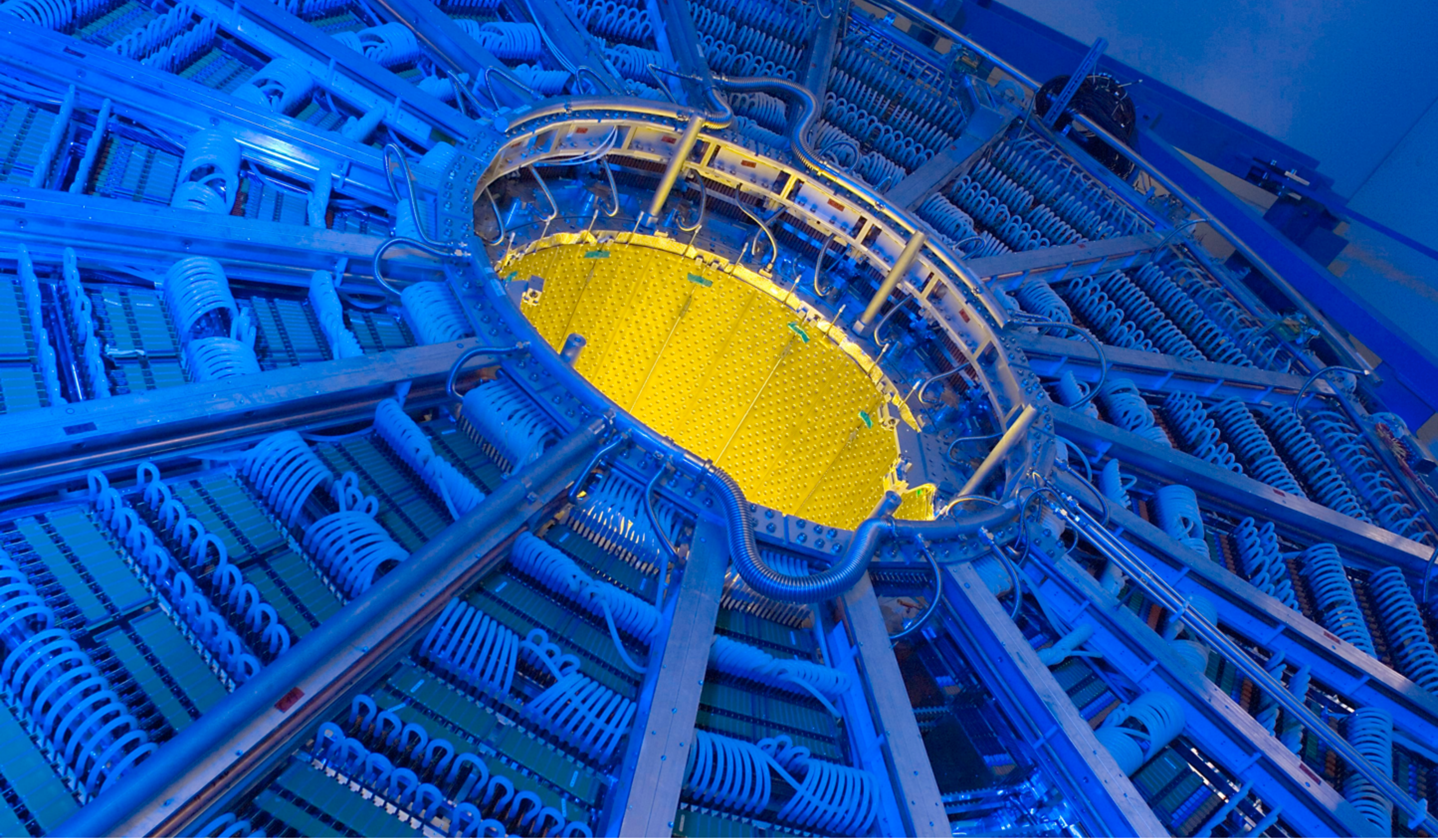


Summary

M Floris (CERN)
Collectivity in Small Systems
Copenhagen, May 2017

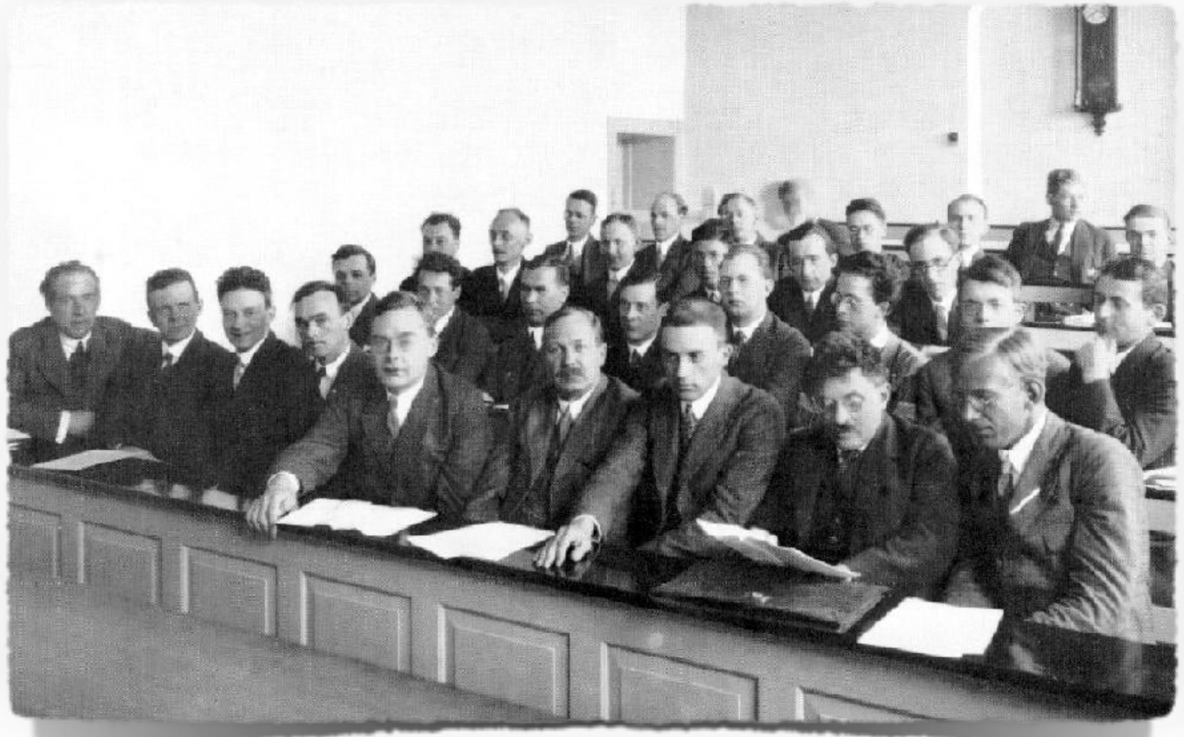
Outline

What is collectivity and why do we care?

Experimental methods and non-flow

Theory vs Data: What are we trying to learn?

Other relevant non-collectivity measurements



Thanks a lot to the NBI Colleagues and You for the hospitality!

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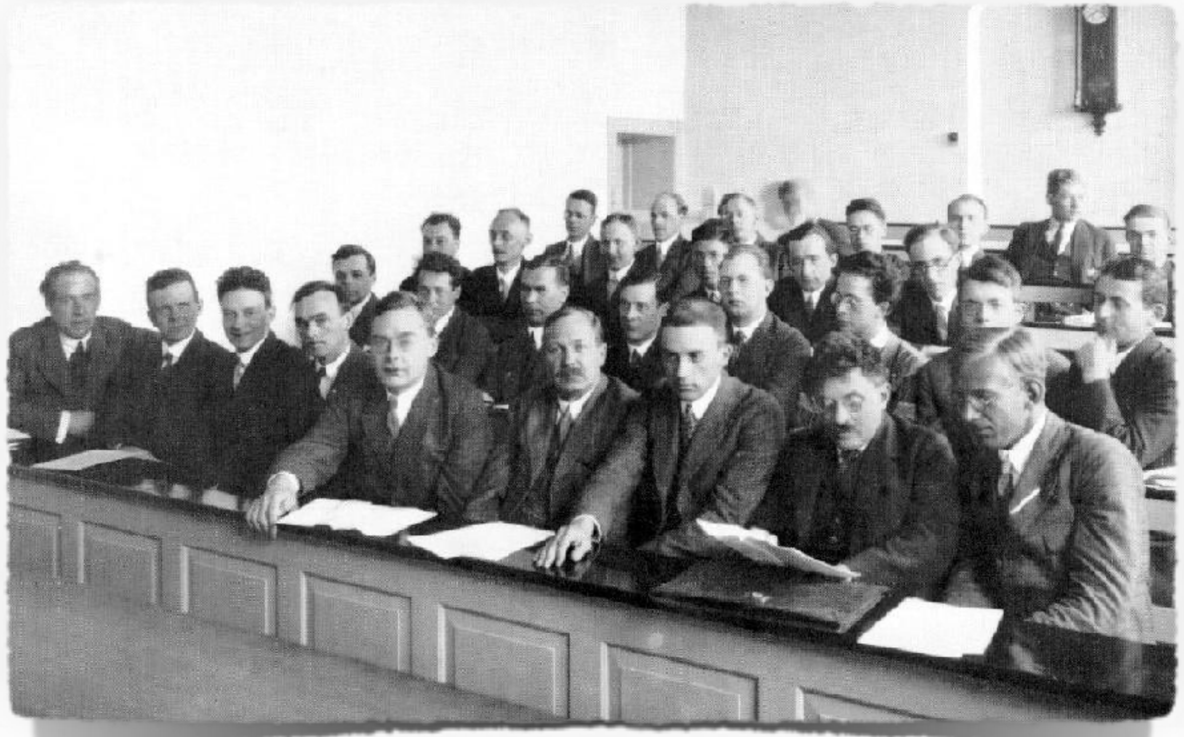
Disclaimer: will not be exhaustive, but it will also not be brief (sorry!)



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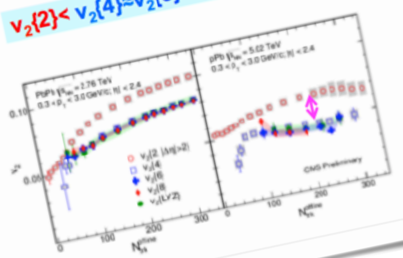
Definitions of collectivity

Collectivity

- weak (mathematical) definition:
  - ⇨ SIMILAR effect/probability for ALL particles (of some kind, say p_T/PID) in (almost) ALL events
    - drawn from the same inclusive single particle probability distribution (e.g. dN/dφ)
    - probability can be arbitrarily small ! as long as it's the same for all particles/events
  - ⇨ Collectivity is experimentally proven in AA & pA

$v_2\{2\} < v_2\{4\} \approx v_2\{6\} \approx \ldots \approx v_2\{\infty\}$



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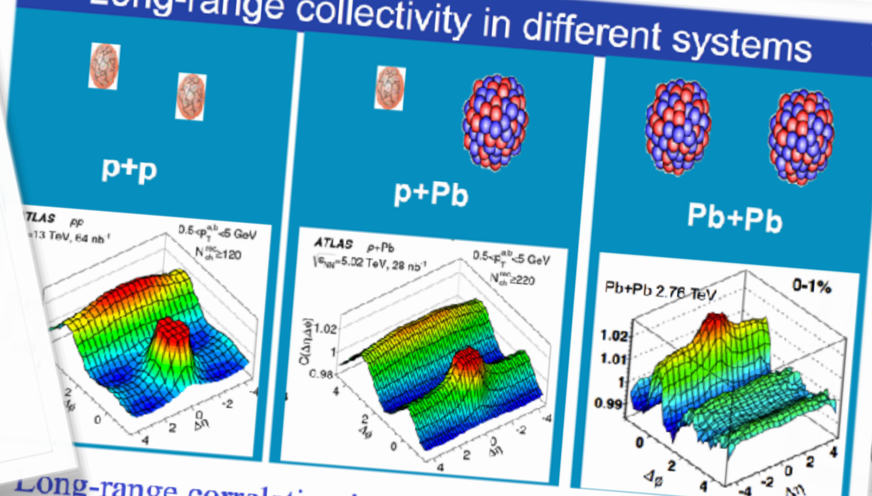
Long-range collectivity in different systems

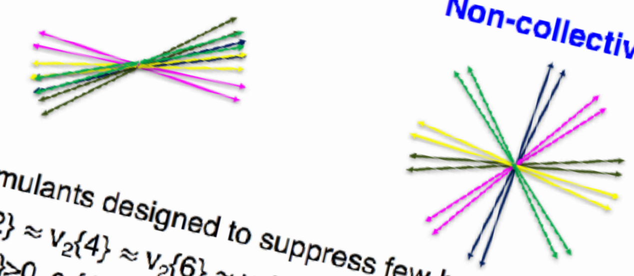


Long-range correlation in momentum space comes

- directly from early time t~0 (CGC)
- or it is a final state response to spatial fluctuation at t=0 (hydro).

What is collective and what is not?

More interested in **multi-particle** collectivity:
"High" Multiplicity >> cluster size

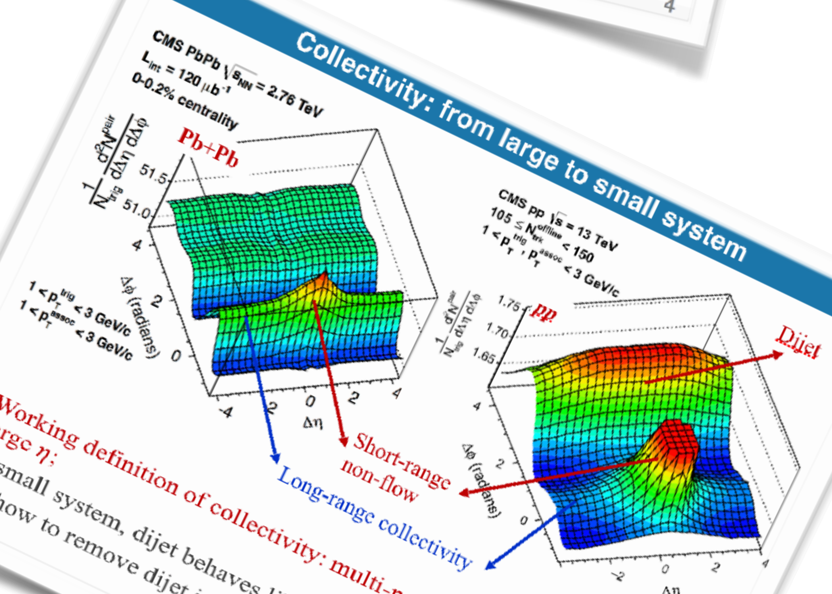


Cumulants designed to suppress few-body correlations

$v_2\{2\} \approx v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
($c_2\{2\}>0$, $c_2\{4\}<0$, $c_2\{6\}>0$, $c_2\{8\}<0$) ⇨ A strong evidence for collectivity

4

Collectivity: from large to small system



- Working definition of collectivity: multi-particle correlation across large η;
- In small system, dijet behaves like long-range correlation;
- So, how to remove dijet in 2PC?

'Collectivity'

'Standard Model' of heavy ion physics

- strong definition: ('thermo' + 'hydro') - dynamics
  - ⇨ emerging-f(t)- strongly interacting equilibrated matter with density/pressure gradients
  - ⇨ hydro-dynamics:
    - LO: radial (v_0) & elliptic (v_2) flow for > 95% of all particles (p_t < few GeV)
    - NLO: higher harmonics v_n, PID (m dependence) of v_n ('mode mixing' of v_0 & v_2)
    - NNLO: non-linear mode mixing ($v_n \neq \varepsilon_n$), factorization violation $r(p_T)$, EbE $P(v_n)$, …
  - ⇨ thermo-dynamics:
    - particle ratios (Statistical Model) to 10-30%
    - in pp/pA: γ_s -> 1
  - ⇨ thermo + hydro: => Space Time Evolution (STE)
    - HBT f(T, β): ($R(m_T)$, $R(N_{ch}{}^{1/3})$, $R_{out}/R_{side} \approx 1$)
    - Charge Balance functions
- strong Collectivity consistent with ≈ all data in pp/pA/AA
  to (very) good accuracy, where it was measured..

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Particle emission in hydrodynamics

- Particles emitted independently (no correlations) on the freeze-out surface
- The anisotropy of the single-particle momentum distribution (v_n) is driven by the initial density profile.
- There is certainly more, but we can use these two properties as a first definition of *collectivity*.

3

What is collectivity?

Working definition: multiple particles correlated across rapidity (**long range**) due to a common origin

(same as Jurgen's "weak definition", with the additional requirement of long η range)

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- Initial state **momentum** correlations (CGC)

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- Learn about the medium (**transport**)
- Learn about the initial state (**saturation**)
- Small and dilute system: chance to learn about microscopic processes (**MPI, strings, parton ladders …**)

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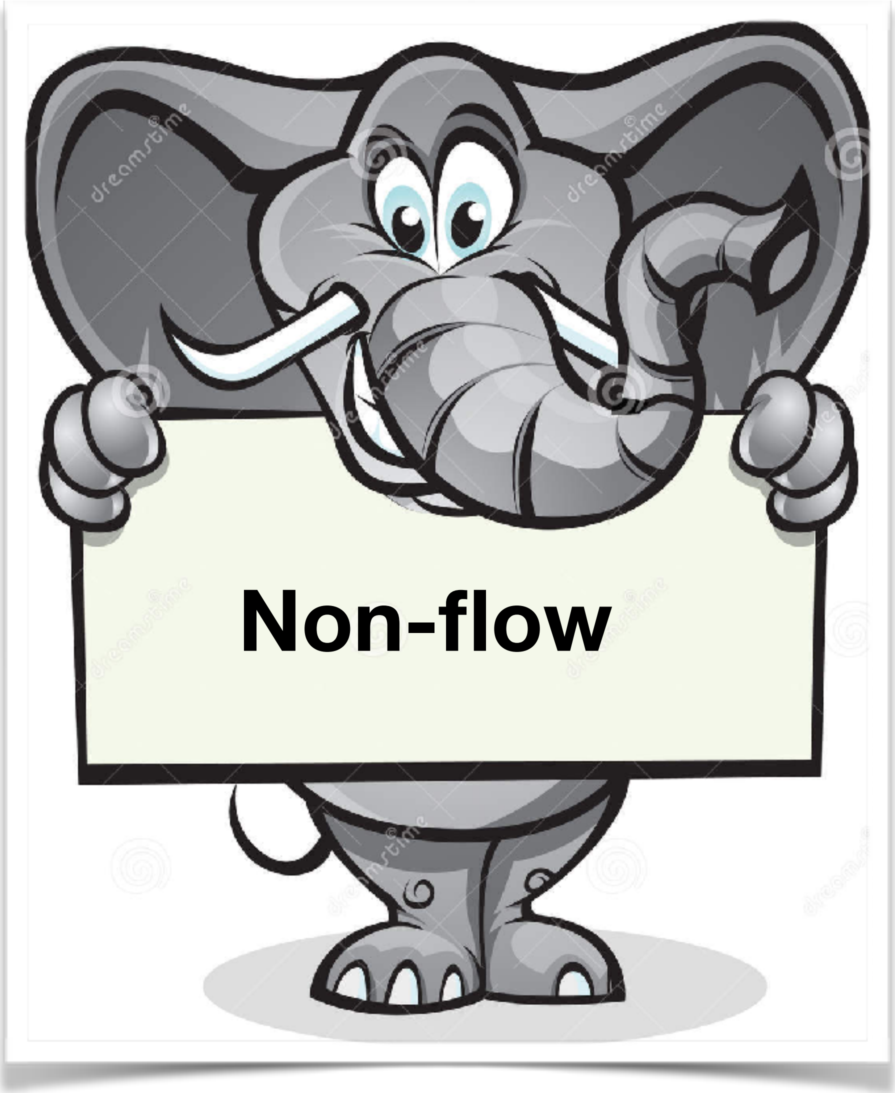
How do we measure?
- Can be inferred via **multiparticle correlations**
- **Non Flow** is the elephant in the room



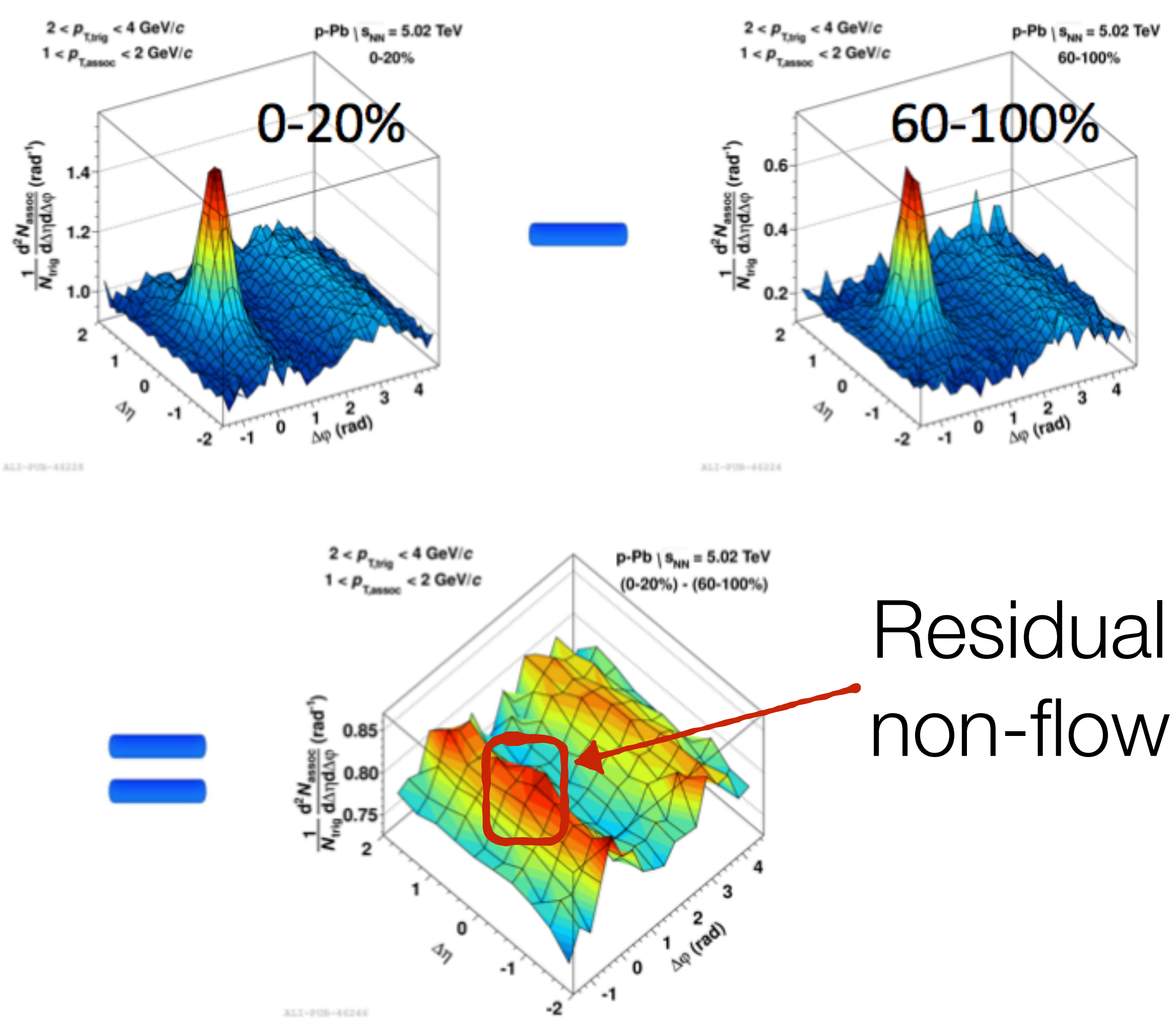
Collectivity measurements

Techniques, caveats and (some) key results

Dealing with non-flow

Subtract peripheral events

Assumption: Low multiplicity events dominated by non-flow, representative of non-flow in high multiplicity events



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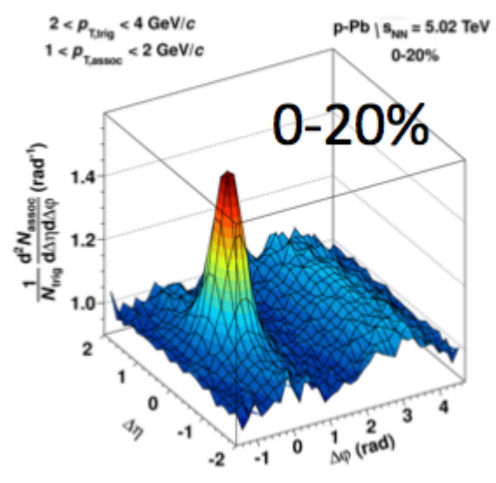

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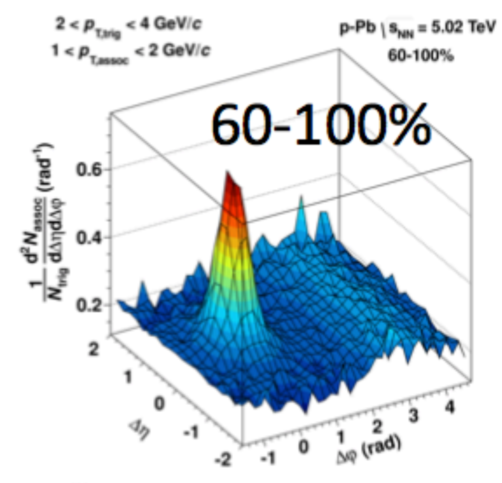

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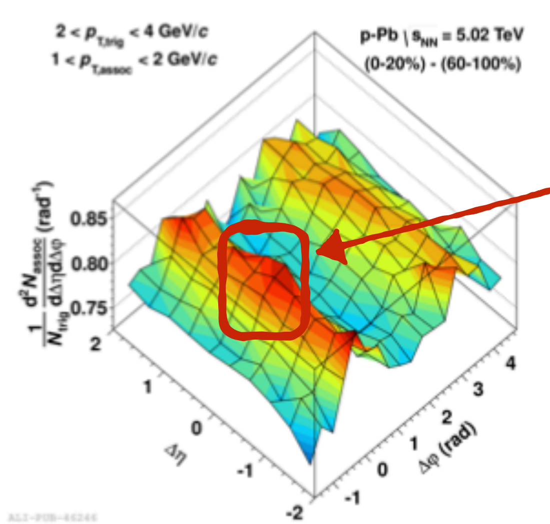
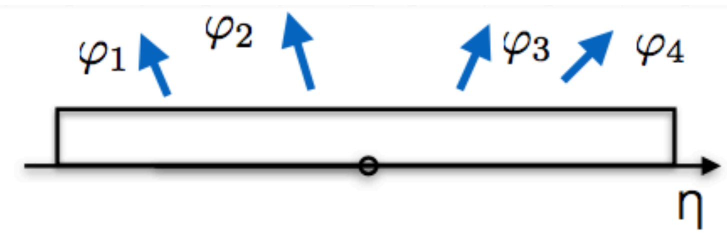


Residual non-flow

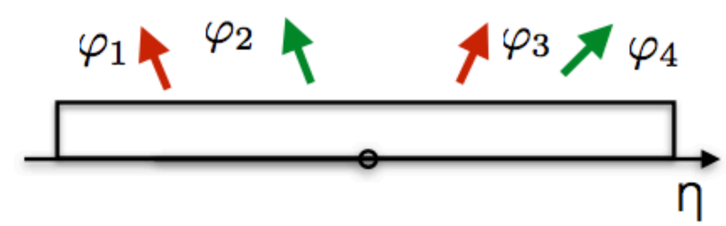
Multi-particle correlations

Assumption: if genuine 4-particle (or more) correlations, most likely flow

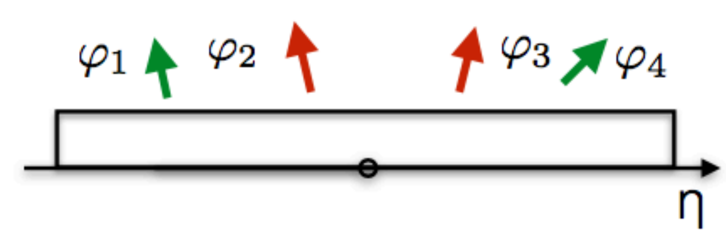
Recent versions: η gaps



$$\langle\langle \cos n(\varphi_1+\varphi_2-\varphi_3-\varphi_4)\rangle\rangle \ldots \langle\langle 4\rangle\rangle$$



$$\langle\langle \cos n(\varphi_1-\varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2-\varphi_4)\rangle\rangle \ldots \langle\langle 2\rangle\rangle^2$$



$$\langle\langle \cos n(\varphi_2-\varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_1-\varphi_4)\rangle\rangle \ldots \langle\langle 2\rangle\rangle^2$$

cumulant

$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$

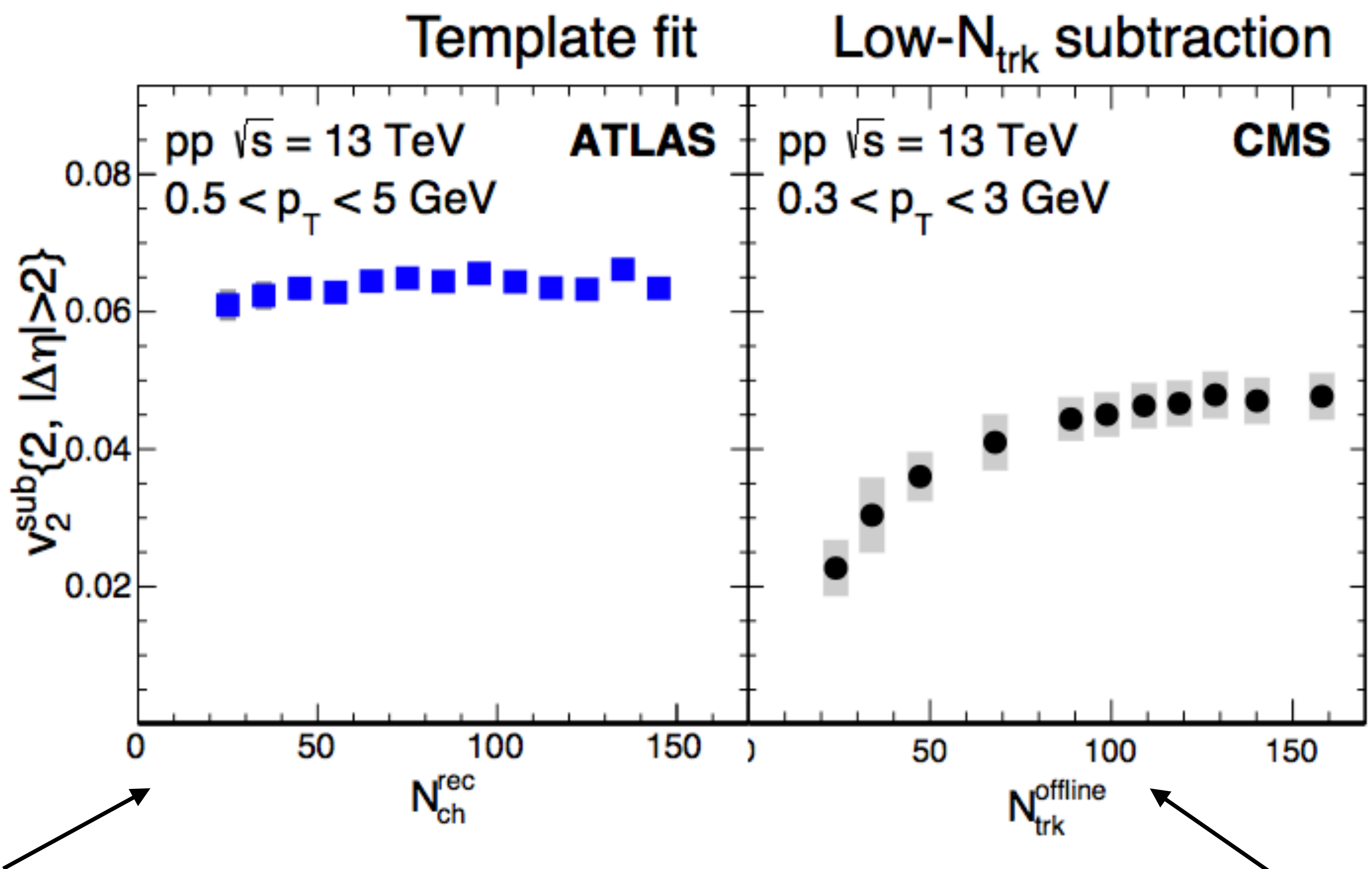
↓

$$c_n\{4\} = -v_n\{4\}^4$$

Ambiguities in the subtraction method

Subtraction method allows to go to **low multiplicity**

Crucial: how **low in N_{trk}** can we still talk about collectivity?



flow in bin n and n+1 equal

no flow in peripheral collisions

Z. Chen, CMS, QM17

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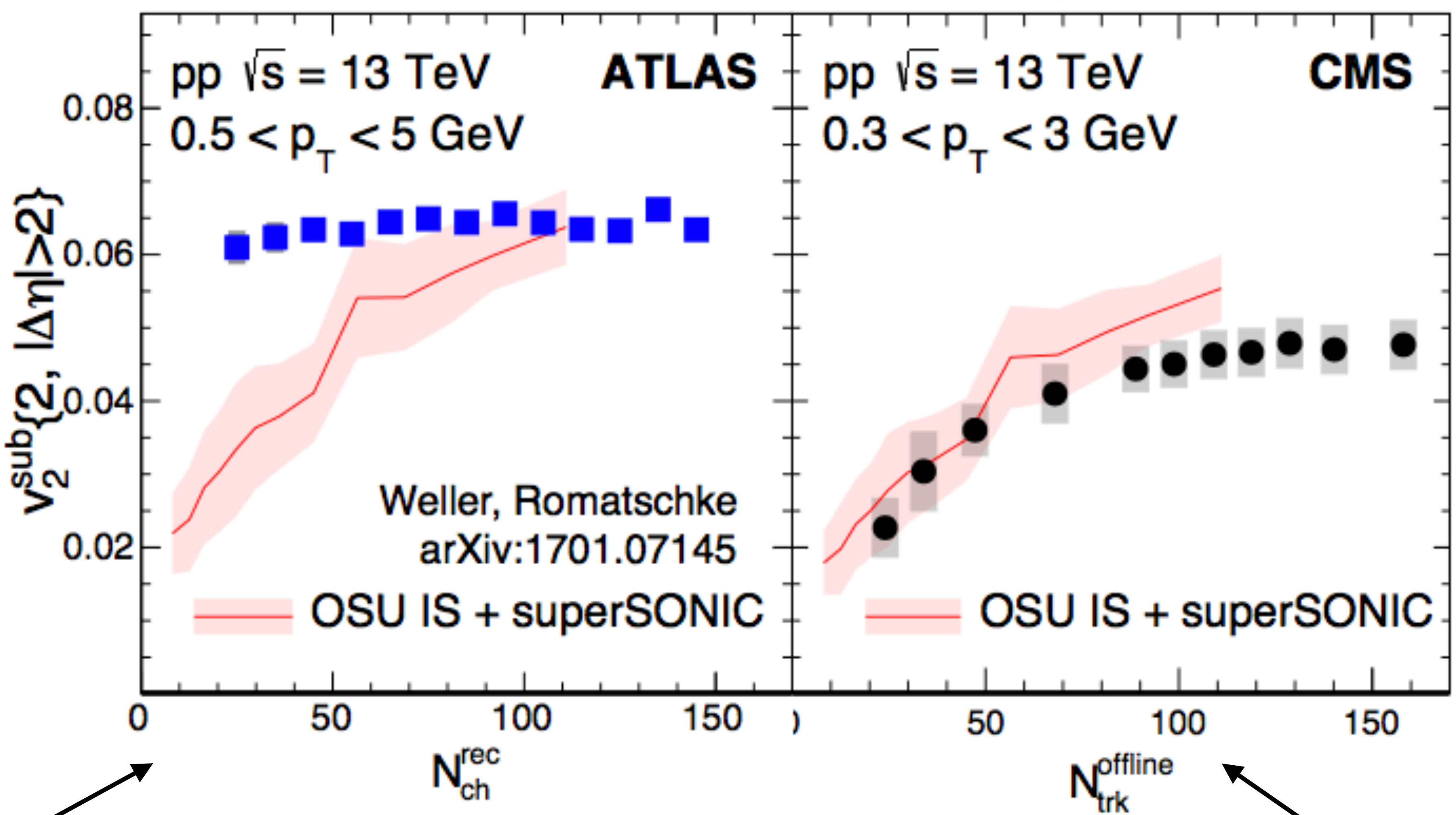
Template fit | Low-N_{trk} subtraction



flow in bin n and n+1 equal

no flow in peripheral collisions

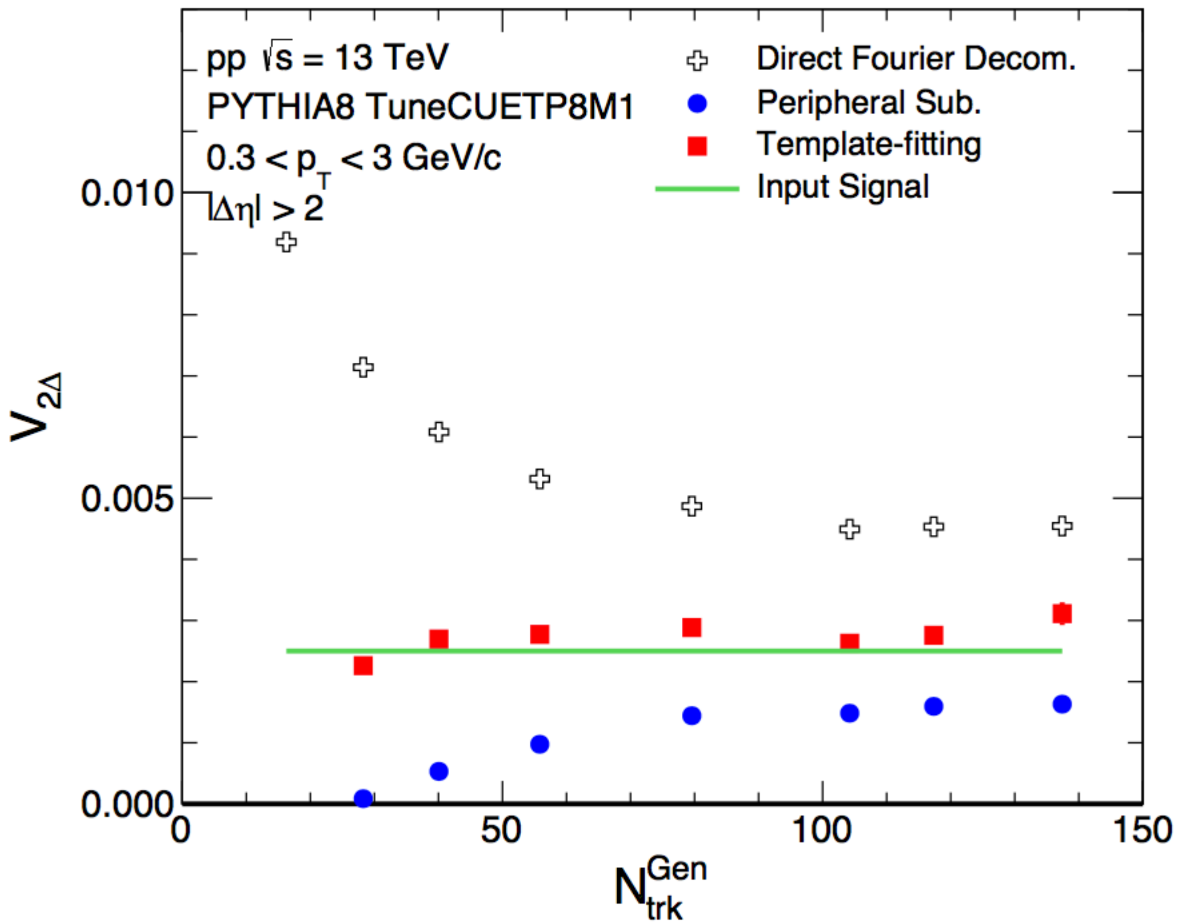
Comparison to theory?

