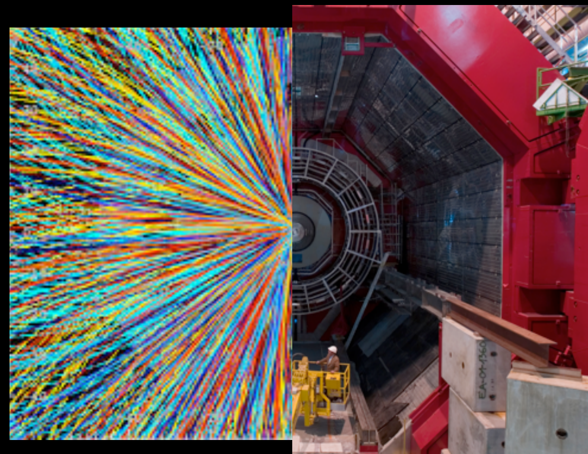
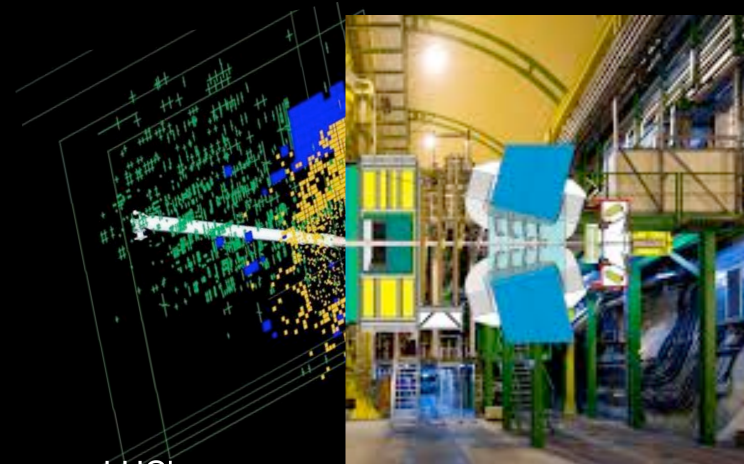
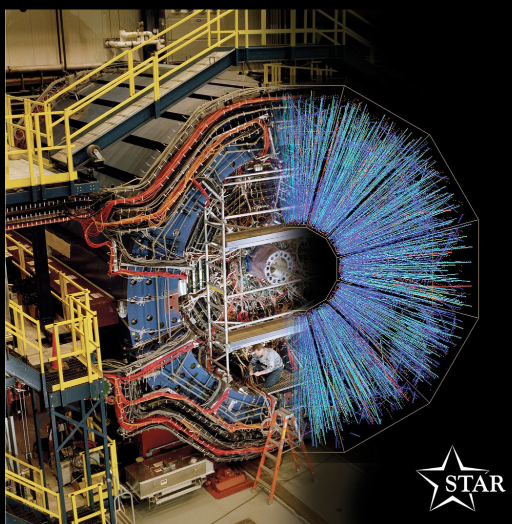
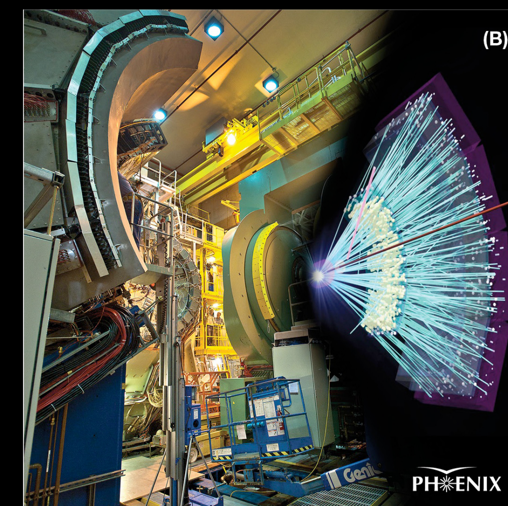




LHCb

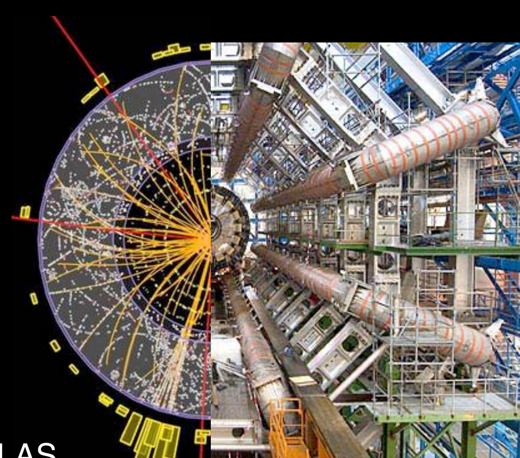


QCD in Heavy-Ion Physics

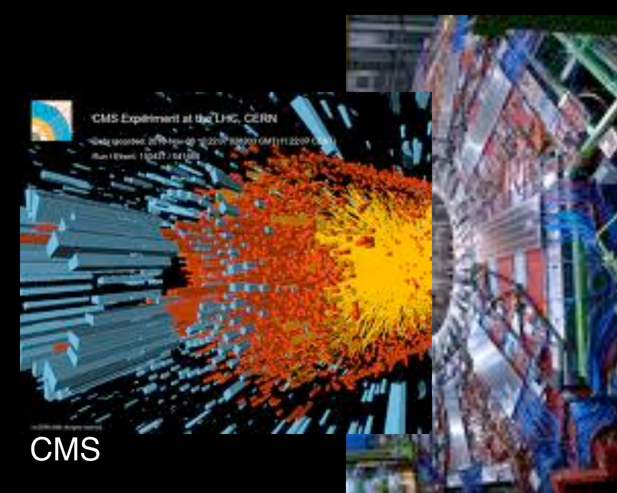


Helen Caines - Yale University

ALICE



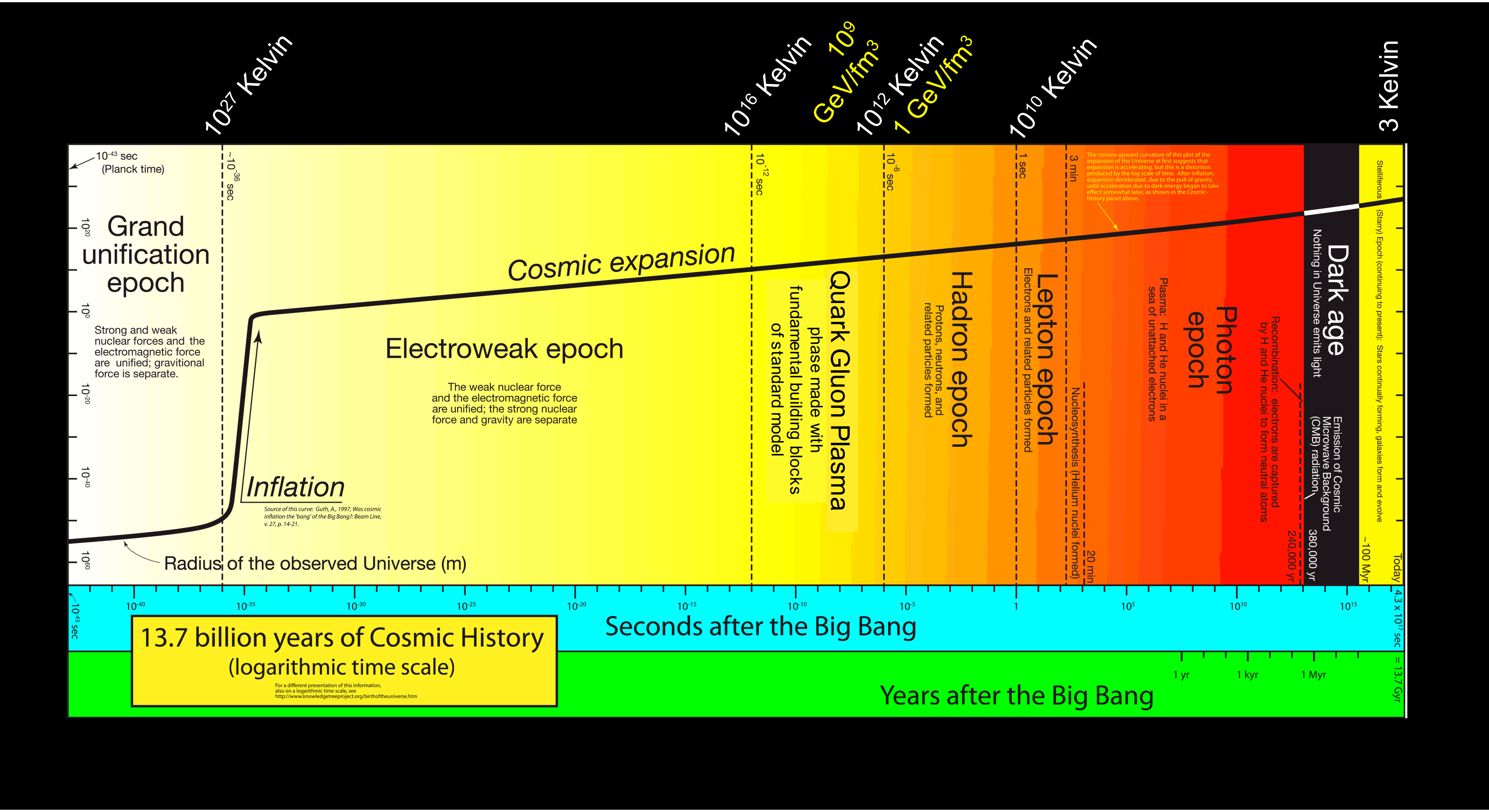
ATLAS



CMS

Our cosmic history

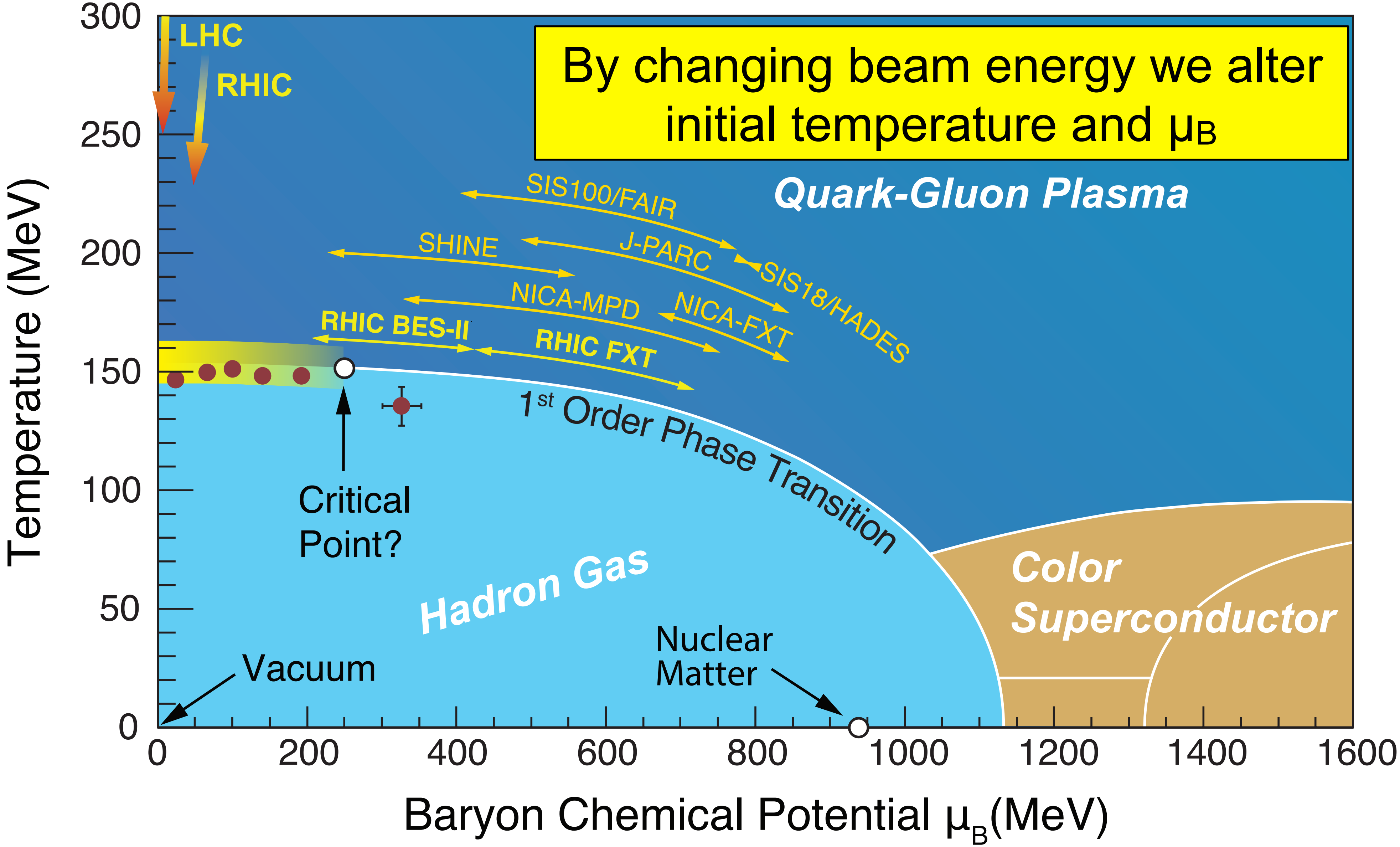
Image:P.Sorensen



Many phases and phase transitions in the early universe

So far only QGP-hadron phase transition can be recreated and studied in lab

Exploring the phase diagram of QCD



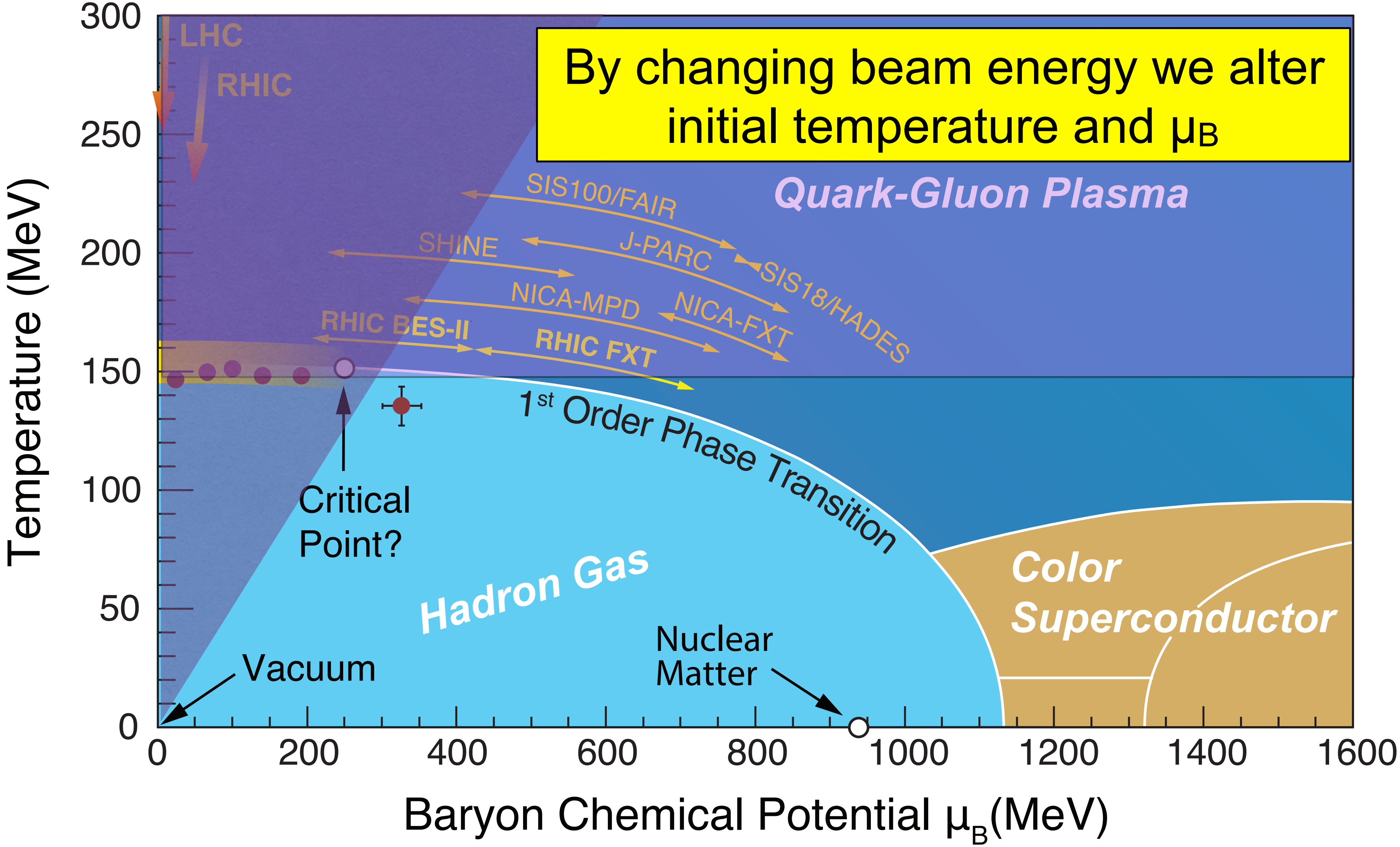
Lattice Gauge Theory - increasing accuracy at μ_B=0

T_c = 154(9) MeV

ε_c = 0.18-0.5 GeV/fm^3 = (1.2-3.3) $\rho_{nuclear}$

Exploring the phase diagram

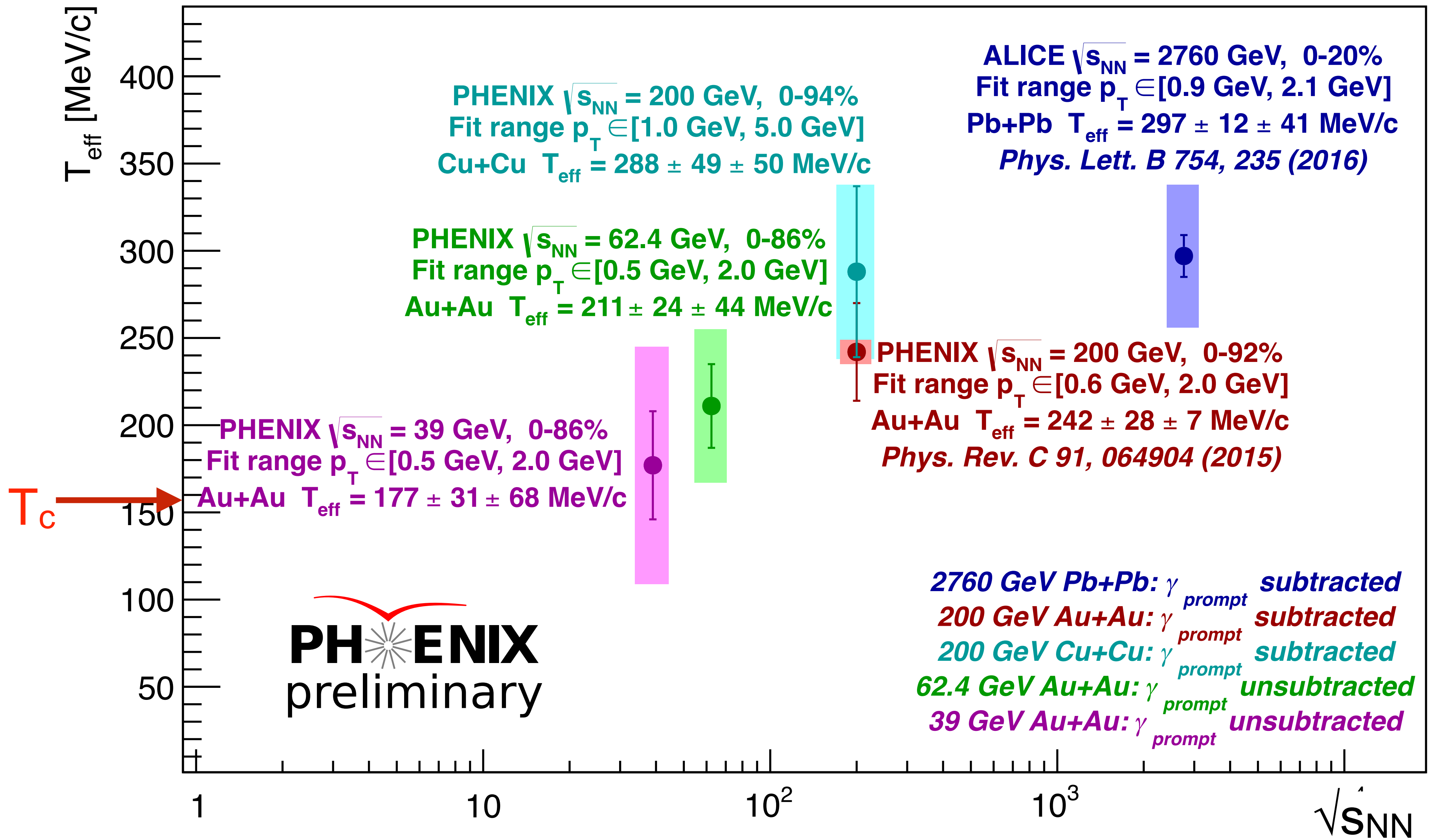
Bazavov et al, arXiv:1701.04325
Karsch INT-BES 2017



Calculations disfavor C.P. in region
$\mu_B/T < 2$ and $T/T_C(\mu_B=0) > 0.9$

Early conditions: Temperature

Initial temperature well above T_C even at $\sqrt{s_{NN}}$ = 39 GeV



T from direct photon p_T spectra

Searching for a Critical Point

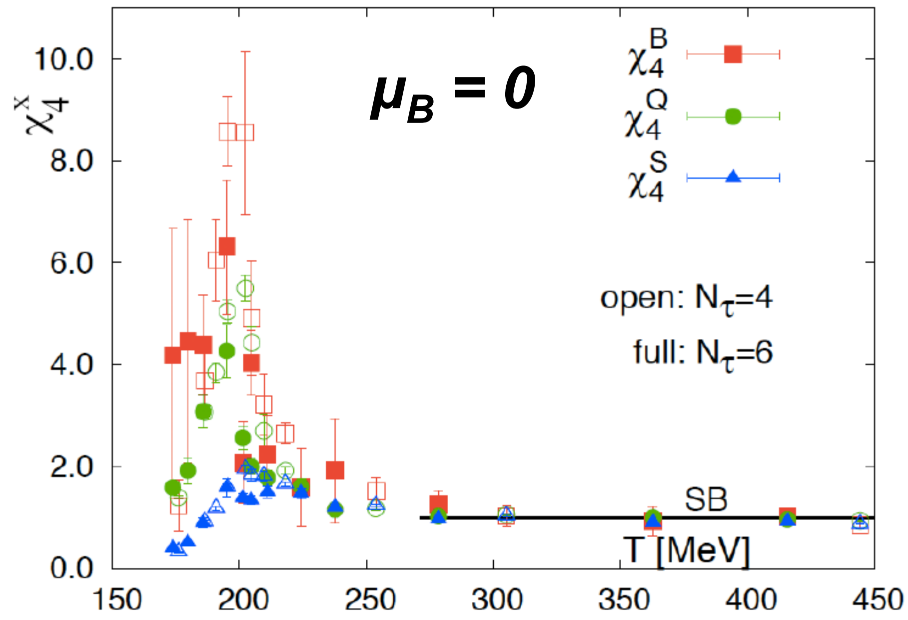
Critical Points:

divergence of susceptibilities

e.g. magnetism transitions

divergence of correlation lengths

e.g. critical opalescence



Lattice QCD:

Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point

Searching for a Critical Point

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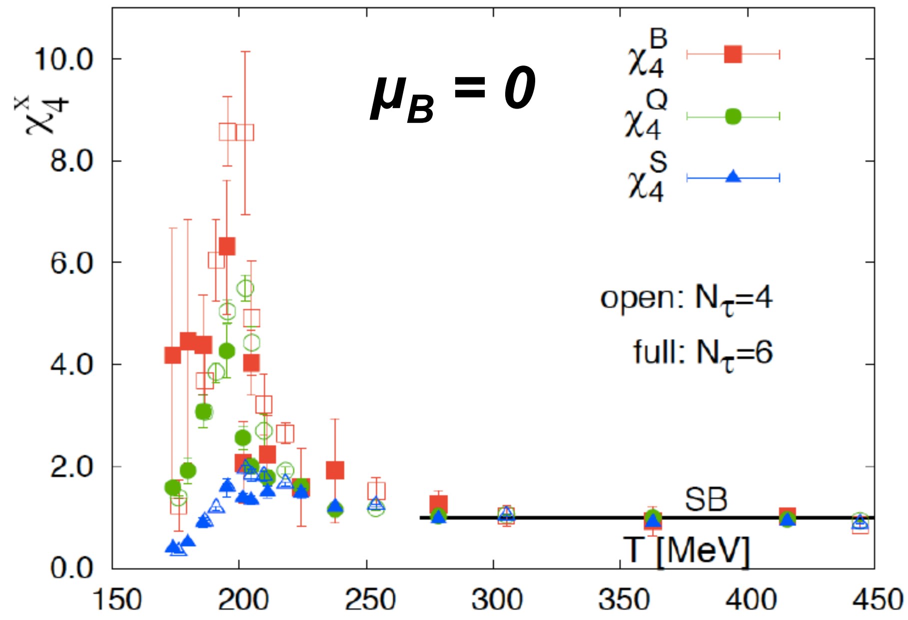

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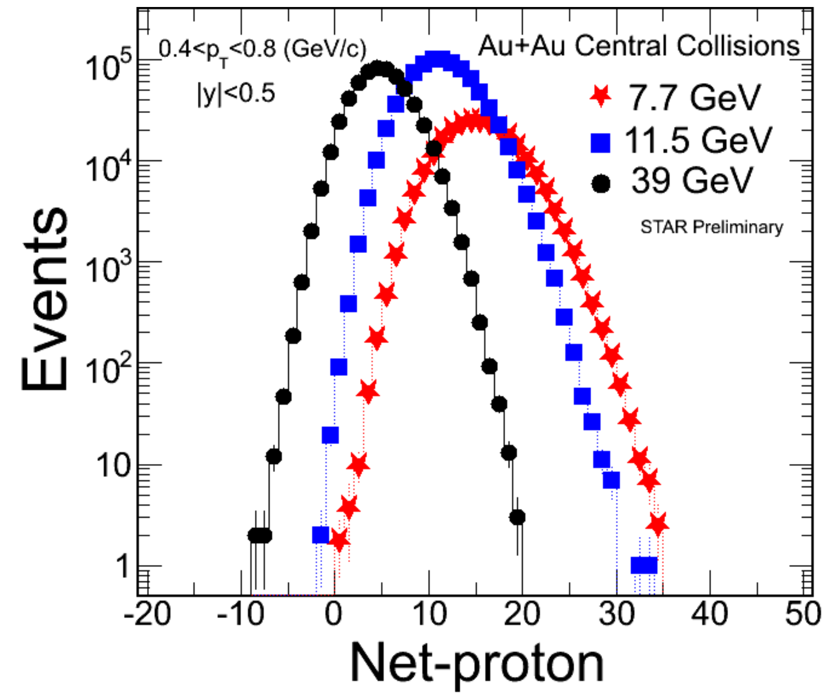


Divergences of conserved quantities may survive in the final state

⇒ non-gaussian fluctuations of net-baryon density

Kurtosis x Variance² ~ $\chi^{(4)}/\chi^{(2)}$

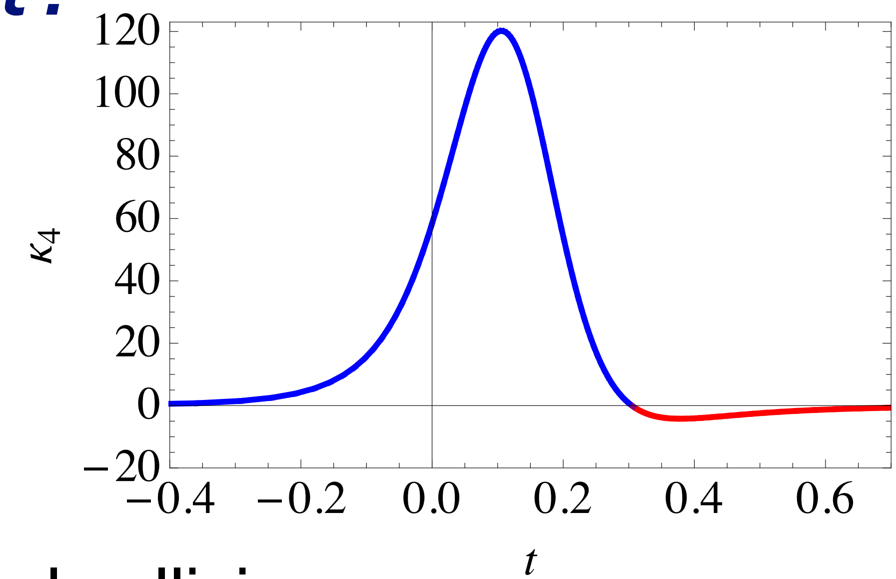
Kurtosis - 4th moment - “tailiness” of distribution

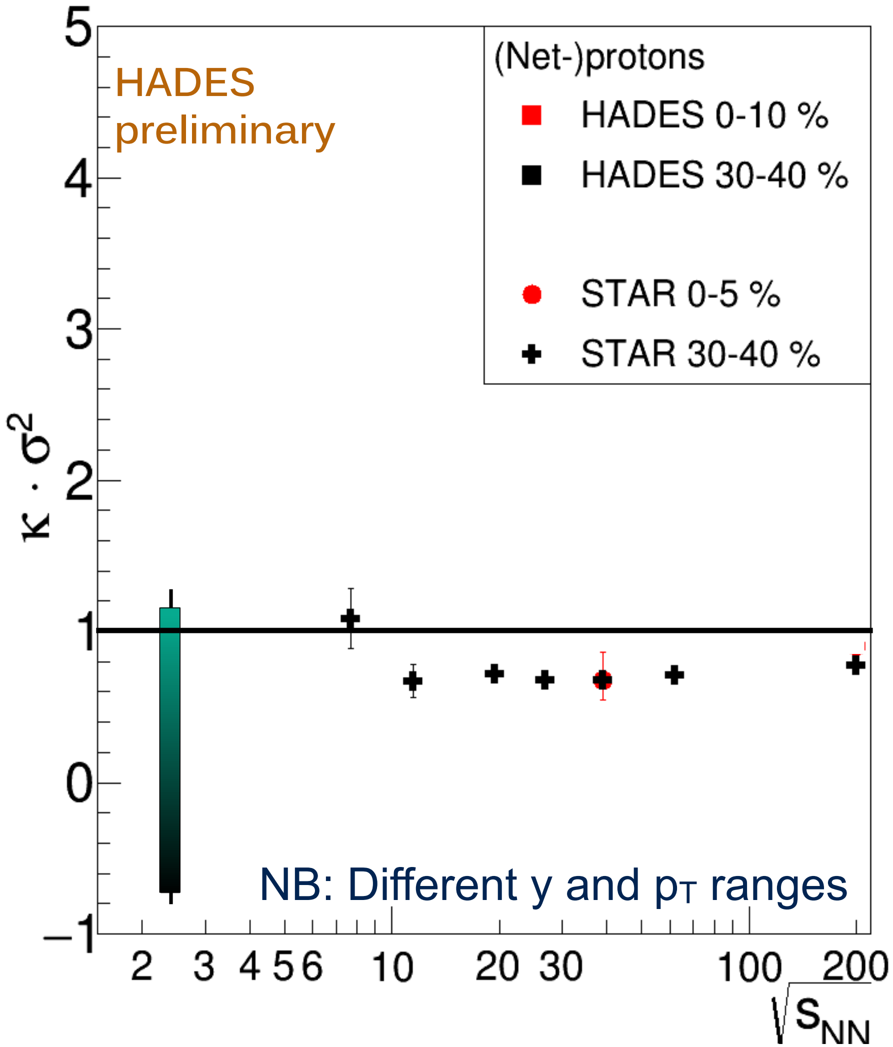
Presence of Critical Point?

