Heavy Ion collisions at ATLAS

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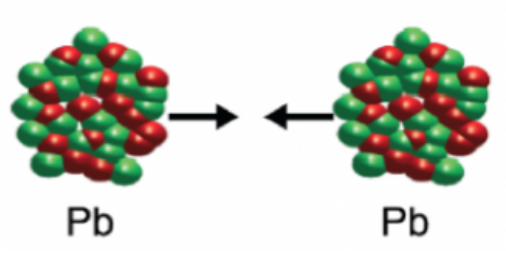
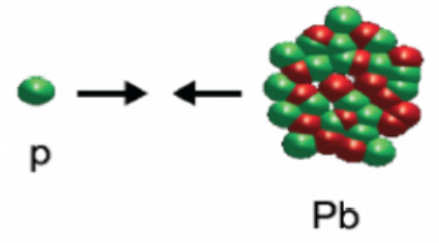
Physics interest of Heavy Ion WG



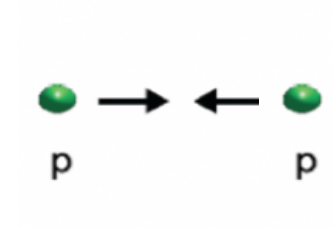
Pb+Pb, Xe+Xe collisions:

- Hot, **deconfined QCD matter** – QGP (collective / non-perturbative aspects of strong interaction, similar to matter in early stages of the universe)
- **Ultra-peripheral** collisions (em. processes, growing program)



p+Pb collisions:

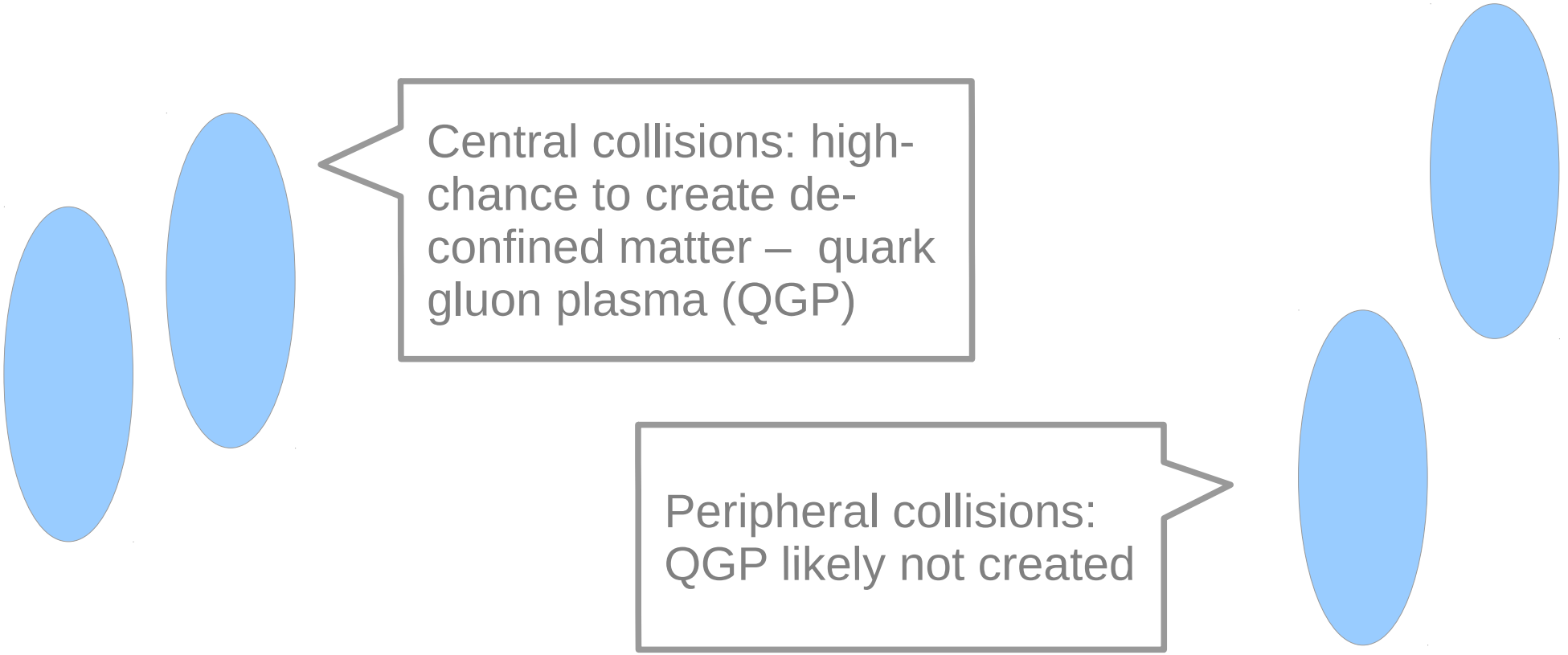
- **nuclear** modifications of **PDFs**, **initial state** of Pb+Pb collision
- QGP in small systems?, **collectivity** in hadronic collisions



p+p collisions:

- **reference** for Pb+Pb and p+Pb
- QGP in small systems?, **collectivity** in hadronic collisions

Centrality



- It is not possible to directly measure the impact parameter. The degree of overlap of two colliding ions is quantified by a measure called **centrality**.
- Centrality is based on information from FCal or forward detectors.
- Centrality is expressed **in percentiles** (e.g. 0-10% refers to the 10% of the most central collisions; 80-100% is 20% of the most peripheral collisions)

Inclusive jets: R_{AA}

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

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Jet yield in heavy-ion collisions

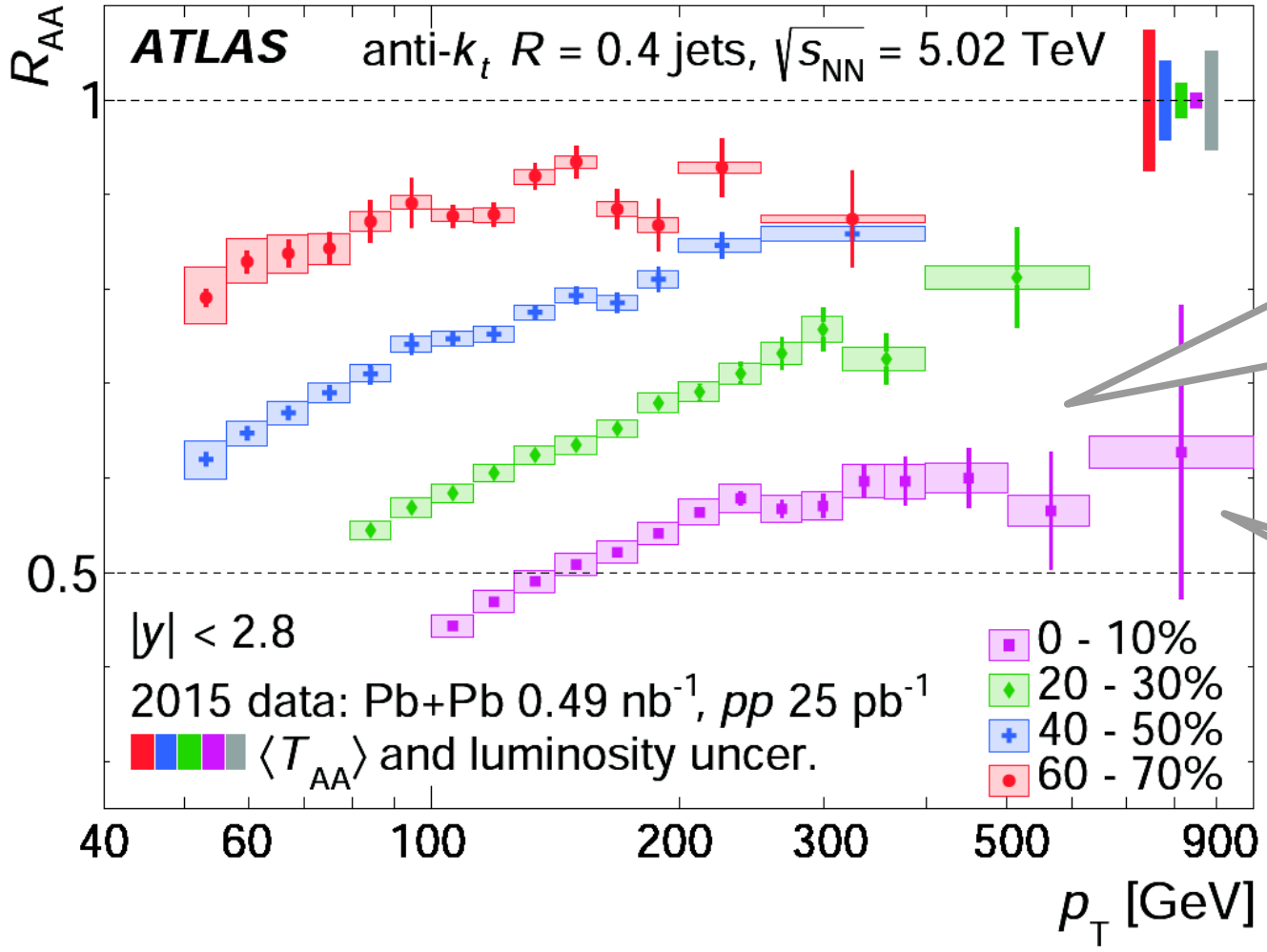
Nuclear thickness fuction

Jet cross-section in *pp* collisions

Number of expected jets per event of a given centrality

- Nuclear modification factor quantifies the magnitude of the jet suppression in Pb+Pb collisions wrt pp collisions.
- If there was no modification of the jet yield in heavy-ion collision, then $R_{AA} = 1$.

Inclusive jets: R_{AA}



Only modest grow with p_T, flattening for p_T>200 GeV

Suppression seen up to 1 TeV!

Jet quenching is a very significant phenomenon present even at the TeV scale!

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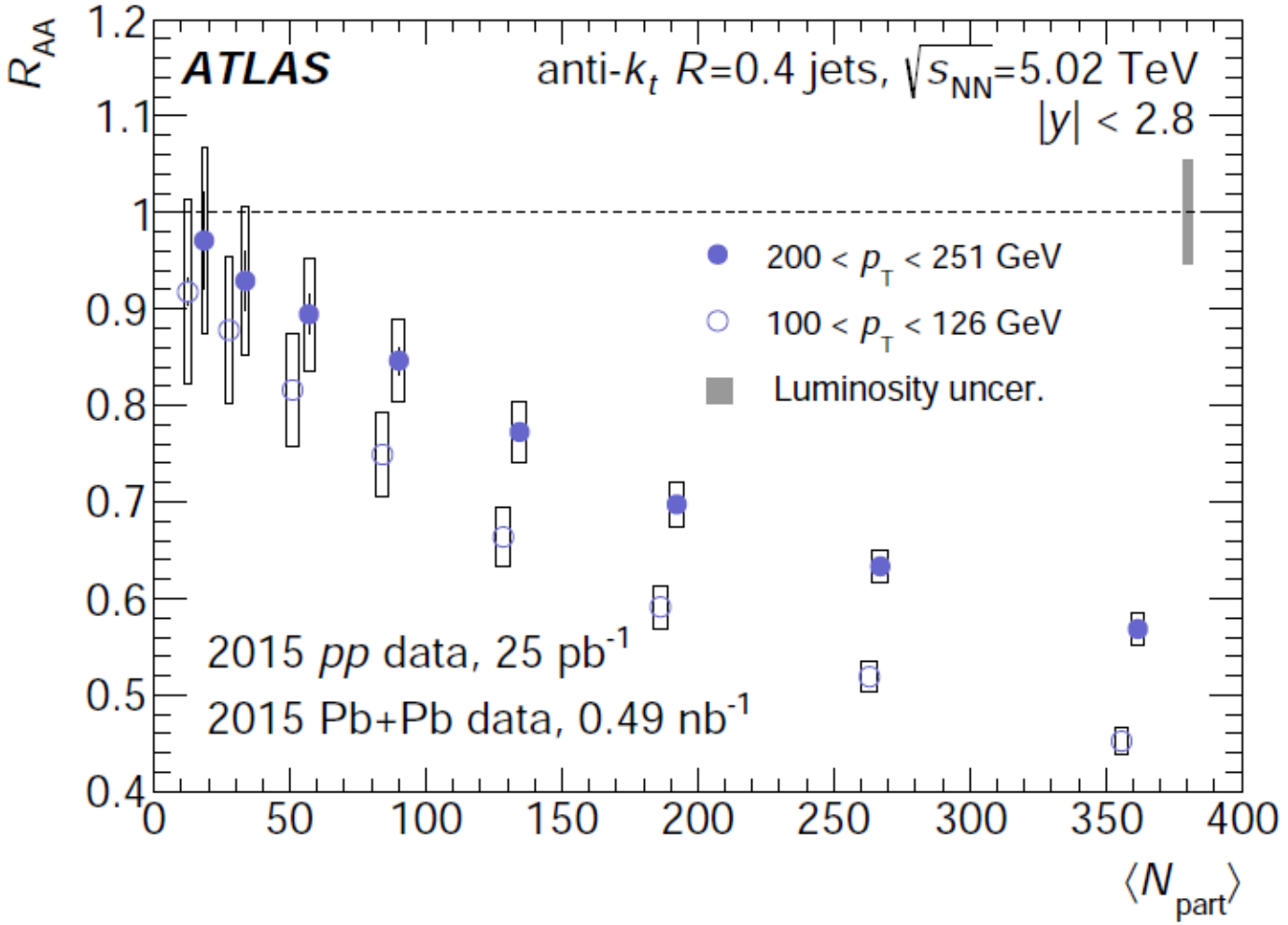
Inclusive jets: R_{AA}



- Central collisions = large N_{part} – small R_{AA} = significant suppression
- Peripheral collisions = small N_{part} – R_{AA} nearly unity = minimal suppression

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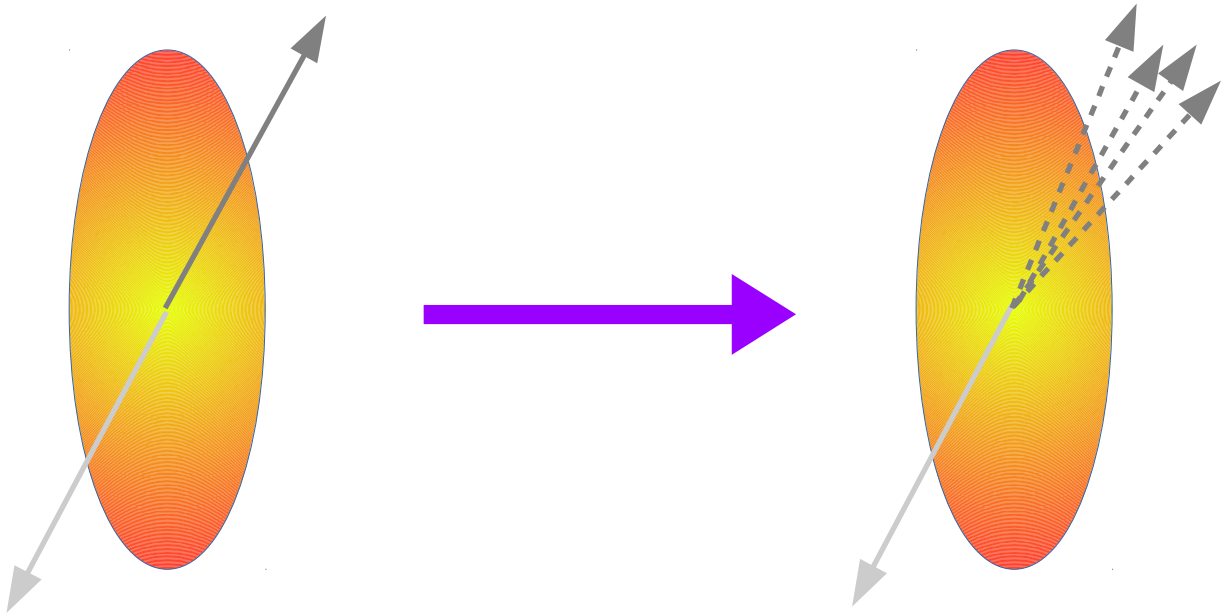
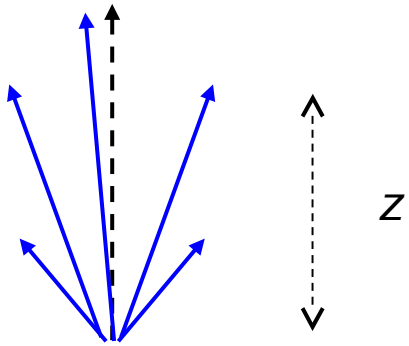
Going inside jets

Q: Jets are suppressed. Is the internal structure of the jet modified?



