QGP-like effects in Small Systems with LHC Run3+

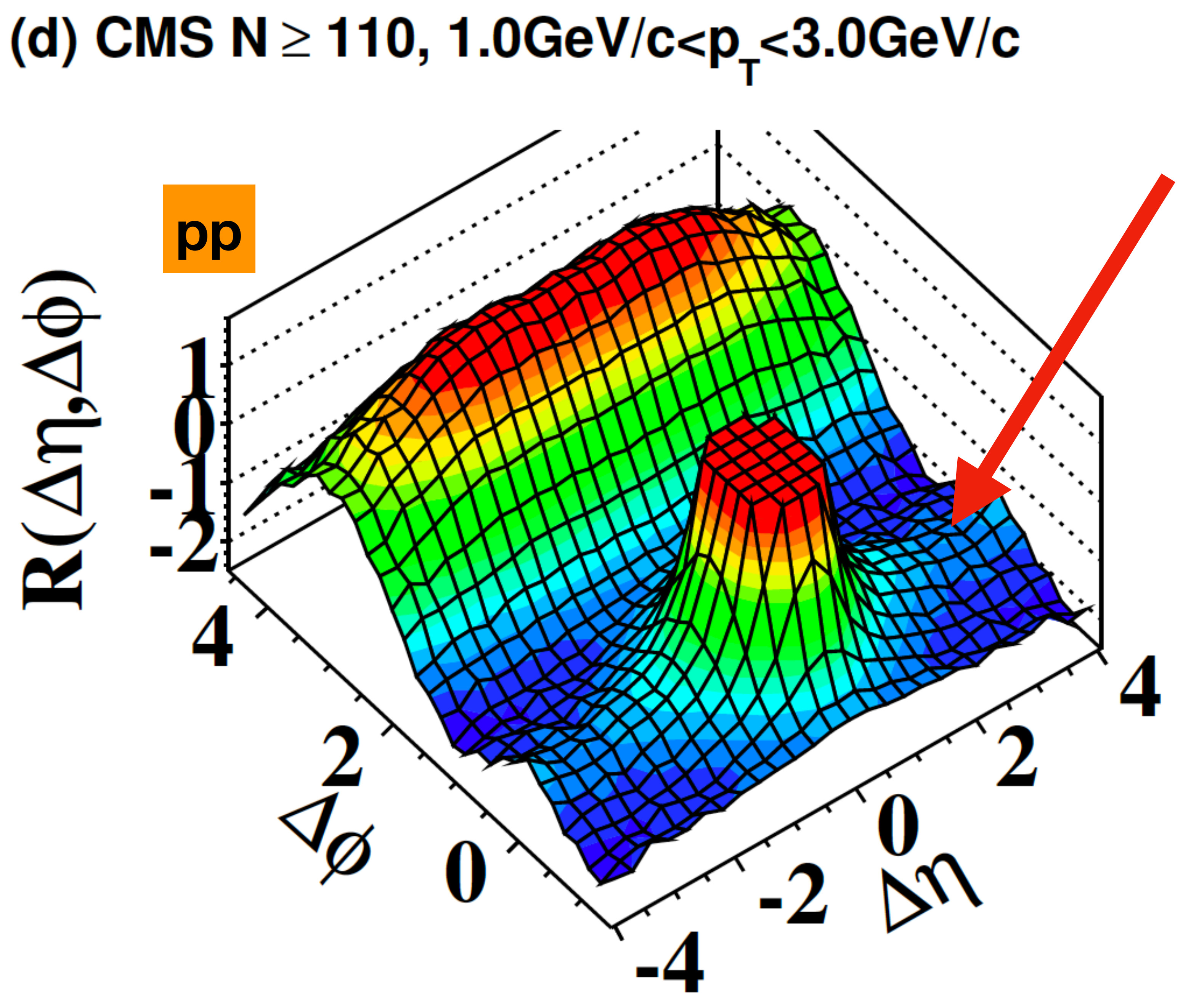
Naghmeh Mohammadi

arxiv:1812.06772 (HL-LHC WG5 yellow report)

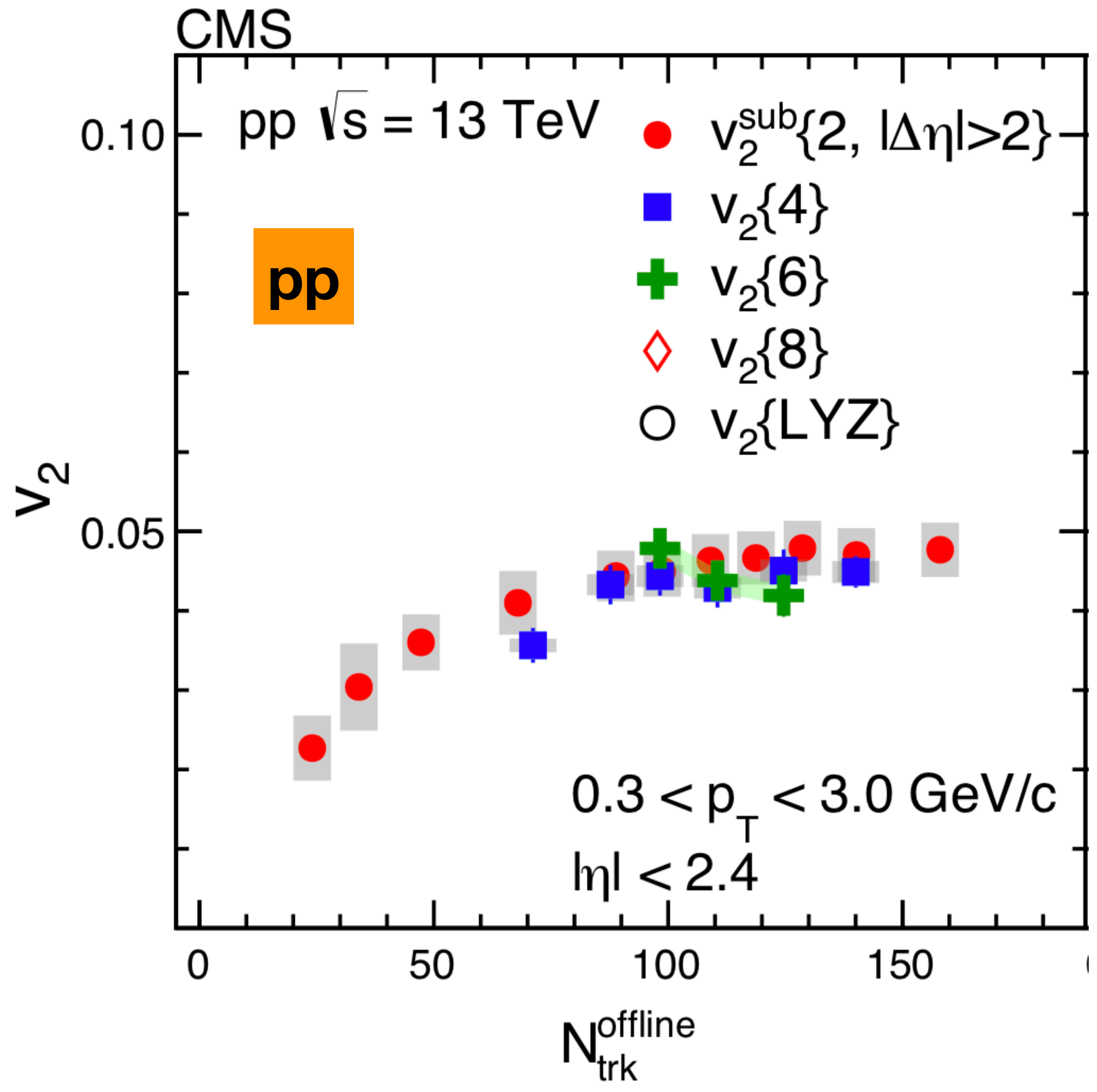
Emergence of Hot and Dense QCD in Small Systems

- **Initially a reference for the effects observed in Pb-Pb collisions**

- **Observations in high multiplicity pp collisions:**
  - Azimuthal correlations of final state hadrons



JHEP09(2010)091



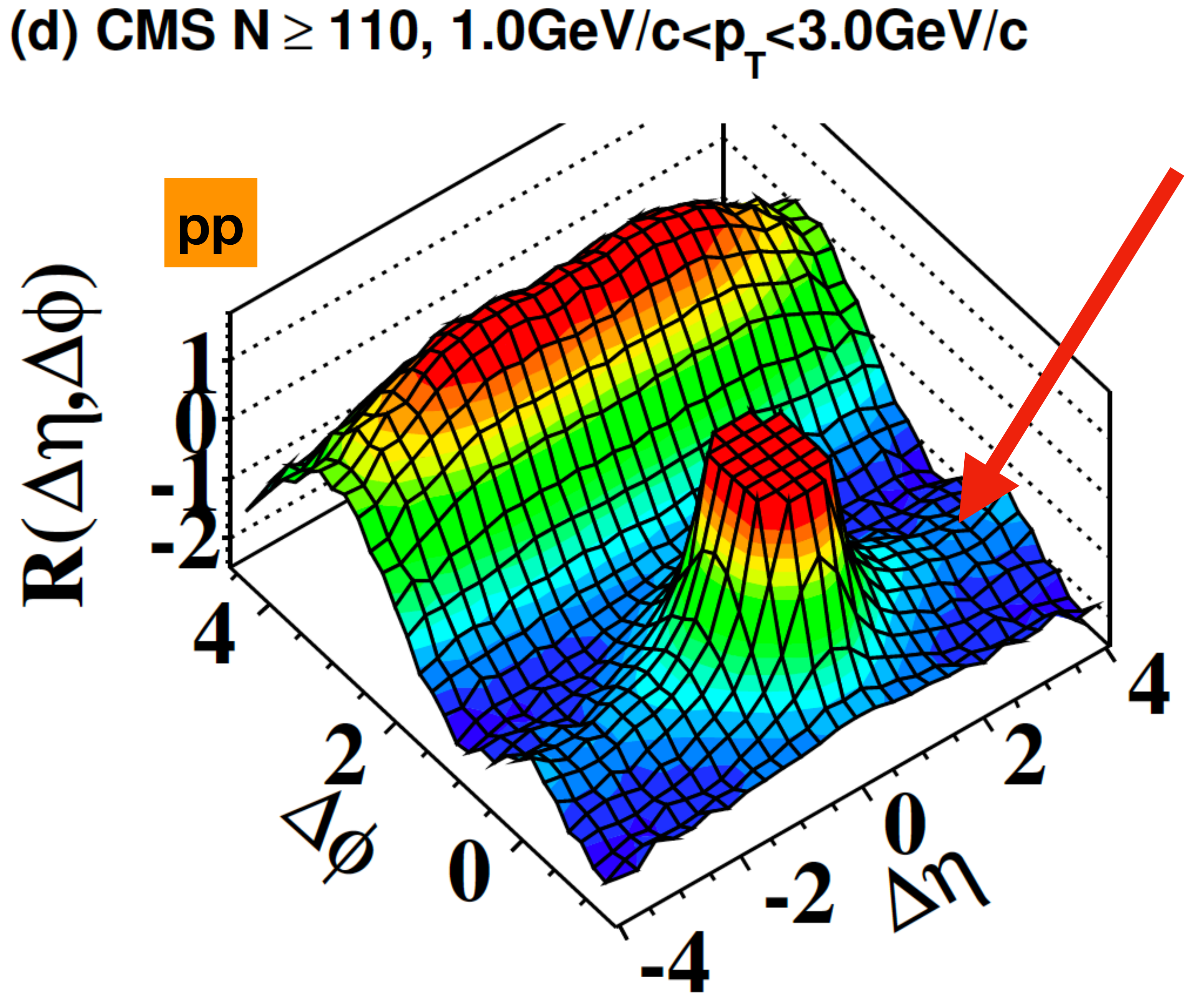
Phys. Lett. B 765 (2017) 193

Emergence of Hot and Dense QCD in Small Systems

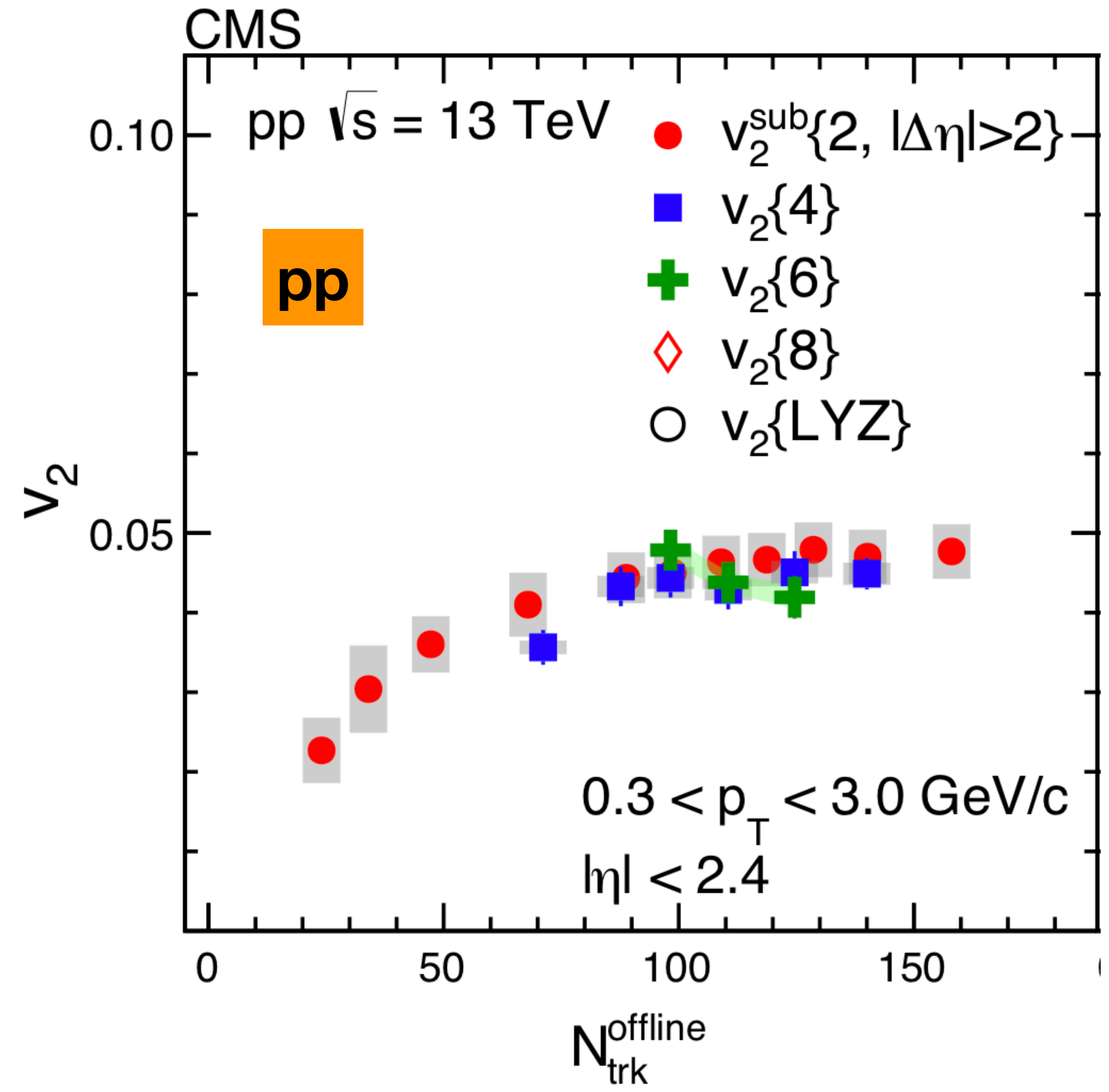
- **Initially a reference for the effects observed in Pb-Pb collisions**

- **Observations in high multiplicity pp collisions:**
  - Azimuthal correlations of final state hadrons

  - Enhanced production of multi-strange hadrons

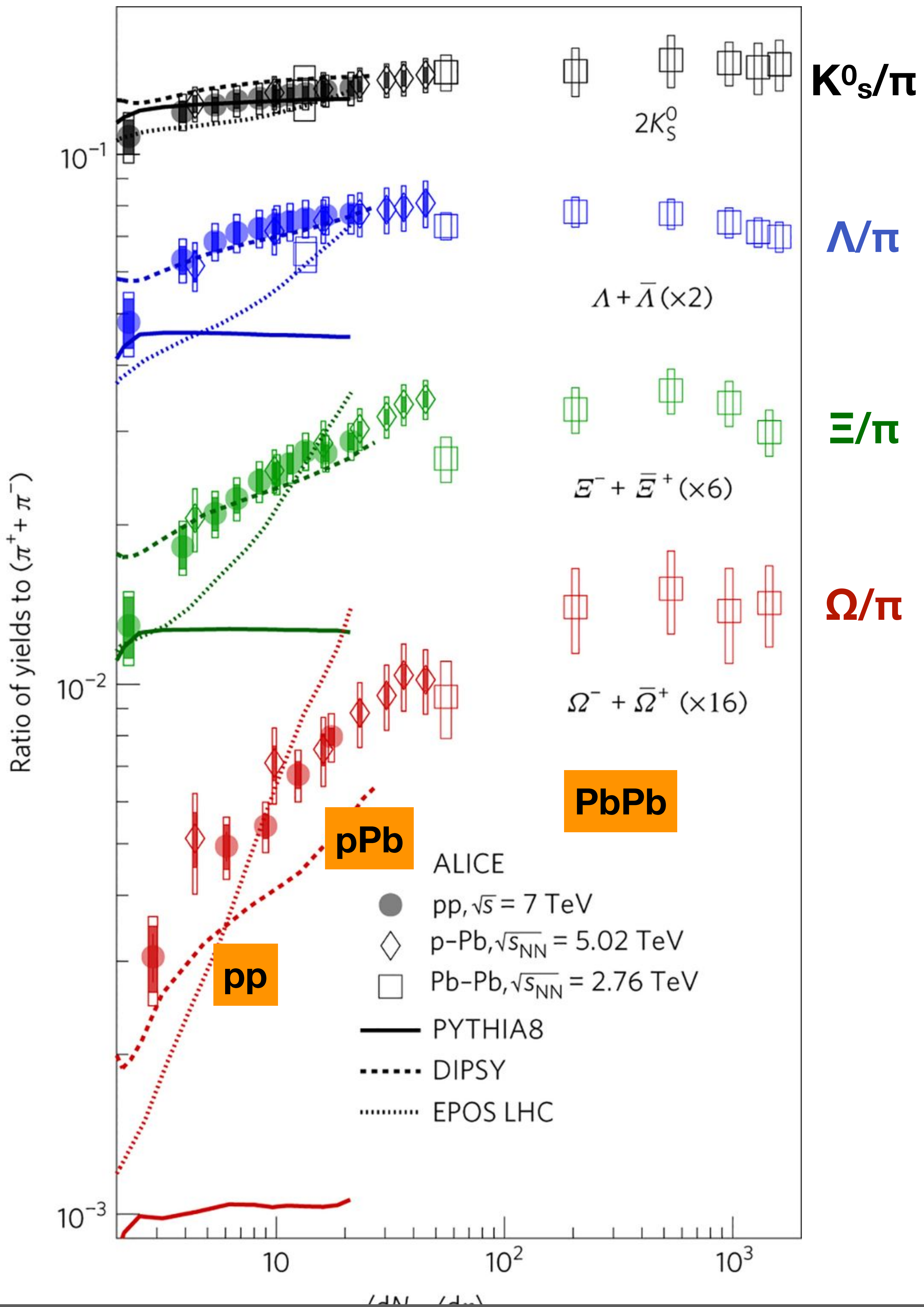


JHEP09(2010)091



Phys. Lett. B 765 (2017) 193

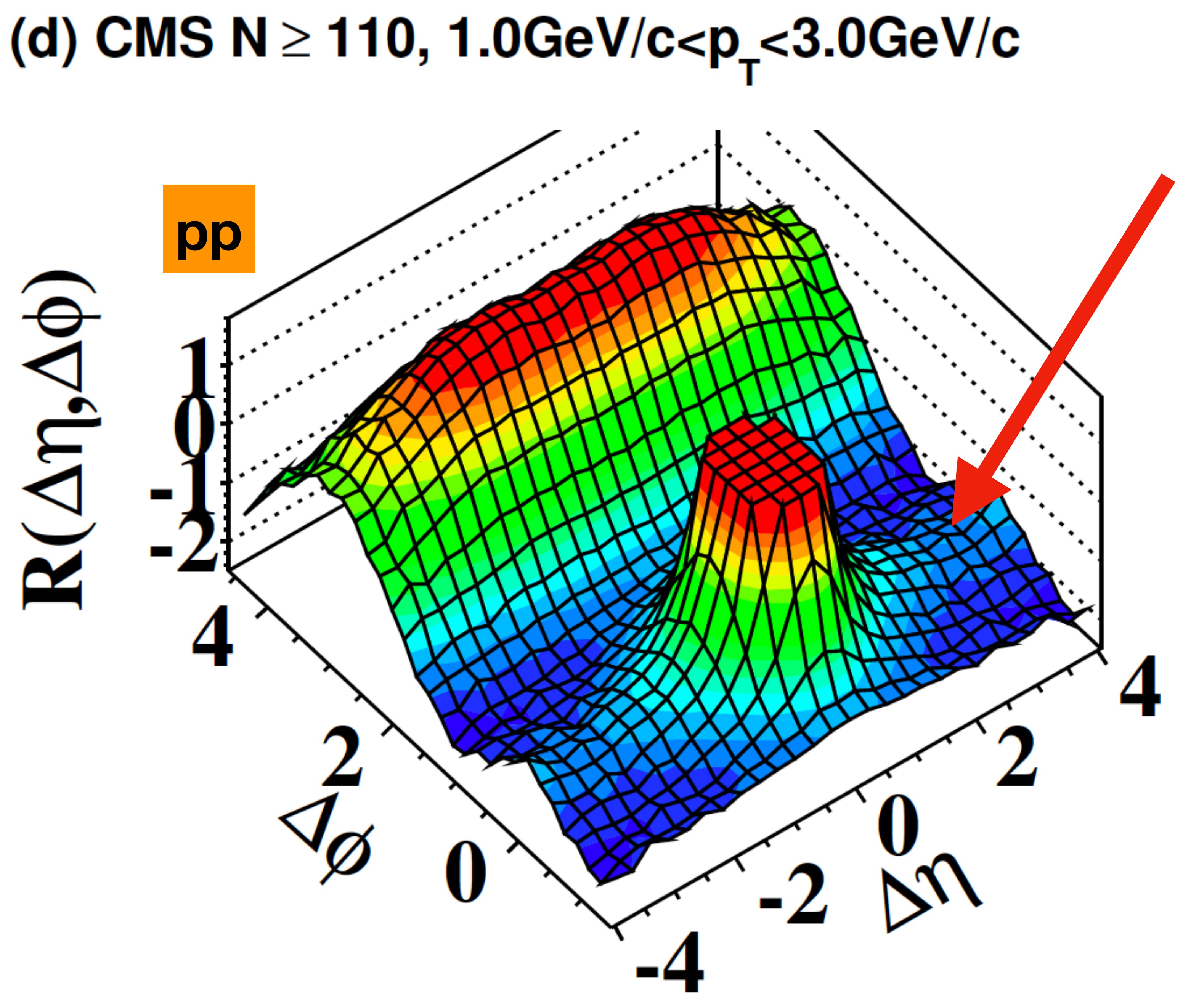
Nature Physics 13, 535–539 (2017)



