Introduction to Heavy Ion Collisions – Experimental

Part3 Heavy Flavor

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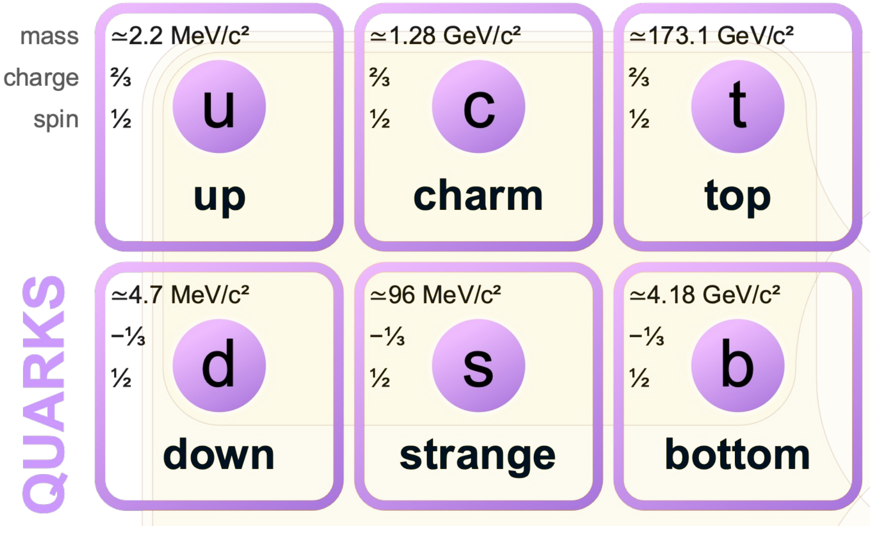
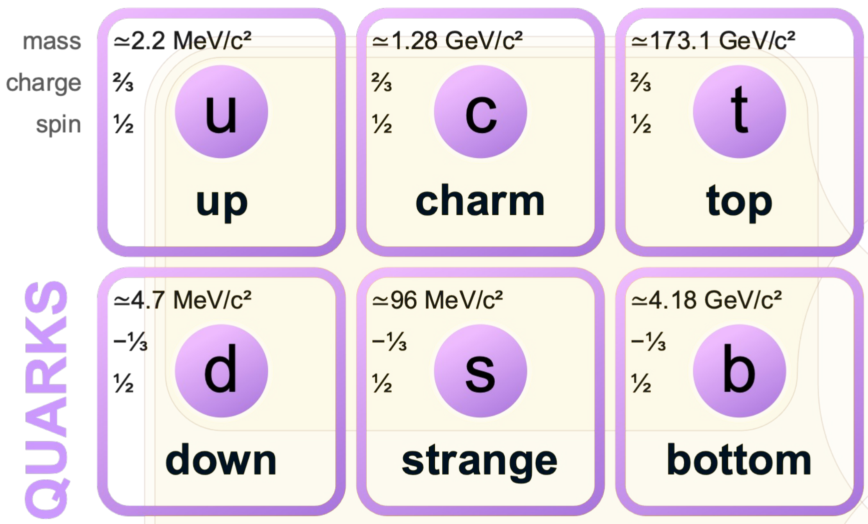
What is heavy flavor?



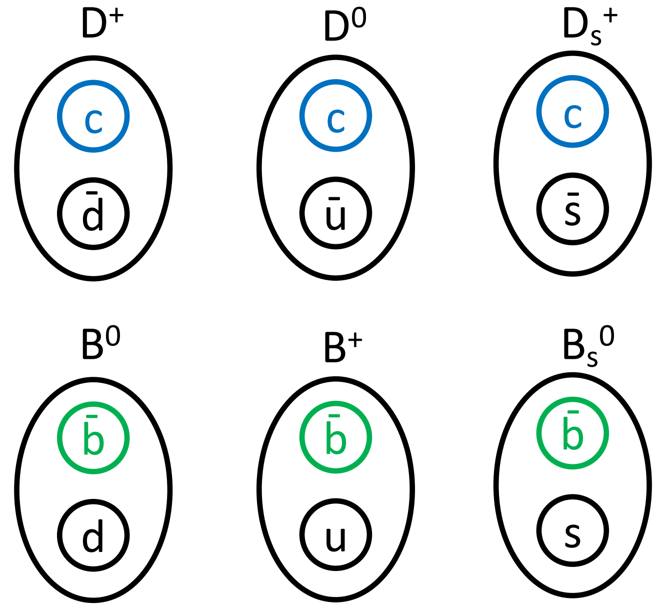
Hadrons with large mass quarks
Charm, Bottom

What is heavy flavor?

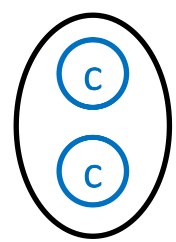


Hadrons with large mass quarks
Charm, Bottom

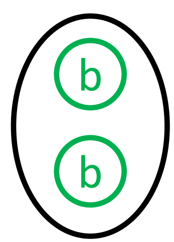
Open heavy flavor



Quarkomium



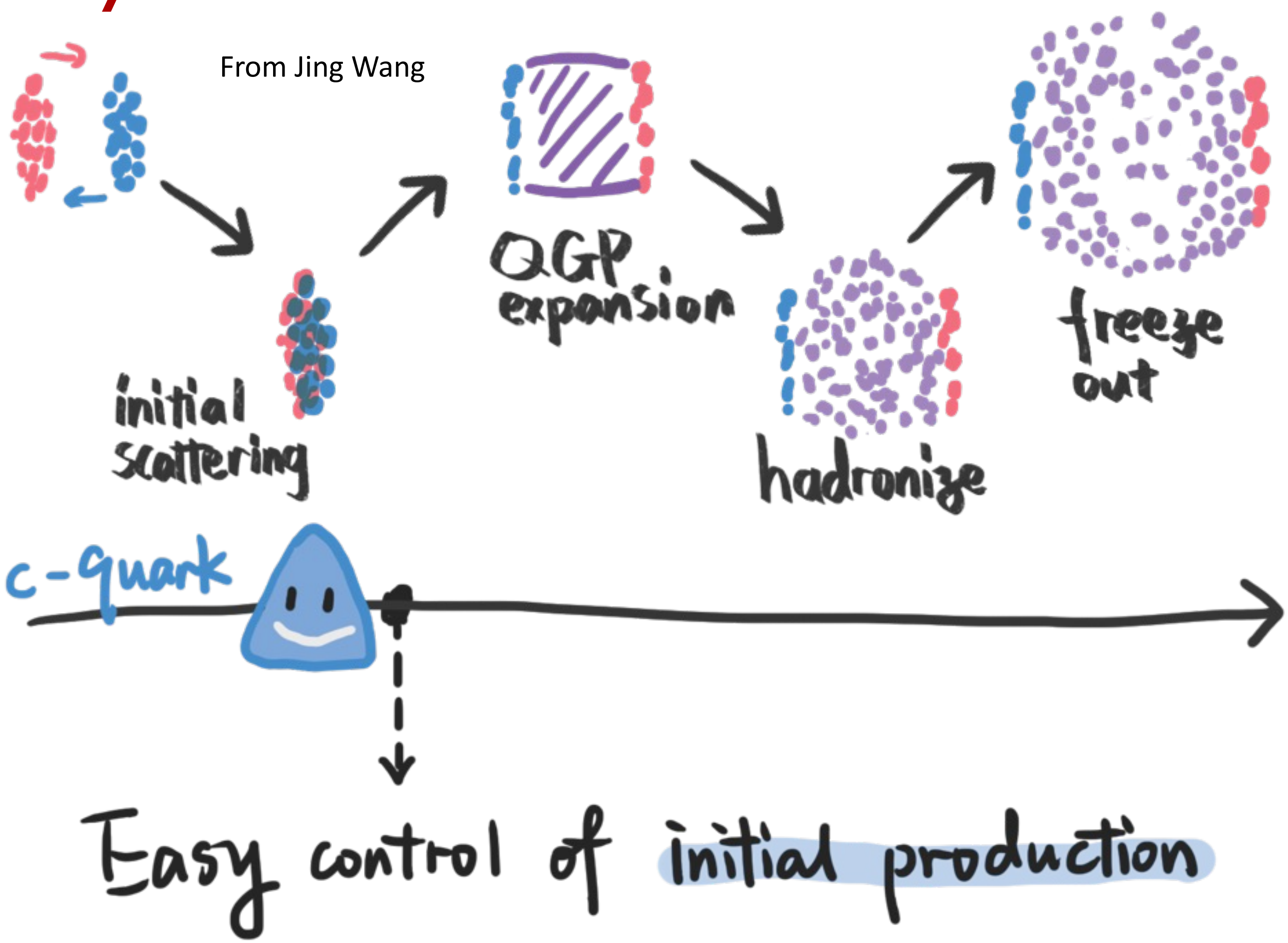
Charmonium
J/ψ, ψ(2S)



Bottomonium
ϒ(1S), ϒ(2S), ϒ(3S)

Why heavy flavor?

Why heavy flavor?



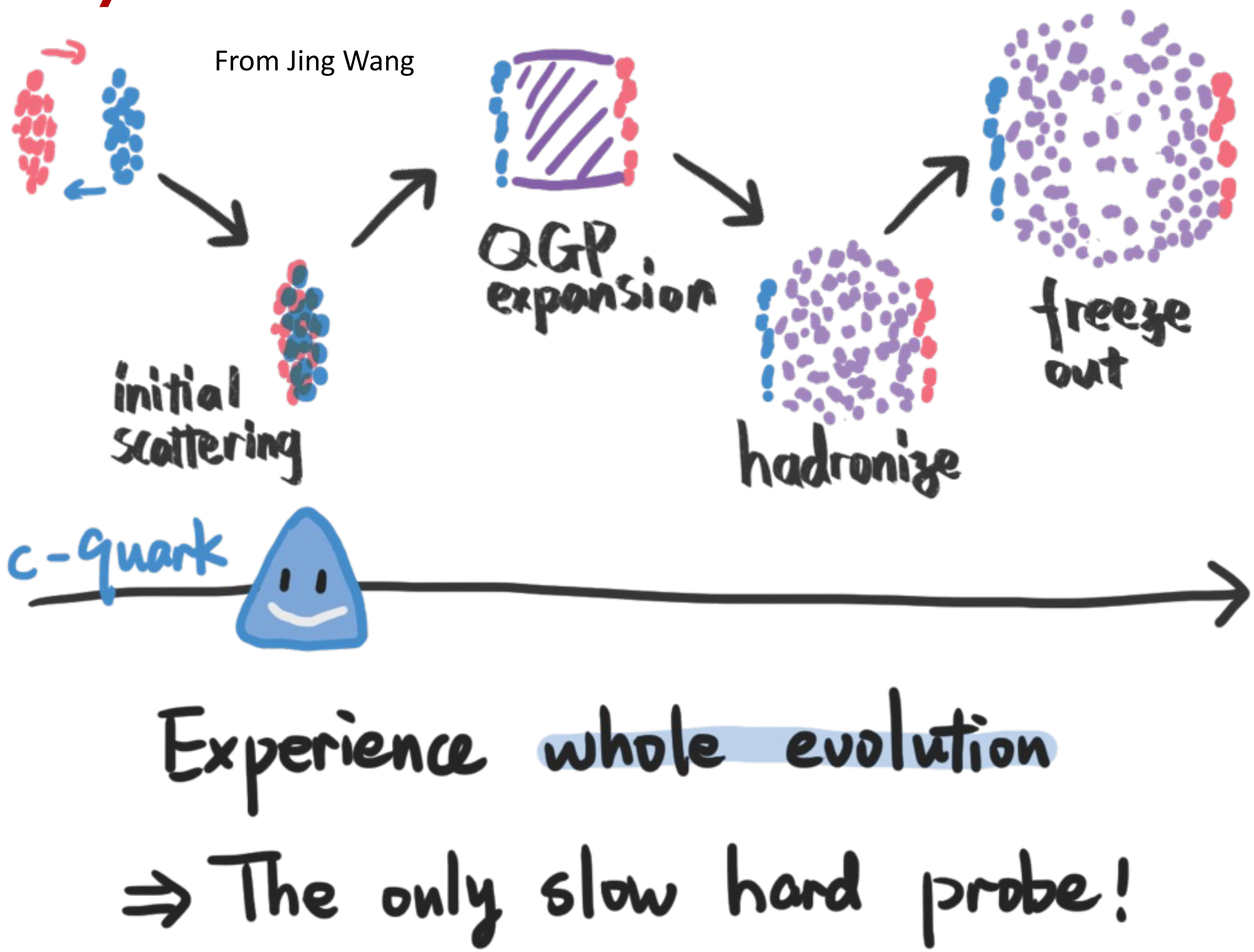
Produced at early stage, $\tau \sim 1/Q \sim 1/m_Q$

Feasible: $m_Q \gg \Lambda_{QCD}$

Production calculable with pQCD

Why heavy flavor?