Fragmentation functions

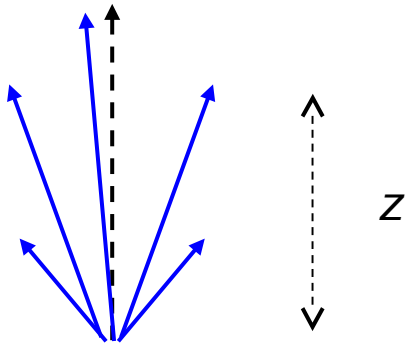


$$z = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{jet}} \cos \Delta R$$

$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z}$$

$$R_{D(z)} = \frac{D(z)|_{\mathrm{cent}}}{D(z)|_{pp}}$$

Fragmentation functions



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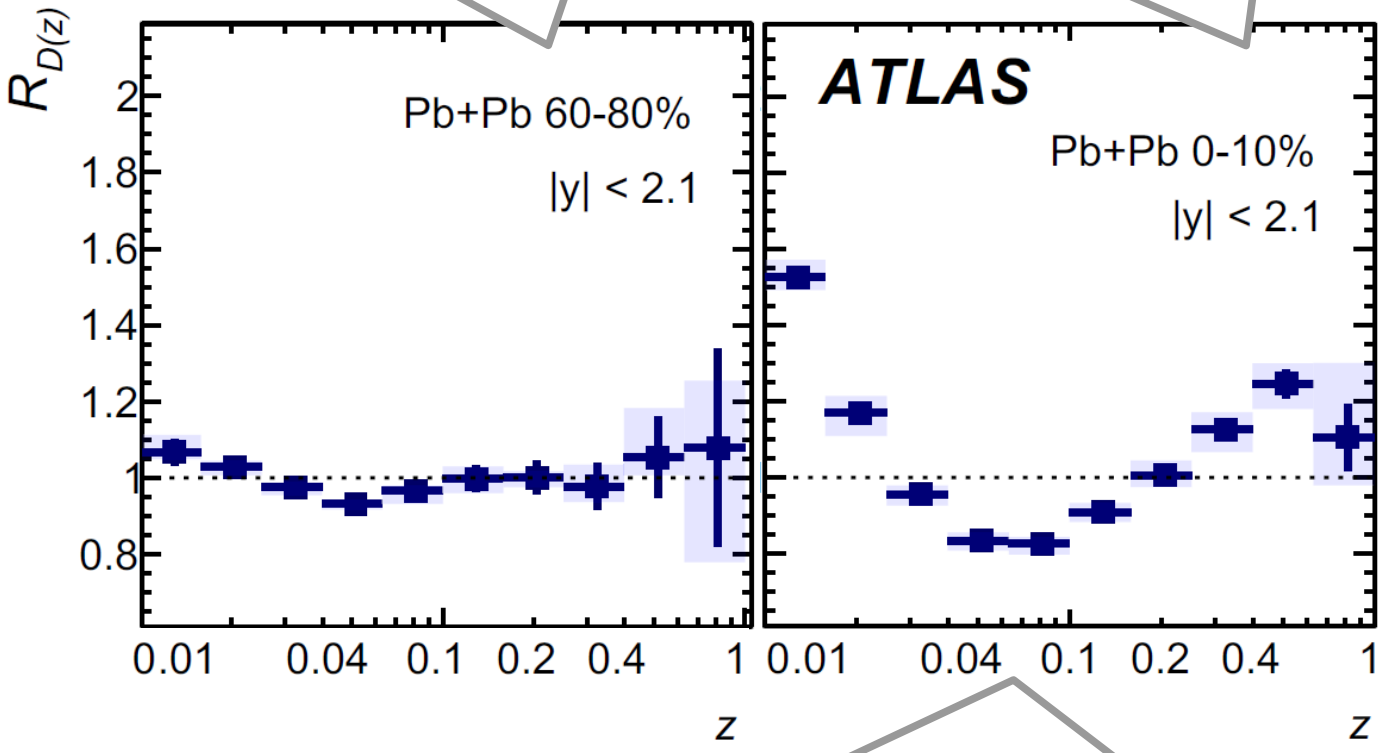
No modification in peripheral collisions

Significant modification in central collisions

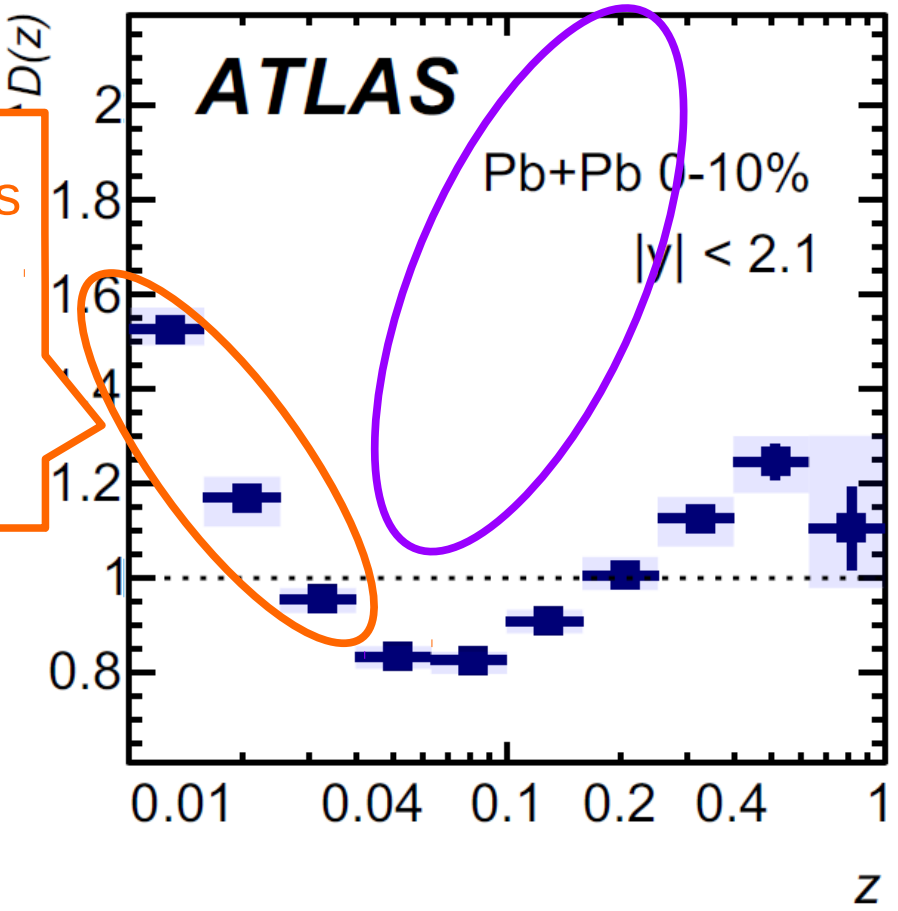


Namely: enhancement at low z and high z and suppression at intermediate z

Eur. Phys. J. C77 (2017) no.6, 379

Fragmentation functions – basic understanding

Lost energy goes to soft particles and/or “back-reaction” of medium to jet



One of possible explanations: Flavor effect (gluon jets are suppressed more than quark jets)

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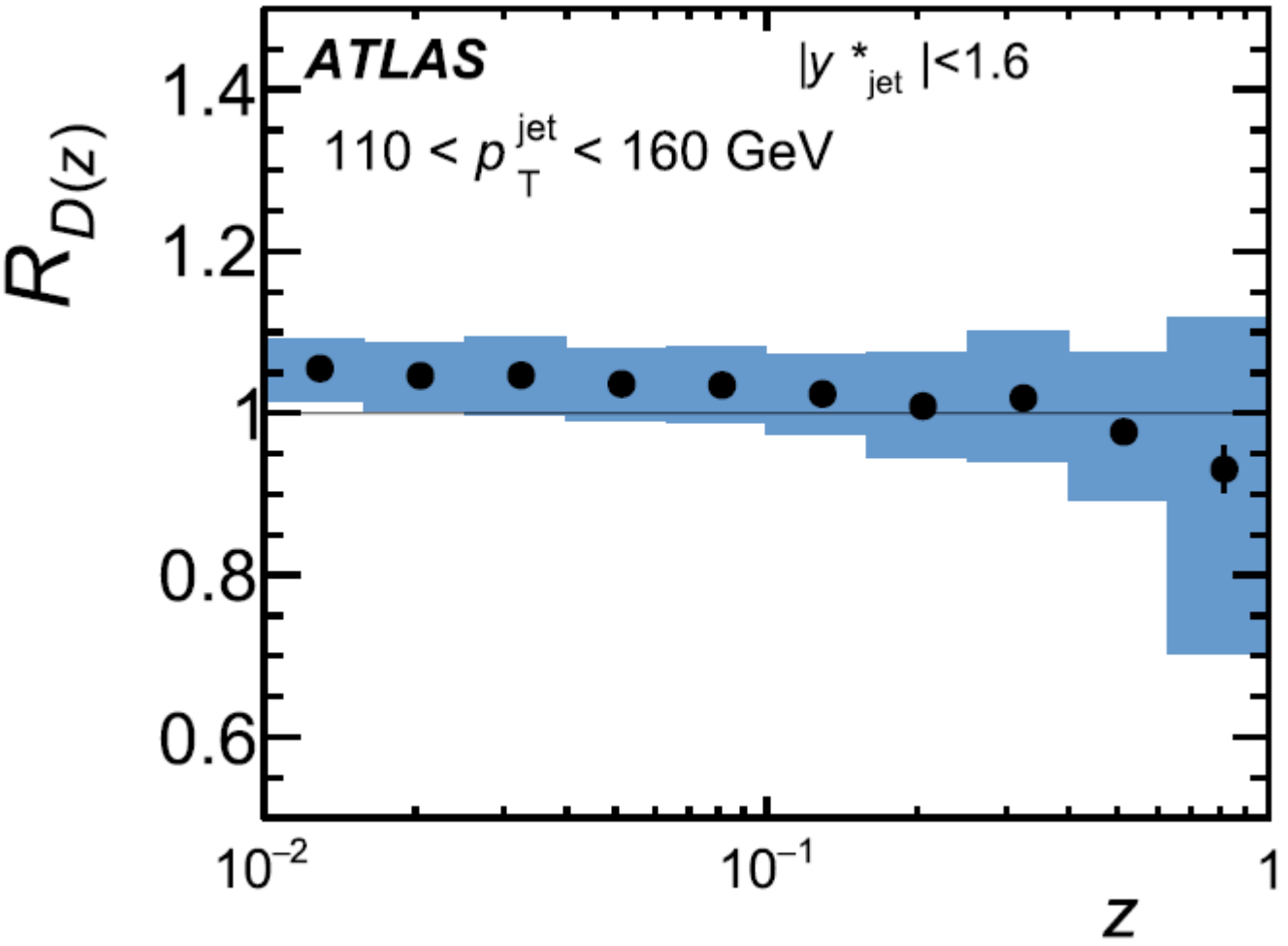
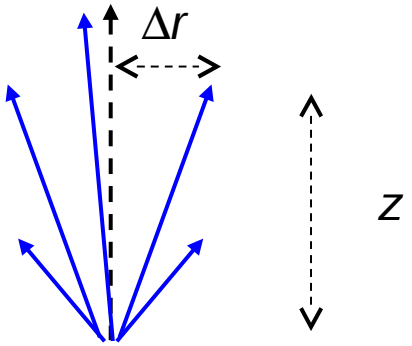
Reference: Fragmentation in p+Pb





- No modification with respect to pp observed.
- Modifications seen in Pb+Pb do not come from initial state effects

