Overview* of the ATLAS heavy-ion program

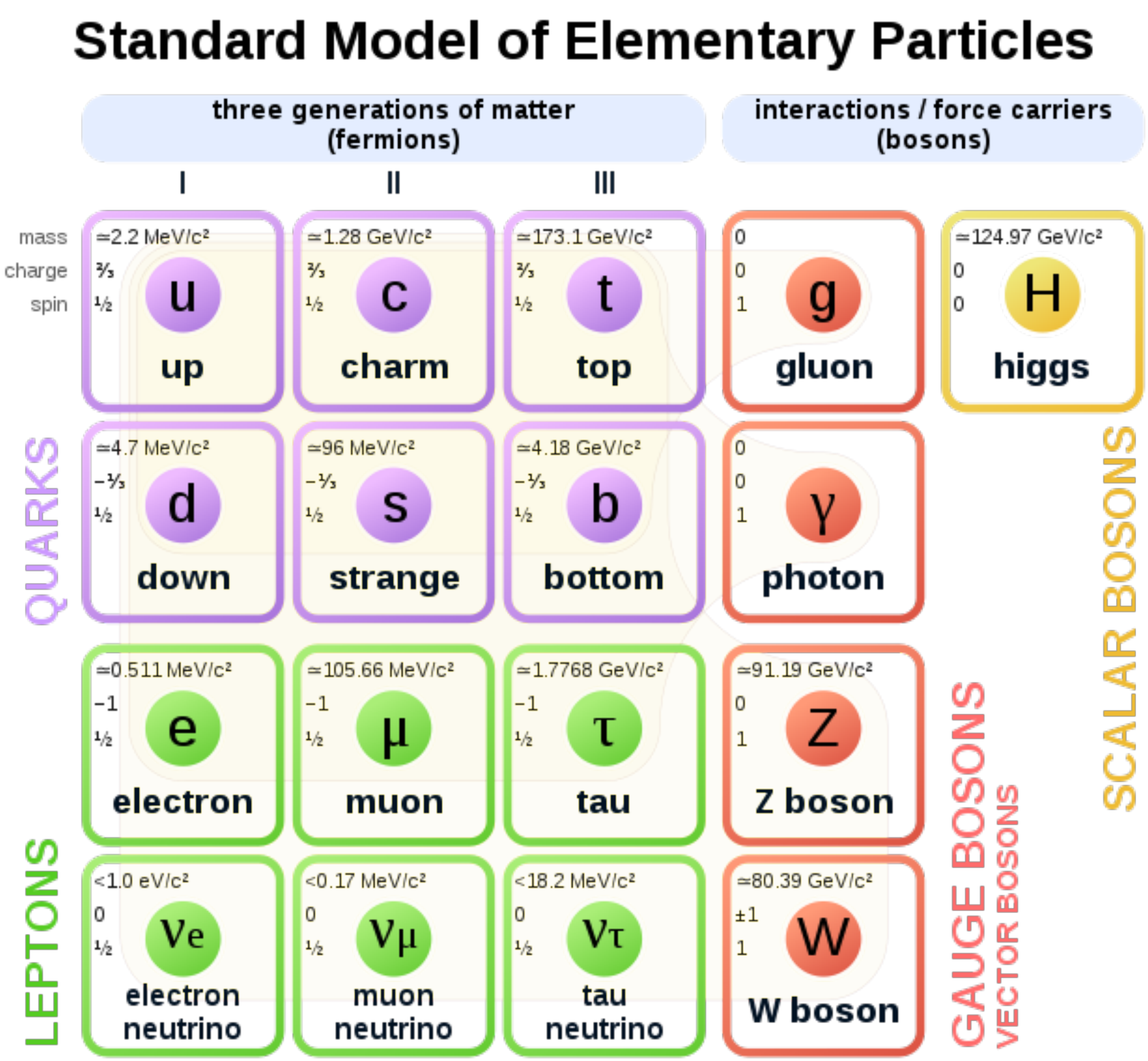
Seminar on Particle Physics
Phenomenology and Experiments

Dominik Derendarz

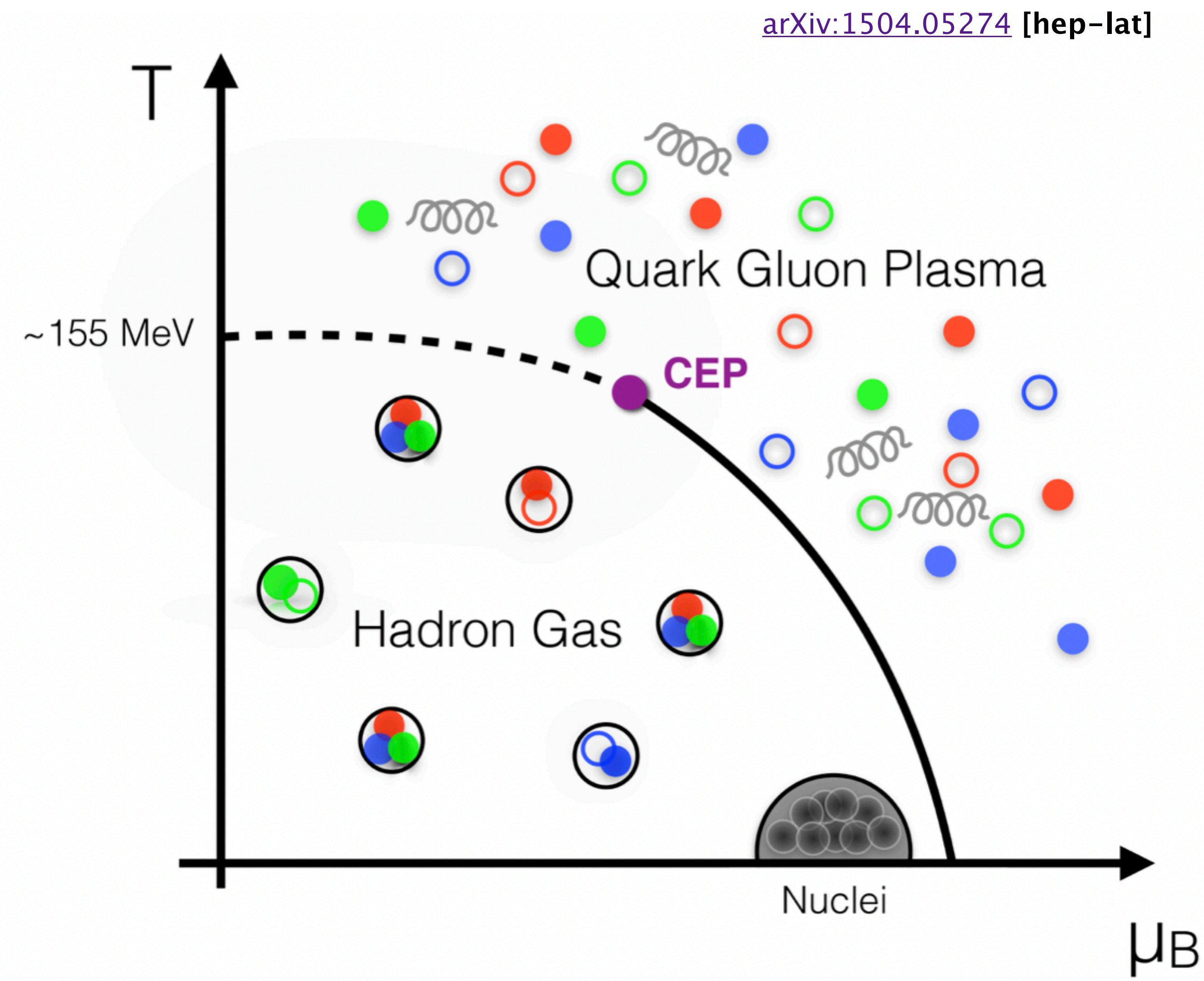
March 20, 2023

*personal biased selection

Heavy ion collisions - QCD laboratory

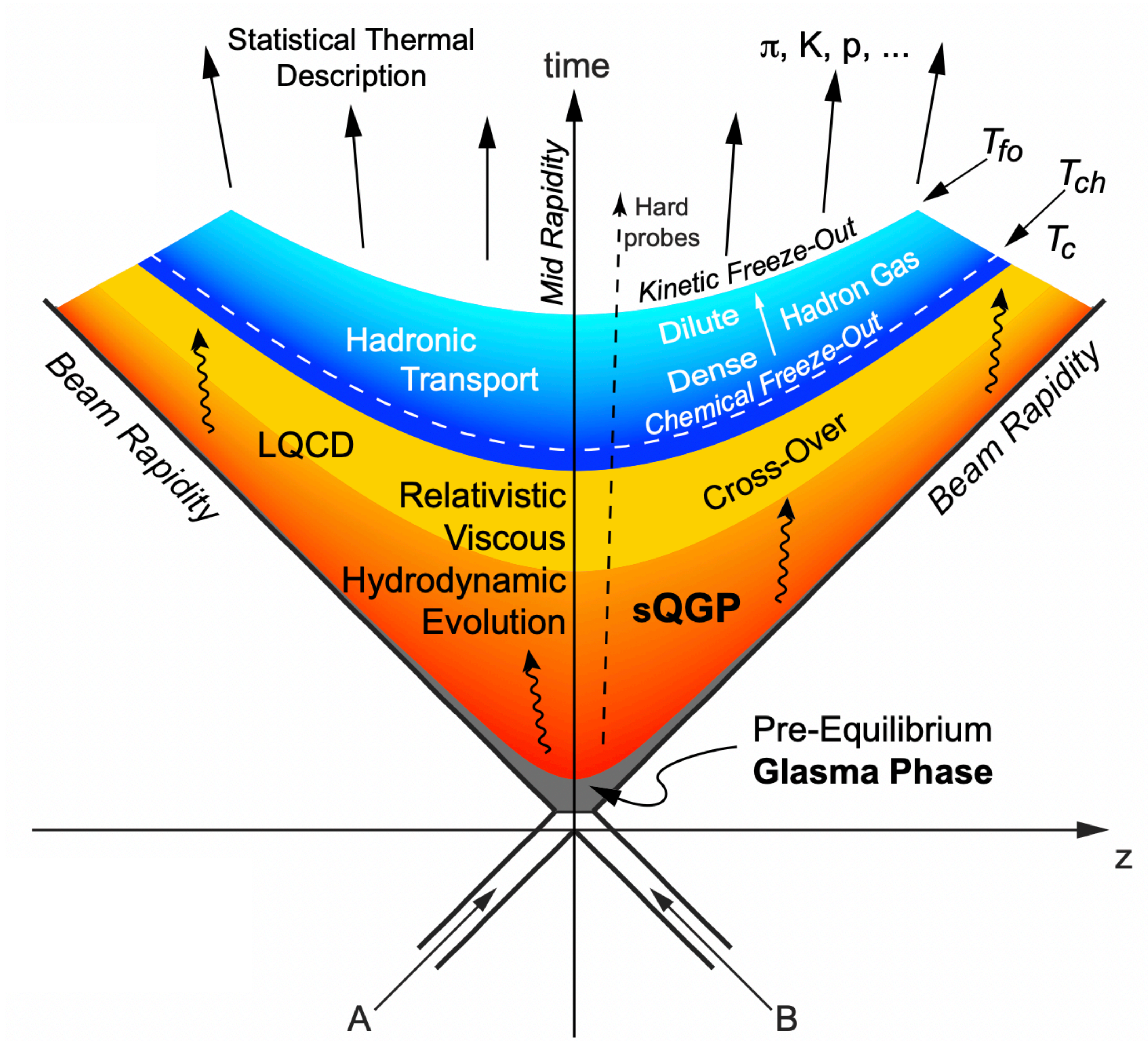


Schematic QCD phase diagram



Phase transition at sufficiently high temperature

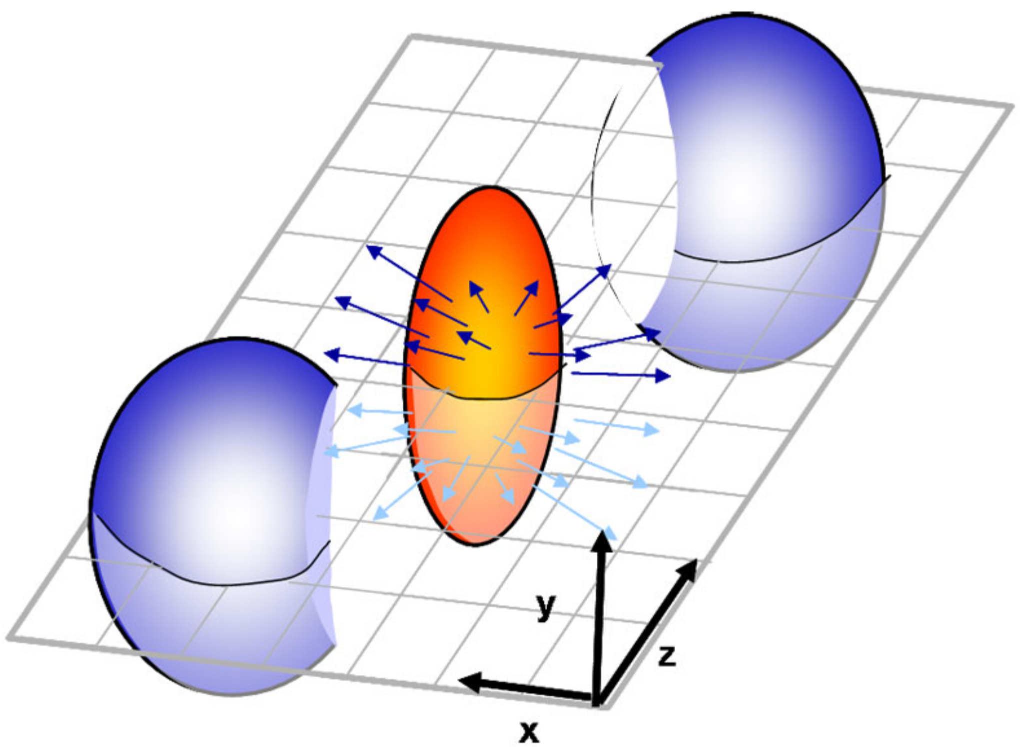
Heavy ion collisions - QCD laboratory



Heavy ion collisions allows to reach high enough temperature to trigger the phase transition to QGP (for about few fermi or few 10^{-23} s)

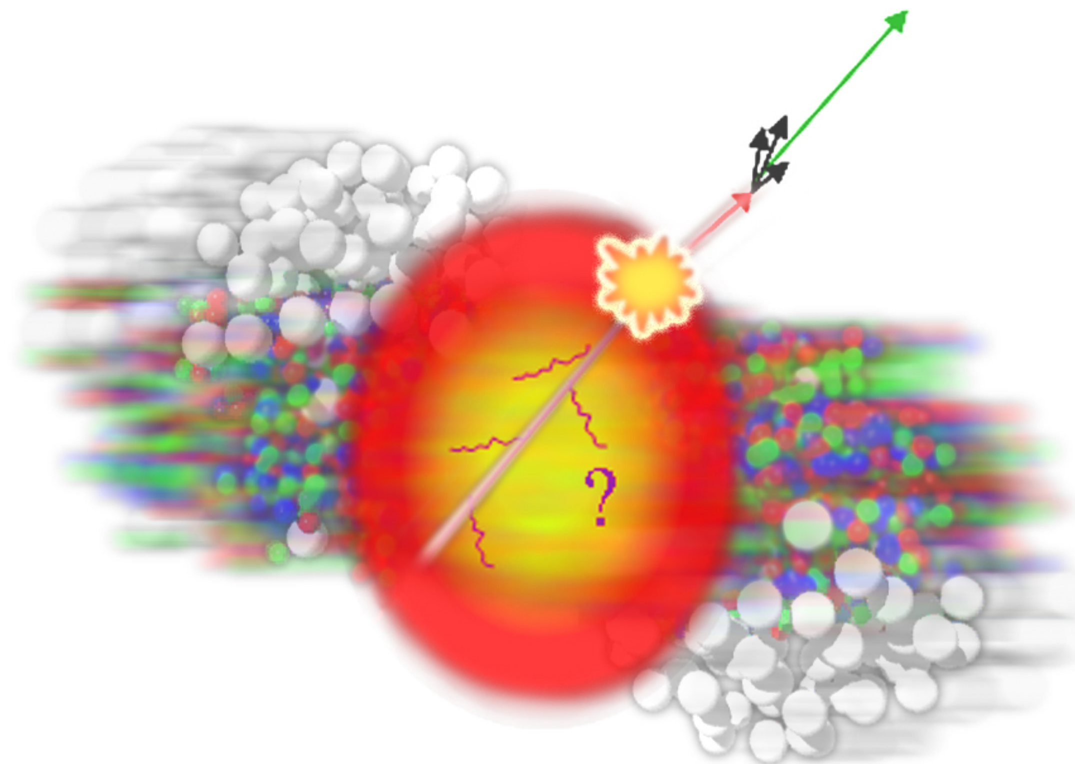
Signatures of QGP formation

Collective phenomena



- Initial **spatial** anisotropy is converted to **momentum** anisotropy of final state particles

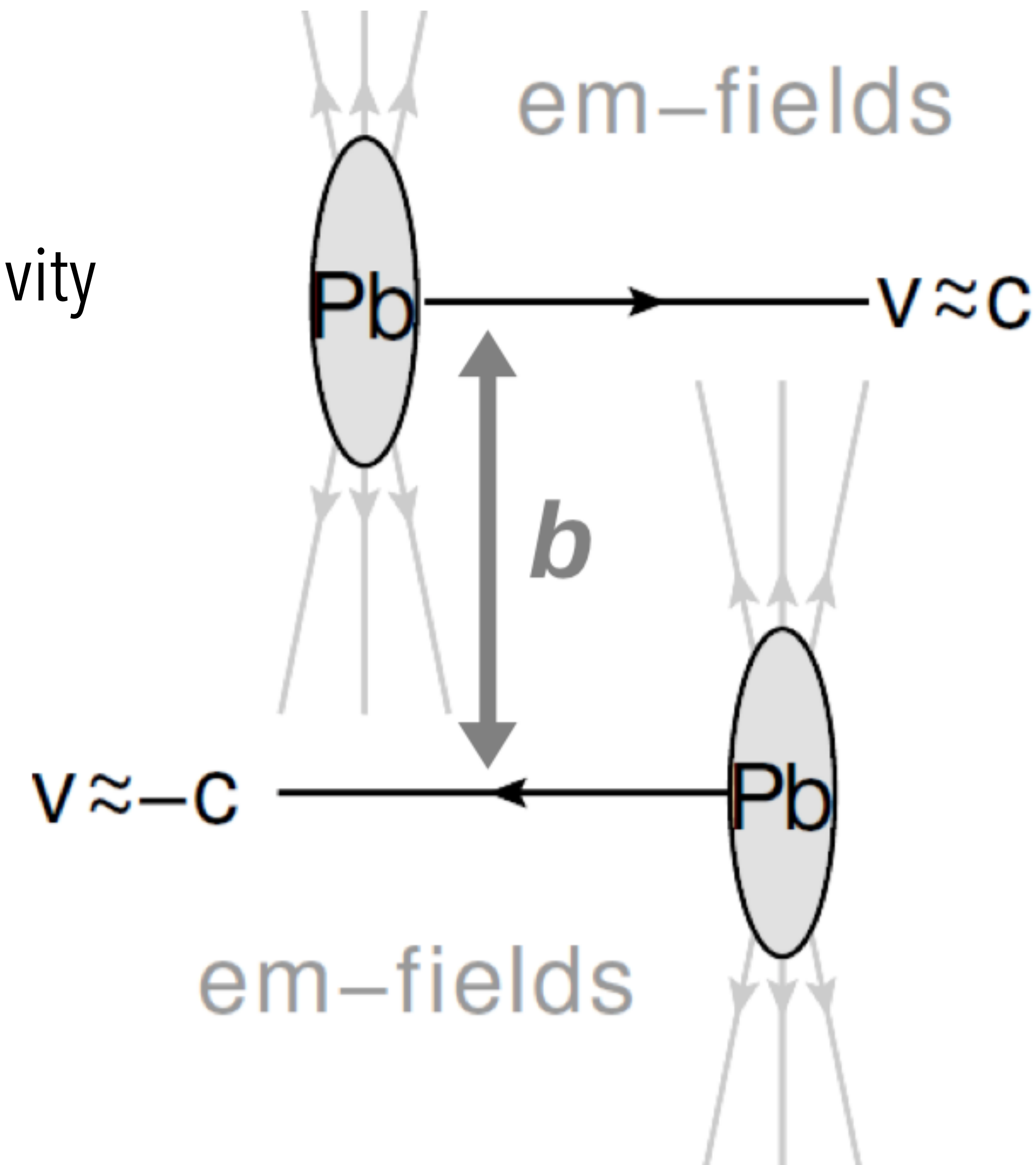
Jet quenching



- Energy loss of high pT patron due to the interactions with the QGP medium

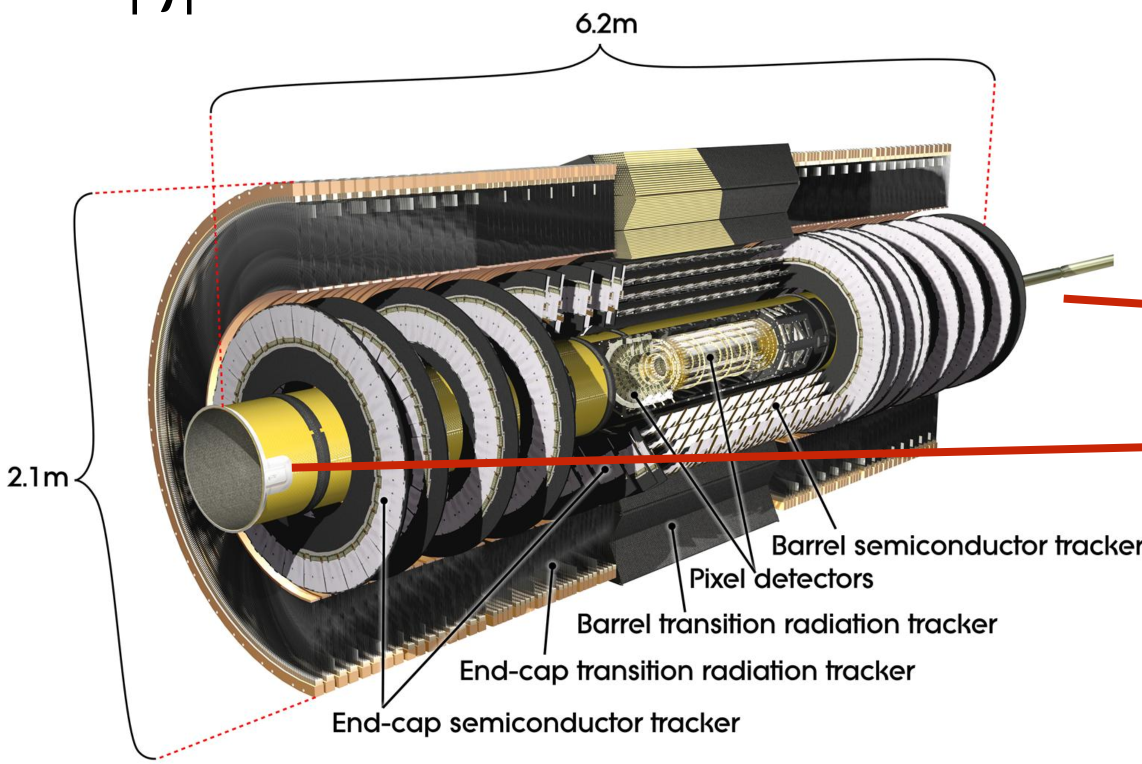
Photon induced processes

QED laboratory with sensitivity for new physics.

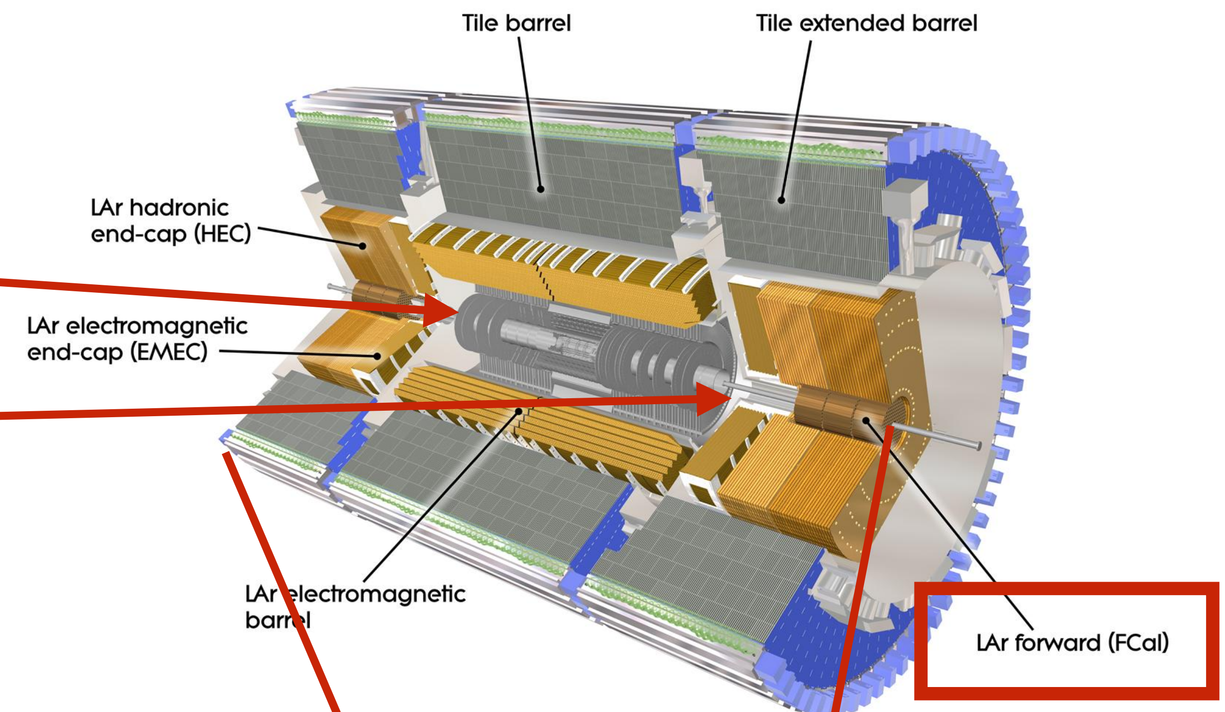


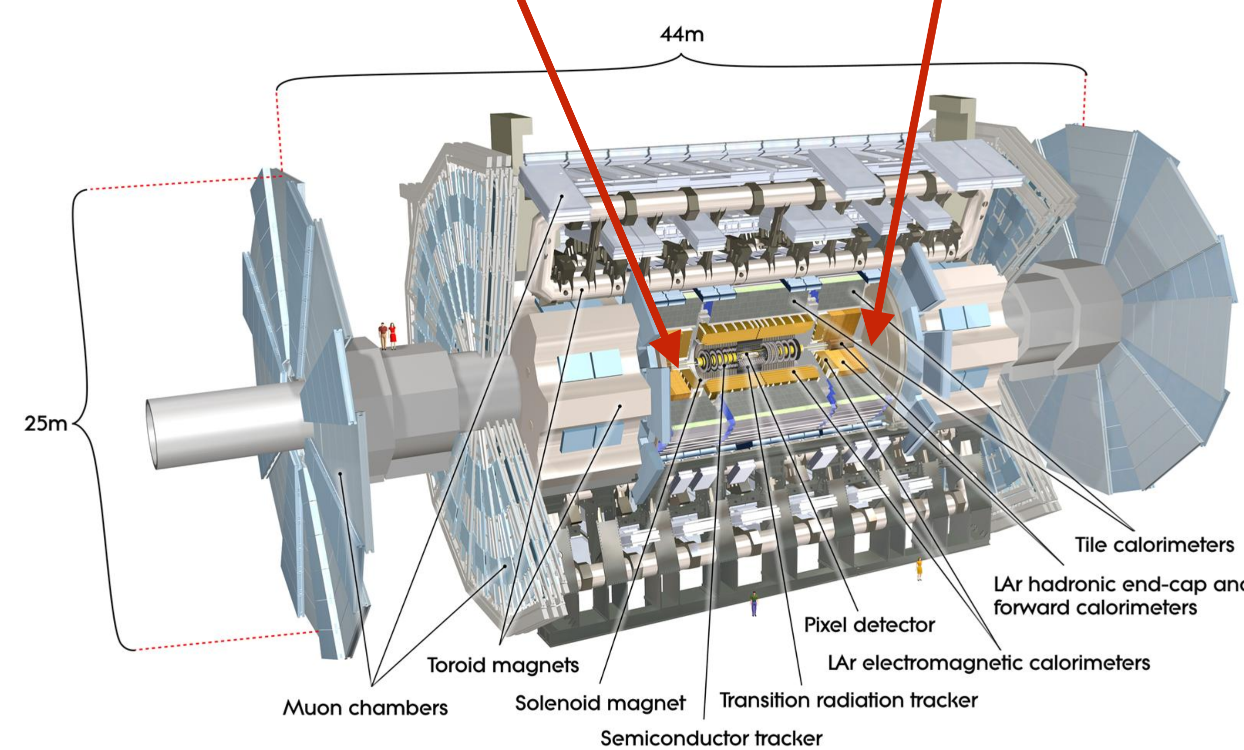
ATLAS detector

Tracker $|\eta| < 2.5$



Calorimeters $|\eta| < 4.9$





- And forward detectors located far far away from the interaction point ZDC (140m), AFP & ALFA (~240m)

Heavy ion datasets

	System	Year	sqrt(s_{NN}) [TeV]	L_{int}
Run1	Pb+Pb	2010	2.76	7 μb^{-1}
	Pb+Pb	2011	2.76	0.14 nb^{-1}
	pp	2012	8	19.4 fb^{-1}
	pp	2013	2.76	4 pb^{-1}
	p+Pb	2013	5.02	29 nb^{-1}
Run2	pp	2015	5.02	28 pb^{-1}
	Pb+Pb	2015	5.02	0.49 nb^{-1}
	p+Pb	2016	5.02	0.5 nb^{-1}
	p+Pb	2016	8.16	0.16 pb^{-1}
	Xe+Xe	2017	5.44	3 μb^{-1}
	pp	2017	5.02	270 pb^{-1}
	Pb+Pb	2018	5.02	1.76 nb^{-1}

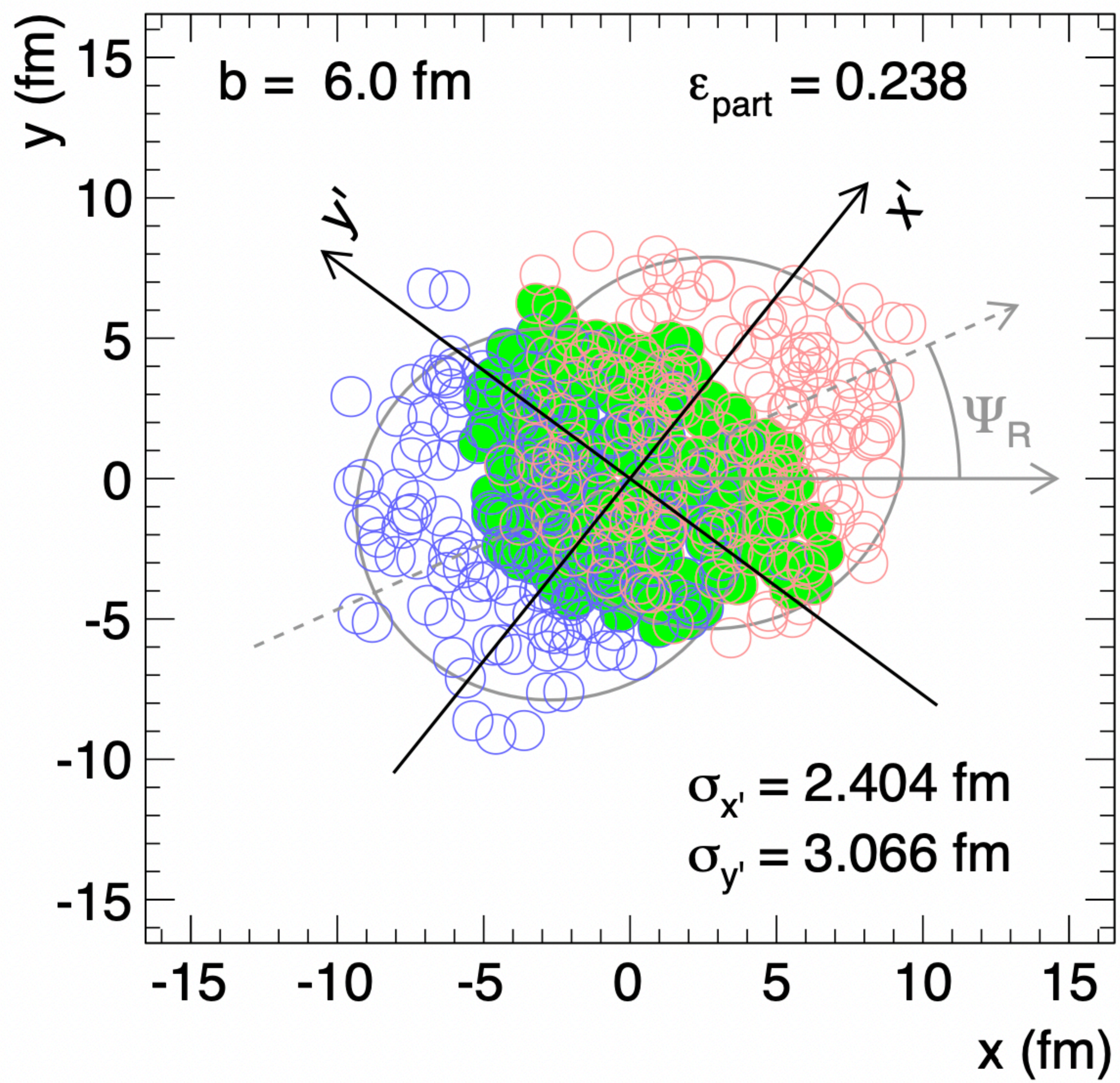
For **Run3** (2022-2024) expected:

- ~6nb^{-1} of Pb+Pb
- p+Pb ~X nb^{-1}
- Short pilot run with O+O and p+O

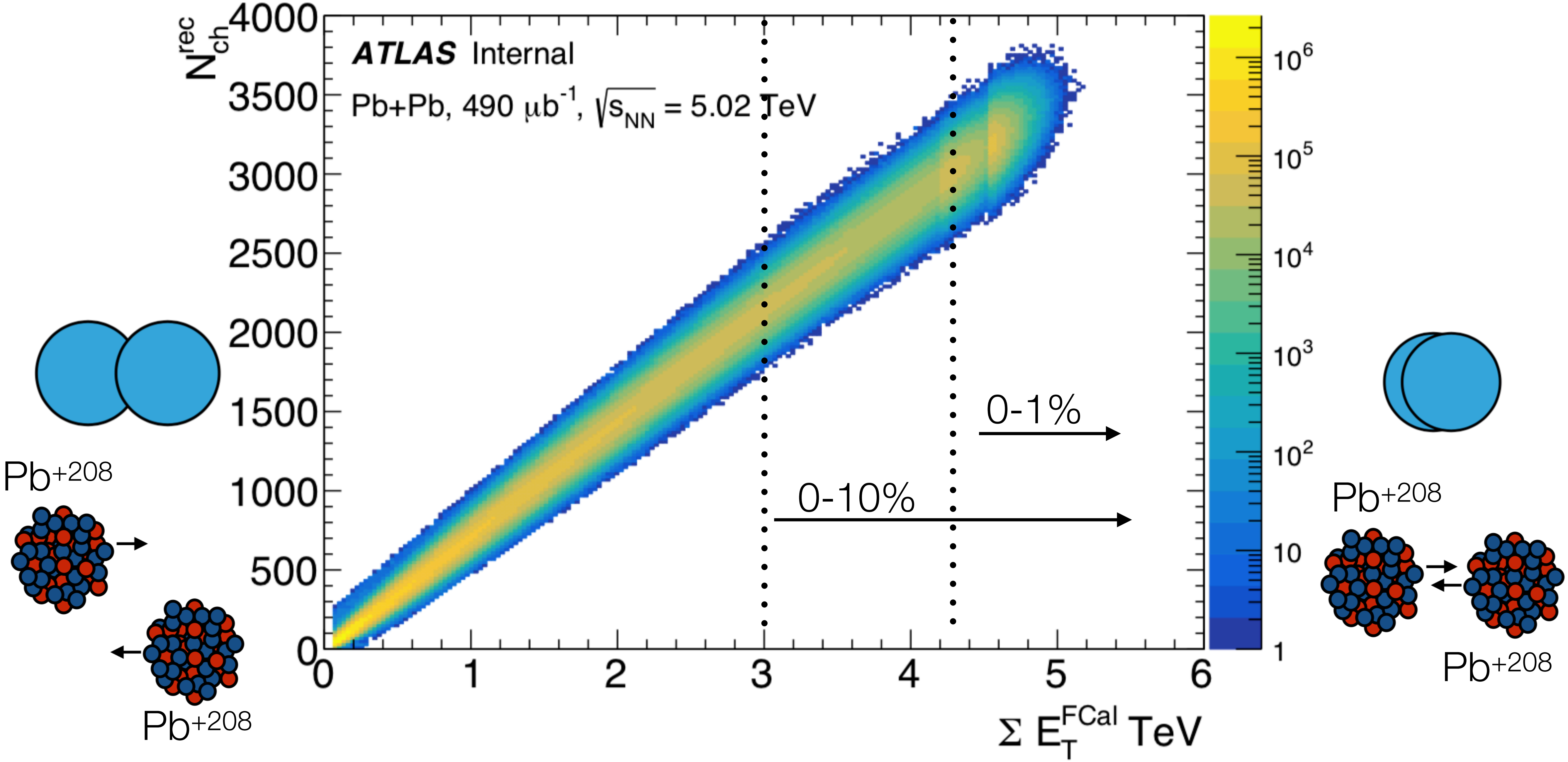
Centrality of heavy ion collision

- One nucleon can interact many times due to the thickness of the other nuclei that he see
- <N_{part}>, <N_{coll}> estimated based on MC Glauber fits to data

arXiv:1204.1409 [nucl-ex]



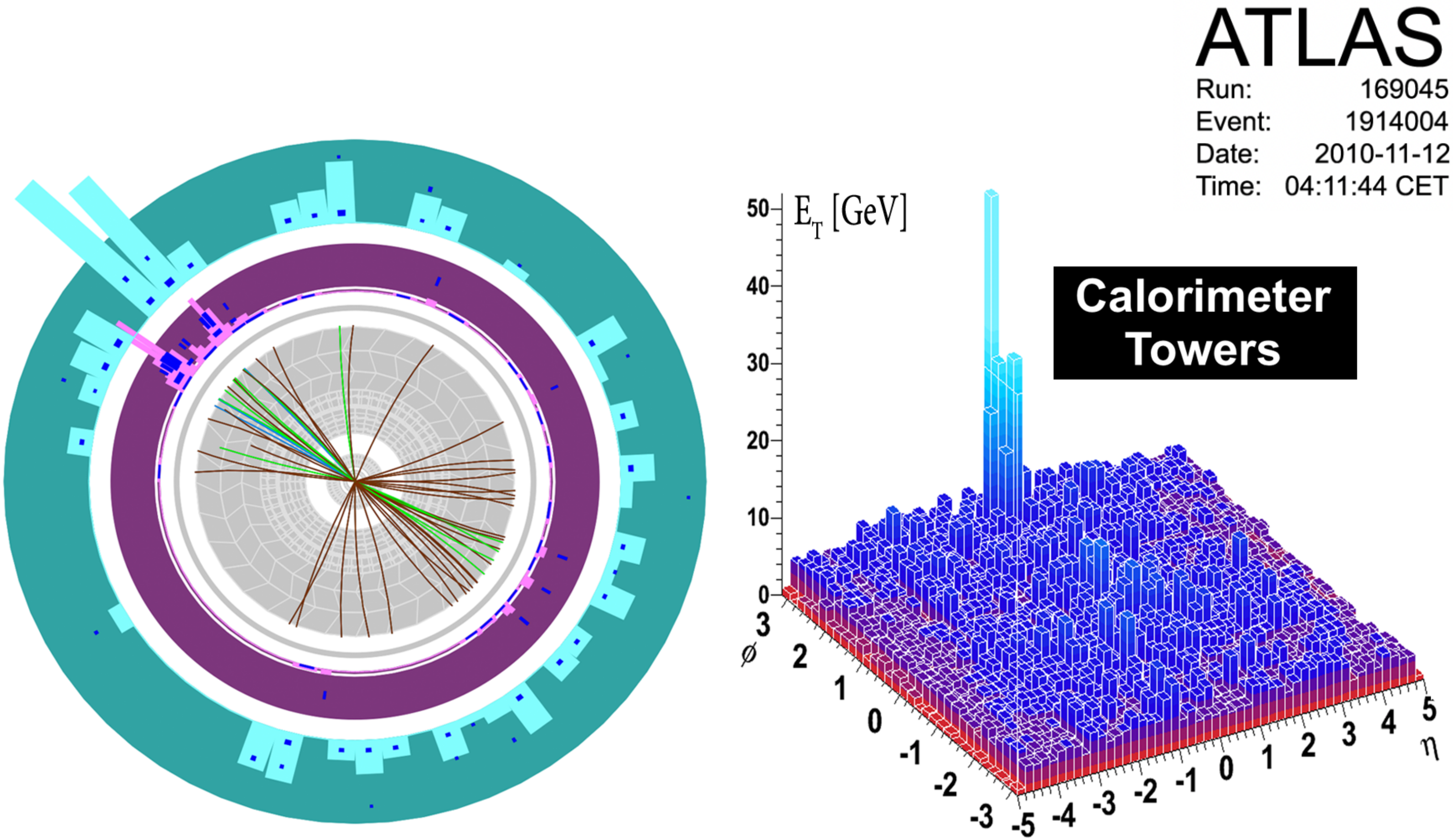
Centrality of heavy ion collision



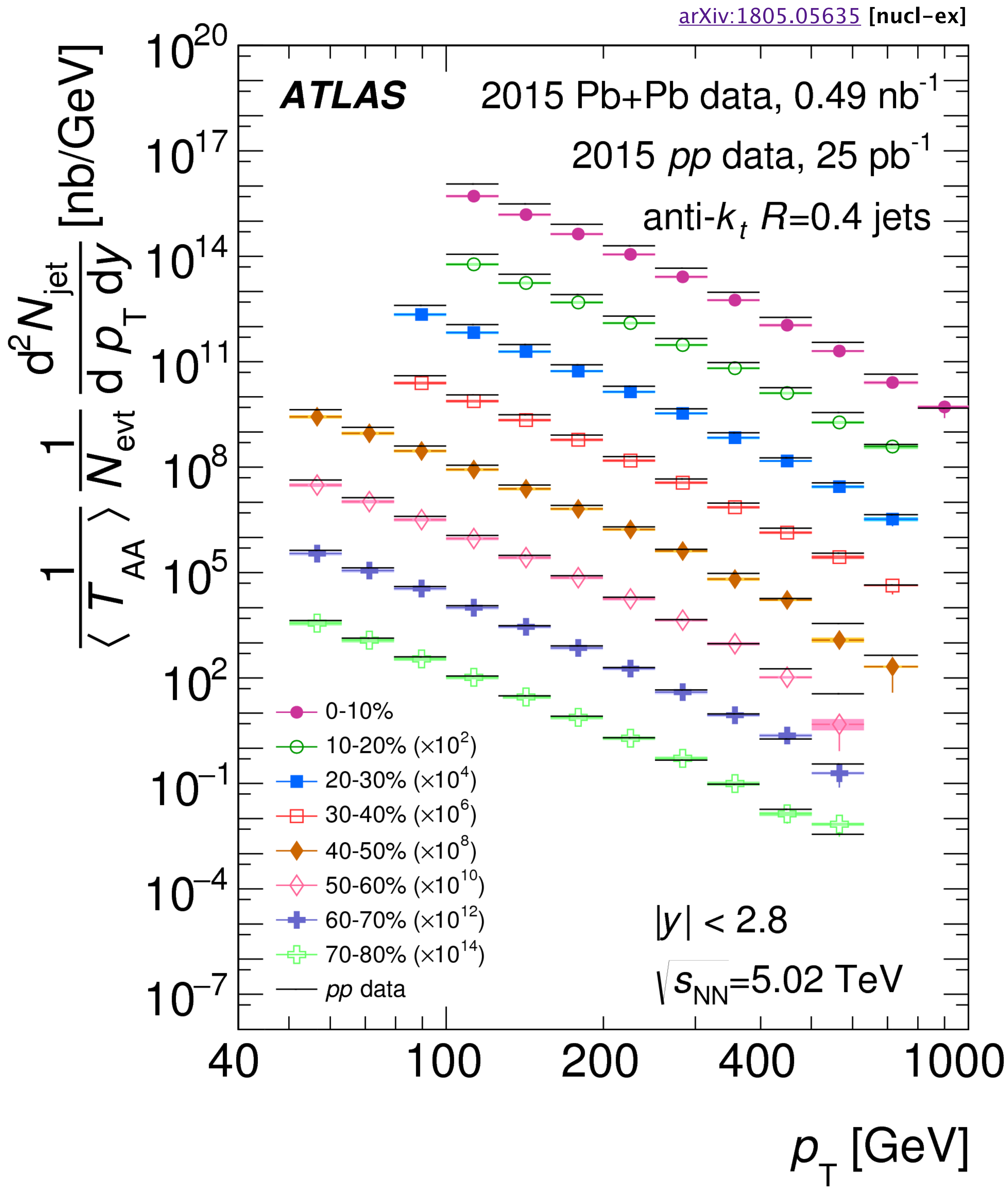
Peripheral collision

Central collision

Bare eye jet quenching from 2010



Inclusive jet spectra



Nuclear modification factor R_{AA}

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{\mathrm{d}^2 N_{\text{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\text{cent}}}{\langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma_{\text{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{pp}}$$

Scaled Pb+Pb

Reference p+p

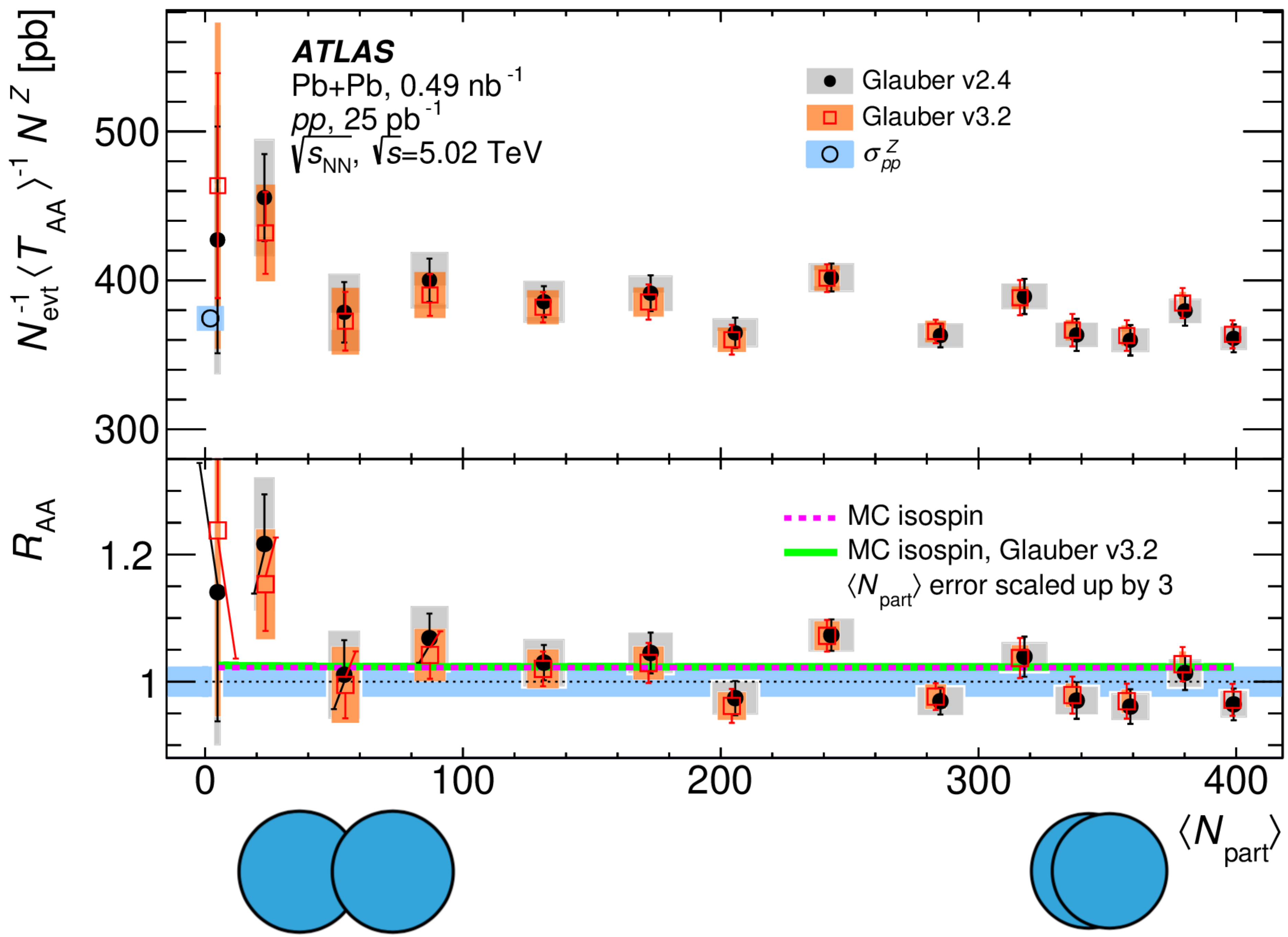
Where nuclear overlap function $\langle T_{AA} \rangle$

$$\langle T_{\mathrm{AB}} \rangle_{\mathrm{f}} = \langle N_{\text{coll}} \rangle_{\mathrm{f}} / \sigma_{\text{inel}}^{\text{NN}}$$

calculated in the Glauber MC approach (arXiv:nucl-ex/0701025)

Calibration of the T_{AA} scaling

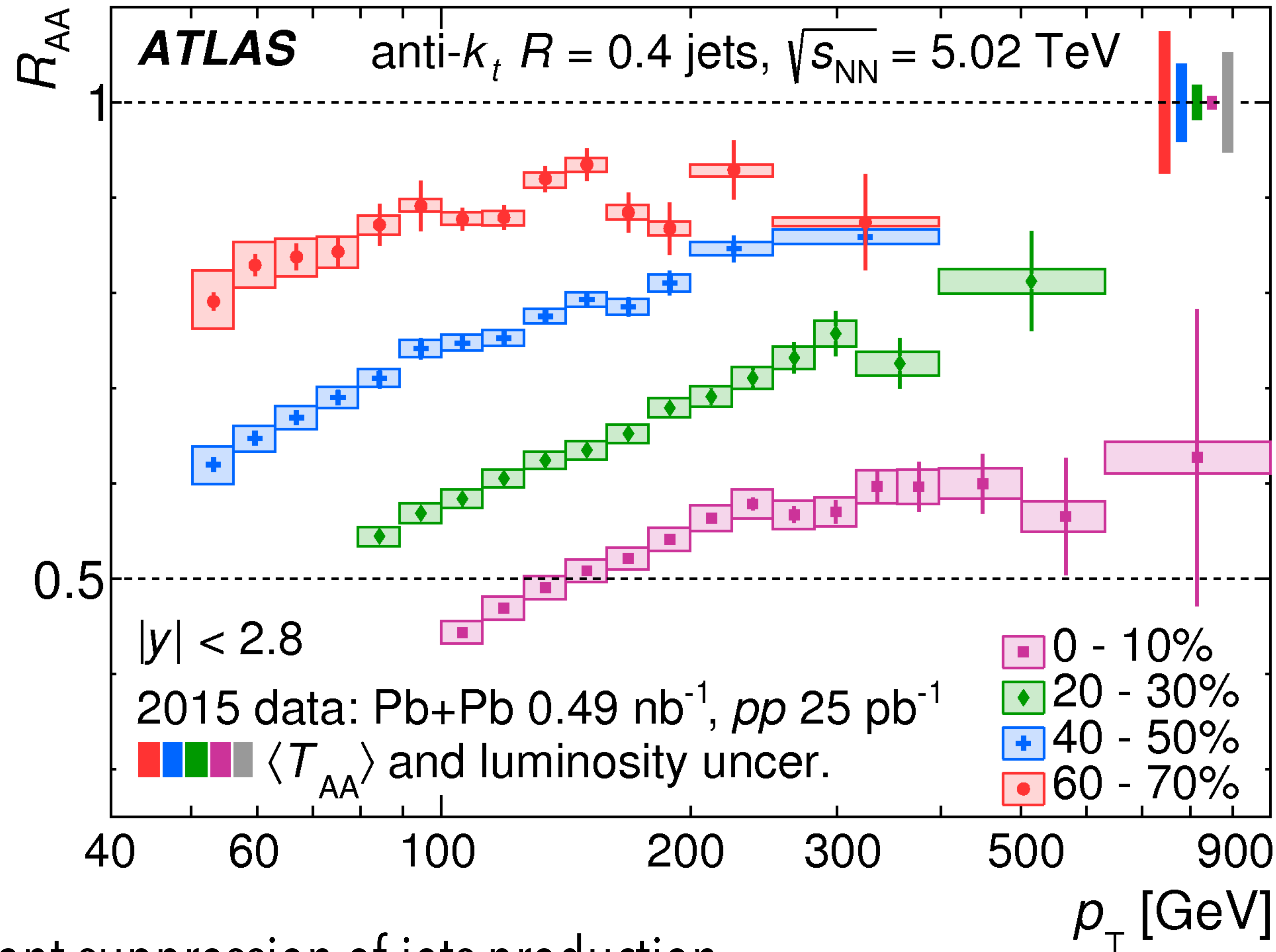
arXiv:1910.13396 [nucl-ex]



Probes that are not interacting with the QGP medium (W, Z, γ) follows the <T_{AA}> scaling.

Jets R_{AA}

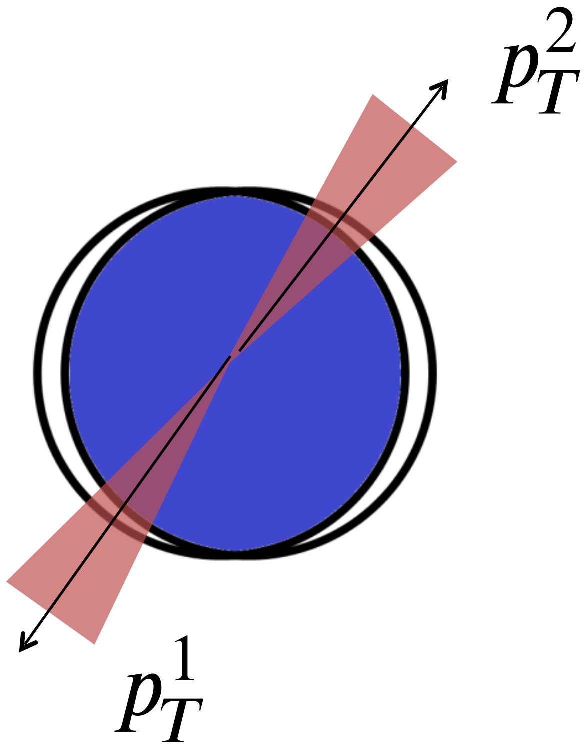
arXiv:1805.05635 [nucl-ex]



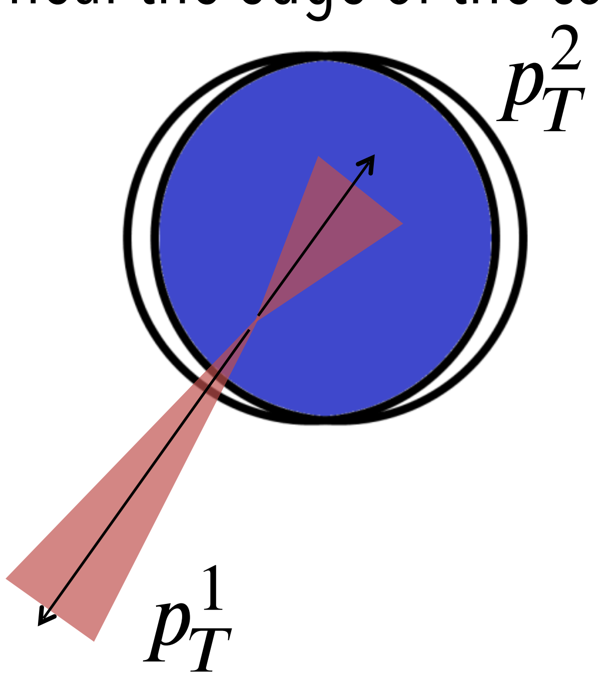
Significant suppression of jets production in the entire kinematic range

Dijet asymmetry

Balanced pair of jets produced near the centre of the collisions zone



Unbalanced pair of jets produced near the edge of the collisions zone



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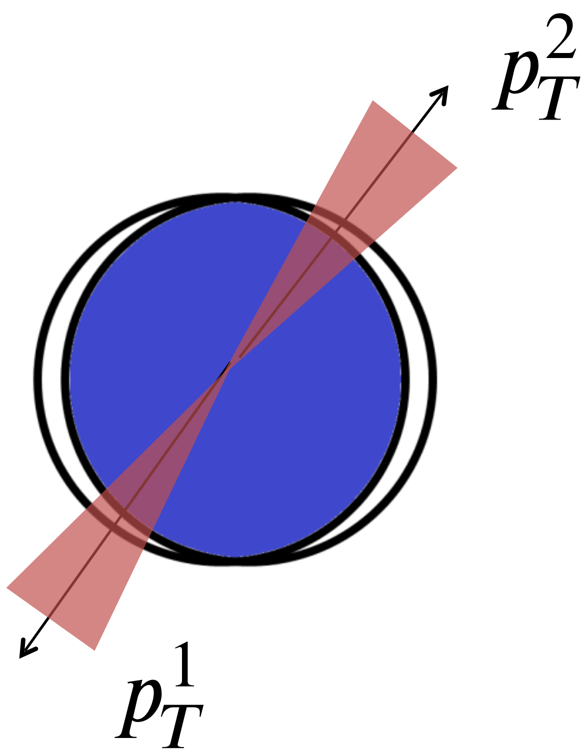

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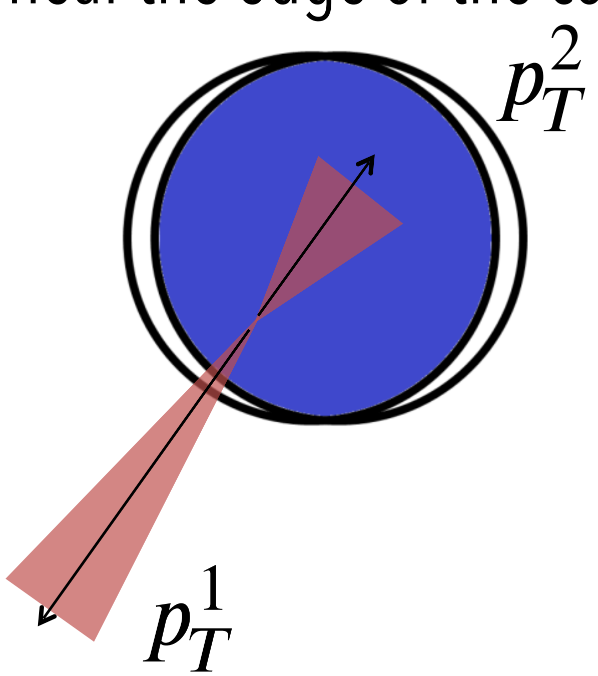
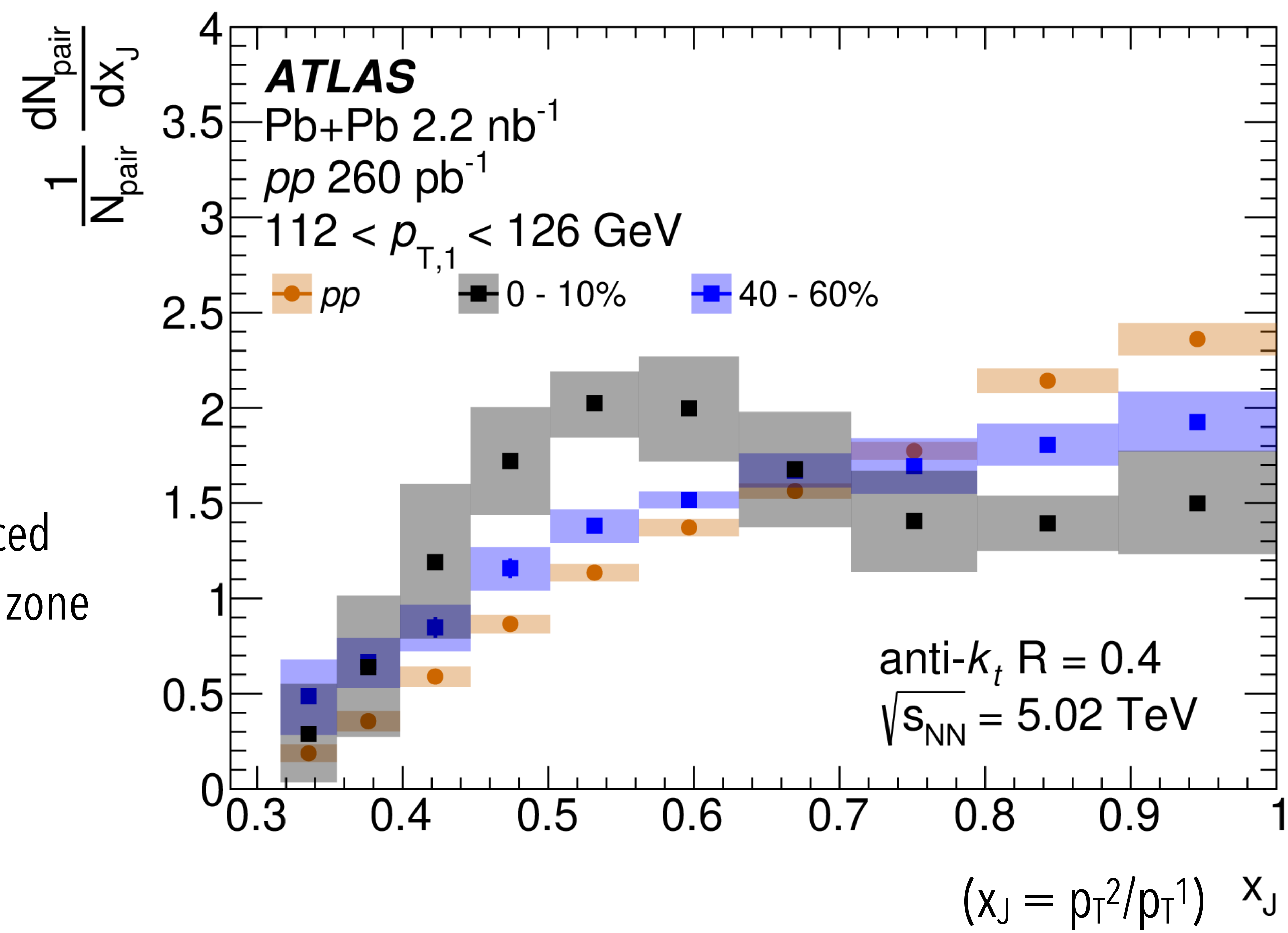


arXiv:2205.00682 [nucl-ex]



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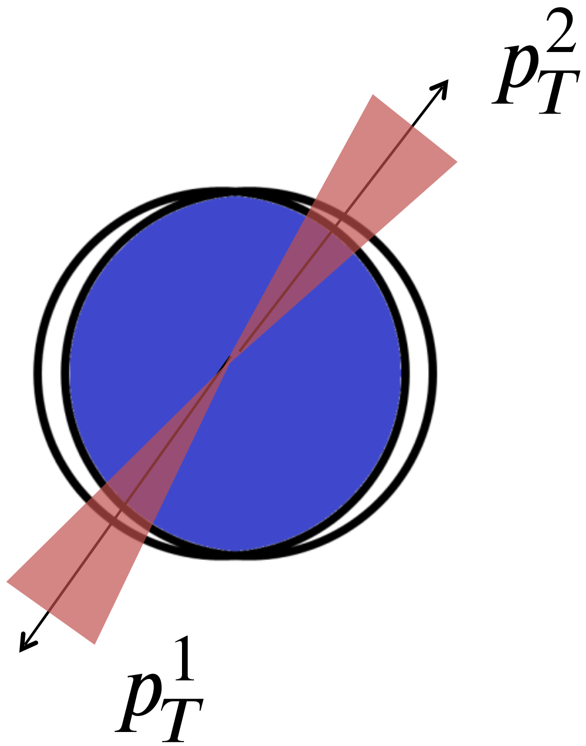

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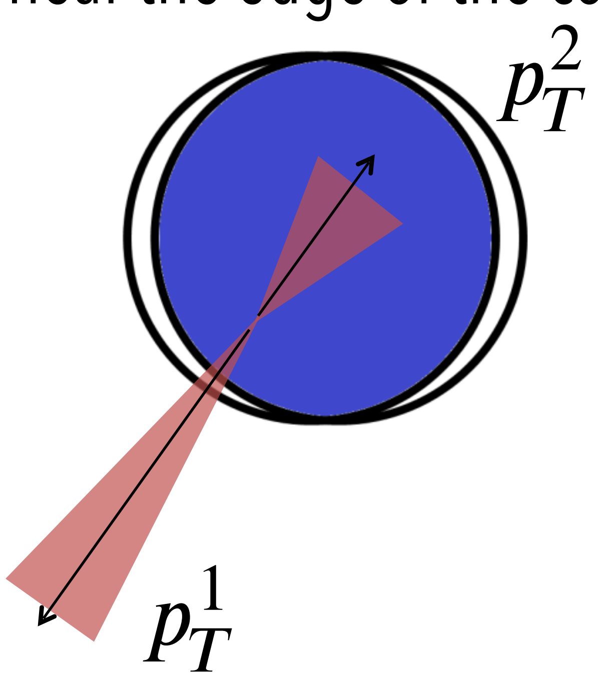

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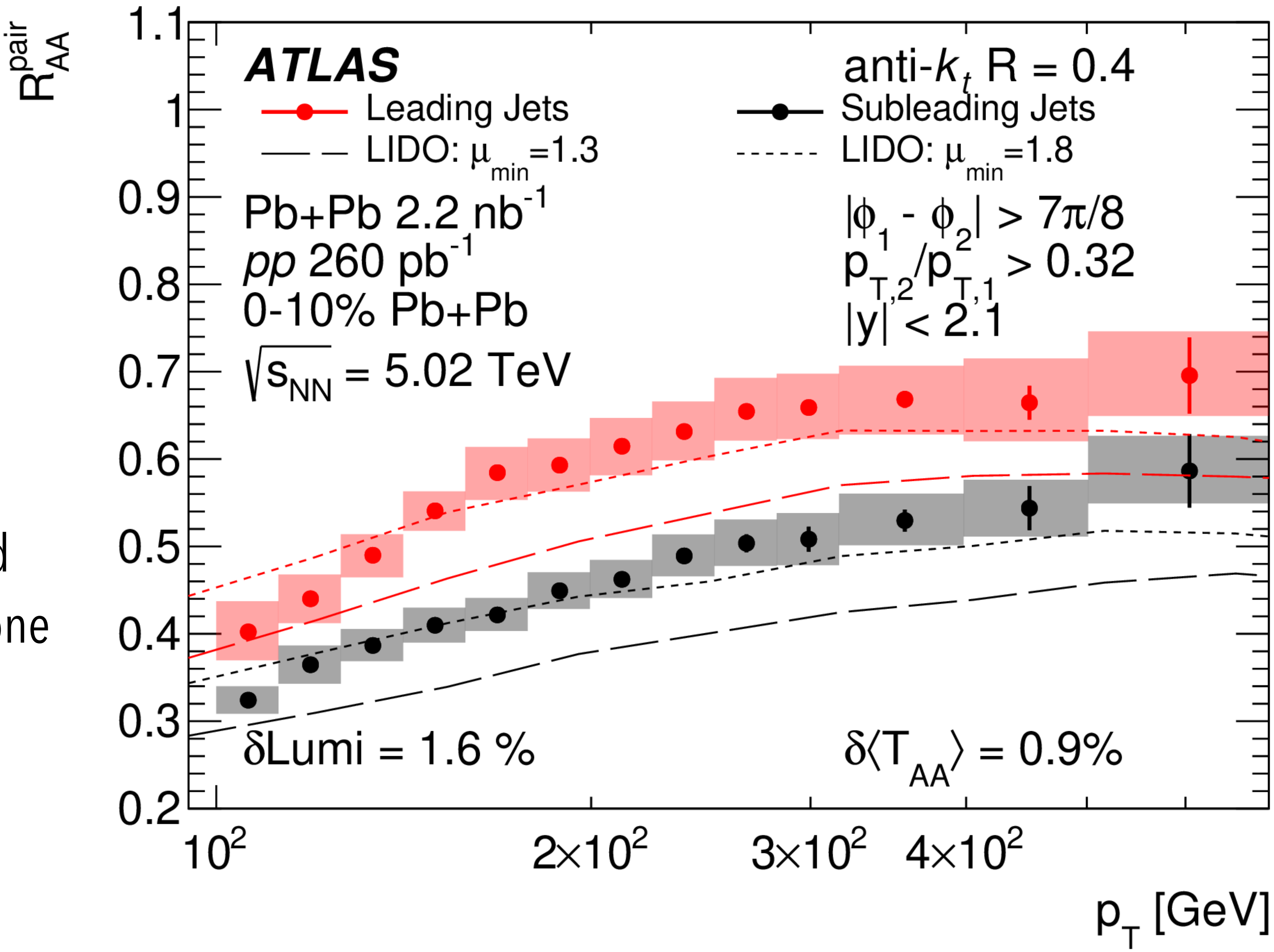
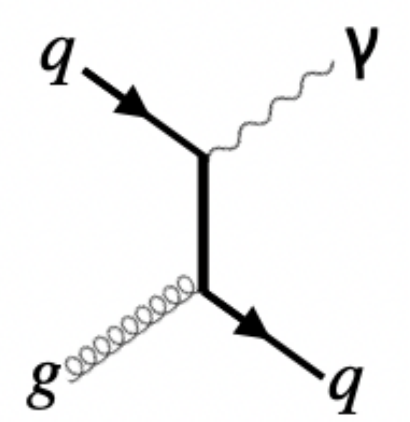
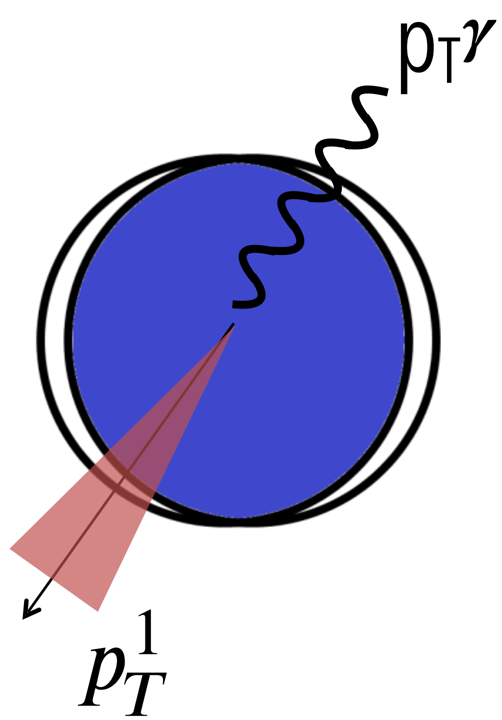


