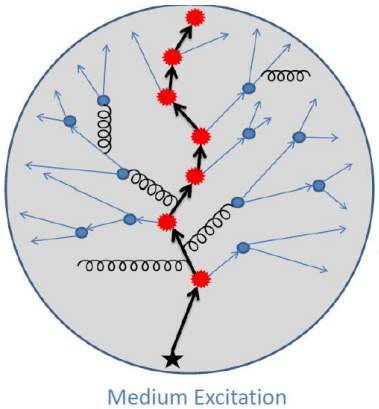
Z+jets in pp collisions with Sherpa

- 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 at $\Delta\phi_{jZ} \simeq \pi$, while Z+multijets dominate at $\Delta\phi_{jZ} < 2.2$ 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. I. 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.

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

Elastic Scattering−Complete set of 2-2 scattering precesses.

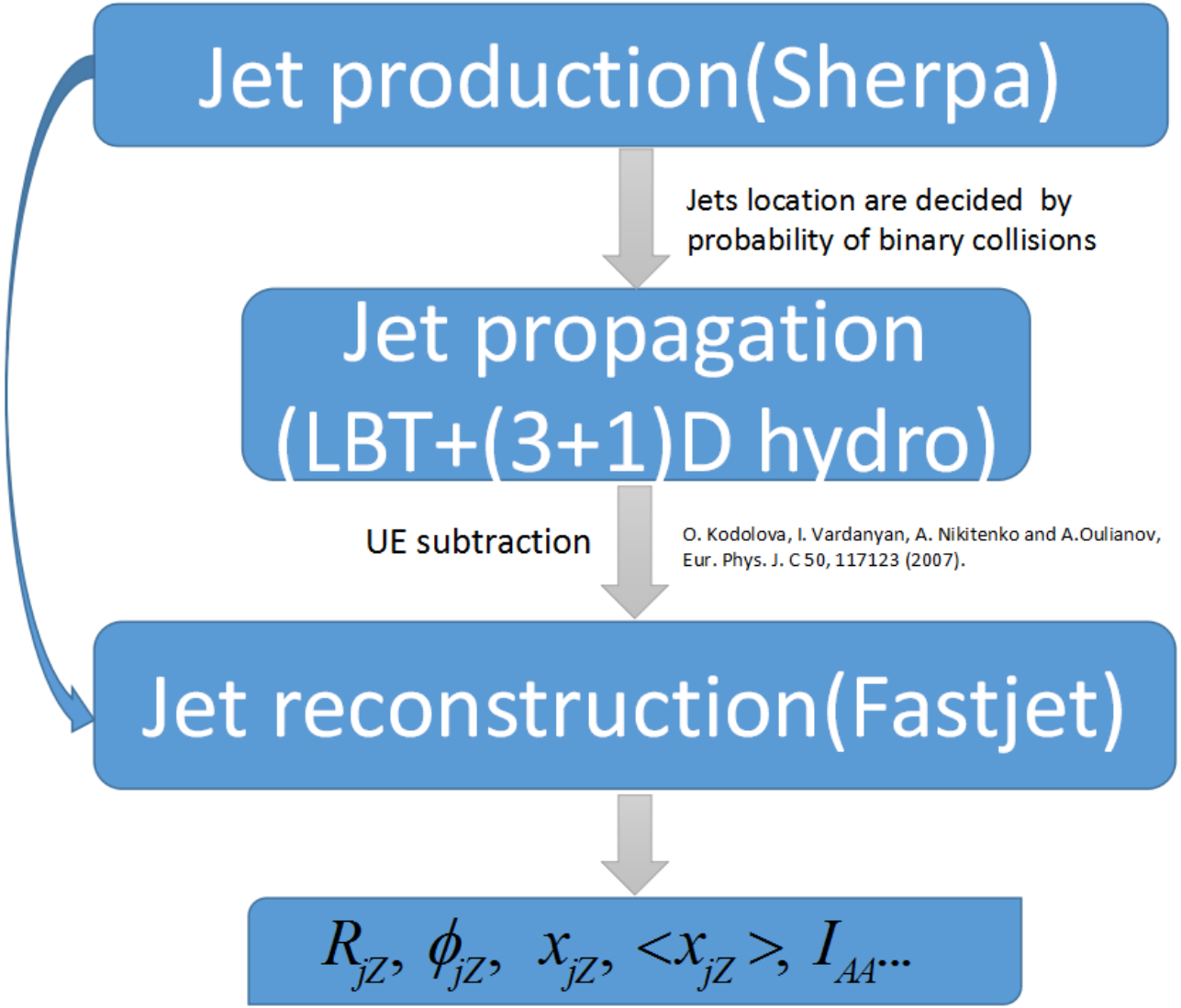
Radiation−Higher Twist: Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004).

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

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).