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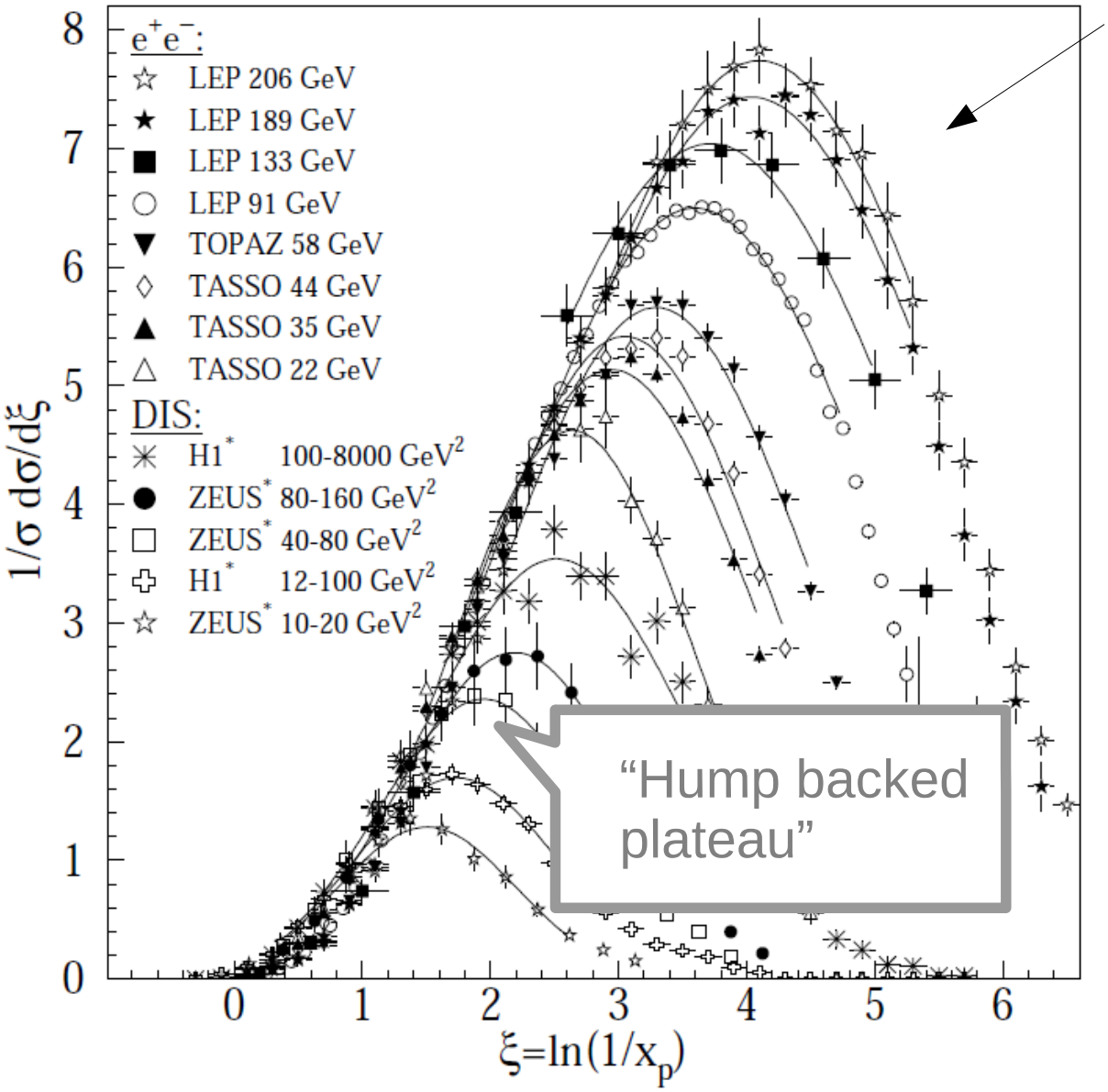
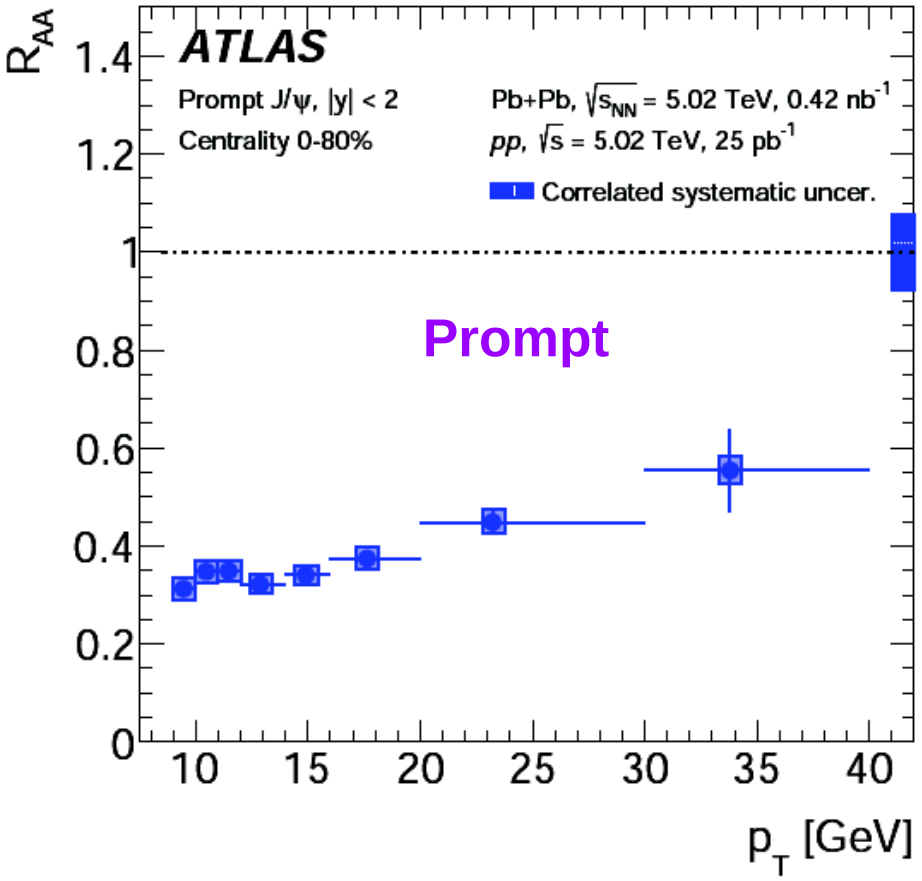
Some of what we can learn ...

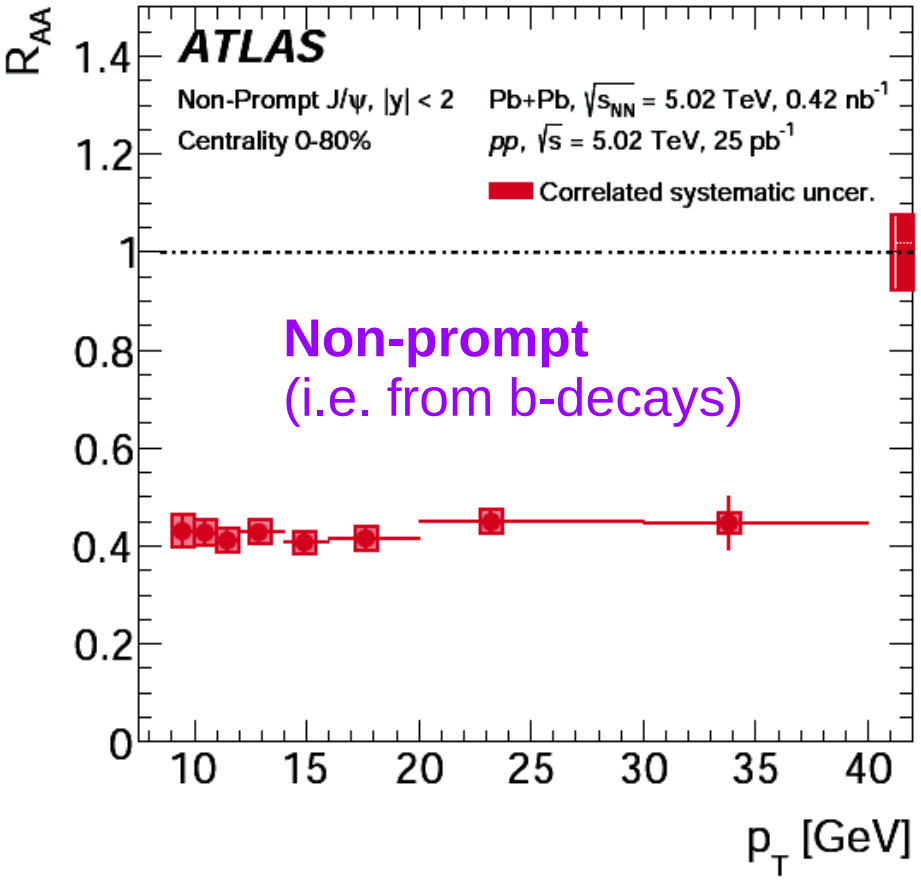


- MLLA is successful, speaks in favor of local parton-hadron duality (LPHD).
- More modern and precise calculations (e.g. SCET) are less successful (!).
- Longitudinal fragmentation functions are simple to model, but e.g. transverse structure or jet periphery is hard to get by pQCD.
- => Hadronization is more than LPHD & fragmentation is non-trivial.
- Placing these processes into the medium of well defined space-time scales should improve the understanding.

Phys. Rev. D 98 (2018) 030001

Many other suppression measurements ...



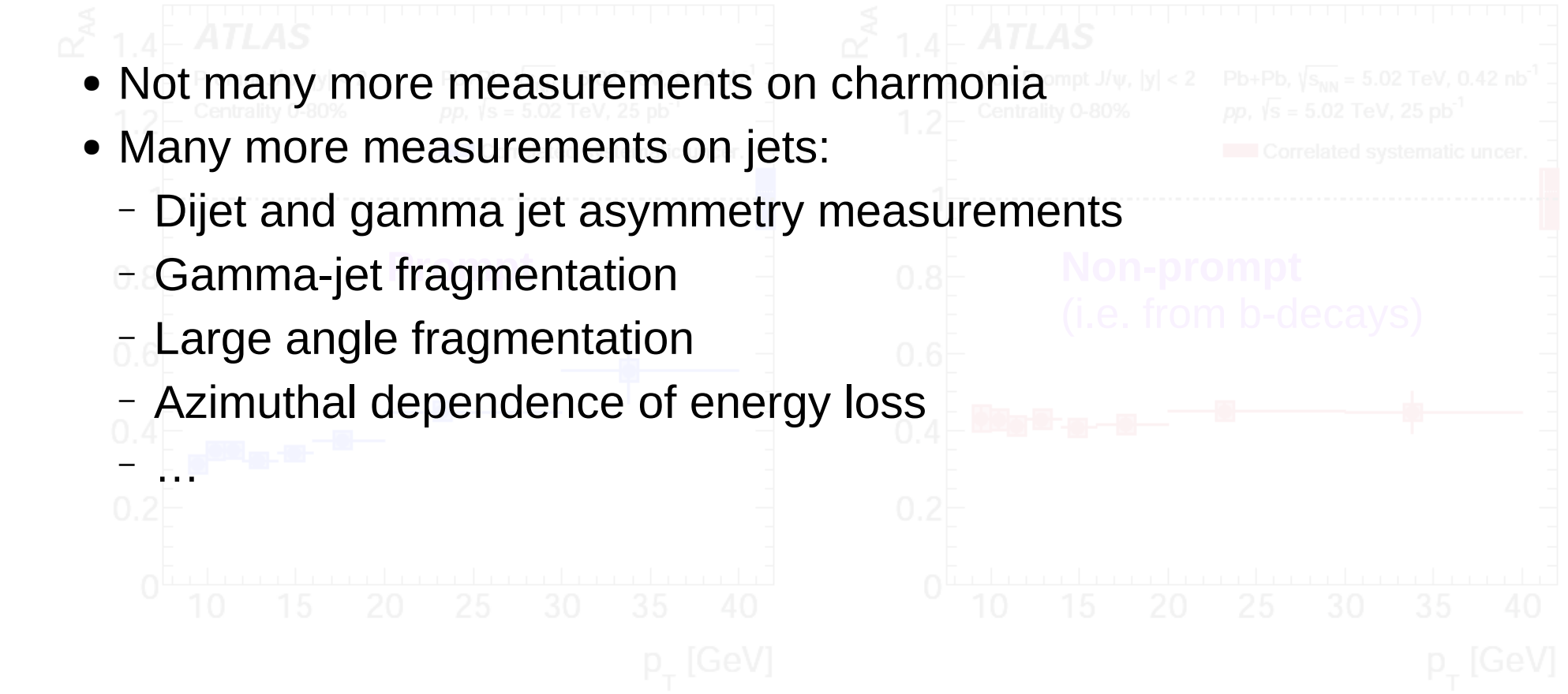


- Strong suppression of charmonia … similar to that of the suppression of jets => some universality? See e.g. PLB 767 (2017) 10.
- Again, this may tell us something not only about QGP, but also about the mechanism of charmonia production which is not understood.

Eur. Phys. J C 78 (2018) 762

Many other suppression measurements ...

- Not many more measurements on charmonia
- Many more measurements on jets:
  - Dijet and gamma jet asymmetry measurements
  - Gamma-jet fragmentation
  - Large angle fragmentation
  - Azimuthal dependence of energy loss
  - …



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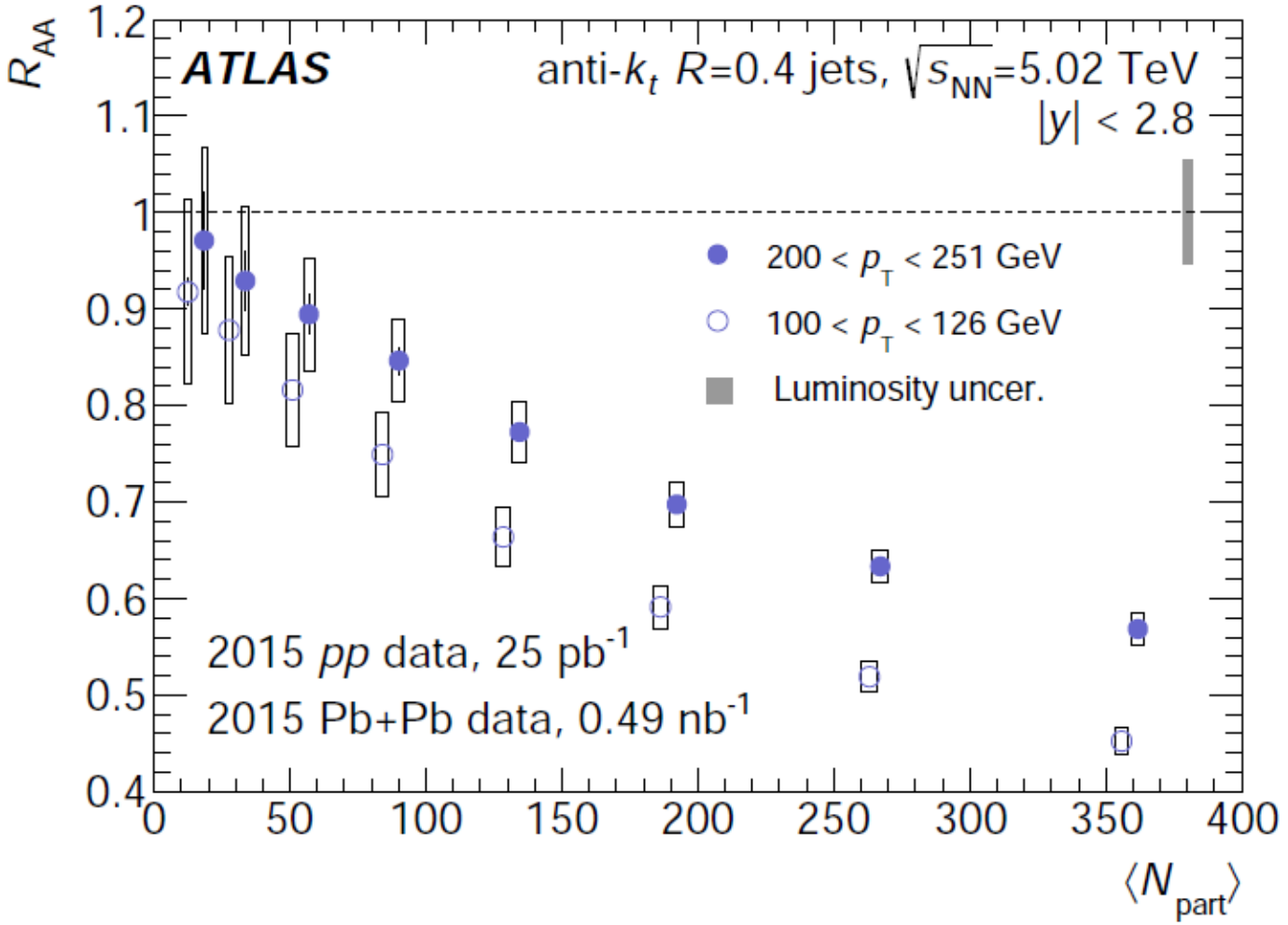
Can we trust these suppression measurements?