Photon tagged jet R_{AA}

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2022-14/





Photons and Z's can help to calibrate the parton energy, however:

- Rare process compared to the dijets production
- Flavour fraction differs compared to dijets

Photon tagged jet R_{AA}

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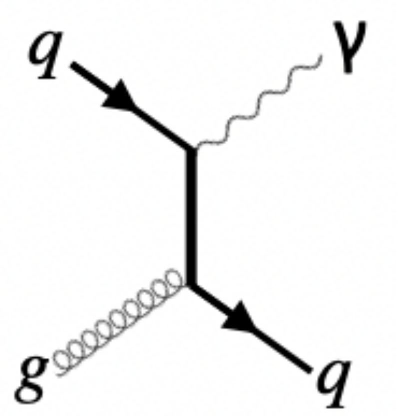
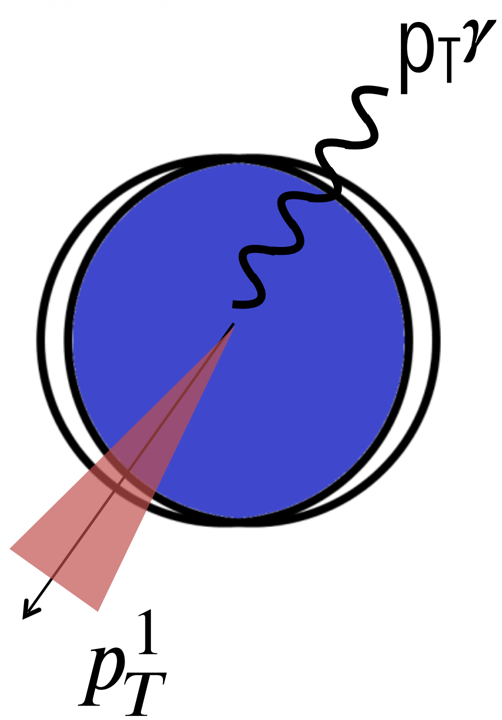
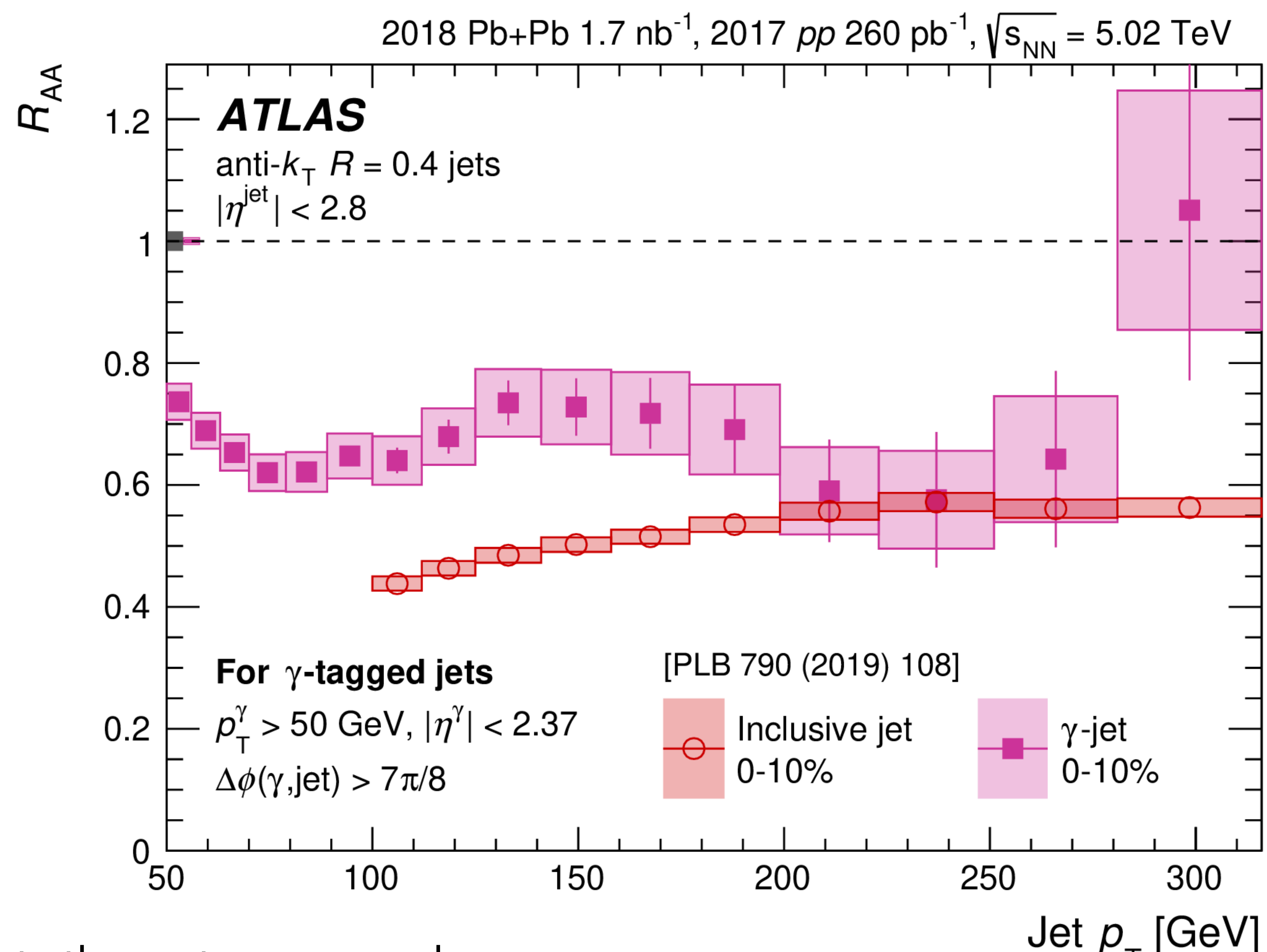
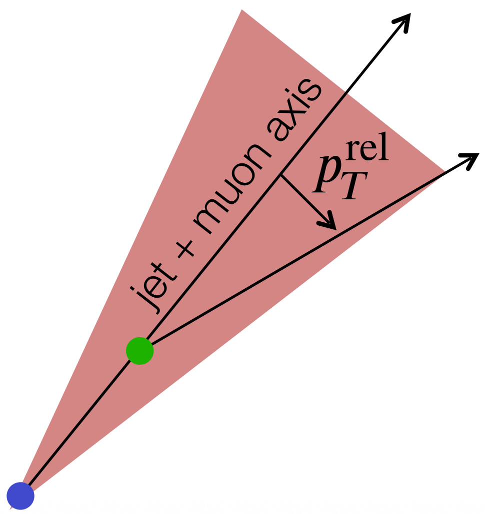






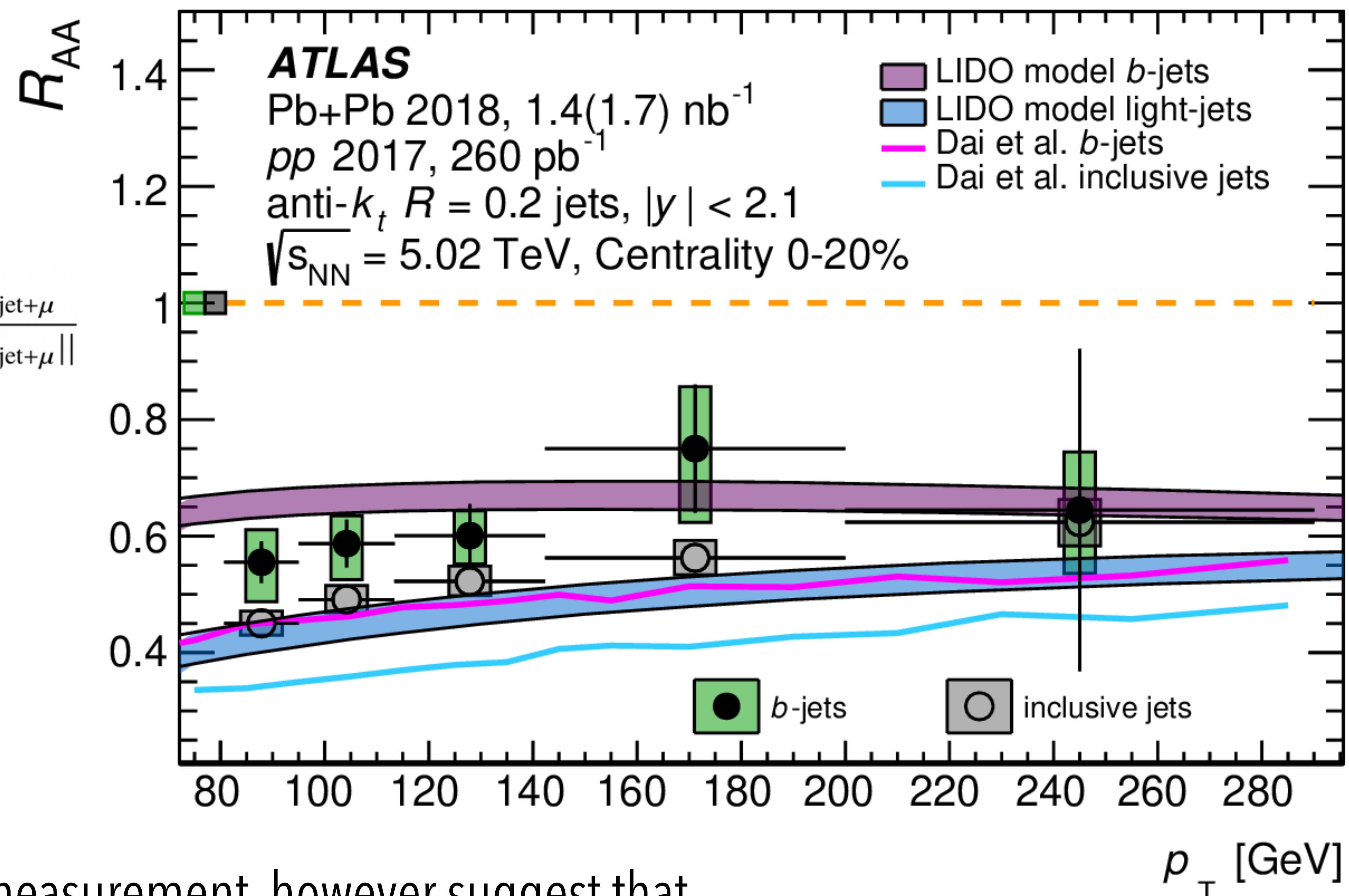
Photons and Z's can help to calibrate the parton energy, however:

- Rare process compared to the dijets production
- Flavour fraction differs compared to dijets - **sample dominated by quark initiated jets**



$$p_T^{rel} = ||\vec{p}_\mu \times \vec{u}||, \text{ where } \vec{u} = \frac{\vec{p}_{\text{jet}+\mu}}{||\vec{p}_{\text{jet}+\mu}||}$$

arXiv:2204.13530 [nucl-ex]

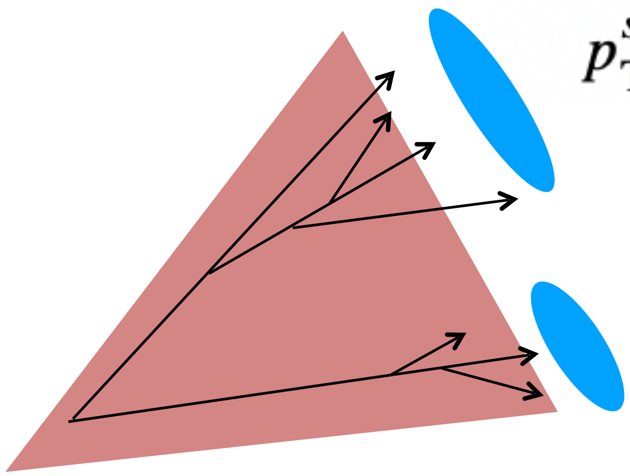


Particularly difficult measurement, however suggest that

***b*-jets are less** suppressed than **inclusive jets**

Energy loss dependence on the jet substructure

$$\frac{\min(p_{\mathrm{T}}^{sj_1}, p_{\mathrm{T}}^{sj_2})}{p_{\mathrm{T}}^{sj_1} + p_{\mathrm{T}}^{sj_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$



- The soft drop grooming procedure ($\beta = 0$ and $\mathbf{z_{cut}} = 0.2$) is applied to determined opening angle of the hardest splitting ($\mathbf{r_g}$)
- Jets re-clustered using Track-CaloClusters as constituents to improve angular resolution

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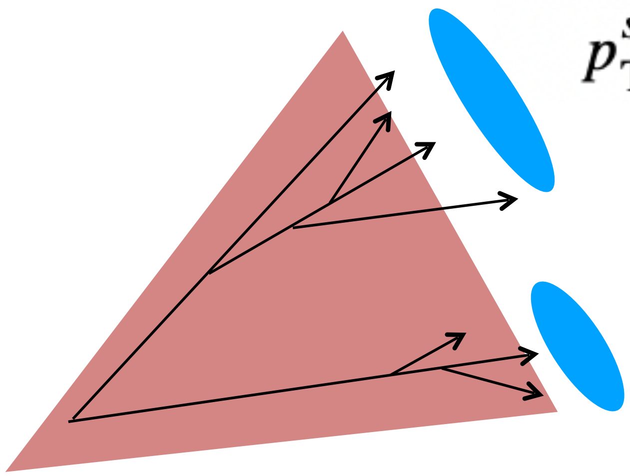

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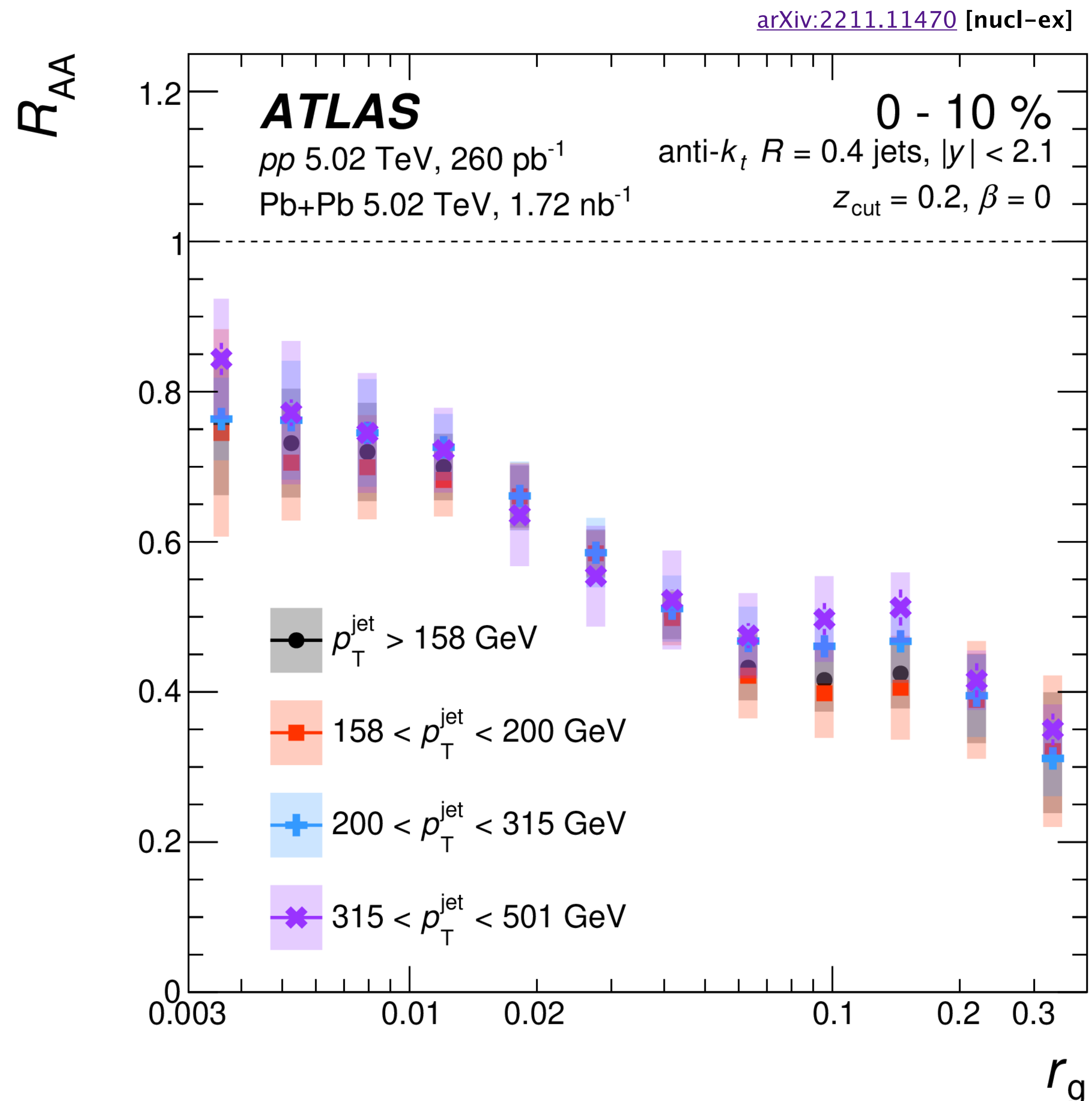

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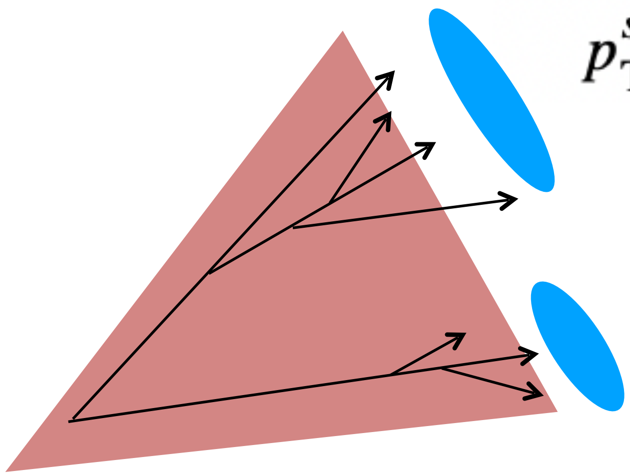

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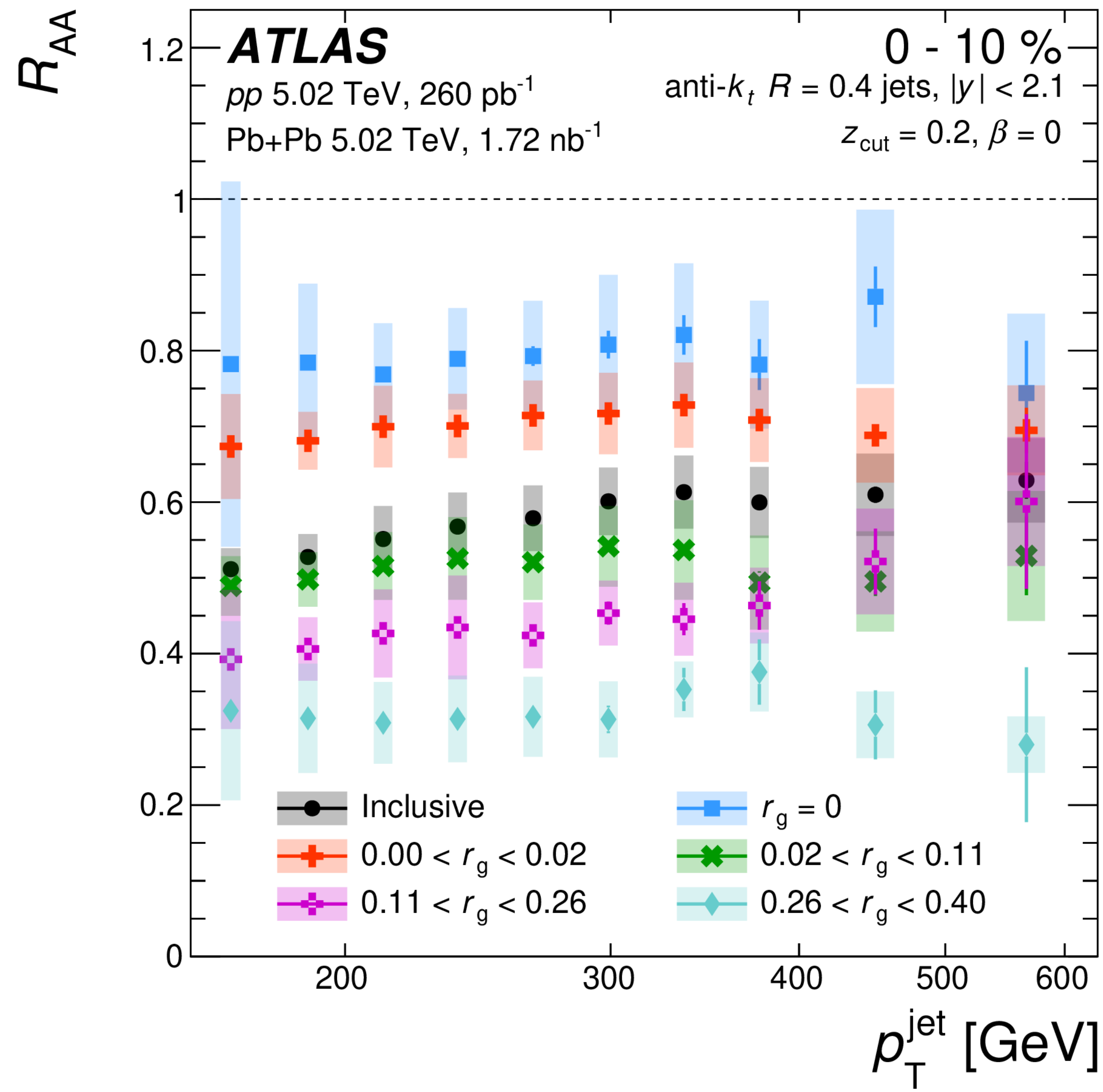
arXiv:2211.11470 [nucl-ex]



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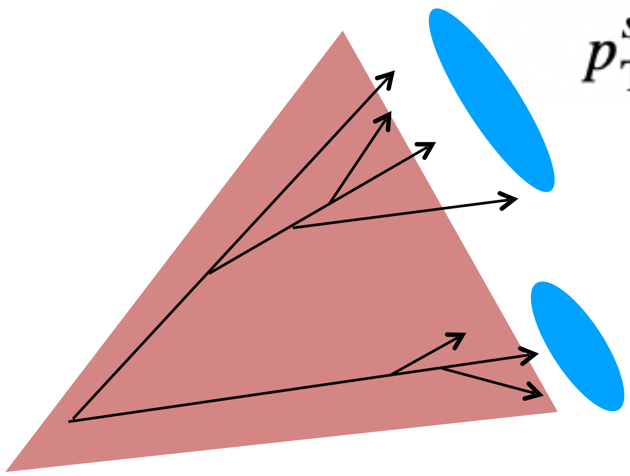

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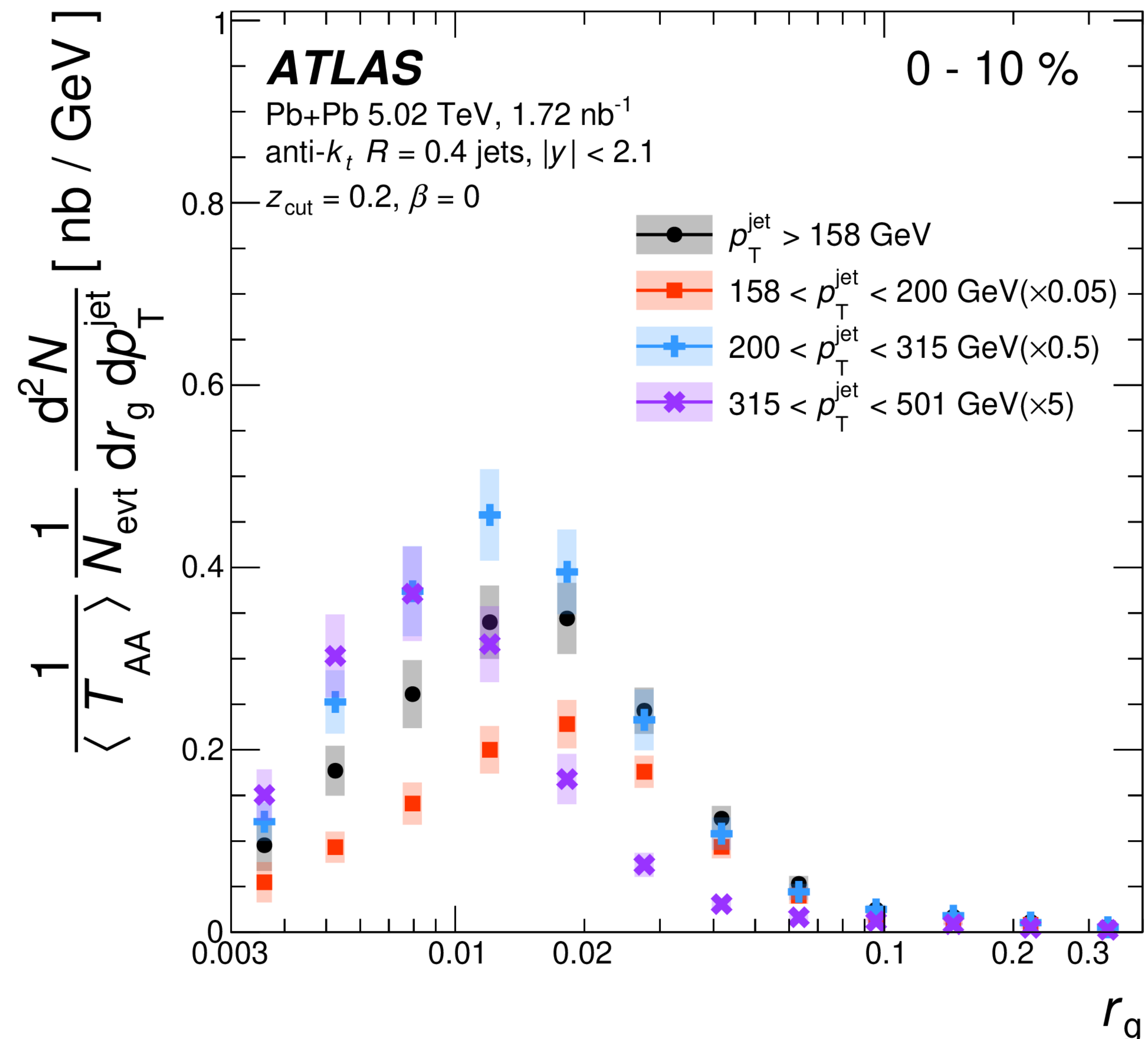
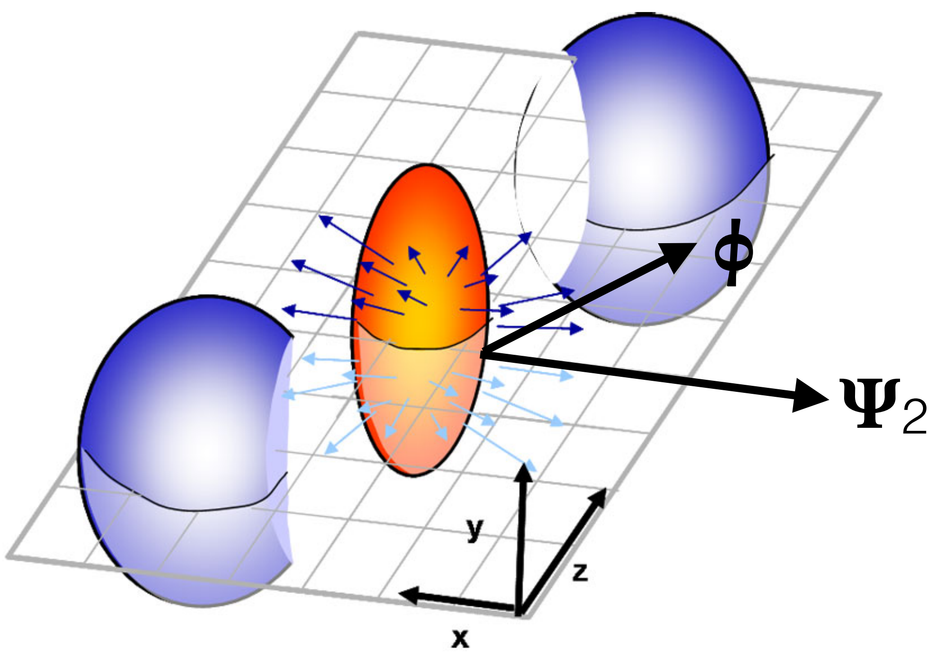
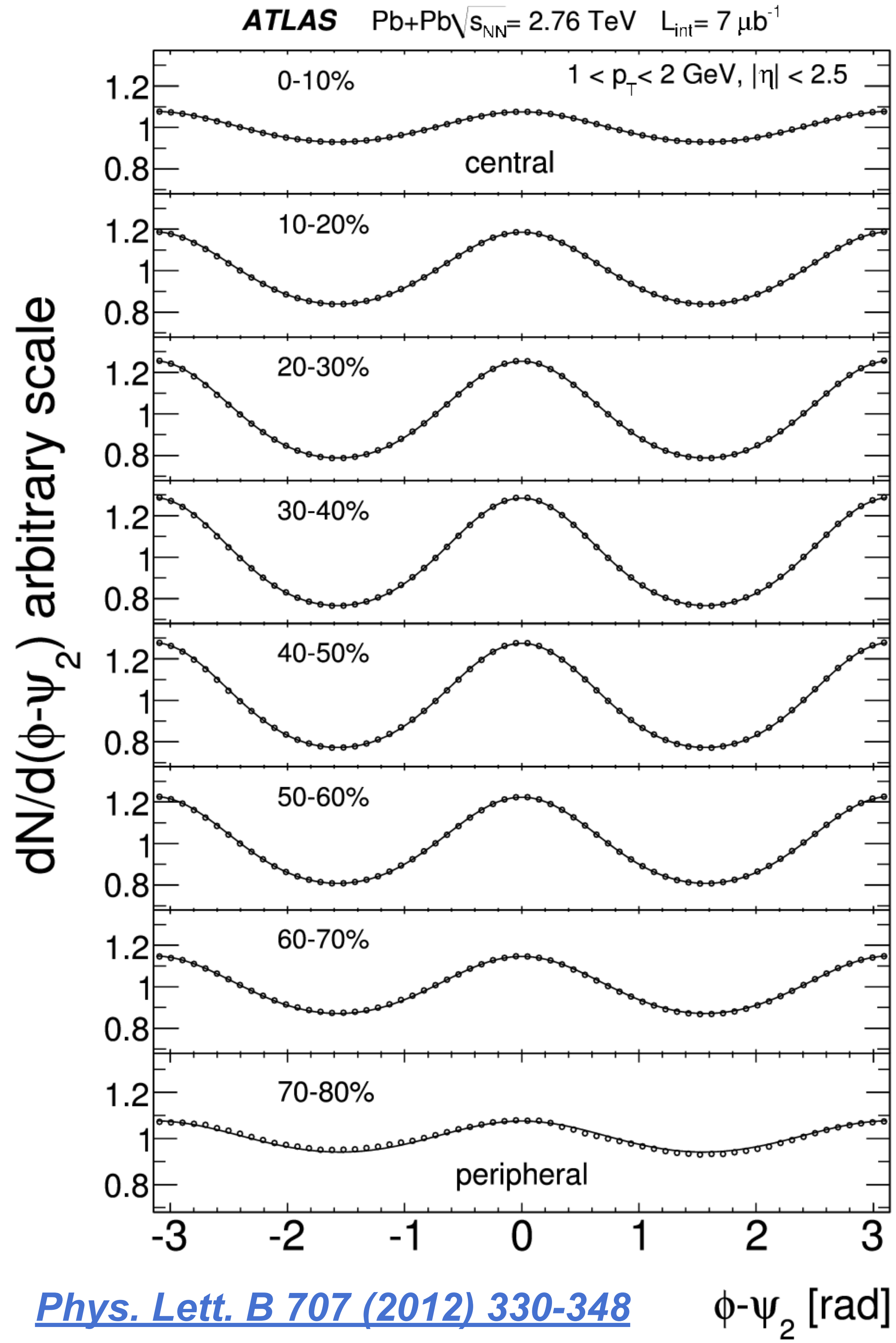


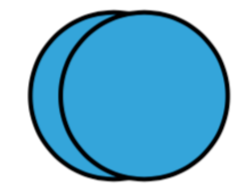
Collectivity in heavy-ion collisions

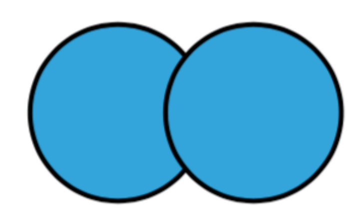
$$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$

Geometry driven v_2









[Phys. Lett. B 707 (2012) 330-348](#)

