A hybrid transport model for heavy quarks

Weiyao Ke*, Yingru Xu, Steffen A. Bass, *Duke University*
*wk42@phy.duke.edu

Introduction

- A hybrid transport model of heavy quark evolution in a QGP medium:
  - Scattering with medium partons using LO pQCD.
  - Non-perturbative interactions missing from the LO pQCD picture are treated via a diffusion equation.
- Calibrate model and extract transport properties.
- Validate model and predict novel observables.

Leading order pQCD scattering

Linearized Boltzmann equation $df/dt = \mathcal{C}^{2\leftrightarrow 2}[f] + \mathcal{C}^{2\leftrightarrow 3}[f]$.

- Elastic: $Qq(g) \to Qq(g)$
  Radiation (Gunion-Bertsch): $Qq(g) \to Qq(g) + g$
  Absorption: $Qq(g) + g \to Qq(g)$
- Matrix-elements screened by m_D, m_g.
- Model Landau-Pomeranchuk-Migdal effect by modifying radiated/absorbed gluon phase space,

$$\int \frac{dk^3}{2k} \to \int \frac{dk^3}{2k} 2\left[1 - \cos\left(\frac{t-t_0}{\tau_f}\right)\right],$$

t_0: time of last radiation/absorption. τ_f: gluon formation time. Suppress inelastic channel for $\Delta t \ll \tau_f$.

*Parameters of the pQCD interactions:

- μ: medium scale parameter controls the minimum Q in the running coupling constant $\alpha_s(\max\{Q, \mu\pi T\})$.

Diffusion

Langevin equations govern non-perturbative and soft interactions between heavy quarks and the QGP medium,

$$\Delta p_i = -\eta_D p_i \Delta t + \sqrt{\kappa \Delta t}\xi_i(t), \langle \xi_i(t)\xi_j(t)\rangle = \delta_{ij}$$

- Empirical diffusion coefficients parametrization,

$$\frac{\kappa}{T^3} = \kappa_D\left(x_D + (1-x_D)\frac{\mathrm{GeV}^2}{ET}\right), \eta_D = \frac{\kappa}{2ET} - \frac{d\kappa}{dp^2}$$

*Parameters of the diffusion coefficients:

- κ_D: the magnitude of diffusion at $ET = 1$ GeV^2.
- x_D: E-independent fraction of κ at $ET = 1$ GeV^2.

Coupling to medium evolution

Medium evolution model was calibrated to $dN_{\rm ch}/d\eta$, v_n, $\langle p_T\rangle$, $\langle p_T\rangle$ fluctuation at the LHC.

Time [fm/c]	Medium	Heavy quark
$\tau = 0^+$	TRENTo	nPDF + FONLL
$\tau < \tau_{\rm HQ}$	Free streaming	Free streaming*
$\tau_{\rm HQ} < \tau < 1.2$	Free streaming	pQCD + diffusion
$T > 154$ MeV	2+1D v-hydro	pQCD + diffusion
$T < 154$ MeV	UrQMD	UrQMD

*Additional parameter:

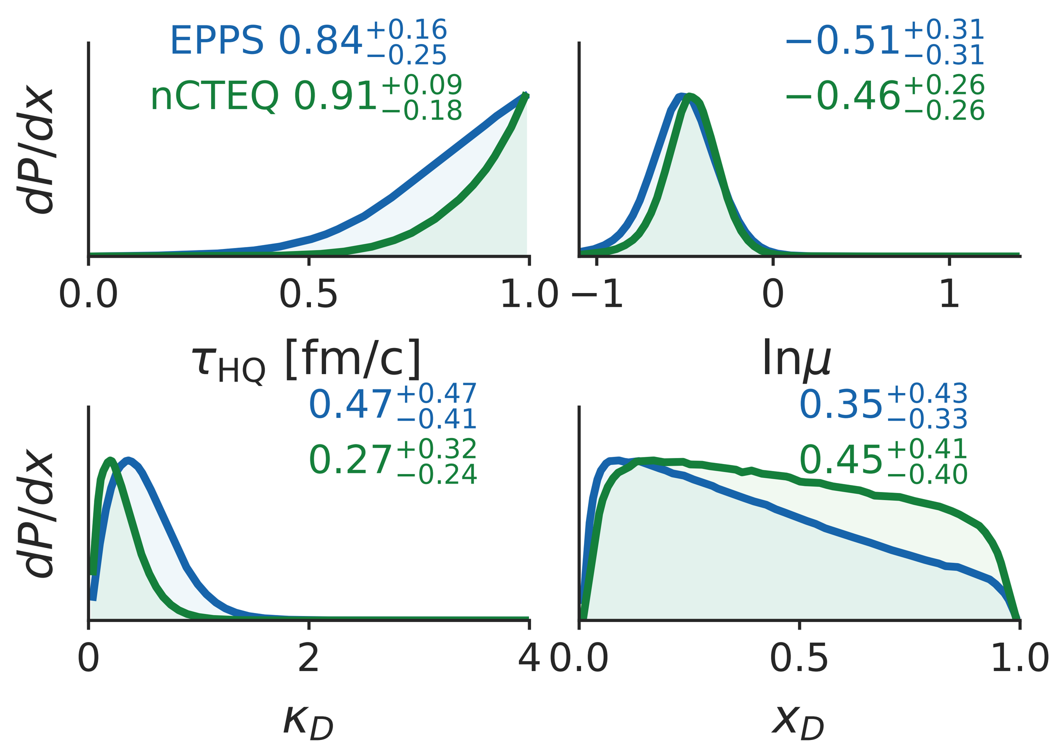
- $\tau_{\rm HQ}$: heavy quark energy loss starting time.