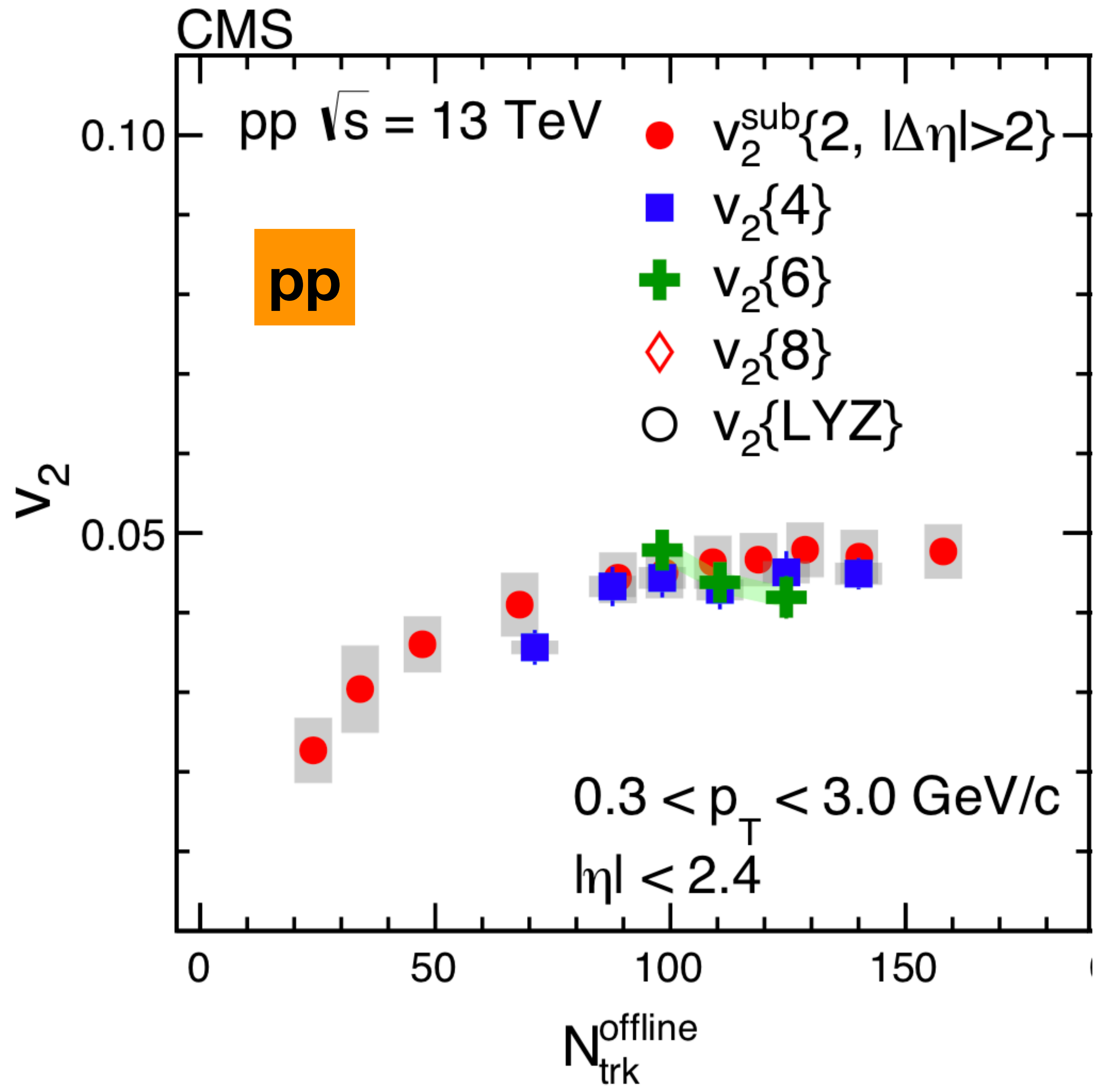
Emergence of Hot and Dense QCD in Small Systems

- Initially a reference for the effects observed in Pb-Pb collisions

- **Observations in high multiplicity pp collisions:**
  - Azimuthal correlations of final state hadrons
    - ➡ *Is the physical **origin of collectivity** the same in small and large systems?*
  - Enhanced production of multi-strange hadrons
    - ➡ Is there a **smooth transition** from pp to PbPb collisions?

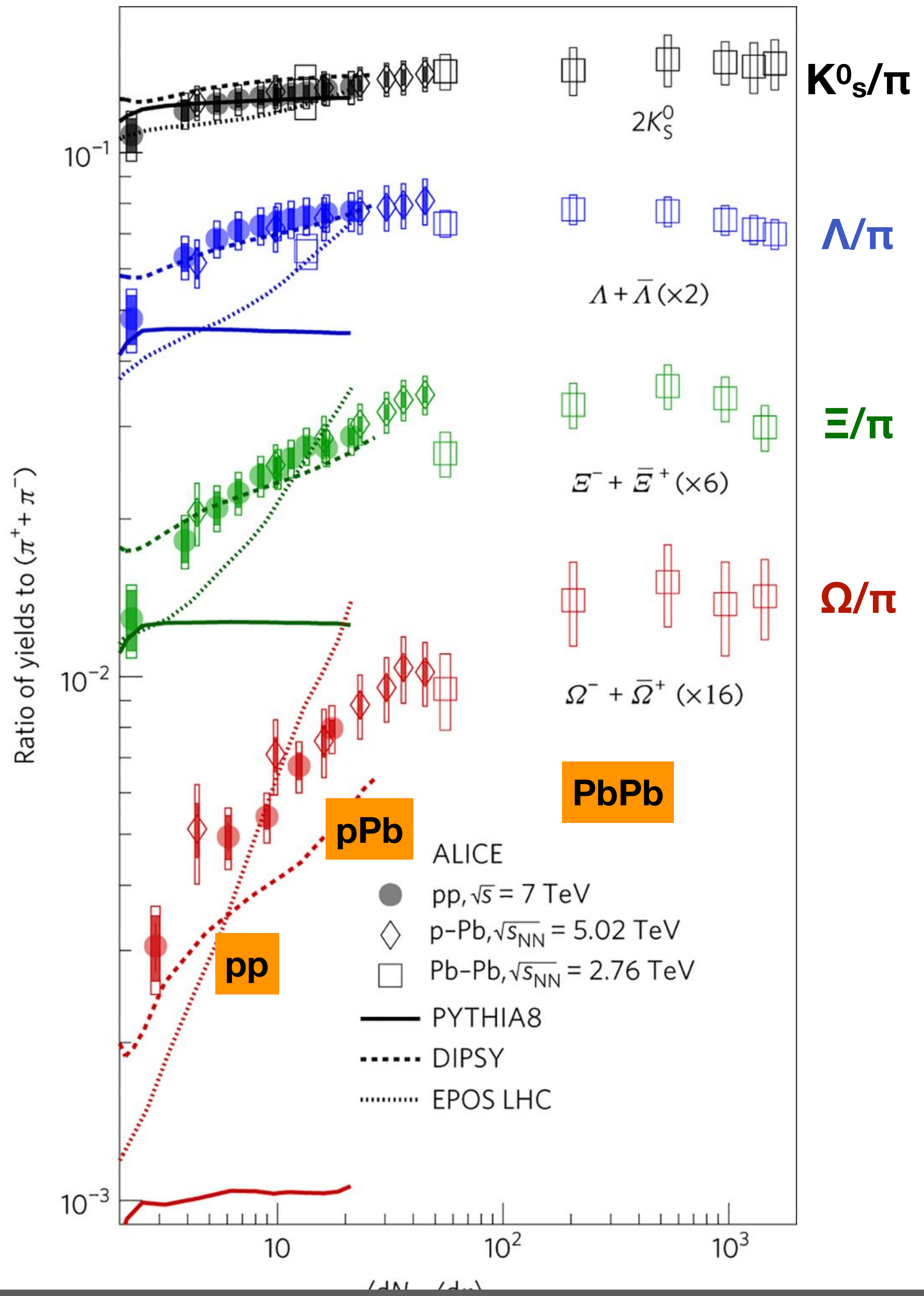


JHEP09(2010)091



Phys. Lett. B 765 (2017) 193

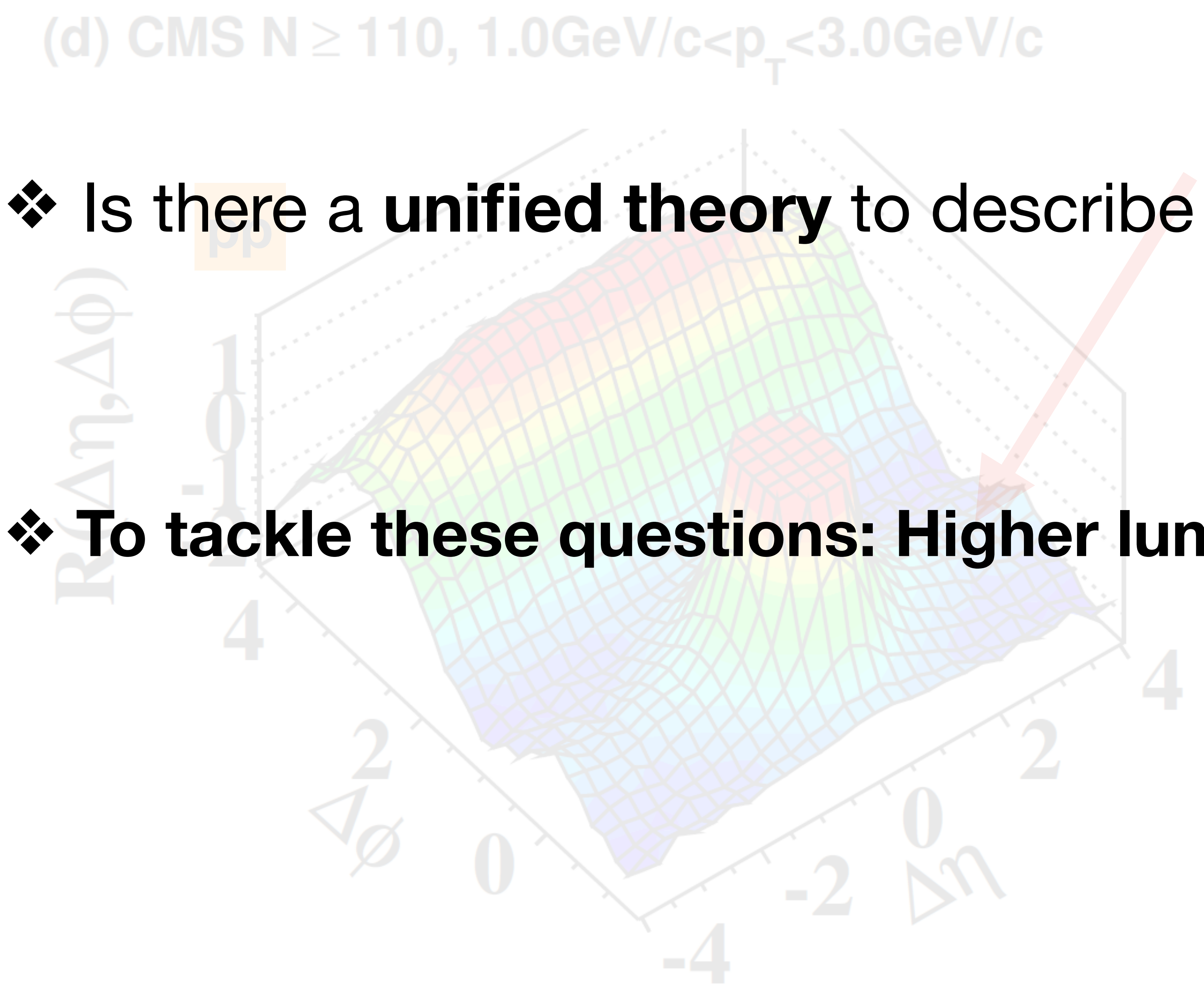
Nature Physics 13, 535–539 (2017)



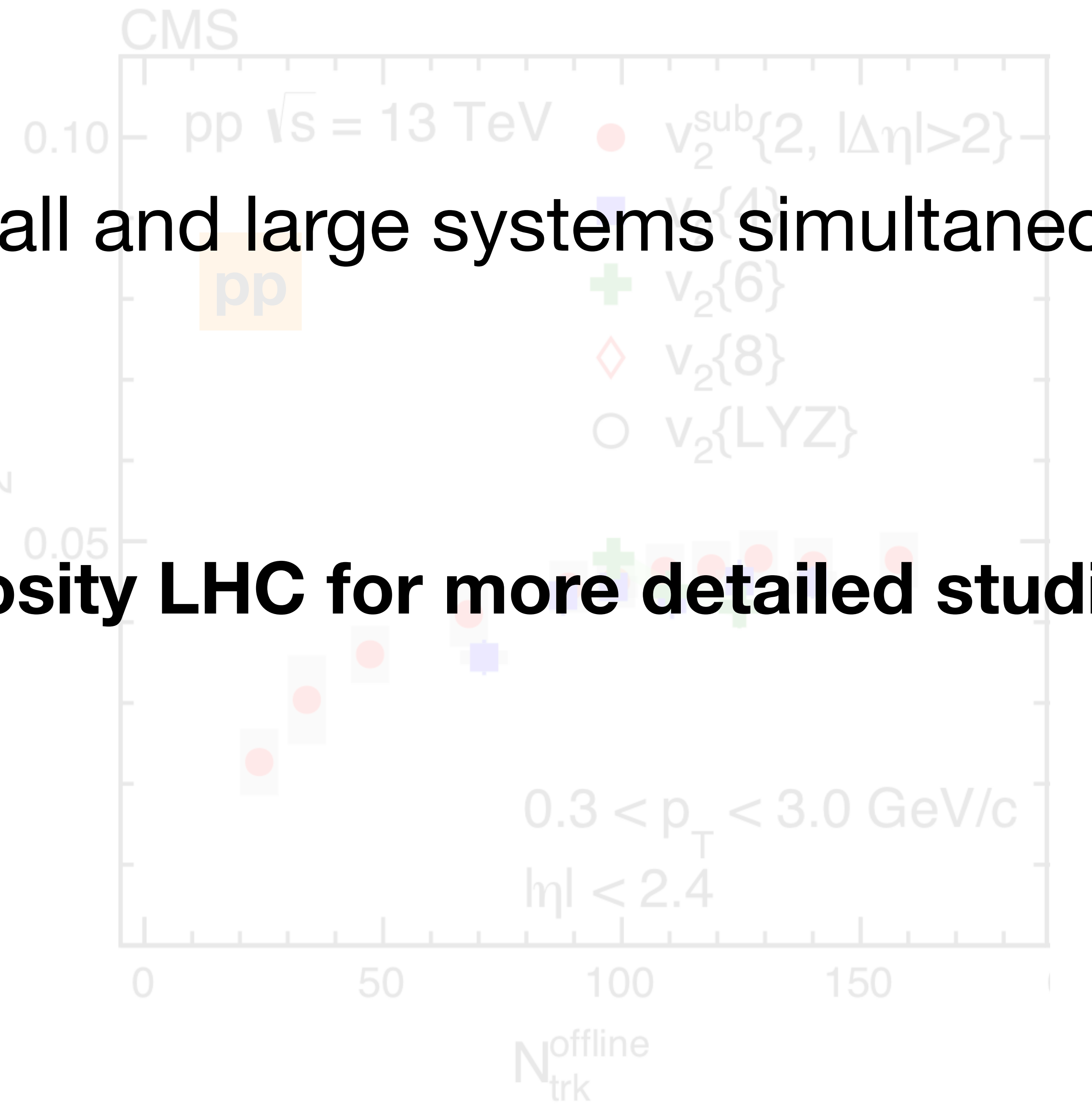
Emergence of Hot and Dense QCD in Small Systems

- ❖ **Initially a reference for the effects observed in Pb-Pb collisions**

- ❖ **Observations in high multiplicity pp collisions:**
  - ❖ Azimuthal correlations of final state hadrons
    - ➡ *Is the physical **origin of collectivity** the same in small and large systems?*
  - ❖ Enhanced production of multi-strange hadrons
    - ➡ Is there a **smooth transition** from pp to PbPb collisions?



JHEP09(2010)091



Phys. Lett. B 765 (2017) 193

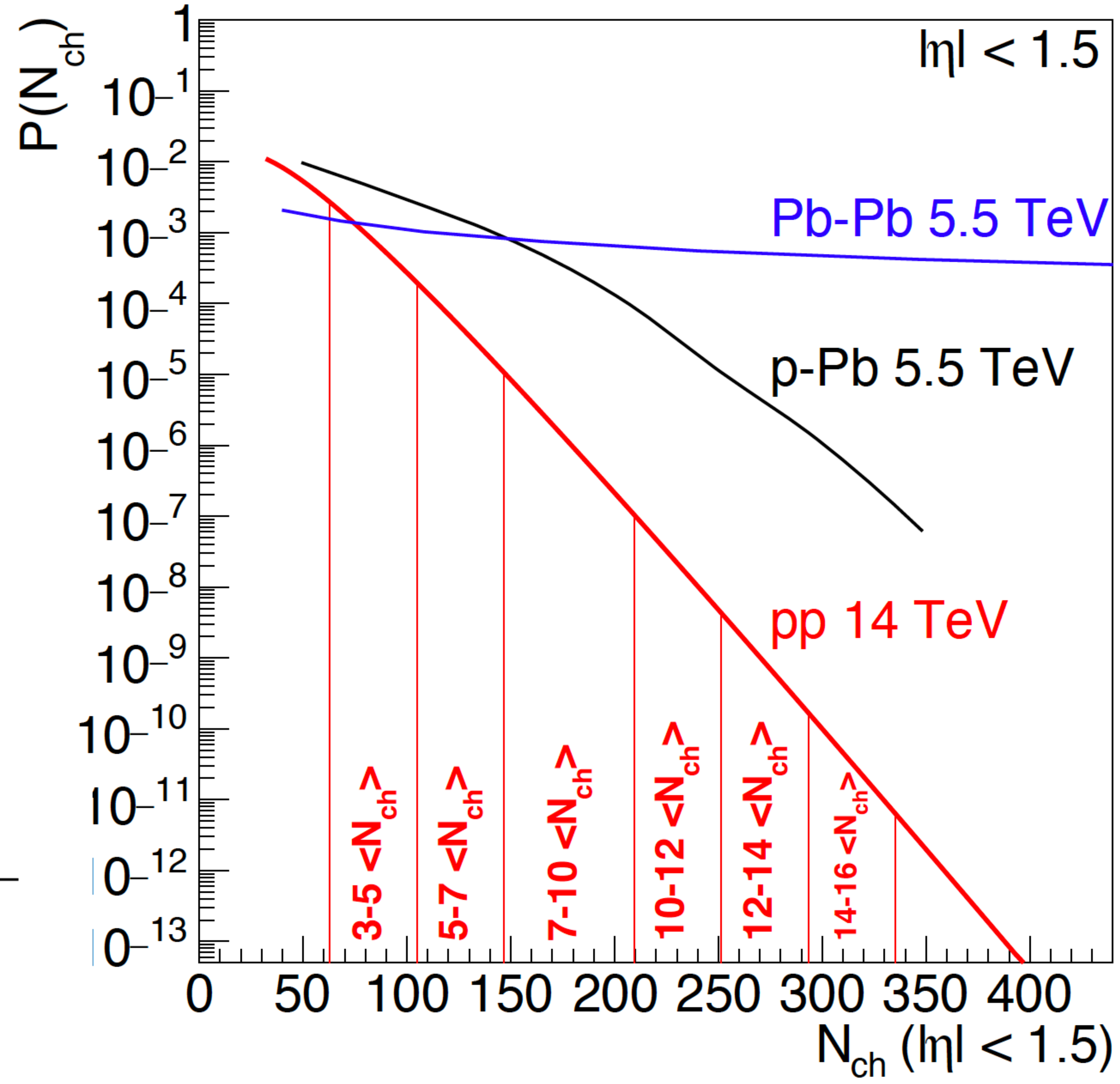
Nature Physics 13, 535–539 (2017)

- ❖ Is there a **unified theory** to describe small and large systems simultaneously?