Reminder: jet R_{AA}



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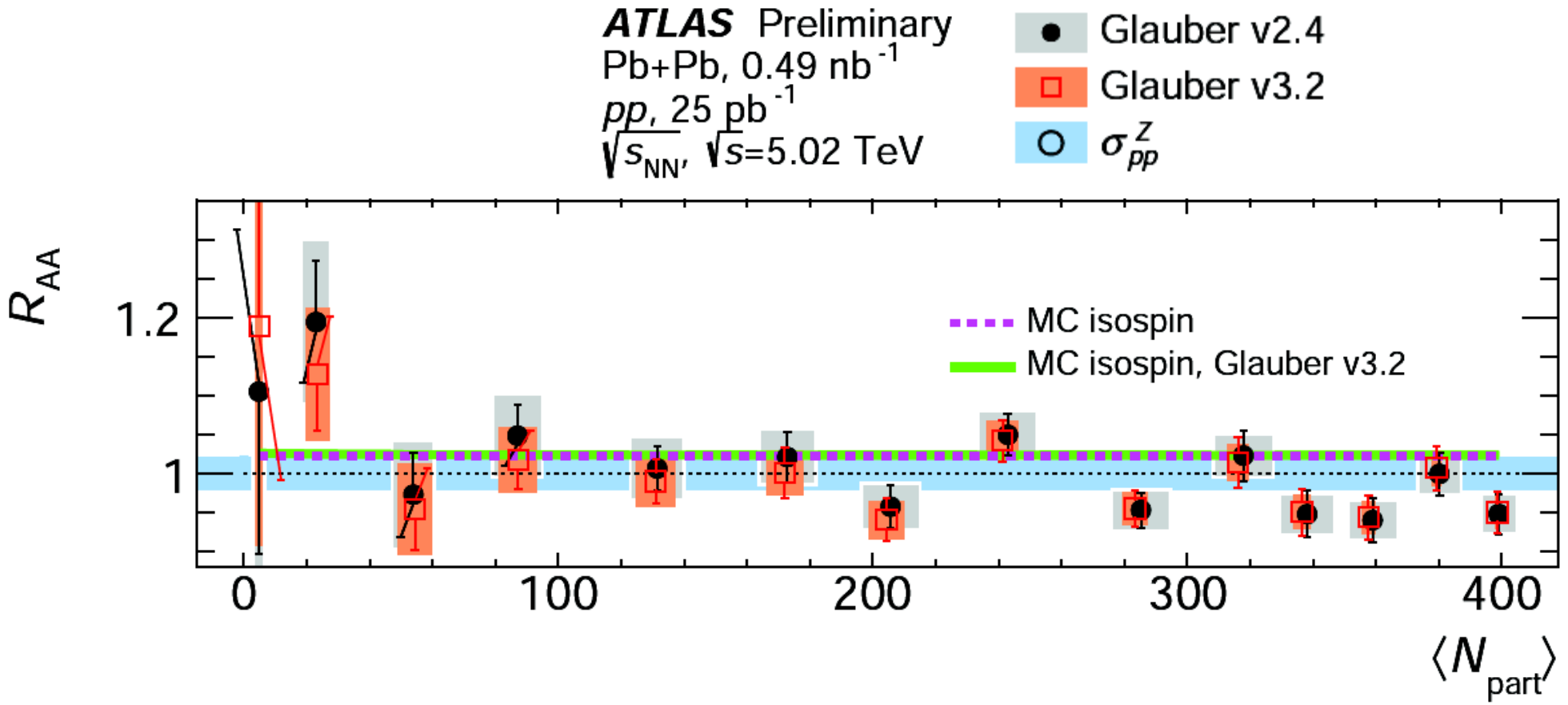
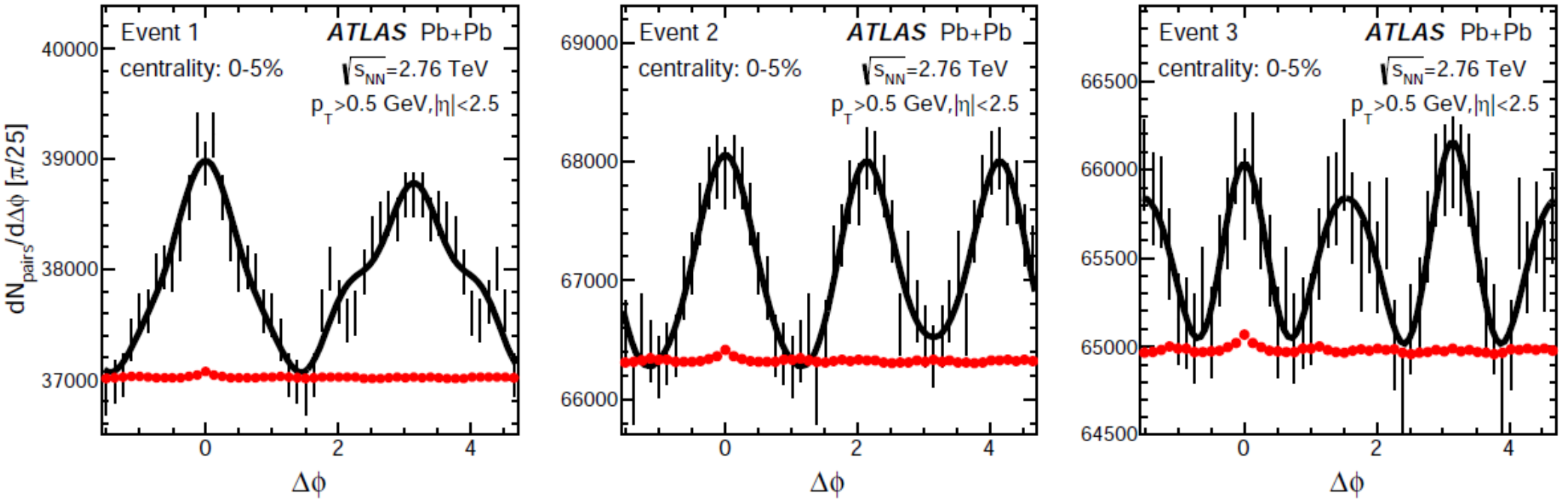
Electro-weak probes: γ, **Z** & W bosons



- R_{AA} of Z and W is unity (modulo isospin) => we understand the geometry.
- Some small deviation from unity => information about high-energy nuclear structure: nuclear-PDFs, neutron skin-effect, …
- We can trust suppression measurements – we have data-driven checks.

ATLAS-CONF-2017-067

Flow phenomenon



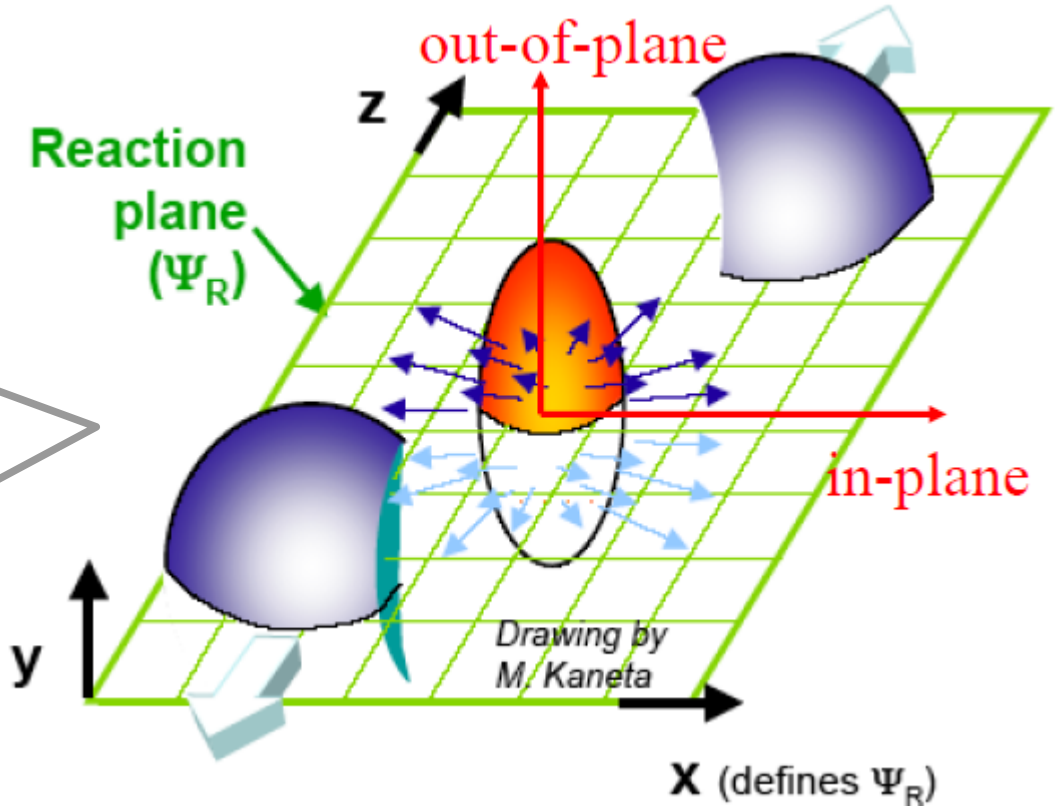
- Flow = characteristic modulation of particle production in azimuth, visible by eye!
- If the heavy-ion collision was just a superposition of pp collisions => no azimuthal modulation would be seen.

Flow phenomenon

Larger pressure grandients in the direction of reaction plane (in-plane)

=>

Larger particle production in-plane compared to out-of-plane

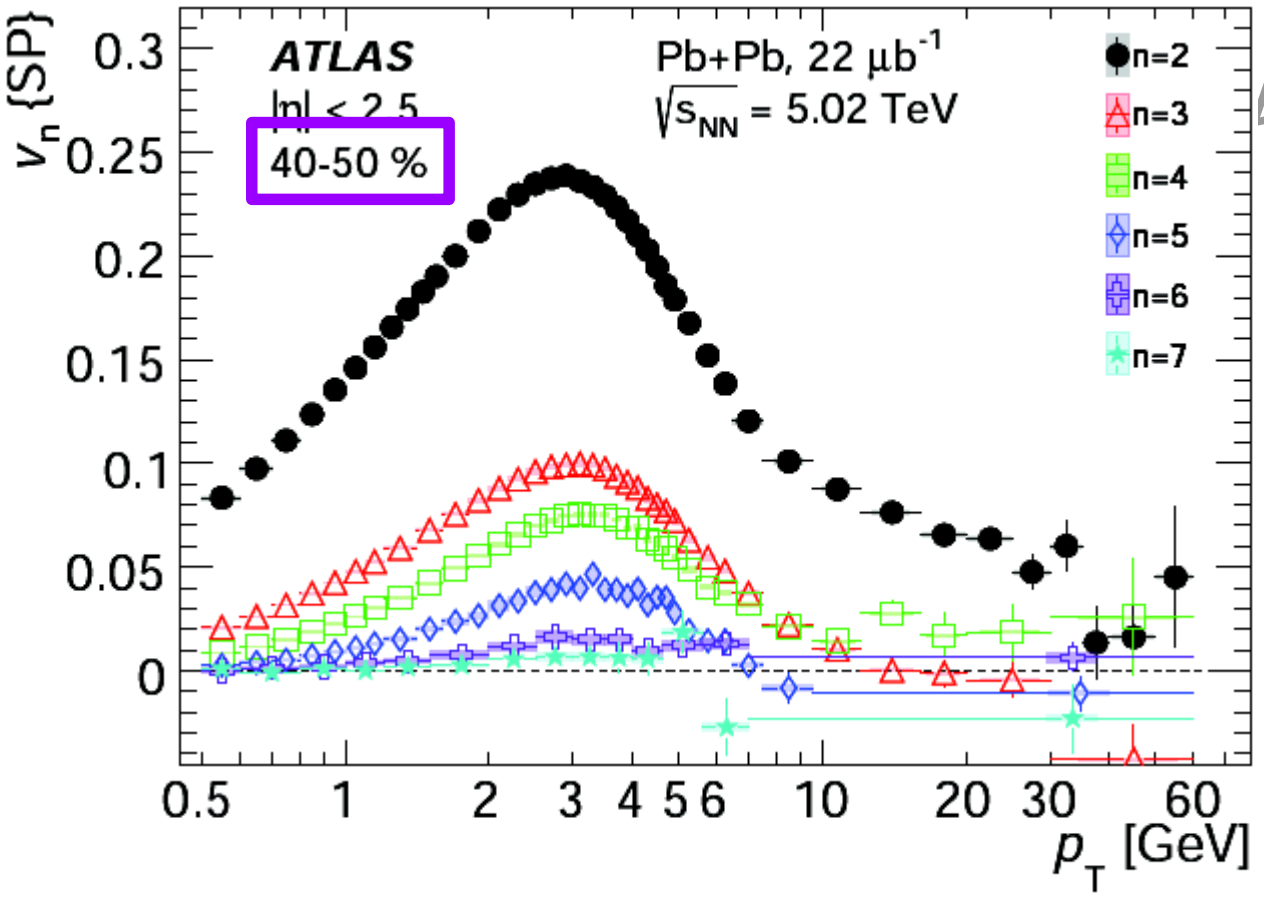


- Characterization using Fourier expansion in $\Delta\phi$ wrt reaction plane:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = N_0\left(1 + 2v_2 \cos 2(\phi - \Phi^{RP})\right) \qquad v_2 = \left\langle \cos 2(\phi - \Phi^{RP}) \right\rangle$$

- Here just first term in the expansion = elliptic flow (v_2).
- Good description by relativistic hydrodynamics … allows extracting parameters such as viscosity-over-entropy ratio.

