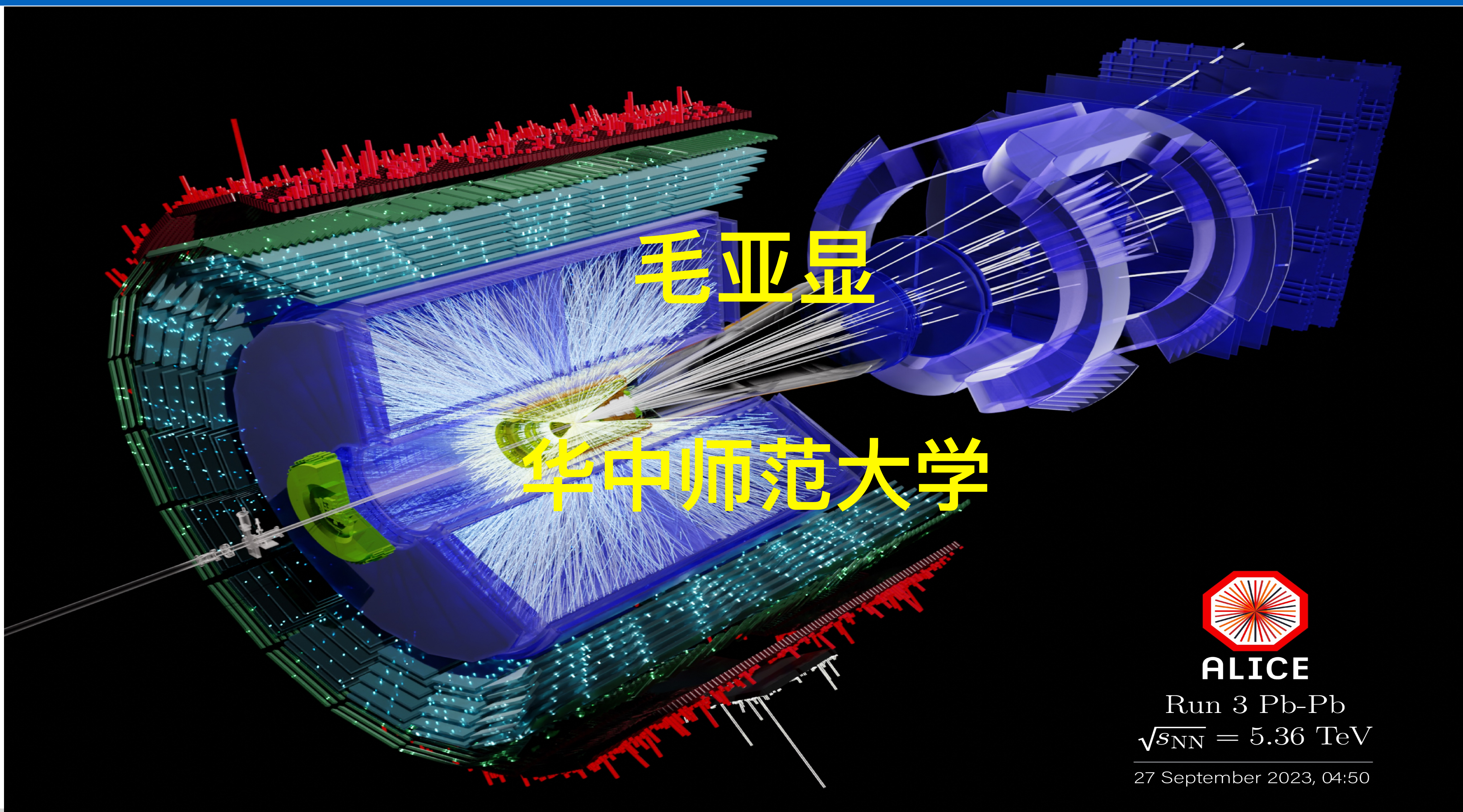
重离子碰撞中的喷注物理



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The Quark-Gluon Plasma (QGP)

