Probing jet quenching and dijet acoplanarity with semi-inclusive hadron+jet measurements

Jaime Norman for the ALICE collaboration
LPSC Grenoble

QGP France, Etretat
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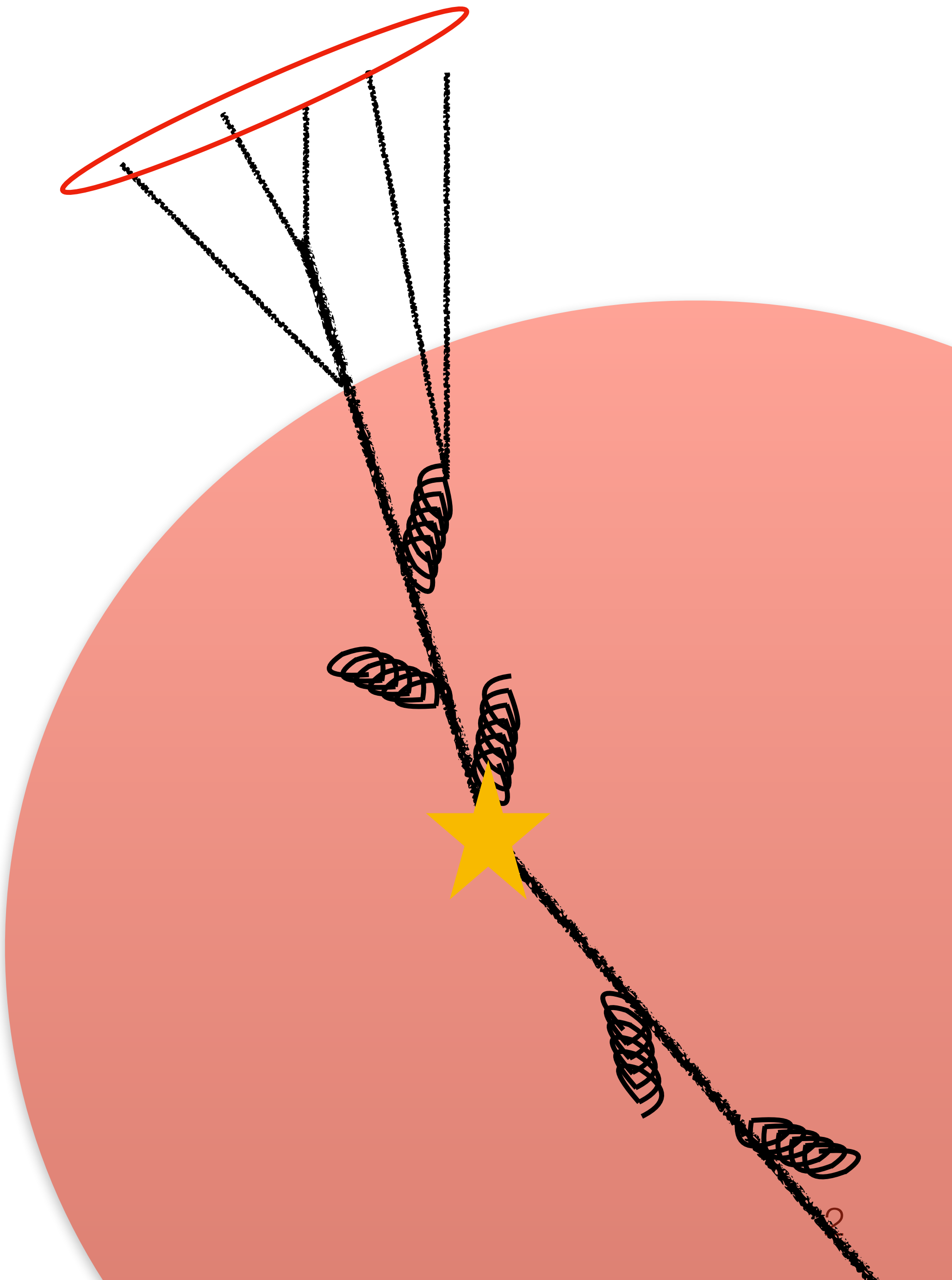
Jets as a probe of the Quark Gluon Plasma

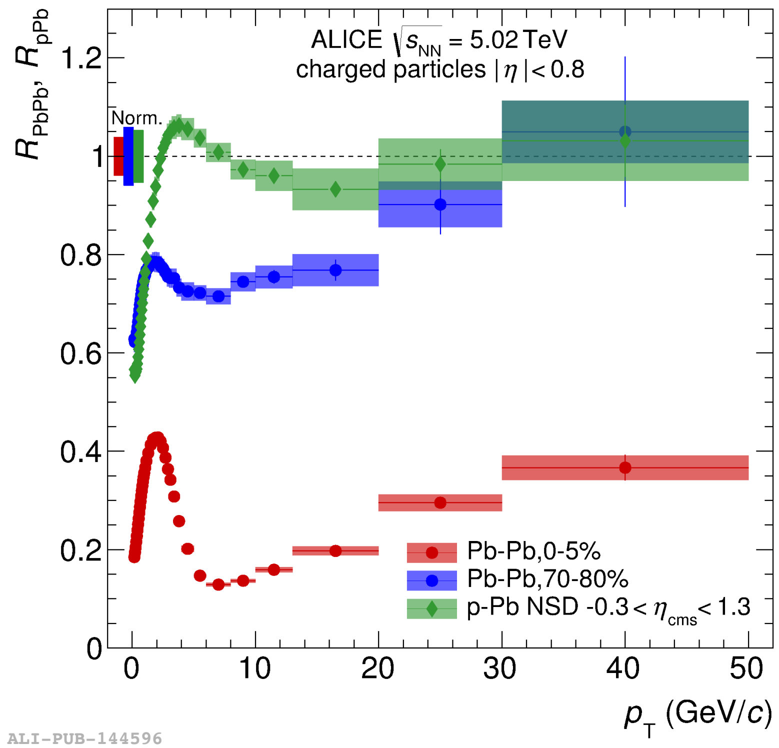
- The measurements of jets in heavy-ion collisions provides a unique probe of the Quark-Gluon Plasma
  - Self-generated probe produced in **hard partonic scattering** processes
  - Production/evolution in vaccum well studied
- Jets lose energy traversing the medium (**jet quenching**), interaction via hard/soft processes
  - Vacuum evolution, high Q^2 interaction with medium, radiative energy loss, multiple soft scattering…

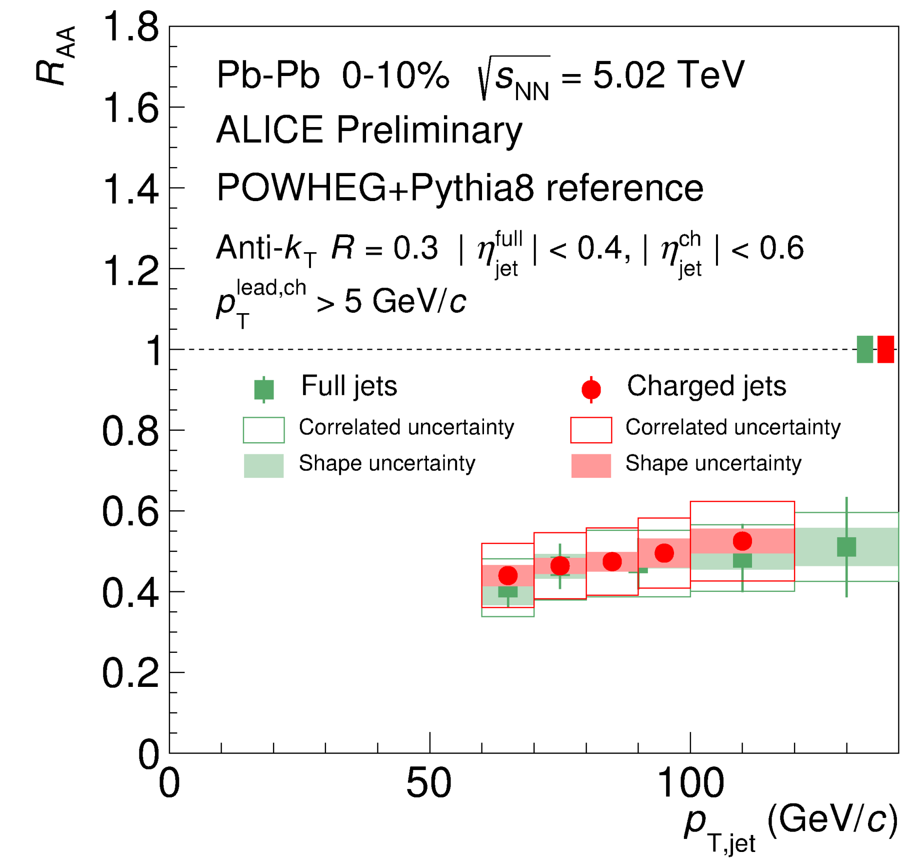


The measurement and characterisation of jets in heavy-ion collisions is a multi-scale test of QCD

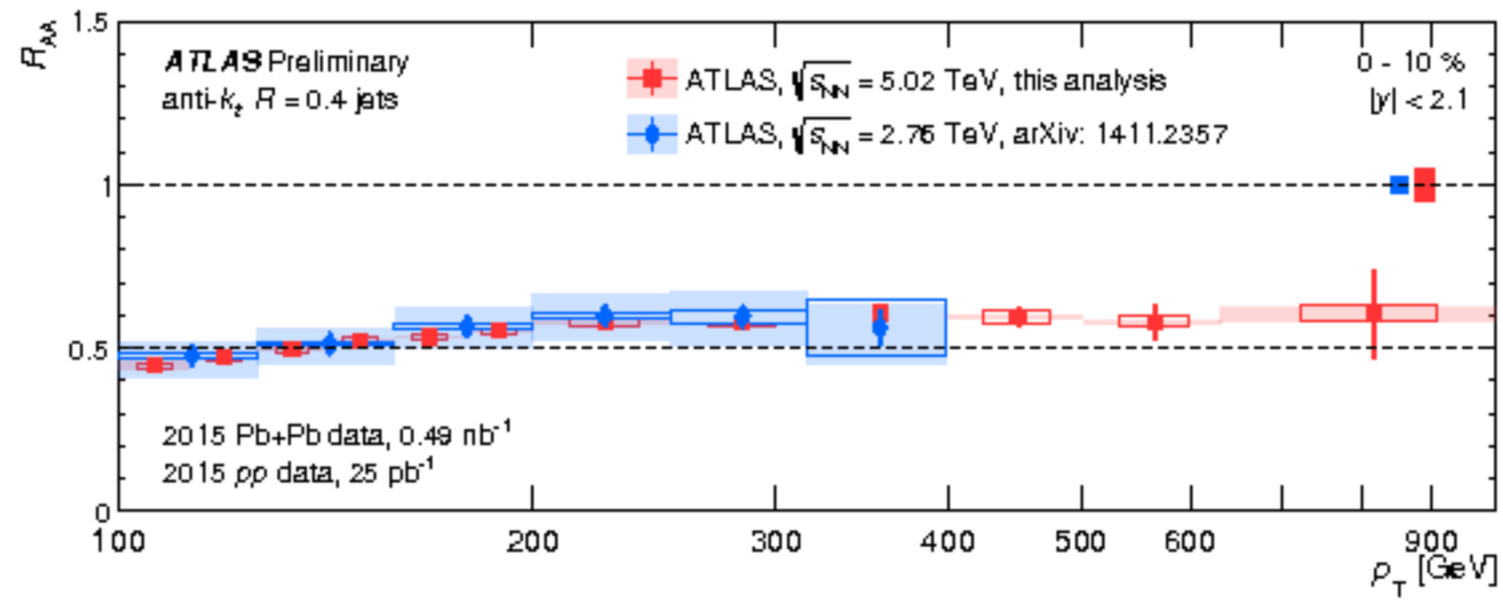
Jet quenching

arXiv:1802.09145





ATLAS-CONF-2017-009

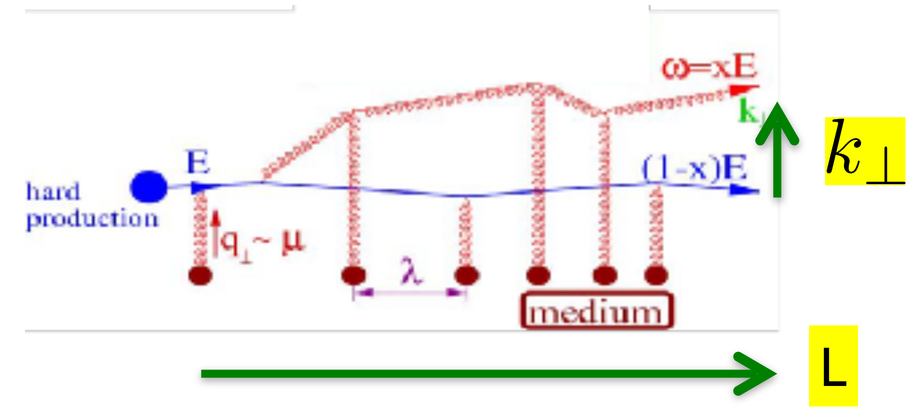


- After first indication of jet quenching from RHIC (suppression of away side peak from charged h-h correlation, hadron R_{AA}), now many direct jet measurements
- **Significant quenching** of **charged** and **full** jets seen in Pb-Pb collisions
- **Quenching up to ~TeV scale**

