Quark Matter 2018 summary

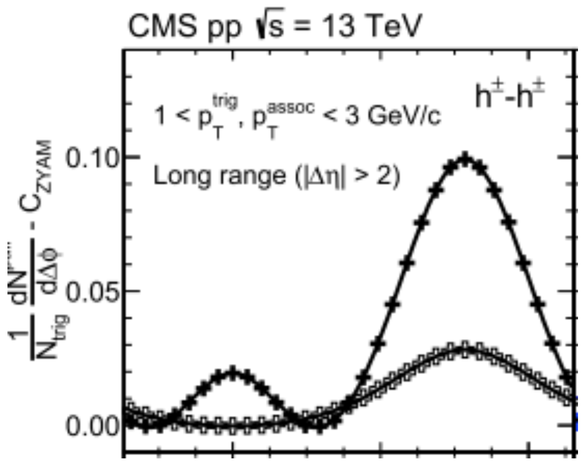
Or: what I take home from the conference…
A biased summary

Marco van Leeuwen, Nikhef and CERN

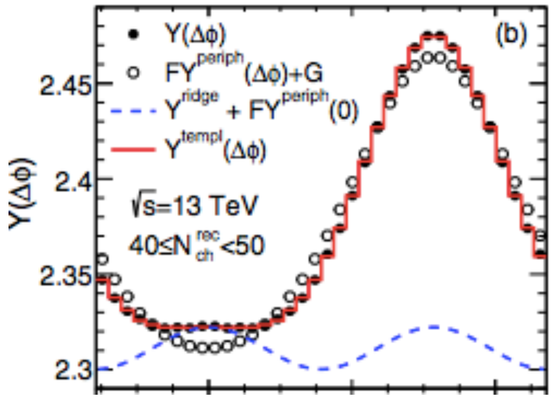
Small systems

Small system flow: fine print !

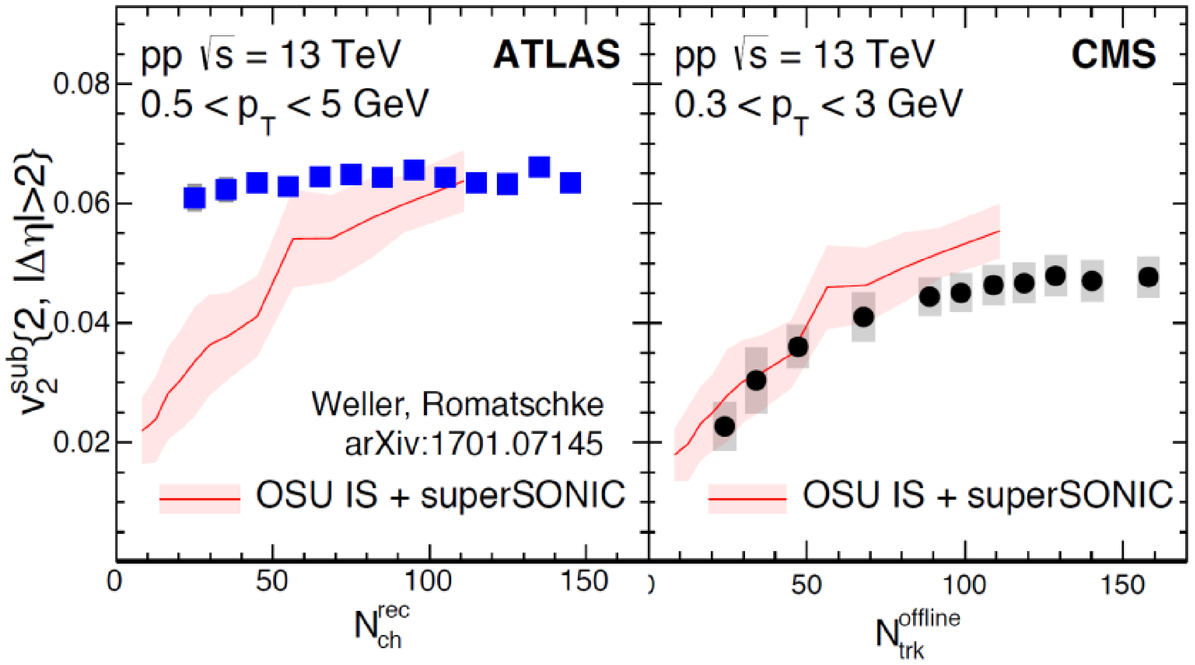
Ansatz: soft production + jets, resonances, etc 'non-flow'



CMS, ALICE:
high-multiplicity minus low-mult



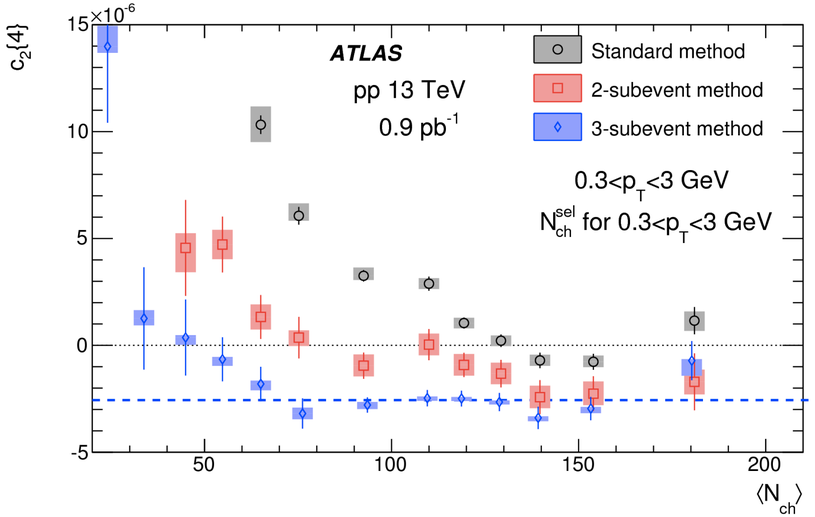
ATLAS:
template fit



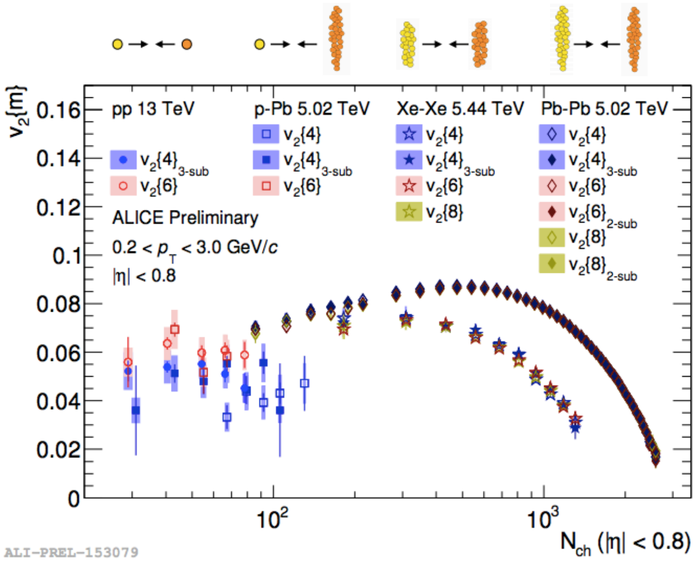
Background scaling in v_2 determination matters!

New techniques: multi-particle subevent cumulants

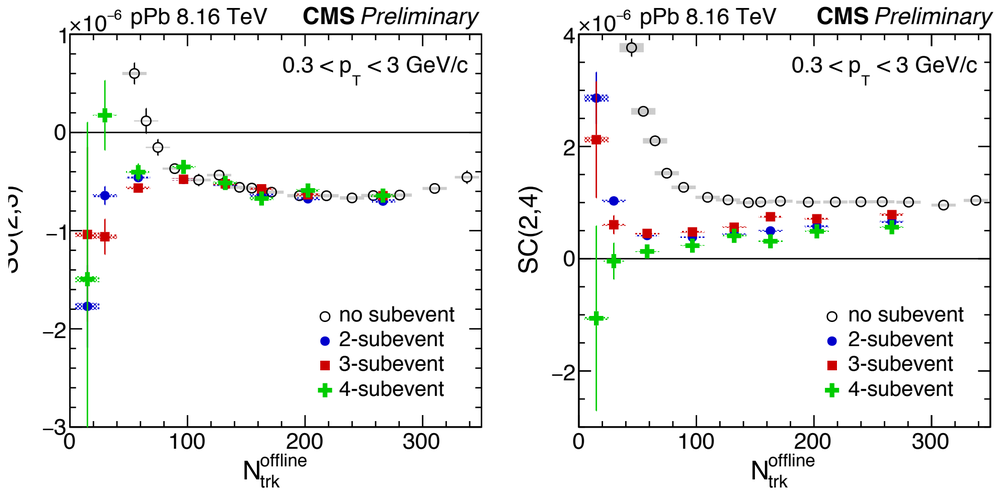
pp at 13 TeV



ATLAS PRC.97.024904



Symmetric cumulants in pPb



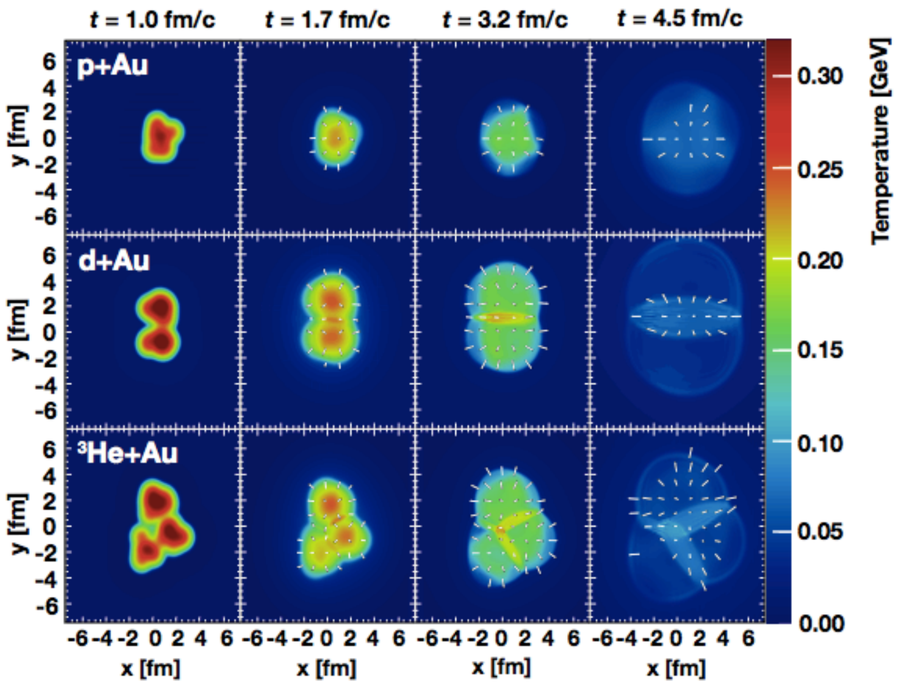
Sensitive to correlations between flow amplitudes

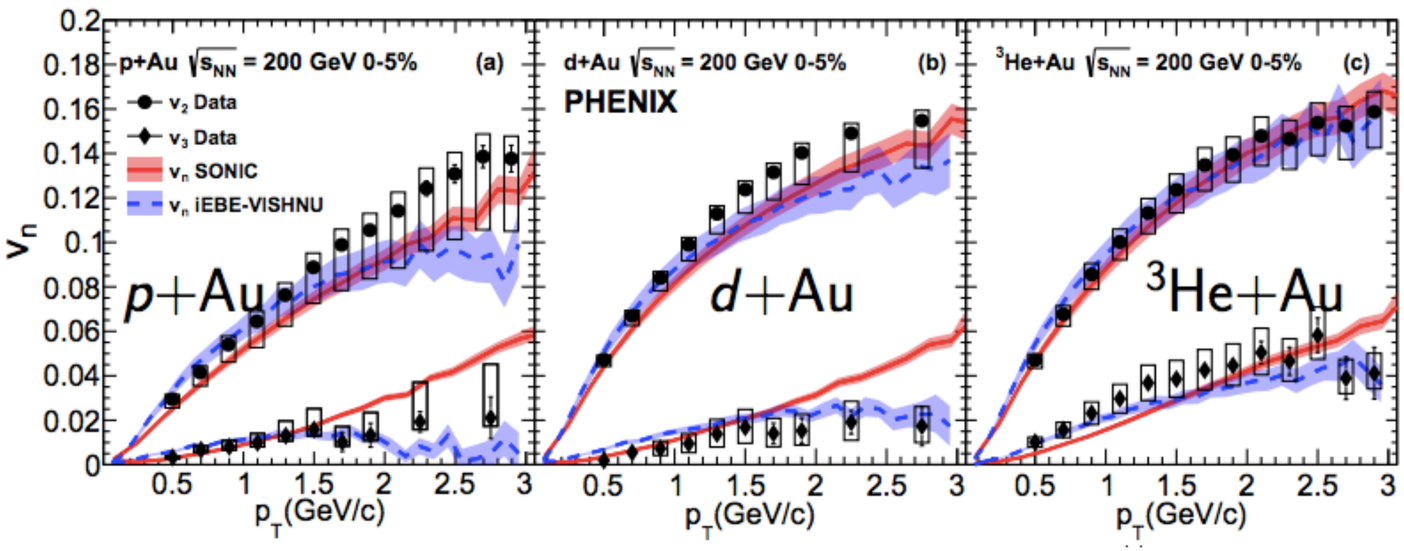
Effectively suppress non-flow with moderate multiplicity/smaller eta gap

Checking geometry; v_2 + v_3

Elegant idea: vary geometry by changing shape of colliding nuclei

PHENIX, arXiv:1805.02973





On top of this: fluctuations, orientation

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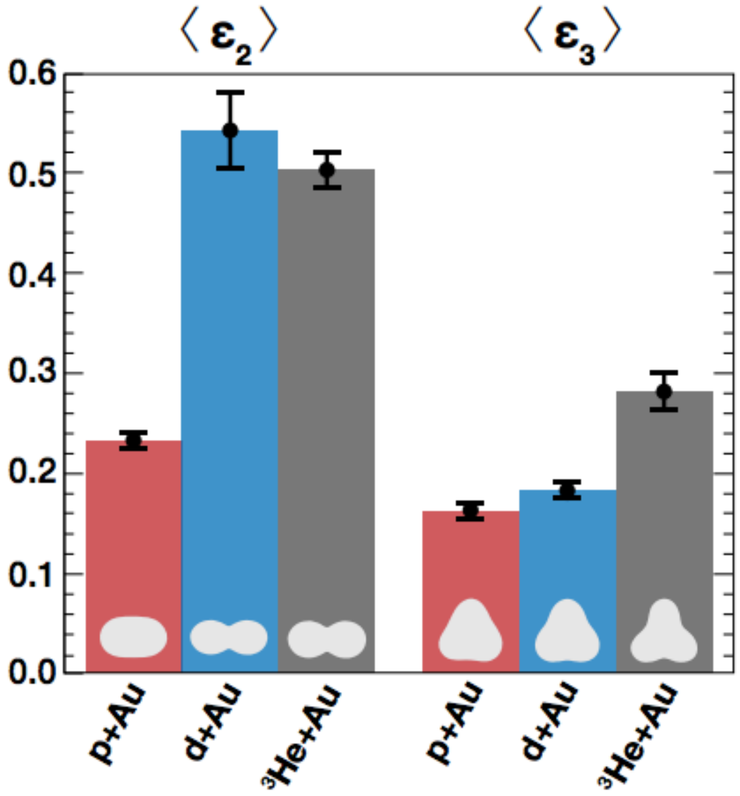
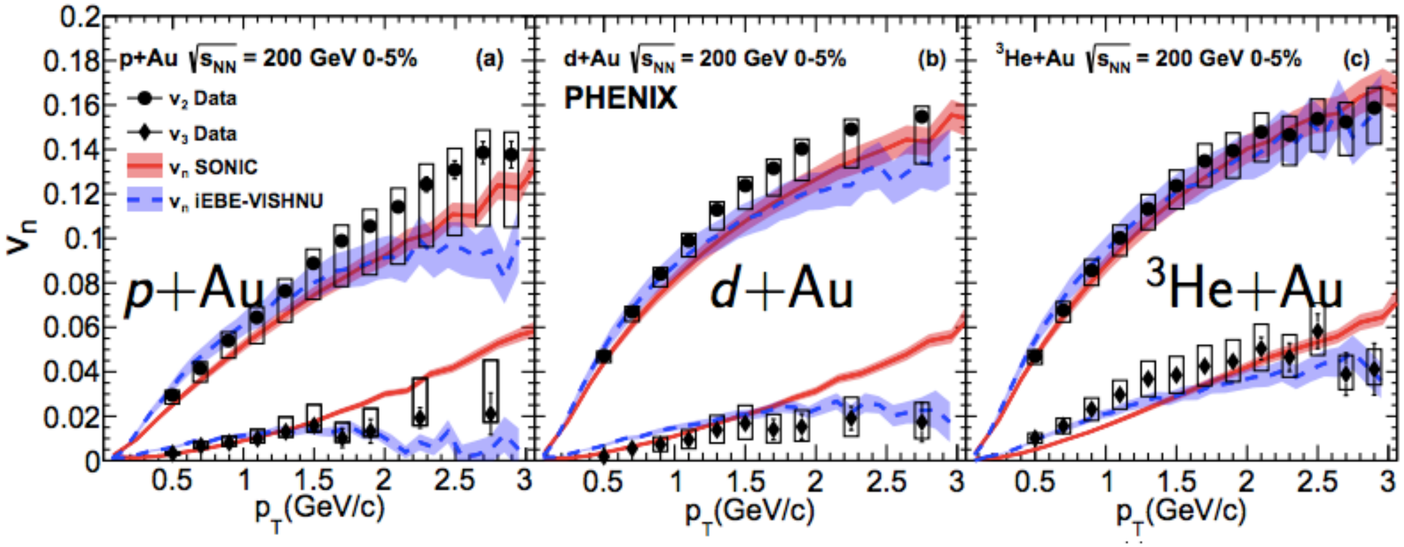


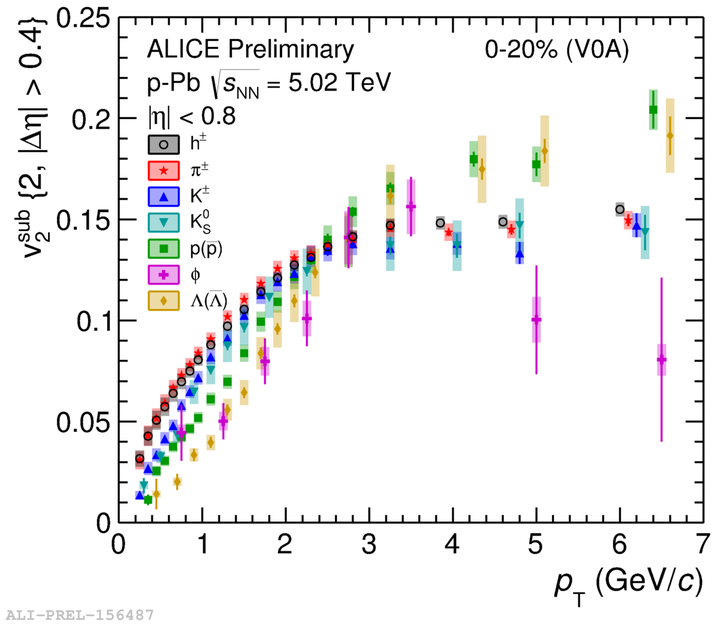
PHENIX, arXiv:1805.02973



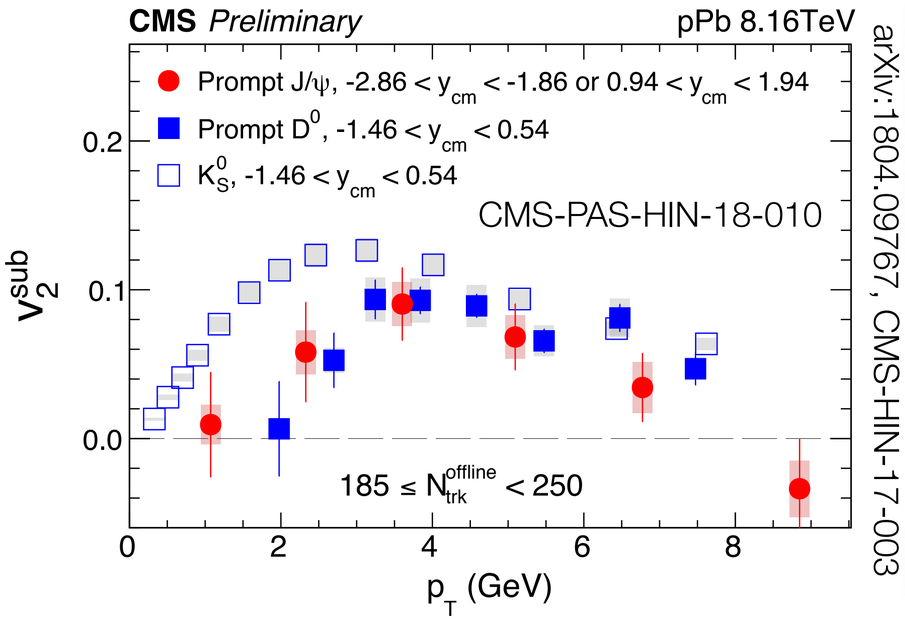
On top of this: fluctuations, orientation

New results on small system flow: LHC

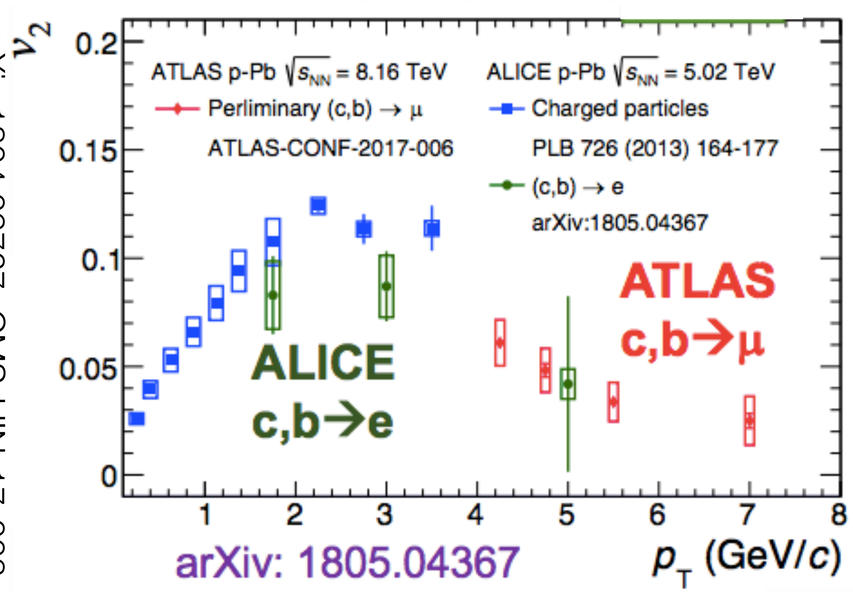
q-vector method; p-Pb - pp



v_2



HF muon flow



arXiv:1804.09767, CMS-HIN-17-003

Light flavours show 'mass ordering'

D mesons and J/ψ also follow flow

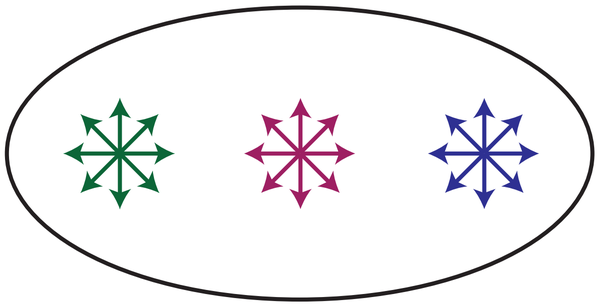
Light and heavy flavour particles show large azimuthal anisotropy

Note also: effect seems to persist to high p_T ~ 8 GeV — details subject to 'fine print'?

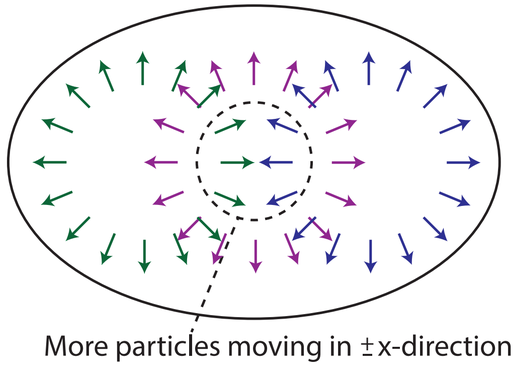
Flow without a liquid

Can you have flow with a few scatterings?
'anisotropic escape' mechanism

Kurkela, Wiedemann, Wu, arXiv:1805.04031



Initially isotropic
momentum distribution



Kurkela, Wiedemann, Wu, arXiv:1803.02072

Scattering randomises directions; more scatterings to 'out-of-plane'

Anisotropic density converted
into anisotropic momentum distribution by few scatterings

Flow without a liquid

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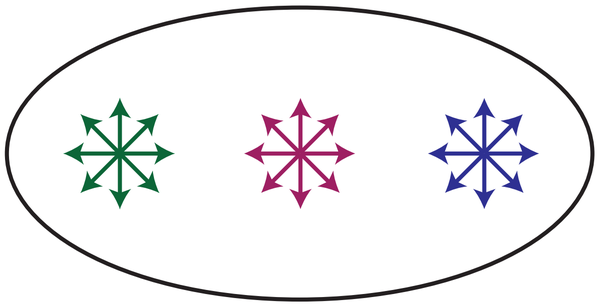

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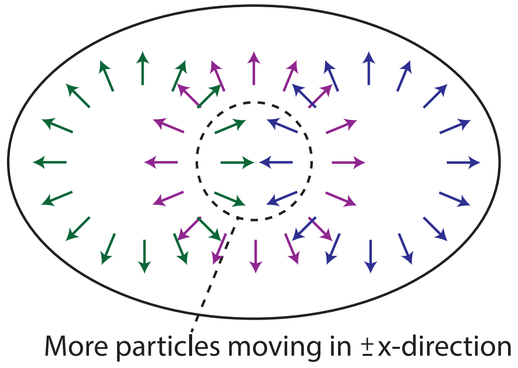

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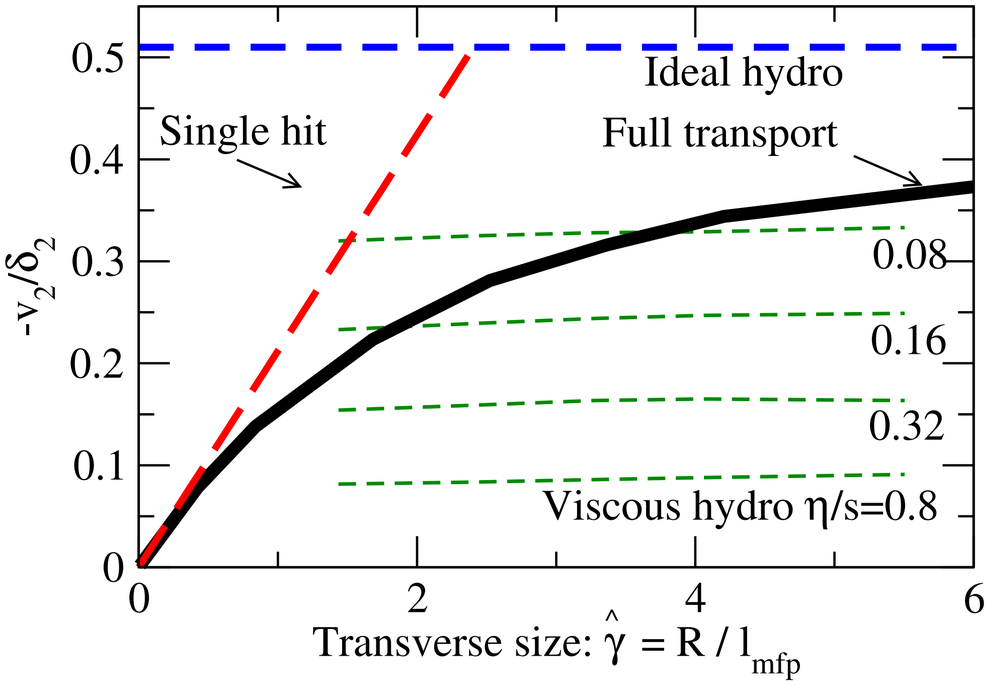
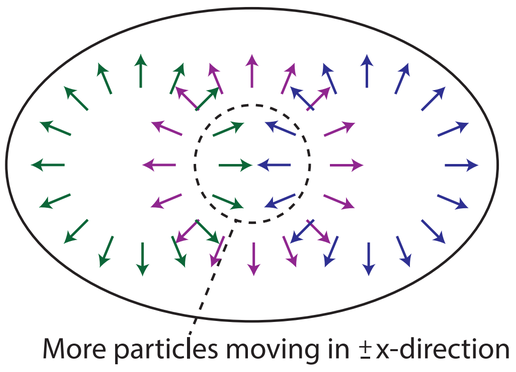


Small systems: 'single hit' kinetic transport
equal to full hydro

Flow without a liquid

Can you have flow with a few scatterings?
'anisotropic escape'



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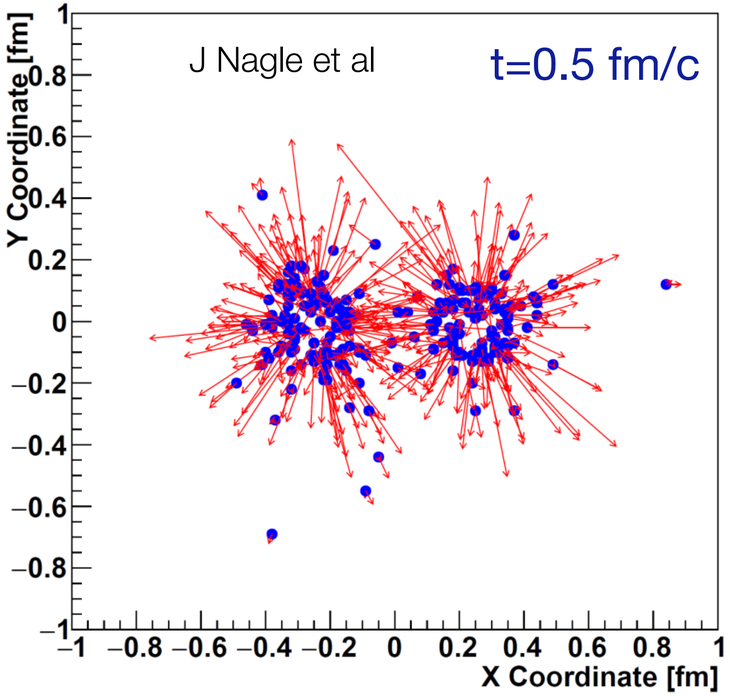
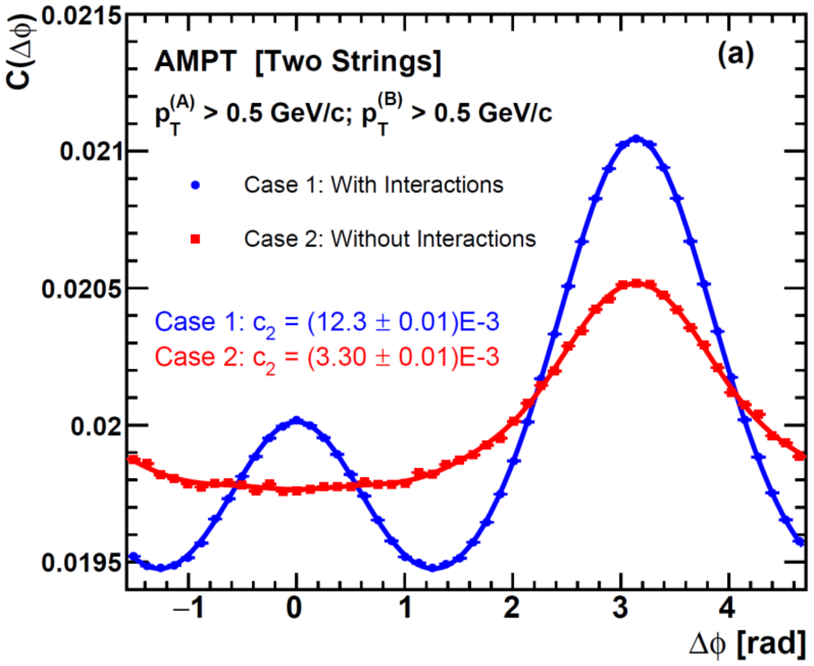
Two parallel strings



Formation time is important

Two-particle correlations



Shows a clear signal
in a transport calculation

Other mechanisms/pictures being discussed: string shoving, CGC
⇒ more field-based; to some extent just a different language?

Review in M Strickland's talk

Connecting small and large systems

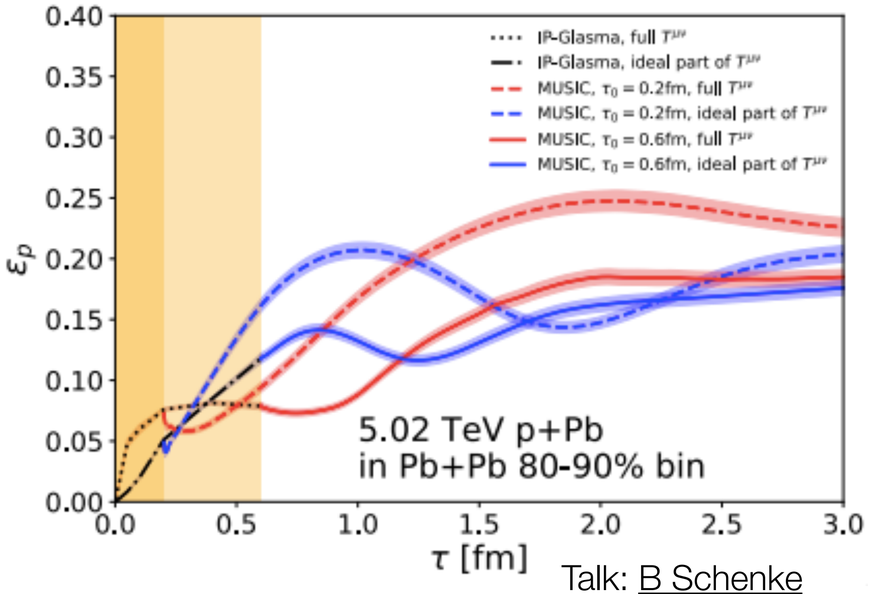
Hydro (behavior) is everywhere

Large flow in small systems

Fast thermalisation/hydrodynamisation

IP Glasma fields

Hydrodynamics



Talk: B Schenke

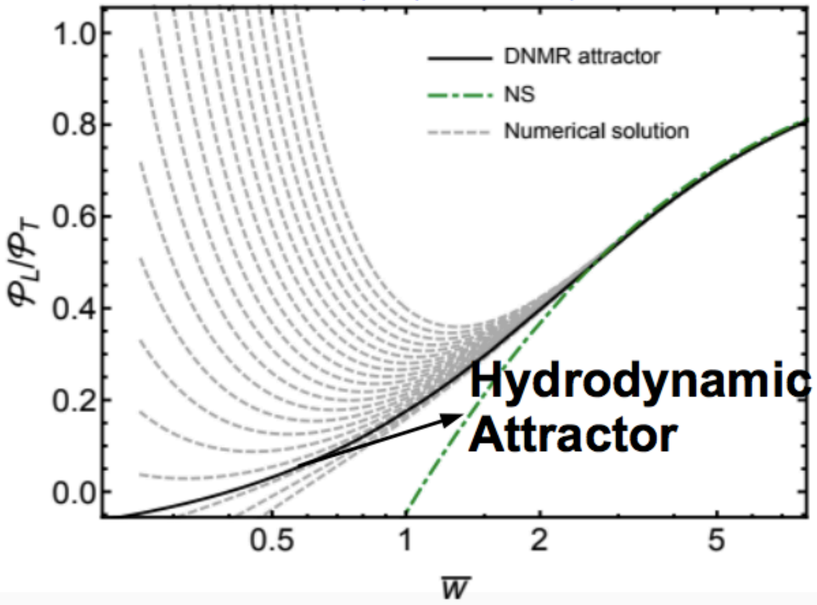
Originally proposed by Heller and Spalinski, PRL (2015)

Review: Florkowski, Heller, Spalinski, 2017

Slide from J Noronha

See also: A Mazeliauskas

M. Strickland, JN, G. Denicol, PRD 2018



See B. Meiring's talk

See L. Yan's talk

See M. Martinez' talk

See C. Chattopadhyay's talk

See U. Heinz' talk

See R. Critelli's poster

See J. C-Solana's poster

See N. C. Cruz' poster

See G. Denicol's poster

See E. Maksymiuk's poster

Connecting small and large systems

Hydro (behavior) is everywhere

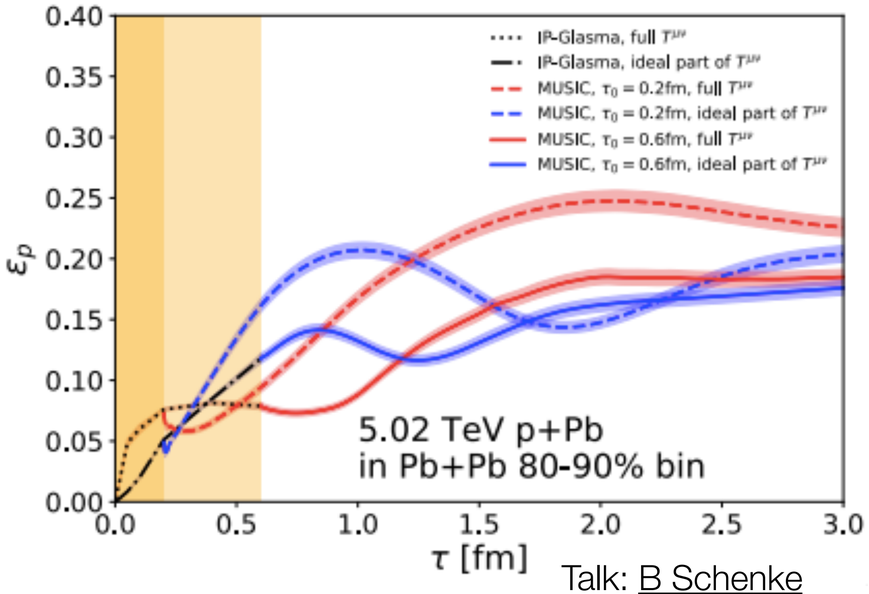
Downside of focusing on energy/momentum flow?