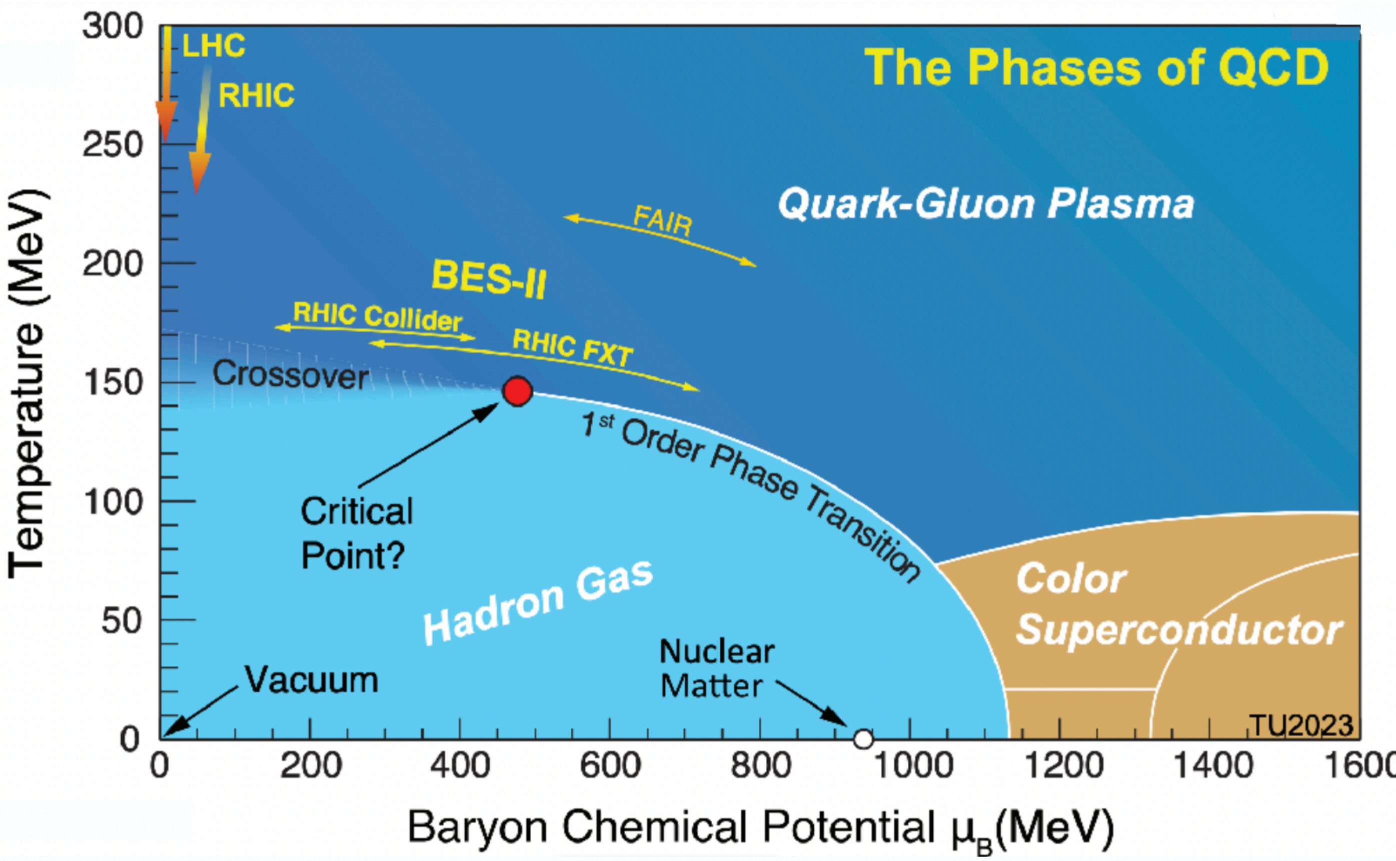
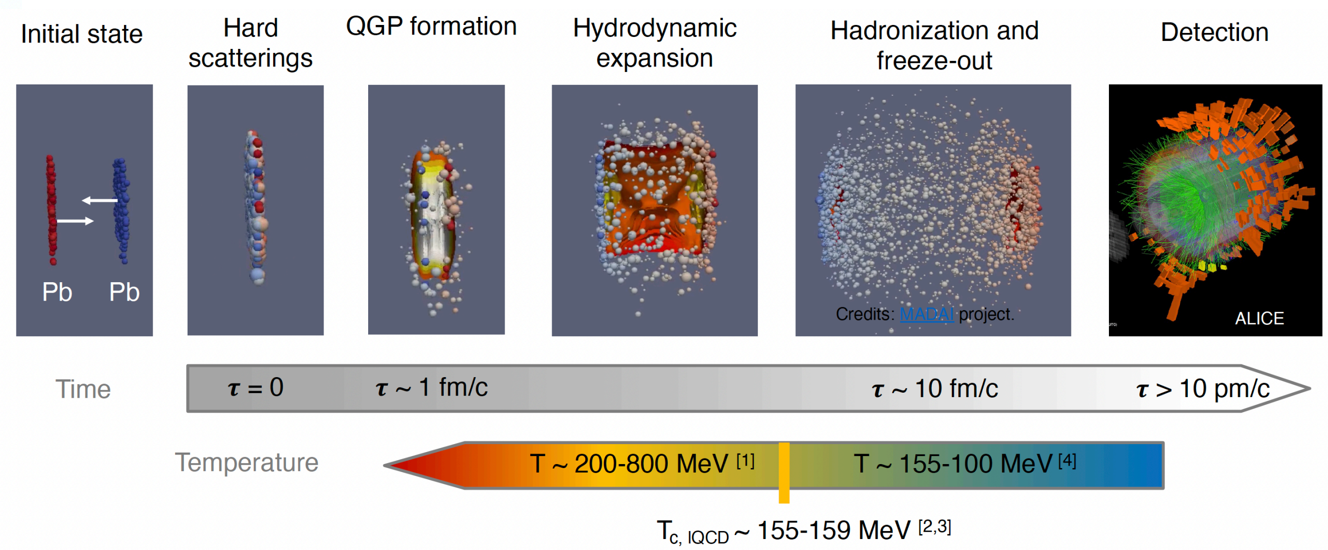