- ❖ **To tackle these questions: Higher luminosity LHC for more detailed studies**

Proton-proton multiplicity distribution

- Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
  - Extrapolated to 200 pb^{-1} 14 TeV high multiplicity pp collisions

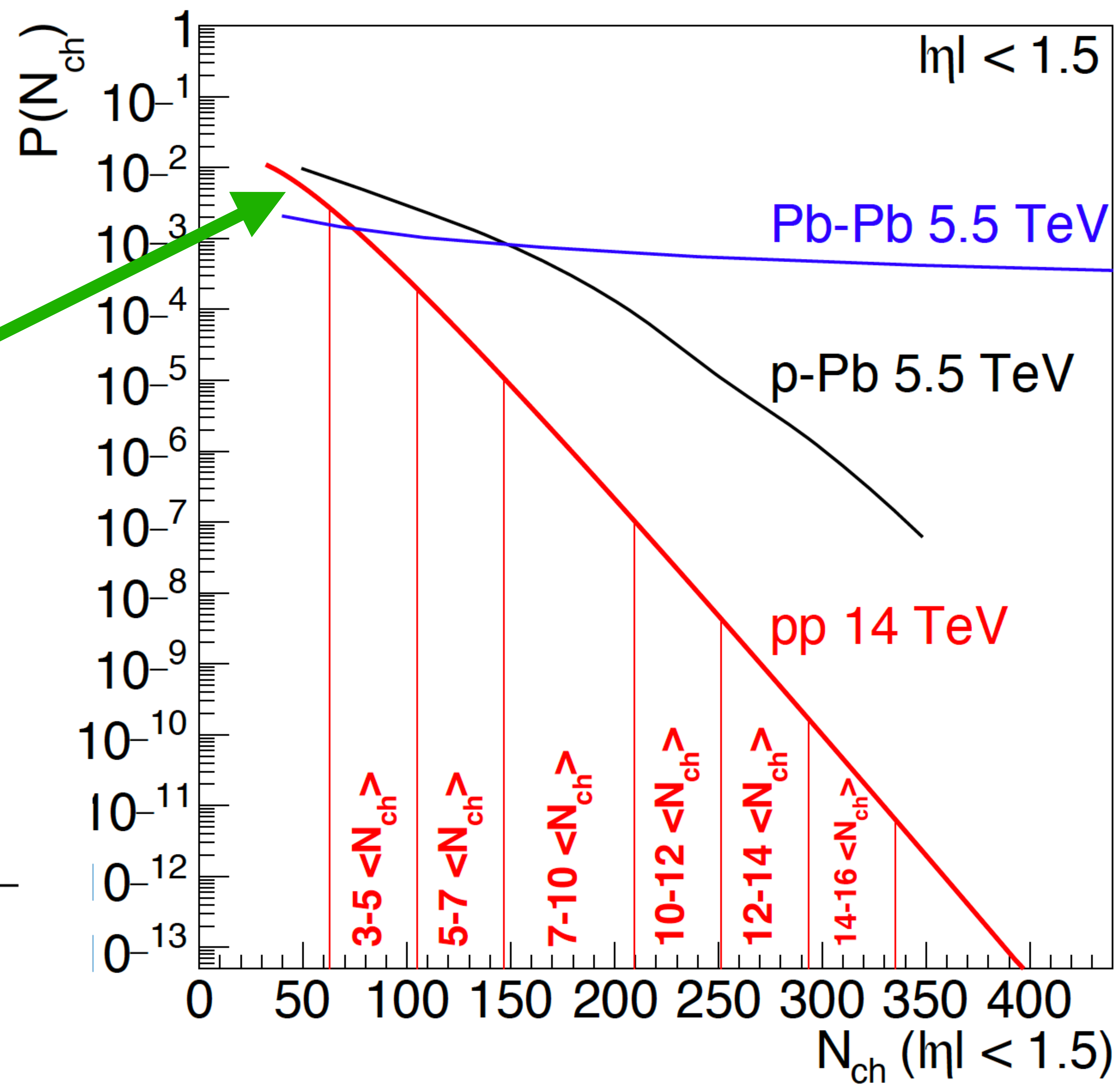


Range	$dN_{ch}/d\eta$	Fraction	Events per pb^{-1}	Events in 200 pb^{-1}
5–7 $\langle N_{ch} \rangle$	35–49	2.4e-03	1.9e+08	3.7e+10
7–10 $\langle N_{ch} \rangle$	49–70	1.3e-04	1.0e+07	2.0e+09
10–12 $\langle N_{ch} \rangle$	70–84	1.1e-06	9.0e+04	1.8e+07
12–14 $\langle N_{ch} \rangle$	84–98	4.7e-08	3.7e+03	7.3e+05
14–16 $\langle N_{ch} \rangle$	98–112	1.8e-09	1.4e+02	2.8e+04

Run 3+4

Proton-proton multiplicity distribution

- ❖ Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
  - ❖ Extrapolated to 200 pb^{-1} 14 TeV high multiplicity pp collisions
    - ❖ Few particle systems to study the onset of collectivity



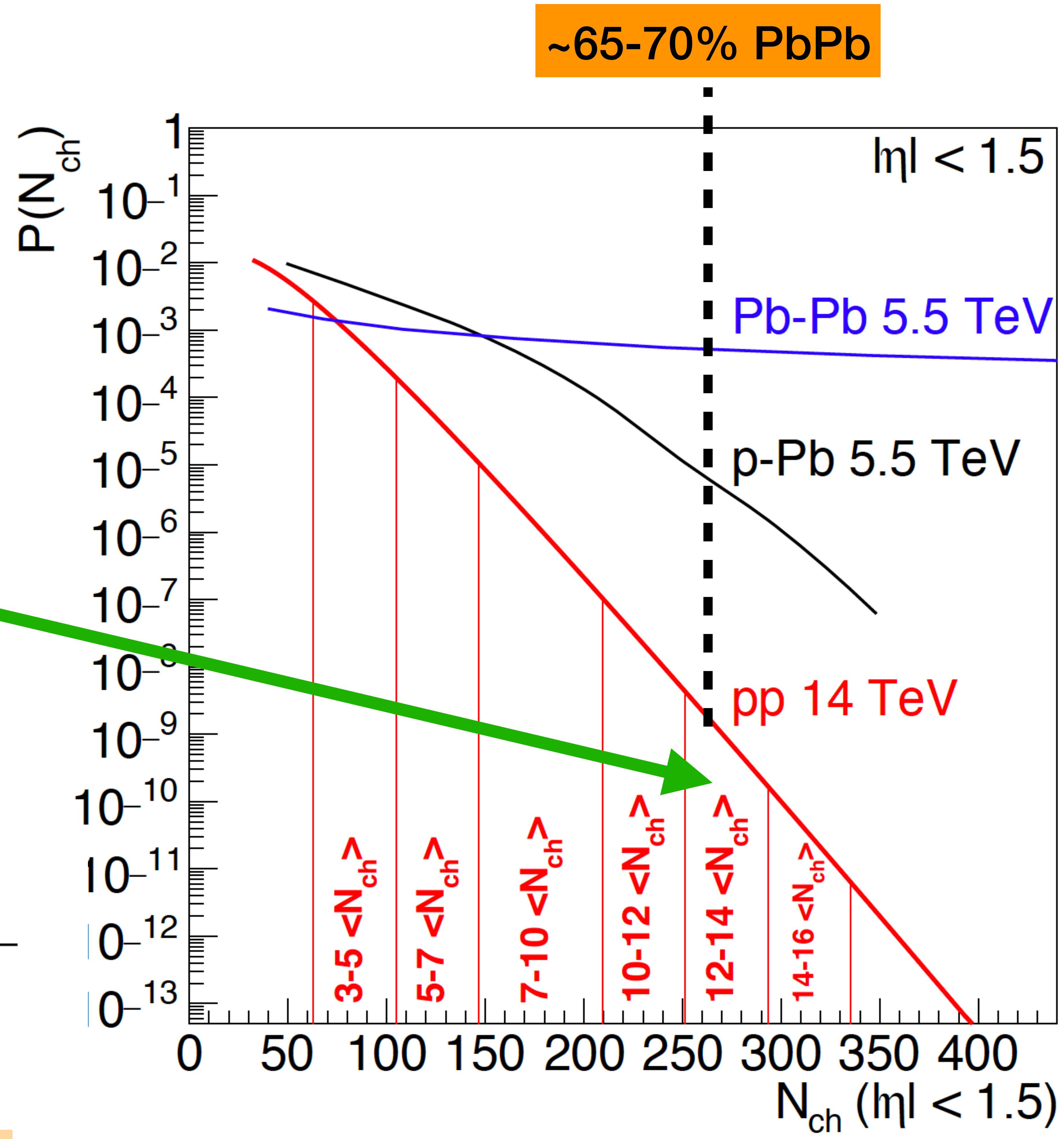
Range	$dN_{ch}/d\eta$	Fraction	Events per pb^{-1}	Events in 200 pb^{-1}
5–7 $\langle N_{ch} \rangle$	35–49	2.4e-03	1.9e+08	3.7e+10
7–10 $\langle N_{ch} \rangle$	49–70	1.3e-04	1.0e+07	2.0e+09
10–12 $\langle N_{ch} \rangle$	70–84	1.1e-06	9.0e+04	1.8e+07
12–14 $\langle N_{ch} \rangle$	84–98	4.7e-08	3.7e+03	7.3e+05
14–16 $\langle N_{ch} \rangle$	98–112	1.8e-09	1.4e+02	2.8e+04

Run 3+4

Proton-proton multiplicity distribution

- Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
  - Extrapolated to 200 pb^{-1} 14 TeV high multiplicity pp collisions
  - 730k events in multiplicity range of 65-70% PbPb collisions
    - Overlap between pp and PbPb allows to compare the two systems

Range	$dN_{ch}/d\eta$	Fraction	Events per pb^{-1}	Events in 200 pb^{-1}
5–7 $\langle N_{ch} \rangle$	35–49	2.4e-03	1.9e+08	3.7e+10
7–10 $\langle N_{ch} \rangle$	49–70	1.3e-04	1.0e+07	2.0e+09
10–12 $\langle N_{ch} \rangle$	70–84	1.1e-06	9.0e+04	1.8e+07
12–14 $\langle N_{ch} \rangle$	84–98	4.7e-08	3.7e+03	7.3e+05
14–16 $\langle N_{ch} \rangle$	98–112	1.8e-09	1.4e+02	2.8e+04

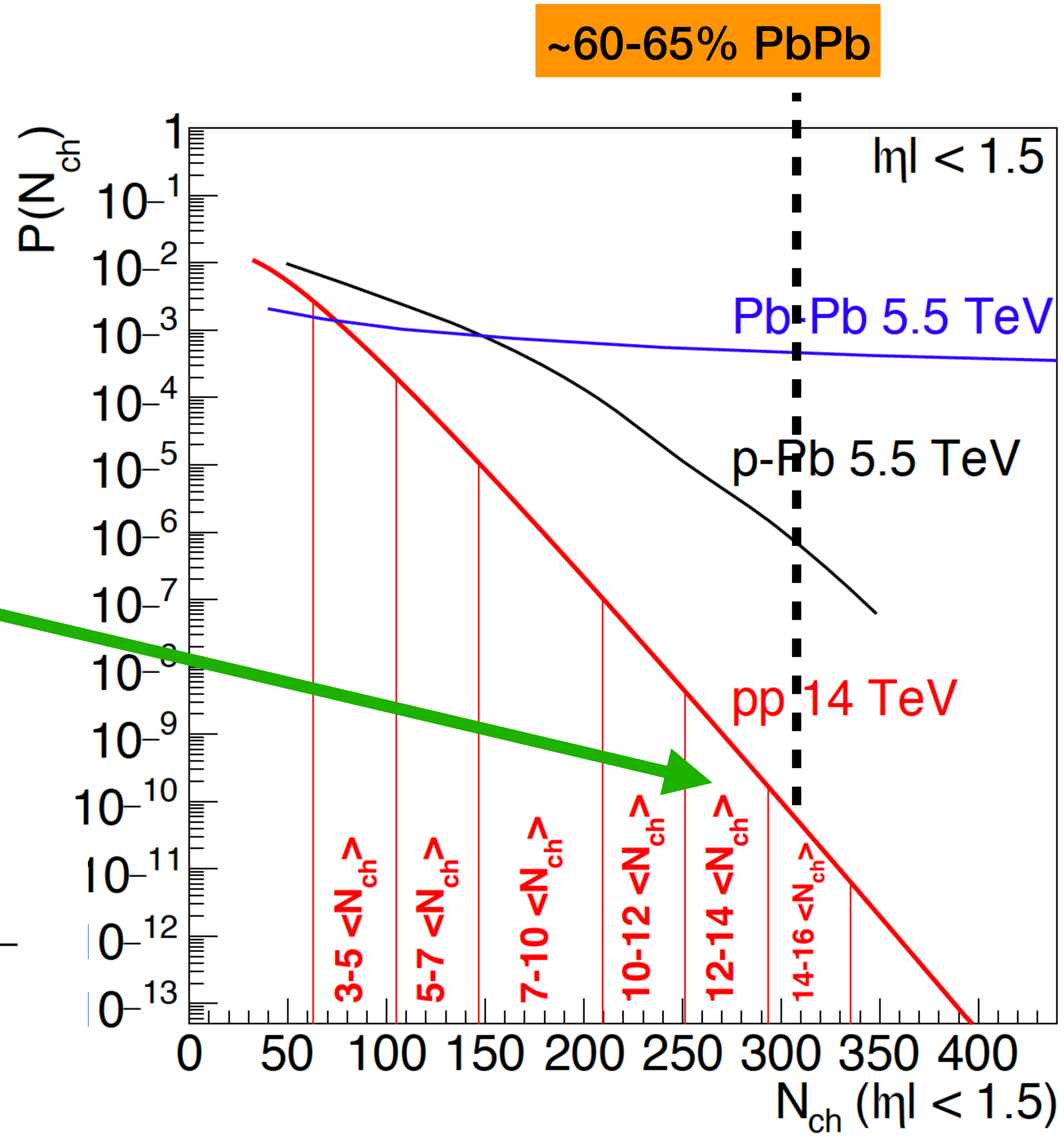


Run 3+4

Proton-proton multiplicity distribution

- ❖ Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
  - ❖ Extrapolated to 200 pb^{-1} 14 TeV high multiplicity pp collisions
  - ❖ 28k events in multiplicity range of 60-65% PbPb collisions
    - ❖ Overlap between pp and PbPb allows to compare the two systems

Range	$dN_{ch}/d\eta$	Fraction	Events per pb^{-1}	Events in 200 pb^{-1}
5–7 $\langle N_{ch}\rangle$	35–49	2.4e-03	1.9e+08	3.7e+10
7–10 $\langle N_{ch}\rangle$	49–70	1.3e-04	1.0e+07	2.0e+09
10–12 $\langle N_{ch}\rangle$	70–84	1.1e-06	9.0e+04	1.8e+07
12–14 $\langle N_{ch}\rangle$	84–98	4.7e-08	3.7e+03	7.3e+05
14–16 $\langle N_{ch}\rangle$	98–112	1.8e-09	1.4e+02	2.8e+04



Run 3+4

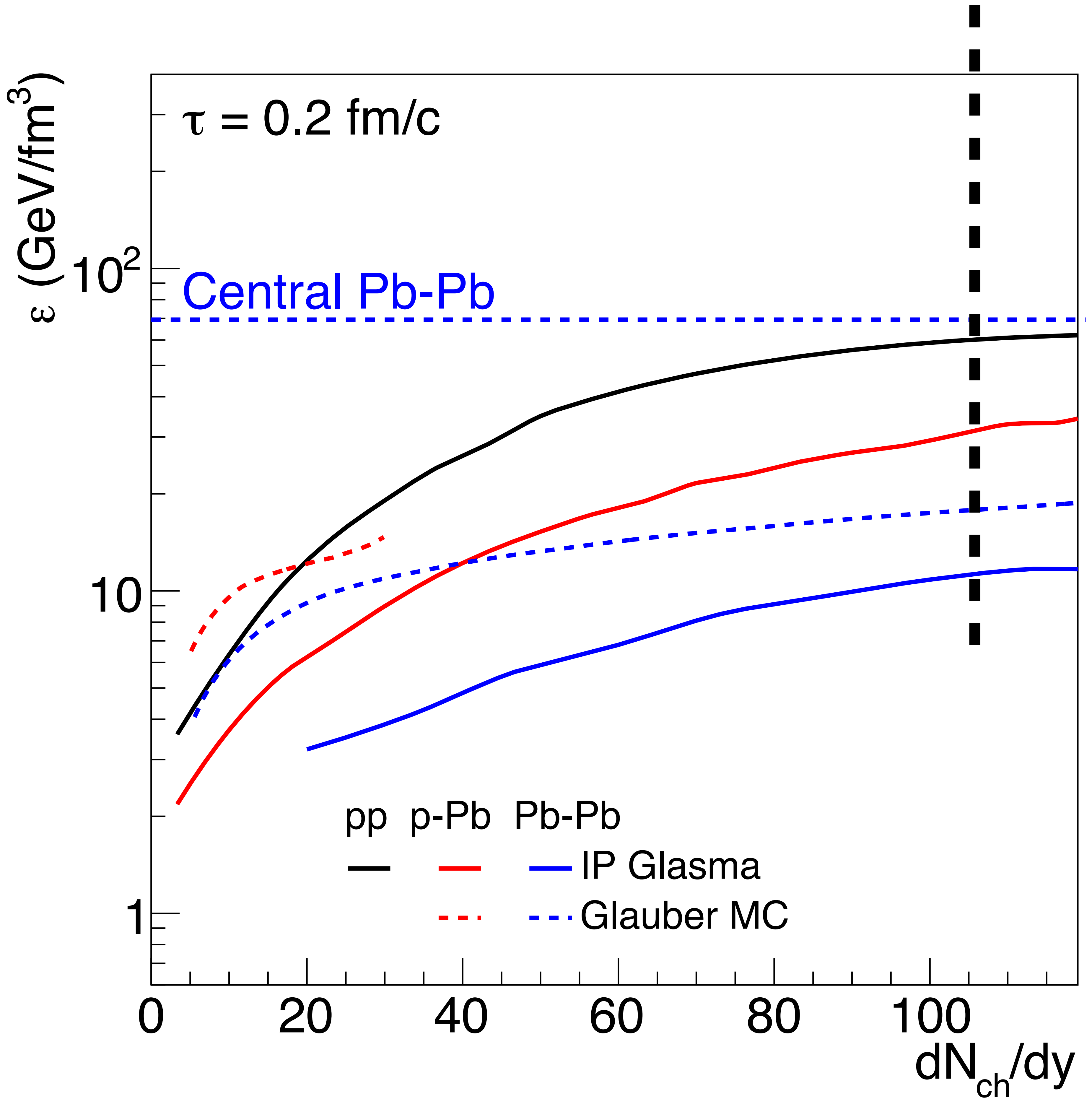
Energy density in different collision systems

- Energy density:
  - An estimate for pp, pPb and Pb-Pb collisions based on
    - IP-Glasma
    - Glauber MC (for pPb and PbPb) + Bjorken estimate

$$\epsilon = \frac{1}{A\tau}\langle E\rangle \frac{3}{2}\frac{dN_{ch}}{dy}.$$

  - Dependent on the system at fixed multiplicity
  - It can reach large values in pp and pPb collisions, of the order of central Pb-Pb collisions
  - **One way of calculating the energy density**

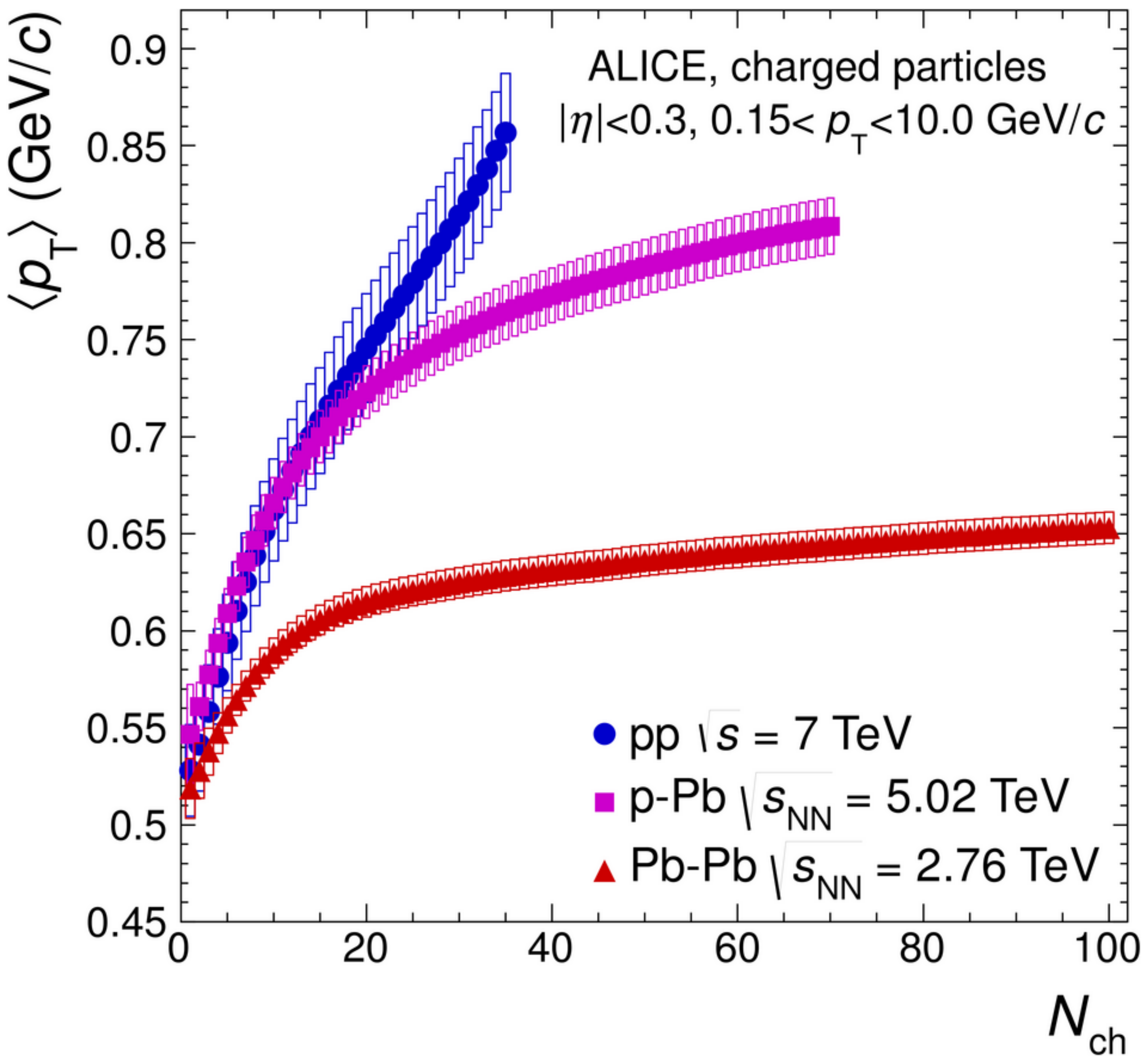
Same multiplicity does not mean same energy density



Global-event properties

- **Shape of the multiplicity distribution**
  - Mechanisms producing very high multiplicity events not clear
- **Mean p_T increases with multiplicity**
  - Measurements exist only up to $dN_{ch}/d\eta$ ~55
  - HL-LHC will provide twice this value

- High multiplicity collisions originate from MPI within the same pp collision
  - Understanding particle production in high energy pp collisions
  - Number of low momentum transfer parton interactions increases linearly with multiplicity
    - Possible saturation at large multiplicity