Large flow in small systems

Fast thermalisation/hydrodynamisation

IP Glasma fields

Hydrodynamics



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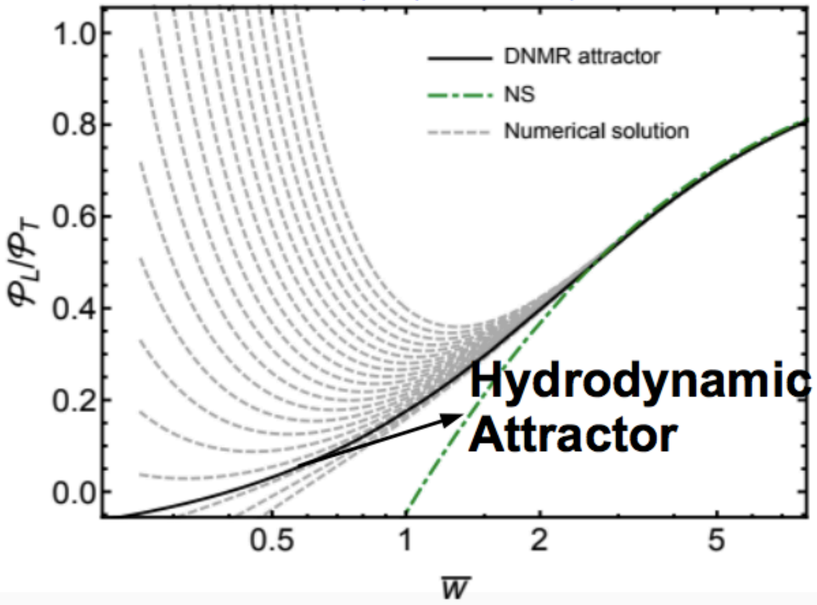

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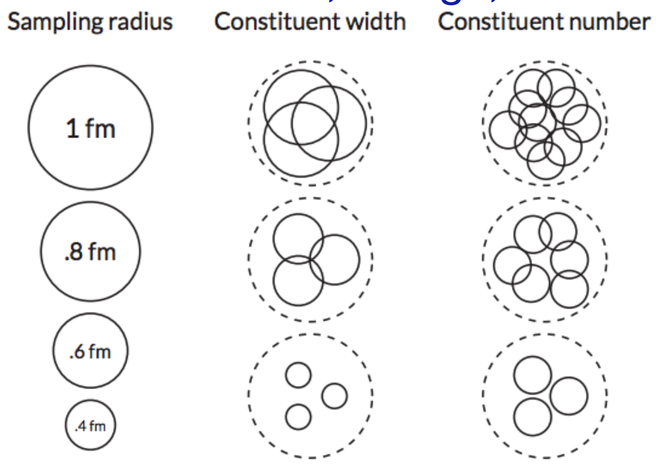
Deriving proton substructure

J.S. Moreland, et al

Flow-like effects in pp require substructure
'constituents', strings, etc



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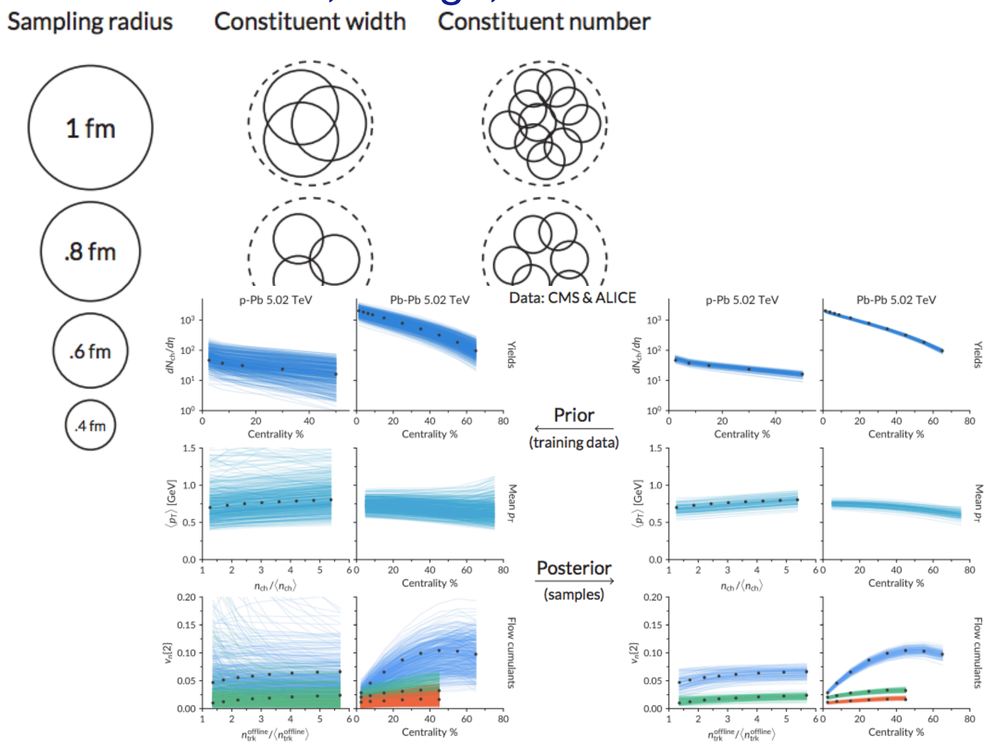

Bayesian fit + gaussian emulator: probe large parameter space
Output: full covariance matrix 15 parameters

input: multiplicity, mean p_T, v_n in PbPb and p-Pb

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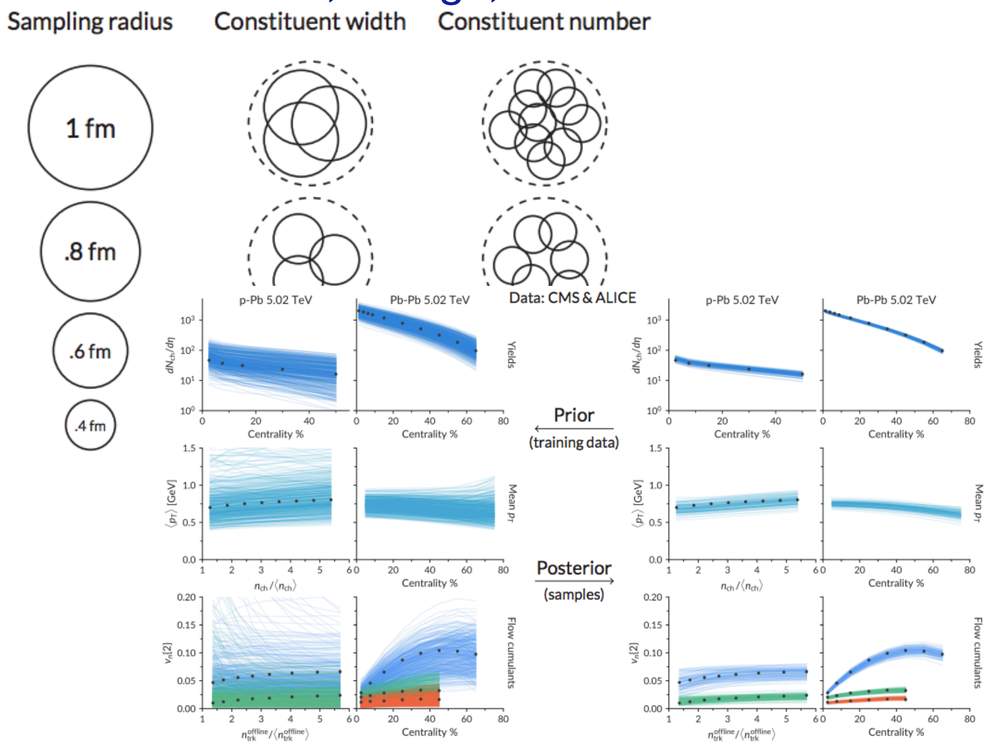

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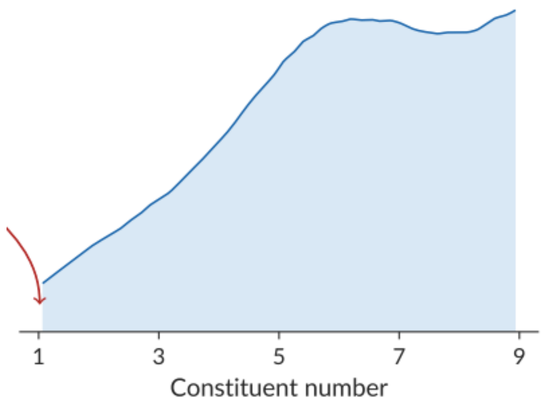
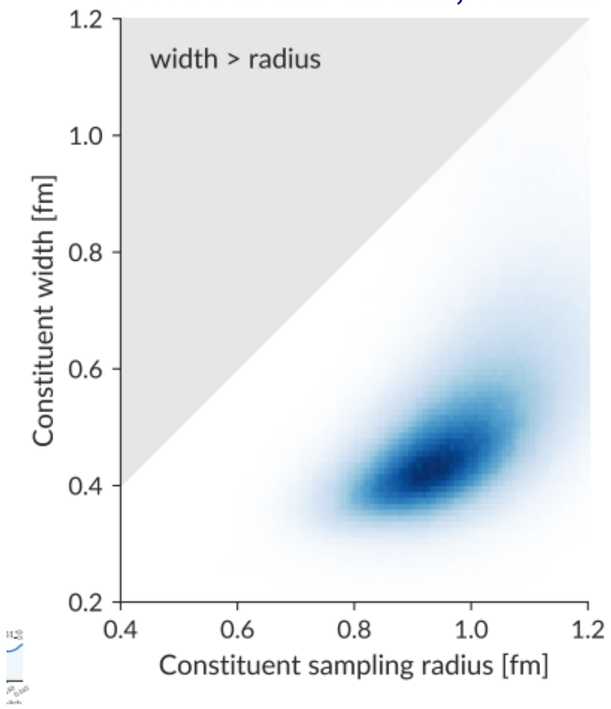
Number of constituents



No strong preference for a specific constituent number

Constituent width, radius



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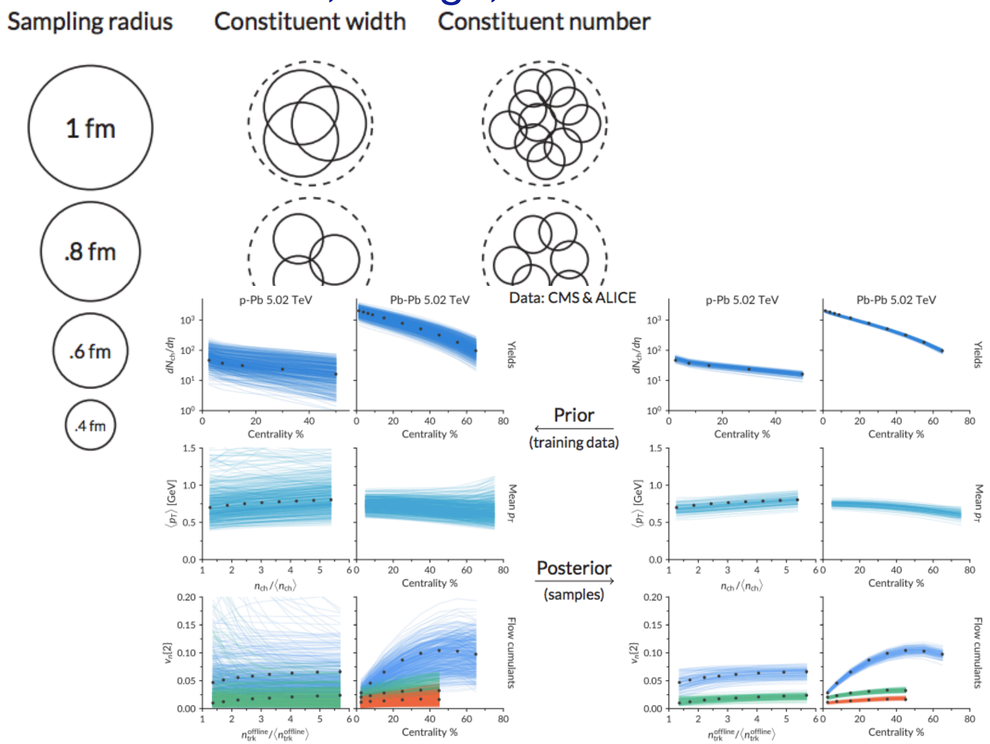

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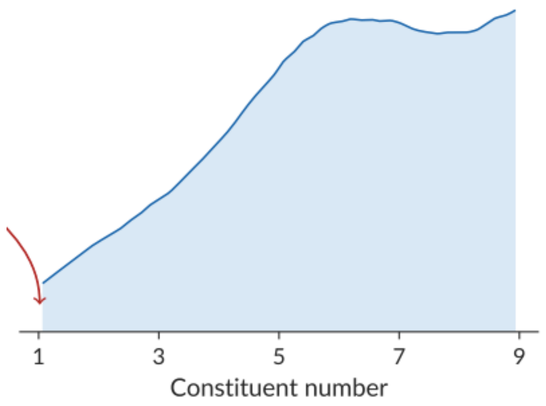

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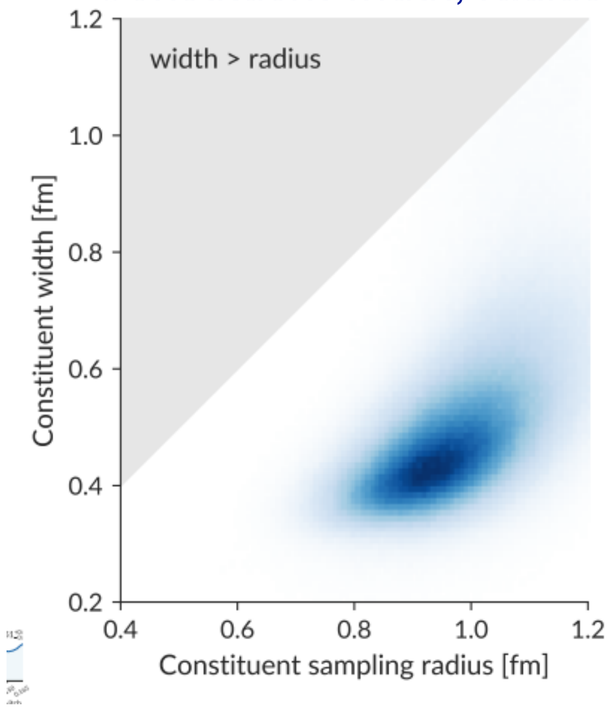
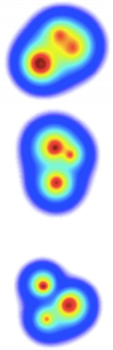


Shows that we are sensitive to nucleon substructure
'configuration space picture of the proton'

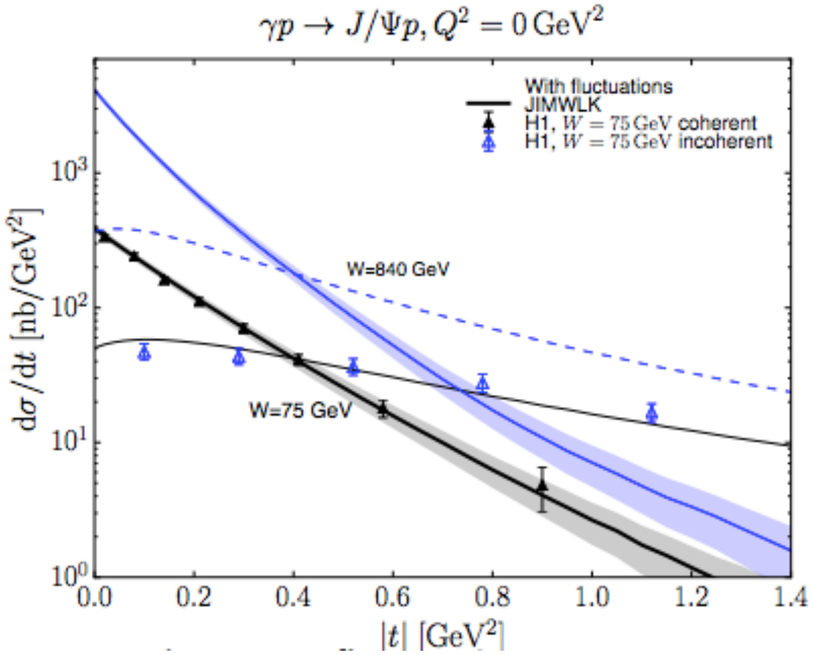
Proton substructure from UPCs

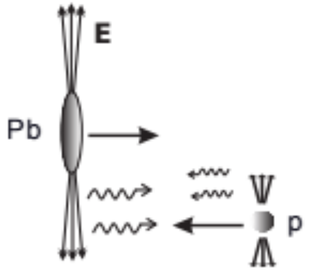
Talk: H Mantysaari
Overview: A Angerami

$W = 75$ GeV:

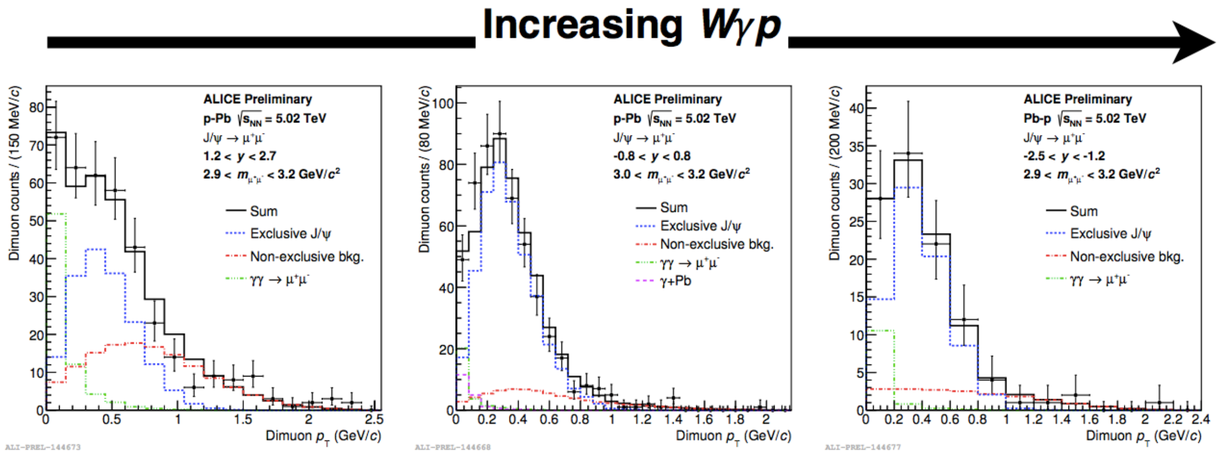


Coherent and incoherent exclusive J/ψ in ep





UPC at the LHC



ALICE: 1406.7819

Coherent: average

$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Incoherent: RMS

$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

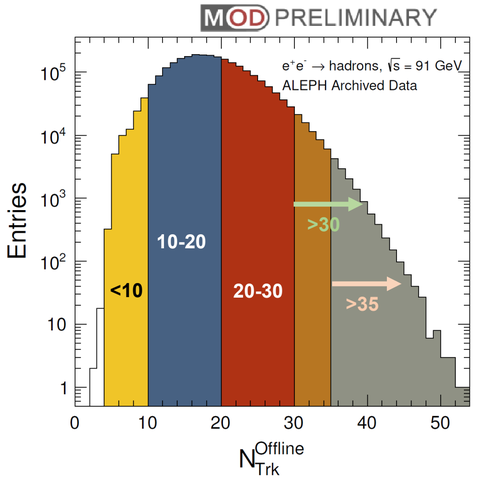
Dissociative increase more slowly than elastic consistent with HERA data

Different angle: Spatial size, fluctuations measured by coherent/incoherent interactions

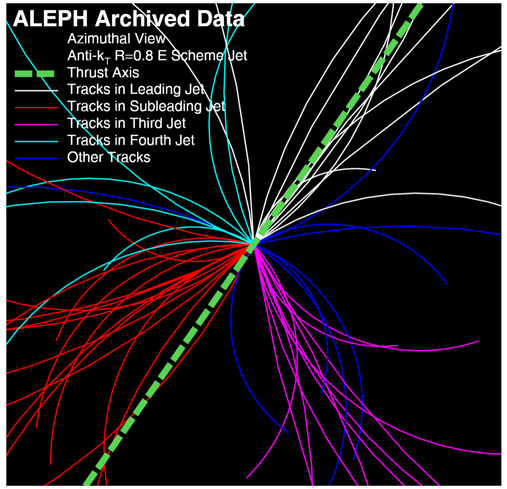
Should compare and contrast conclusions from flow/final state and EM interactions

Switching off the flow: e+e-

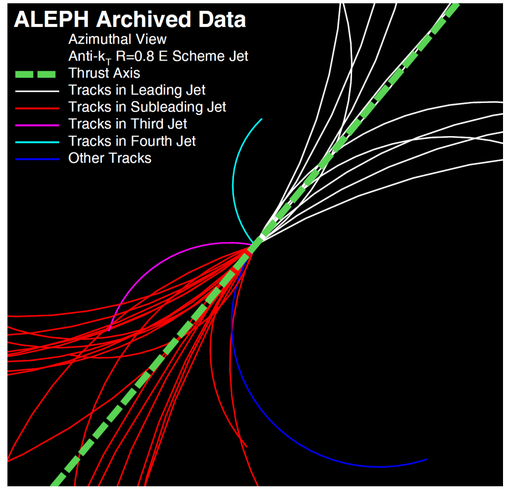
Talk: J-Y Lee



High-multiplicity events



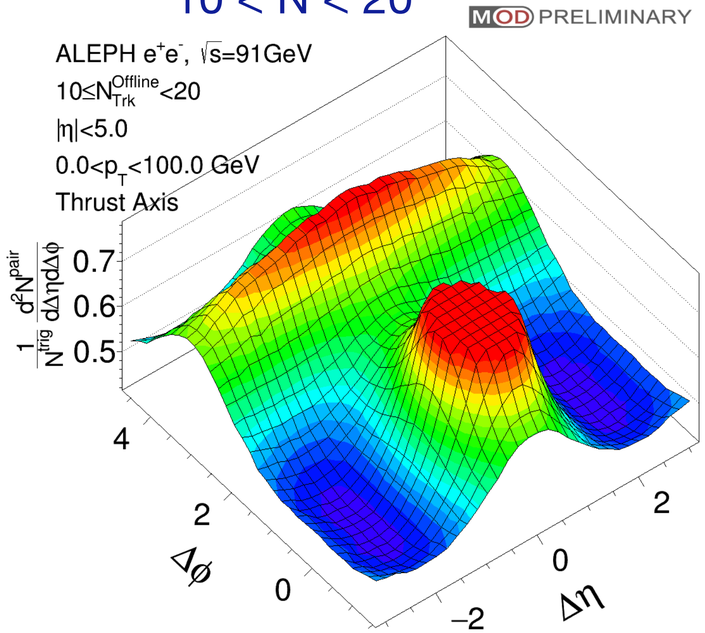
Low T; 'multi-jet'



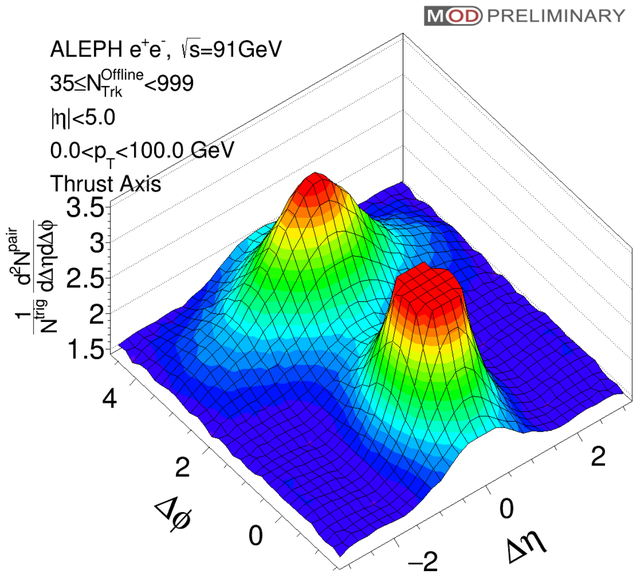
High T; 'di-jet'

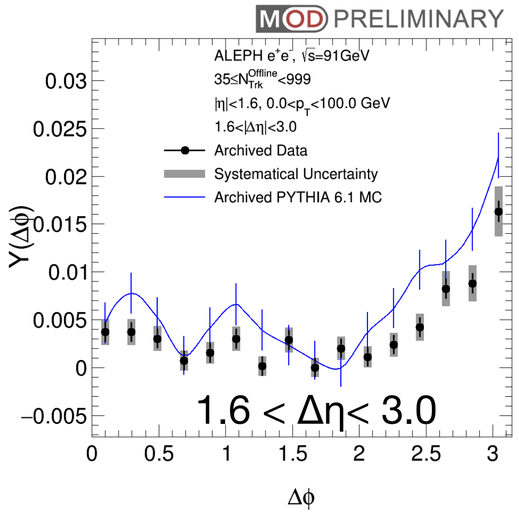
ALEPH e+e- thrust axis

10 < N < 20



N ≥ 35



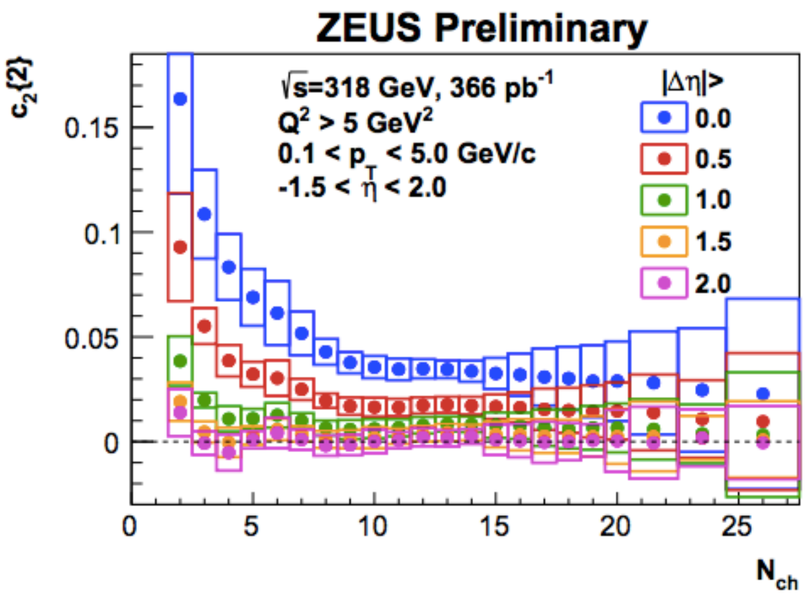


No evidence of long-range correlations beyond Pythia expectation

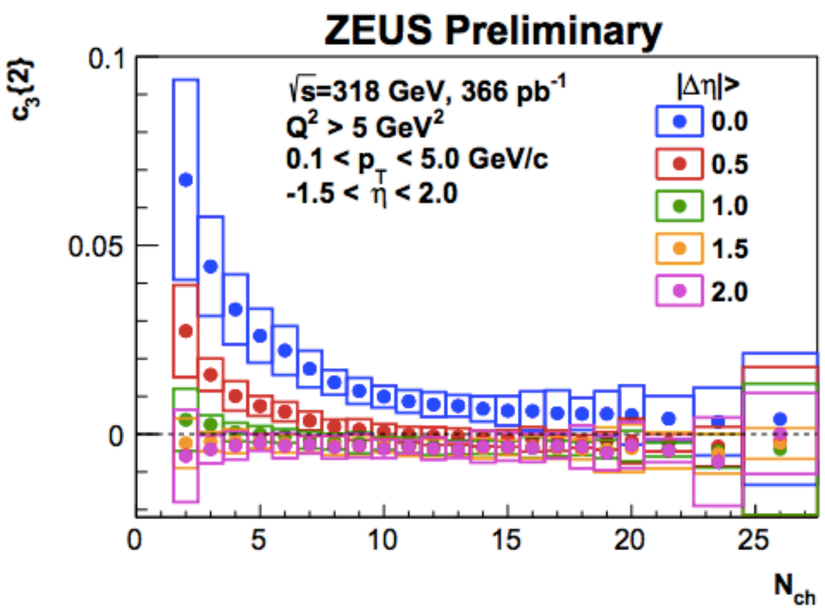
Cumulants from in e-p data from ZEUS

J Onderwaater

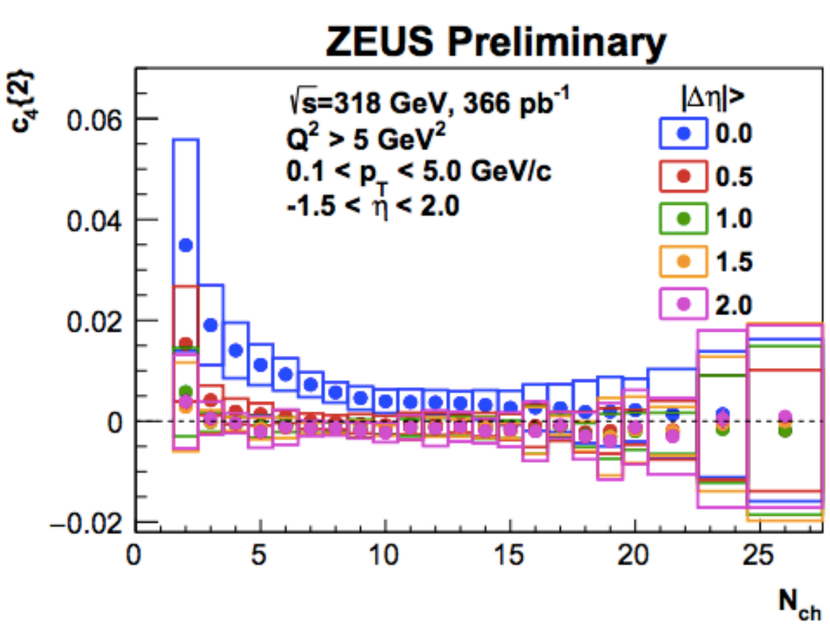
c_2



c_3



c_4



Familiar behaviour: non-flow dominates at small multiplicity and without eta-gap

No flow-like signal seen in high-multiplicity, large eta gap for c_2, c_3, c_4

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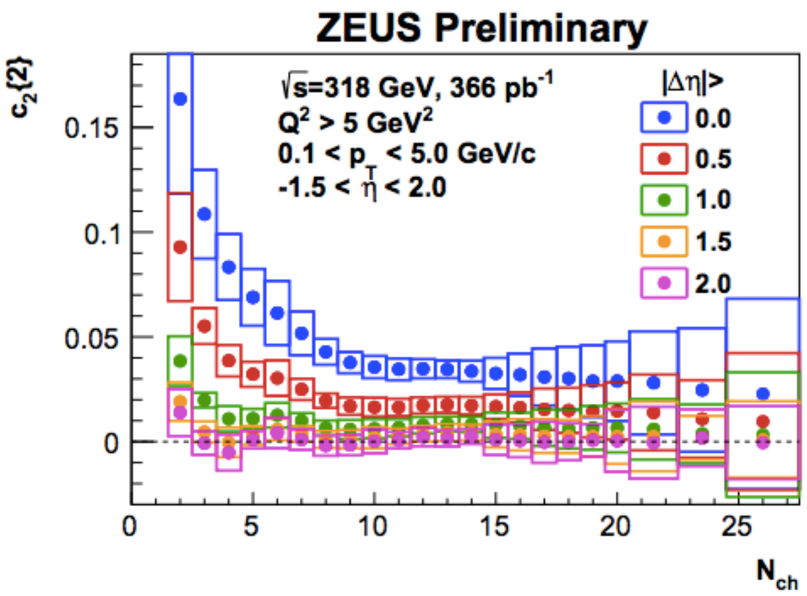
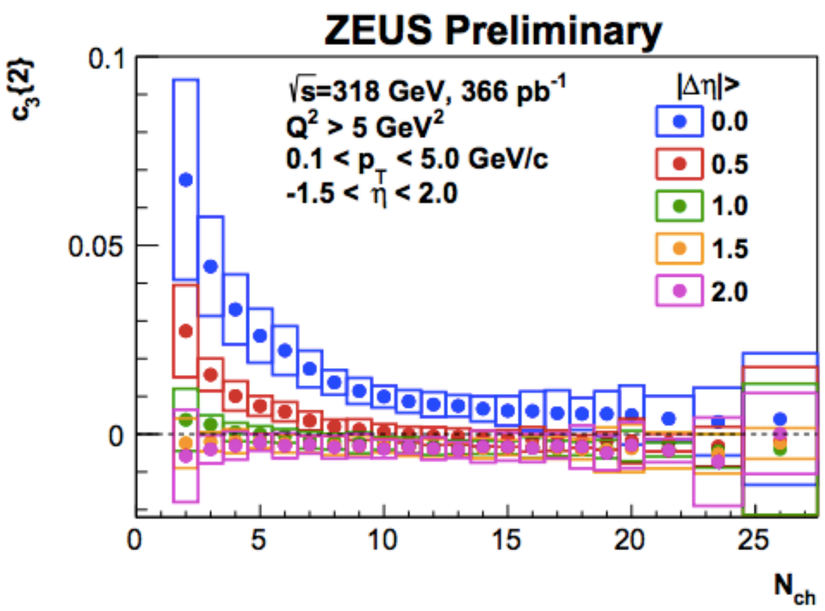
J Onderwaater

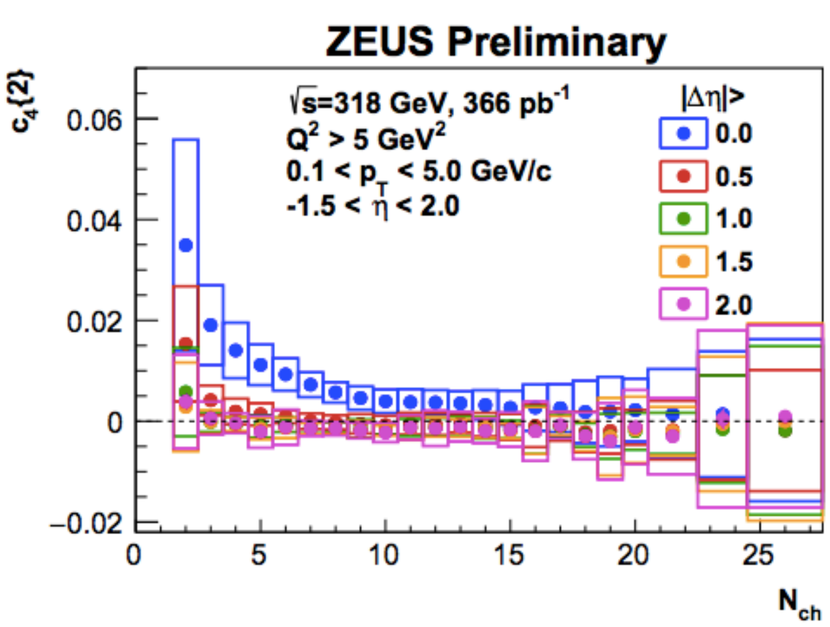
c_2



c_3



c_4



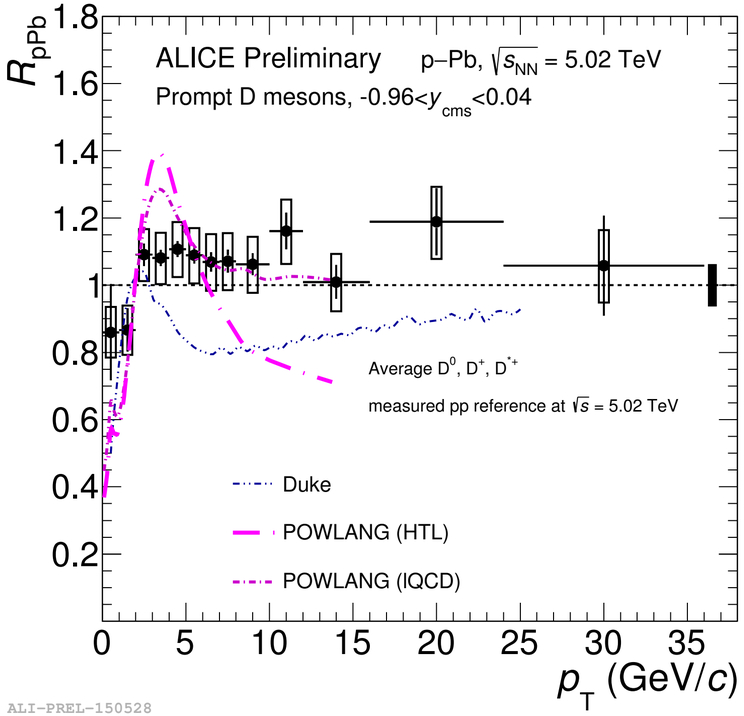
Familiar behaviour: non-flow dominates at small multiplicity and without eta-gap

No flow-like signal seen in high-multiplicity, large eta gap for c_2, c_3, c_4

No flow with ‘single string’ ⇒ Need multiple interactions to set up initial geometry

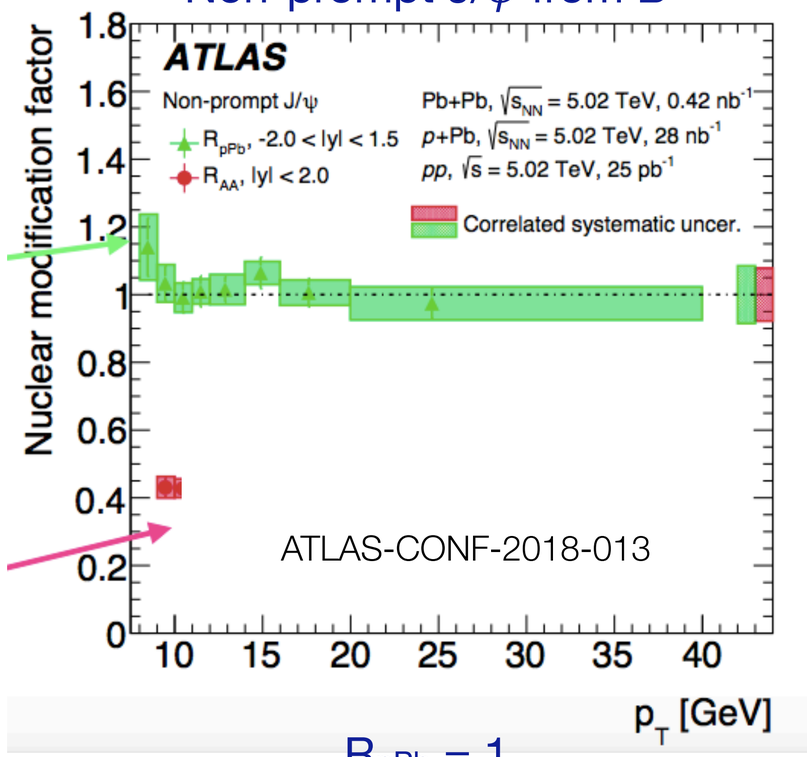
Flow without energy loss?