fig. H. Caines



[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

- Phase transition at high temperature or density to deconfined state of quarks and gluons
  - **quark-gluon plasma (QGP)**
- Calculations on the lattice predicts smooth crossover at ~155 MeV at low baryon density
- Created at the LHC at RHIC using **ultra-relativistic heavy-ion collisions**

Two main laboratories for heavy-ion collisions

AGS : 1986 – 2000

- Si and Au beams ; $\sqrt{s}$ ~ 5 GeV
- only hadronic variables

RHIC : 2000 – ?

- He^3, Cu, Au beams ; up to $\sqrt{s}$ = 200 GeV
- 4 experiments (only two remain)

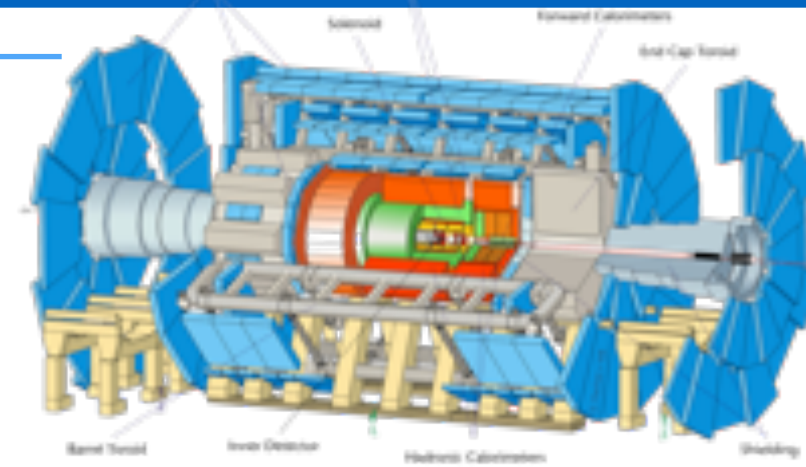
SPS : 1986 – 2003 + 2009 — ?

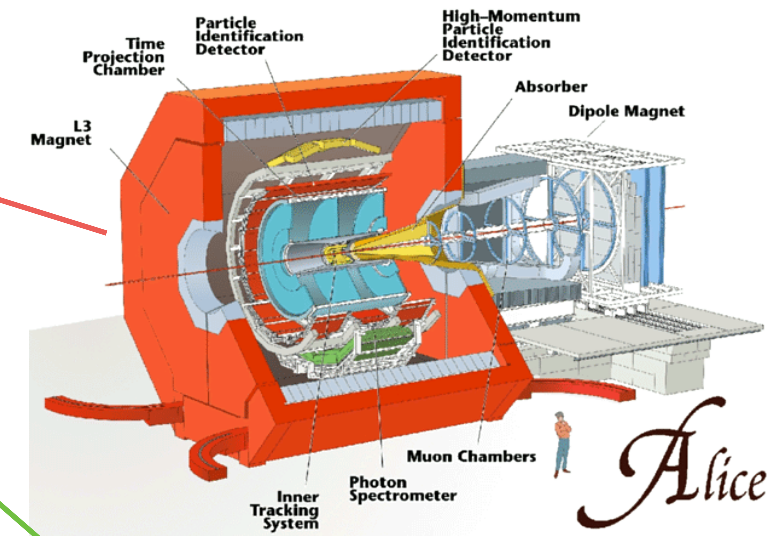
- O, S, In, Pb beams ; $\sqrt{s}$ ~ 20 GeV
- Various experiments in North Area

LHC : 2009 – ?

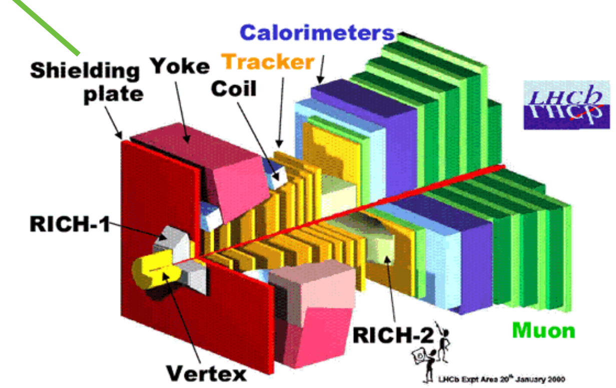
- Pb beams ; up to $\sqrt{s}$ = 5500 GeV
- ALICE, CMS, ATLAS and LHCb