From Jing Wang



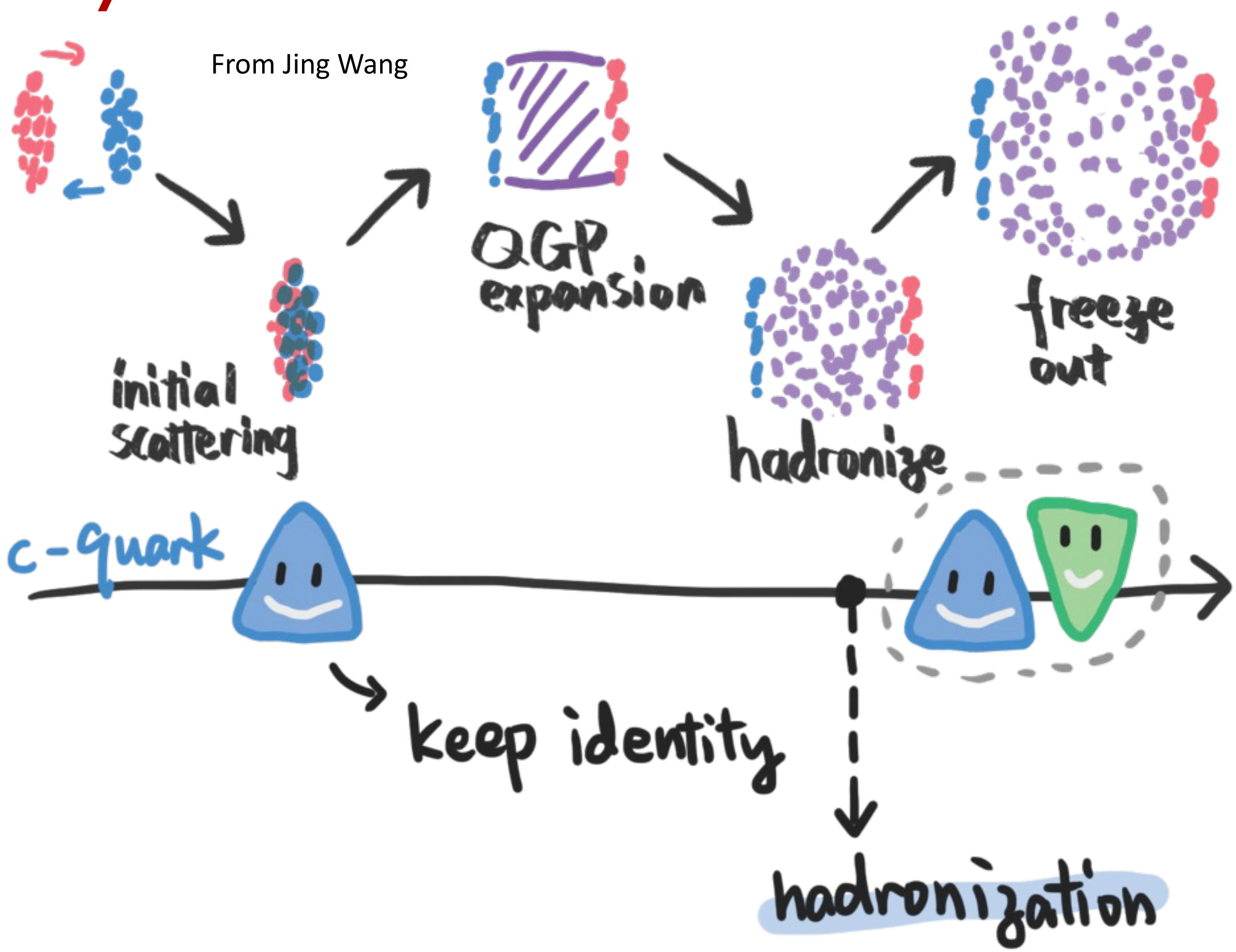
Clean: $m_Q \gg T_{QGP}$

Hardly produced in medium

Low p_T heavy flavor is Slow but Hard

Side note:
Jets Hard but Fast

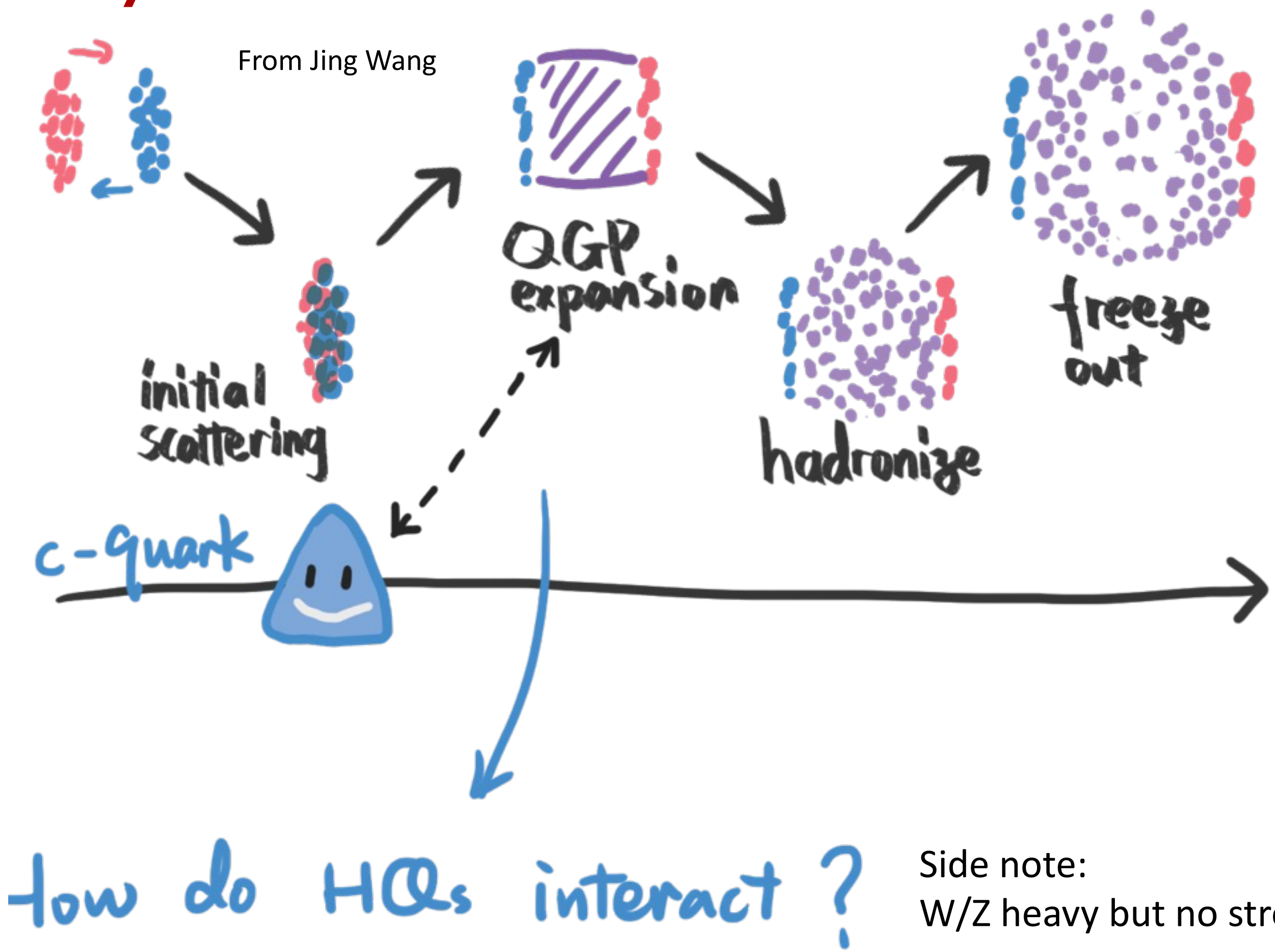
Why heavy flavor?



Does not change flavor during the evolution

Why heavy flavor?

From Jing Wang



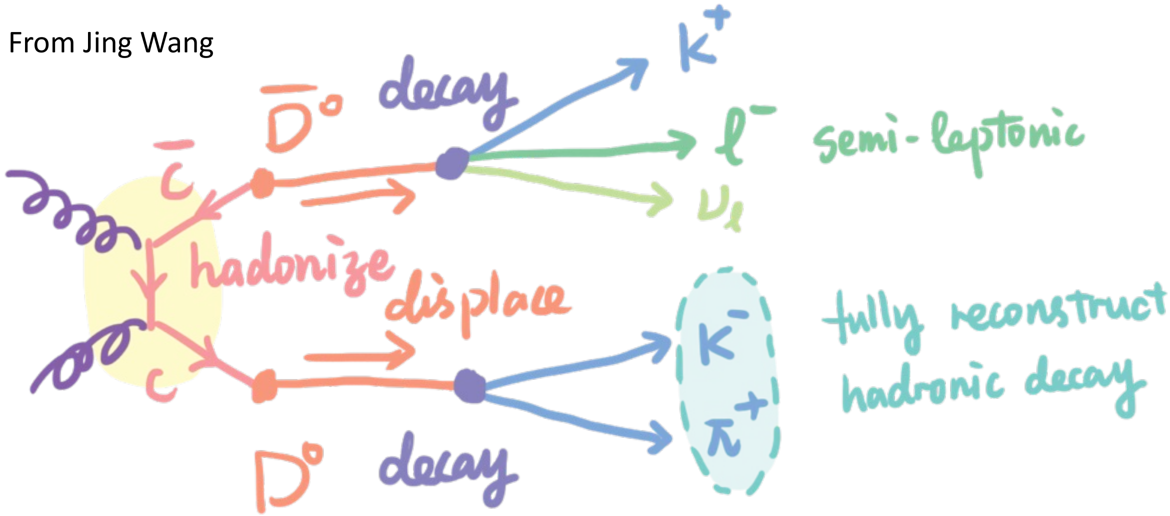
Side note:
W/Z heavy but no strong interaction

Strongly interact with the deconfined medium

Reflect information of QGP

How to detect heavy flavor?

From Jing Wang



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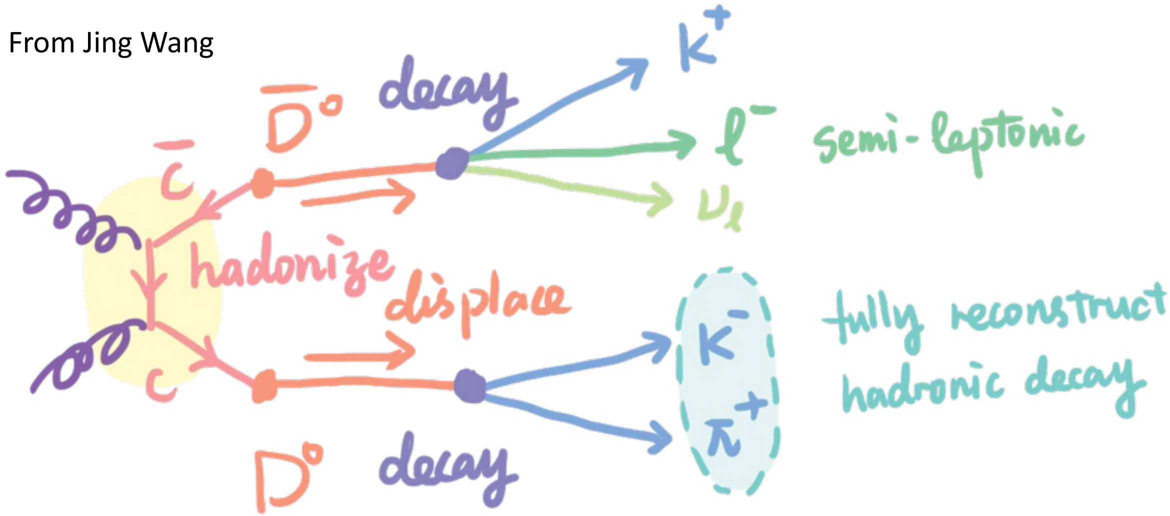