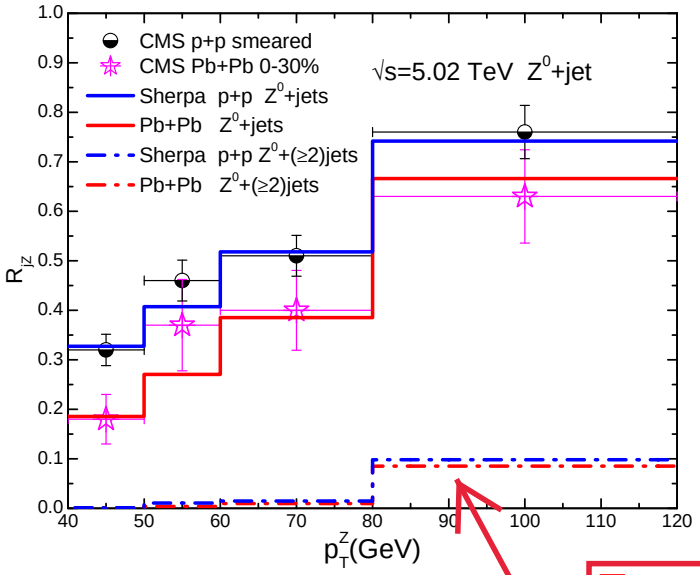
Framework

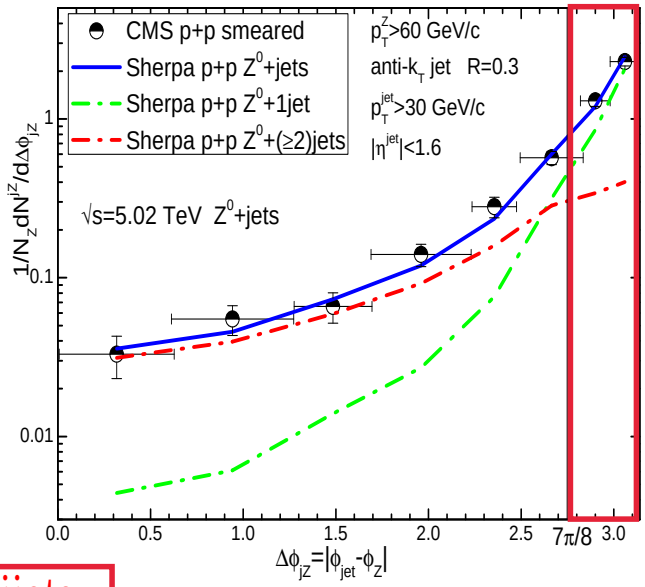

Jet production(Sherpa)
Jets location are decided by probability of binary collisions
Jet propagation (LBT+(3+1)D hydro)
UE subtraction
O. Kodolova, I. Vardanyan, A. Nikitenko and A.Oulianov, Eur. Phys. J. C 50, 117123 (2007).
Jet reconstruction(Fastjet)
R_{jZ}, ϕ_{jZ}, x_{jZ}, $<x_{jZ}>$, I_{AA}...

Z+jet ratio and multi-jets contributions

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

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





Z+multijets

R_{jZ} is overall suppressed.

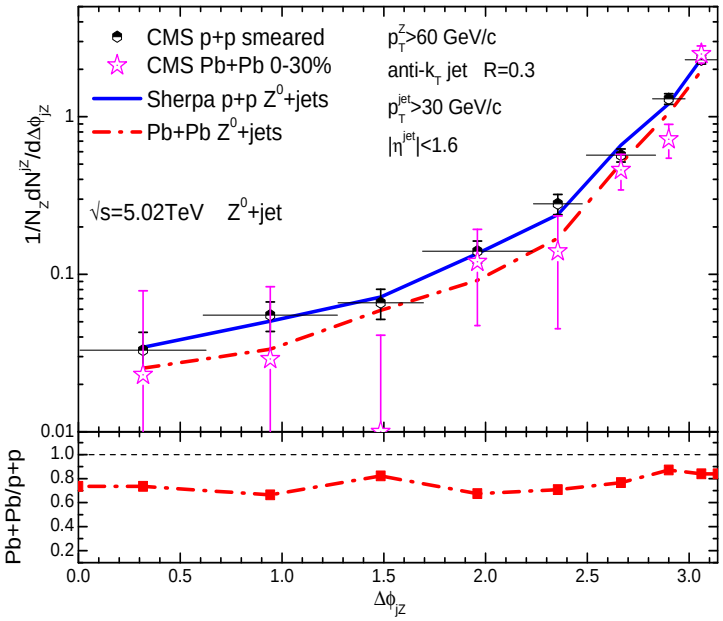
- Large fraction of jets lose energy and fall below 30 GeV threshold.
- $\alpha_s = 0.20$ is fixed to best describe experimental data in Pb+Pb collisions.

Multijets have small contributions to R_{jz}, $p_T^Z > 80$ GeV : 15%.

Z+jet azimuthal angle correlations

- Suppression of azimuthal angle correlations $\Delta\phi_{jZ} = |\phi_{jet} - \phi_Z|$.