Open charm mesons



R_{pPb} = 1

Non-prompt J/ψ from B



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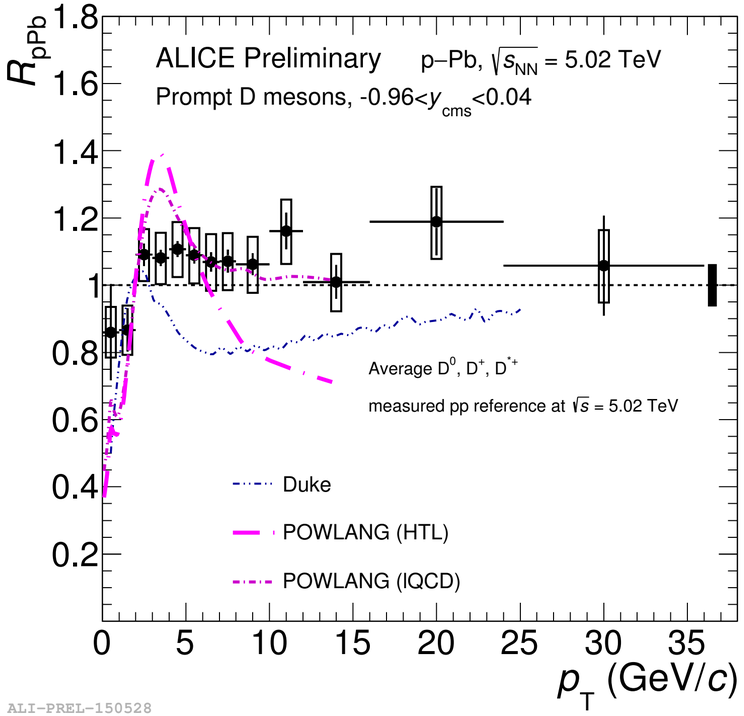

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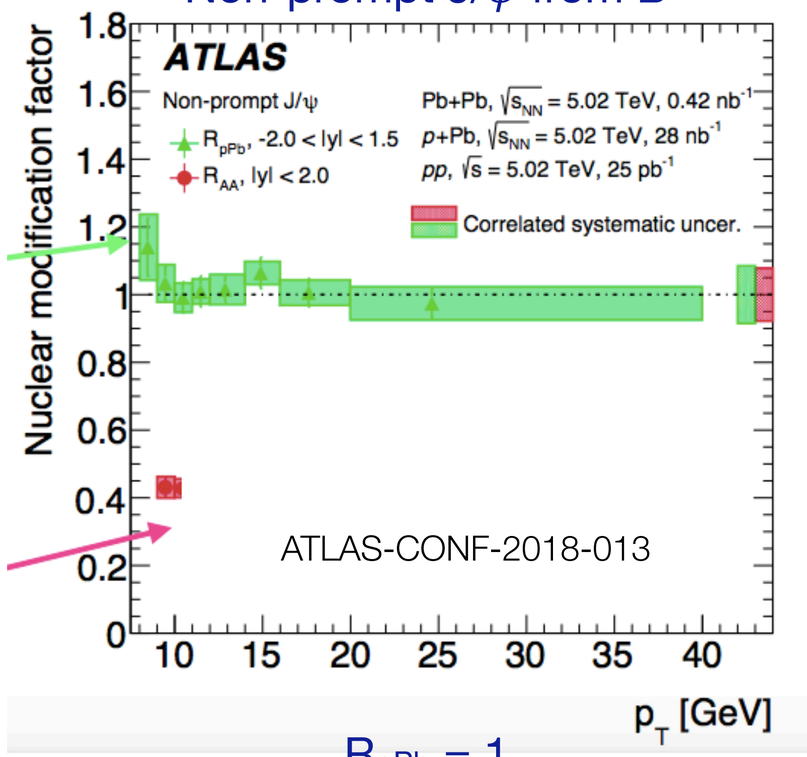
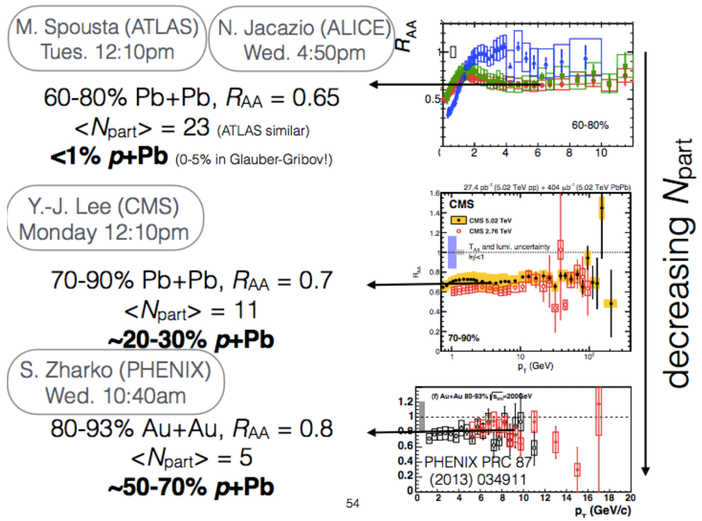


R_{pPb} = 1

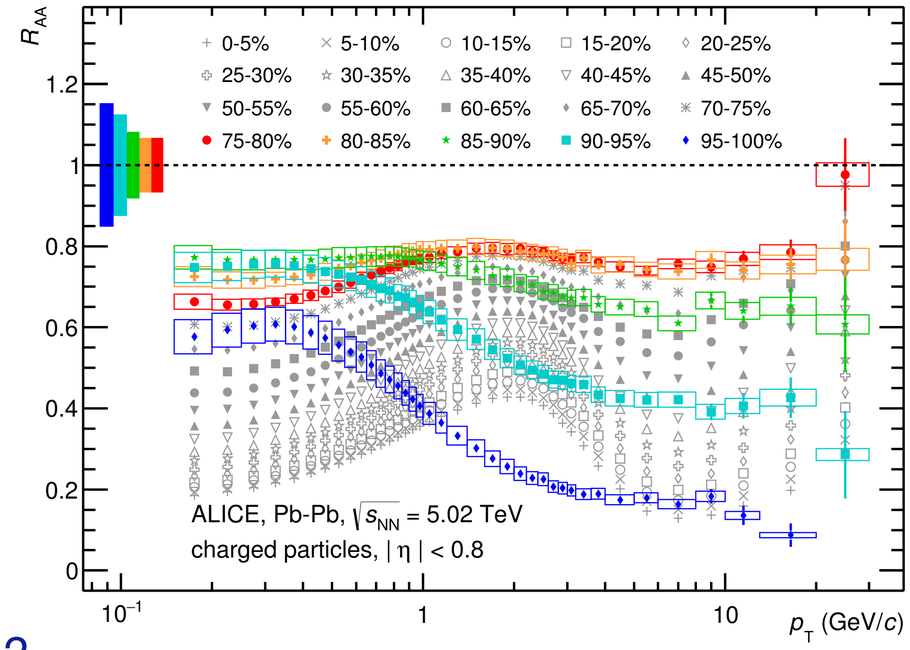
Flow from transport: need only few (elastic) scatterings to generate v_2
energy loss can be small

What about peripheral AA?

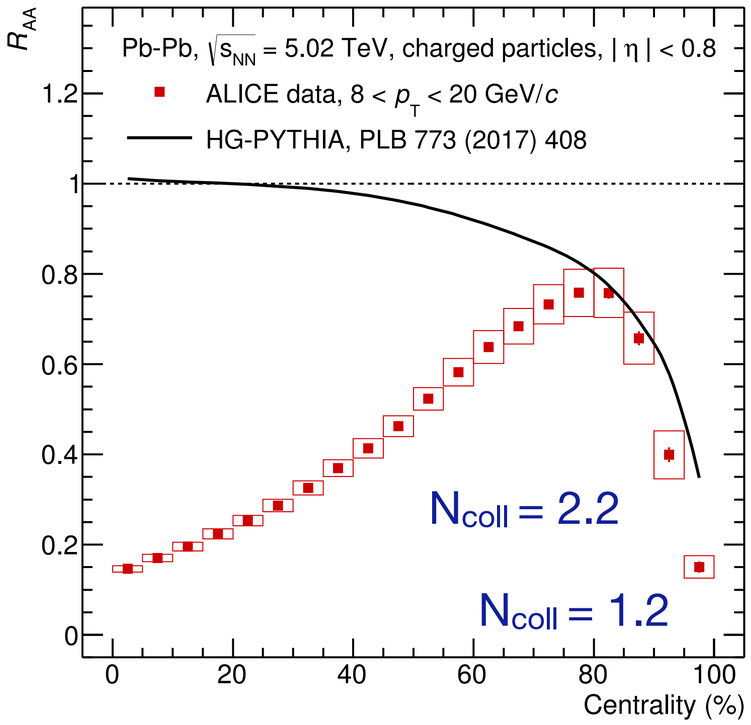
QM2017: D Perepelitsa



R_{AA} for peripheral events



ALICE, arXiv:1805.05212



Why is R_{AA} ~ 0.8 for peripheral events?

N_{part} ~ 5-10 ~ p-Pb

Observation: R_{AA} does not increase for centrality > 80%

It decreases?

Peripheral events described by HG-Pythia

increase of pp impact parameter + multiplicity

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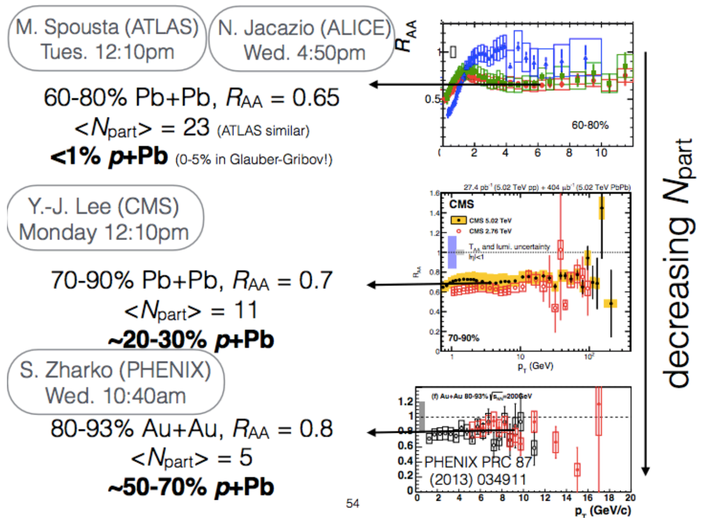

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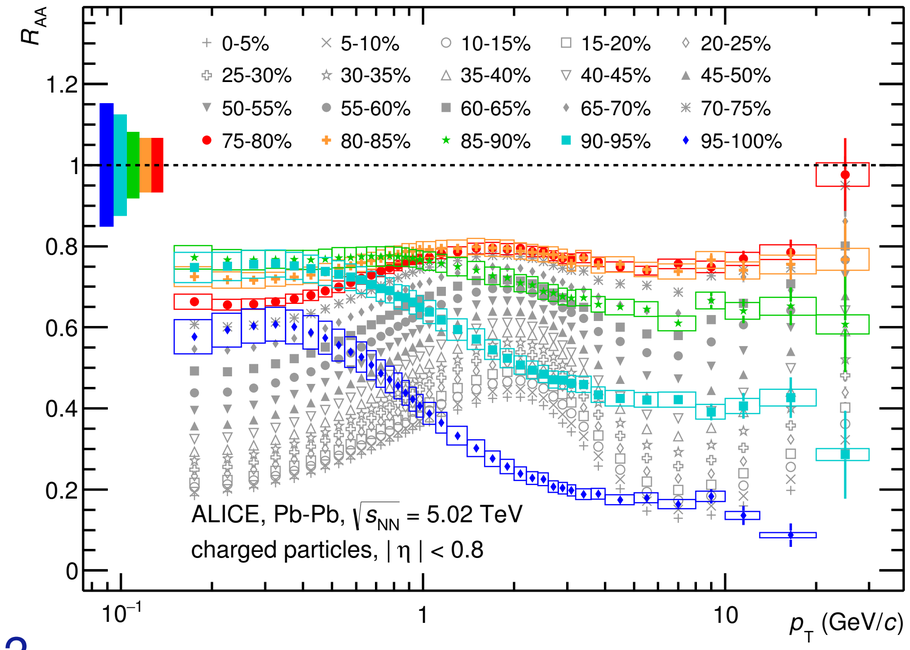

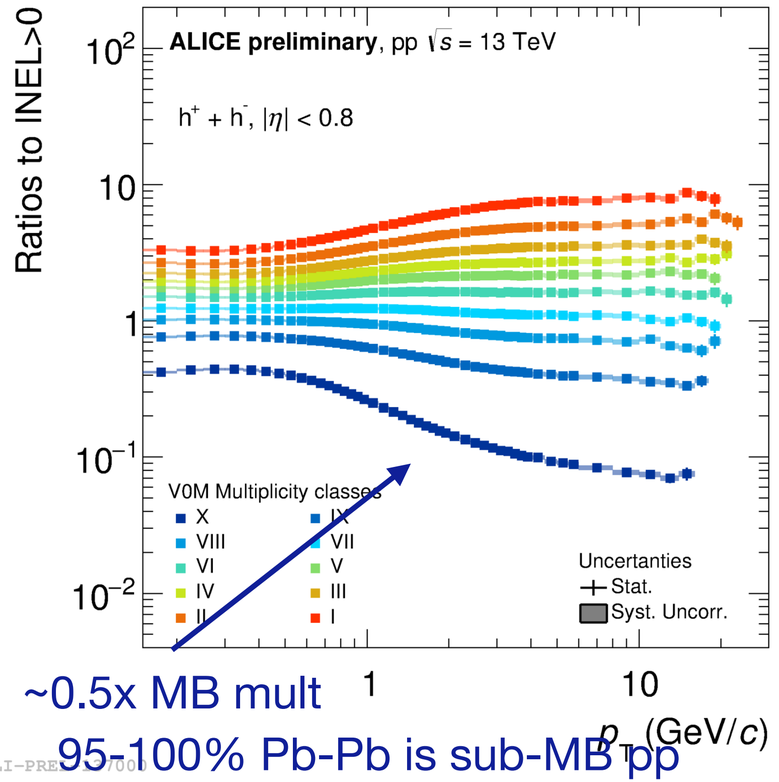

~0.5x MB mult

95-100% Pb-Pb is sub-MB pp

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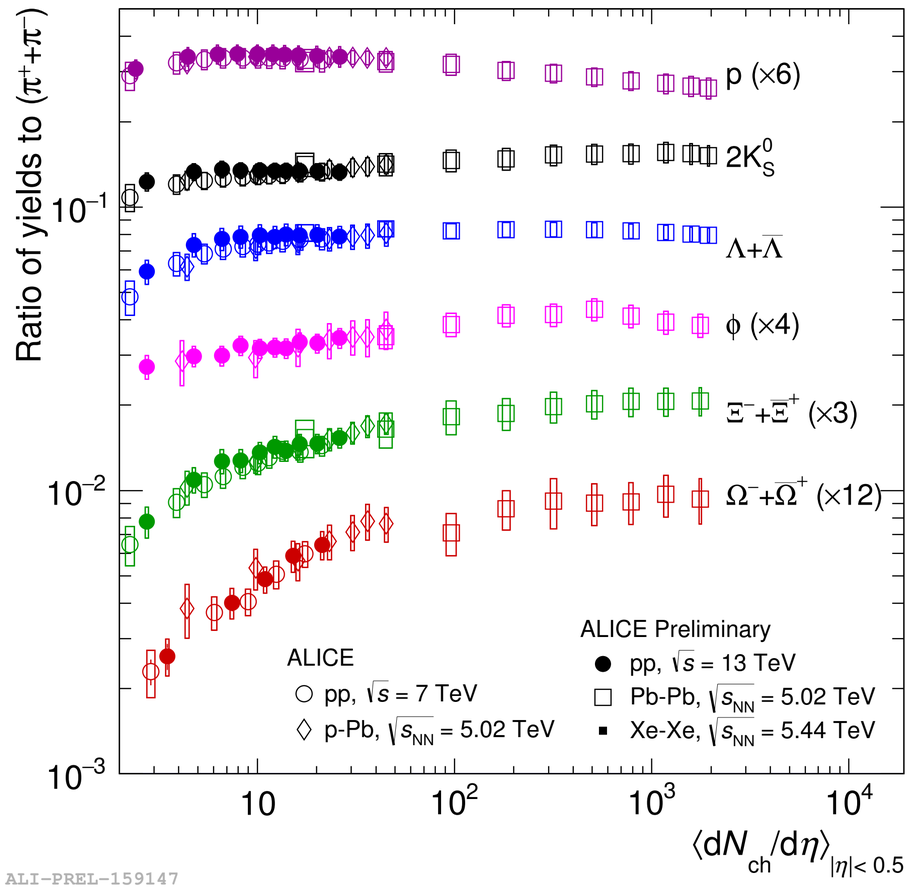
Flavour production in small systems

(Multi-)strange baryon production



Increase of strange baryon production already starts in pp

T. Sjostrand @ QM

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.
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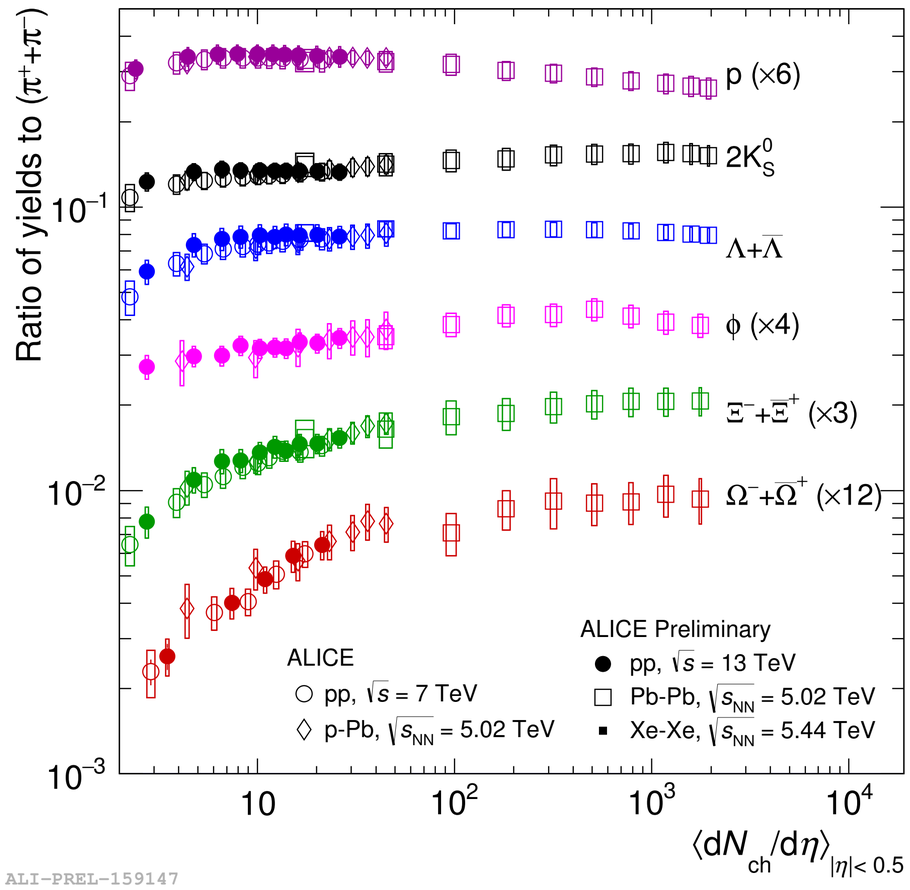

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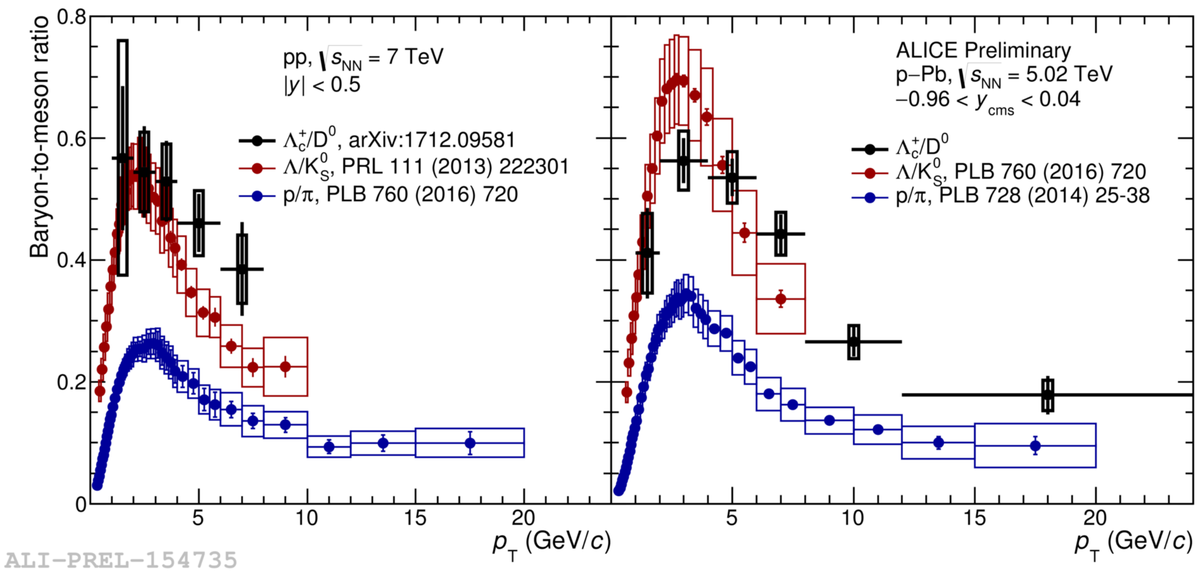
pp p-Pb



Heavy quark baryon/meson ratio similar to Λ/K
Much larger than e.g. Pythia

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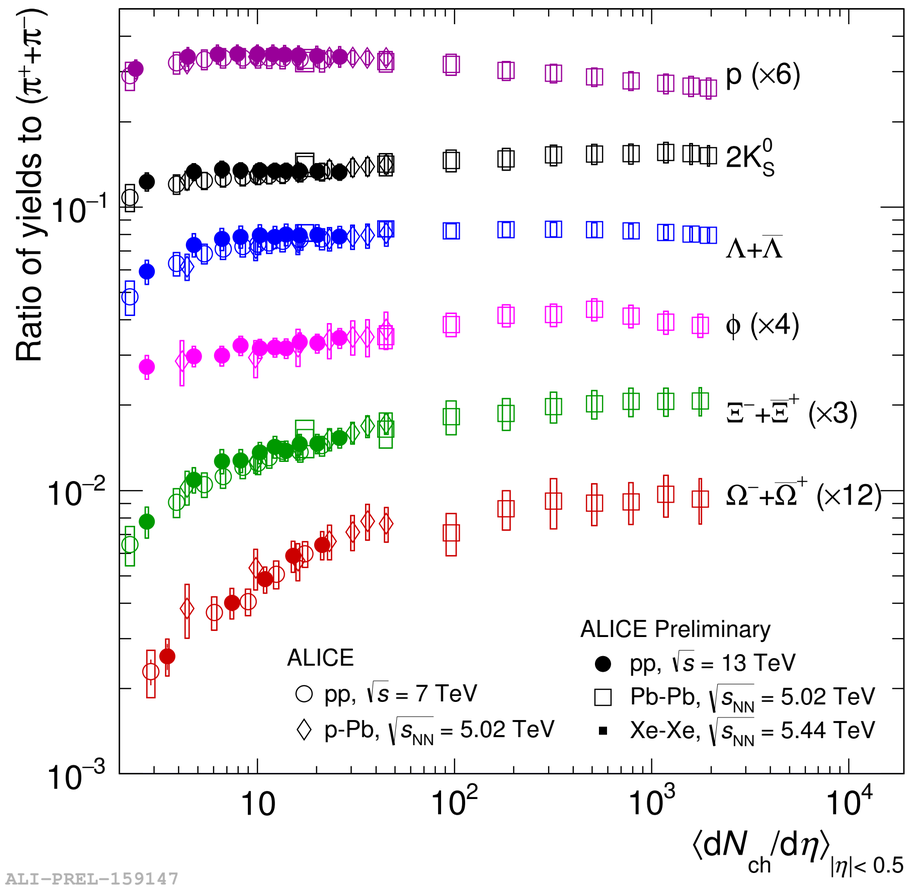

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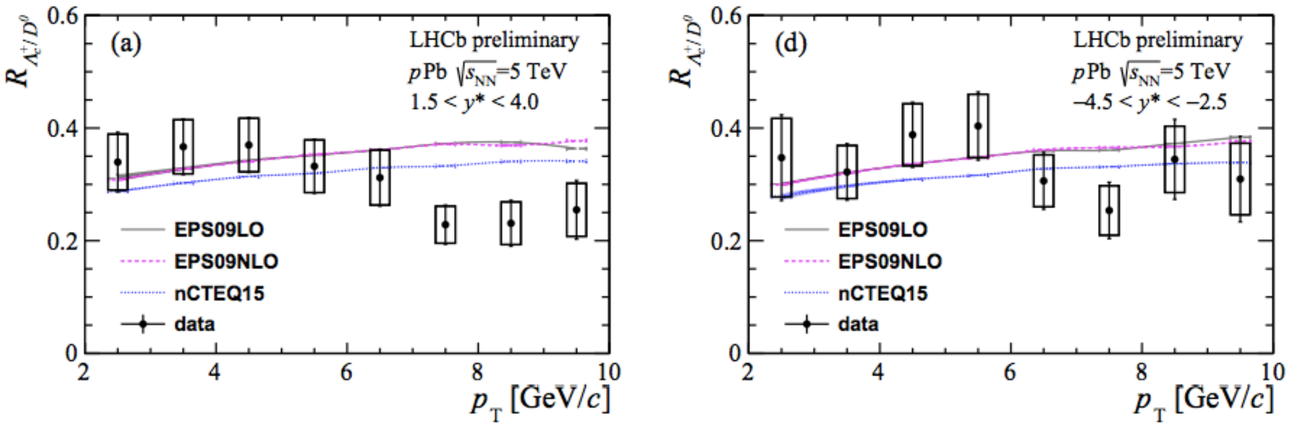
p-Pb forward



LHCb-PAPER-2018-021, in preparation.

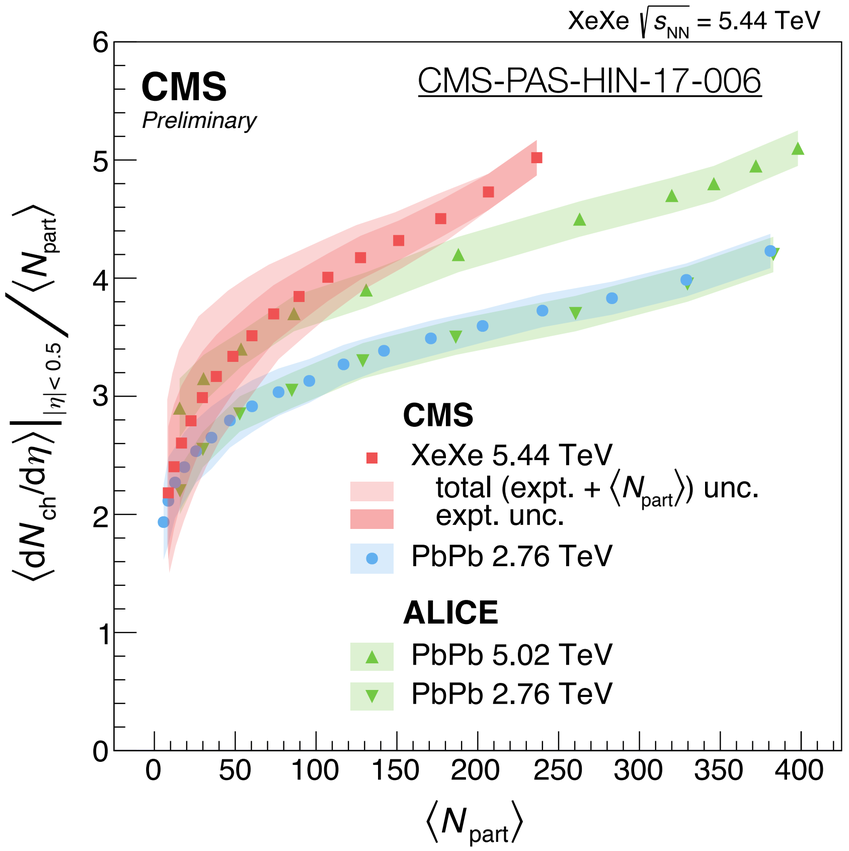
Heavy quark baryon/meson ratio similar to Λ/K
Much larger than e.g. Pythia

Changing the system size: Xe-Xe

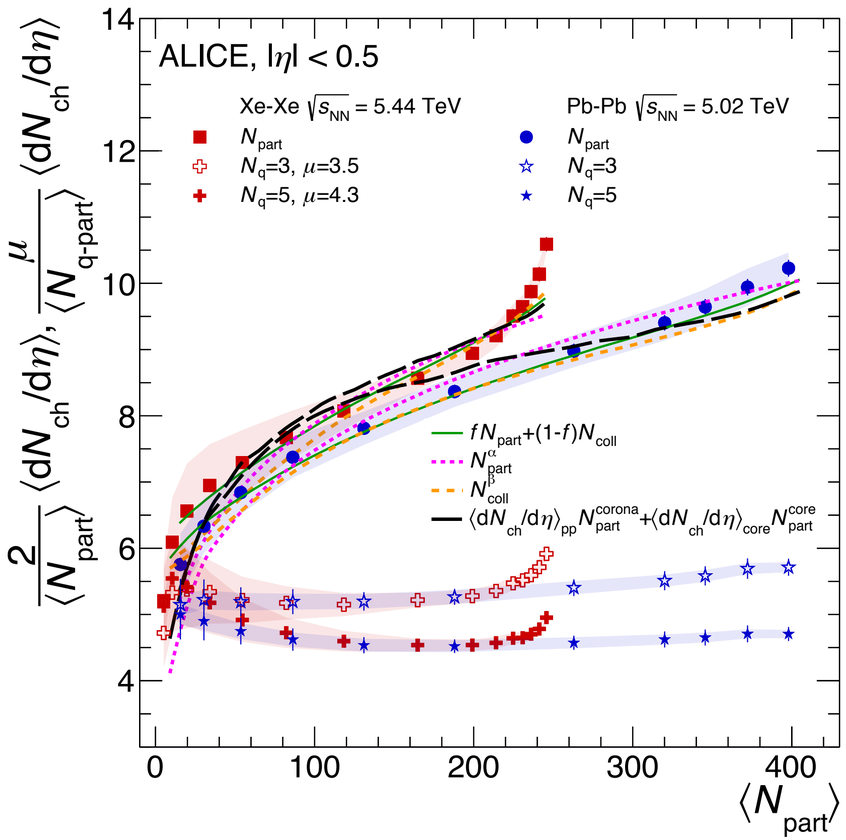
1-day run in Oct 2017
Many new results from ALICE, ATLAS and CMS

Multiplicity production

Multiplicity/N_{part} 'scales' (approximately) between XeXe and PbPb



ALICE, arXiv:1805.04432



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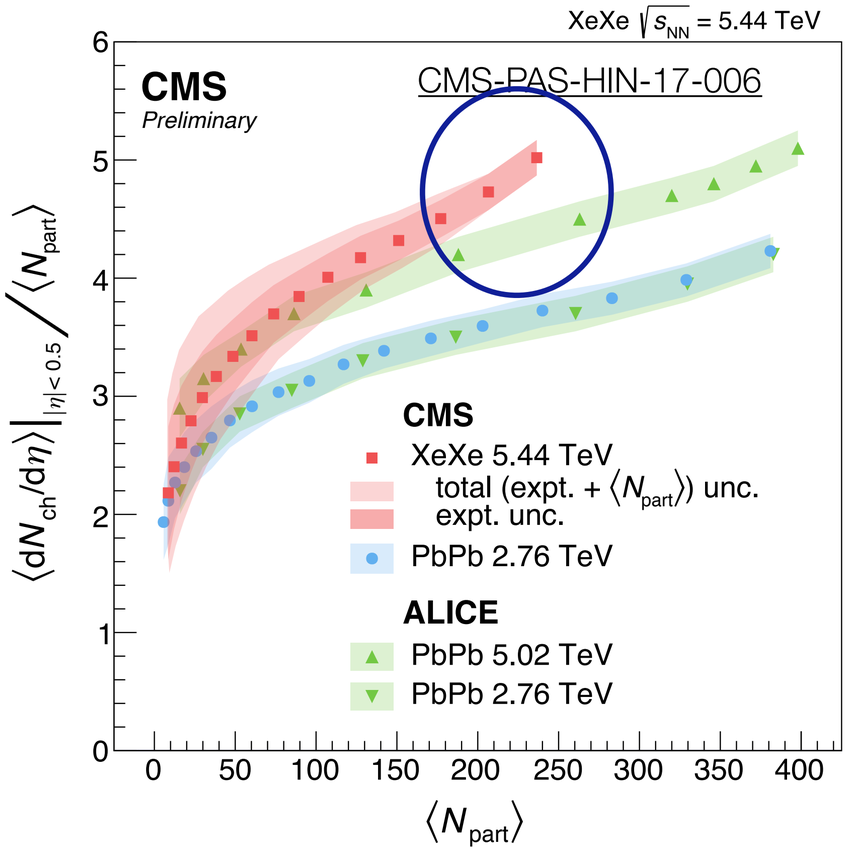

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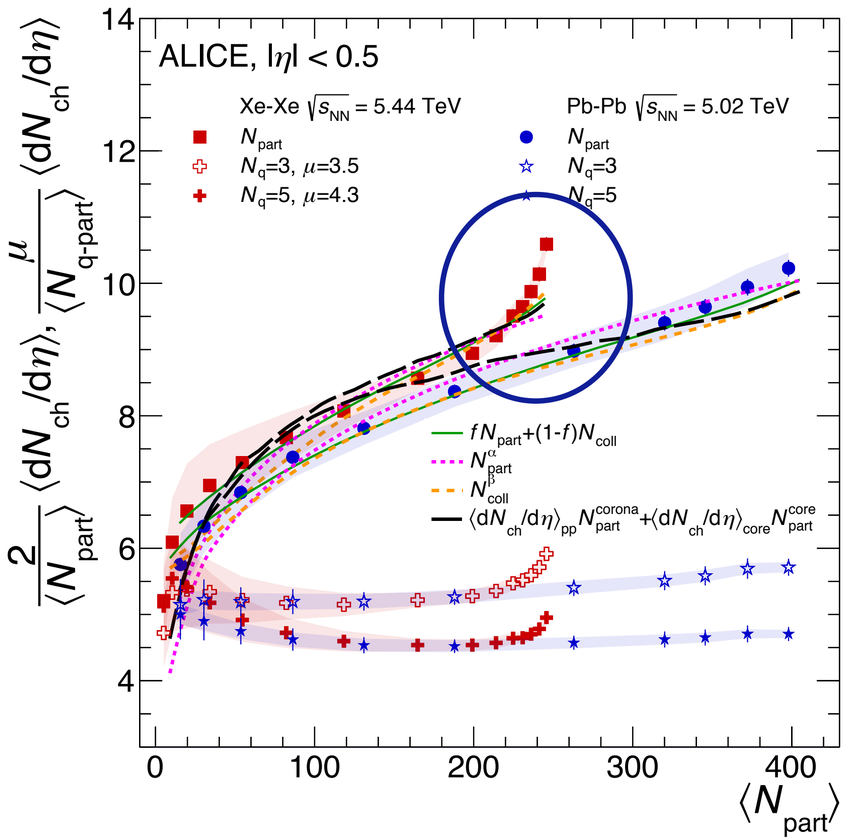
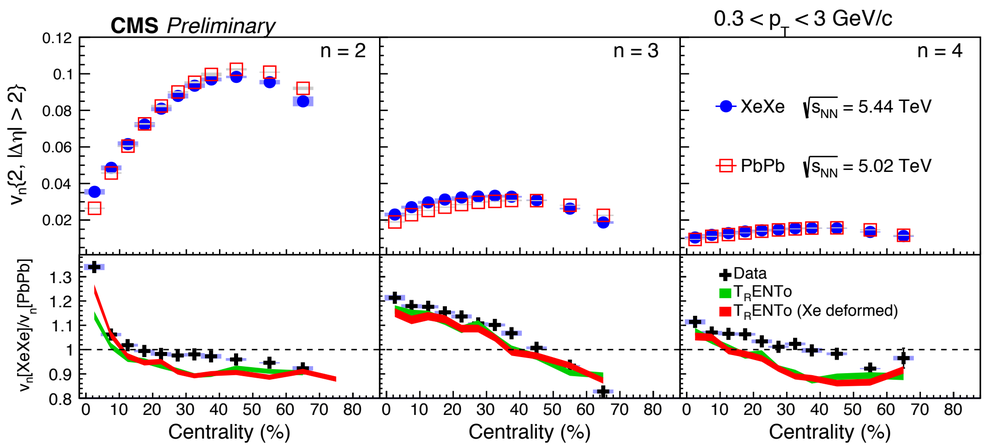
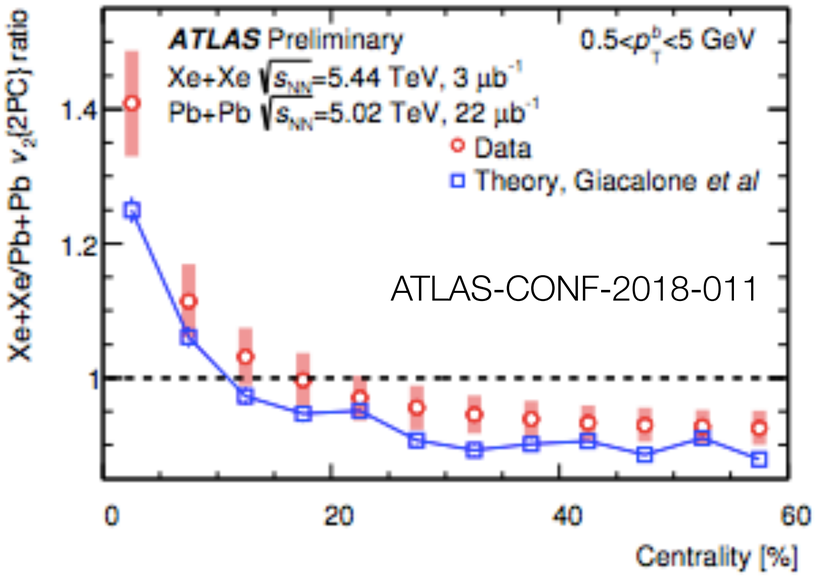


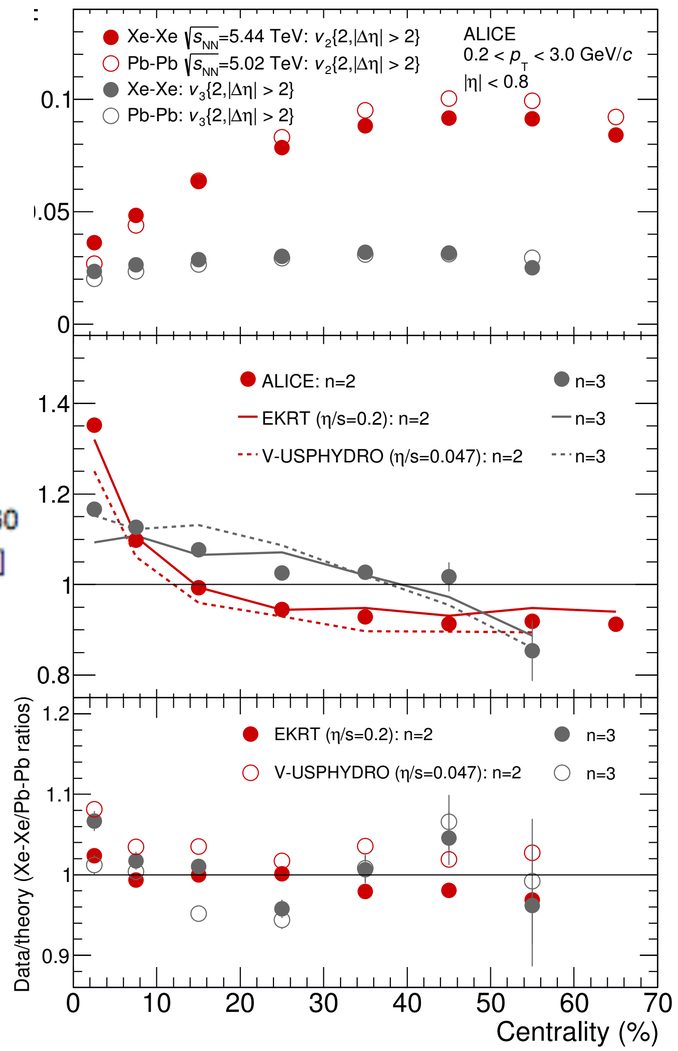
Sharper increase for central collisions
Origin not fully understood?