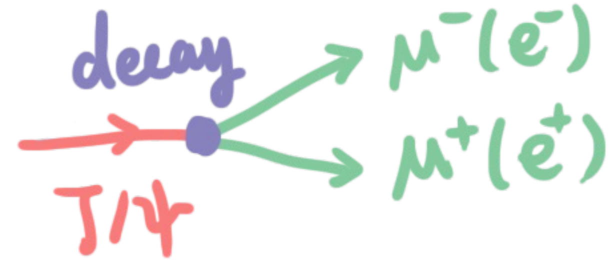

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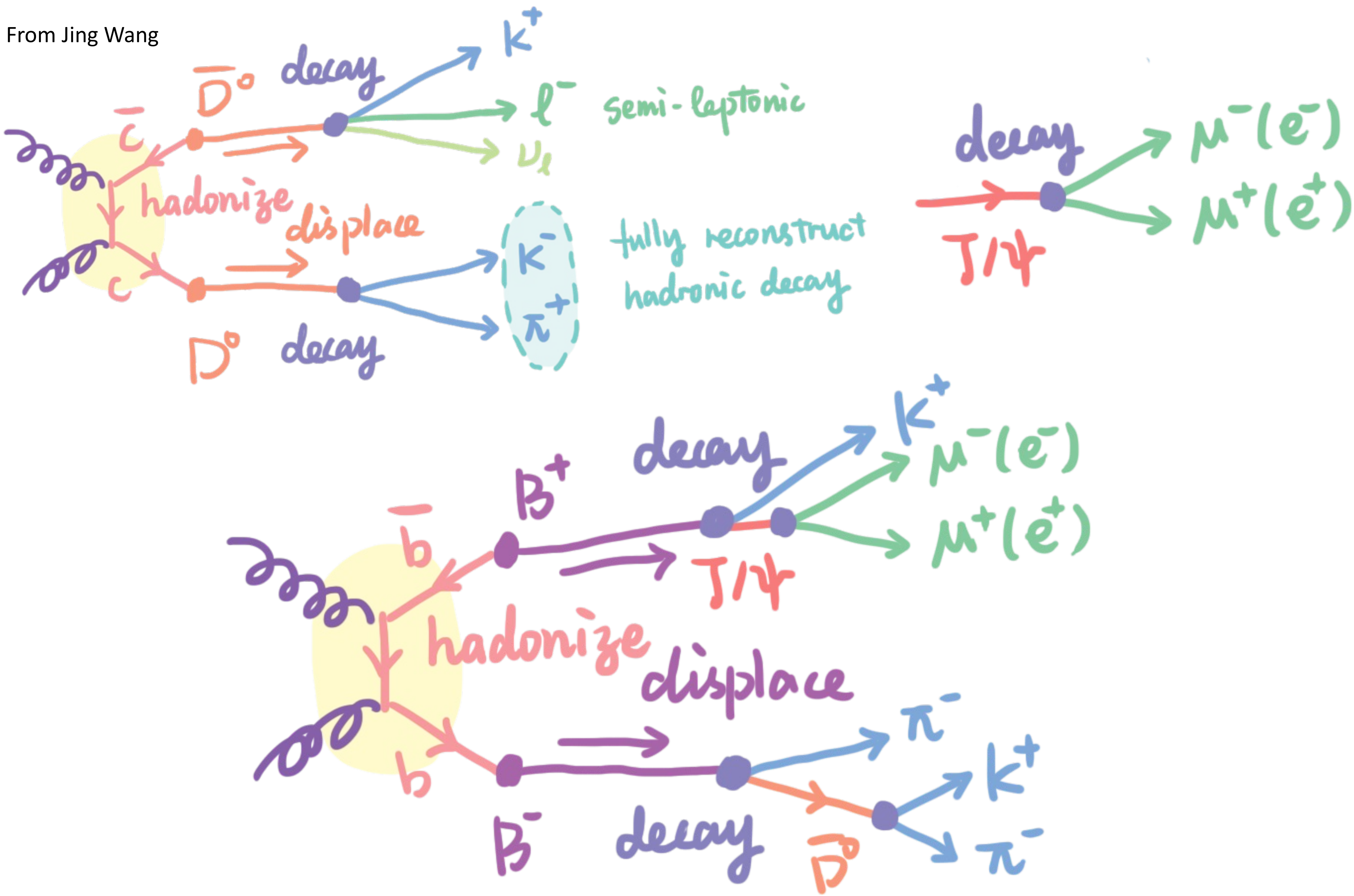
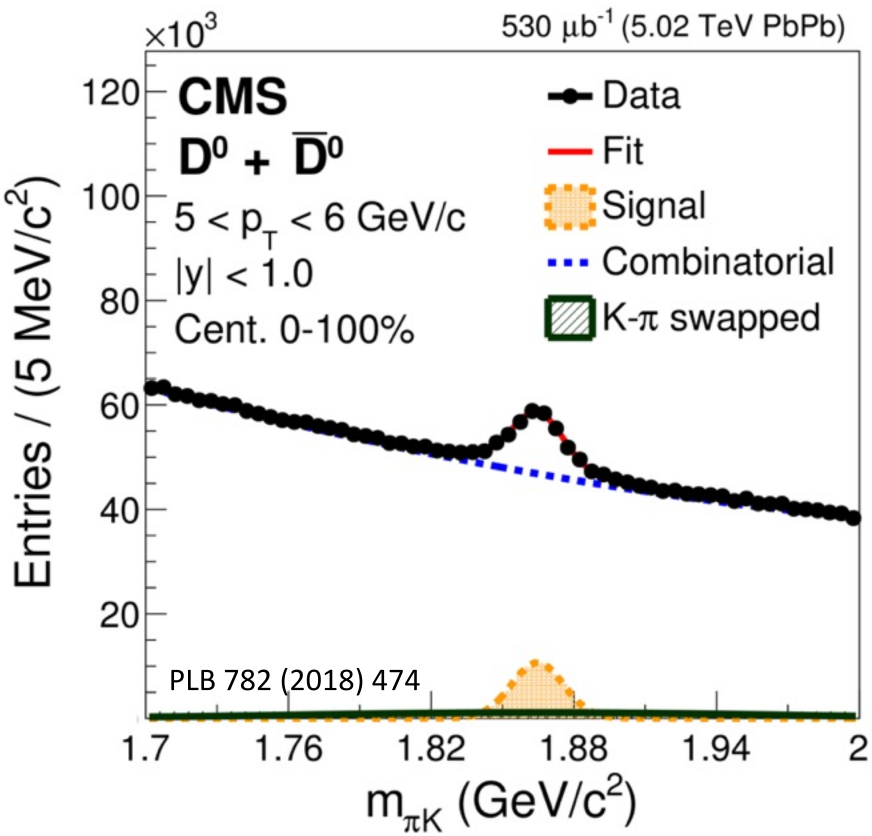
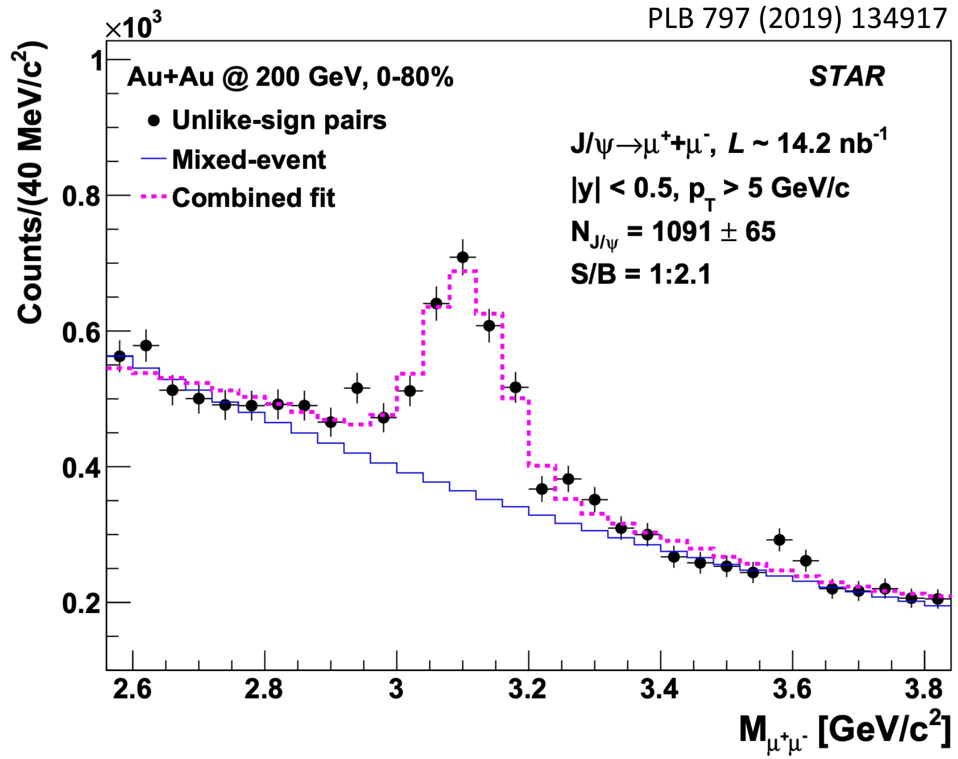


How to detect heavy flavor?





Clear mass peak

Considerable large combinatorial background

Signal extraction technique: mass fit, side-band subtraction, simultaneous fit

What to measure for heavy flavor?

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$

Energy loss in QGP medium

QGP thermal meter

Azimuthal anisotropy v_n

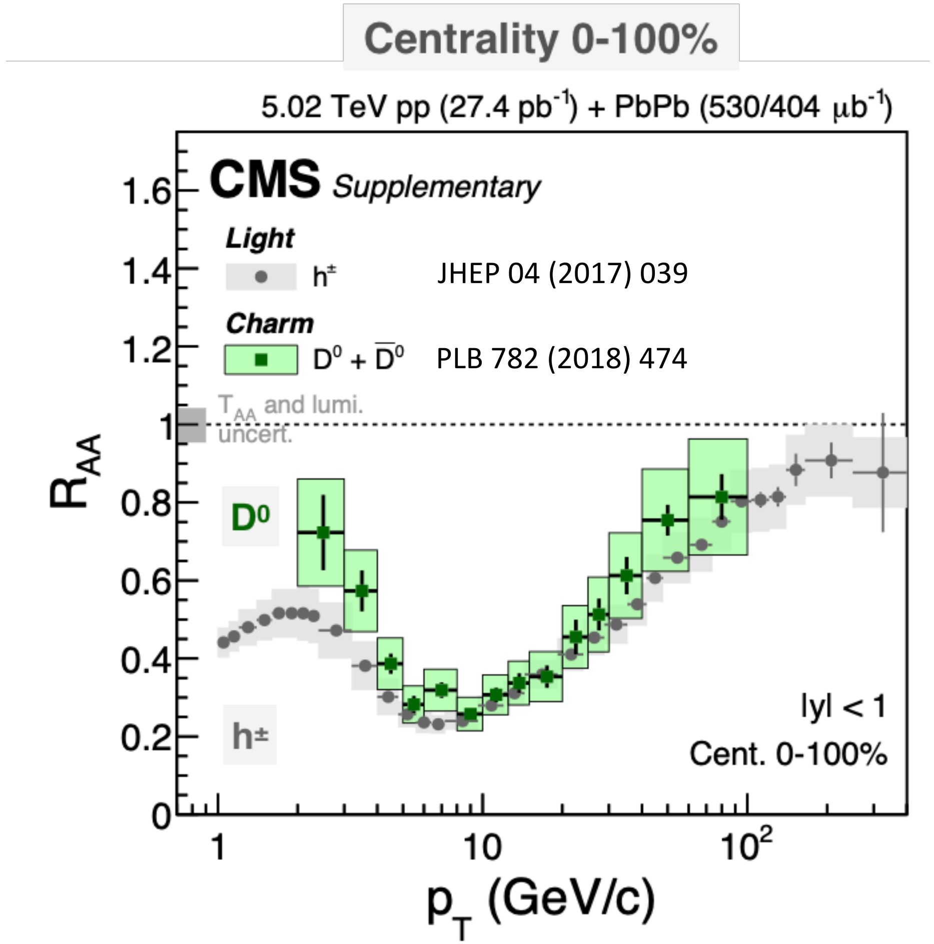
$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Phi_n))$$

Interaction strength in QGP
Thermalization + relaxation time

Open Heavy flavor R_{AA}

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$



High pT: similar energy loss as light flavors

Low pT: weaker suppression than light

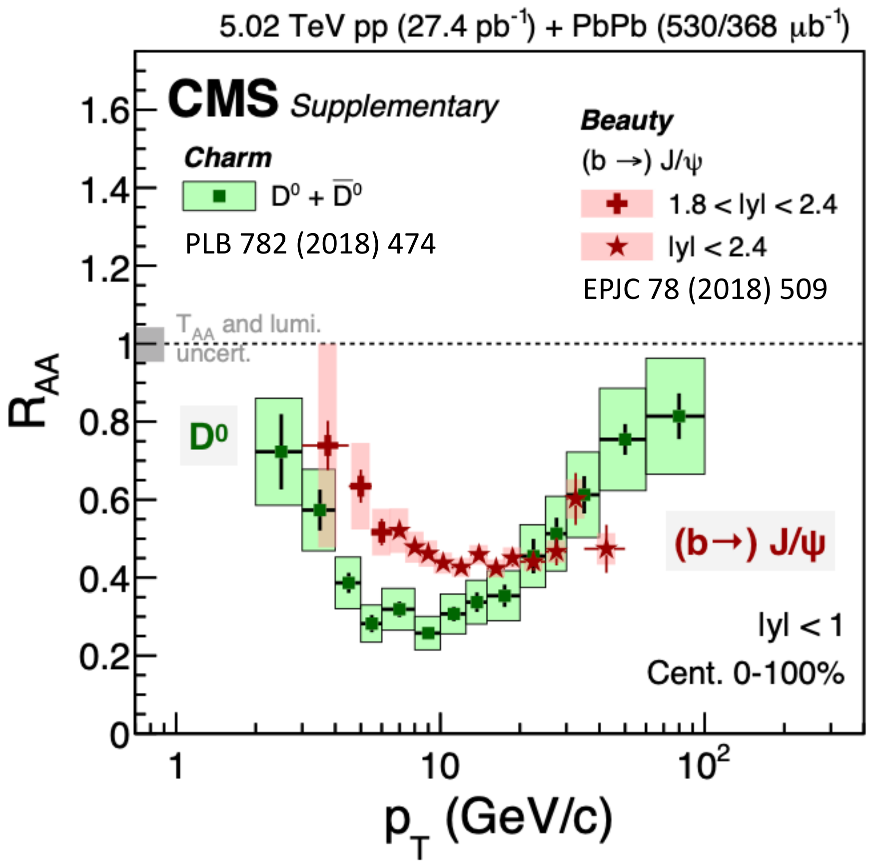
Interplay of energy loss, radial flow, CNM effect, hadronization

Open Heavy flavor R_{AA}

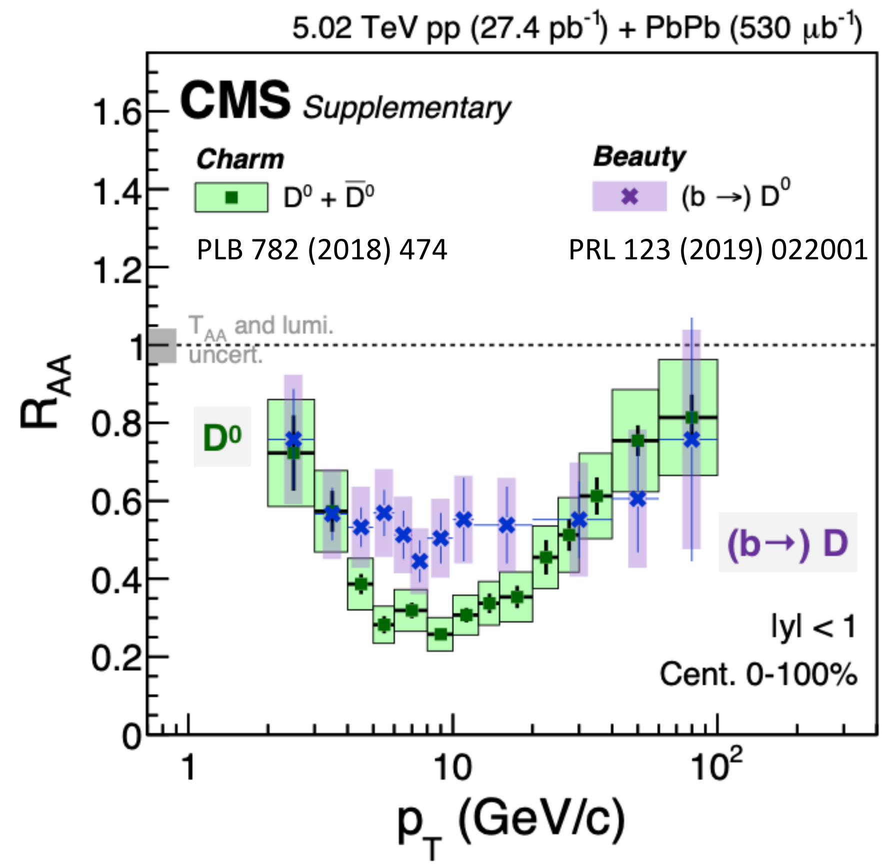
Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$