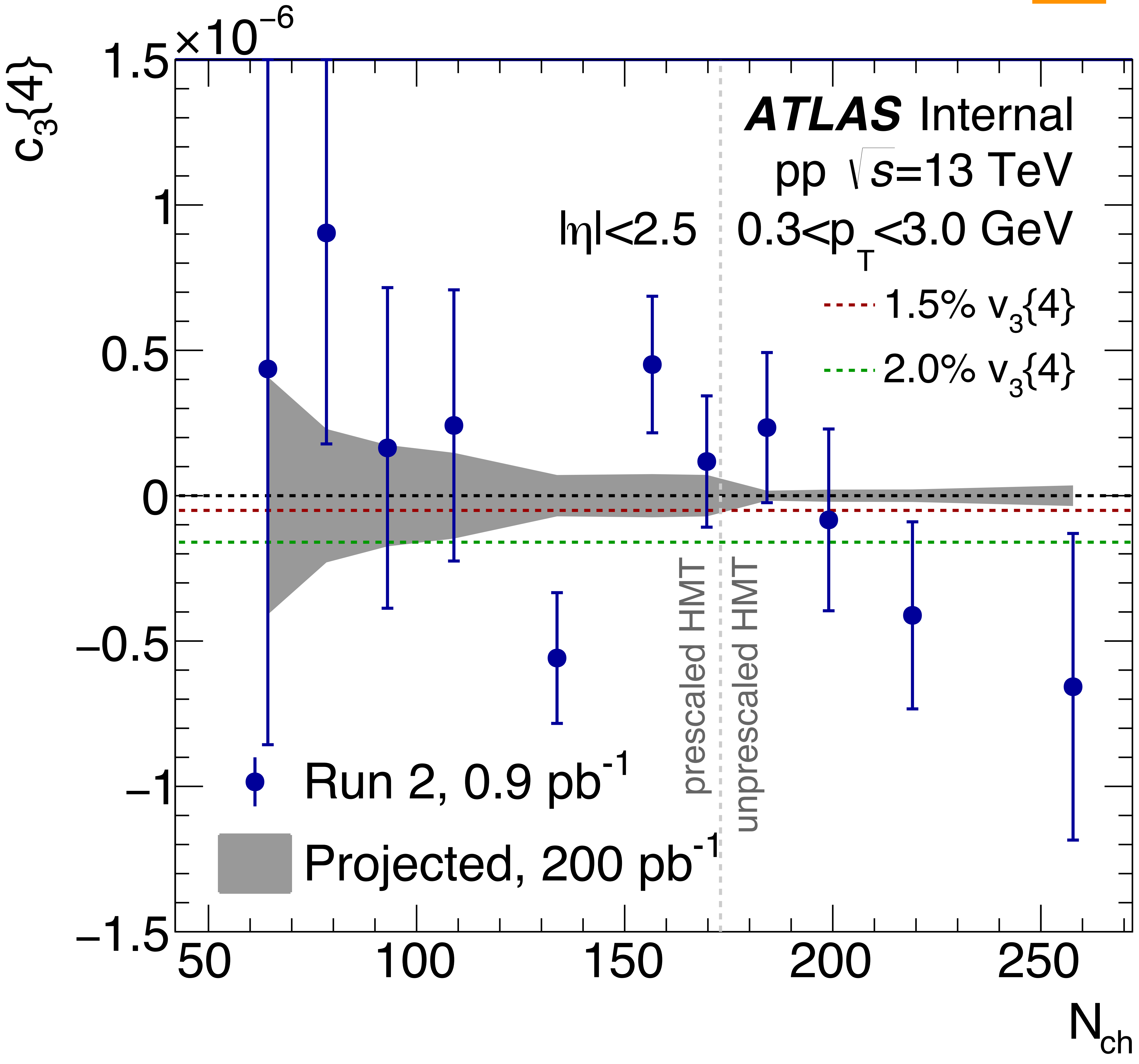
Particle correlations: multi-particle cumulants

- Particle correlations:
  - In high multiplicity pp to compare with pPb and PbPb collisions
  - In low multiplicity regions to investigate the onset of the collective-like effects
- **4 particle cumulants ($c_n\{4\}$)**

$$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

- **Suppresses correlations from jets and dijets**
- Measured in pp and pPb with Run 1 & 2 using 3 subevent method
  - c3{4} lacks statistics in pp and mostly consistent with zero
  - c3{4} negative non zero magnitude in PbPb collisions
    - **Is $c_3\{4\}$ negative in pp collisions?**

pp



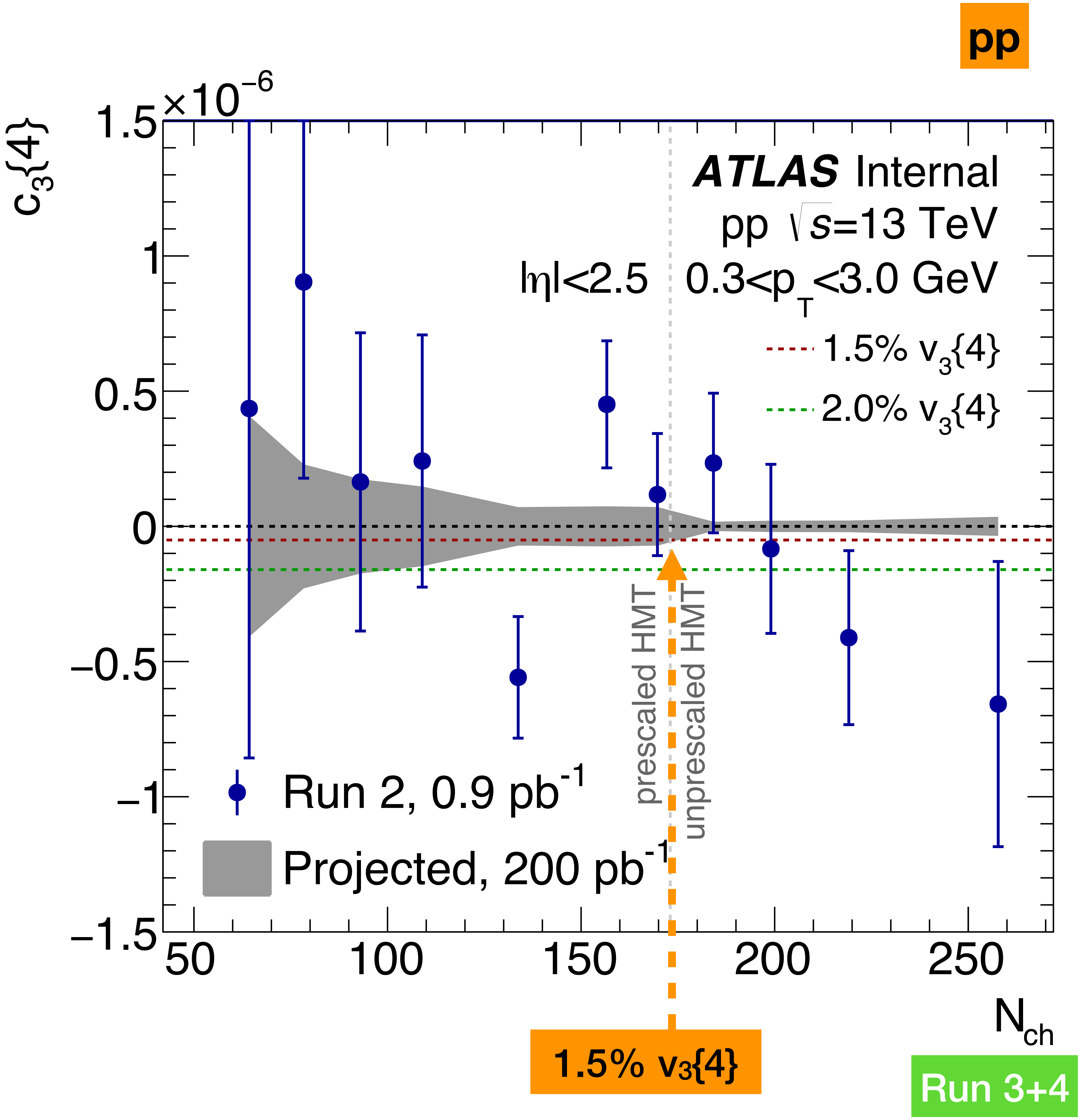
Run 3+4

Particle correlations: multi-particle cumulants

- Particle correlations:
  - In high multiplicity pp to compare with pPb and PbPb collisions
  - In low multiplicity regions to investigate the onset of the collective-like effects
- **4 particle cumulants ($c_n\{4\}$)**

$$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

- **Suppresses correlations from jets and dijets**
- Measured in pp and pPb with Run 1 & 2 using 3 subevent method
  - c3{4} lacks statistics in pp and mostly consistent with zero
  - c3{4} negative non zero magnitude in PbPb collisions
    - **Is $c_3\{4\}$ negative in pp collisions?**



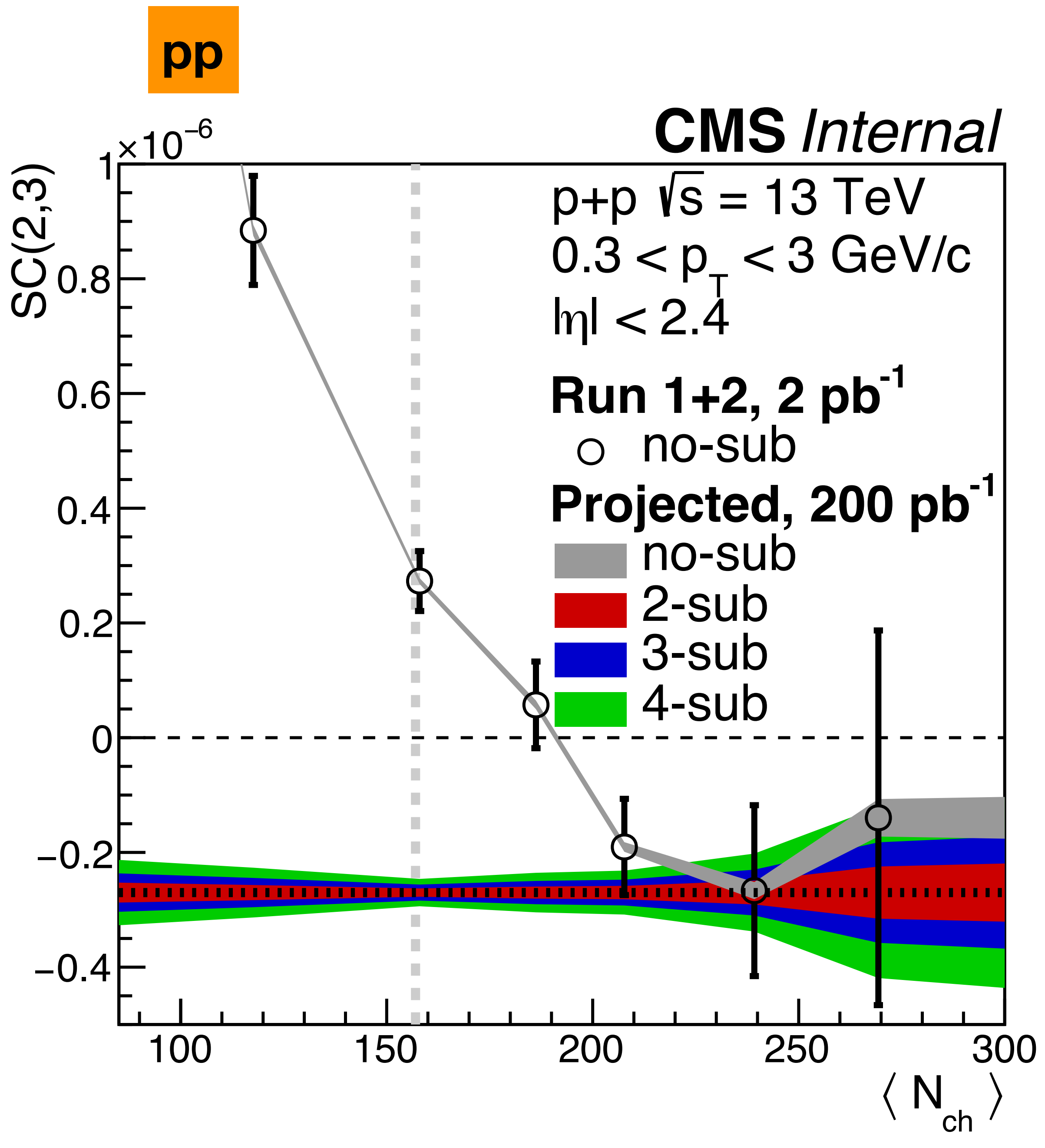
Particle correlations: symmetric cumulants

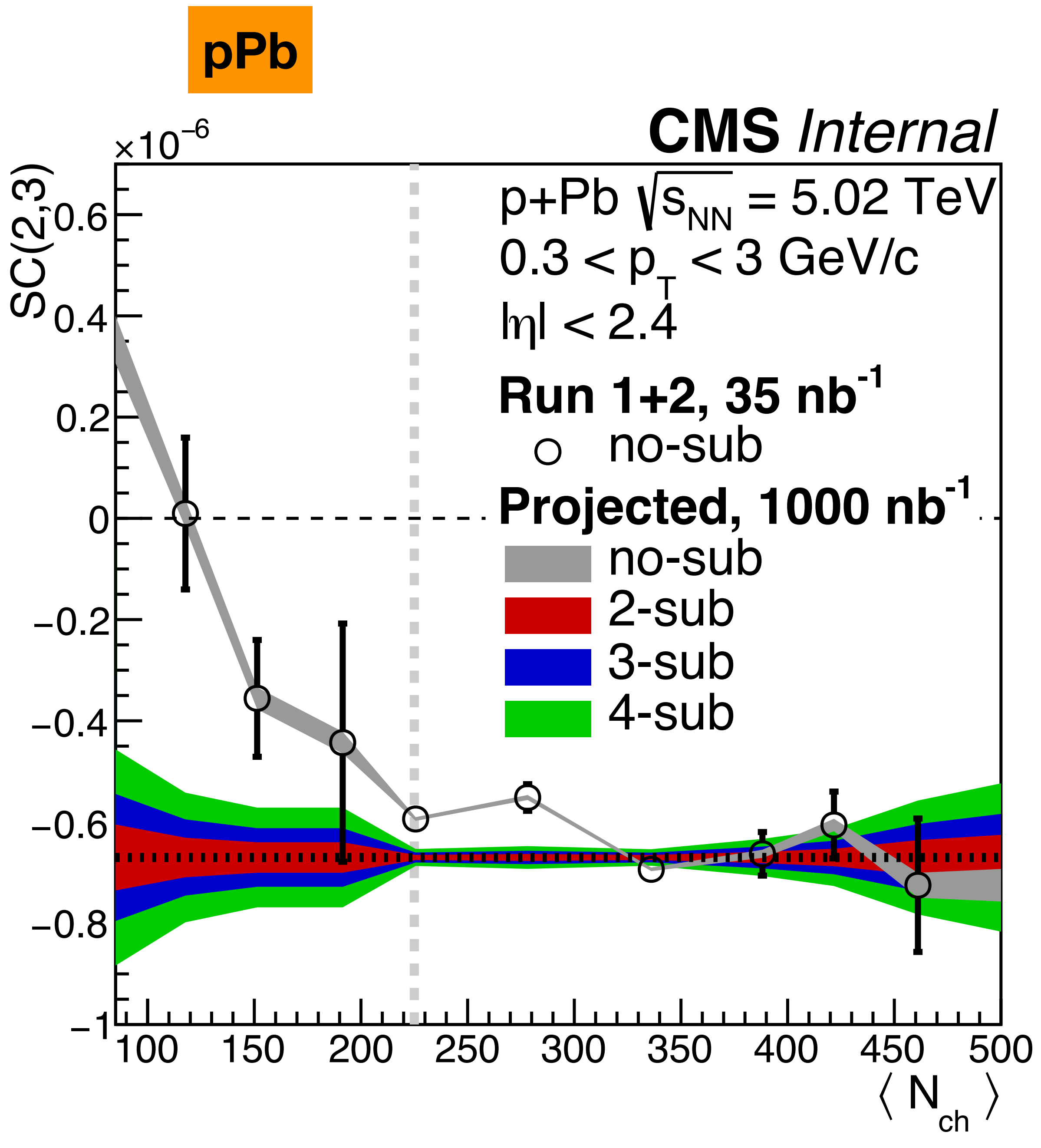
- ❖ Particle correlations:
  - ❖ In high multiplicity pp to compare with pPb and PbPb collisions
  - ❖ In low multiplicity regions to investigate the onset of the collective-like effects

- ❖ Symmetric cumulants: Correlations of different flow harmonics, e.g.

$$SC(3,2) = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle$$

  - ❖ Sensitive to
    - ❖ **Initial conditions**
    - ❖ **Hydrodynamic evolution**
  - ❖ In small systems: better description of the initial condition and proton substructure





Run 3+4

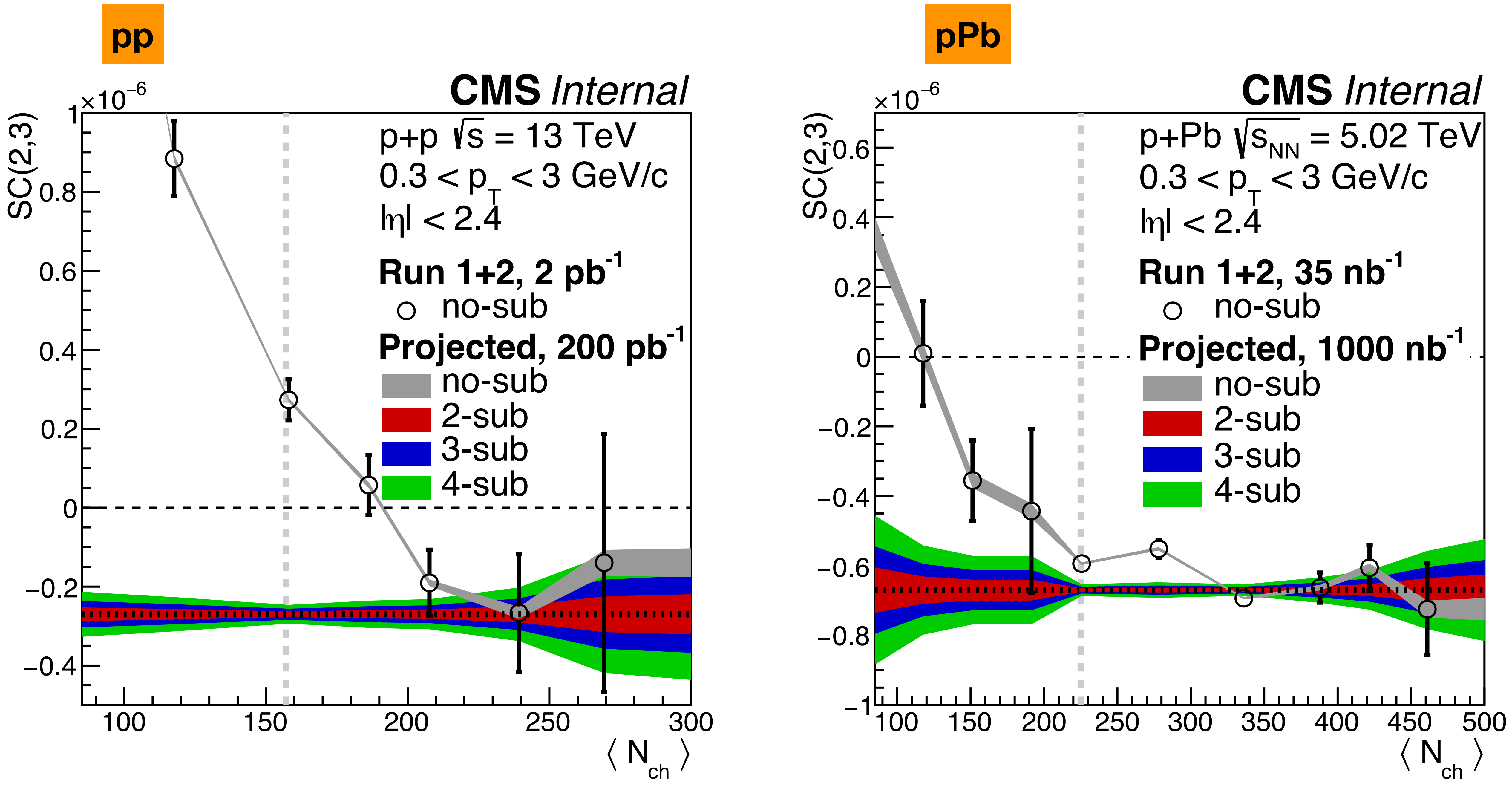
Particle correlations: symmetric cumulants

- Particle correlations:
  - In high multiplicity pp to compare with pPb and PbPb collisions
  - In low multiplicity regions to investigate the onset of the collective-like effects

- Symmetric cumulants: Correlations of different flow harmonics, e.g.

$$\mathrm{SC}(3,2) = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle$$

  - Sensitive to
    - **Initial conditions**
    - **Hydrodynamic evolution**
  - In small systems: better description of the initial condition and proton substructure



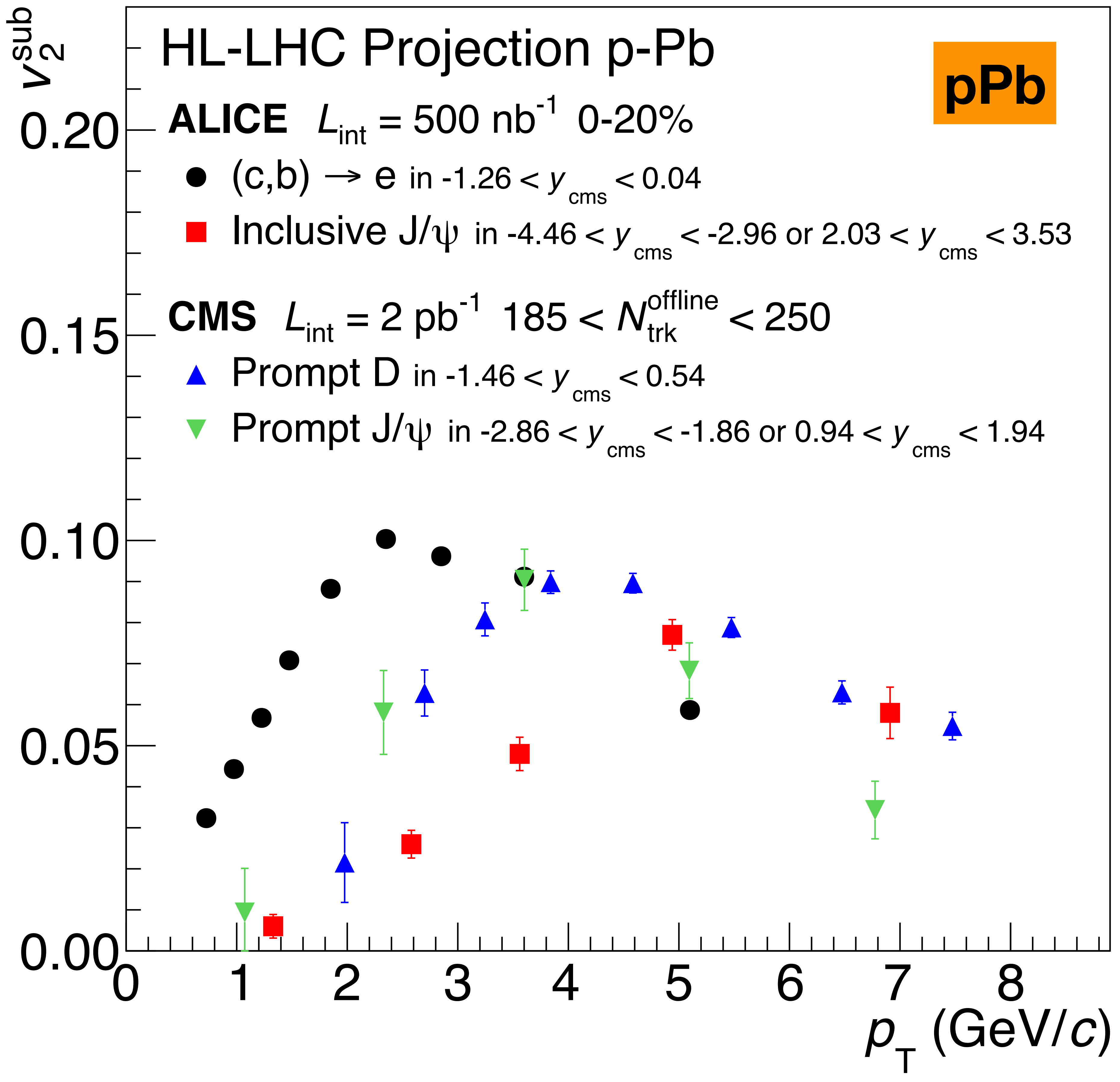
- Current measurements -> large uncertainties
- Projections for SC(3,2) for HL pp and pPb collisions
  - Projections for no-sub: **uncertainties invisible** but largely contaminated with non-flow
  - 2,3 and 4-sub event methods possible: **uncertainties of the order of a few 10^{-7}**