Flow in Xe-Xe



CMS-PAS-HIN-18-001





ALICE, arXiv:1805.01832

Zeroth order:

Centrality dependence of average v_n very similar

Driven by centrality, ε_n, not volume/multiplicity!

Next order: increase of v_2 in central collisions

- Fluctuations
- Deformed Xe

Described by Trento+Hydro

Closer look at v_2 and v_3 scaling

Explore initial state models:

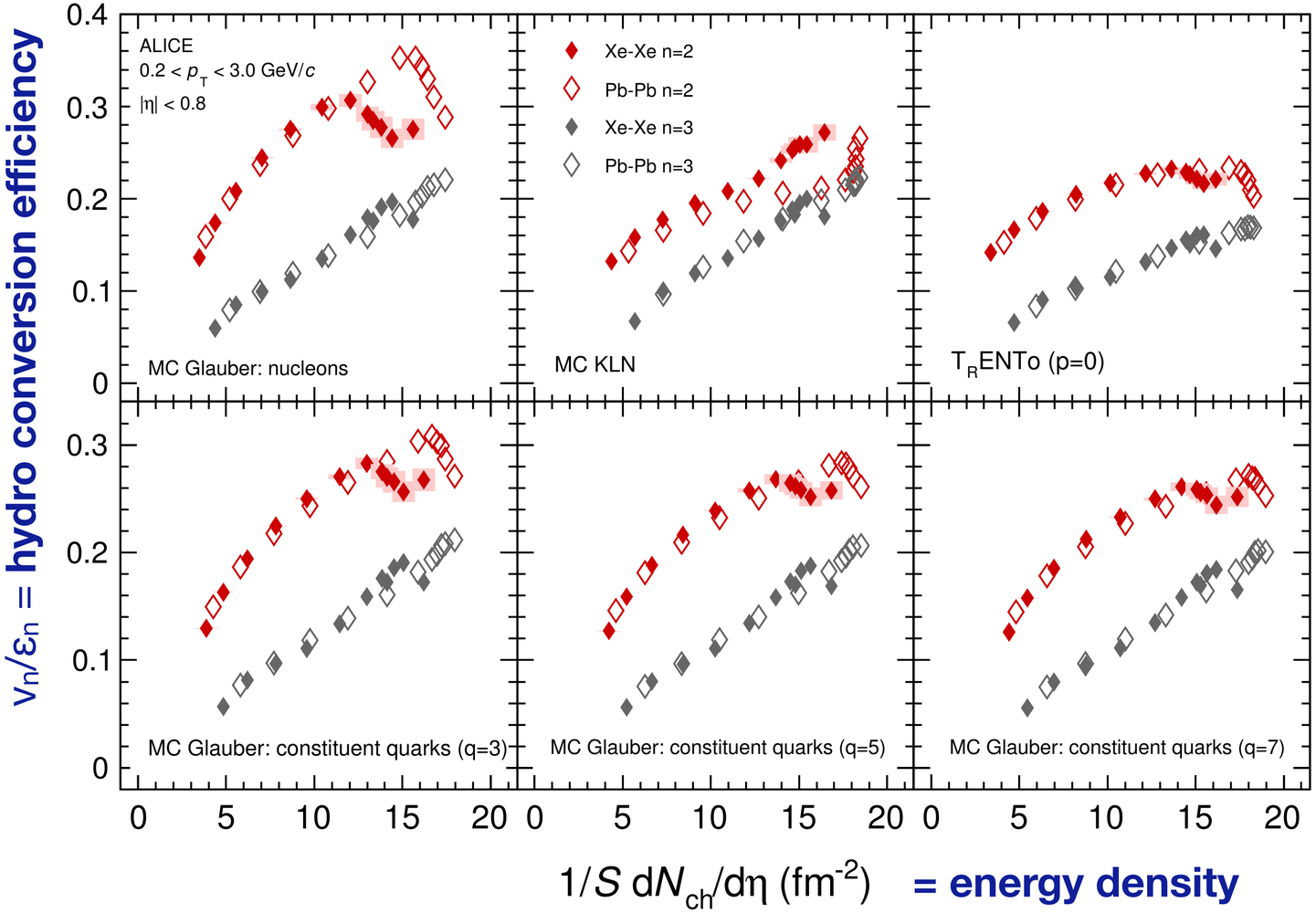
ε_n = f(cent, A)

S = g(cent, A)

Trento p=0 gives a good description of the initial state

$$\rho \propto \sqrt{T_A T_B}$$

As does const quark glauber, with q=5,7



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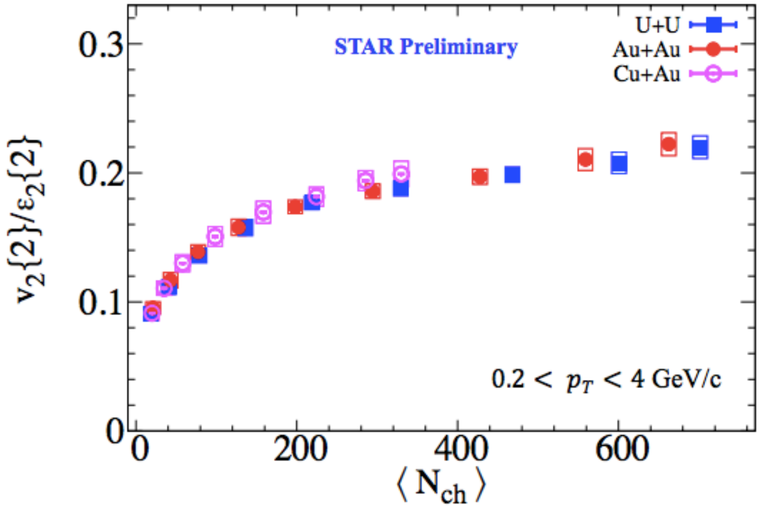
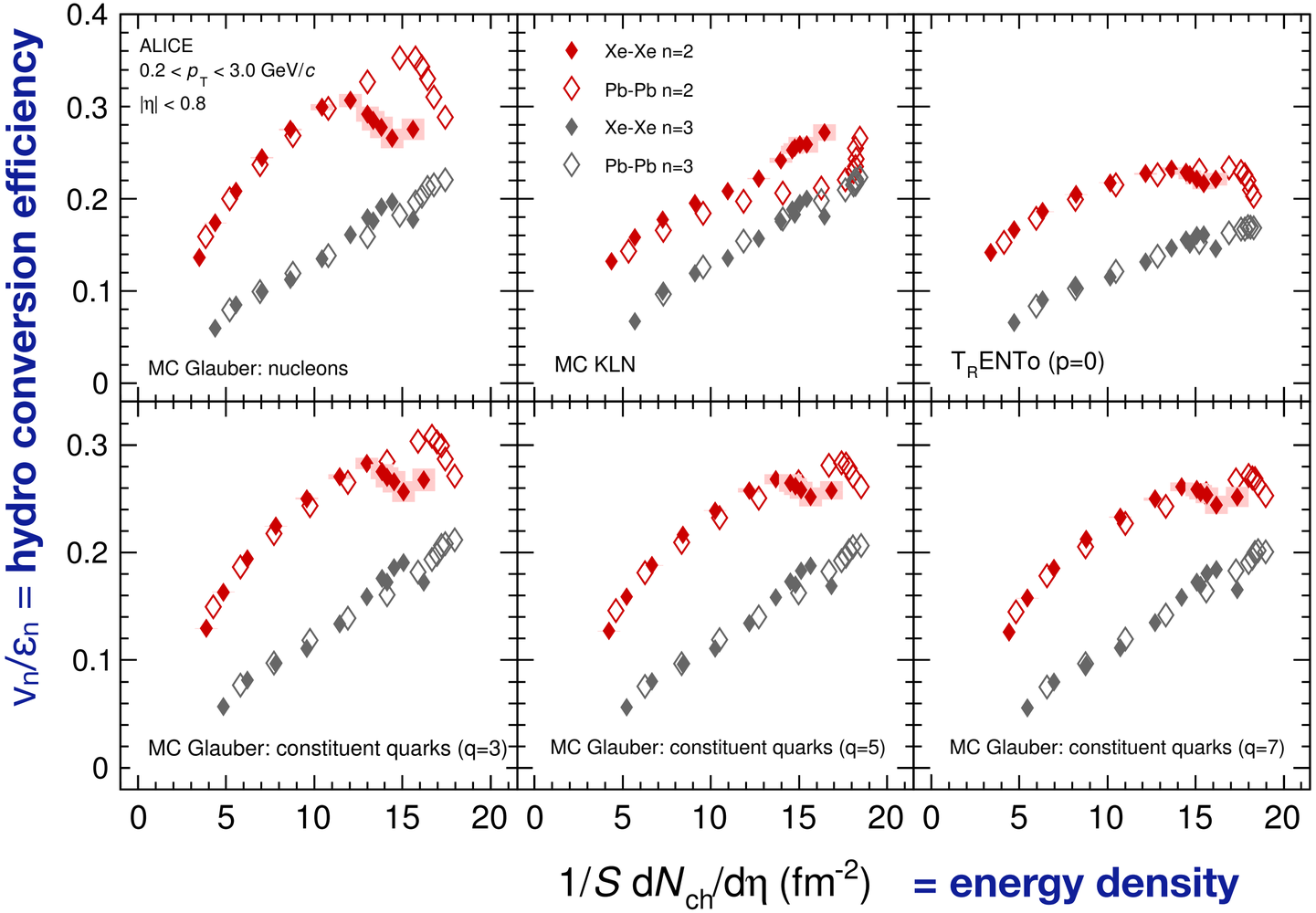
Also being explored at RHIC

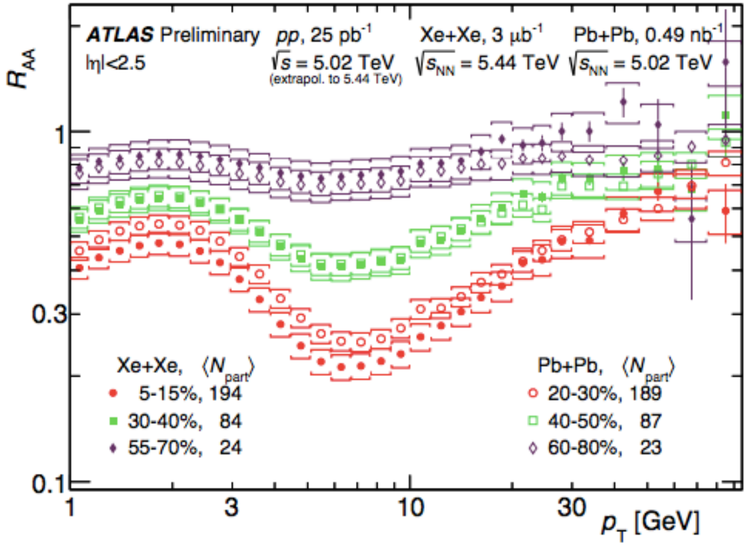


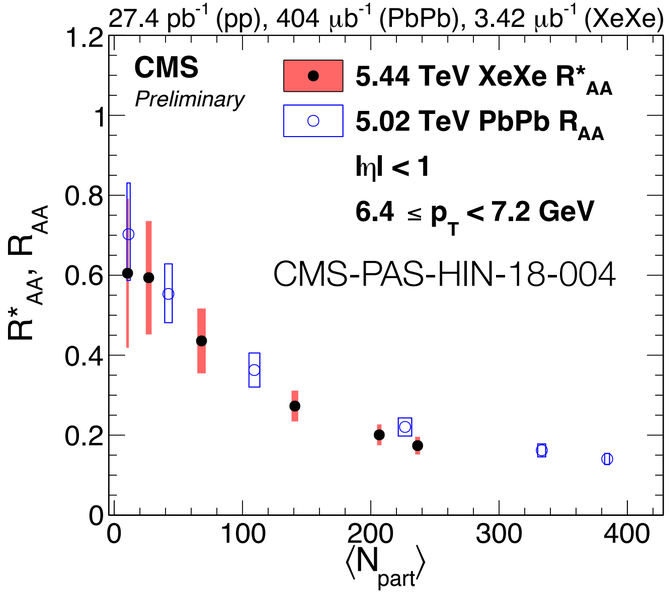


= energy density

Nculear modification factor: centrality dependence

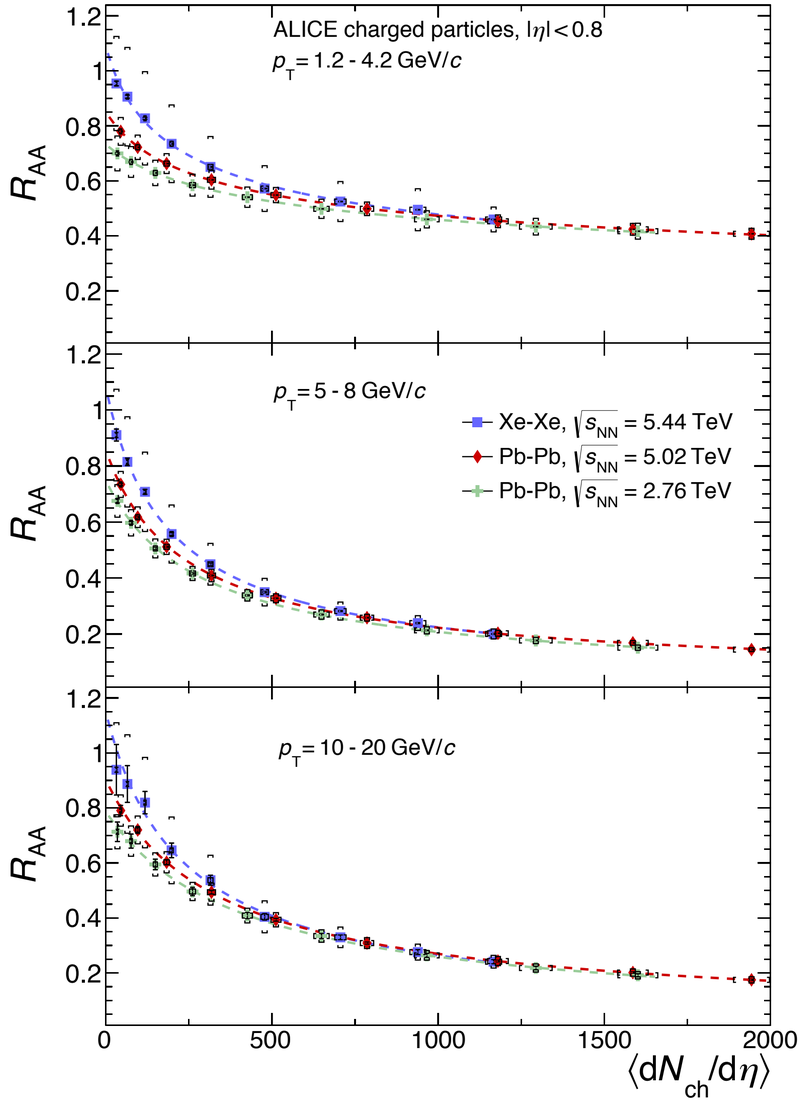
ATLAS-CONF-2018-007





Approximate scaling with N_{part}, or dN/dη

ALICE, arXiv:1805.04399



New scaling proposal:

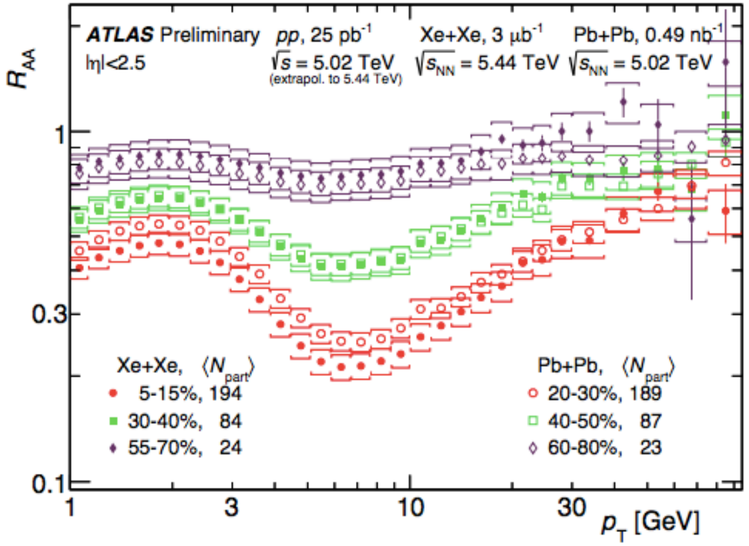
Djordjevic, arXiv:1805.04030

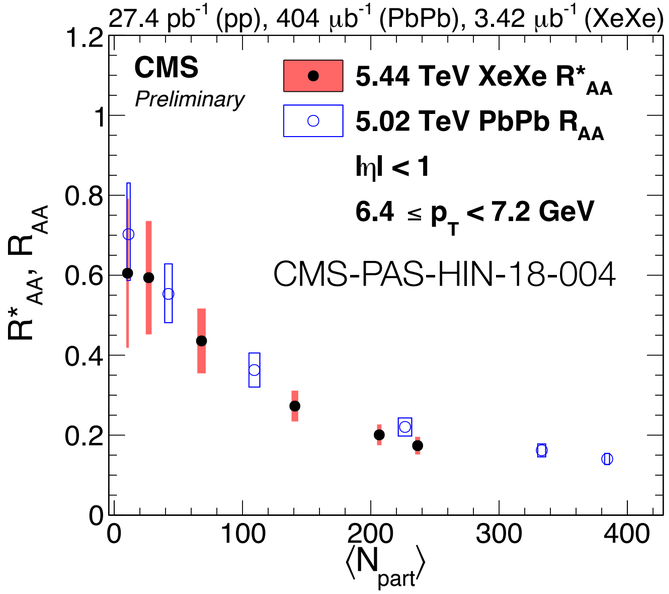
$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \frac{\xi T^a L_{Xe}^b}{\xi T^a L_{Pb}^b} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$

T-dependence drops out when T similar for equal centralities

Nculear modification factor: centrality dependence

ATLAS-CONF-2018-007





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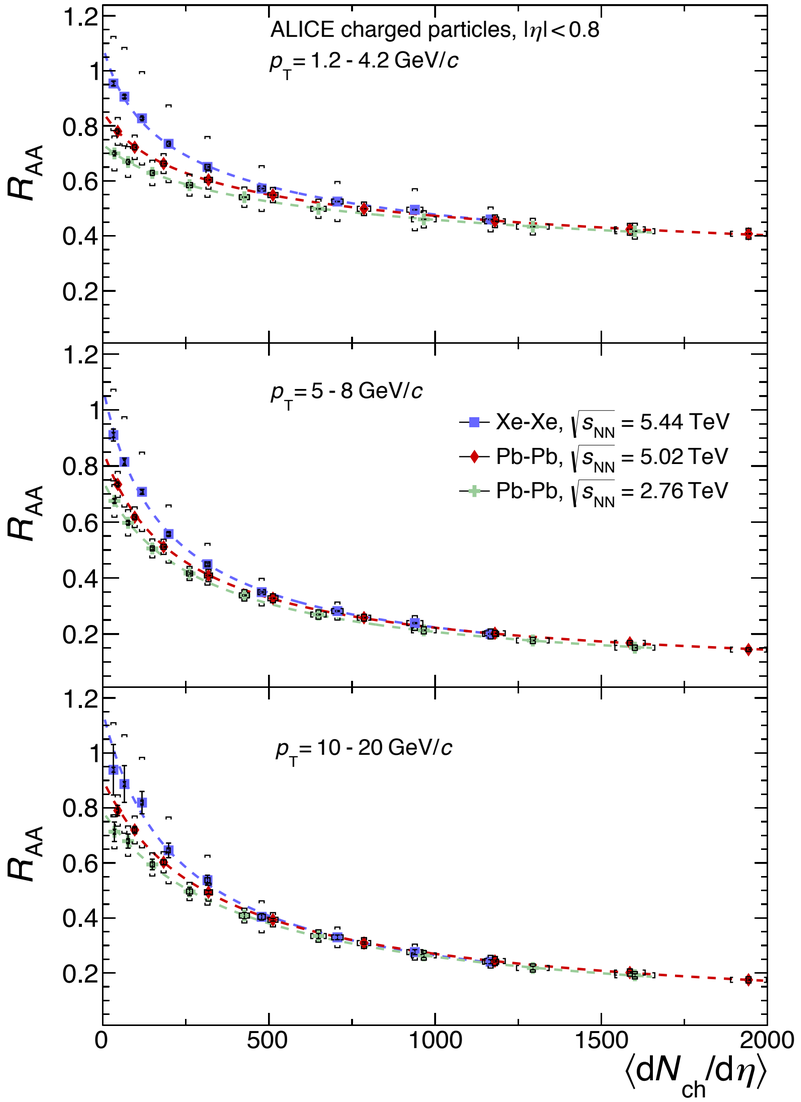

Approximate scaling with N_{part}, or dN/dη

Theory/phenomenology task:
Explore constraints on density, path length dependence

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System size check list

Leveraging the system size as an free parameter:

- Multiplicity production: **quasi-understood**
- Azimuthal anisotropies: **understood**
- Nuclear modification factors: some homework to do, **no surprises**

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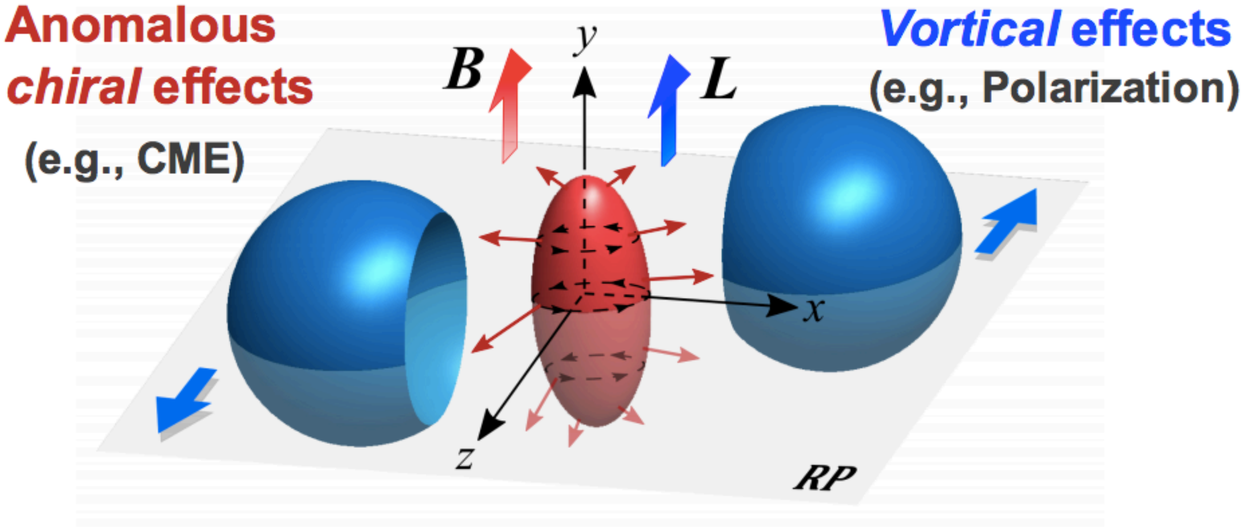
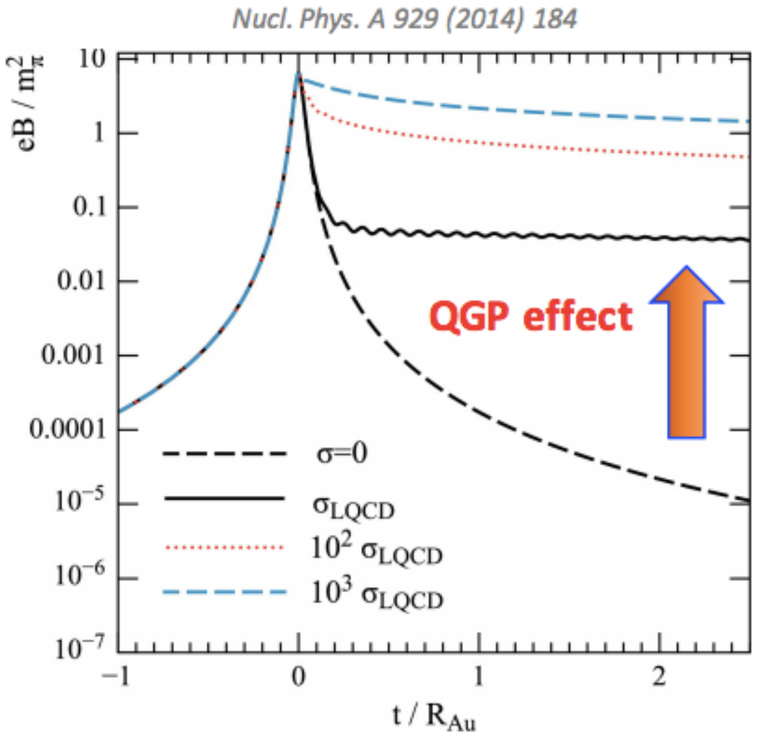
…we understand the dominant dynamics

Magnetic fields and angular momentum

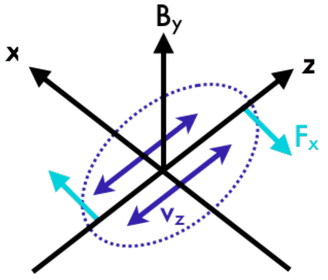




Time evolution of magnetic fields depends on conductivity

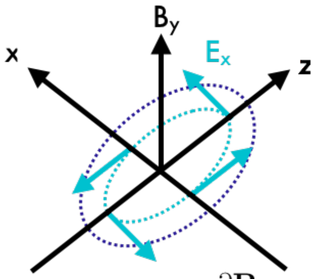
Probing the magnetic field: Charge dependence of directed flow

Classical effects: Lorentz



$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

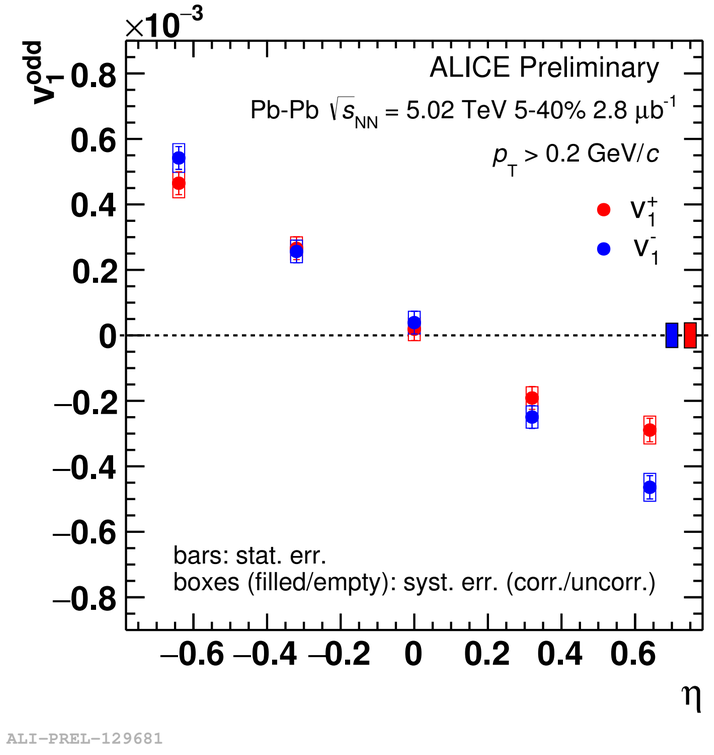
Hall effect



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Sketch: J Margutti

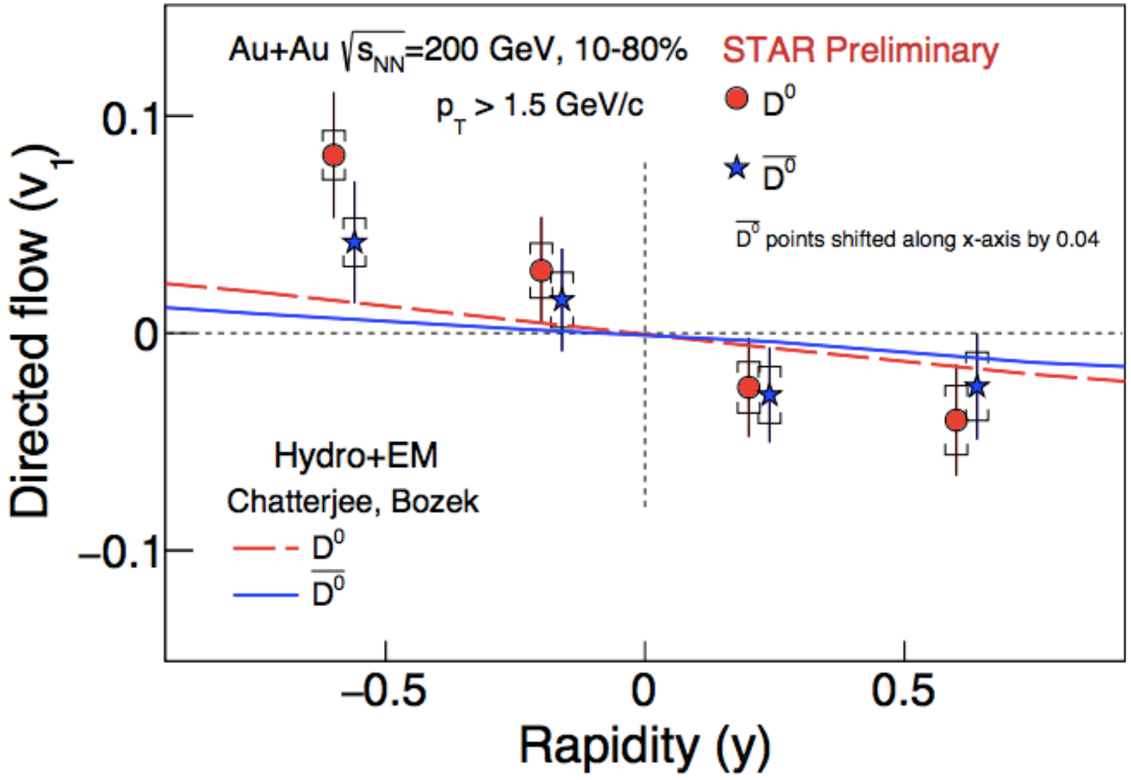
ALICE: charged particles



Hint of charge dependence of v_1

STAR: D mesons

Talk: S Singha



D meson v_1 might be large; quark charge dependence

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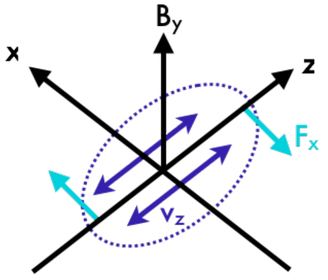

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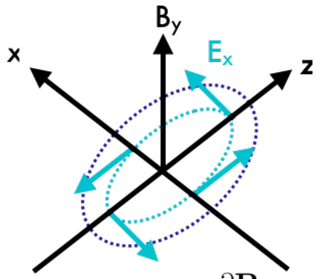

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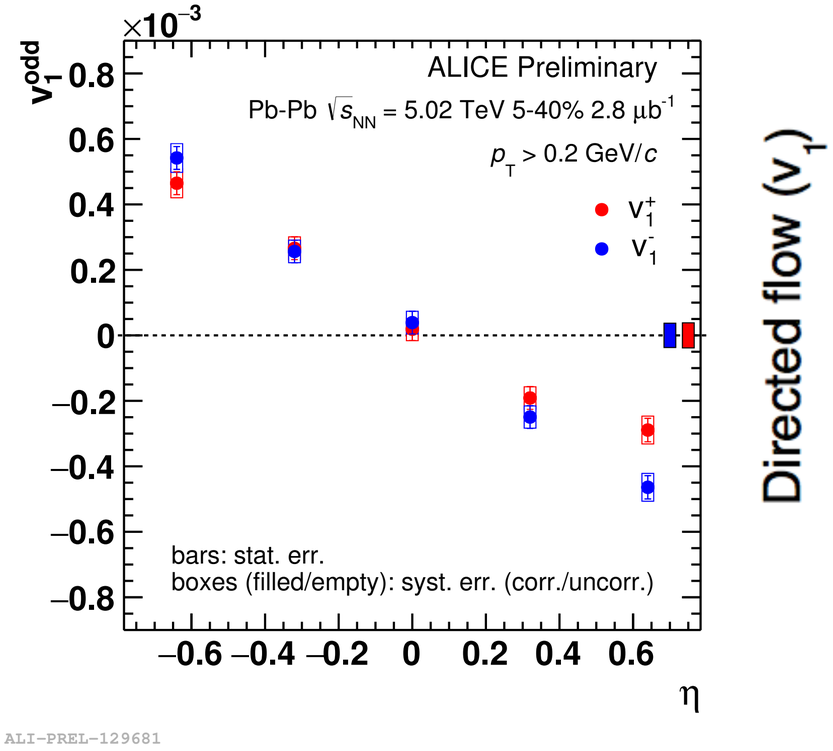
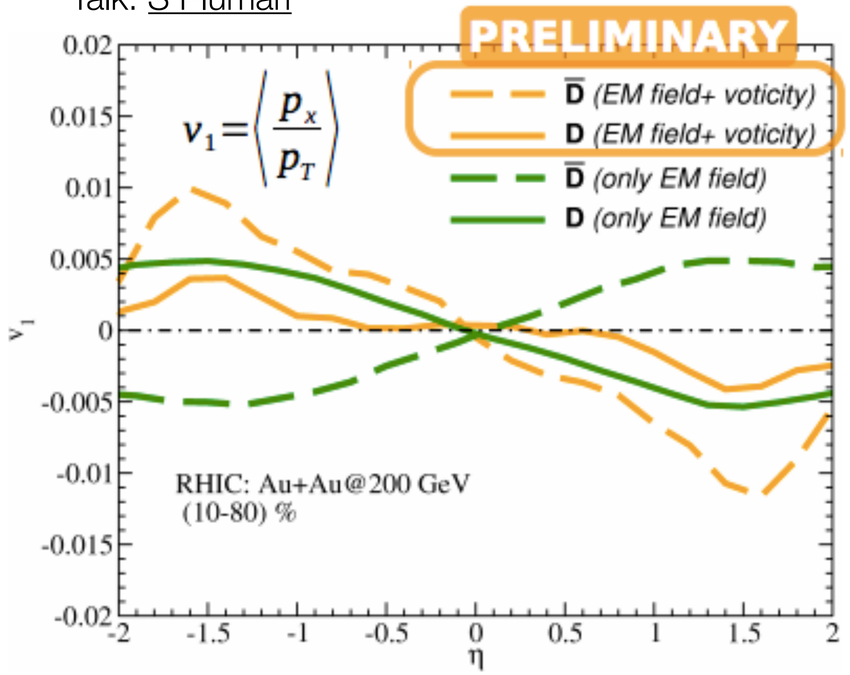


Directed flow (v_1)

Hint of charge dependence of v_1

Talk: S Plumari



Theory update: vorticity reduces signal

D meson v_1 might be large; quark charge dependence

Probing the magnetic field: Charge dependence of directed flow

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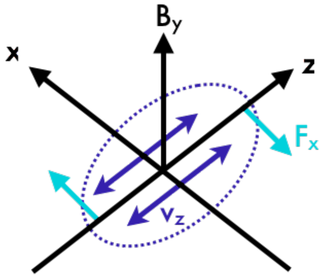

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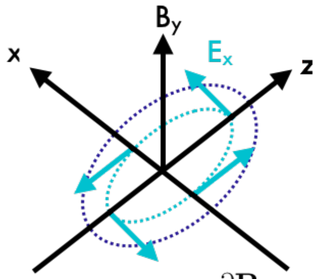

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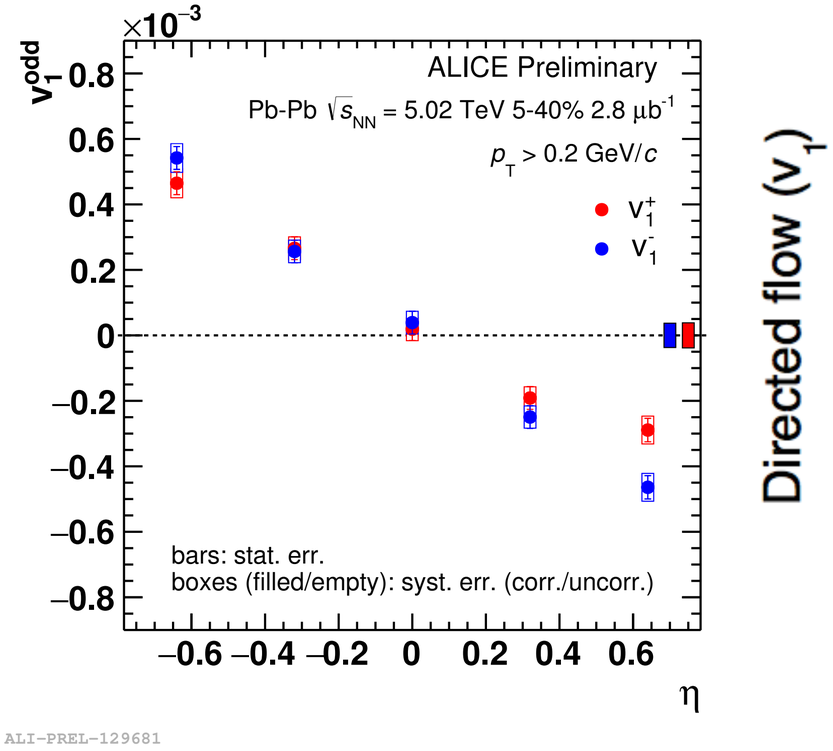