Apply the same procedures to model output?

Z. Chen, CMS, QM17

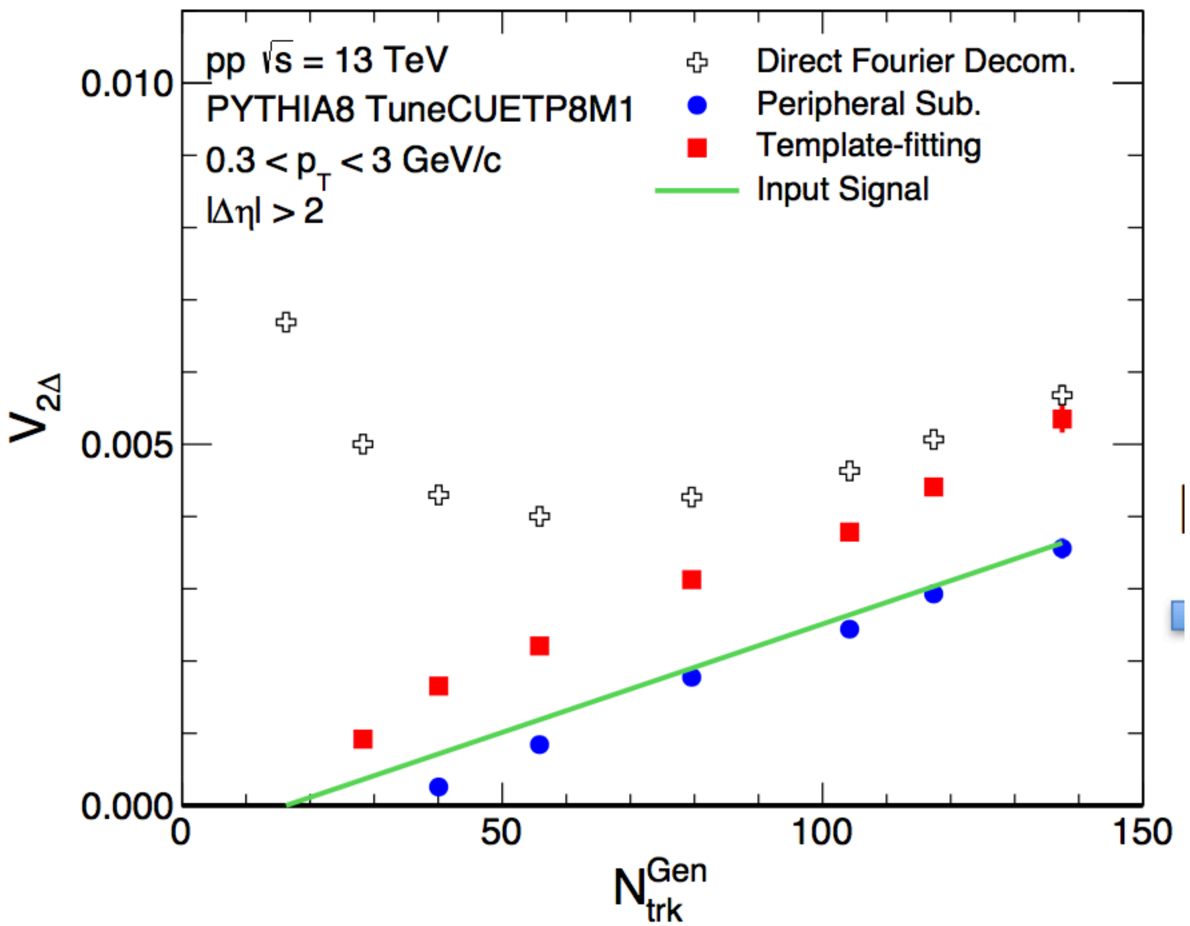
Wei Li

Flat v_2 injected



Template fit better

Rising v_2 injected

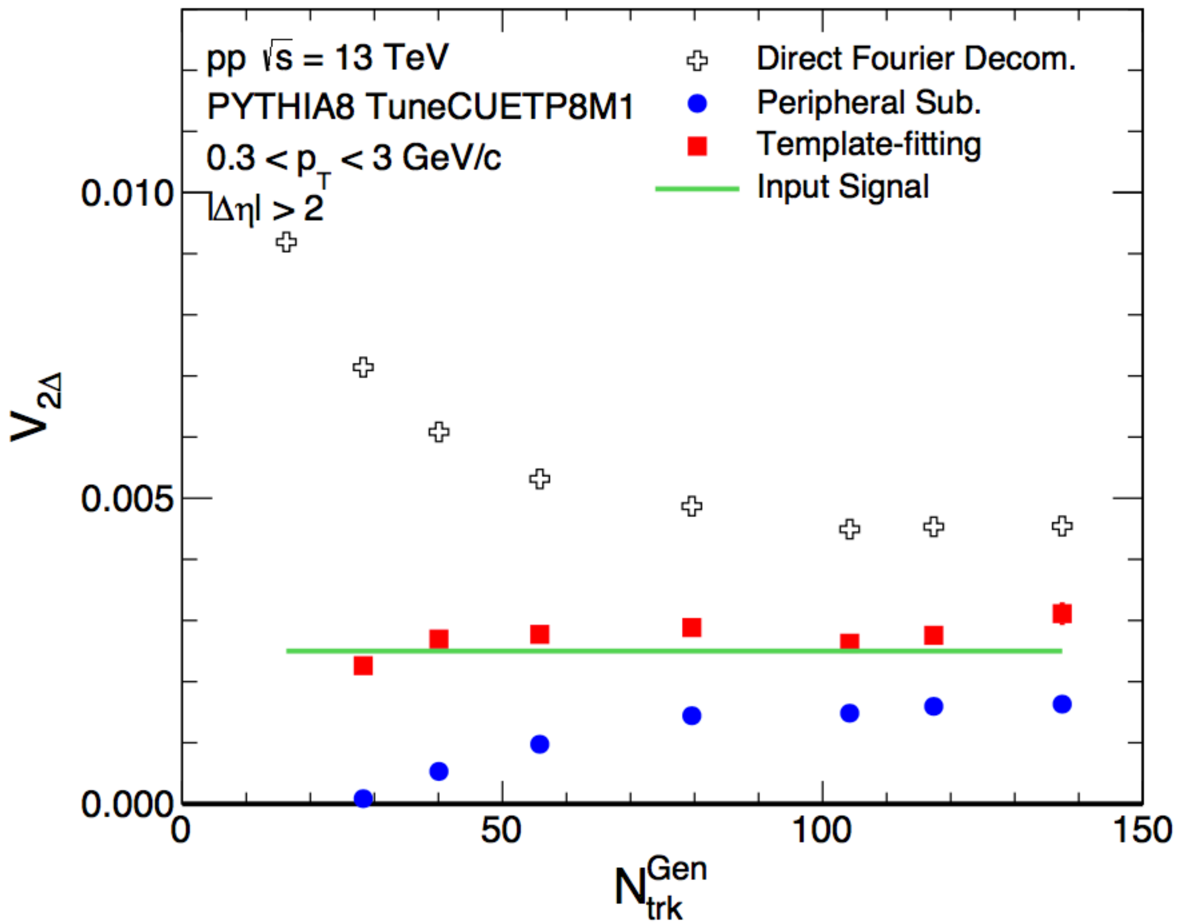


Peripheral subtraction better

Templates vs peripheral subtraction

Wei Li

Flat v_2 injected



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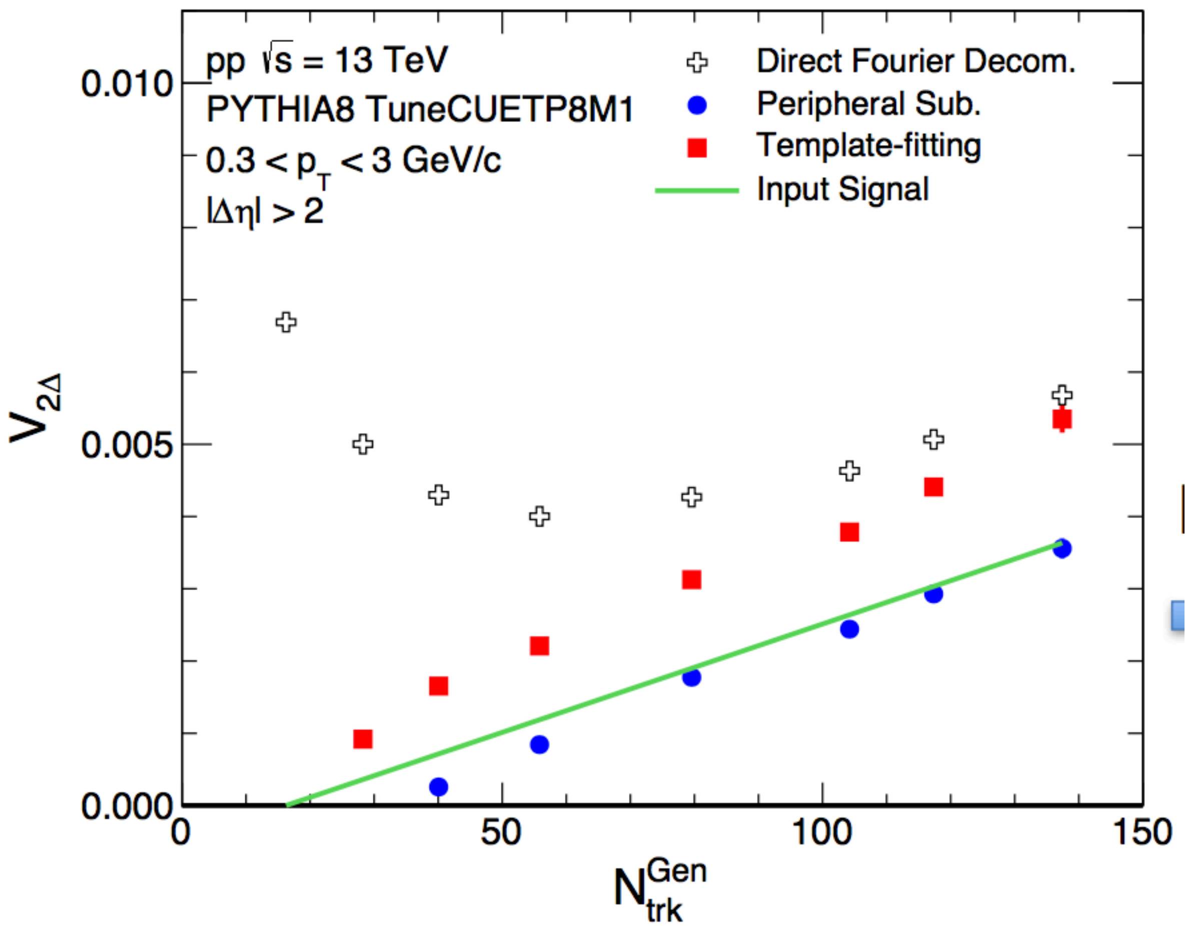


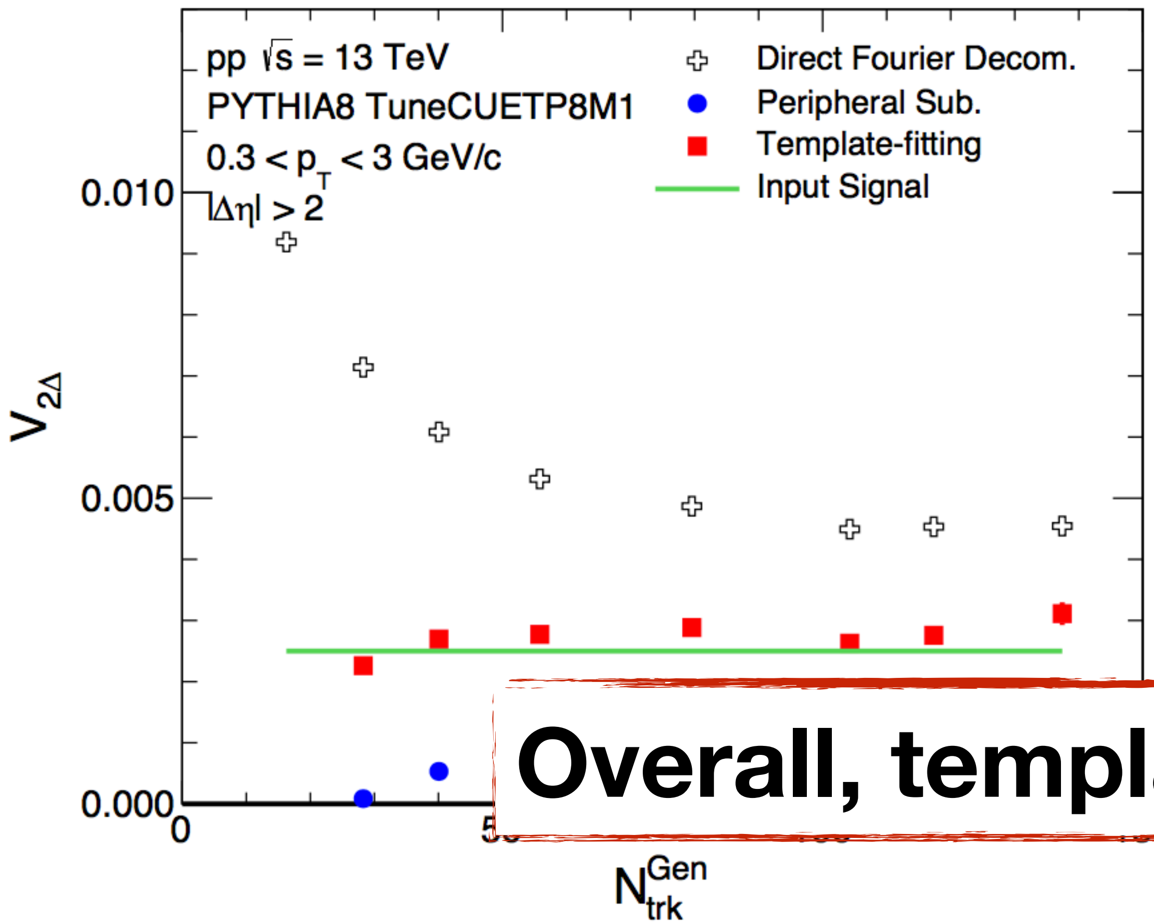
Peripheral subtraction better

But:

1. is there a reasonable **non-flat** v_2 shape which would **lead to flat** v_2 with the template fits?
2. What happens if one injects v2 as measured by CMS?

Wei Li

Flat v_2 injected



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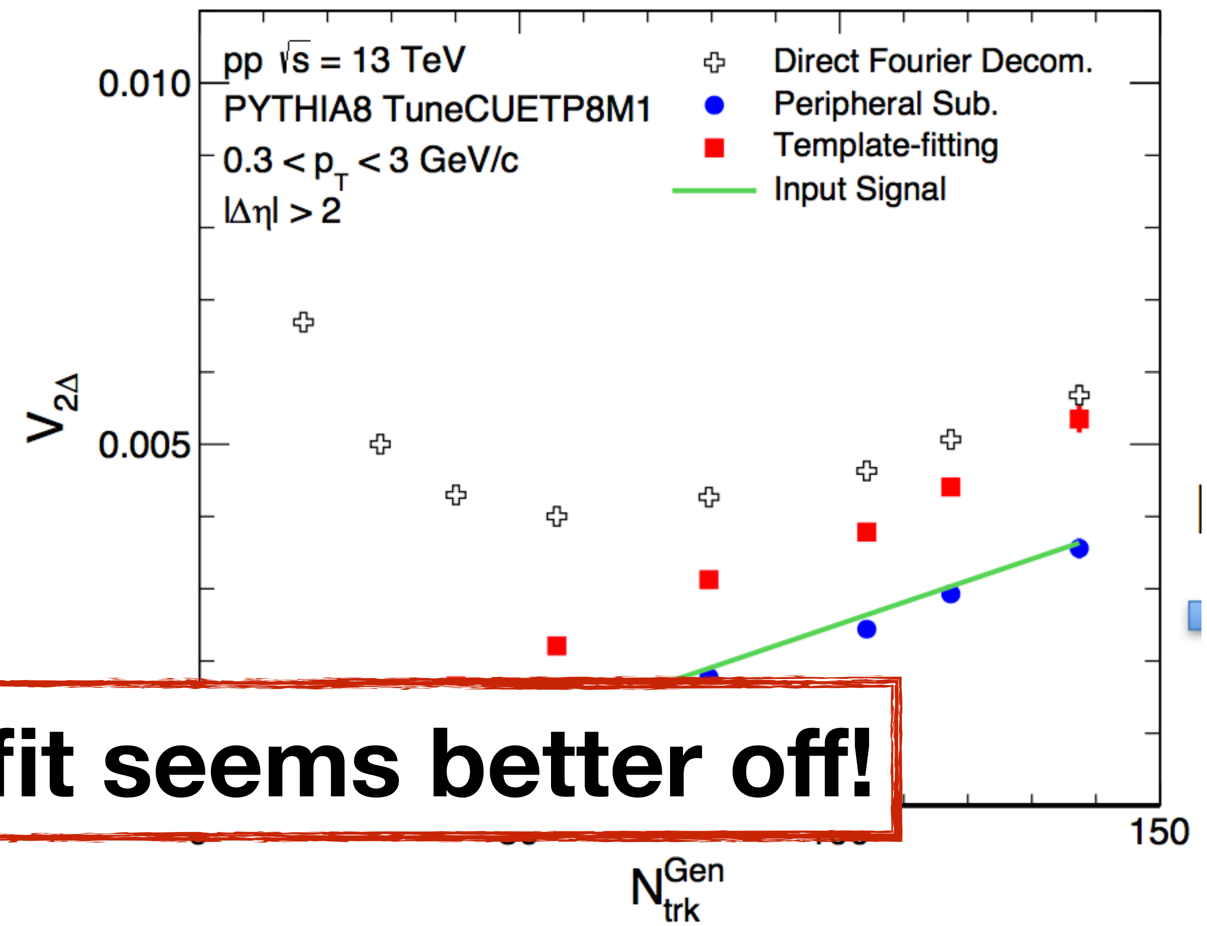

Peripheral subtraction better

Overall, template fit seems better off!

But:

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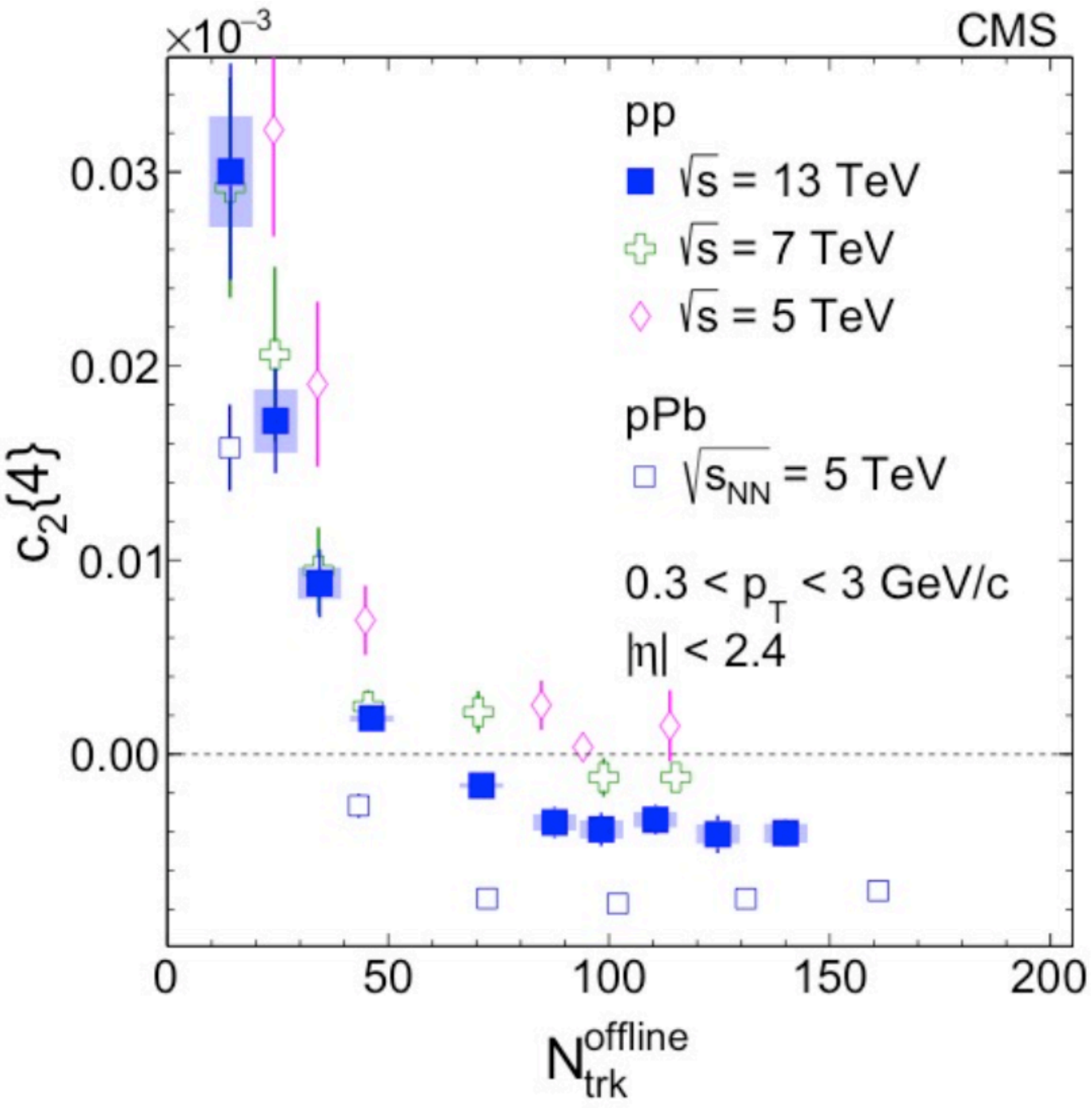
4-order cumulant

Negative $c_2\{4\}$ measured by CMS



Z. Chen, CMS, QM17

M. Zhou, ATLAS, QM17

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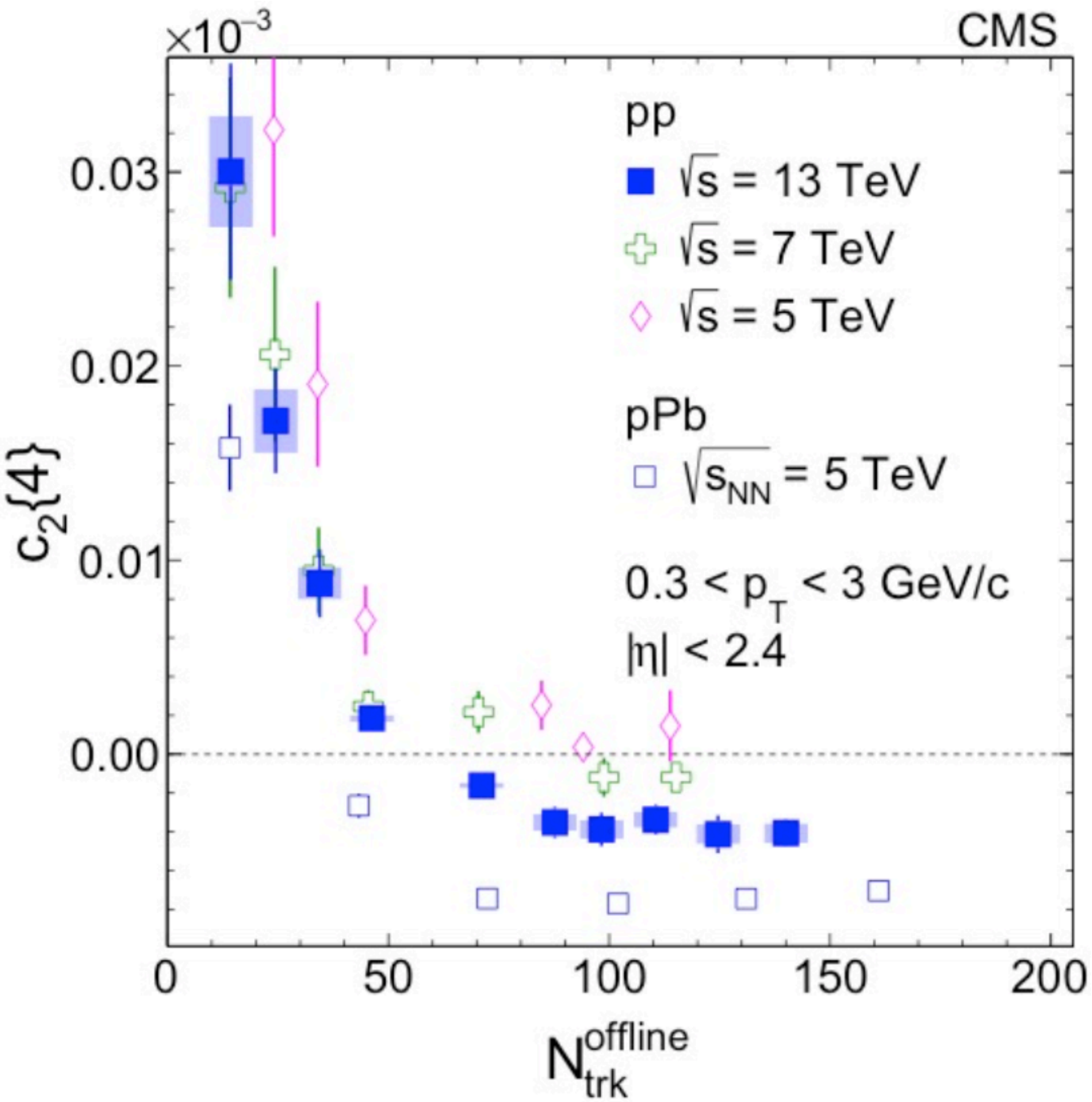

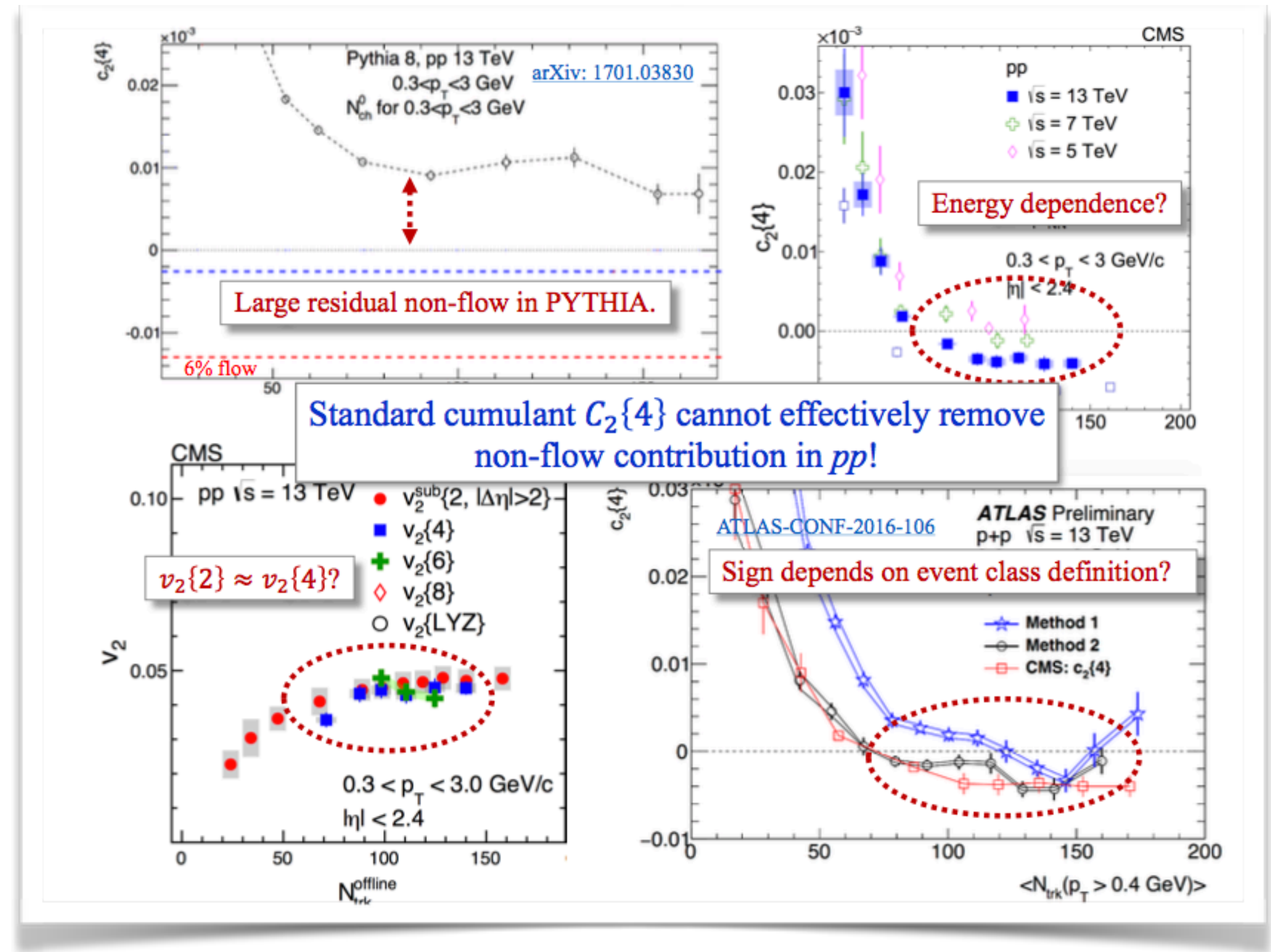

Z. Chen, CMS, QM17

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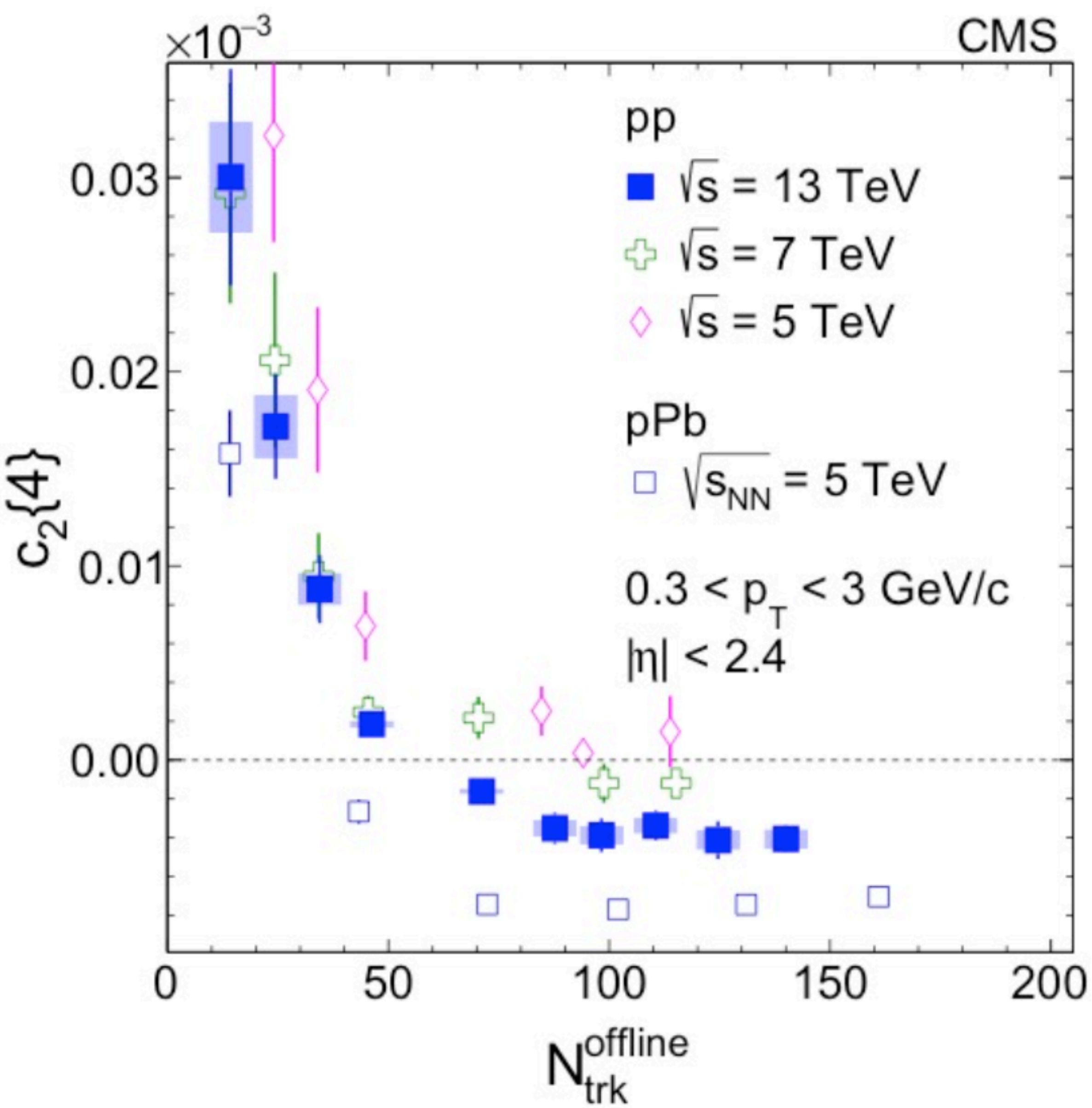
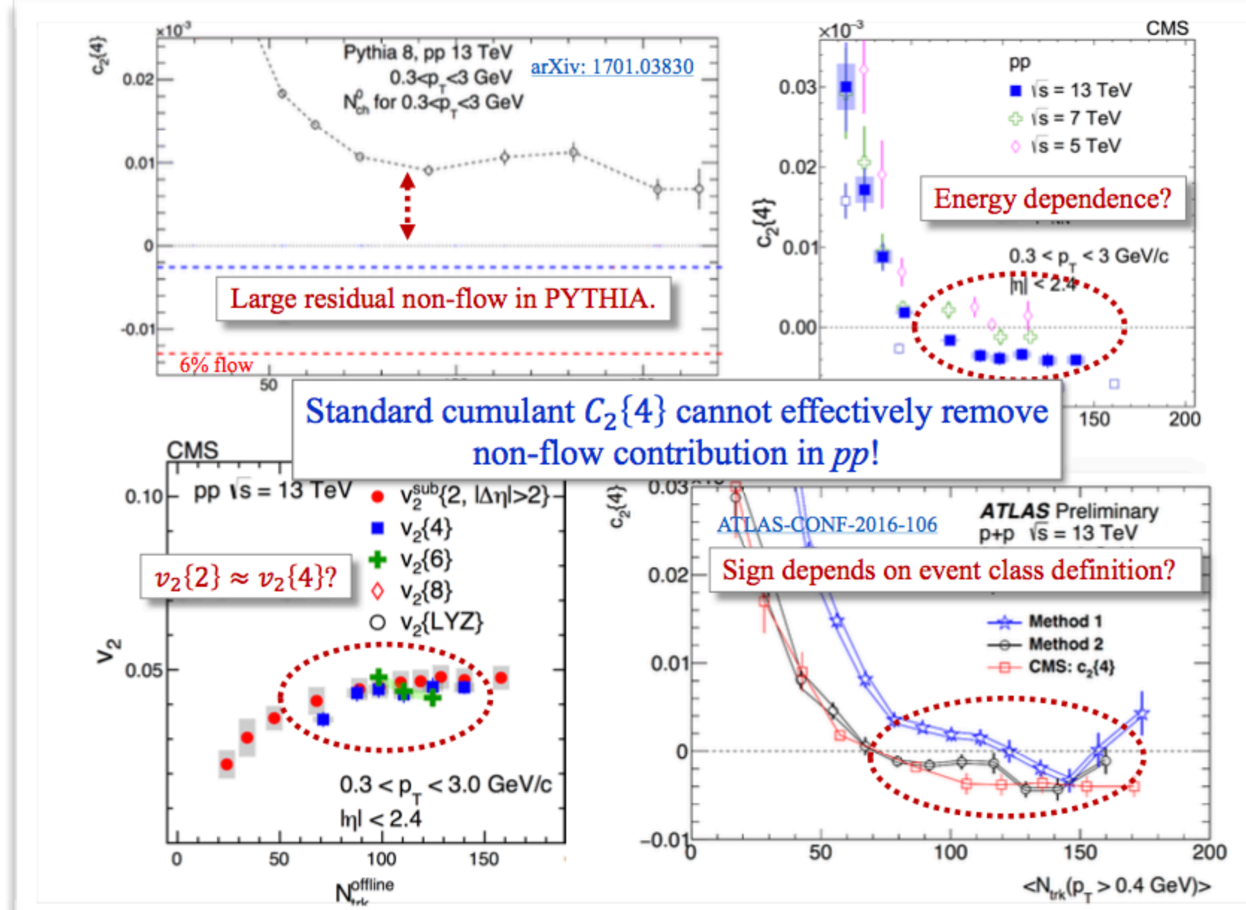