Run 3+4

Particle correlations: heavy flavors in small systems

- **Heavy flavor hadrons** originate from heavy quarks that experienced all stages of the system evolution
- **heavy flavor flow** measurements:
  - Low p_T: test if heavy flavor quarks participate in the **collective expansion dynamics**
  - Intermediate p_T: sensitive to the **heavy-quark hadronization mechanism/recombination**

- v_2 for **heavy flavor objects** feasible in pPb collisions with HL-LHC:
  - Inclusive J/ψ with ALICE, Prompt J/ψ and D by CMS
  - Minor uncertainties expected



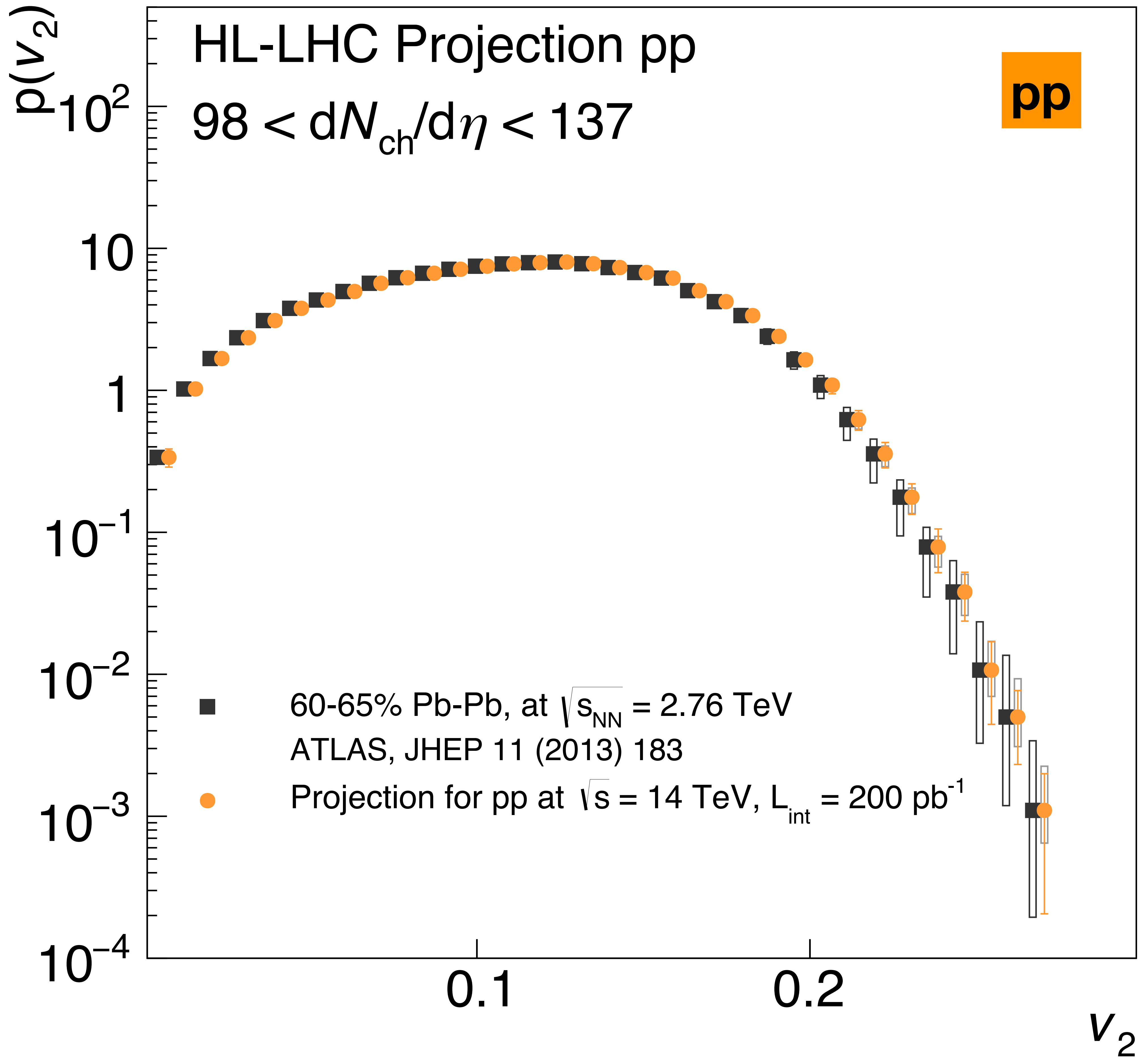
Run 3+4

Particle correlations: probability distribution of event-by-event v_n

- Probability distribution of event-by-event v_2 ($p(v_2)$) in an approximate level:

$$p(\vec{v}_n) = \frac{1}{2\pi\delta^2_{v_n}} e^{-\left(\vec{v}_n - \vec{v}_n^{\,RP}\right)^2 / \left(2\delta^2_{v_n}\right)}$$

- **Sensitive to**
  - **Initial conditions and final state dynamics of the medium**
- Not measured in small systems so far
  - Expected to have a narrower width and smaller <v_2>
- Feasible in small systems in HL-LHC
- Projections for pp at 14 TeV, L_{int} = 200 pb^{-1} :
  - Based on 60-65% Pb-Pb collisions at 2.76 TeV

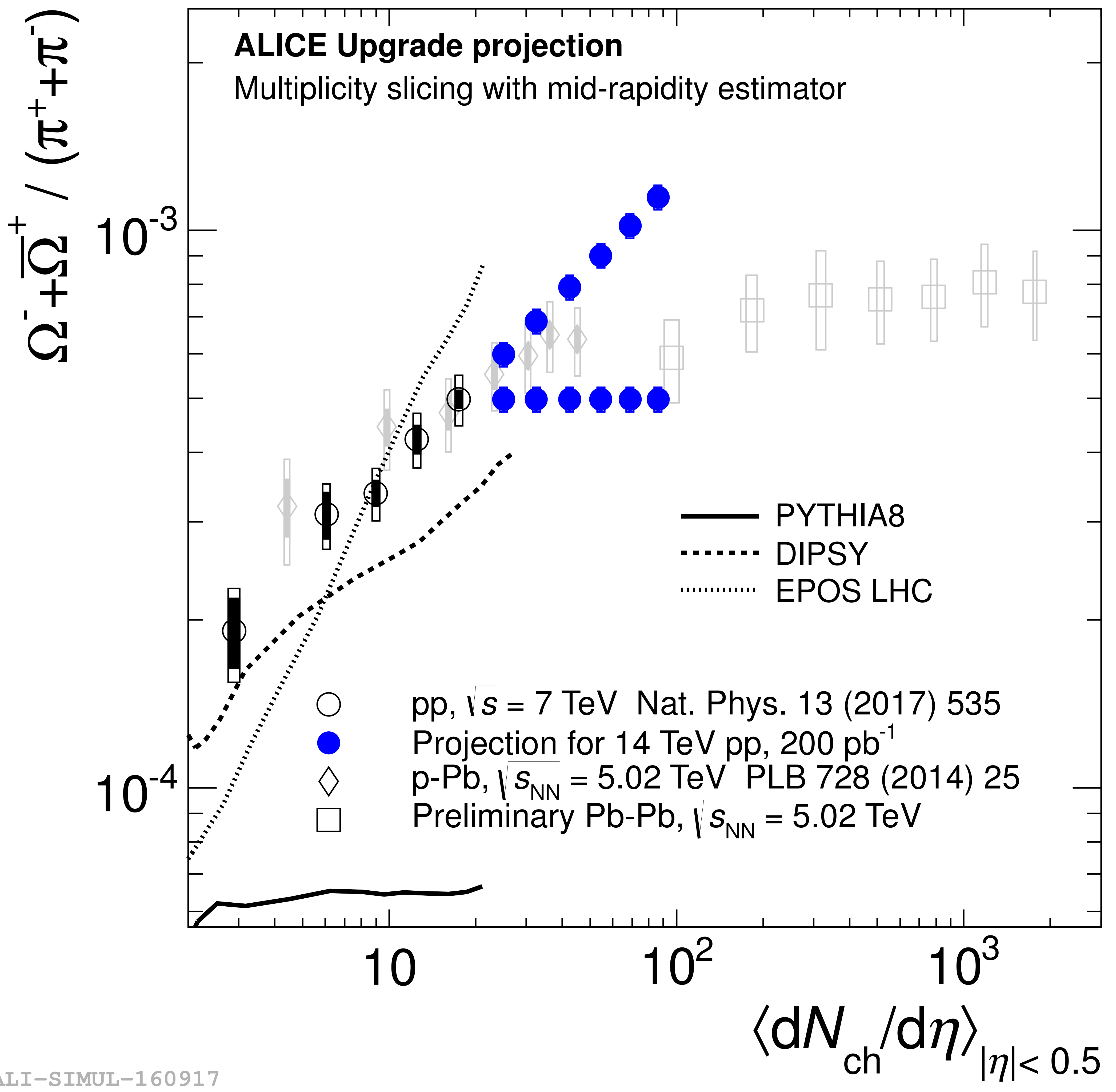


Run 3+4

Strangeness enhancement

- Key observable in run 2 pp physics:
  - Smooth increase in strange-particle production as a function of system size

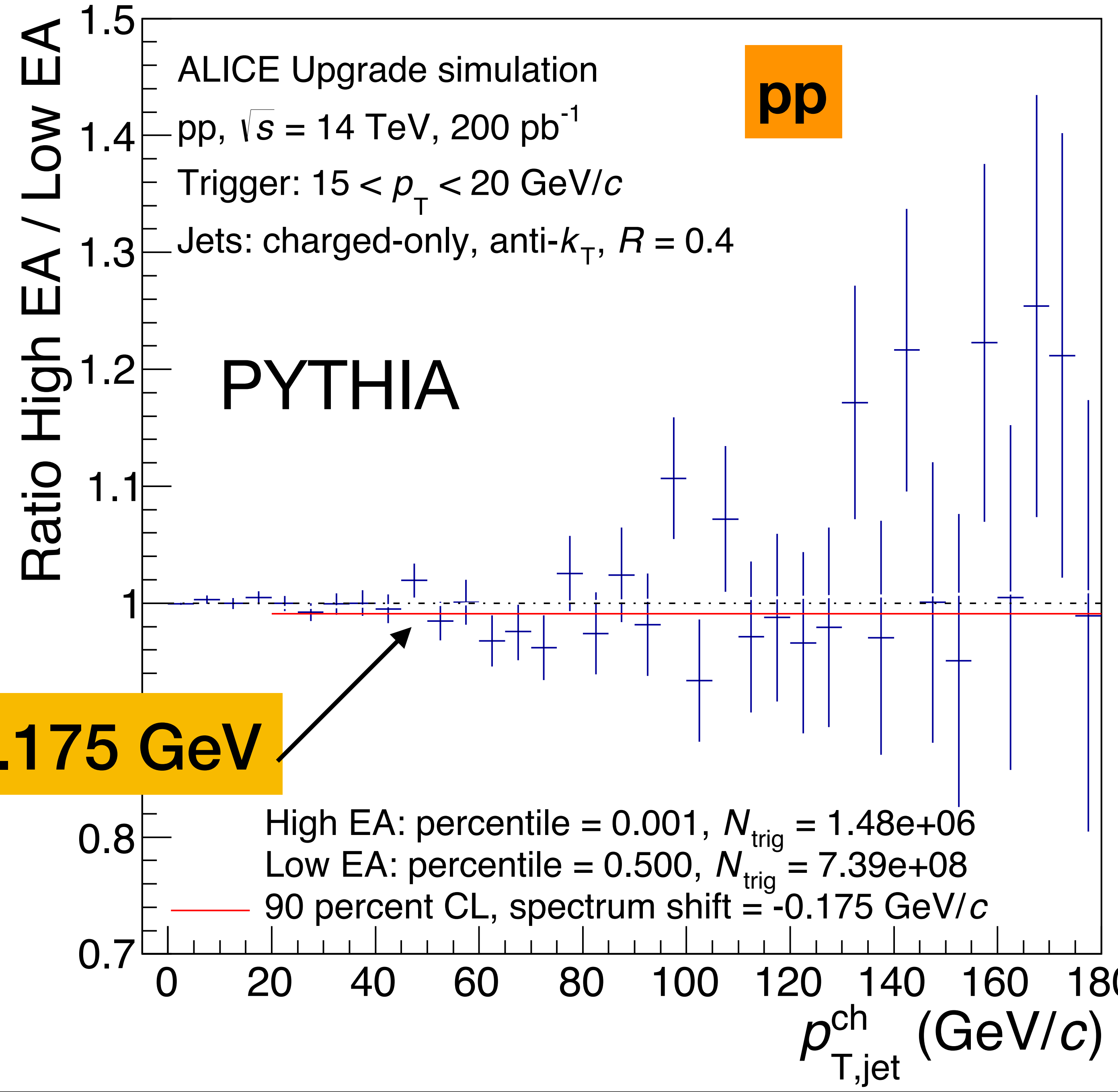
- pp collisions up to $dN_{ch}/d\eta = 17$
- Most peripheral PbPb collisions down to $dN_{ch}/d\eta = 96$
- Projection of the reach with pp collisions in HL-LHC
  - Strangeness enhancement scaling with the energy density of the system
    - **continuous increase**
    - **saturation at PbPb value (thermal limit)**



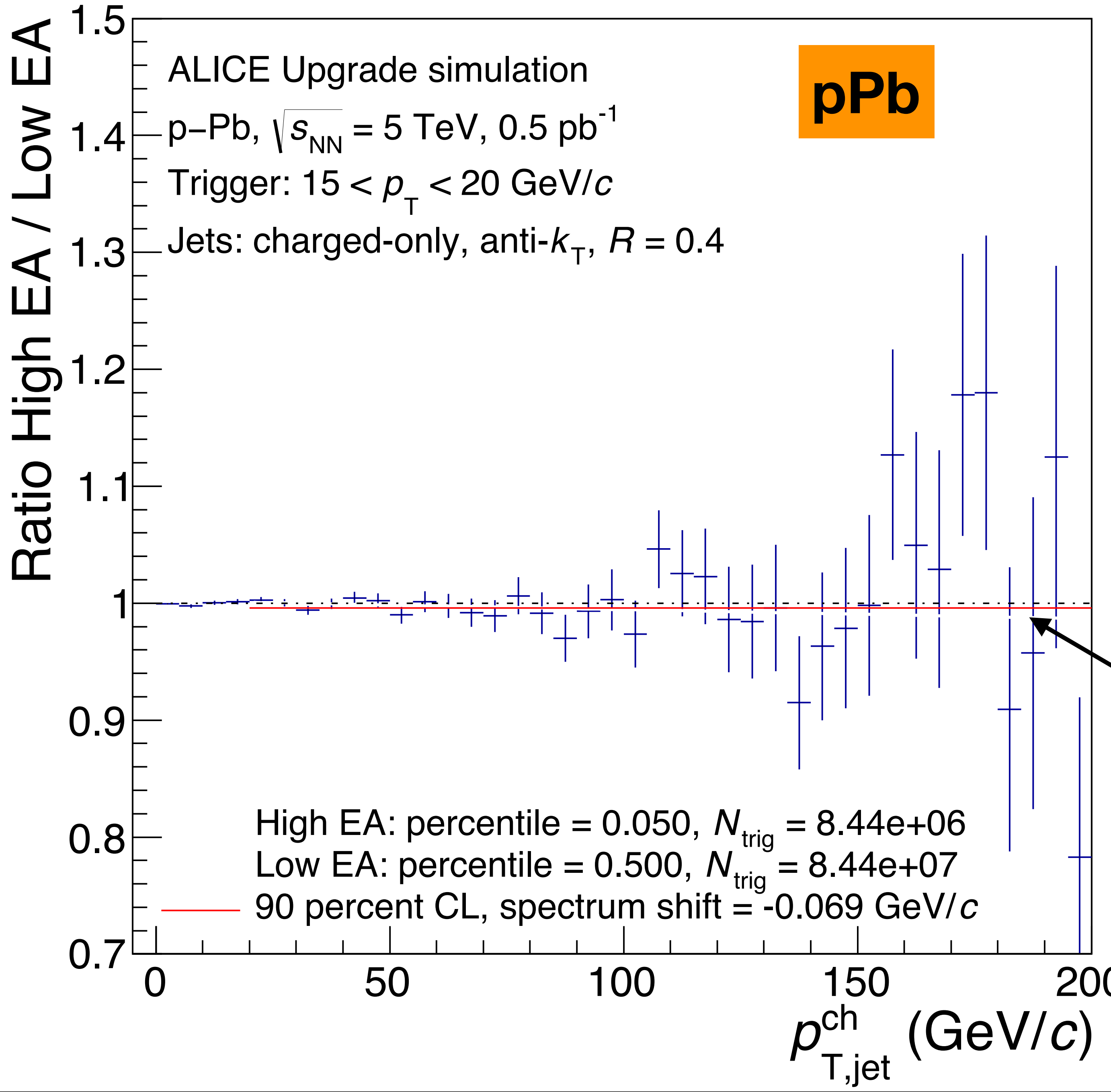
Run 3+4

Energy loss: hadron-jet correlations

- Absence of jet quenching in p-Pb collisions in run 1 & 2
- If final state interactions explain observed collective phenomena
  - energy loss should be measurable OR put stringent limit
- **Potential to identify small energy loss effects in small systems with jet recoil against other objects**
  - Projections for the modification of jet recoil yields extracted from hadron-jet correlations in run 3 and 4 for pp and pPb collision -> 40-100 times smaller than the spectrum shift in PbPb collisions