Characterisation of medium

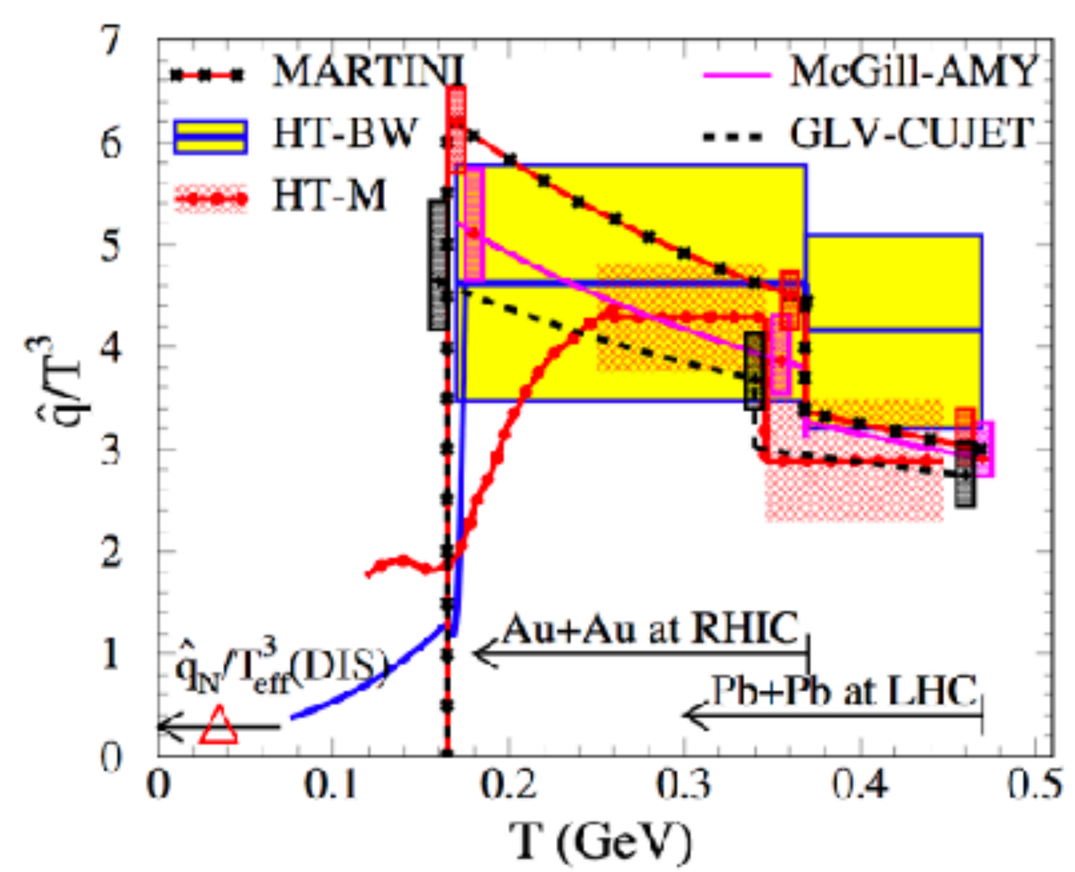
- Strength of jet-medium interaction can be represented by transport coefficient $\hat{q}$, representing the density of the medium

$$\boxed{\hat{q} = d\langle p_{\perp}^{2}\rangle / dL}$$



- Describes strength of both **energy loss** and **momentum broadening**

Phys. Rev. C 90, 014909 (2014)

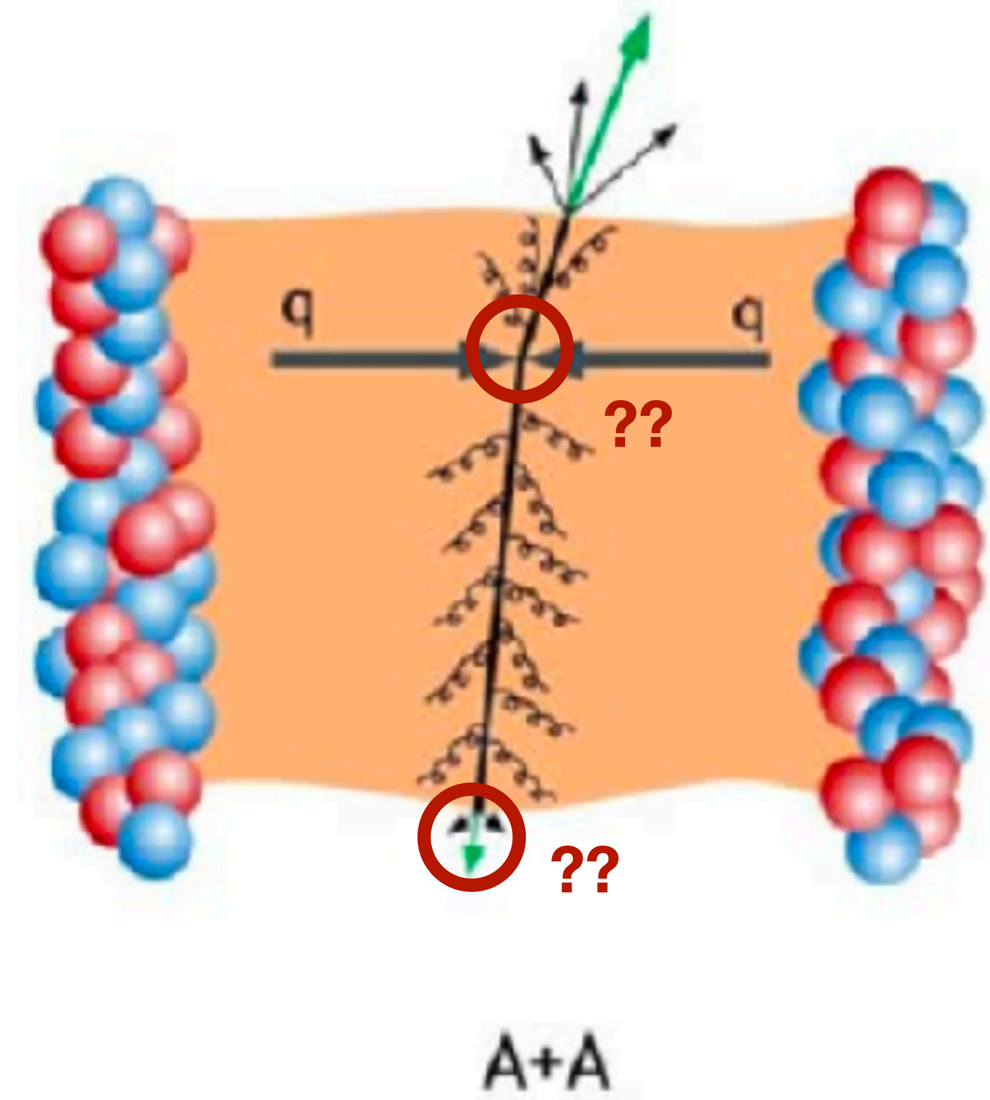


- Hadron suppression measurements used to calculate $\hat{q}$ using different (perturbative) theoretical frameworks
  - $\hat{q}$ = 1.9 GeV^2 / fm for 10 GeV quark jet, T=470 MeV
- Recent work using lattice gauge theories suggest significant non-perturbative contribution

Phys. Rev. Lett. 112, 162001 (2014)

Inclusive measurements

- Inclusive measurements essential as a baseline, but:
  - they do not provide precise constraints on the jet-medium interactions
    - Path length unknown
  - ‘Misses’ the full information of the hard scattering
    - No measurement of recoiling parton
  - **Definition of jets crucial but no rigorous way to distinguish signal from combinatorial background in heavy-ion collisions**



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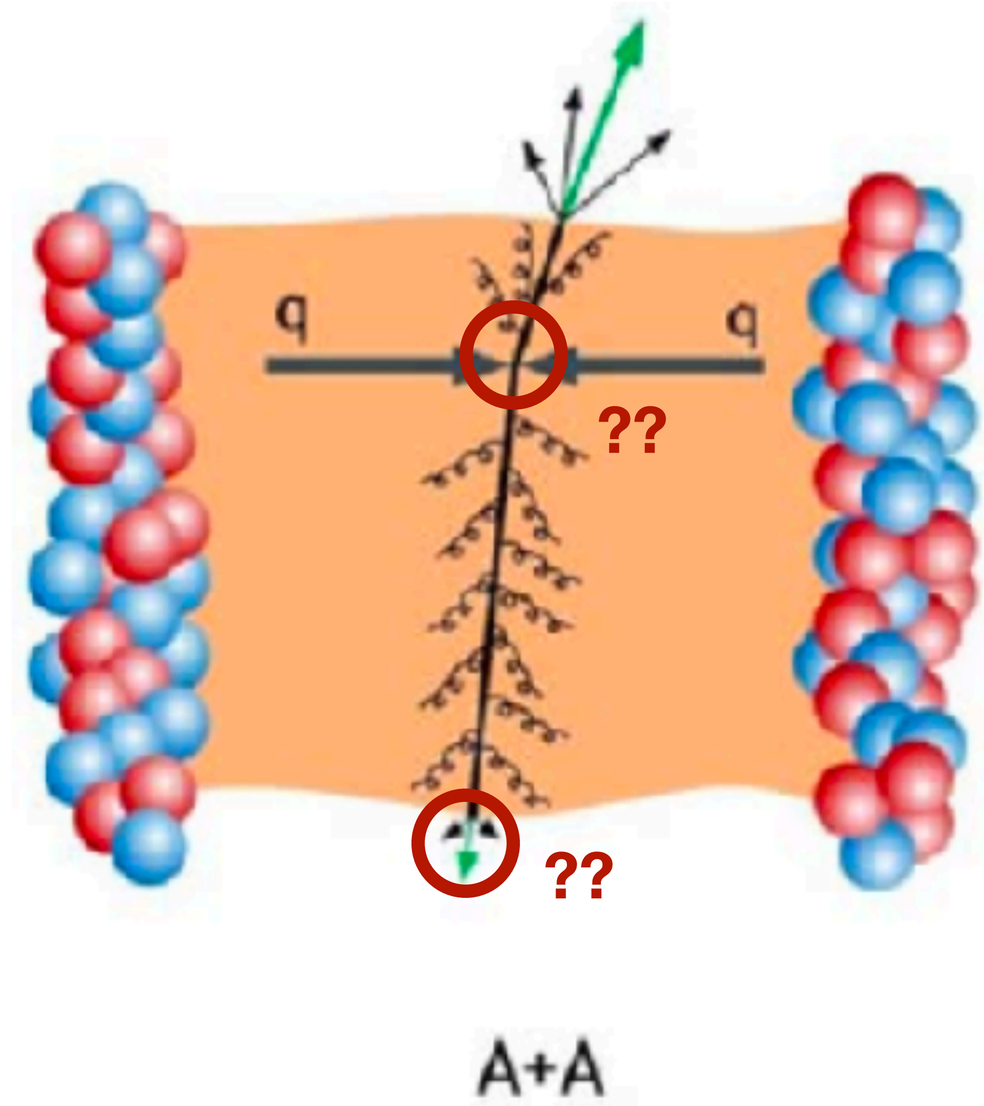
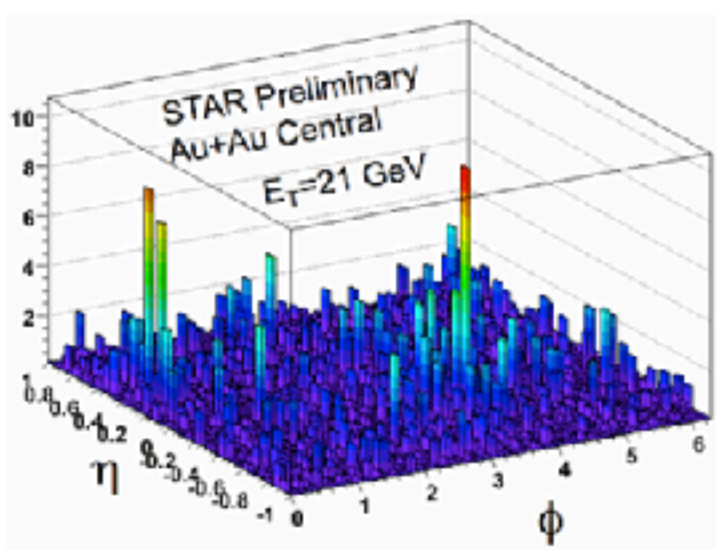


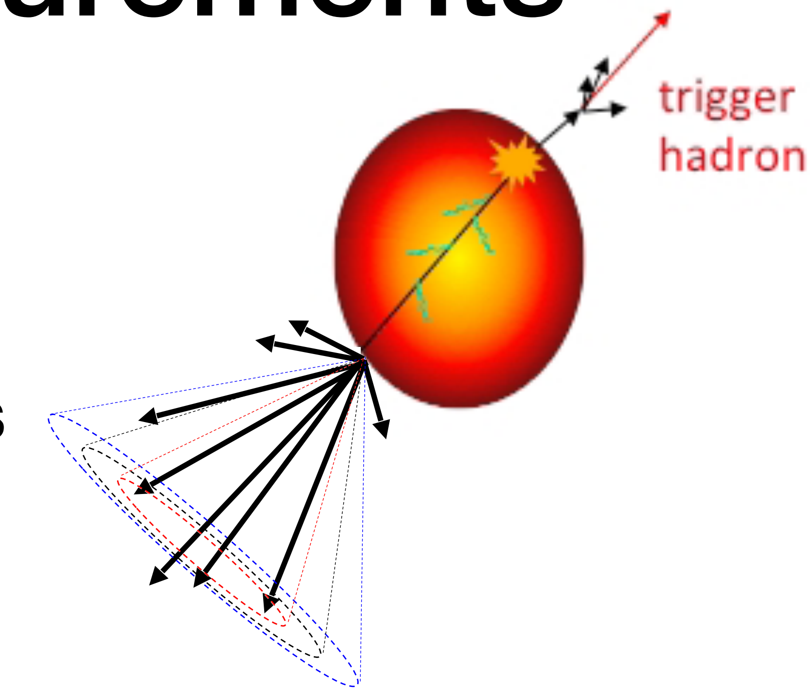


$$p_{T,i}^{reco} = p_{T,i}^{raw} - \rho \cdot A_i$$

Usual prescription to remove background can be:
- subtract 'background' density
- Leading track p_T cut
- Min. Jet p_T cut

low p_T/high R jets especially challenging!