$$C_2\{4\} \equiv \langle \text{nonflow} + \text{flow} \rangle_{evt}$$

Non-flow changes greatly EbyE

Flow changes little EbyE

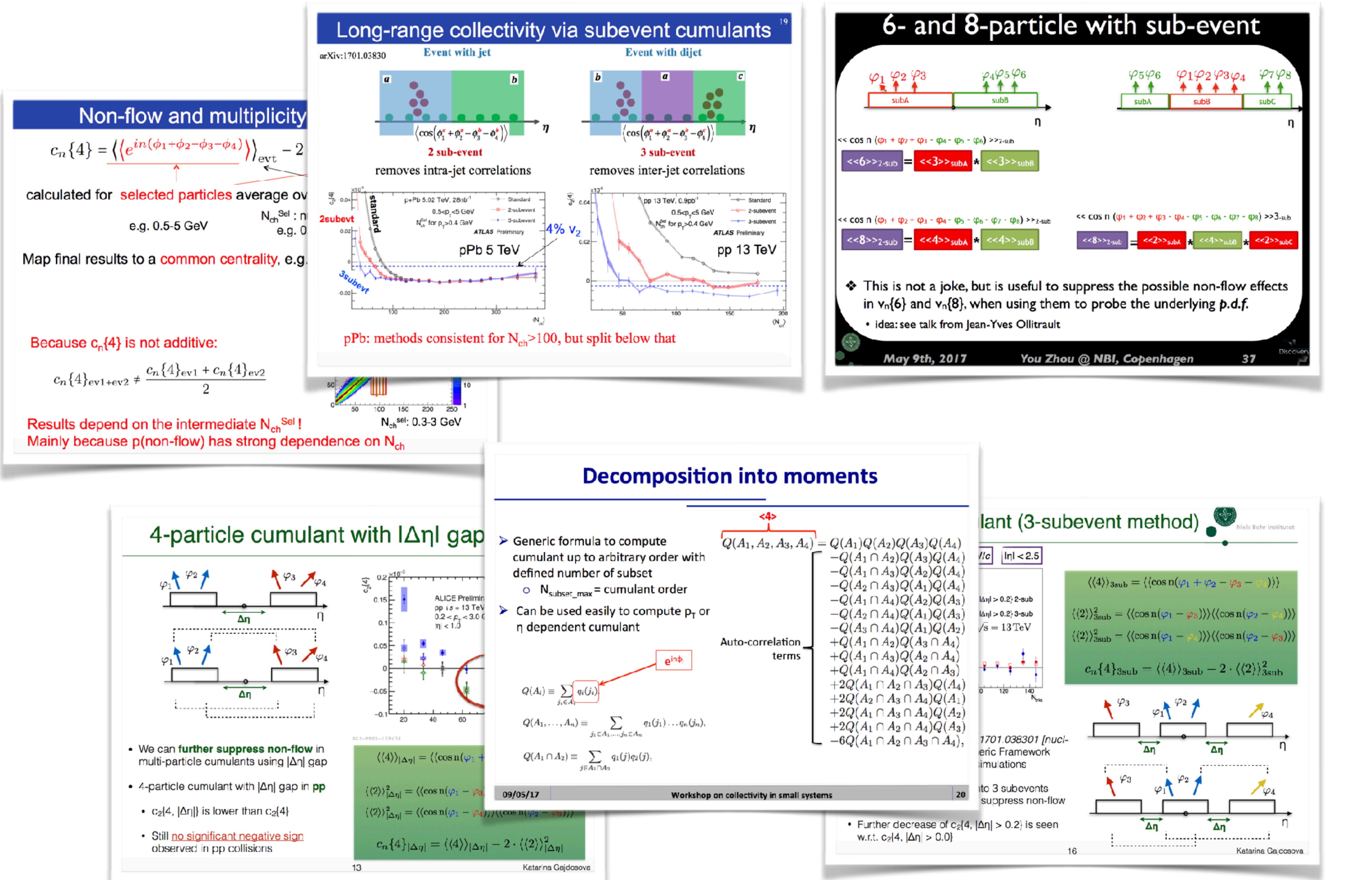
Non-Gaussian fluctuations of non-flow may produce any $c_2\{4\}$ (including negative)!

Z. Chen, CMS, QM17

J. Jia, M. Zhou

M. Zhou, ATLAS, QM17

Multi-particle cumulants, methods



See also J. Jia, M. Zhou, Y. Zhou, K. Gajdosova

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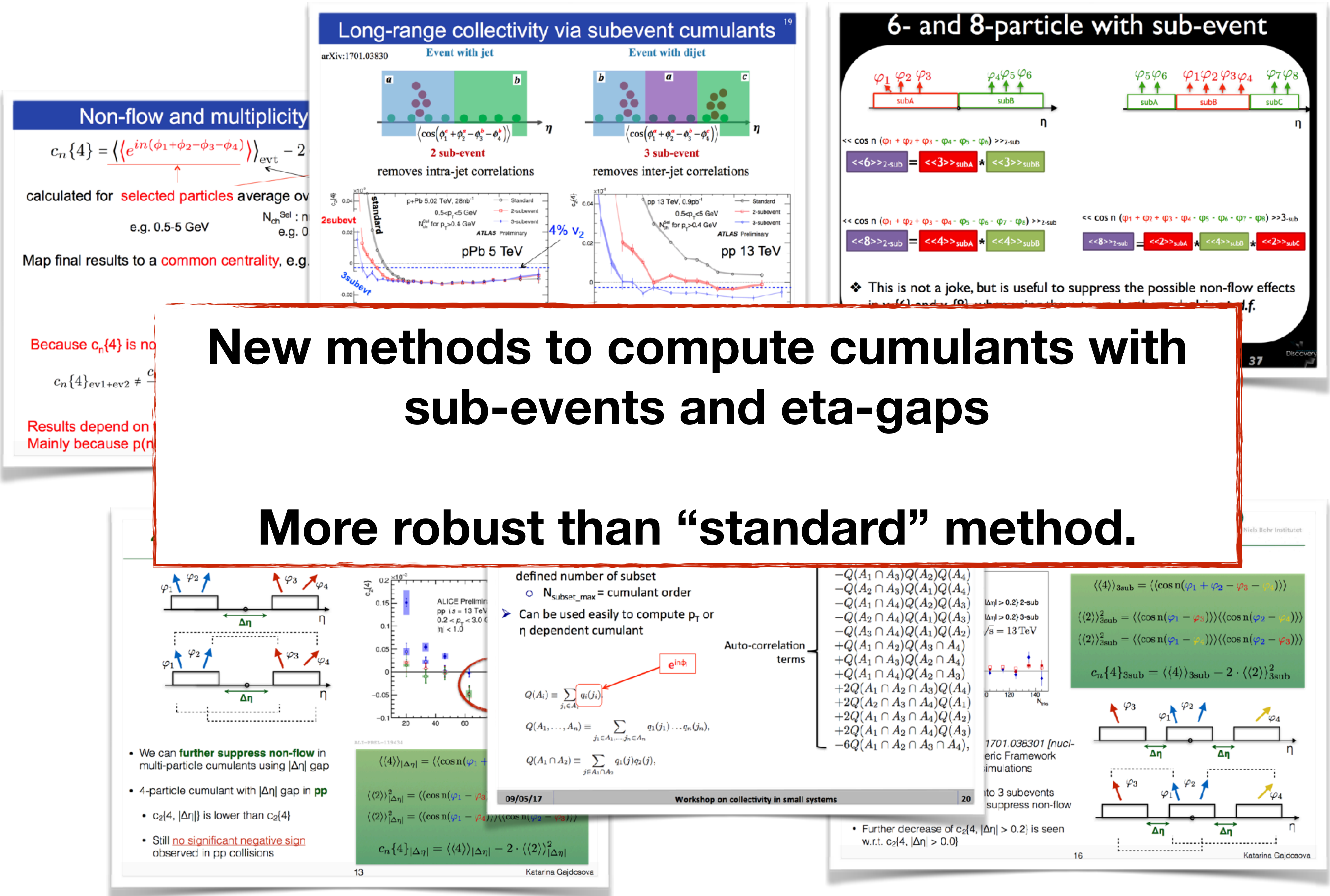


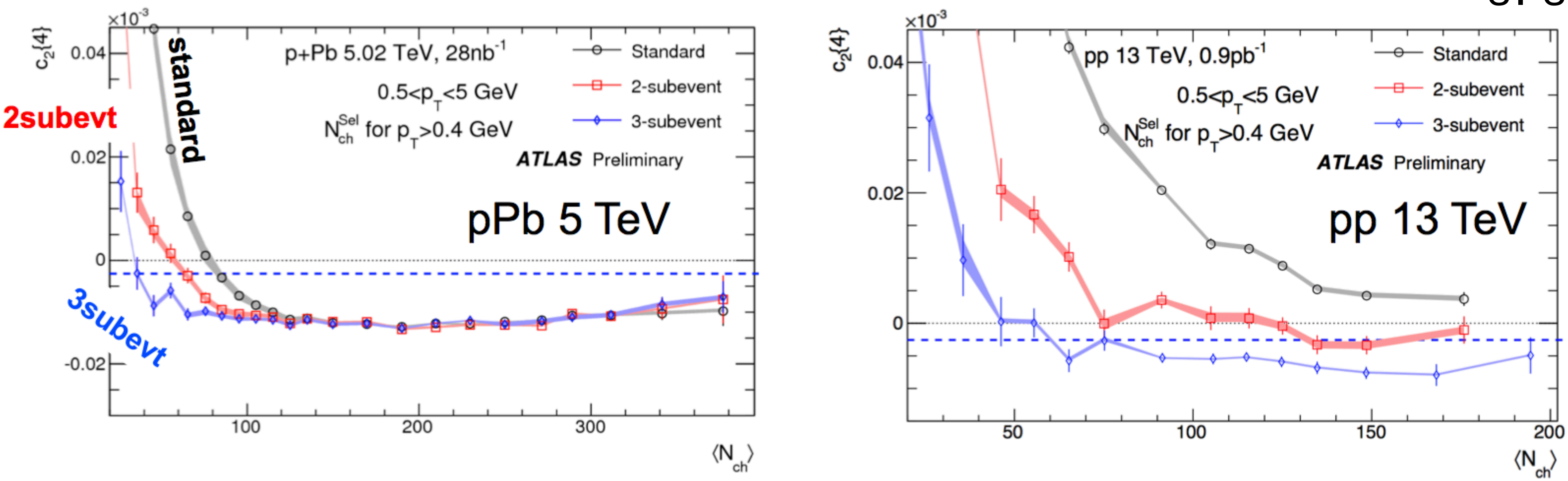
New methods to compute cumulants with sub-events and eta-gaps

More robust than “standard” method.

See also J. Jia, M. Zhou, Y. Zhou, K. Gajdosova

Results from n-subevents

J. Jia



3 subevents method **less sensitive to non flow**

Confirms **negative $c_2\{4\}$,** seems to work down to **low multiplicity**

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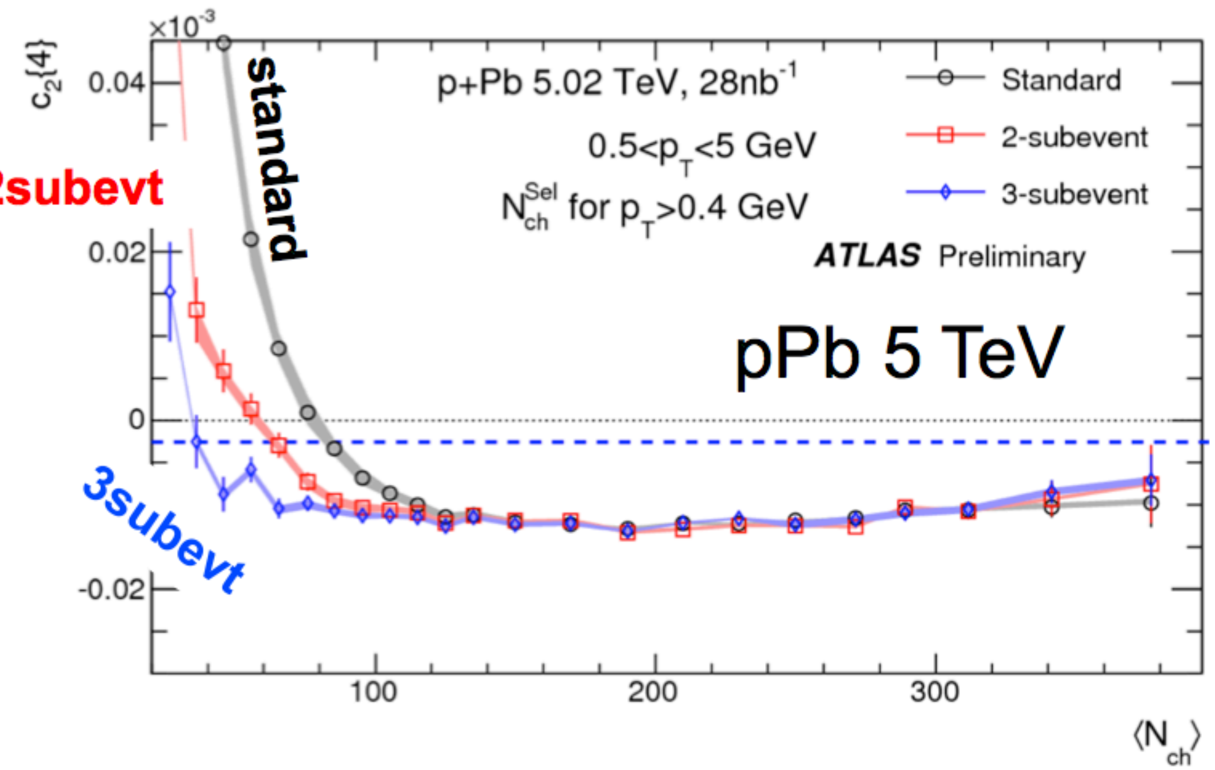

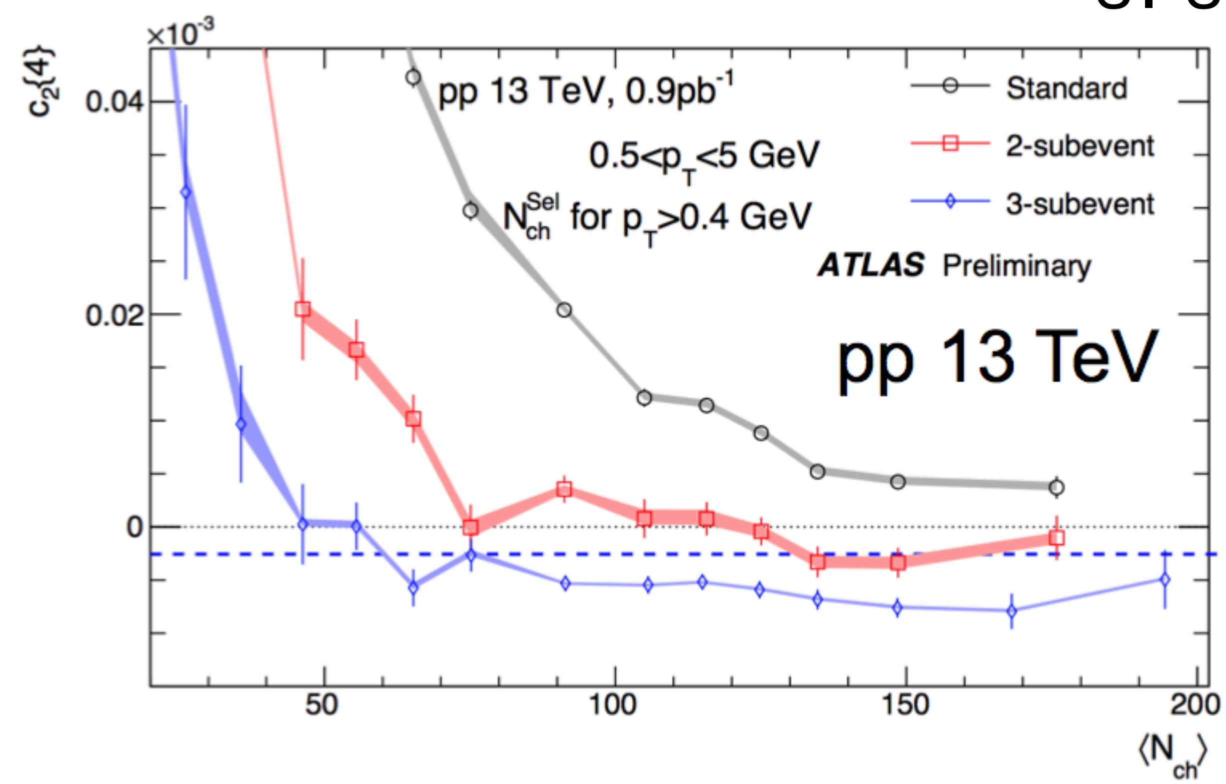

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Considerable **cooking** on the calculation of v2{4}
Variety of methods, eta gaps, track cuts, sub-events, …

We need to **agree** on a set of **common plots**,
to compare exp vs exp and exp vs theory
→ Wed: kick off session within **CERN's MB&UE group**

Results from n-subevents

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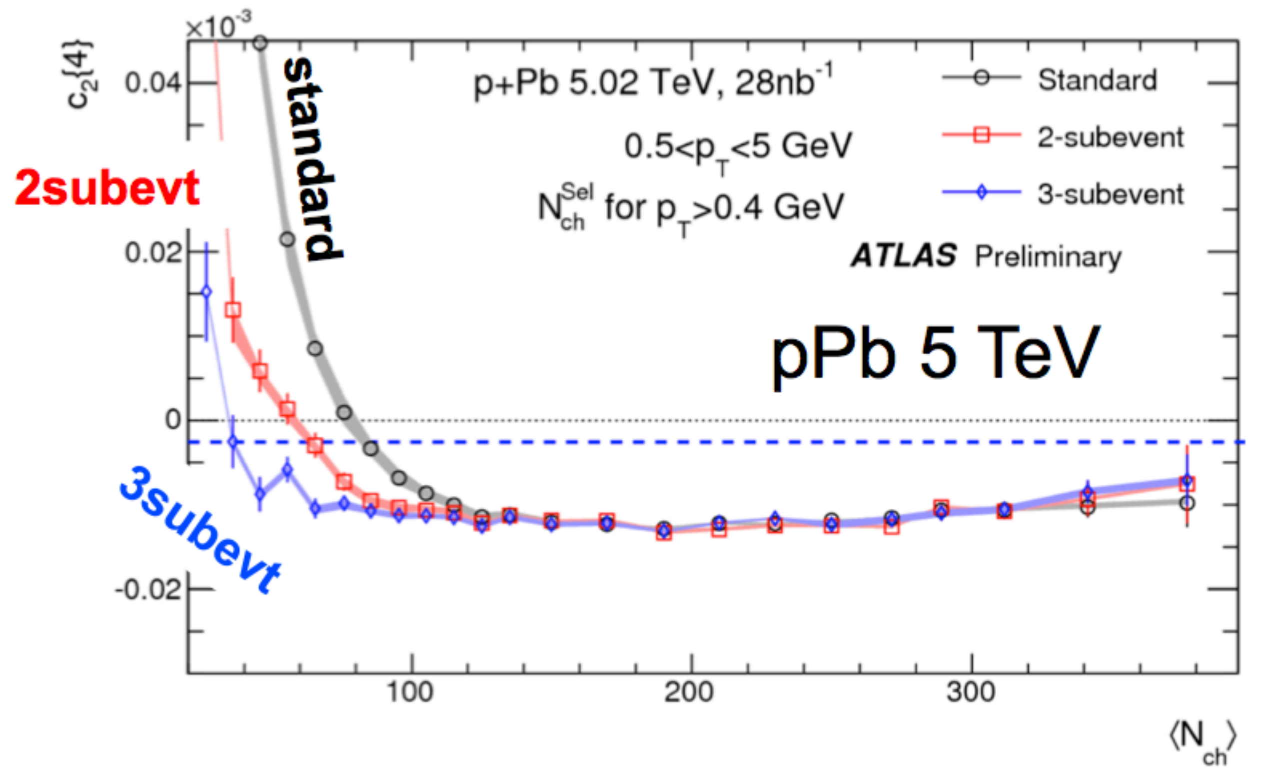

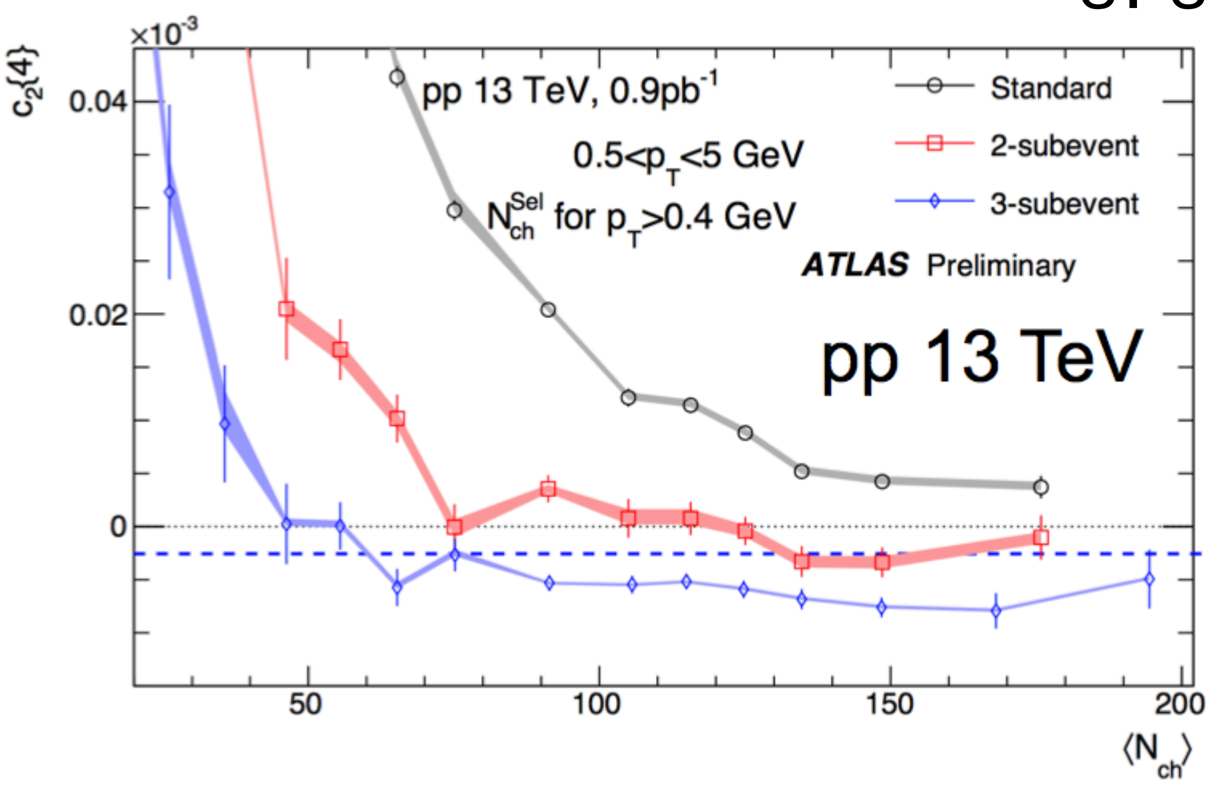

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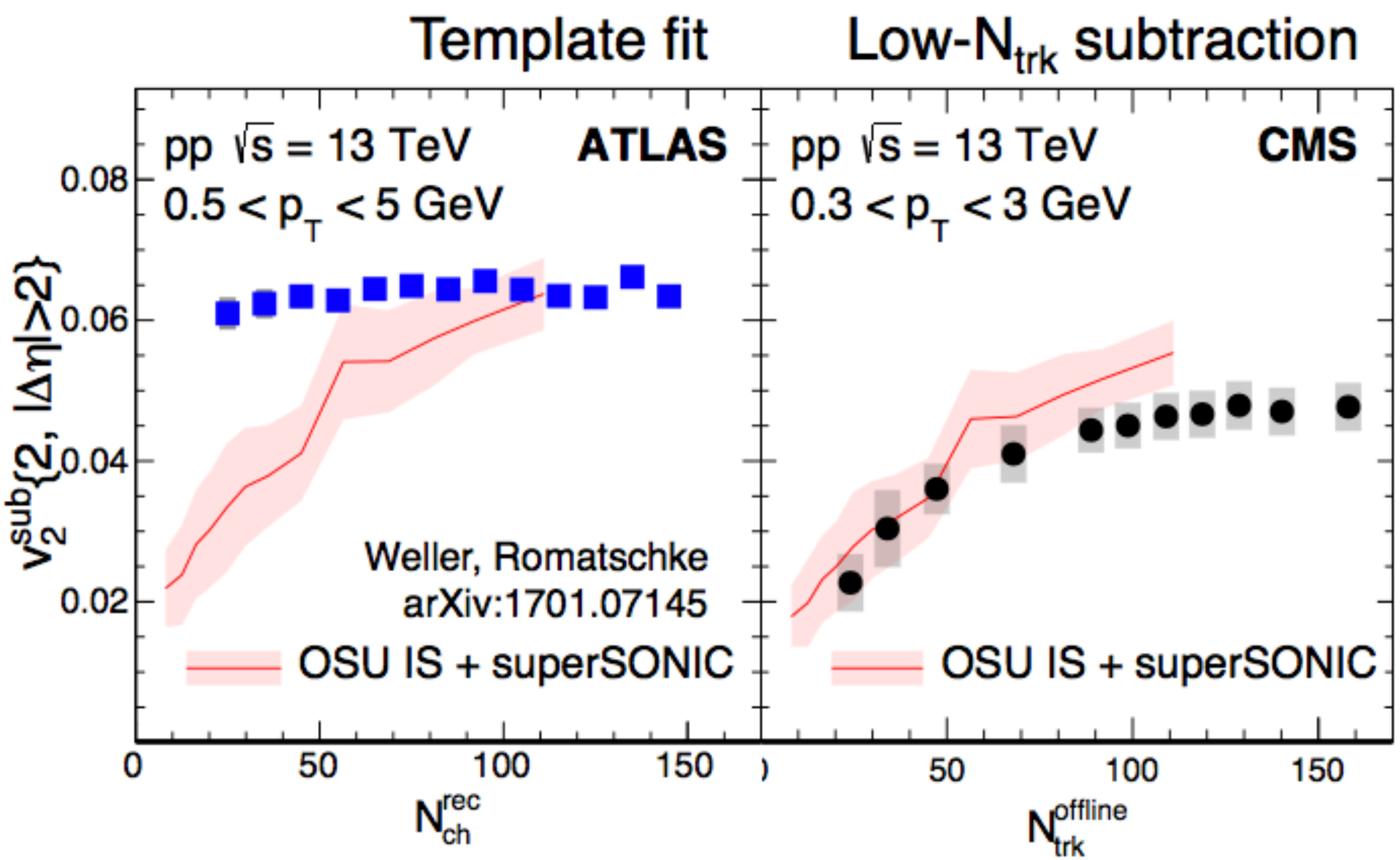
Subtraction method vs sub-events $c_2\{4\}$ vs hydro



J. Jia

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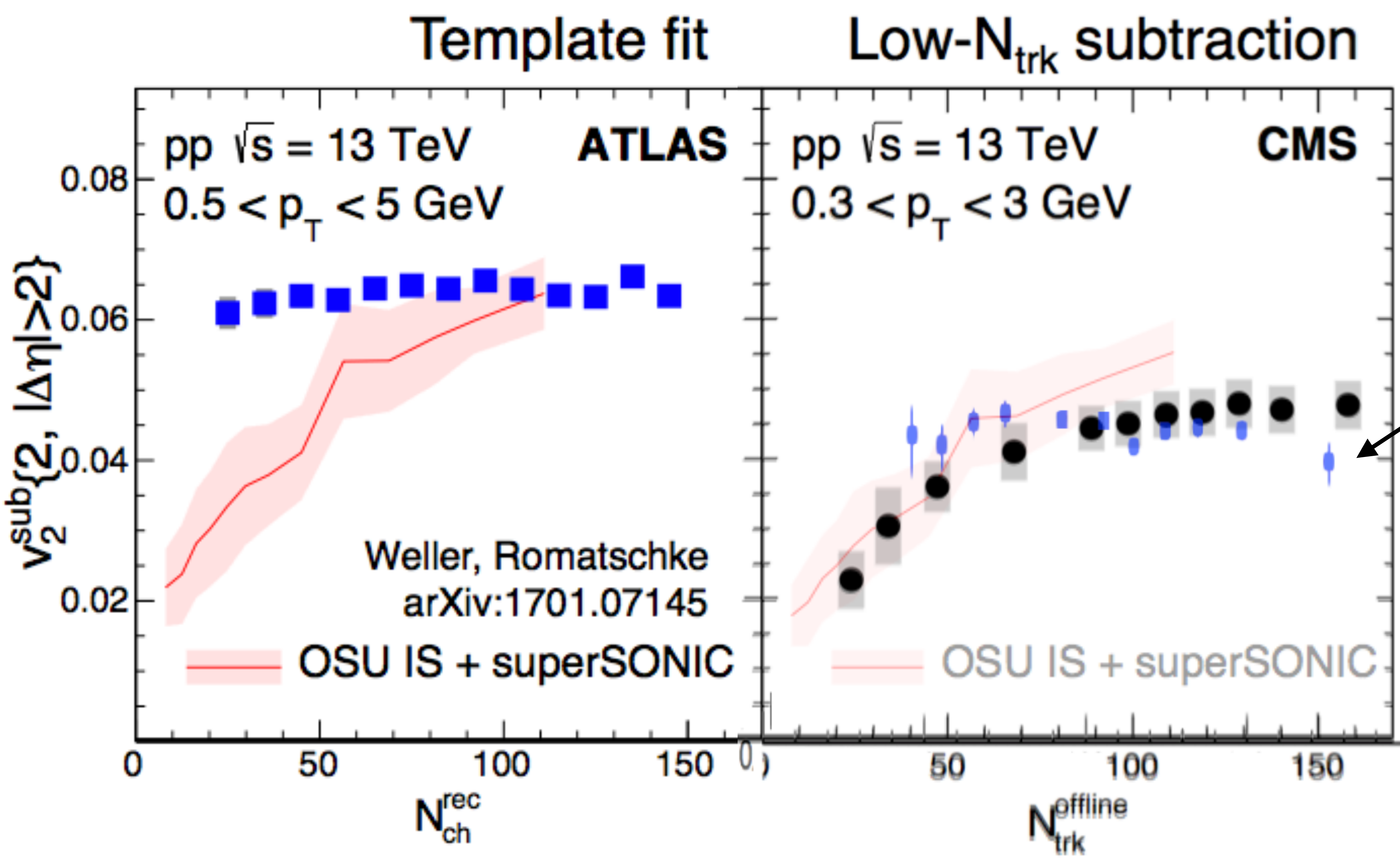
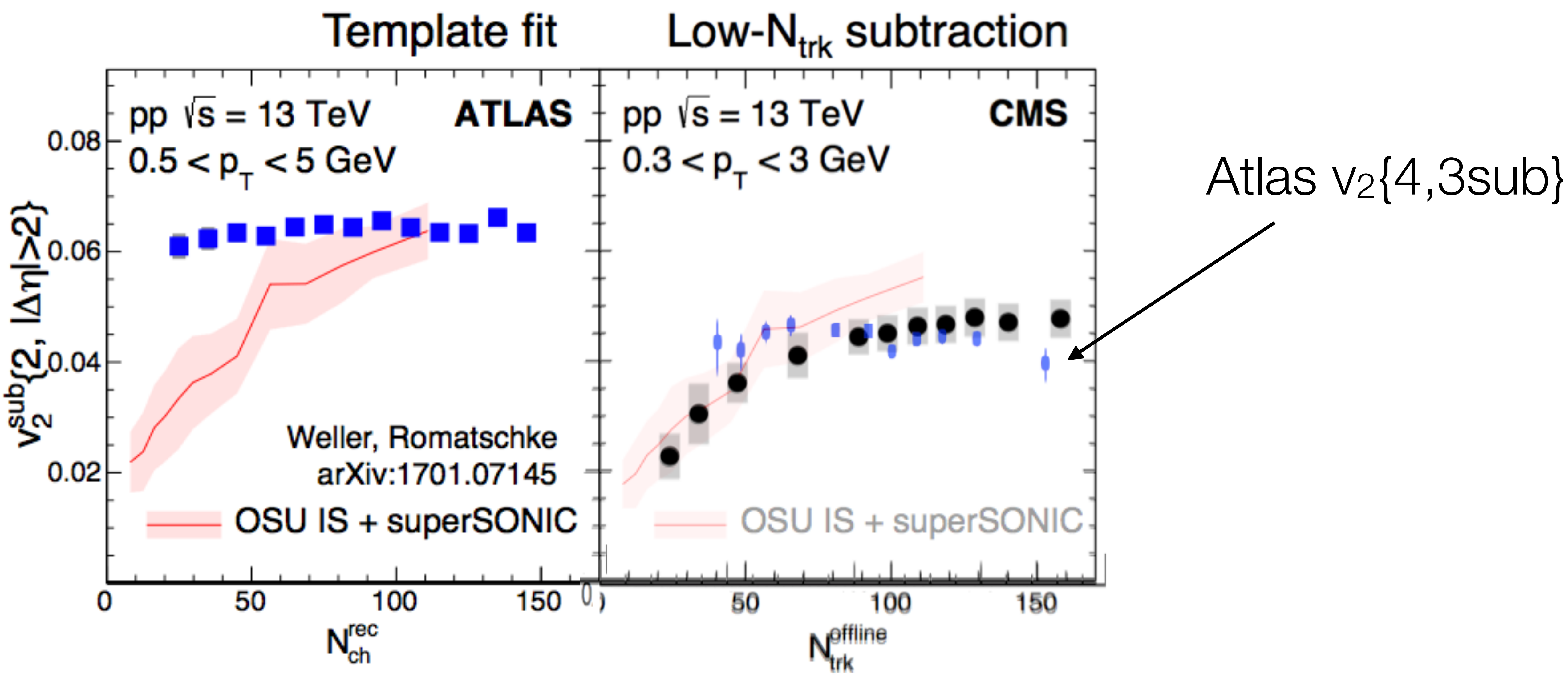


