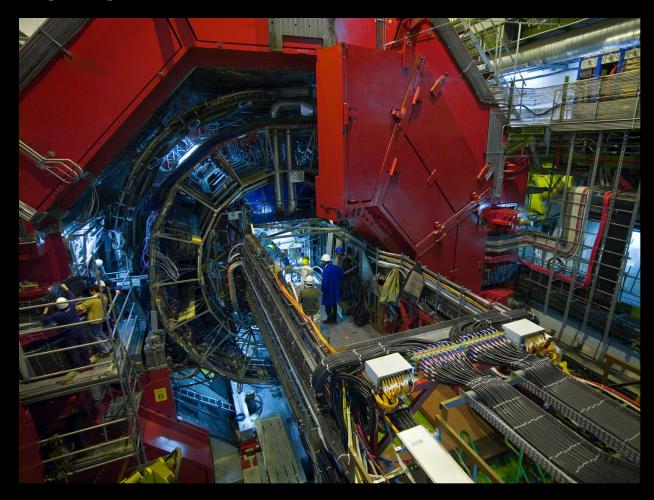
Selected Highlights of Recent Results from RHIC & LHC



Benvenuto in Italia!



Dear Guest, Welcome!

Why do we call Enoteca Nuvolari, "Italy winning?"

Because of all the victories that racing car driver

Tazio Nuvolari achieved for our nation, between 1920 and 1950.

Taking part in 353 races, many crossing the Chianti Area – Nuvolari won more than half of them. He won the "Mille Miglia" in 1930 with flat tyres, without a seat, using a wrench instead of the steering wheel and with his mechanic passed out at his side.

Our National hero showed the whole world that victories come

to whoever has the courage and heart to overcome difficulties.

It is with our most heartfelt pride, that we present to you our traditional Tuscan Cuisine in honour of Nuvolari the great achiever.

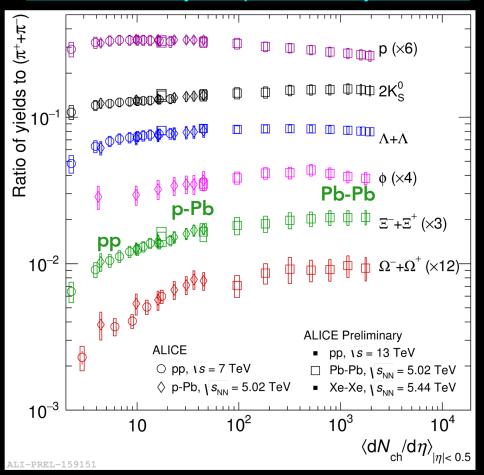
Good food and wine to celebrate your daily victories, great and small ones. Cheers!



Global Experimental Observations (pp, pPb, PbPb)

- → Smooth evolution of particle chemistry from small to large systems as a function of charged particle multiplicity ⇒ common origin in all systems
- → Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau).

Particle chemistry independent of System Size

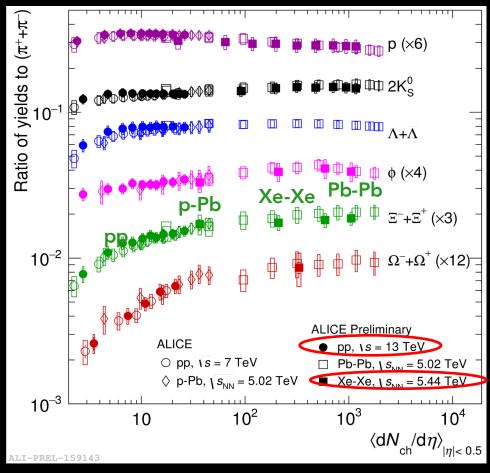


Global Experimental Observations (pp, pPb, XeXe, PbPb)

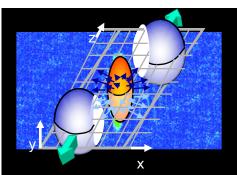
- → Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity

 ⇒ common origin in all systems
- → Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached.
- → Confirmed with new pp √s=13 TeV and Xe-Xe data!

Particle chemistry independent of System Size



Collective Flow



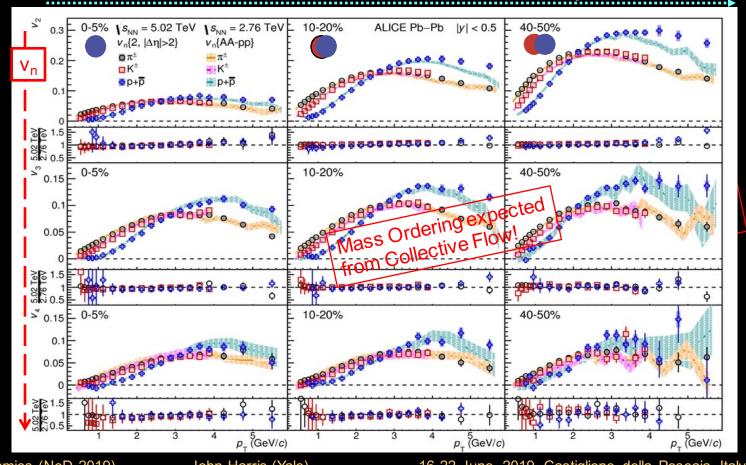
Elliptic Flow of Particles

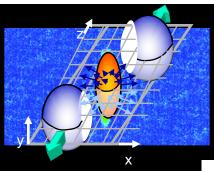
ALICE Collaboration, JHEP09(2018)006

Described well by hydrodynamics with low η/s

Peripheral collisions **Central collisions**

- **Fourier** decomposition of identified particle distributions eventby-event.
- Azimuthal asymmetries
- Vertical panels: $v_2(p_T), v_3(p_T), v_4(p_T)$
- Horizontal panels vs centrality





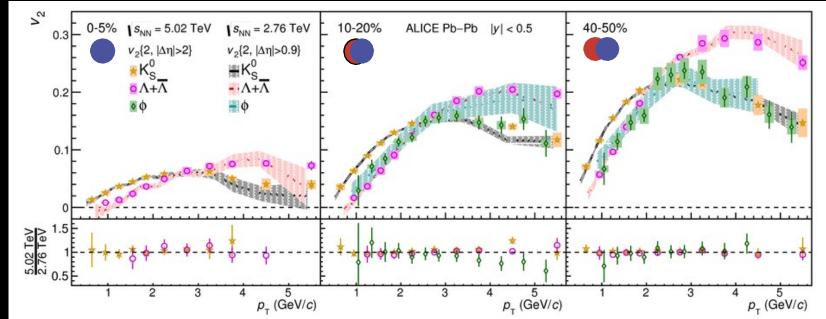
Elliptic Flow

ALICE Collaboration, JHEP09(2018)006

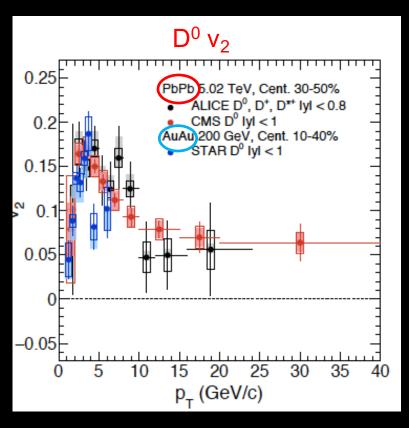
All measured light and strange quarks observed to flow!

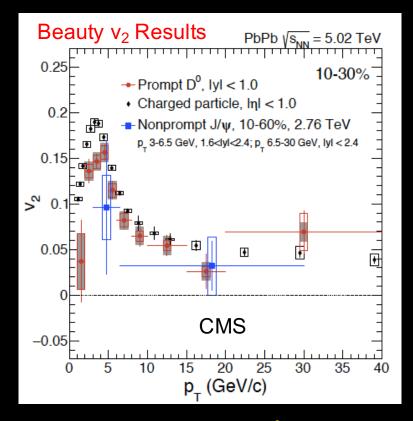
Central collisions

Peripheral collisions



v₂ Heavy Flavor Results



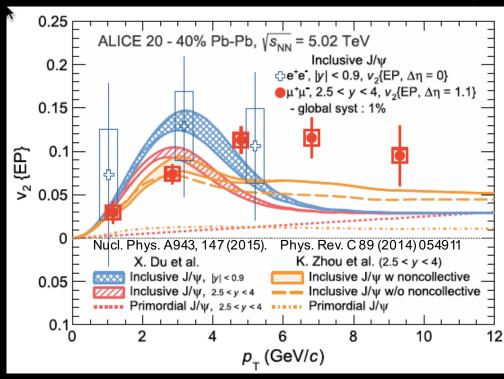


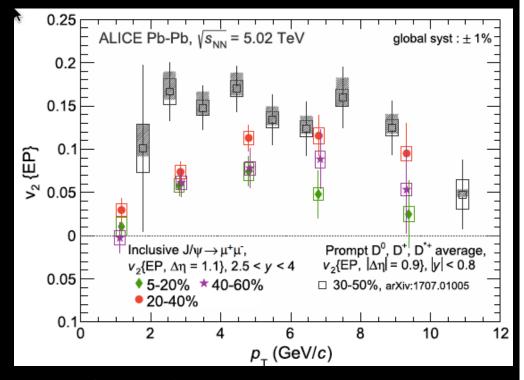
D⁰ results consistent over energy & experiments

Beauty results similar to D⁰...statistics?