Semi-inclusive h+jet measurements



- Methods developed to remove uncorrelated background
- **—> Measure trigger-normalised yield of jets recoiling from a trigger hadron**

$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{d^2 N_{\rm jet}^{\rm AA}}{dp_{\rm T,jet}^{\rm ch} d\eta_{\rm jet}}\bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{d^2\sigma^{\rm AA\to h+jet+X}}{dp_{\rm T,jet}^{\rm ch} d\eta_{\rm jet}} \right)\bigg|_{p_{\rm T,h}\in {\rm TT}}$$

—> Well defined in pQCD (ratio of high p_T hadron/jet cross sections)

—> Information about recoil parton

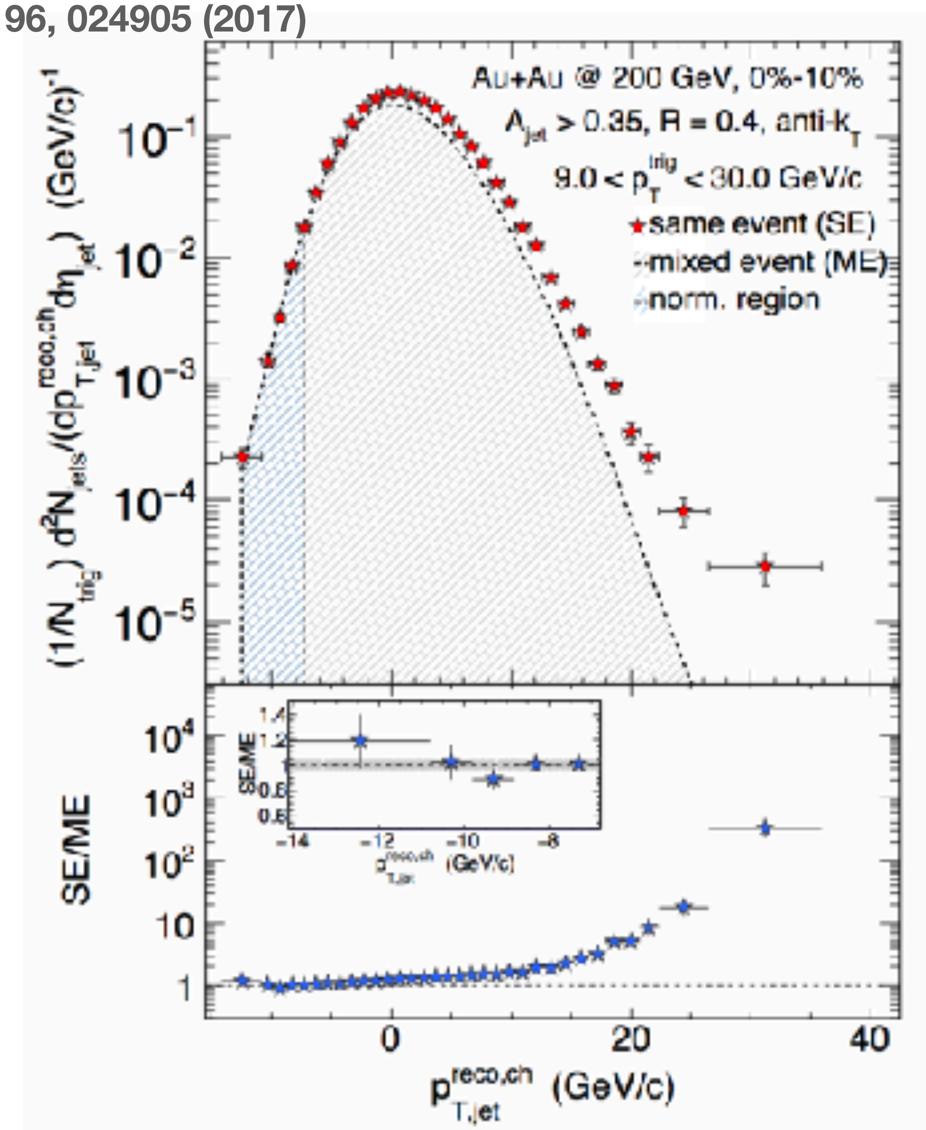
—> Background subtraction techniques allow for arbitrarily low p_T / high R jet measurements

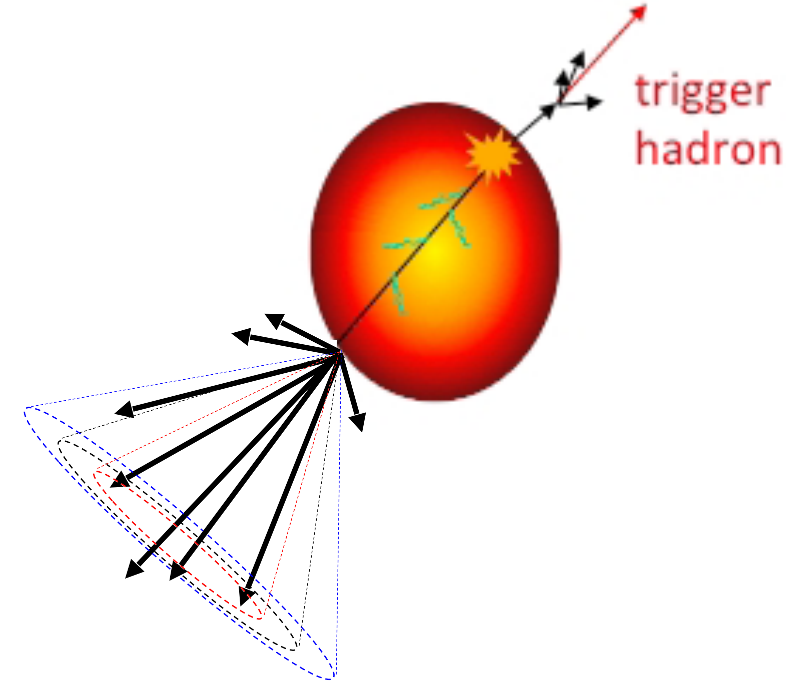
Unfolding of background subtracted distribution for detector effects / background fluctuations crucial

h+jet measurements

- Ways to subtract uncorrelated background jets:
  - STAR: **mixed-event technique** in subtracting combinatorial background

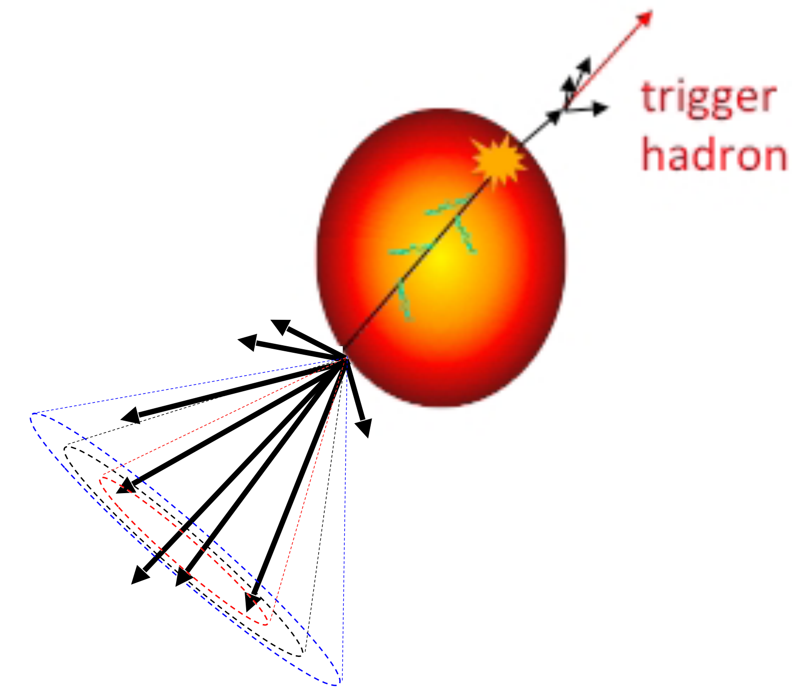
Phys. Rev. C 96, 024905 (2017)





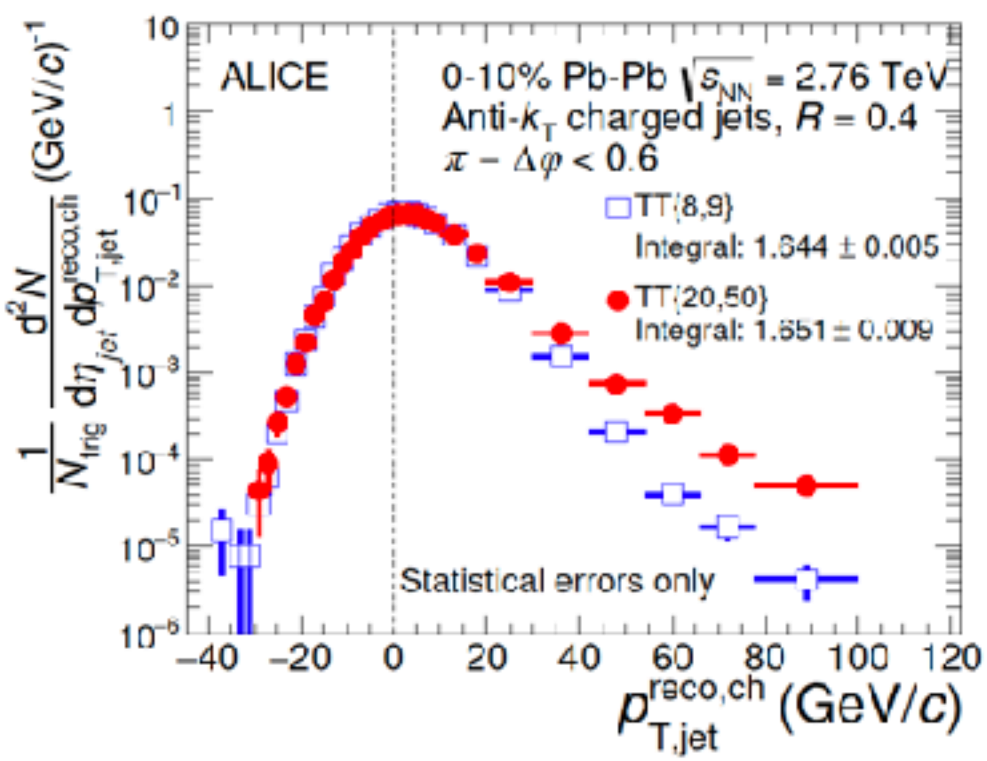
$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{d^2N_{\rm jet}^{\rm AA}}{dp_{\rm T,jet}^{\rm ch}\, d\eta_{\rm jet}}\bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{d^2\sigma^{\rm AA\to h+jet+X}}{dp_{\rm T,jet}^{\rm ch}\, d\eta_{\rm jet}} \right)\bigg|_{p_{\rm T,h}\in {\rm TT}}$$

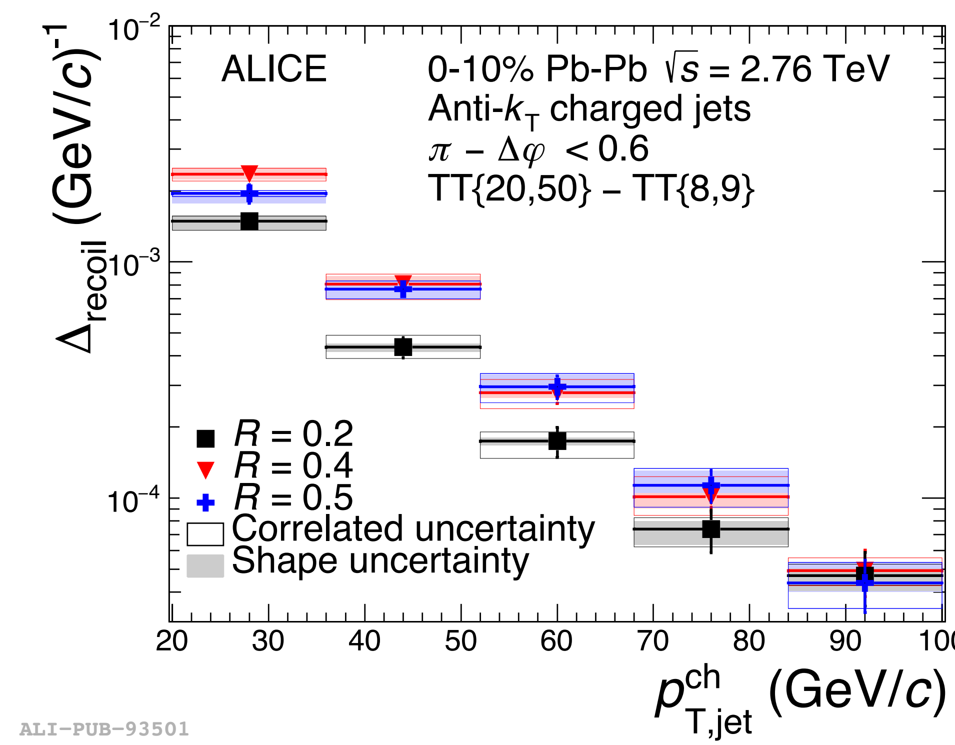
h+jet measurements



- Ways to subtract uncorrelated background jets:
  - STAR: **mixed-event technique** in subtracting combinatorial background
  - ALICE: **Subtraction** of normalised recoil jet distribution in '**reference**' trigger track interval from '**signal**' trigger track interval