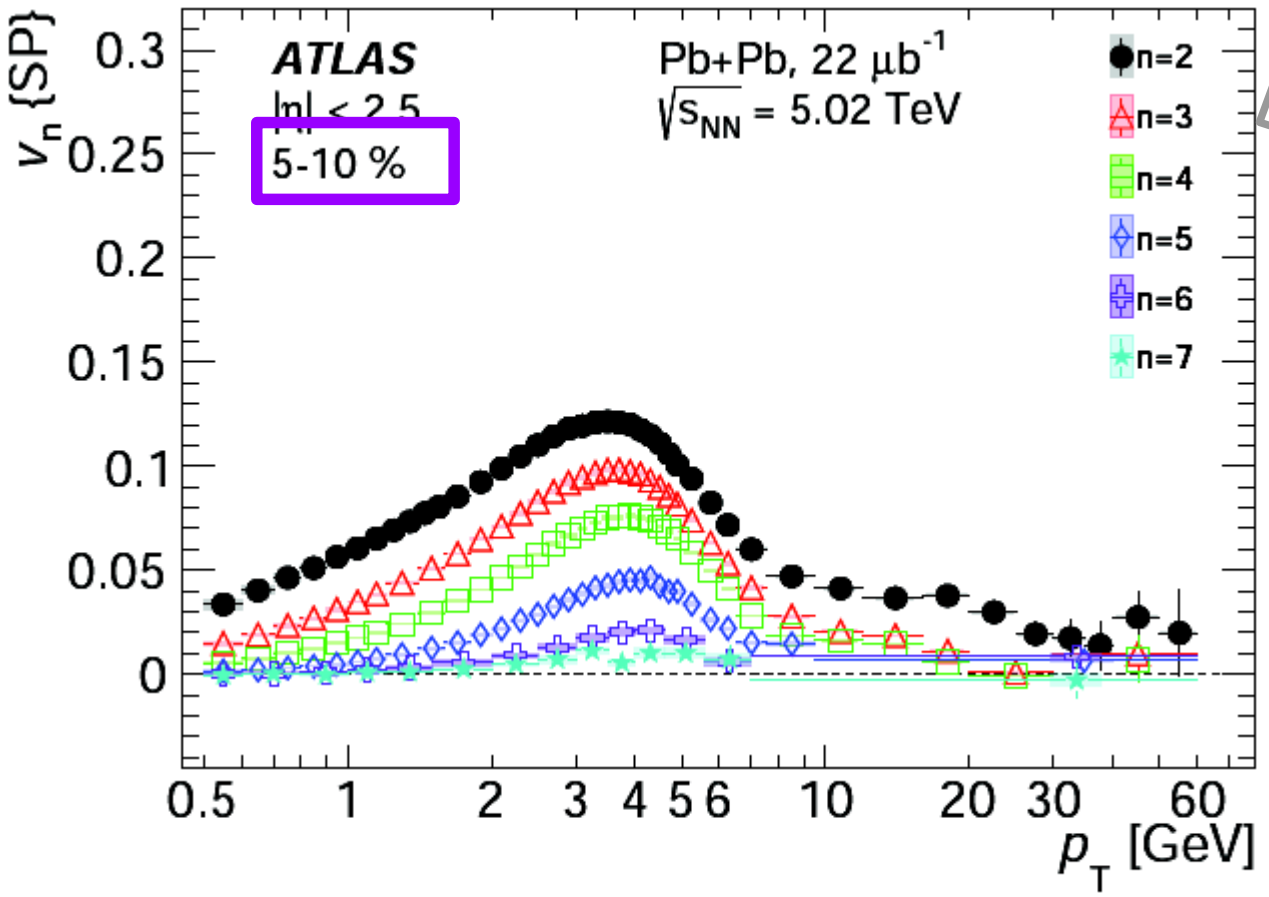
Flow in Pb+Pb



Peripheral collisions – ordering: v_2 (largest) –> v_7 (smallest)

- Precision measurement of $v_2 - v_7$ => more insight into the fluctuating anisotropic initial state.
- Characteristic shape predicted by rel. hydrodynamics up to 4 – 6 GeV.
- v_n at high-p_T due to path length dependent energy loss

Flow in Pb+Pb



Central collisions: smaller v_2 due smaller initial eccentricity

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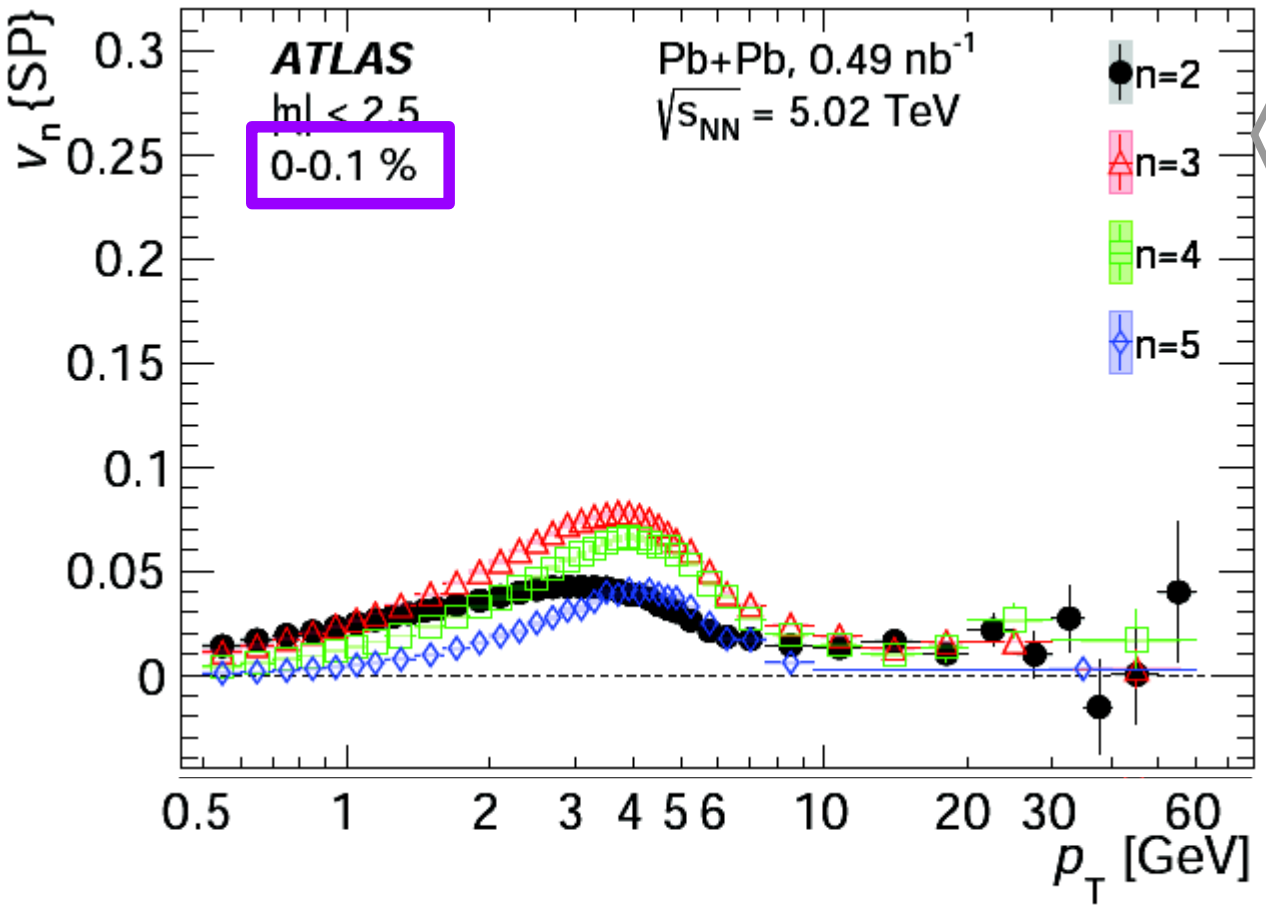
Flow in Pb+Pb



Very central collisions => v_2 smaller than higher order flow which is driven by fluctuations

- Precision measurement of $v_2 - v_7$ => more insight into the fluctuating anisotropic initial state.
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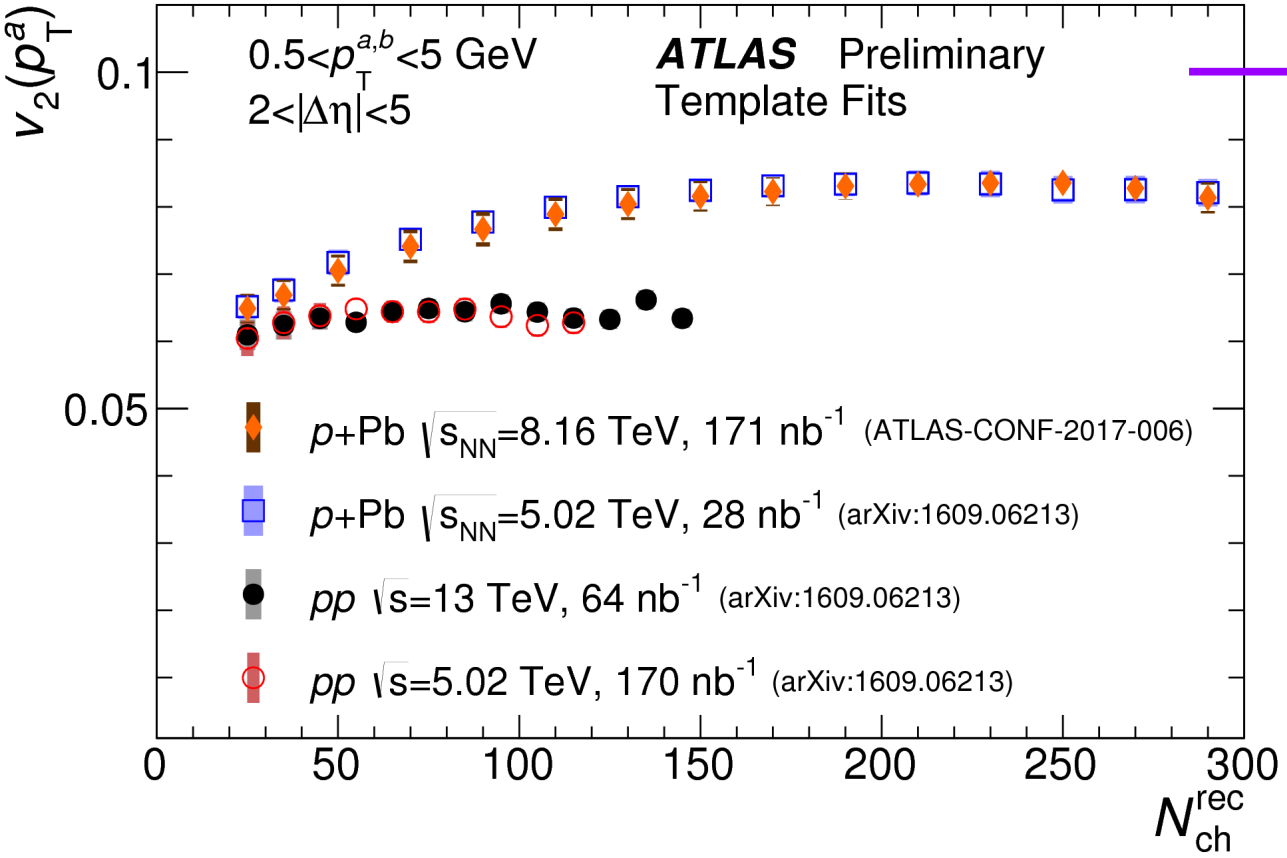
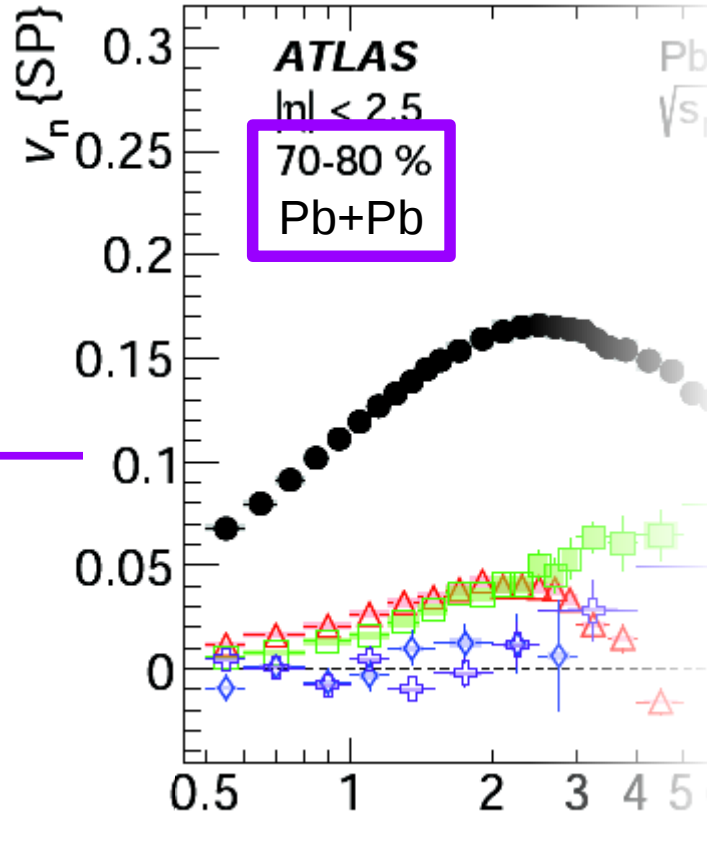
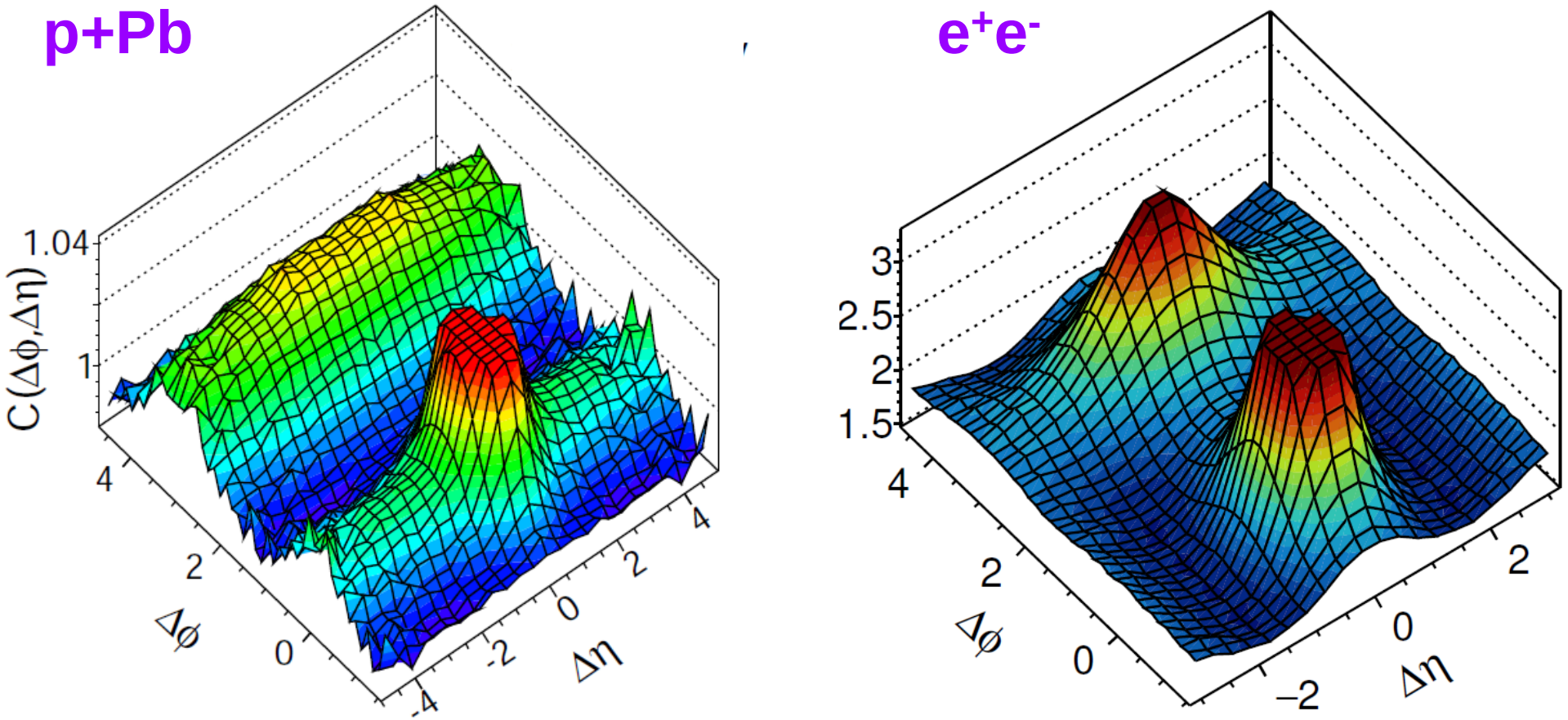
But flow is also in smaller systems!