$J/\psi - v_2$ Results

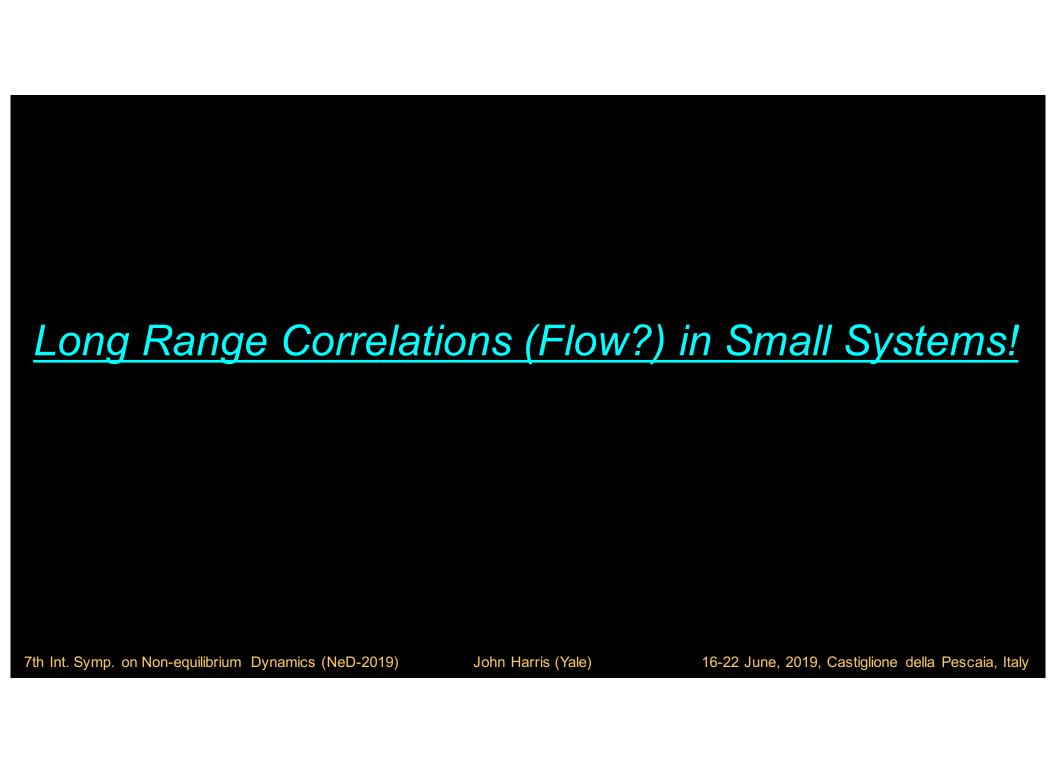
PRL 119, 242301 (2017)



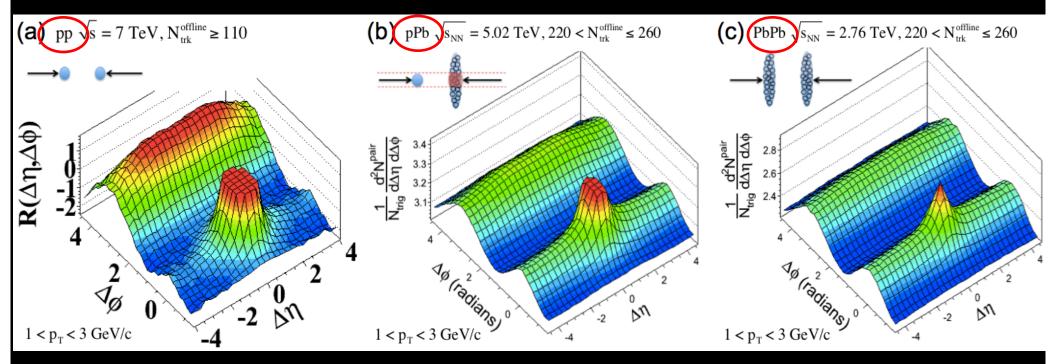


Inclusive J/ ψ v₂ at forward and midrapidity Significant forward J/ ψ v₂ , mid-y similar (statistics?) Transport Model calculations

J/ ψ v2 at forward rapidity in Pb-Pb Centralities 5–20%, 20–40%, and 40–60%. Compared to average of D-mesons at mid-y



<u>Small Systems – Long Range Correlations</u>



Long-range correlations in momentum space may arise from the initial state (glasma, hard scatterings (mini-jets), CGC?), or a final-state response to these and spatial fluctuations in initial geometry, and/or non-equilibrium hydro/transport and collective expansion?

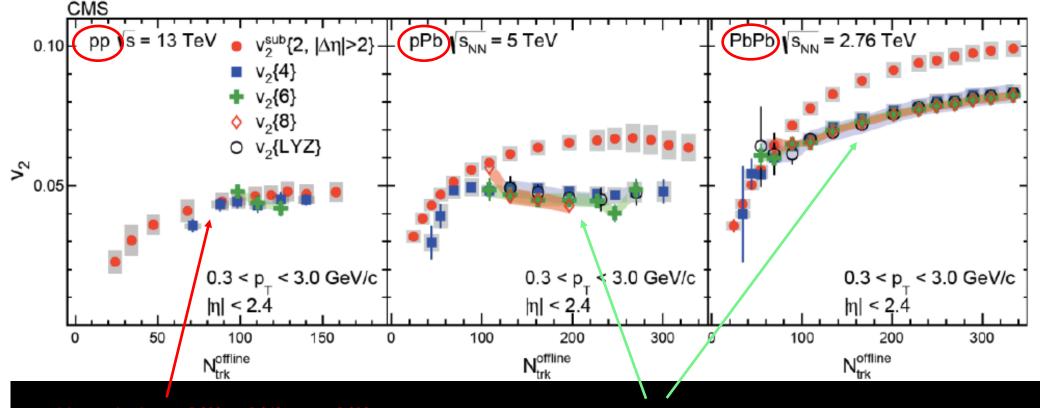
Need to disentangle the timescales for hydrodynamization mechanisms and collectivity

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

v₂ for Charged Particles in pp, pPb and PbPb at LHC

CMS Results from LHC



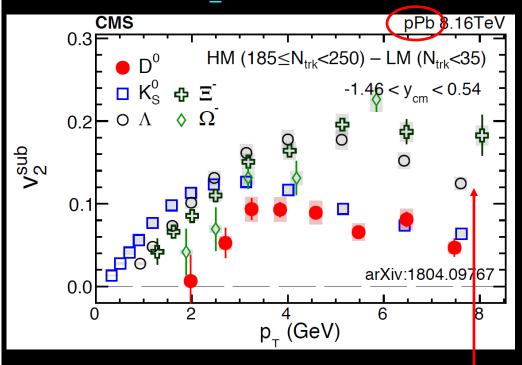
No ordering v2{2}, v2{4},v2{8}

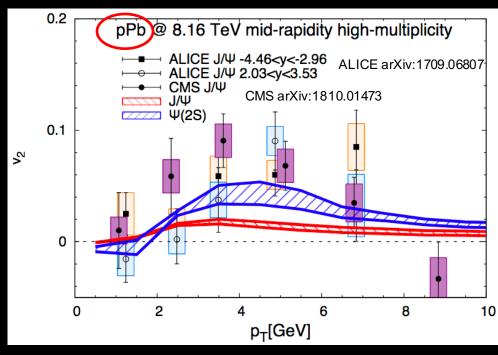
Note ordering $v2\{2\} > v2\{4.....8\}$

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

<u>v₂ for Identified Particles in pPb at the LHC</u>





Identified particle v_2 up to $p_T \sim 8 \text{ GeV/c}$

Residual non-flow effects?

Combination of different effects?

Geometry / "escape" mechanism?

Contains / Cocape mechanism:

CGC, fluctuations, other non-flow effects?

 $J/\psi v_2$ up to $p_T \sim 7$ GeV/c

Geometry response models under-predict.

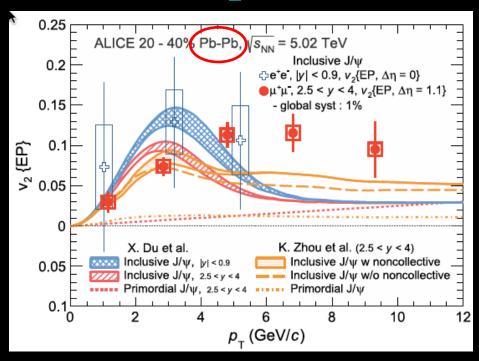
→ Suggests recombination!

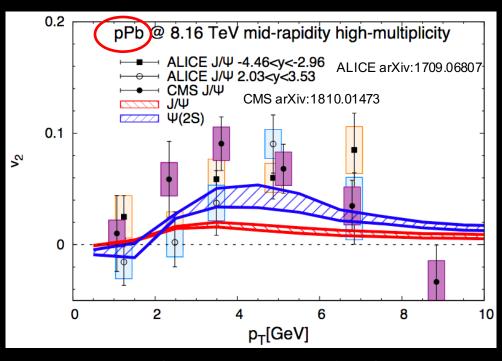
(some models suggest this alone is insufficient)

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

v_2 for J/ψ in pPb Compared to Pb-Pb





Identified particle v_2 up to $p_T \sim 8 \text{ GeV/c}$

Residual non-flow effects?
Combination of different effects?

Geometry / "escape" mechanism?

CGC, fluctuations, other non-flow effects?

$J/\psi v_2$ up to $p_T \sim 8 \text{ GeV/c}$

Geometry response models under-predict.

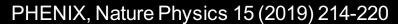
→ Suggests recombination!