Atlas $v_2\{4,3sub\}$

J. Jia

Subtraction method vs sub-events $c_2\{4\}$ vs hydro



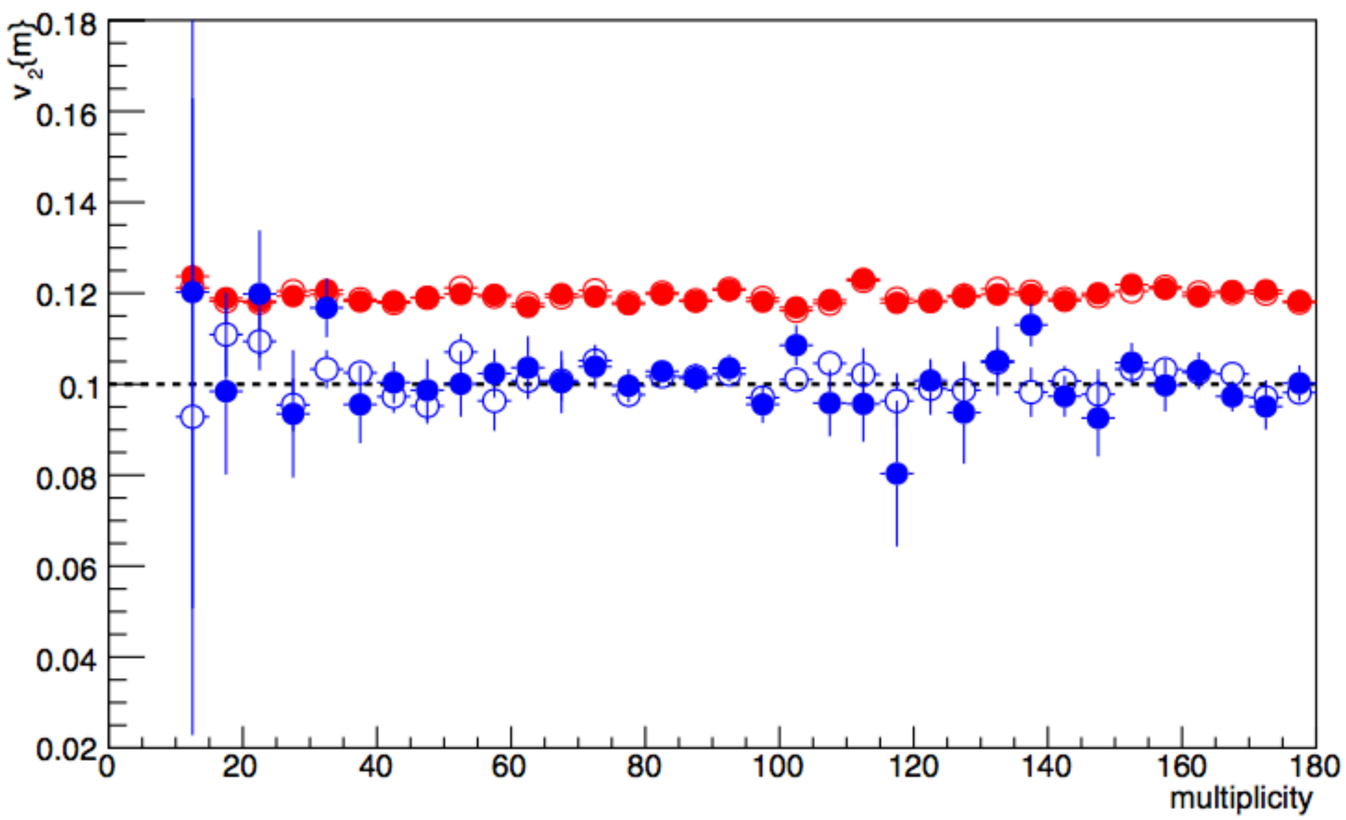
Tension with hydro?

- Hydro calculations: ***v_2* should decrease** at low multiplicity (but possibly at a lower range than measured?)
- $v_2\{4,3sub\}$ still **compatible** with hydro within uncertainties
- Can we trust 4 particle cumulants at **N_{trk}~40**?

J. Jia

Applicability of v_2\{sub\} at low mult

$v_2\{4\}$ sub **recovers injected** flow in Toy MC



Simple toy MC: $\mathbf{v_n}$ **fluc**, no mult fluct

········· Truth

$v_2\{4\}$ std — $v_2\{2\}$ std

$v_2\{4\}$ sub evt — $v_2\{2\}$ sub evt

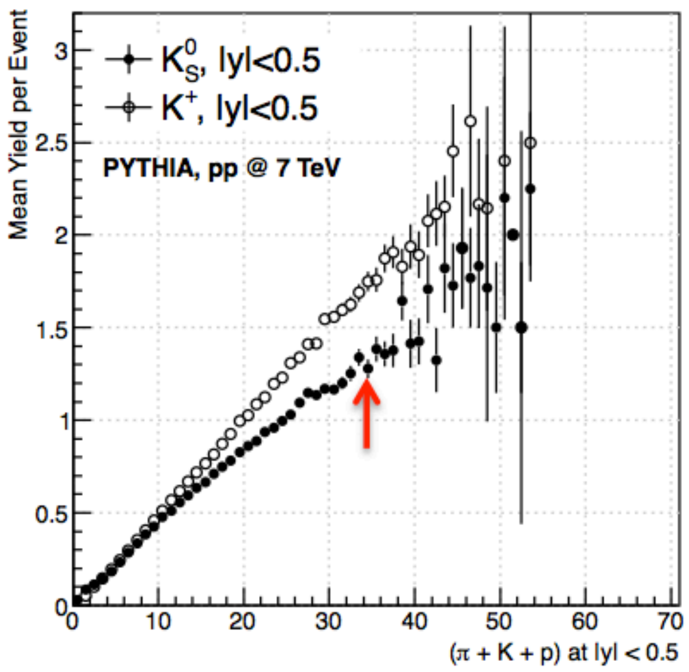
Promising, but very low mult can be very **tricky**: needs **full simulation** studies

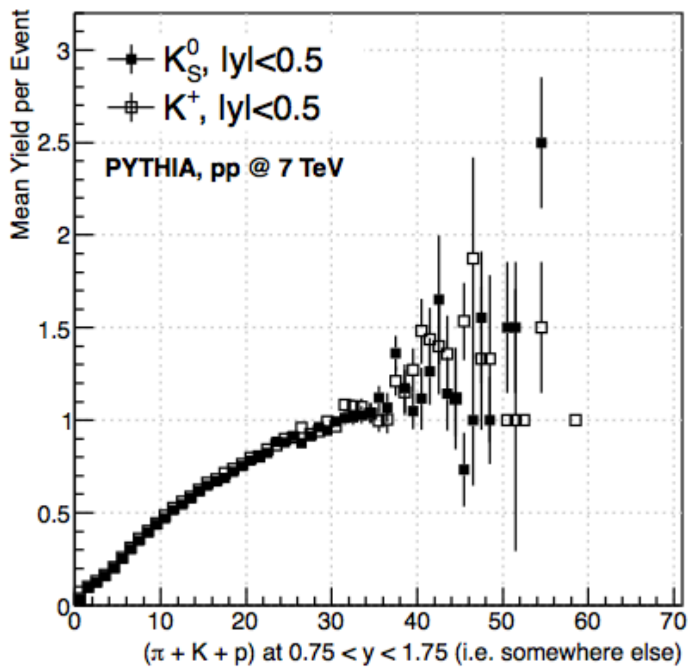
For instance:
Non-constant v_n + detector **reconstruction**: additional event-by-event fluctuations

M Guilbaud

Estimator biases

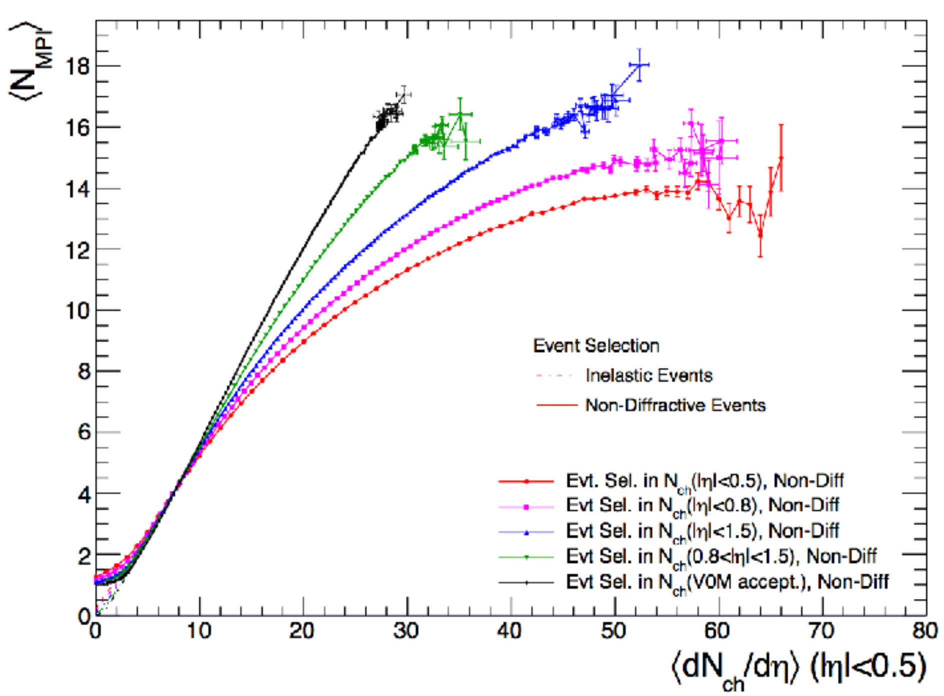
The region where multiplicity is selected imposes biases on the data
Some non trivial!





Hadrochemistry Bias

Charged particles selected more often, also affects fraction of secondaries.



MPI Bias

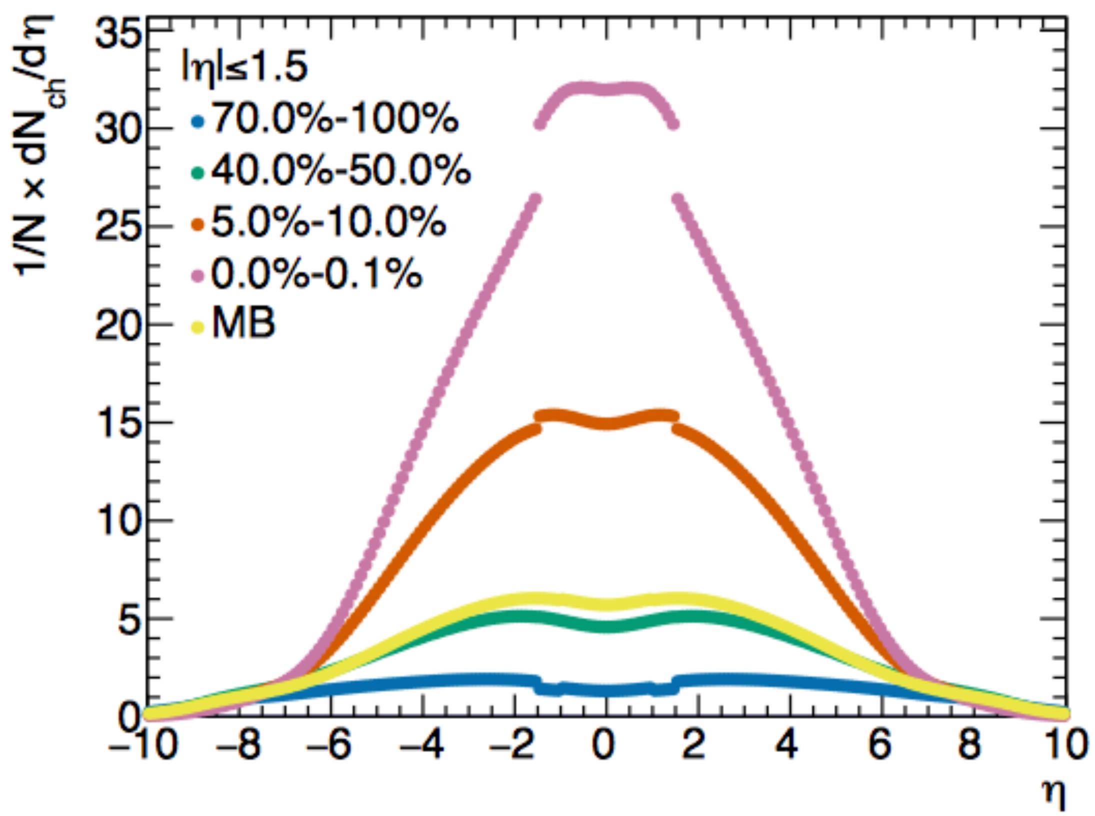
Qualitatively different events may be selected (in this example MPI)

Plots by D. Chinellato, Pythia 6, Perugia 2011

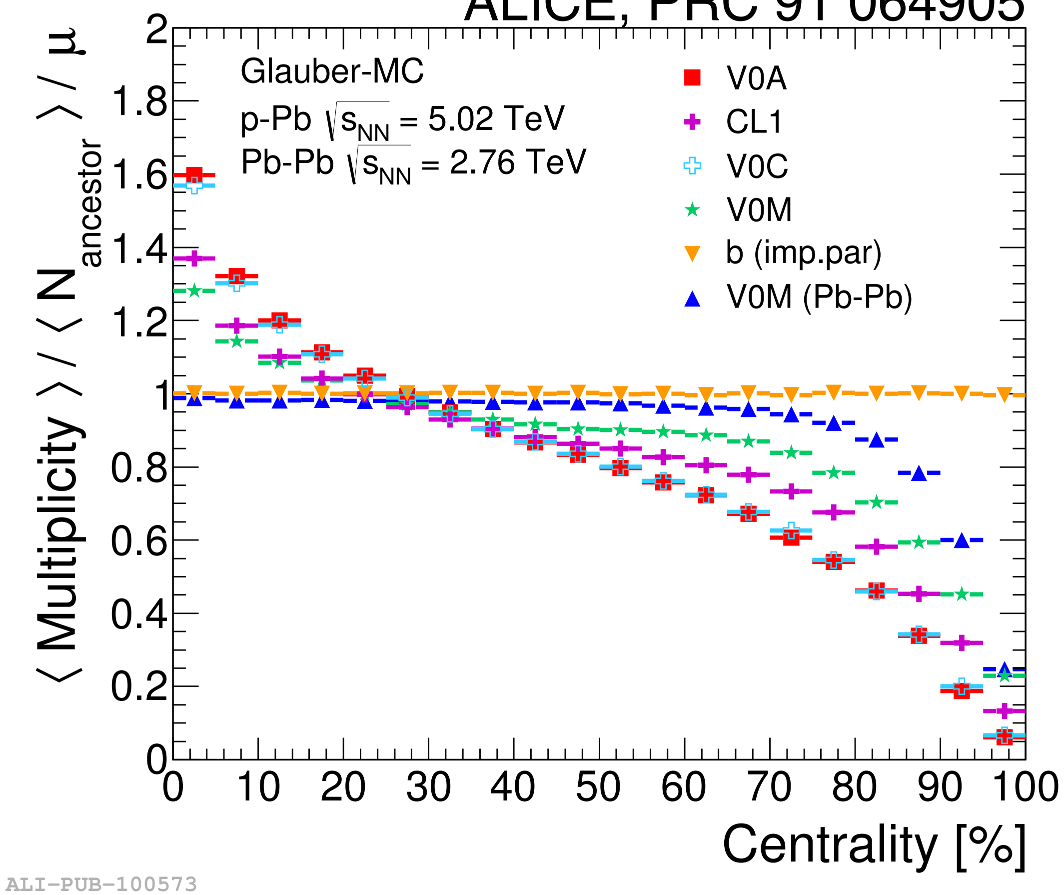
Multiplicity and Fragmentation Bias

Increase in multiplicity is local in η

Multiplicity per "ancestor" depends on centrality and estimator



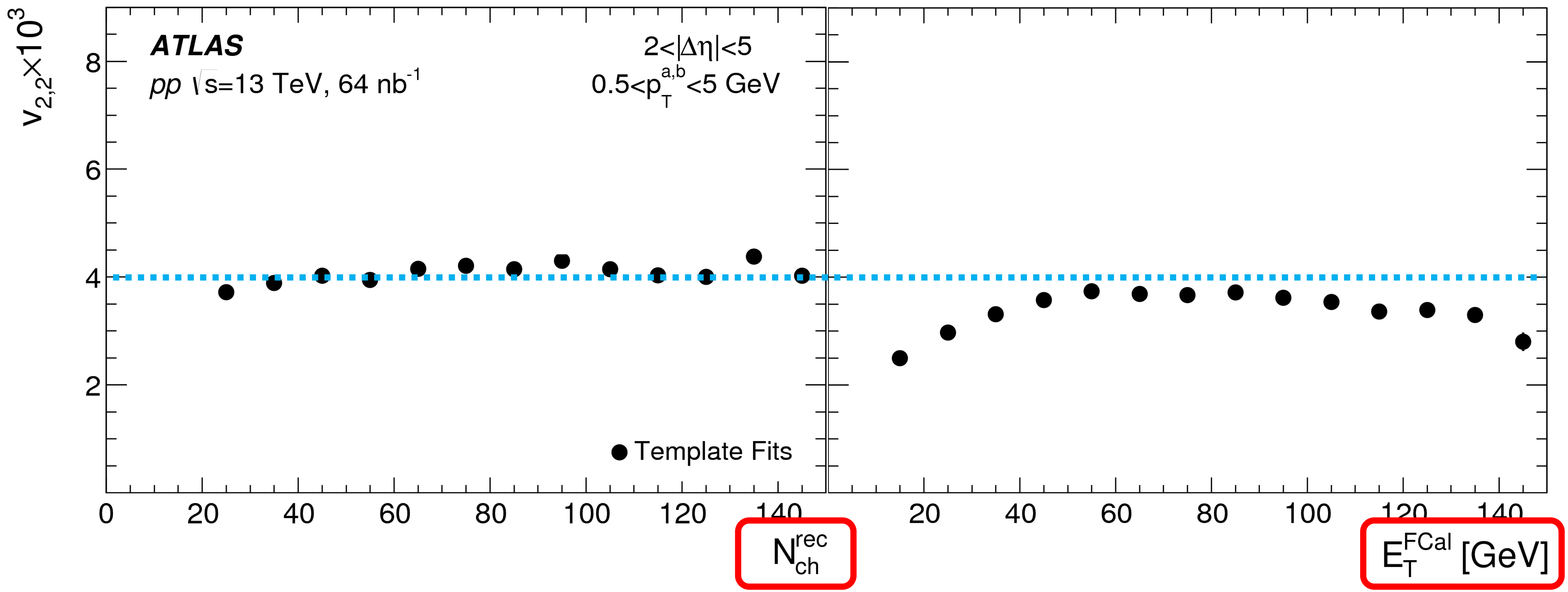
ALICE, PRC 91 064905



Leads to a **Jet Bias**: more likely to find (near and away side) jet in the η region of the multiplicity estimator:

- May affect subtraction procedure or non-flow in sample
- Multiplicity bins in theory (reduced for wide η acceptance)

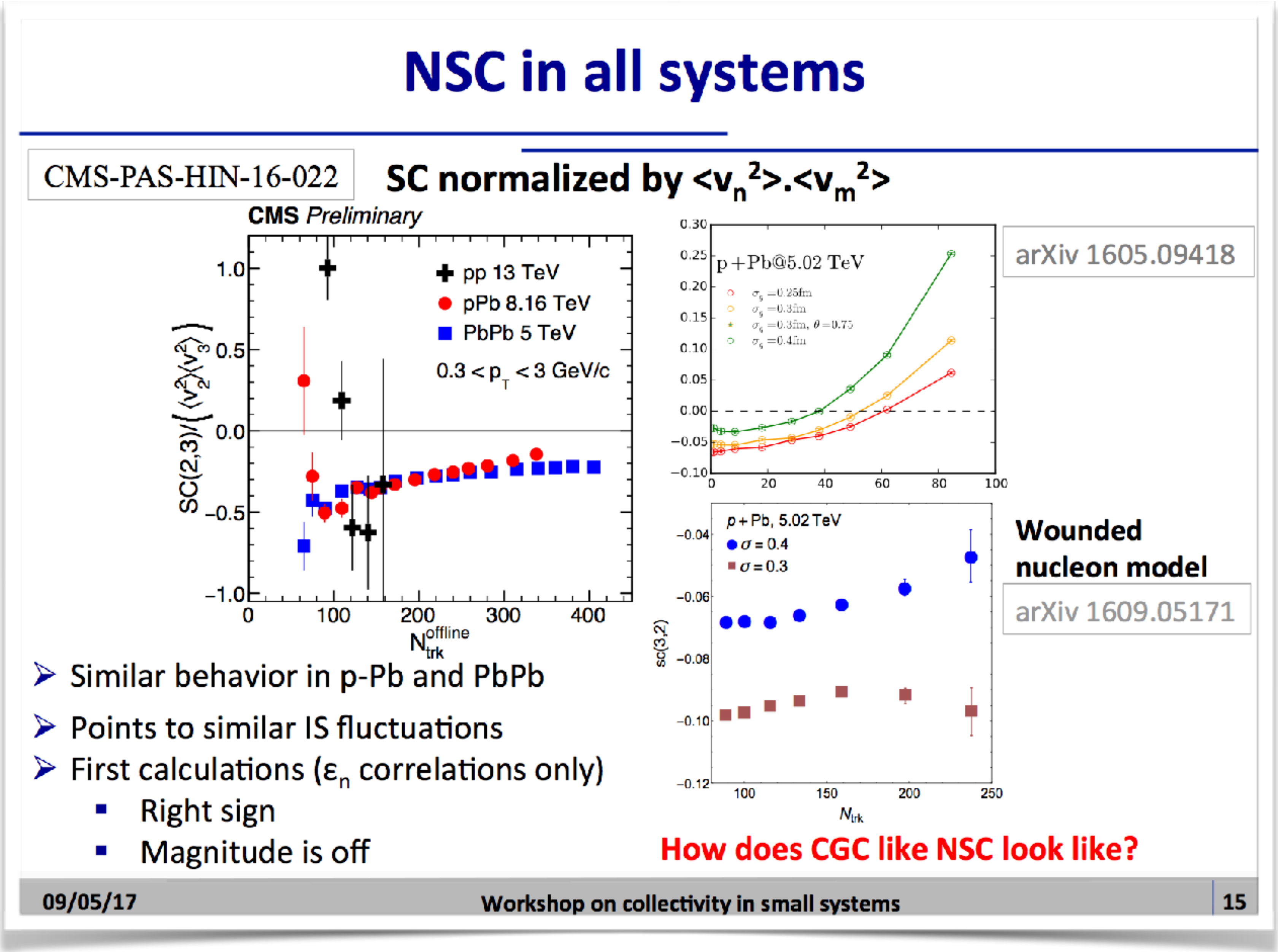
Plot by C. Bourjau, Pythia 6, Perugia 2011



- Try FCal E_T to quantify the event activity;
- v_2 correlated more with local multiplicity;
- "Centrality" may not be well defined by N_{ch} in *pp*.

M. Zhou

(Normalized) Symmetric Cumulants



- Sensitive to number of sources (fluctuations)
- **pp (?) pA, AA similar**
    - **pA** sensitive to sub-nucleonic fluctuations
    - **AA** sensitive to nucleons fluctuations
- Why are they similar?
- Residual non flow?

M Guilbaud, K Gajdosova, Y Zhou

(Normalized) Symmetric Cumulants

SC(3,2), SC(4,2) with 3-subevent

Niels Bohr Institutet

$$\langle\langle 4\rangle\rangle_{m,n,-m,-n} = \langle\langle \cos(\mathrm{m}\varphi_1 + \mathrm{n}\varphi_2 - \mathrm{m}\varphi_3 - \mathrm{n}\varphi_4)\rangle\rangle$$

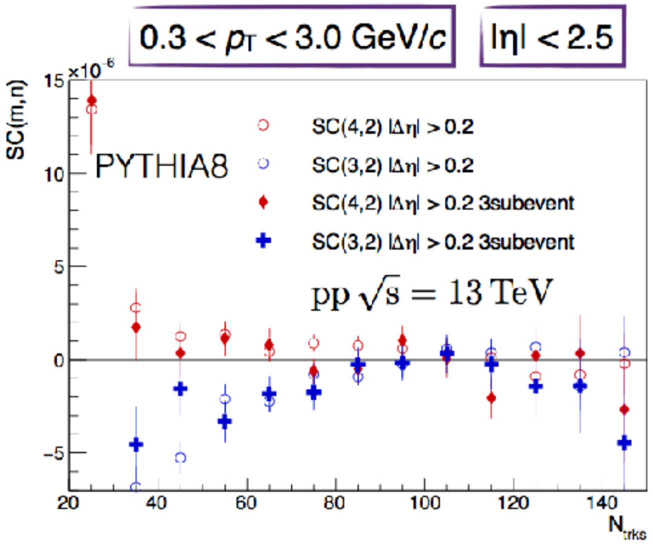
$$\langle\langle 2\rangle\rangle_{m,-m}\langle\langle 2\rangle\rangle_{n,-n} = \langle\langle \cos \mathrm{m}(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_4)\rangle\rangle$$

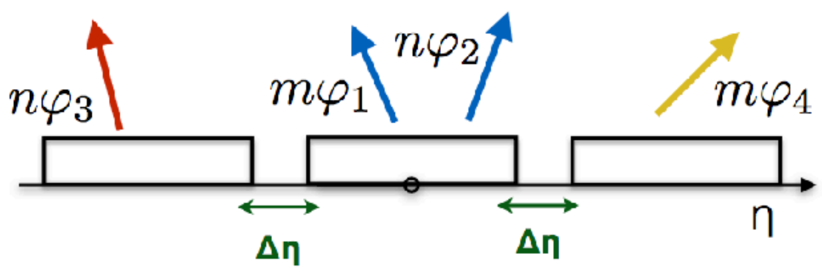
$$\langle\langle 4\rangle\rangle_{m,n,-n,-m} = \langle\langle \cos(\mathrm{m}\varphi_1 + \mathrm{n}\varphi_2 - \mathrm{n}\varphi_3 - \mathrm{m}\varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle_{n,-n}\langle\langle 2\rangle\rangle_{m,-m} = \langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_3)\rangle\rangle\langle\langle \cos \mathrm{m}(\varphi_1 - \varphi_4)\rangle\rangle$$

$$SC(m,n)_A = \langle\langle 4\rangle\rangle_{m,n,-m,-n} - 2\cdot\langle\langle 2\rangle\rangle_{m,-m}\langle\langle 2\rangle\rangle_{n,-n}$$

$$SC(m,n)_B = \langle\langle 4\rangle\rangle_{m,n,-n,-m} - 2\cdot\langle\langle 2\rangle\rangle_{n,-n}\langle\langle 2\rangle\rangle_{m,-m}$$





- We calculate SC(m,n) with 3-subevent method
- There is no significant difference between 2- or 3-subevent method

28 Katarina Gajdosova

- Sensitive to number of sources (fluctuations)
- **pp (?) pA, AA similar**
  - **pA** sensitive to sub-nucleonic fluctuations
  - **AA** sensitive to nucleons fluctuations
- Why are they similar?
- Residual non flow?

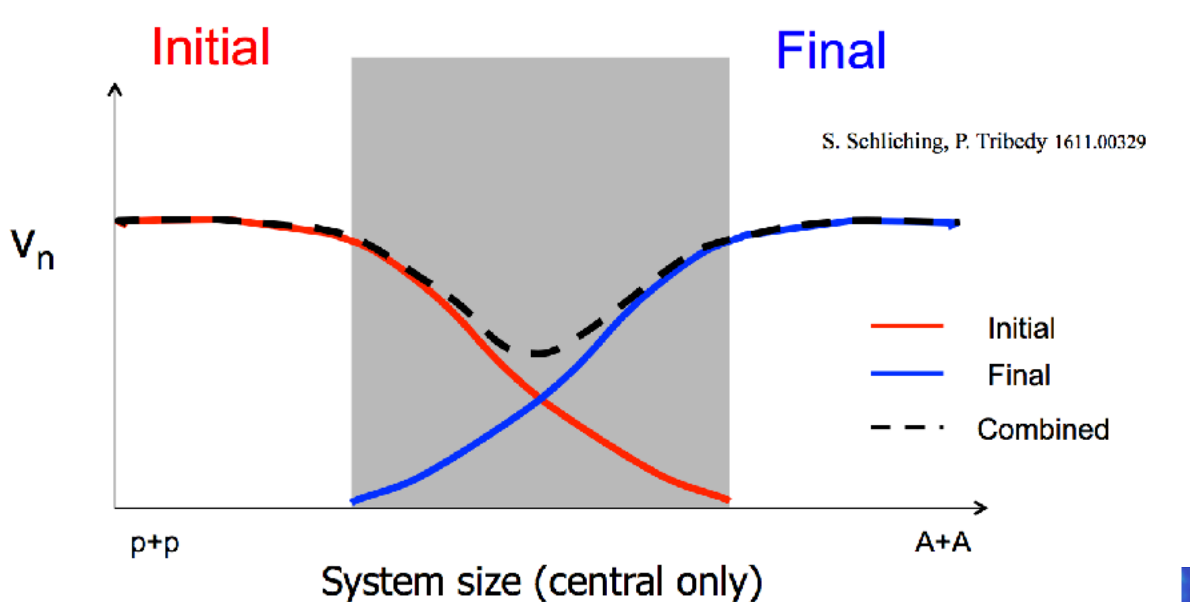
Looking forward to results with subevents + improved theory

M Guilbaud, K Gajdosova, Y Zhou

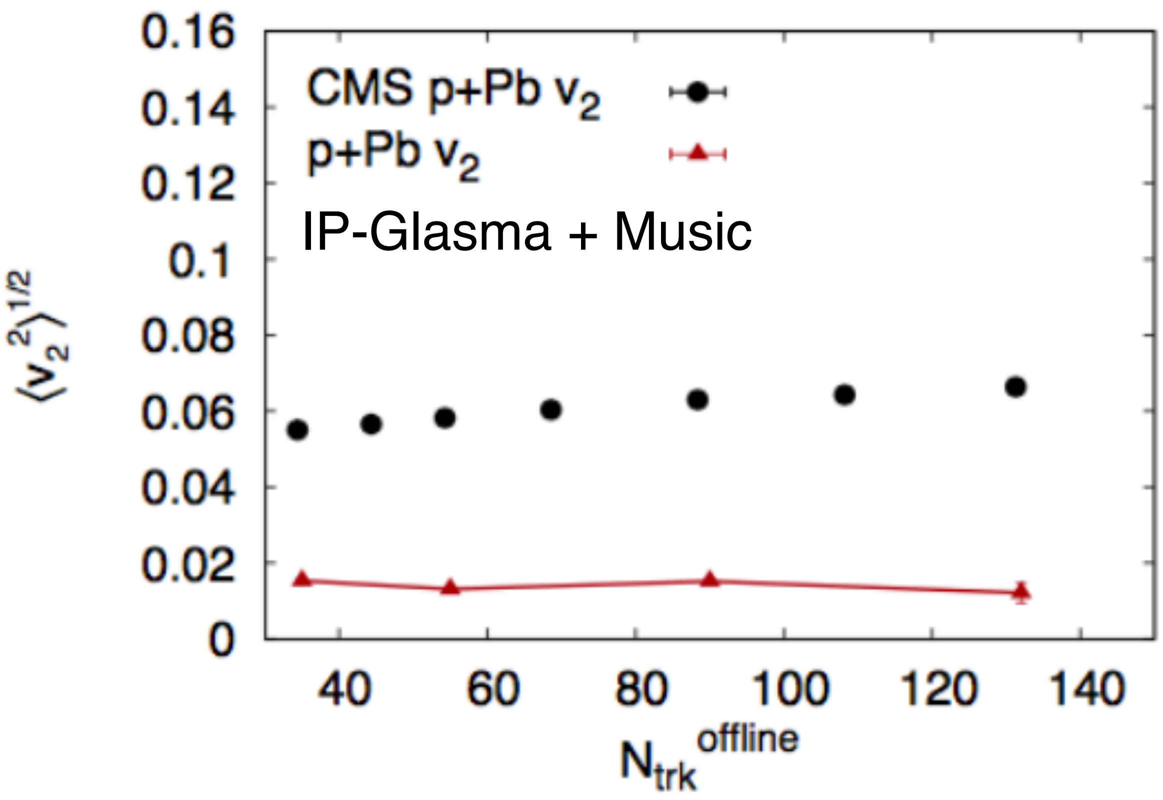
What do we want to learn?

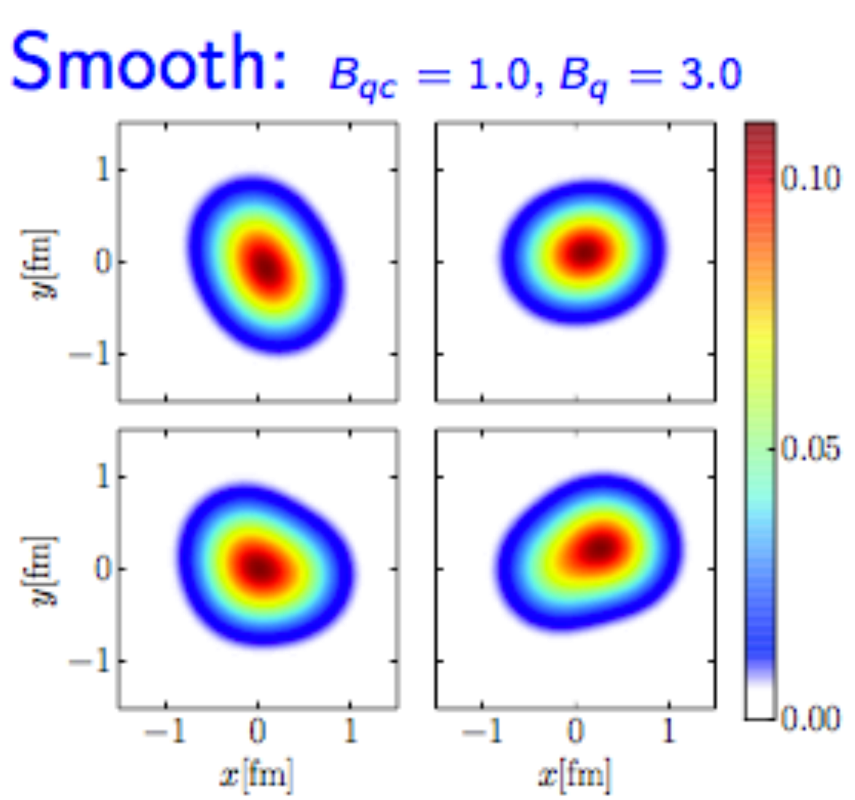
1. Initial State (CGC) or Final State (Hydro) Correlations?
   If hydro: learn about the medium properties
   If initial state: learn about saturation
2. **Microscopic processes**: reconcile with "traditional" pp Monte Carlos

Status:
Hydro describes reasonably well **systematics of data** across energies and colliding systems
Saturation more "**qualitative**"
(proof of principle mechanisms to describe most observables advocated, but no systematic comparisons)



Describing all systems simultaneously difficult → nucleon substructure?