JHEP 09 (2015) 170





$$\Delta_{\mathrm{recoil}} = \frac{1}{N^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2 N^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Sig}}} - c \cdot \frac{1}{N^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2 N^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Ref}}}$$

Recoil jet modification (ALICE)

$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Sig}}} - c \cdot \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Ref}}}$$

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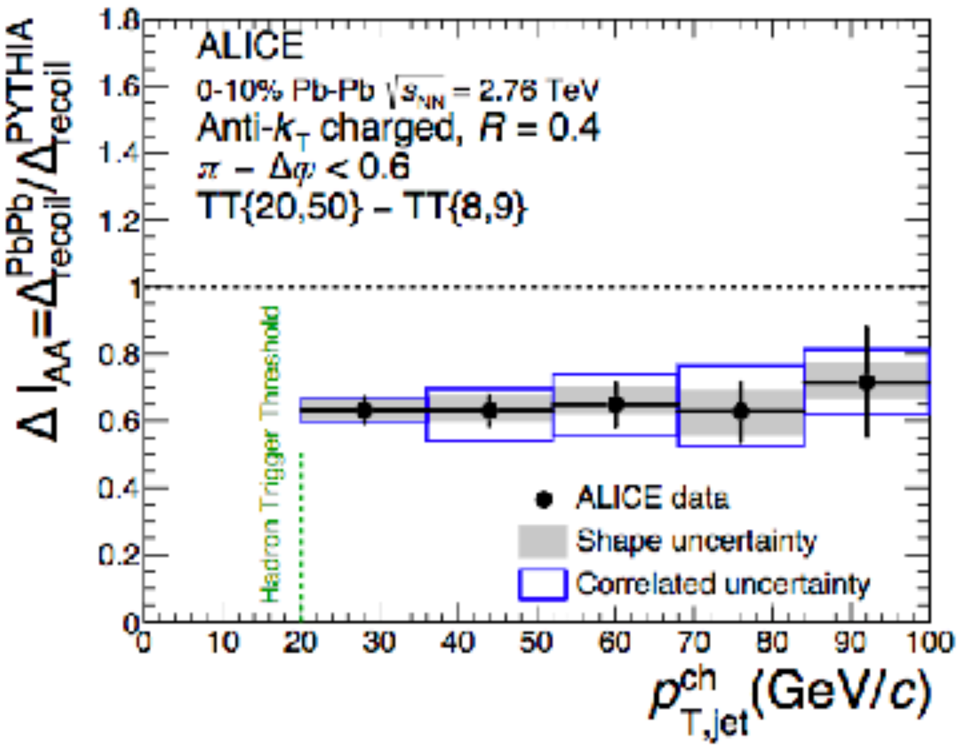
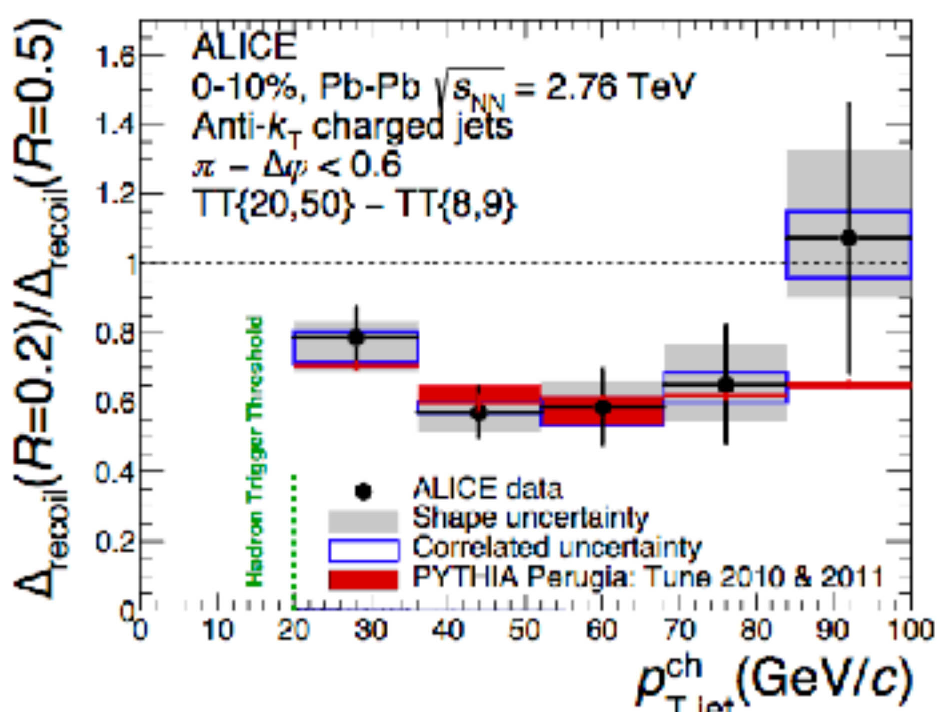




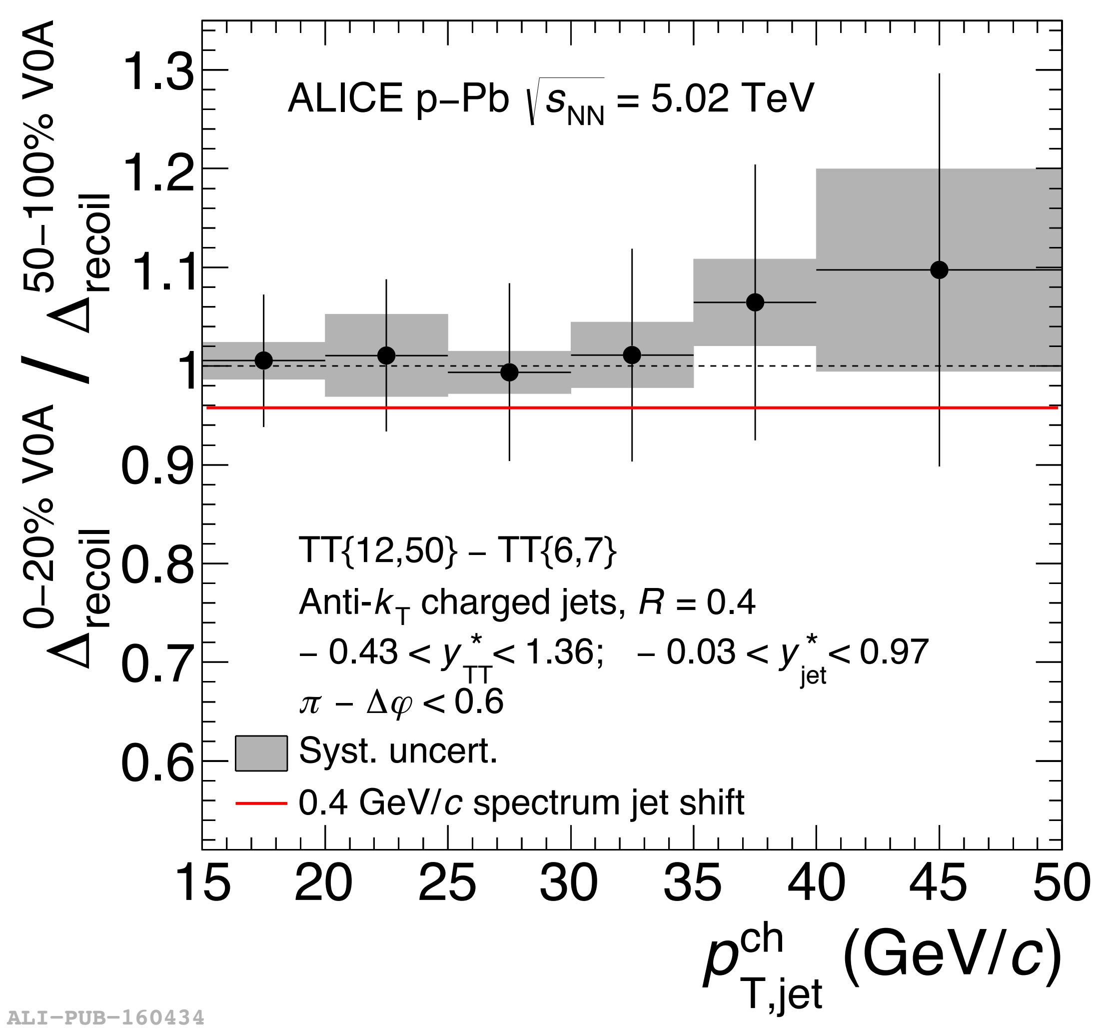
- Ratio of Δ_{recoil} in heavy-ion collisions with a reference gives access to jet quenching information (ΔI_{AA})
  - Differential recoil jet yield **suppressed by up to a factor 2** with respect to pp (PYTHIA) reference
- Measurement at different jet cone radii R gives access to jet energy redistribution
  - Energy predominantly **radiated to angles larger than R=0.5**

Note: PYTHIA (simulation) reference

Jet quenching in smaller systems?

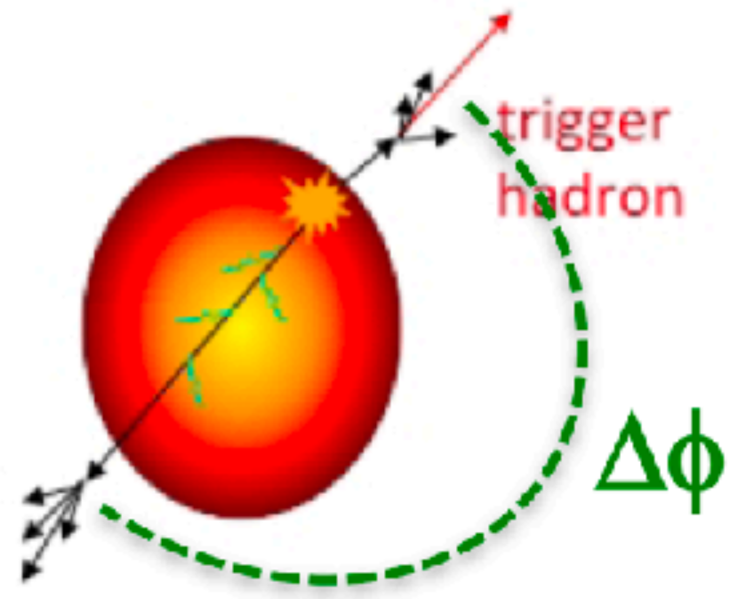
- Measurement in p-Pb collisions gives access to cold nuclear matter effects / centrality dependence of jet production
  - Jet quenching in smaller systems?
- Ratio of Δ_{recoil} in different centrality intervals **consistent with unity**, indicates **minimal jet quenching in p-Pb collisions**
  - < 0.4 GeV energy loss out-of-cone for jets 15 < pT < 50 GeV/c, R=0.4 (90% CL)
- **Consistent with conclusions** drawn from charged particle, HF R_{AA} in p-Pb collisions

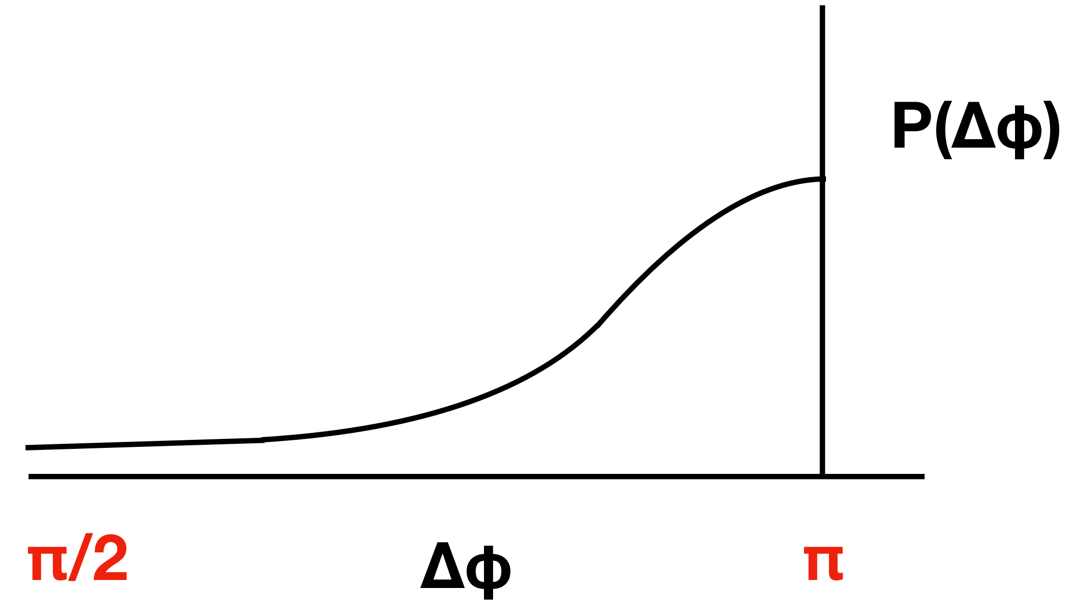
arXiv:1712.05603



Di-jet azimuthal correlation

- Azimuthal distribution of recoil jet can give important insight into properties of the Quark-Gluon plasma