spectrum shift: 0.175 GeV



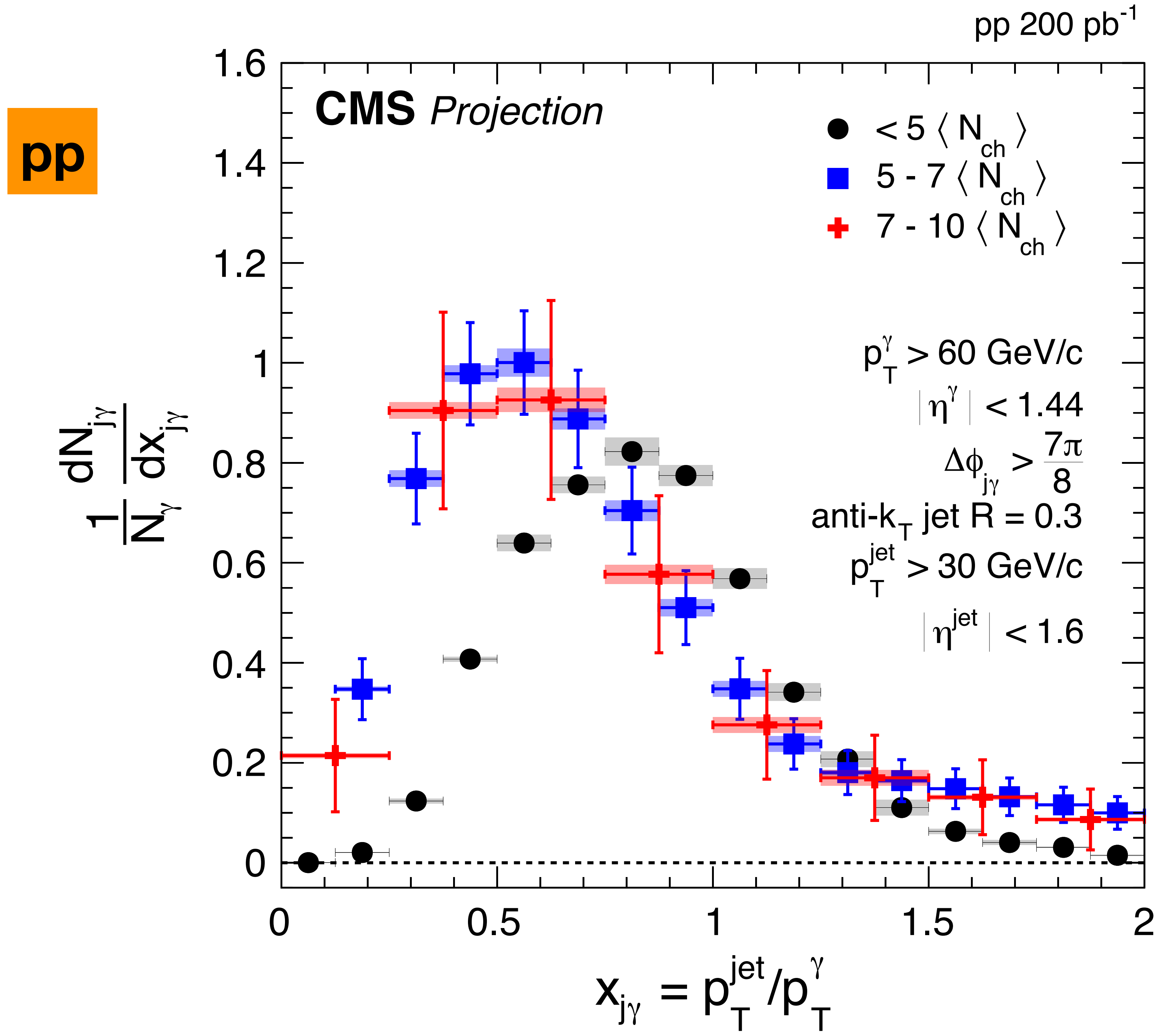
spectrum shift: 0.069 GeV

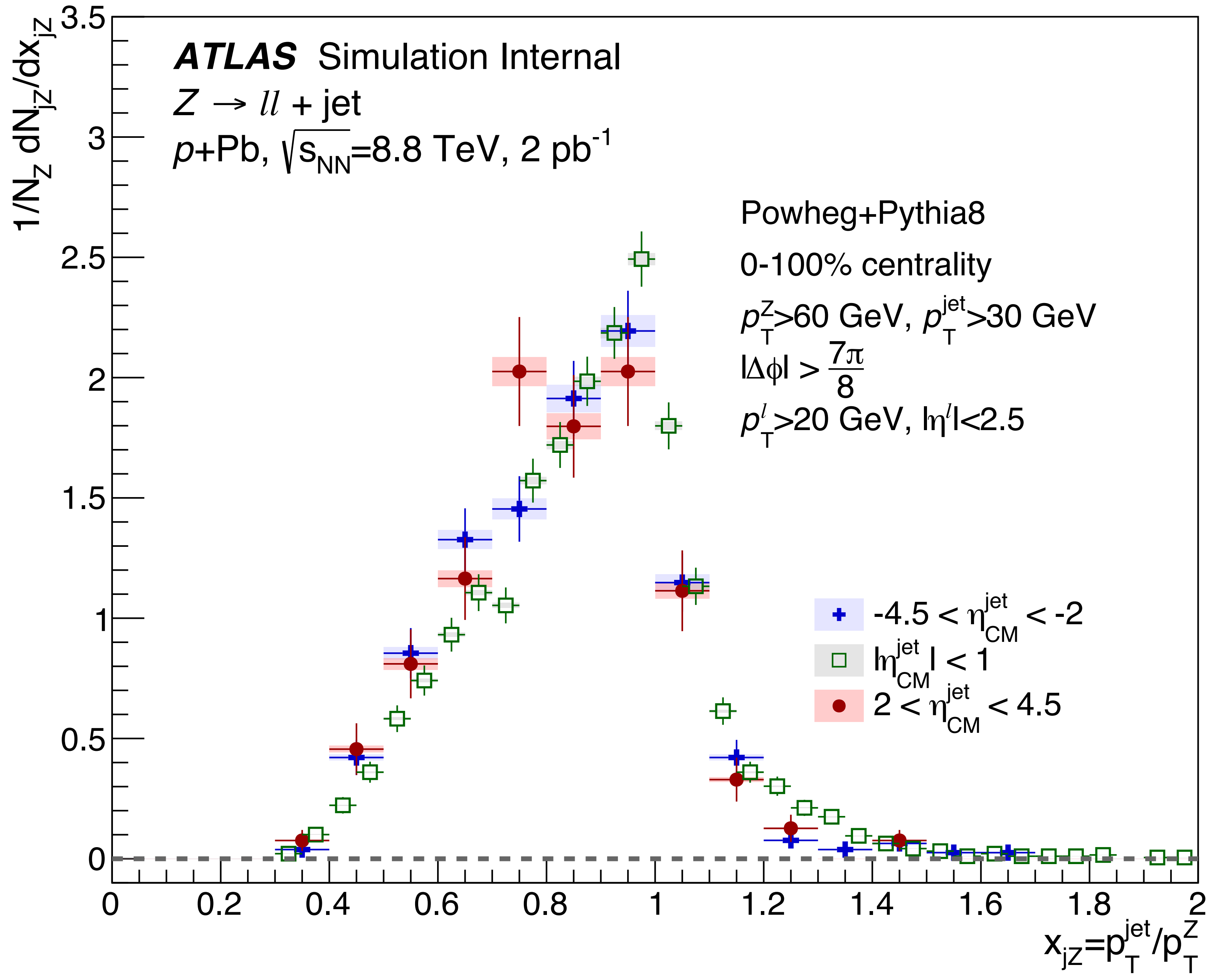
Run 3+4

Energy loss: γ and Z + jet correlations

- Absence of jet quenching in p-Pb collisions in run 1 & 2
- If final state interactions explain observed collective phenomena
  - energy loss should be measurable OR put stringent limit
- **Potential to identify small energy loss effects in small systems with jet recoil against other objects**
  - Projections for the correlations between jet, γ and Z in run 3 and 4 for pp and pPb collision
    - **γ and Z unmodified by final state interactions**

pp





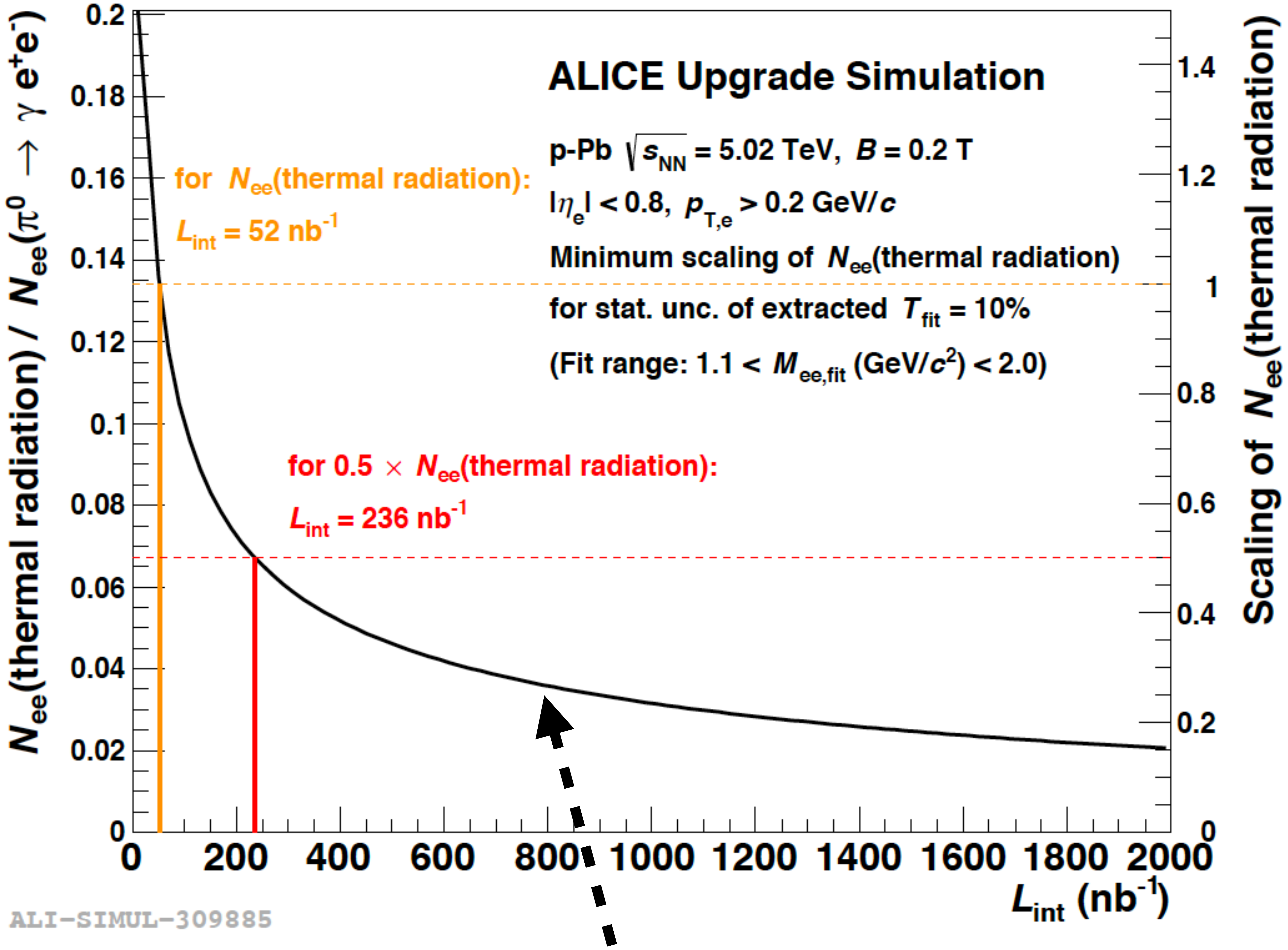
pPb

Run 3+4

Thermal radiation

- ❖ Search for thermal dilepton signal in pp and pPb
  - ❖ QGP thermal radiation detection in pPb
    - ❖ Extract the medium temperature
- ❖ Measurements in pPb collisions
  - ❖ Statistical uncertainty of 10% on the temperature
    - ❖ If predictions accurate -> L_{int} = 50 nb^{-1} sufficient for the measurement
    - ❖ If signal 50% smaller -> 5 times the statistics is needed
    - ❖ Run 3+4 sensitive to down to 25% of the predicted signal by R. Rapp [Acta Phys. Polon. B42 (2011) 2823]

pPb



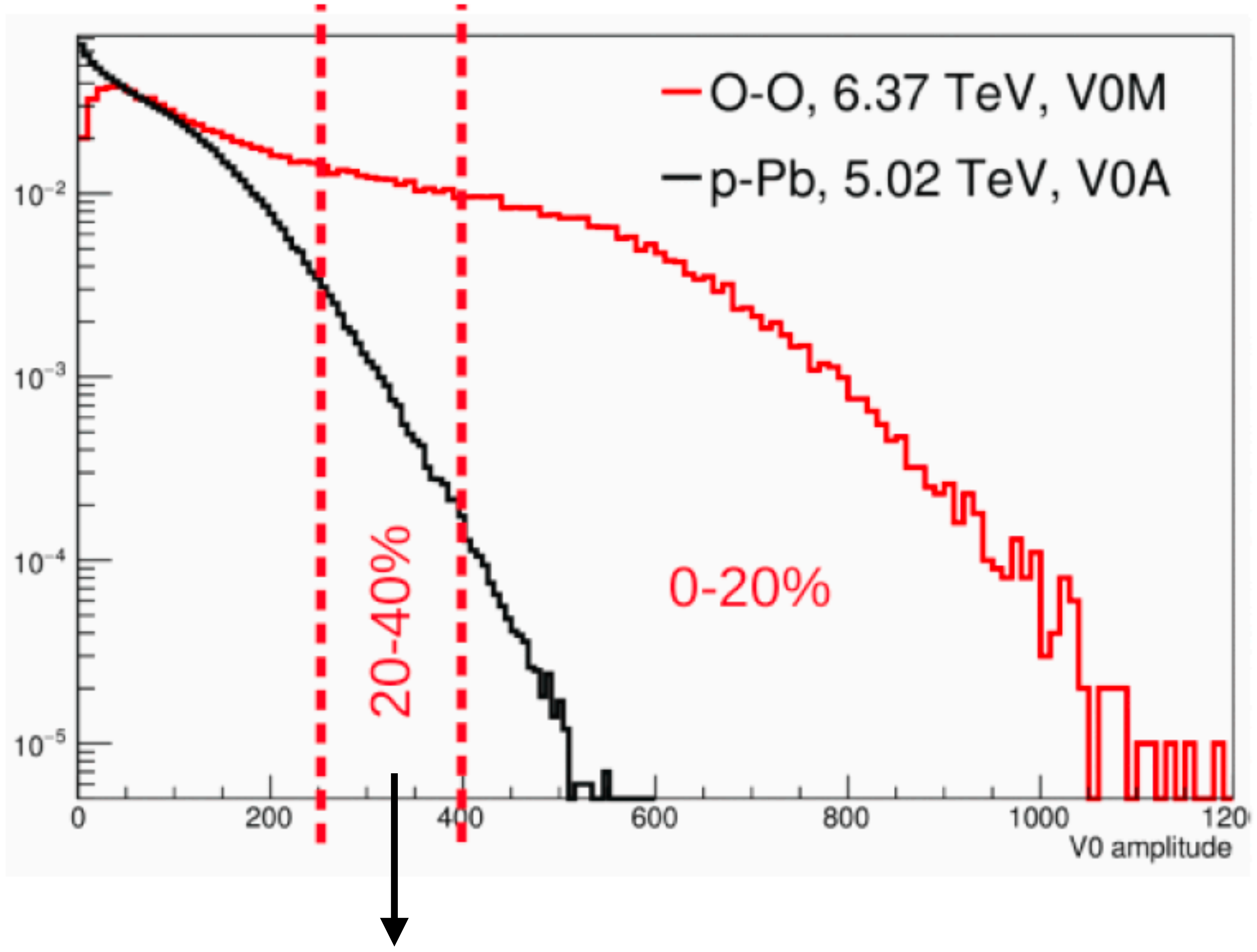
Detectable signal vs. L_{int}

Run 3+4

Oxygen-Oxygen collisions

- ❖ Study properties of low multiplicity (peripheral) Pb-Pb collisions
  - ❖ **O-O collision multiplicities similar to p-Pb collisions**
  - ❖ **Collision geometry well defined**

- ❖ An opportunity to study
  - ❖ **The emergence of collective phenomena**
  - ❖ **Possible energy loss**



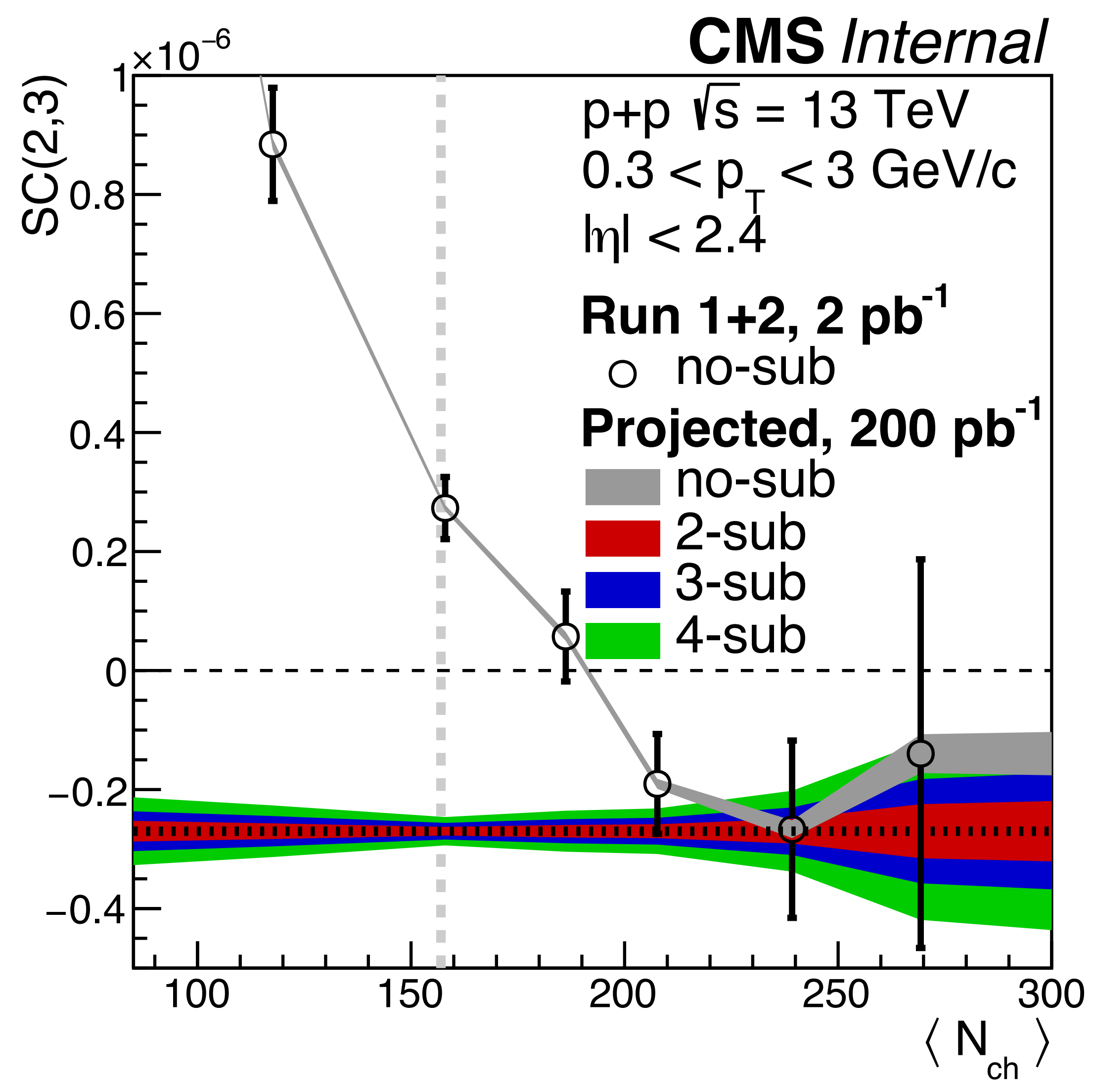
Highest multiplicities in pPb in the tail of the distribution
Similar multiplicities reached in O-O collisions

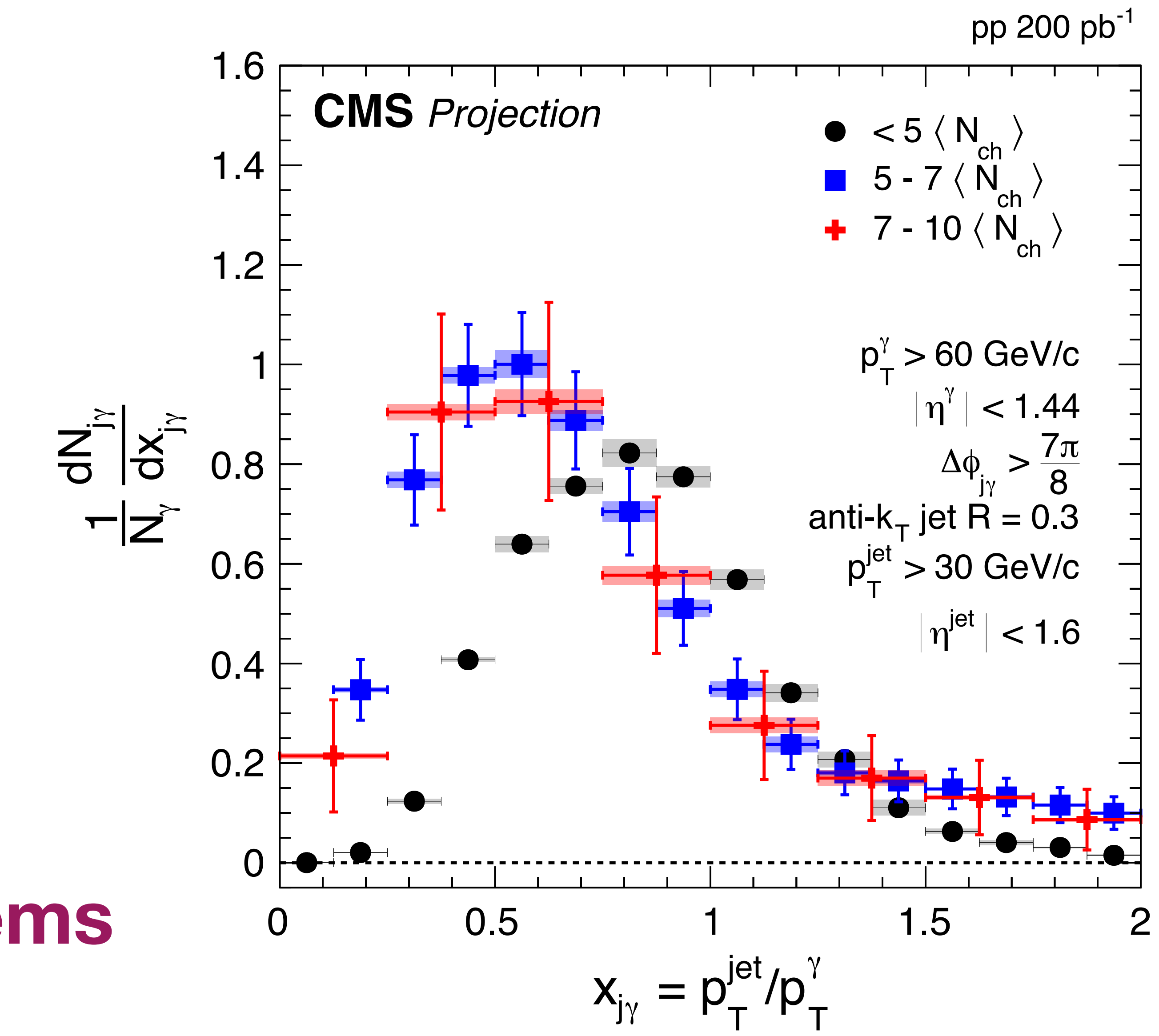
Run 3+4

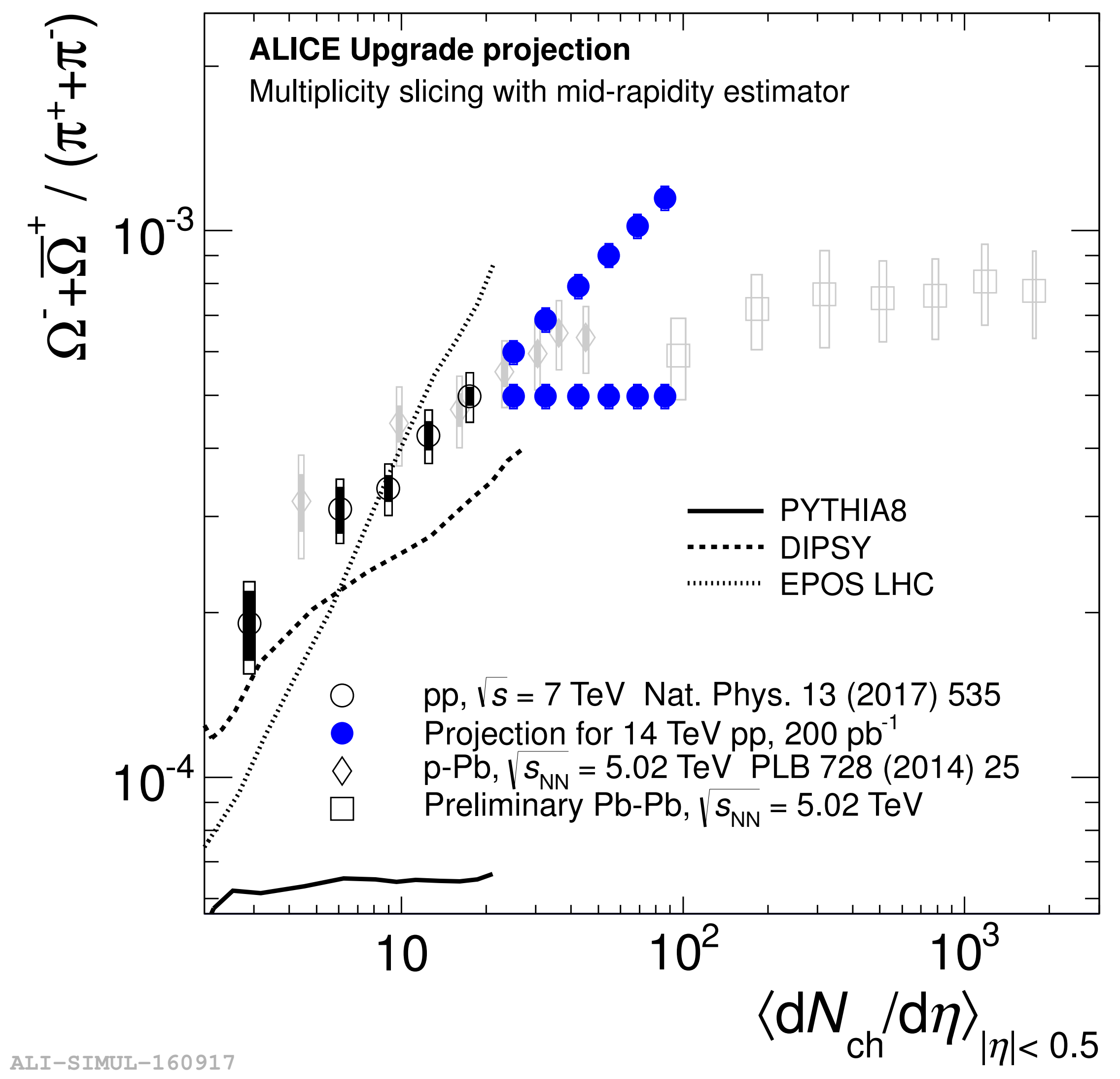
Summary and outlook

- ❖ Discoveries in recent years caused a paradigm shift in modelling:
  - ❖ Heavy ion collisions
  - ❖ Underlying events in pp collisions
- ❖ **Multi-particle correlations** present also in small systems
  - ❖ No evidence for other features related to final state interactions, e.g. **energy loss**
- ❖ HL-LHC provides the data required for understanding the remaining open question in small systems
  - ❖ **Higher order correlations**
  - ❖ **Strange-particle yields**
  - ❖ **Thermal radiation**
  - ❖ **Energy loss signals**
  - ❖ …