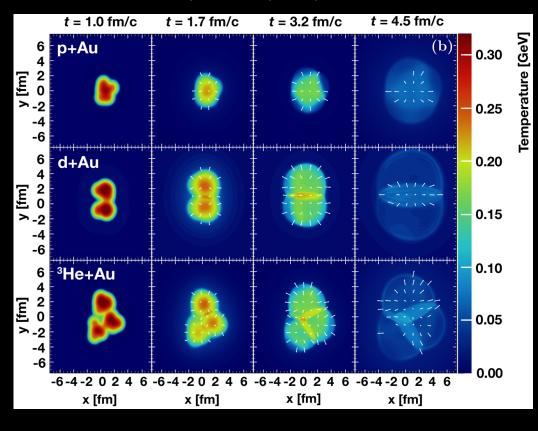
(some models suggest this alone is insufficient)

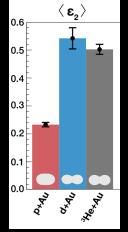
7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

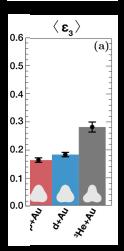
John Harris (Yale)

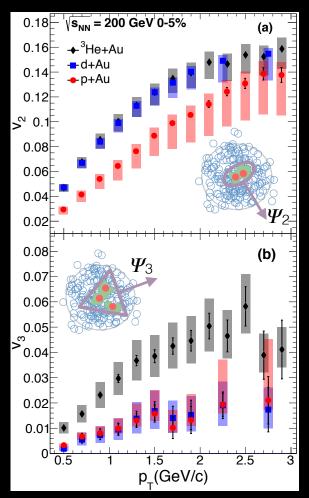
RHIC - Changing the Initial Geometry of the System







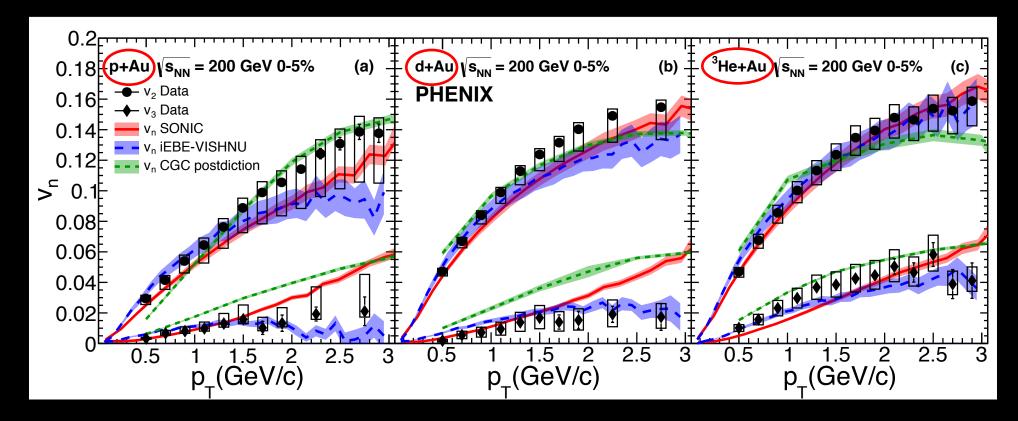




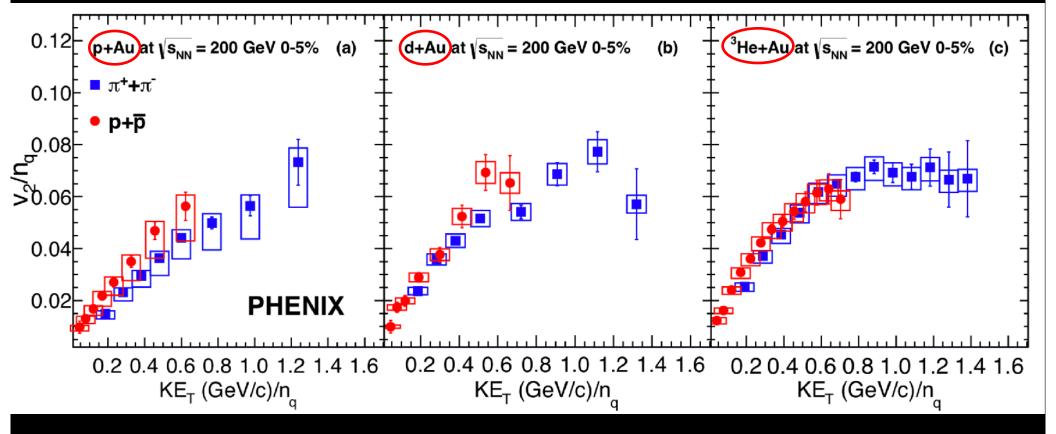
16-22 June, 2019, Castiglione della Pescaia,

Some Model Comparisons

PHENIX, Nature Physics 15 (2019) 214-220



Constituent Quark Scaling



Quark number scaling observed similar to AA Improves with system size!

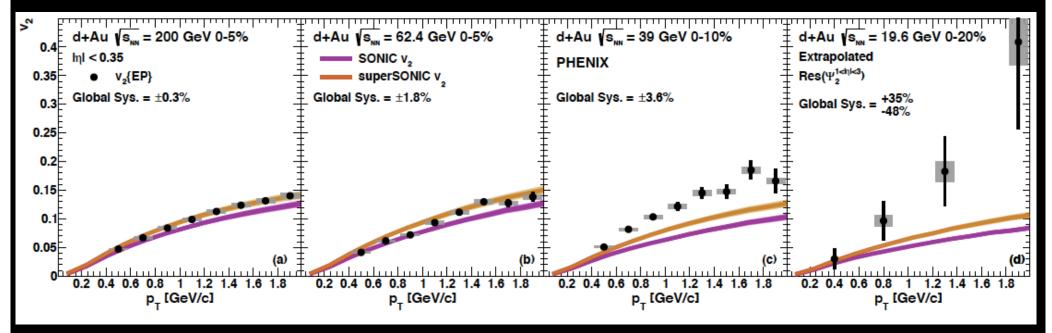
Flow? Rescattering?

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John Harris (Yale)

Hydro for Small Systems at Lower Energies?

PRC 96 (2017) 064905

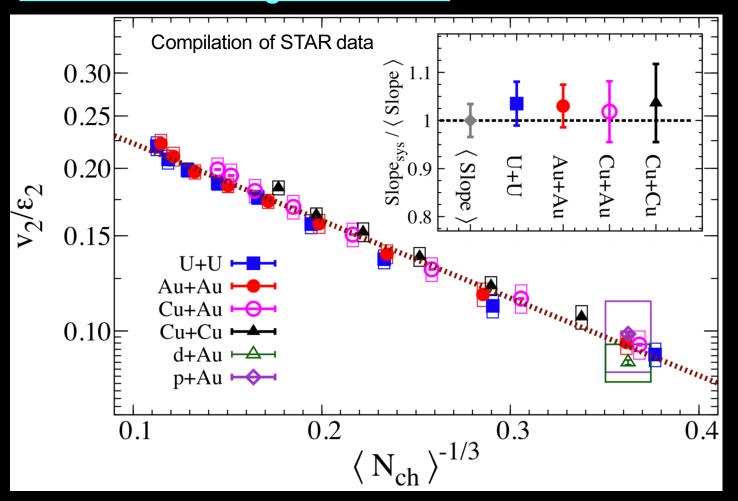


Hydro agrees with data except at lower energies (again non-flow effects?)

Universal Scaling with Size?

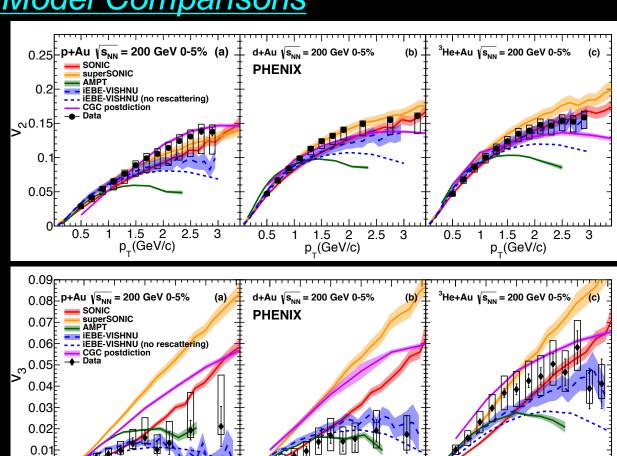
Does Size really matter on the overall scale of things?

Multiplicity matters!



More Model Comparisons

PHENIX, Nature Physics 15 (2019) 214-220



0.5

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

0.5

1 1.5 2 p_T(GeV/c)

16-22 June, 2019, Castiglione della Pescaia, Italy

0.5

2.5

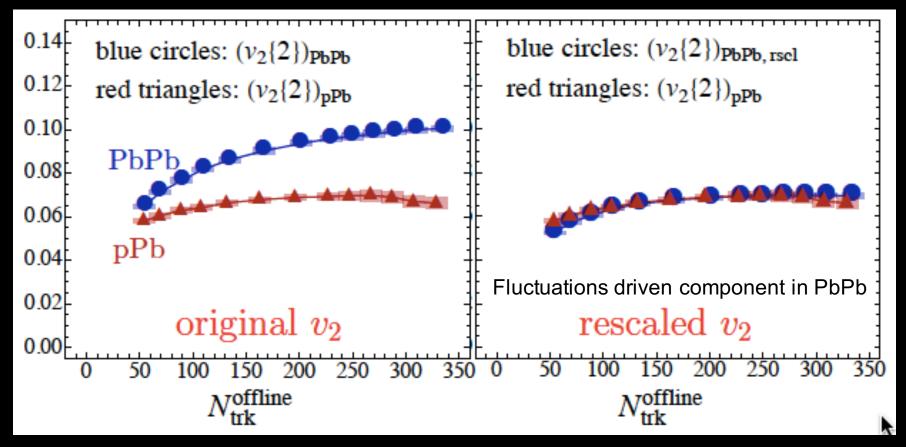
1 1.5 2 p_{_}(GeV/c)

2.5

1.5

p_(GeV/c)

Fluctuations and Geometry



Basar and Teaney, arXiv:1408.3411v1

Future Possibilities with a Symmetric Light System

<u>RHIC</u>

LHC

Table 2: Proposed Run-20 assuming 28 cryo-weeks, including five weeks of LEReC commissioning, an initial one week of cool-down and a one week set-up time for each collider energy.