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



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

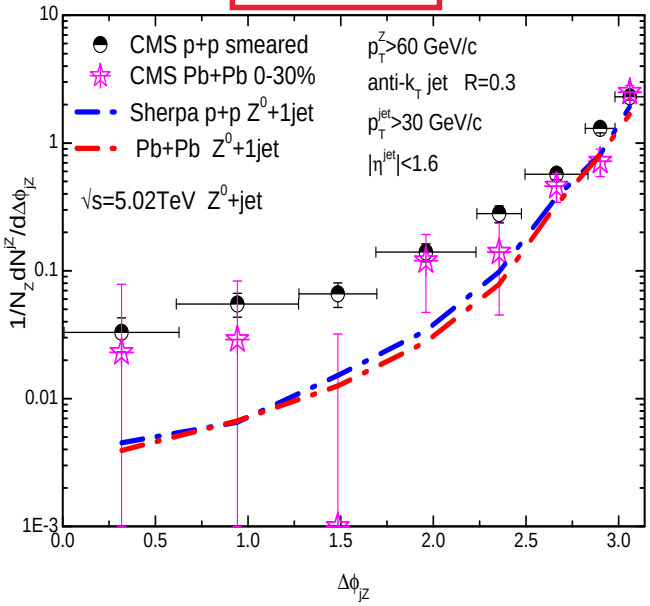
- Z-jet angle correlations is modified by jet-medium interactions?
- Reduction of jet yields above 30 GeV threshold?

The modification of angle correlations due to multi-jets suppression

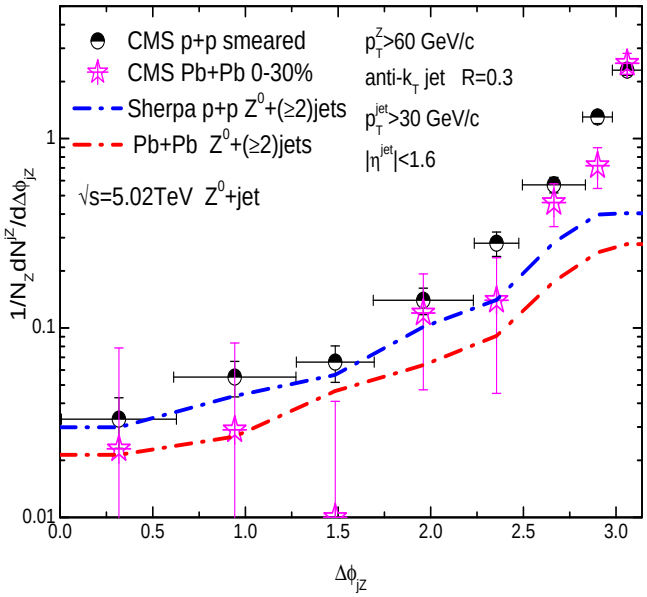
- Z+1jet and Z+multijets contributions to $\Delta\phi_{jZ} = |\phi_{jet} - \phi_Z|$.

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

Z+1jet



Z+multi-jets



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

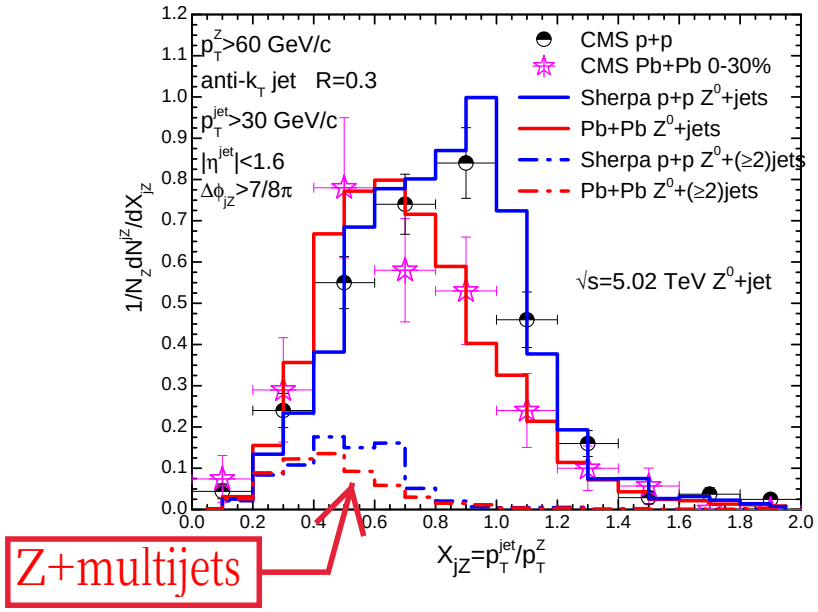
- The suppression of Z+1 jet angle correlations is mild.
- Z+Multi-jets angle correlations is considerably suppressed.