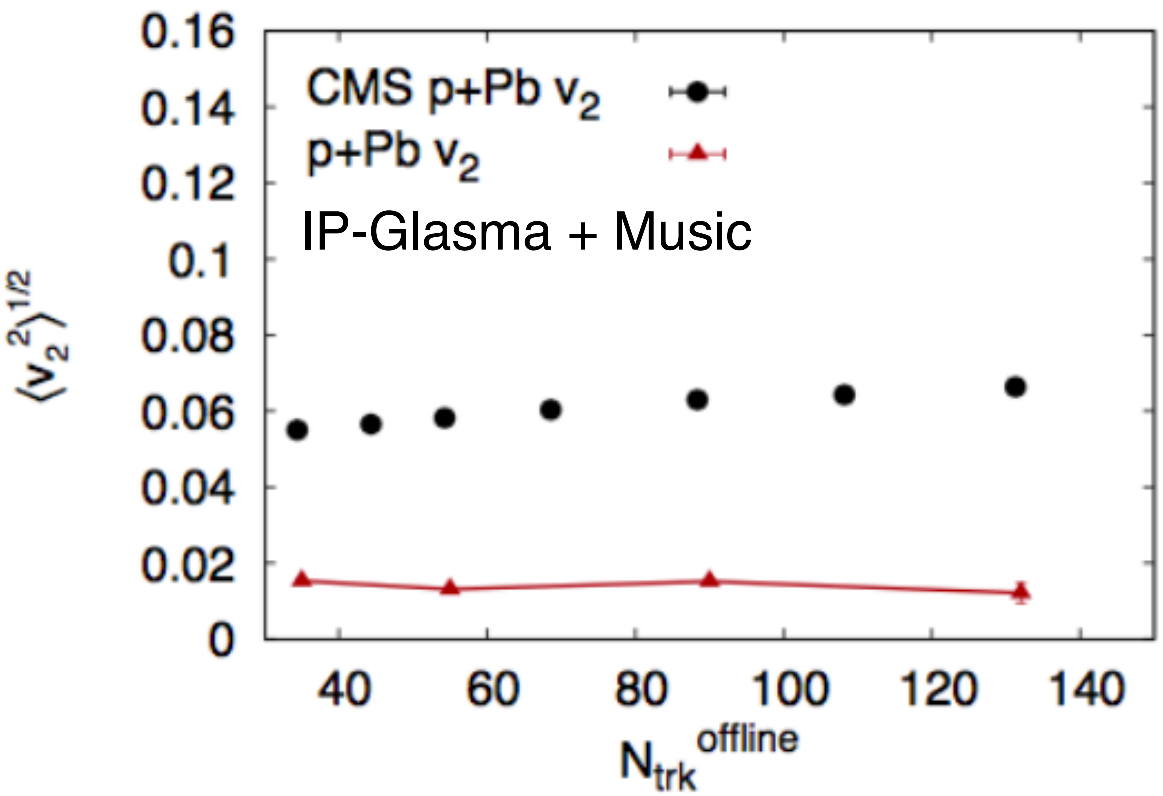


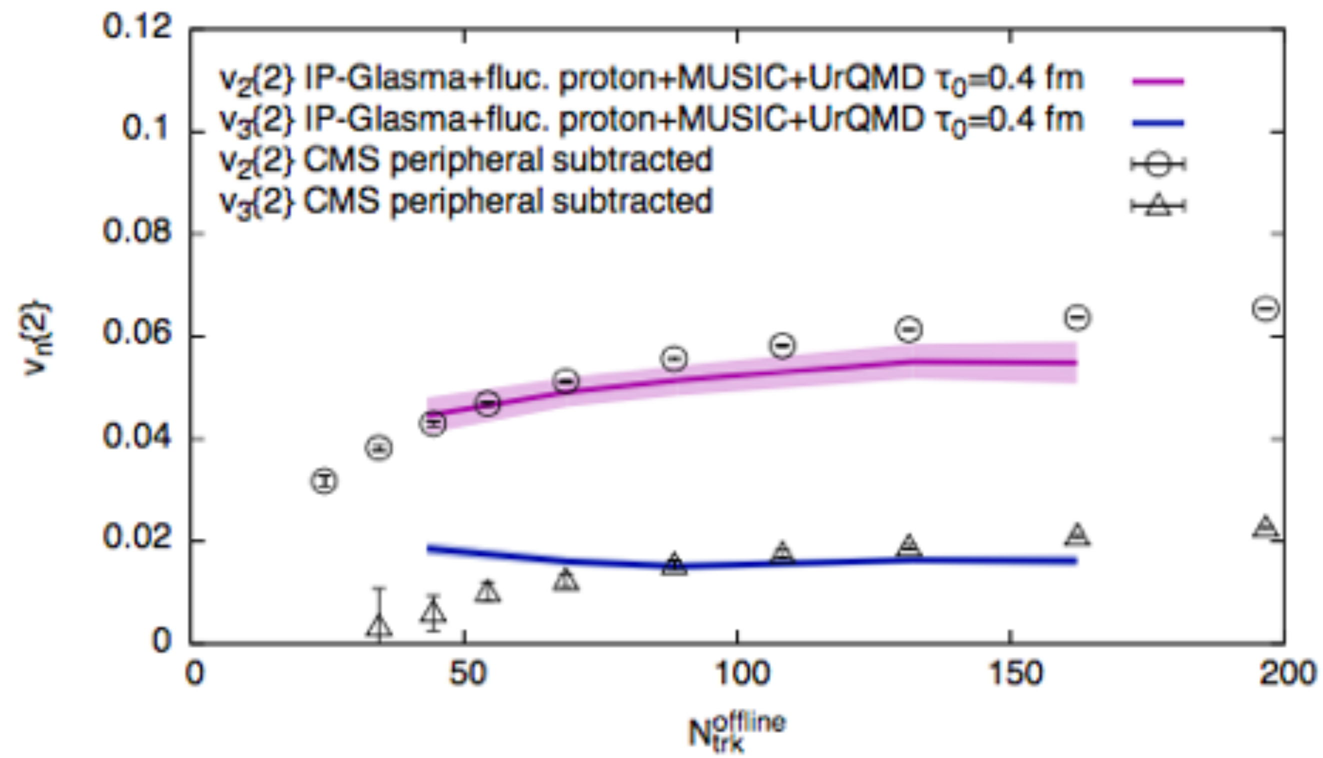


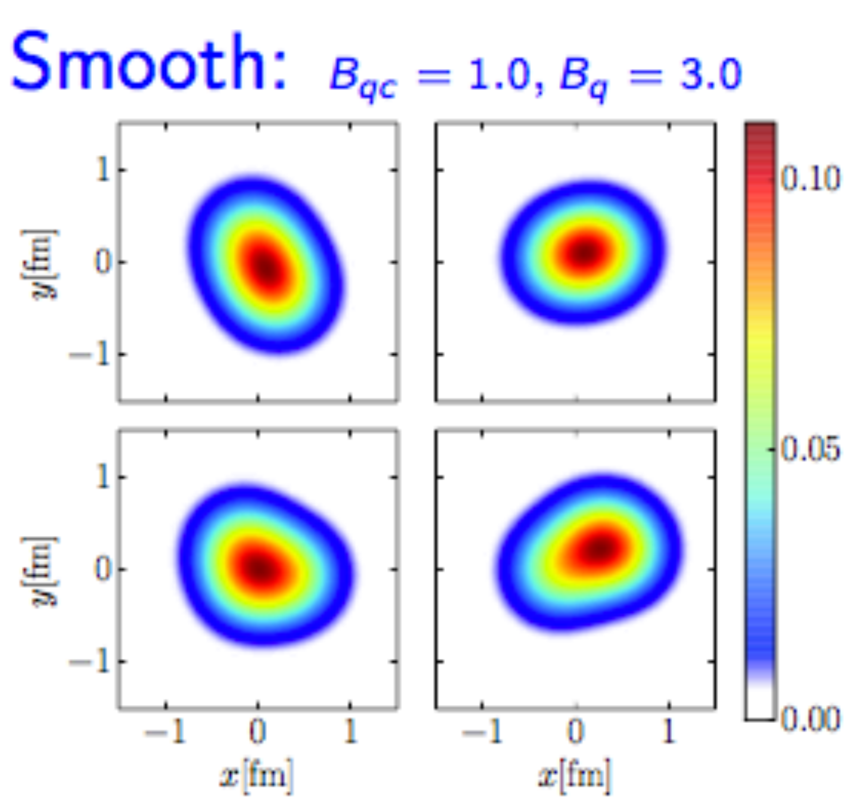
B Schenke

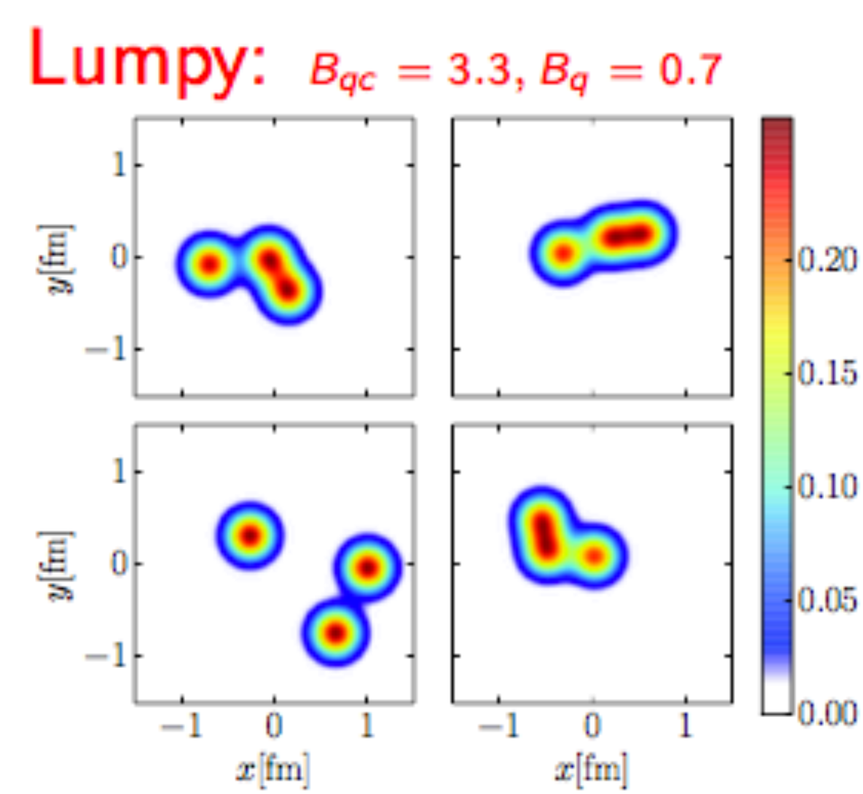
Hydro modeling and nuclear substructure

Describing all systems simultaneously difficult → nucleon substructure?







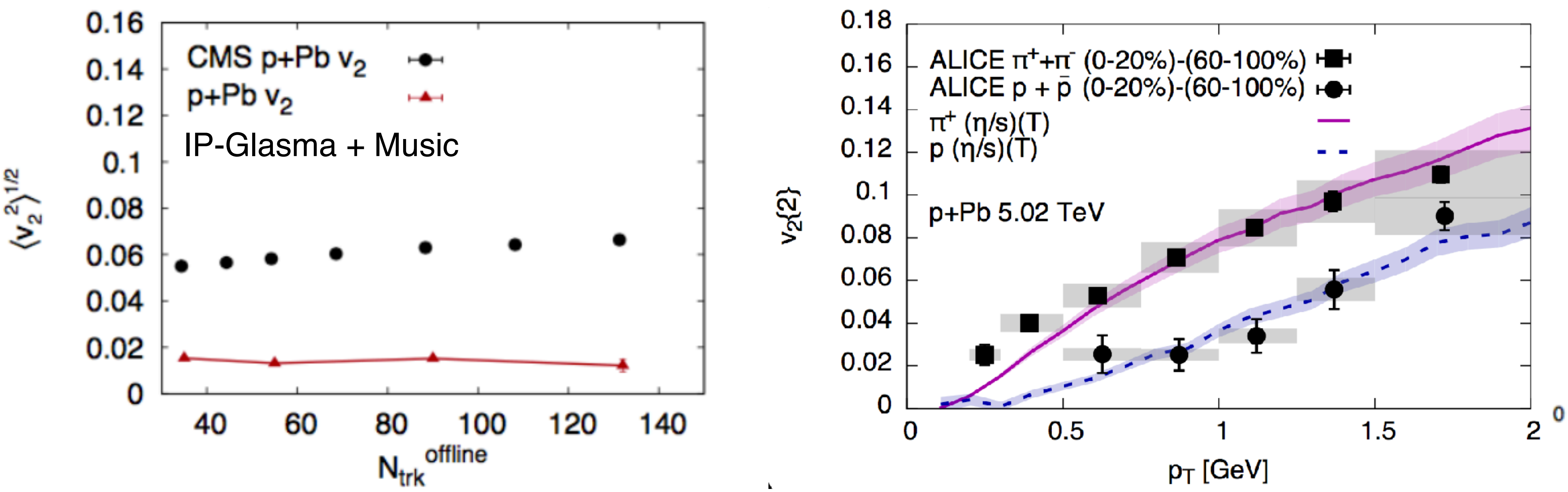


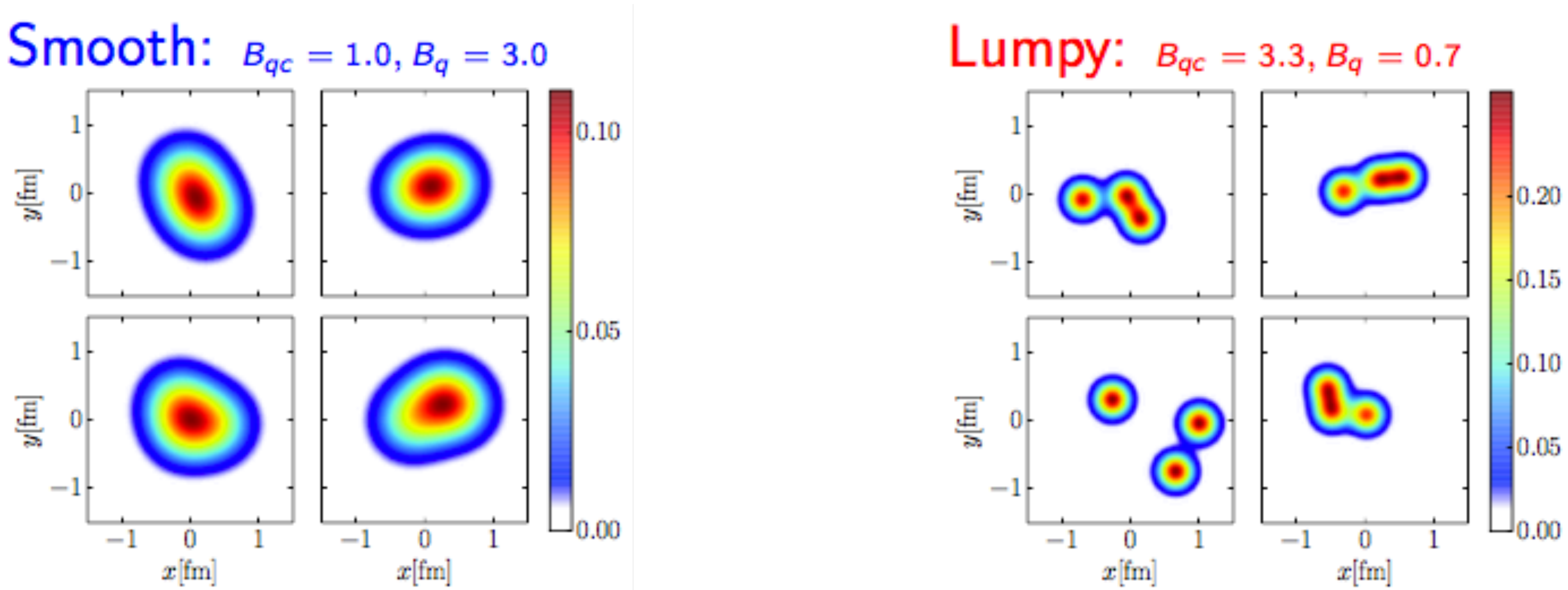
(constrained with diffraction measurements)

B Schenke

Hydro modeling and nuclear substructure

Describing all systems simultaneously difficult → nucleon substructure?





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B Schenke

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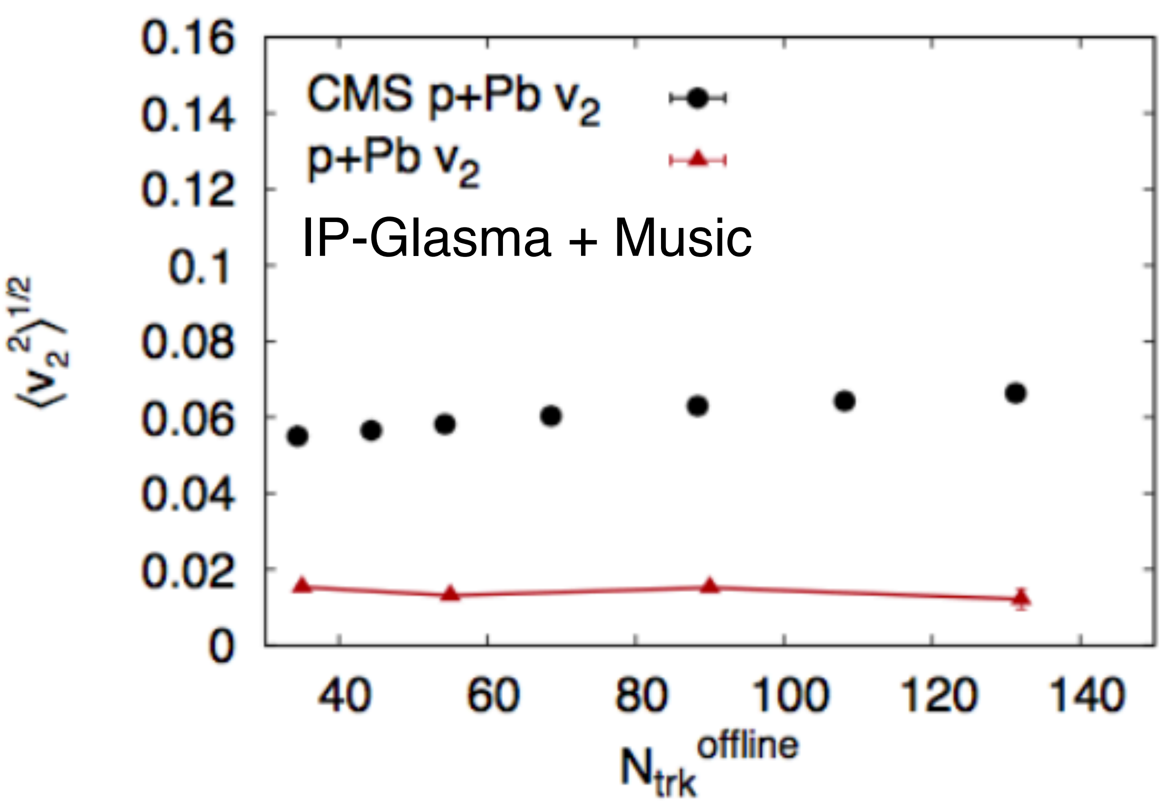
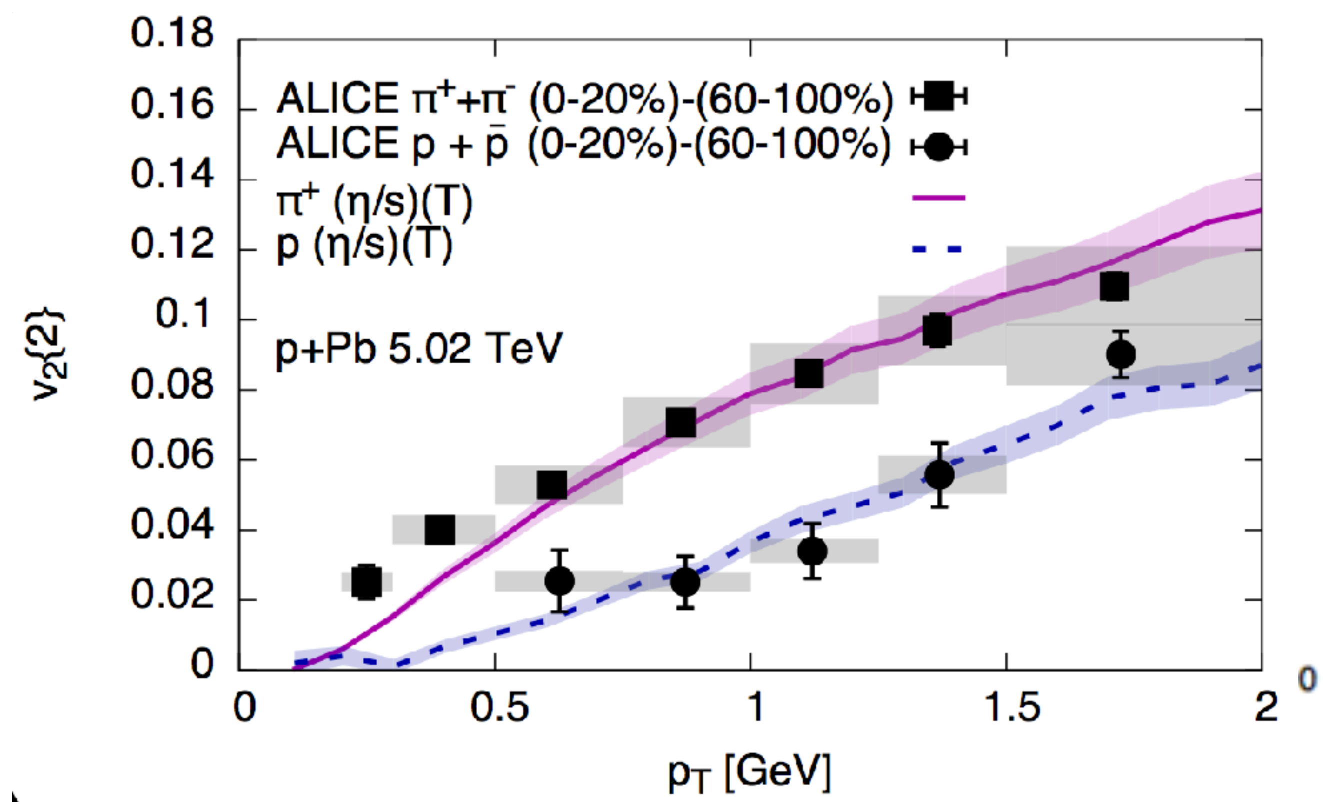
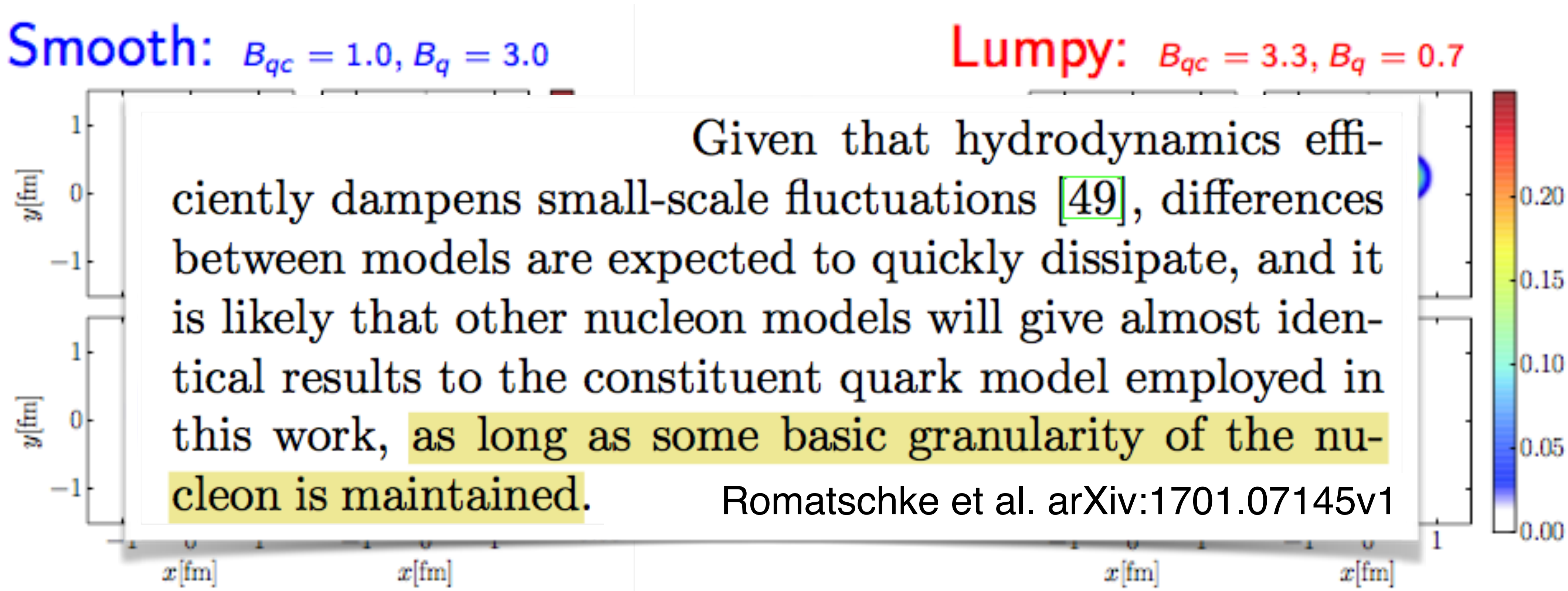






Given that hydrodynamics efficiently dampens small-scale fluctuations [49], differences between models are expected to quickly dissipate, and it is likely that other nucleon models will give almost identical results to the constituent quark model employed in this work, as long as some basic granularity of the nucleon is maintained.

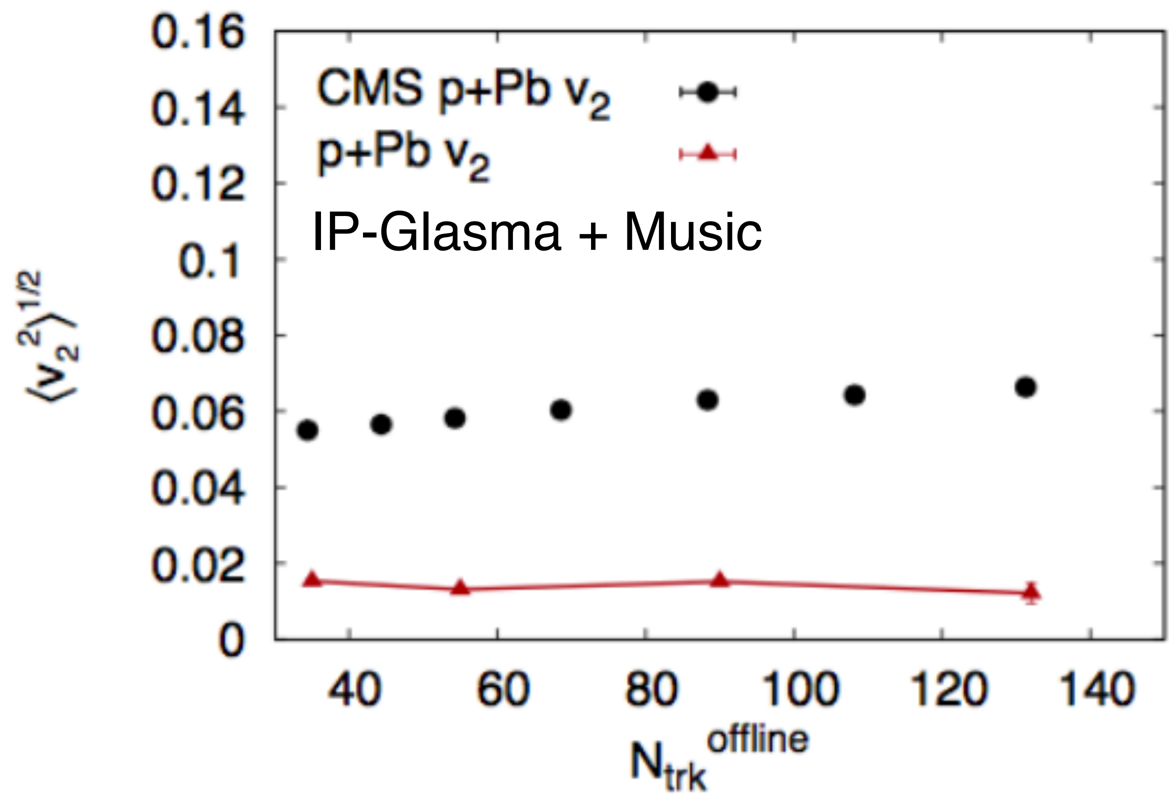
Romatschke et al. arXiv:1701.07145v1

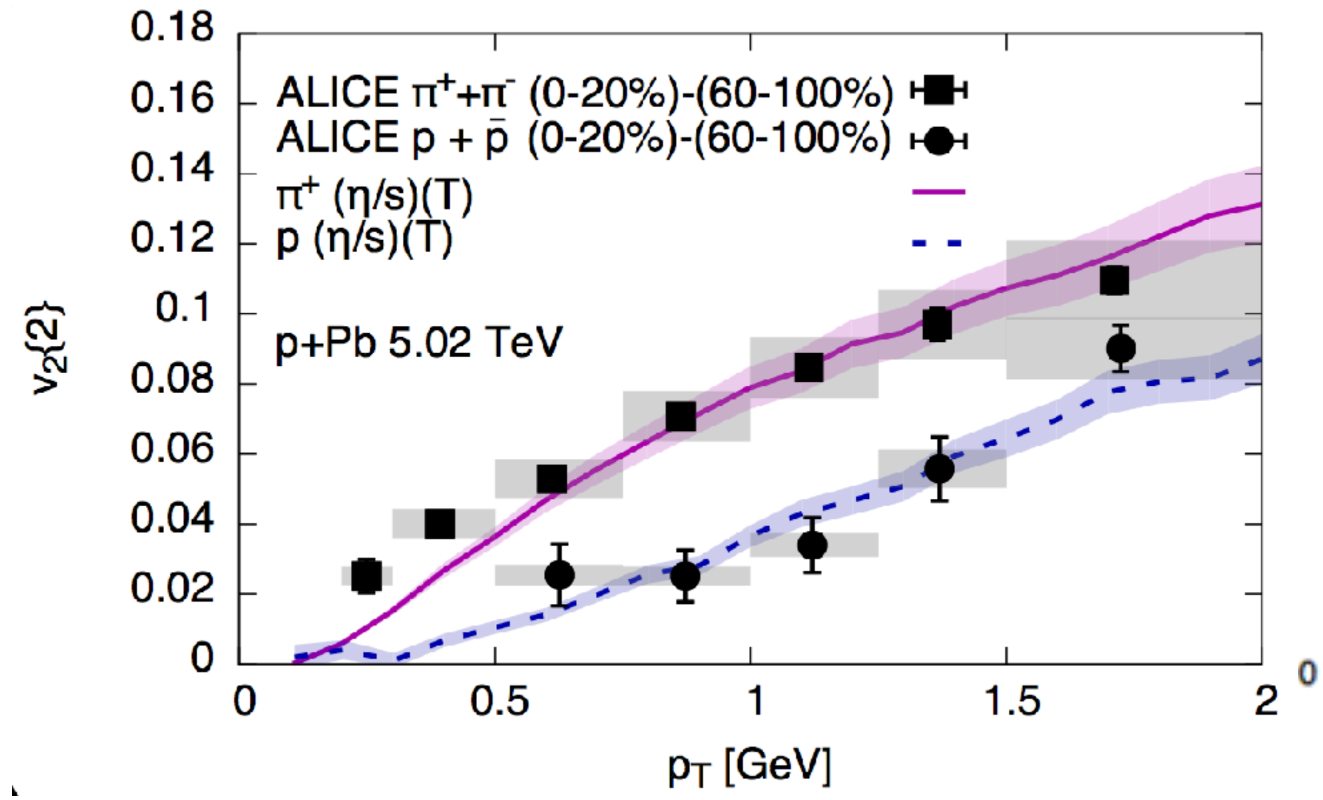
B Schenke

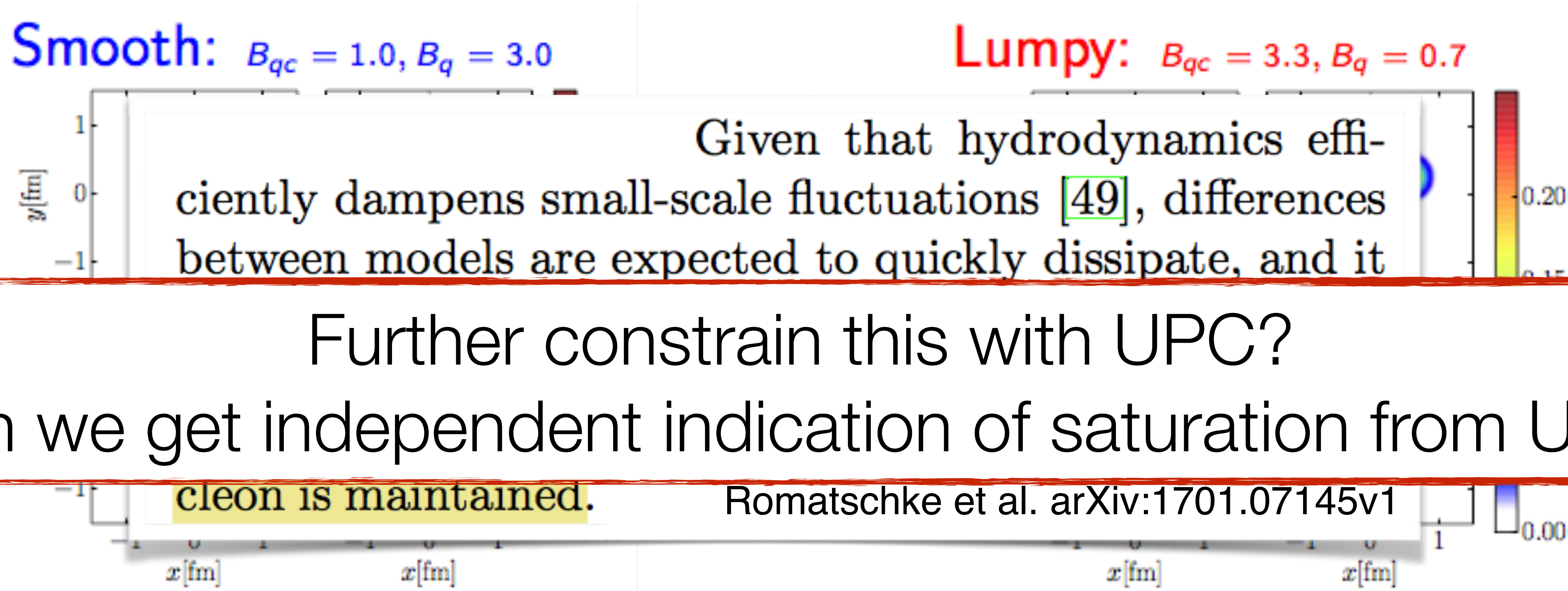
(constrained with diffraction measurements)

Hydro modeling and nuclear substructure

Describing all systems simultaneously difficult → nucleon substructure?







Given that hydrodynamics efficiently dampens small-scale fluctuations [49], differences between models are expected to quickly dissipate, and it

cleon is maintained.