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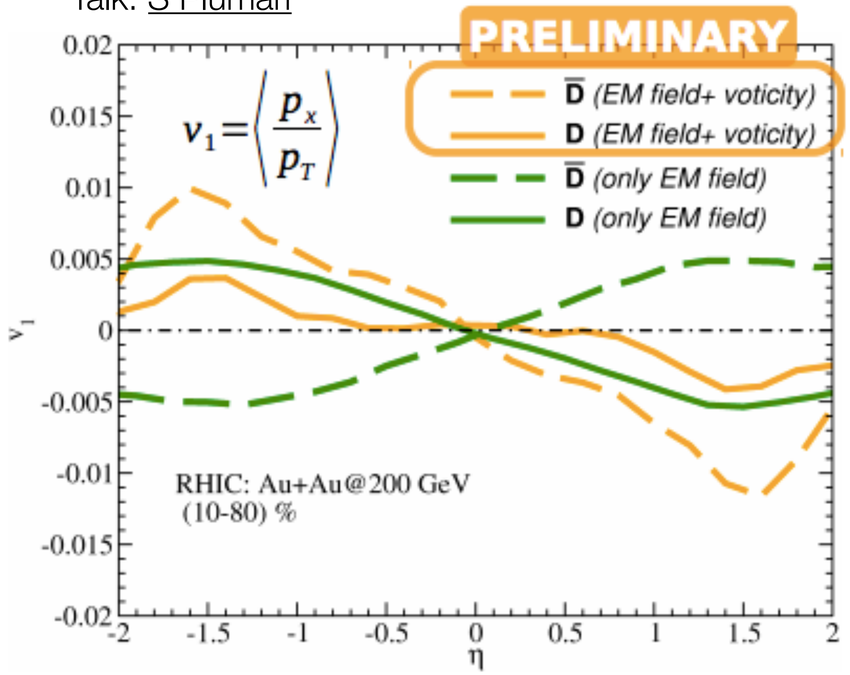

Theory update: vorticity reduces signal

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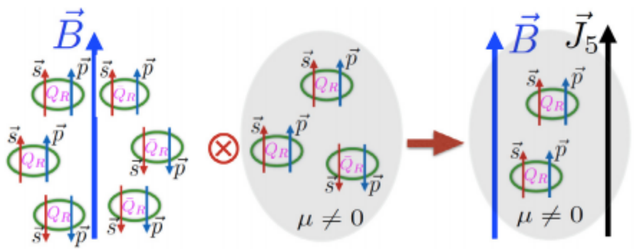
Resulting signals are small, but may be in reach

Chiral Magnetic effect

Observable: charge separation perpendicular to event plane

$$\mathbf{J}_5 \propto \mu_\mathrm{v}\mathbf{B}$$



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Caveat: large backgrounds from v_2

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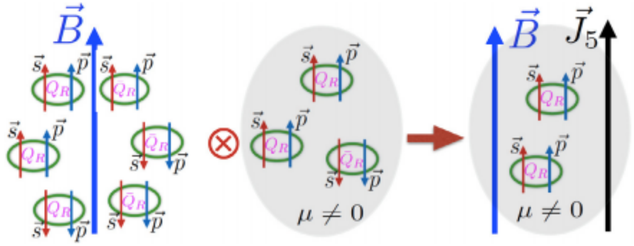

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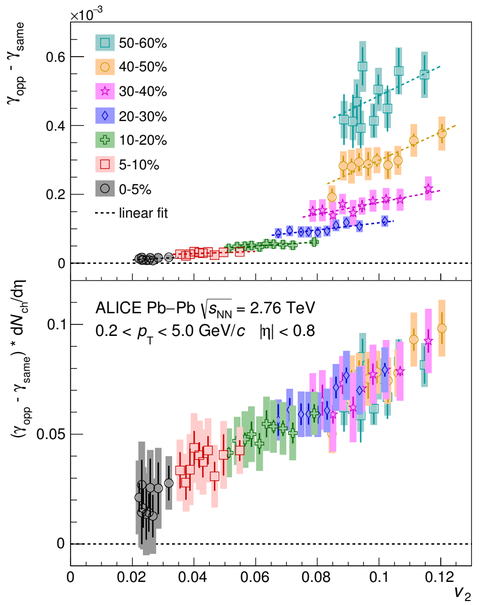
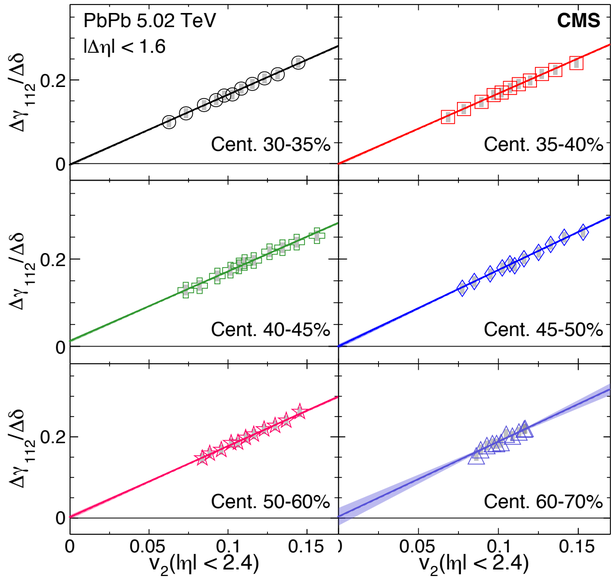
ALICE, CMS: use event-shape engineering to dial background





ALICE, PLB 777, 151

CMS, PRC 97 (2018) 044912

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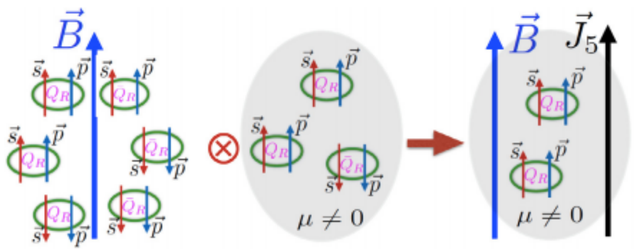

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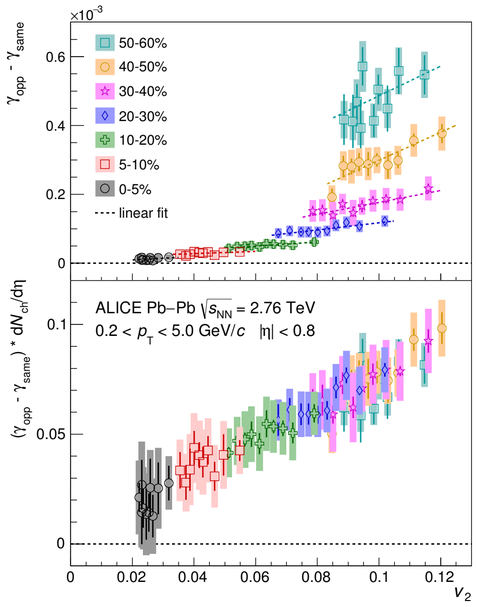
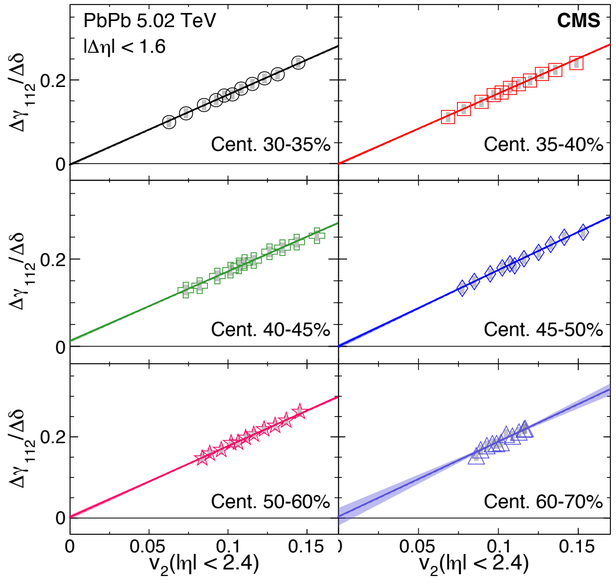
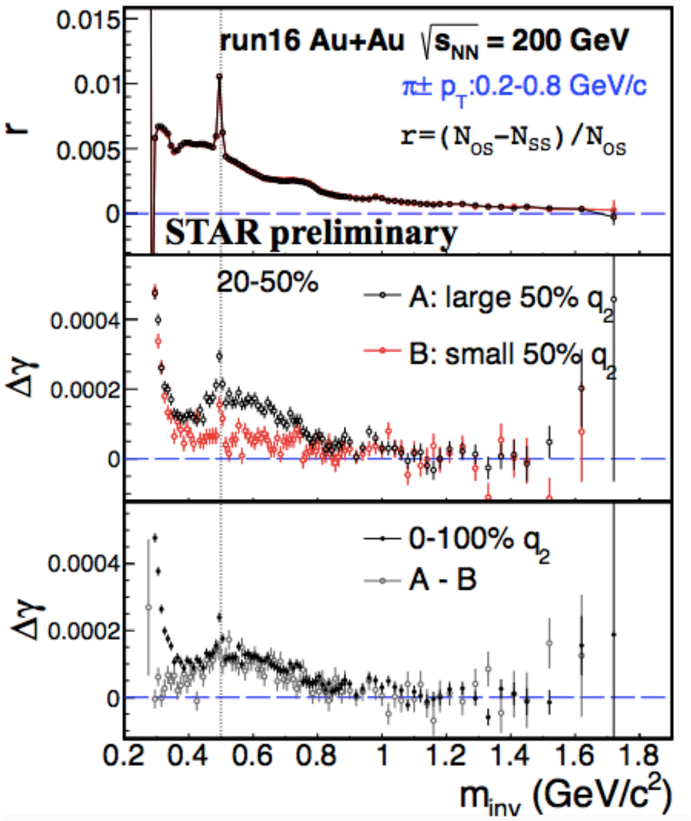


ALICE, PLB 777, 151



CMS, PRC 97 (2018) 044912

STAR: mass dependence + ESE



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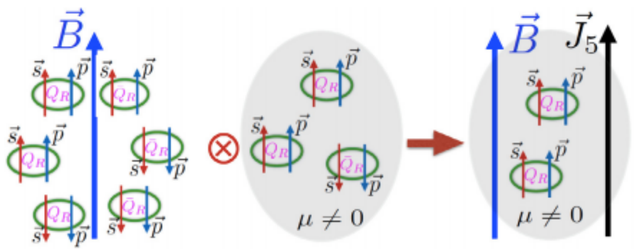

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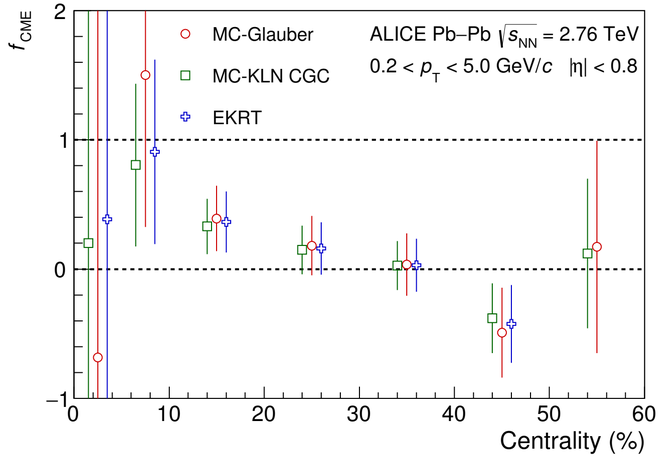
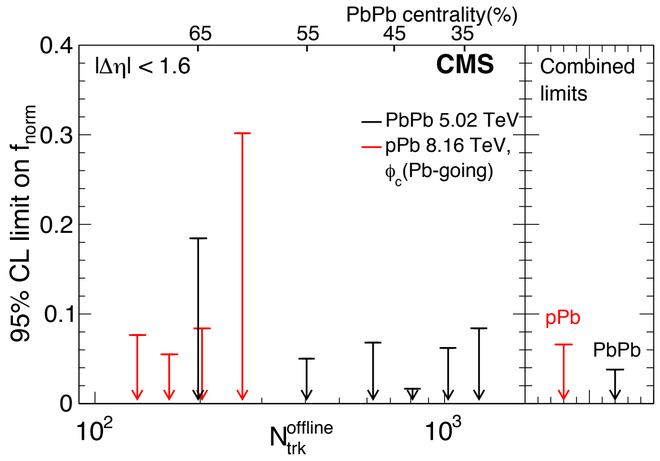
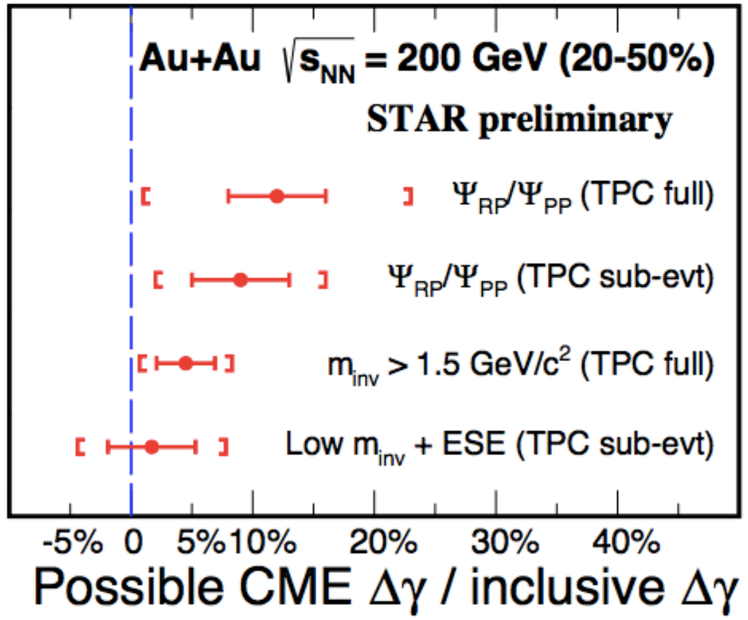
ALICE, PLB 777, 151





CMS, PRC 97 (2018) 044912



Several groups are modeling hydro + magnetic fields
Overview talk: F. Becattini

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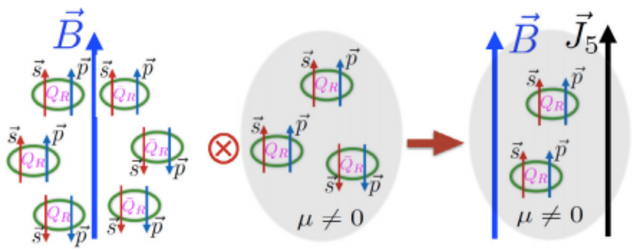

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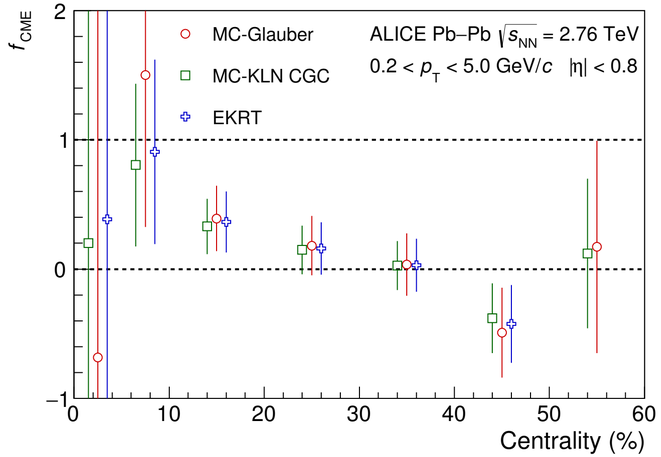
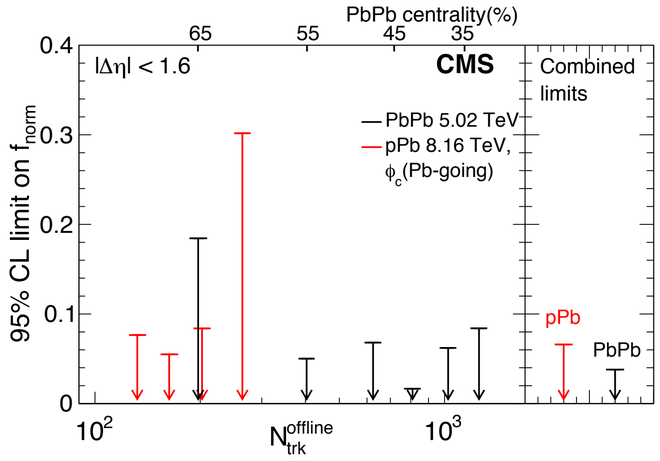
- Backgrounds are large
- Signal fraction may be < 10% at RHIC + LHC

ALICE, PLB 777, 151





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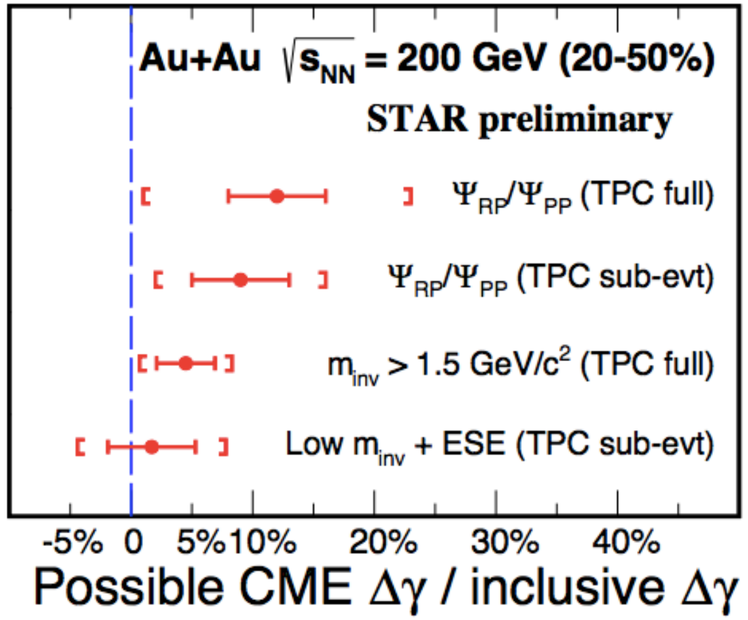

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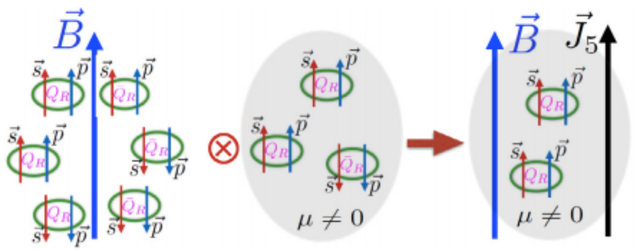

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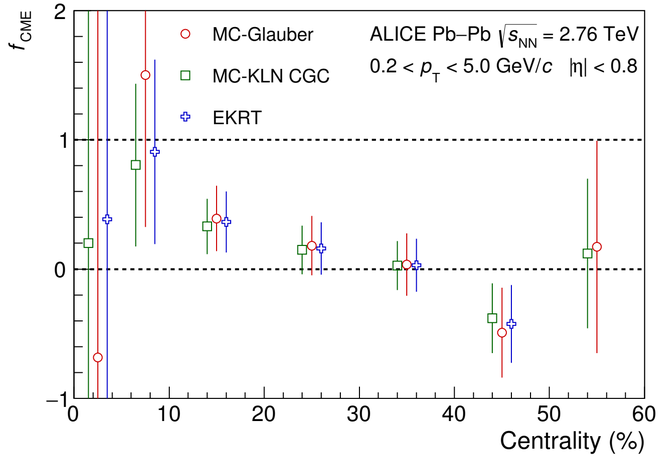
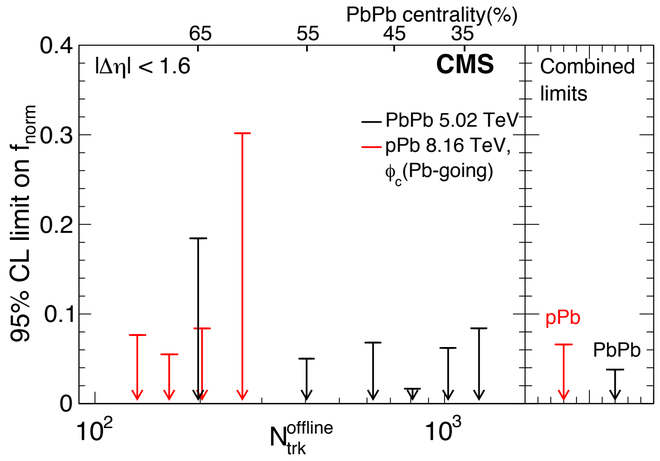
RHIC isobar run dedicated to this topic

ALICE, PLB 777, 151





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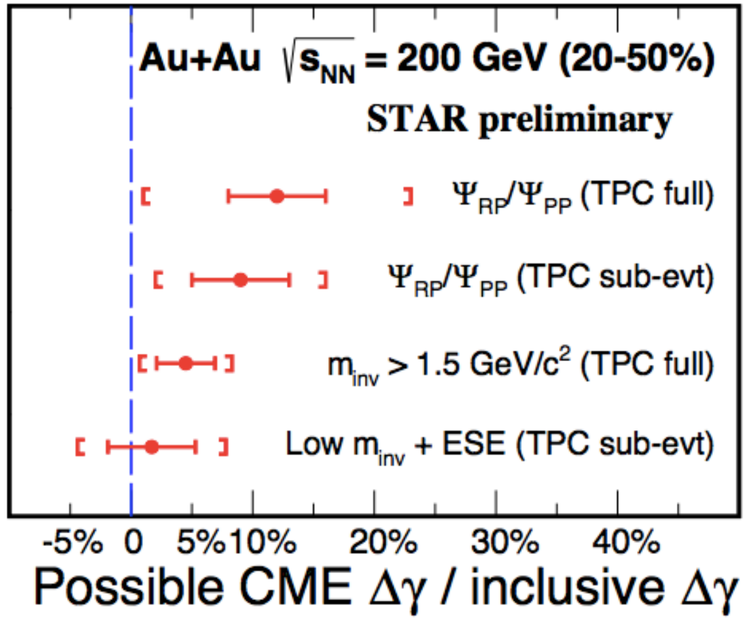

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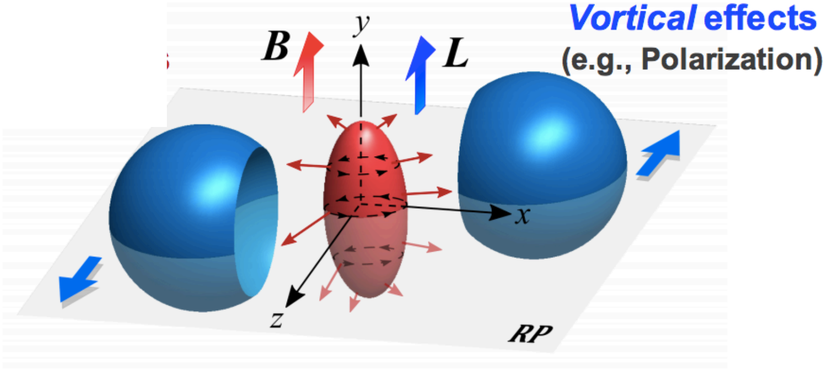
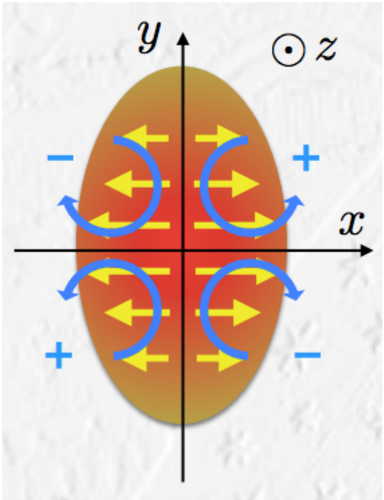
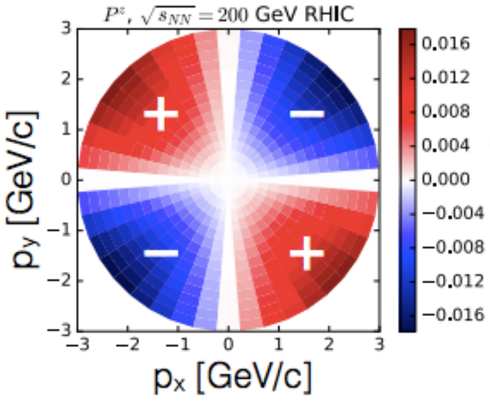
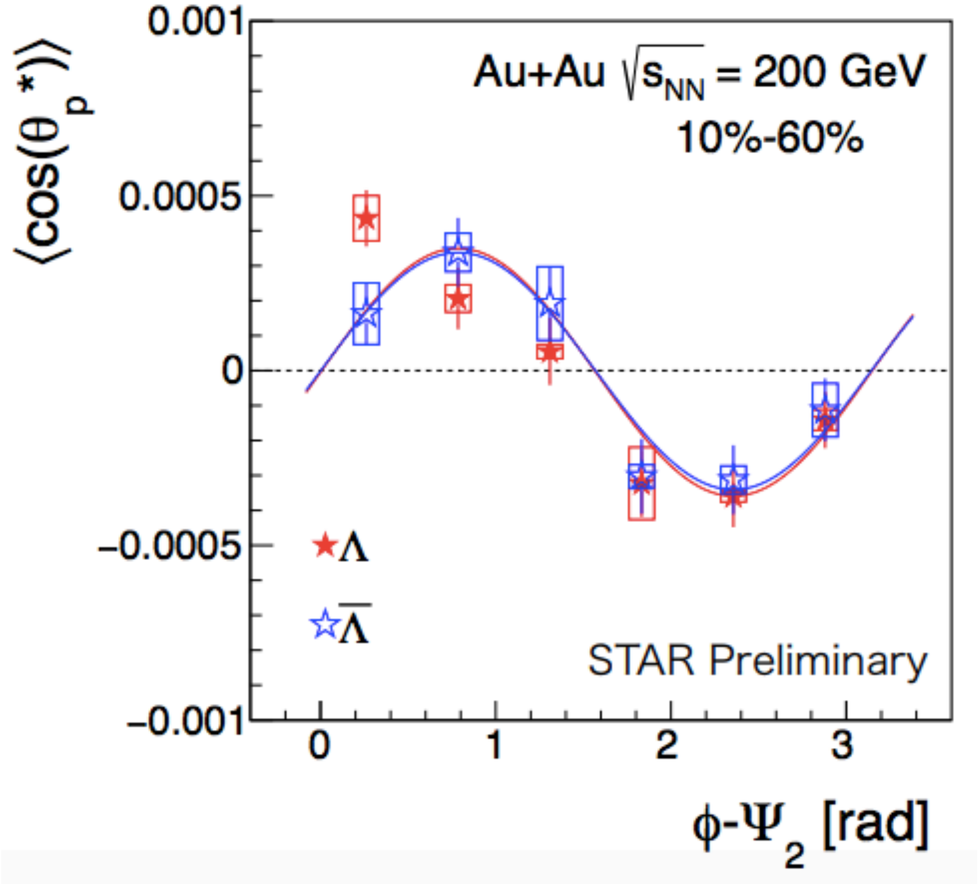
Vorticity





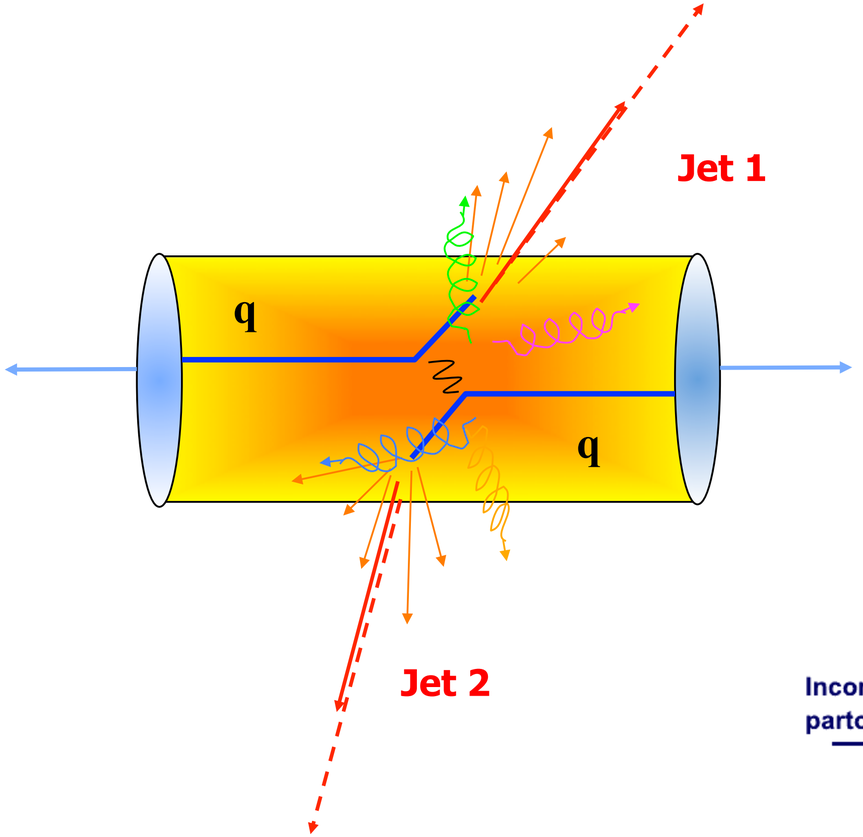


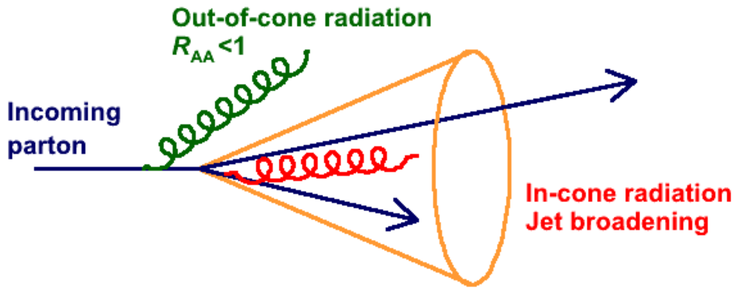


Clear effect seen: modulation of longitudinal spin alignment with angle to event plane

However: sign is opposite of expected!

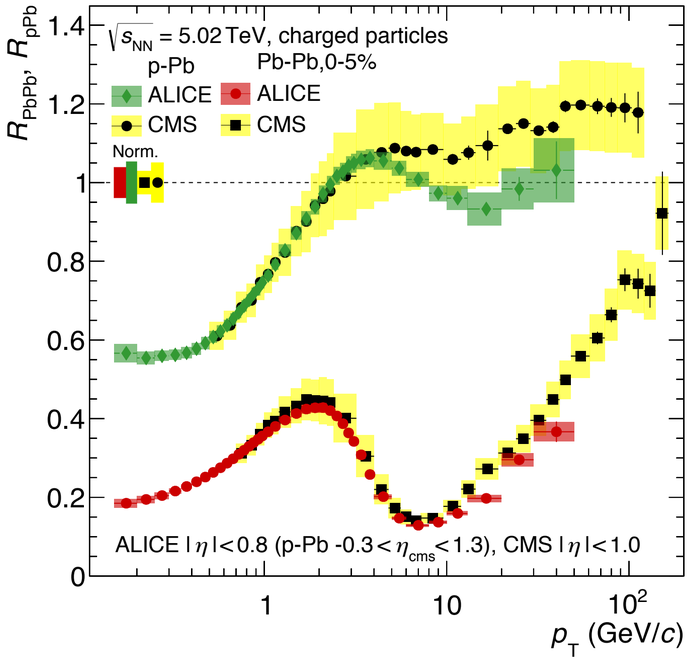
High p_T and Jets



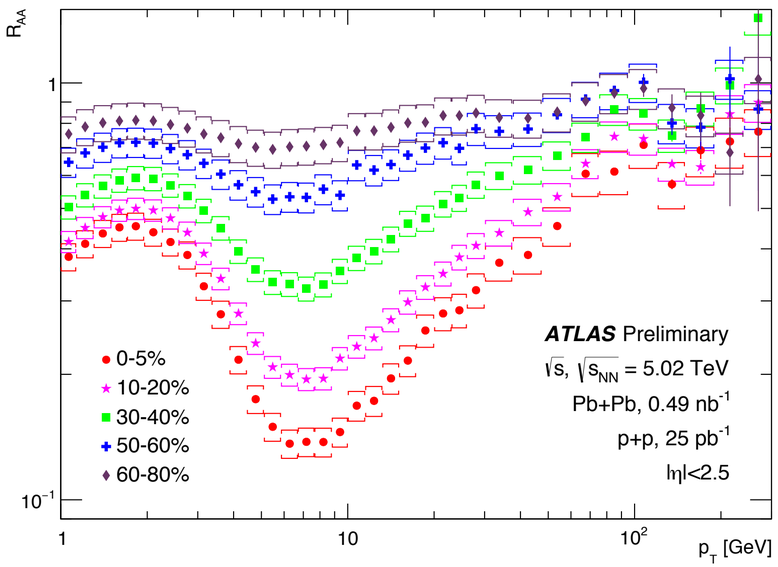


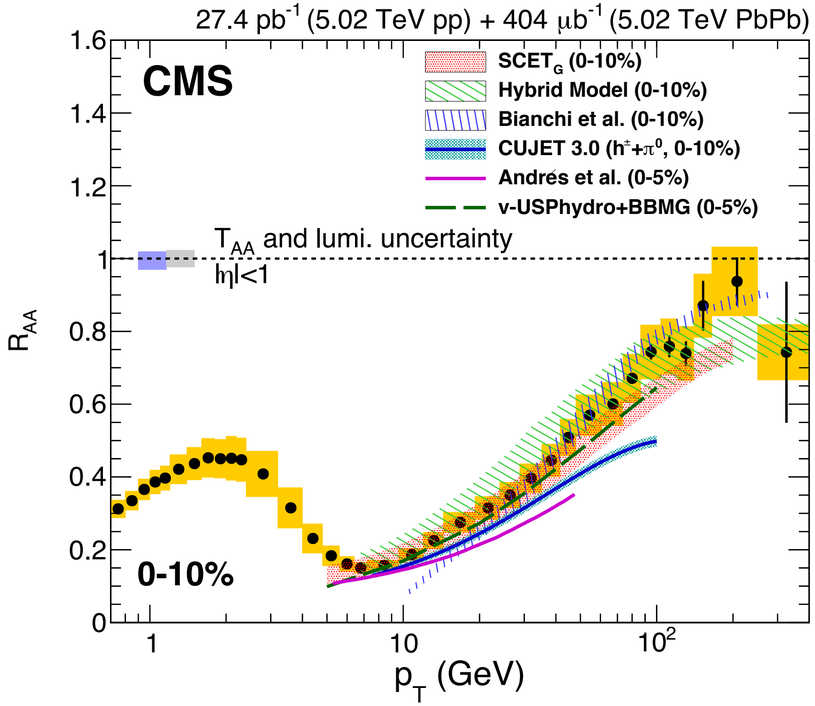
The basics: Charged particle R_{AA}

ALICE, arXiv:1802.09145
CMS, JHEP 04 (2017) 039



ATLAS-CONF-2017-012





Nuclear modification factor results continue to improve uncertainties and extend p_T range

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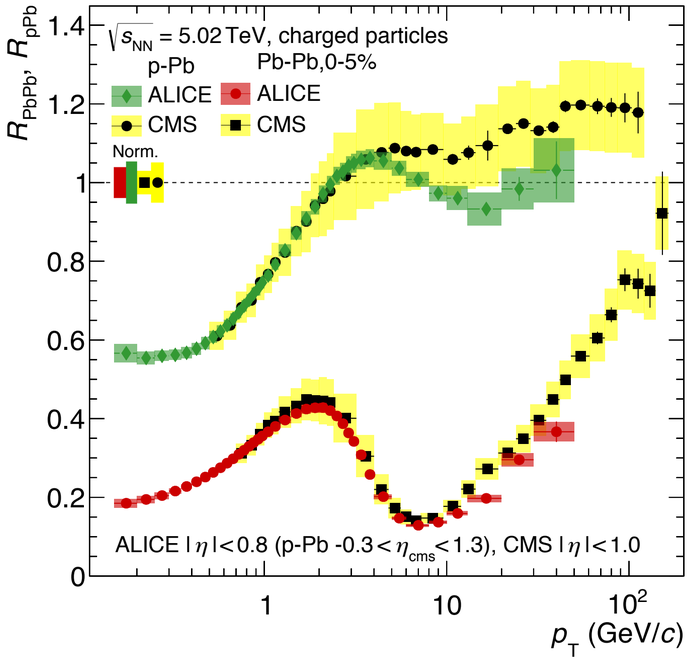

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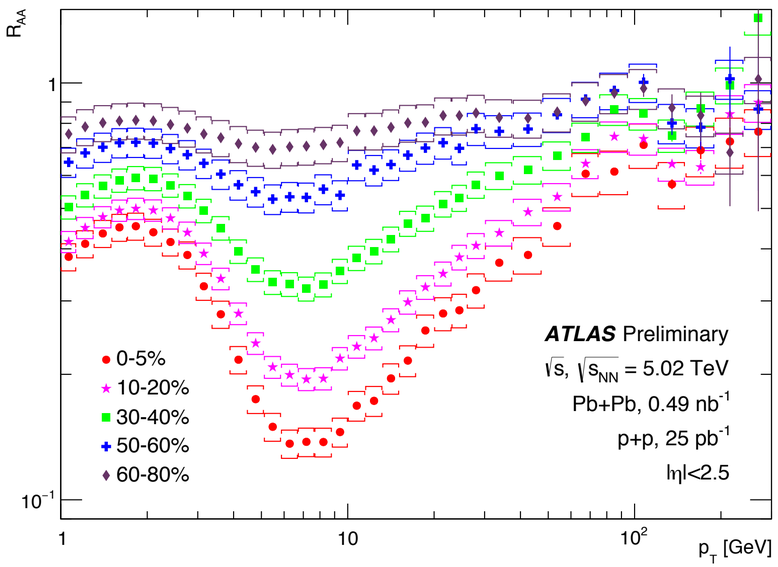
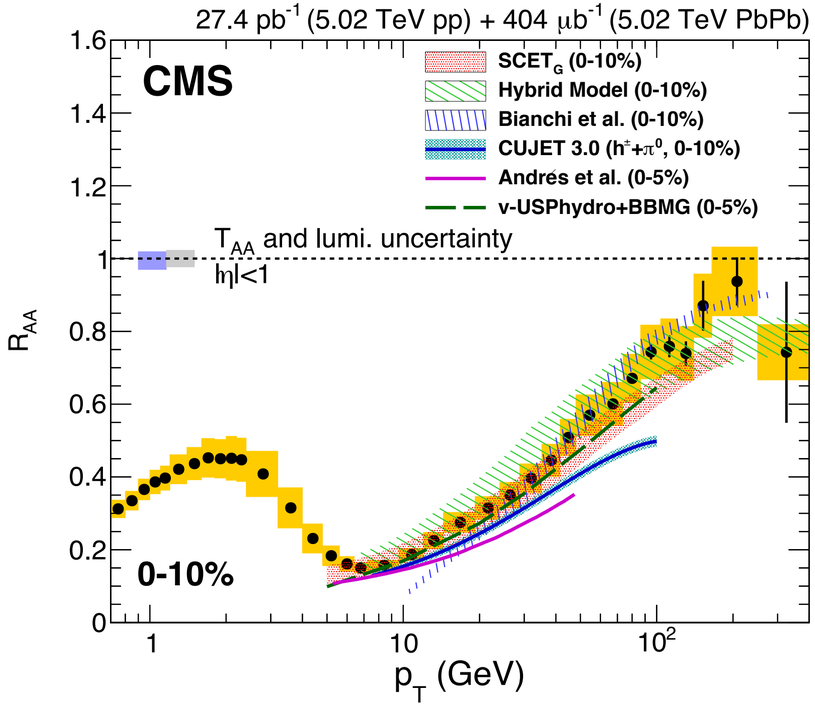




Nuclear modification factor results continue to improve uncertainties and extend p_T range

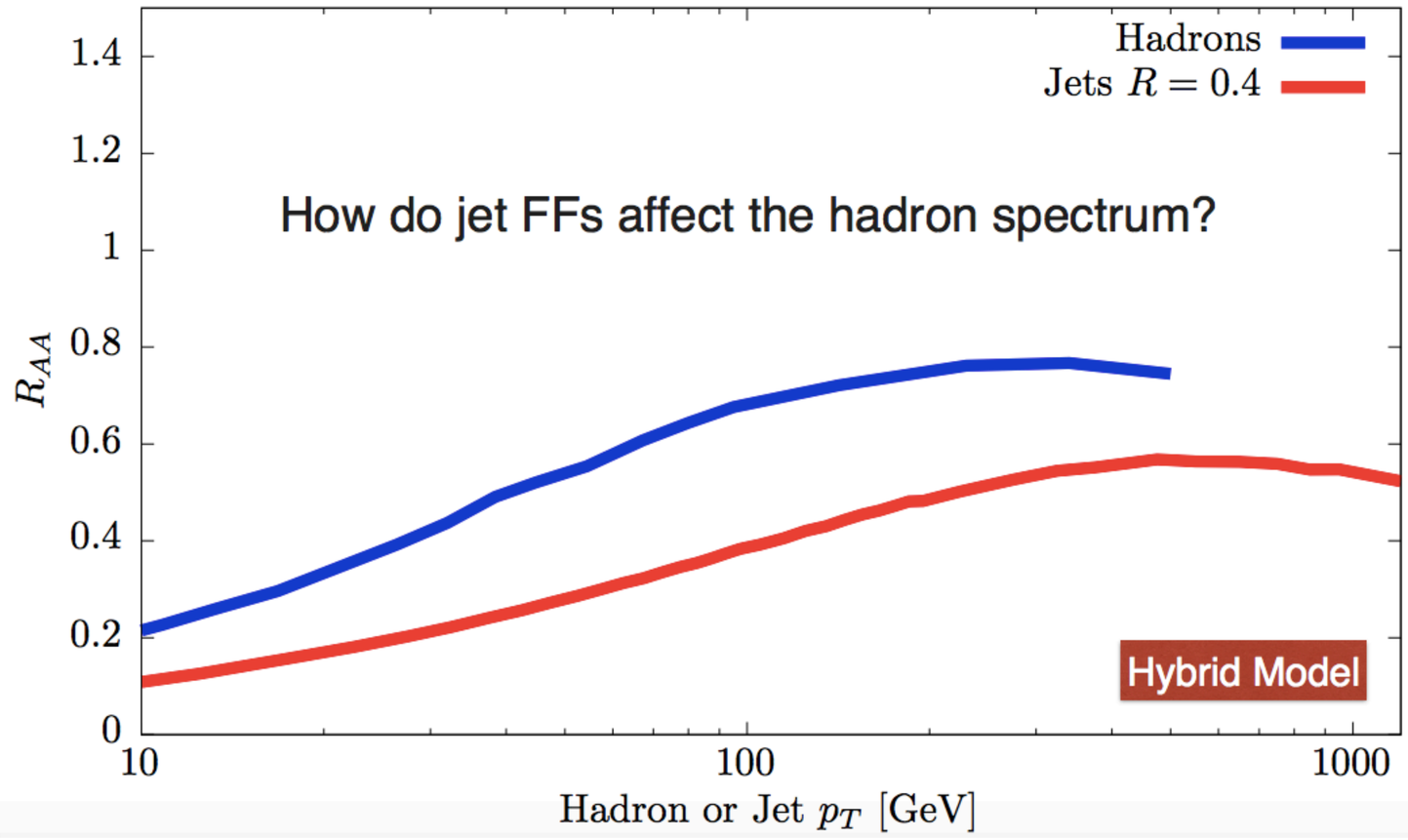
Challenge for models + field
How accurate do we expect models to be?