LHC: the Large Hadron Collider

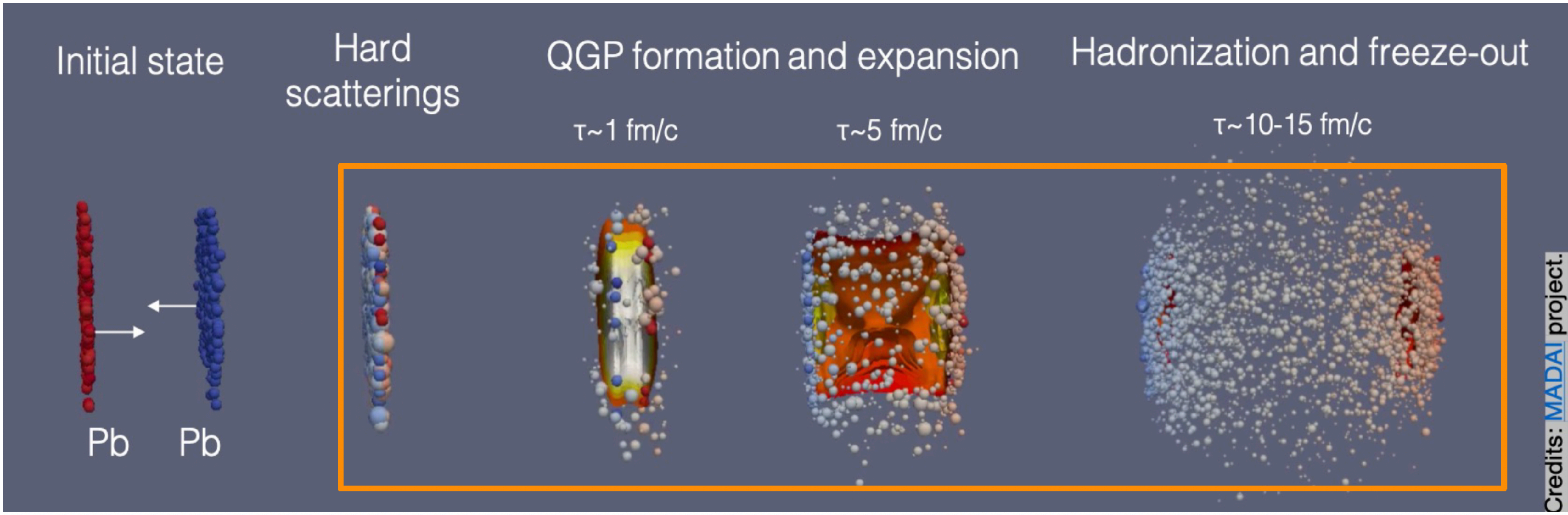




- ALICE dedicated HI experiment
  - Low-pT tracking, PID, mid-rapidity
  - Forward-muon spectrometer
- ATLAS/CMS large HEP experiments
  - Large acceptance, full calorimetry
- LHCb (pPb in 2013, PbPb since 2015)
  - Forward tracking, PID, calorimetry