❖ **Universal description of small to large collision systems**







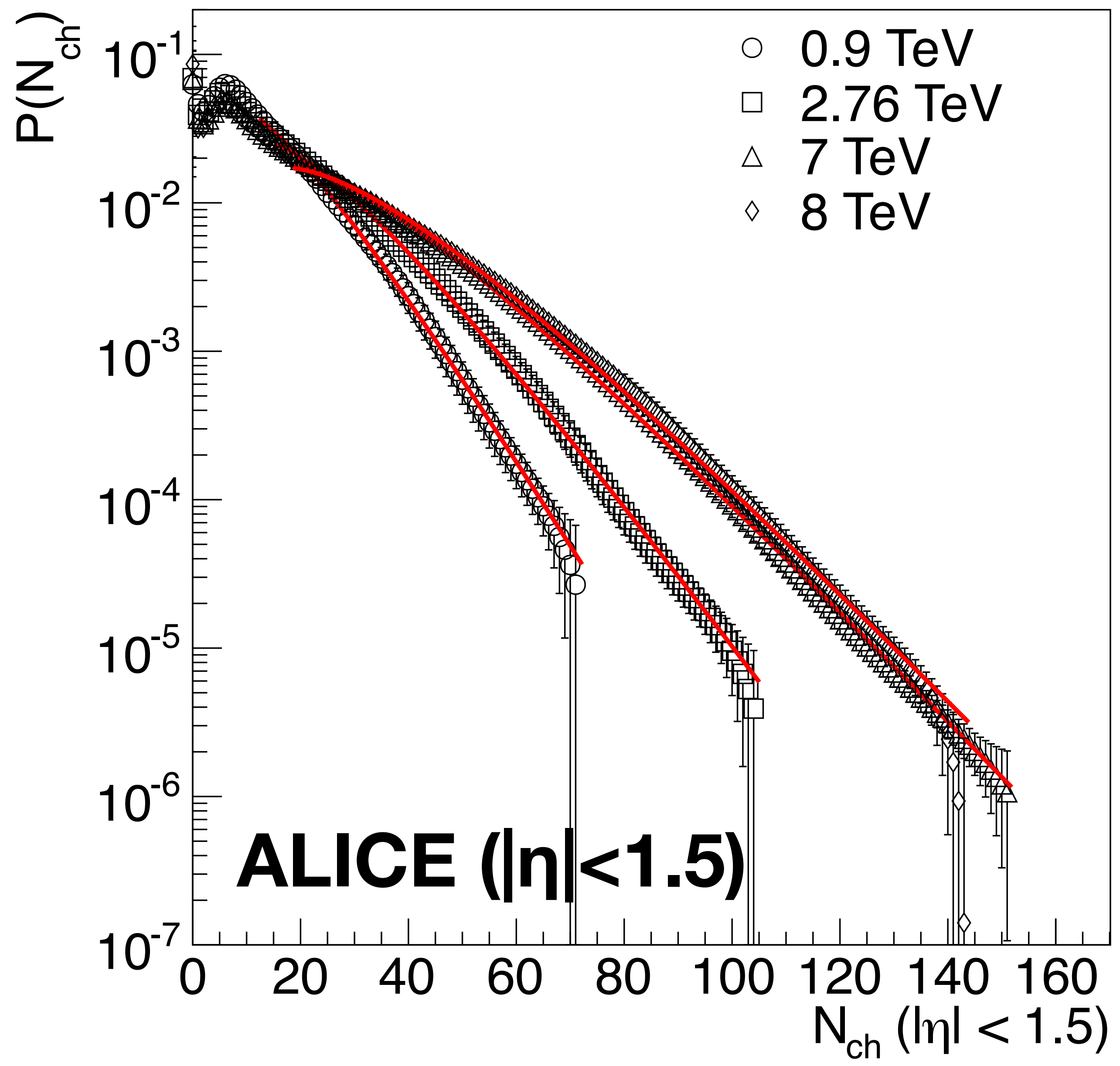
Back-up

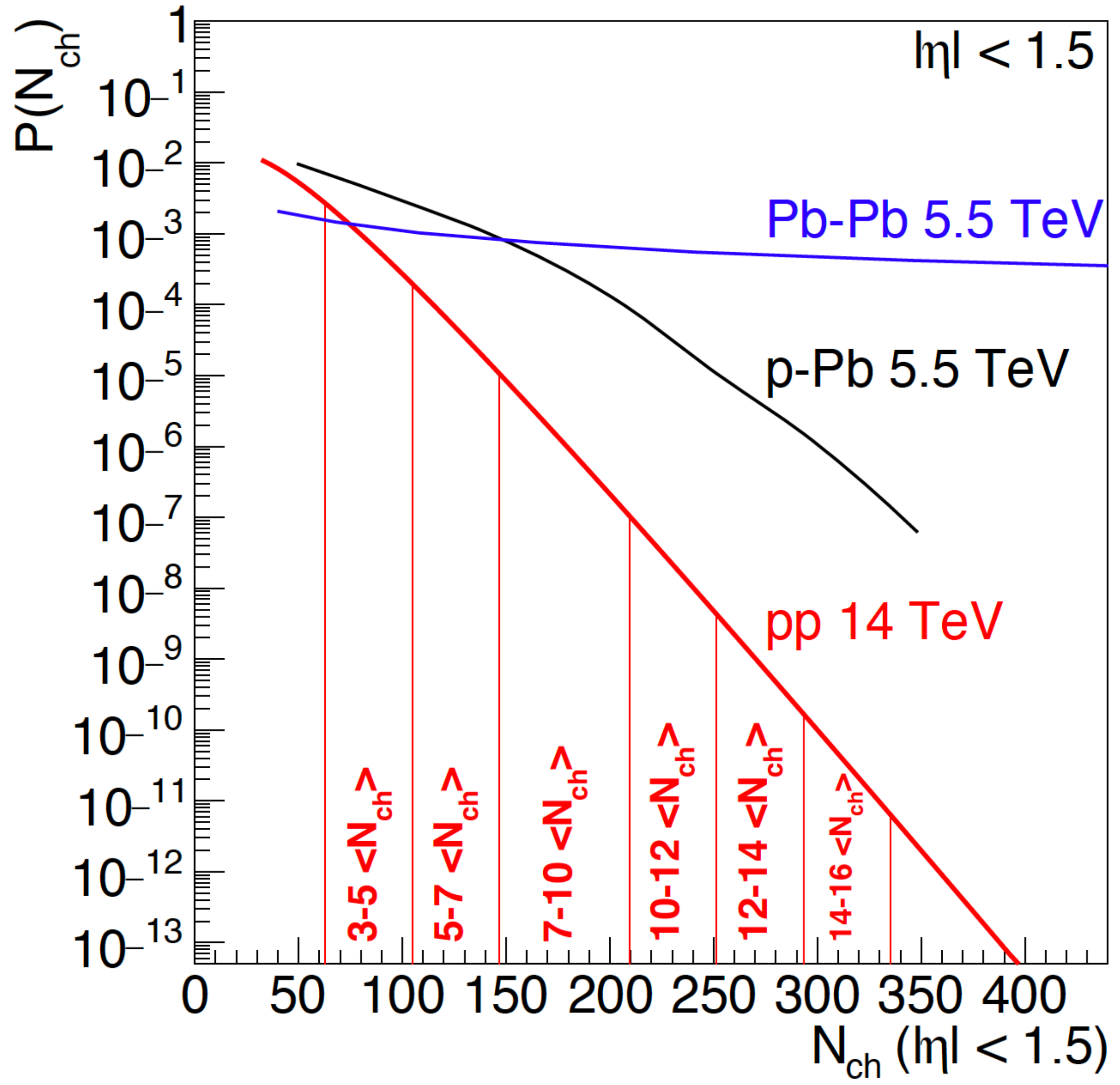
Overview of Experimental Results

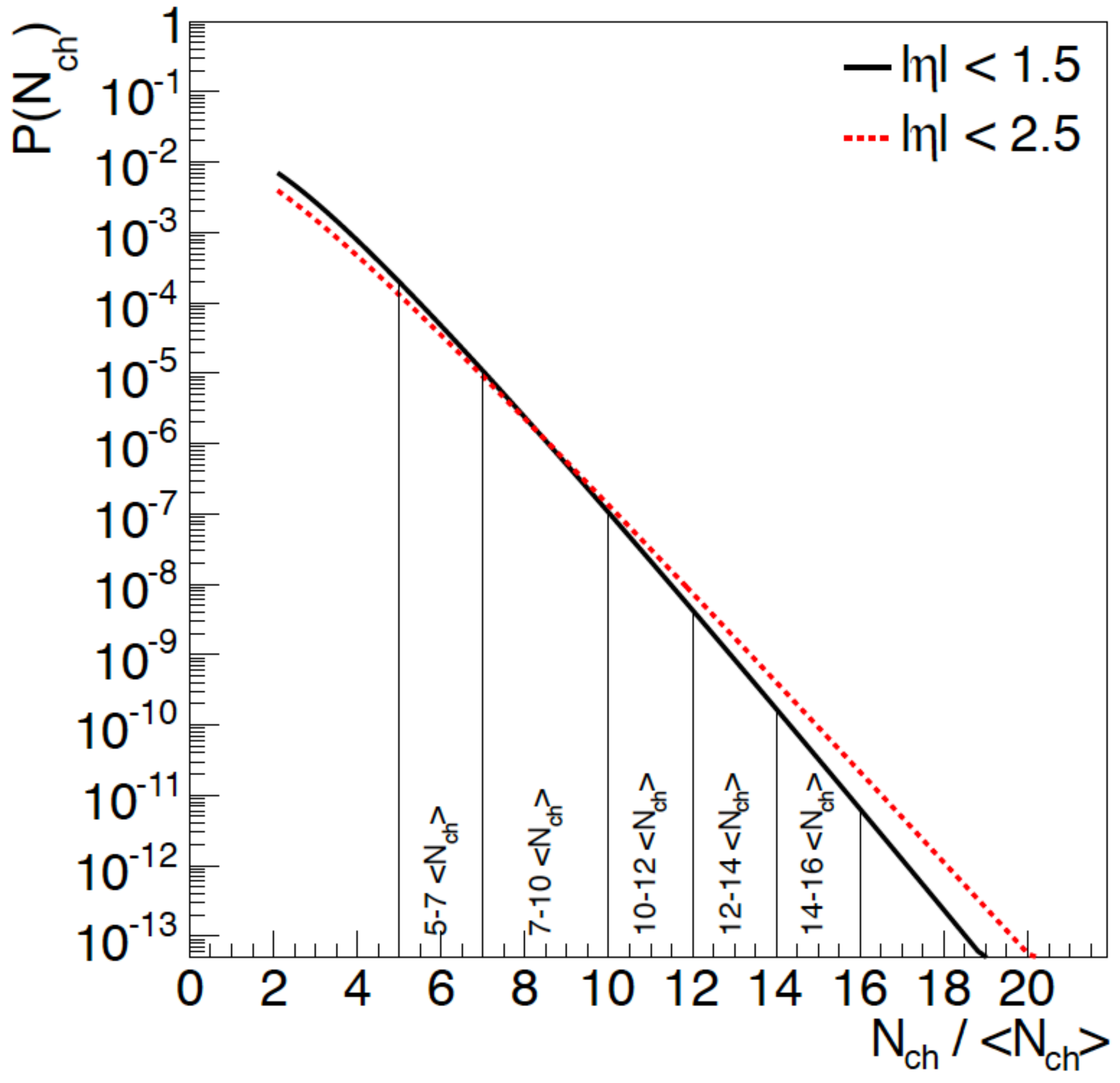
Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[23, 26, 28, 33, 35, 36, 38–41]
Intermed. p_T ("recombination")	yes	yes	yes	[26–33]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[34–37]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[36, 42, 43]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[44–51]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[22, 52–68]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[62, 65, 66, 69–73]
Directed flow (from spectators)	yes	no	no	[74]
Charge dependent correlations	yes	yes	yes	[75–81]
Higher order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"	[62, 68, 82–95]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[67, 96–100]
Linear and non-linear flow modes	up to v_6	not measured	not measured	[101]
Weak η dependence	yes	yes	not measured	[64, 92, 94, 102–107]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[59, 63, 108–110]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[111, 112]
Direct photons at low p_T	yes	not measured	not observed	[113, 114]
Jet quenching through dijet asymmetry	yes	not measured	not observed	[115–119]
Jet quenching through R_{AA}	yes	not observed	not observed	[120–129]
Jet quenching through correlations	yes (Z+jet, γ+jet, h+jet)	not observed (h+jet)	not measured	[127, 130–138]
Heavy flavor anisotropy	yes	yes	not measured	[139–151]
Quarkonia	suppressed [3]	suppressed	not measured	[143, 149, 152–171]

Proton-proton collisions at extreme multiplicities

- Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
- Parametrization with **single negative binomial distribution** for various center of mass energies
- Extrapolated to 14 TeV pp collisions at ALICE and ATLAS
  - Predict no. of events at a given multiplicity using smaller phase space (|η|<1.5)
  - Extrapolate up to |η|<2.5 using flat η distribution
  - Use PYTHIA to go to |η|<4.0 for run 4



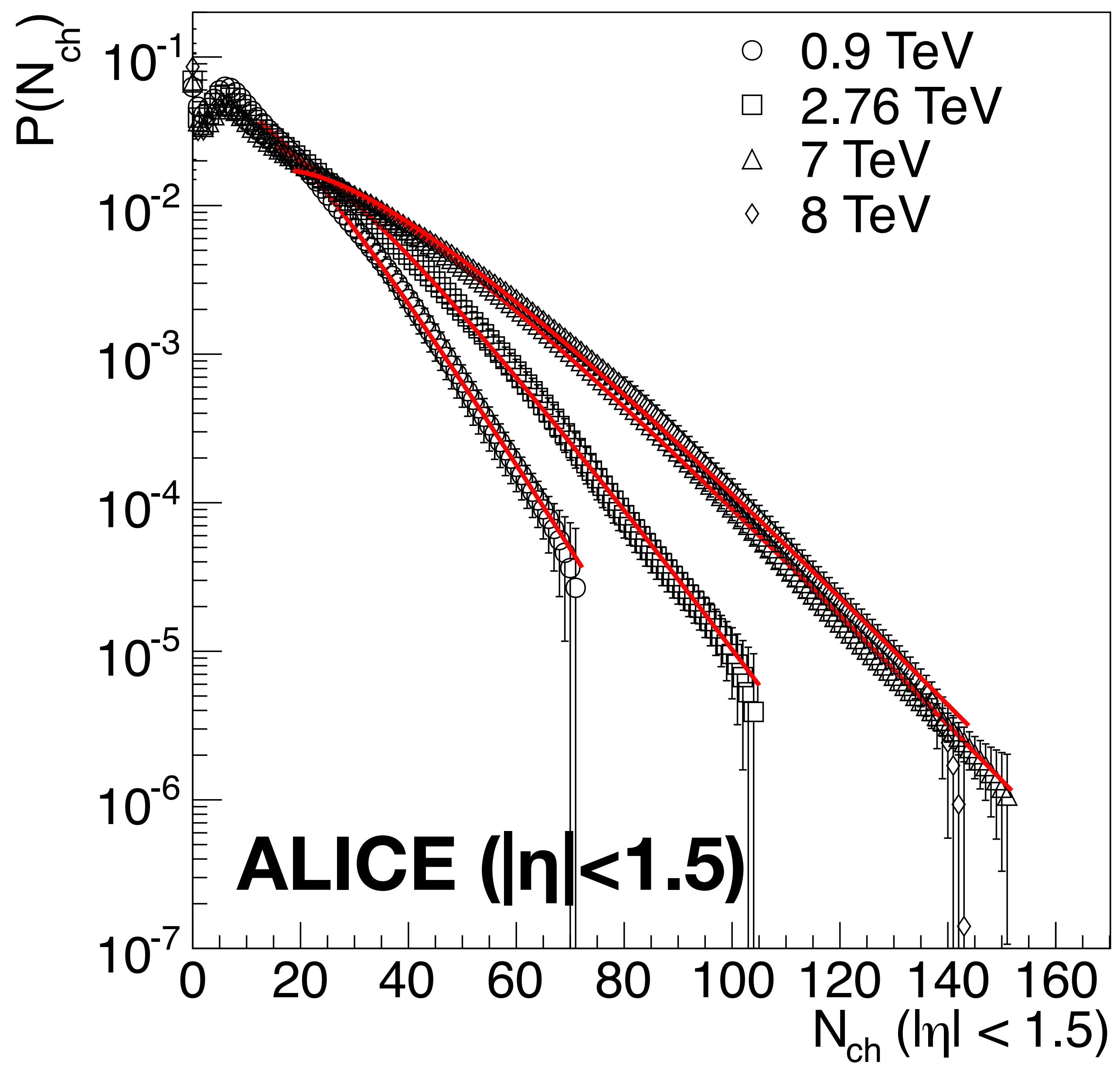




+4

Proton-proton collisions at extreme multiplicities

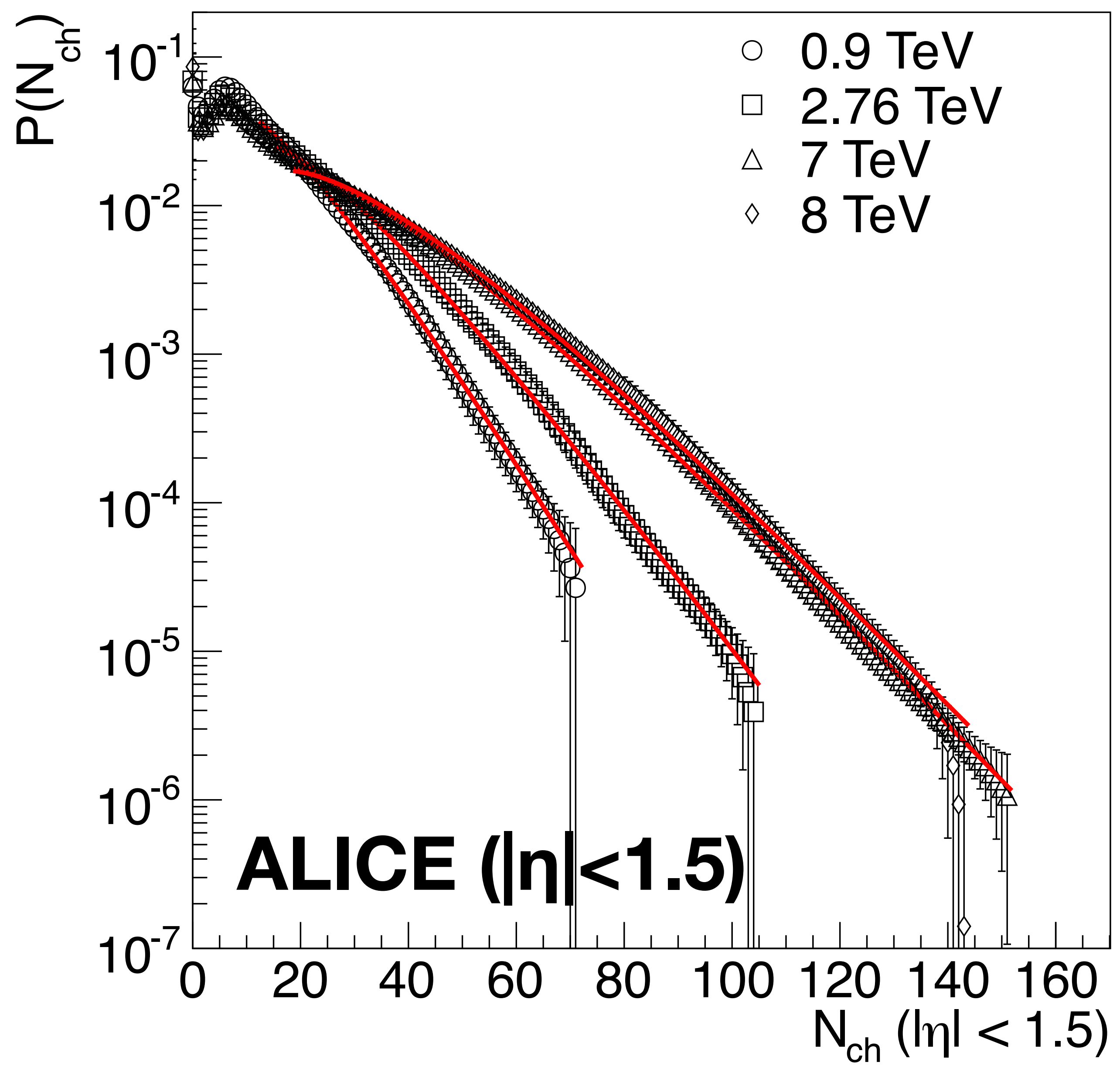
- Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
- Parametrization with **single negative binomial distribution** for various center of mass energies
- Extrapolated to 14 TeV pp collisions at ALICE and ATLAS
  - Predict no. of events at a given multiplicity using smaller phase space (|η|<1.5)
  - Extrapolate up to |η|<2.5 using flat η distribution
  - Use PYTHIA to go to |η|<4.0 for run 4