Prompt D vs. b→J/ψ



Prompt D vs. b→D



Weaker suppression of b-hadron at intermediate p_T

Not fully investigated yet

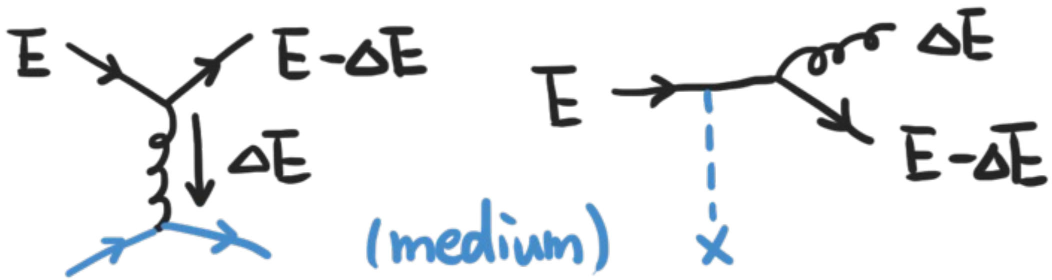
Open Heavy flavor R_{AA}

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$

Collisional energy loss

Radiative energy loss



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Collisional energy loss

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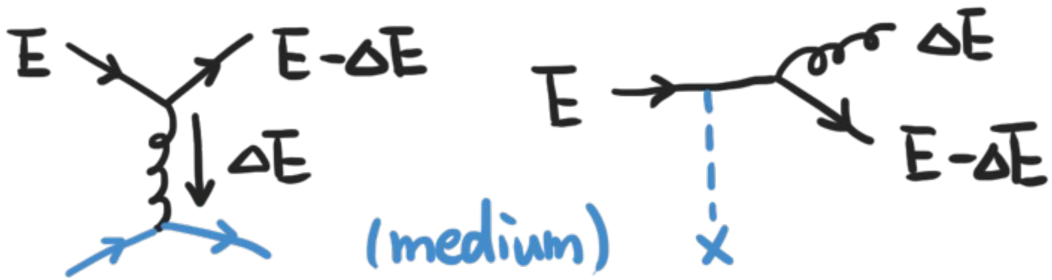
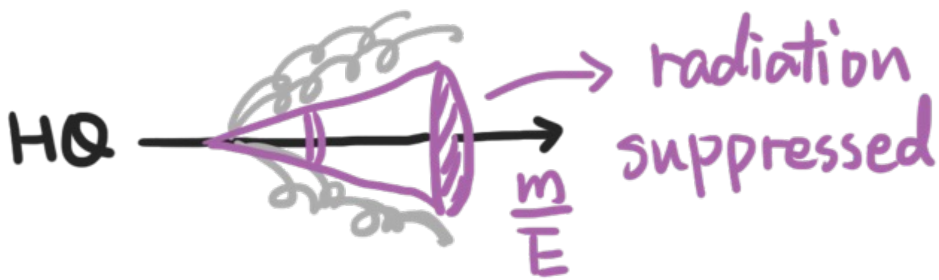


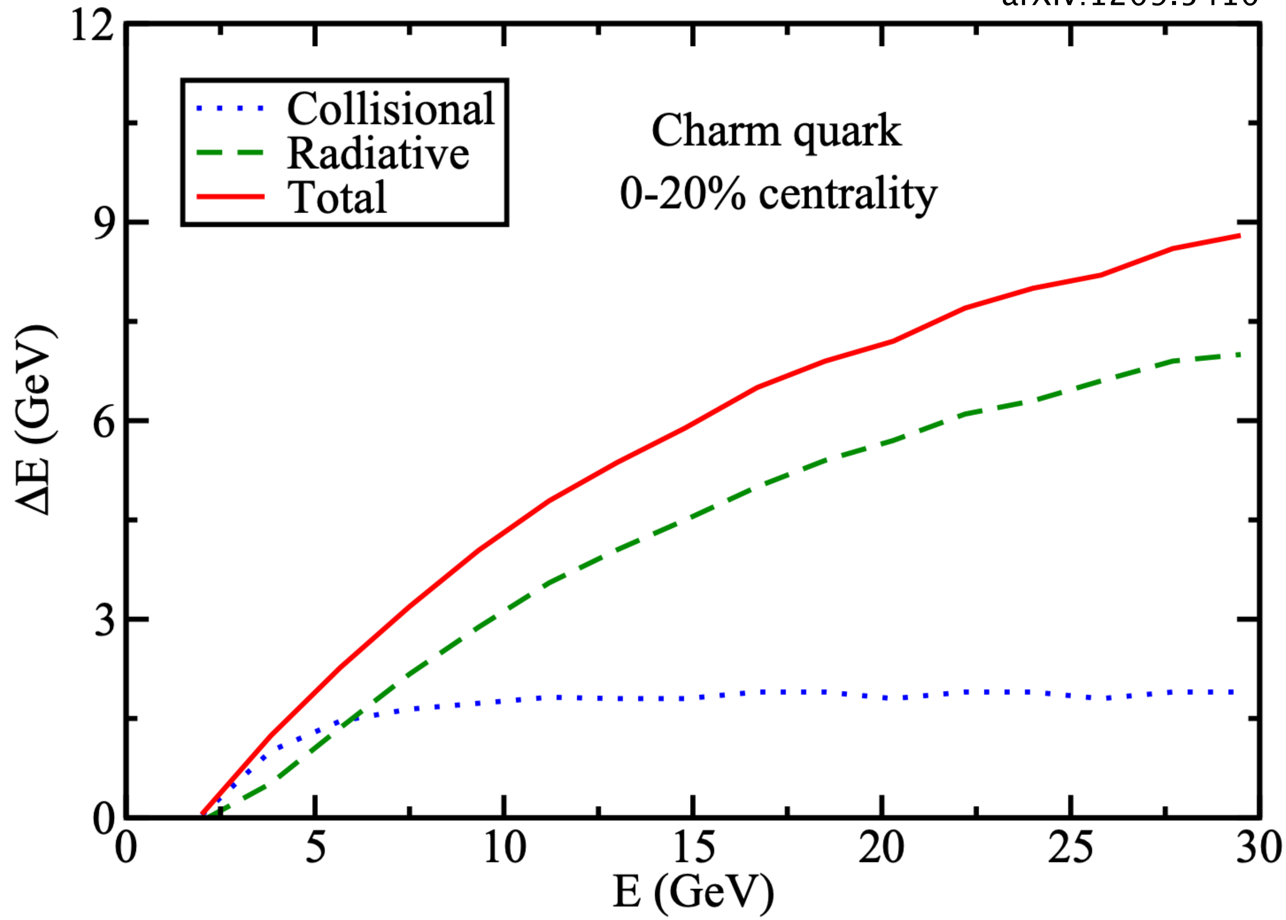
Dead cone effect



Radiative energy loss suppressed for (slow) heavy quarks
Compare to light quarks to disentangle radiative vs collisional E-loss

QGP transport coefficients

arXiv:1209.5410

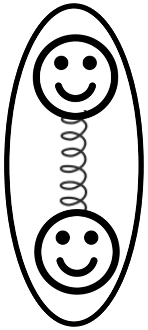


Different type of energy loss extracted with Heavy Flavor results

Quarkonium R_{AA}

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$



Quarkonium

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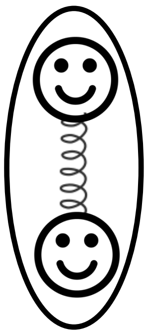
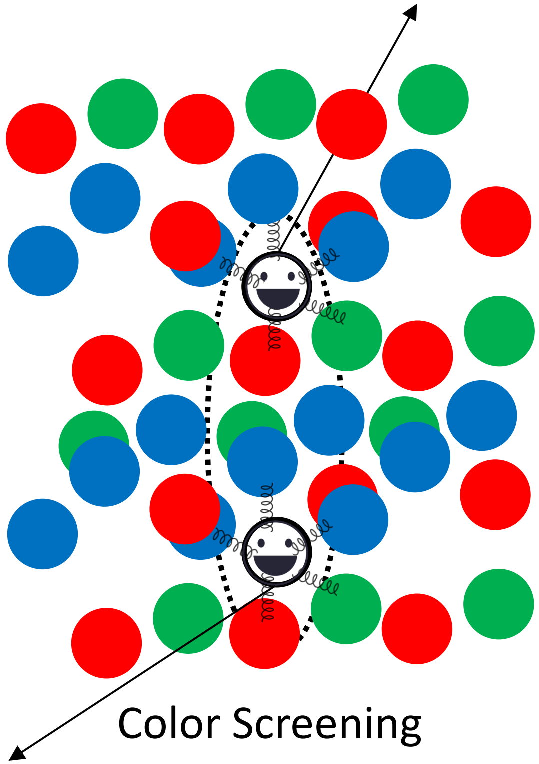


Quarkonium



Color Screening

High temperature leads to QCD Debye screening

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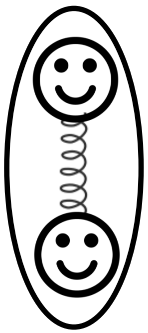
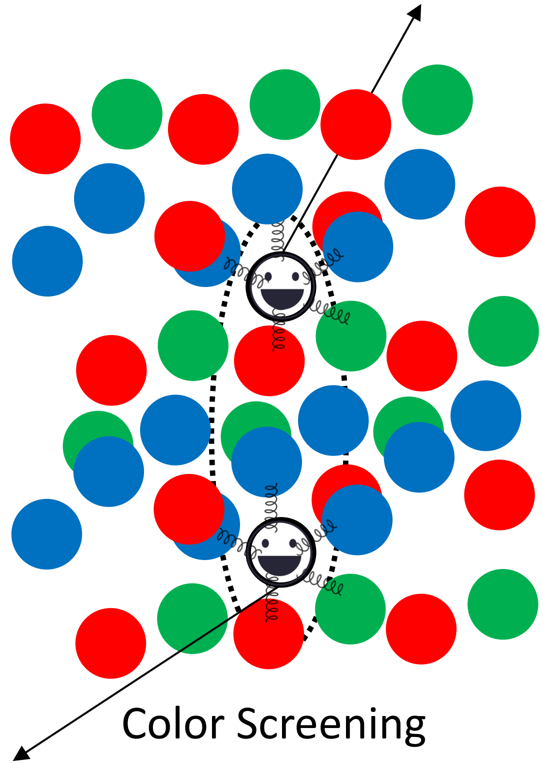


Quarkonium



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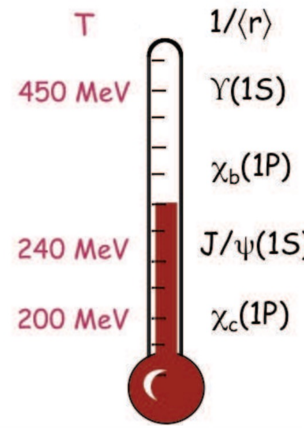
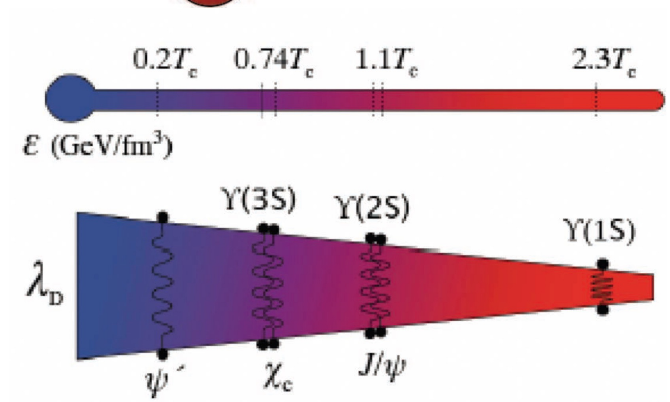




	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200

High temperature leads to QCD Debye screening

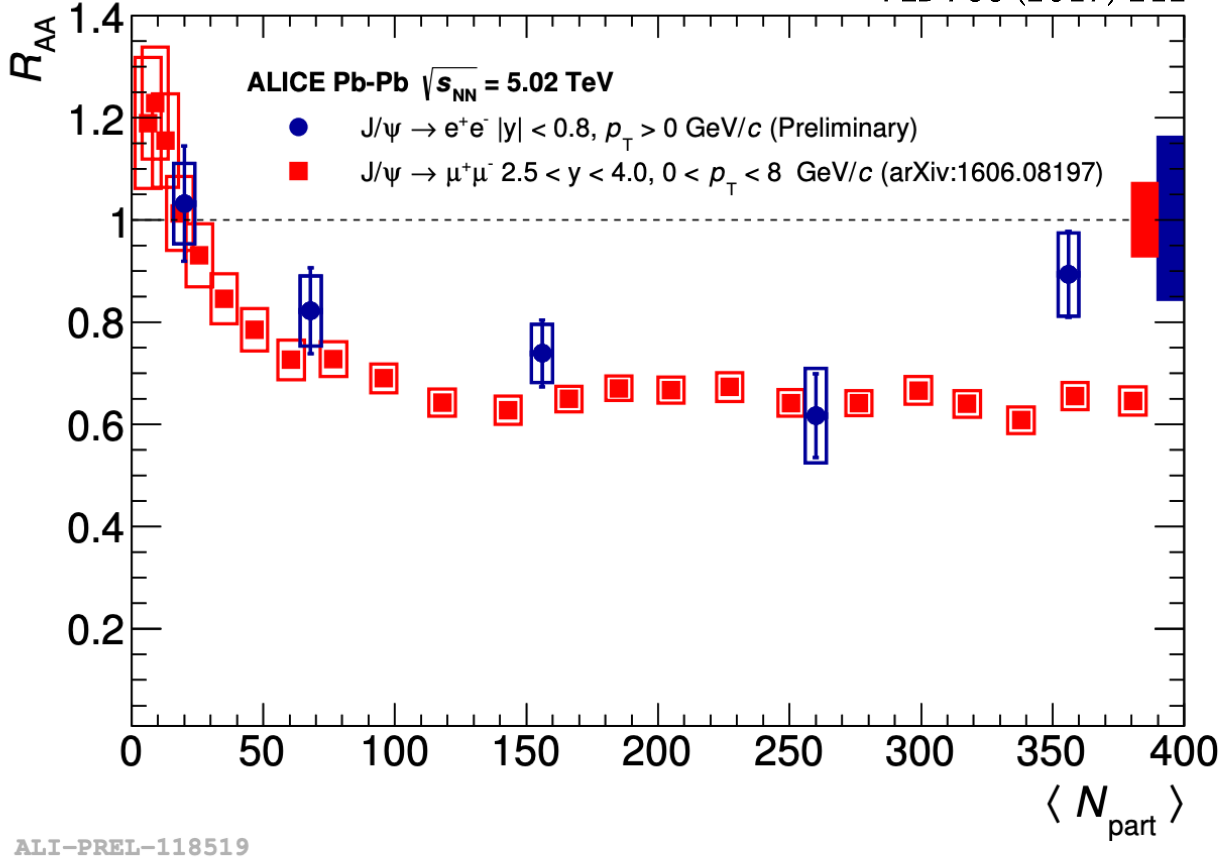
Quarkonium melts at different temperature – QGP thermal meter