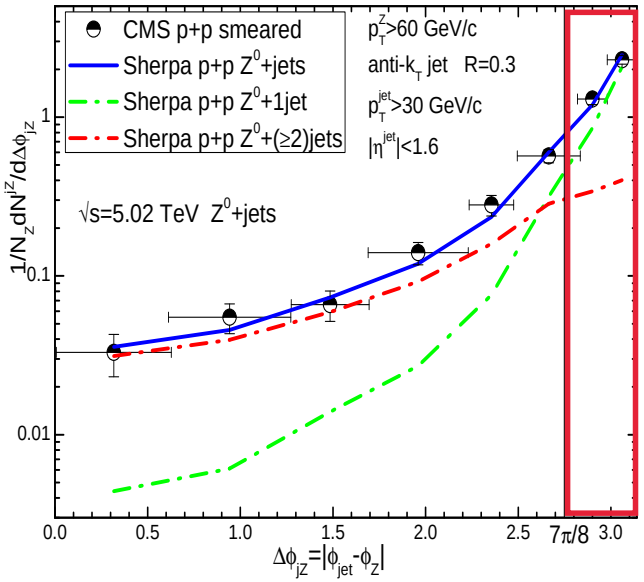
Suppression of multi-jets lead to the modification of Z+jet azimuthal angle correlations.

Z+jet asymmetry and multi-jets contributions

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

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





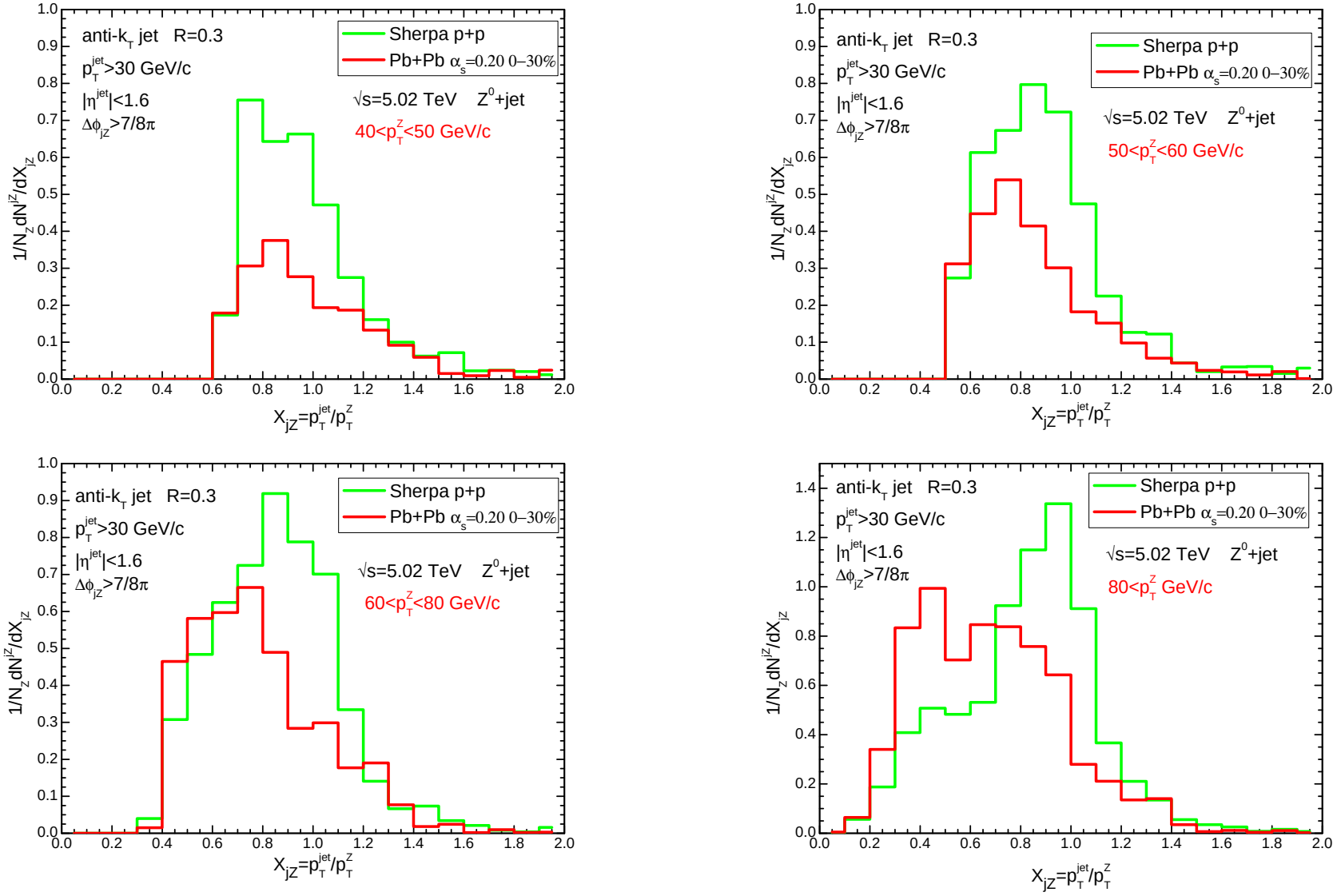
x_{jZ} is shifted to smaller value.