Collectivity in heavy-ion collisions

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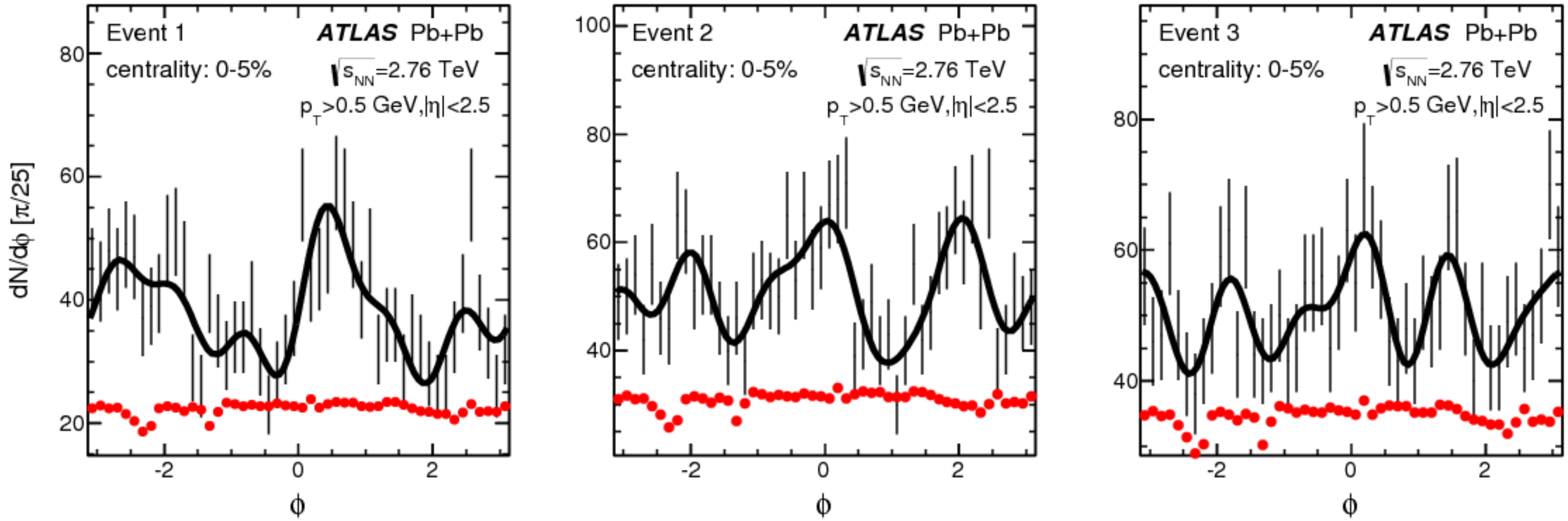
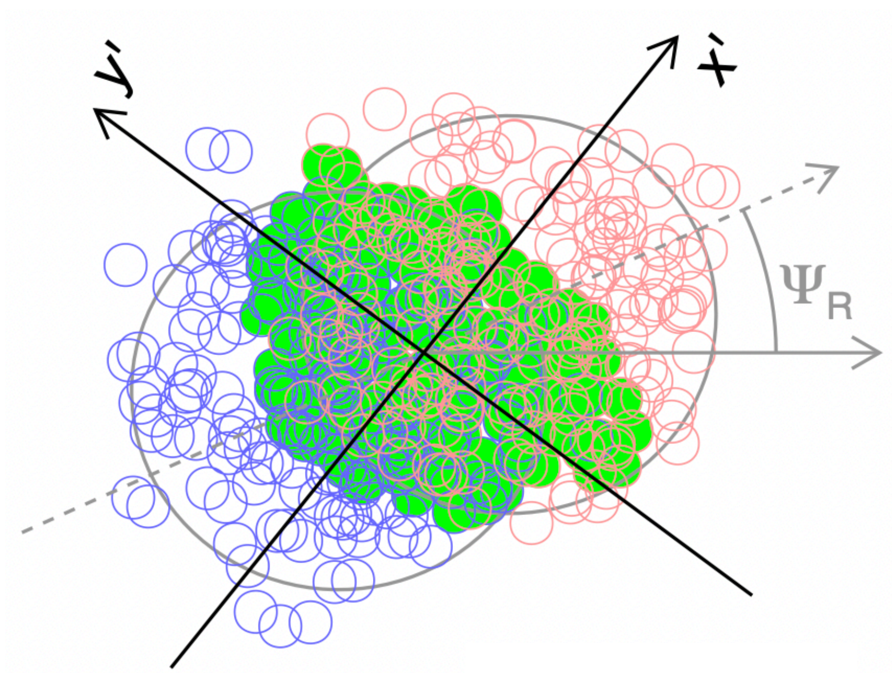
JHEP 11 (2013) 183

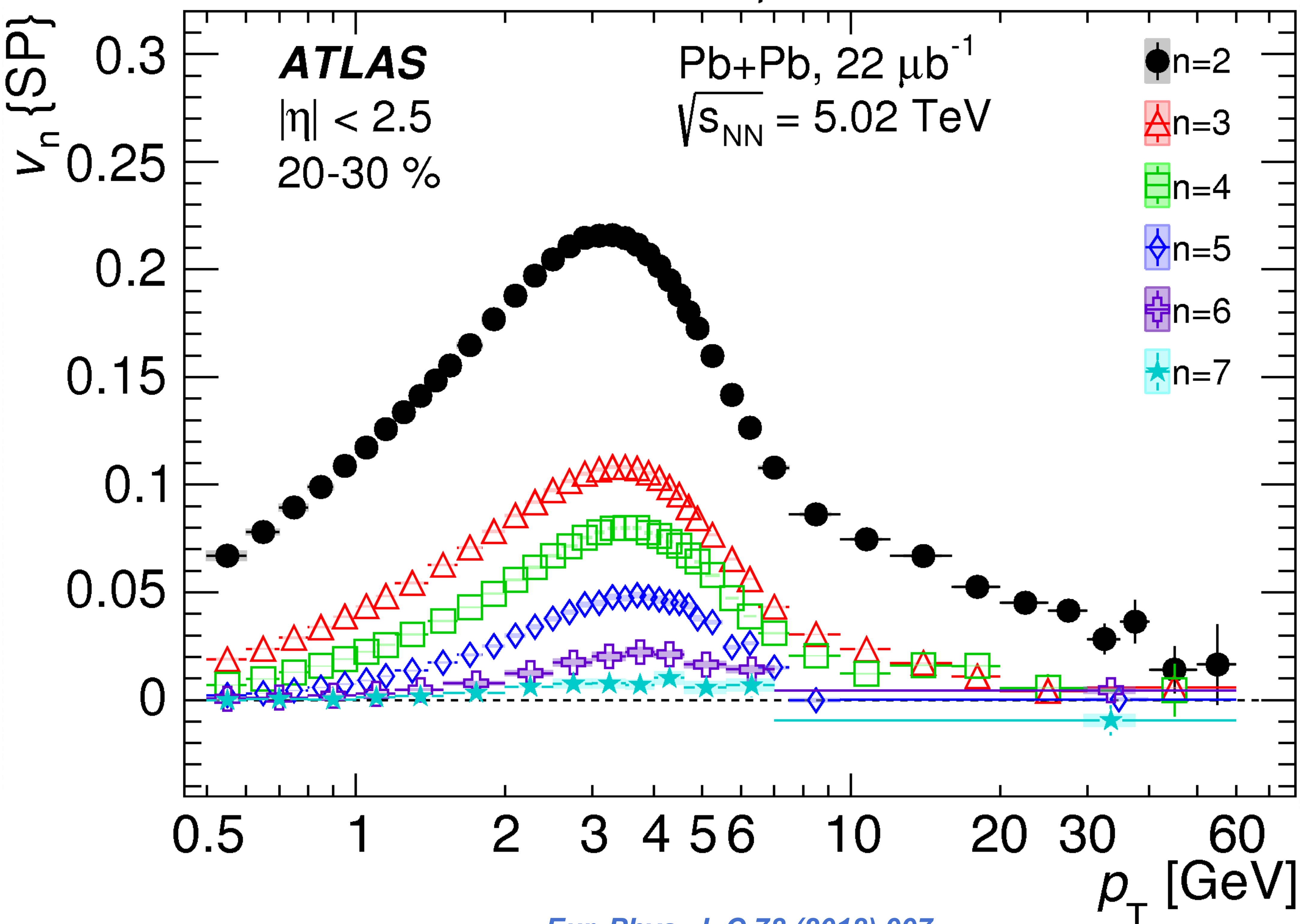




Fluctuation driven higher order harmonics v_n (n>2)

Collectivity in heavy-ion collisions

$$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$

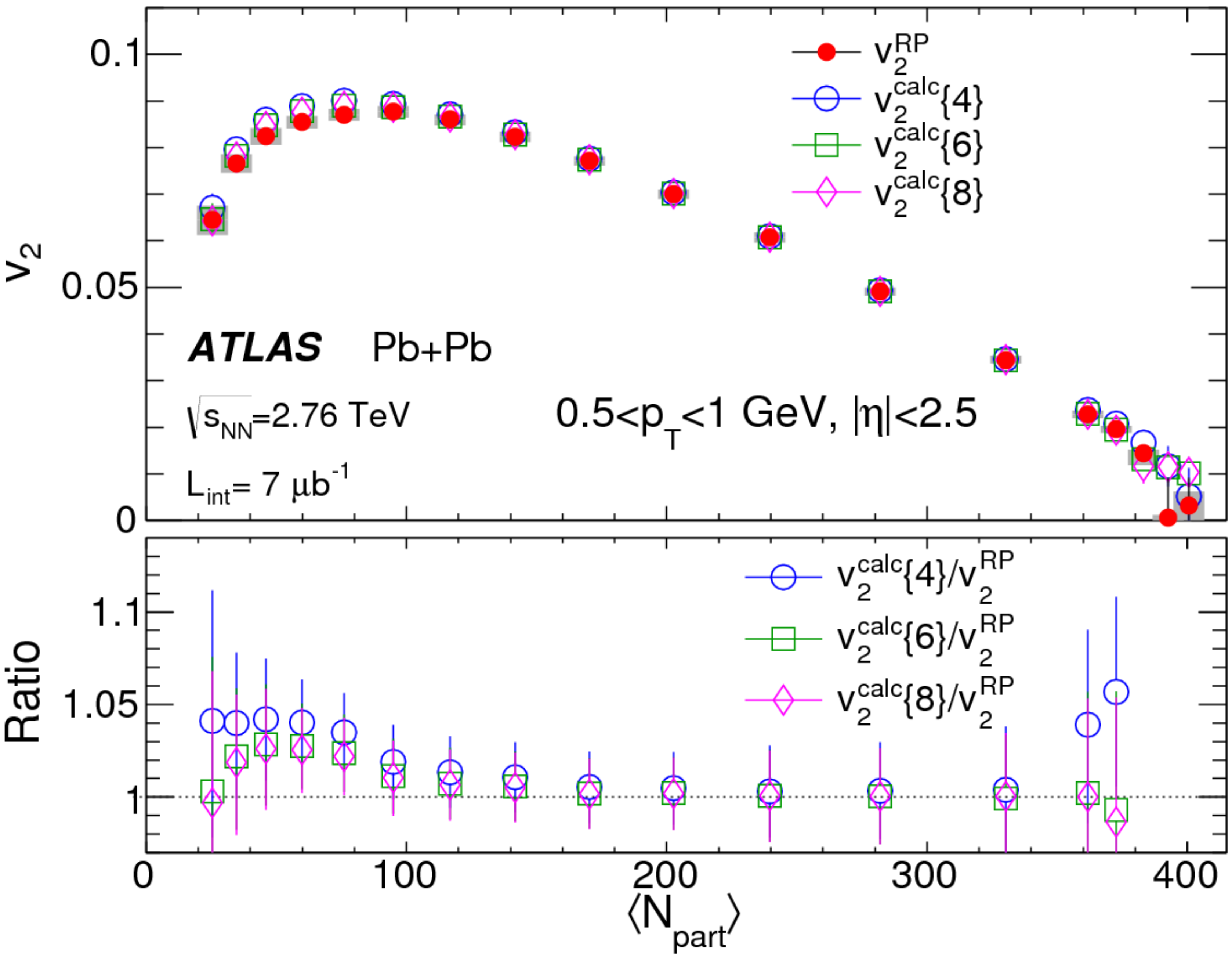


Single v_n harmonics measurement with 2 particle correlations methods

[Eur. Phys. J. C 78 (2018) 997]

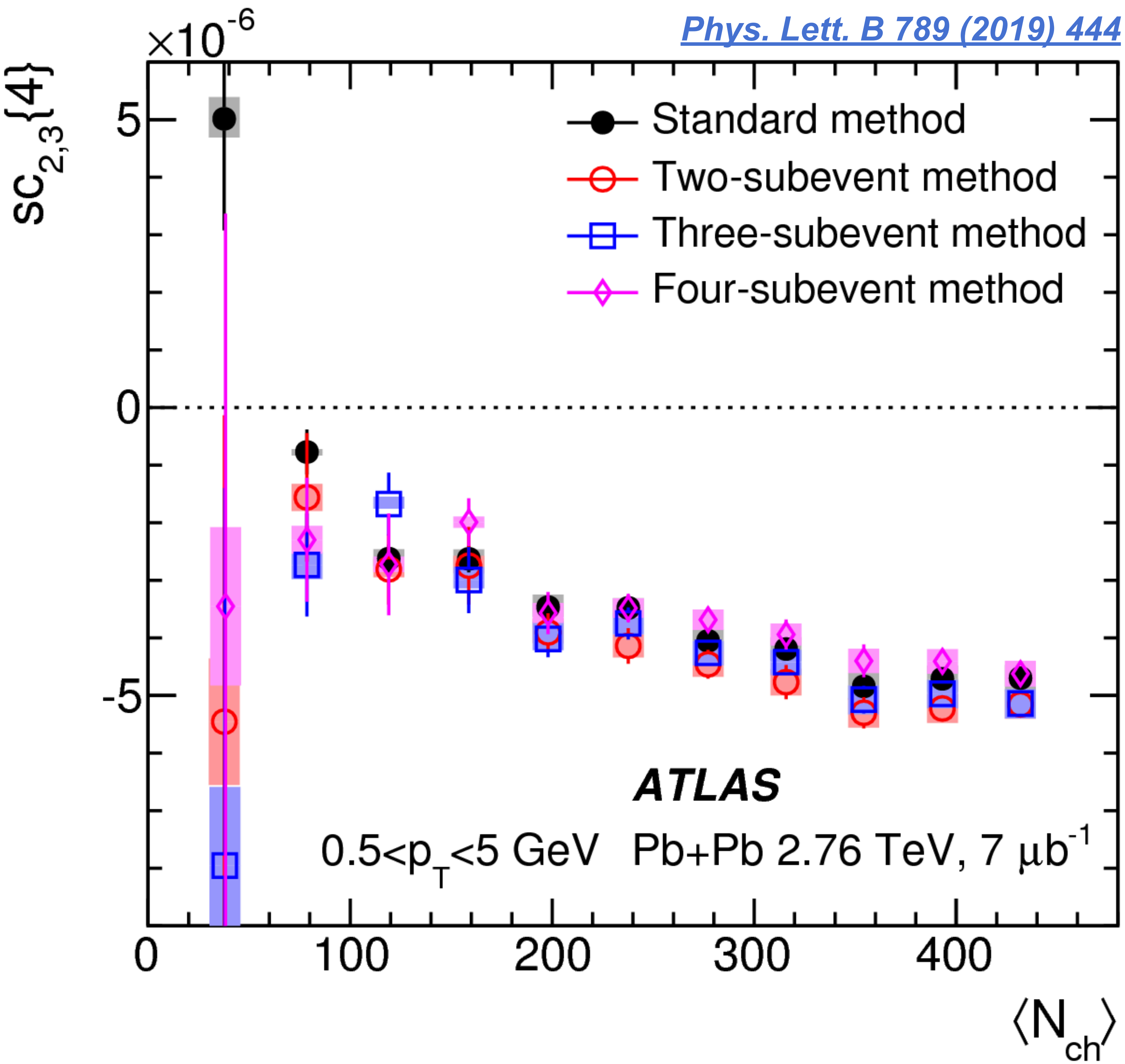
Evolution of collectivity measurements

JHEP 11 (2013) 183



Multi particle cumulants

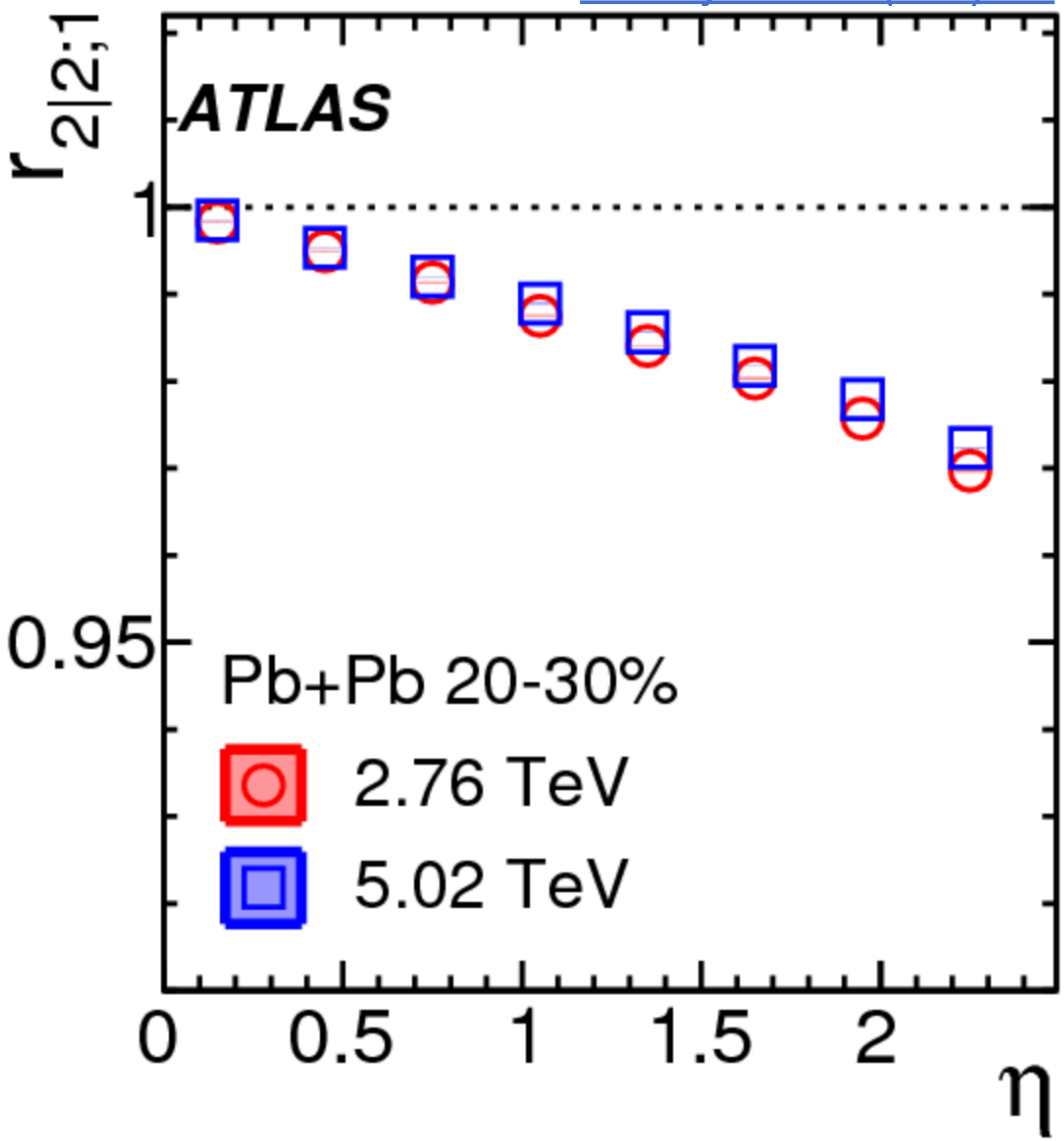
Evolution of collectivity measurements



Correlation between harmonics of different order with symmetric cumulants(here anti-correlation between v_2 and v_3)

Evolution of collectivity measurements

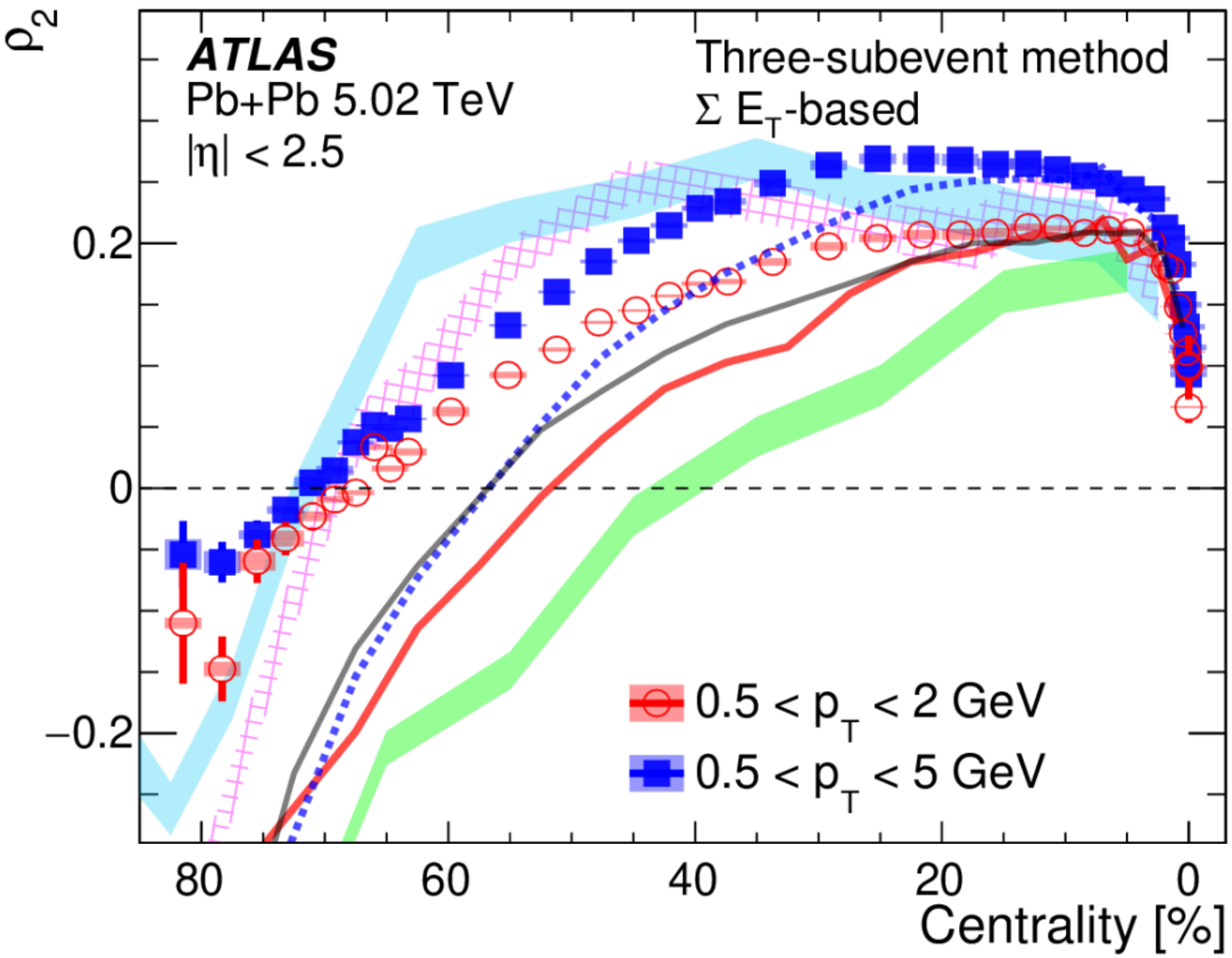
Eur. Phys. J. C 76 (2018) 142



Longitudinal flow de-correlation (here de-correlation of v_2 at increasing η distance)

Evolution of collectivity measurements

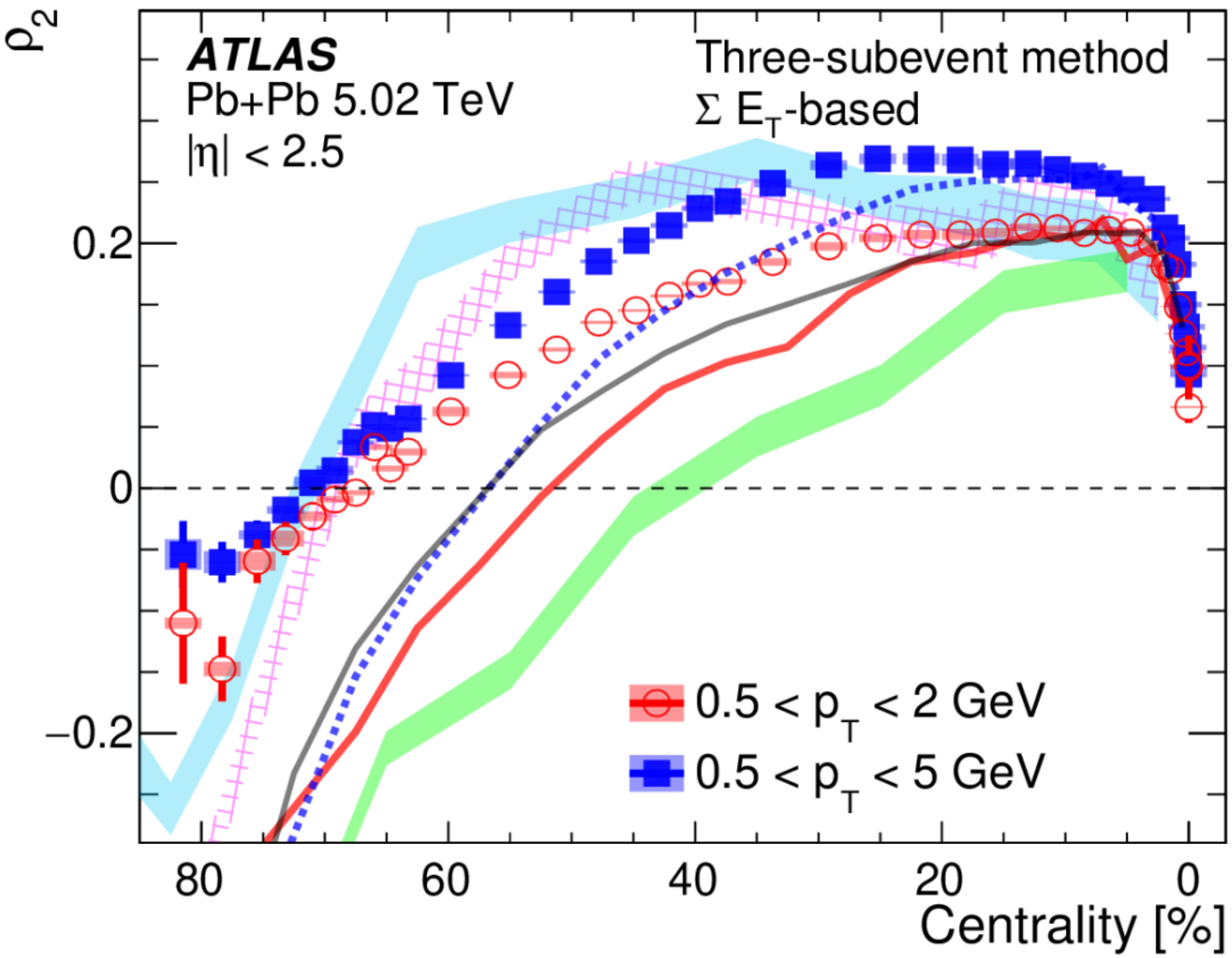
arXiv:2205.00039 **[nucl-ex]**



Correlation between v_n harmonics and mean p_T in the event (here for v_2)

Evolution of collectivity measurements

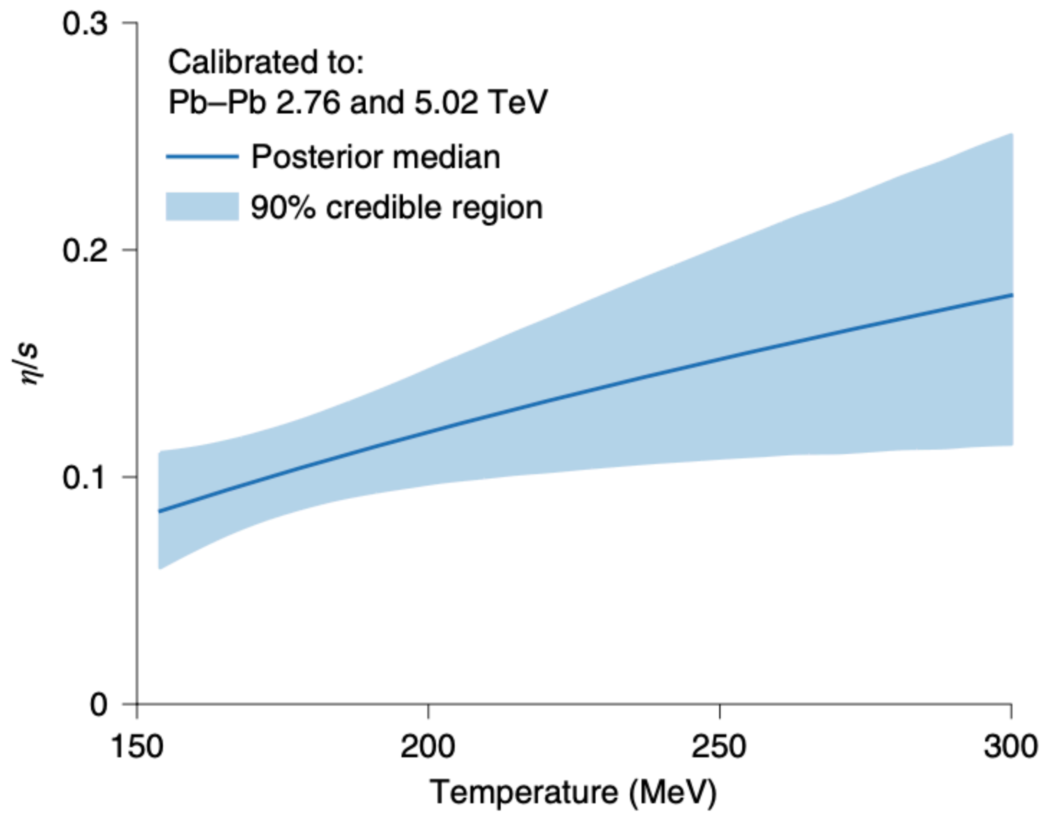
arXiv:2205.00039 [nucl-ex]

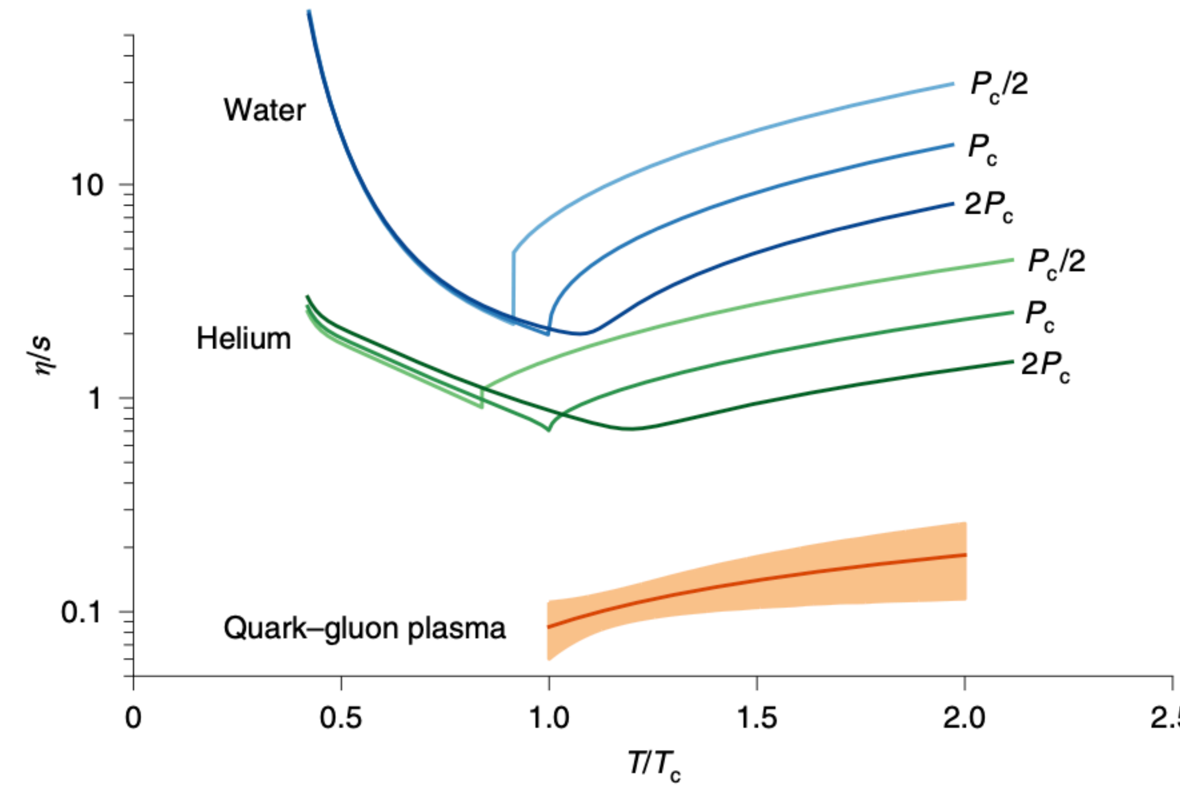


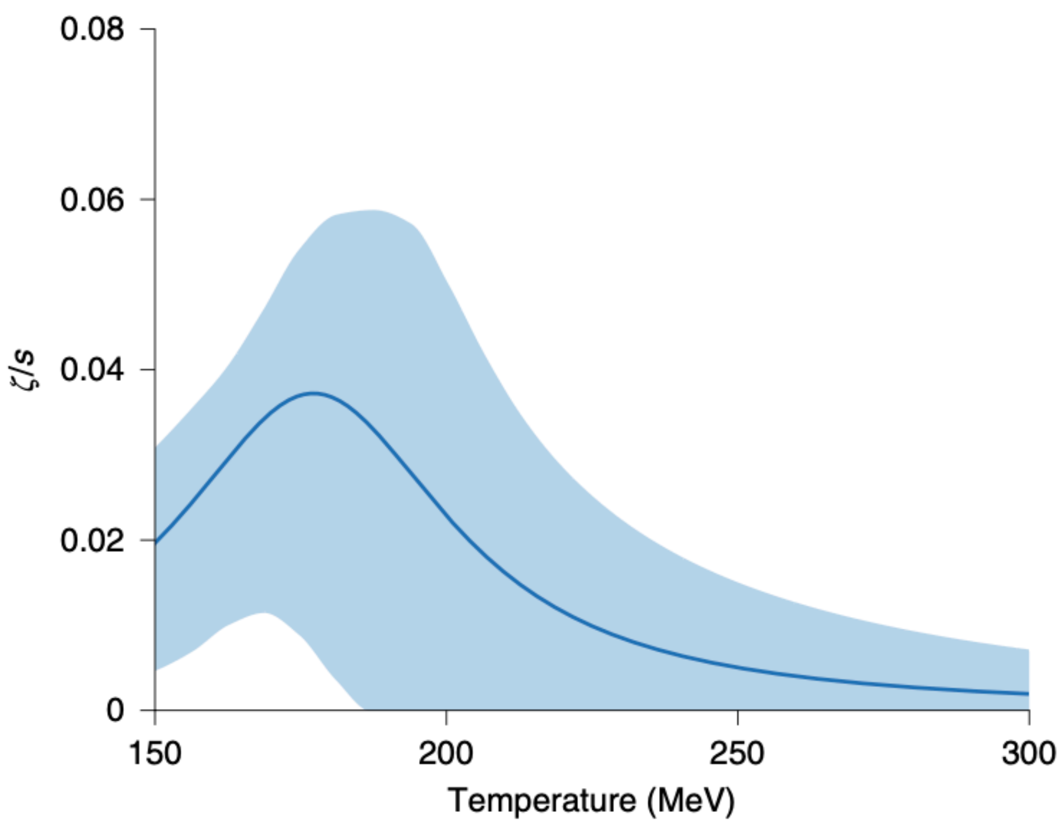
Correlation between v_n harmonics and mean p_T in the event (here for v_2)

Disclaimer - by no means this is not complete list, it is only meant to show increasing complexity

Constraining QGP parameters







LHC data are used to constrain shear (η) and bulk (ζ) viscosity of the QPG ….