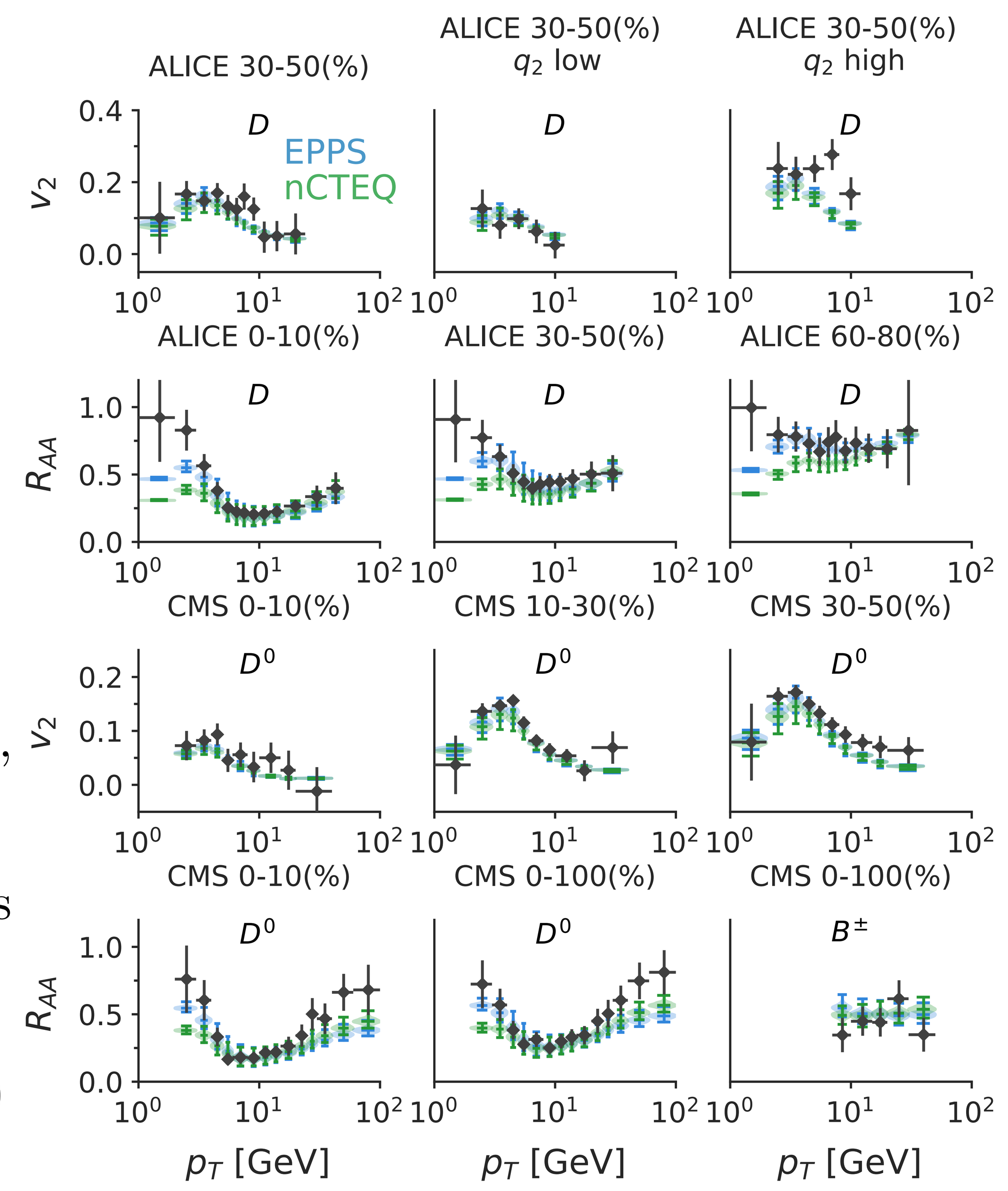
Summary

- New hybrid transport model for heavy quark evolution in a QGP medium. Heavy quarks undergo perturbative scattering and non-perturbative diffusion.
- The calibrated model describes the experimental data at the RHIC and the LHC.
- The extracted transport coefficients overlap with previous work and static lattice calculations.

This work was supported by Grant #DE-FG02-05ER41367 (DOE) and Grant #OAC-1550225 (NSF).

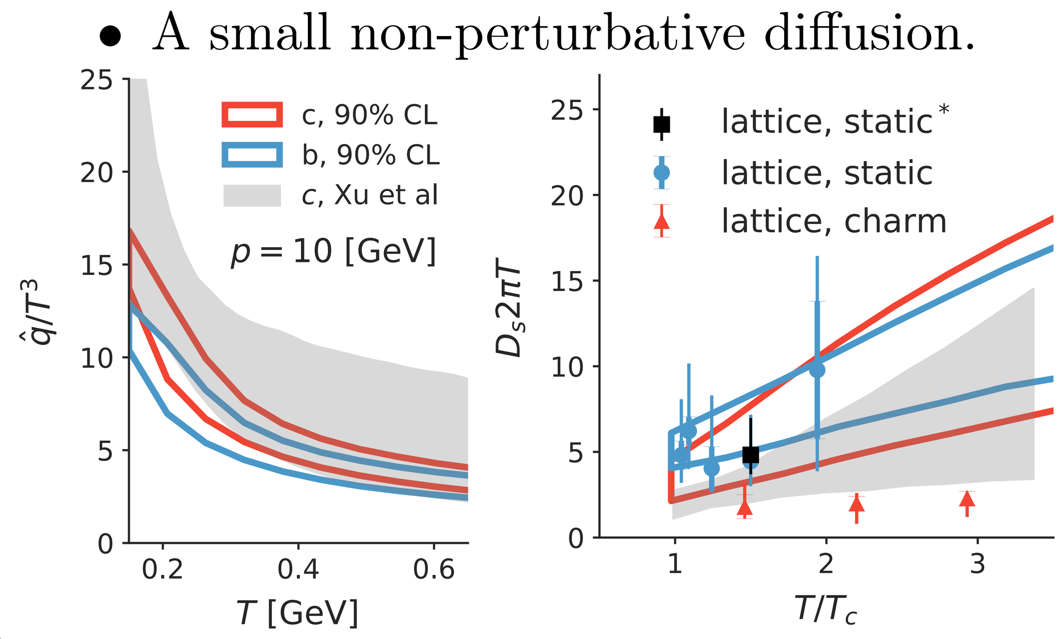
Bayesian parameter calibration at 5.02 TeV Pb+Pb





Calibrate on R_{AA}^D, v_2^D, event-engineered v_2^D, R_{AA}^B. Nuclear PDFs: EPPS and nCTEQ. ▹

- Different nuclear PDF barely affects parameter extraction.
- Relatively large $\alpha_s(\max\{Q, 0.6\pi T\})$. $\alpha_s(Q=0, 0.2<T<0.4\mathrm{GeV}) \sim 0.5 - 1.0$
- A small non-perturbative diffusion.