- 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

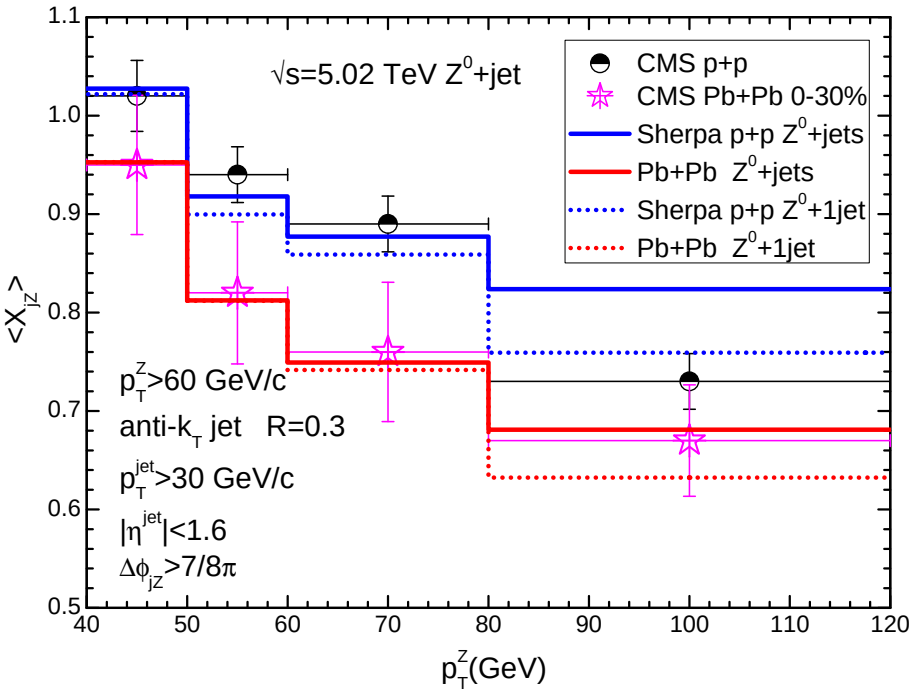
- Shift of momentum asymmetry $x_{jZ} = p_T^{jet}/p_T^Z$ in different p_T^Z bins.



Mean value of momentum imbalance

- Reduction of mean value of momentum imbalance.

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



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

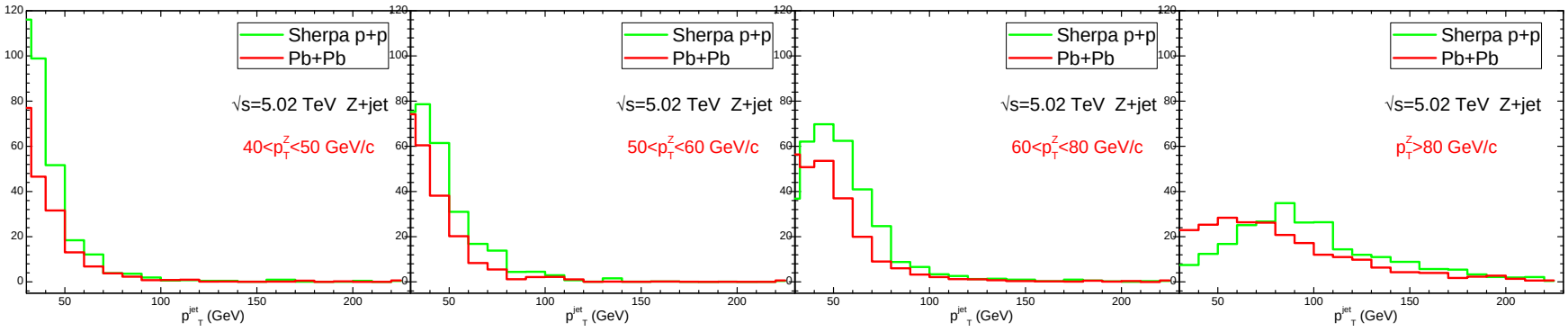
p_T^Z >60 GeV: $\langle x_{jZ} \rangle$ is lowered by 15%.

$$\Delta\langle x_{jZ} \rangle = \langle x_{jZ} \rangle_{pp} - \langle x_{jZ} \rangle_{PbPb}$$

p_T^Z	40-50	50-60	60-80	80-
CMS	0.07 ± 0.106	0.12±0.148	0.13±0.158	0.06±0.088
$\Delta\langle x_{jZ} \rangle$	0.074873	0.105597	0.127888	0.142805