M. Stephanov. PRL 107:052301(2011)
HADES: QM17

Correlation lengths diverge

→ Net-p $\kappa\sigma^2$ diverge





Peripheral collisions:

smooth trend

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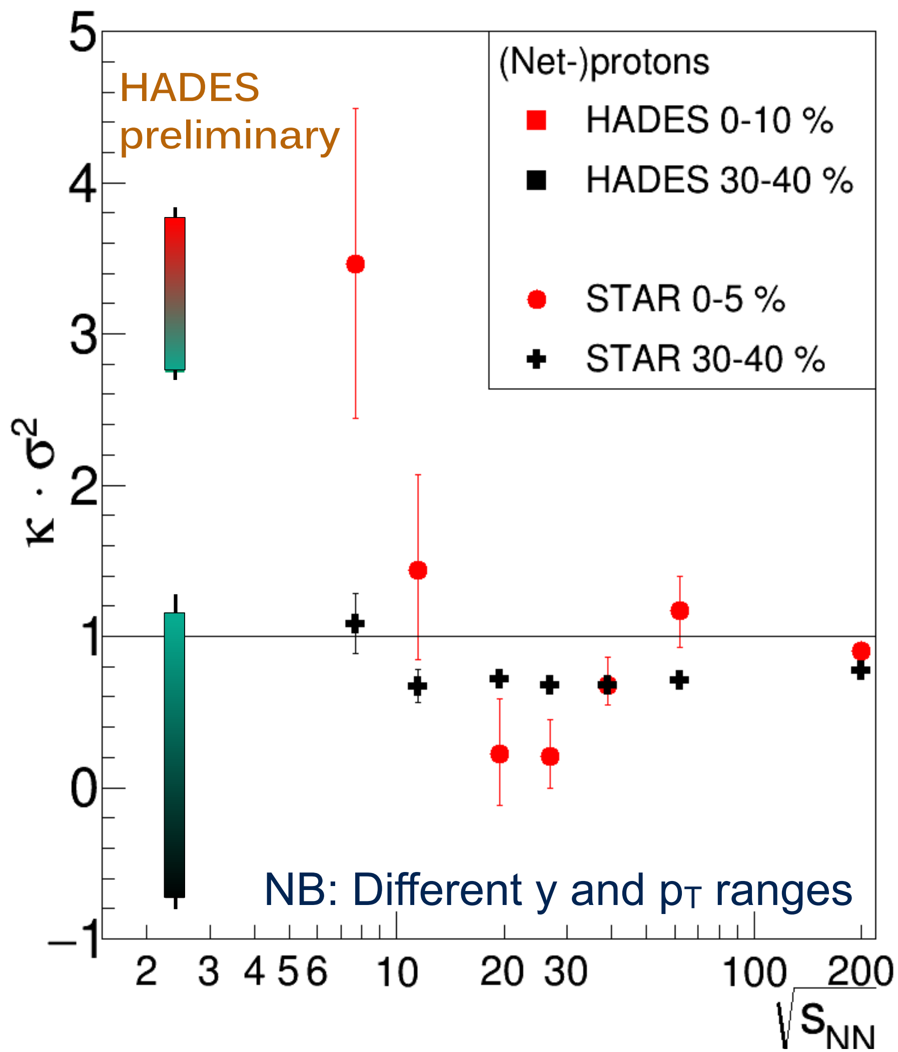

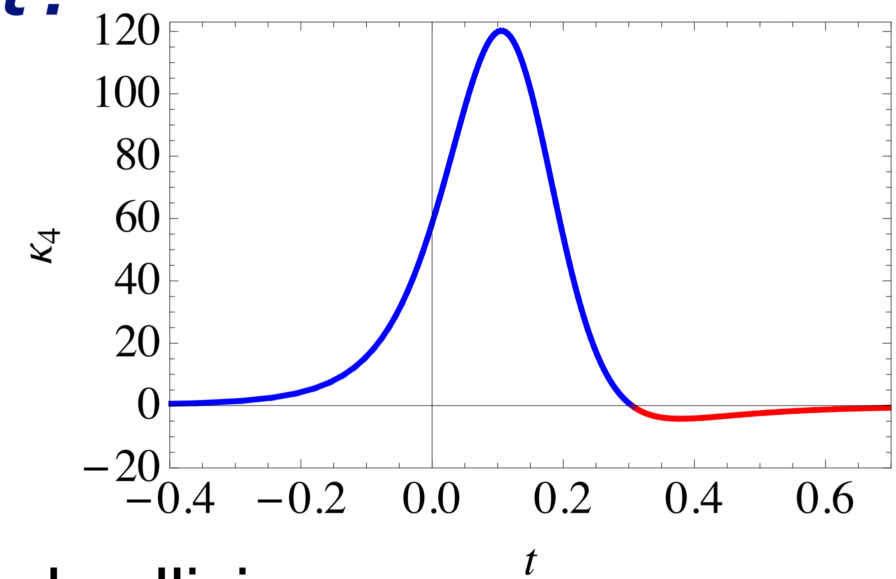

Peripheral collisions:

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Top 5% central collisions:

Non-monotonic behavior

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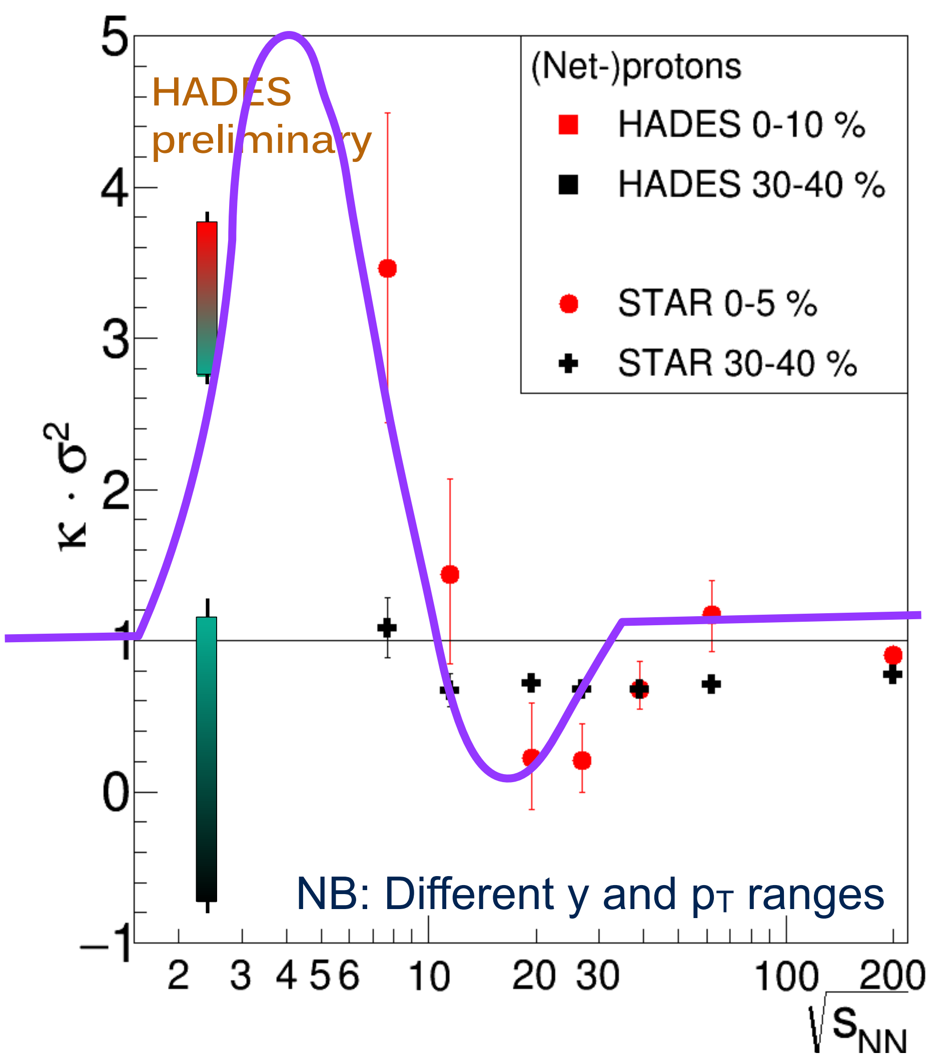

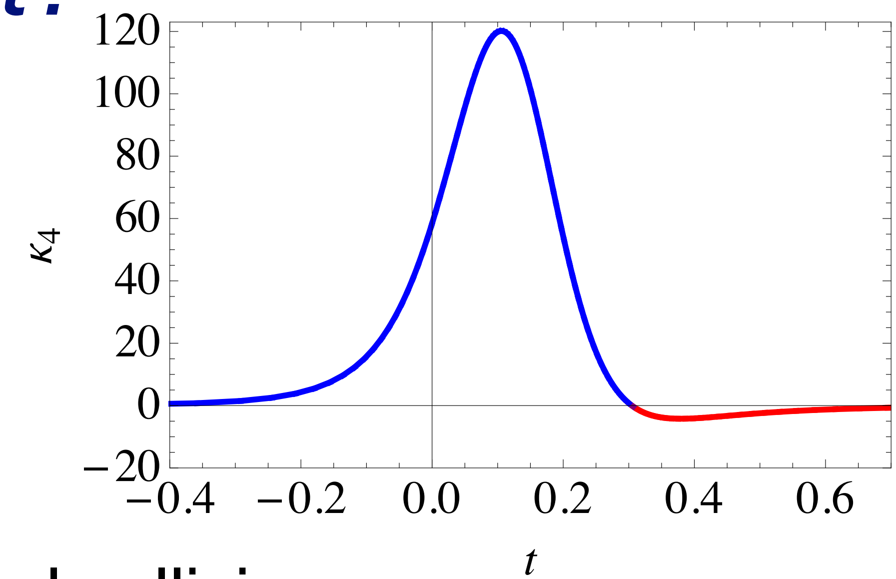

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Hints of Critical fluctuations

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M. Stephanov. PRL 107:052301(2011)
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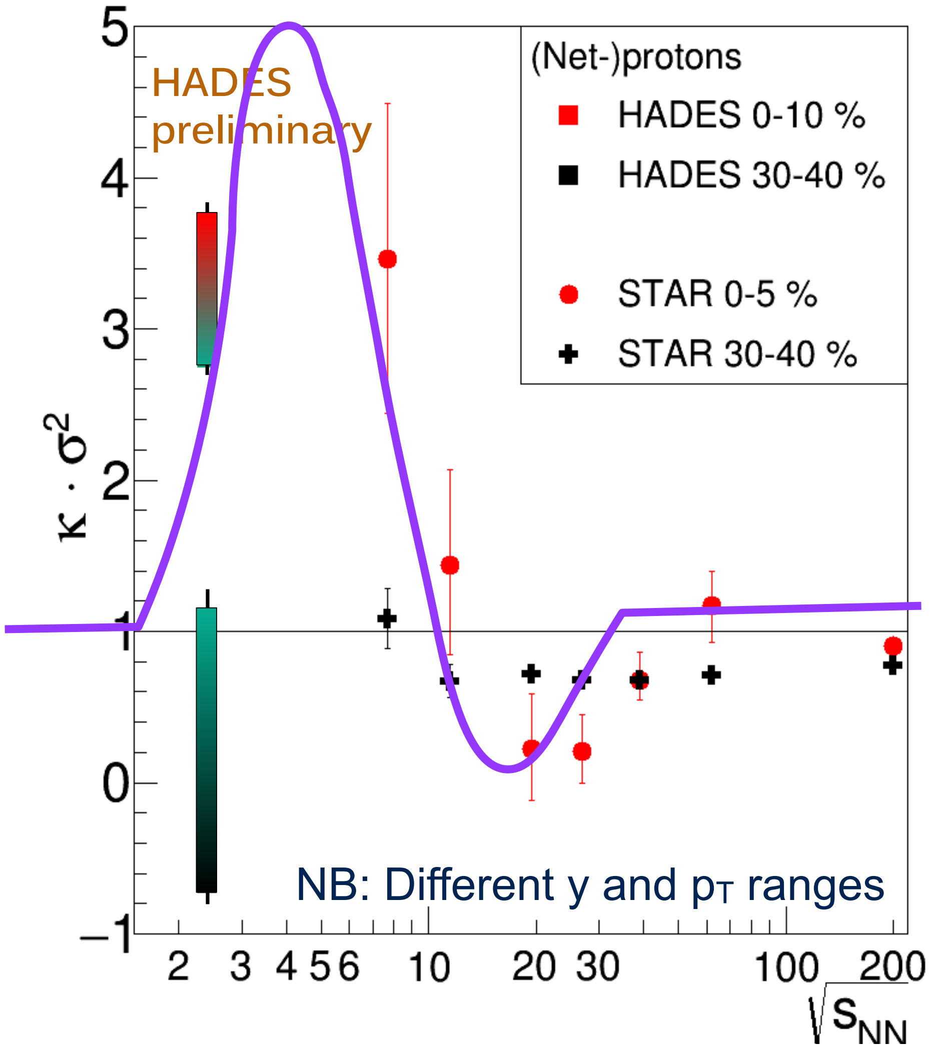
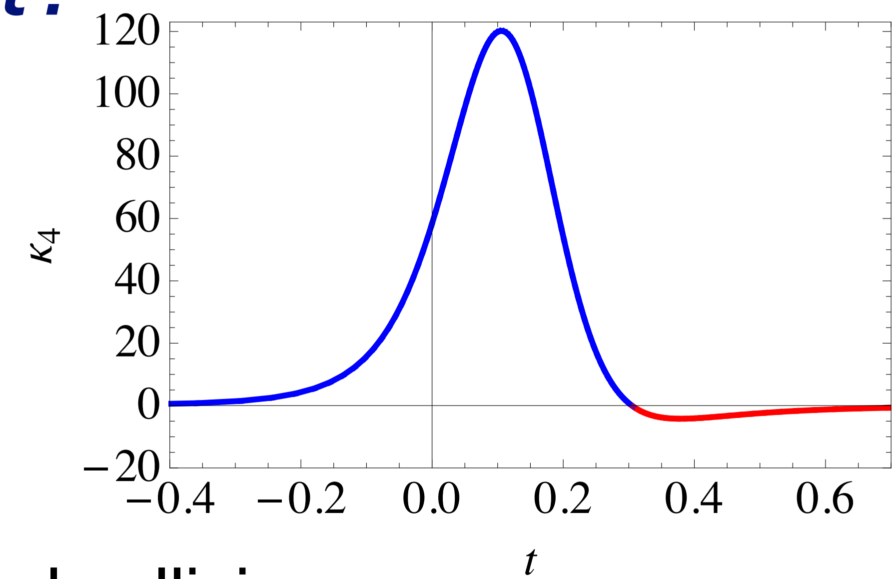




Hints of Critical fluctuations

Peripheral collisions:

smooth trend

Top 5% central collisions:

Non-monotonic behavior

Hadron gas model (UrQMD) no CP:

shows suppression at lower energies

- baryon number conservation

Intermediate summary

A lot happening around 20 GeV - hard to believe its multiple different causes

High statistics exploration of QCD phase diagram and its key features is about to begin

New data from FAIR, NICA, RHIC and SPS just around the corner

Significantly extended detection capabilities compared to existing data

Strong theoretical interest focussed in BEST and HICforFAIR, increased number of focussed workshops

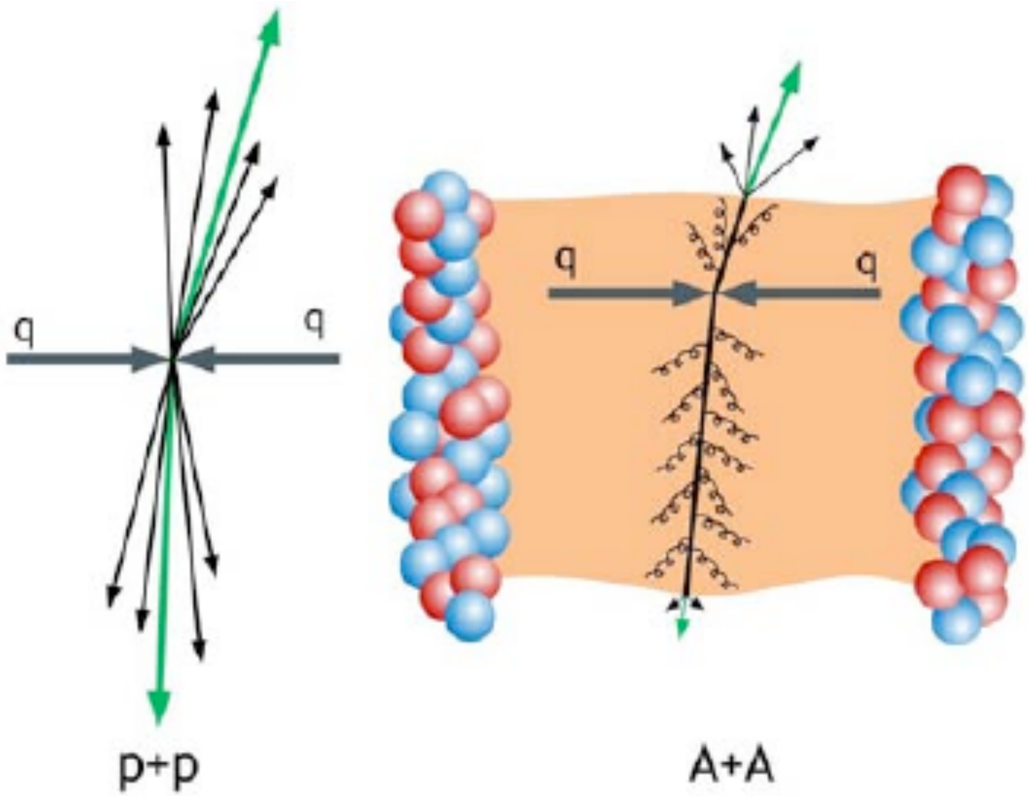
STAR BES-II (2019-2020) Turn trends and features into definitive conclusions

Using "hard" particles as probes

'Hard' processes have a large scale in calculation
→ pQCD applicable:

- high momentum transfer Q^2
- high transverse momentum p_T
- high mass m (N.B.: since m>>0 heavy quark production is 'hard' process even at low p_T)

Early production in parton-parton scatterings with large Q^2



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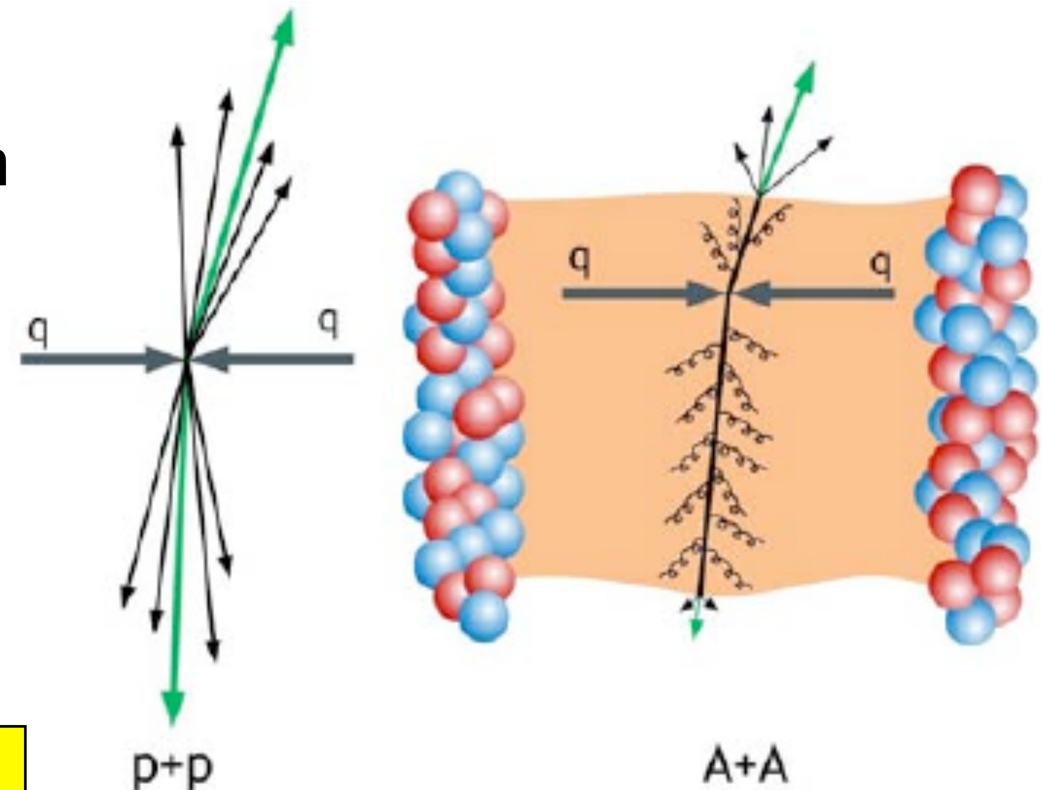
Early production in parton-parton scatterings with large Q^2

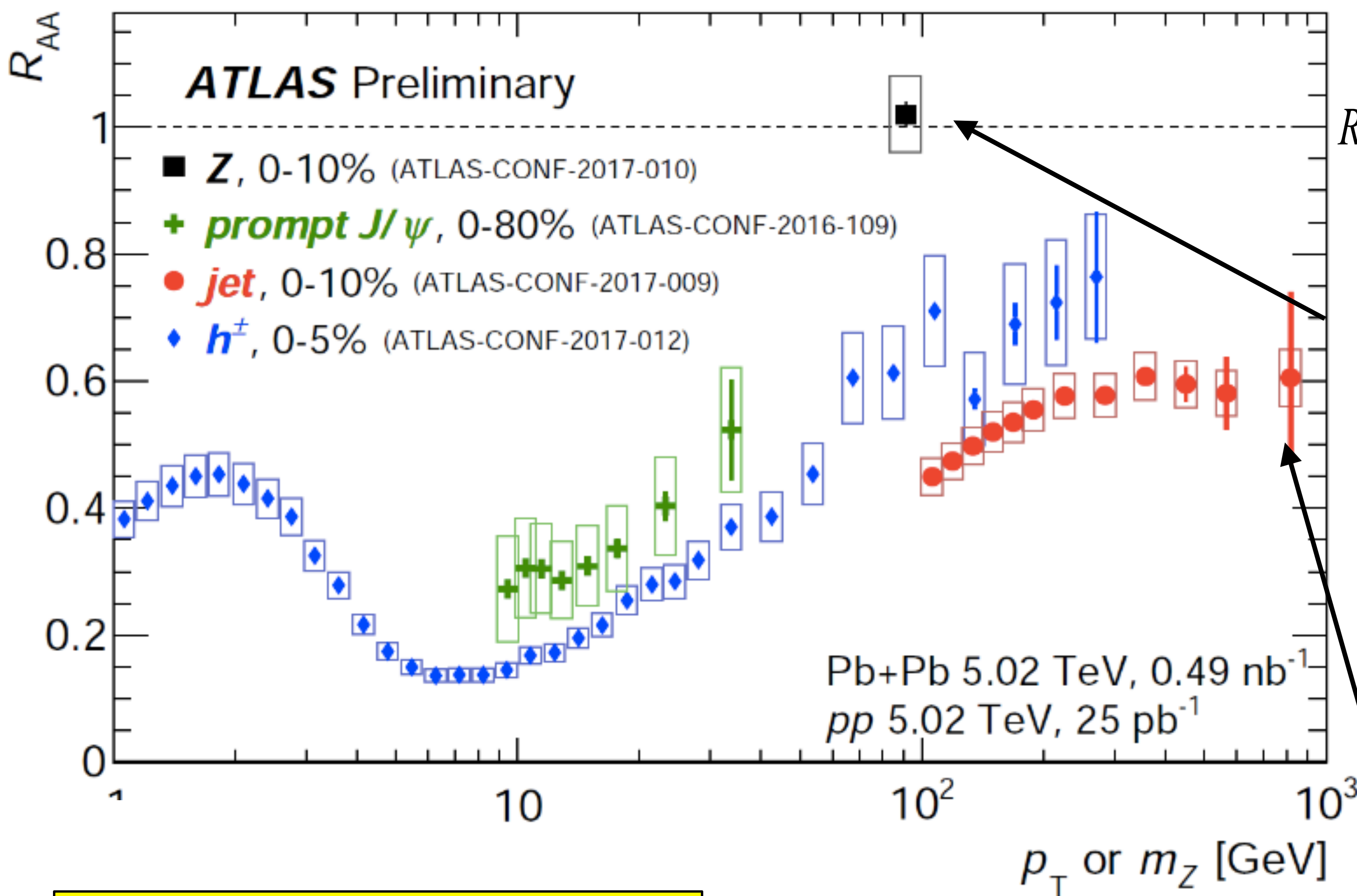
Direct interaction with partonic phases of the reaction

i.e. a calibrated probe



Look for attenuation/absorption/ modification of probe

Jet quenching at 5 TeV



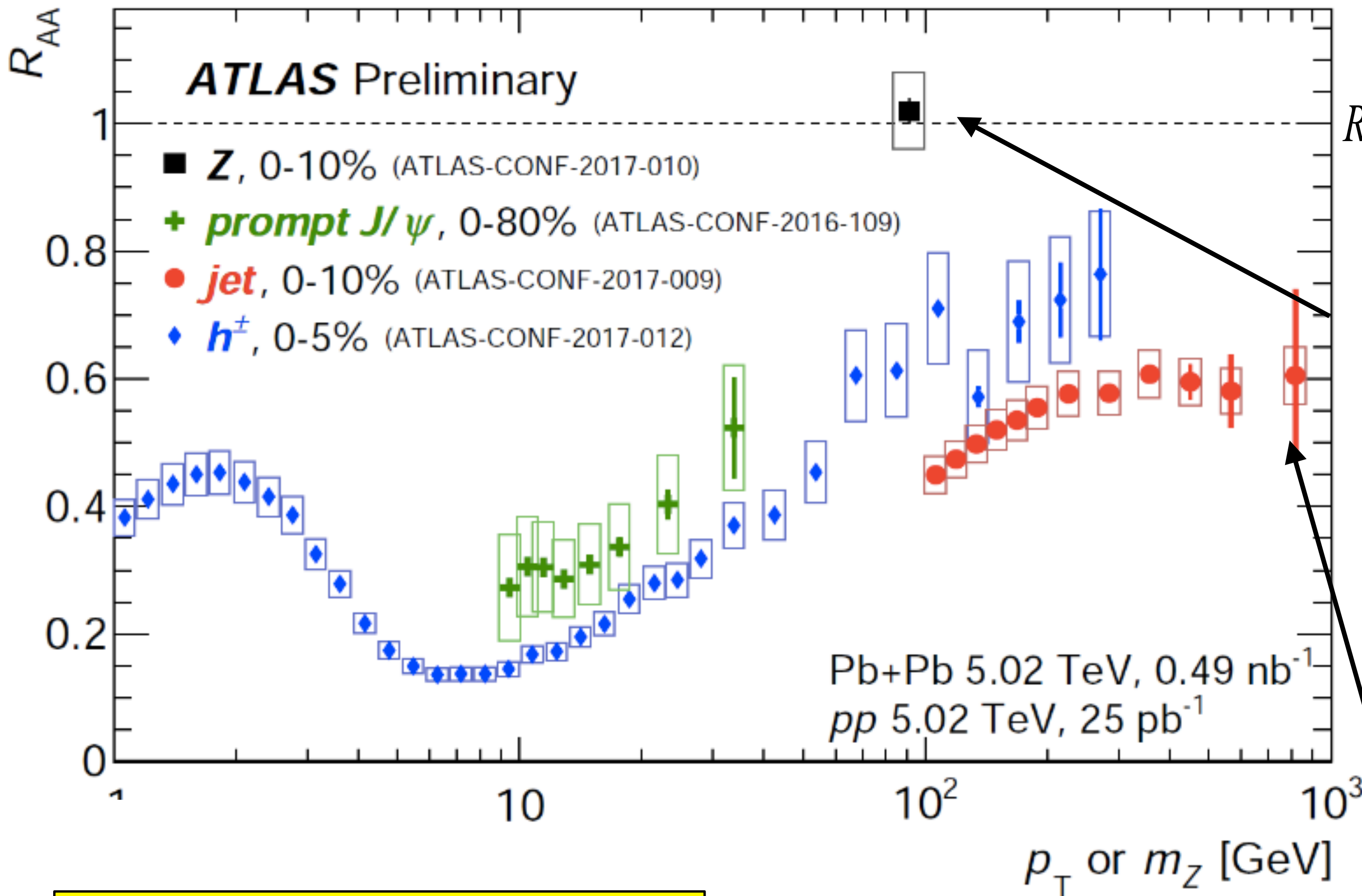
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Colorless objects should not interact with colored QGP
no suppression