Single-Beam	$\sqrt{s_{NN}}$	Run Time	Species	Events	Priority	Sequence
Energy (GeV/n)	(GeV)		•	(MinBias)		•
5.75	11.5	9.5 weeks	Au+Au	230M	1	1
4.55	9.1	9.5 weeks	Au+Au	160M	1	3
19.5	6.2 (FXT)	2 days	Au+Au	100M	2	5
13.5	5.2 (FXT)	2 days	Au+Au	100M	2	6
5.75	3.5 (FXT)	2 days	Au+Au	100M	2	2
4.55	3.2 (FXT)	2 days	Au+Au	100M	2	4
3.85	3.0 (FXT)	2 days	Au+Au	100M	2	7
100	200	1 week ²	0+0	400M	3	8
100	200	1 week		200M (central))	

Year	Systems, $\sqrt{s_{_{\rm NN}}}$	Time	$L_{ m int}$
2021	Pb-Pb 5.5 TeV	3 weeks	$2.3~\mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb-Pb 5.5 TeV	5 weeks	$3.9~\mathrm{nb}^{-1}$
	O–O, p–O	1 week	$500~\mu { m b}^{-1} { m and} ~ 200~\mu { m b}^{-1}$
2023	p-Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb-Pb 5.5 TeV	5 weeks	$3.8~\mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p-Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb-Pb 5.5 TeV	4 weeks	$3 \mathrm{nb}^{-1}$
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb ⁻¹ (optimal species to be defined)
	pp reference	1 week	

Table 4: Proposed Run-21 assuming 20 cryo-weeks, including an initial one week of cool-down and a one week set-up time for each collider energy.

Single-Beam	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events	Priority	Sequence
Energy (GeV/n)) .			(MinBias)		
3.85	7.7	12 weeks	Au+Au	100M	1	1
8.35	16.7	5 weeks	Au+Au	250M	2	2
100	200	1 week^4	О+О	400M 200M (central)	2	3

O+O run at RHIC in 2020 or 2021 for comparison between RHIC & LHC.

Identical Glauber geometry but different sub-nucleon fluctuations and 10x energy difference!

Why not rather $\alpha\alpha$ or AIAI?

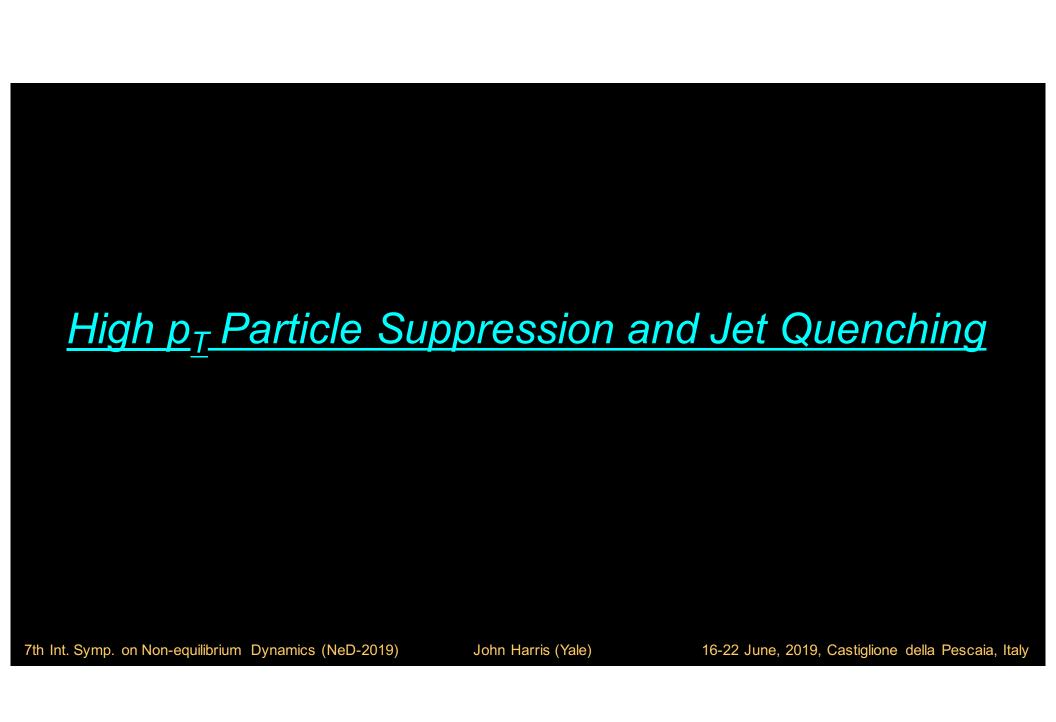
7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

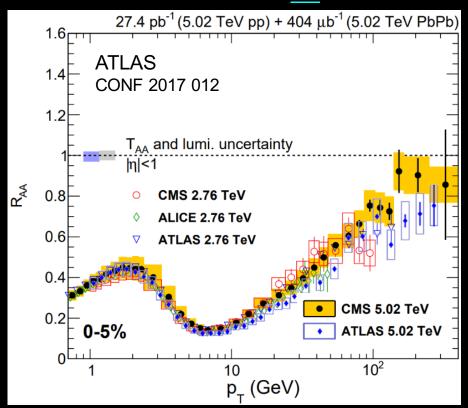
Now let's turn from the study of bulk phenomena to

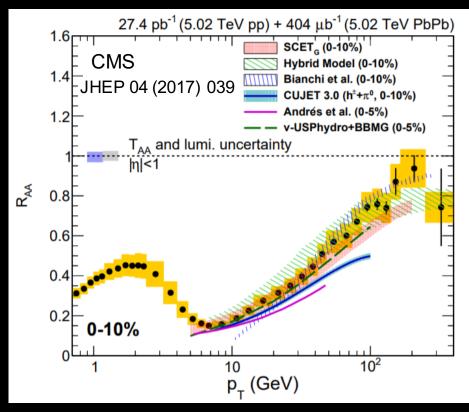
the use of penetrating probes!

i.e. high transverse momentum (p_T) particles and jets



<u> R_{AA} – LHC 5.02 TeV Pb-Pb</u>





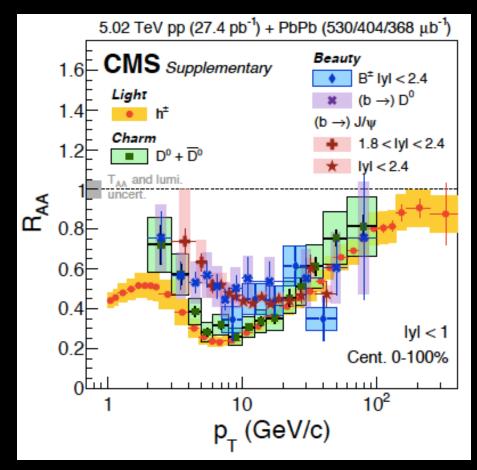
Strong suppression at RHIC and LHC & the same at lower p_T LHC suppression ~same at 2.76 and 5.02 TeV Much less suppression at LHC at highest p_T

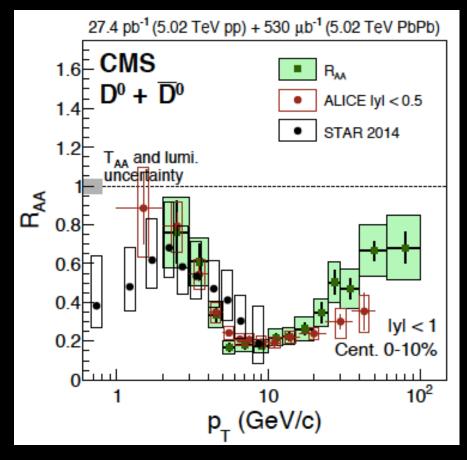
Models? Comments?

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R_{AA} – Heavy Flavor Results & LHC/RHIC Comparisons





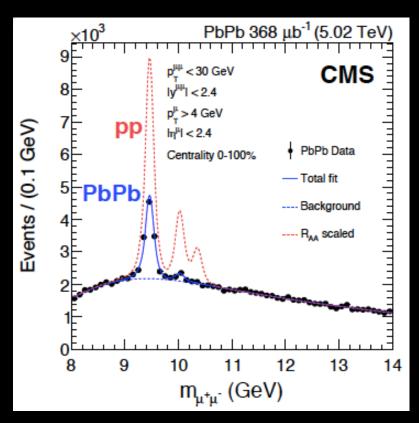
"Suppression hierarchy"?