Di-jet azimuthal correlation

- Azimuthal distribution of recoil jet can give important insight into properties of the Quark-Gluon plasma
    1. Broadening of away side peak could give direct access to transport coefficient $\hat{q}$ of the medium
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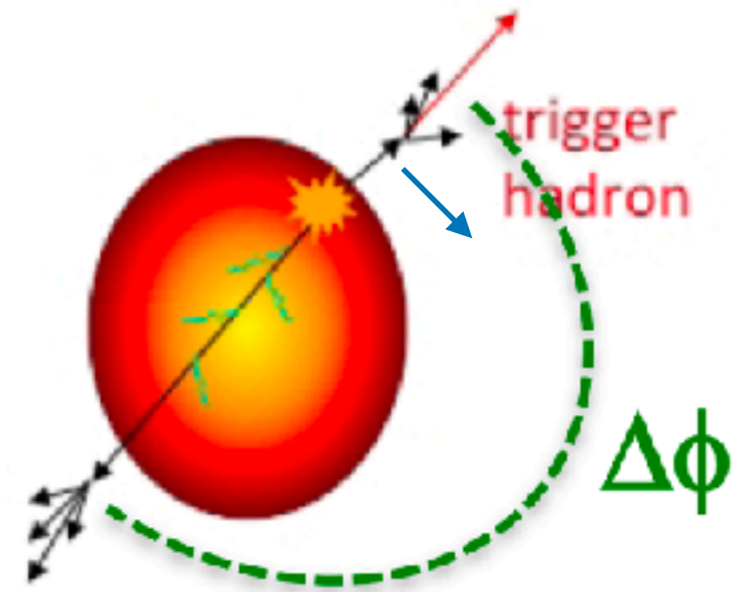
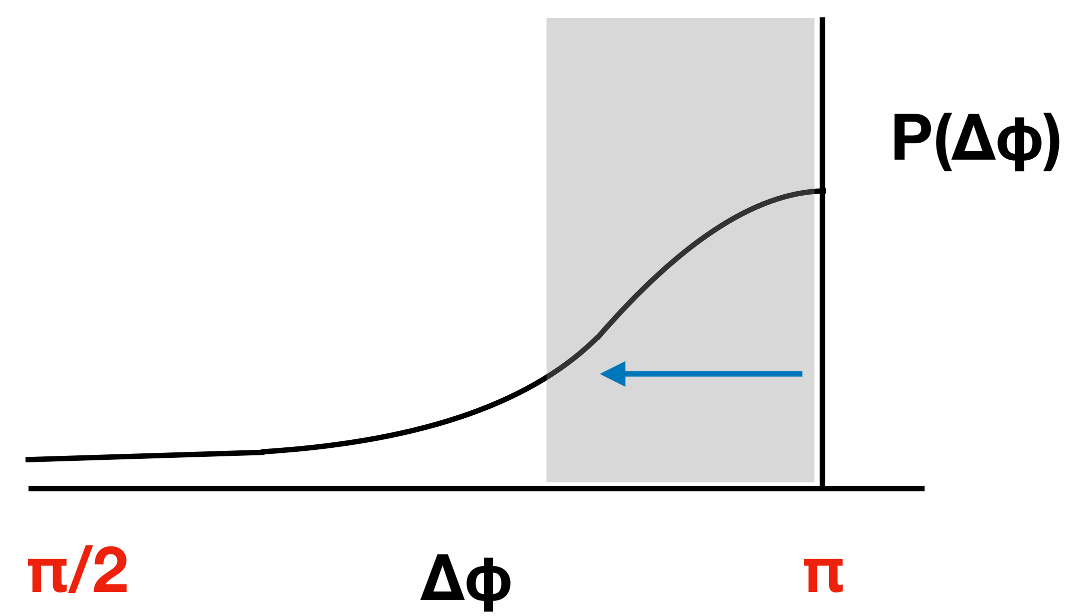
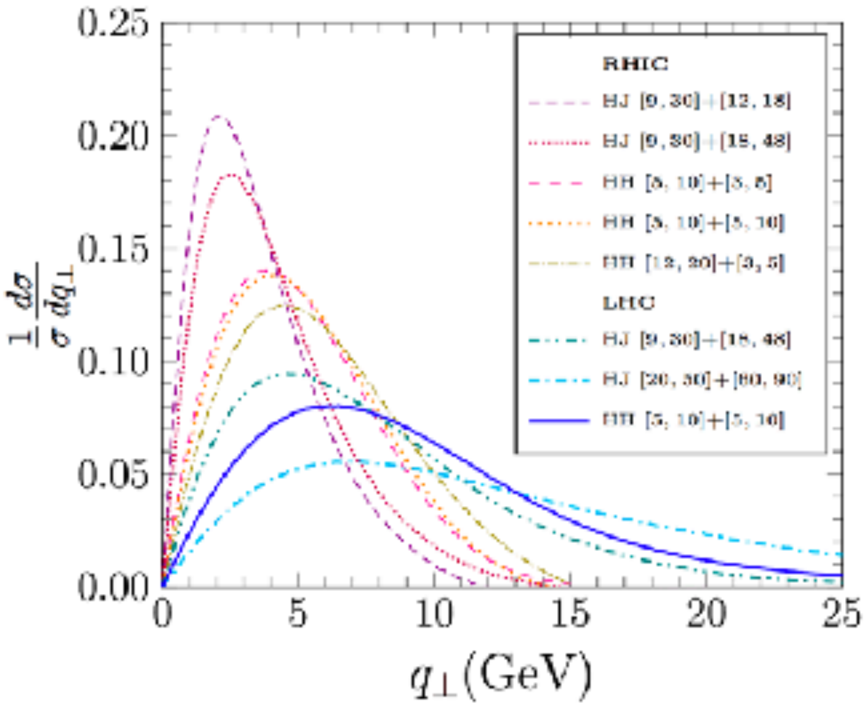




$$\hat{q} = d\langle p_{\perp}^{2} \rangle / dL$$

1) Medium induced broadening



Vacuum (Sudakov) expectation

- Gluon showers cause broadening in vacuum
- Calculations in excellent agreement with experiment
  - ‘Reference’ to study medium-induced broadening
- Broader q distribution at LHC energies as jet pT increases —> **lower pT jets more effective at probing medium effects**

Phys.Lett. B773 (2017) 672-676

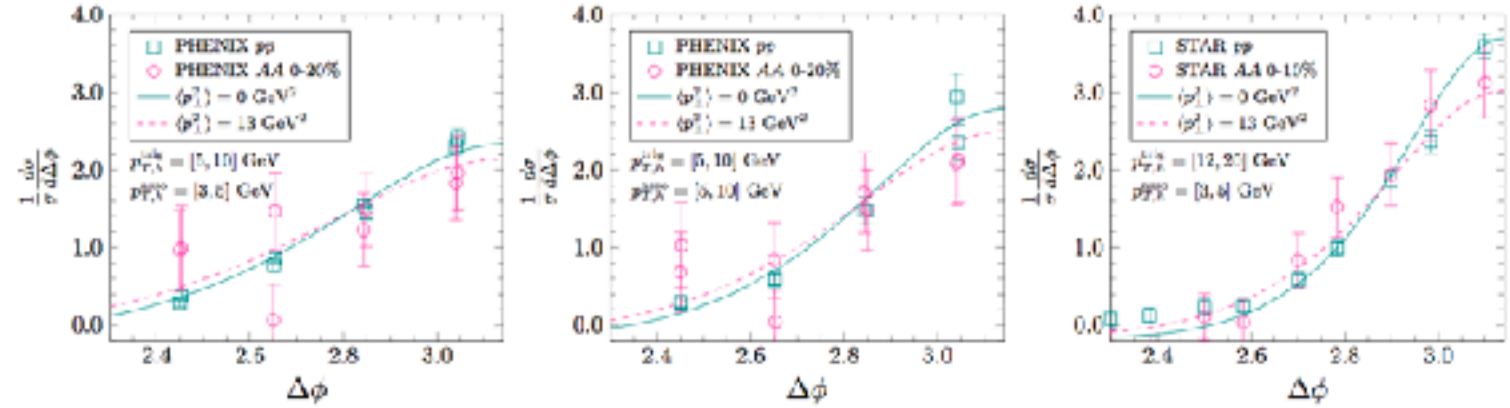
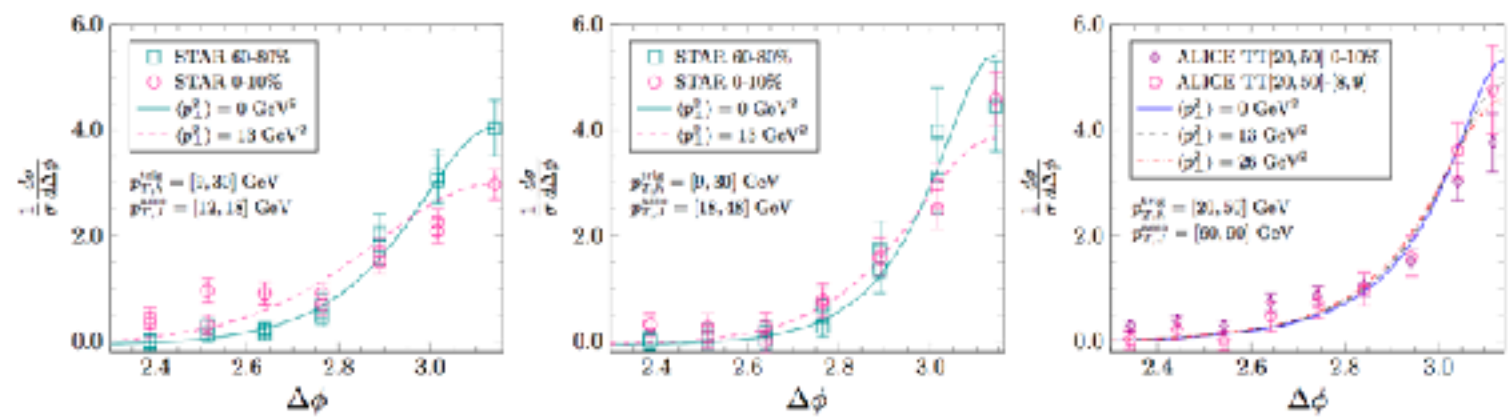


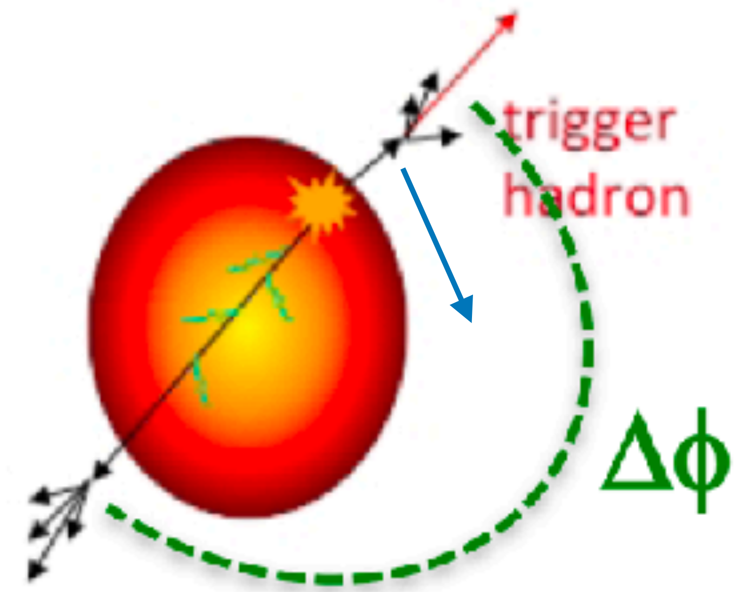
FIG. 1. Normalized dihadron angular correlation compared with PHENIX [50] and STAR [51] data.