…. a lot of assumptions on the form of initial state, exact hydrodynamic model, transition to hadrons …

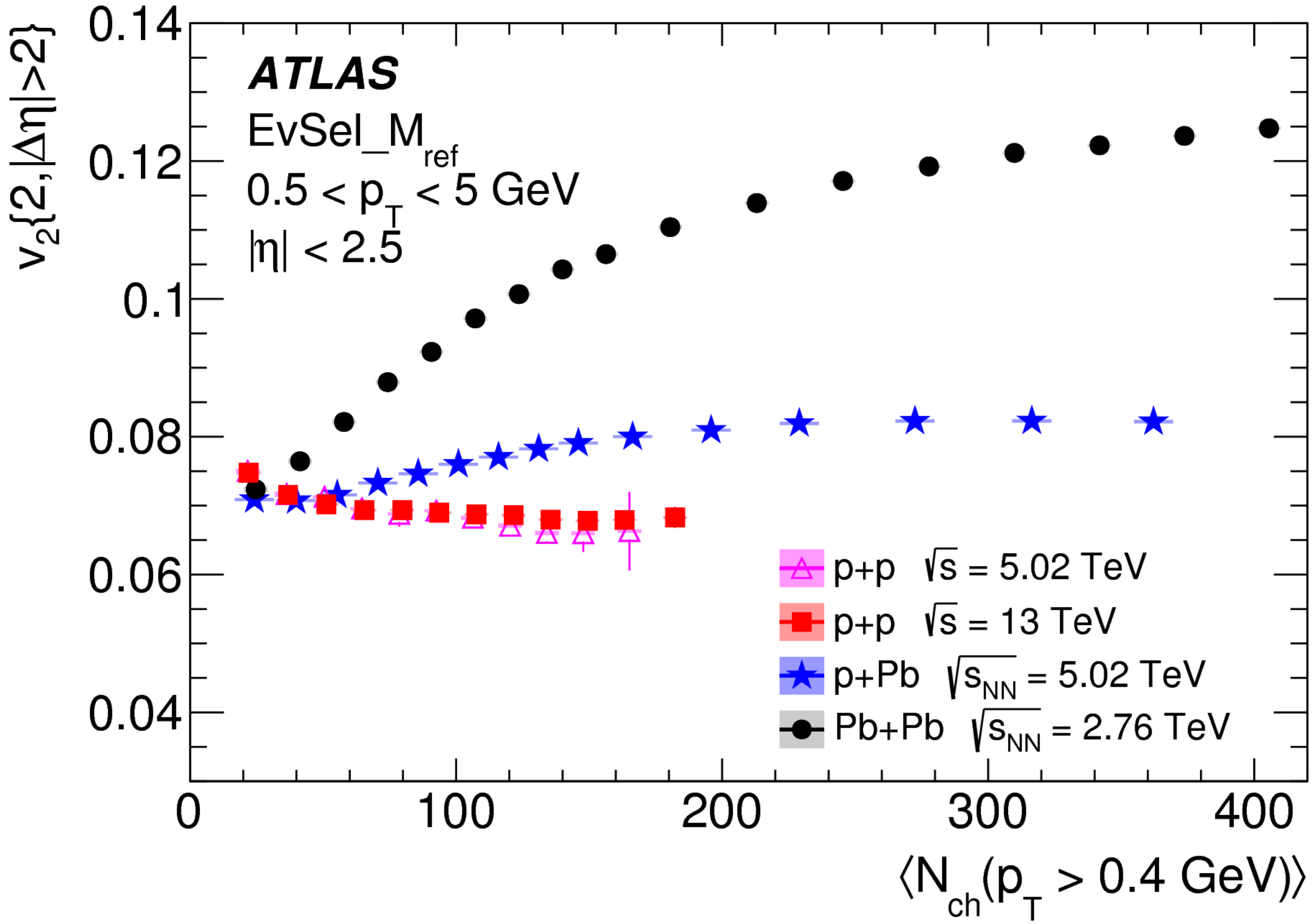
More data, different collisions systems helps

Bernhard, J.E., Moreland, J.S. & Bass, S.A. Nat. Phys. 15, 1113–1117 (2019).

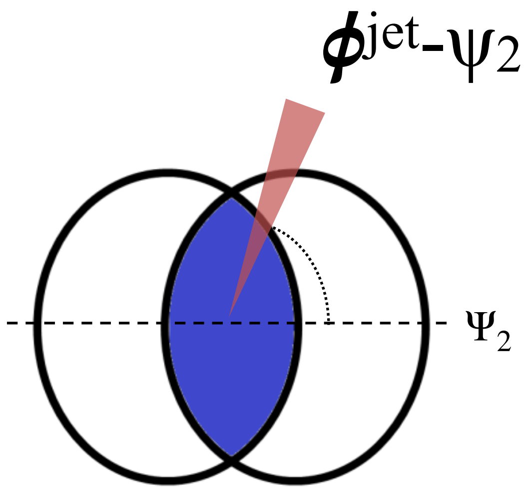
Collectivity in small systems

One of the most striking observations from LHC data is a presence of collective effects in p+Pb, pp and even smaller collision systems.

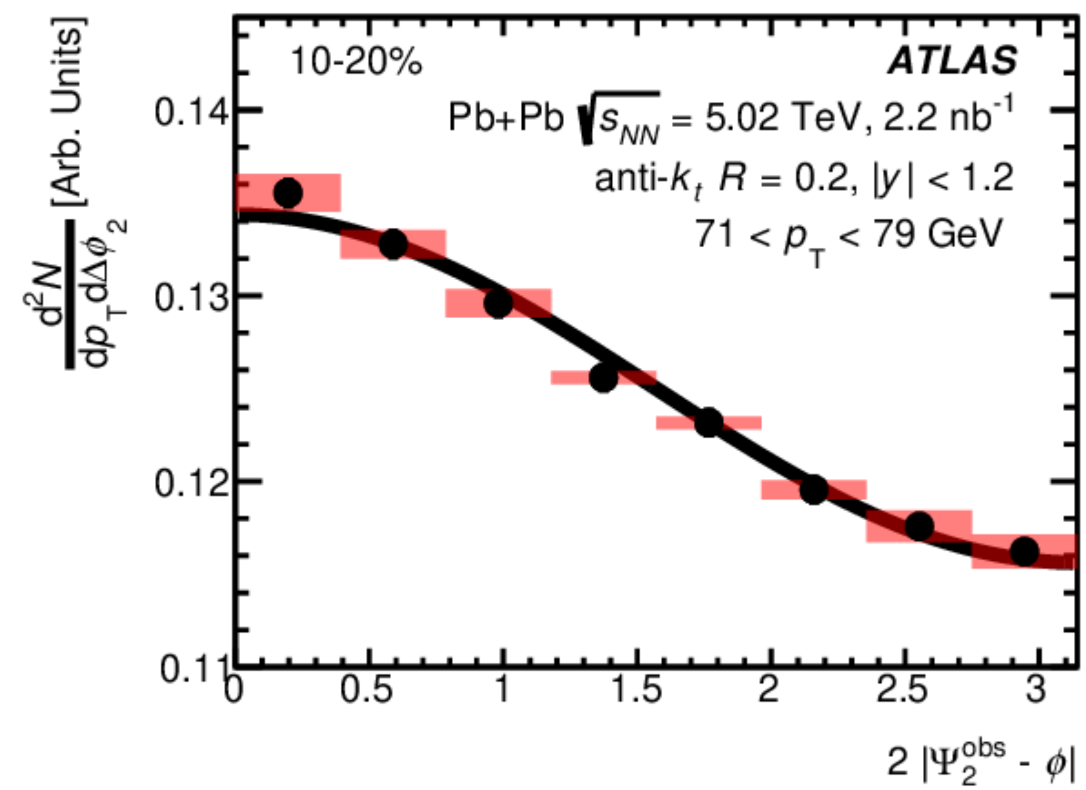
arXiv:1705.04176



- It is still unclear what is the smallest droplet of QGP that behaves hydrodynamically
- Are there any other QGP like effects present in small systems ?



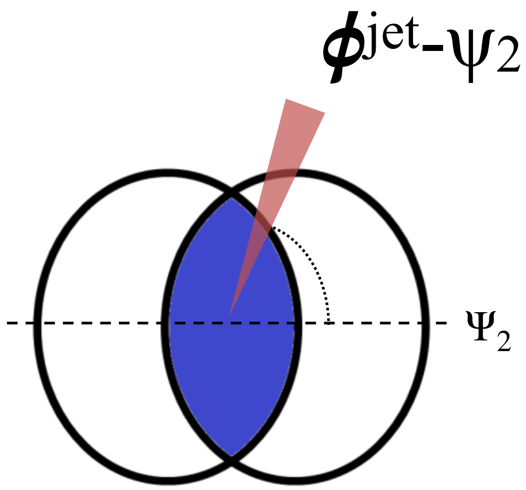
Phys. Rev. C 105 (2022) 064903



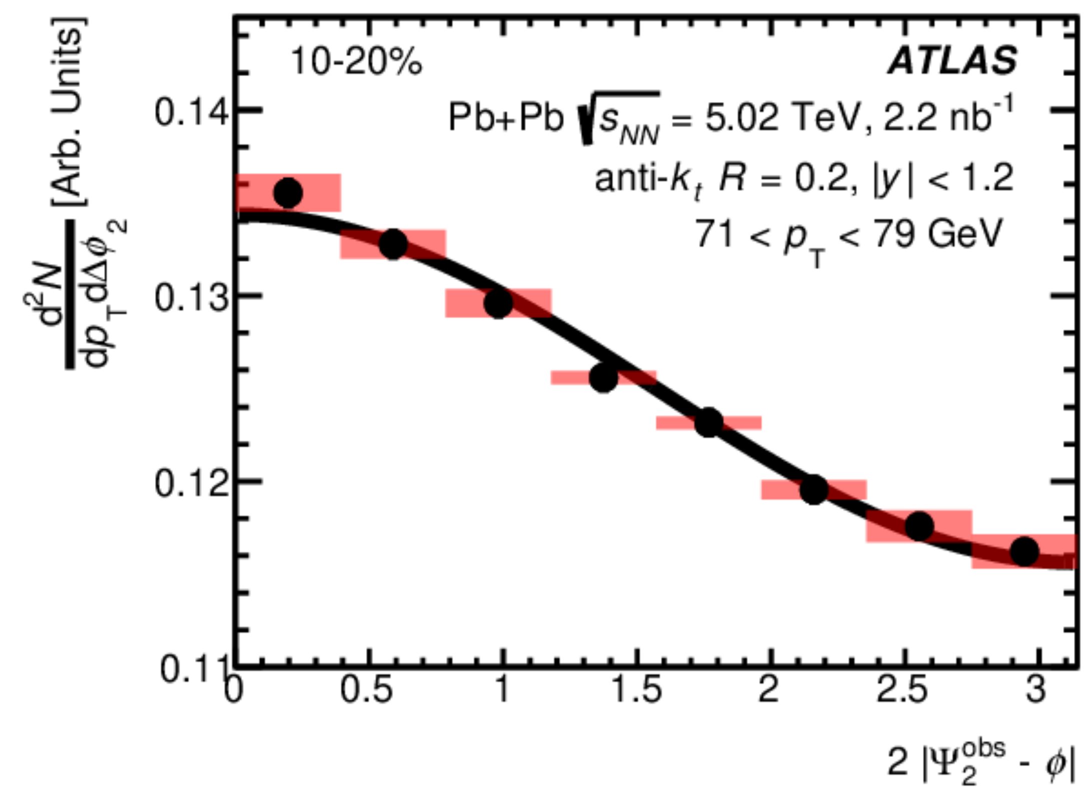
measurement of the jets wrt. collision geometry

this varies the amount of QGP that the jet sees

Jet vn

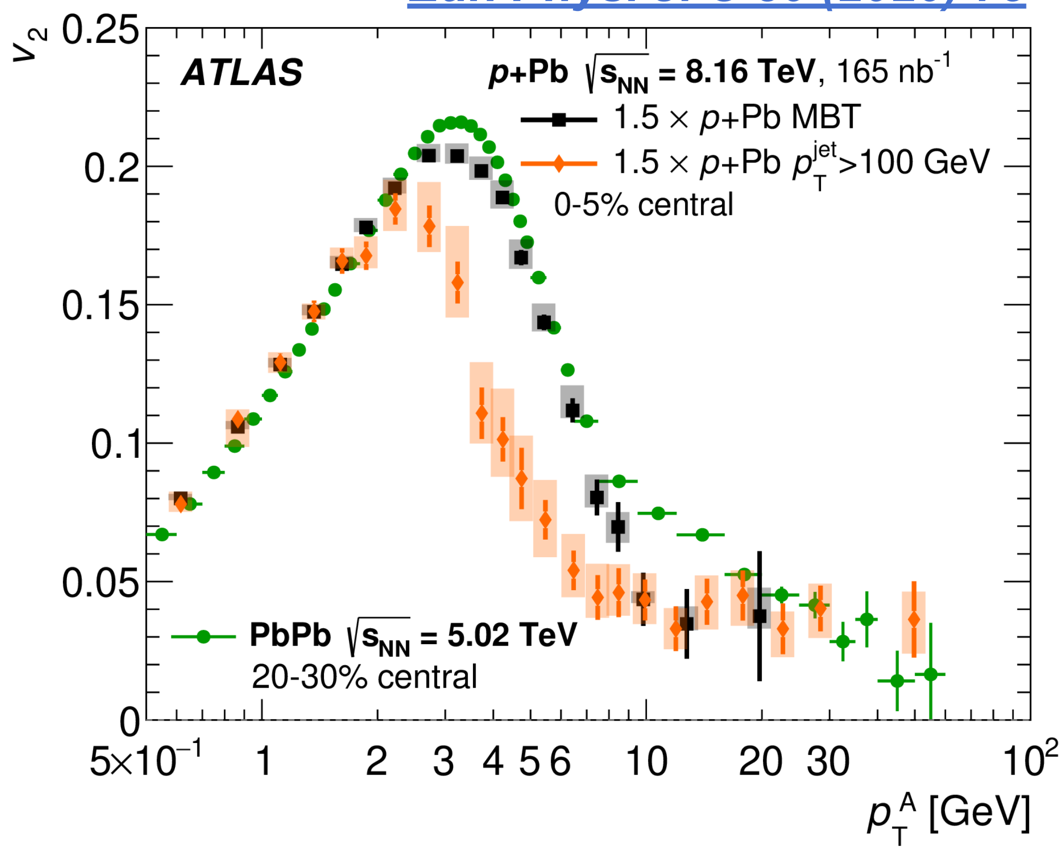


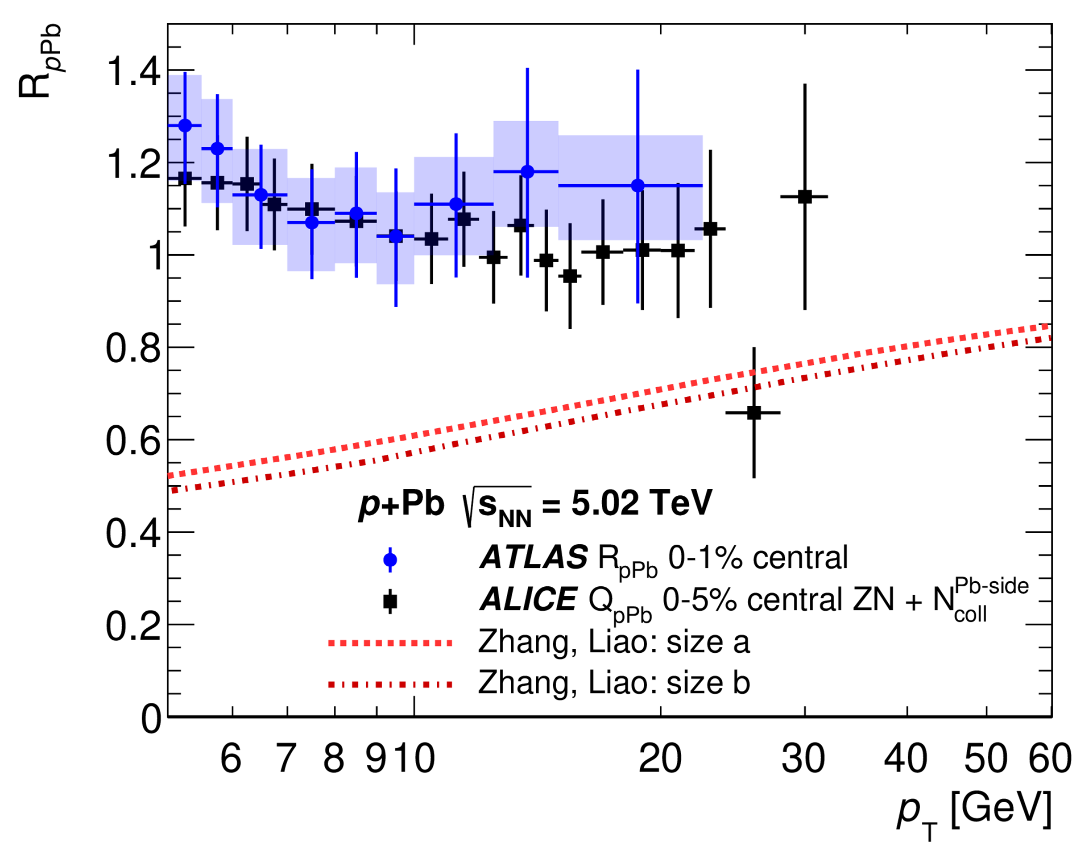
Phys. Rev. C 105 (2022) 064903



measurement of the jets wrt. collision geometry this varies the amount of QGP that the jet sees

Eur. Phys. J. C 80 (2020) 73





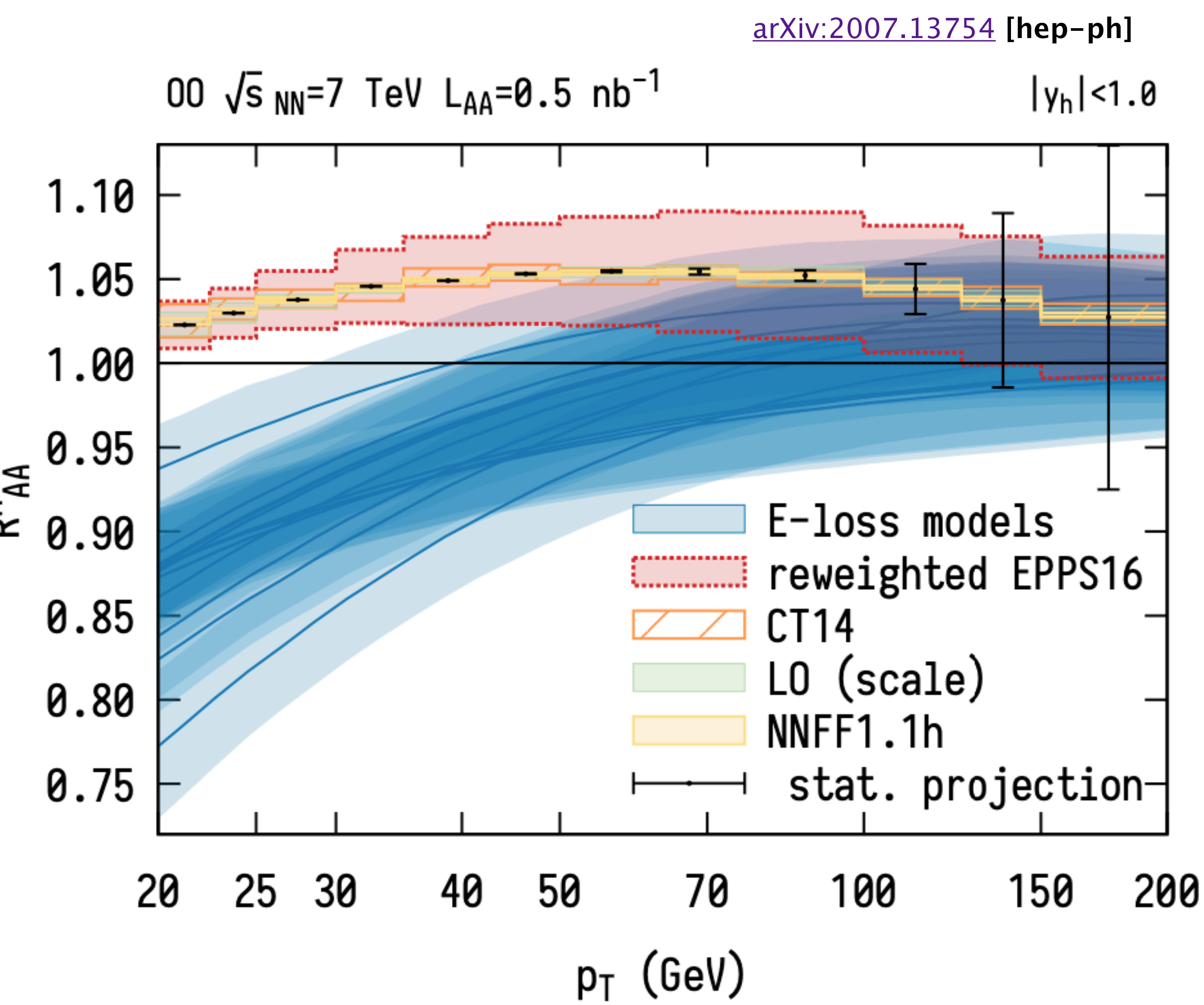
p+Pb:

Non zero v_2

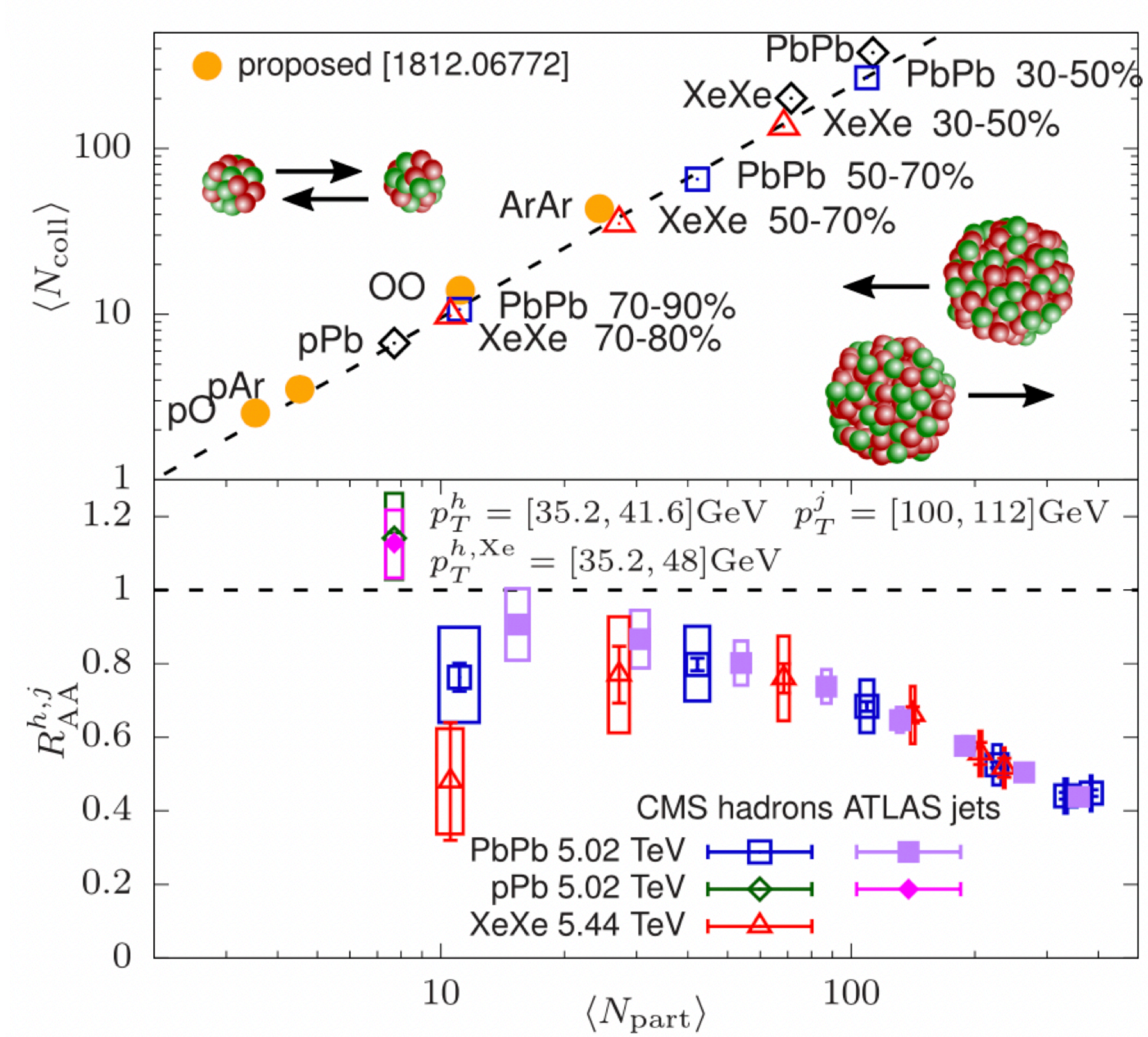
No signs of R_{AA} modification

Jet quenching in light ions collisions

Measurements of p+A type of collisions at LHC and RHIC left us with unresolved problem: ***how to connect soft QGP with lack of modification in the hard sector?***



OO is a symmetric system about the size of p+Pb

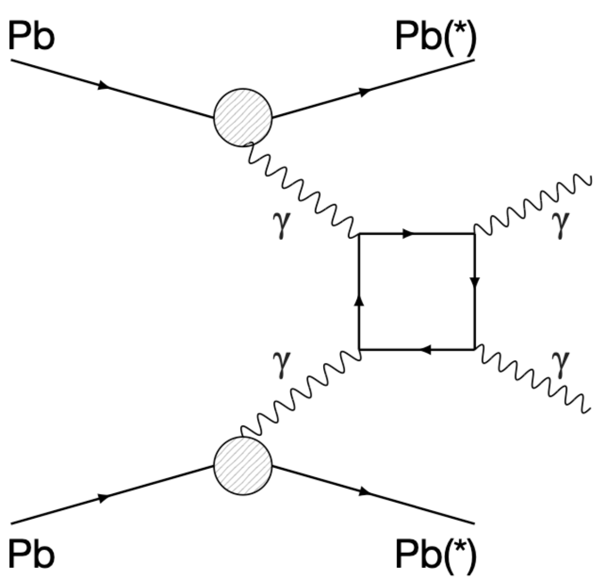


Photon induced process

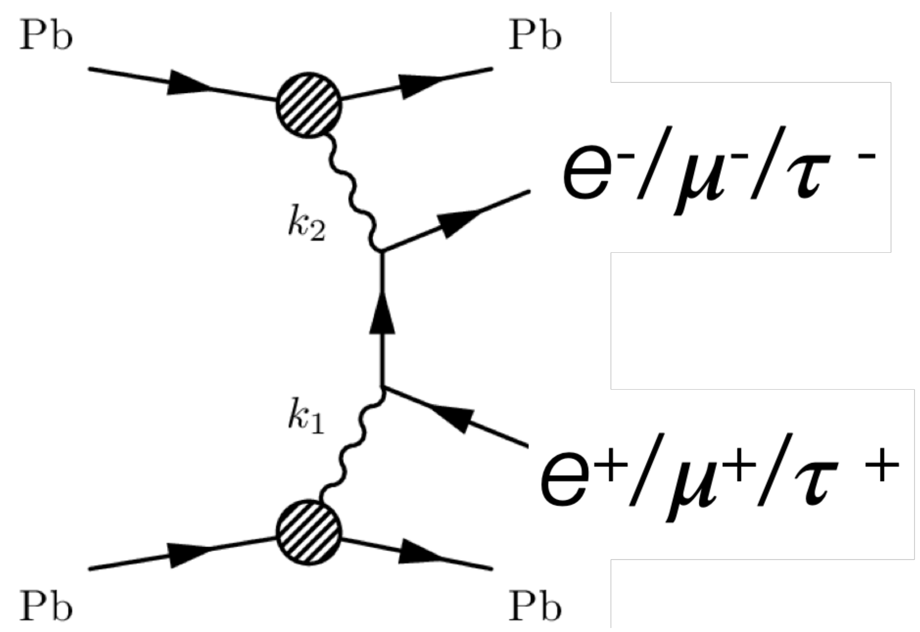
Boosted nuclei are intense source of photons

- Coherent photon flux with **Emax ~ 80 GeV @ LHC**

Various types of interactions possible:



Light-by-light scattering



Di-lepton production

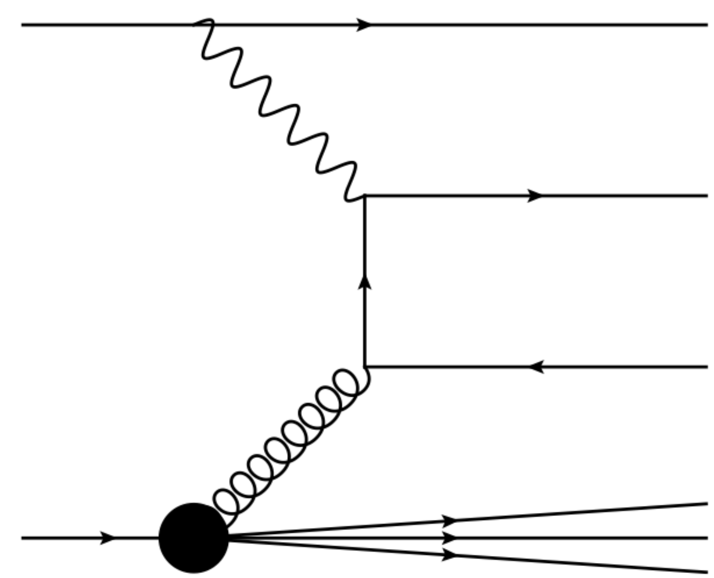
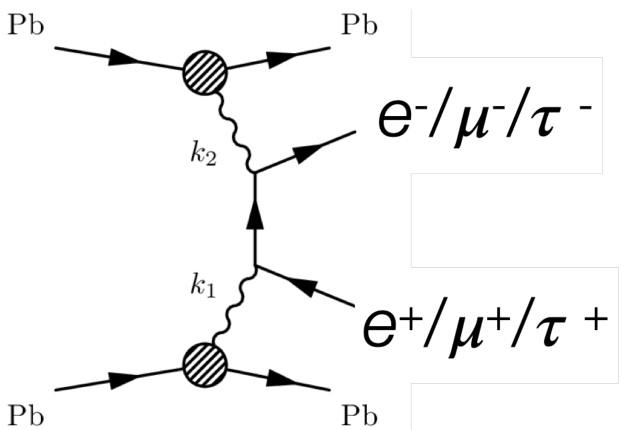


Photo nuclear

- Using ZDC to categorize events (0n, Xn)
- Rapidity gap helps to distinguish photo nuclear from inelastic Pb+Pb events

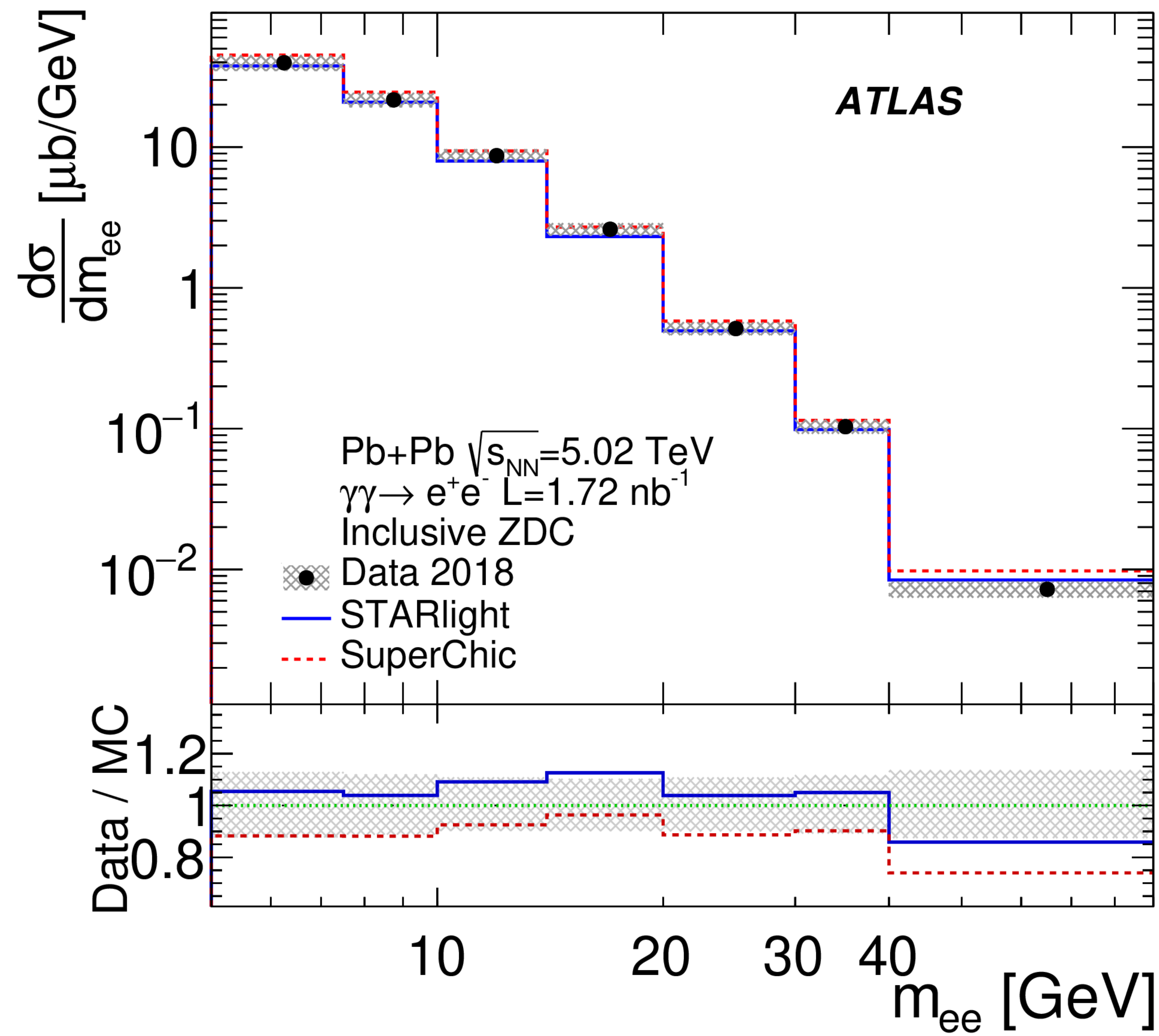
Exclusive di-lepton production in UPC



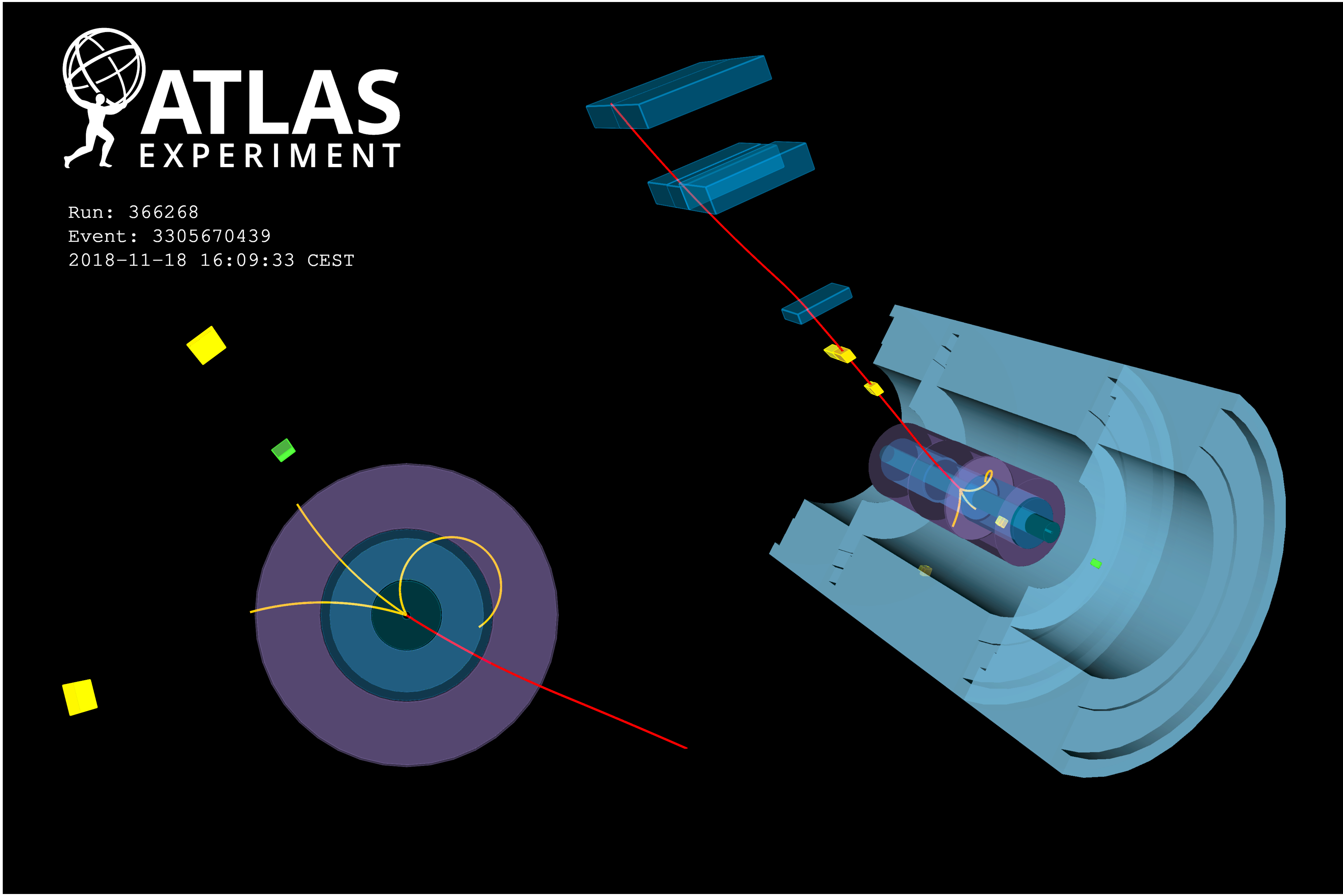
Exclusive di-lepton production is one of the fundamental processes in $\gamma+\gamma$ interaction → benchmark process to understand other γ induced processes.