Strong suppression up to p_T ~1 TeV

Not significantly different to values at 2.76 TeV

Jet quenching at 5 TeV



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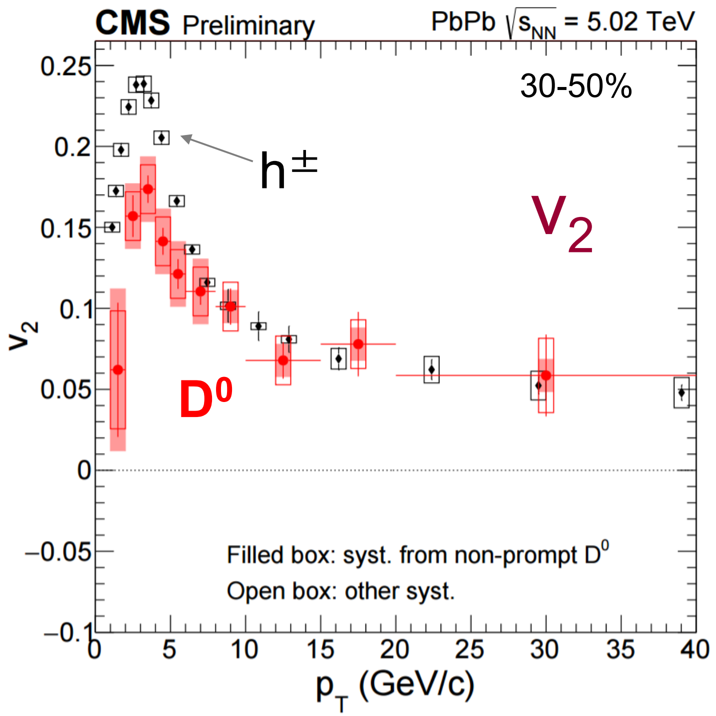
Not significantly different to values at 2.76 TeV

Compensating effects of higher E_{loss}, flatter p_T spectrum,q/g differences

Charm-medium interactions

CMS-PAS-HIN-15-014
STAR arXiv:1701.06060

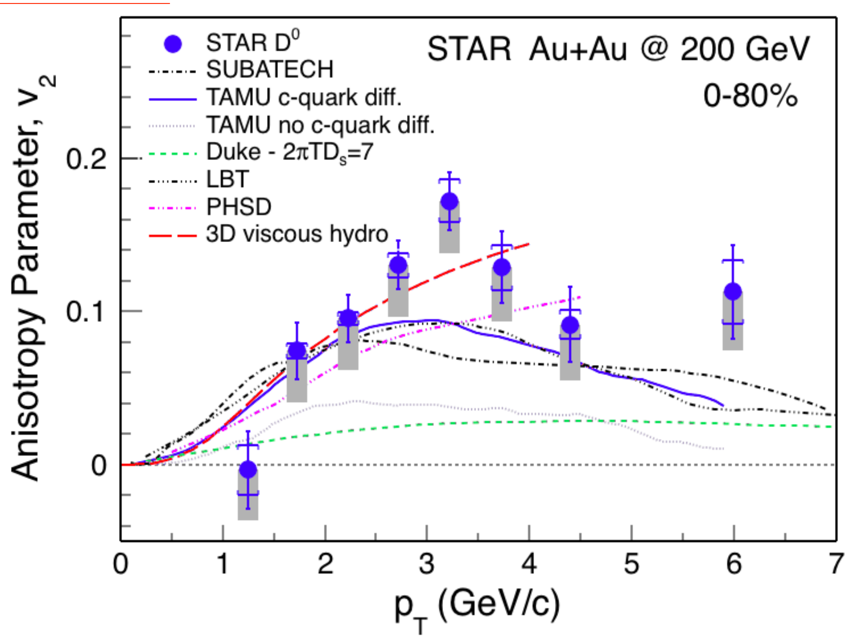


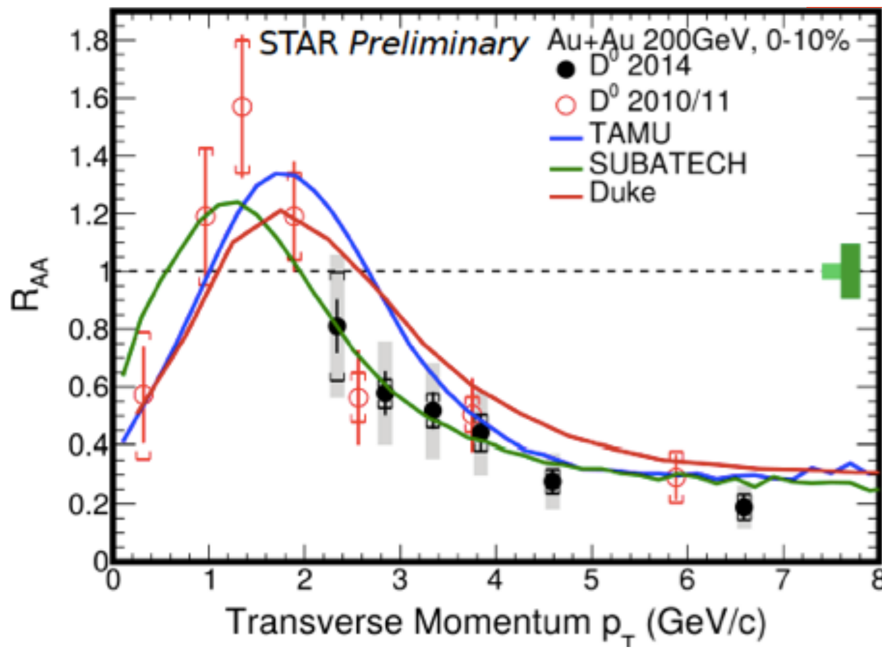
At both RHIC and LHC:

low p_T: D^0 v_2

high p_T: D^0 R_{AA} ~ light hadron R_{AA}

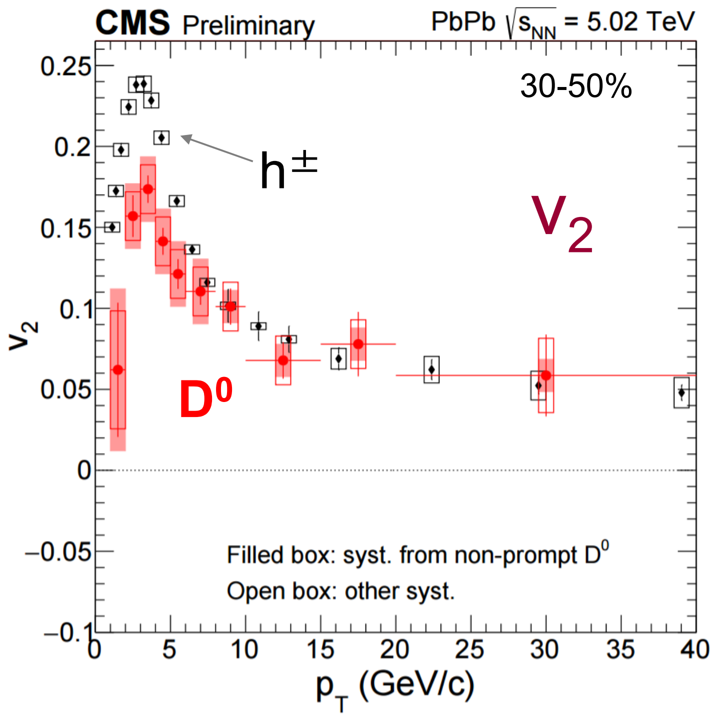
Strong charm-medium interactions at LHC and RHIC





Charm-medium interactions

CMS-PAS-HIN-15-014
STAR arXiv:1701.06060



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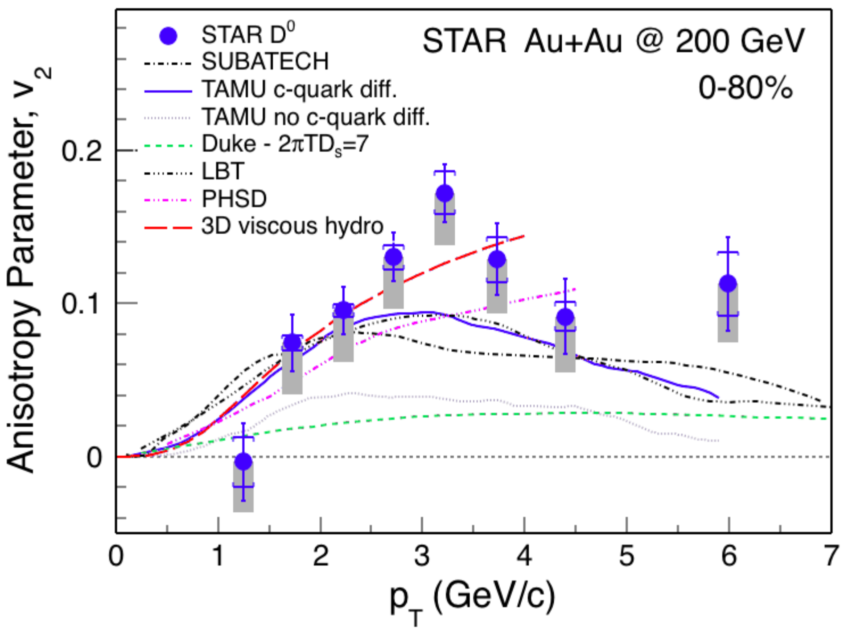
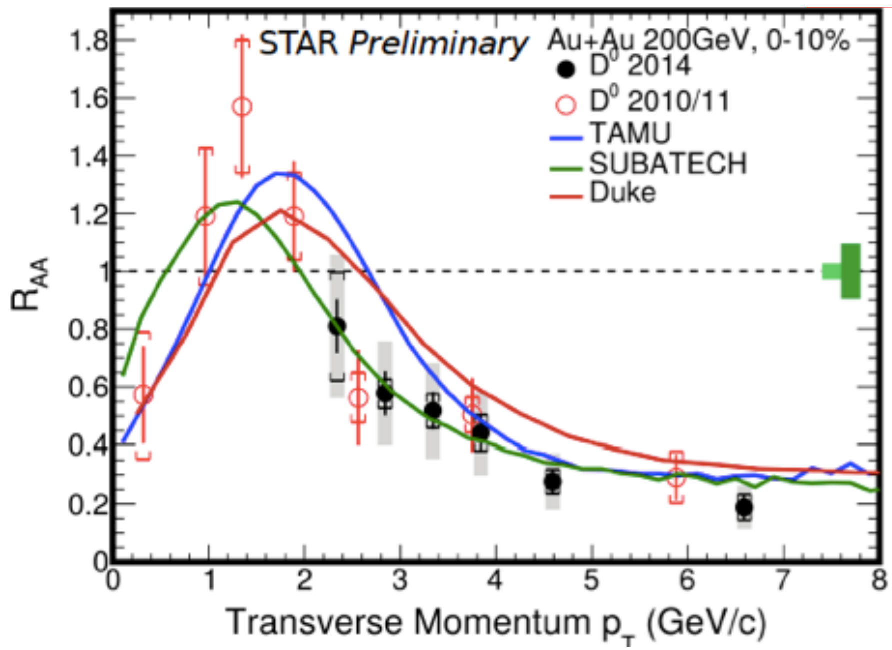
Strong charm-medium interactions at LHC and RHIC

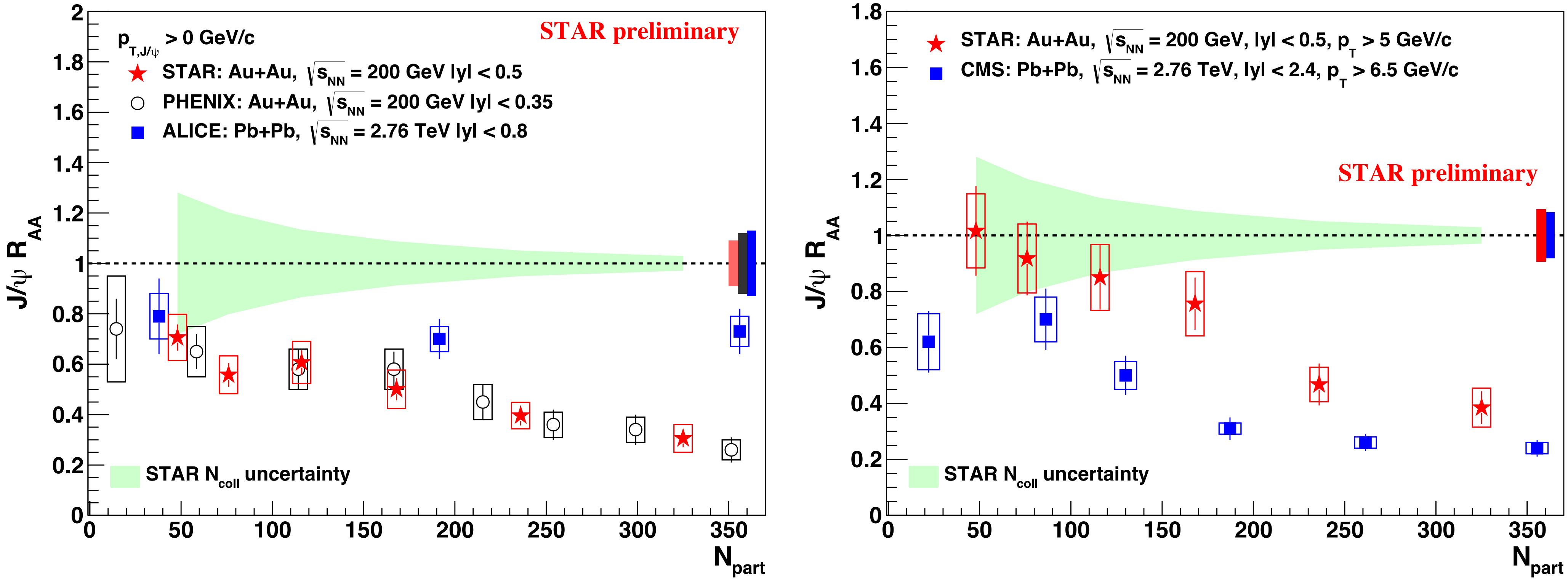
Joint fit: Diffusion coefficient $D_s \sim 1/(2\pi T) * (2\text{-}12)$

Even at RHIC charm thermalized





Melting charmonia



Low p_T: $LHC_{2.76} > RHIC$

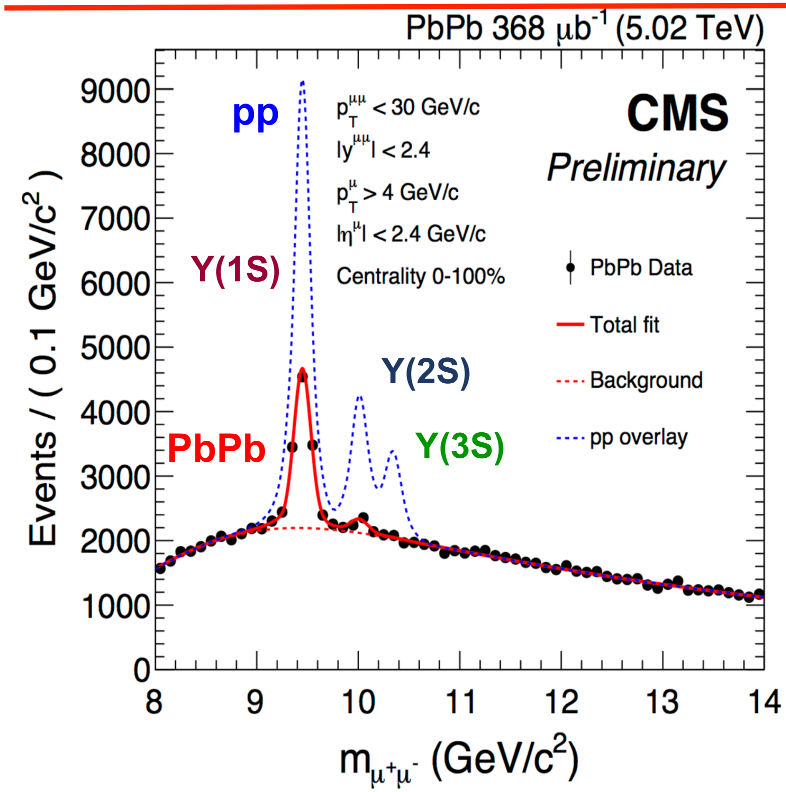
decreasing regeneration; less c quarks

High p_T: $LHC_{2.76} < RHIC$

decreasing dissociation; cooler medium

At LHC many J/ψ result of coalesced thermalized charm

Melting bottomonia

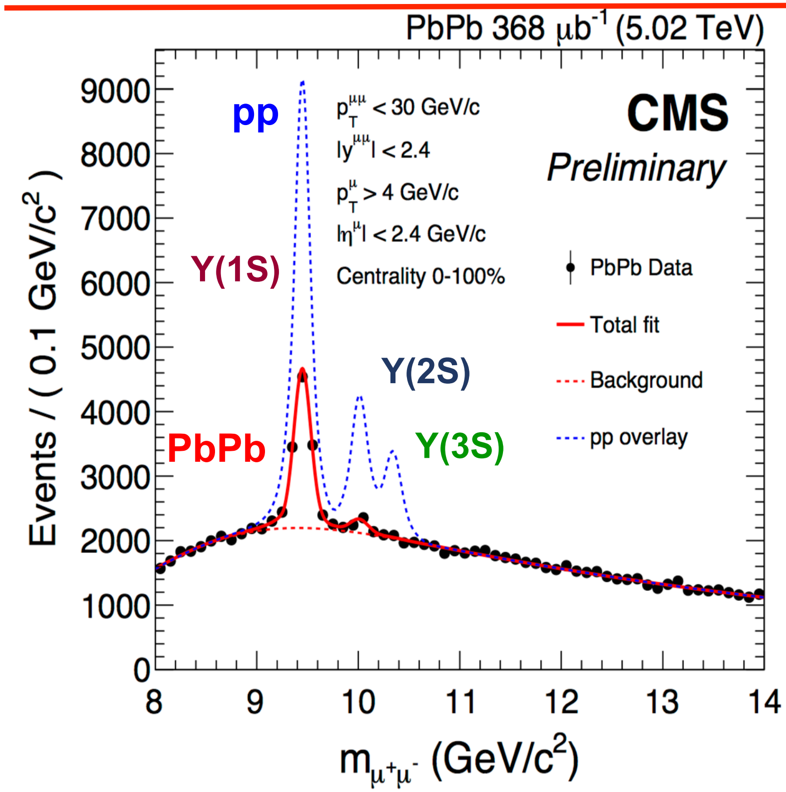


At LHC
5 TeV - Highest precision yet

Sequential suppression
R_{AA}(Y(1S)) < R_{AA}(Y(2S))

Y(3S)) still no observation

Melting bottomonia



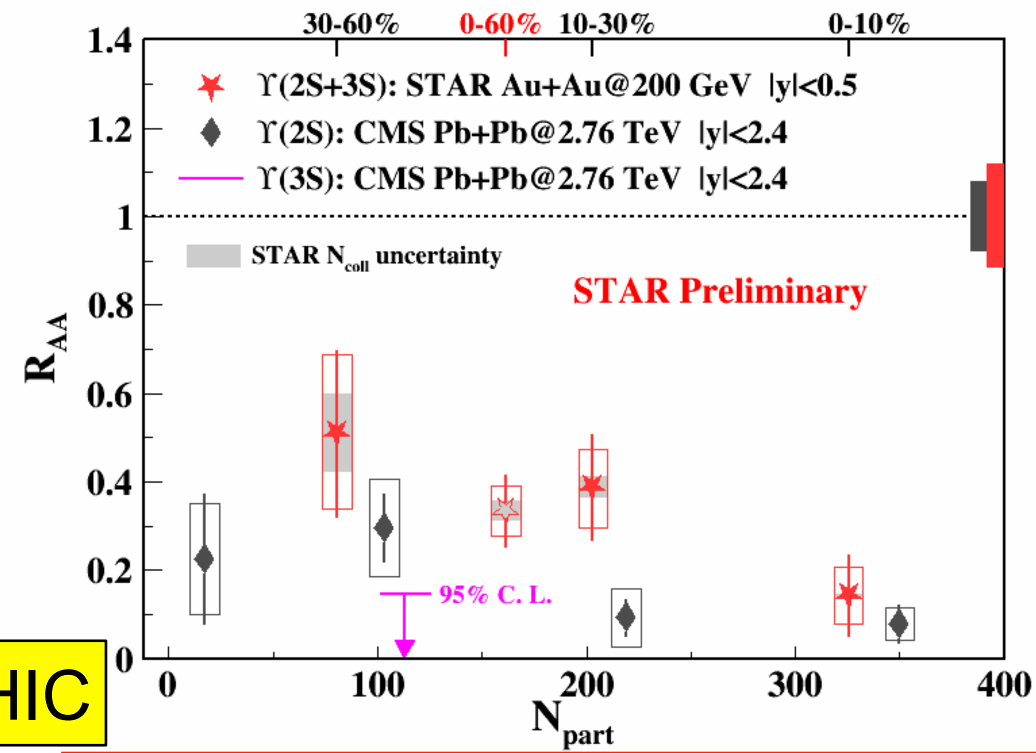
At LHC
5 TeV - Highest precision yet

Sequential suppression
R_{AA}(Υ(1S)) < R_{AA}(Υ(2S))

Υ(3S)) still no observation

At RHIC: First precise results

Sequential suppression
R_{AA}(Υ(1S)) < R_{AA}(Υ(2S+3S))