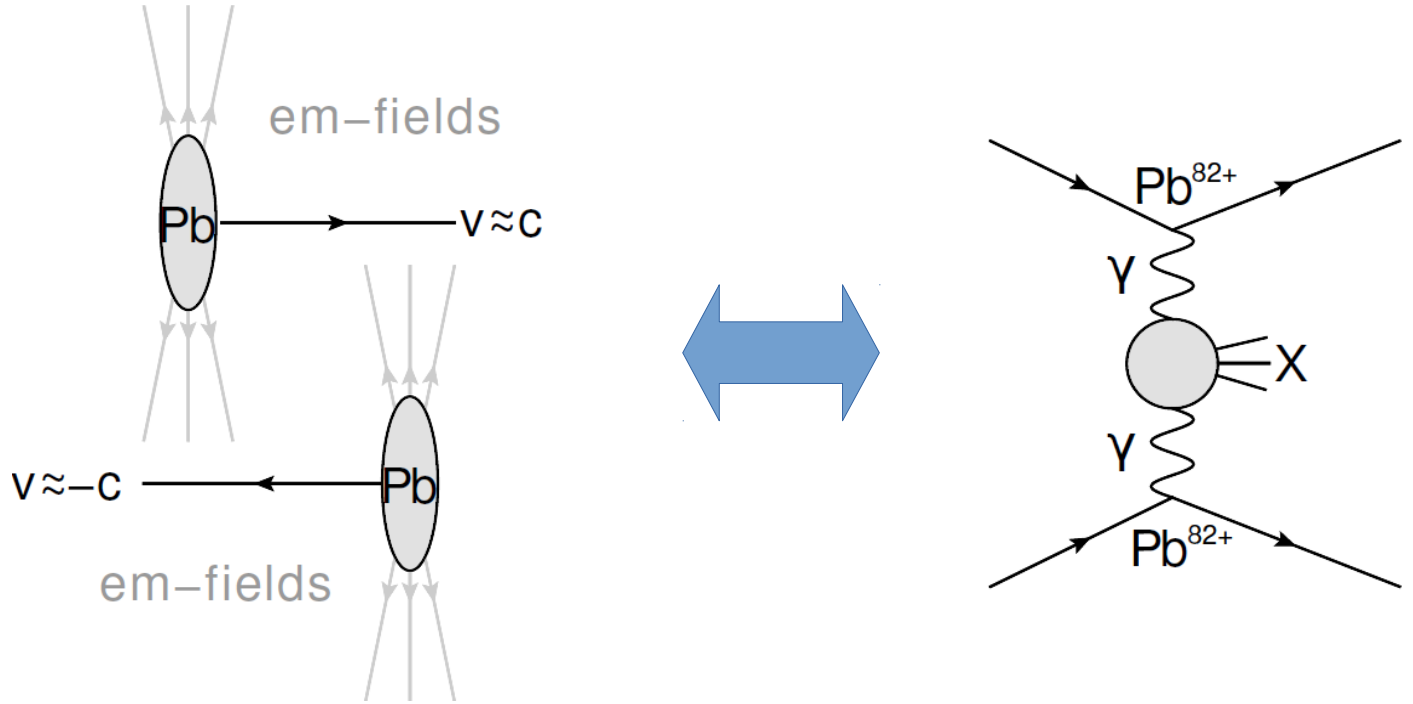
- Obviously, zero flow in MC generators (Pythia, Hijing) (not shown).
- But flow of comparable magnitude also in p+Pb collisions and high-multiplicity p+p collisions!
- Is the deconfined matter created in p+p and p+Pb? Or is the flow some universal pQCD phenomenon? Or one observable but two different physics mechanisms behind?

Re-analysis of LEP data



- To move forward in addressing the pQCD part, CMS people re-analyzed open LEP data.
- No sign for “ridge” (= long-range azimuthal correlations) <=> no evidence for flow in e+e- collisions.

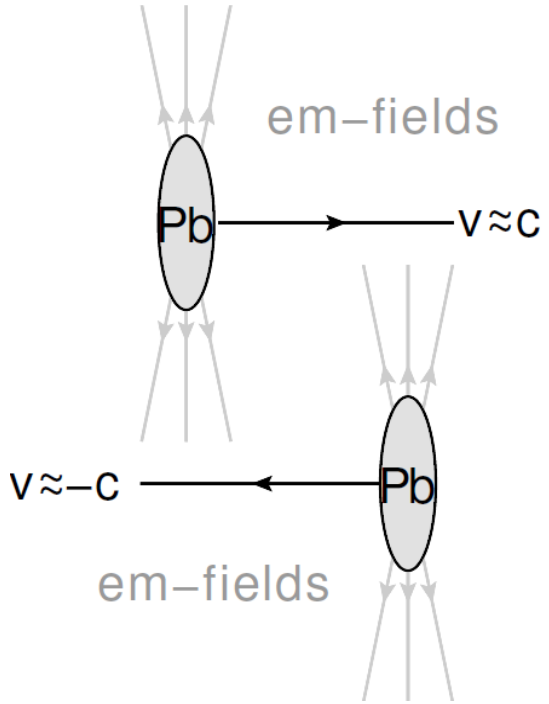
Ultra-peripheral collisions

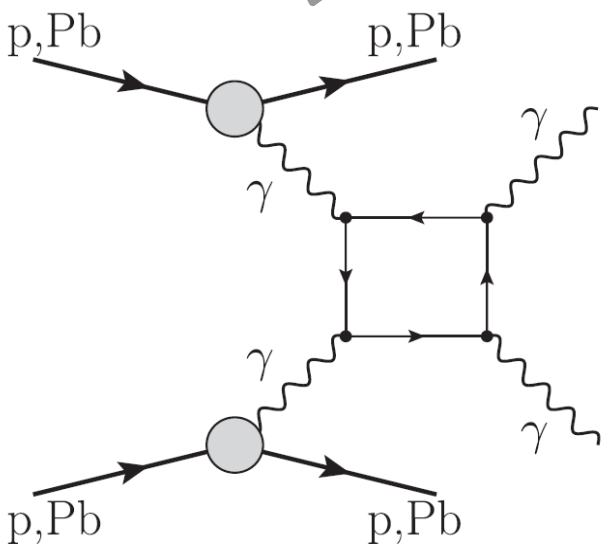


- Boosted protons / nuclei are source of photons of small virtuality ($Q^2<1/R^2=10^{-3}GeV^2$) described using equivalent photon approximation.
- Electromagnetic interactions dominate at large impact parameters.
- Pb+Pb & UPC turn LHC into photon-photon collider!

Ultra-peripheral col

One of processes:
light-by-light scattering





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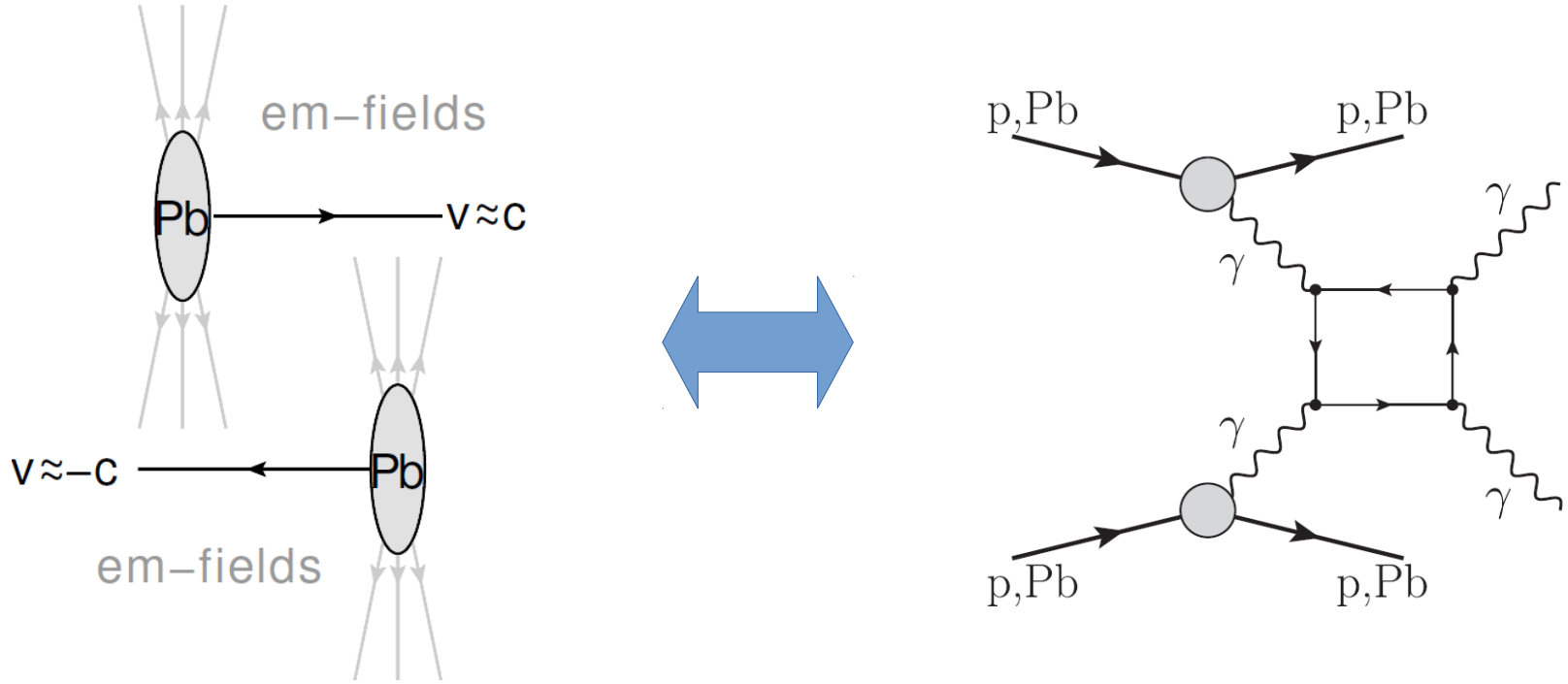
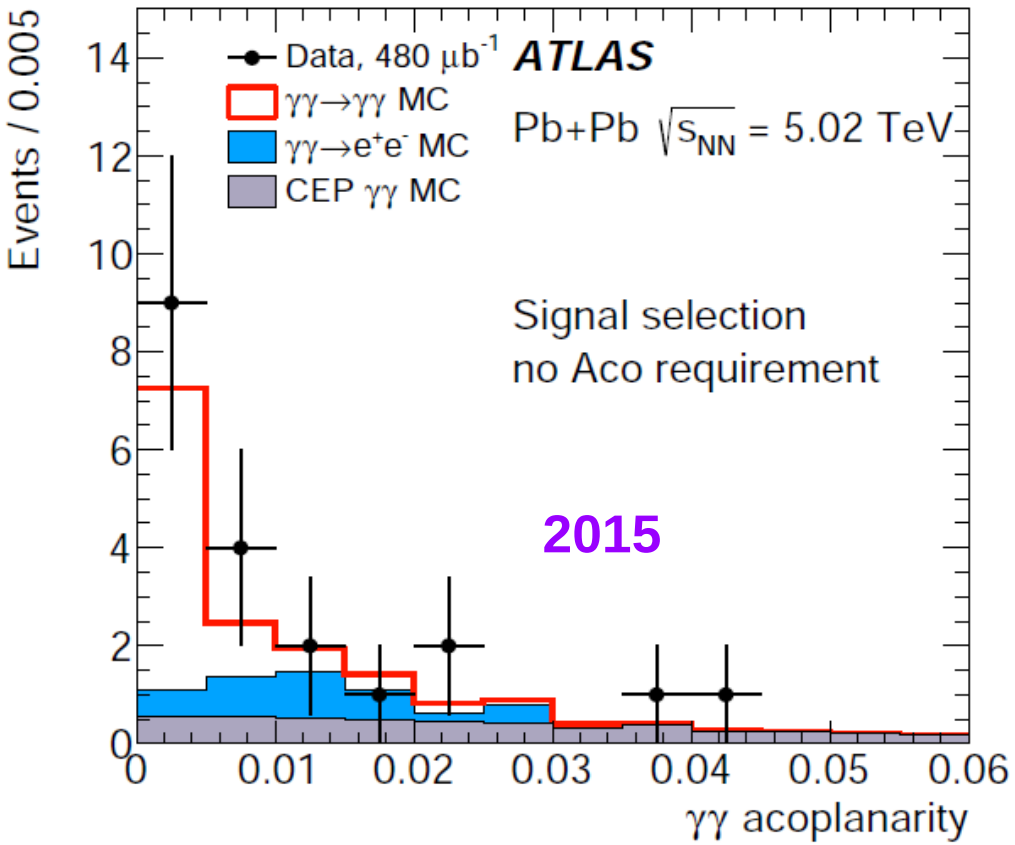
Light-by-light scattering



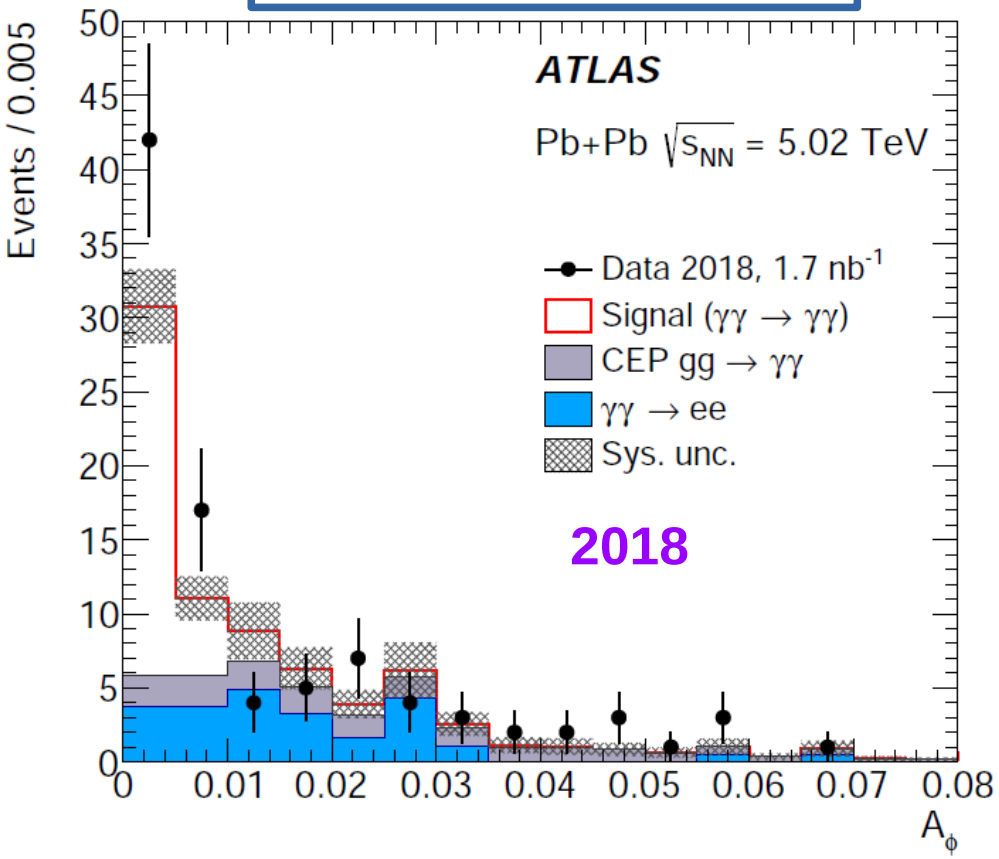
- First evidence for light-by-light scattering by ATLAS in 2017
- No direct observation before, only:
  - in g-2 of muons and electrons
  - in Delbruck scattering (= photon scattering in Coulomb field of a nucleus)
  - Not (yet) observed in vacuum birefringence (= photon splitting in a strong magnetic field)