- Fits to data then gives potential to directly extract $\hat{q}$
- Fits to STAR data give $\langle p_T^2 \rangle$ ~ 13 GeV/c

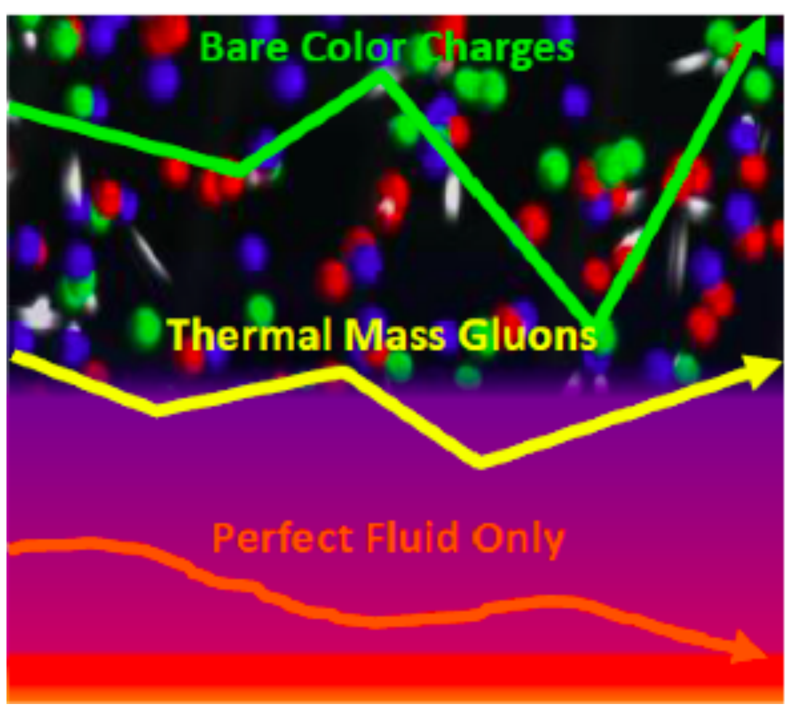
Di-jet azimuthal correlation

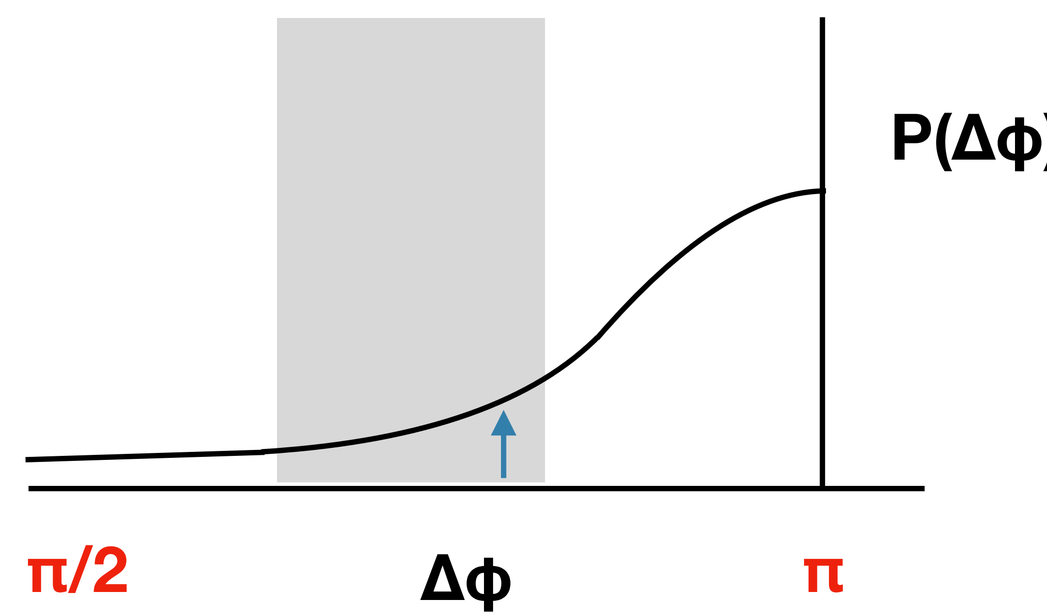
- Azimuthal distribution of recoil jet can give important insight into properties of the Quark-Gluon plasma
    1. Broadening of away side peak could give direct access to transport coefficient $\hat{q}$ of the medium
    2. Measurement of yield at large angles could reveal strong/weak degrees of freedom within the QGP
        - Rare but non-zero probability of large-angle deflection if bare colour charges can be resolved



Discreet scattering centres

Effectively continuous medium



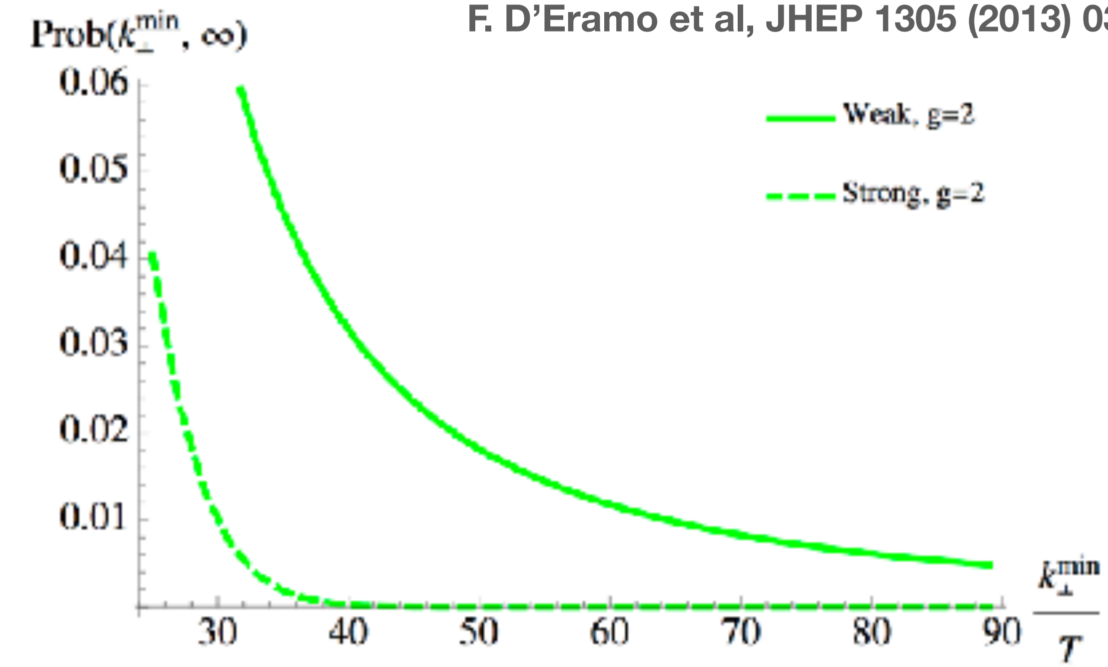


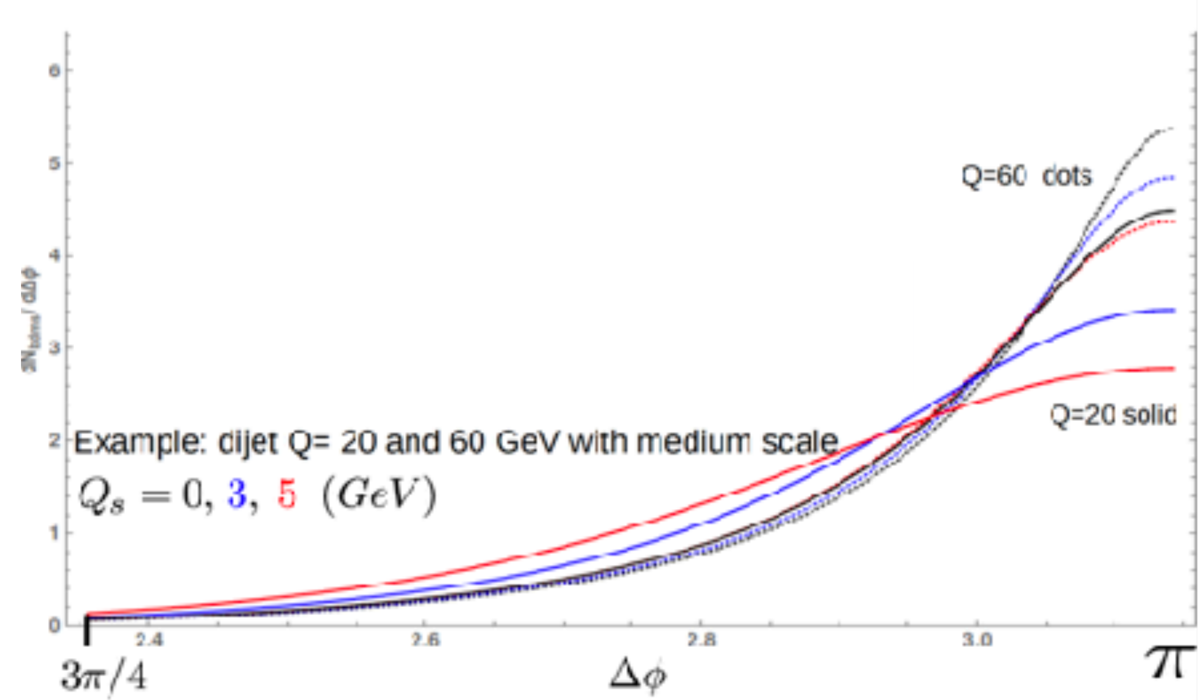
2) Large-angle scattering

- Rare ‘hard’ scattering processes in-medium can deflect jets to large angles (Moliere scattering)
  - Equivalent to Rutherford scattering experiment in heavy-ion collisions
- Measuring an **excess of large angle deflections** in heavy ion collisions relative to the vacuum reference would give evidence towards quasi-particle (weakly coupled) nature of QGP
- Some recent theoretical interest **highlights motivation of measuring low-Q^2 interactions**

arXiv:1211.1922

F. D’Eramo et al, JHEP 1305 (2013) 031





M. Gylassy, QM18

ALICE h+jet measurement in Pb-Pb collisions

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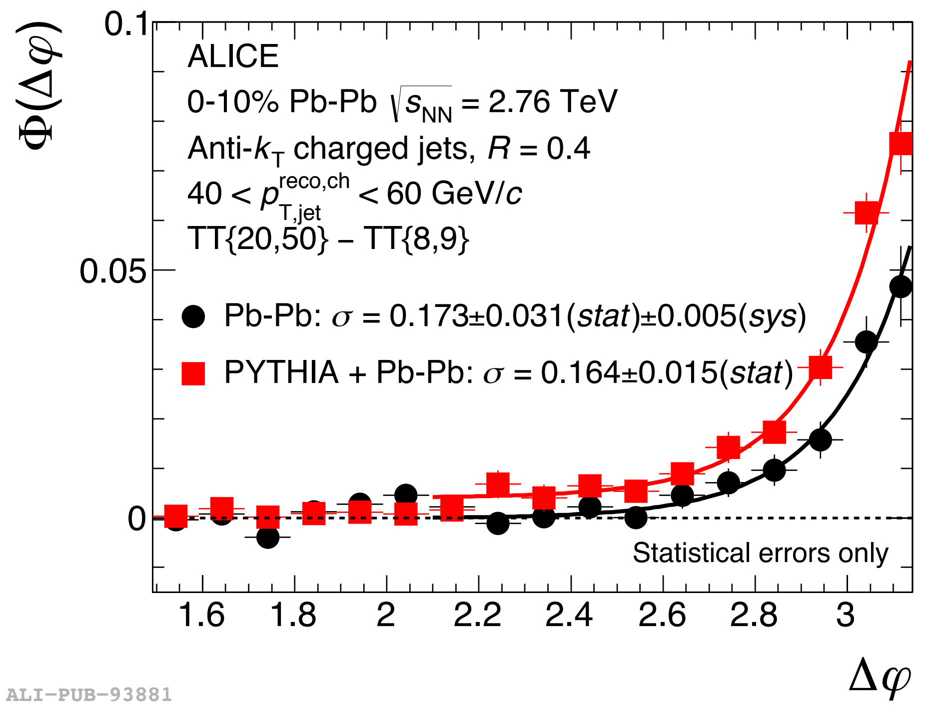
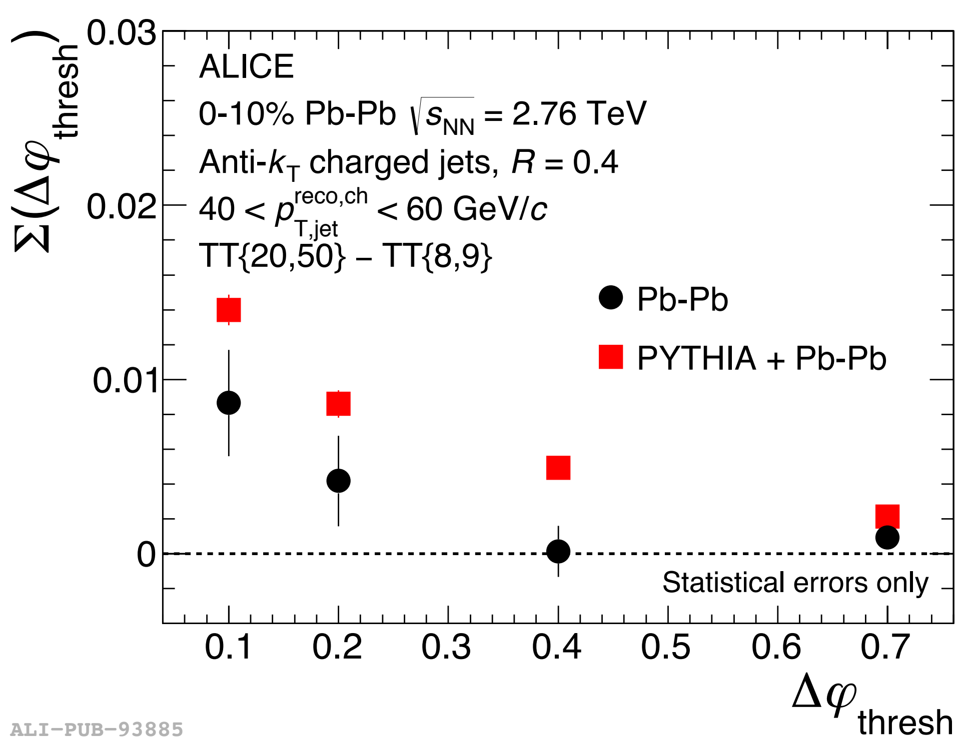