Cross section for di-lepton production depends on the photon fluxes from each nucleons.

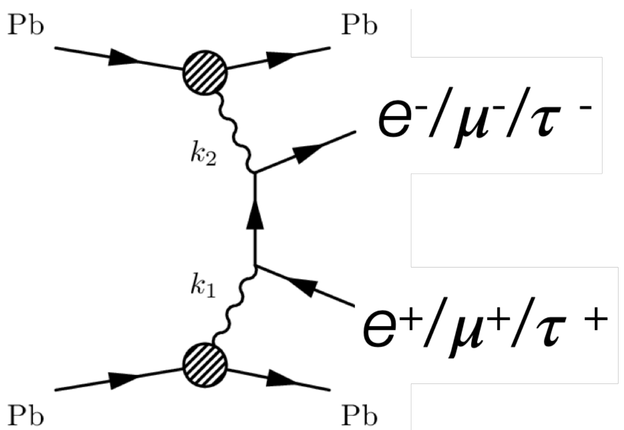
arXiv:2207.12781 **[nucl-ex]**



Exclusive di-lepton production in UPC



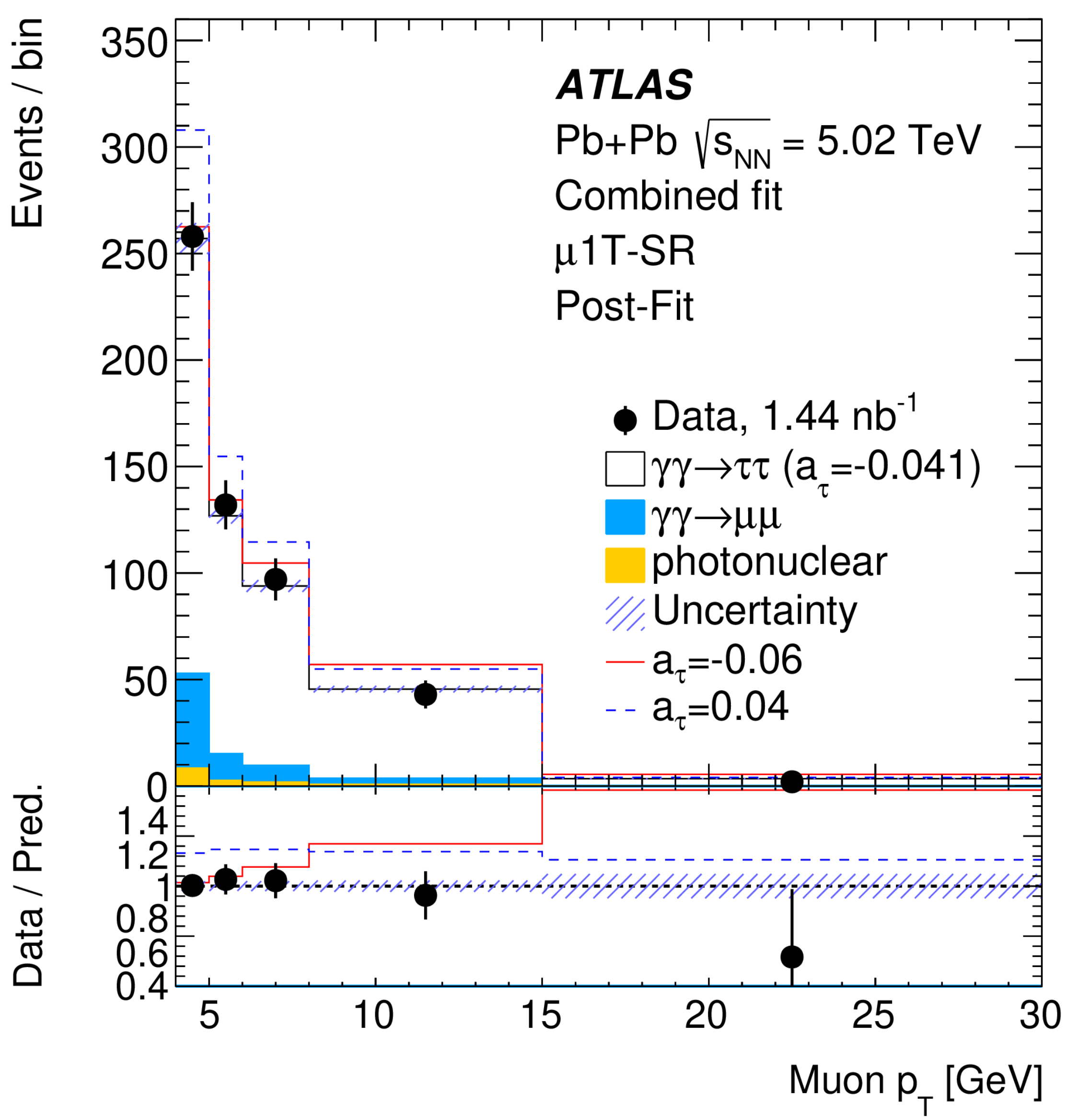
Exclusive di-lepton production in UPC



Using $\gamma\gamma$ -> $\tau\tau$ process to set limits on anomalous magnetic moment of tau lepton (a_τ)

(Much less constrained than a_e a_μ)

arXiv:2204.13478 [hep-ex]



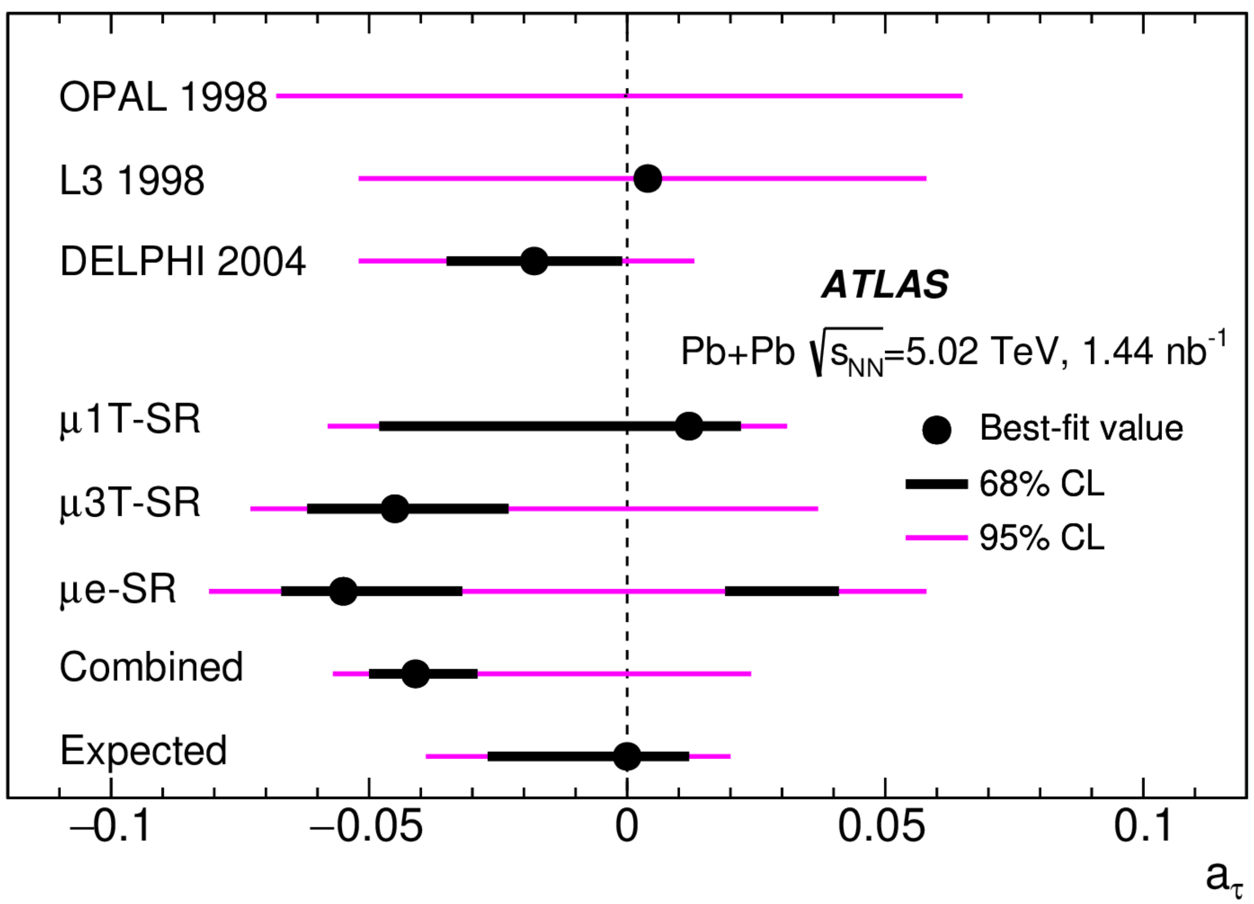
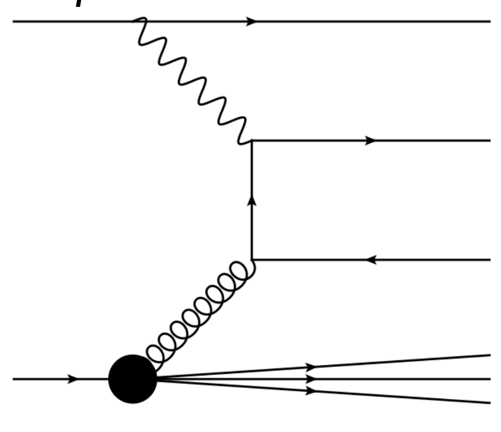


Photo-nuclear production of di-jets

Direct photon



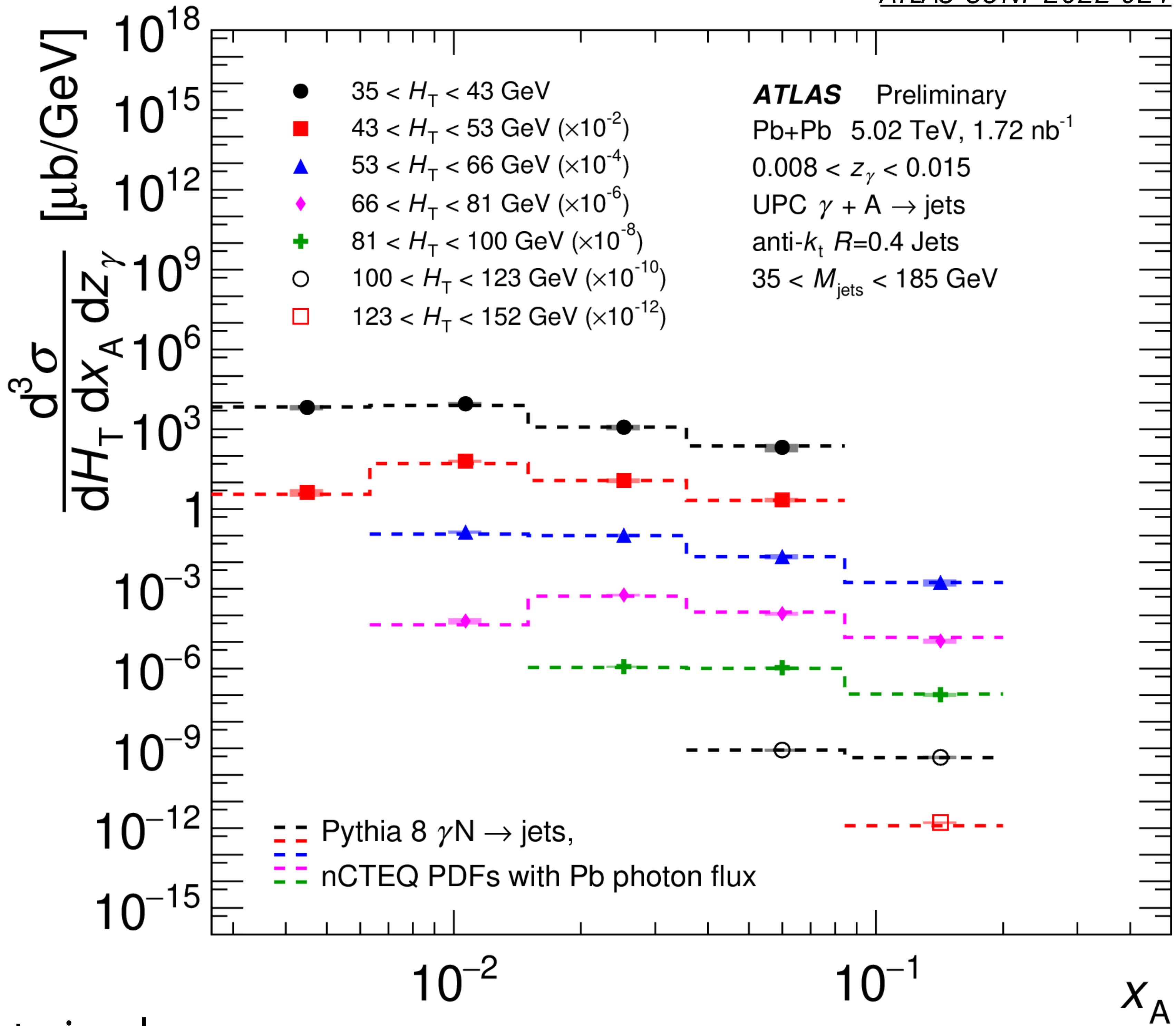
Di-jet kinematics corresponds to the hard scattering kinematics

$$H_T \equiv \sum_i p_{T\,i}$$

$$z_\gamma \equiv \frac{M_{jets}}{\sqrt{s}} e^{+y_{jets}}$$

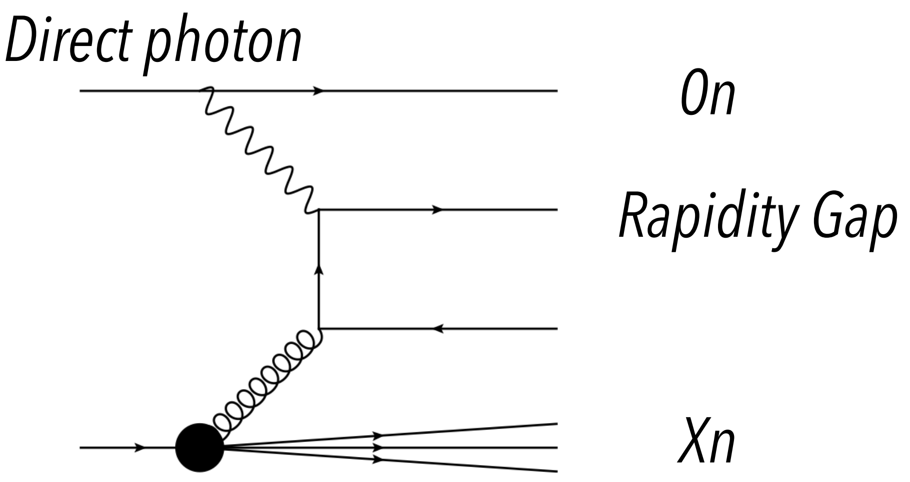
$$x_A \equiv \frac{M_{jets}}{\sqrt{s}} e^{-y_{jets}}$$

ATLAS-CONF-2022-021

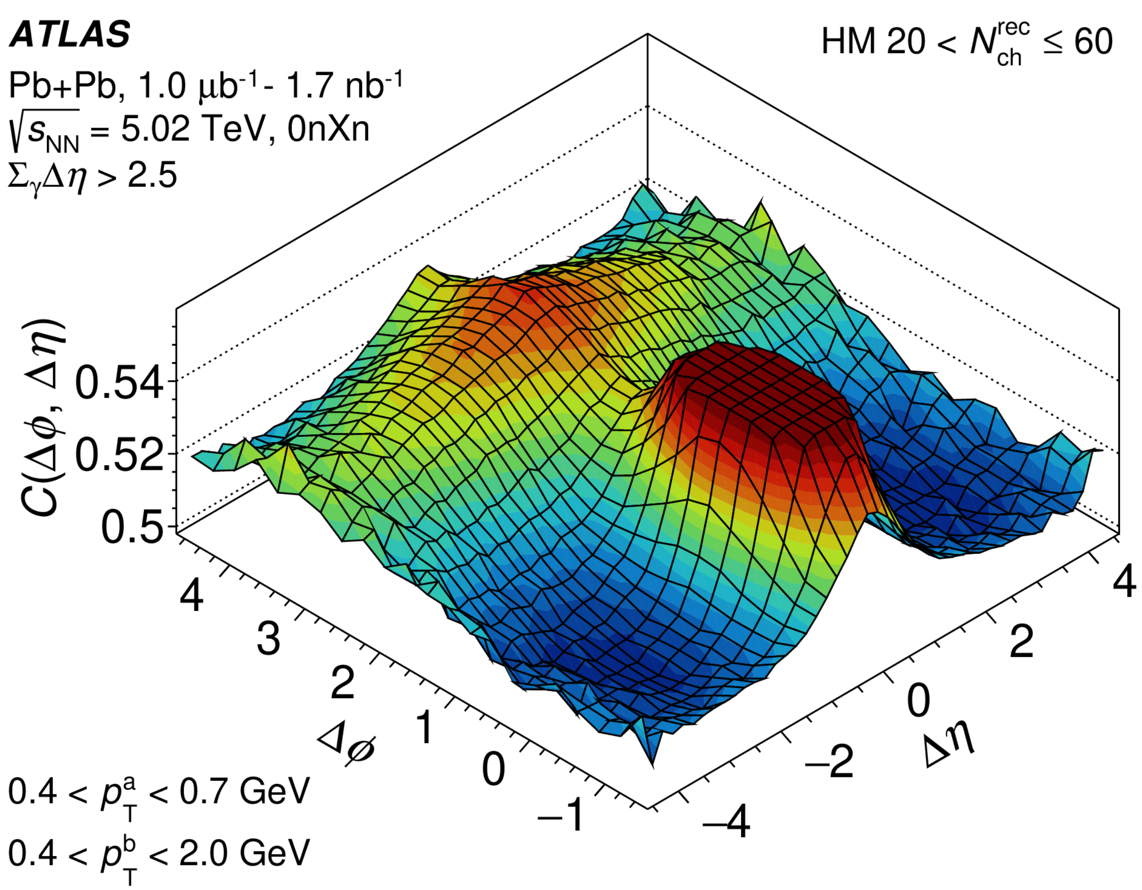


Clean probe to explore poorly constrained region at low-x and intermediate Q^2

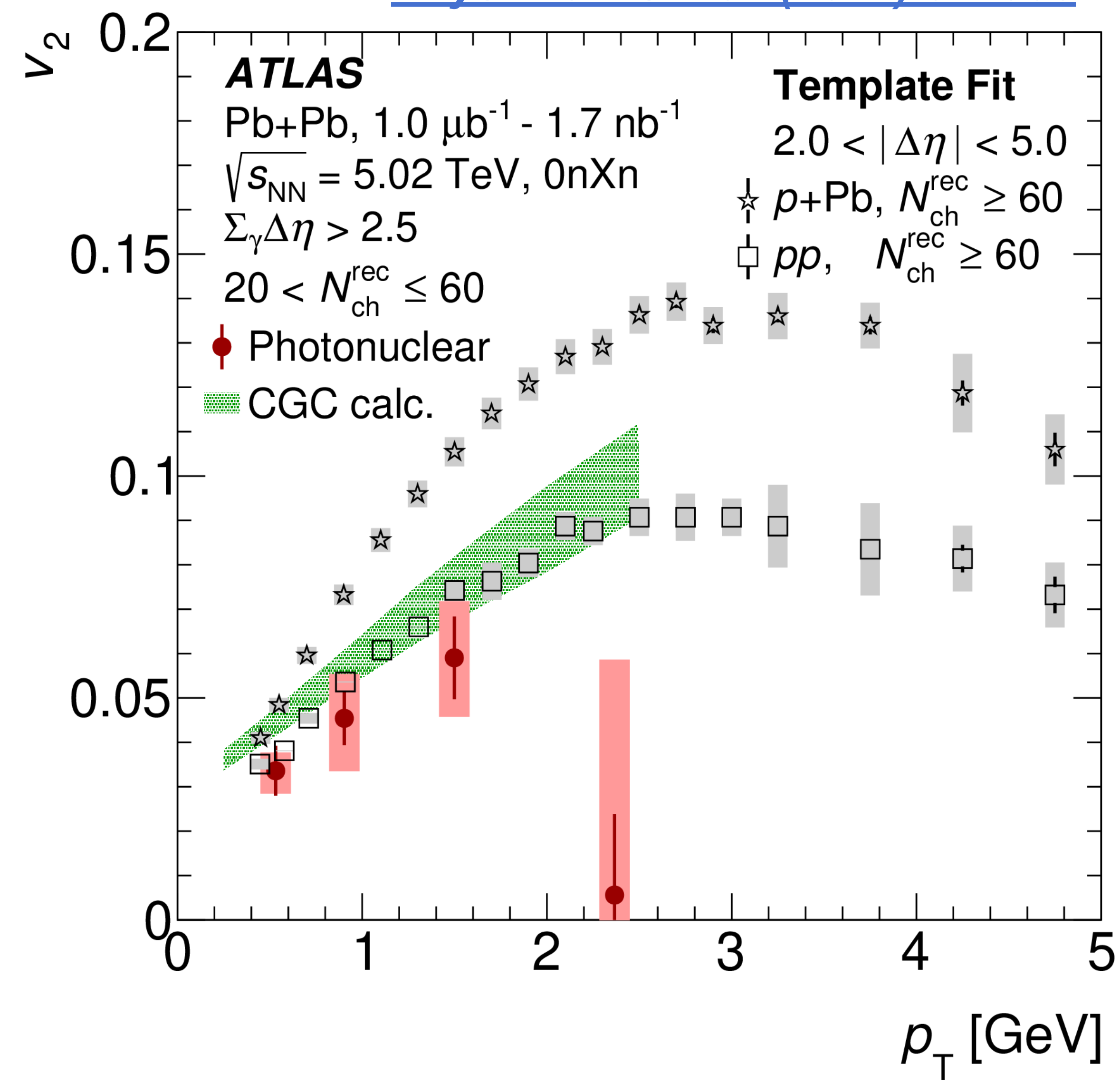
Flow in photo-nuclear collisions



Comparable v2 what is seen in pp

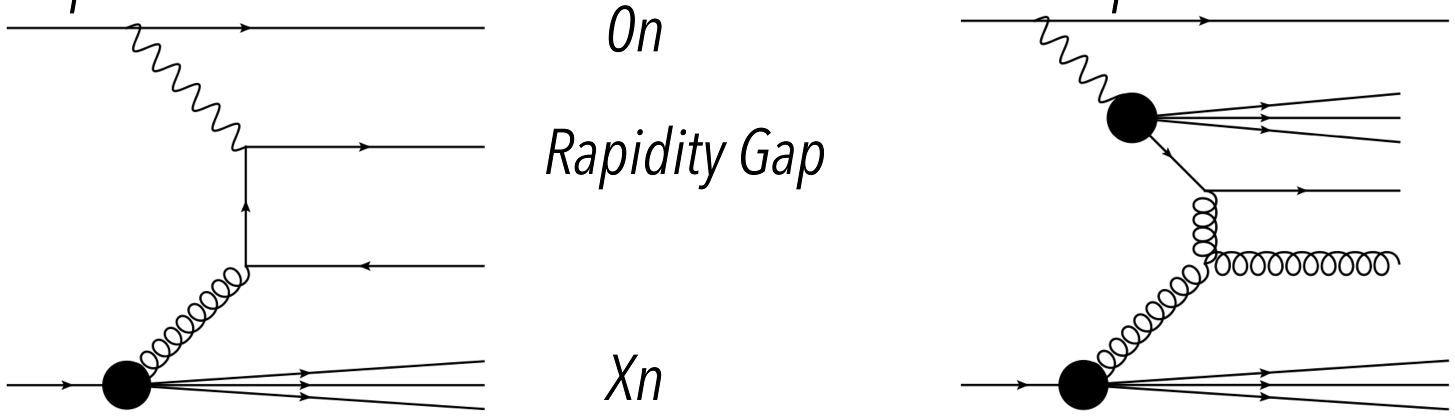


Phys. Rev. C. 104 (2021) 014903



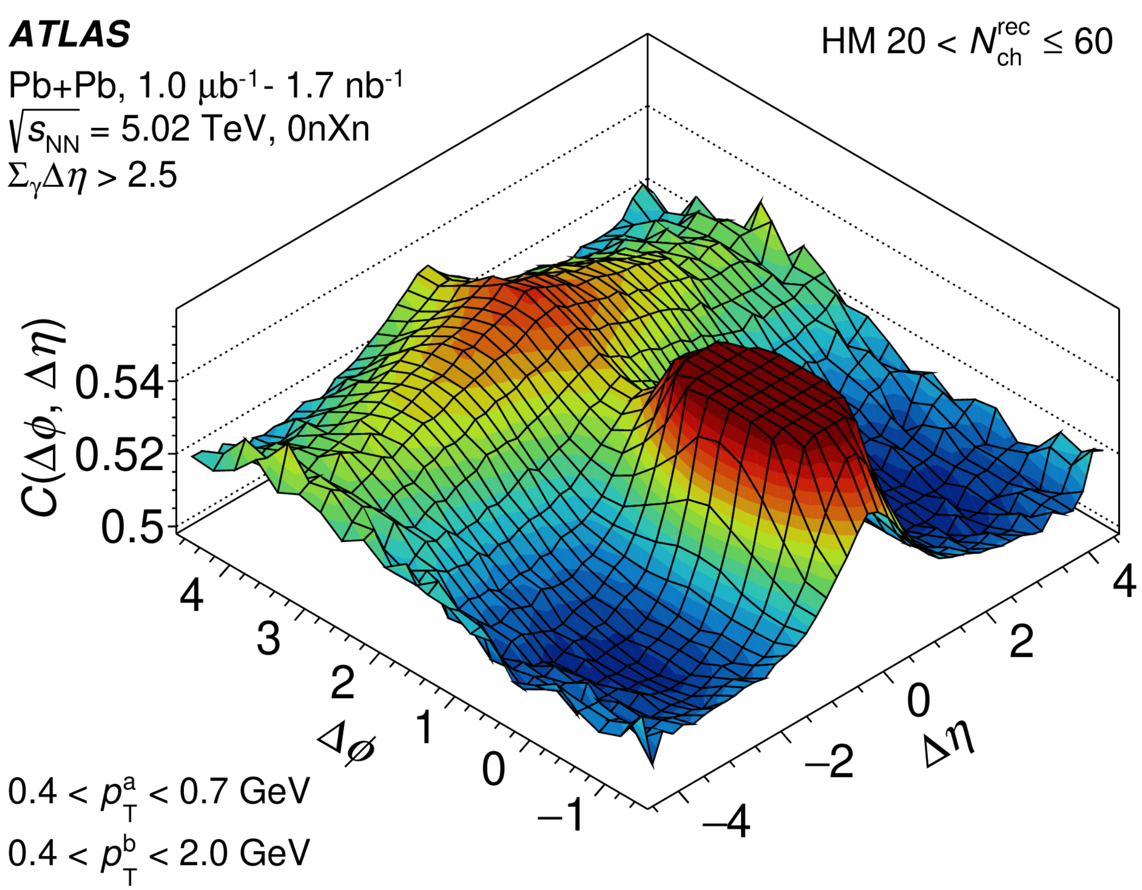
Flow in photo-nuclear collisions

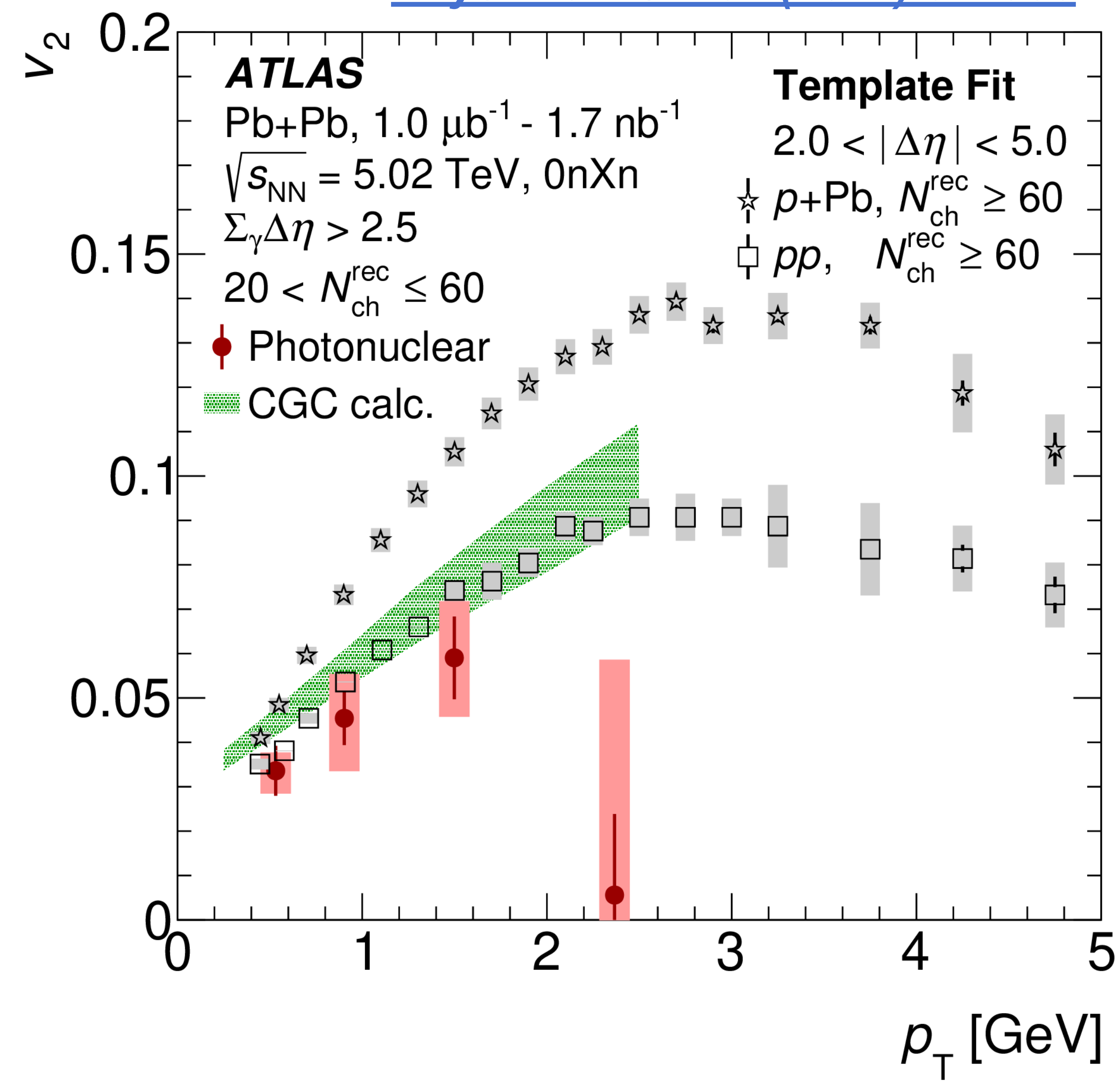
Direct photon *Resolved photon*



Comparable v2 what is seen in pp

[Phys. Rev. C. 104 (2021) 014903]