Relating jets and hadrons: fragment distributions

Talk: D Pablos

Reminder: jets are also suppressed

jet R_{AA} < hadron R_{AA} (at fixed p_T)



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Link: fragment distributions
'fragmentation functions'

NB: While not 'fragmentation functions'
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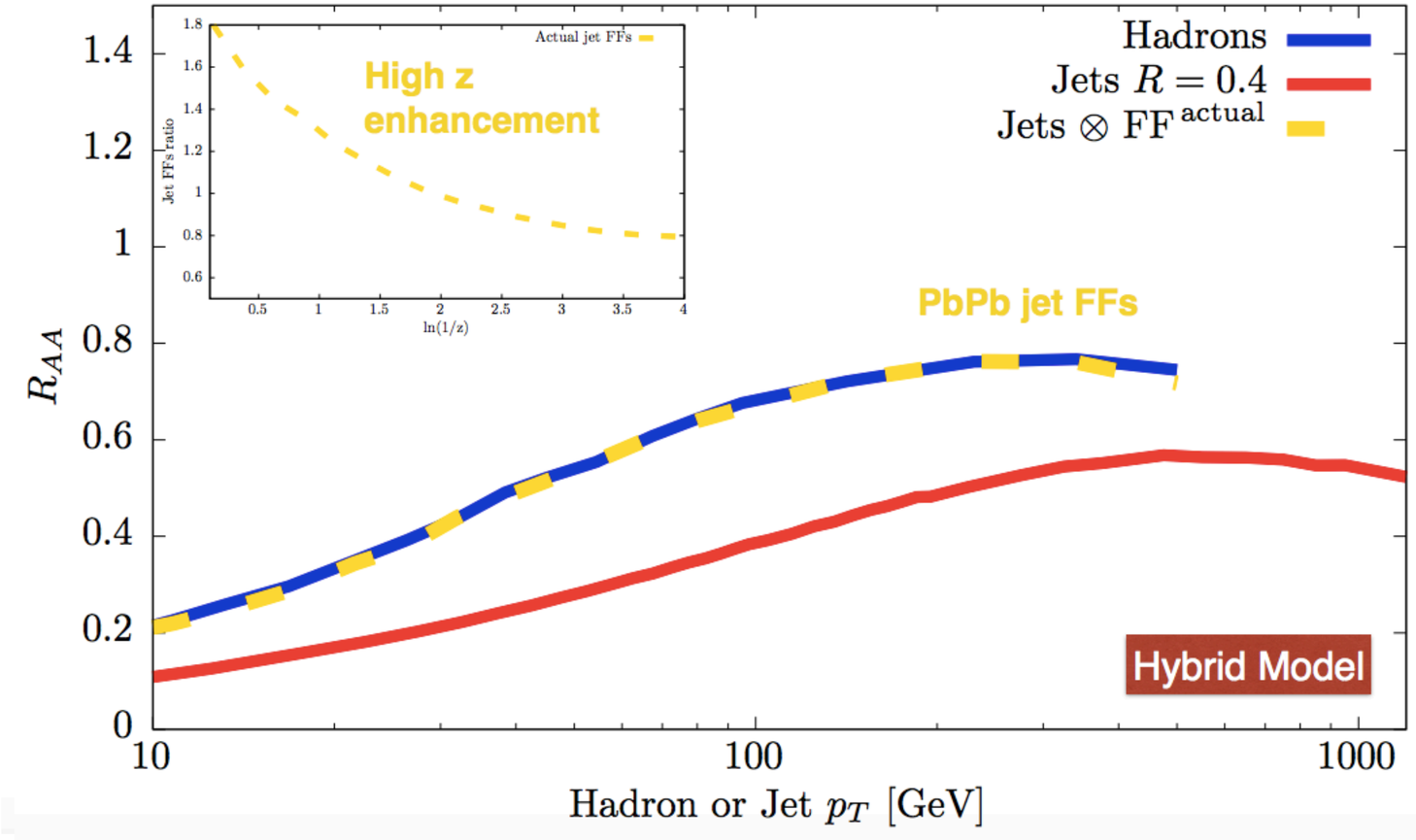
fragment distributions also evolve slowly with jet pt



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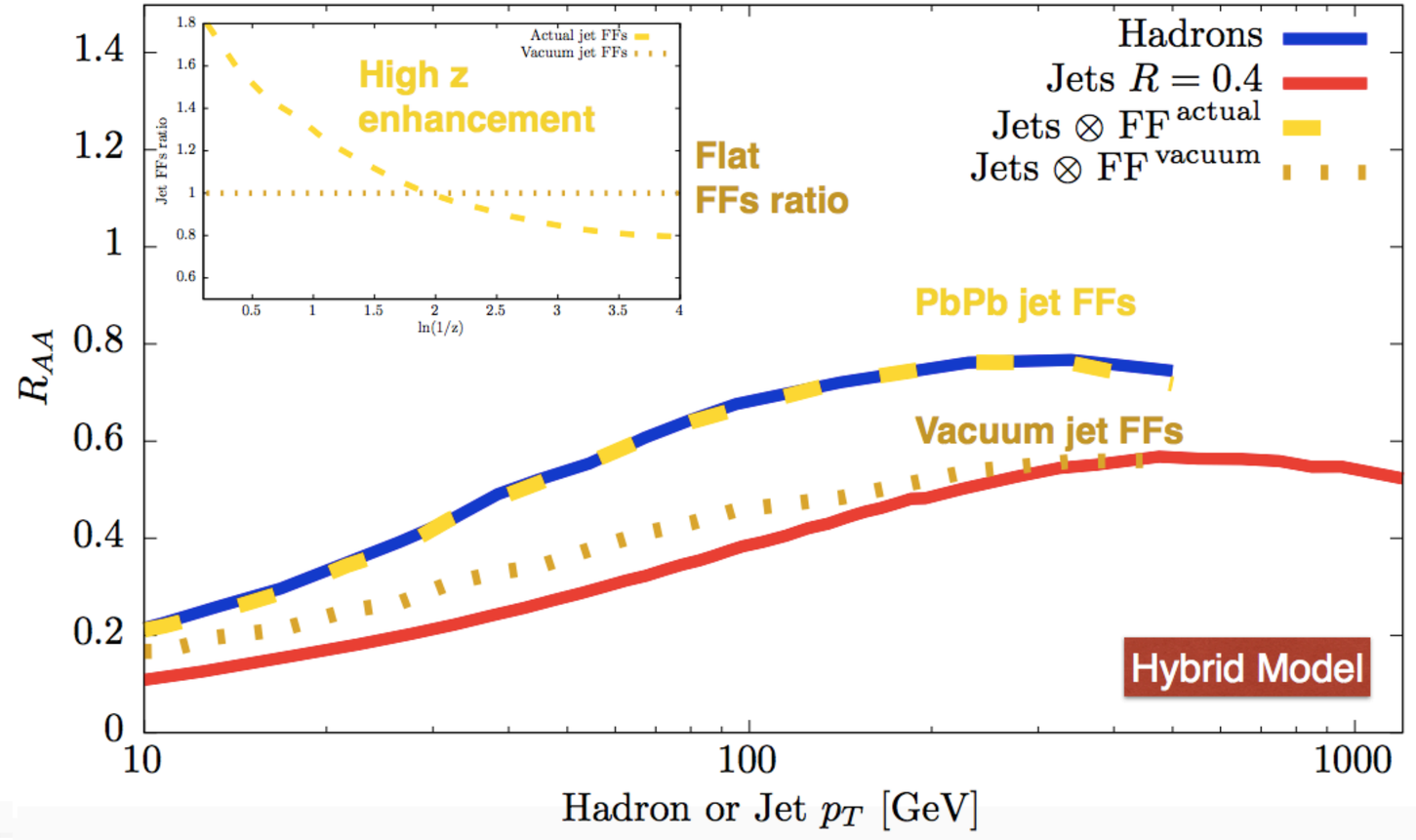

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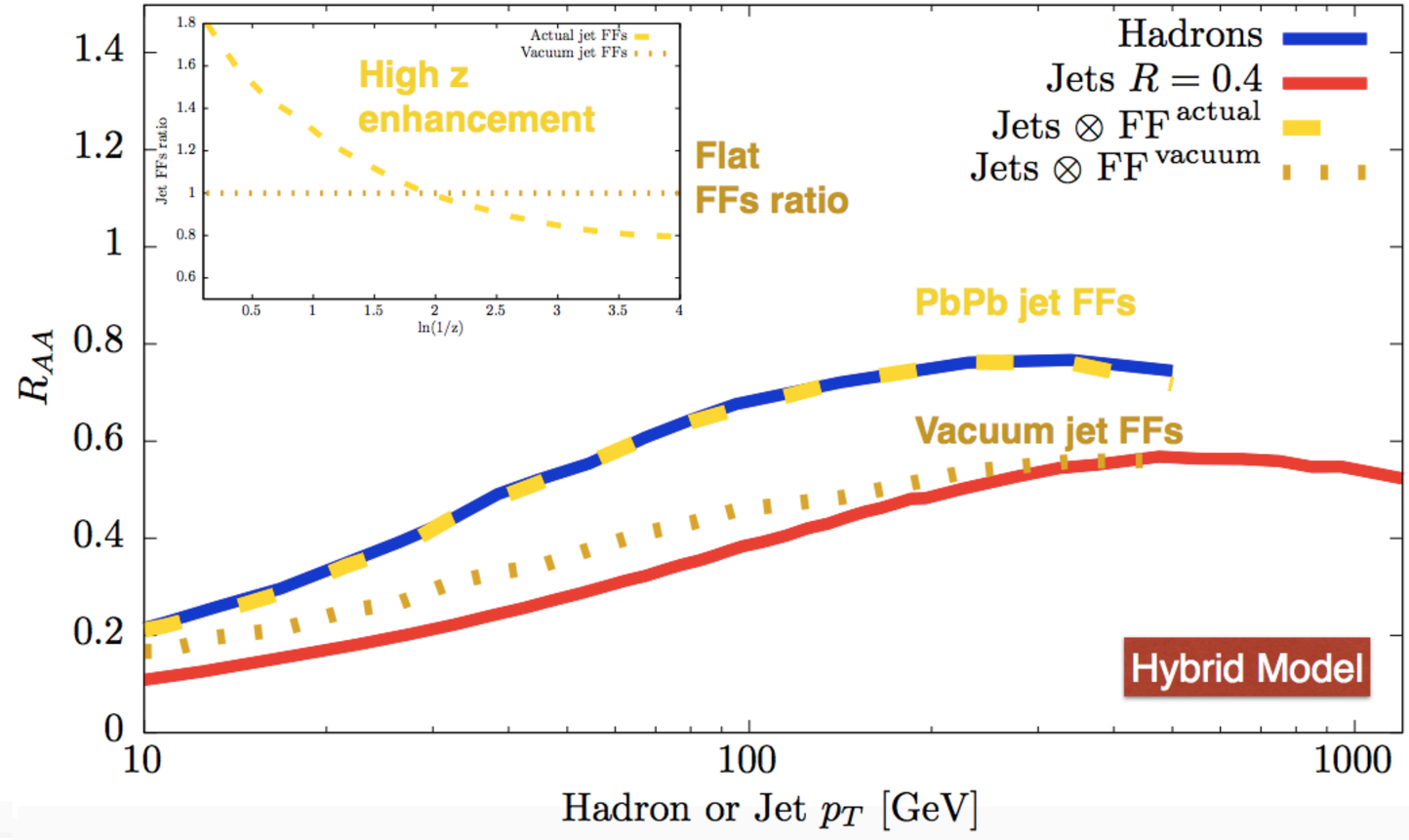
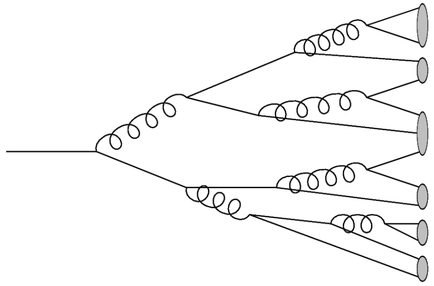
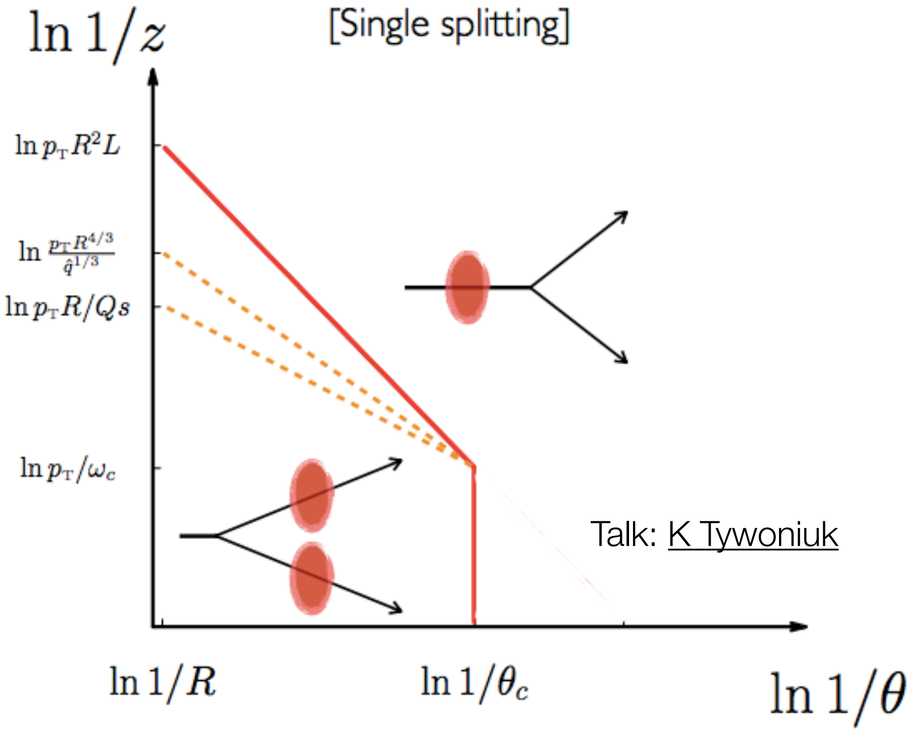


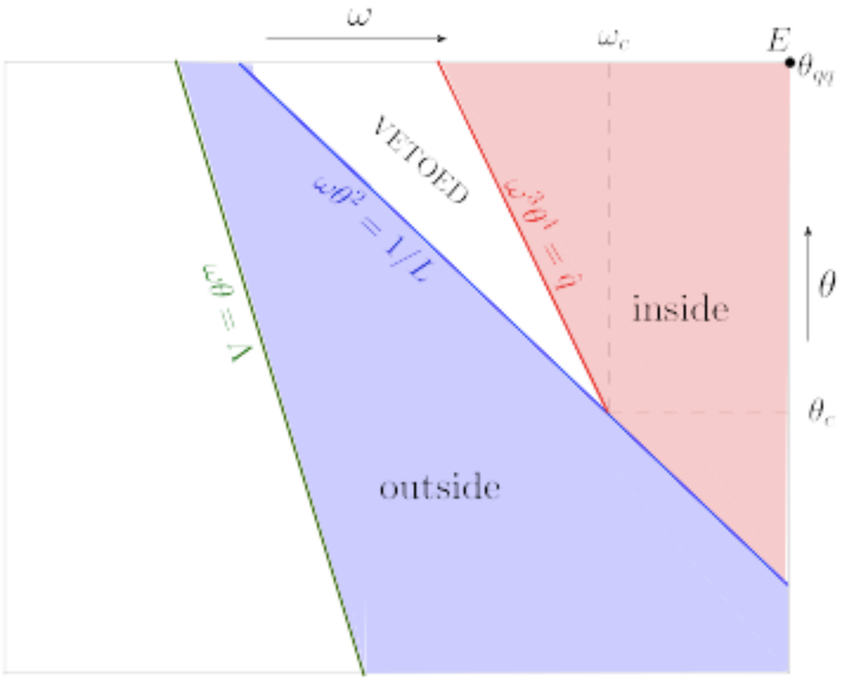


Next step: jets as multi-parton states; do the partons lose energy independently?

Medium-induced and vacuum splittings; coherence



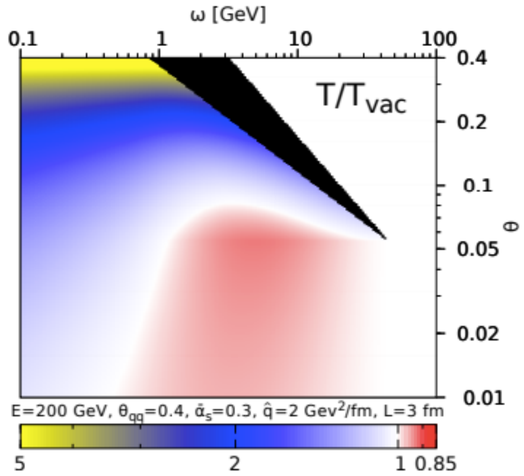
Formation time set by angle, momenta

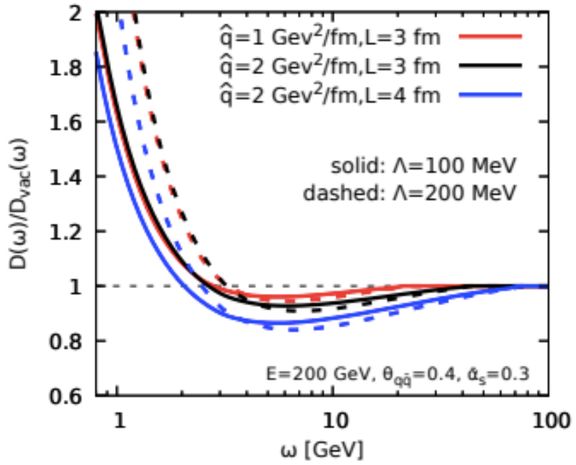


Caucal, Iancu et al, arXiv:1801.09703

$$t_f|_{\rm vac} \equiv \frac{1}{\omega\theta^2} \ll t_f|_{\rm med} \equiv \sqrt{\frac{\omega}{\hat{q}}} \iff \omega \gg \left(\frac{\hat{q}}{\theta^4}\right)^{\frac{1}{3}}$$

Expect radiation outside medium

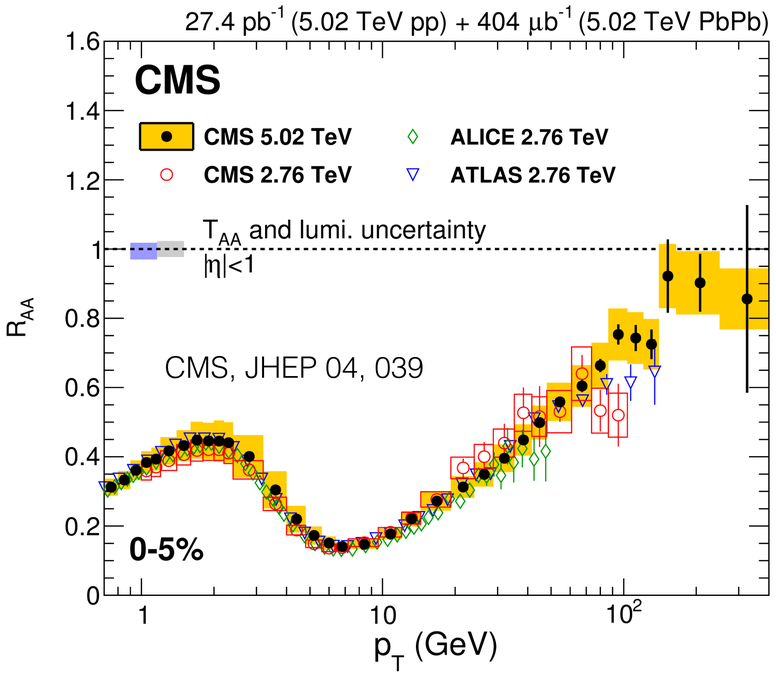




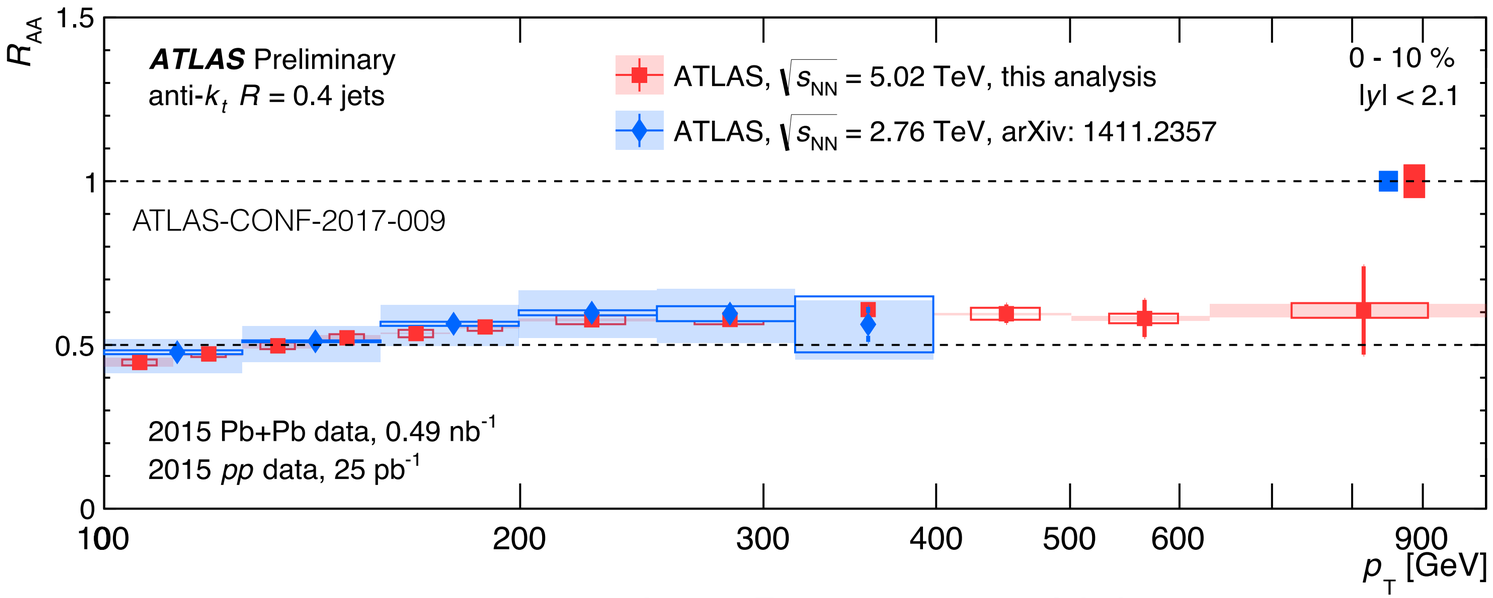
Qualitatively has the right behavior:
Large angle radiation is formed outside the medium?

High-p_T jets vs hadrons

Charged particle R_{AA}



Jet R_{AA}



Jets: $R_{AA} < 1$ out to high p_T

p_T-dependence:

Single particles: consistent with expected constant (log E) dependence

Jets: suggest increase of ΔE vs E

Tentative interpretation: in jets, multiple partons lose energy; more partons in high-E jets ⇒ more E-loss

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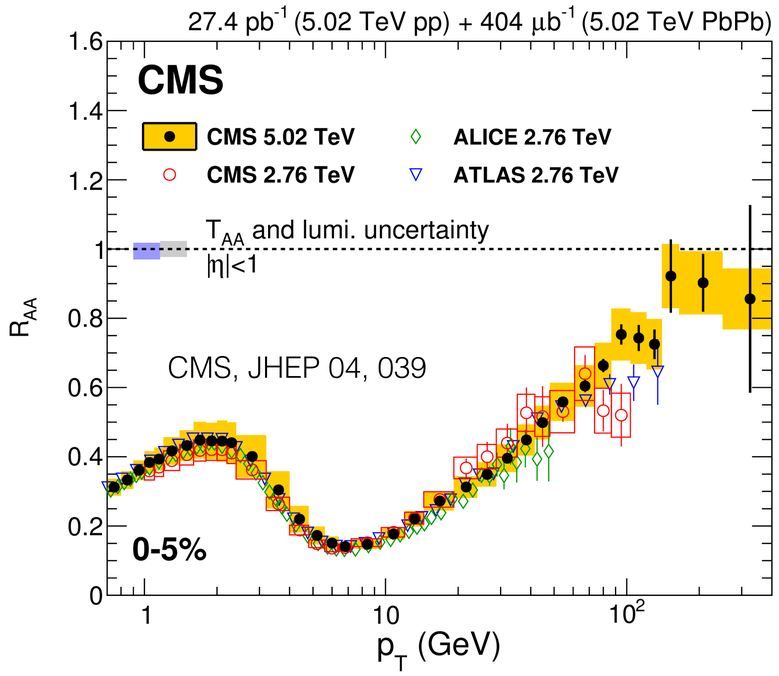

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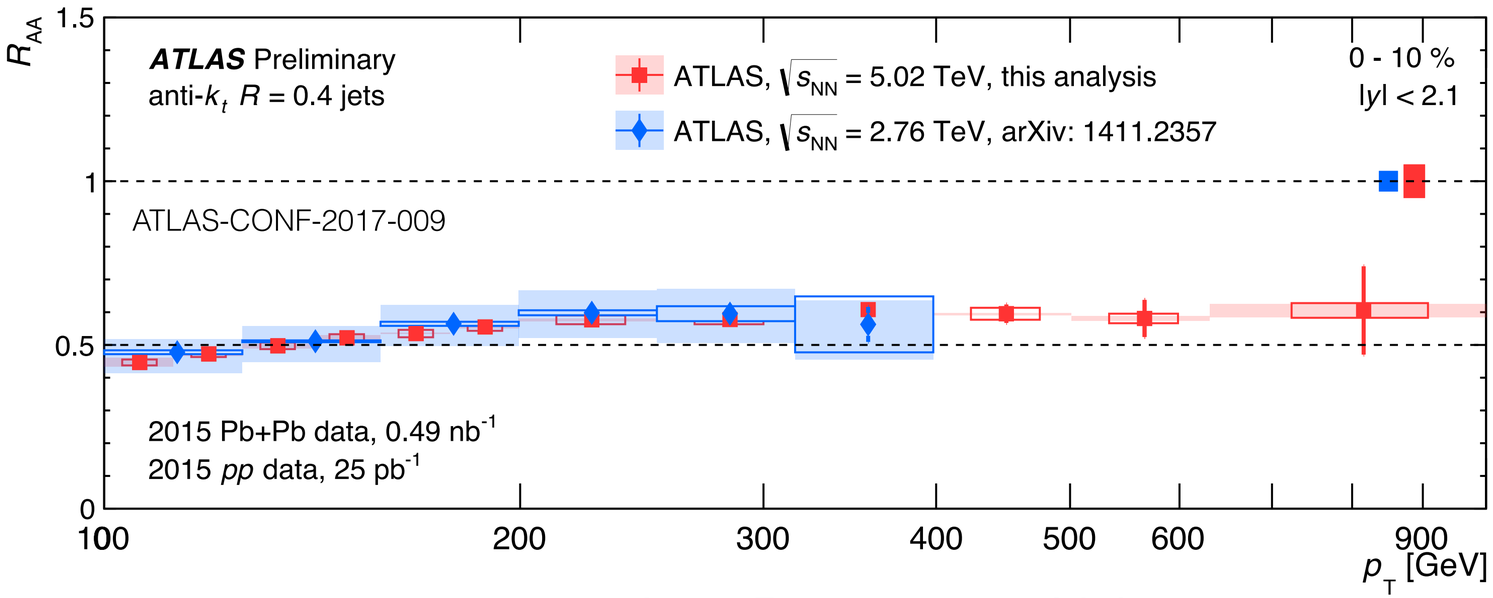

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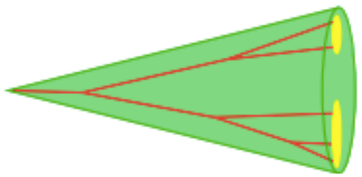
First glimpse of jets as scale-dependent probes

Opens up a field of study: p_T-dependence of jet modifications

Jet sub-structure: measuring partons

Declustering:
'peel apart' the shower

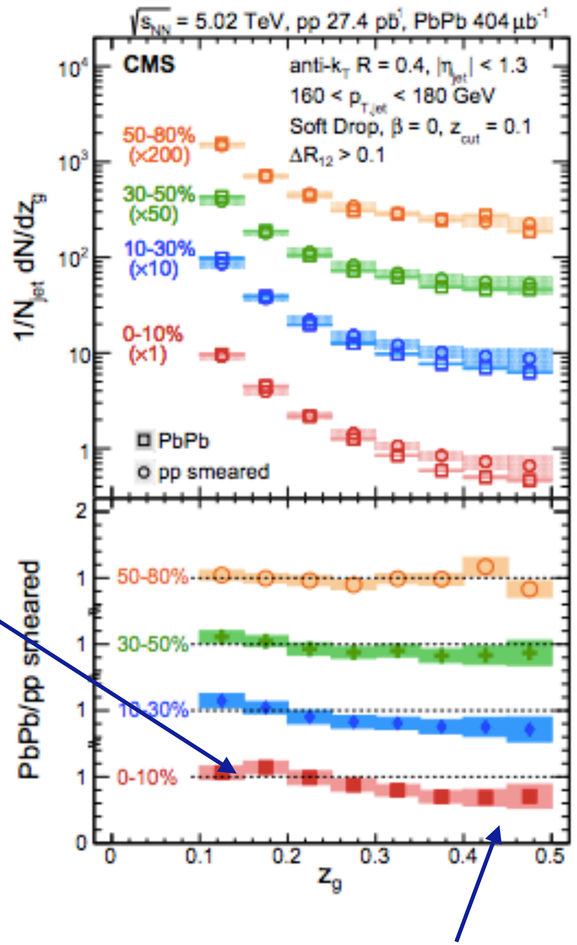


$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

Increase in asymmetric splittings

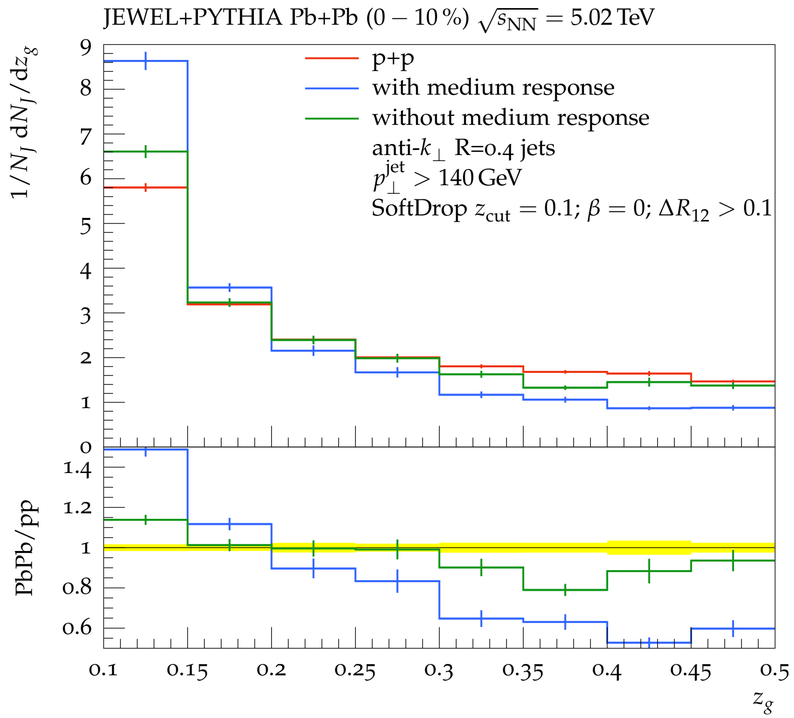
Normalisation: probability distribution per jet that passes the cut

CMS, PRL 120 (2018) 142302



Reduction in (rare) symmetric splittings

Zapp and Milhano, PLB 779 (2018) 409



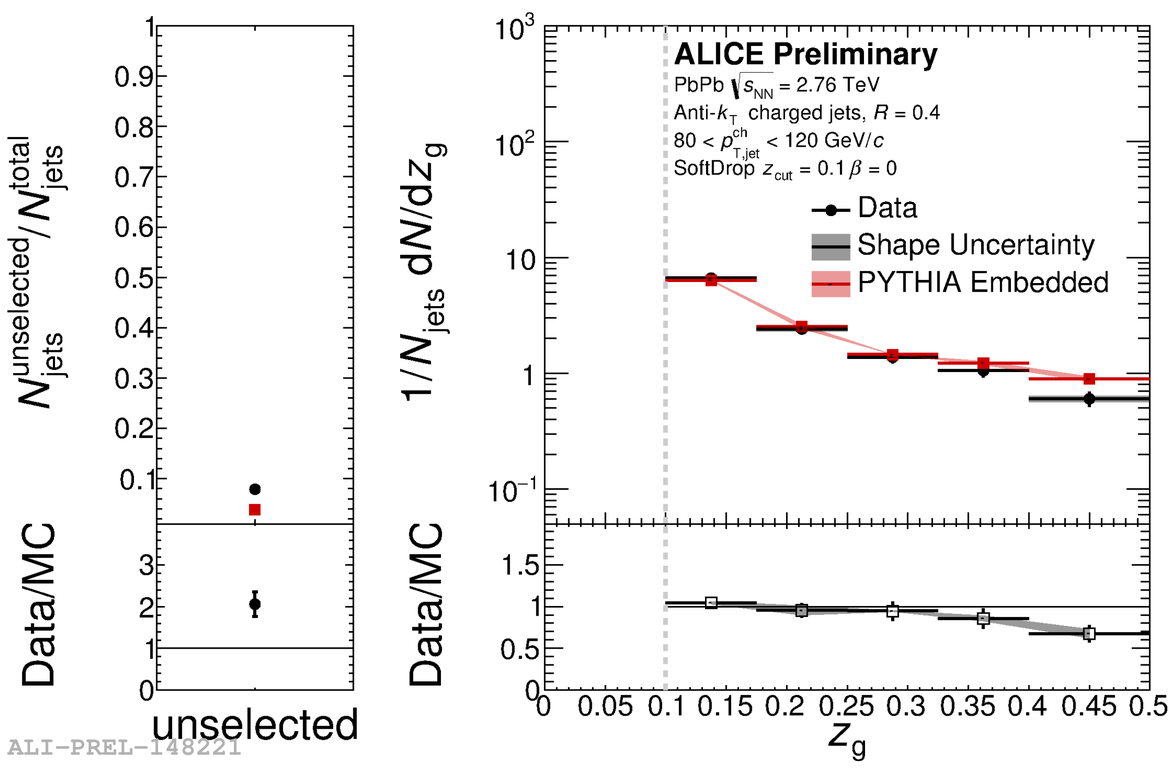
What drives the change?