Quarkonium R_{AA}

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$

PLB 766 (2017) 212



Significant J/Psi suppression towards central collisions

Quarkonium R_{AA}

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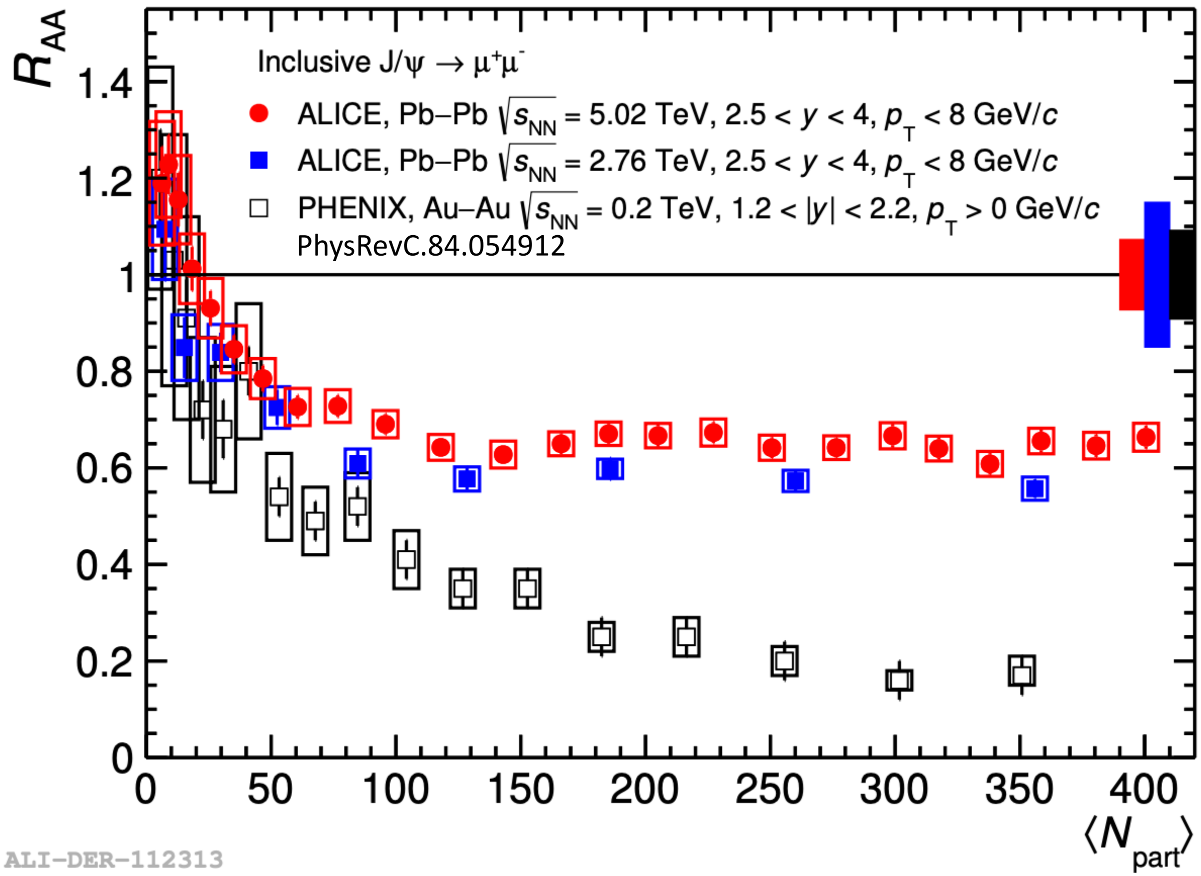

Significant J/Psi suppression towards central collisions
Strong energy dependence => contradiction?

Quarkonium R_{AA}

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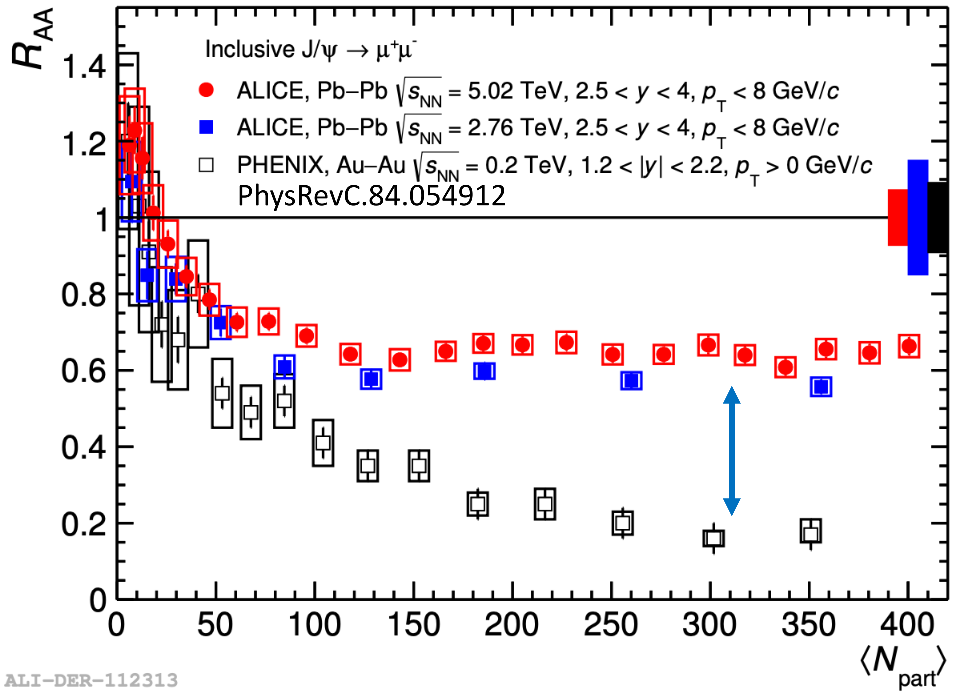
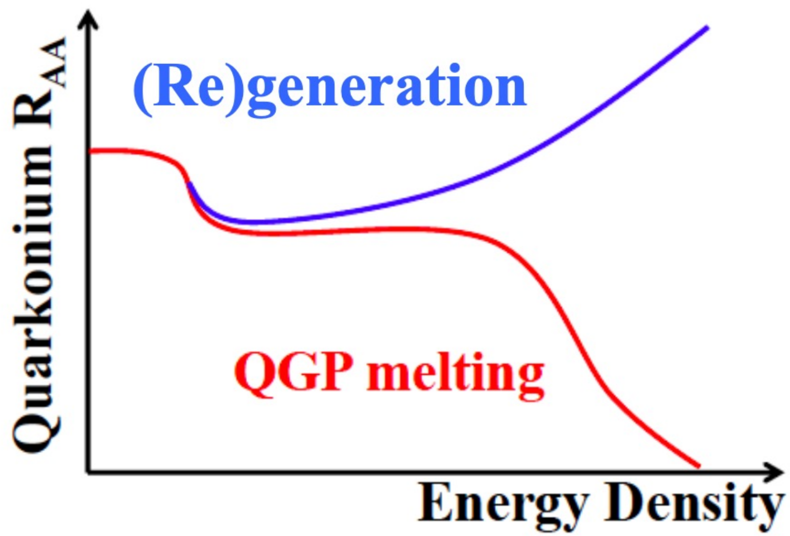
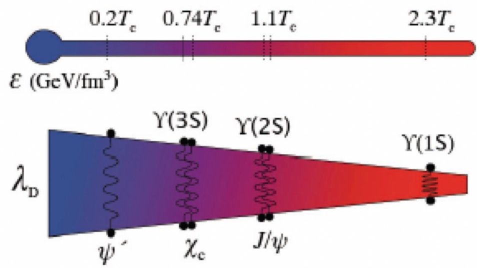




Significant J/Psi suppression towards central collisions
Strong energy dependence due to regeneration

Quarkonium R_{AA}

	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200



Quarkonium R_{AA}

	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
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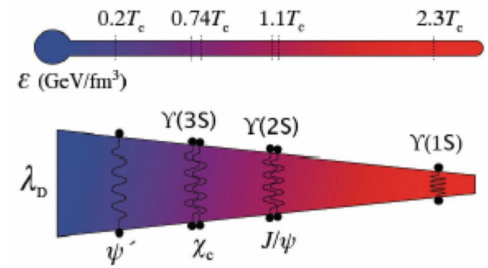