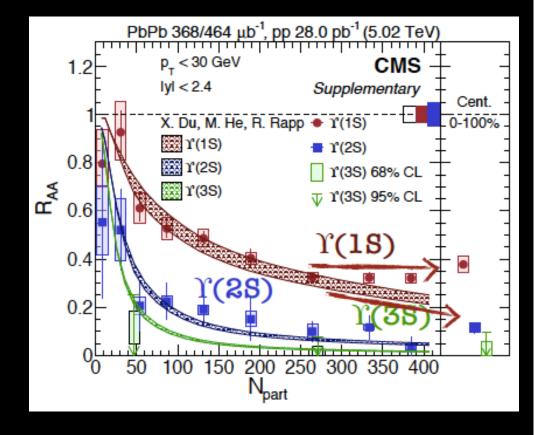
D⁰ results consistent over energy & experiments

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High Statistics CMS Quarkonium Results

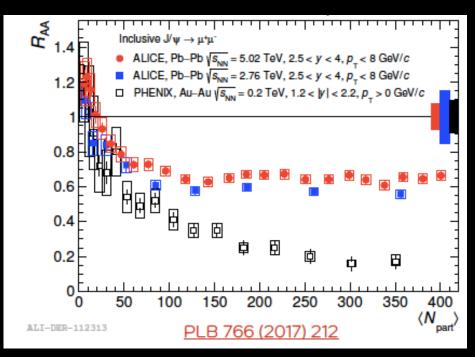


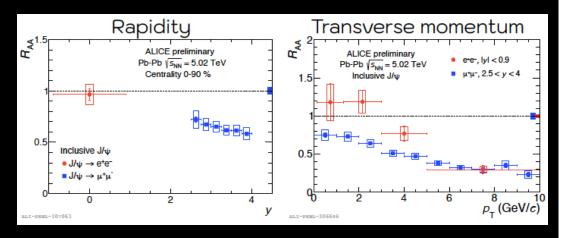


Y(3S) not visible

Y suppression agrees with transport models Some deviation in most central events

J/ψ Results: Comparison RHIC and LHC





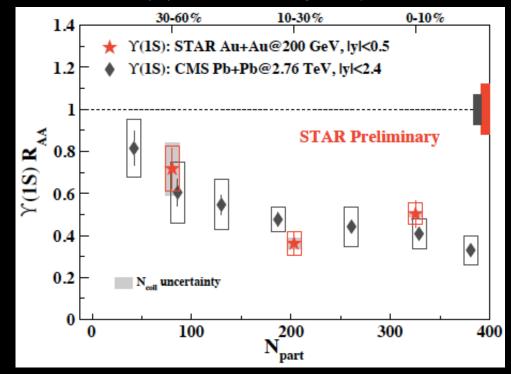
More suppression forward. Less suppression at low p_T

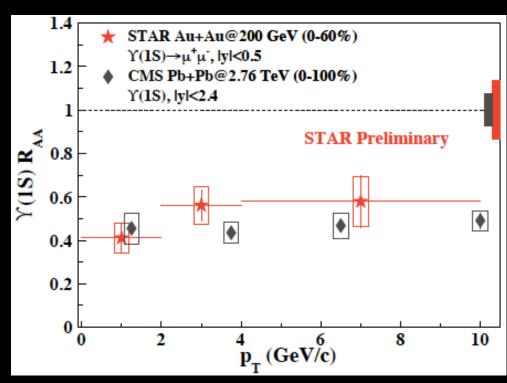
Forward results:
Suppression stronger at RHIC
Suppression ~10% less for 5.02 vs 2.76 TeV

Y(1S) Comparison RHIC and LHC

CMS, PLB 770 (2017) 357.

STAR preliminary (RHIC Users Mtg 2019)



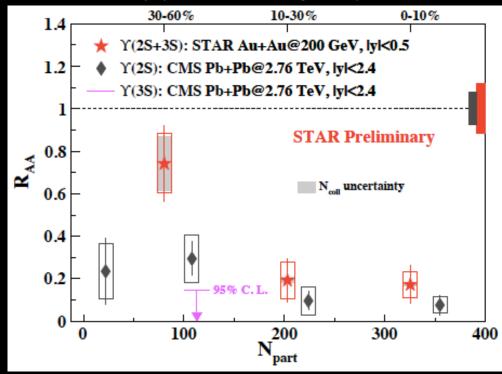


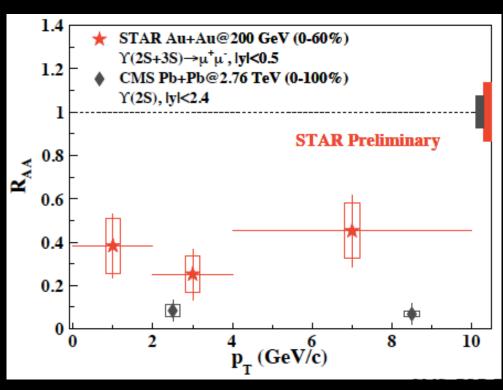
Y(1S) suppression similar for RHIC and LHC

Y(2S) and Y(3S) Comparison RHIC and LHC

CMS, PLB 770 (2017) 357.

STAR preliminary (RHIC Users Mtg 2019)





Y(2S) and Y(3S) strongly suppressed

Less suppression at RHIC than LHC in peripheral collisions Low cross yields & statistics!

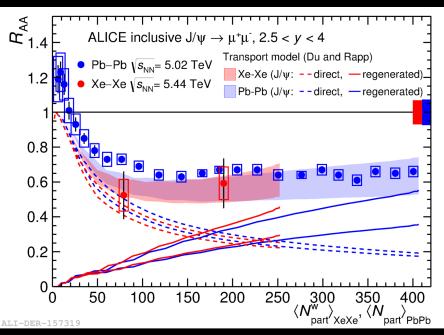
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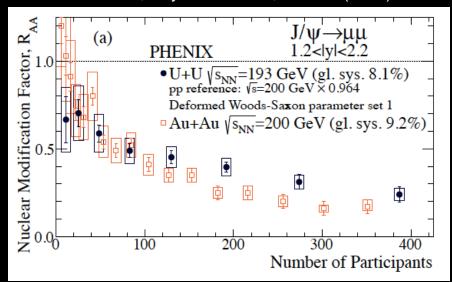
J/W Suppression at LHC and RHIC Compared to Transport Model

J/Ψ: $R_{AA}(LHC) > R_{AA}(RHIC) \rightarrow less suppression at LHC?$

ALICE, arXiv:1805.04383



PHENIX, Phys. Rev. C 93, 034903 (2016)



Pb-Pb and Xe-Xe at LHC:

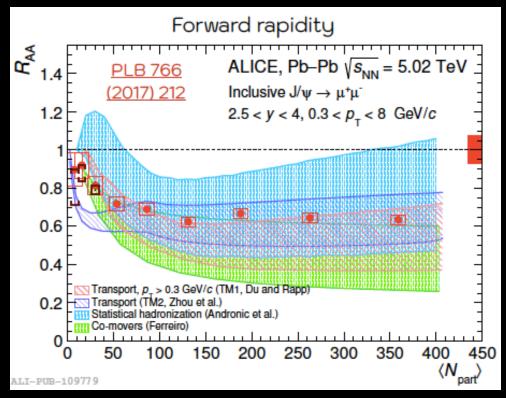
Transport models indicate stronger suppression & more regeneration in Xe-Xe vs Pb-Pb

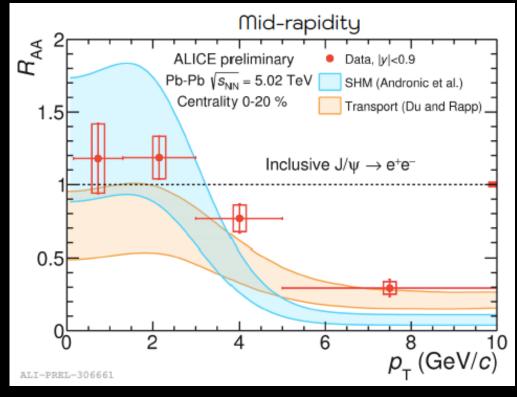
J/y in fact has significant regeneration (recombination of c c-bar quarks) at LHC

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John Harris (Yale)

J/ψ Results: Comparison Theory and Data





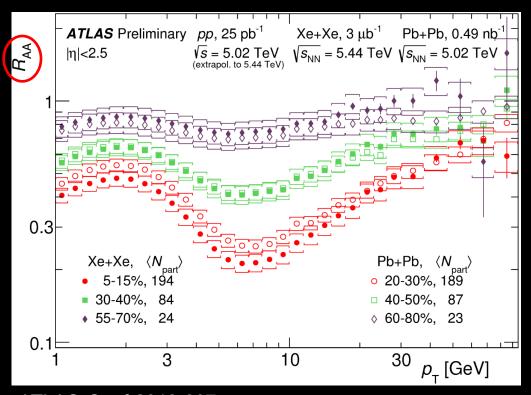
Less suppression at low p_T, regeneration! Approximate agreement data and models Theory uncertainties large –

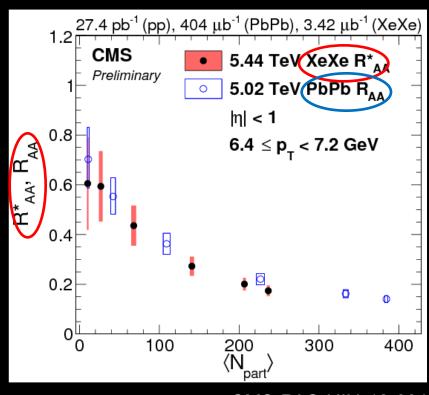
need more precise cc-bar cross section measurements vs rapidity (uncertainties)

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John Harris (Yale)