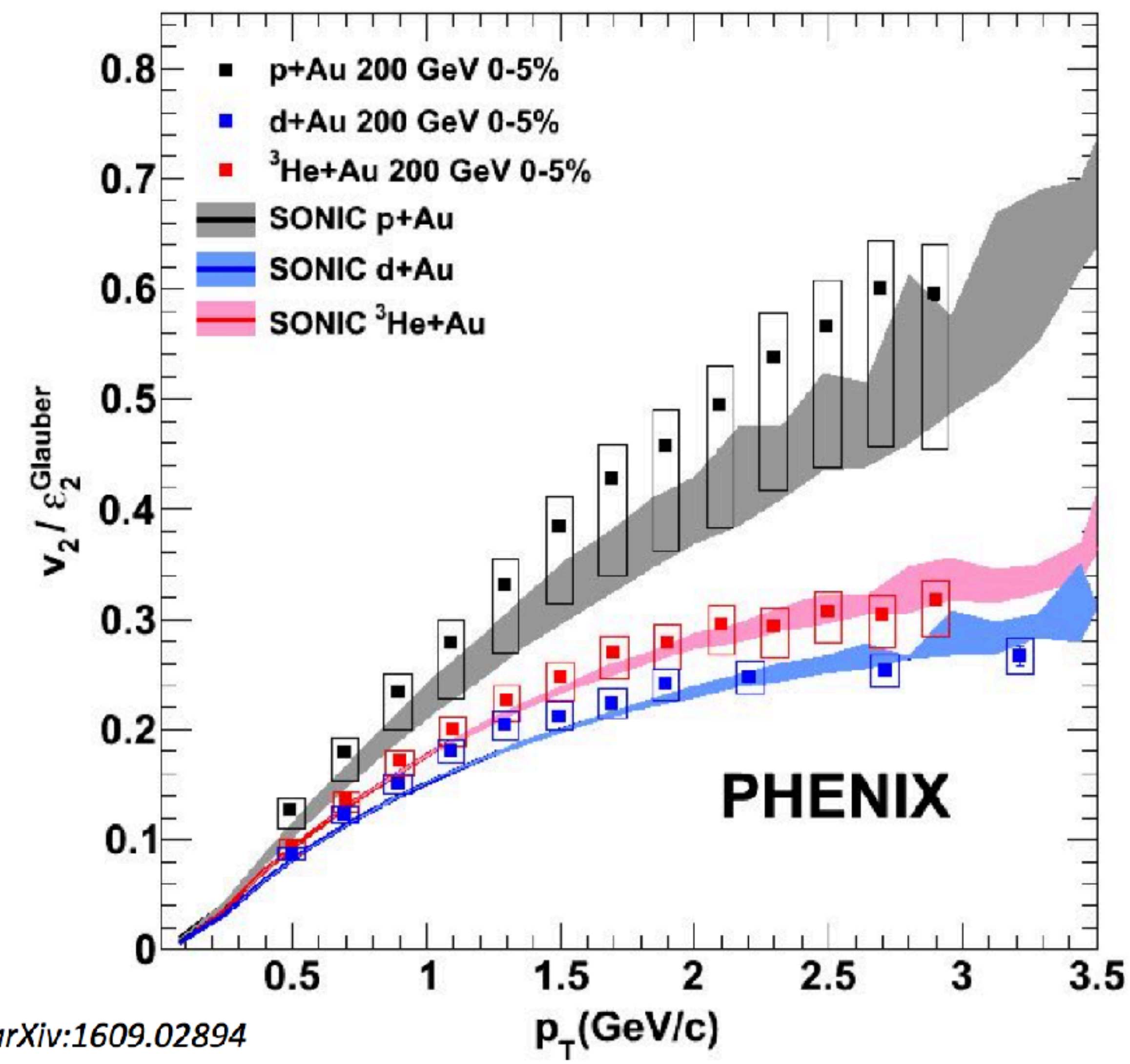
Romatschke et al. arXiv:1701.07145v1

Further constrain this with UPC?
Can we get independent indication of saturation from UPC?

B Schenke

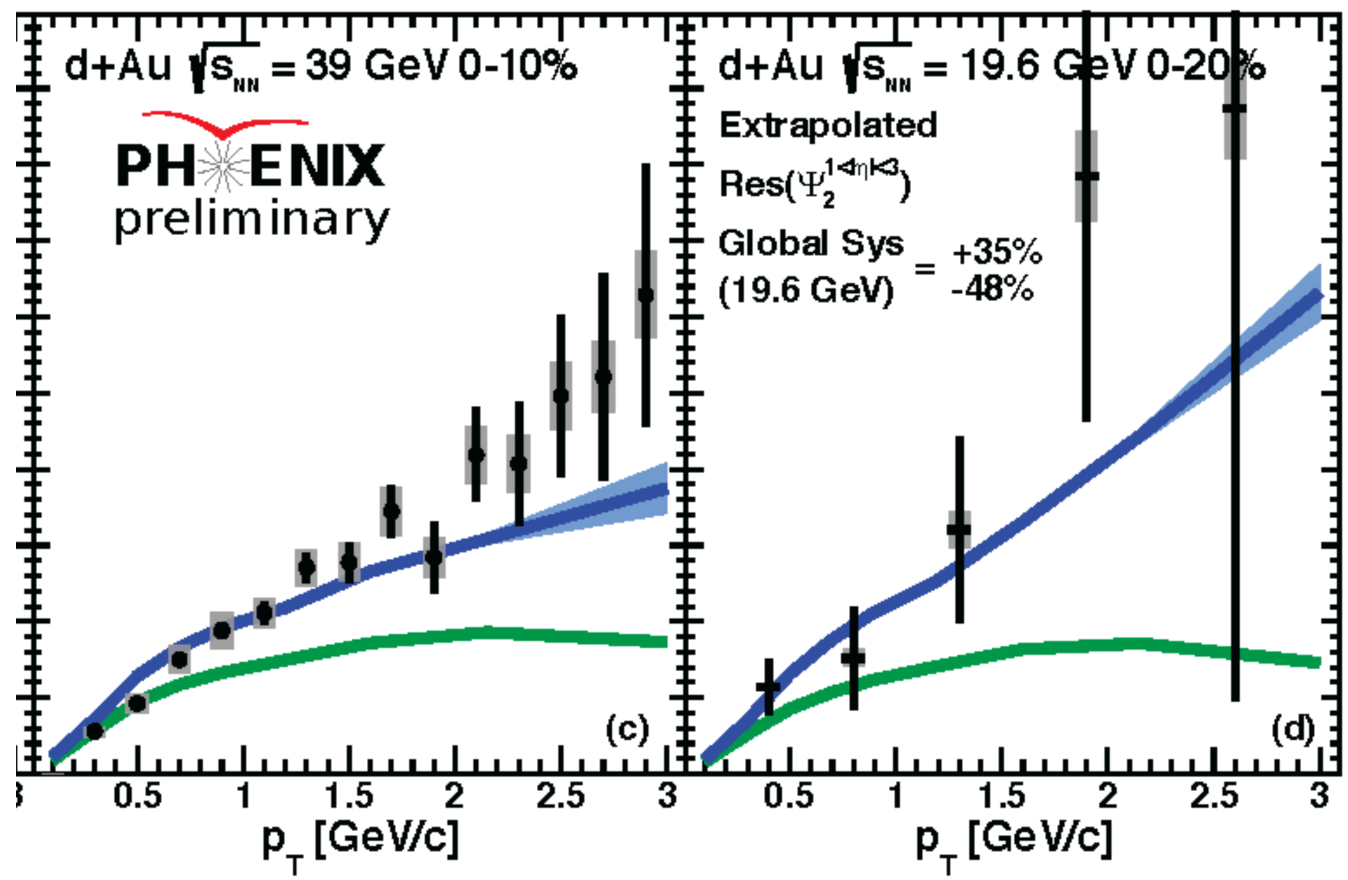
(constrained with diffraction measurements)

Hydro and system size systematics



arXiv:1609.02894

39 GeV **20 GeV**



Pure Flow

With Non-Flow

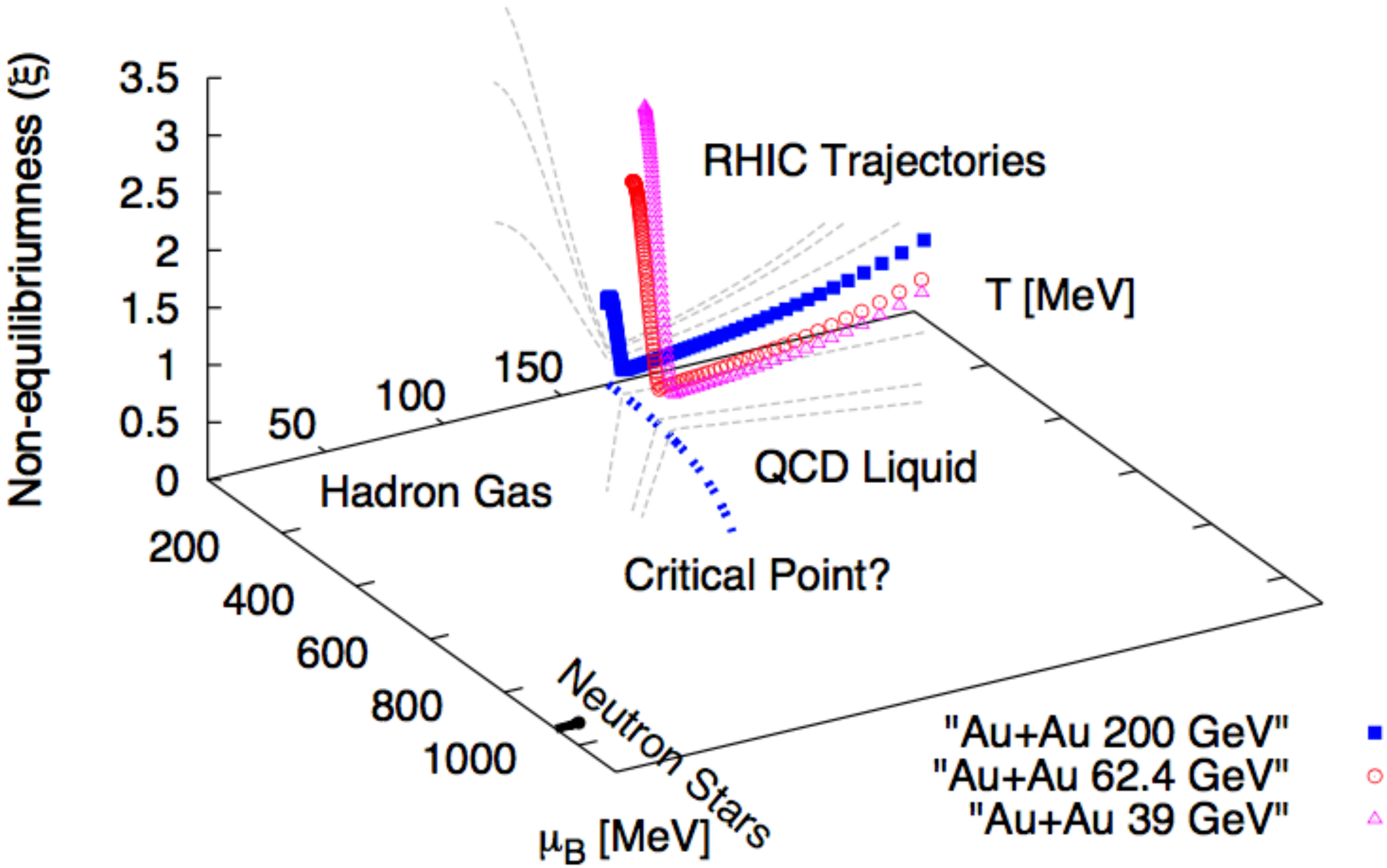
Geometry engineering:
Colliding systems control for the initial geometry
Very good agreement with hydro **predictions**

Evidence for collective effects down to **39 GeV**?

J Velkovska

Implications for heavy ions?

Implications for heavy ions?



[PR, 1609.02820]

Hydro ⇏ Equilibration!

Do nuclear collisions equilibrate?

No

P. Romatschke, QM17

P. Romatschke, arXiv:1704.08699

Hydro as an **effective theory**:
Various microscopic models shown to converge to **attractor solution**, **consistent with viscous hydro** far from equilibrium
(for not-too-large gradients)

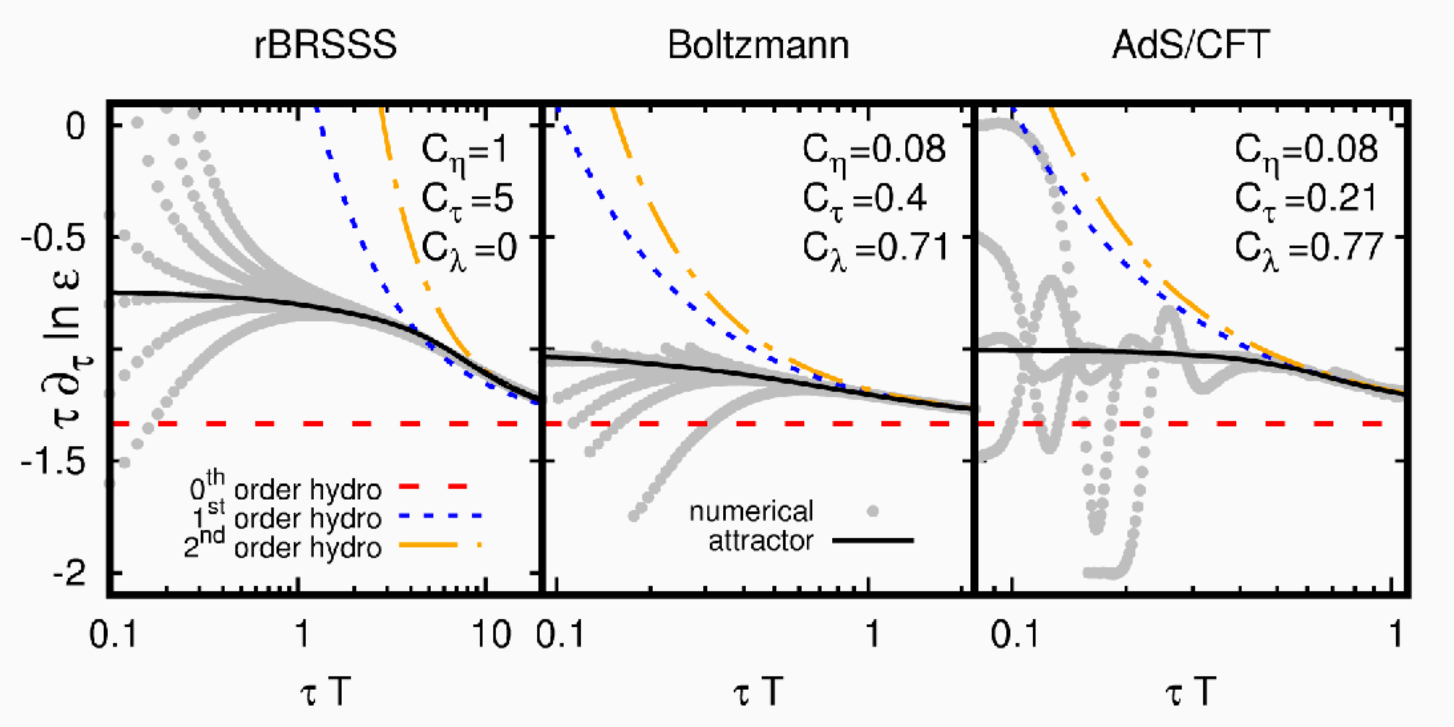


FIG. 1. Numerical results for energy density evolution as a function of inverse gradient strength τT for conformal Bjorken flow in three different microscopic theories. See text for details.

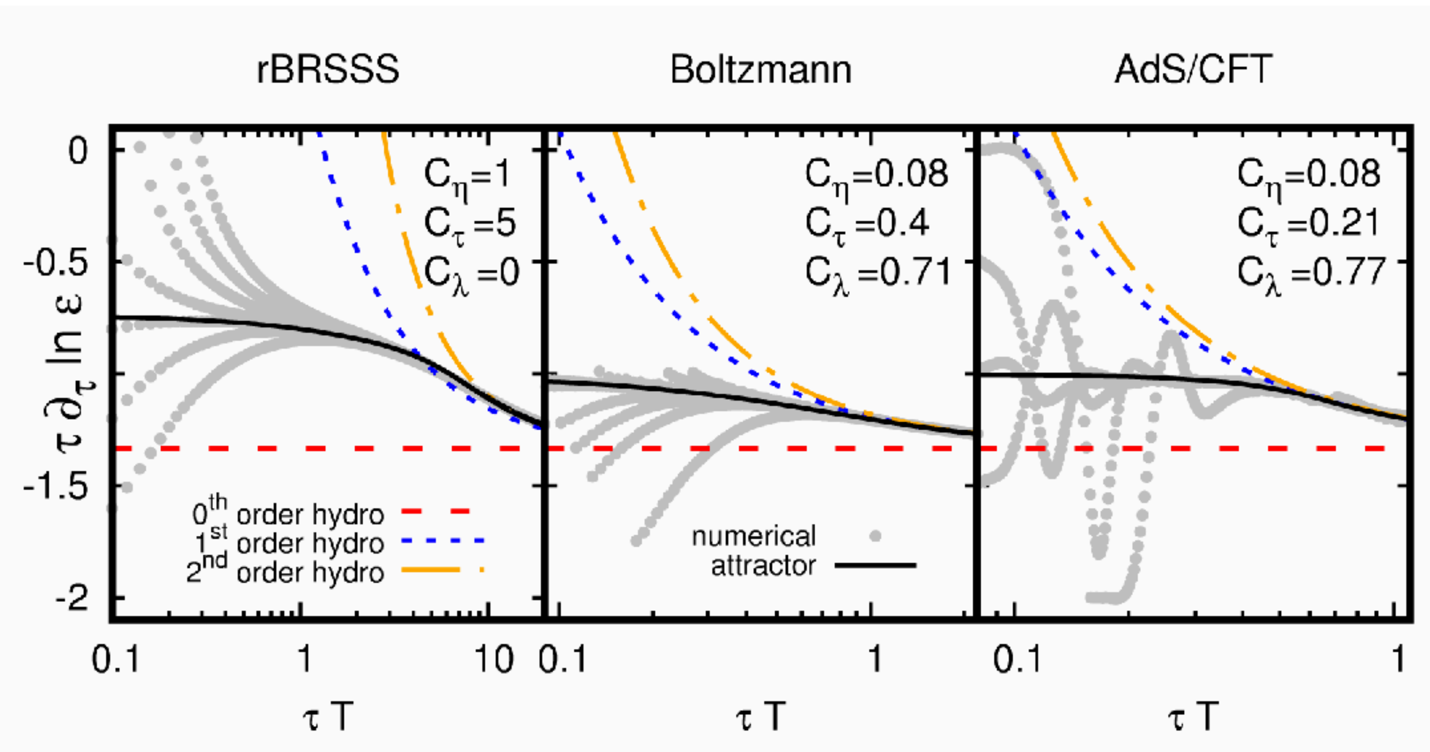
What are we actually measuring?

P. Romatschke, arXiv:1704.08699

Hydro as an **effective theory**:
Various microscopic models shown to converge to **attractor solution**, **consistent with viscous hydro** far from equilibrium
(for not-too-large gradients)

Leads to an **effective viscosity** η_B:

→ what are we actually learning about the medium?



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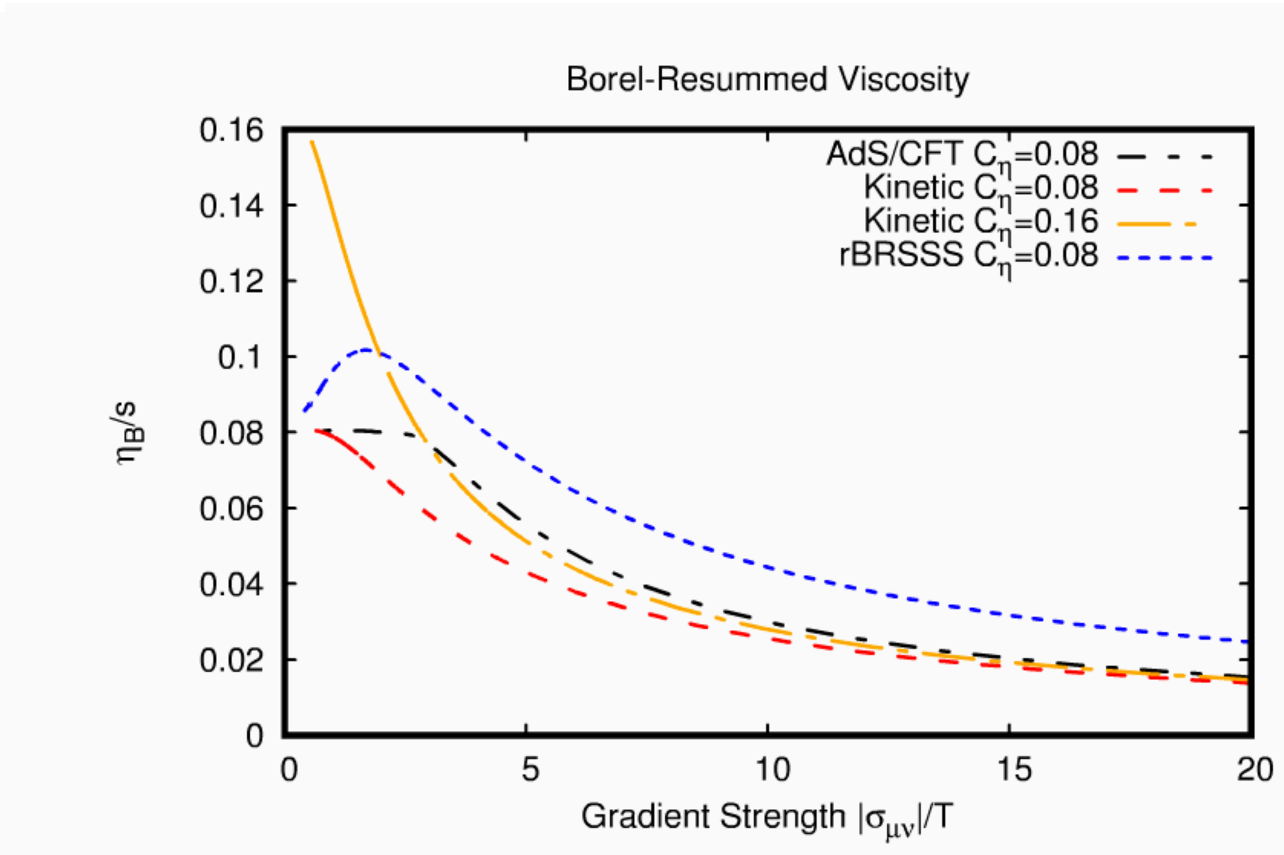


Other measurements and observables

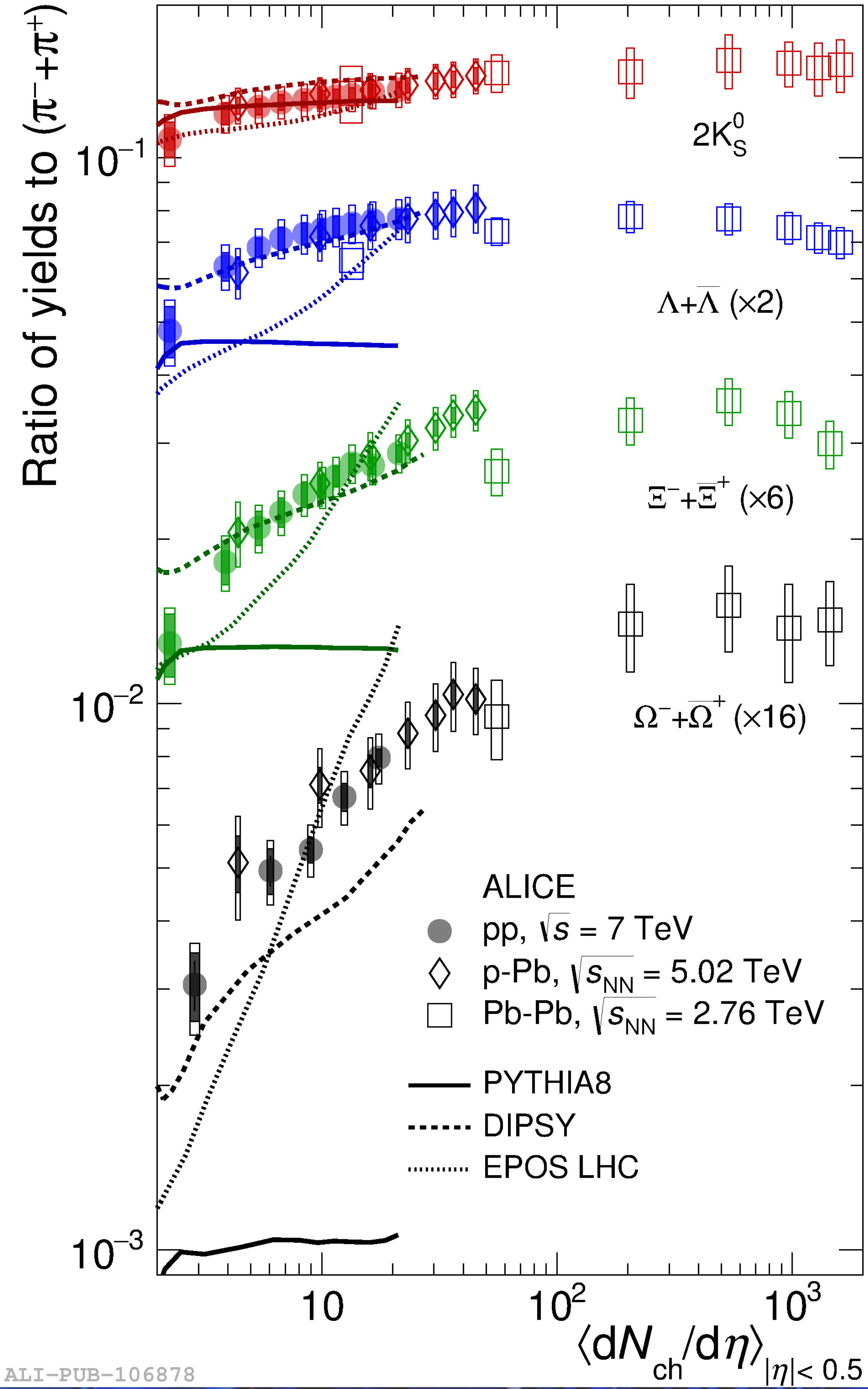
What about **other phenomena** once considered the **hallmark of heavy ions** in small systems**?**

- **Identified particles** -> strangeness enhancement in pp/pA
- **Thermal diletpons/photons** -> not measured, but predicted if interacting medium
- **Energy loss** -> negative measurements so far

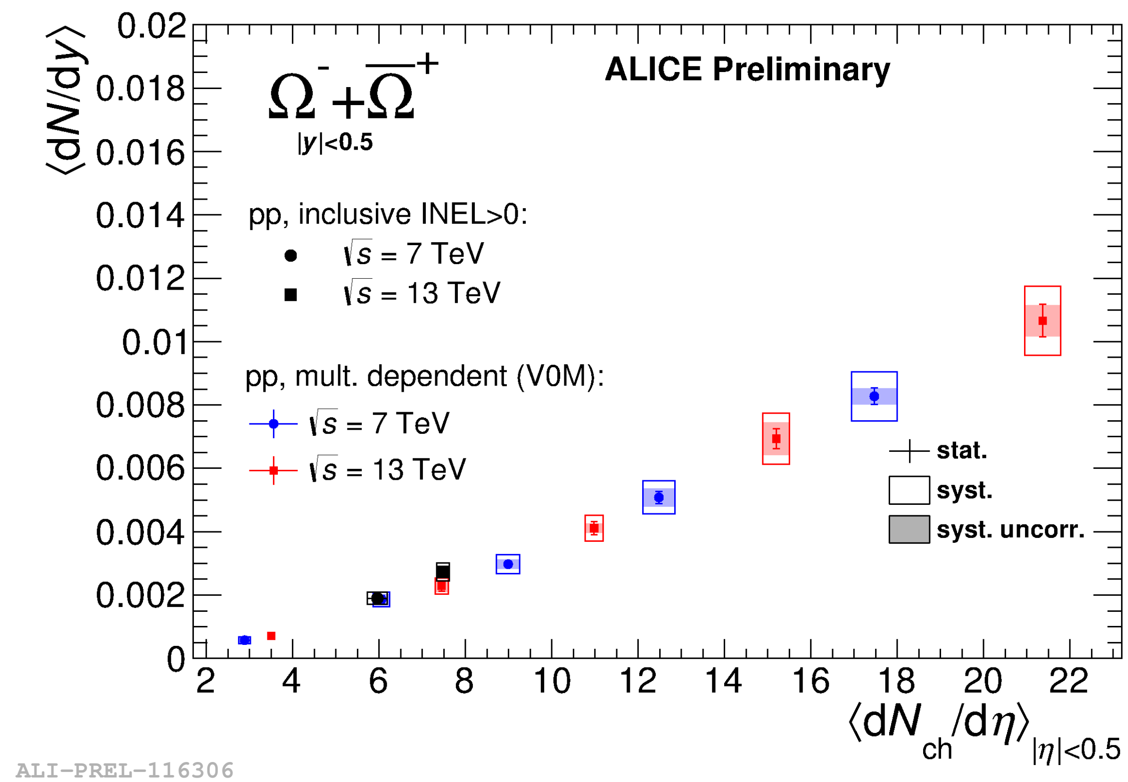
Ideally: consistent theoretical framework and unified description

Identified Particles

Ratios vs Multiplicity



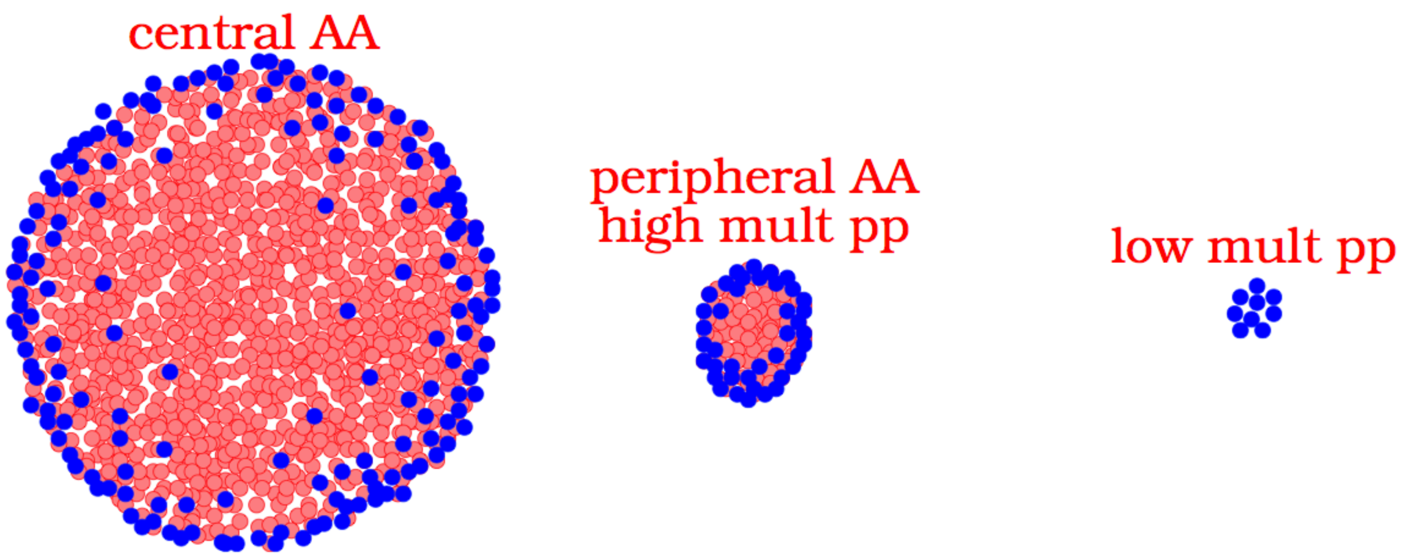
- **Smooth evolution** of particle ratios across different systems
- **Enhancement** of relative **strangeness** content with multiplicity
- Traditional **soft QCD models** (e.g. Pythia) do not reproduce this
  - But EPOS and DIPSY -> dynamics
- **ALICE @ QM17**: √s dependence



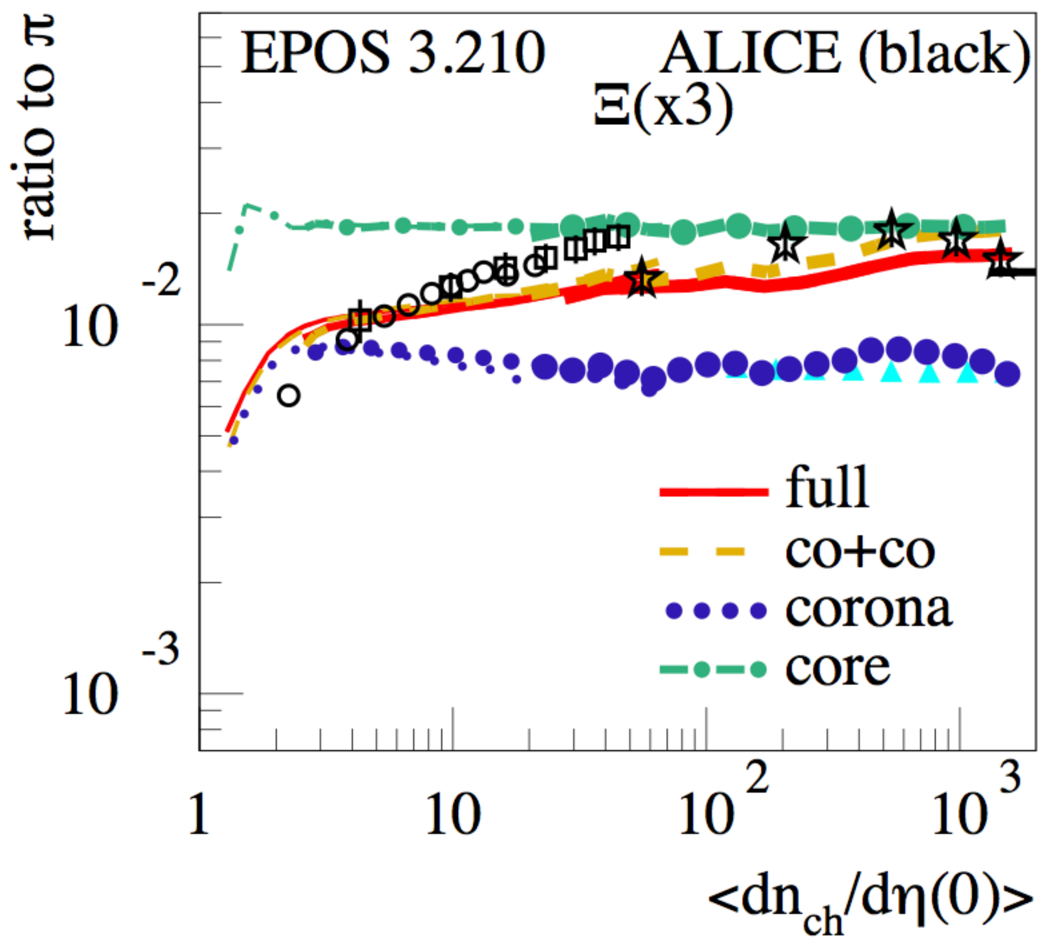
arXiv:1606.07424 , V. Vislavicius, ALICE, QM17

EPOS and Core-Corona

Core-Corona Approach to describe change in hadrochemistry in EPOS



Core evolves collectively
→ flow



Qualitatively **describes data** (but not an explanation of the strangeness enhancement)

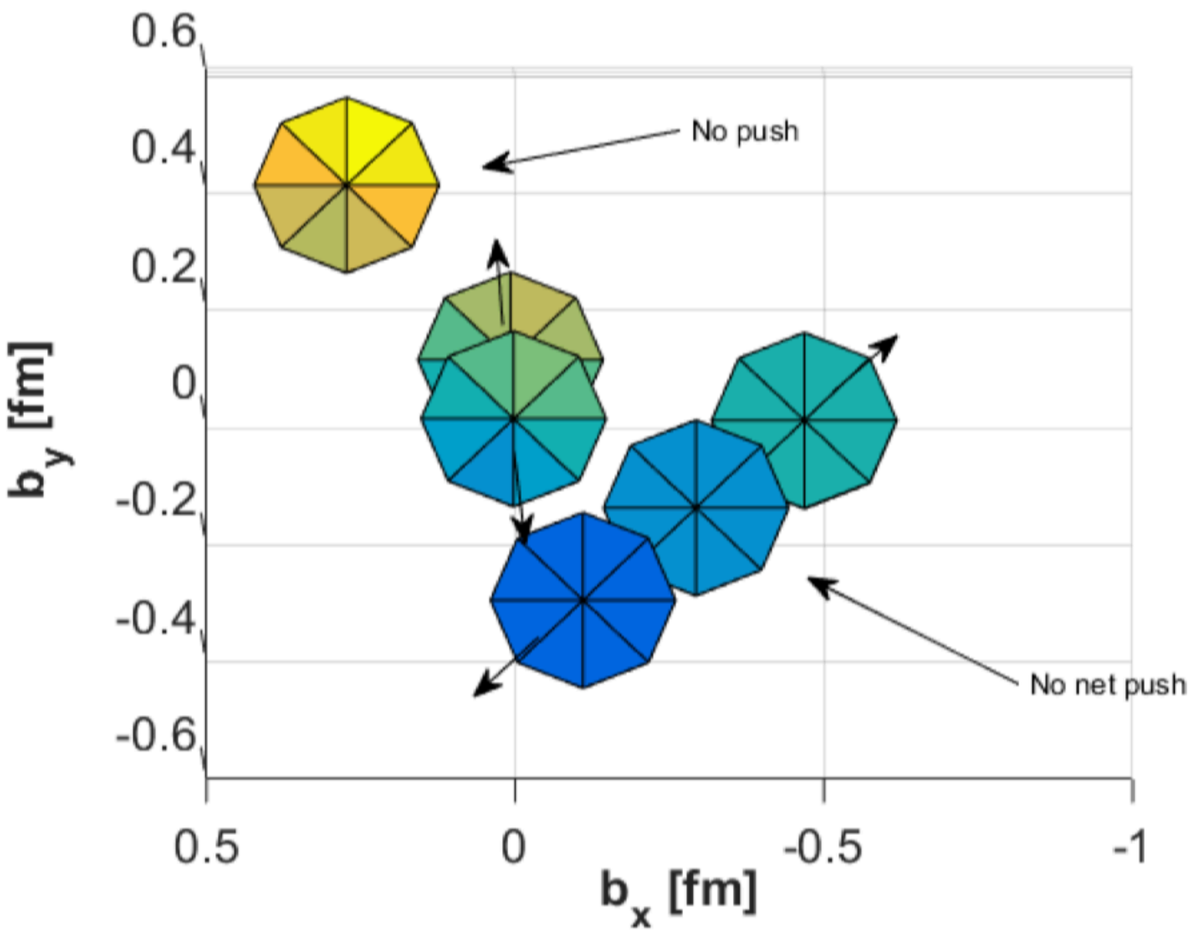
EPOS 3 also describes collective behavior

DIPSY and Color Ropes

Color Ropes: Overlapping strings → excess energy

Ropes increase effective **string tension** → strangeness enhancement

String shoving: local transverse pressure → **anisotropy**



(Is this conceptually similar to core-corona?)