Tagged jet $p_T^{\rm jet}$ spectrums

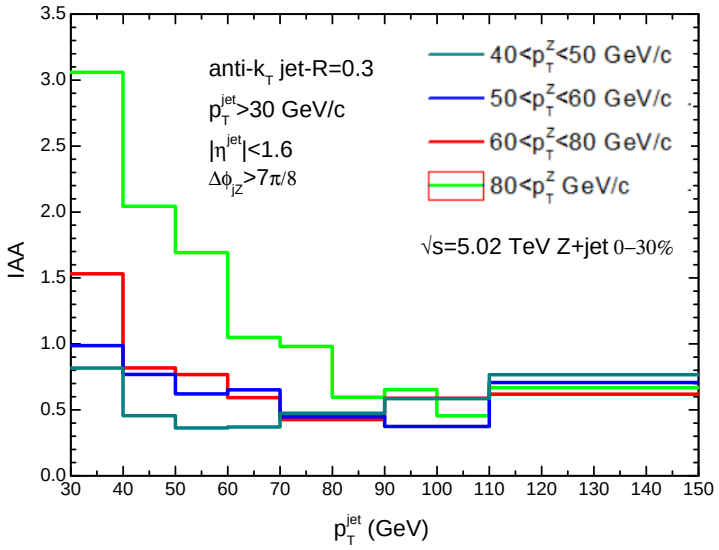
- Shift of $p_T^{\rm jet}$ spectrum in different p_T^Z bins.



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

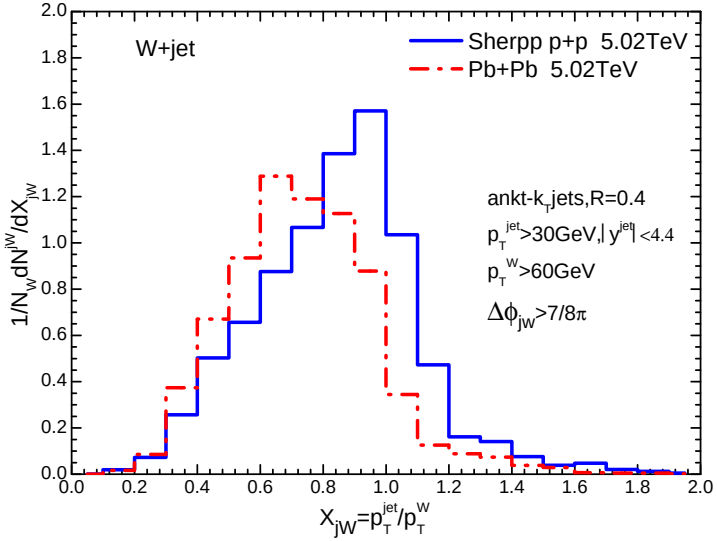
$p_T^{\rm jet}$ spectrums are shifted to lower value.

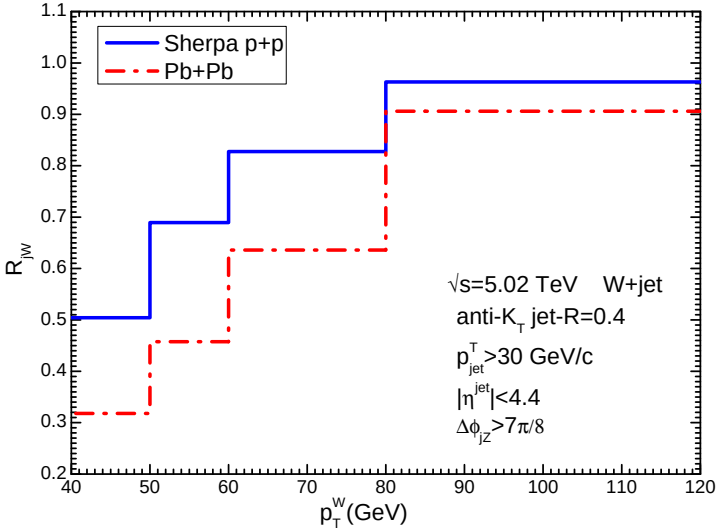
The largest suppression is near $p_T^{jet} \simeq p_T^Z$.