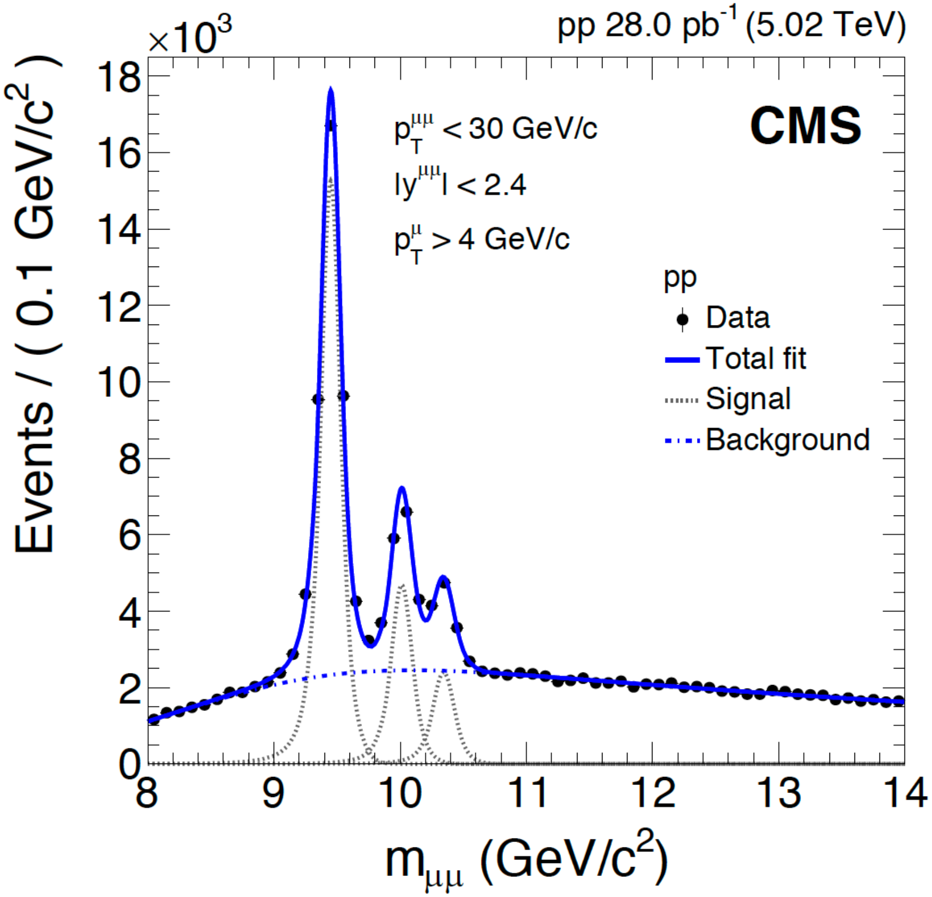

Quarkonium R_{AA}

	J/ψ	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
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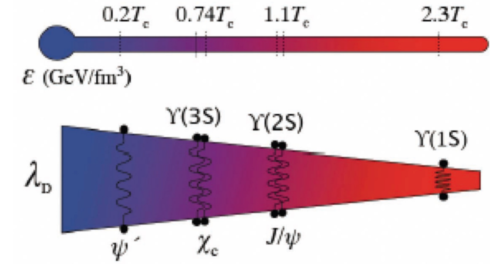
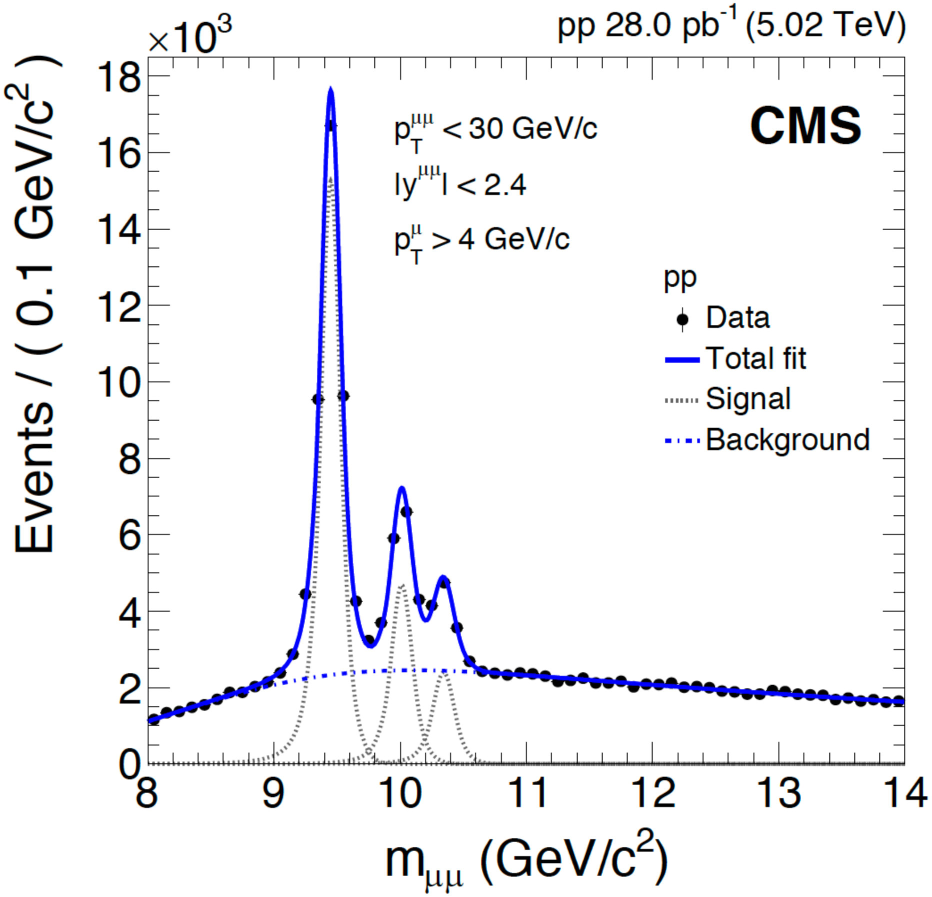
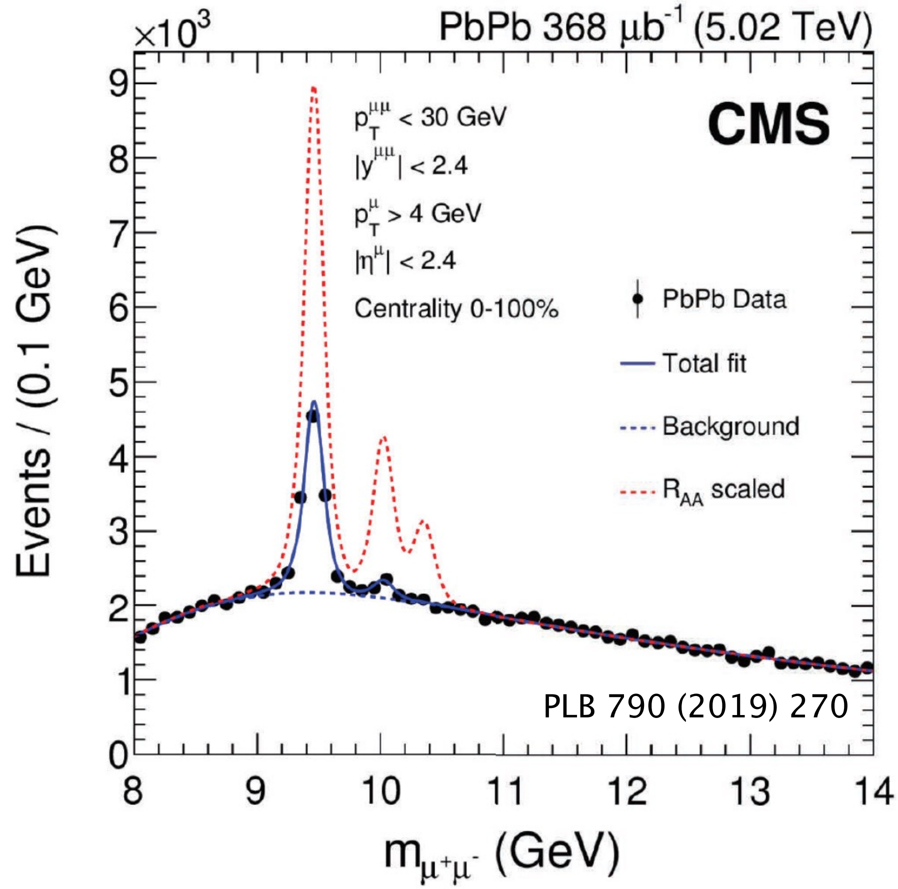
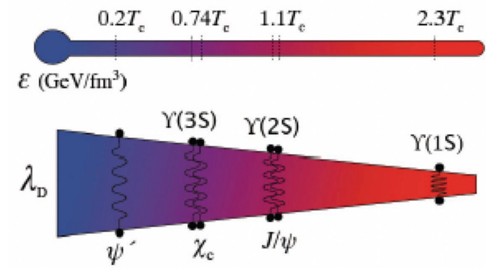






Huge suppression of Upsilon states

Quarkonium R_{AA}



	J/ψ	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
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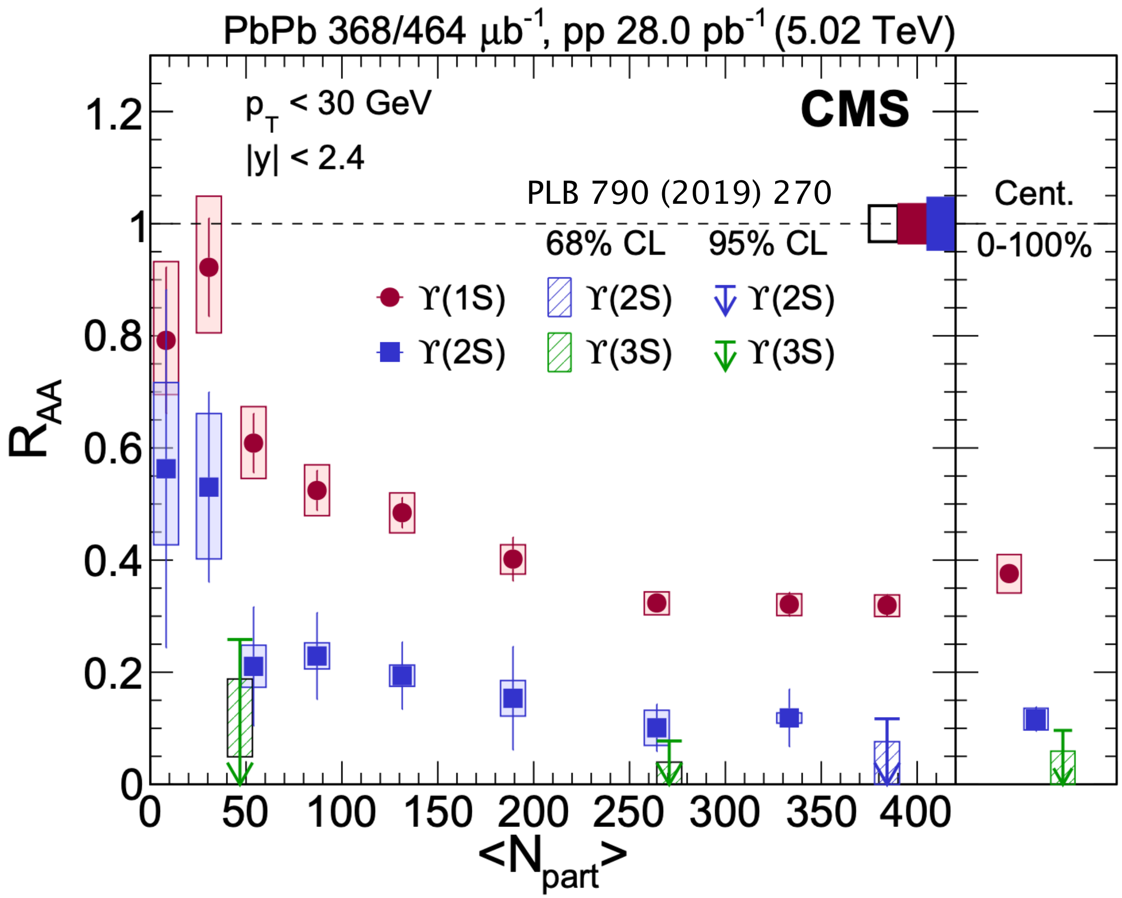

Sequential suppression of Upsilon states

Quarkonium R_{AA}

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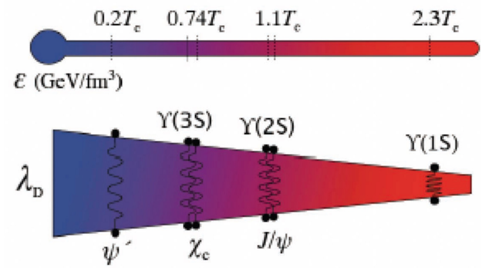
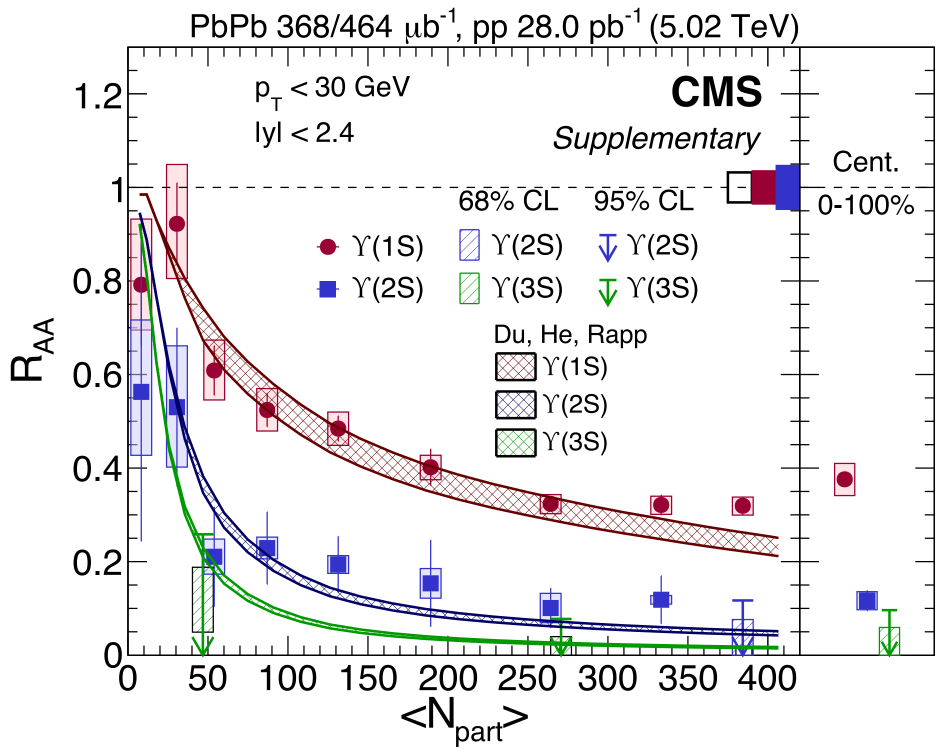
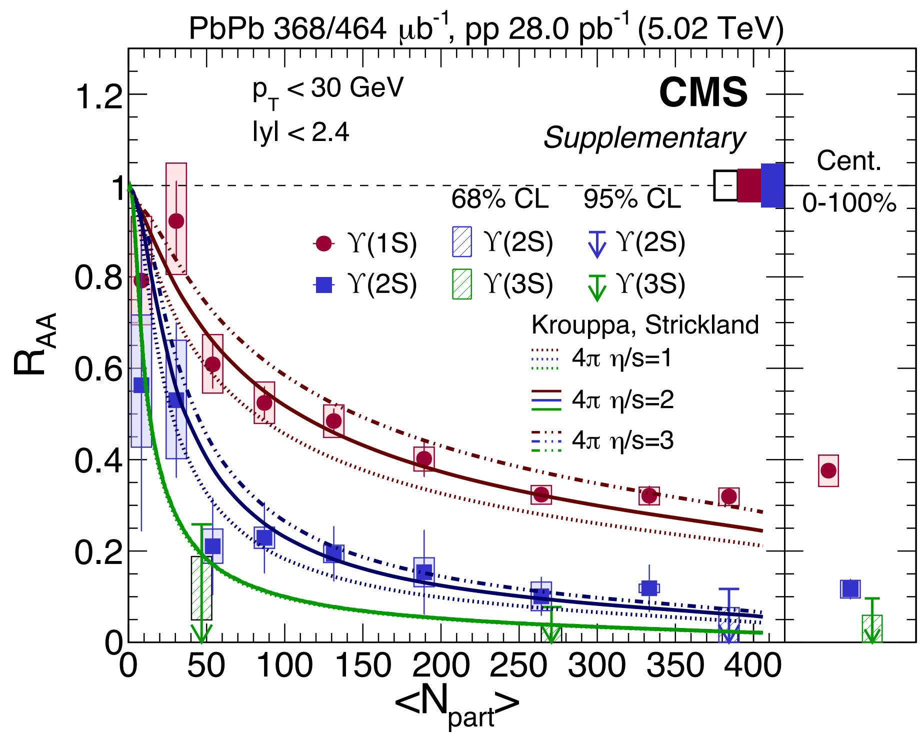






Constrain on initial temperature

PRC 96 (2017) 054901
2.76 TeV: 520 – 750 MeV
5.02 TeV: 7% increase

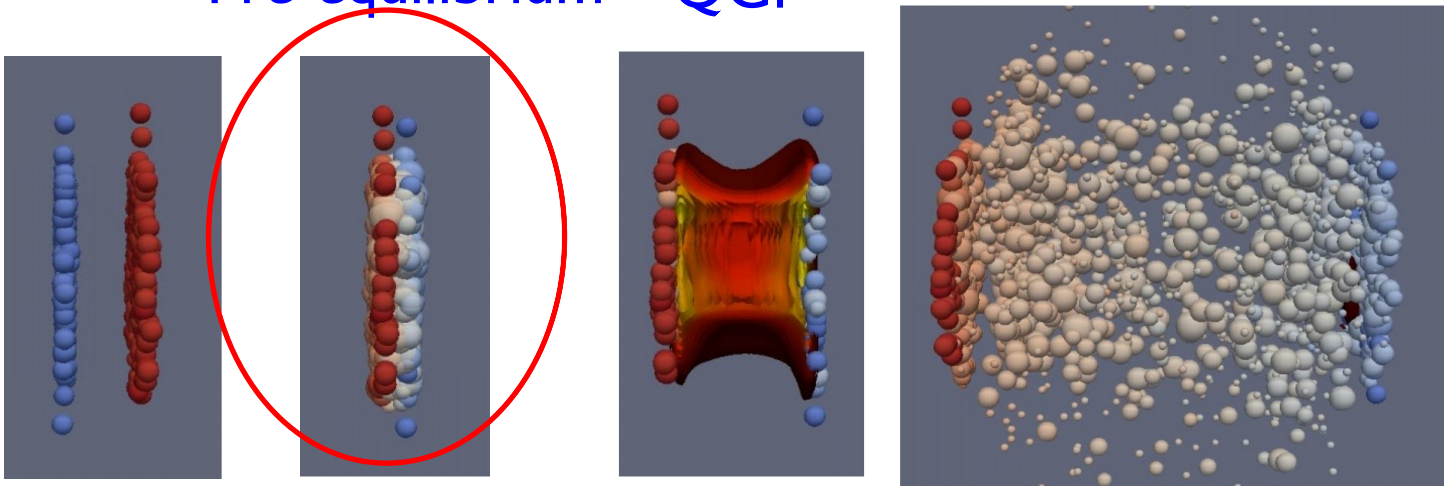
Universe 2 (2016) 16
2.76 TeV: 544 – 552 MeV
5.02 TeV: 629 – 641 MeV