R_{AA} and System Size





ATLAS-Conf-2018-007

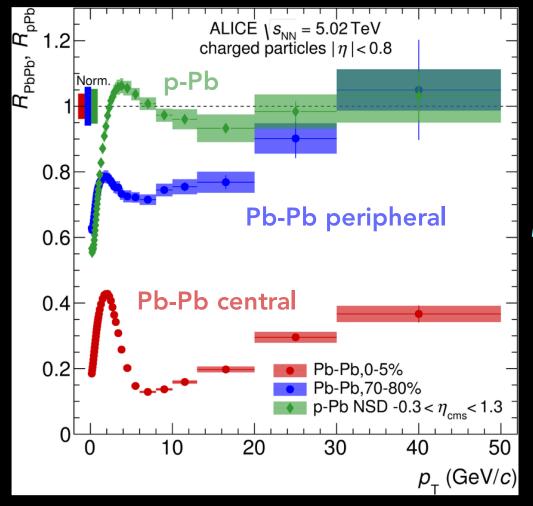
CMS-PAS-HIN-18-004

Approximate scaling of charged particle R_{AA} with N_{part} (System Size)

R_{pPb} Compared to R_{PbPb} (a) pp $\sqrt{s} = 7 \text{ TeV}, N_{trk}^{offline} \ge 110$ **(b)** pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}, 220 < N_{trk}^{offline} \le 260$ (C) PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}, 220 < N_{trk}^{offline} \le 260$ $\mathbf{R}(\Delta\eta,\Delta\phi)$ φΔρ μΔρ 3.3 3.3 3.1 3.1 $1 < p_T < 3 \text{ GeV/c}$ $1 < p_T < 3 \text{ GeV/c}$ $1 < p_T < 3 \text{ GeV/c}$ $27.4 \text{ pb}^{-1}(pp) + 35 \text{ nb}^{-1}(pPb) + 404 \mu b^{-1}(PbPb) 5.02 \text{ TeV}$ $\Delta_{ m recoil}^{50-100\%}$ ZNA $s_{NN} = 5.02 \text{ TeV } R$ CMS T_{pA} uncertainty Nuclear modification factor pp lumi. uncertainty $\Delta_{\text{recoil}}^{\text{0-20}\% \, \text{ZNA}}$ 8.0 8.0 pp, $\sqrt{s} = 5.02 \text{ TeV}$ $L_{int}^{pp} = 25 \text{ pb}^{-1}$ 0.8 $TT{12,50} - TT{6,7}$ 0.6 Anti- $k_{\rm T}$ charged jets, R = 0.2 $-0.43 < y_{TT}^* < 1.36$; $-0.23 < y_{jet}^* < 1.17$ $\pi - \Delta \varphi < 0.6$ pPb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ $L_{int}^{pPb} = 25 \text{ nb}^{-1}$ 0-90% **ATLAS** Preliminary -2.0<y<1.5 0.6 Syst. uncert. - 0.4 GeV/c spectrum jet shift ATLAS-CONF-2016-108 0-100% CMS-HIN-15-015 20 25 30 35 35 40 45 p_{_} [GeV] $\overline{{}^{10^2}}$ 10 10^{2} $p_{_{\mathrm{T}}}^{10}(\mathrm{GeV})$ $p_{\mathrm{T.iet}}^{\mathrm{ch}}\left(\mathrm{GeV}/c\right)$

No suppression for high p_T probes $-p-Pb \sim pp$

<u>High p_T Hadrons in p-Pb NOT Suppressed – Compared to Pb-Pb</u>



p-Pb and Pb-Pb Collisions

$$R_{\rm AA} = \frac{N_{\rm AA}^{\rm particle}}{N_{\rm coll} N_{pp}^{\rm particle}}$$

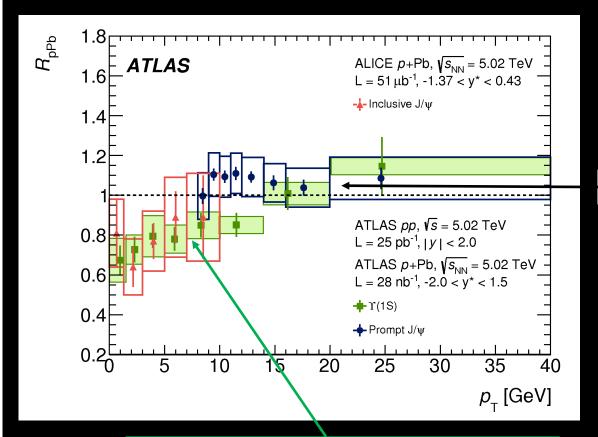
 R_{AA} (p-Pb) ~ 1 R_{AA} (Pb-Pb) more suppressed in central collisions than peripheral

[arXiv:1805.04399]

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

LHC p-Pb Quarkonia Results

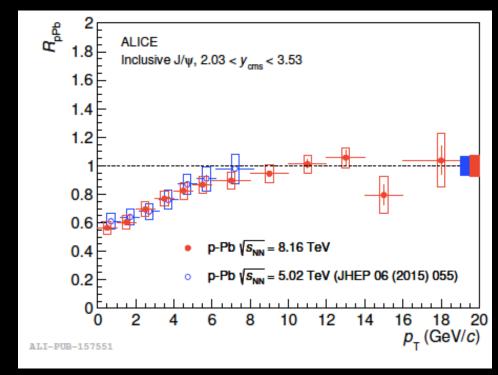


 $-J/\psi - R_{pPb} \sim \text{unity for } p_T \sim 8-40 \text{ GeV}$

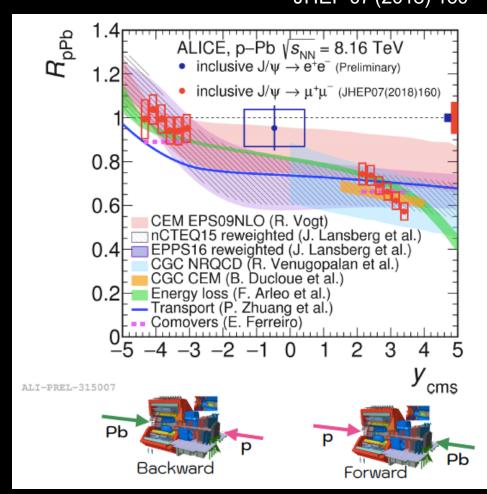
 $Y(1S) - R_{pPb}$ is suppressed for $p_T < 15 \text{ GeV}$

ALICE p-Pb Quarkonia Results

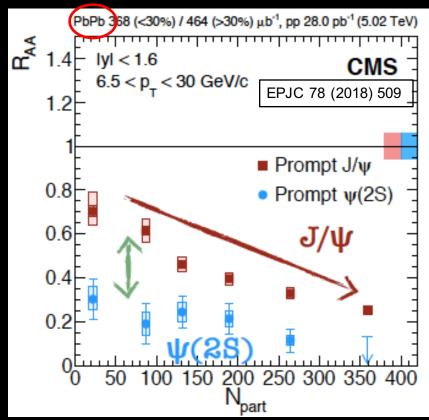
JHEP 07 (2018) 160



Forward suppression of low p_T J/ψ No significant suppression in backward or midrapidity Agreement between models and data

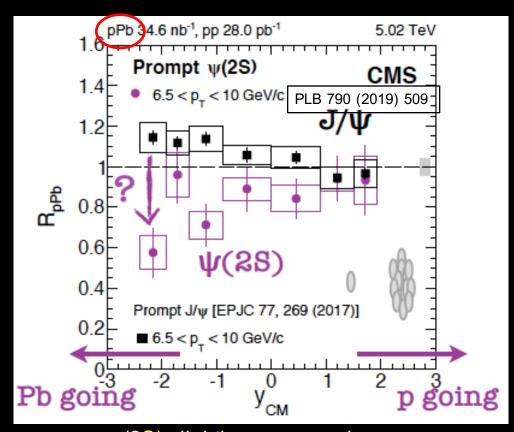


CMS p-Pb (Compared to Pb-Pb) Quarkonium Results



J/ ψ and ψ (2S) strongly suppressed ψ (2S) more strongly suppressed than J/ ψ Increasing suppression with centrality

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

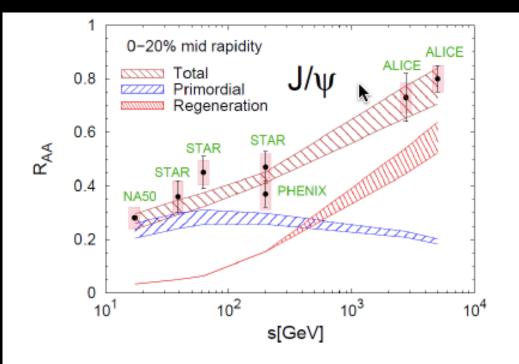


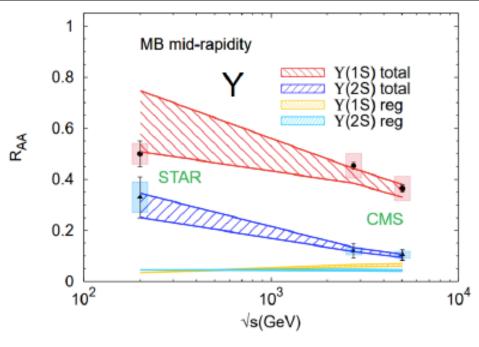
 $\psi(2S)$ slightly suppressed Should be ~ J/ ψ (nPDFs & E-loss) Indicates comover medium effect?