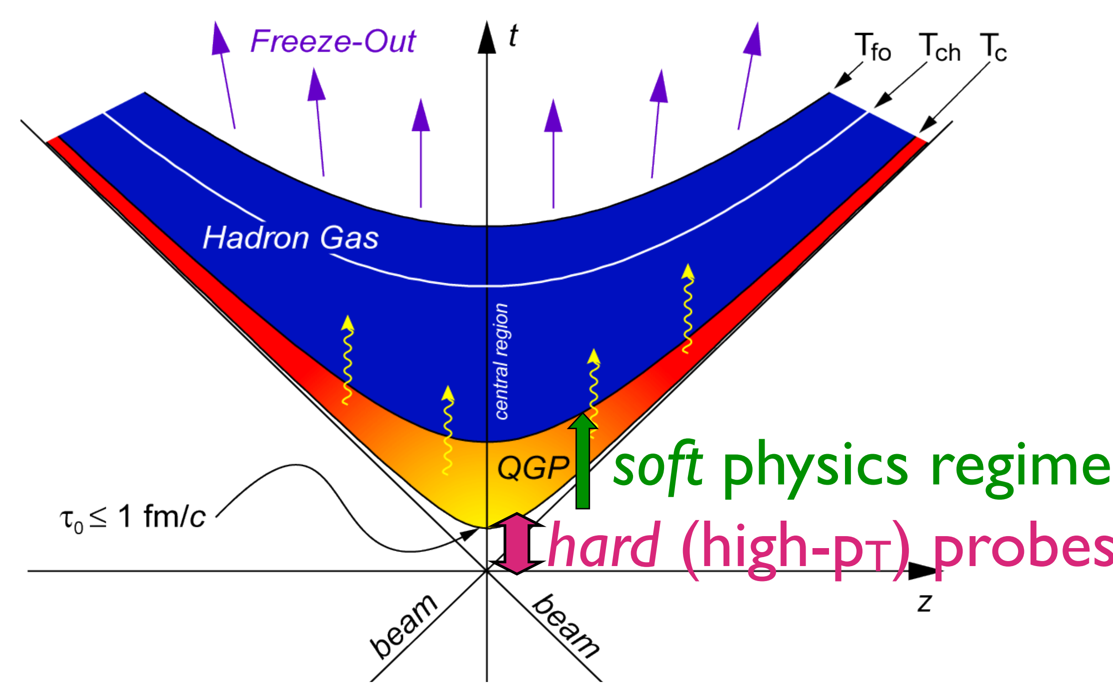


Probing the QGP

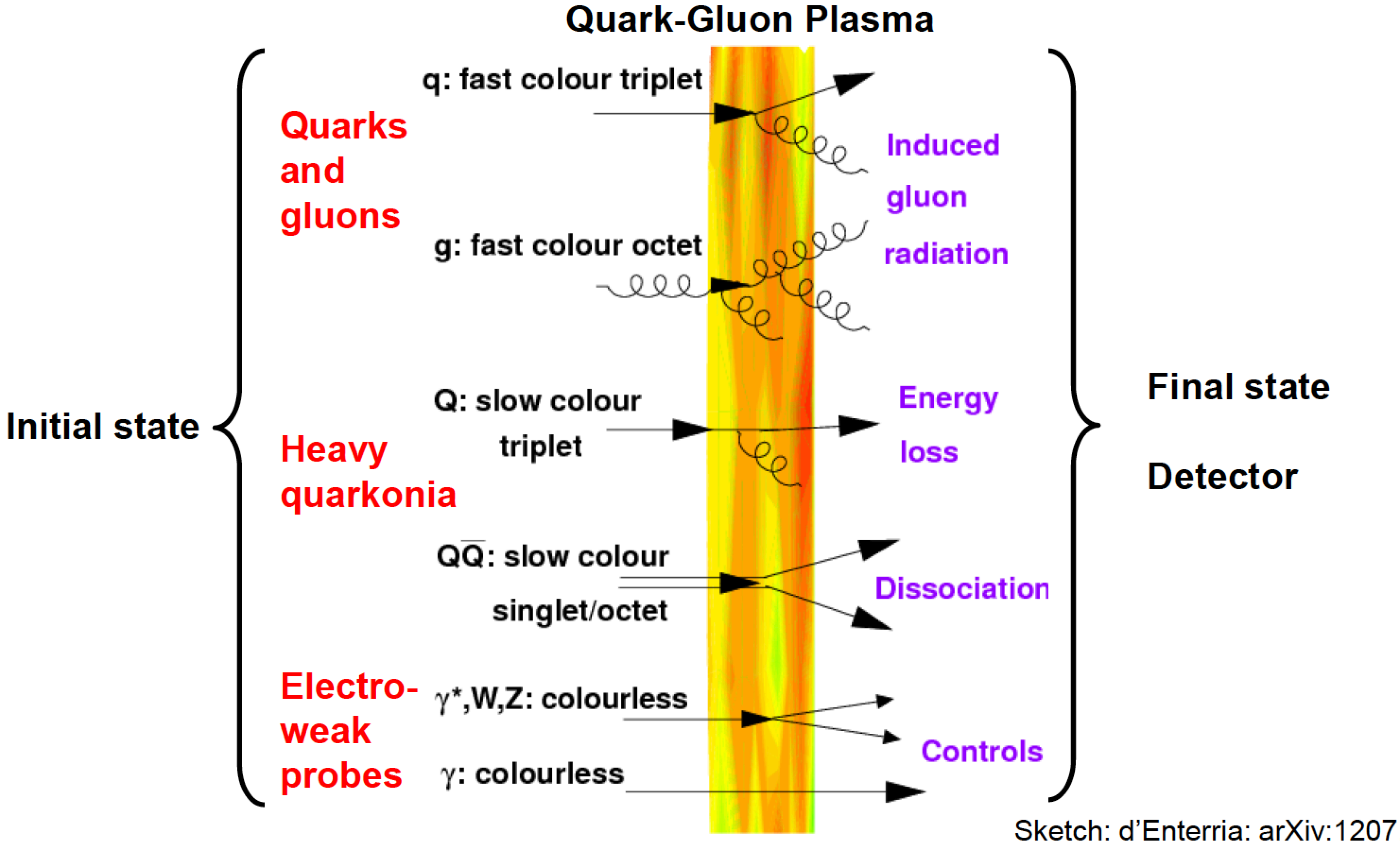


1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

- To probe the QGP, we have many tools in our toolbox
  - hydrodynamic flow
  - hadron chemistry and kinematics
  - electromagnetic radiation from QGP
  - quarkonium disassociation/regeneration
  - partonic interactions with QGP → heavy quarks and jets