Summary

Using high statistics LHC data and new techniques bring us to era of precise measurements of QGP produced in heavy-ion collisions

We still need new measurements

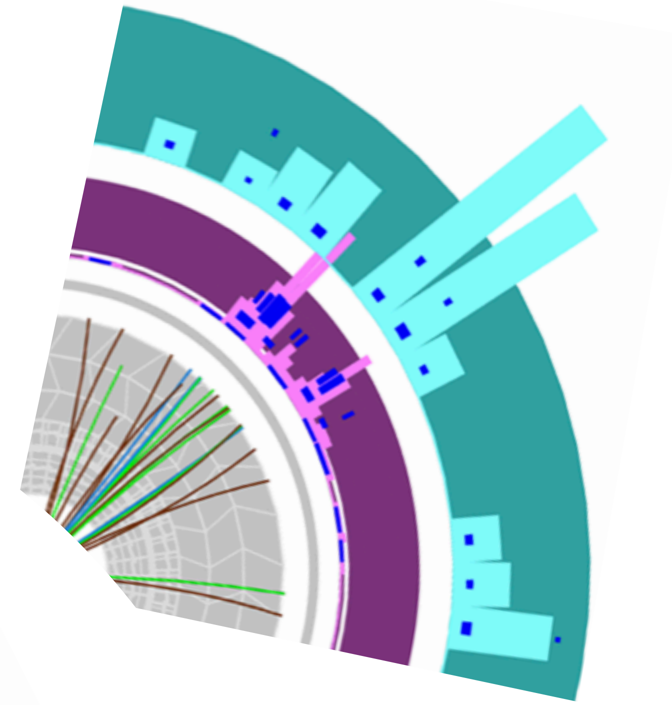
- Each observable is sensitive to different aspect of probing the QGP
- Some observables are statistics hungry - looking forward for more data
- Interesting opportunity to study new collision system(s) (O+O LHC Run3, future of heavy ion program?)
- Growing interest in UPC physics

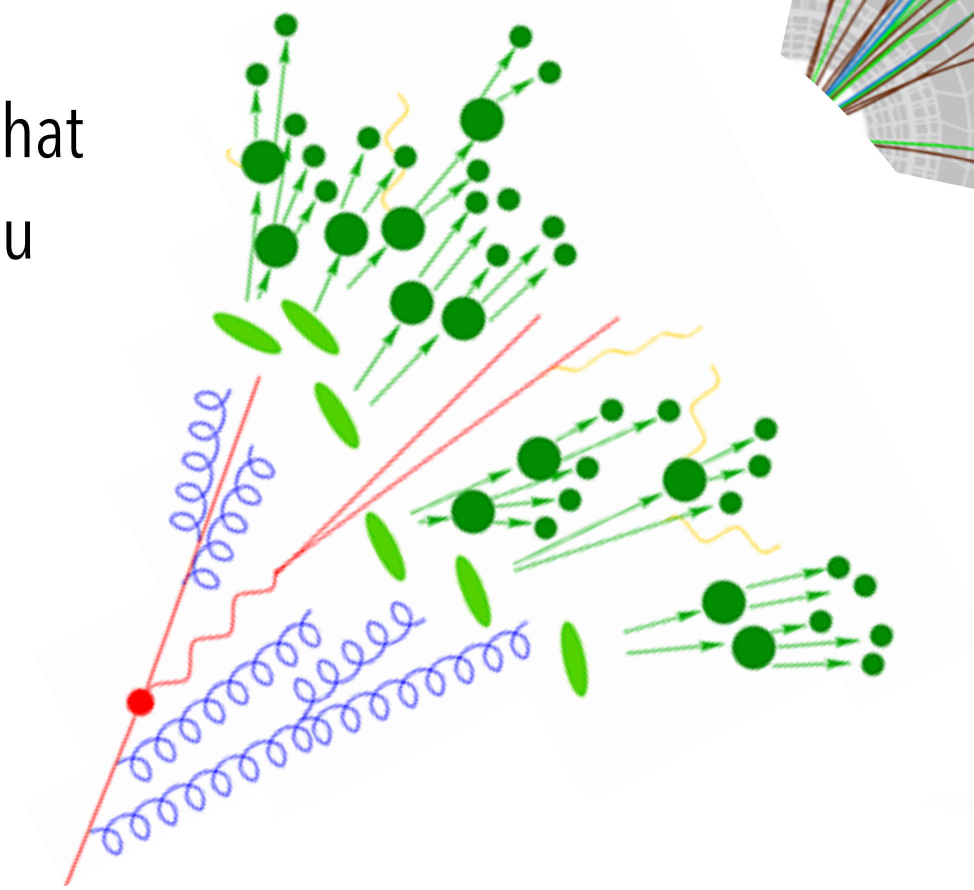
More details on ATLAS public results page:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

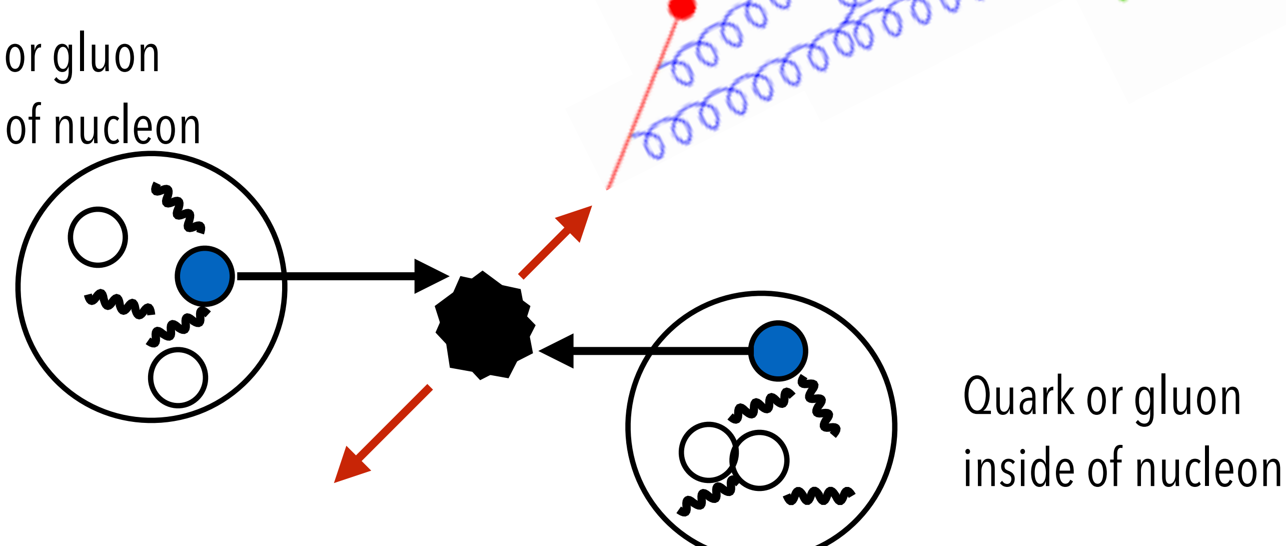
Jets in vacuum

Jets: collimated showers of energetic particles that carry a large fraction of the energy available in the collisions

- In Theory: jets are proxies for hard-scattered partons
- In Experiment: jet is what your jet-finder gives you



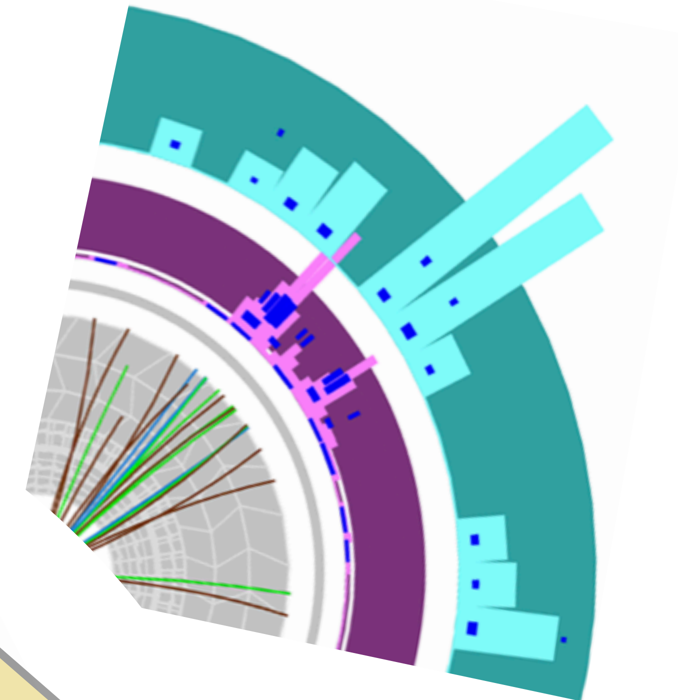


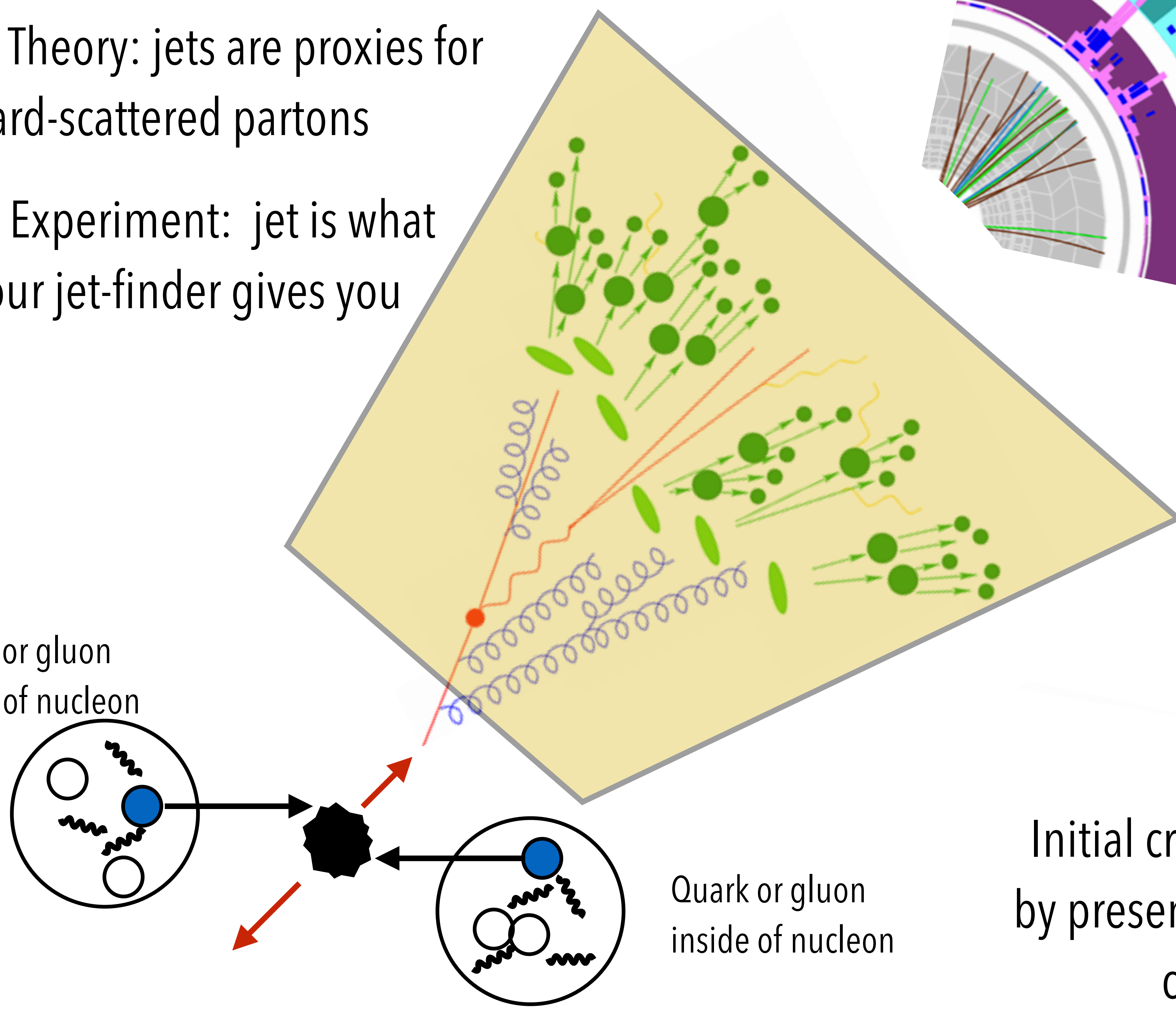


Jets in the medium

Jets: collimated showers of energetic particles that carry a large fraction of the energy available in the collisions

- In Theory: jets are proxies for hard-scattered partons
- In Experiment: jet is what your jet-finder gives you





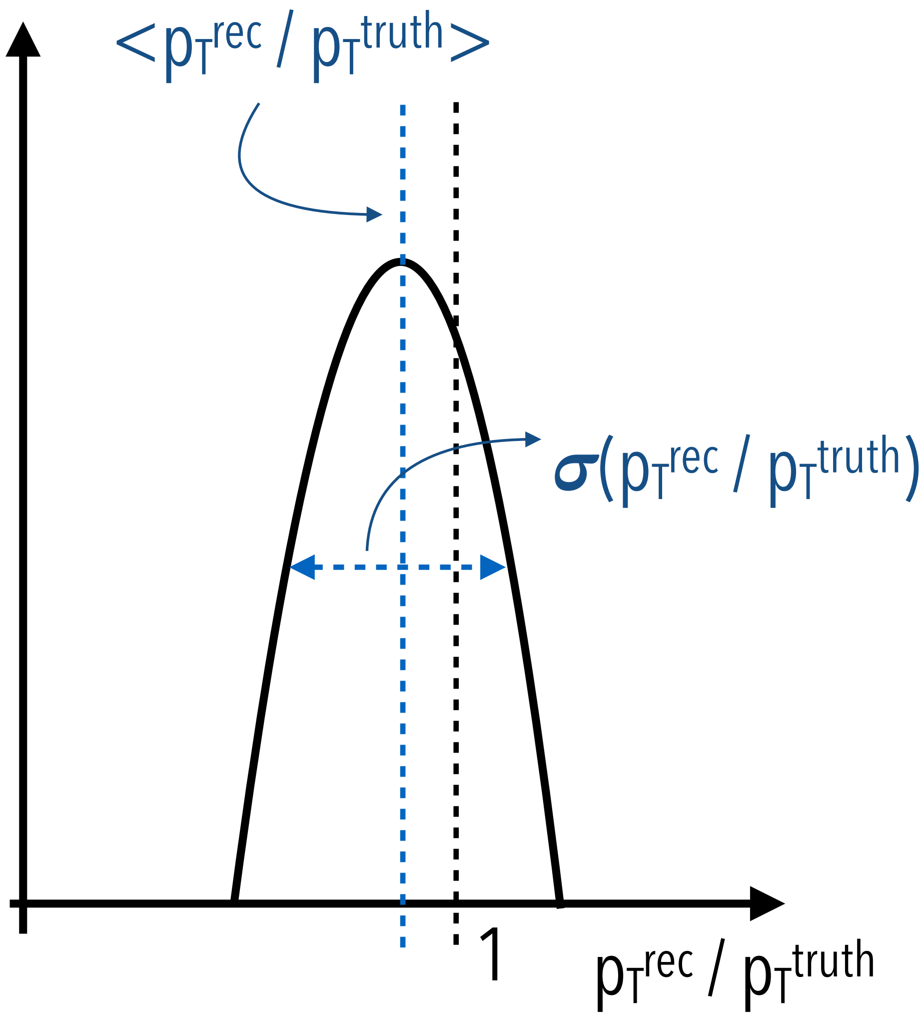
Quark or gluon inside of nucleon

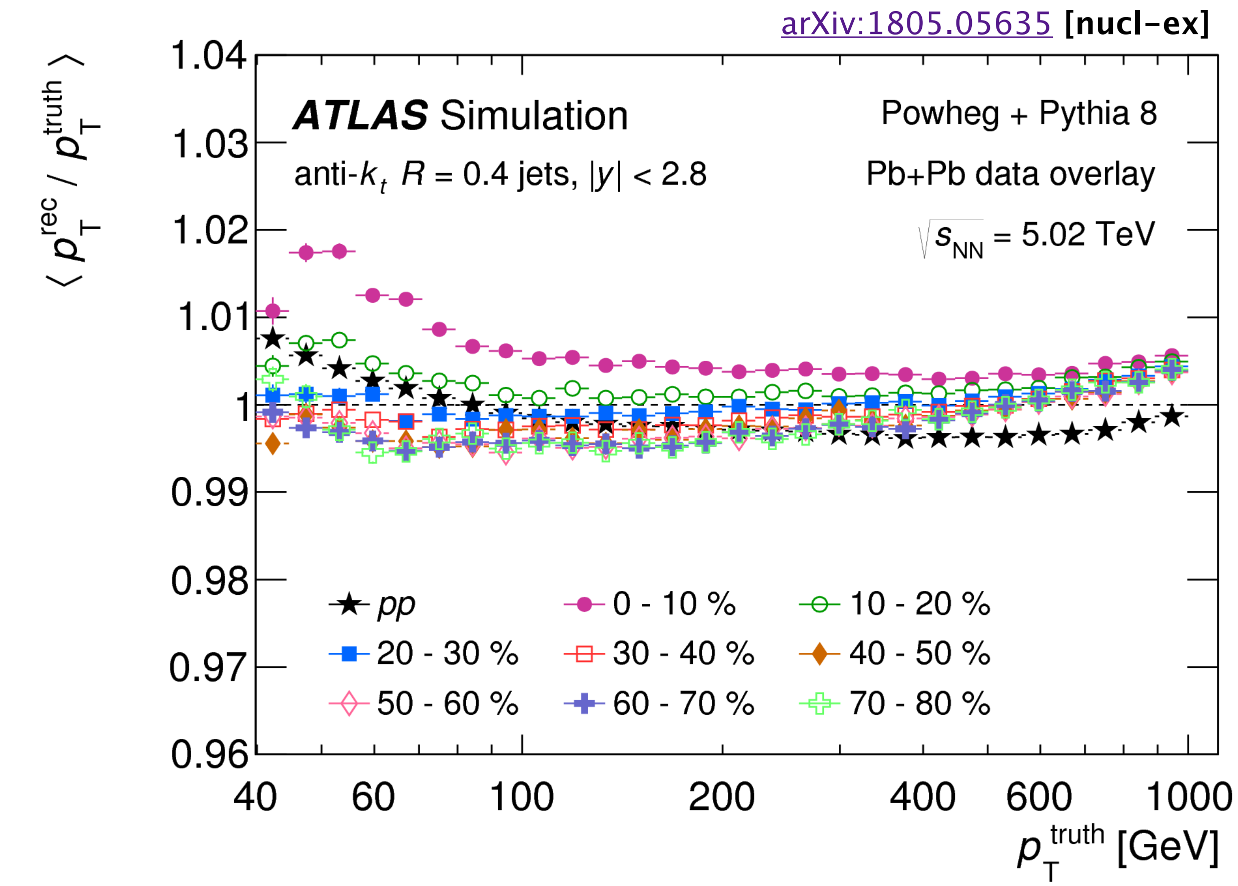
Quark or gluon inside of nucleon

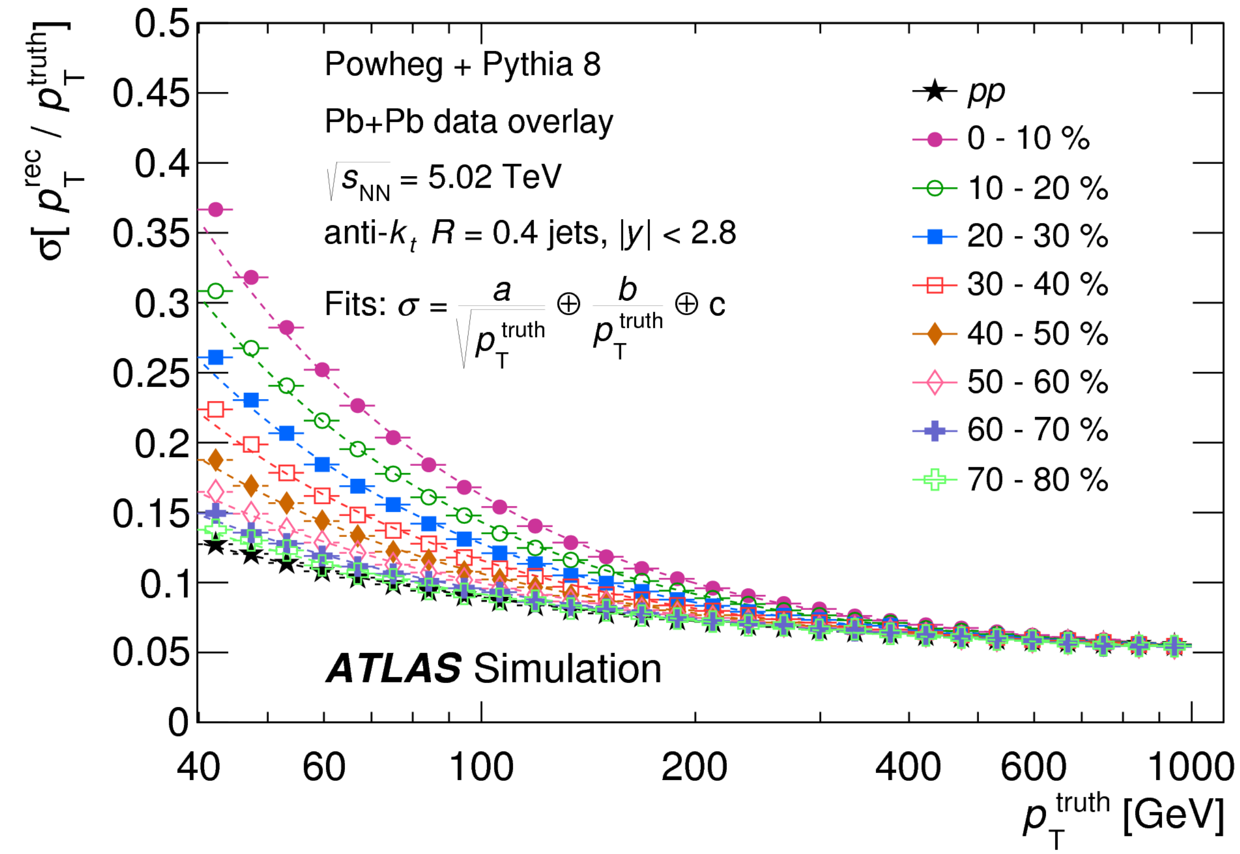
Interactions of medium and colored probe: elastic scattering, medium induced radiation, “drag force”, medium excitation ?

Initial cross-section unchanged by presence of medium (modulo change in nPDF)

Jets reconstruction - ATLAS heavy ion style

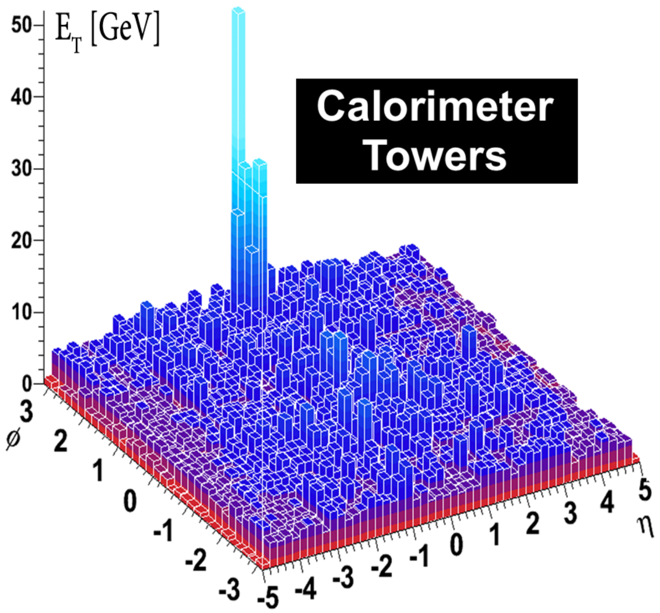




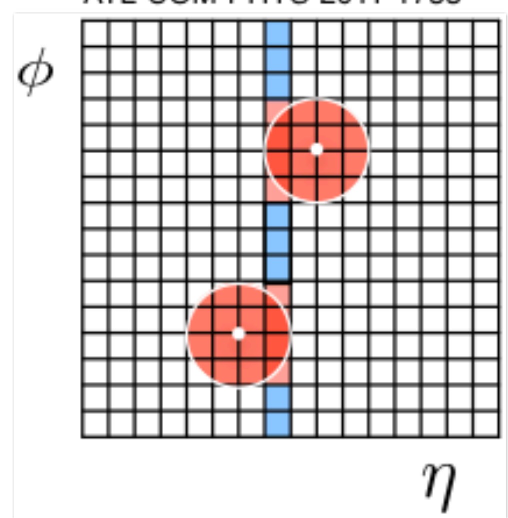


- Average response ($<p_T^{rec} / p_T^{truth}>$) within 1% from unity almost independent on centrality
- Jet energy resolution ($\sigma(p_T^{rec} / p_T^{truth})$) dominated by the underlying event fluctuations.

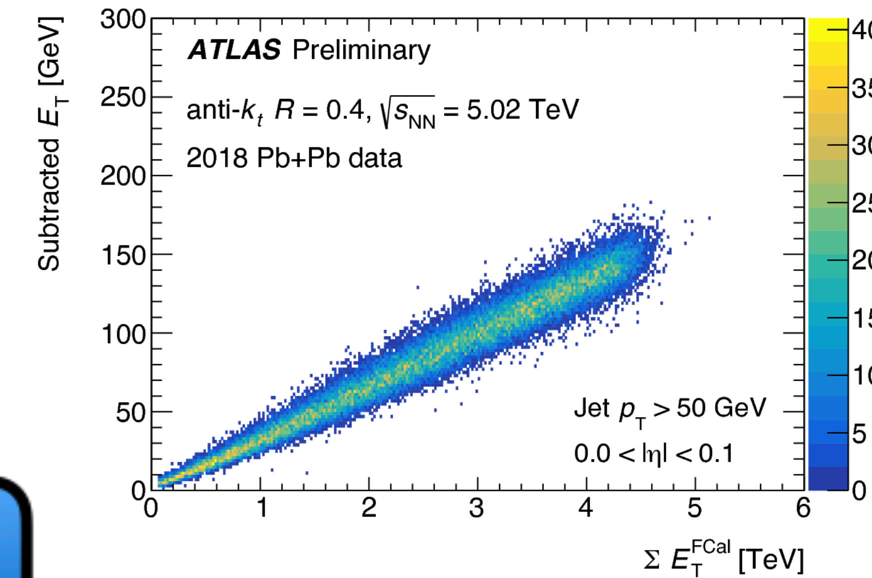
Jets reconstruction - ATLAS heavy ion style



ATL-COM-PHYS-2011-1733

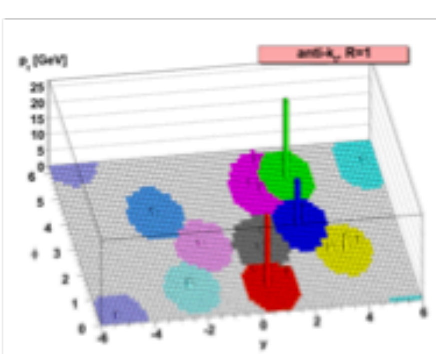


HION-2018-001

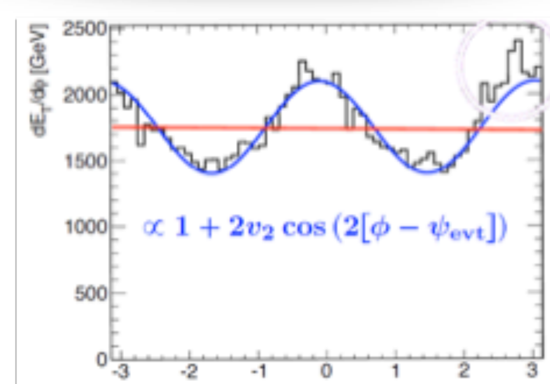


Calorimeter towers + Anti-k_t Algorithm → Jets → + Average E_T density: ρ(η, layer) + Flow modulation (v_2, v_3, v_4) → Reconstructed Jets