Hints of less suppression at RHIC

Determining initial parton energy

Di-jet expectations

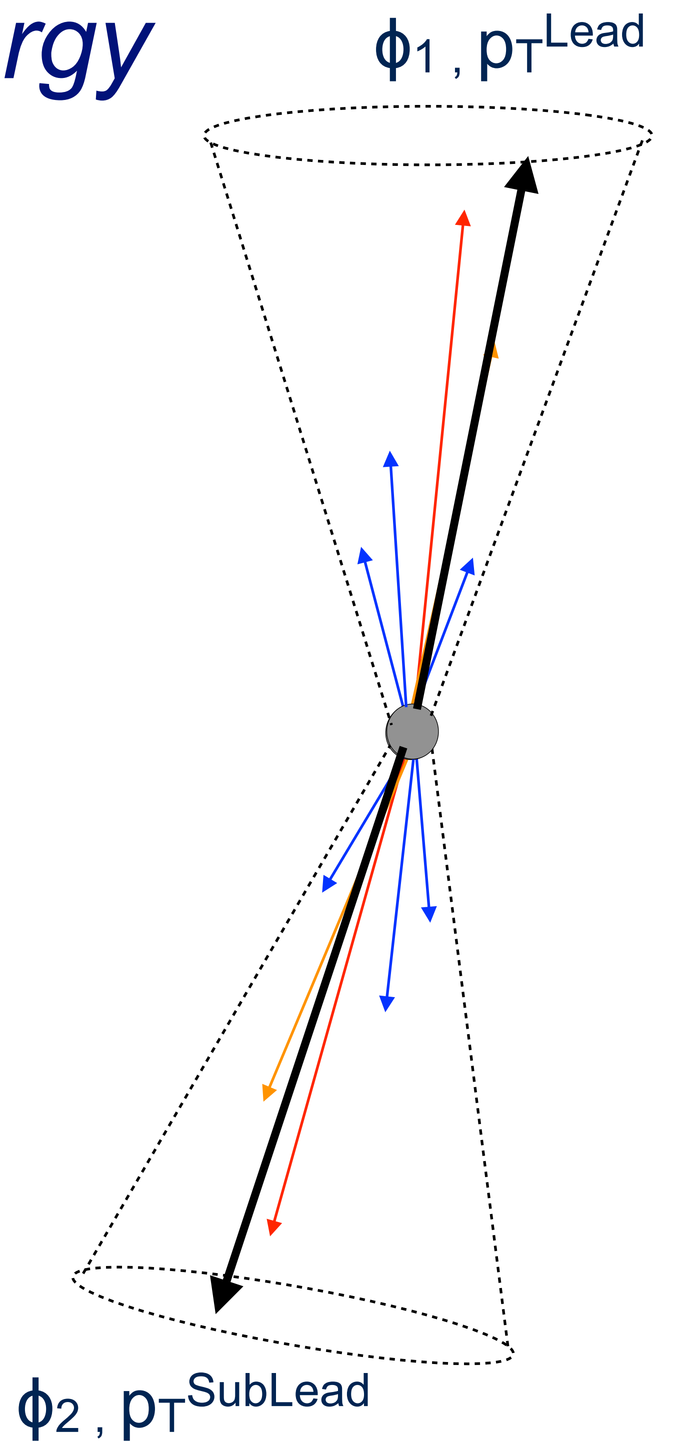
Back-to-back in ϕ

$$\Delta\phi = \phi_1 - \phi_2$$

Equal but opposite momenta

$$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$$

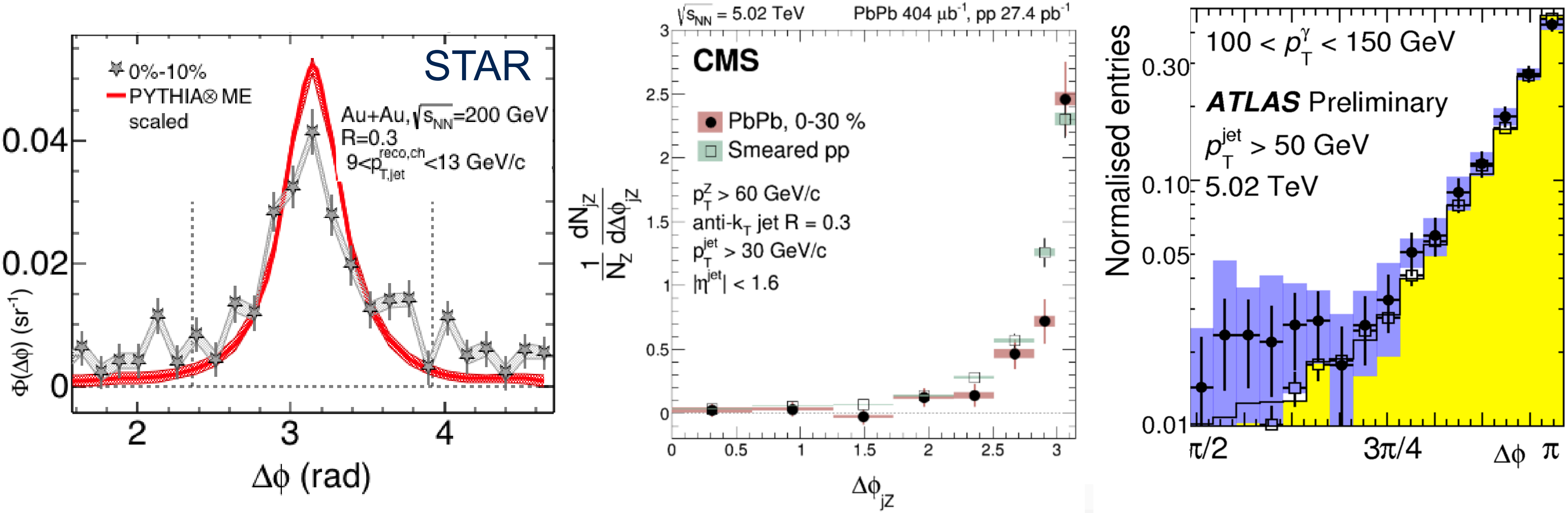
$$x_J = \frac{p_T^{Jet}}{p_T^{Trig}}$$



Modification from p-p
- reveal details of interaction with QGP

Di-jets are not deflected

STAR arXiv:1702.01108
CMS: arXiv:1702.01060
ATLAS: CONF-2016-110



Examine Δϕ - azimuthal angle between hadron-jets, z-jet, γ-jet

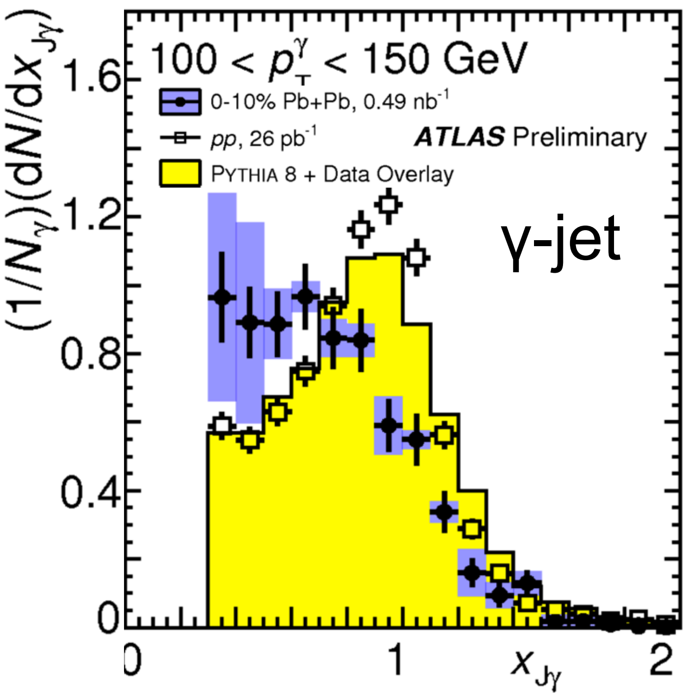
Leading order expectation: Δϕ ~π

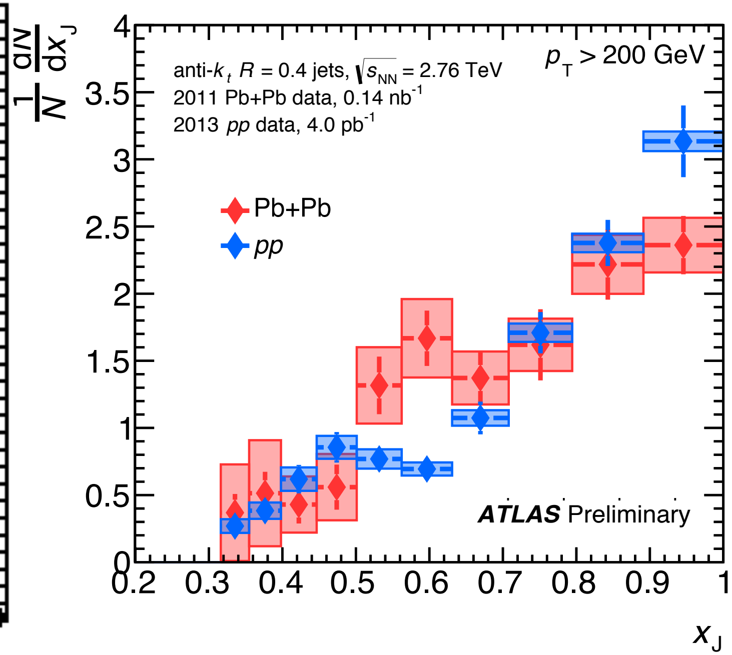
Little to no azimuthal de-correlation observed

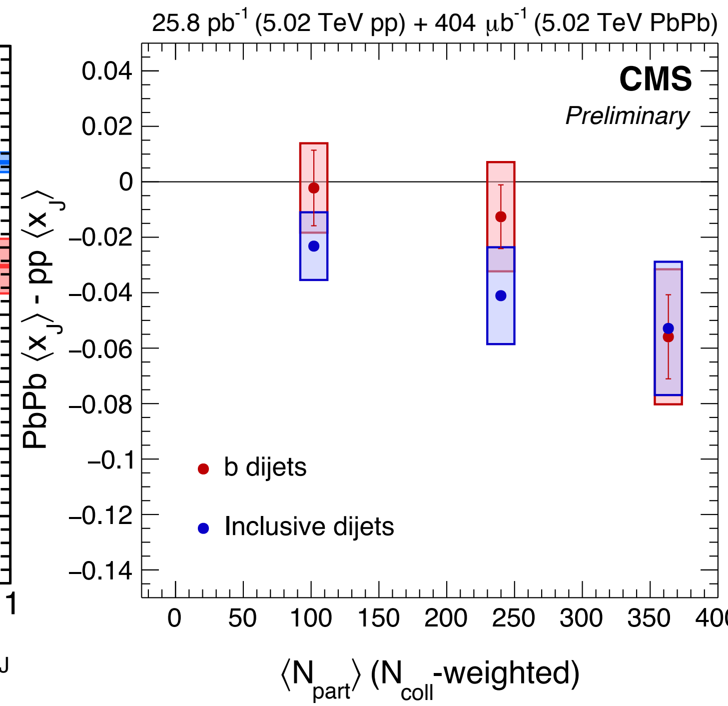
Partons lose energy but are not deflected from original path

Di-jets are imbalanced

ATLAS:CONF-2016-110
ATLAS-CONF-2015-052
CMS-PAS-HIN-16-005







γ (Z) triggers "Absolute" E_{loss} calibration.

Z-jet distribution consistent with γ-jet

Fractional E_{loss} decreases with p_T

p_T> 200 GeV Pb-Pb approaches pp

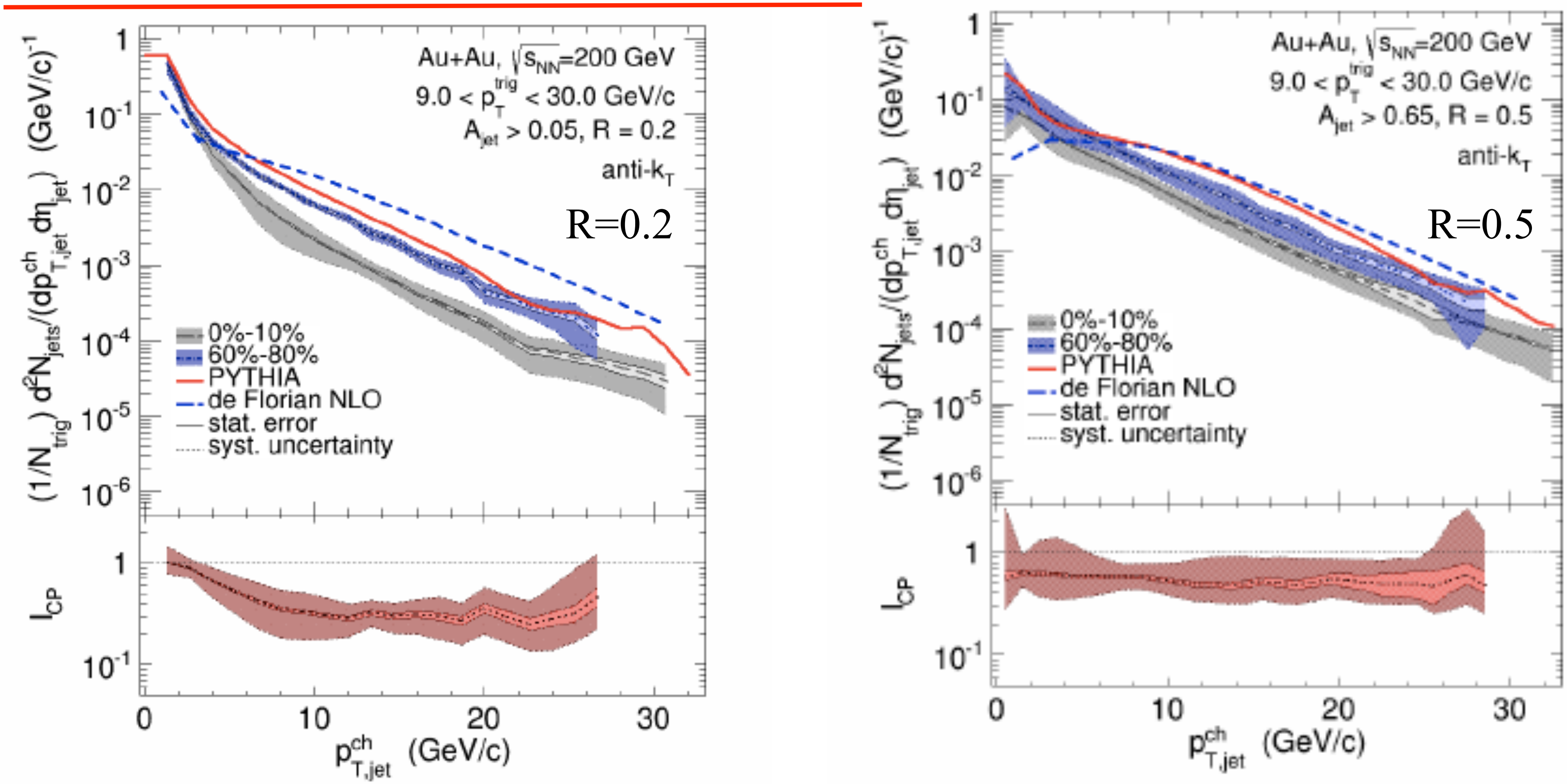
For all centrality inclusive ~ di-b

Inclusive: q and g
di-b: q

Probing parton flavor energy loss with ever enhancing precision

Lost energy of a recoil jet

ALICE JHEP 09 (2015) 170
STAR arXiv:1702.01108



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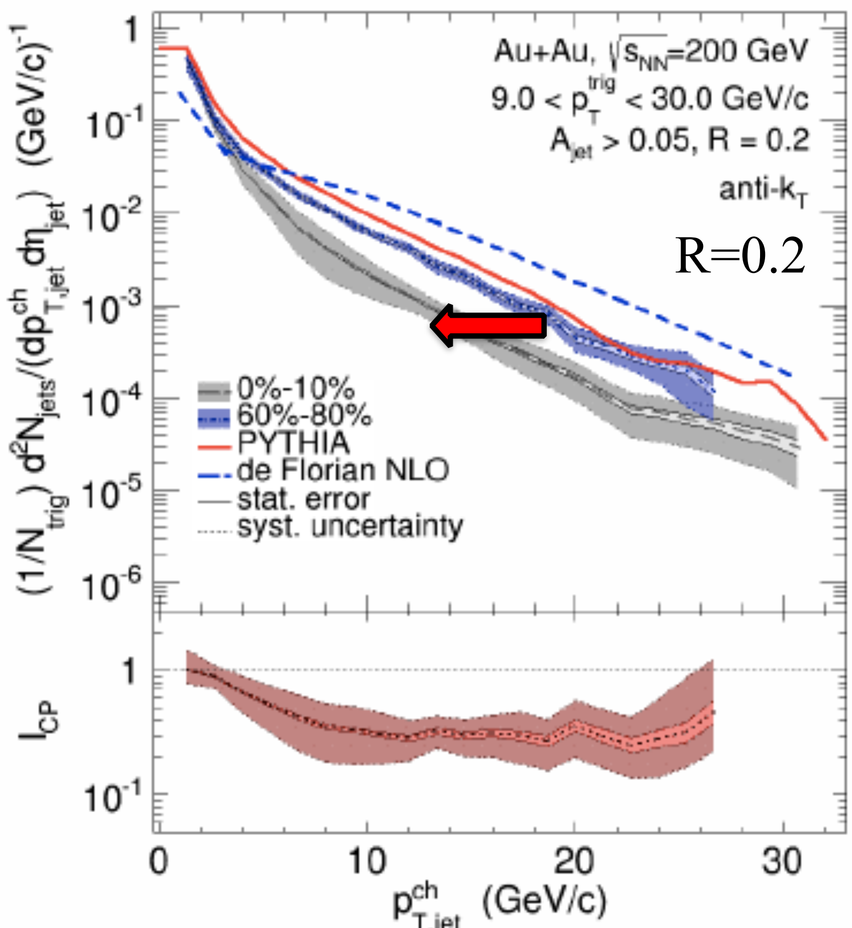

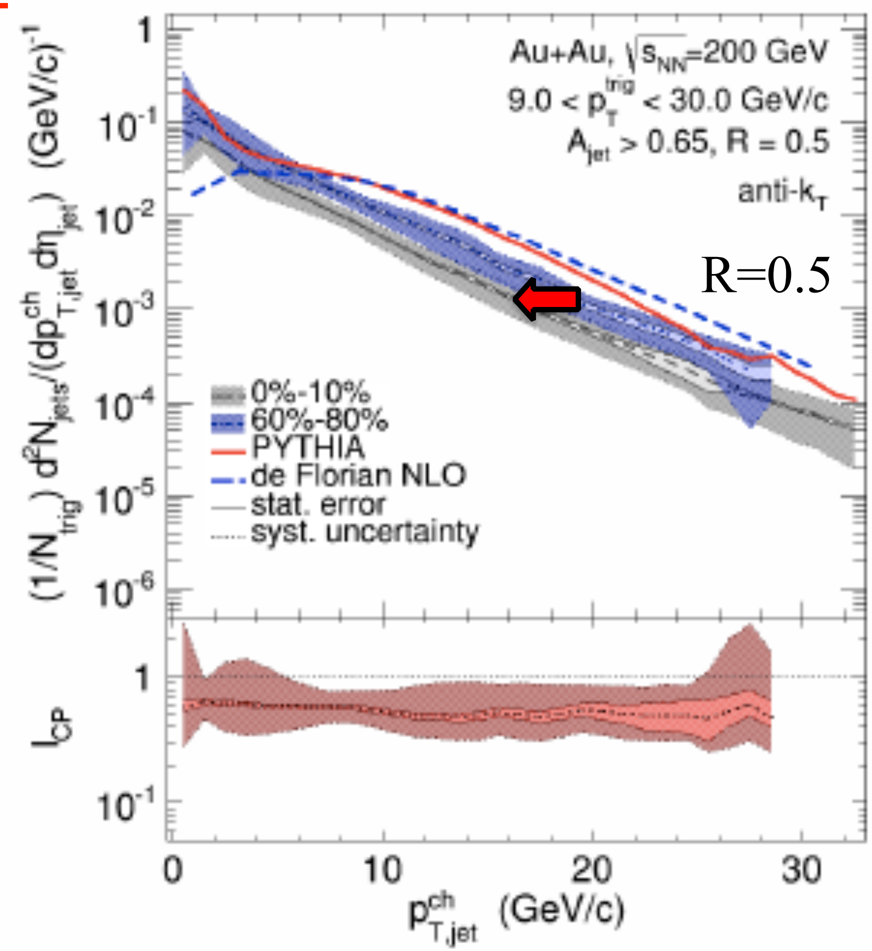

RHIC: Jet p_T =10-20 GeV

R=0.2: $p_{T,Shift}$ ~ -4.4 ± 0.2 ± 1.2 GeV

R=0.5: $p_{T,Shift}$ ~ -2.8 ± 0.5 ± 1.2 GeV

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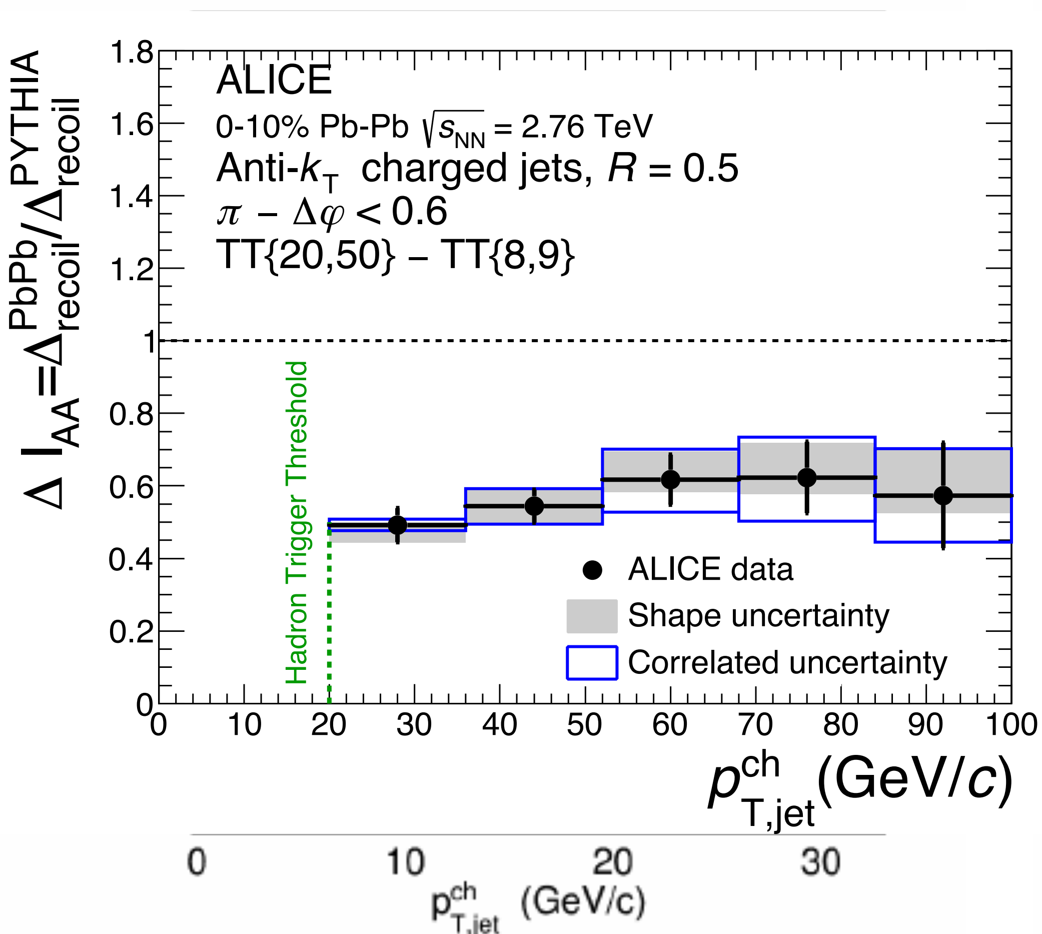

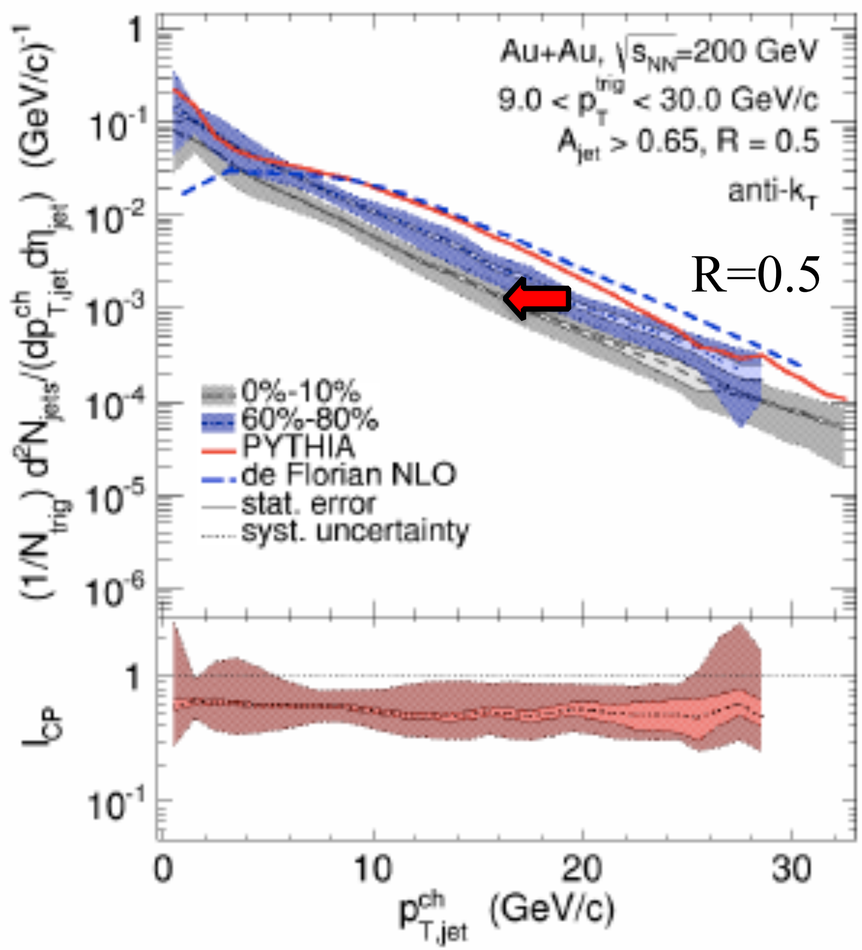

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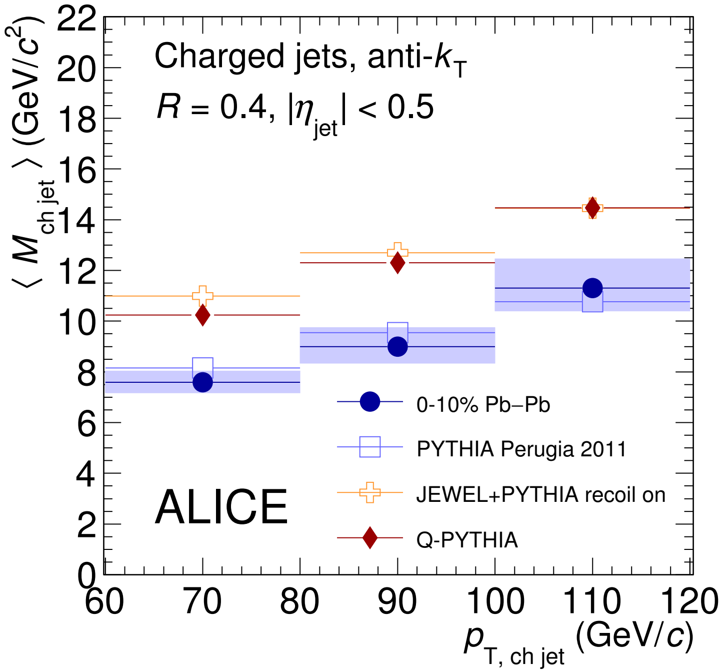
LHC: Jet p_T =60-100 GeV

R=0.5: $p_{T,Shift}$ ~ -8 ± 2GeV

Energy almost recovered at moderate angles at RHIC but not at LHC

Probing the jet substructure

ALICE: arXiv:1702.00804
CMS-PAS-HIN-16-006



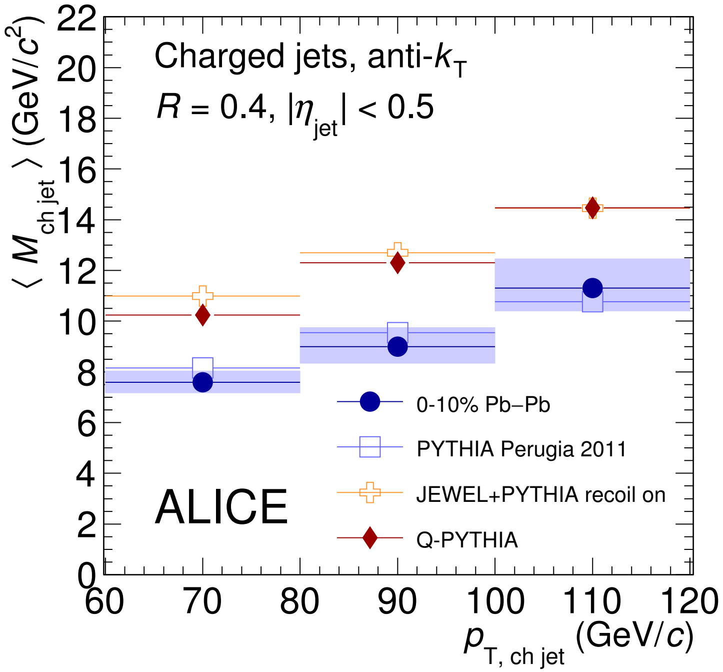
Jet mass: $M = \sqrt{E^2 - p^2}$

Angular spread of constituents “generates” mass

Pb-Pb : Closer to pp than quenching models

Probing the jet substructure

ALICE: arXiv:1702.00804
CMS-PAS-HIN-16-006

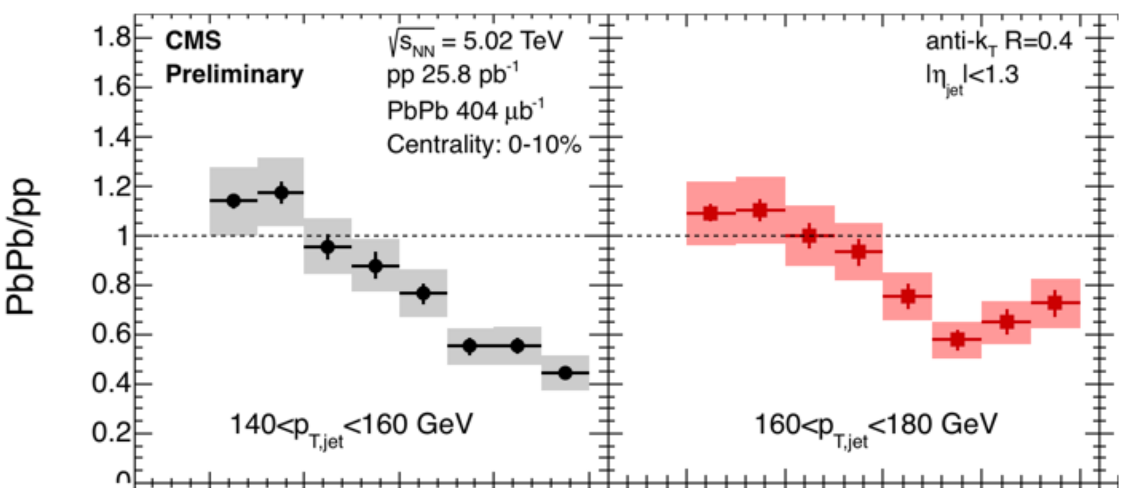


Jet mass: $M = \sqrt{E^2 - p^2}$

Angular spread of constituents "generates" mass

Pb-Pb : Closer to pp than quenching models

Pb-Pb inclusive jets have "harder cores" than pp jets of same energy



"Groom" jet into two subjets

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Significant change at LHC for inclusive jets 140<p_T<200 GeV/c

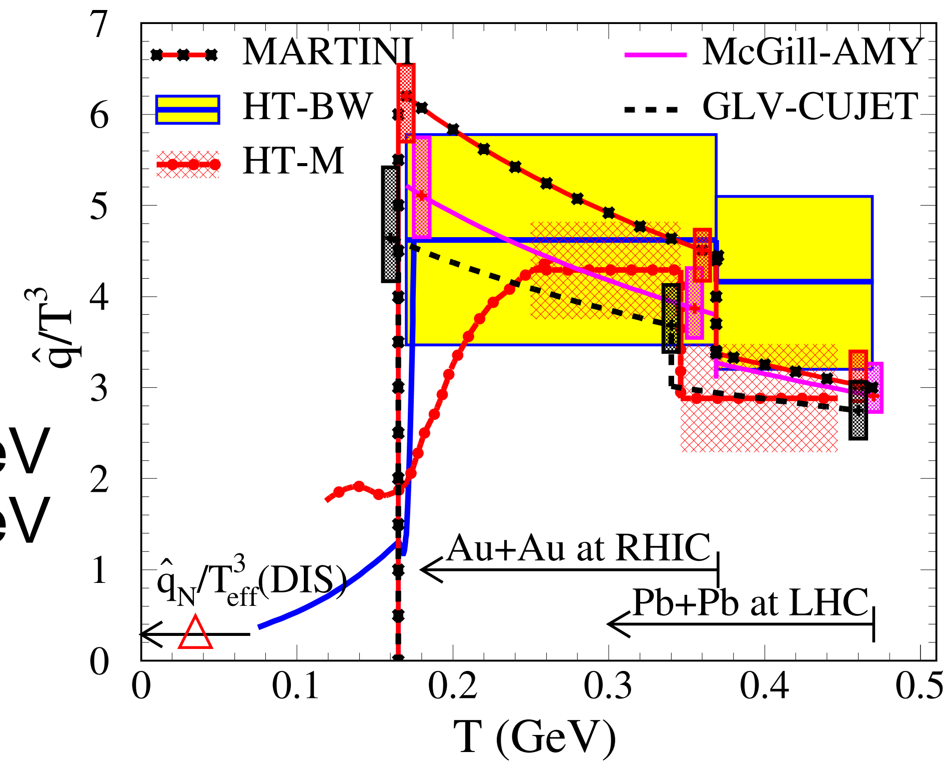
What has all this taught us?