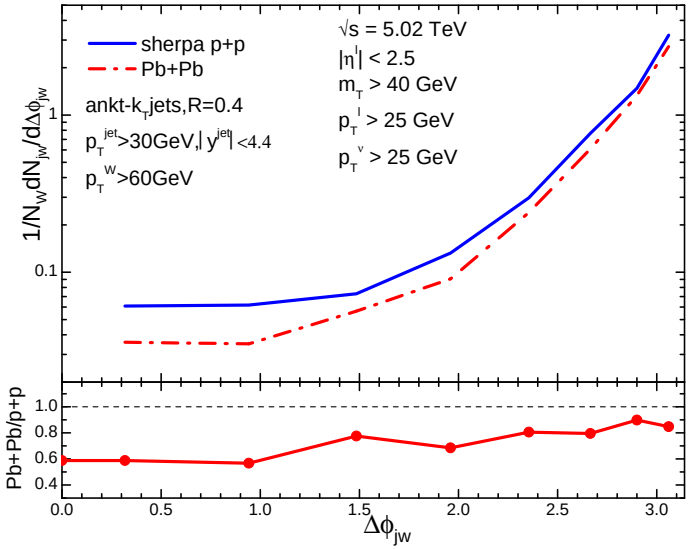


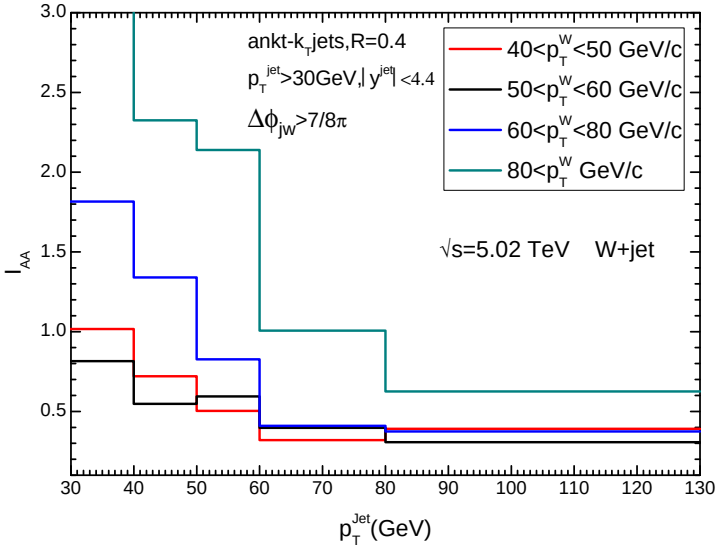
W+jet correlations

W+jet have similarly behaviors as Z+jet.









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 shift their final transverse momentum below p_T^{jet} threshold.
- $\Delta\phi_{\mathrm{jZ}}$ is moderately suppressed in Pb+Pb collisions.
  Suppression of multijets lead to the modification of Z+jet azimuthal angle correlations.
- x_{jZ} is shifted to smaller value.
- $\langle x_{\mathrm{jZ}} \rangle$ is smaller in Pb+Pb.
  NLO+PS LBT describe precisely Z+jet asymmetry.
- W+jet correlations are calculated in our model.

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

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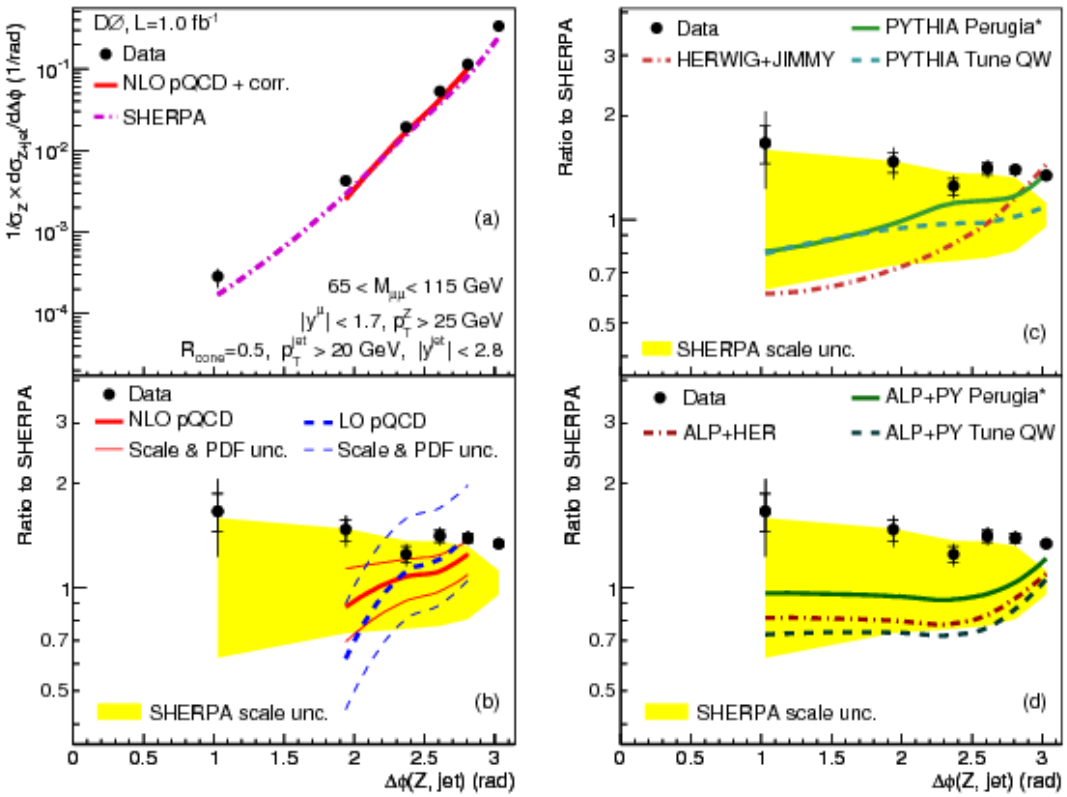
Azimuthal angle correlations of Z+jets.