Flow modulation → Anti-k_t Algorithm: **Iterative subtraction**



arXiv - 0802.1189

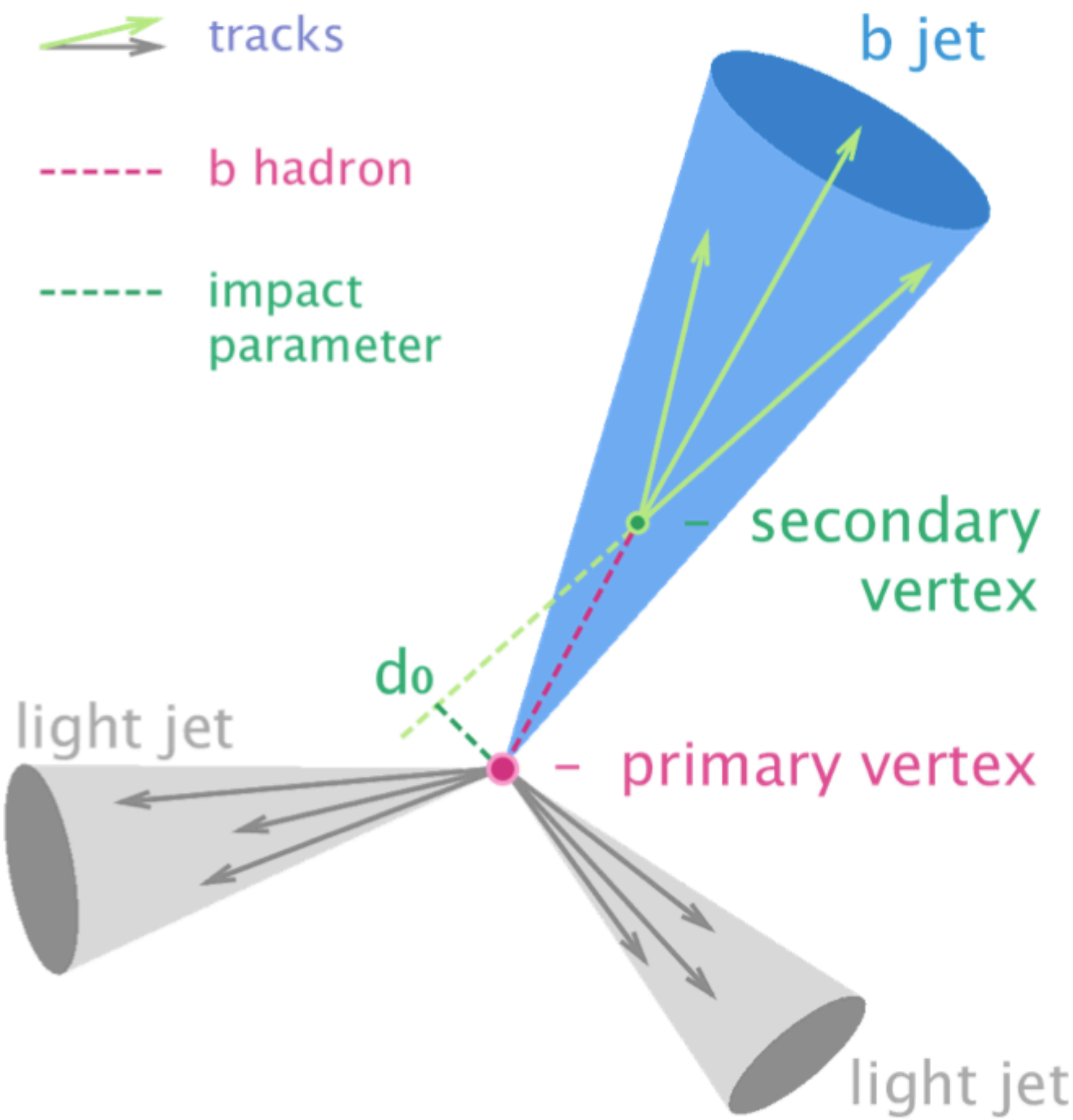


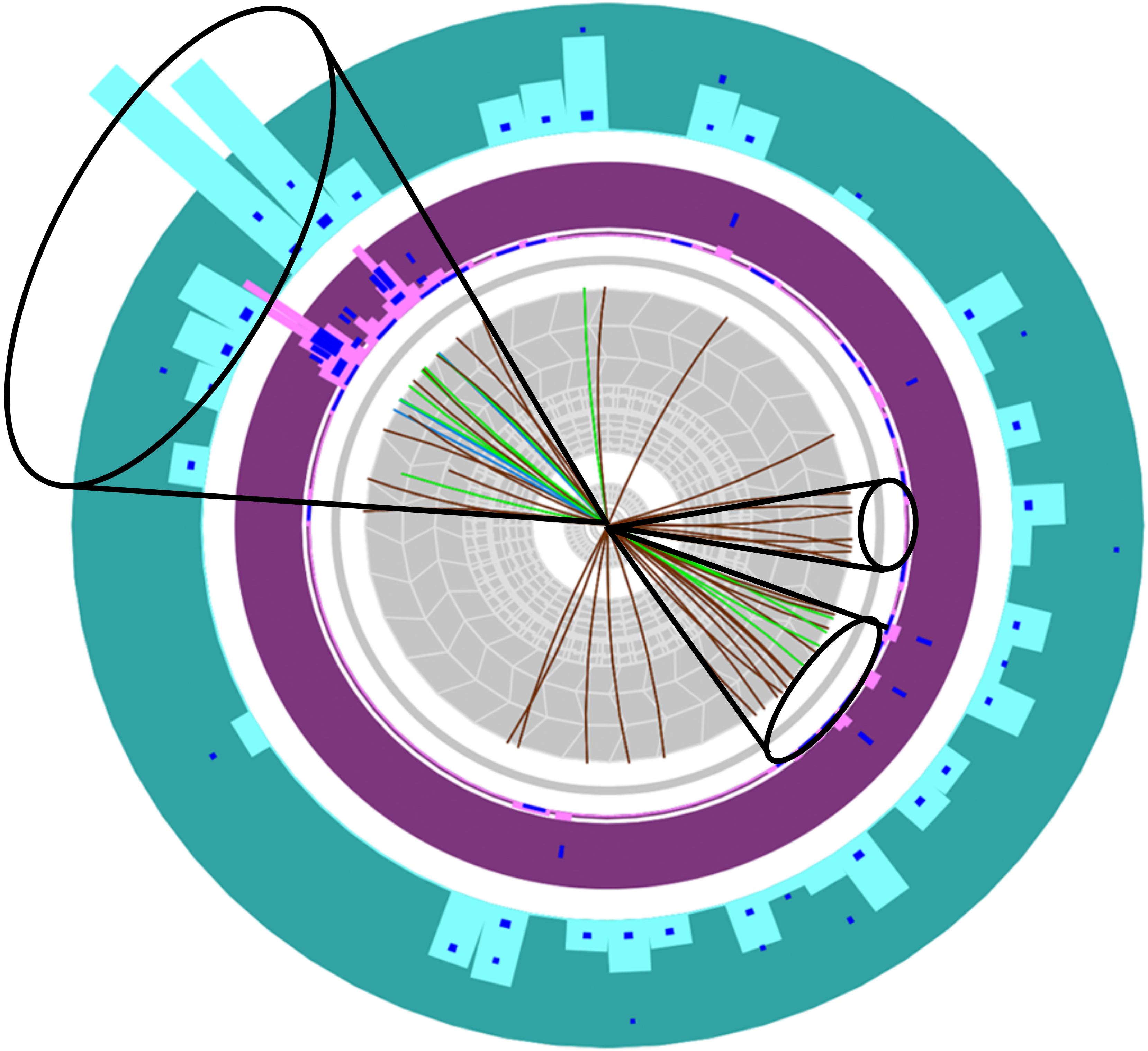
ATL-COM-PHYS-2012-628

Quenching of b-jets

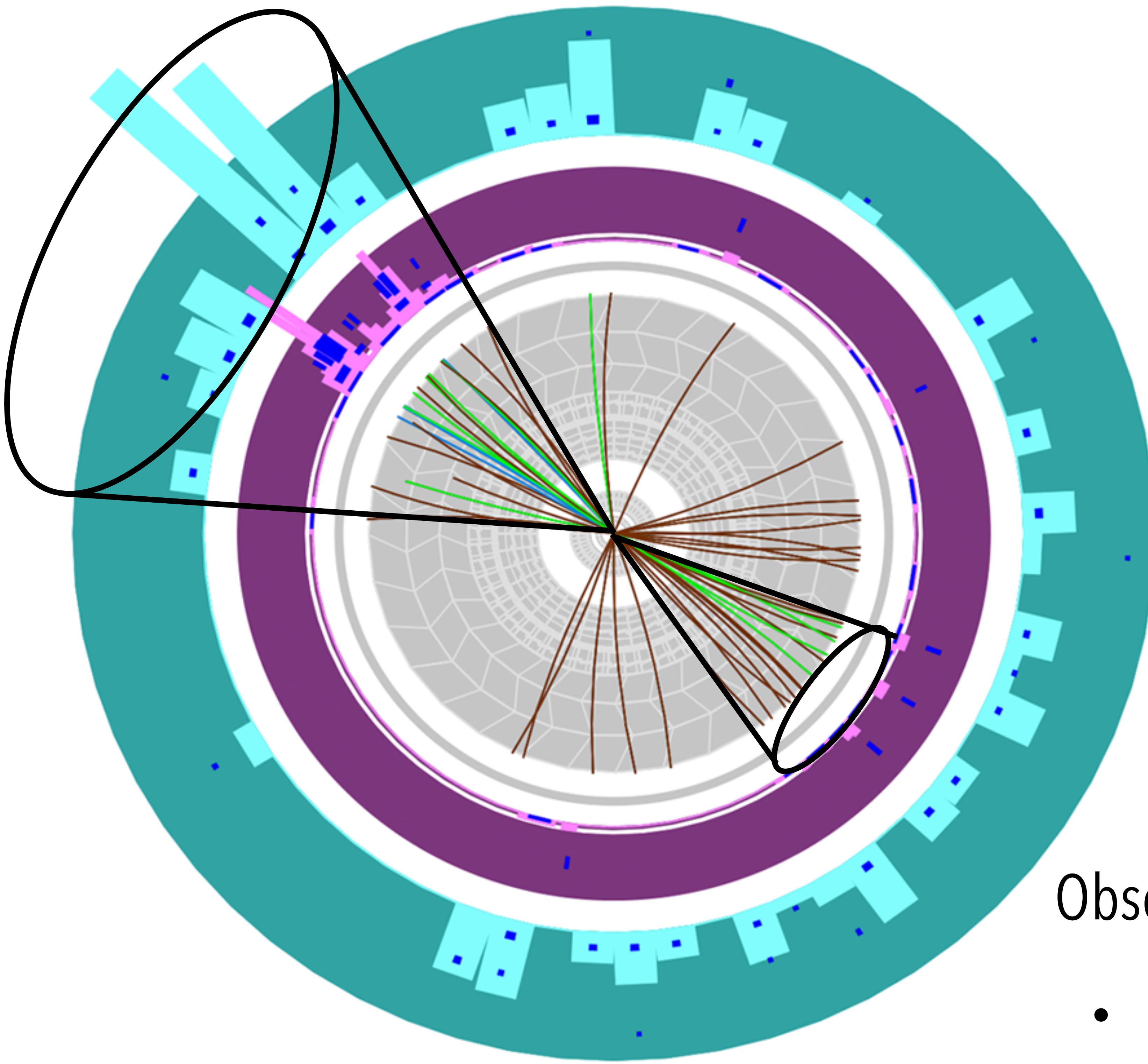
The dependence of quenching on the type of parton that initiates the jet may provide insight into the underlying dynamics

- Type of parton that initiates the jet is difficult to determine experimentally
- Machine learning techniques used in experiments to identify b-jets





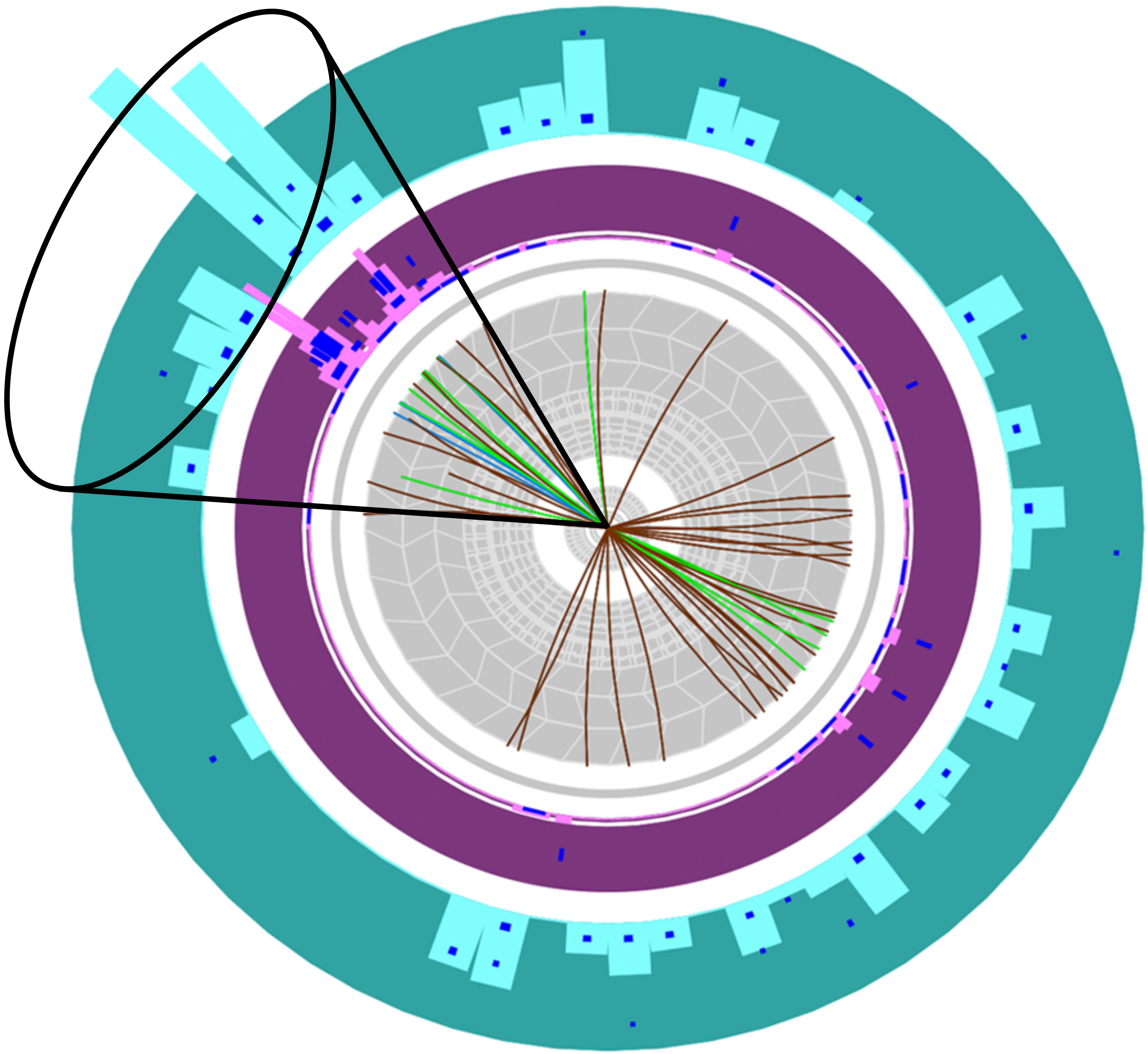
Path length dependent energy loss



Observables:

- Dijet asymmetry
- Jet v_n

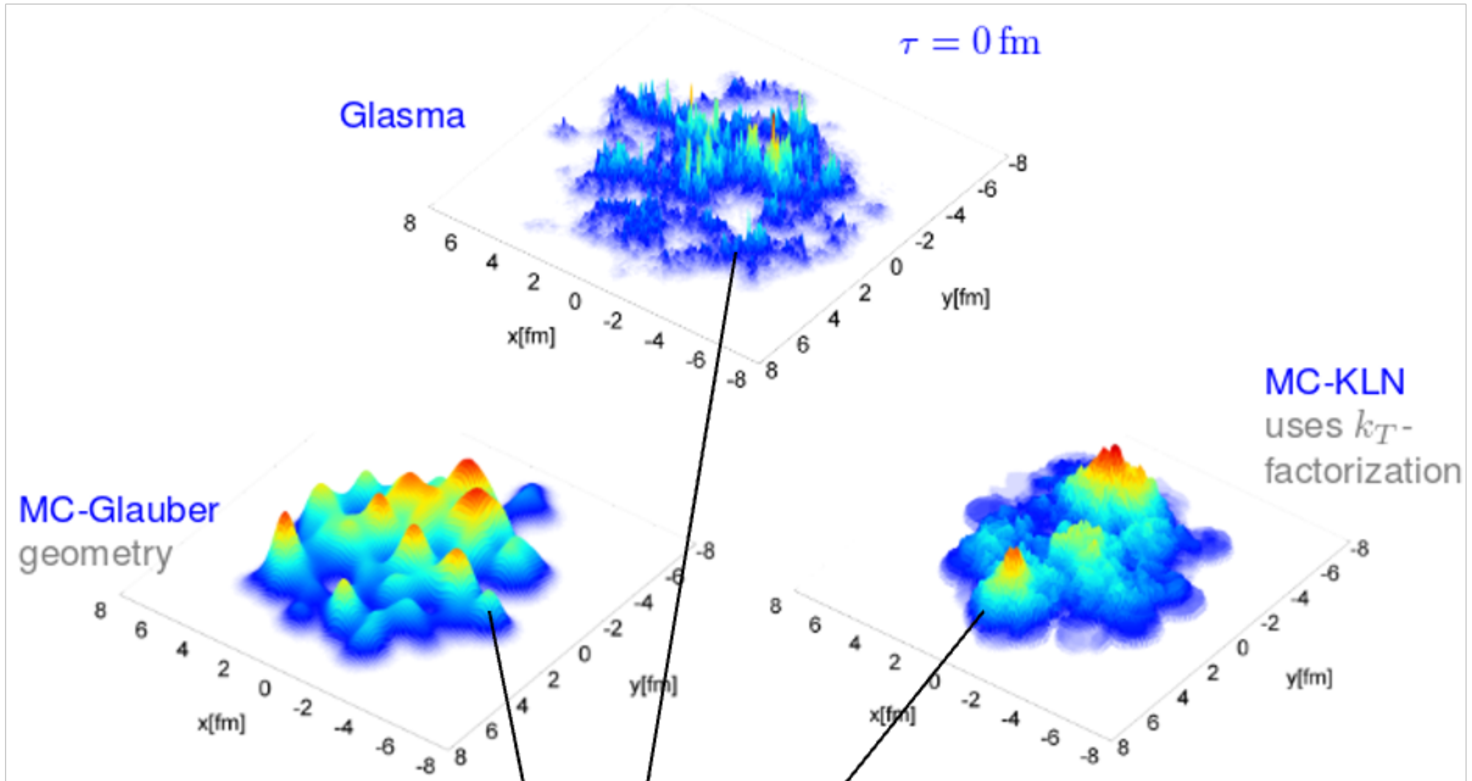
Jet structure



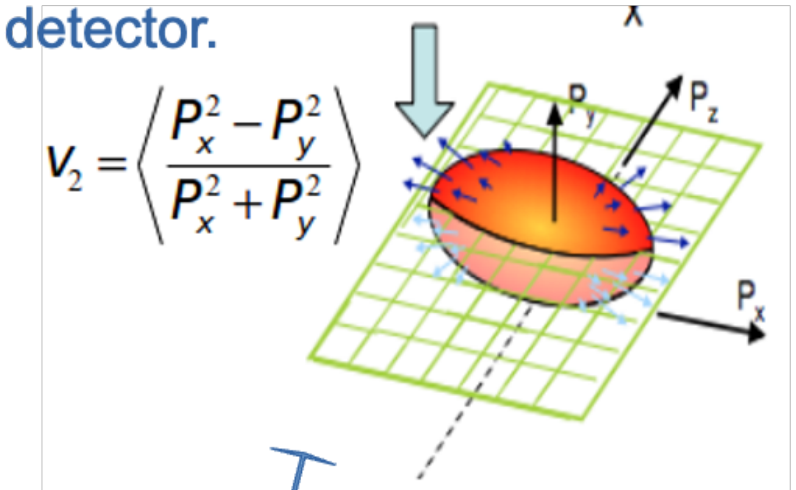
Flow measurements

Method	**Pros**	**Cons**
Event plane	Simple to use Used widely by experiment and theory	Results susceptible to non-flow effects Comparison between experiment depend on event plane resolution
Scalar product	Simple to use Uniform treating of detector acceptance	Results susceptible to non-flow effects
Two particle correlation	Simple to use Used widely by experiment and theory	Results susceptible to non-flow effects
Multiparticle cumulants	Large reduction of non-flow effects	Difficult in computation (large cpu resources) Requires large signal
Lee Yang Zeros	Complete reduction of non-flow effects	Difficult in computation (large cpu resources) Requires large signal

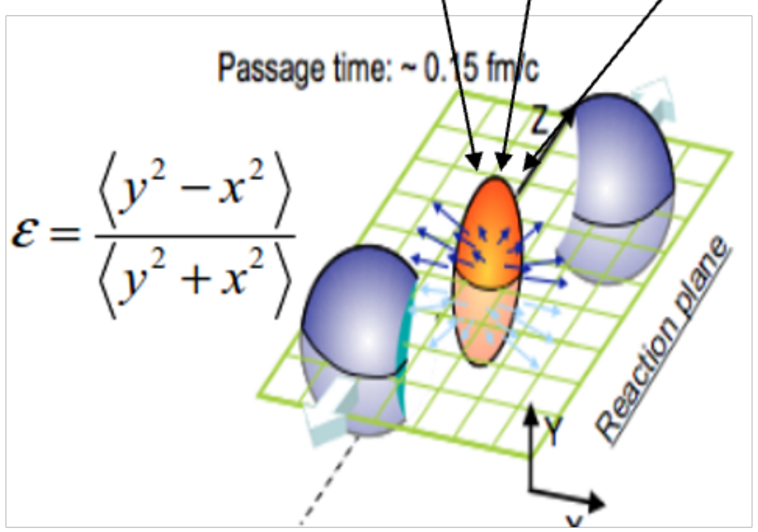
Stages of HI collision

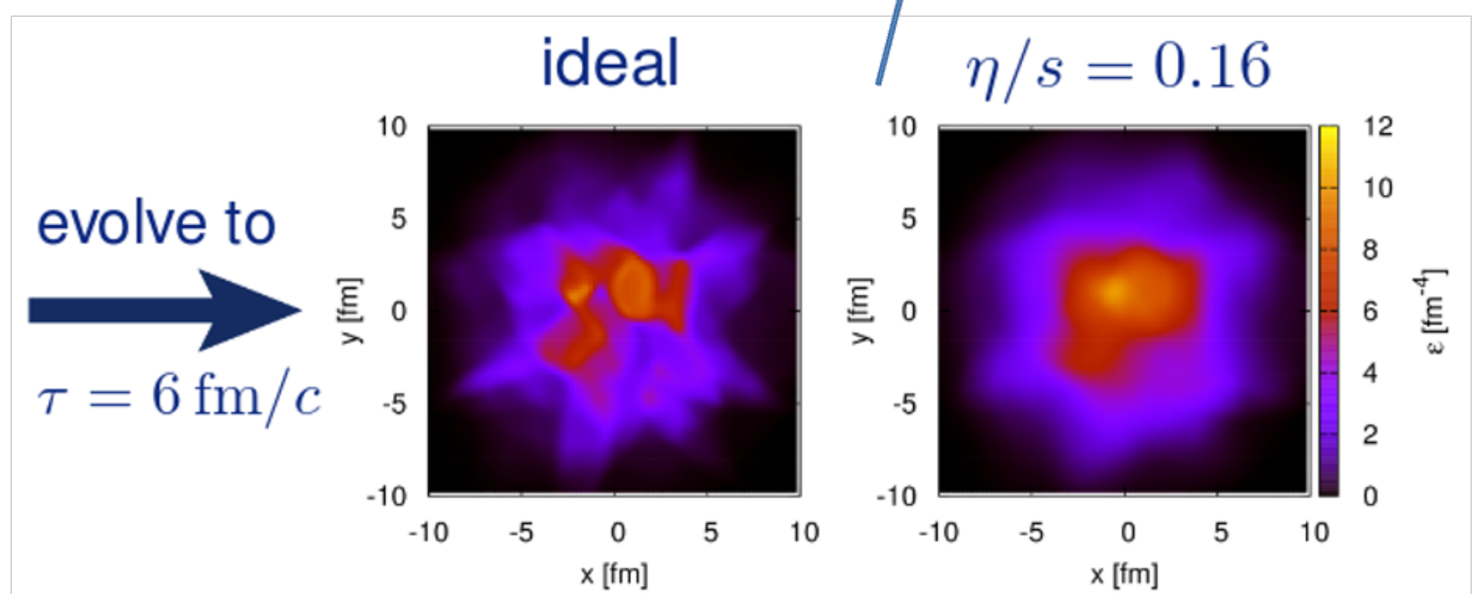


Particles observed in the detector.



Hadronization – transition from QGP to hadronic matter.



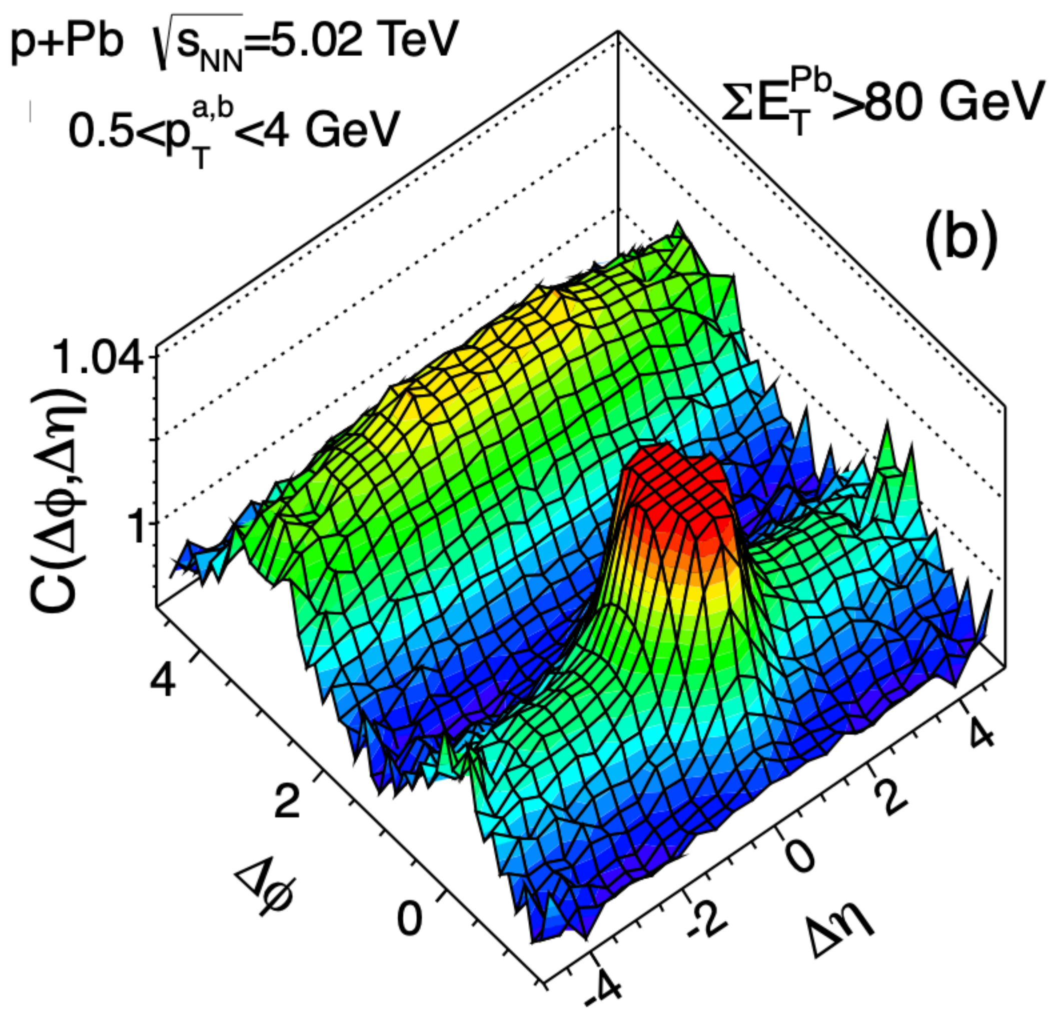


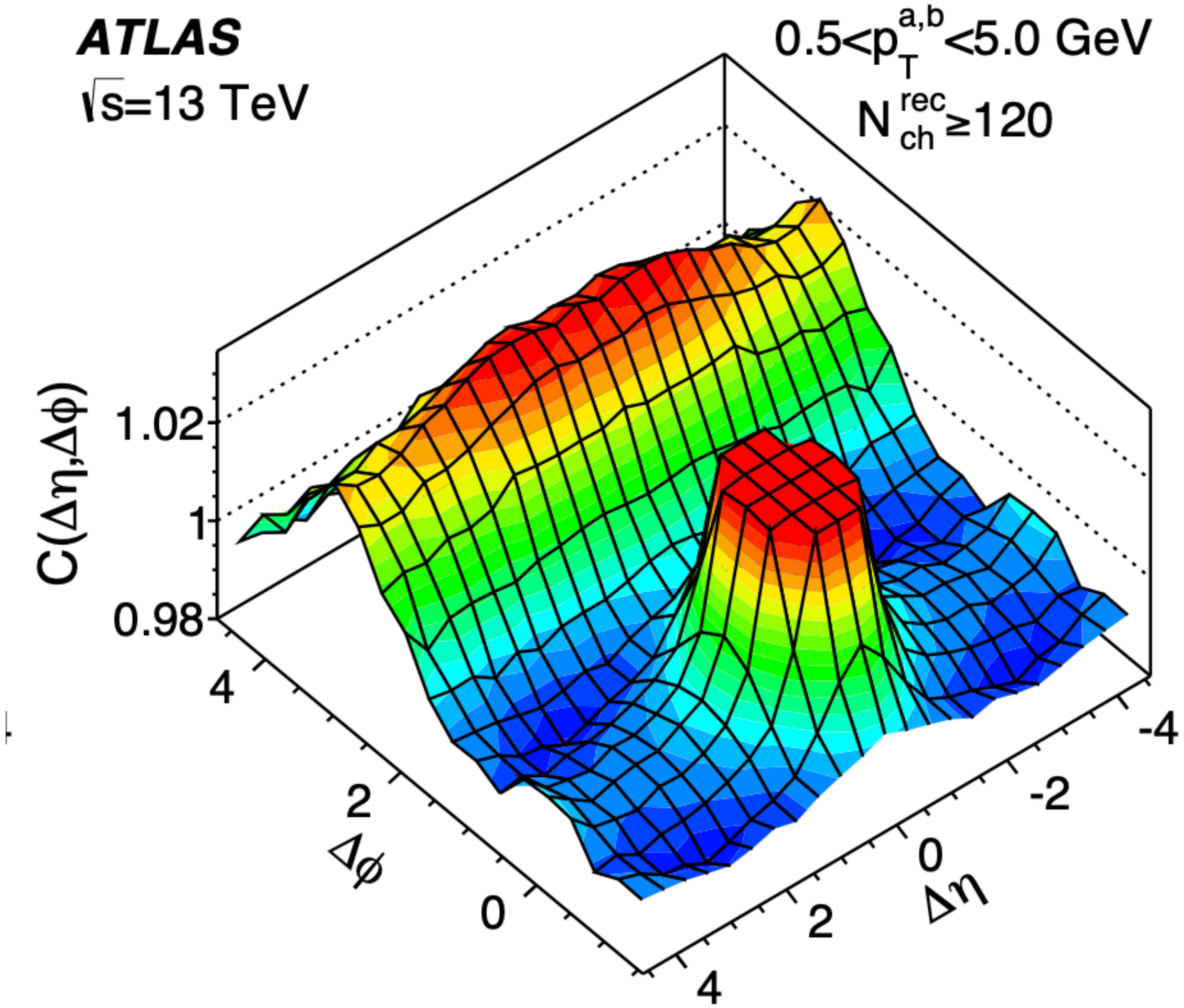
Just after collision – large eccentricity (ε) in the nucleons distributions gives rise to the internal pressure gradients.

Hydrodynamic evolution; properties of QGP state.

Magic of the template fit

PRL 110 182302 (2013)
PRL 116 172301 (2016)

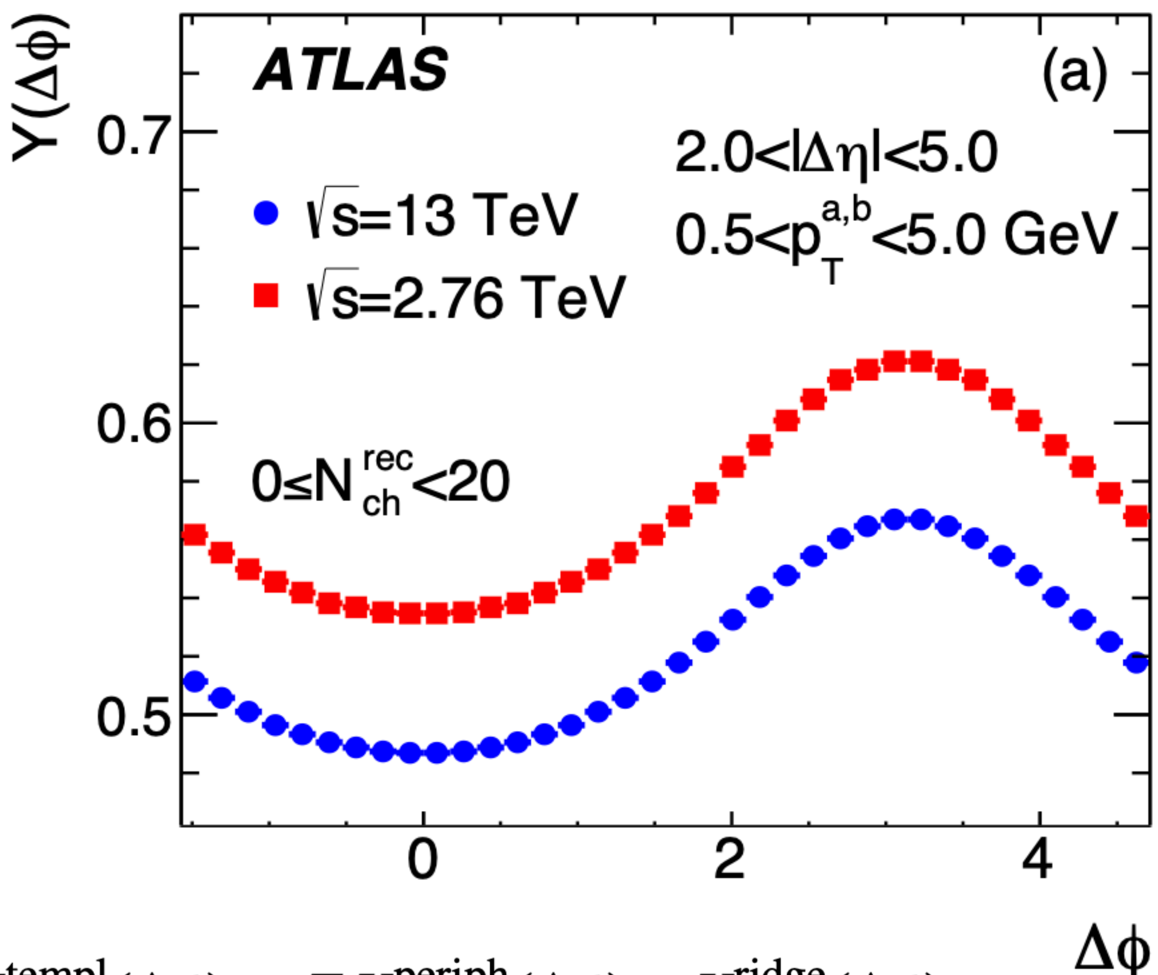




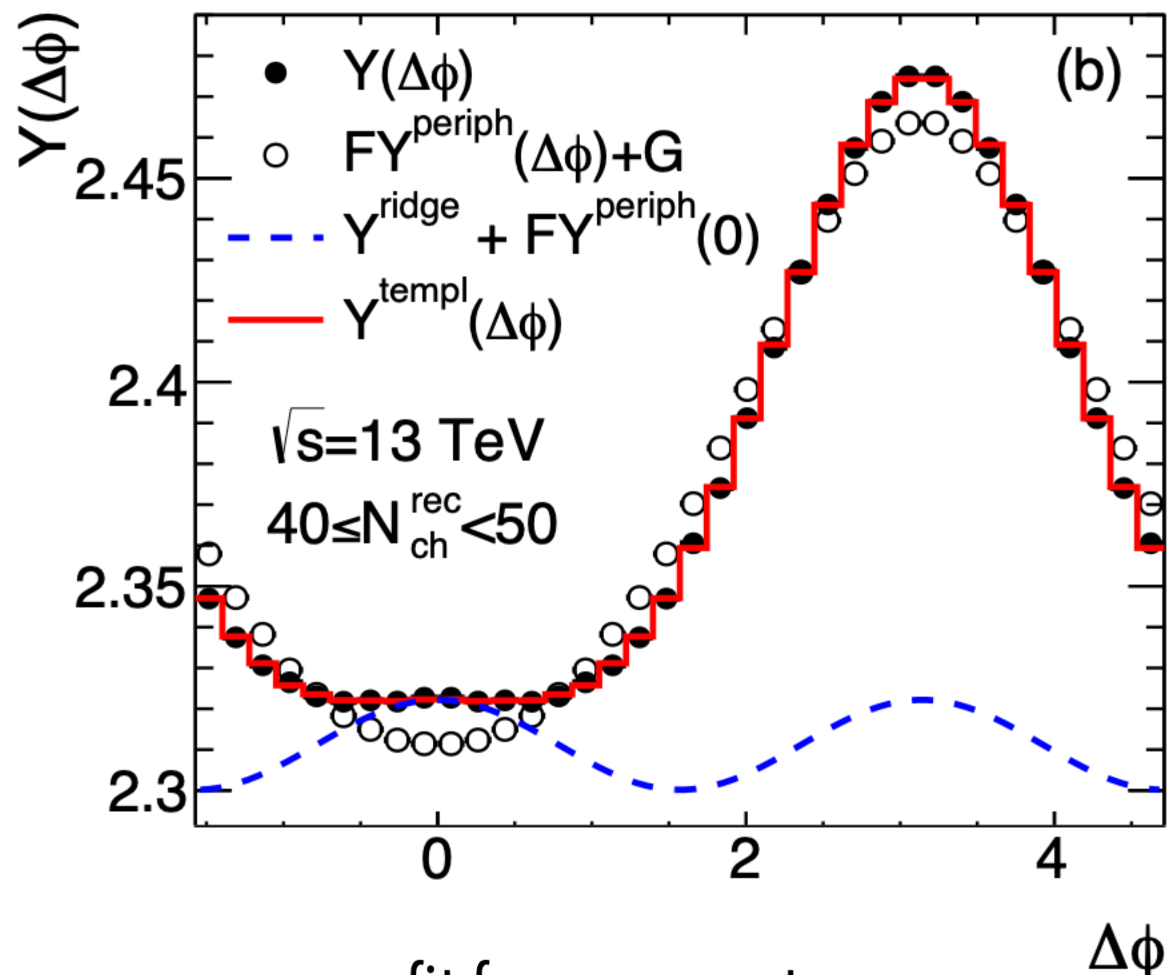
Looking for v_n in smaller systems is challenging due the presence of the large non-flow background

Magic of the template fit

$Y^{periph}(\Delta\Phi)$, $N_{ch}^{rec} < 20$



$40 < N_{ch}^{rec} < 50$



$$Y^{\rm templ}(\Delta\phi) = F\, Y^{\rm periph}(\Delta\phi) + Y^{\rm ridge}(\Delta\phi)\,,$$

$$Y^{\rm ridge}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi))\ ,$$

fit free parameters:

F & $v_{2,2}$

G fixed such that:

$$\int_0^{\pi} \mathrm{d}\Delta\phi\ \ Y^{\rm templ} = \int_0^{\pi} \mathrm{d}\Delta\phi\ \ Y$$