Collectivity of Heavy Flavor

Azimuthal anisotropy v_n

$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Phi_n))$$

Pre-equilibrium QGP Hadronization



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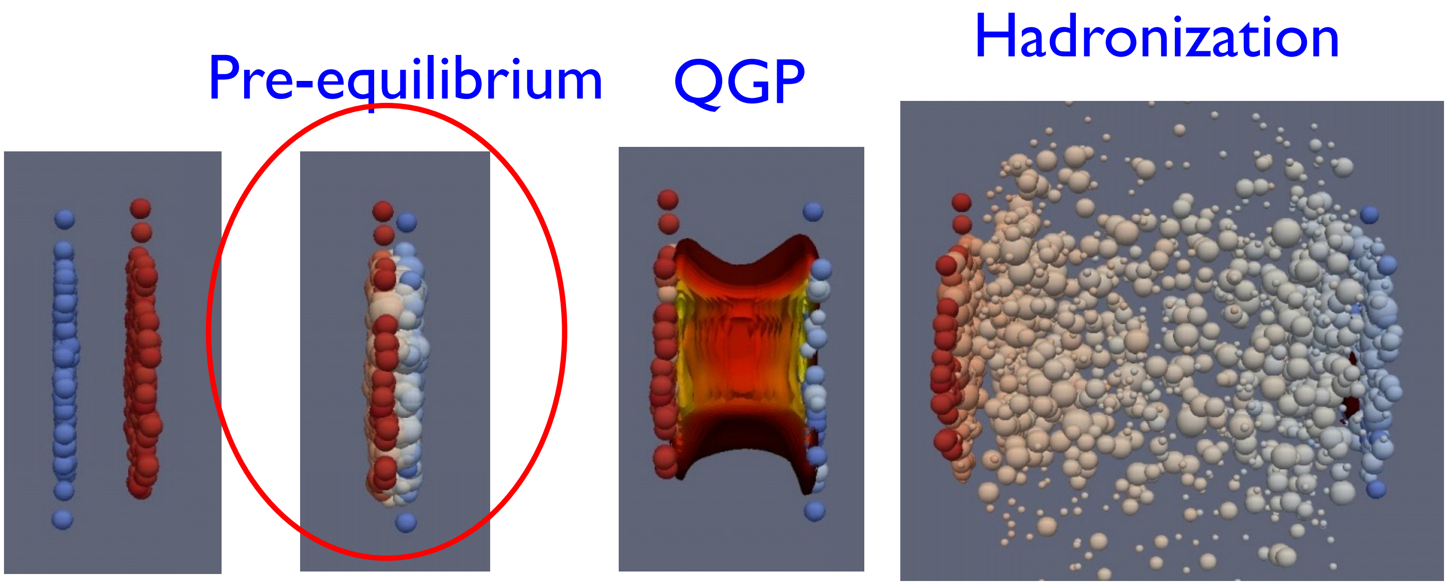

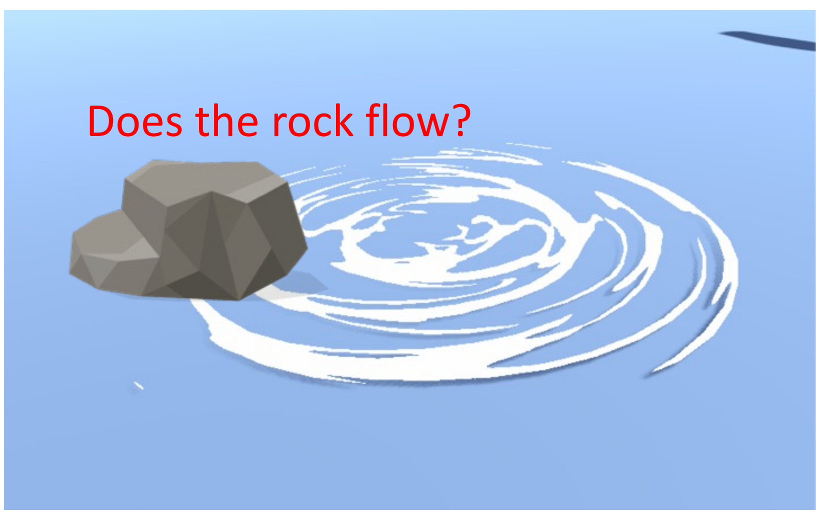

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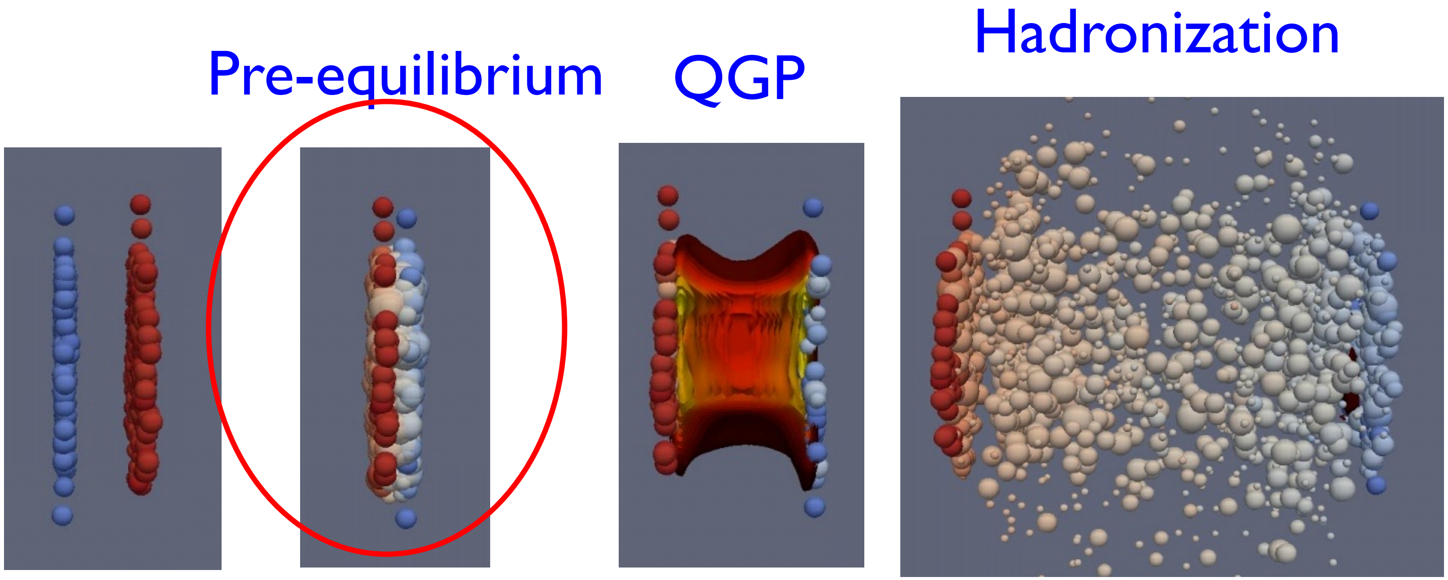
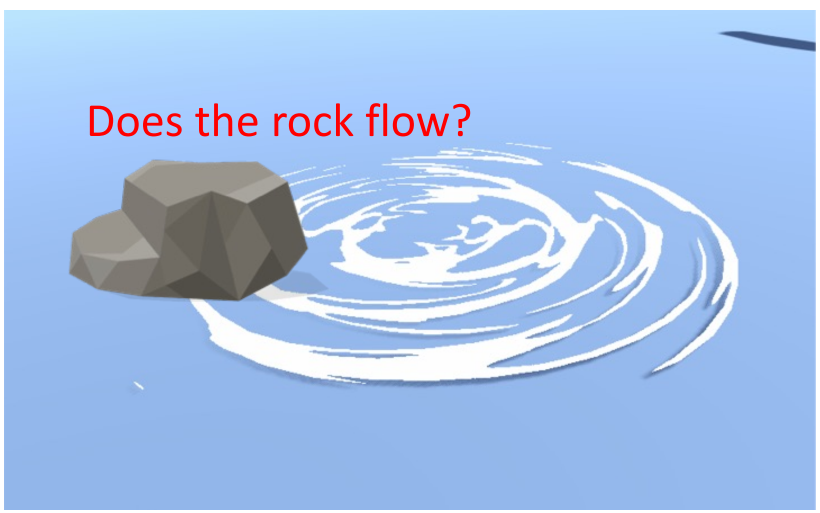
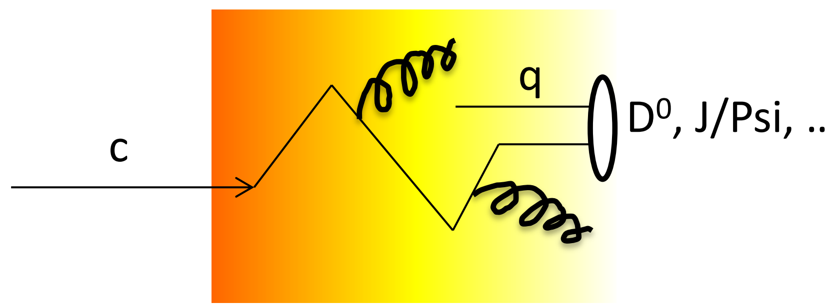






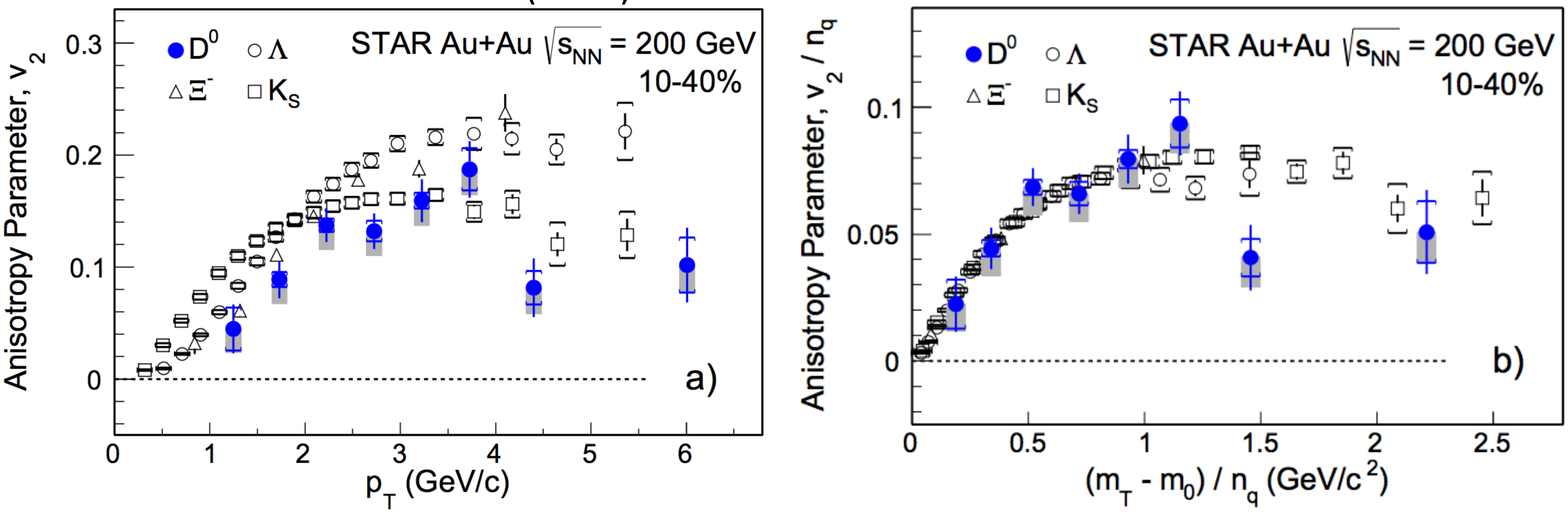
Low p_T charm expected to pick up medium flow!

Collectivity of Heavy Flavor

Azimuthal anisotropy v_n

$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Phi_n))$$

PRL 118 (2017) 212301



Significant flow of open Heavy Flavor hadron

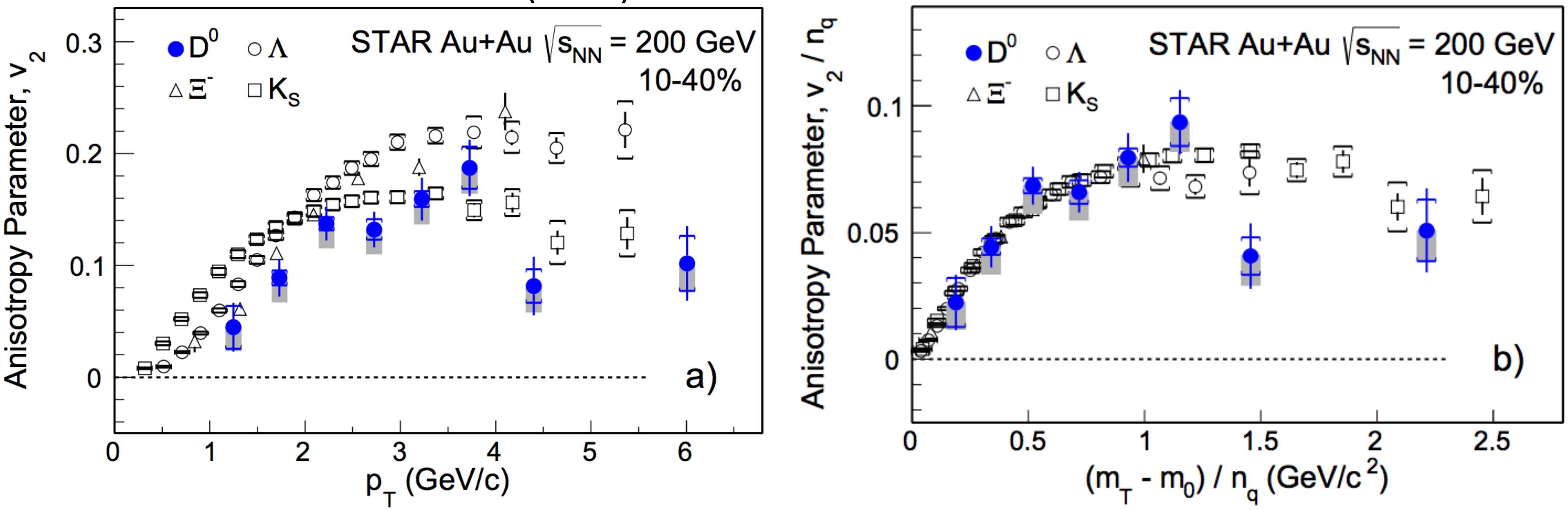
Charm quark fully "thermalized" with medium?