John Harris (Yale)

16-22 June, 2019, Castiglione della Pescaia, Italy

Charmonium and Bottomonium Energy Dependence & Transport

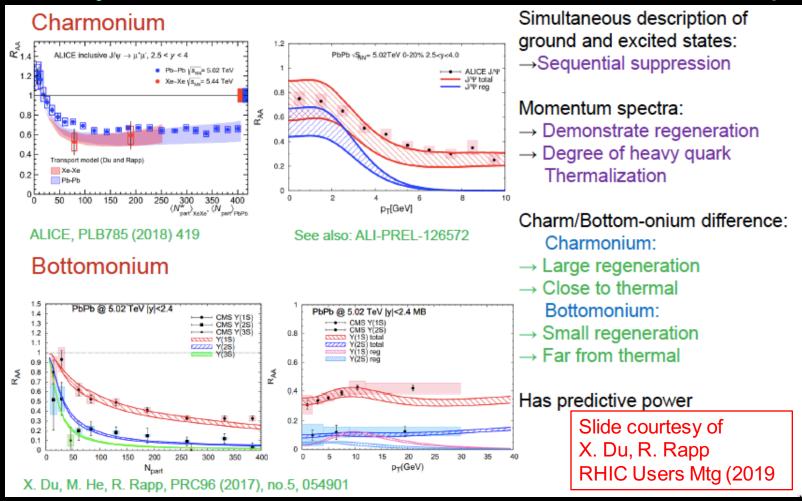




R. Rapp, X. Du, NPA967 (2017) 216

Slide courtesy of X. Du, RHIC Users Mtg (2019)

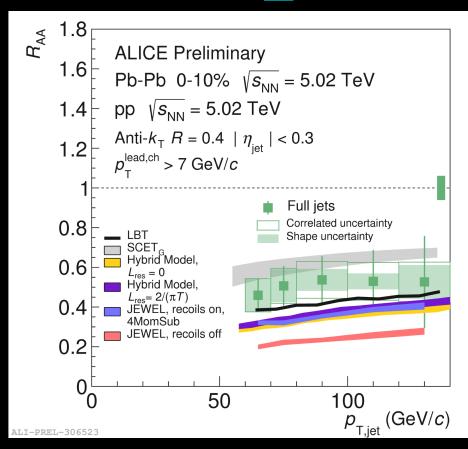
Summary from Charmonium and Bottomonium Transport

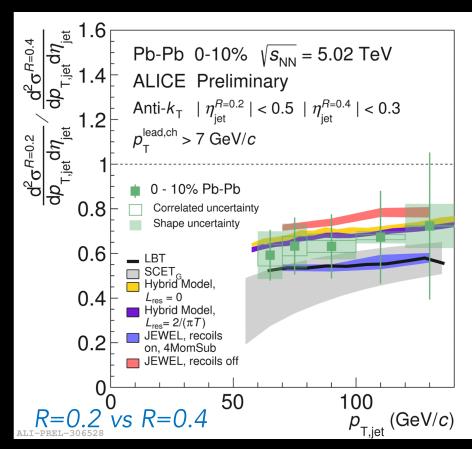




Jets & Jet Substructure

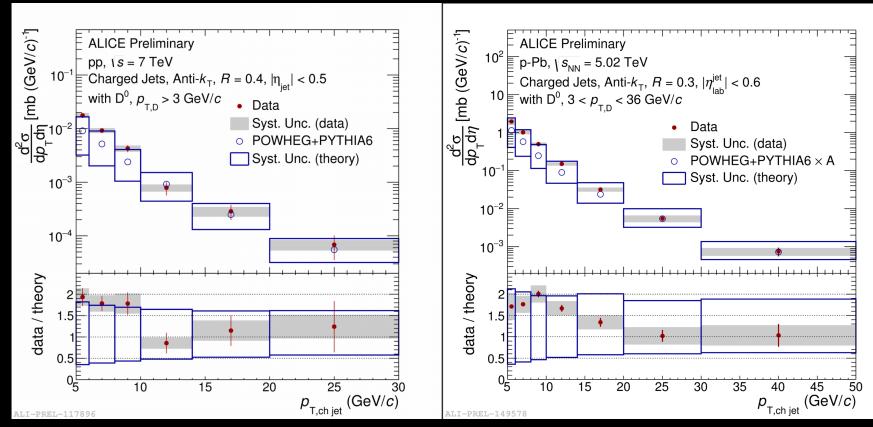
Jet R_{AA} in Pb-Pb Collisions in ALICE





Low p_T Jet R_{AA} – Models describe trends of the data with some differences!

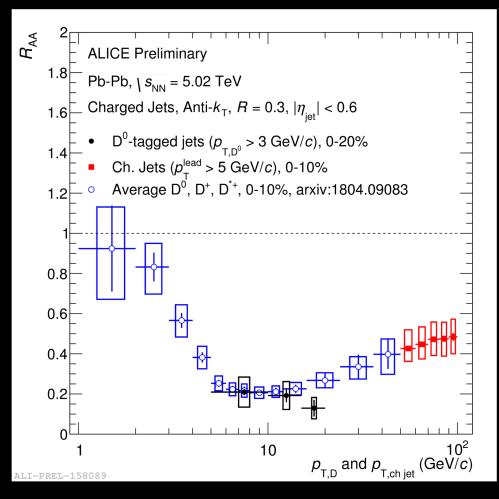
<u>D-Tagged Jets in pp and p-Pb – Described by pQCD</u>



D-meson tagged jets agree with pQCD predictions in both systems

→ presents a well understood baseline for Pb-Pb collisions.

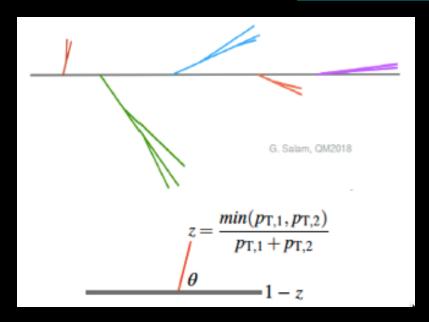
D-Tagged Jets vs Inclusive Full Jets in Pb-Pb



Suppression of D^0 -tagged jets similar to that of D^0 -mesons at low p_T .

Suppression of charged jets observed up to 100 GeV/c.

Groomed Jet Substructure



Soft Drop Refs:

M. Dasgupta et al. JHEP 1309 (2013) 029,

A. Larkoski et al, JHEP 1405 (2014) 146.

Soft Drop Approach – attempts to reconstruct the shower history of the jet to understand parton energy loss mechanisms in medium

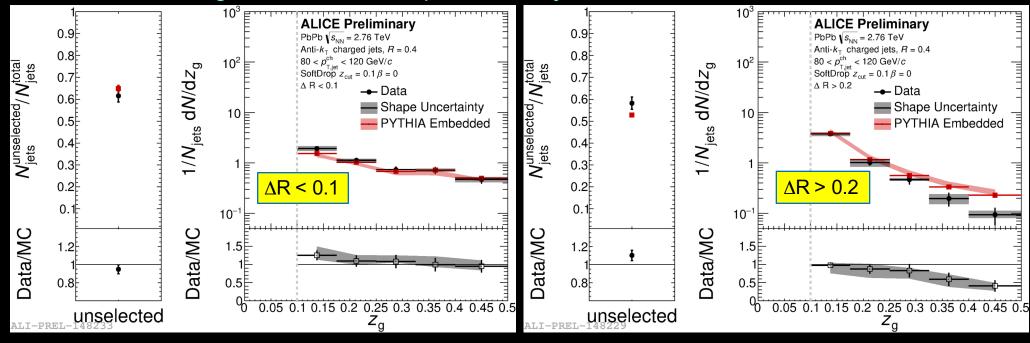
- Cluster jets with anti-k_T
- Then re-cluster with C/A to get angularly-ordered sequence in the parton shower.
- Undo the last clustering step and check $z > z_{cut} (\Delta R/R_0)^{\beta}$
- Discard softer subjet and repeat.

Splittings described by the

z_g- momentum fraction of 1st splitting R_g- angular separation of 1st splitting

Groomed Jet Substructure in ALICE

Here are 2 groomed sub-samples of sub-jets based on ΔR between the two.



 ΔR < 0.1 – suggestive of enhanced collinear splittings at small z_q

 ΔR > 0.2 a depletion of large angle splittings appears at large z_q

Note: R_q- angular separation of 1st splitting

z_q - momentum fraction of 1st splitting

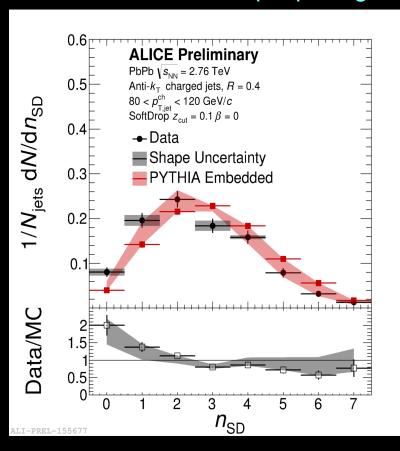
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Groomed Jet Substructure

Number of Soft Drop Splittings

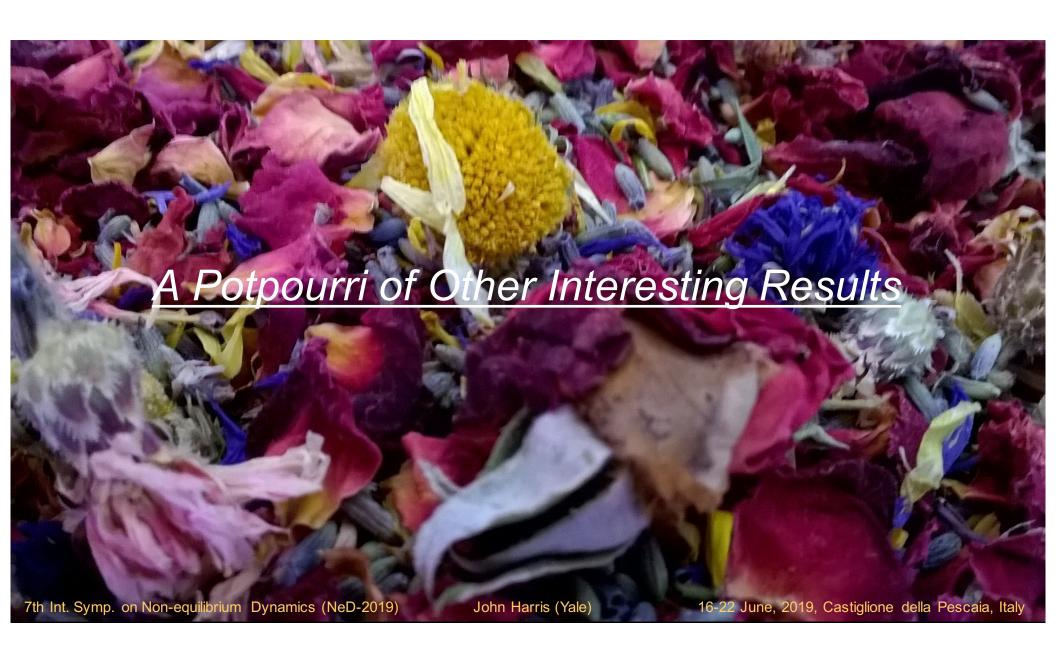


Soft Drop Approach -

- Cluster jets with anti-k_T
- Then re-cluster with C/A to get angularlyordered sequence in the parton shower.
- Check if splitting fulfills Soft Drop condition on z_{cut}

Jet substructure appears unmodified despite large energy loss in the medium.