Different initial conditions and evolutionary paths:

$\hat{q} = Q^2/L$ Q - mtm transfer to medium
L - path length

$\hat{q}$(t=0.6fm/c) ~ 1.2 ± 0.3 GeV²/fm T=370 MeV
1.9 ± 0.7 GeV²/fm T=470 MeV

Probes behave differently at RHIC and LHC



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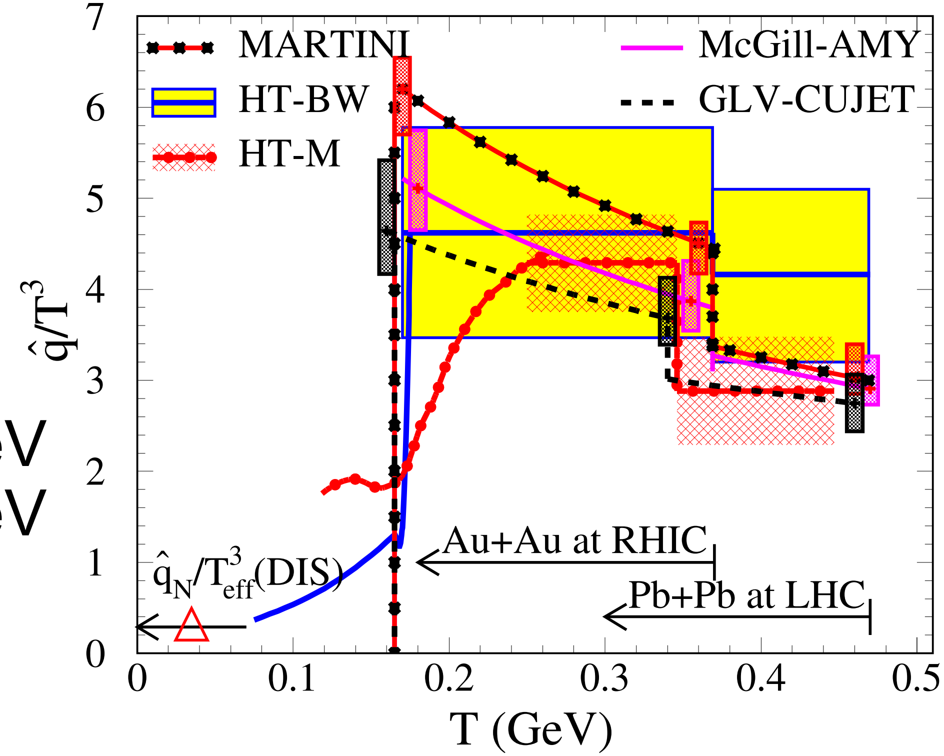
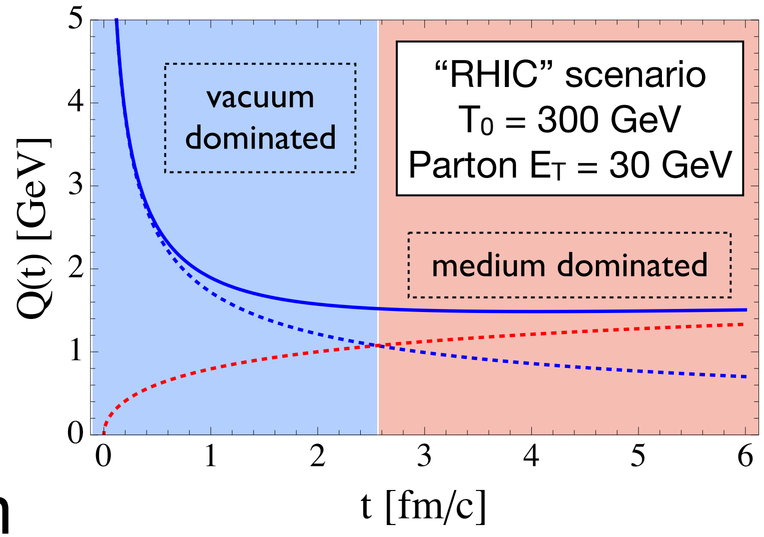
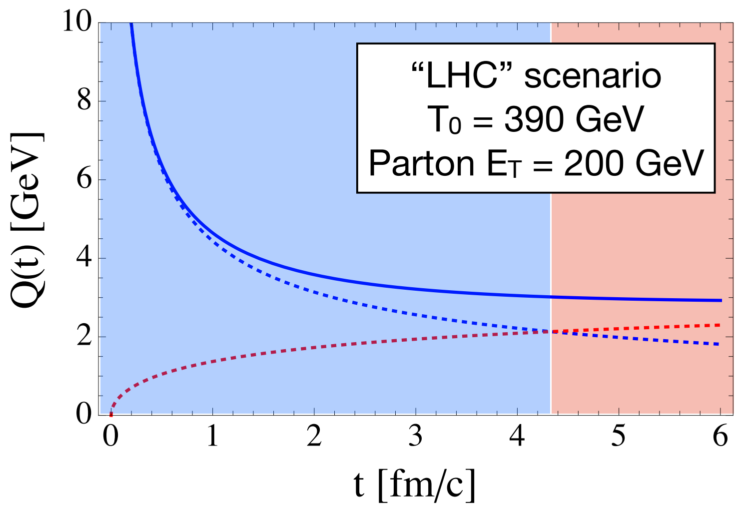


Probes behave differently at RHIC and LHC

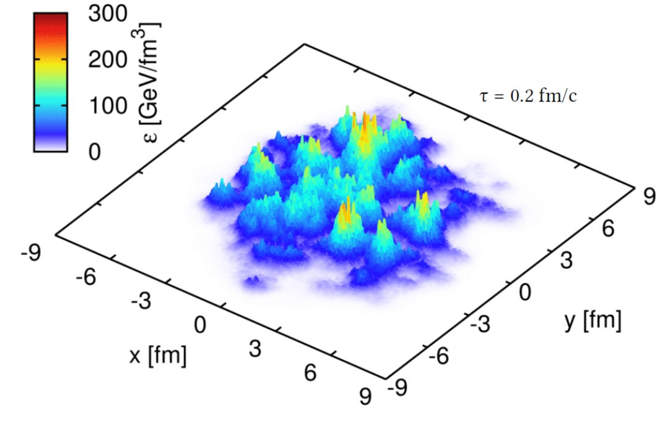
Different virtuality evolutions:

How/when does parton become "aware" of medium





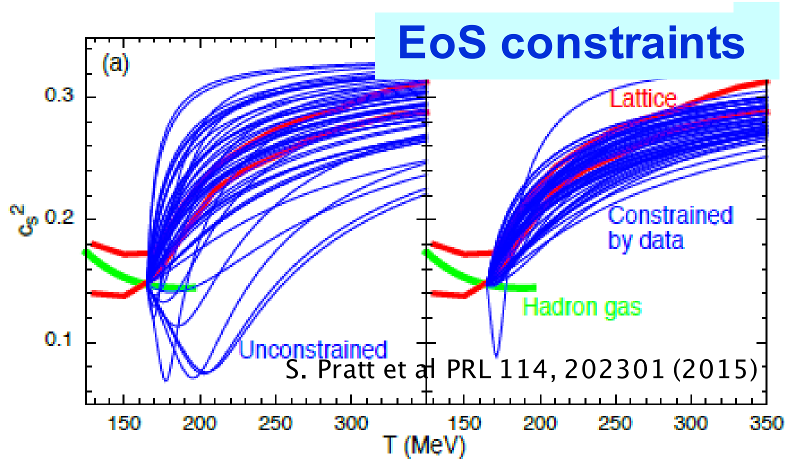
Other significant recent progress



Sophisticated multi-stage modeling

Fluctuating lumpy initial conditions

Event-by-event calculations just as for real data

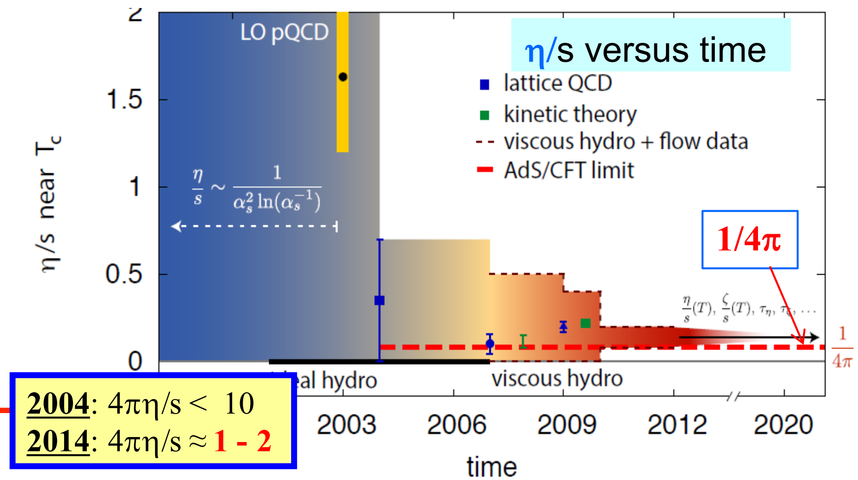


Bayesian multi-parameter fits

Data prefer:

EoS determined by LQCD

IP-Glasma initial conditions



Precision estimates of η/s approaching ever closer to lower bound

- also as function of $\sqrt{s_{NN}}$

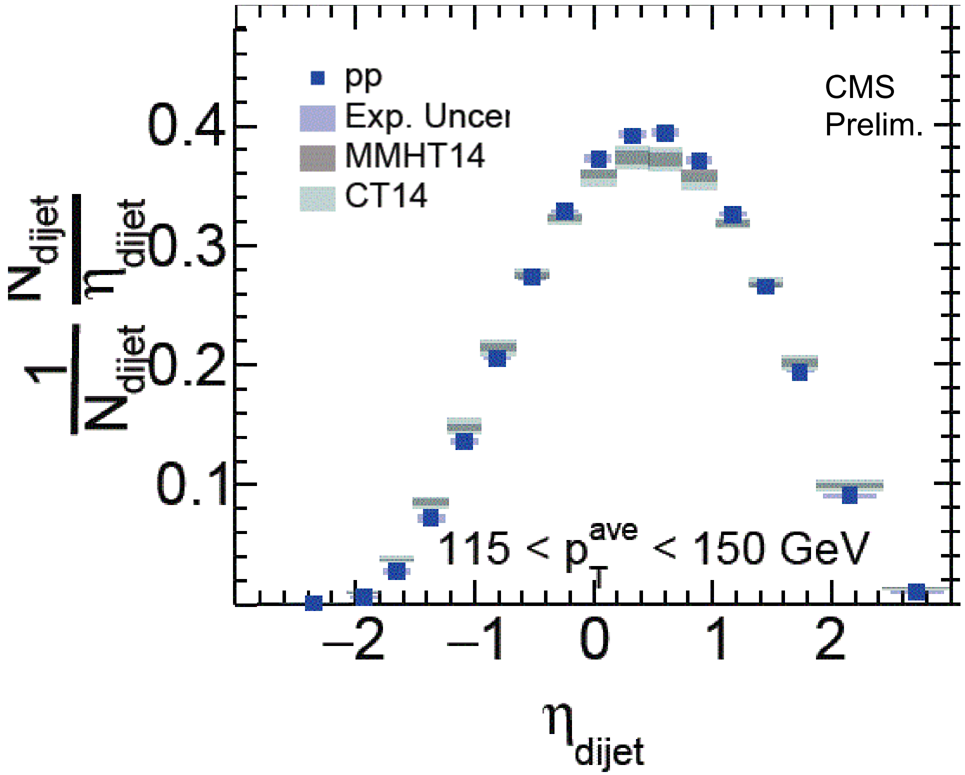
p-Pb : Constraining gluon (n)PDFs

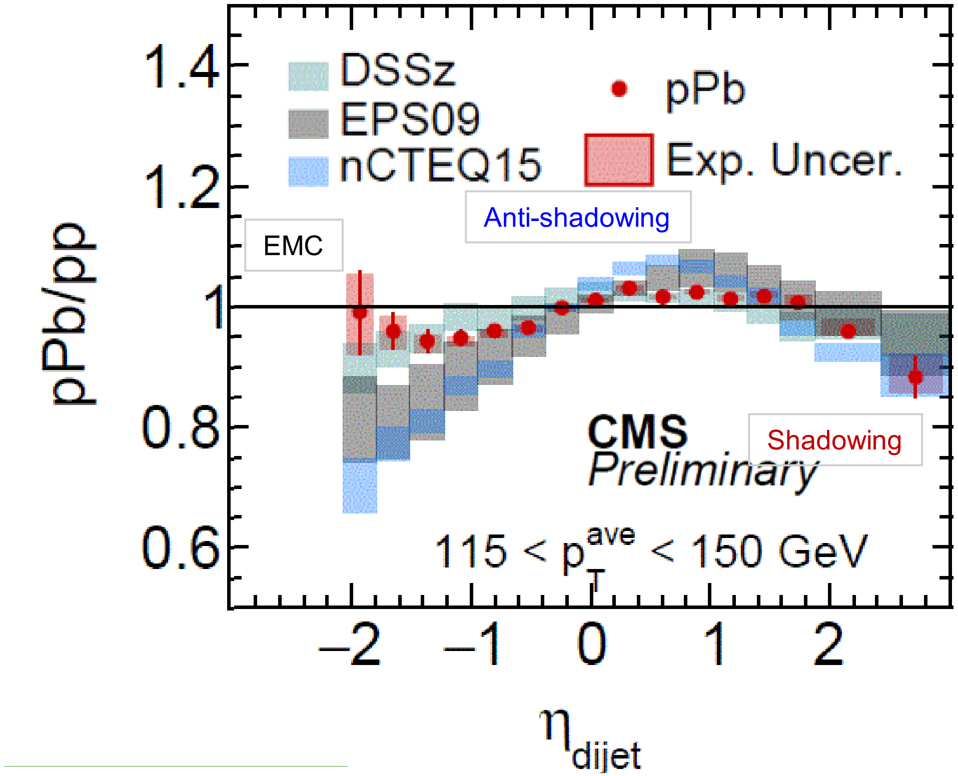
Precision measurements of $\eta_{dijet} = (\eta_1+\eta_2)/2 \propto 0.5 \log(x_p/x_{pB}) + \eta_{CM}$

η_{dijet} Theoretically: can be calculated in pQCD

Experimentally: "avoid" fragmentation and hadronization effects

p_T^{ave} Access to Q^2



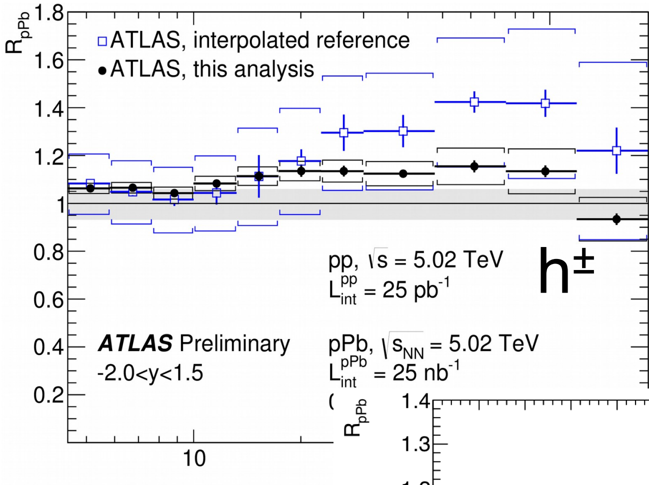


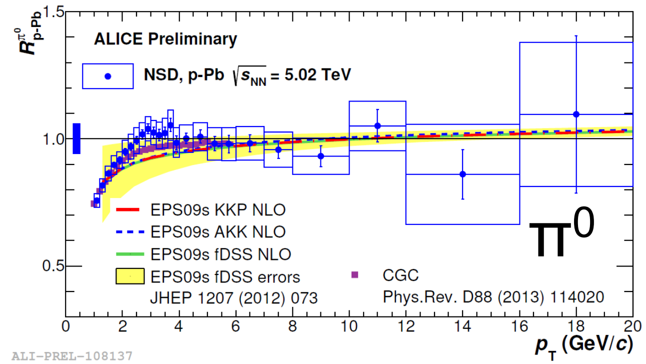
Neither PDFs nor nPDFs gives good fit across whole range

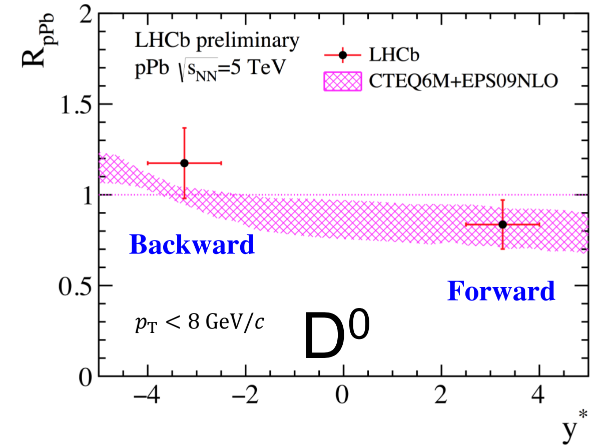
Evidence of gluon modification in EMC region x>0.3

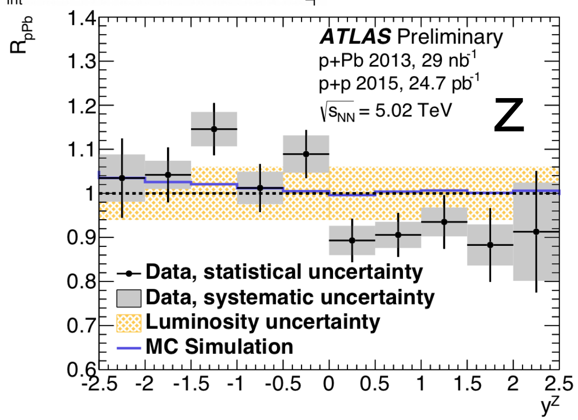
Minbias R_{pPb}

P. Balek (ATLAS), A. Dubla (ALICE), M. Dumancic (ATLAS),
T. Okubo (ALICE), B. Schmidt (LHCb), X. Zhu (LHCb)

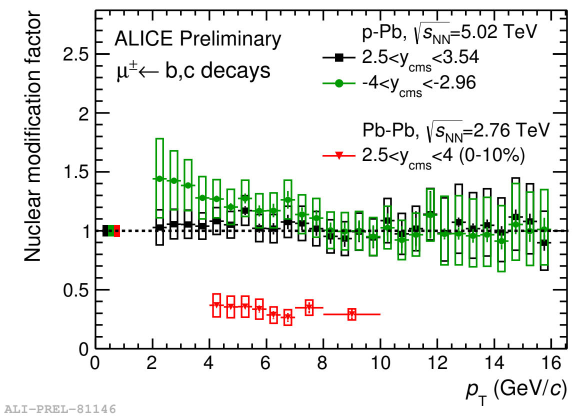


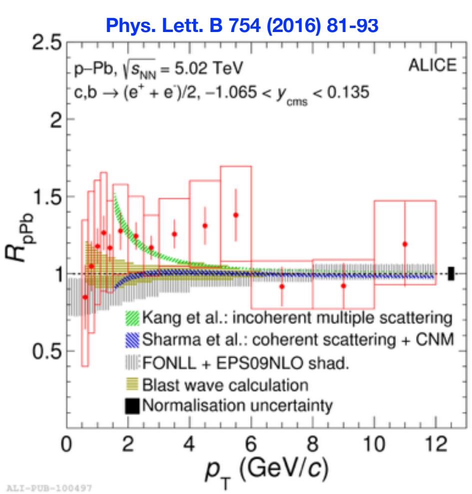


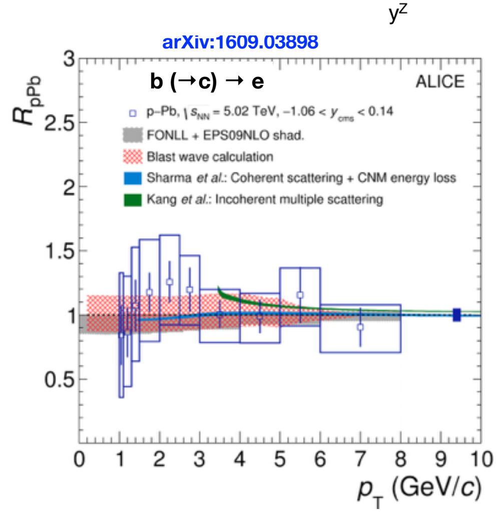


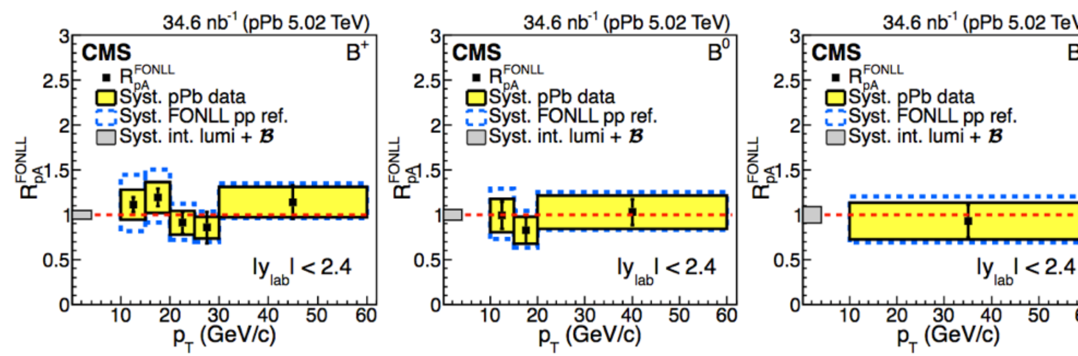


Consistent with nPDF expectations







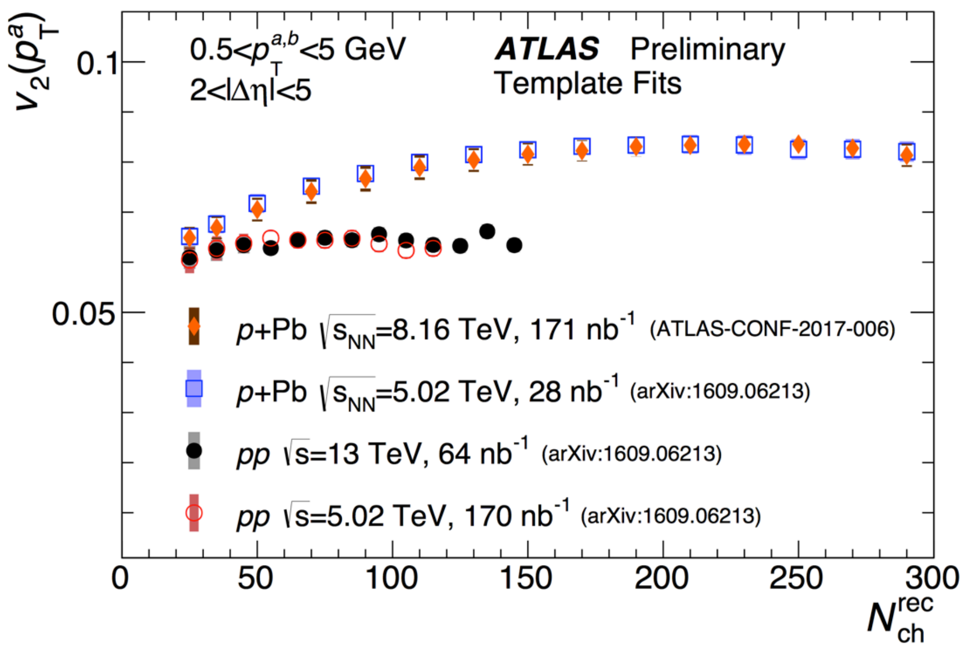


R^{FONLL}_{pA} vs p_T of B^+ R^{FONLL}_{pA} vs p_T of B^0 R^{FONLL}_{pA} vs p_T of B^0_s

Nothing enormously unexpected is occurring!

Collectivity in pp and p-Pb

ATLAS: CONF-2017-006



pp:

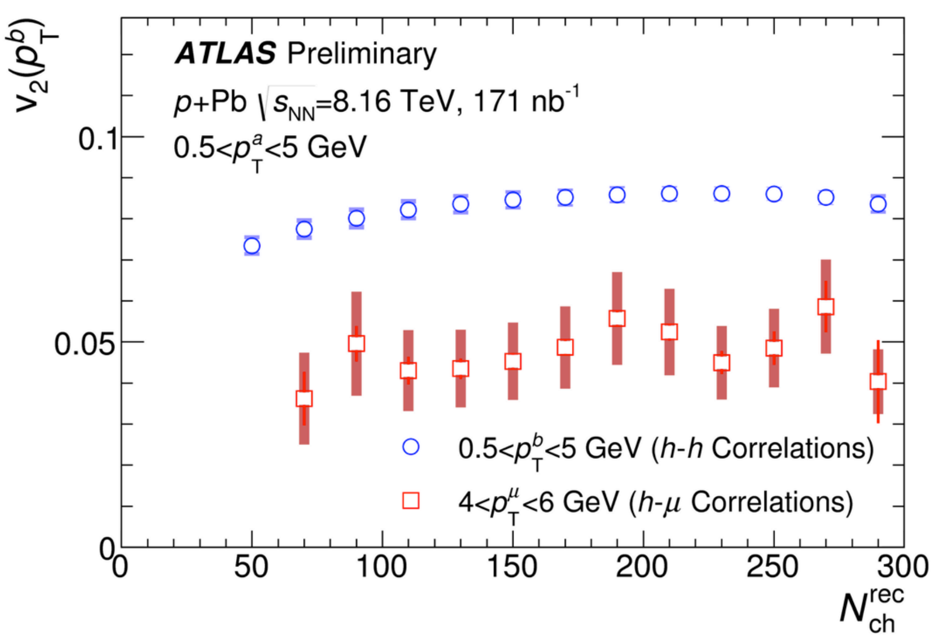
No dependence on √s

No dependence of event activity

p-Pb:

No dependence on √s

Some dependence of event activity

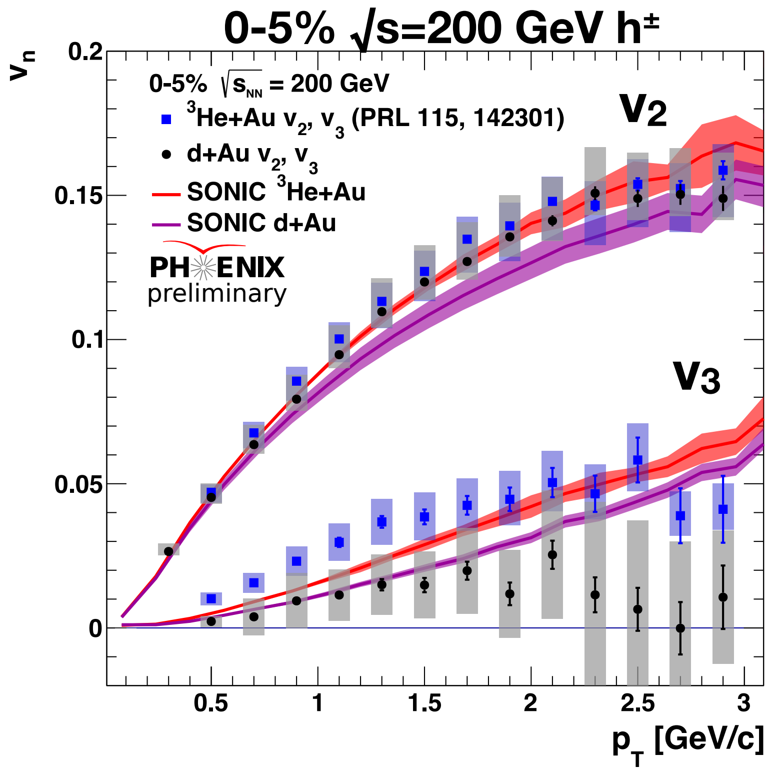


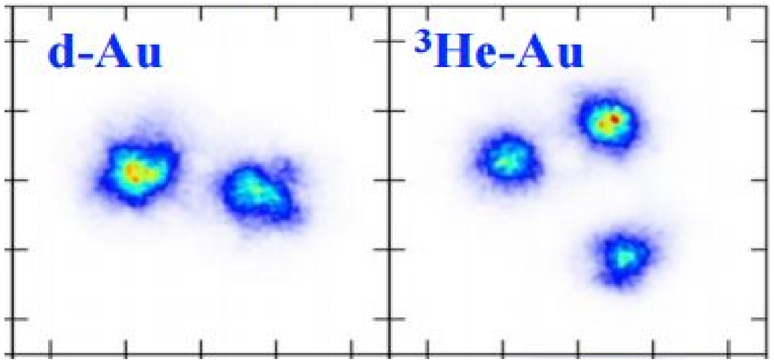
Heavy quarks also reveal signal but $v_2^\mu < v_2^h$

Sufficient (re-)interactions to (partially) thermalize heavy quarks?