Light-by-light scattering

Nat. Phys. 13 (2017) 852



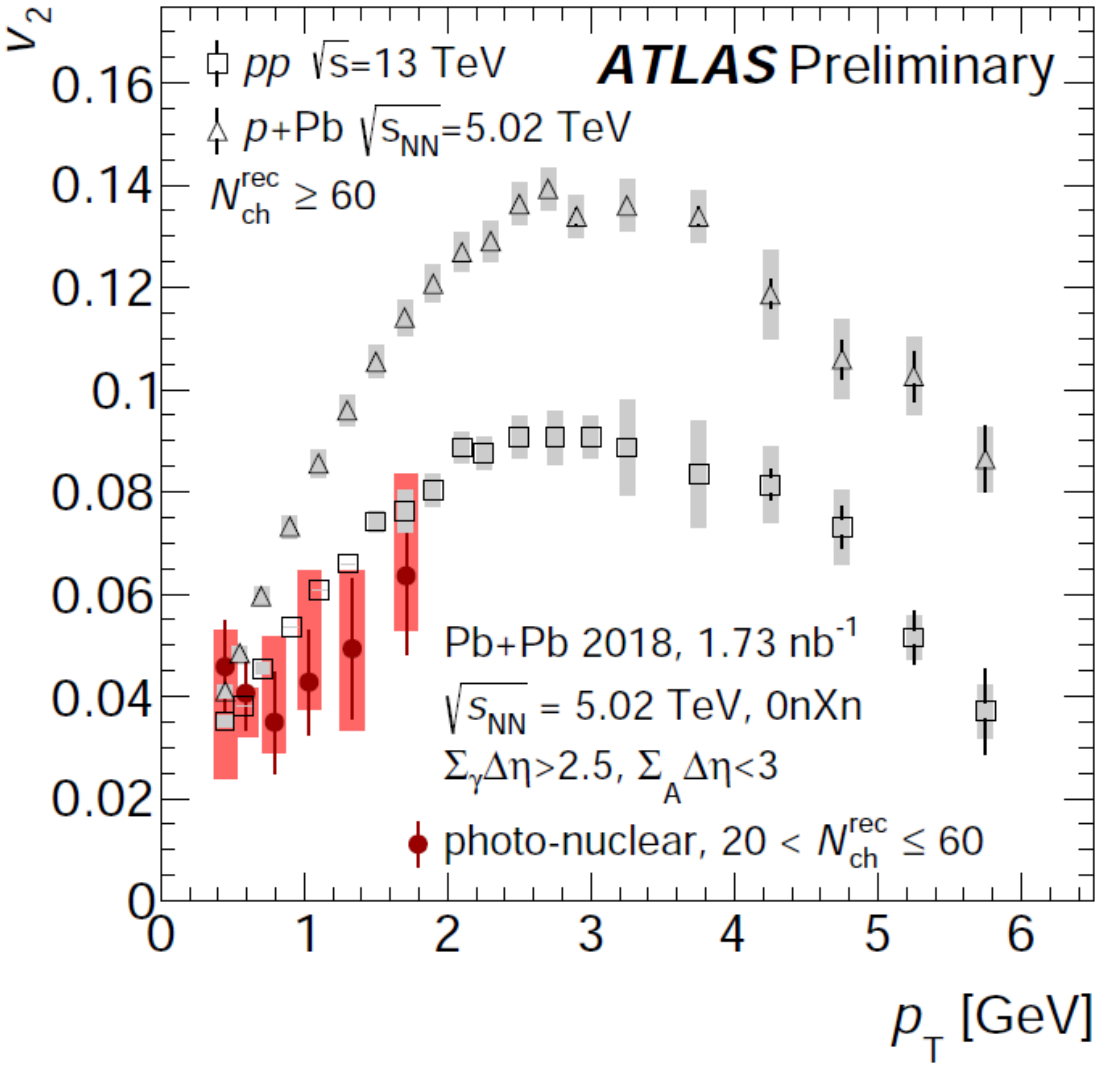
arXiv: 1904.03536



- Event selection: 2 photons: E_T>6 GeV, |η|<2.37, $m_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < (1)2 GeV, Aco = (1-Δφ/π)<0.01; no tracks
- **2015:** 13 events (2.6 expected bkgr), **4.4 σ significance**
- **2018:** 59 events (12 expected bkgr), **8.2 σ observation**

What else can be done with “γγ-LHC”?

- Quite a lot of things, one of them is the measurement of flow ...



- Flow in γ+Pb collisions ?!?

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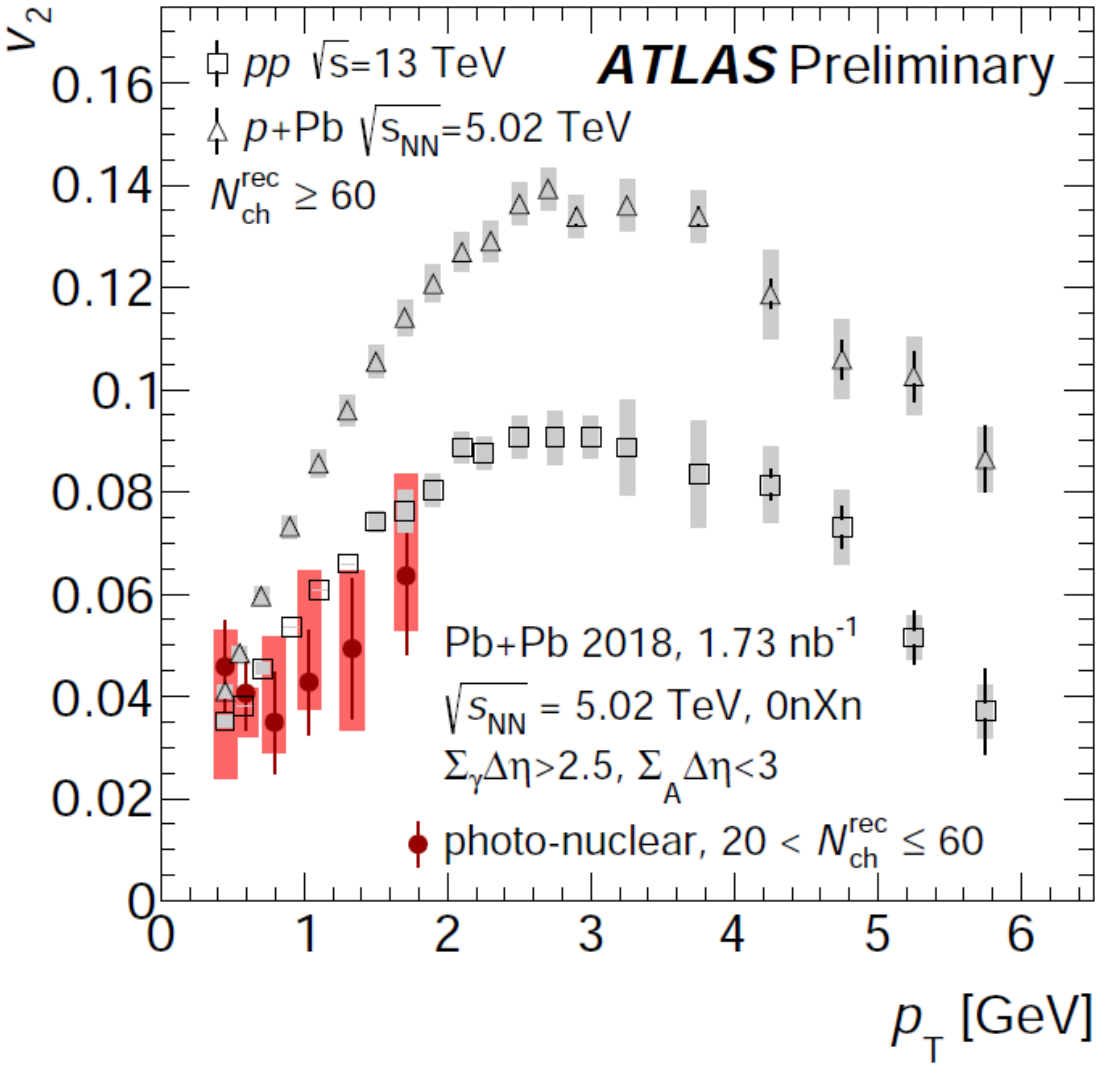
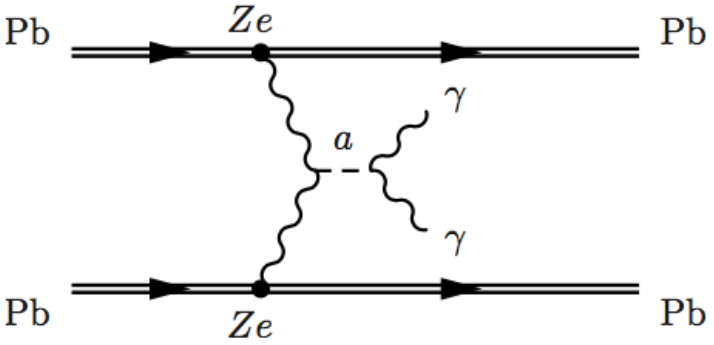


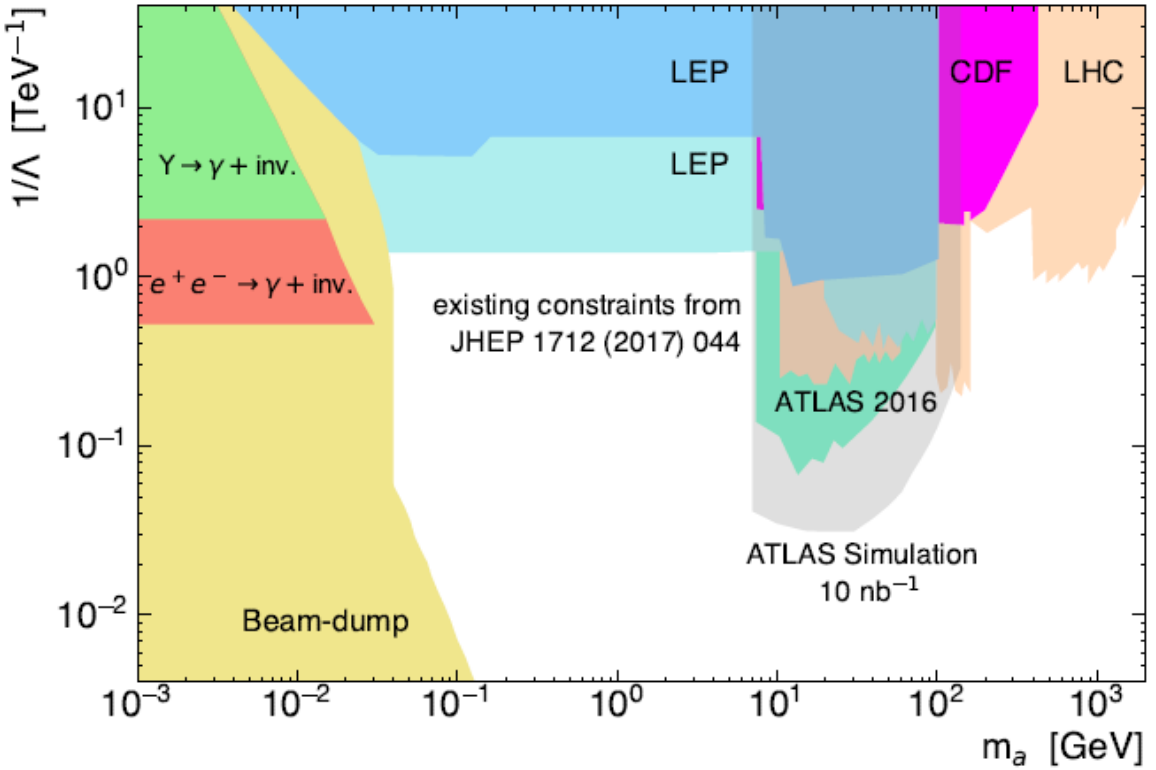
- Flow in γ+Pb collisions ?!?
- In the vector meson dominance picture, photon fluctuates to vector meson: γ+Pb <=> ρ+Pb

What else can be done with “γγ-LHC”?

- Quite a lot of things, one of them is the measurement of flow ...
- Another one is measurement of nuclear-PDFs in a new regime …
- But also BSM searches, e.g. axions or monoples …

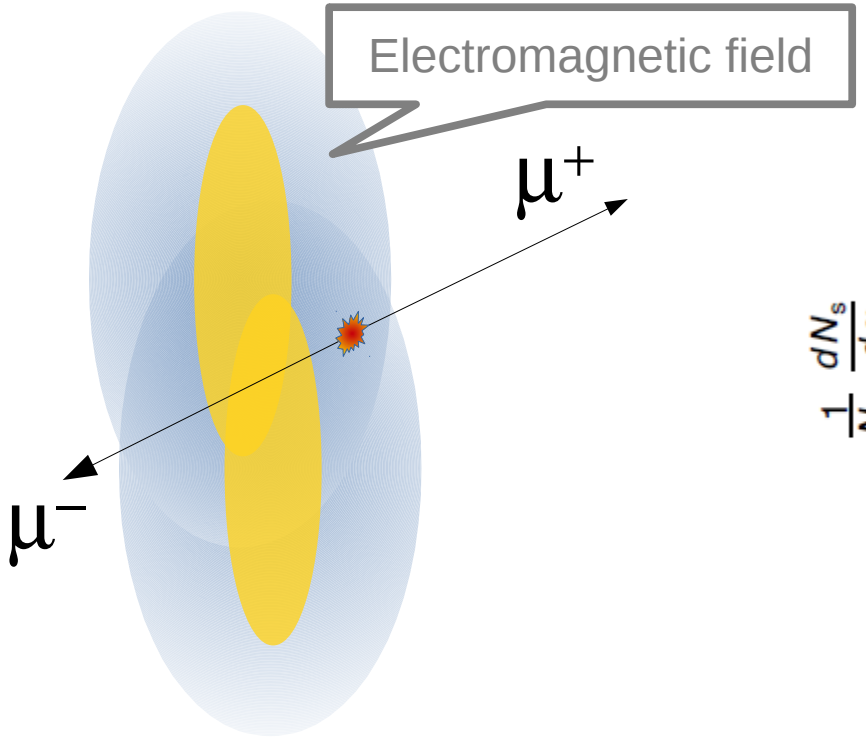
$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu} = \frac{1}{\Lambda} a \mathbf{E} \cdot \mathbf{B}$$