Without recoil: **energy loss** suppress symmetric splittings

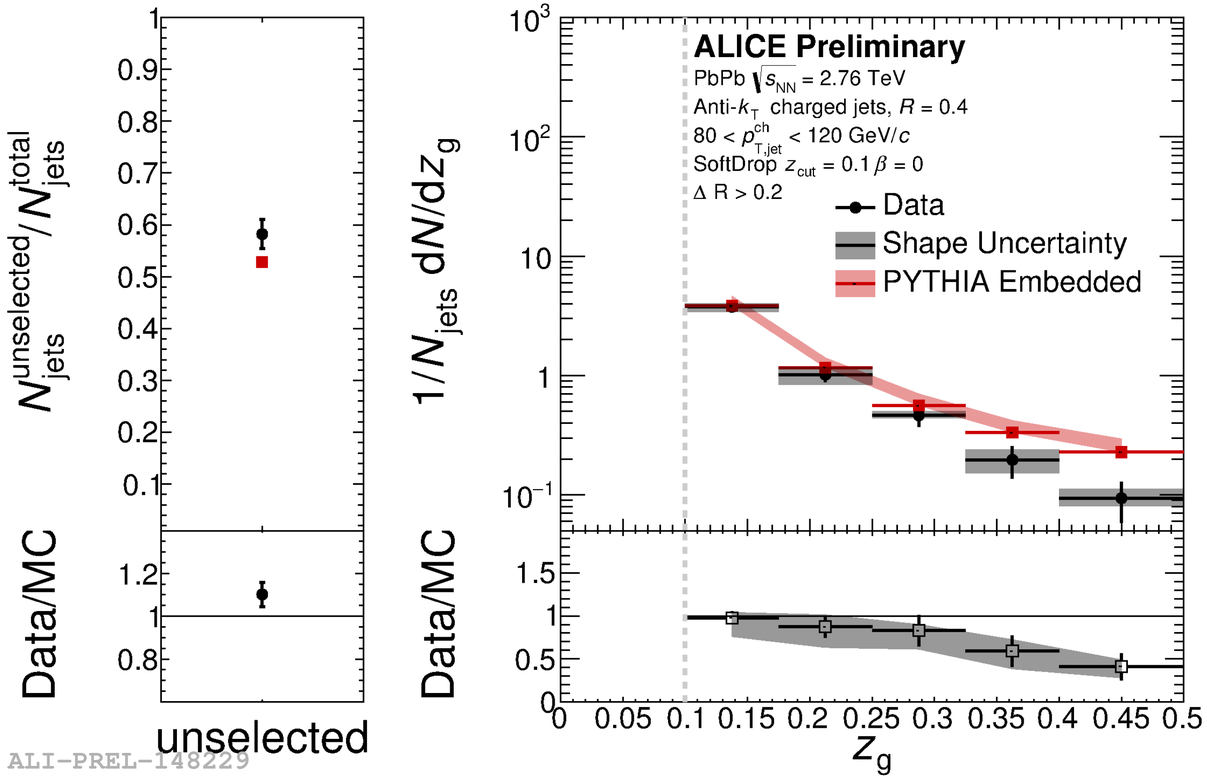
With recoil: **soft fragments/medium** enhancement at small z

Jet sub-structure: measuring partons

z_g, all angles



z_g, $\Delta R > 0.2$



- Suppression at large z (symmetric splittings)
- increase of unselected jets ($z_g < 0.1$; or $\Delta R < 0.2$ for right panel)

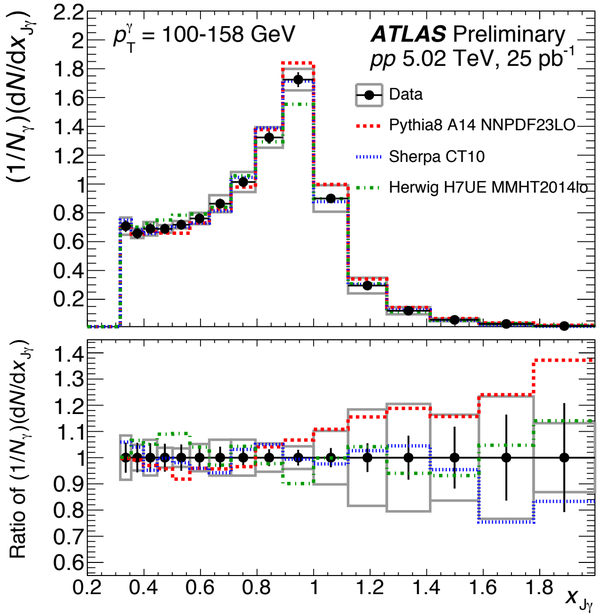
Effect increases with ΔR

Consistent with independent energy loss of large angle splittings

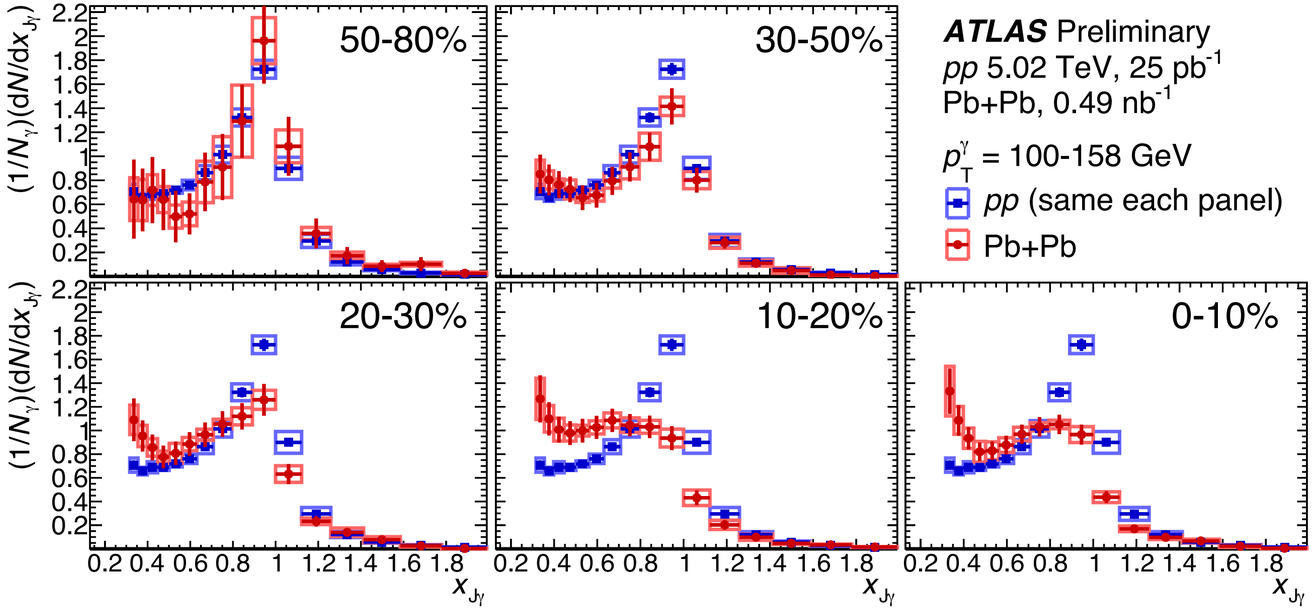
Direct photons: ‘fixing’ the jet energy and color charge

ATLAS-CONF-2018-009

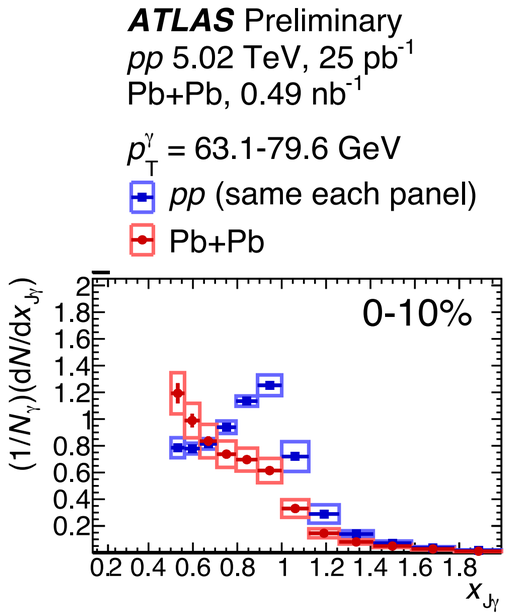
γ-jet momentum balance pp



Centrality dependence; $p_{T\gamma}$ = 100-158 GeV



$p_{T\gamma}$ = 63.1–79.6 GeV



Even in pp balance not perfect
Described well by
Pythia, Herwig, and NLO

Clear increase in asymmetry: energy loss
NB: some recoil jets may fall below the cut

Shape depends on $p_{T,\gamma}$
low p_T more asymmetric

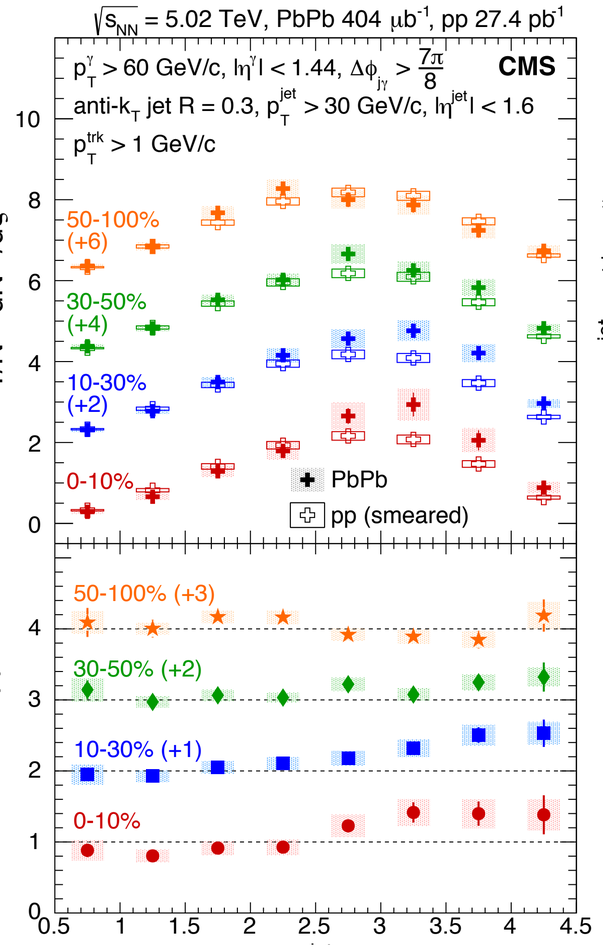
See also: CMS, HIN-16-002

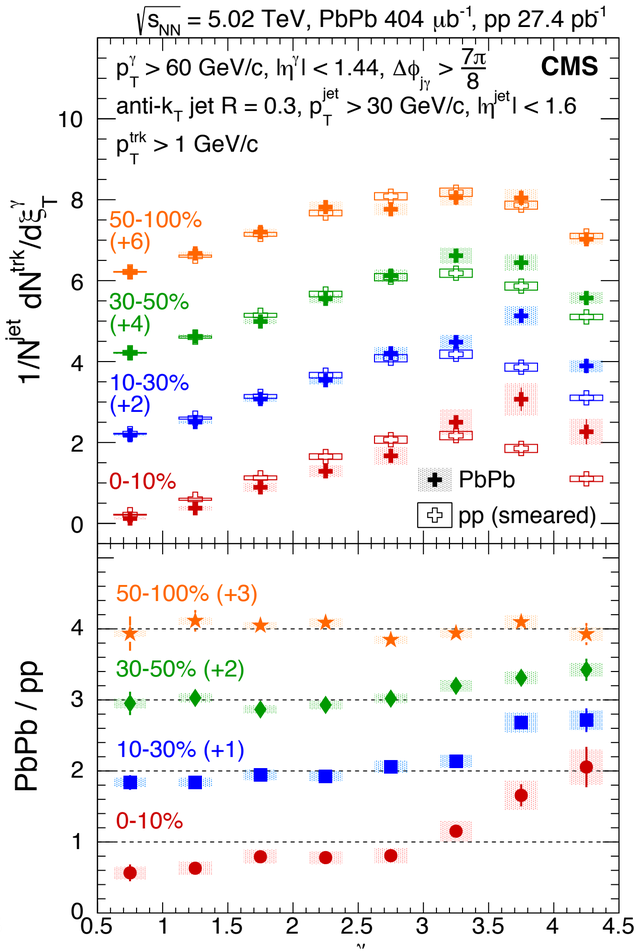
ATLAS-CONF-2017-074

CMS, arXiv:1801.04895

Recoil fragment distributions

Recoil fragment distributions $p_{T,\gamma}$ >60 GeV

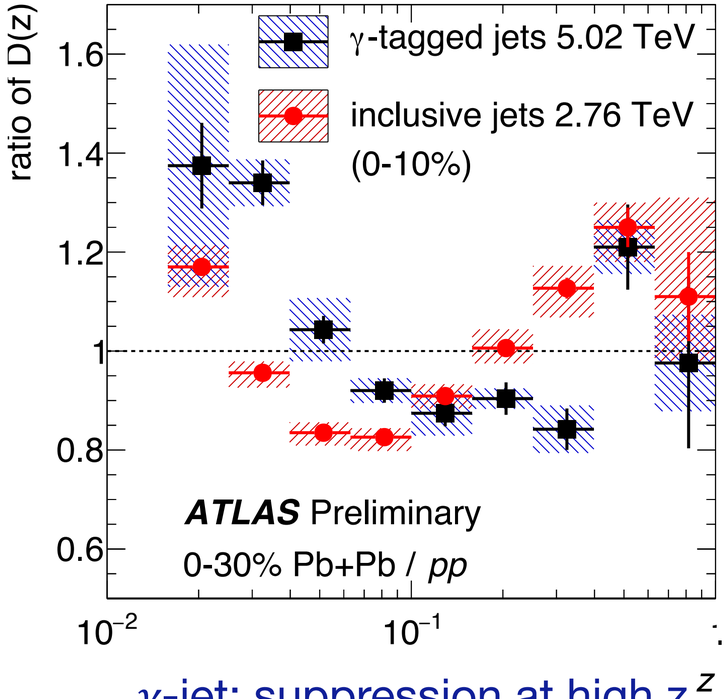




$$\xi_{jet} = \ln\left(p_{T,jet}/p_{T,h}\right) \qquad \xi_\gamma = \ln\left(p_{T,\gamma}/p_{T,h}\right)$$

Enhancement of soft fragments; reduction of hard fragments

Recoil fragment distributions: γ-jet and di-jet

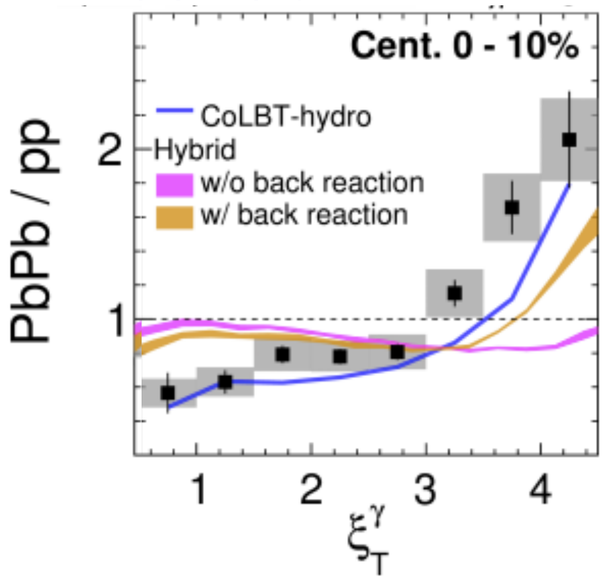


γ-jet: suppression at high z
di-jet: enhancement at large z

Different bias/selection
quark vs gluon jets

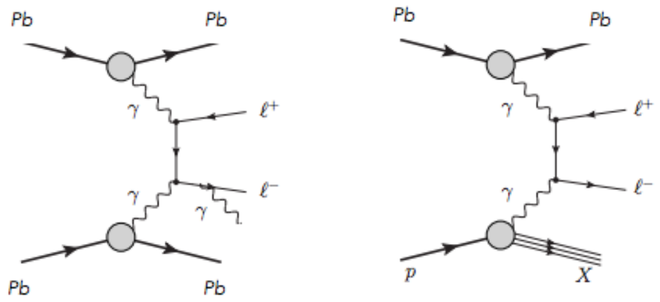
ξ=0.7 ~ z = 0.5

γ-jet, $p_{T\gamma}$ > 60 GeV

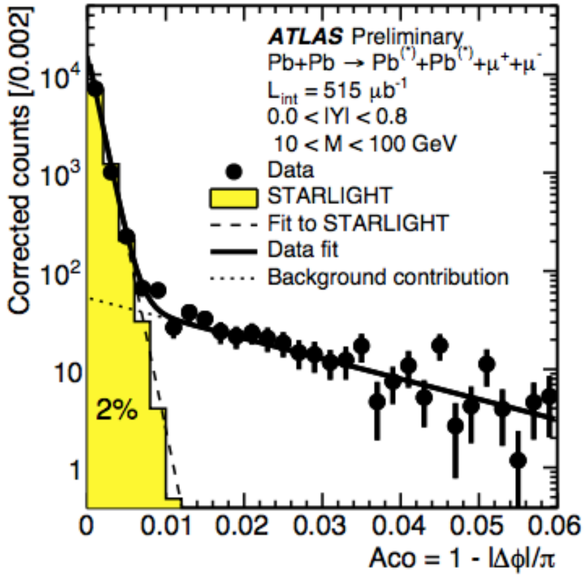


Models capture trends
Need mechanism
for soft fragments

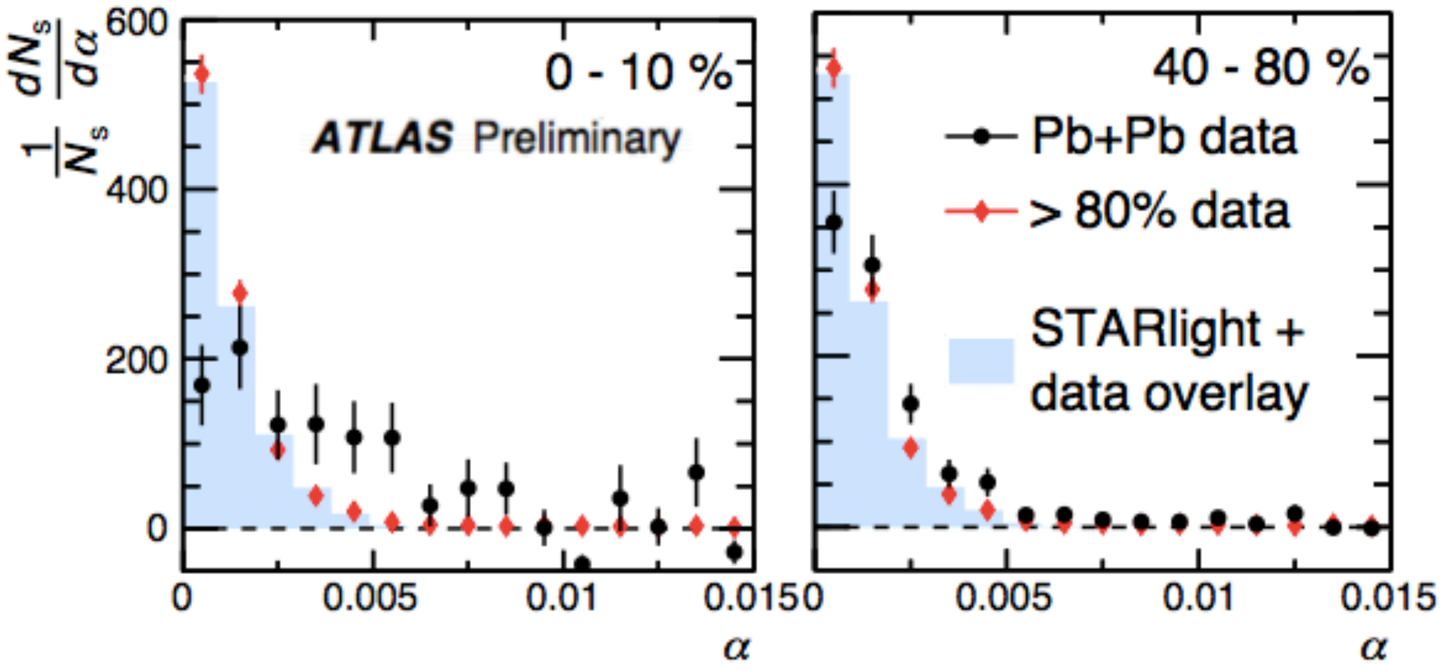
Electromagnetic hard probes: muon pairs



UPC process:
gg -> m m

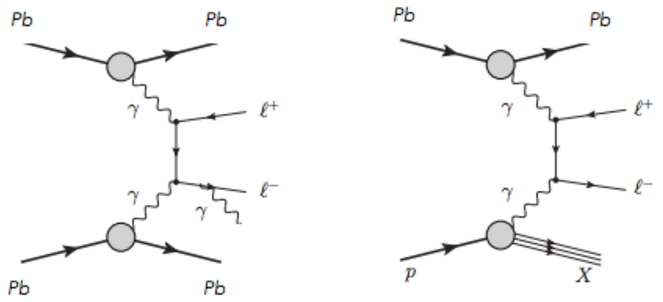


$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

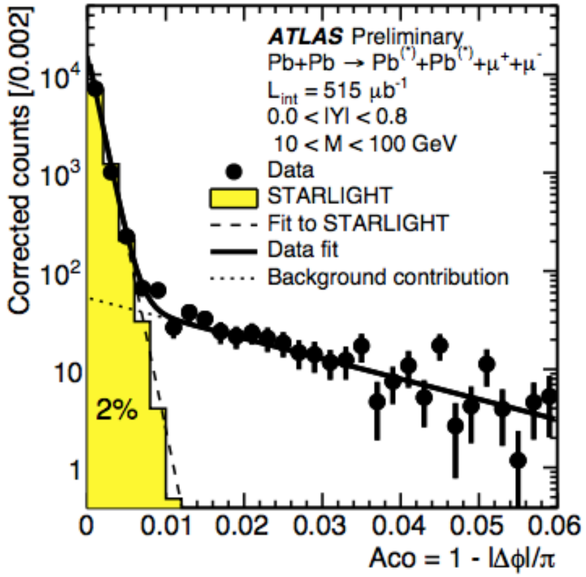


Heavy flavour background subtracted with DCA, momentum balance

Electromagnetic hard probes: muon pairs

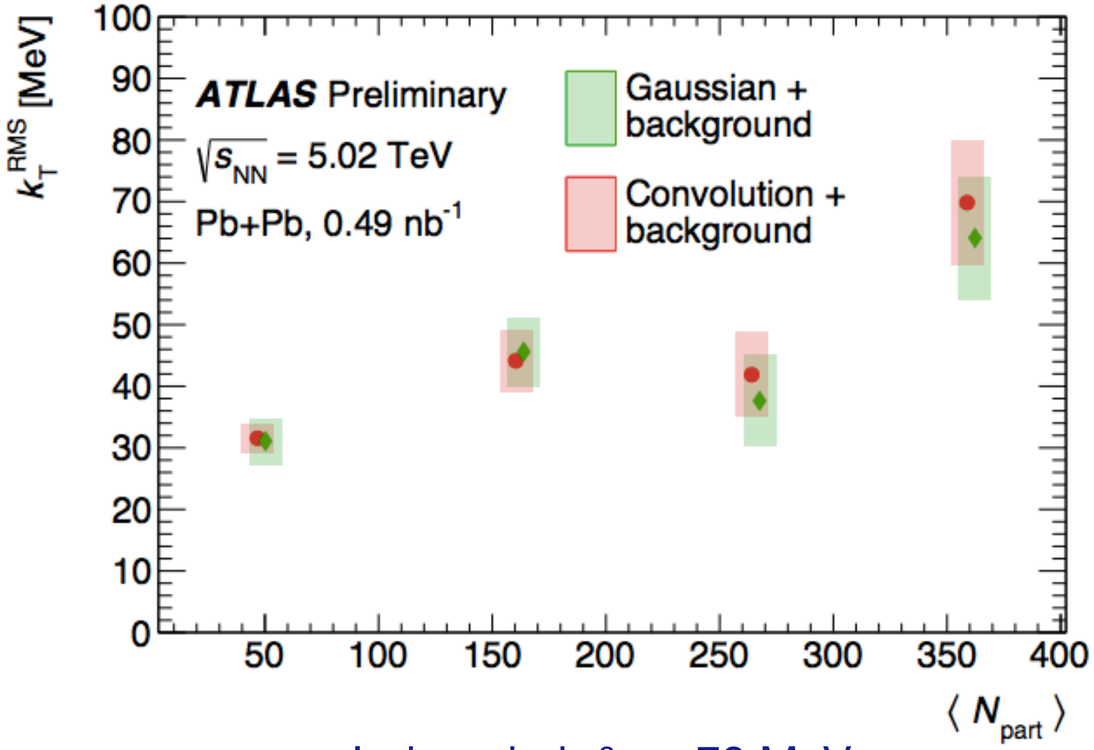


UPC process:
gg -> m m



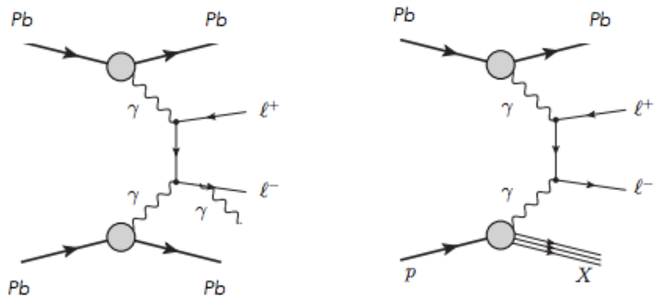
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

Acoplanarity

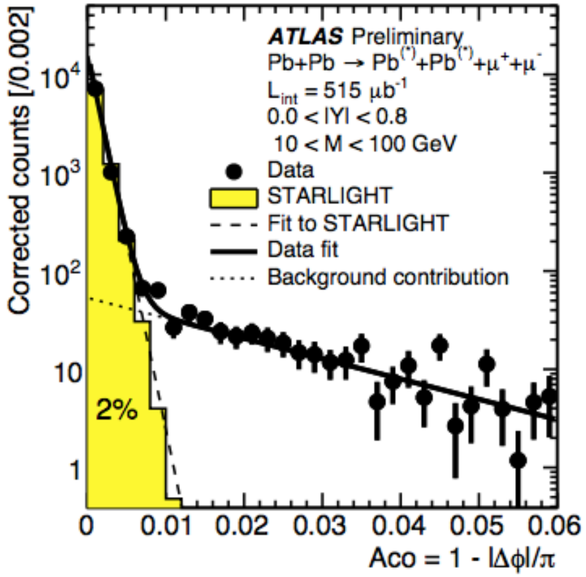


Induced $\langle k_T^2 \rangle \approx 70$ MeV

Electromagnetic hard probes: muon pairs

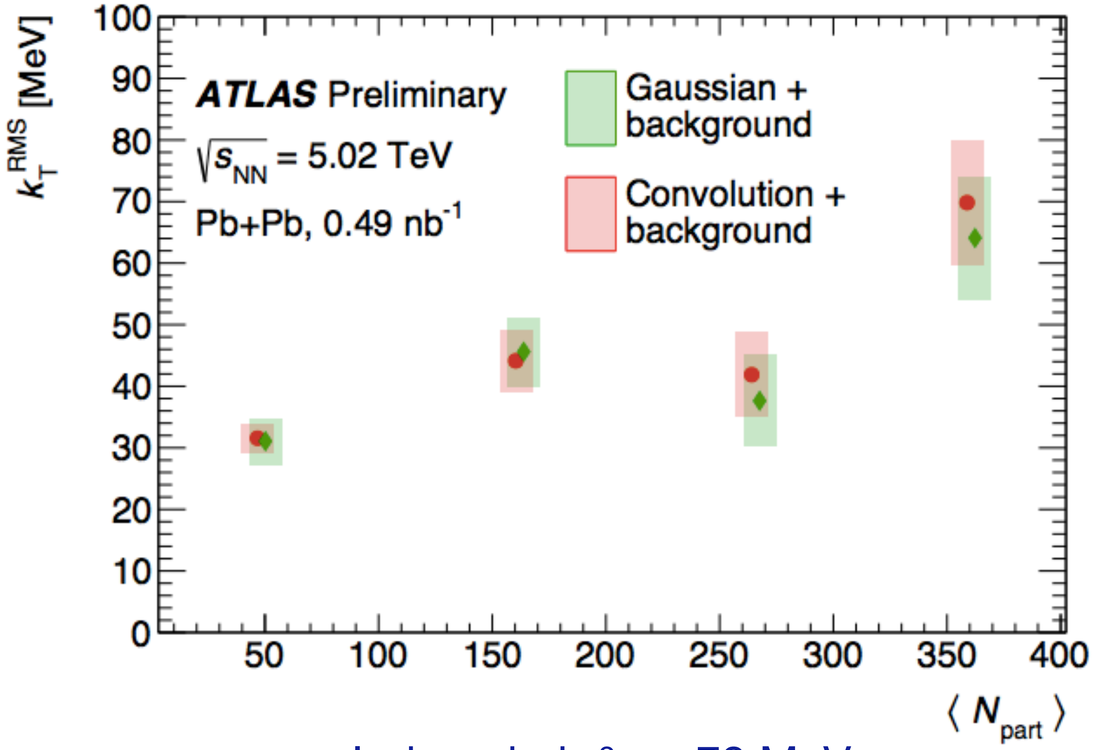


UPC process:
gg -> m m



$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

Acoplanarity



Induced $\langle k_T^2 \rangle \approx 70$ MeV

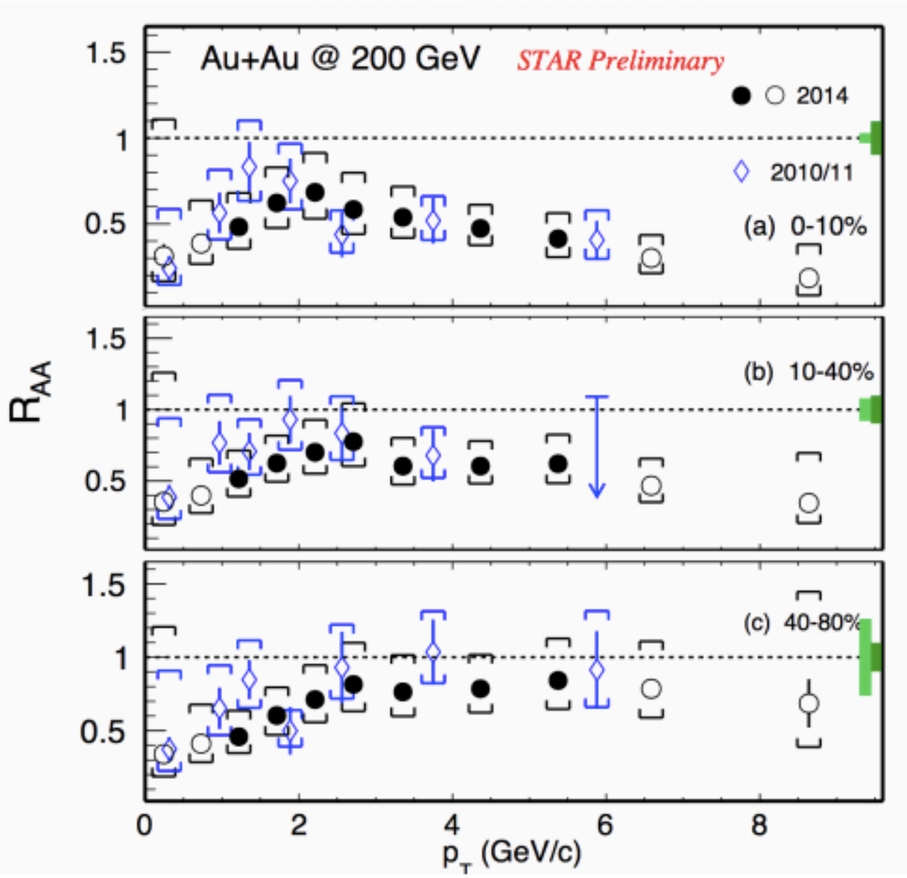
Is this EM tomography of the QGP?

Small effect, but measurable with di-muons

Heavy Flavor

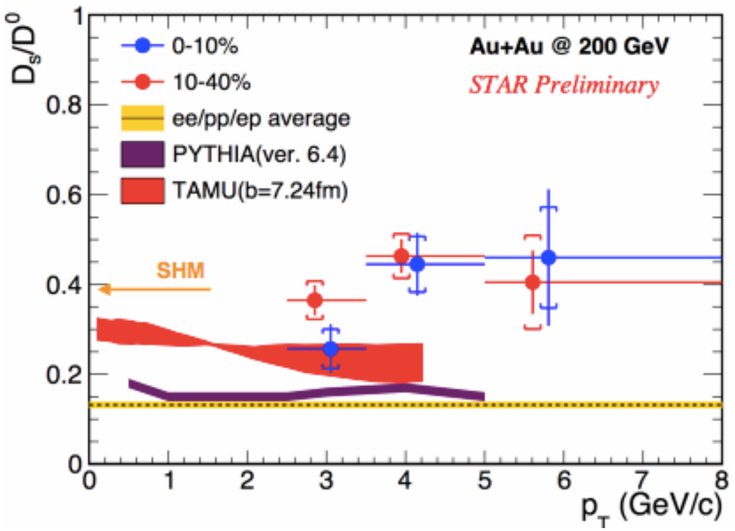
Open charm at RHIC energies

New D meson RAA

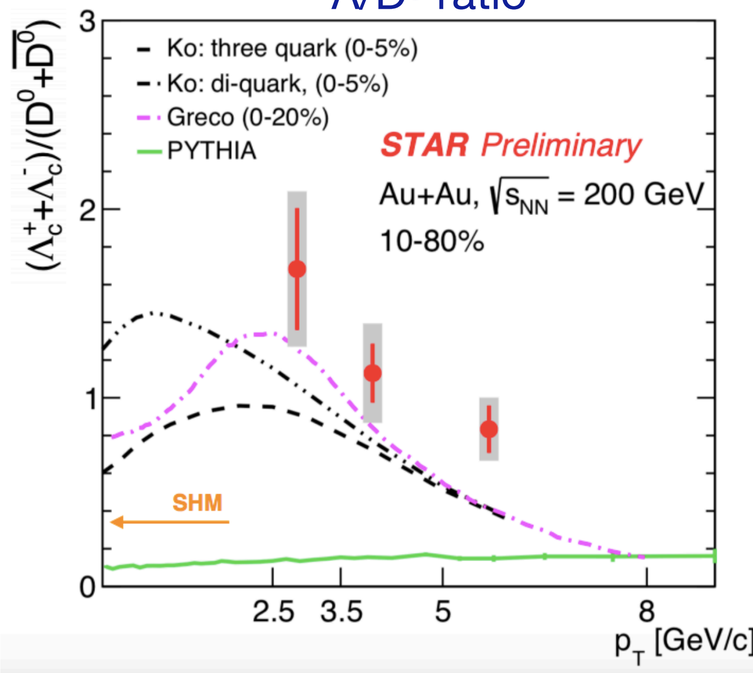


Updated results: $R_{AA} < 1$ at all p_T

D_s/D^0 ratio



Λ/D^0 ratio



Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

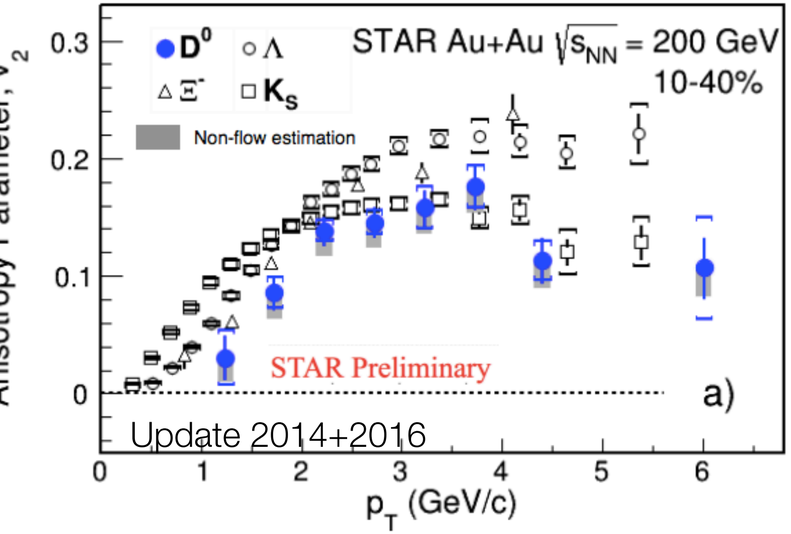
D_s and Λ_c production larger than pp

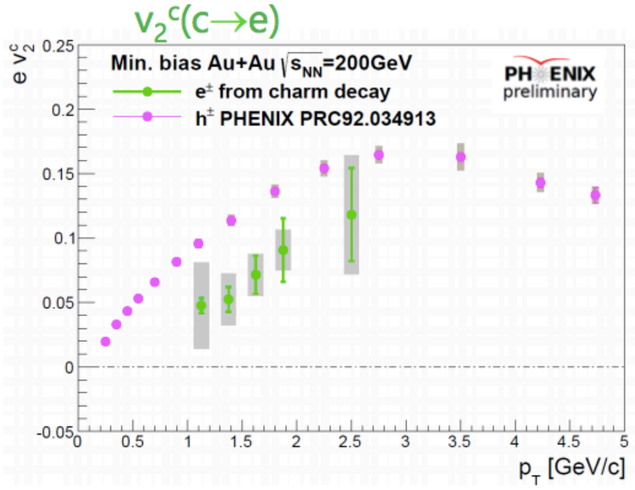
Charm redistributed over hadronic channels?