- Δϕ distribution in Pb-Pb collisions shows no difference in yield at large angles with respect to pp expectation
- But..
  - Result not unfolded for detector/background effects
  - Relatively high jet pT
  - Statistics-limited

Similar observations made by STAR

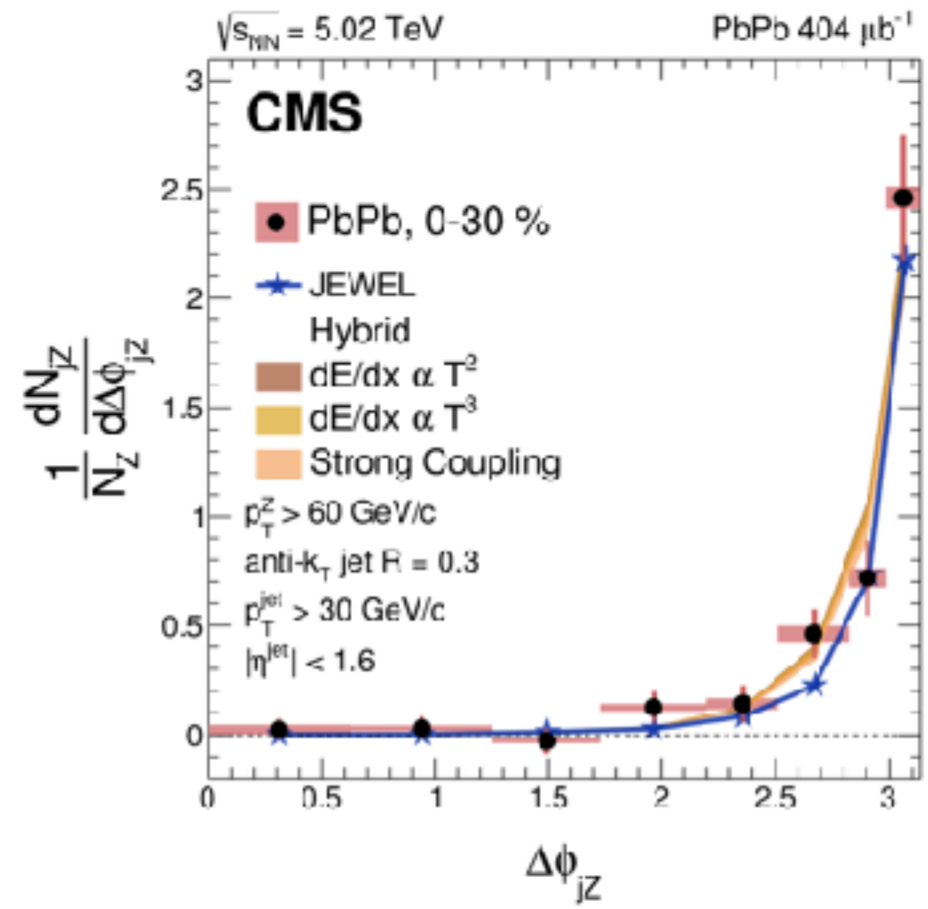
Other LHC measurements

Boson-jet measurements experimentally clean

Z+jet

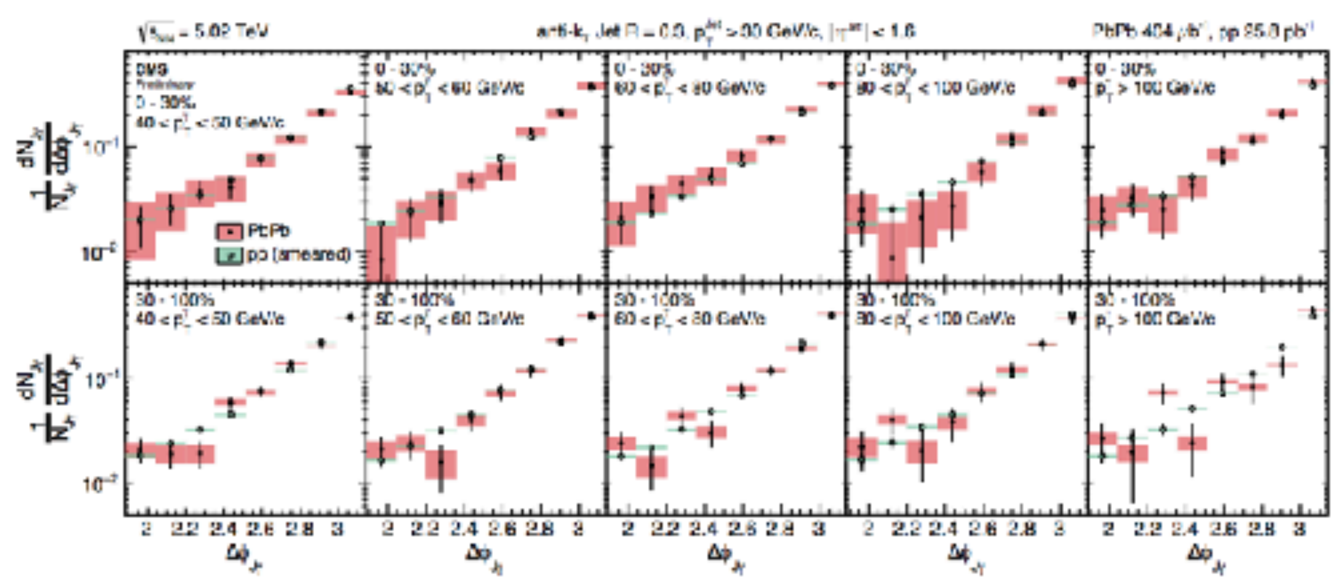
- CMS measured z+jet correlation in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- In the kinematic region of CMS, very different coupling/energy loss scenarios gives negligible change in Δφ distribution

Phys. Rev. Lett. 119, 082301 (2017)



photon+jet

- CMS measured γ+jet correlation in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Measurement in Pb-Pb collisions consistent with pp collisions within uncertainties

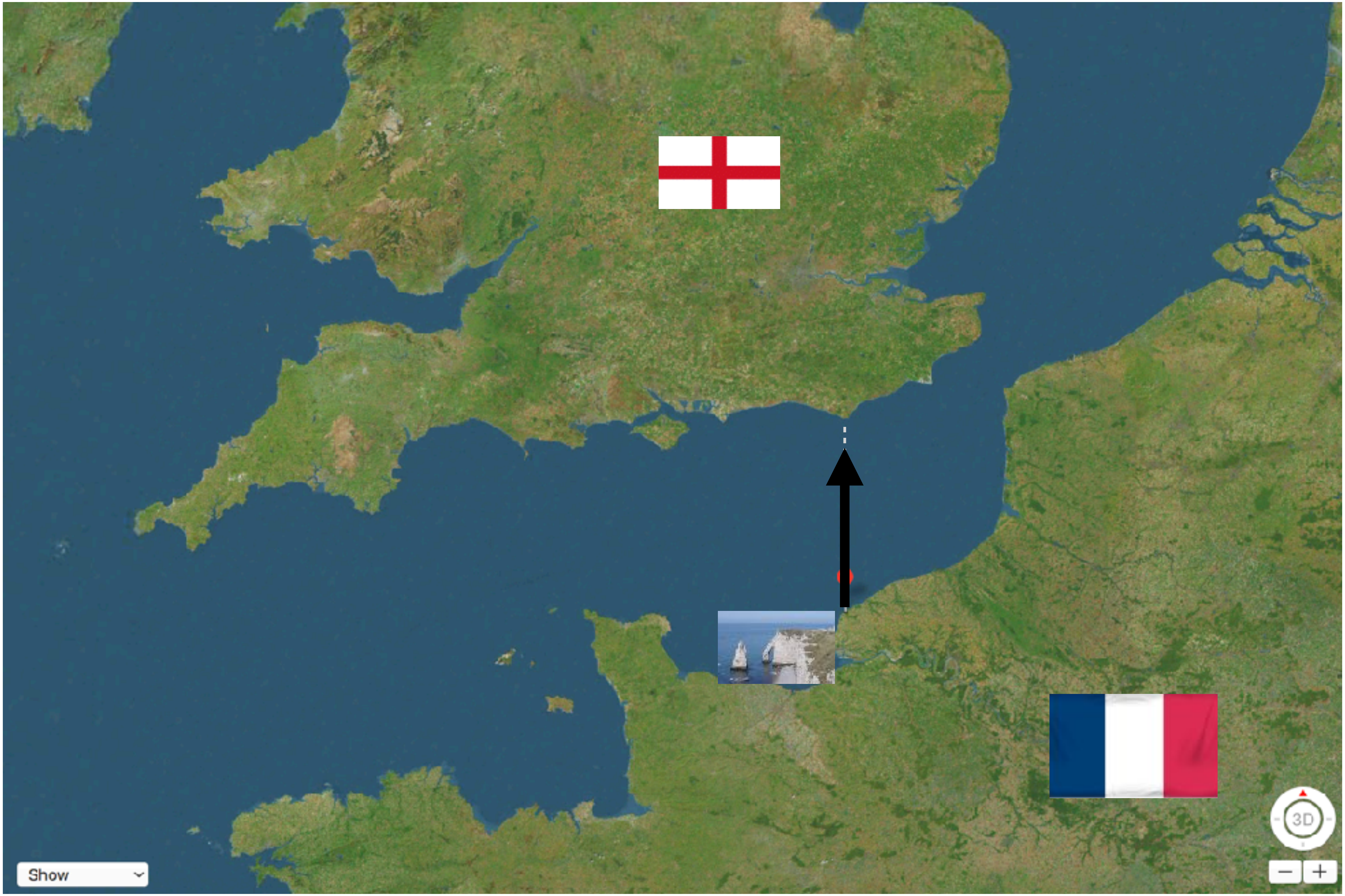


arXiv:1711.09738

Summary and Outlook

- Semi-inclusive measurement of jets recoiling from trigger hadron gives insight into jet-medium interactions:
  - Jet quenching effects seen at R=0.2-0.5, indications that jet energy radiated to angles < 0.5
  - No indication yet seen for large angle scattering
- Theoretical advances suggest low-pT jets most sensitive to large-angle scattering
- Current measurements limited by statistics