Range	$dN_{ch}/d\eta$	Fraction	Events per pb^{-1}	Events in 200 pb^{-1}
5–7 $\langle N_{ch}\rangle$	35–49	2.4e-03	1.9e+08	3.7e+10
7–10 $\langle N_{ch}\rangle$	49–70	1.3e-04	1.0e+07	2.0e+09
10–12 $\langle N_{ch}\rangle$	70–84	1.1e-06	9.0e+04	1.8e+07
12–14 $\langle N_{ch}\rangle$	84–98	4.7e-08	3.7e+03	7.3e+05
14–16 $\langle N_{ch}\rangle$	98–112	1.8e-09	1.4e+02	2.8e+04

Proton-proton collisions at extreme multiplicities

- ❖ Multiplicity distribution extrapolation based on the current ALICE and ATLAS data
- ❖ Parametrization with **single negative binomial distribution** for various center of mass energies
- ❖ Extrapolated to 14 TeV pp collisions at ALICE and ATLAS
  - ❖ Predict no. of events at a given multiplicity using smaller phase space (|η|<1.5)
  - ❖ Extrapolate up to |η|<2.5 using flat η distribution
  - ❖ Use PYTHIA to go to |η|<4.0 for run 4
  - ❖ Number of events with equivalent multiplicity ranges in pPb and Pb-Pb collisions



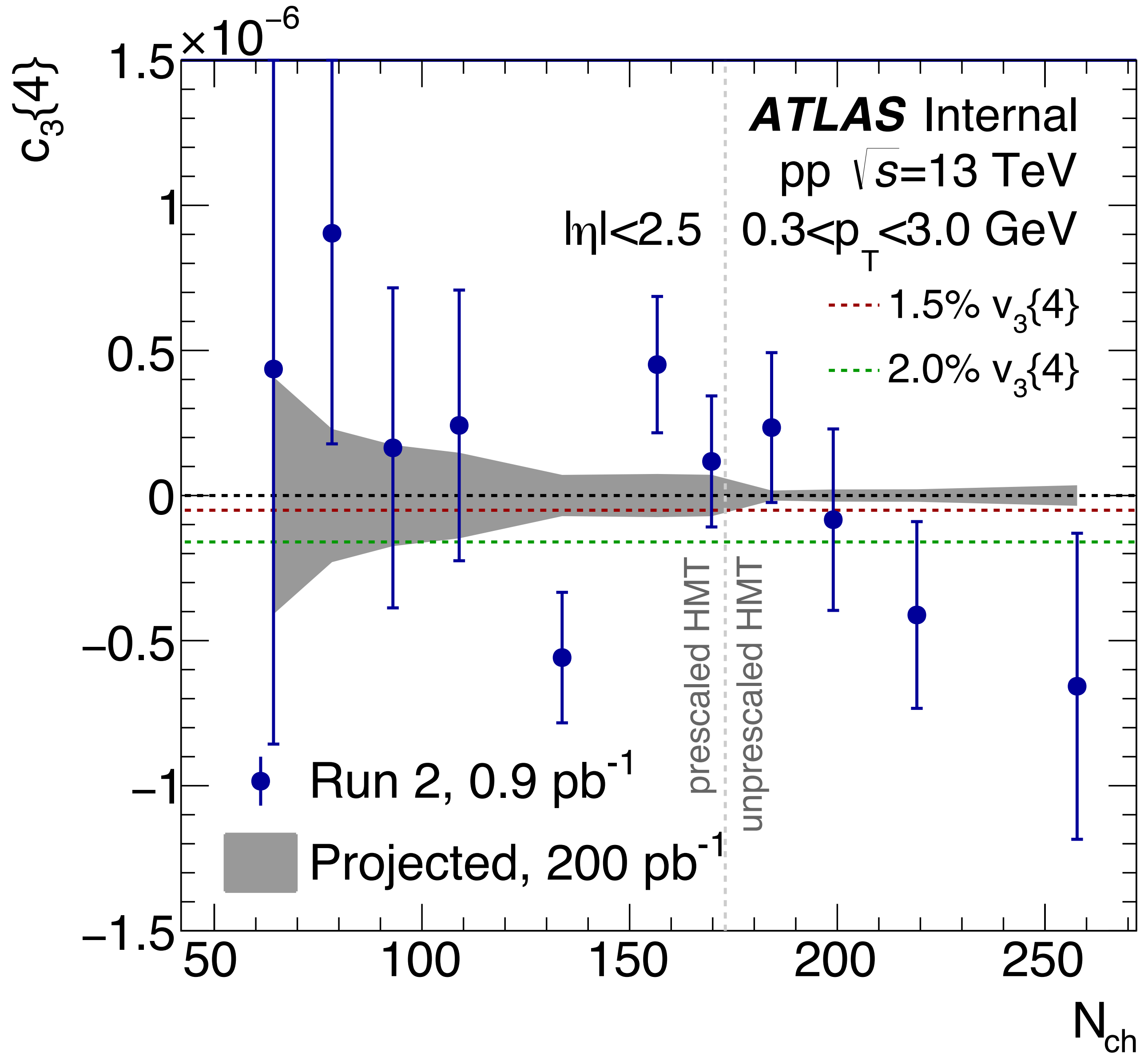
Range	$dN_{ch}/d\eta$	Events per pb^{-1}	Events in 200 pb^{-1}
0–5% p–Pb	41–56	4.9e+07	9.8e+09
5–10% p–Pb	34–41	1.9e+08	3.8e+10
10–20% p–Pb	27–34	6.6e+08	1.3e+11
60–65% Pb–Pb	98–137	1.5e+02	3.0e+04
65–70% Pb–Pb	68–98	1.6e+05	3.1e+07
70–75% Pb–Pb	45–68	2.1e+07	4.2e+09
75–80% Pb–Pb	29–45	5.9e+08	1.2e+11

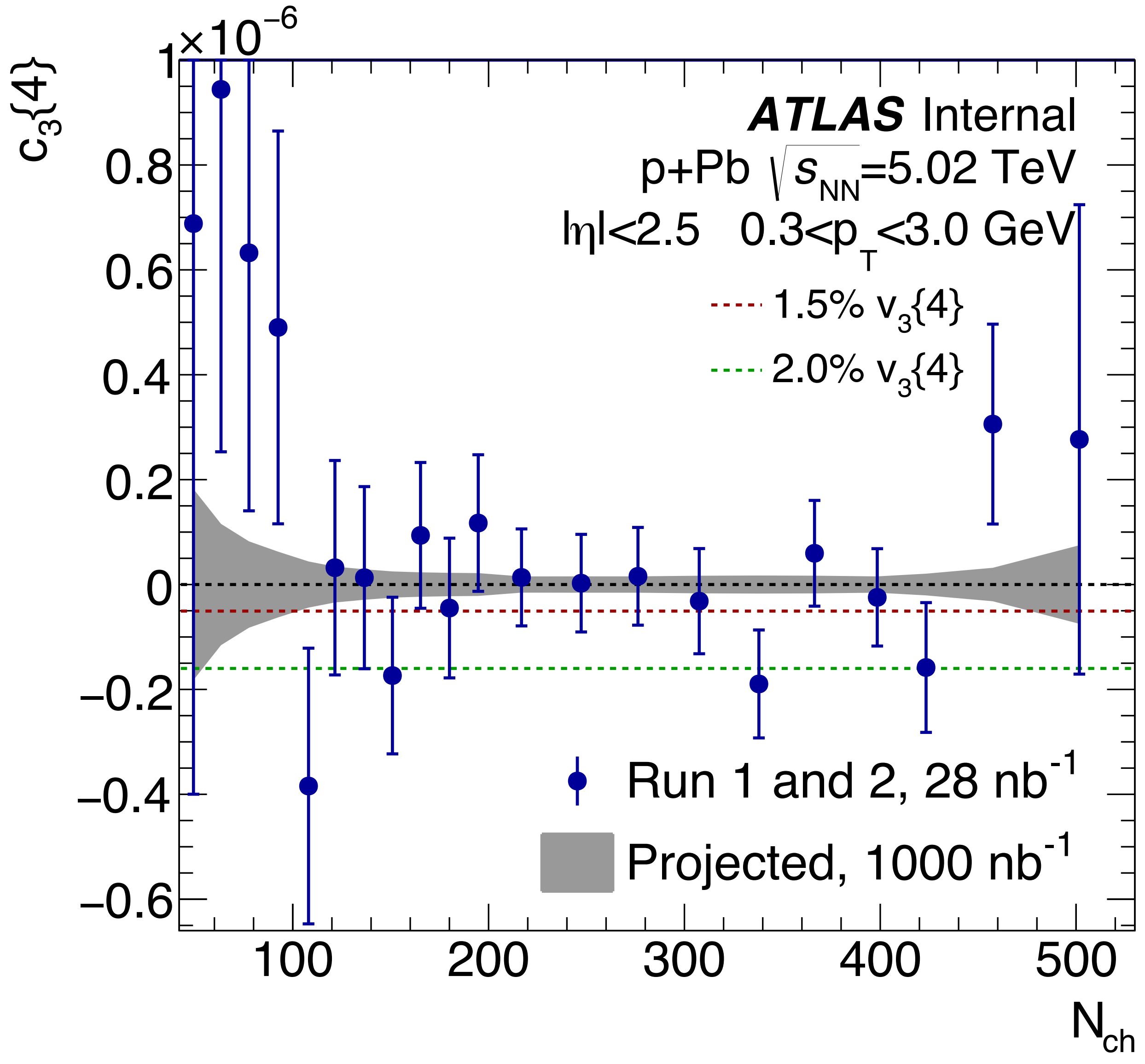
Particle correlations: multi-particle cumulants

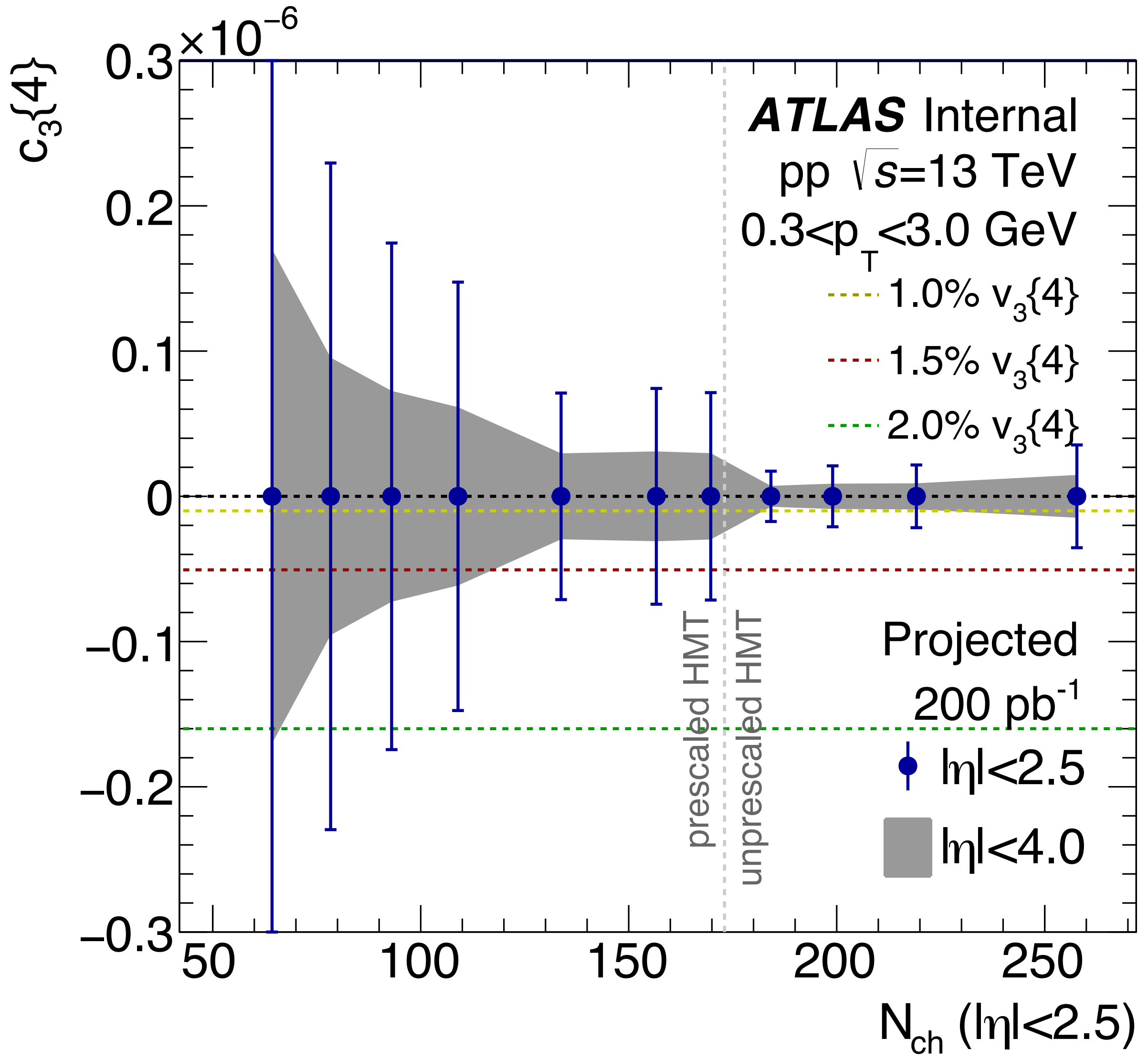
- Particle correlations:
  - In high multiplicity pp to compare with pPb and PbPb collisions
  - In low multiplicity regions to investigate the onset of the collective-like effects
- **4 particle cumulants ($c_n\{4\}$)**

$$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

- pp: **1.5% $v_3\{4\}$** accessible for N_{ch}> 170
- pPb: **1.5% $v_3\{4\}$** accessible for 100 < N_{ch} < 500
- Larger tracker acceptance in run 4 ATLAS & CMS -> **1% v3{4}** accessible





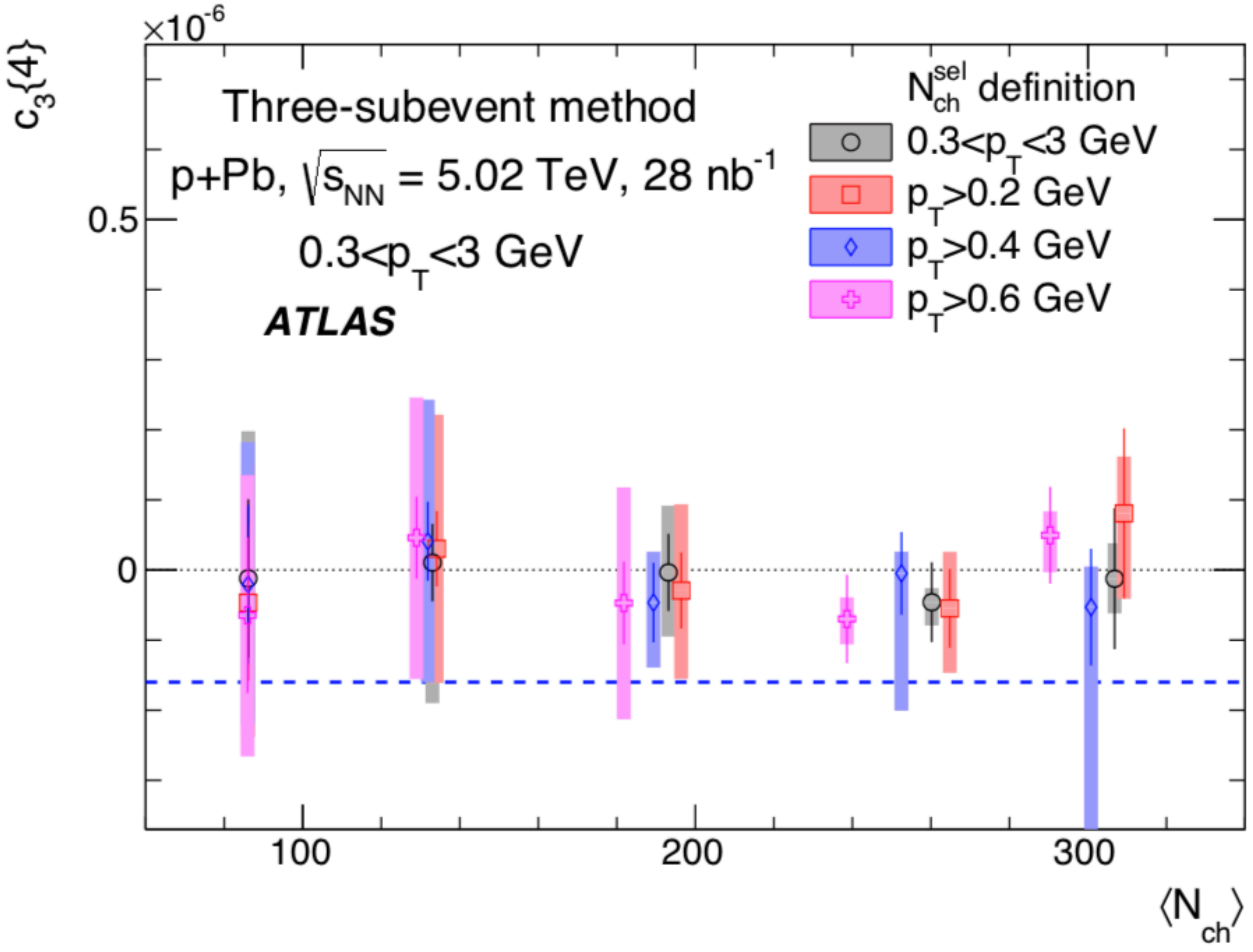


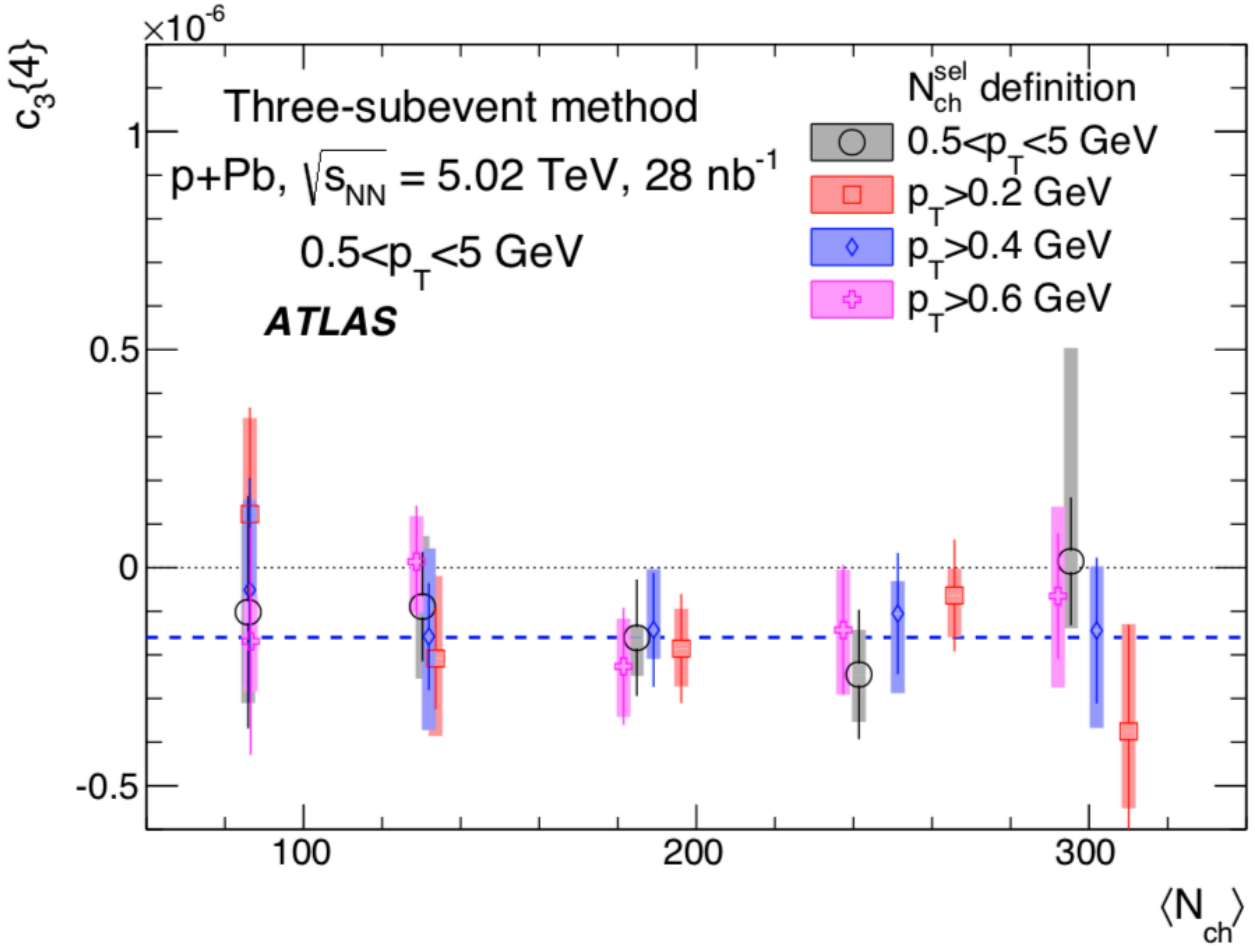
Run 3+4

Particle correlations: multi-particle cumulants

- Particle correlations:
  - In high multiplicity pp to compare with pPb and PbPb collisions
  - In low multiplicity regions to investigate the onset of the collective-like effects
- **4 particle cumulants ($c_n\{4\}$)** $$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

c3{4} in pPb collisions





Run 3+4