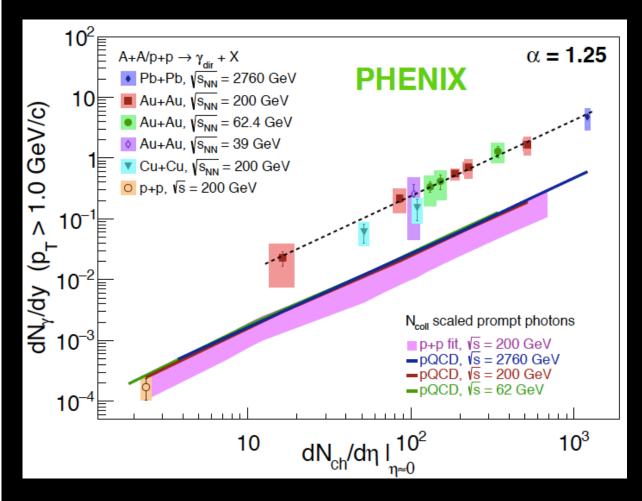
Data on number of soft drop splittings in medium shifted only slightly lower compared to PYTHIA.



Photons

see: PHENIX arXiv:1805.04.084 (to appear in PRL)

RHIC & LHC Photon Yields for Different Systems



PHENIX arXiv:1805.04.084 (tbp in PRL)

Common Scaling at RHIC and LHC Ncol-scaled pp not in line!

7th Int. Symp. on Non-equilibrium Dynamics (NeD-2019)

John Harris (Yale)

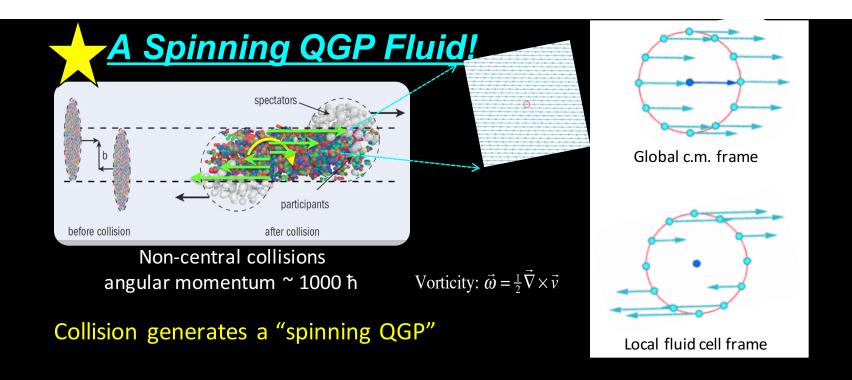
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Vortical Flow

see: Nature 548, 62-65 (2017), STAR Collaboration

and

new STAR paper arXiv:1905.11917v1 last week

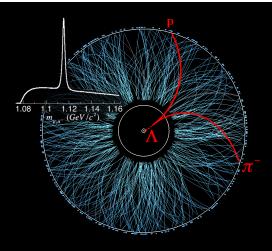


A large vorticity is measured!

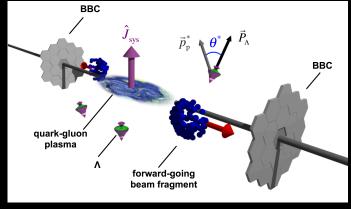
Nature 548, 62–65 (2017), STAR Collaboration

Local orbital angular momentum (vorticity), transferred to spin degree of freedom of final-state hadrons, is measured!

Graphics courtesy M. Lisa and Wikipedia



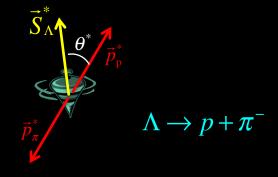
<u>STAR</u>



Forward BBCs estimate Reaction Plane: $\vec{B} \parallel \vec{\omega} \parallel \hat{J}_{\text{sys}}$

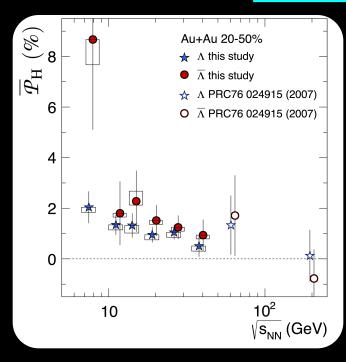
Λ Baryon is "self-analyzing"

- reveals its polarization by preferentially emitting daughter proton in spin direction
 - E. Cummins, Weak Interactions (McGraw-Hill, 1973)



Correlate $ec{p}_{ extsf{p}}^{*}$ and $\widehat{J}_{ ext{sys}}$

STAR Nature Result



√s _{NN} (GeV)	7.7	11.5	14.5	19.6	27	39
٨	3.6σ	3.5σ	2.4σ	3.1σ	3.5σ	1.1σ
anti-∧	2.2σ	2.1σ	1.1σ	2.4σ	2.9σ	1.6σ

	BES average		
٨	6.8σ		
anti-∧	3.7σ		

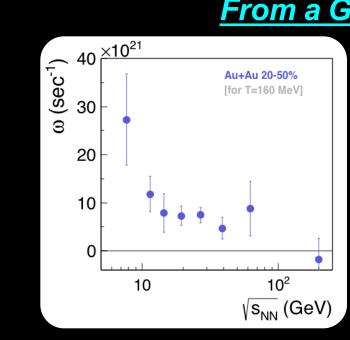
How is fluid/transport affected?

- Localized vortex generation
- Viscosity dissipates vorticity at larger scale

Vorticity – a fundamental (sub-femtoscopic) structure of the QGP and its generation

Nature 548, 62-65 (2017), STAR Collaboration

From a Global Perspective



- Solar subsurface flow: $\omega \sim 10^{-6} \text{ s}^{-1}$
- Ocean flows: ω ~ 10⁻⁵ s⁻¹
- Terrestrial atmosphere: $\omega \sim 10^{-4} \text{ s}^{-1}$
- High vorticity (10⁻⁴ s⁻¹) in the "collar" of Jupiter's Great Red Spot
- Core of supercell tornado : $\omega \sim 10^{-1} \text{ s}^{-1}$
- Heated, rotating soap bubbles: $\omega \sim 10^2 \text{ s}^{-1}$
- Max vorticity in bulk superfluid He: ω ~ 150 s⁻¹
 - R. Donnelly, Ann. Rev. Fluid Mech. 25, 325 (1993)
- Max vorticity in nanodroplets of superfluid He: 10⁶ s⁻¹
 - Gomez et al, Science 345 (2014) 906

Photon-photon Scattering

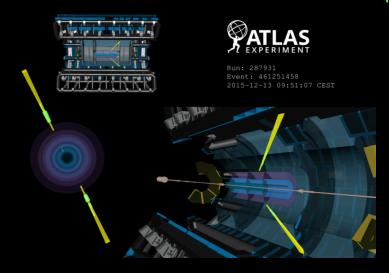
see: Nature Physics 13, 852-858 (2017), ATLAS Collaboration

Photon-photon Scattering in Pb-Pb

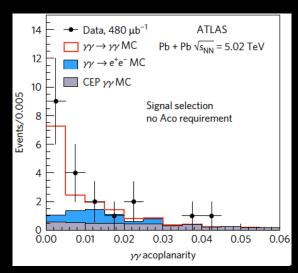
Nature Physics 13, 852-858 (2017), ATLAS Collaboration

5.02 TeV Pb-Pb "Ultra-peripheral Collisions"

Coherent production enhanced by $Z^4 \sim 4.5 \times 10^7$ in Pb-Pb relative to pp



Back-to-back γ (m_{$\gamma\gamma$}=24 GeV) with no other production



Significance vs background = 4.4

Trento, Italy, 11 - 15 Sett. 2017

Società Italiana di Fisica, 103° Congresso Nazionale

John Harris (Yale)

Enhanced Strange Particle Production

see: Nature Physics 13, 535-539 (2017), ALICE Collaboration

Enhanced production of multi-strange hadrons in

high-multiplicity pp collisions

Nature Physics 13, 535-539 (2017), ALICE Collaboration

- Strangeness enhanced in high multiplicity pp
- At high multiplicity pp reaches values where Pb-Pb saturates
- pp and p-Pb ratios have similar behavior and values
- No apparent dependence on cm energy
- Models cannot reproduce pp data!