Hard probes traverse the QGP

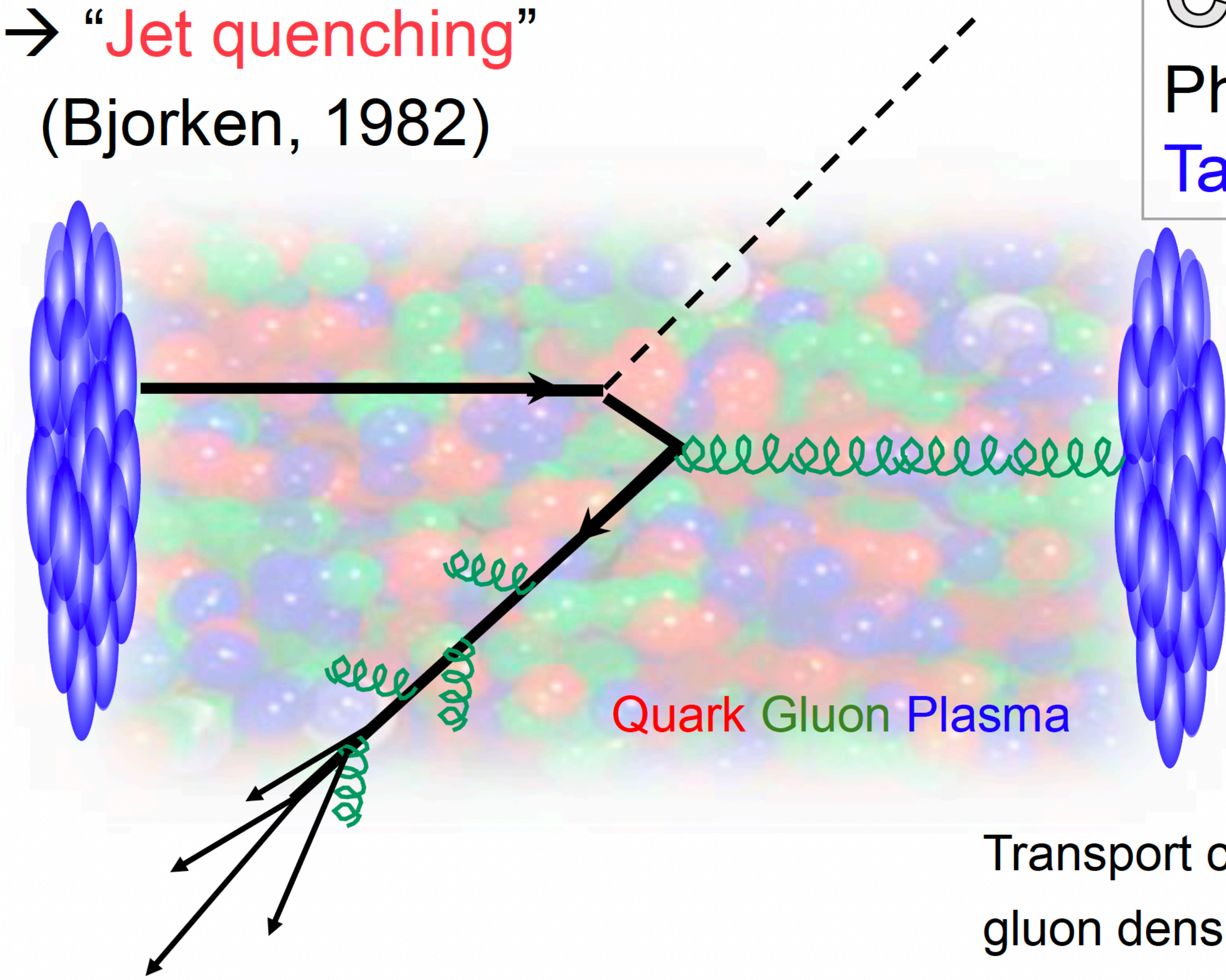


Sketch: d'Enterria: arXiv:1207.4362

The importance of the control measurement(s) cannot be overstated!