- ALICE measurement at 5.02 should further knowledge about jet medium interactions:
  - **ALICE Run 2:** Large Pb-Pb + pp data samples at 5.02 TeV, plus more data expected at the end of the year
  - **ALICE upgrade:** up to 100x min. bias stats expected + improved tracking at low p_T due to Inner Tracking System upgrade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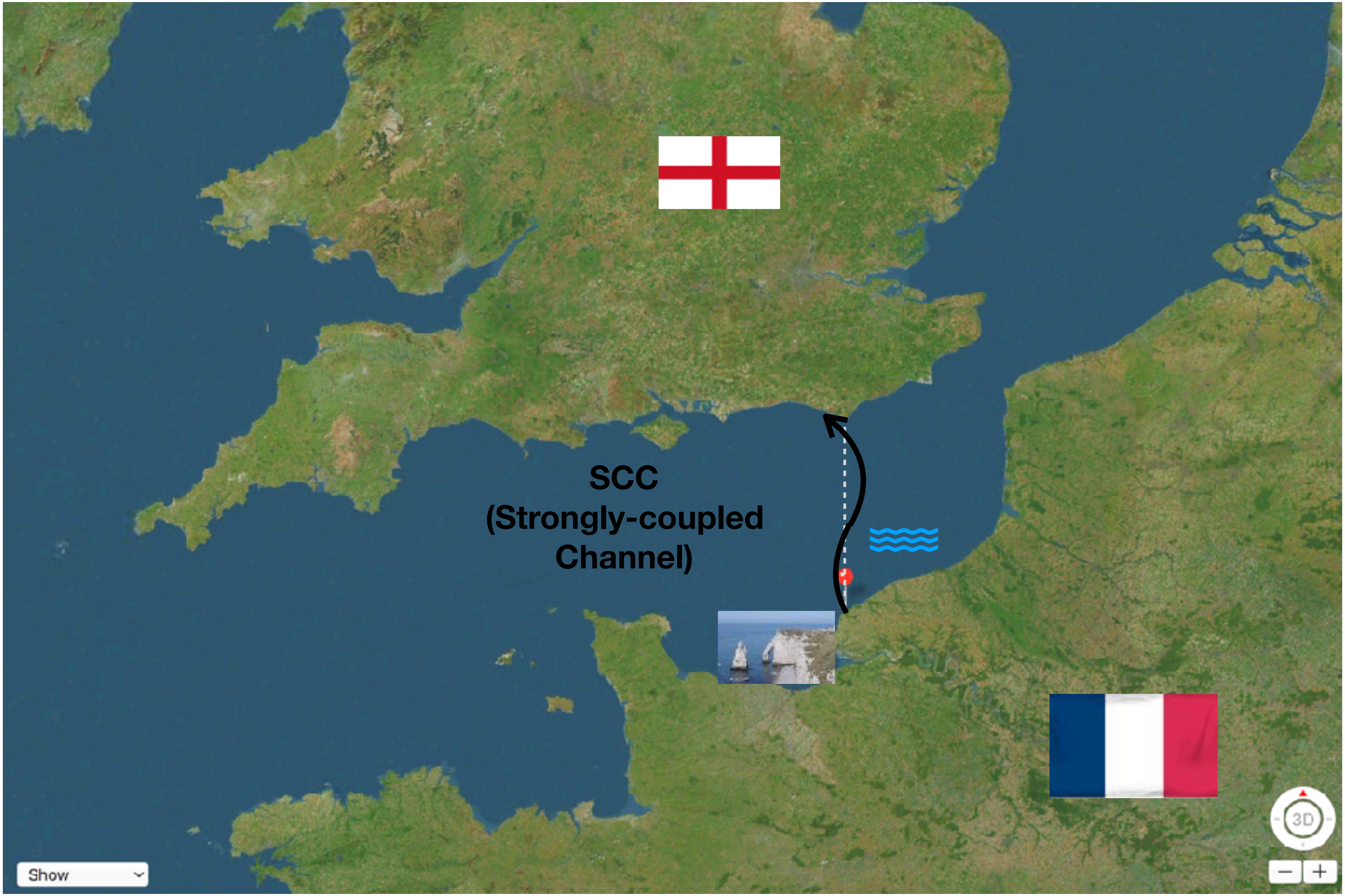
SCC
(Strongly-coupled
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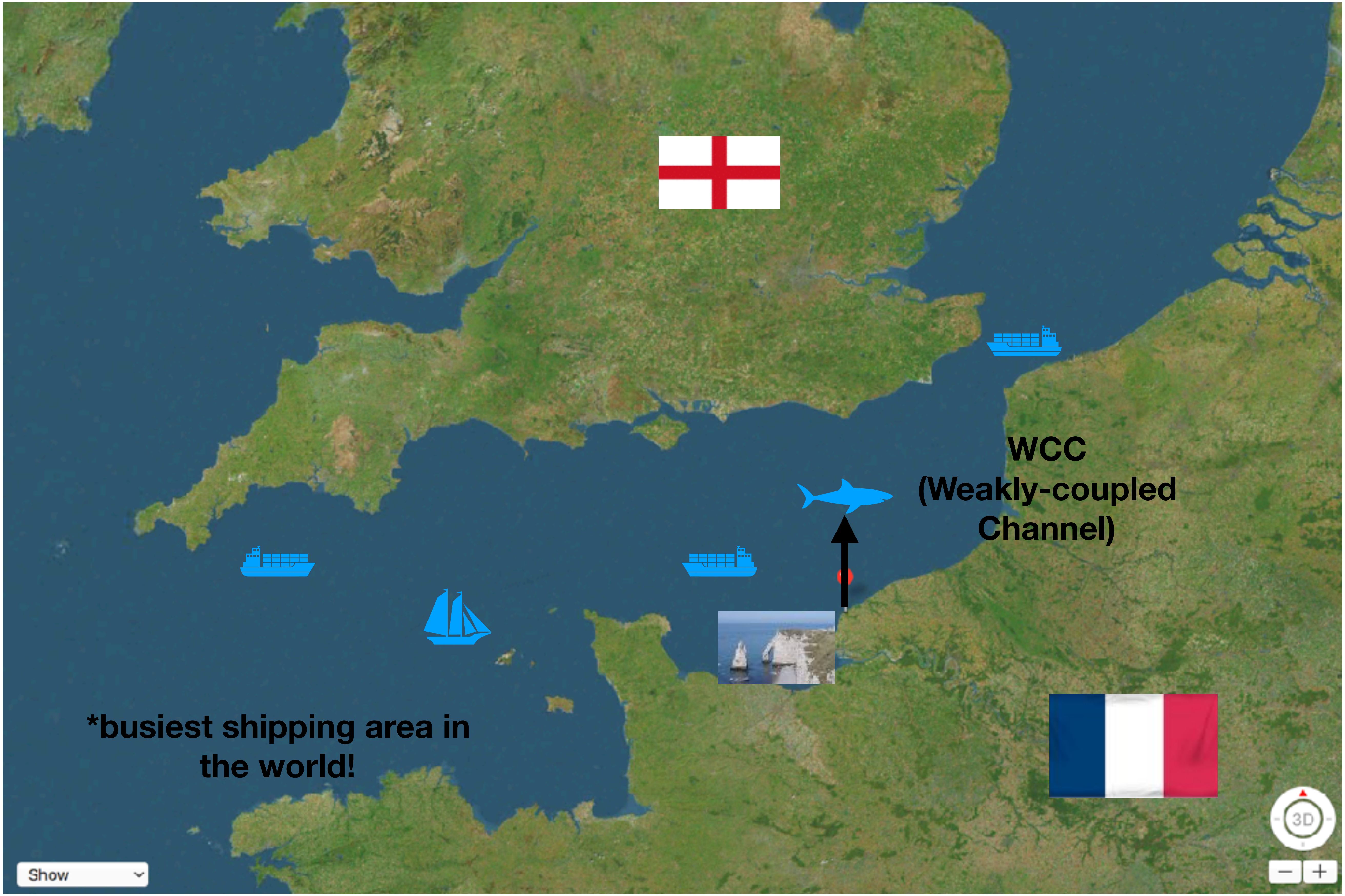
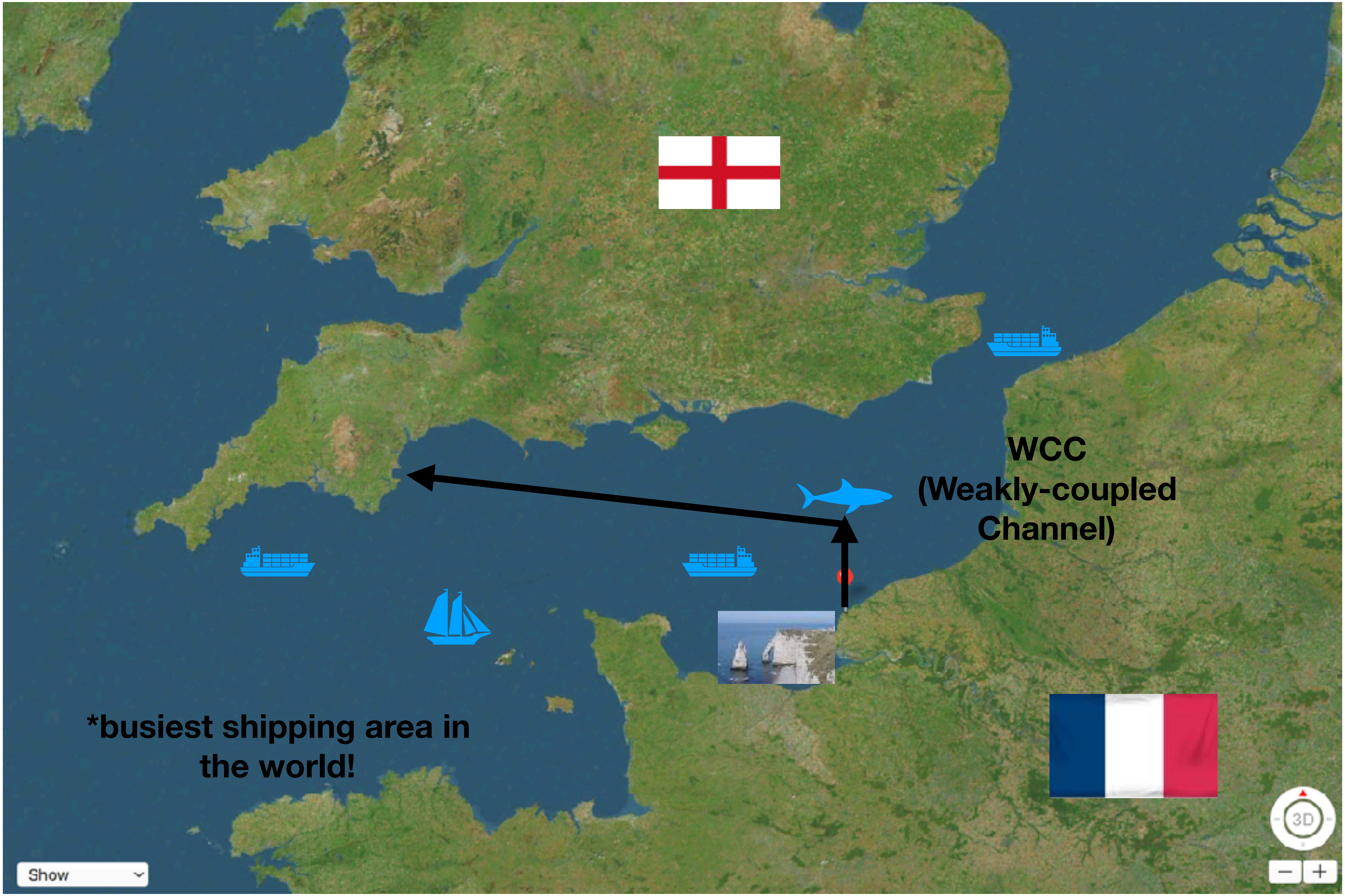

WCC
(Weakly-coupled
Channel)
*busiest shipping area in
the world!
Show
3D



WCC
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*busiest shipping area in
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Show
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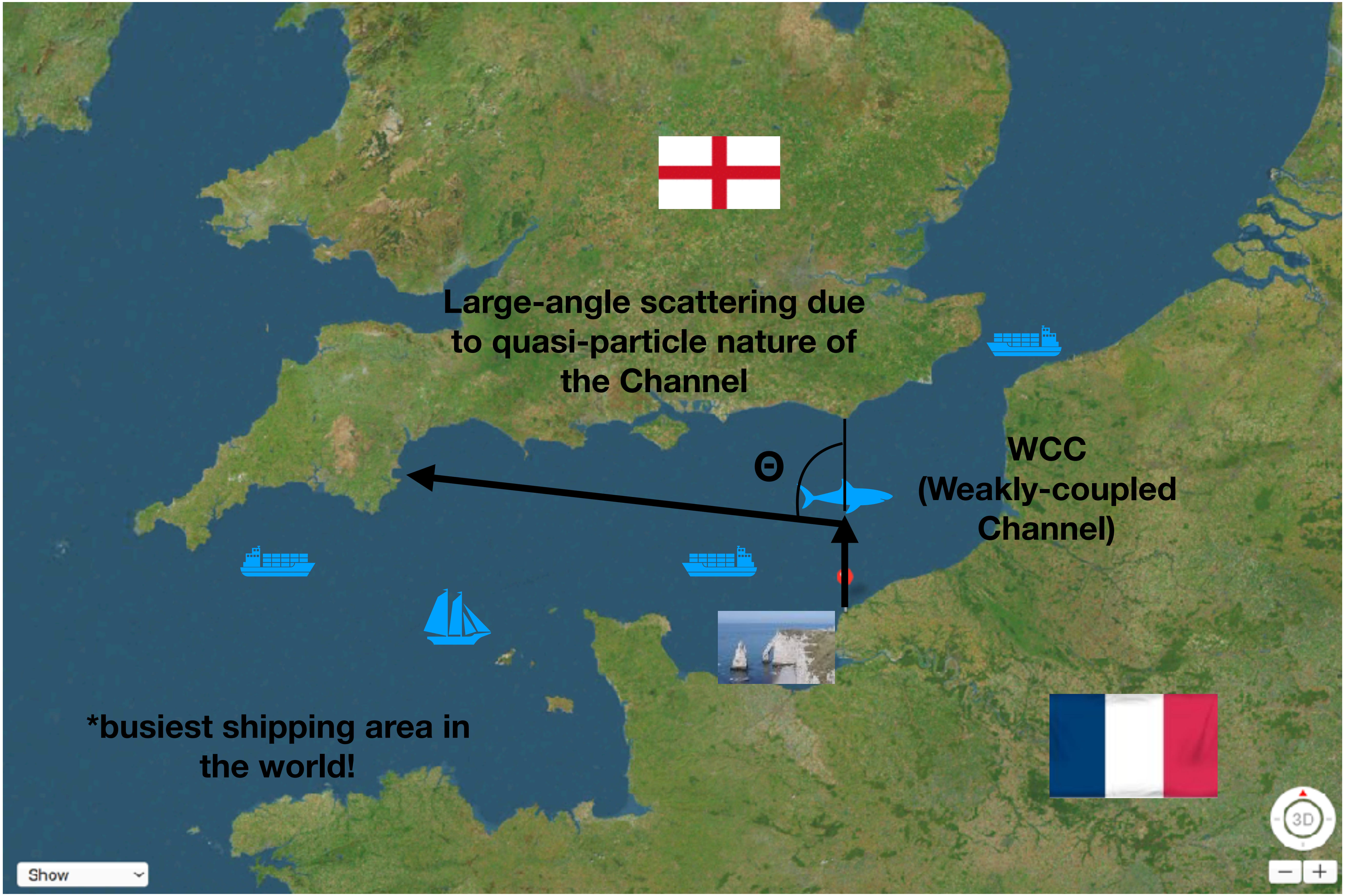
Large-angle scattering due
to quasi-particle nature of
the Channel
Θ
WCC
(Weakly-coupled
Channel)
*busiest shipping area in
the world!
Show
3D


Merci!

Backup

STAR h+jet measurement in Au-Au collisions

- Recoil jet yield **suppressed in central Au-Au collisions**
- **No evidence seen** for large-angle in-medium scattering
    - Excess yield in Pb-Pb collisions at large angles < 50±30% of large-angle yield in pp collisions (90% CL)

Phys. Rev. C 96, 024905 (2017)