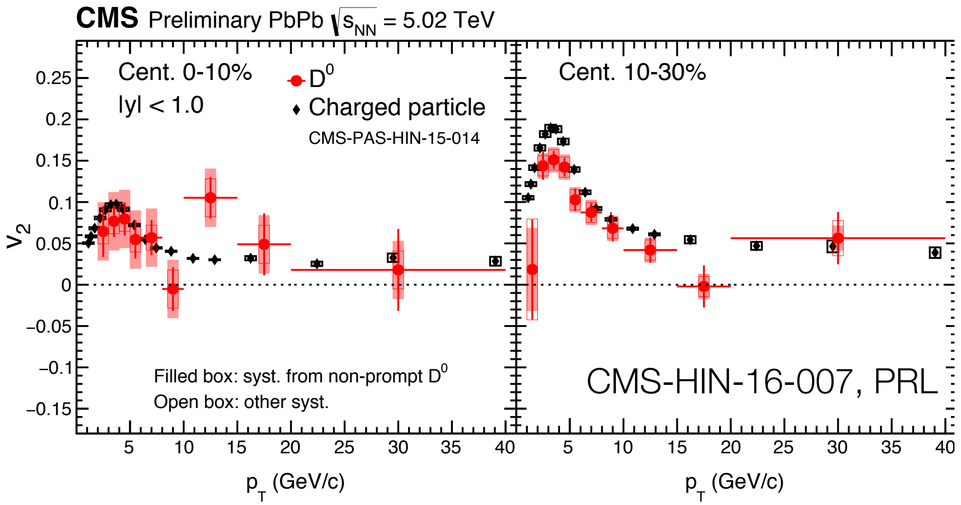
Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

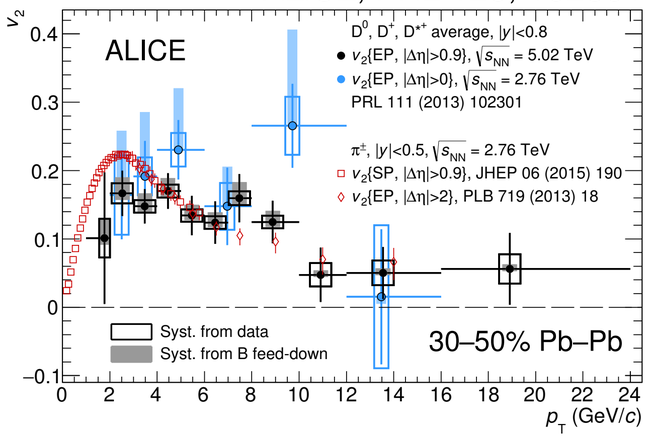
Heavy flavor flow







ALICE, PRL 120, 102301



Heavy flavor participates in the collective dynamics
at RHIC and LHC energies
Flow strength similar to light hadrons

Heavy flavor modeling

Overview: P Gossiaux

Challenge for theory: understand modelling landscape; what features are essential?
What further experimental input can be generated?

Model strategies

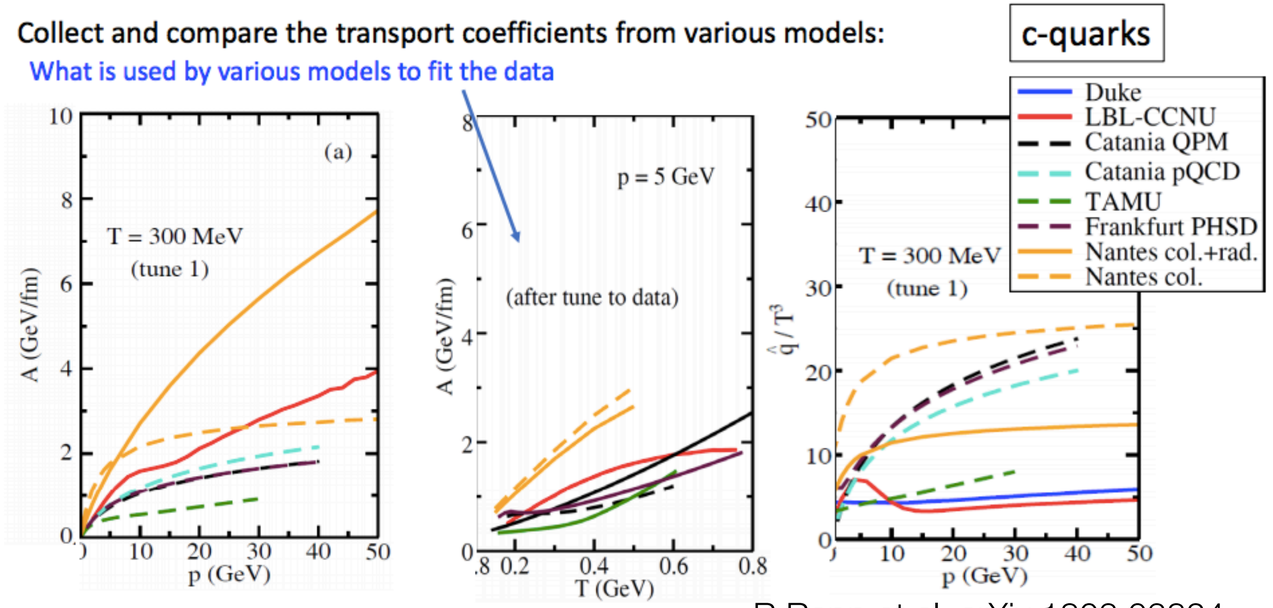
	elastic	Elastic + radiative	radiative	Other
Transport coeff based (LV,...)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG lQCD *DABMOD (poster R. Katz)* *S. Li et al, arXiv:1803.01508*
Cross section (or $\|M\|^2$) based (Boltzmann,...)	AMPT MC@sHQ el URQMD PHSD Catania BM	Djordjevic et al MC@sHQ el + rad BAMPS CUJET3 Abir and Mustafa LBL-CCNU VNI/BMS *LIDO (DUKE; poster W. Ke)*	$SCET_{G,M}$	

Red: Transport models

Benchmarking the theories 'apples-to-apples'

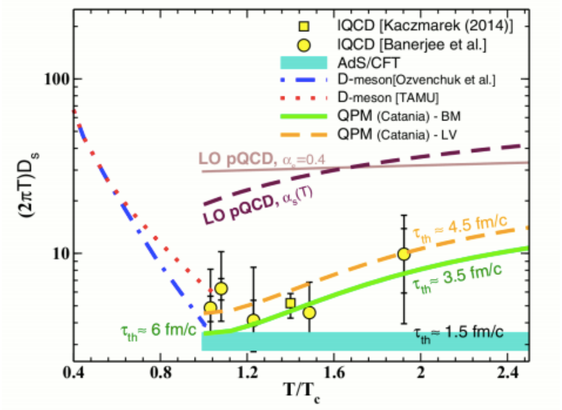
- Collect and compare the transport coefficients from various models:

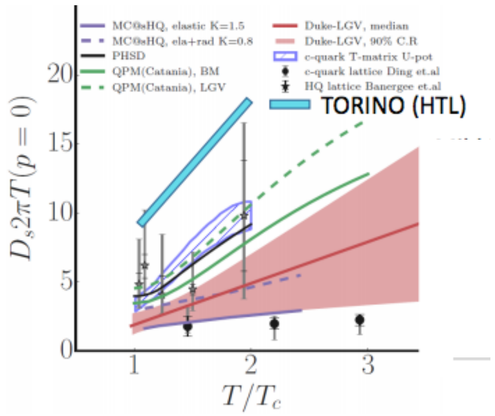
What is used by various models to fit the data



R Rapp et al, arXiv:1803.03824

End game: determine $D_s(T)$

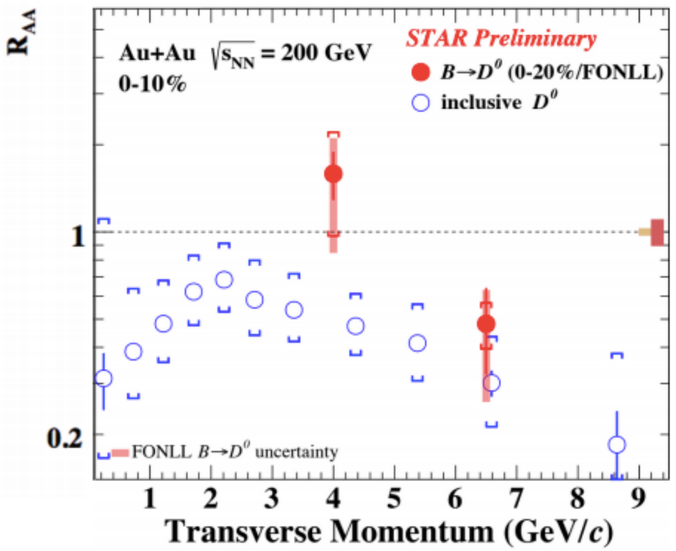


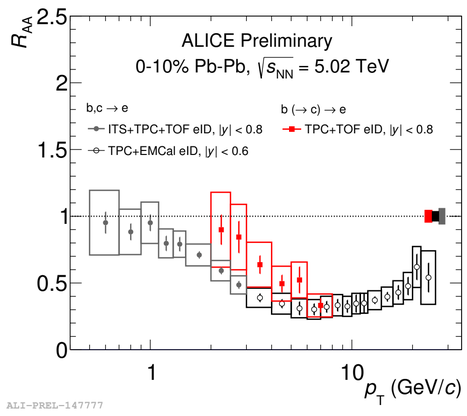


… and compare to related quantities

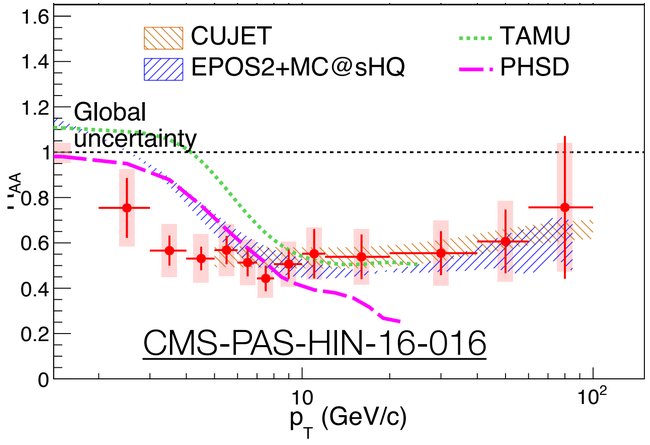
Heavier flavor: B mesons

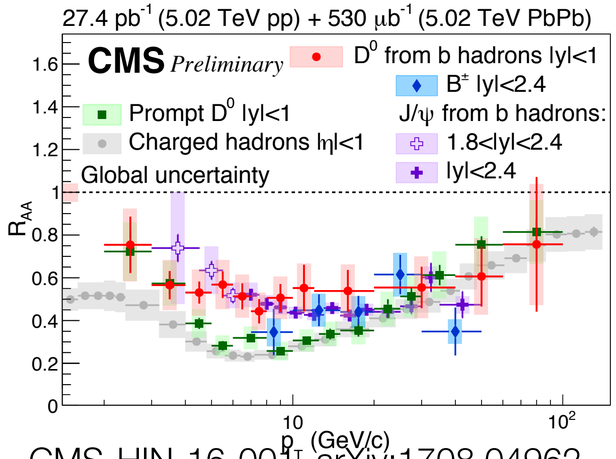
STAR: D^0 from B mesons





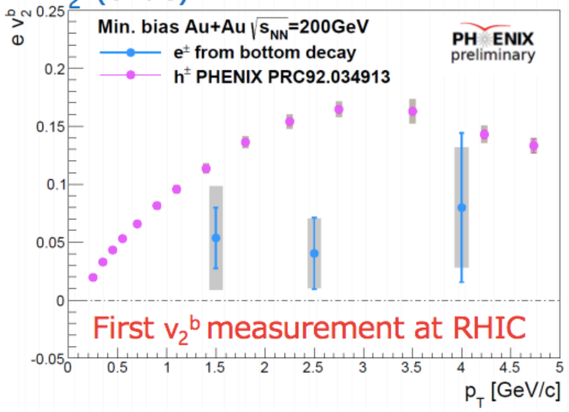
CMS: D^0 from B mesons





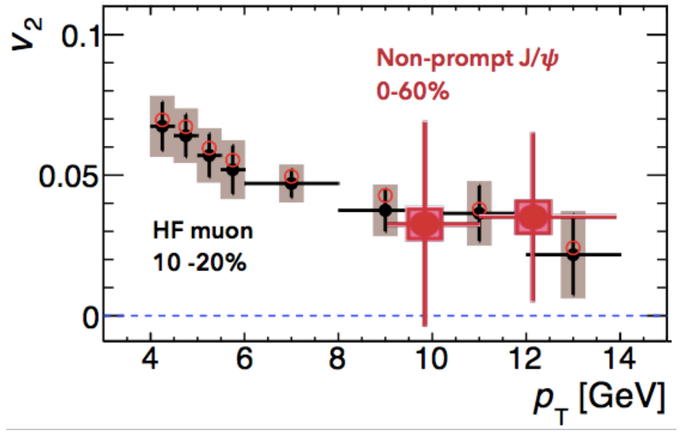
CMS-HIN-16-001, arXiv:1708.04962

$v_2^b(b \to e)$



First v_2^b measurement at RHIC

ATLAS-CONF-2018-013



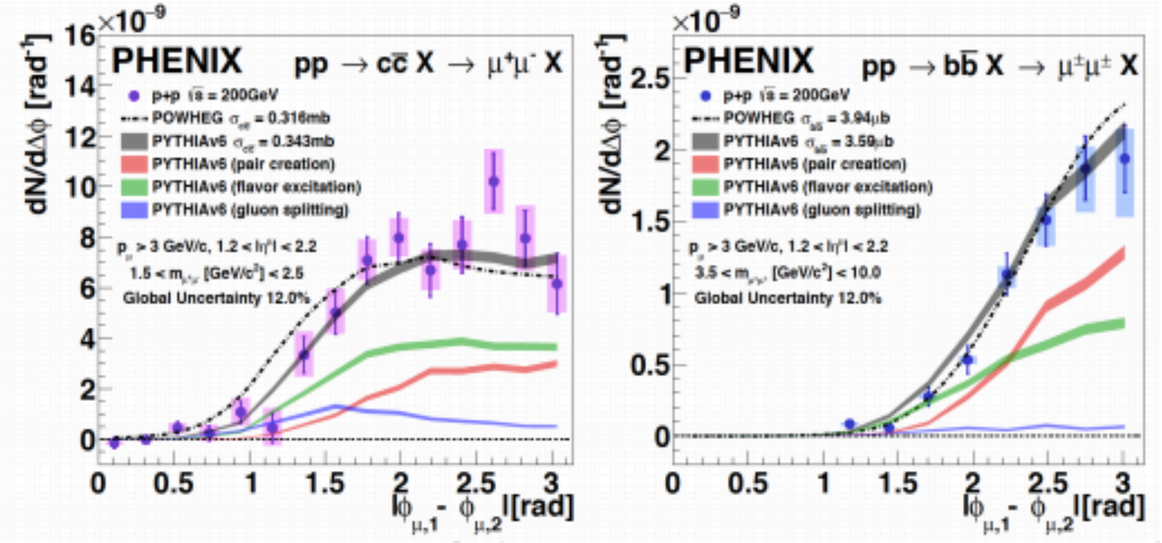
Beauty production and flow being explored

Qualitatively consistent with expectations:
B less suppressioned than D

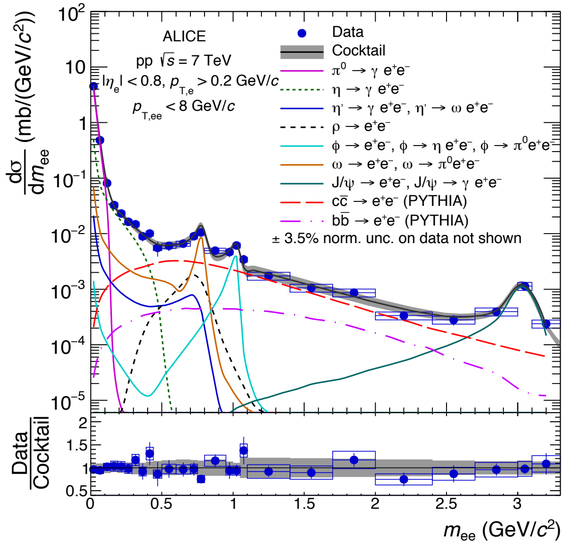
Further test of heavy flavor transport

HF production dynamics: direct pairs vs gluon jets

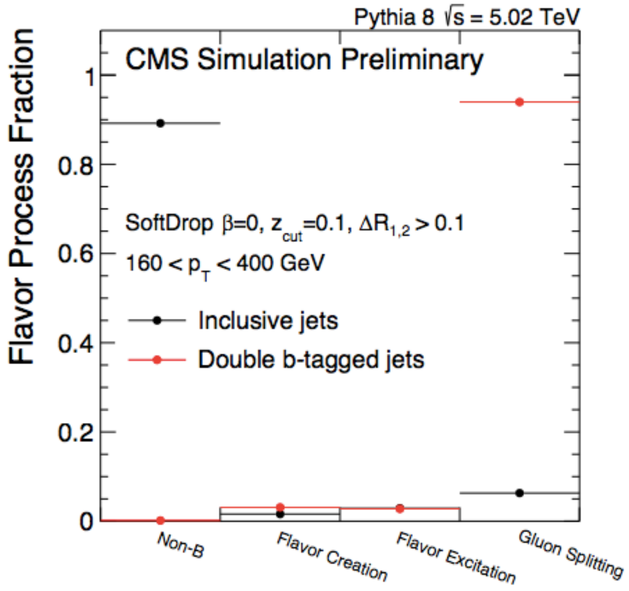
PHENIX: arXiv:1805.04075, arXiv:1805.02448



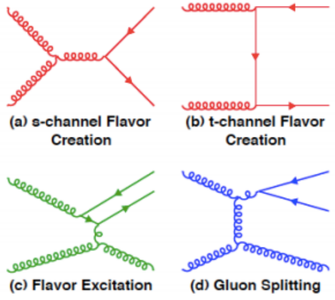
Use di-muon angle distributions to differentiate
pair creation: back-to-back pairs
gluon splitting: near side pairs



electron-positron mass distribution depends on angular distributions



Future direction:
single vs double b-tag jets

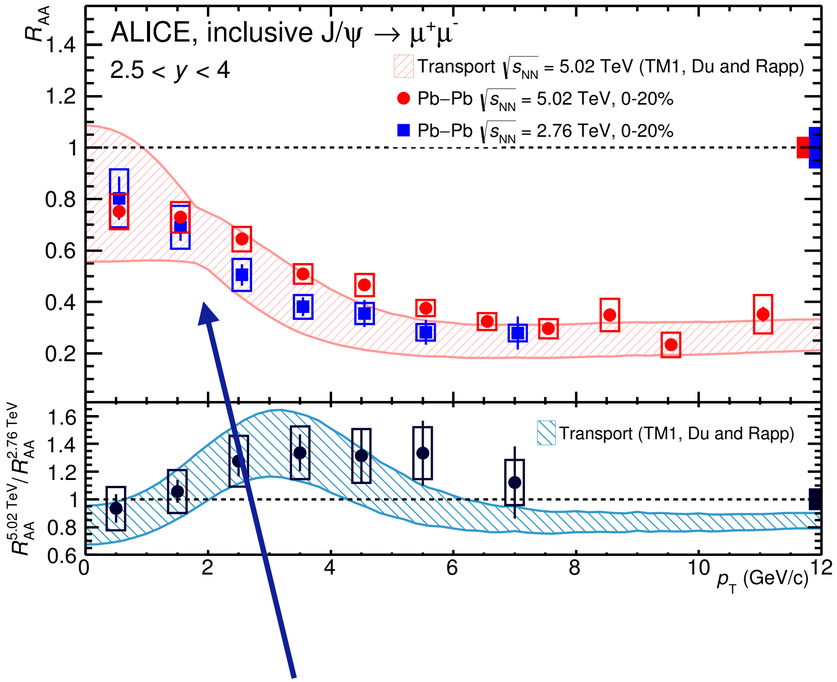


+several new results on D mesons in jets from ALICE+CMS

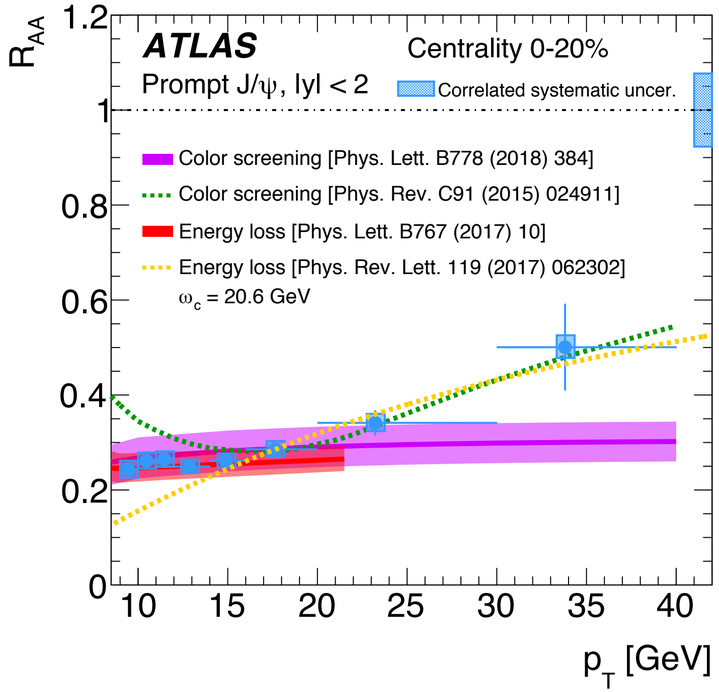
Exciting prospects: use heavy flavors to tag shower prongs and follow energy loss
Multi-parton energy loss

J/ψ at high p_T

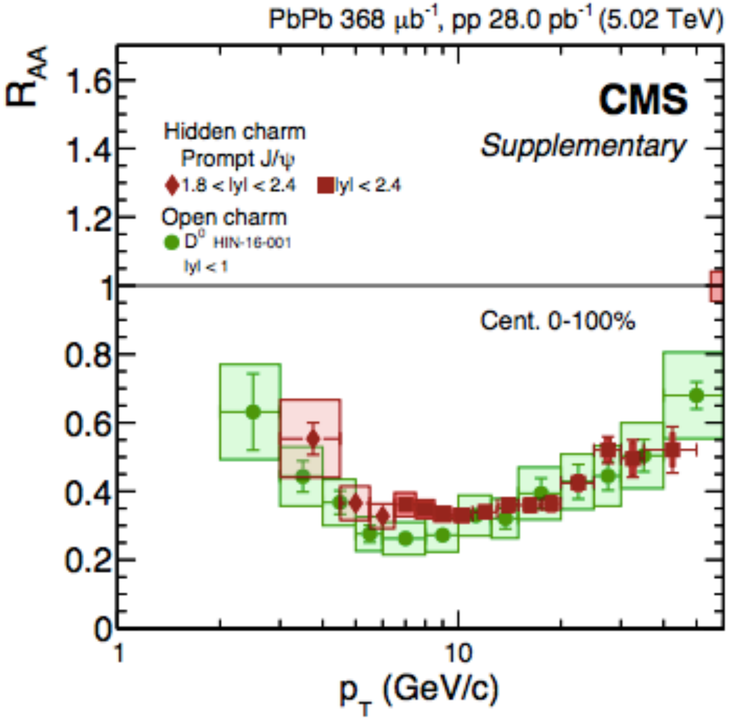
ALICE, PLB 766, 212



ATLAS, arXiv:1805.04077



Open charm and prompt J/ψ



Low p_T: coalescence/recombination important

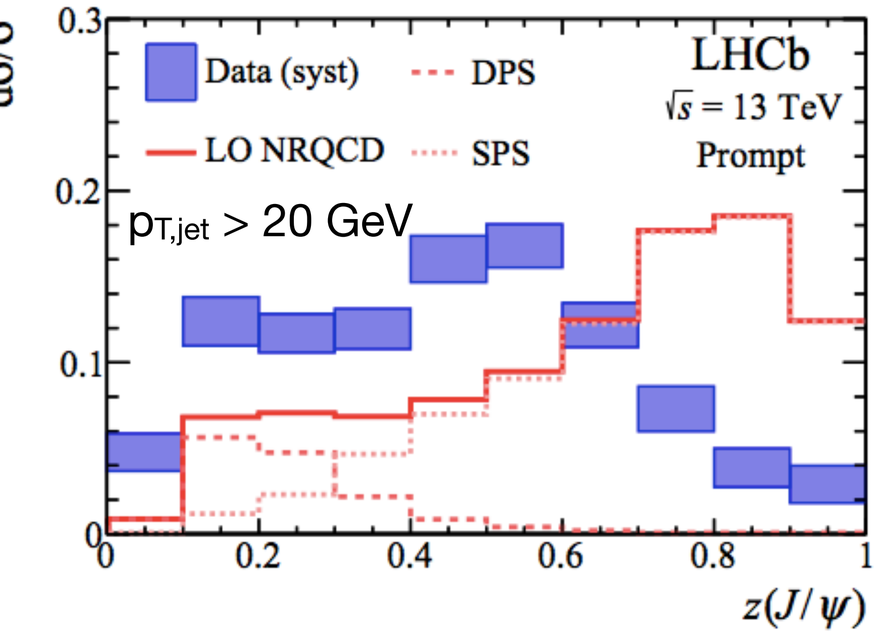
High p_T: open and hidden charm R_{AA} similar

J/ψ suppression at high p_T driven by parton energy loss?

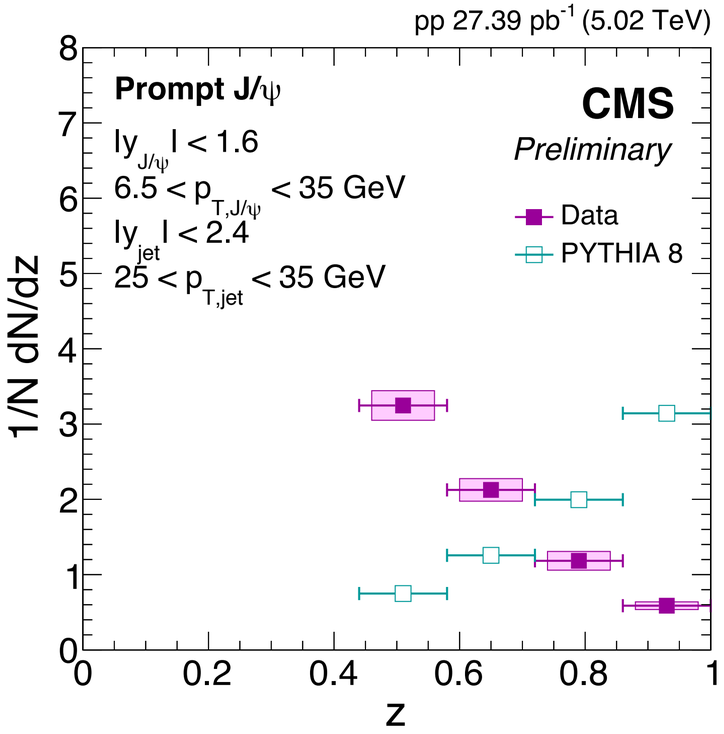
Talk: I Vitev

Production mechanism: J/ψ in jets

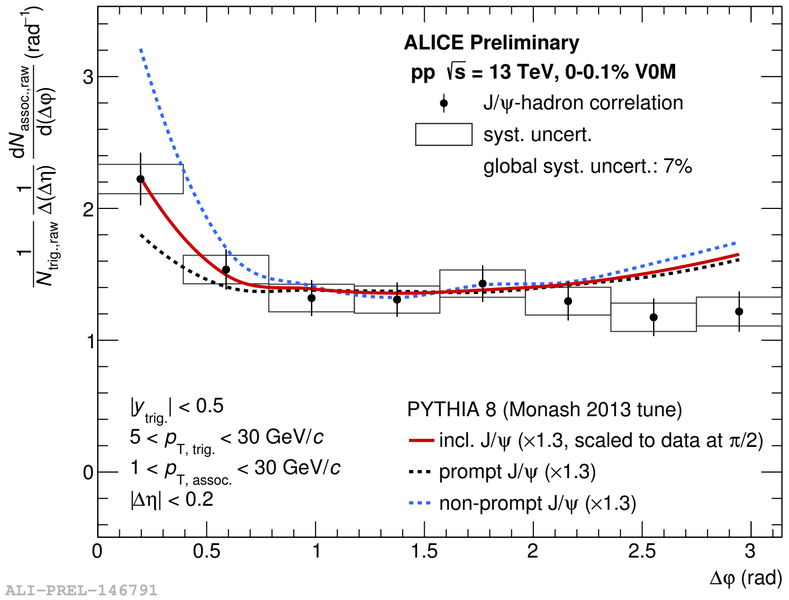
LHCb, PRL 118, 192001 (2017)



CMS-PAS-HIN-18-012



J/ψ-hadron correlations



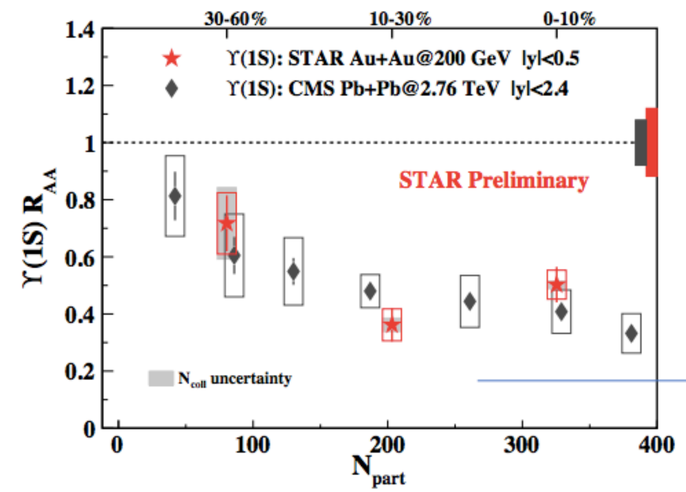
Near-side peak:
hadrons accompany the J/ψ

Initial expectation: color-singlet J/ψ could be produced without accompanying fragments
New insight: high-p_T J/ψ produced in jets

Overviews: R Ma and E Ferreiro

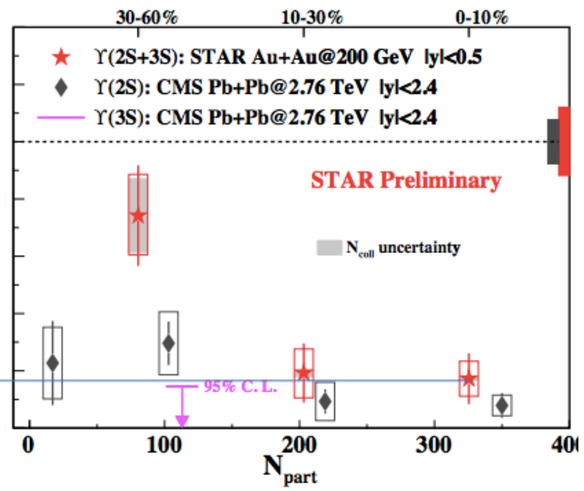
Bottomonia melting

Υ(1S)



CMS PLB 04, 031 (2017)

Υ(2+3S)

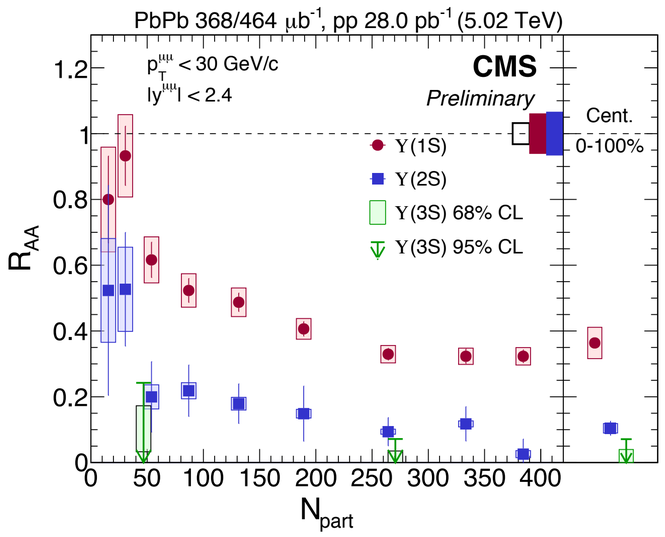


TAMU, X. Du et al PRC 96, 054901

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	500	240	190

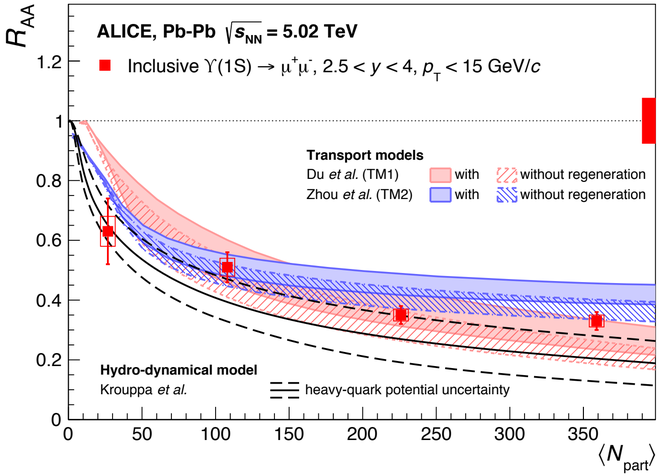
B. Krouppa, et al PRD 97, 016017

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	600	230	170



CMS-HIN-16-023

ALICE, arXiv:1805.04387

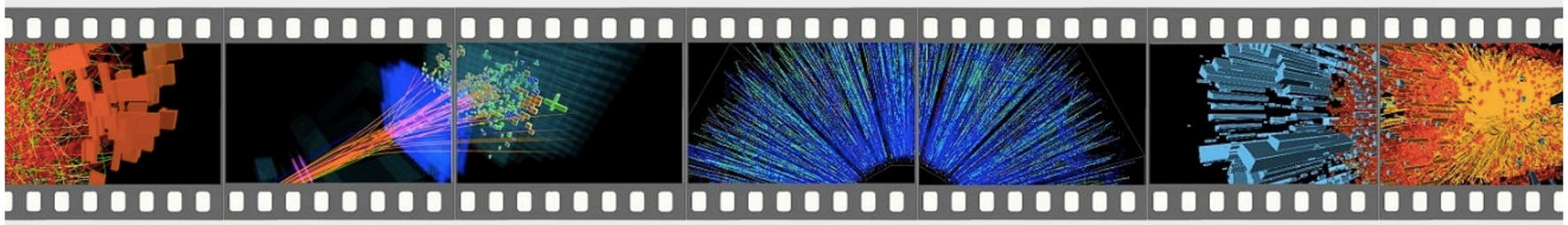


Clear hierarchy of suppression, but no sudden turn-on

- T does not change rapidly with centrality
- Average over system
- Melting sets in for $T < T_m$

A very productive conference: many new results

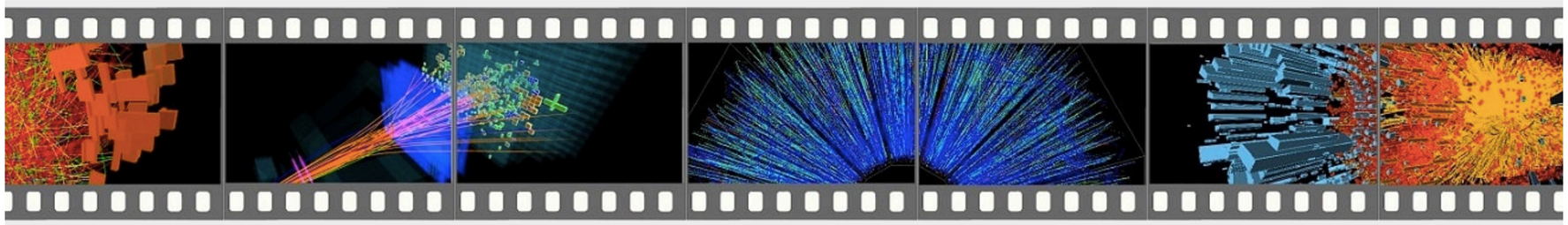
… more than fits in this talk



A very productive conference: many new results

… more than fits in this talk

Improving our understanding of the parton nature of the QGP



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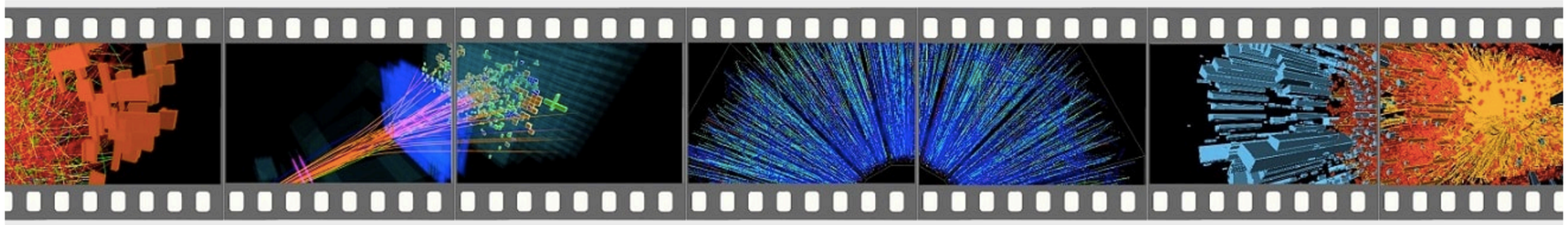
… of small systems



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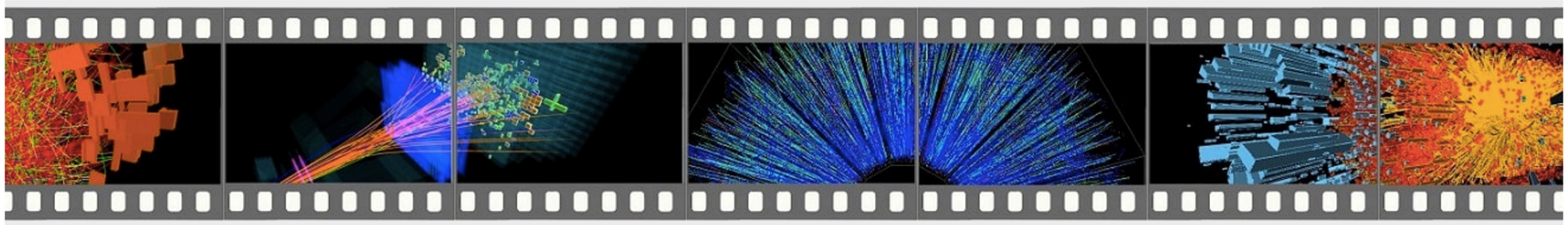
… of small systems

… and of energetic probes of the plasma



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Thank you for your attention

And to all who provided input