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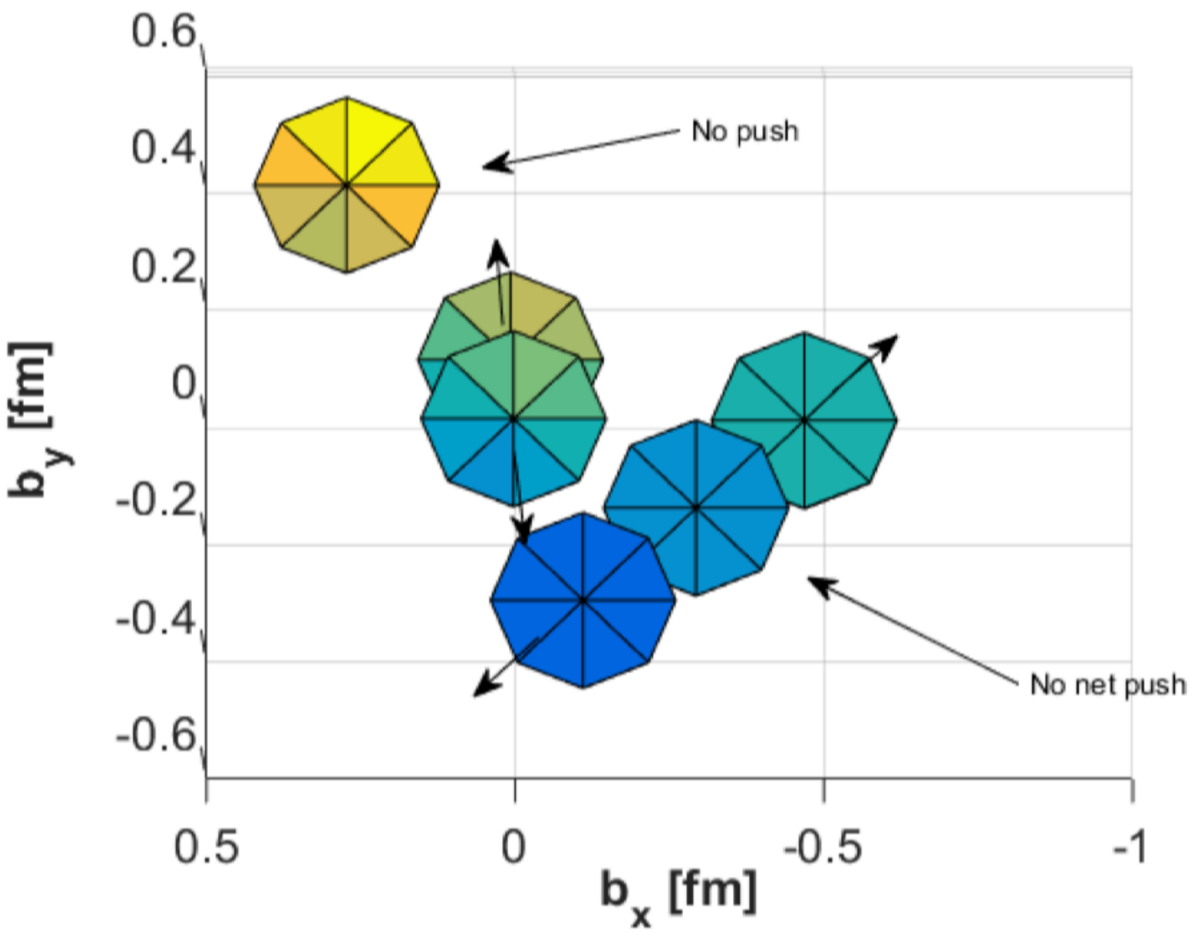

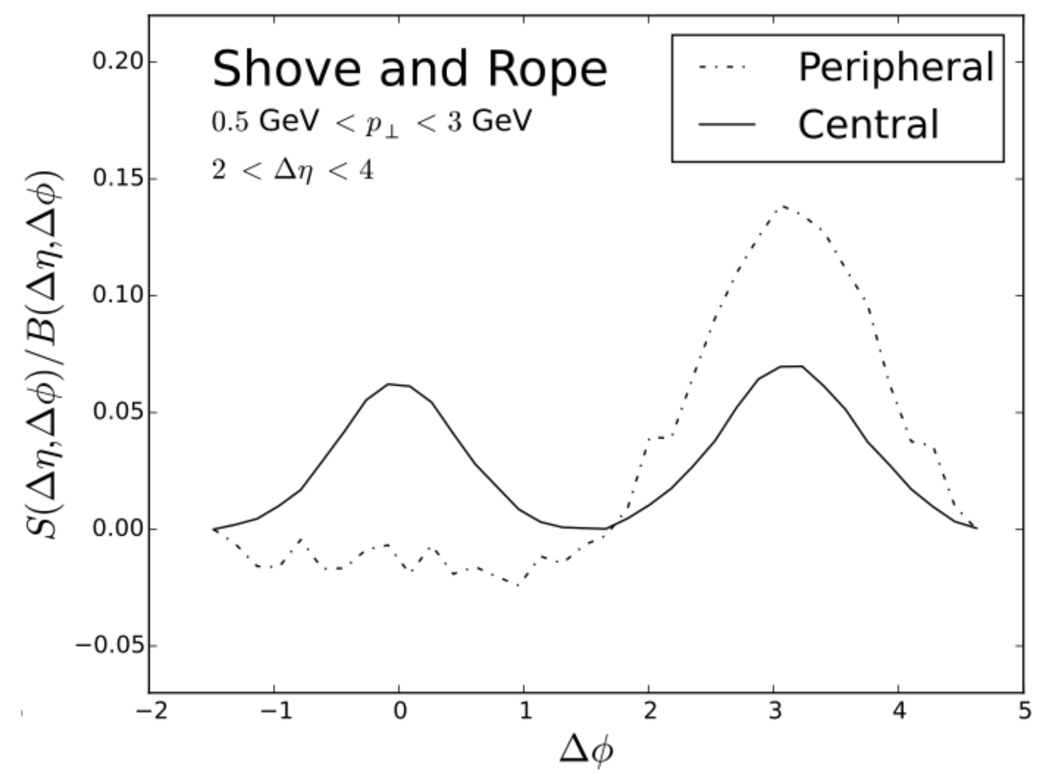

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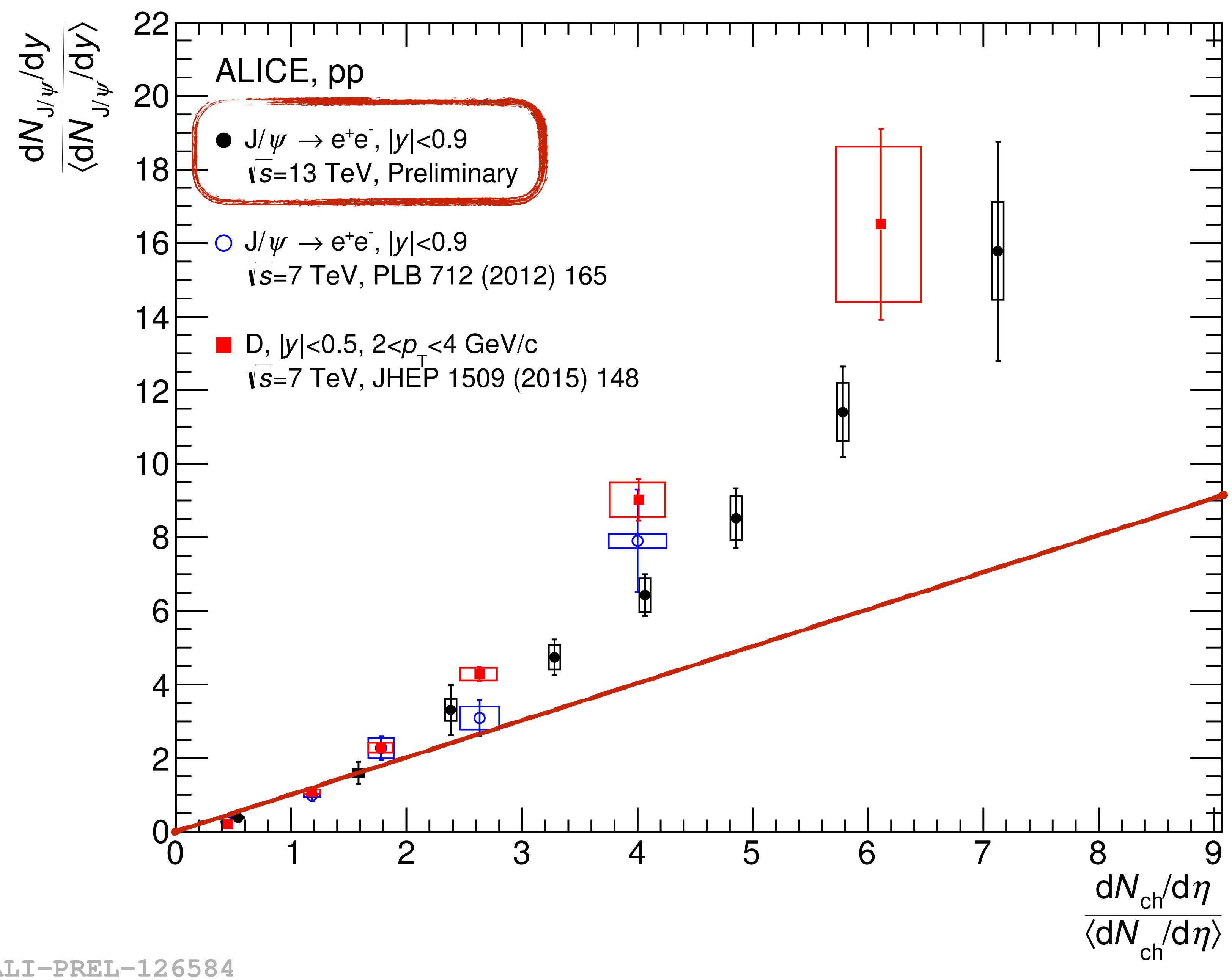
S. Weber, ALICE, QM17



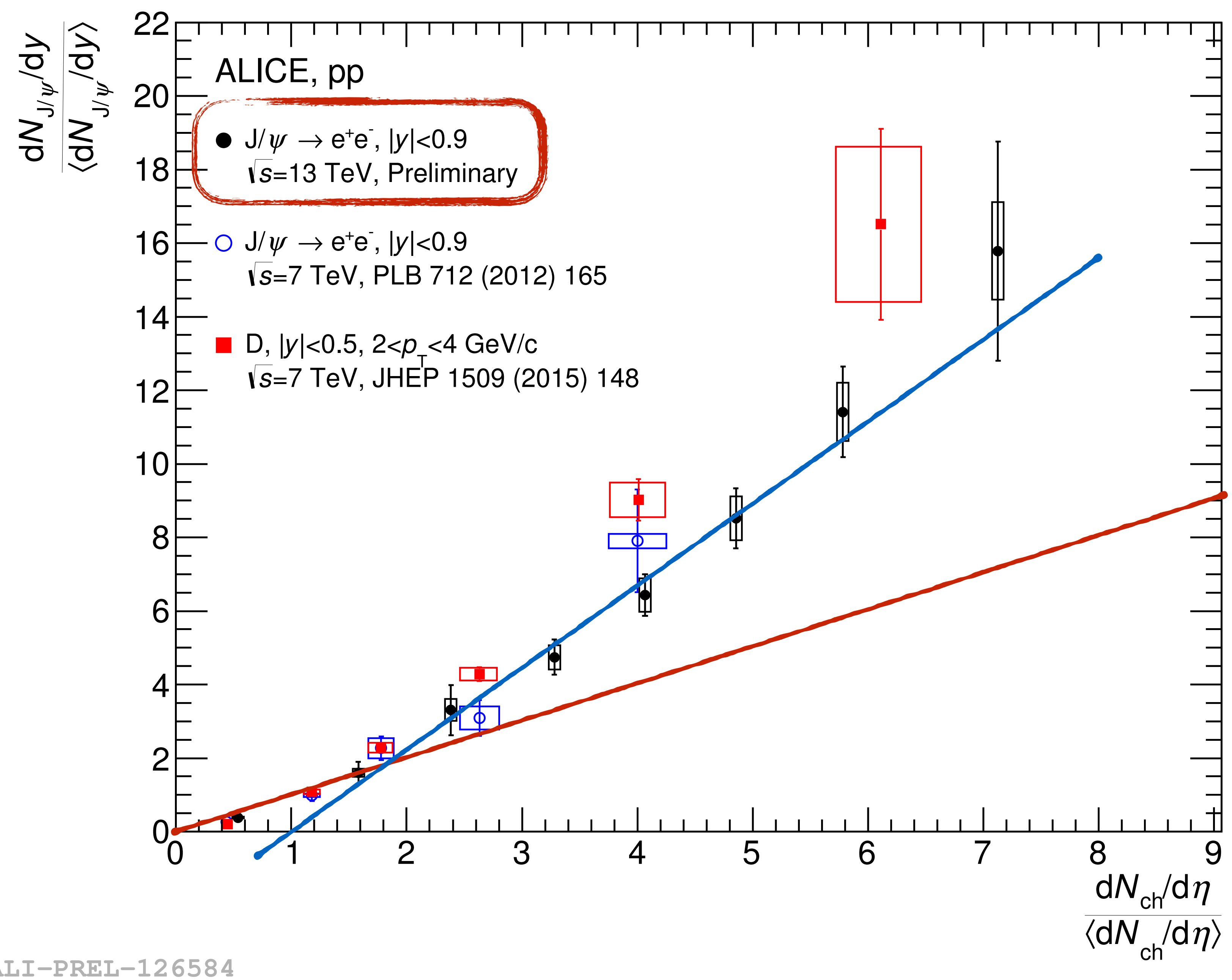
Similar behavior observed for **high p_T strangeness**

Faster than diagonal! Non linear? Or only linear at high multiplicity?

Constrains MPI vs bulk particle production

Heavy flavor at high p_T

S. Weber, ALICE, QM17



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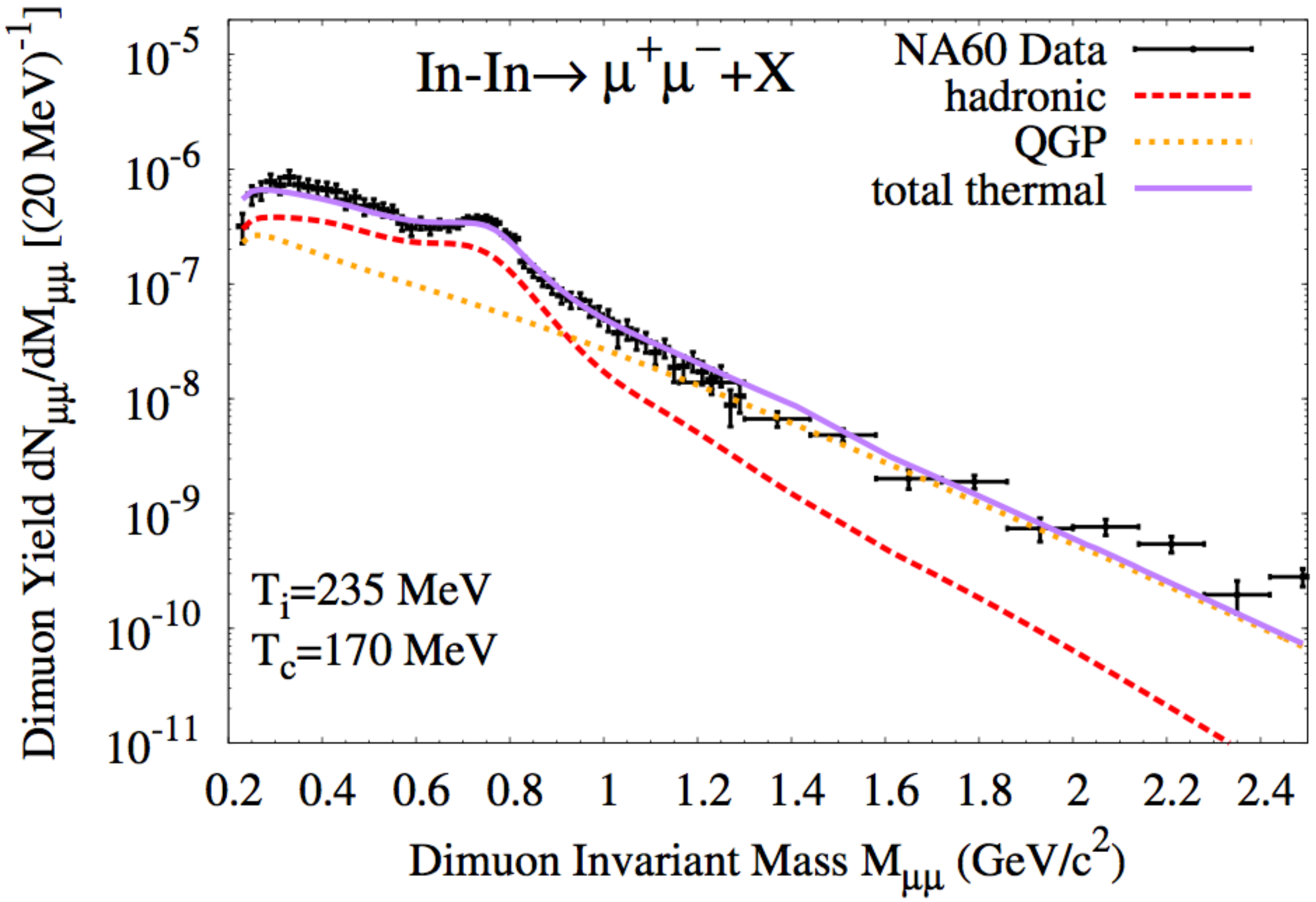
Thermal Radiation

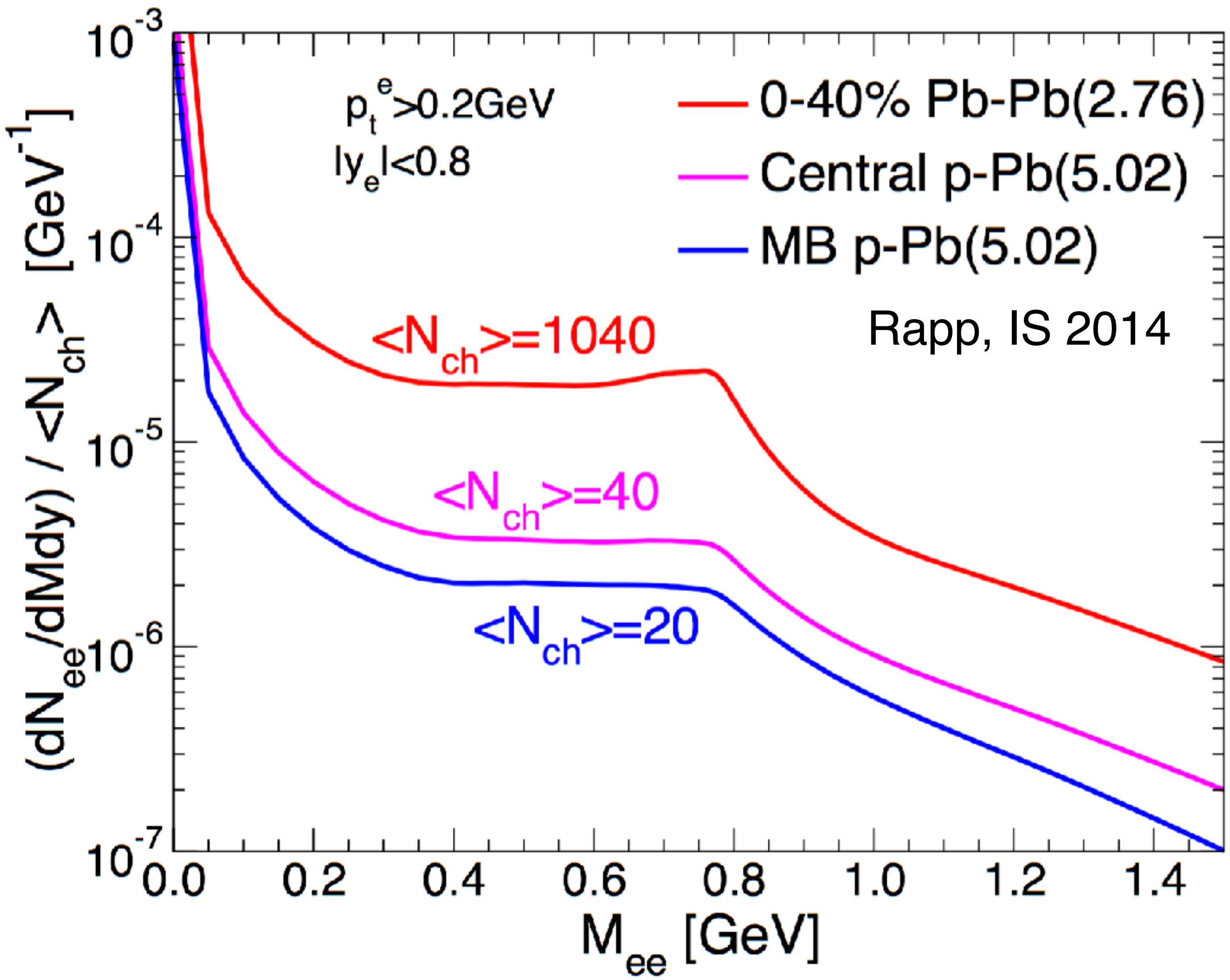
Thermal radiation

Rapp et al, PLB 753, 586 (2016)



A system close to thermal equilibrium emits **thermal radiation**
Seen as **excess** in virtual (**dileptons**) and real **photons**

Thermal radiation



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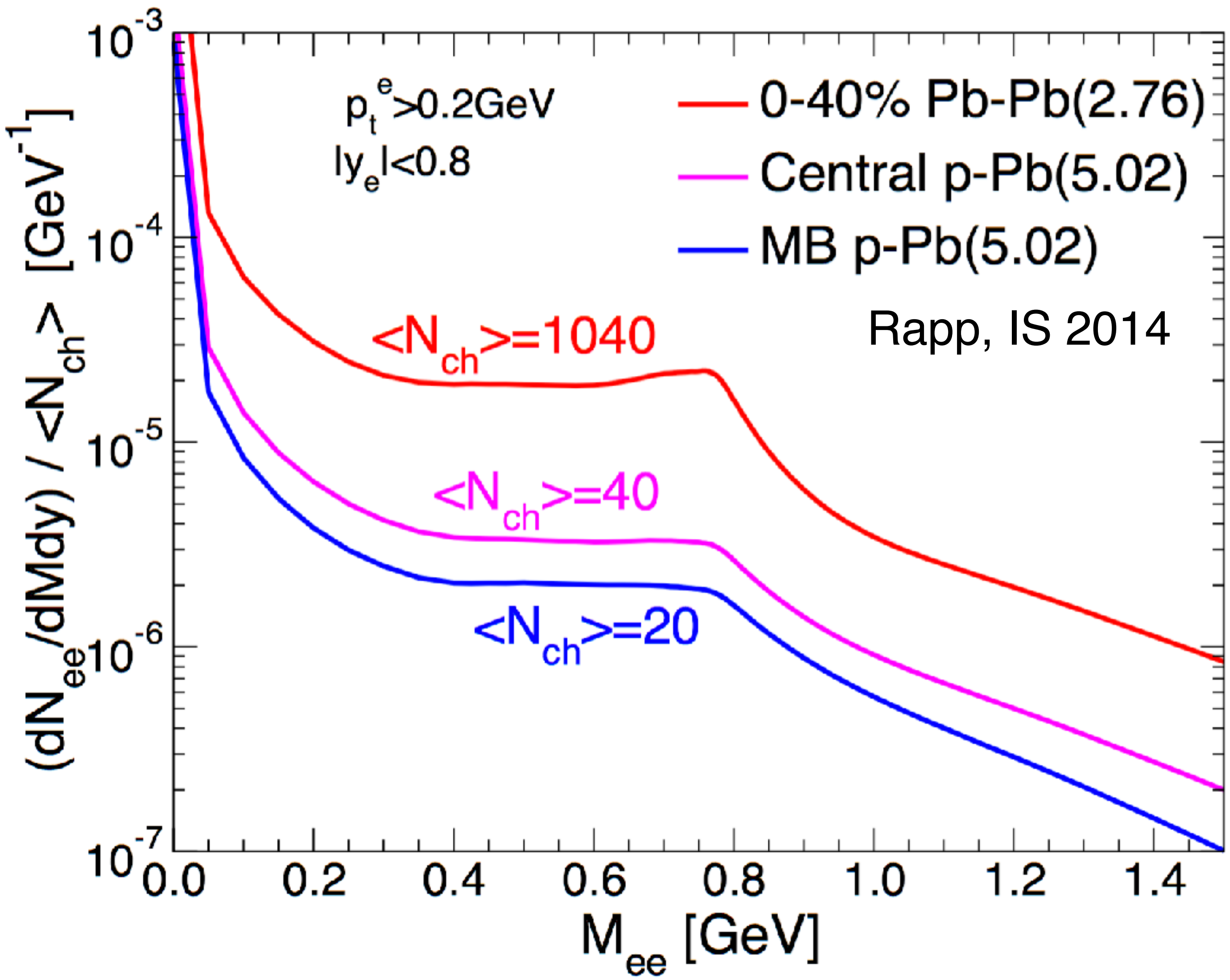
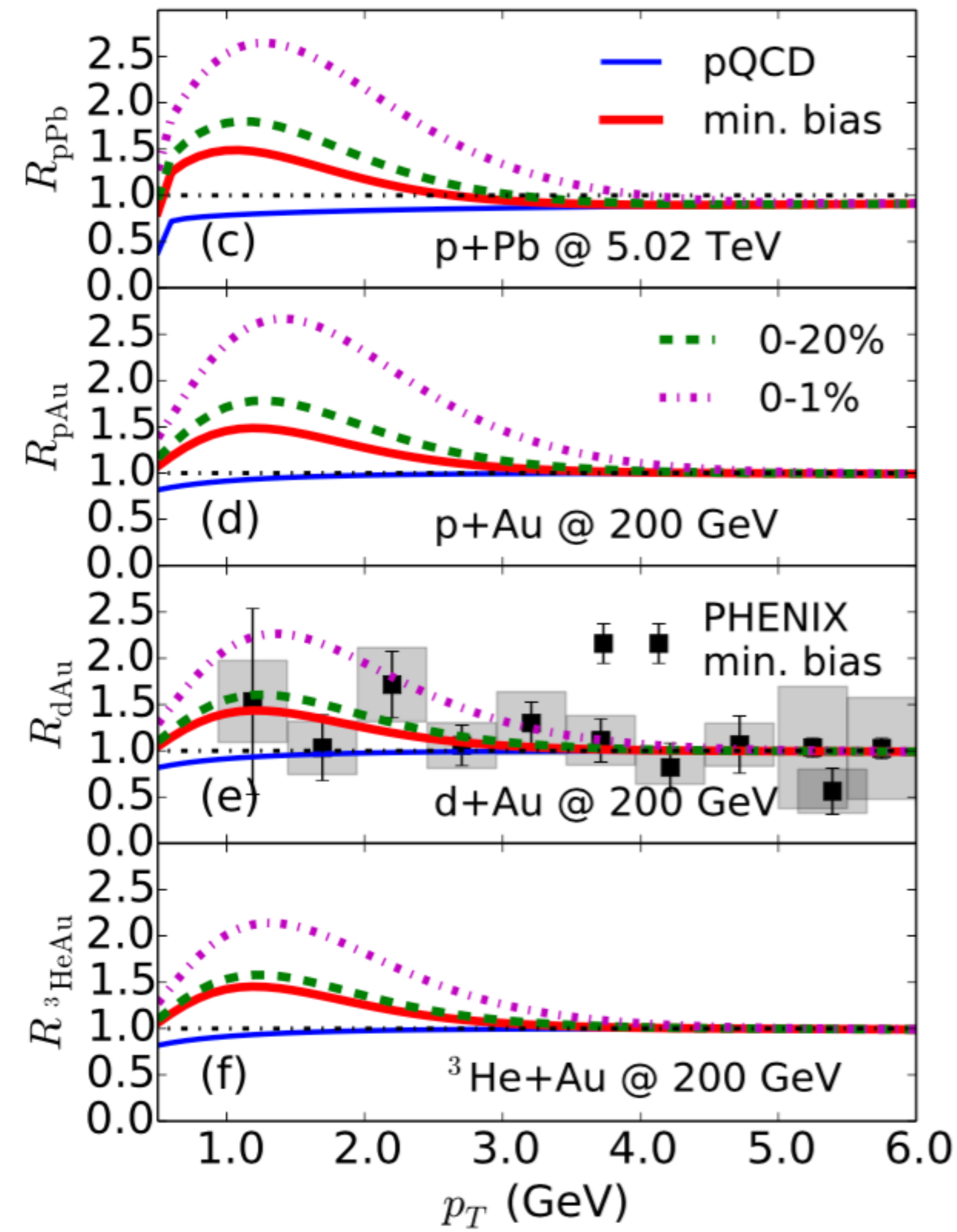
Thermal radiation



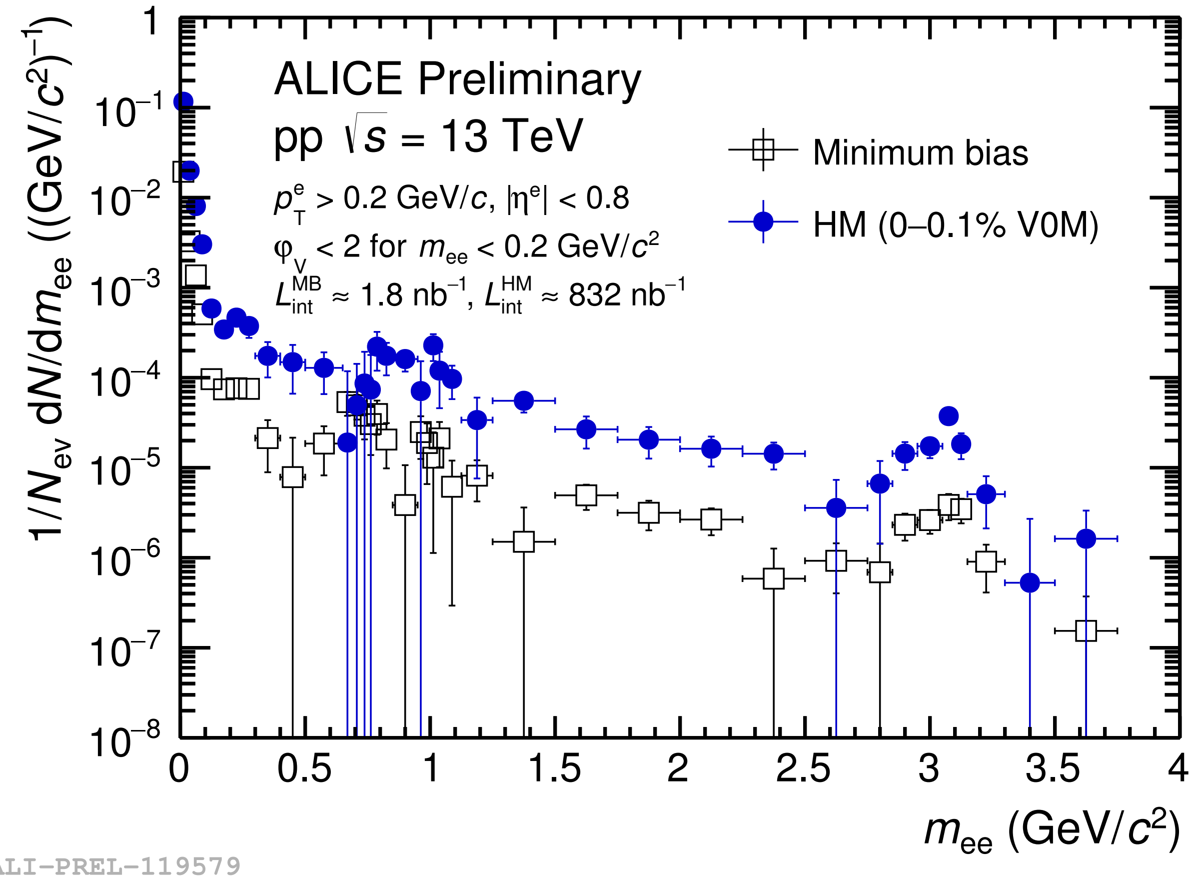
Shen et al, arXiv:1601.03070

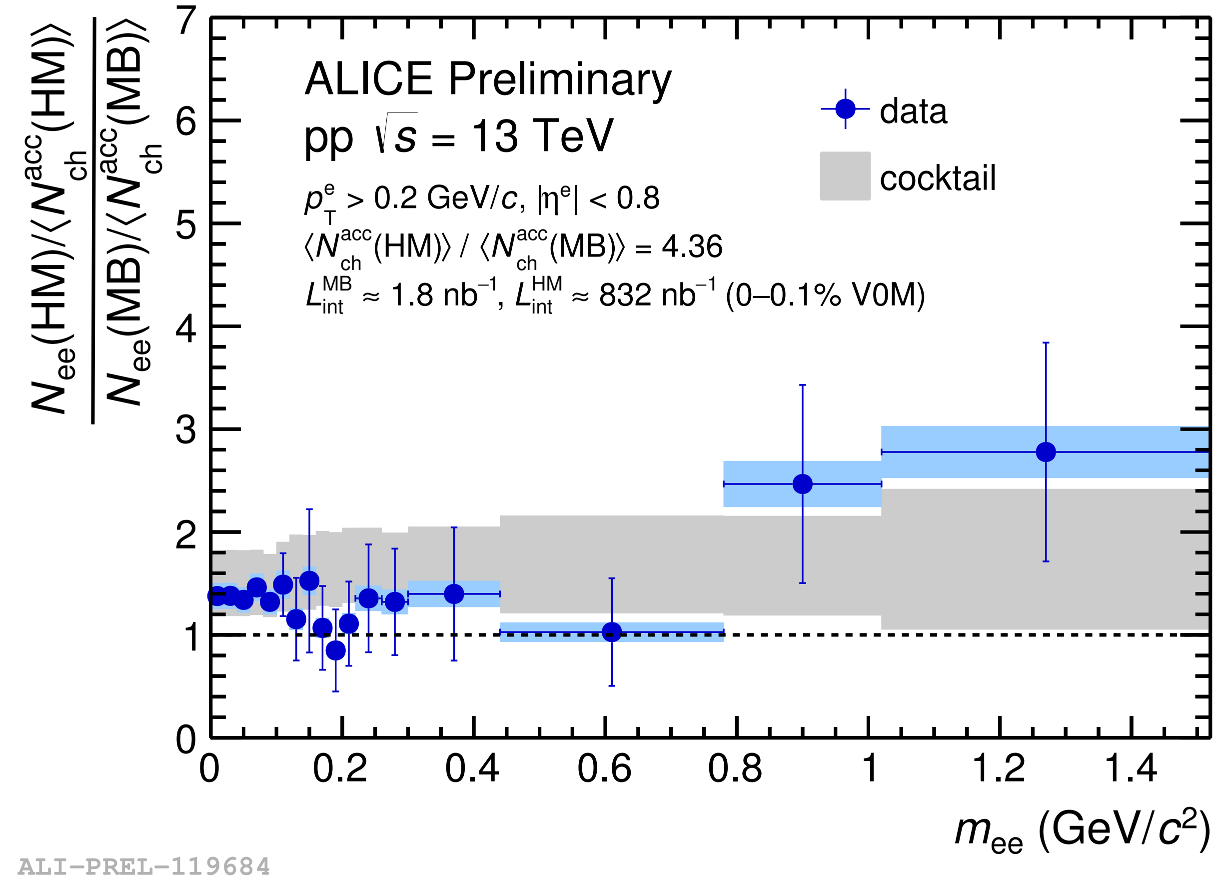


A system close to thermal equilibrium emits **thermal radiation**
Seen as **excess** in virtual (**dileptons**) and real **photons**

A first attempt to measure dielectrons in HM pp!