High multiplicity events lead to universal observation of long range collective phenomena

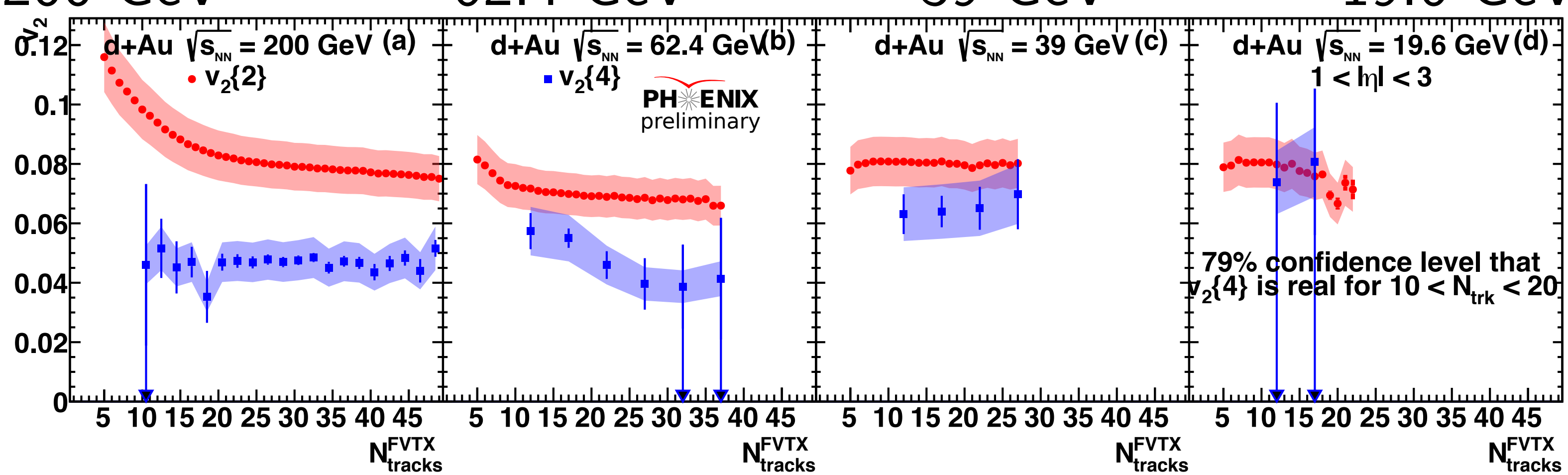
Varying the small systems





Changing initial collision geometry changes v_n as expected from models

200 GeV 62.4 GeV 39 GeV 19.6 GeV

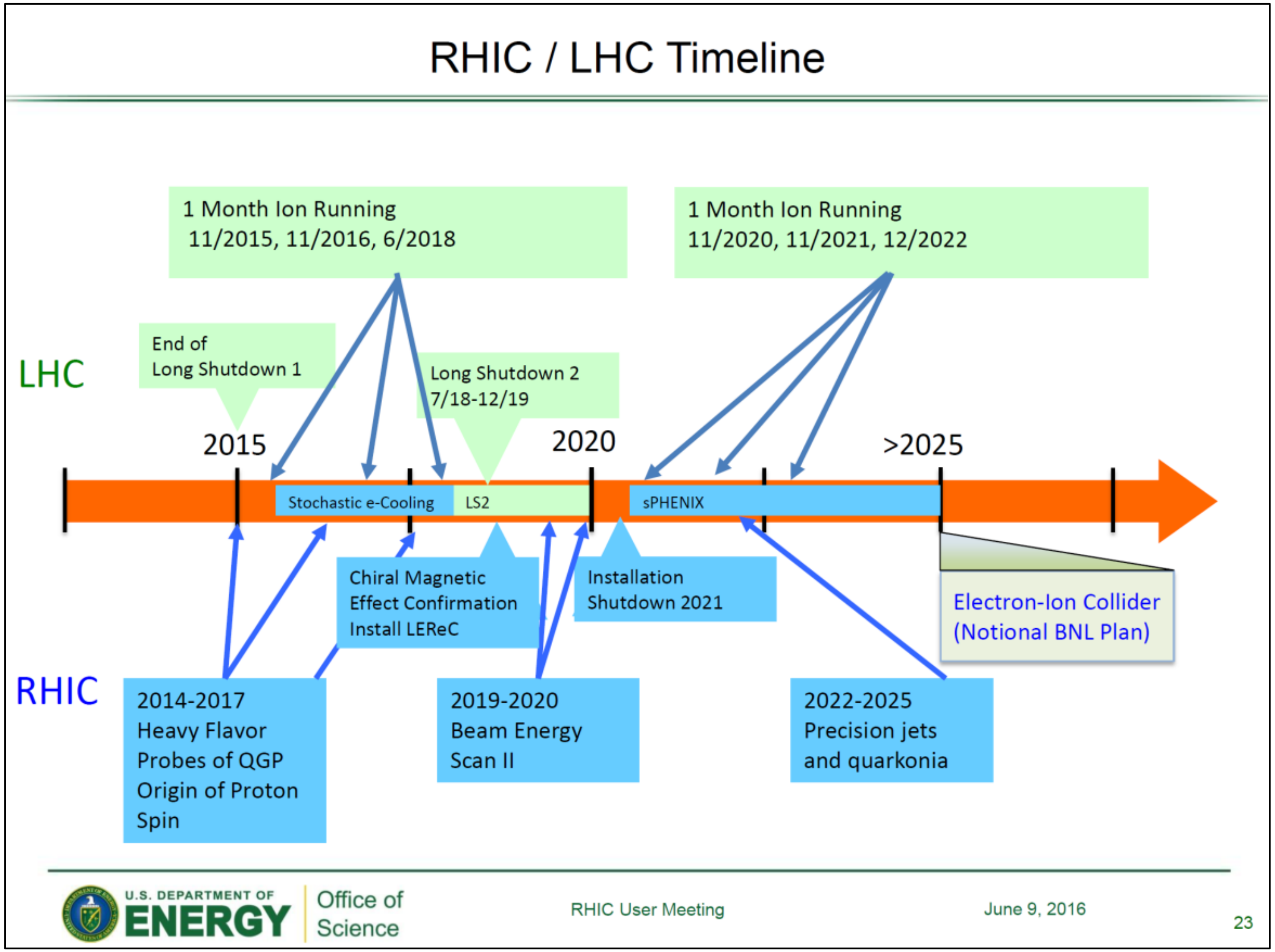


v_2 real down to 20 GeV

No signs of "rapid" onset in √s or mult.

Our Long Range Plan

Continues as a vibrant field with wide ranging international support



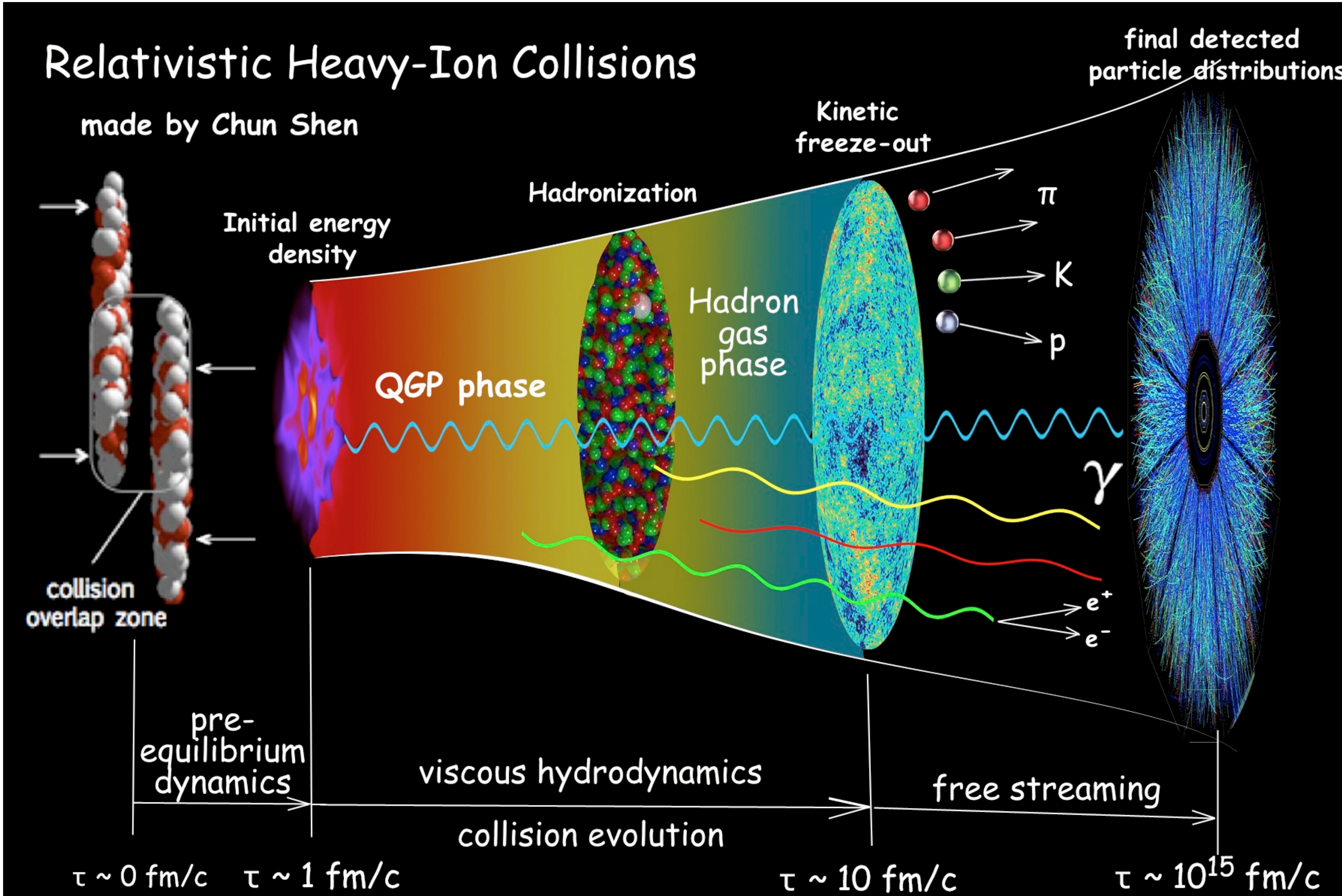
New detectors being designed and built NOW!

New accelerator facilities being designed and built NOW!

sPHENIX, Forward upgrades at STAR, upgrades at LHC, FAIR, NICA, EIC

Spares

The timeline of a heavy-ion collision

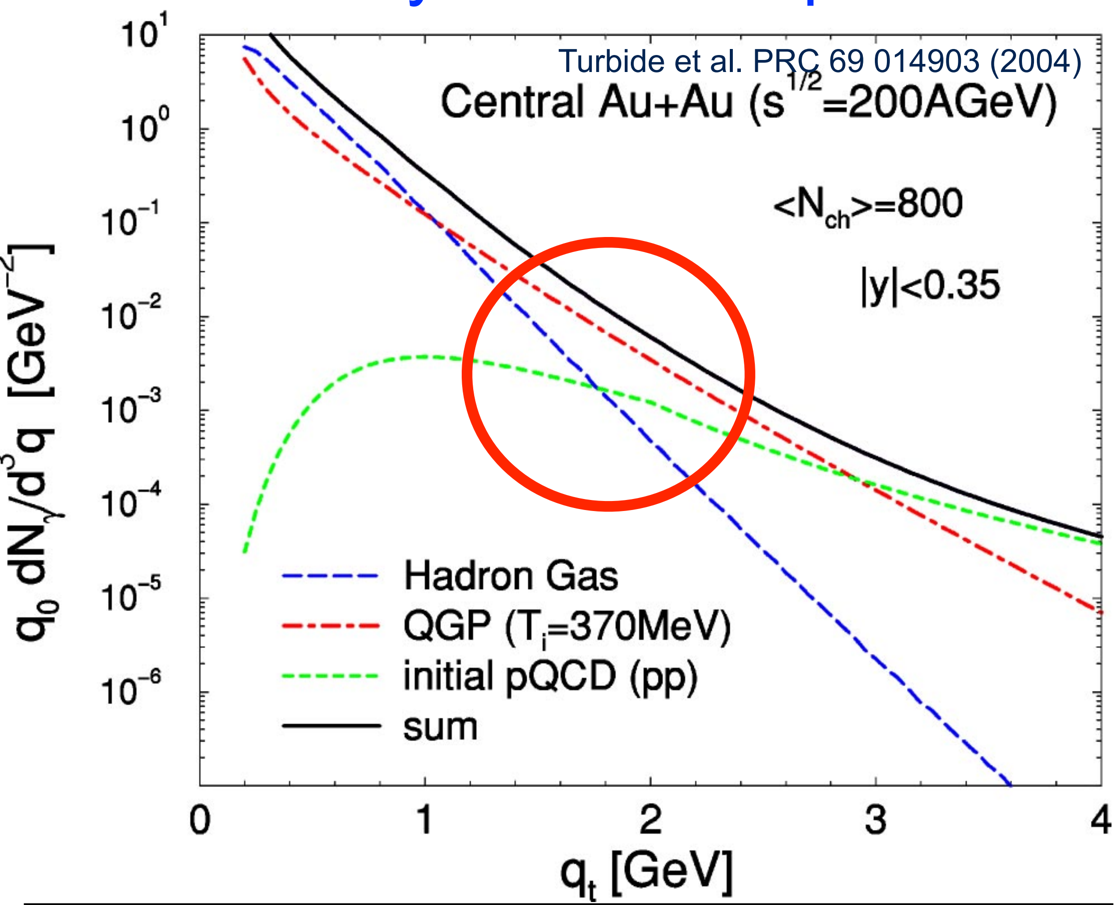


Early conditions: Temperature

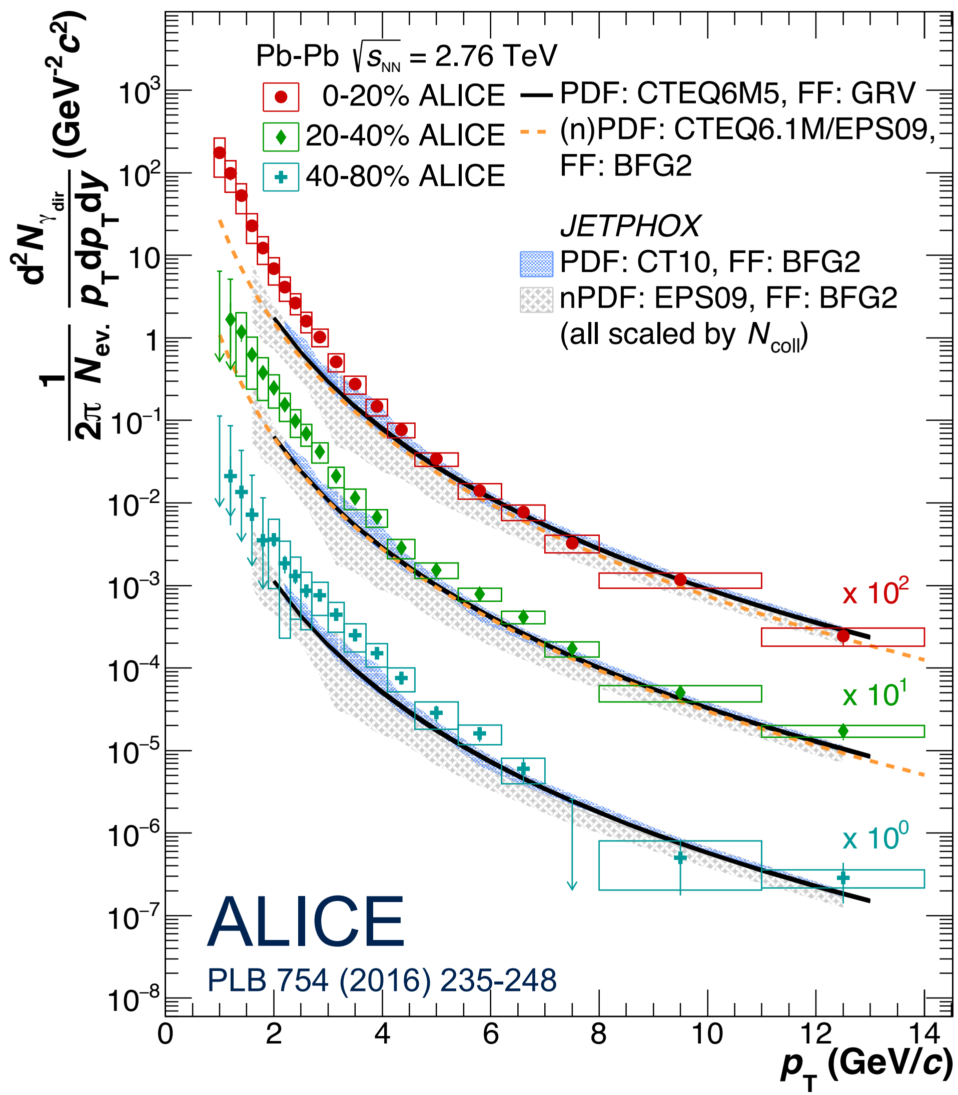
Direct Photons:

- no charge or color → don't interact with medium
- emitted over all lifetime → convolution of all T

Theory well developed



QGP dominates: $1 < p_T < 3$ GeV/c



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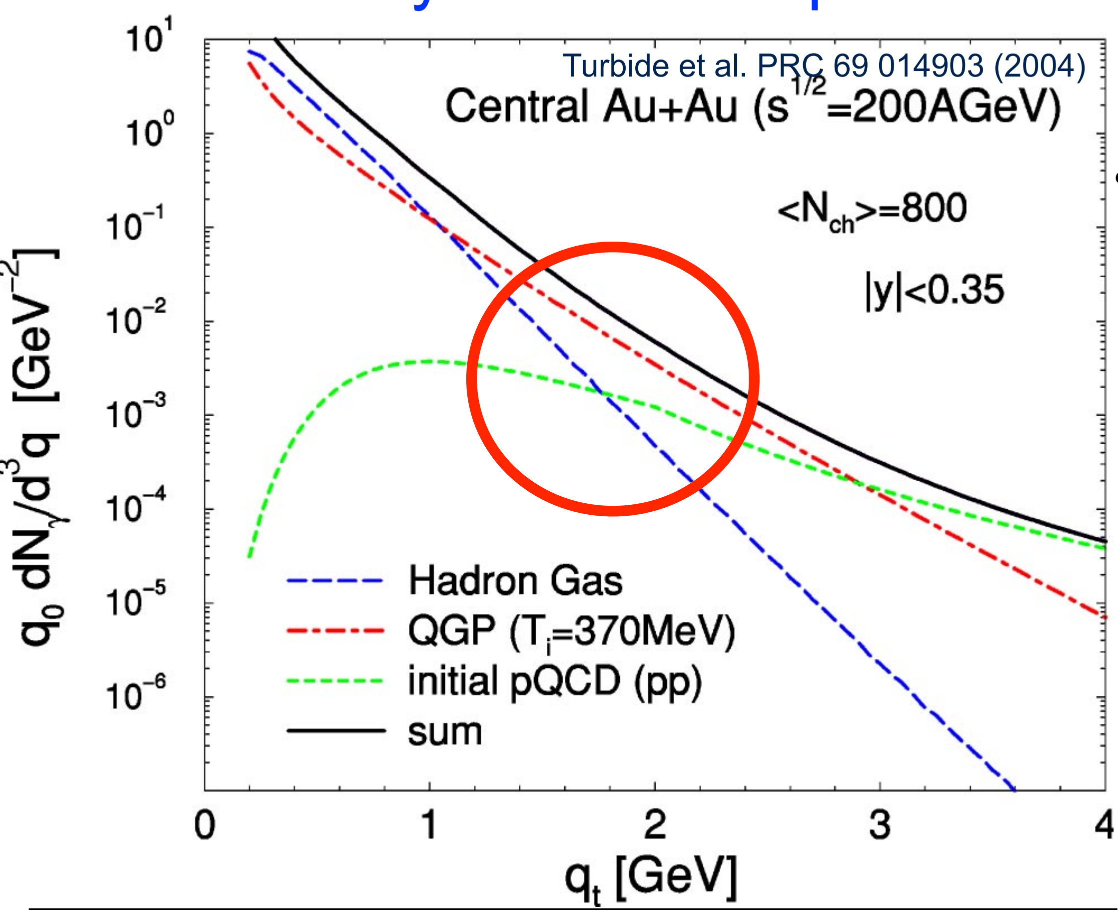

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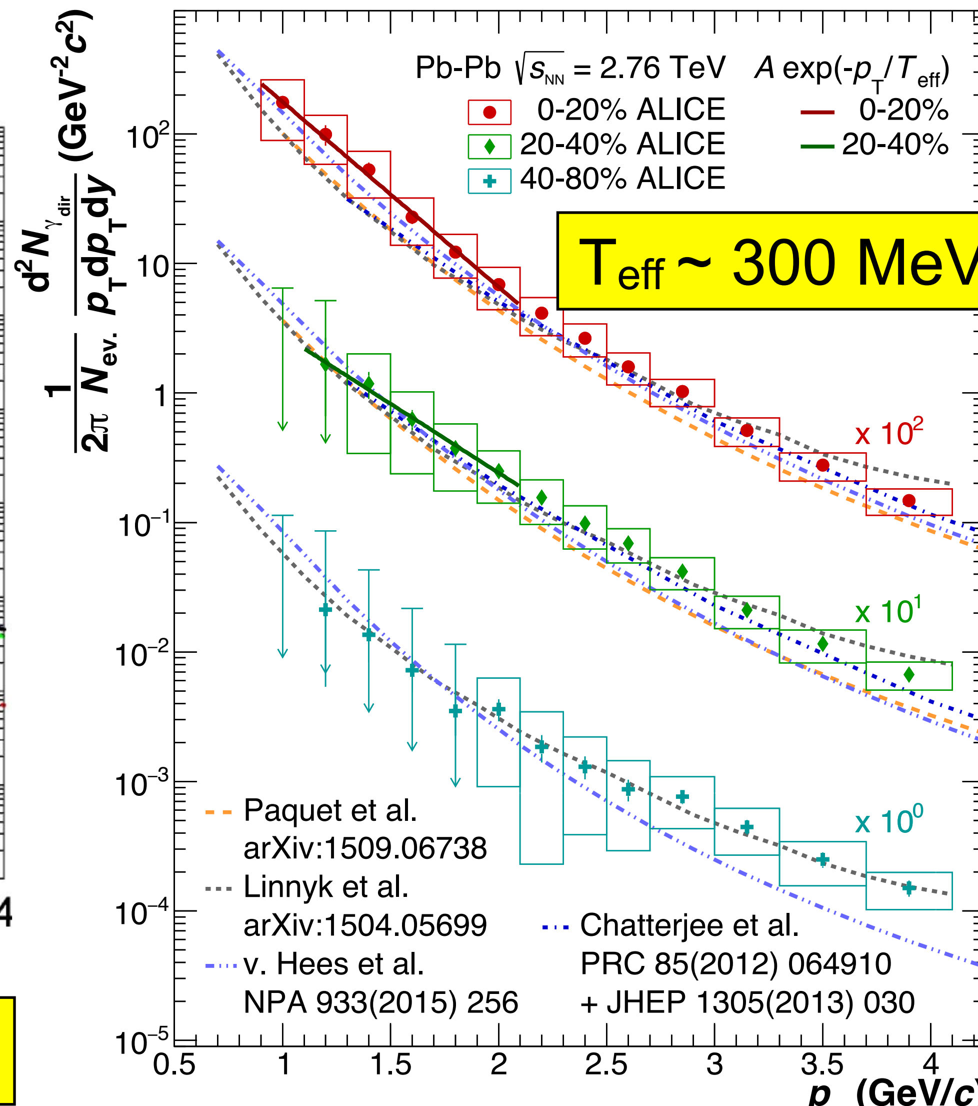


$T_{eff} \sim 300$ MeV

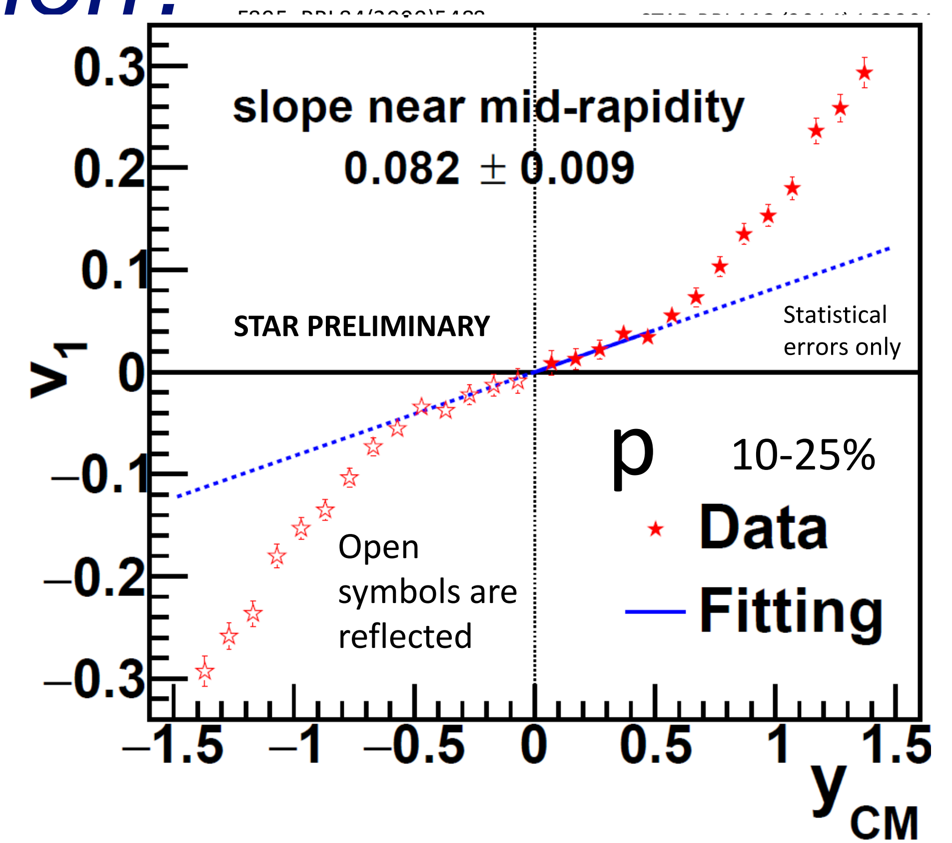
First order phase transition?