◃ Transport parameter and spatial diffusion coefficient of charm (red) and bottom (blue):

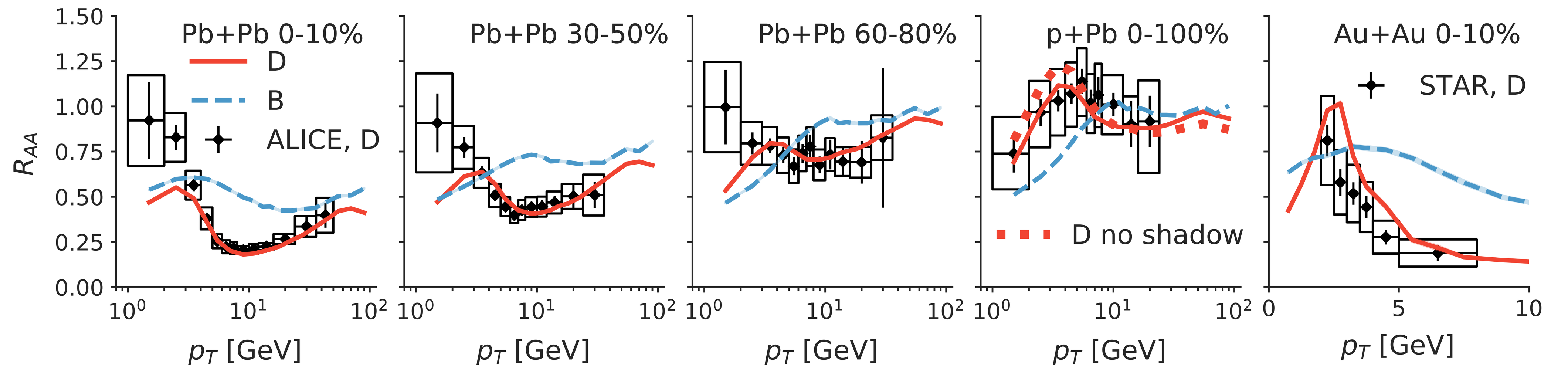
$$\hat{q} = \hat{q}[\text{el scatter}] + \hat{q}[\text{NP}],$$
$$2\pi T D_s = 8\pi T^3/\hat{q}(p=0)$$

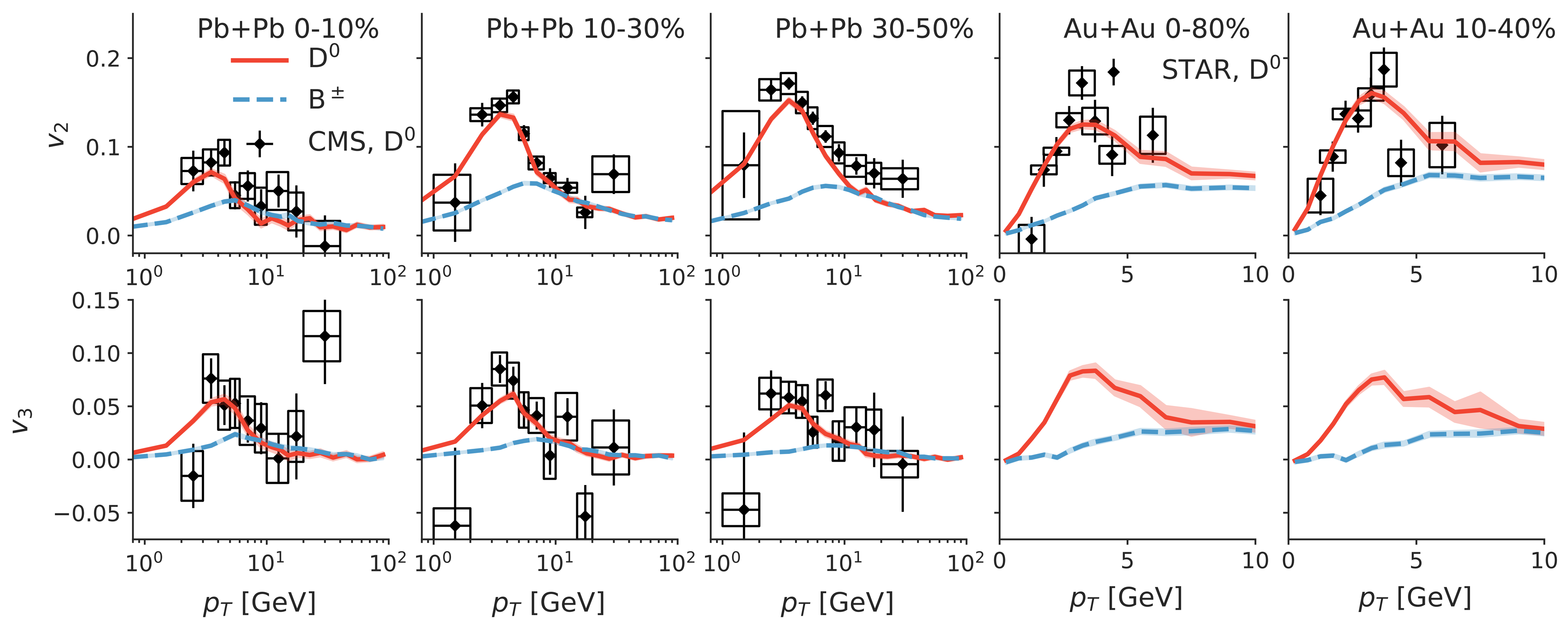
◃ Comparison to earlier extraction (Xu et al) and lattice calculations. This work overlaps with lattice calculation in the static limit*.