Jets: a tomographic probe of the medium

In medium parton energy loss
→ “Jet quenching”
(Bjorken, 1982)



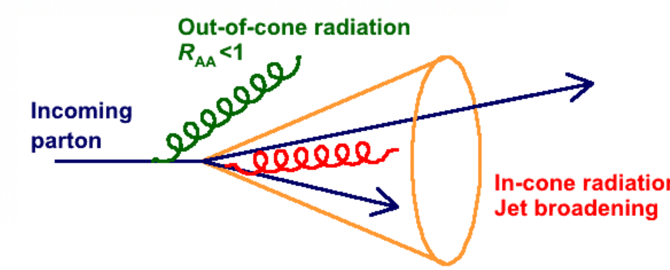
Colorless Probes

Photons, electroweak bosons
Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

Colored Probes:

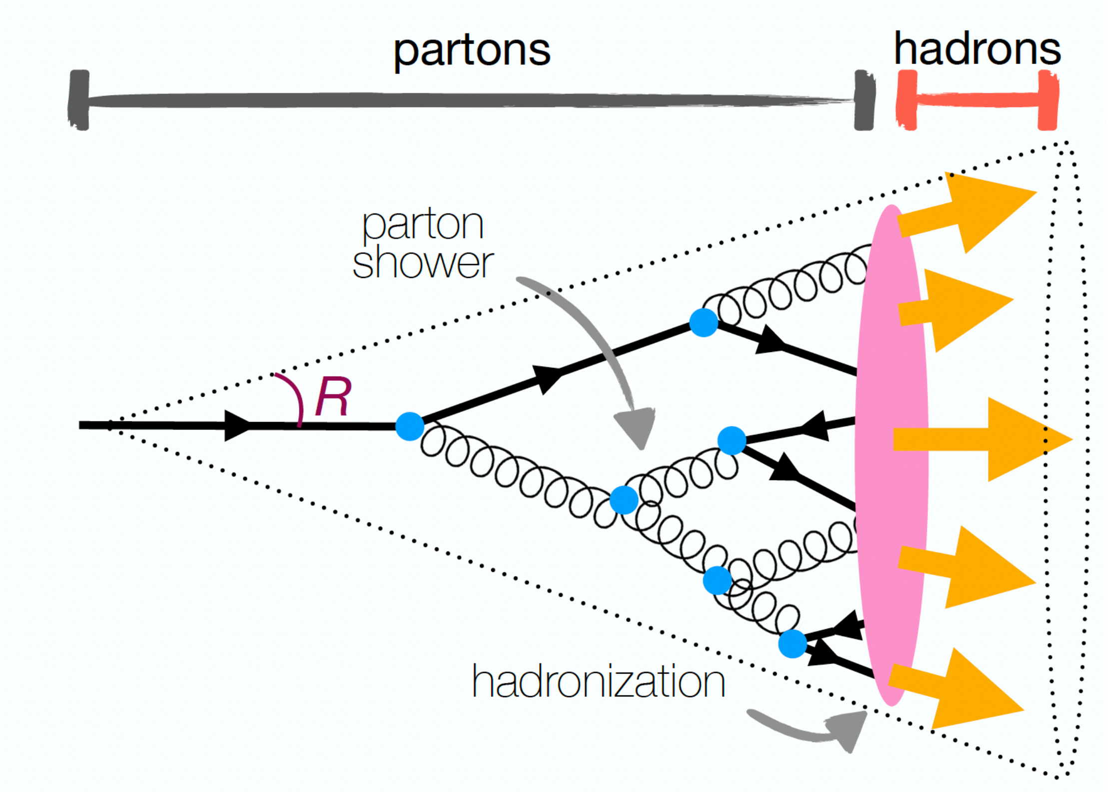
high energy quarks and gluons, heavy quarks
Studies of the medium properties



Probing QGP with jets

Vacuum fragmentation (e.g. pp collisions)

Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)