Low √s : slope v_1(baryons) positive
slope v_1 (mesons) negative

Beam energy baryon dv_1/dy trend
complex interplay of:

v_1 baryons transported from beam

v_1 from pair production



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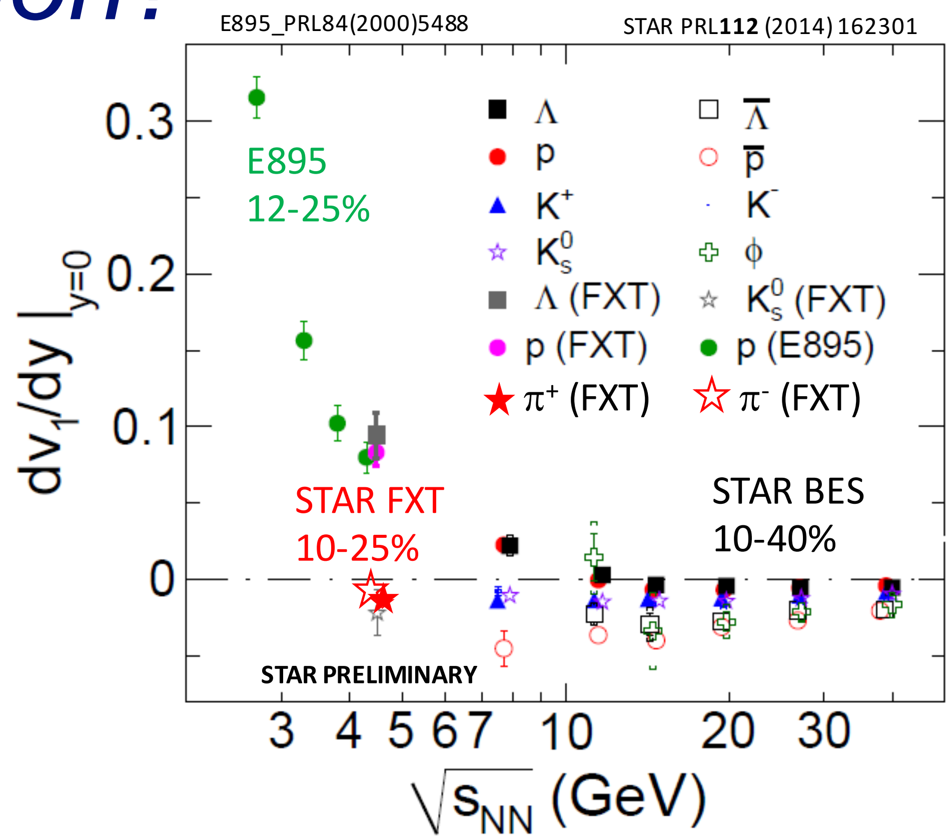
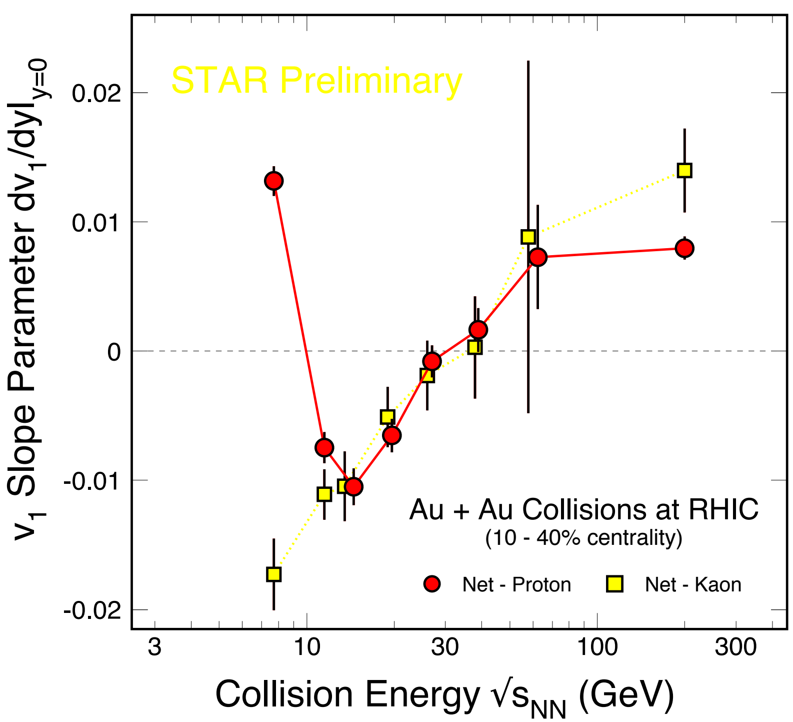




Net-proton isolates directed flow of transported baryons:

Double sign change in dv_1/dy

Not seen in net-kaons

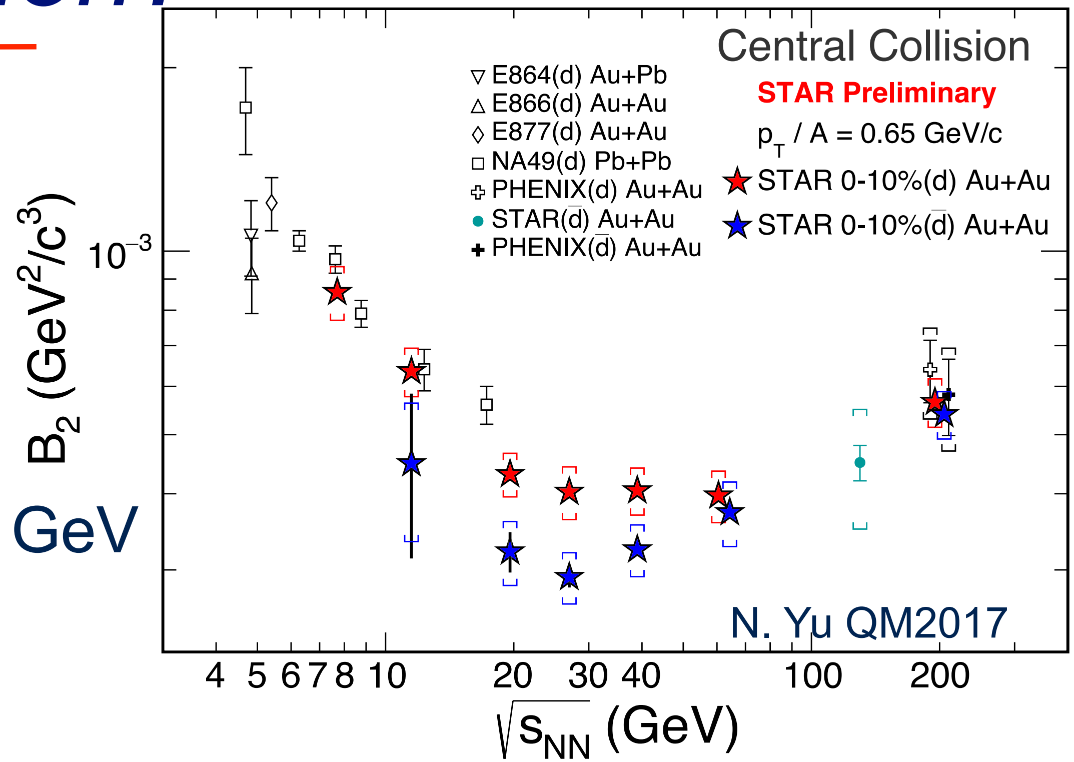
Results not yet reproduced by theory

Softening of EoS ?

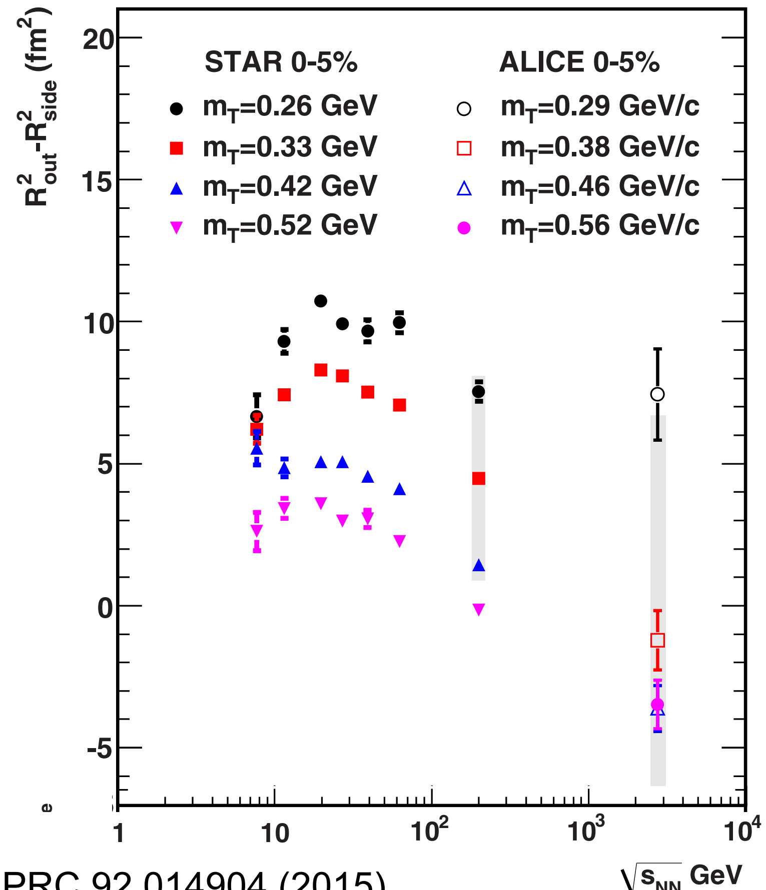
Stalling of the expansion?

d final state coalescence access to nucleon freeze-out volume

$$E_A \frac{d^3N_A}{d^3p_A} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A \quad B_2 = \frac{6\pi^3 R_{np} m_d}{m_p^2 V_f}$$



B_2 minimum (V maximum) $\sqrt{s_{NN}}$ ~ 20 GeV



PRC 92 014904 (2015)

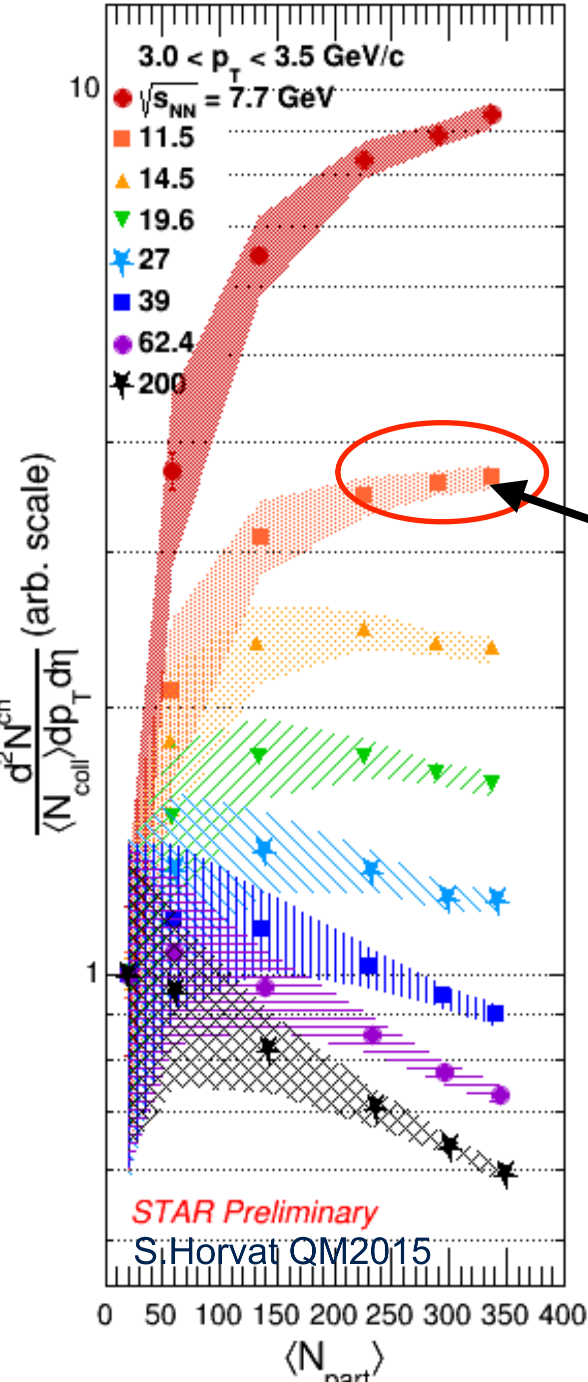
(R^2_{out} - R^2_{side}) sensitive to emission duration

Maximum at $\sqrt{s_{NN}}$ ~ 20 GeV

Softening of EoS?

Sign of entering compressed baryonic matter regime?

Disappearance of QGP?

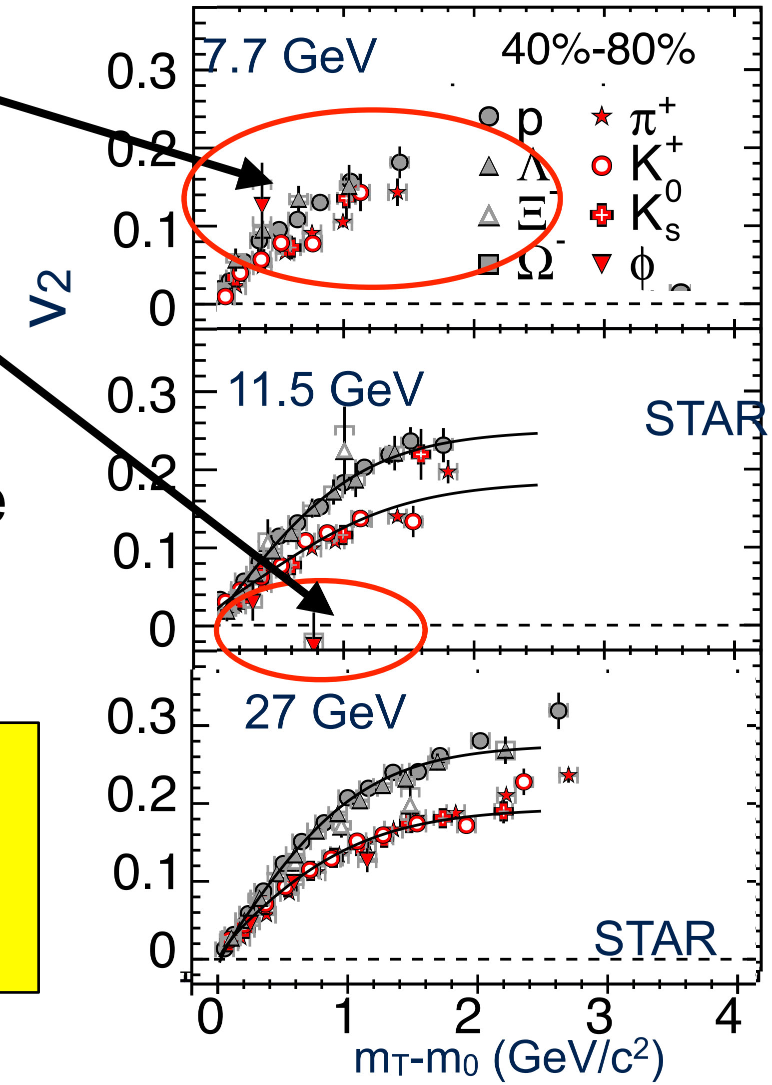


B-M v_2 separation gone

ϕ v_2 ~ 0

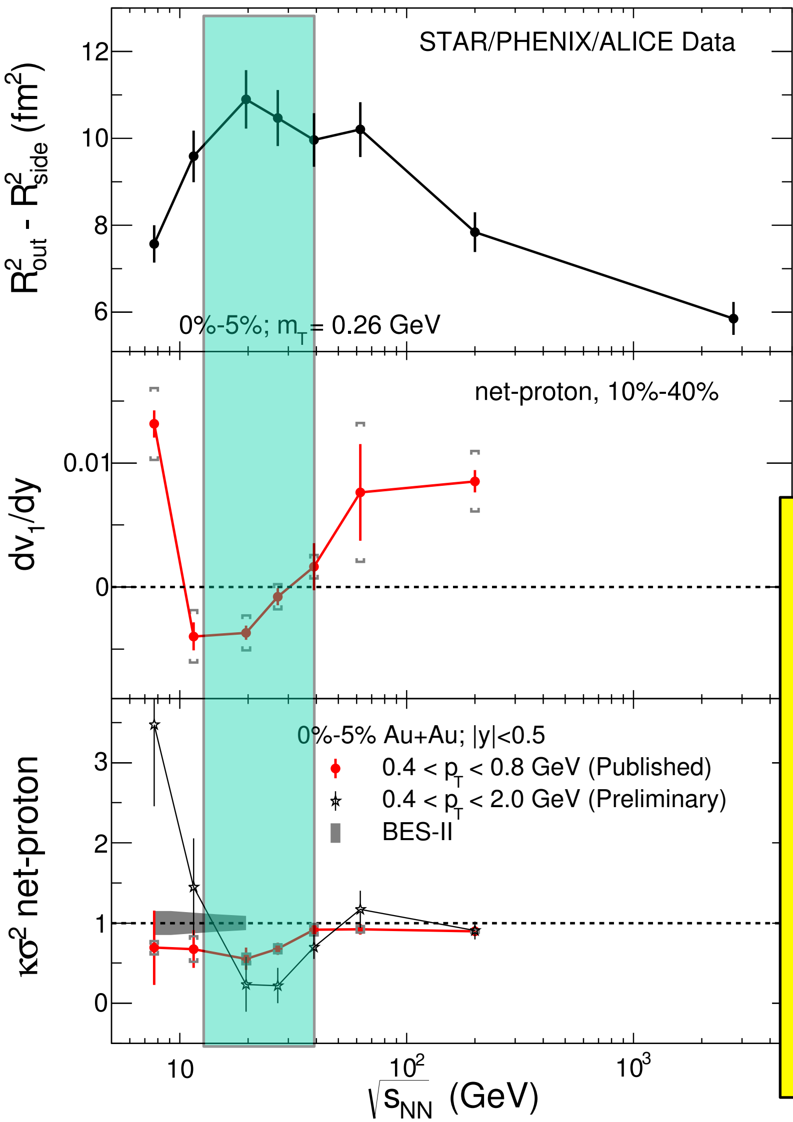
High p_T suppression gone

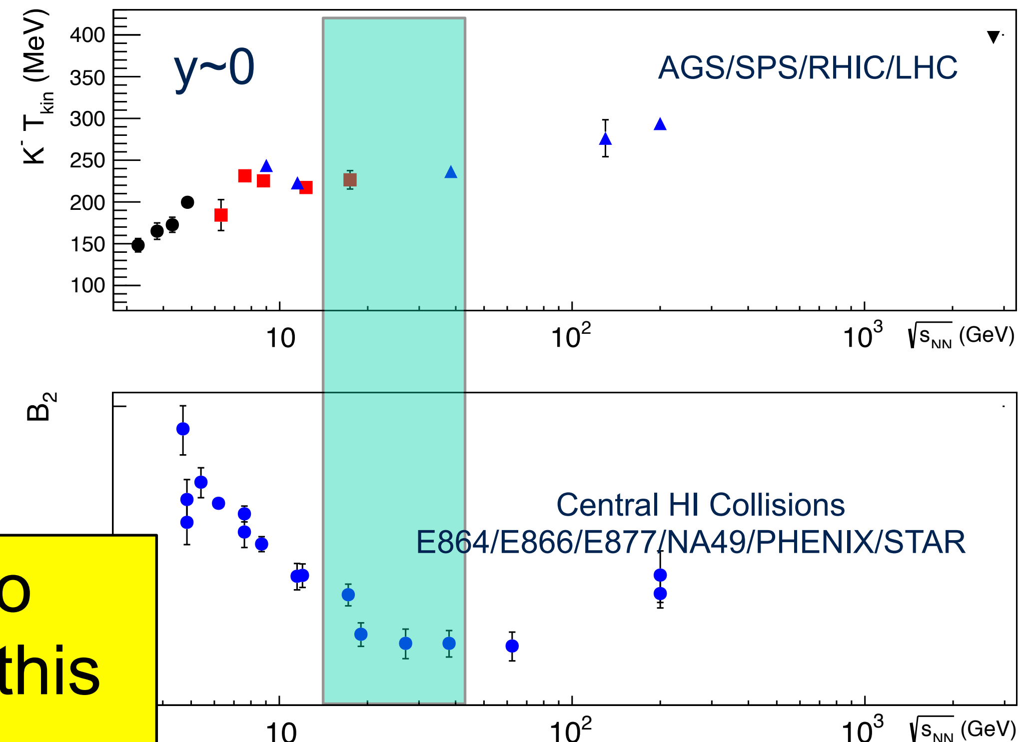
Several standard signals disappear at $\sqrt{s}$ < 15 GeV



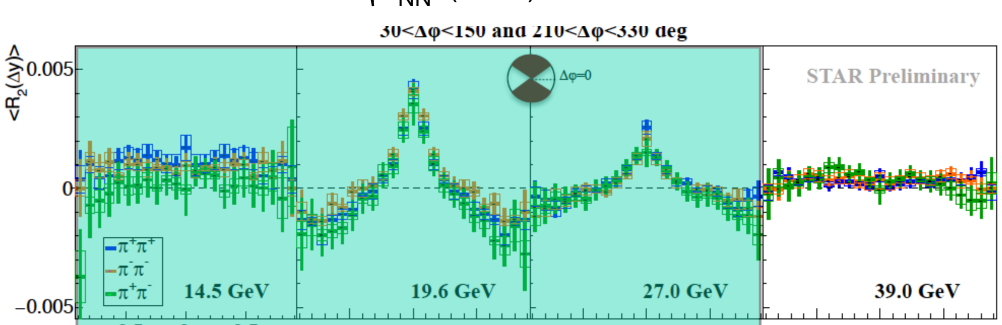
PRC 93 (2016) 14907

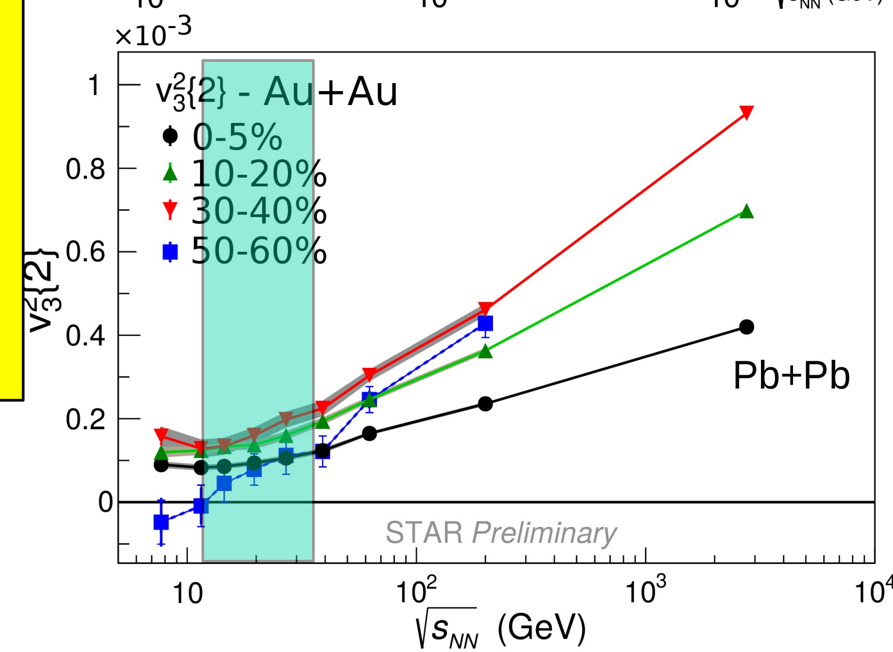
A lot is happening around 20 GeV





Hard to believe this is a conspiracy of different underlying causes





Improving on current data

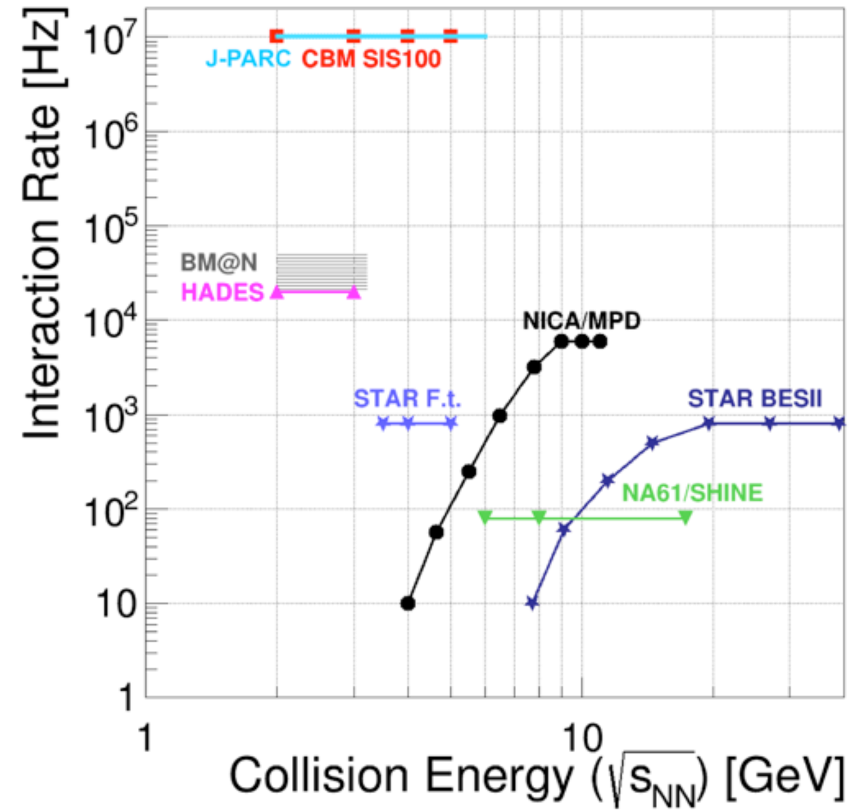
Current low energy data:
Hints that at low √s

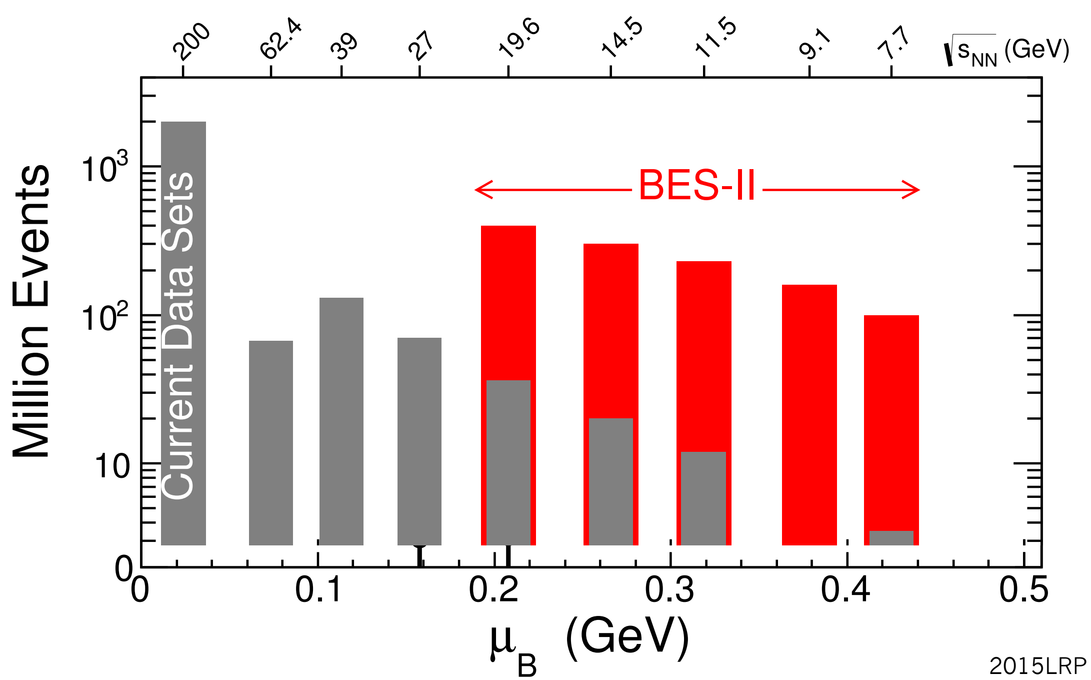
- QGP turns off
- Ordered phase transition
- Critical Point

Future data:

- Examine regions of interest
- Maximizing fraction particles measured
- Probe lower √s
- High(er) luminosities
- Change species