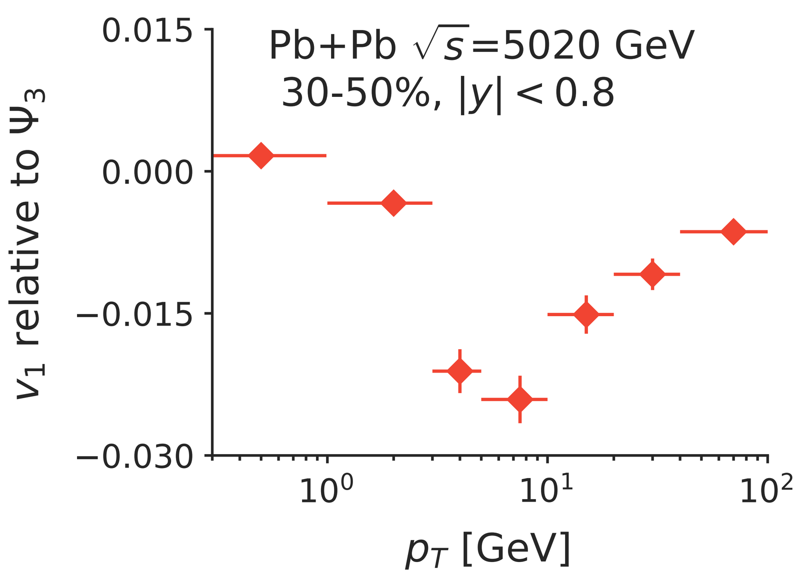
Validation and predictions

Pick high-probability parameter set, $\tau_{\rm HQ} = 0.9$ fm/c, $\mu = 0.6$, $\kappa_D = 0.4$, $x_D = 0.5$.

- Validation: compare to experimental data that are **not** calibrated on. ALICE R_{pPb}^D, CMS v_3^D, STAR R_{AuAu}^D, and STAR v_2^D.
- Predictions: v_3^D, v_n^B, R_{AA}^B and D-meson v_1 relative to event-plane Ψ_3.







◃ D-meson v_1 relative to Ψ_3 at mid-rapidity.

- Align events by Ψ_3 → reflection asymmetry.
- Induce different energy loss for heavy quarks moving parallel/antiparallel to the direction of Ψ_3.
- Impact of event-by-event initial condition fluctuations on the heavy quark energy loss.

References

Lattice (top to bottom): Francis et al PRD **92**, 116003. Banerjee et al PRD **85**, 014510. Ding et al PRD **86**, 014509. Earlier Bayesian parameter extraction: Xu et al PRC **97**, 014907.
ALICE: PRL **113**, 232301; PRL **120**, 102301; EPJ **17**, 11800; arXiv:1804.09083.
CMS: PRL **119**, 152301; arXiv:1708.03497; arXiv:1708.04962.
STAR: PRL **118**; 212301, NPA **956**, 473-476.