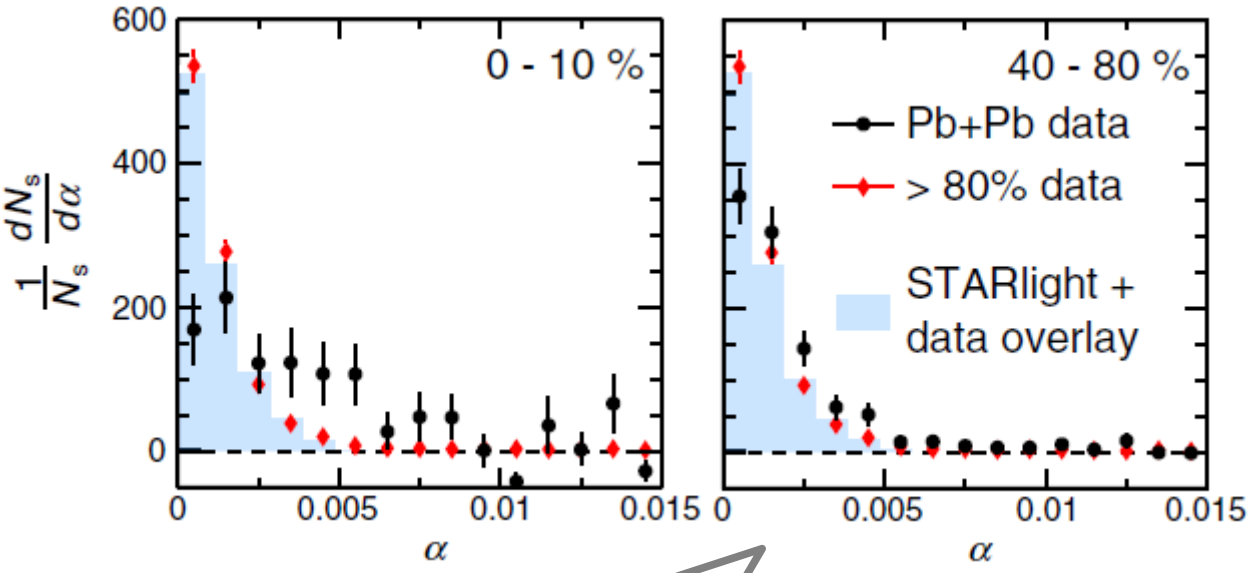




- Axion-like particles (ALP): scalar or pseudoscalar particles that couple to EM fields … $m_{\gamma\gamma}$ limits $1/\Lambda$ coupling.

Probing electromagnetic degrees of freedom of QGP





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

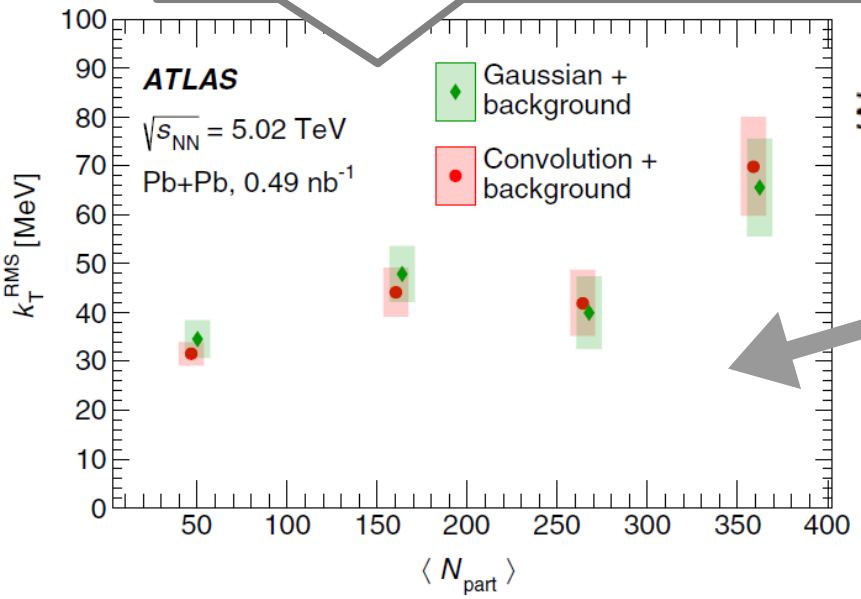
- Dimuons from electromagnetic interaction **penetrating through QGP**
- Modification of **acoplanarity** distribution in central collisions

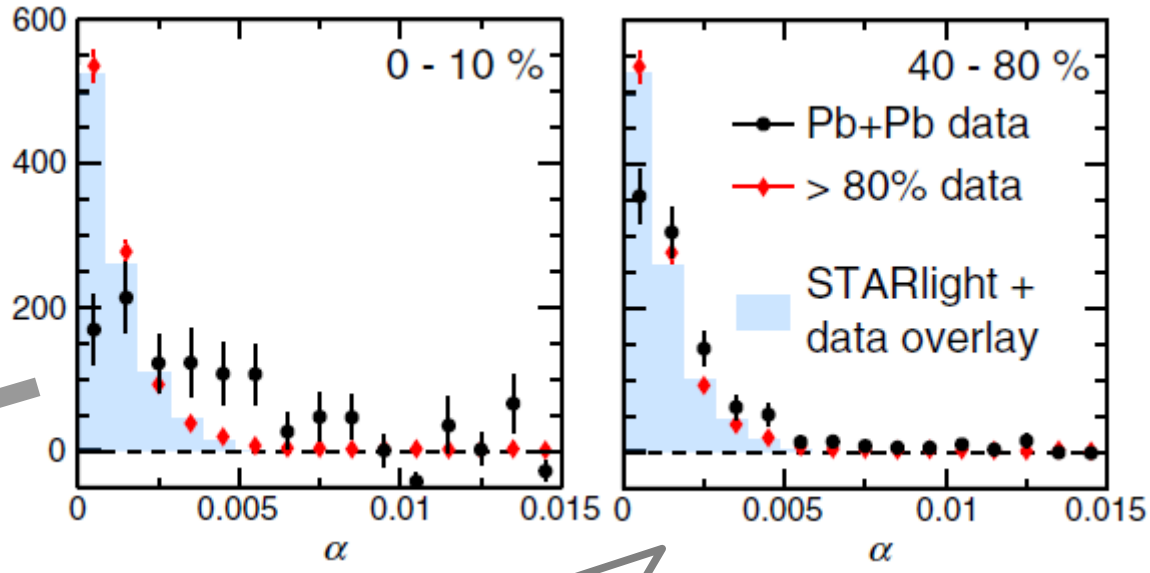
Phys. Rev. Lett. 121 (2018) 212301

Probing electromagnetic degrees of freedom of QGP

$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2} \frac{\langle \vec{k}_T^2 \rangle}{\langle p_{T\,avg}^2 \rangle}$$

… kT from fitting





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

- Dimuons from electromagnetic interaction **penetrating through QGP**
- Modification of **acoplanarity** distribution in central collisions
- About **70 MeV k_T deflection**

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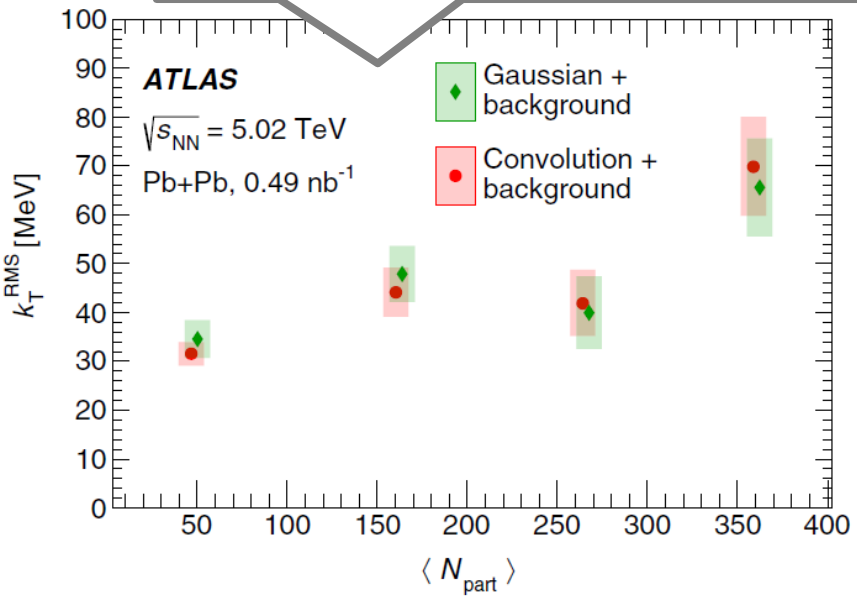
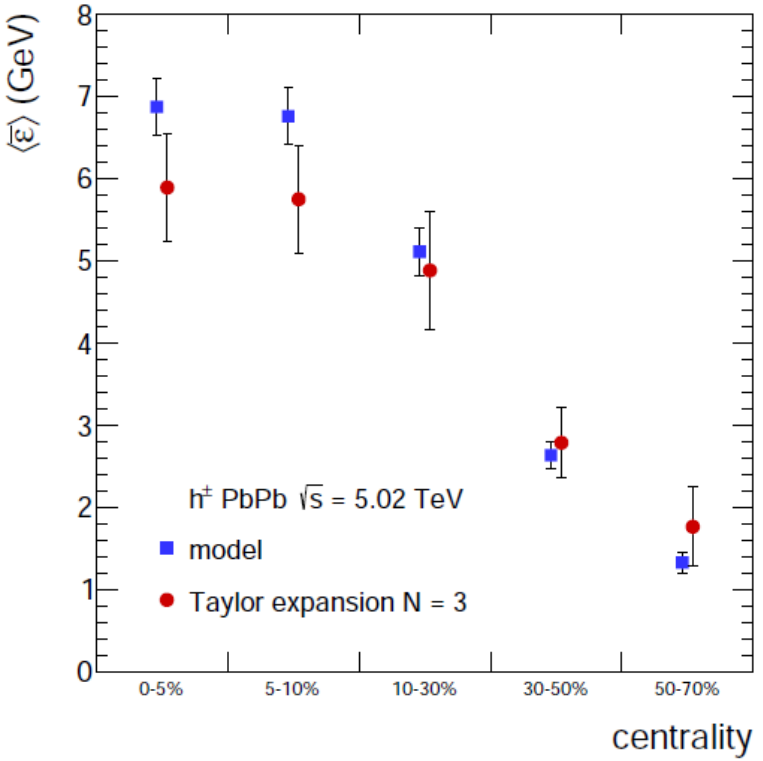


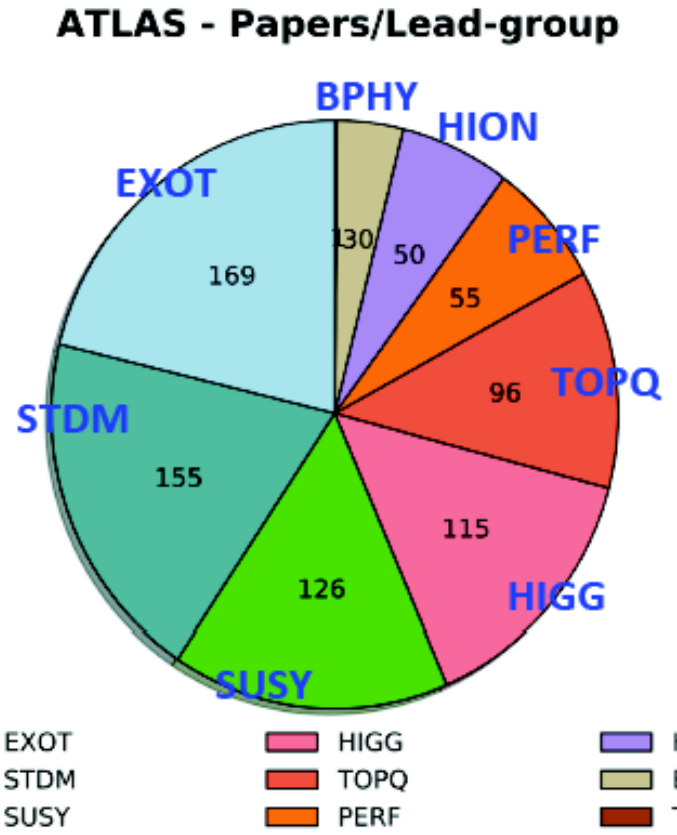
e.g. Phys. Rev. Lett. 119 (2017) no.6, 062302 or Eur. Phys. J. C76 (2016) no.2, 50



- Dimuons from electromagnetic interaction **penetrating through QGP**
- Modification of **acoplanarity** distribution in central collisions
- About **70 MeV k_T deflection** … compare with > 1 GeV for parton energy loss

Heavy-ion WG of ATLAS

- HI WG produced ~20 papers over the last 2 years + about 20 papers / CONF expected to come before Quark Matter 2019
- HI WG is (among) the most productive groups per “OTP capita”
  (e.g. HI: ~50 papers by ~50 people,
  EXOT: 170 papers by 630 people)



Most popular paper

H-index

Average # published citations (no self)

BPHY	EXOT	HIGG	HION	STDM	SUSY	TOPQ
18.5	33.3	90.4	41.5	20.2	40.2	19.1
14	42	42	22	31	43	25
72	229	4308	319	126	223	92

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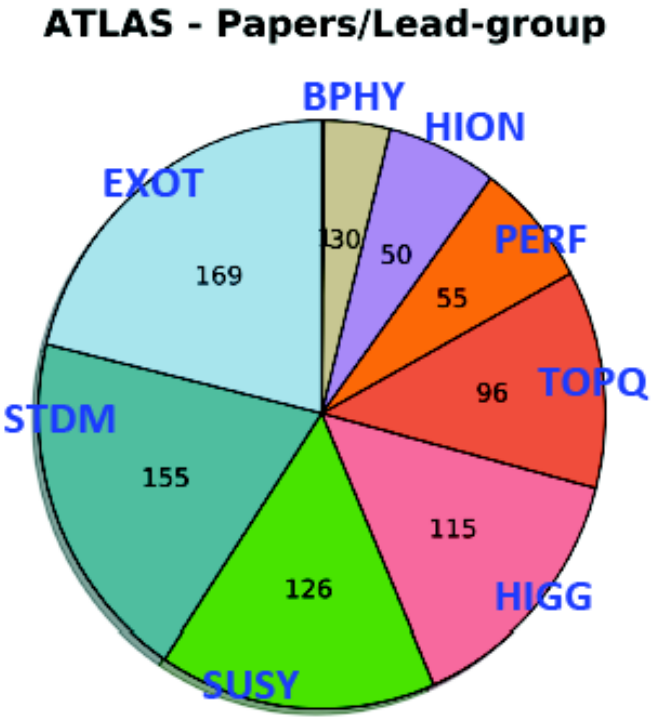

- Diverse physics program: soft-QCD physics, jets, quarkonia, vector bosons, top-quark measurement, UPC collisions and little of BSM
- Diverse datasets: pp, p+Pb, Xe+Xe, Pb+Pb … and negotiating O+O and p+O collisions
- Allows for diverse physics and technical experience: inputs to planning of LHC running, work on data-preparation, trigger, simulation infrastructure

You are welcome to join!