Increase in the per-event yield, explained by hadronic sources



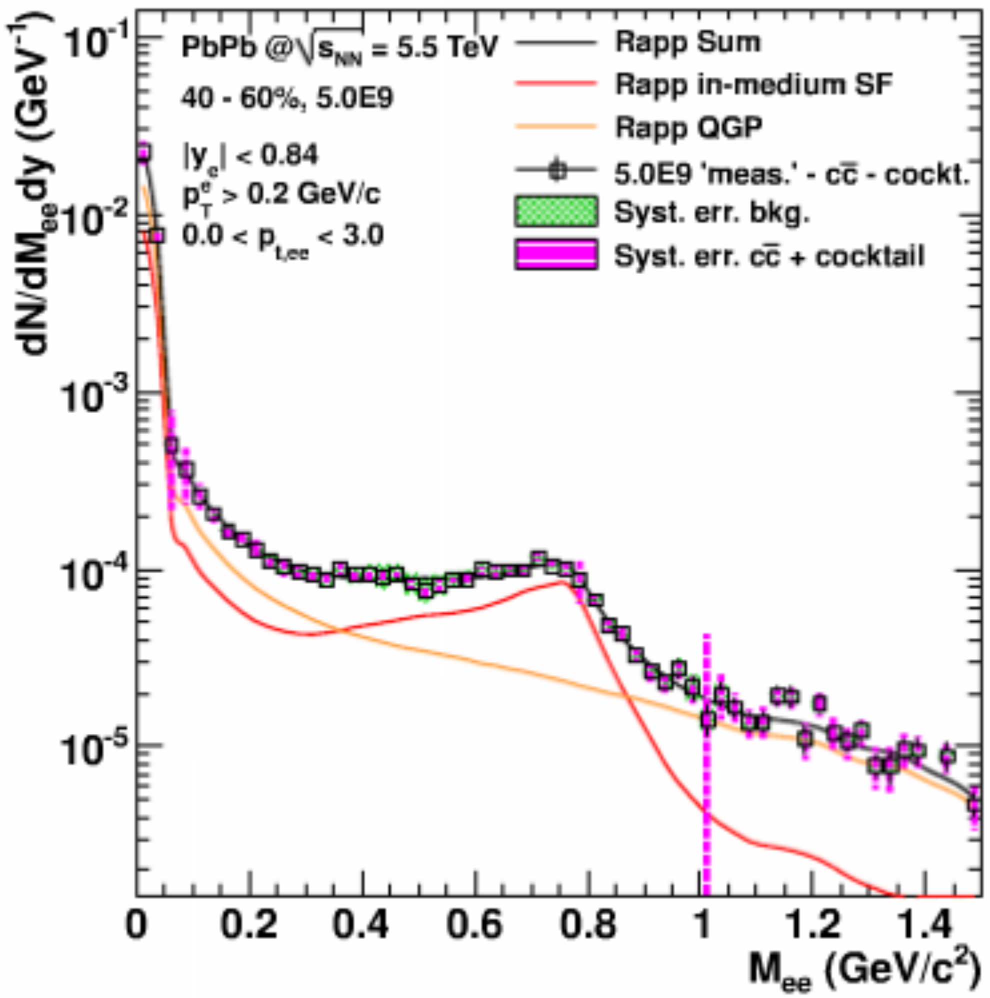


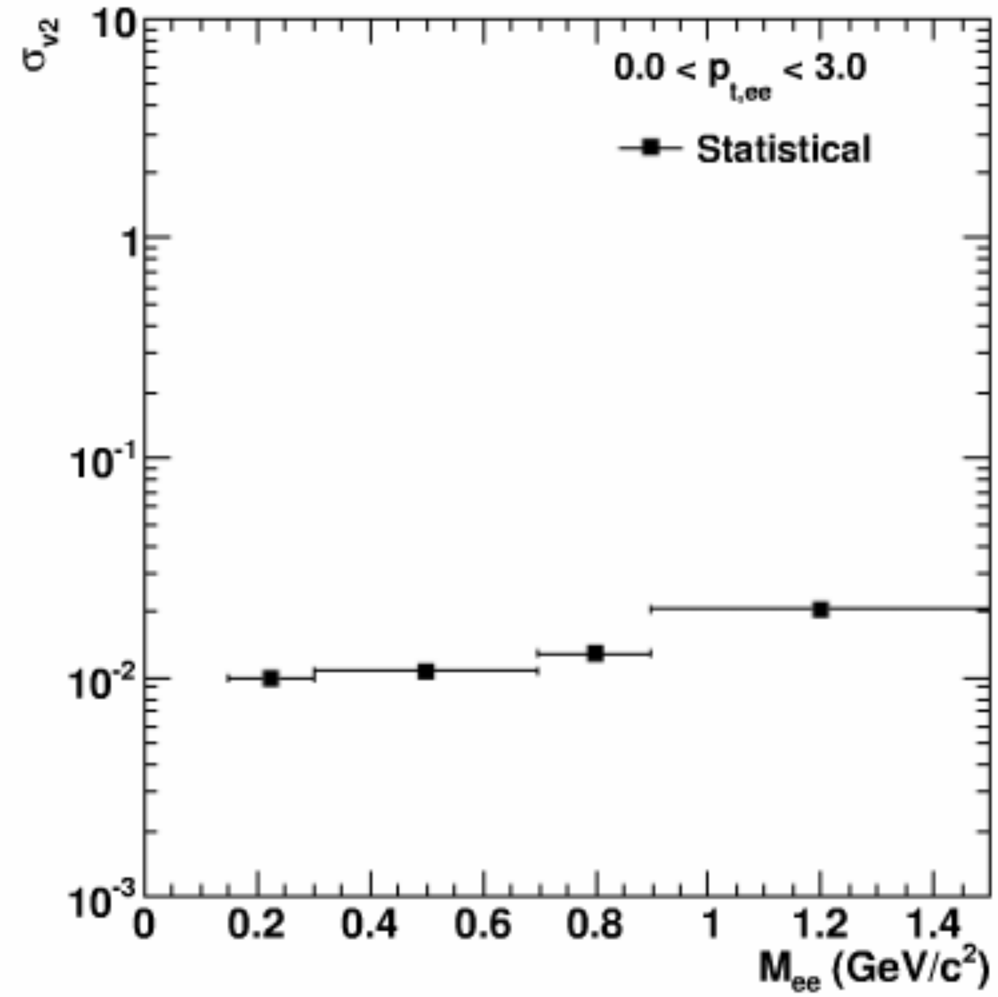
Needs larger statistics and much reduced cocktail uncertainty

Real photons?

O. Doce, ALICE, QM17

I. Vorobyev, ALICE, QM17





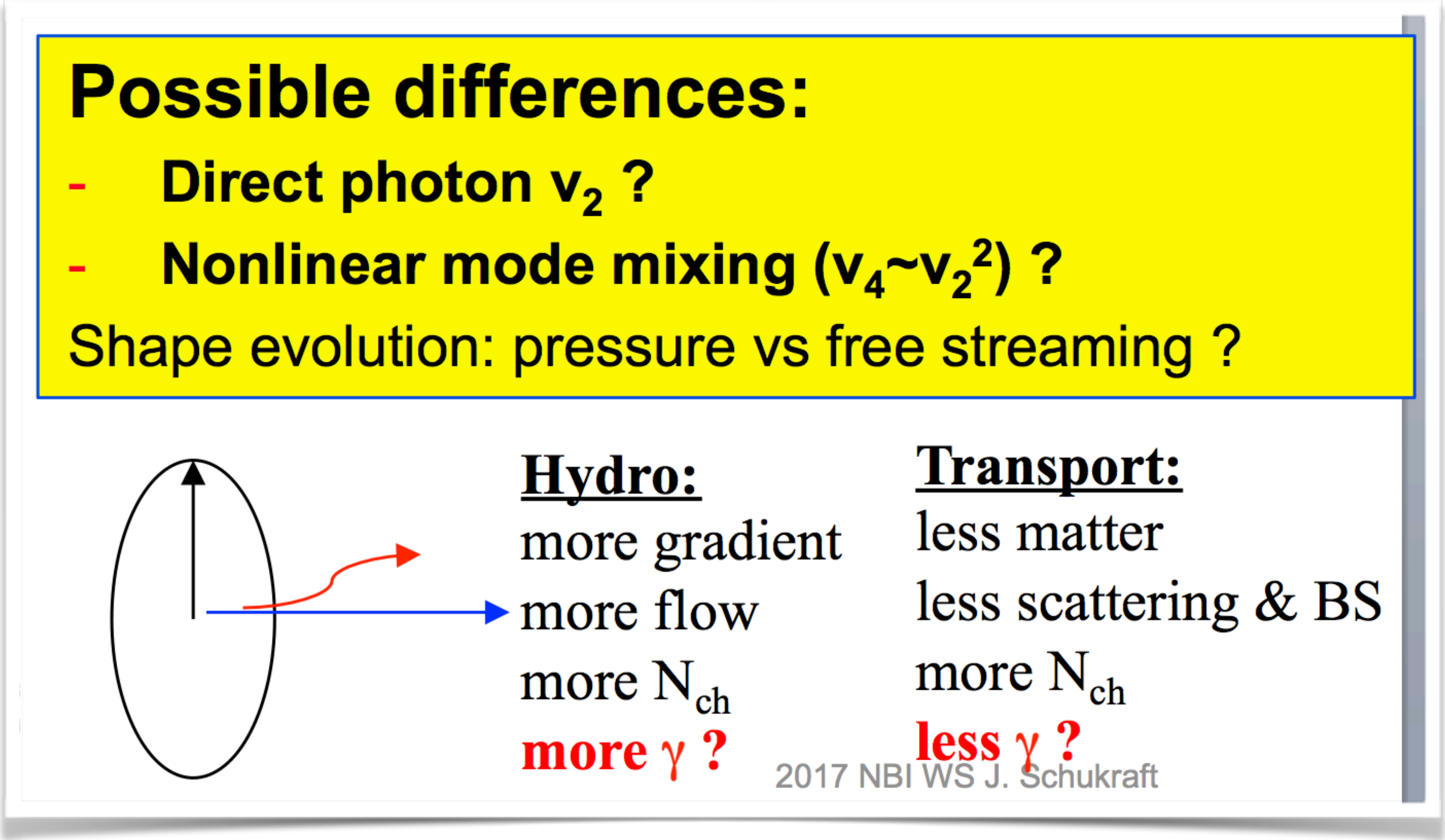
ALICE Upgrade LOI:

e+e– excess spectra in 40–60% Pb–Pb at √sNN= 5.5 TeV

Feasibility in pp?

Key measurements, but challenging

J. Schukraft



Distinguish “Hydro” from “Parton escape” with photon v_2?
Can be this studied with “direct photons” event-shape engineering?
(correlation between LF v_2 and γ v_2

Energy Loss

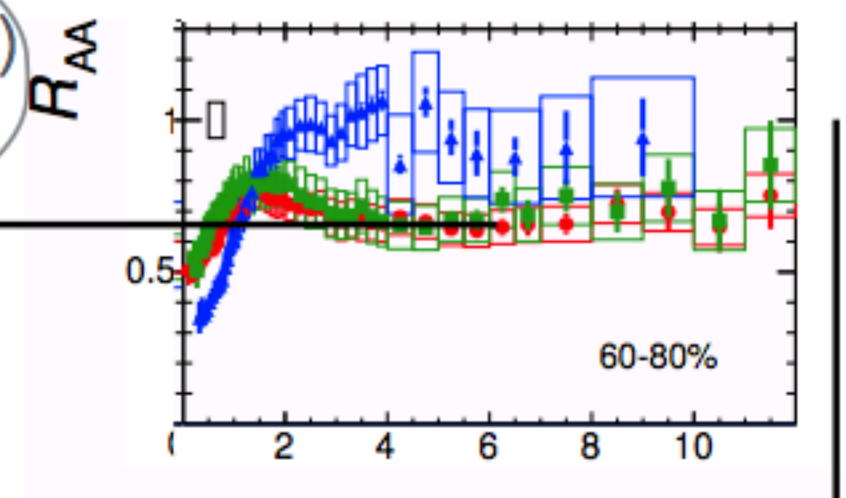
M. Spousta (ATLAS)
Tues. 12:10pm

N. Jacazio (ALICE)
Wed. 4:50pm

60-80% Pb+Pb, R_{AA} = 0.65

<N_{part}> = 23 (ATLAS similar)

<1% *p*+Pb (0-5% in Glauber-Gribov!)

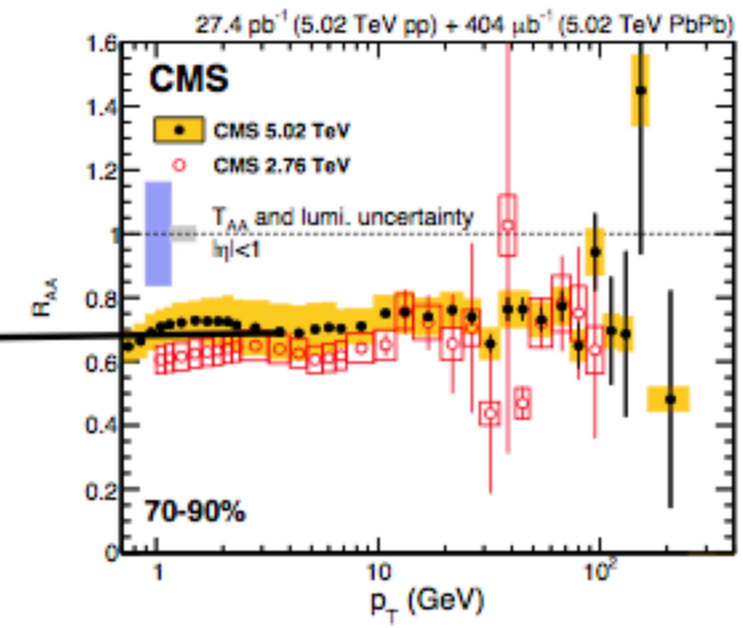


Y.-J. Lee (CMS)
Monday 12:10pm

70-90% Pb+Pb, R_{AA} = 0.7

<N_{part}> = 11

~20-30% *p*+Pb

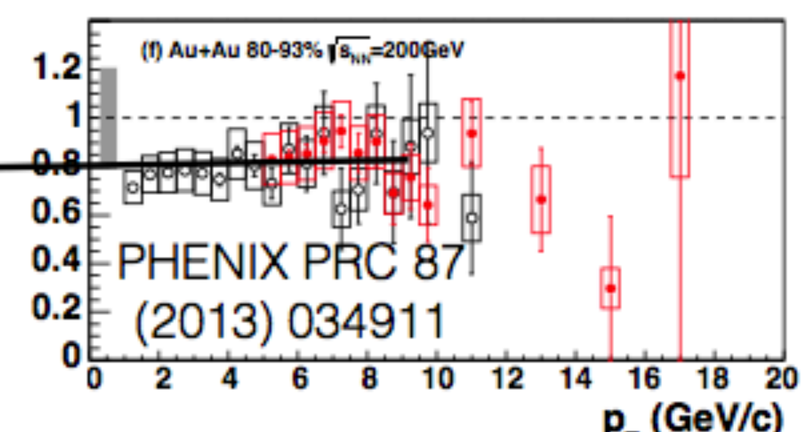


S. Zharko (PHENIX)
Wed. 10:40am

80-93% Au+Au, R_{AA} = 0.8

<N_{part}> = 5

~50-70% *p*+Pb



decreasing N_{part}

54

D. Perepelitsa, QM17

Bias in peripheral AA?

C. Loizides

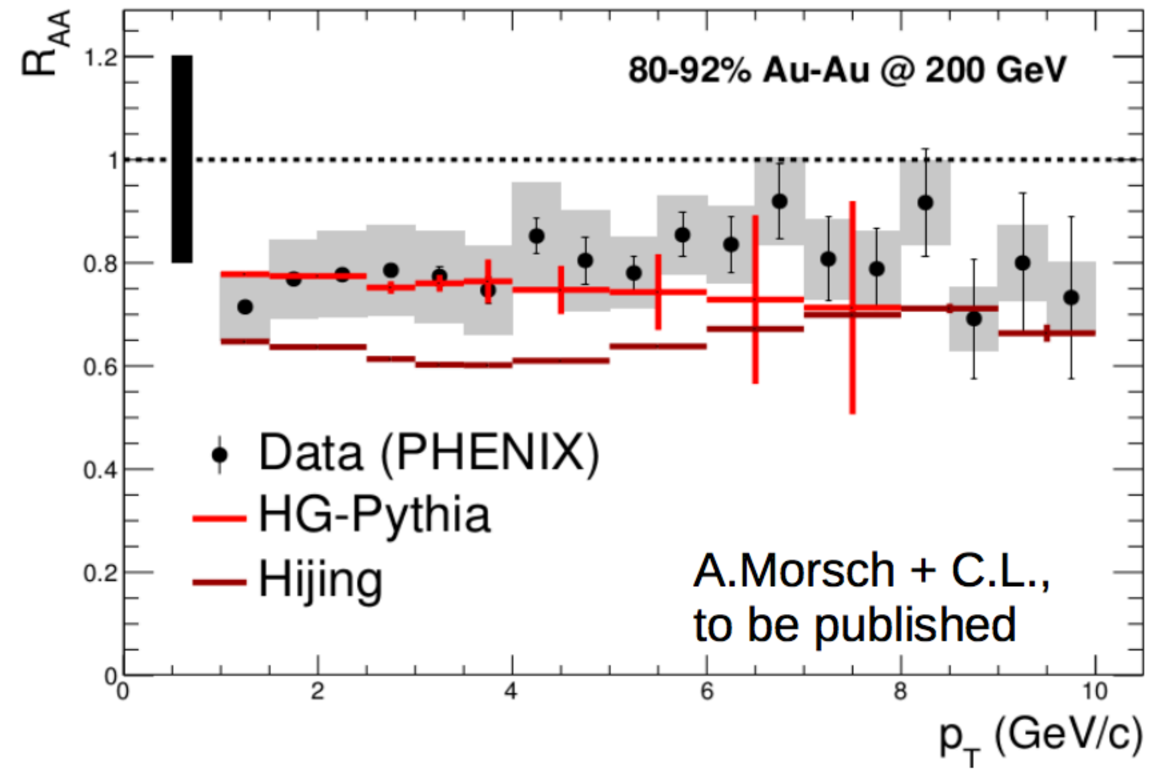
14 Model comparison

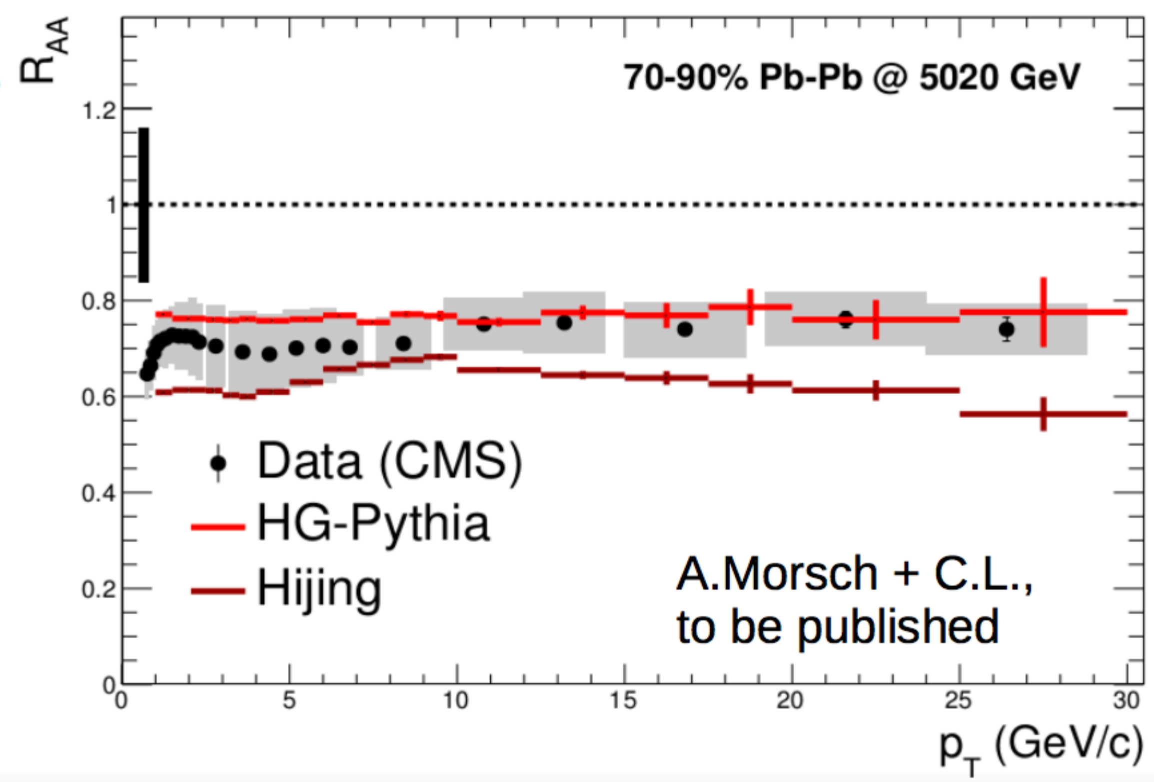
Hijing:
- No quenching, no shadowing, but ad-hoc momentum conservation and multiple scattering
- Does not give $R_{AA} \rightarrow 1$ at high p_T for central collisions

HG-Pythia:
- Use as HIJING nhard distribution as input but just superimpose PYTHIA (Perugia 2011) events
- Does not reproduce multiplicity

Results obtained using event ordering (slicing) for forward multiplicity (2.5<|η|<5)

Multiplicity bias can cause the apparent suppression!

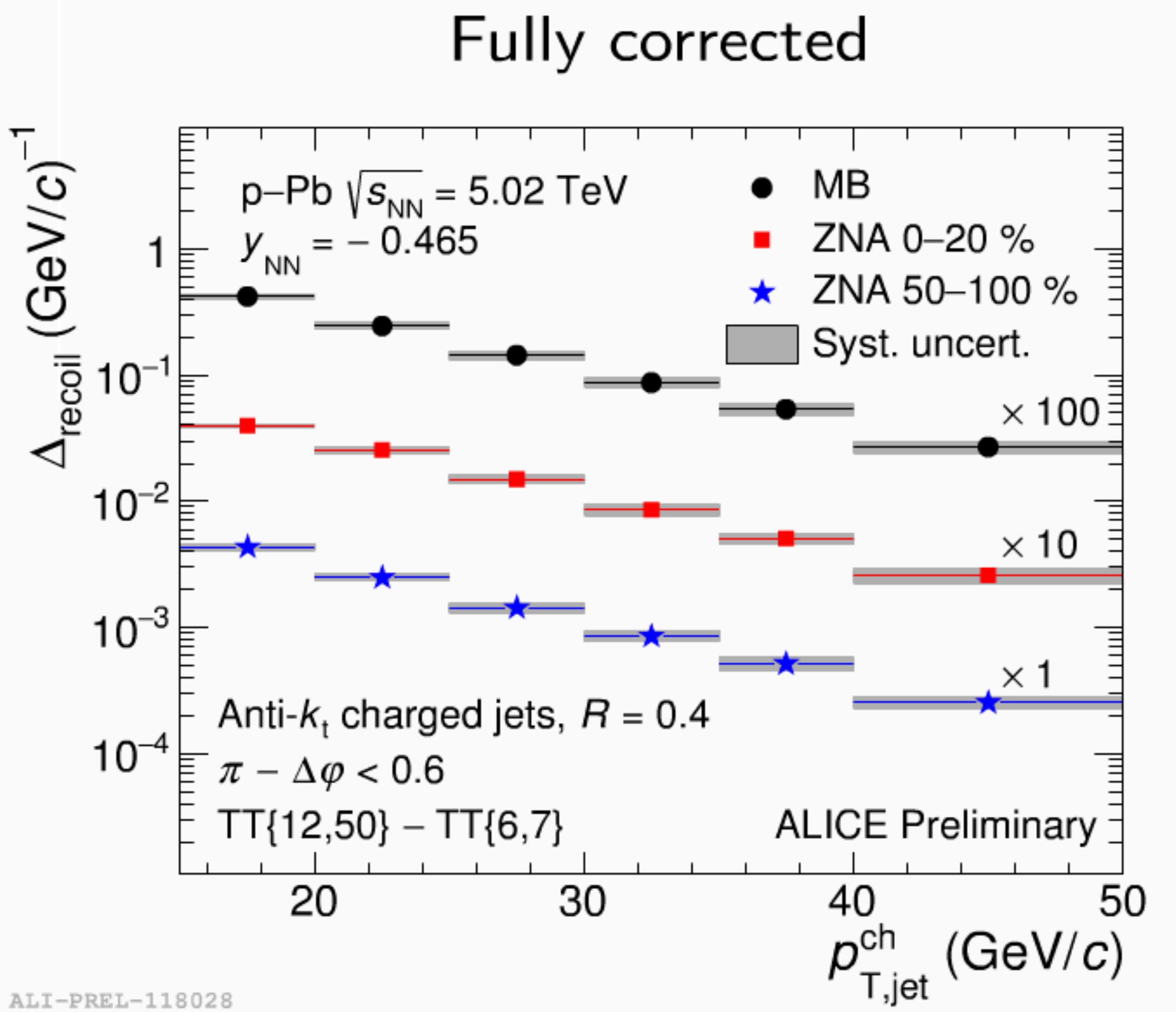




Direct measurement of RAA difficult:
biases and reliability of glauber for TAA

Δ_{recoil} "self normalized", directly comparable to theory

$$\Delta_{\rm recoil} = \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta}\bigg|_{p_{\rm T,trig}\in {\rm TT}\{20,50\}} - c_{\rm Ref}\cdot \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta}\bigg|_{p_{\rm T,trig}\in {\rm TT}\{8,9\}}$$



Measured in different p-Pb mult bins

Ratio

$$\frac{\Delta_{\rm recoil}|_{0-20\,\%}}{\Delta_{\rm recoil}|_{50-100\,\%}}$$

compatible with unity

Same in peripheral Pb-Pb?

Other Self Normalized approaches?
(High p_T v2?)

Why ~~Collectivity~~ High Multiplicity pp?

Observations that we **didn't expect** and we **don't** (fully) **understand**!

Why ~~Collectivity~~ High Multiplicity pp?

Observations that we **didn't expect** and we **don't** (fully) **understand**!

Much **progress** in HI in the past few years driven (directly or indirectly) by results in small systems!

Why ~~Collectivity~~ High Multiplicity pp?

Observations that we **didn’t expect** and we **don’t** (fully) **understand**!

Much **progress** in HI in the past few years driven (directly or indirectly) by results in small systems!

“Why should we study HM pp collisions?”

Observations that we **didn't expect** and we **don't** (fully) **understand**!

Much **progress** in HI in the past few years driven (directly or indirectly) by results in small systems!

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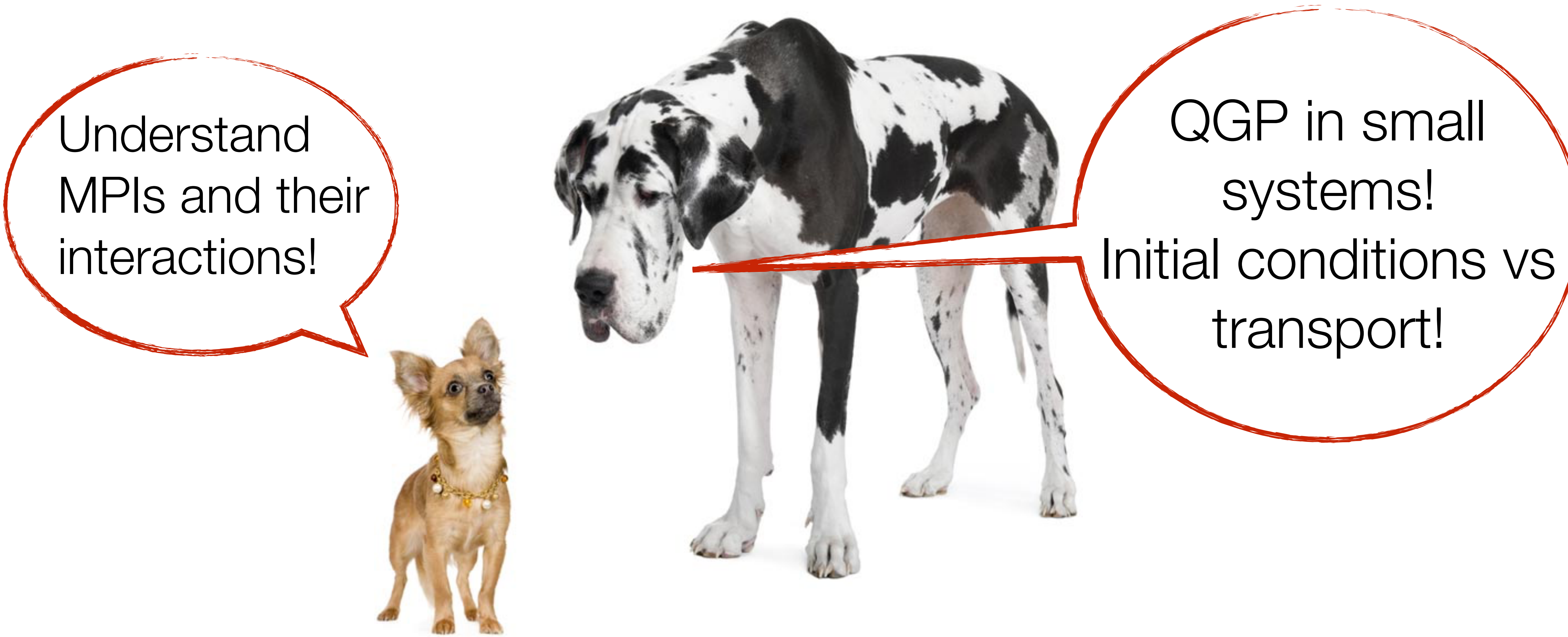

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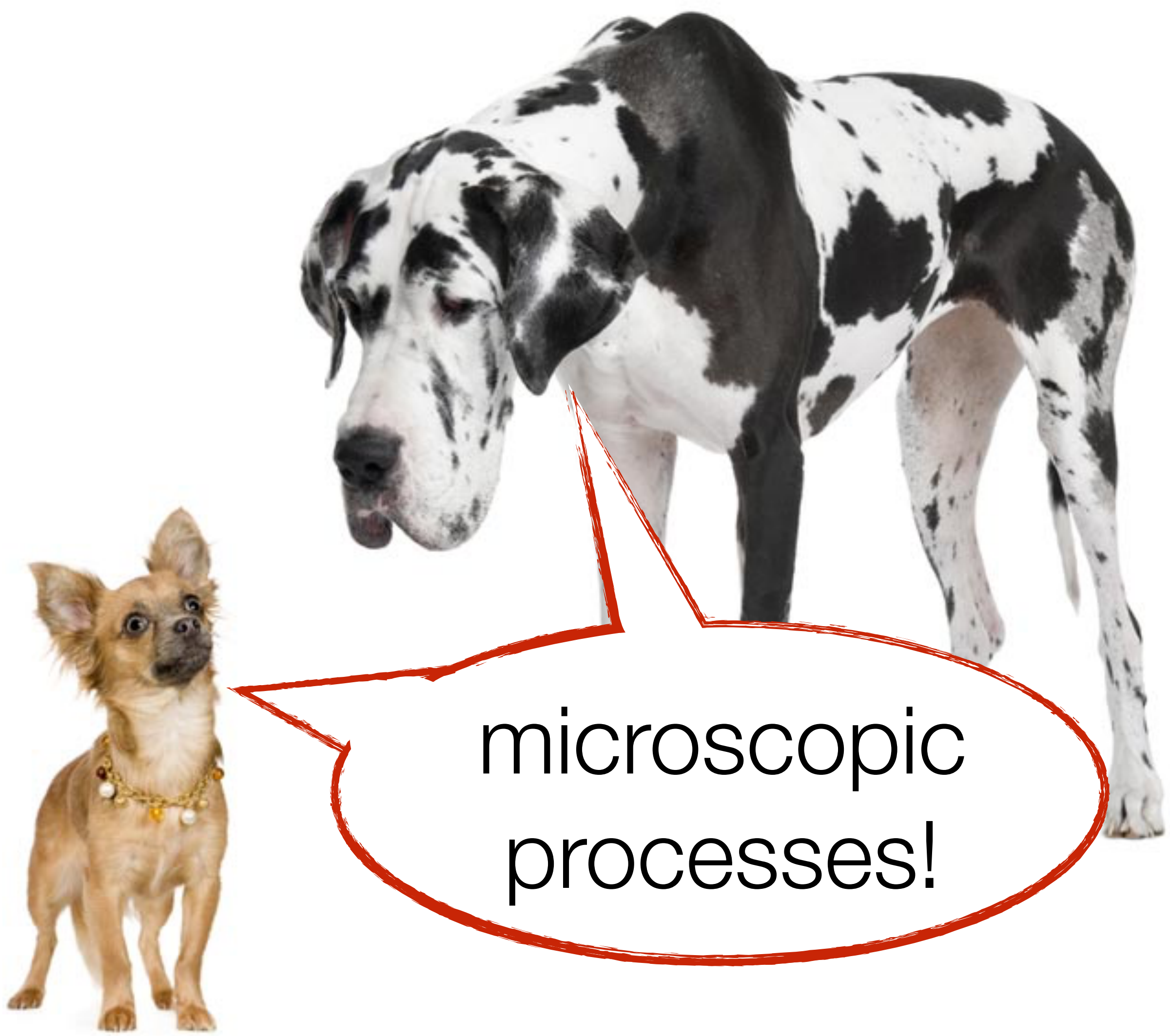

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