– NLO calculations is divergency at $\Delta\phi_{jZ} \sim \pi$ ×.
– LO+PS calculations underestimate at $\Delta\phi_{jZ} < 2.5$ ×.

Sherpa- MC@NLO event generator

ME(Hard emissions)-Subtraction method hep-ph/0001040,0105291

$$\langle O\rangle^{(NLO)} = \int d\Phi_B \left[B + \widetilde{V} + I^S\right](\Phi_B)O(\Phi_B) + \int d\Phi_R \left[R(\Phi_R) - D^S(\Phi_B * \Phi_1)\right] O(\Phi_R) \quad (1)$$

- PDFS and FFS are emitted.
- Φ_B is Born(Virtual) phase-space, Φ_R is real phase-space
- B,$\widetilde{V}$ and R is born, virtual and real matrix element respectively
- D ($I^S = \int d\Phi_1 D^{(S)}$) is the (Integrated)subtraction terms which has the same divergency as the real terms.
- Both term are finite.

PS(Soft emissions)-Sudakov form factor
arXiv:1111.1220,0709.1027,0709.2881

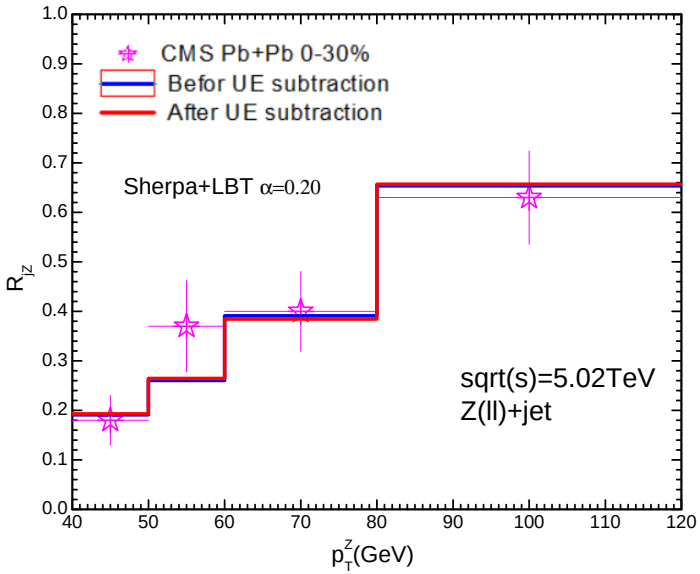
$$\mathbb{PS}_n(\mu_Q^2, O) = \Delta(t_c, \mu_Q^2)O(\phi_n) + \int_{t_c}^{\mu_Q^2} \Delta(t, \mu_Q^2)\kappa(\phi_1)\mathbb{PS}_{n+1}(t, O)dtd\phi_1 \quad (2)$$

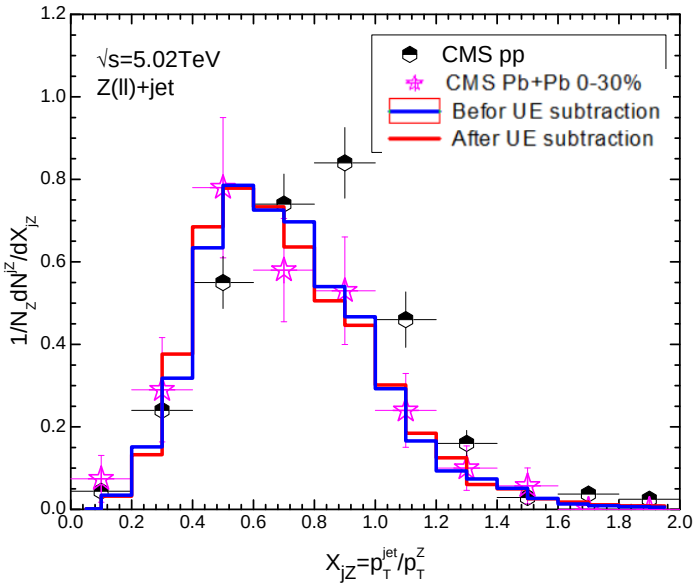
$$\Delta(t_c, \mu_Q^2) = \exp\left\{-\int_{t_c}^{\mu_Q^2} dt \int d\phi\, \kappa(\phi_1(t,\phi))\right\} \quad (3)$$

$\kappa_{ab}(z,t) \to \frac{\alpha_s(z,t)}{2\pi} P_{ab}(z)$ are evolution kernels,$P_{ab}(z)$ are splitting functions.

Underlying Event Subtraction

Following the procedure in CMS experiment.





- UE subtraction has negligible effect on R_{jz}
- UE subtraction has a little effect on x_{jz}.