Turn trends and features into definitive conclusions





2015LRP

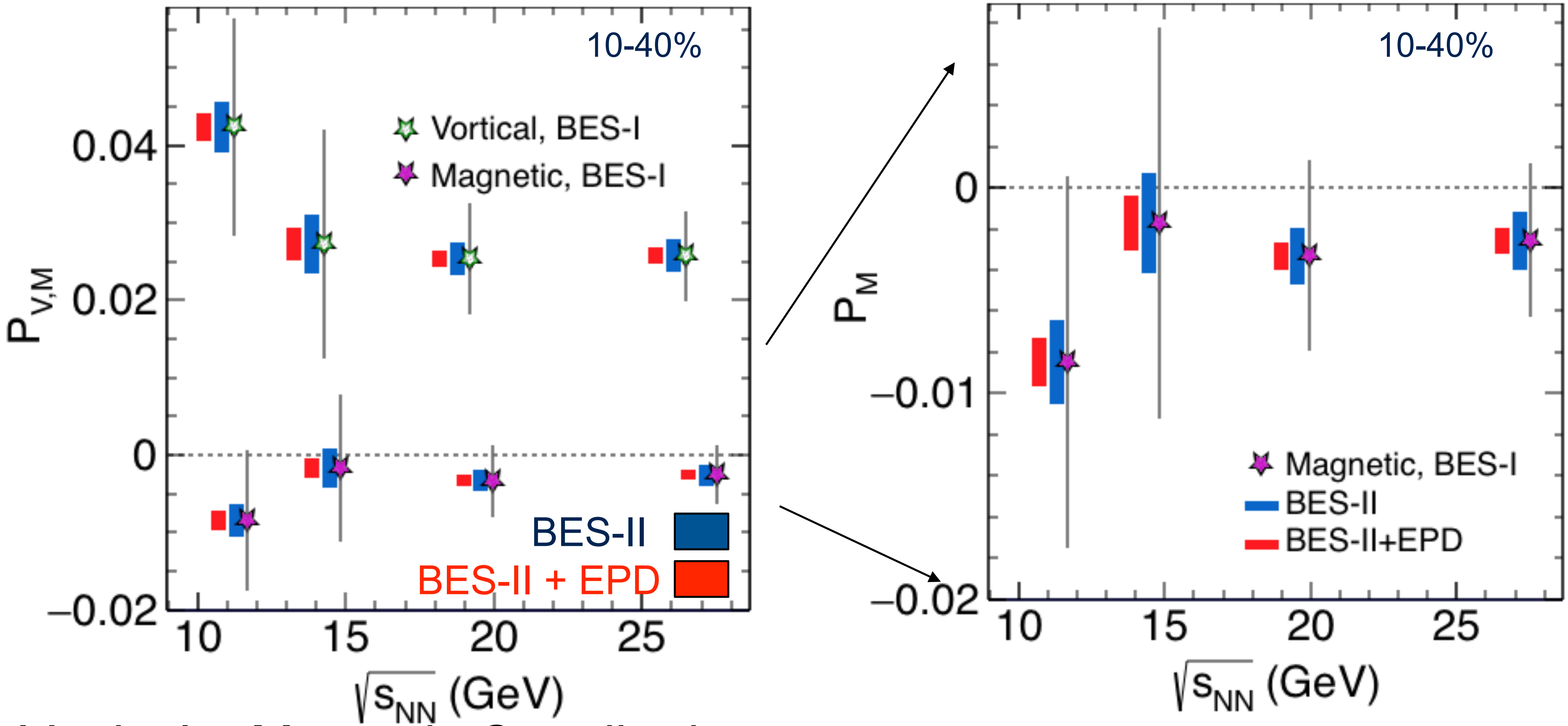
Planned low energy running

μ_B (MeV)	560 - 230	850 - 670	790	720 - 210	750 - 330	780 - 400	850 - 490
$\sqrt{s_{NN}}$ (GeV)	4.9-17.3	2-3.5	2.4	3-19.6	2.7-11	2.7-8.2	2-6.2
Facility	SPS	NICA	SIS-18	RHIC	NICA	SIS-100	J-PARC HI
Experiment	NA61/ SHINE	FXT	HADES	STAR	MPD	CBM	
Start Year	2009	2017	2018	2019	2020	2022	2025
Physics	CP & Onset	Dense Baryon	Dense Baryon	CP and Onset	Onset & Dense Baryon	Onset & Dense Baryon	Onset & Dense Baryon

Expect wealth of new insights over next ~5 years

BES-II: Vorticity and Initial B-field

BES-I: First measurement of Λ **Global** Polarization



Vortical + Magnetic Contributions:

Current data barely stat. significant

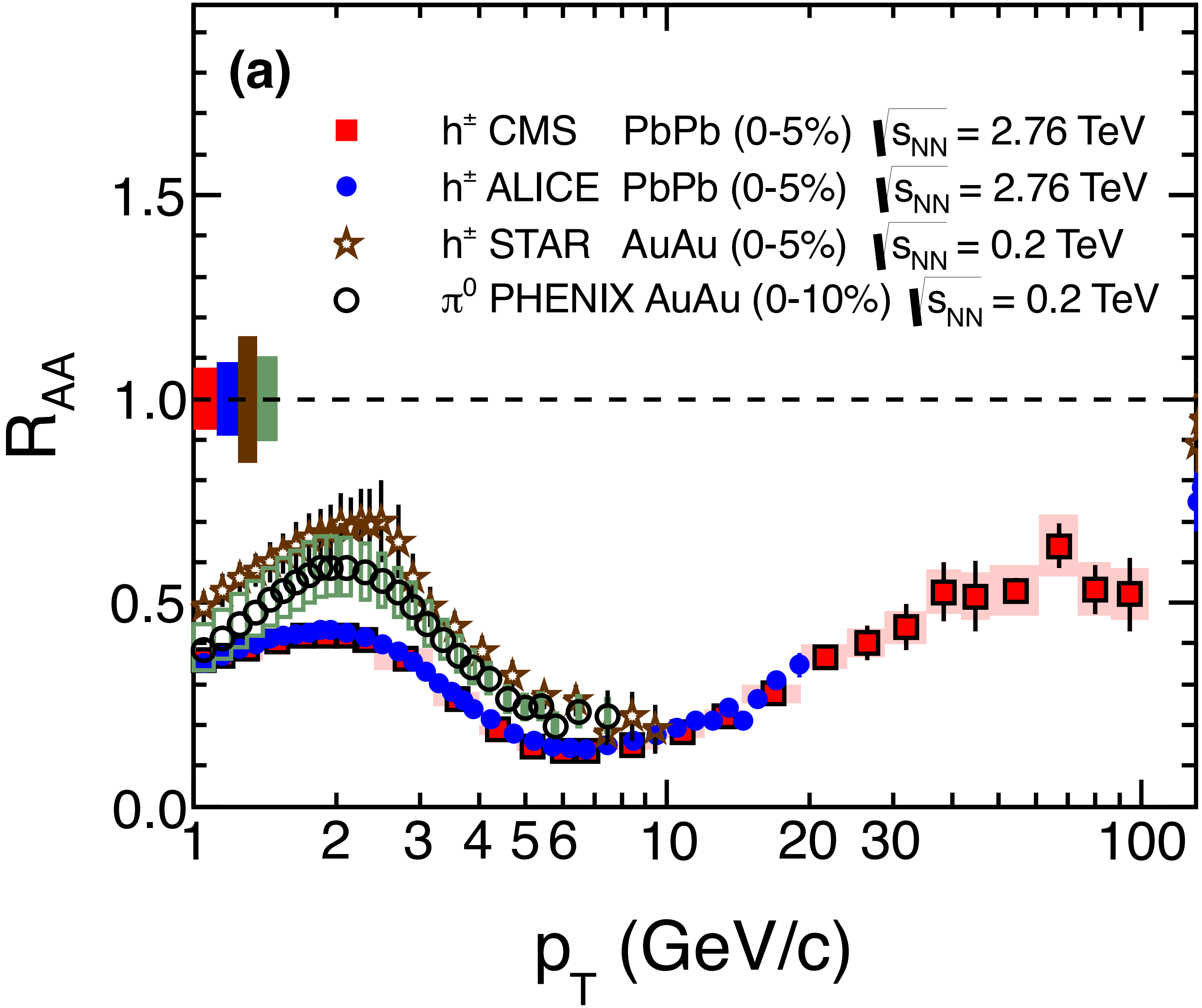
EPD:

Improved EP resolution

BES-II: 3σ effect

Unique measurement of B
Significant input to CME/CVE interpretations

Strong suppression of high p_T particles



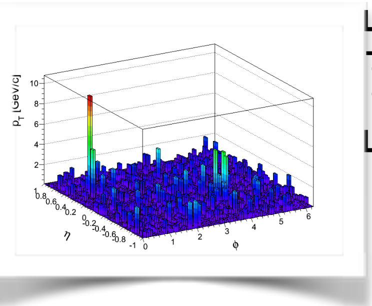
High p_T hadrons:

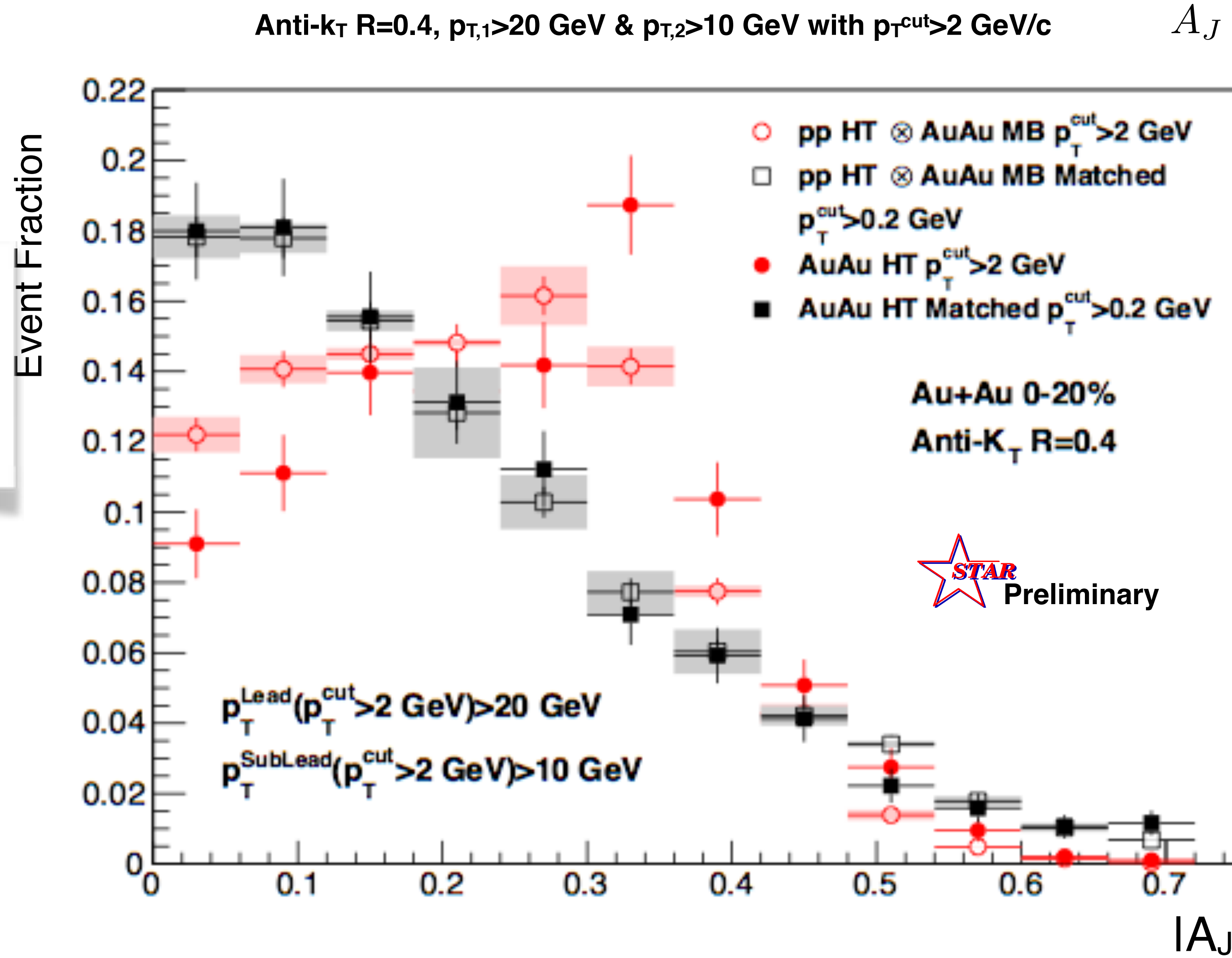
at RHIC: from quarks
at LHC: from gluons

Light quarks and gluons strongly coupled to the medium

Di-jet imbalance A_J Au-Au 0-20% R=0.4

$$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} - p_T^{SubLead}}$$





p-value<10^{-5}
(stat. error only)

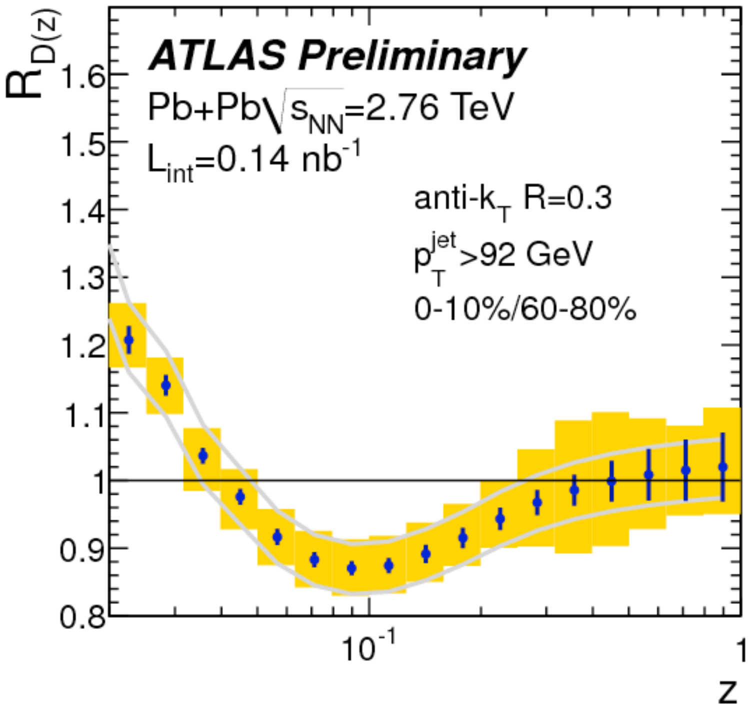
p-value~0.8
(stat. error only)

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au-Au di-jets more imbalanced than p-p for p_T^{cut}>2 GeV/c

Au-Au A_J ~ p-p A_J for matched di-jets (R=0.4)

Where does the energy go?



ATLAS-CONF-2012-115

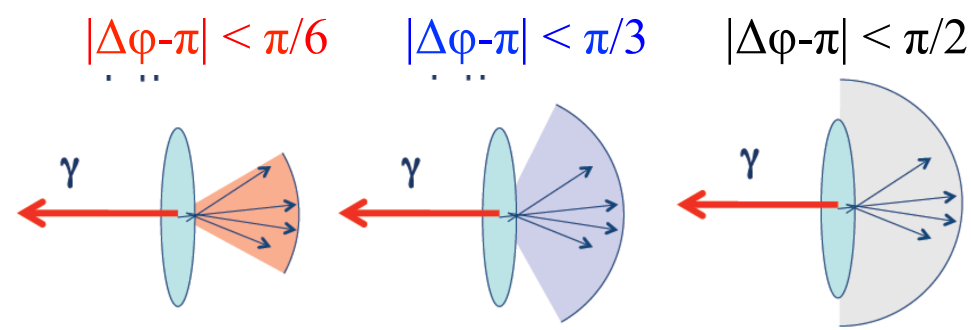
γ-hadron correlations

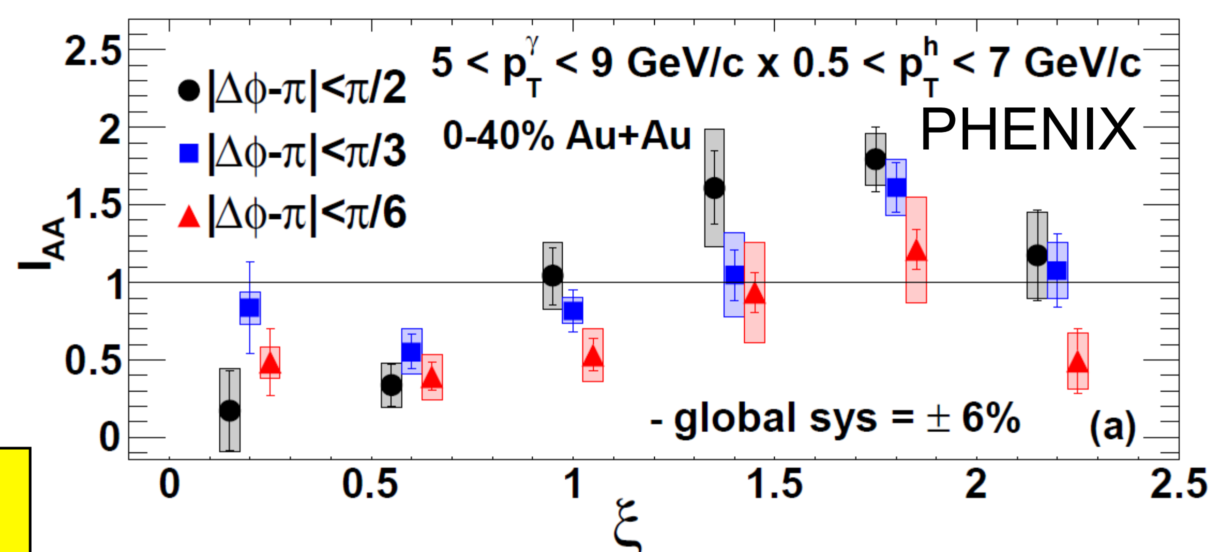
γ - Energy calibration

I_{AA} as function of "cone R"

E remains correlated to jet axis but at large angles

"Lost" hard particles emerge as multiple soft particles



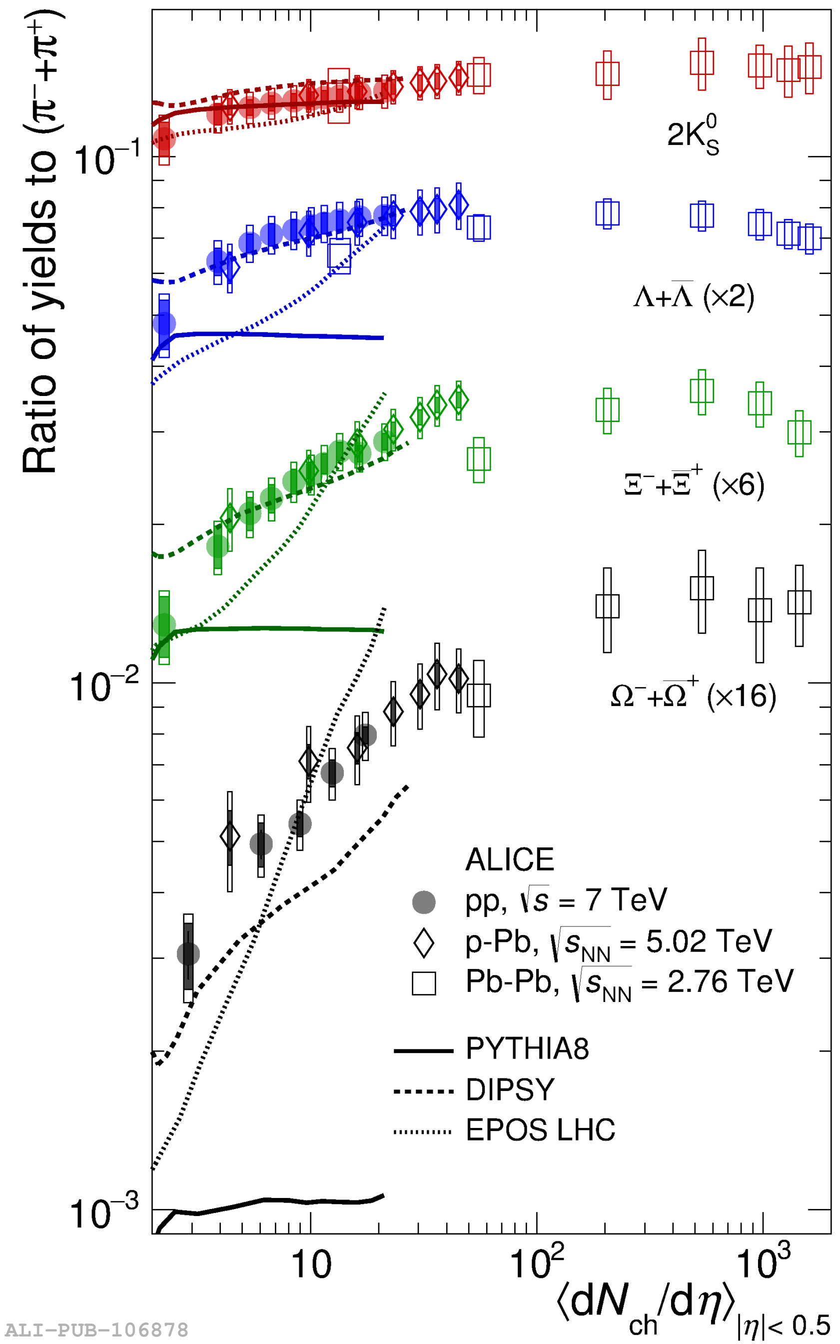


arXiv:1212.3323

Strangeness saturation in pp?

O. Busch (ALICE)

ALICE arXiv:1606.07424



Steep rise in strangeness yields per π as function of event activity

Strong function of strangeness content

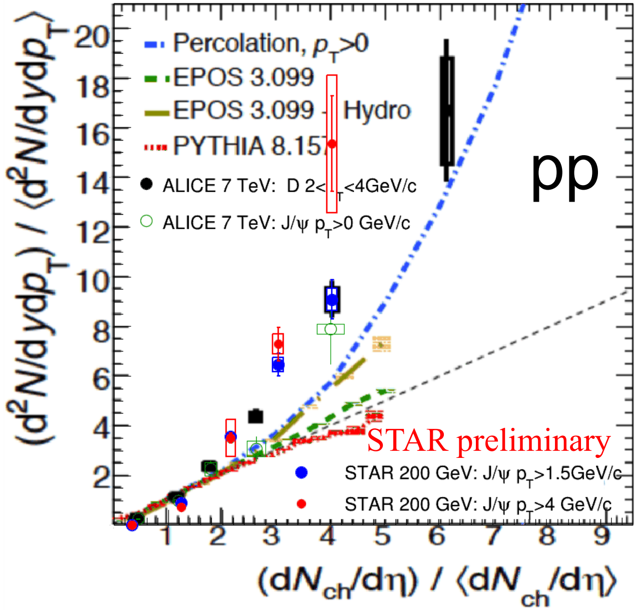
Trend in pp same as that in p+Pb with smooth transition to Pb+Pb

Not reproduced by models

Is this increase dependent on p_T and/or event activity definition as for HF?

HF production versus event activity

G. Luparello (ALICE)



Self normalized yields grows faster than event activity at both LHC and RHIC

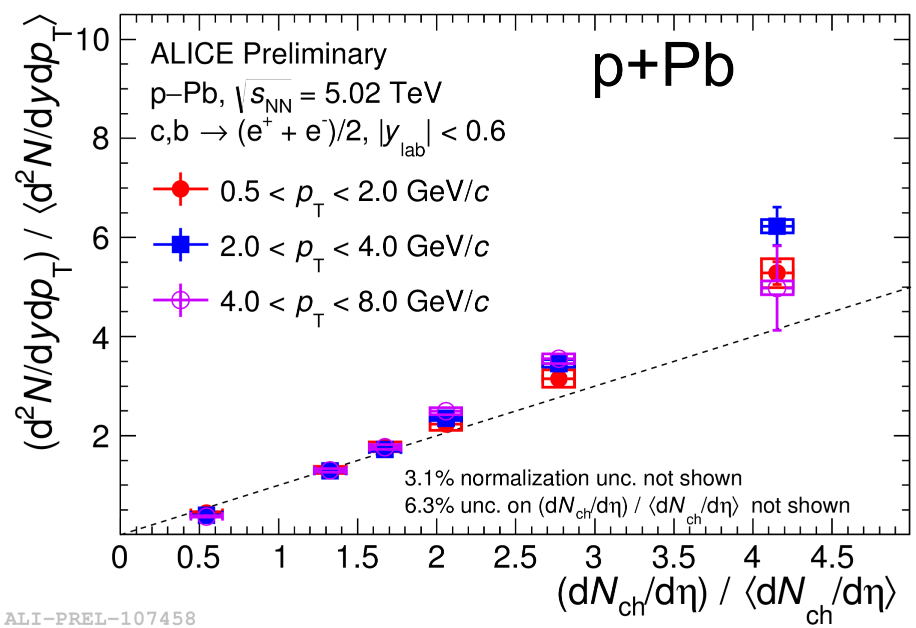
Soft vs hard processes competing?

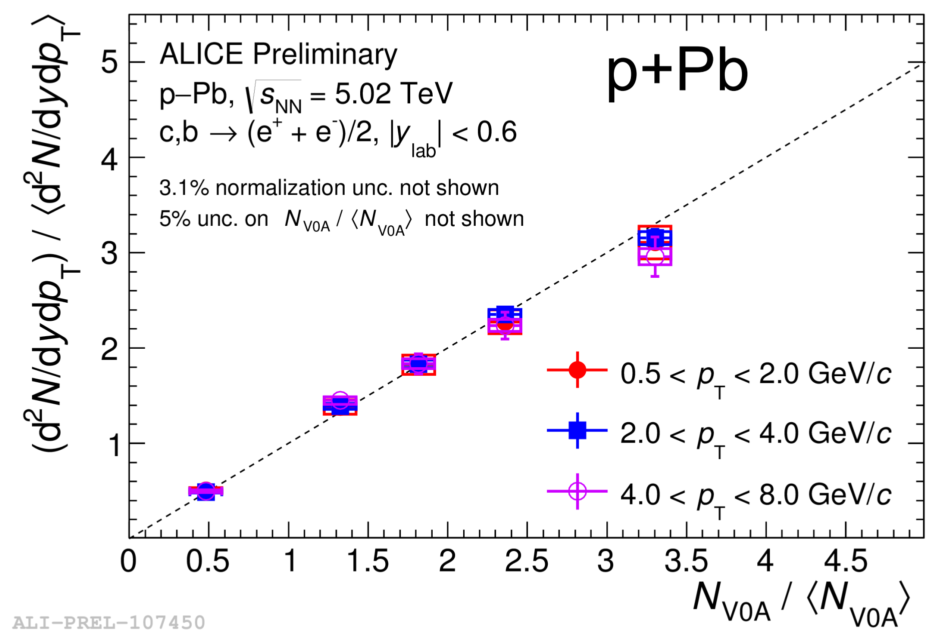
MPI at work?

Also seen in p+Pb

NPE show no difference above/below 4 GeV/c

b behaves like c

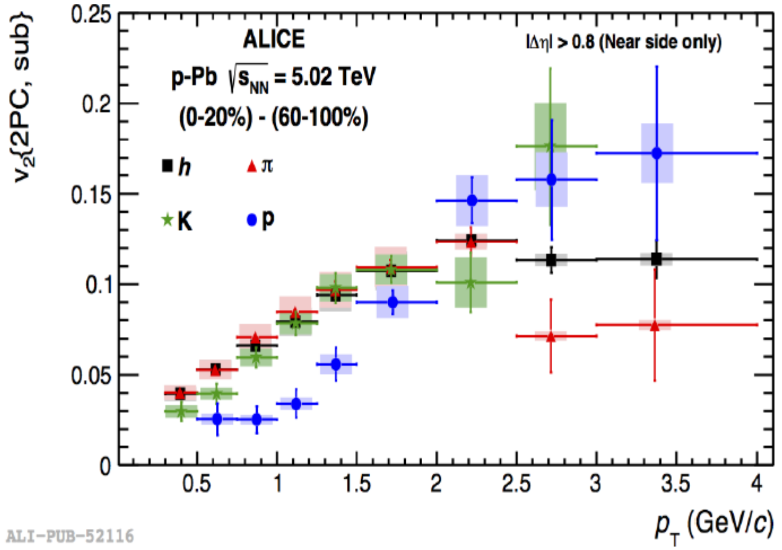




Results depend on where event activity measured

Physics or ill defined reference?

Small systems - an ongoing debate



Evidence of collective motion in high multiplicity p-p, p-Pb, He^3-Au, p-Au, p-Al, and d-Au

Some trends fit with those from A-A

Magnitude reduces with $\sqrt{s_{NN}}$

limited evidence at 19.6 GeV