Collectivity of Heavy Flavor

Azimuthal anisotropy v_n

$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Psi_n))$

PRL 118 (2017) 212301



Significant flow of open Heavy Flavor hadron

Charm quark fully “thermalized” with medium?

Collectivity from coalescence?

Collectivity of Heavy Flavor

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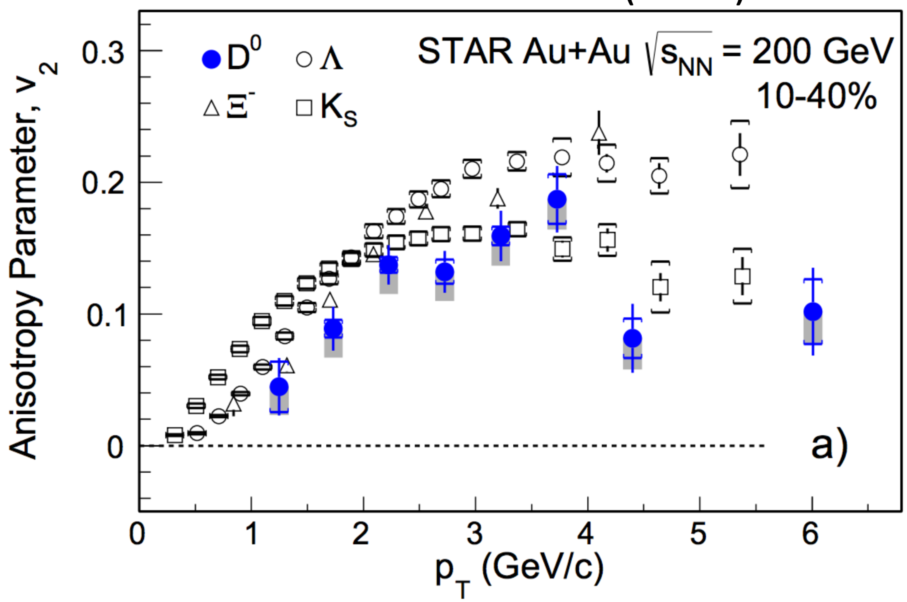
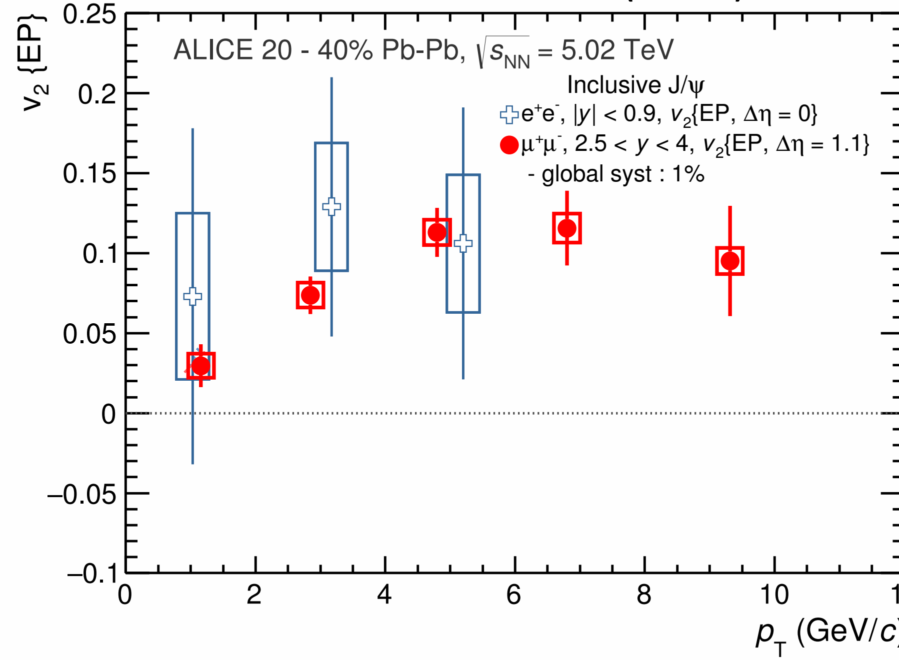
PRL 118 (2017) 212301



PRL 119 (2017) 242301



Significant flow of open Heavy Flavor hadron

Charm quark fully “thermalized” with medium?

J/Psi confirm charm quark collectivity

Collectivity of Heavy Flavor

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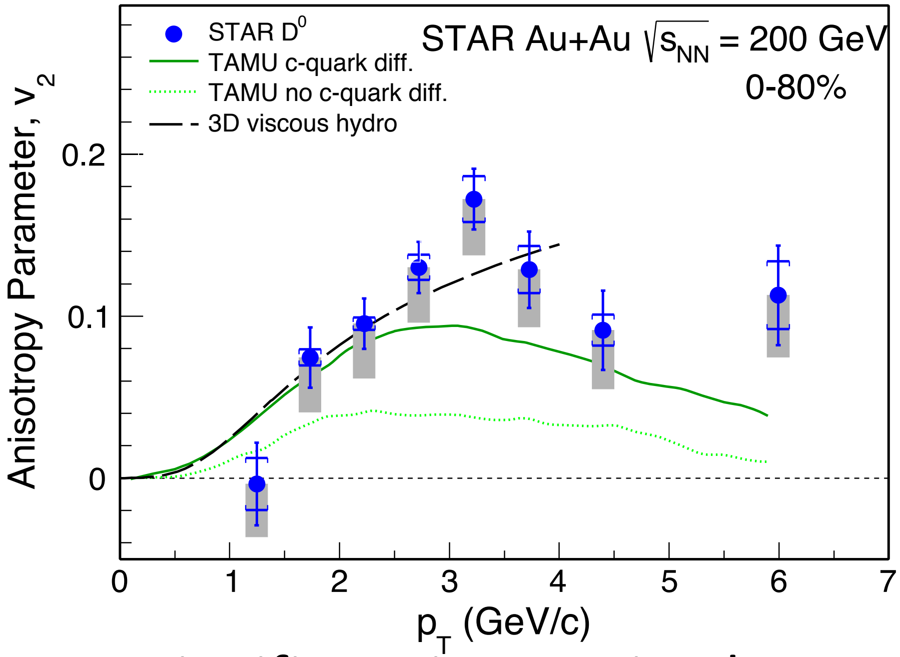
PRL 118 (2017) 212301



Significant interaction between open HF hadron and QGP

Charm quark fully “thermalized” with medium?

J/Psi confirm charm quark collectivity

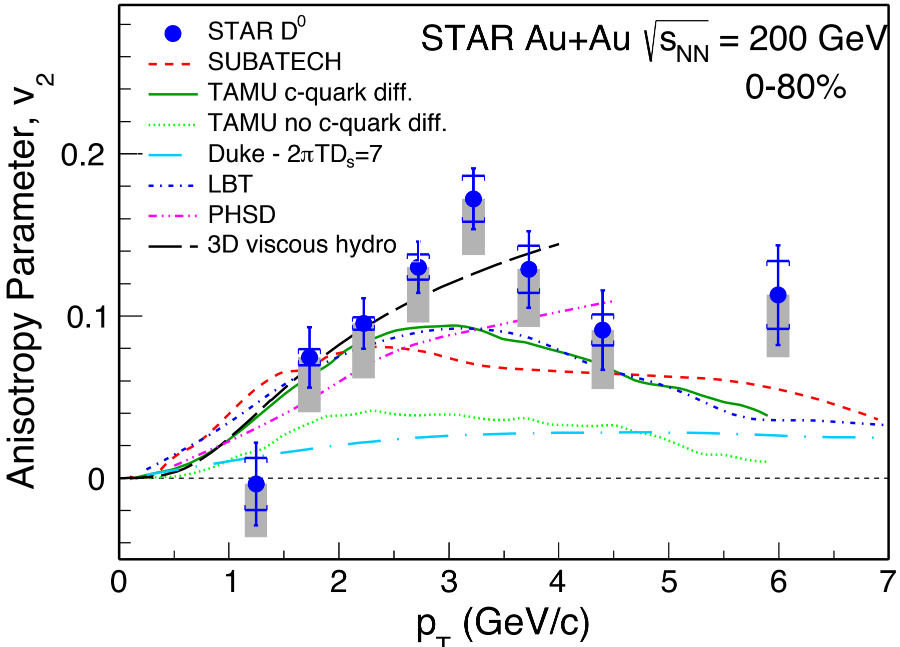
Charm quark diffusion needed to explain data

Collectivity of Heavy Flavor

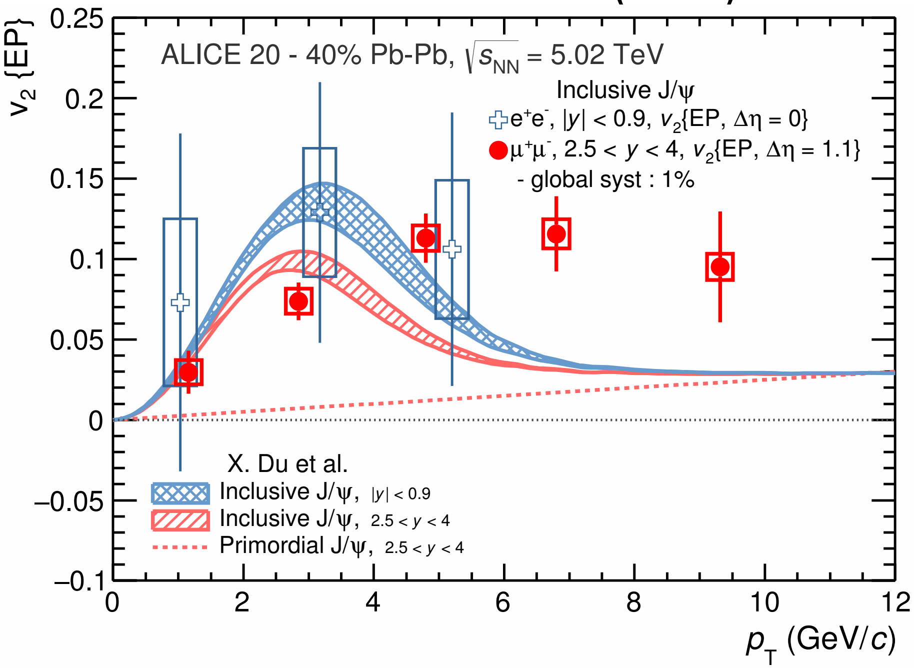
Azimuthal anisotropy v_n

$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Phi_n))$

PRL 118 (2017) 212301



PRL 119 (2017) 242301



Significant interaction between open HF hadron and QGP

Charm quark fully "thermalized" with medium?

J/Psi confirm charm quark collectivity

Charm quark diffusion needed to explain data

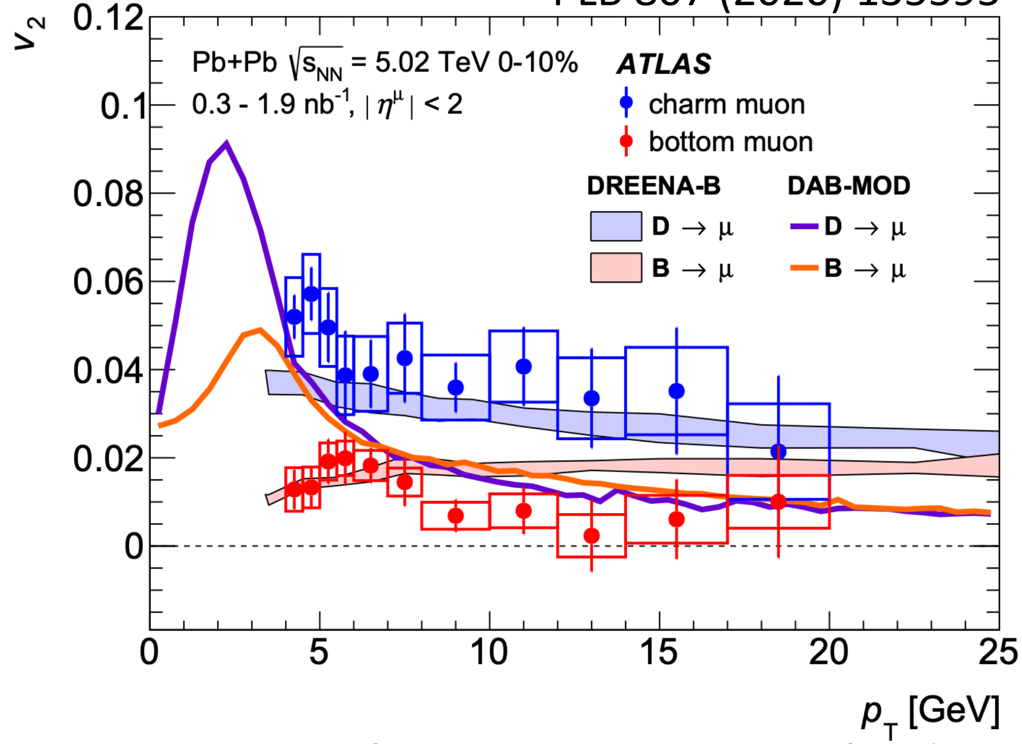
J/Psi flow mainly from regeneration

Collectivity of Heavy Flavor

Azimuthal anisotropy v_n

$\frac{dN}{d\phi} \propto 1+2\sum v_n \cos(n(\phi-\Phi_n))$

PLB 807 (2020) 135595



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Even bottom quark flows

Summary

Heavy flavor is the only slow hard probe for QGP studies

R_{AA}

Open Heavy Flavor provide unique constrain on collisional energy loss

Quarkonium serves as thermal meter of QGP

Flow

Strong evidence of QGP

Probe interaction strength in QGP at low p_T