Probing QGP with jets

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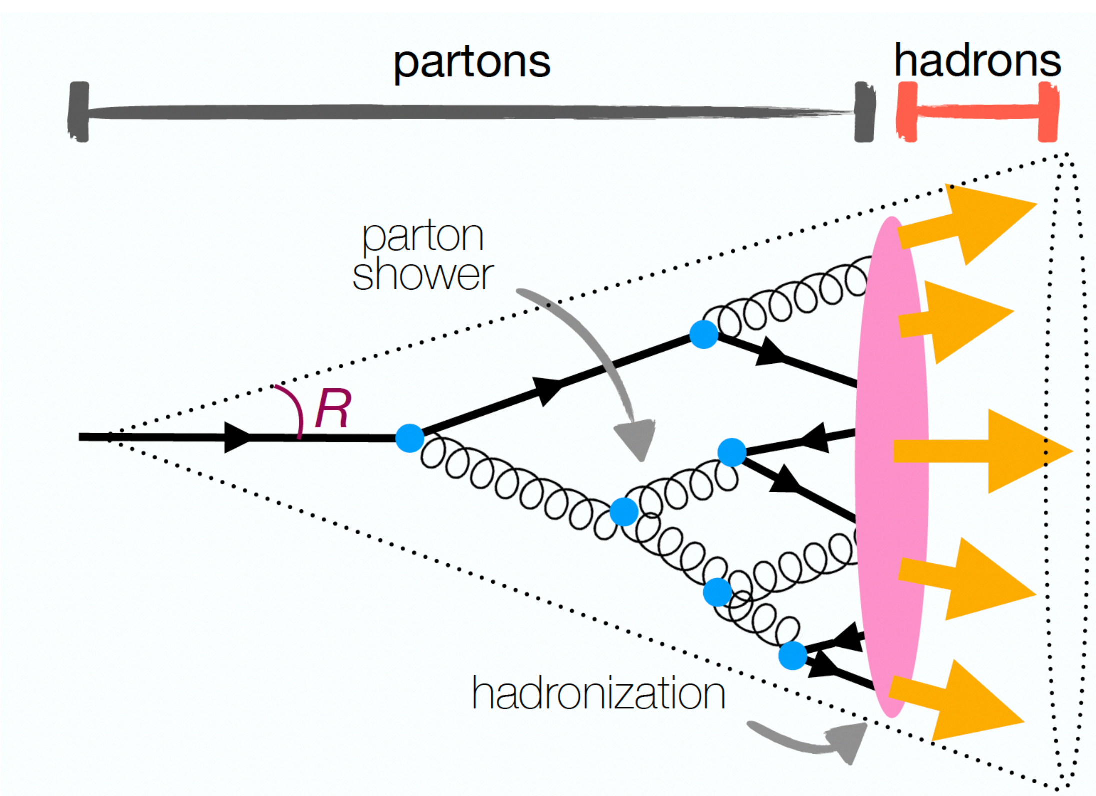
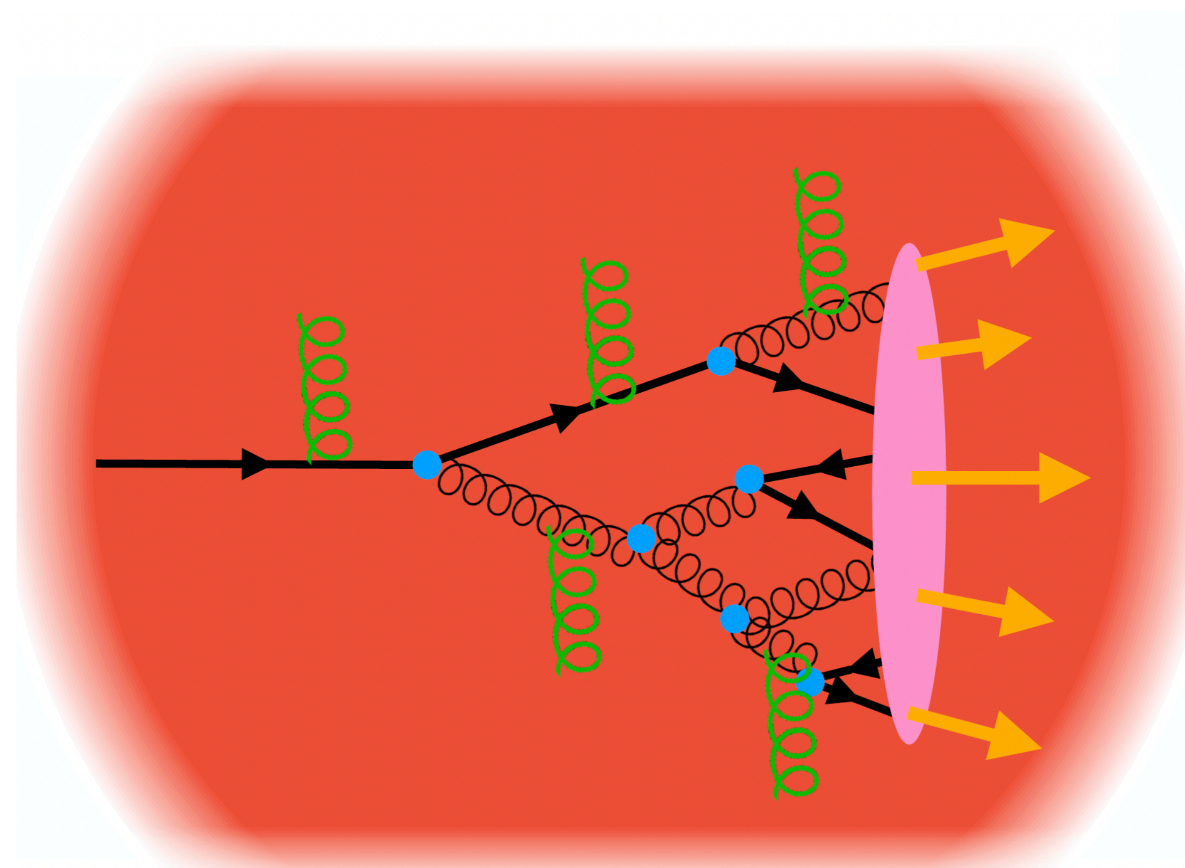


In-medium fragmentation (e.g. Pb-Pb collisions)

Quenching→parton lose energy through medium-induced gluon radiations and collisions with medium constituents



Jet observables

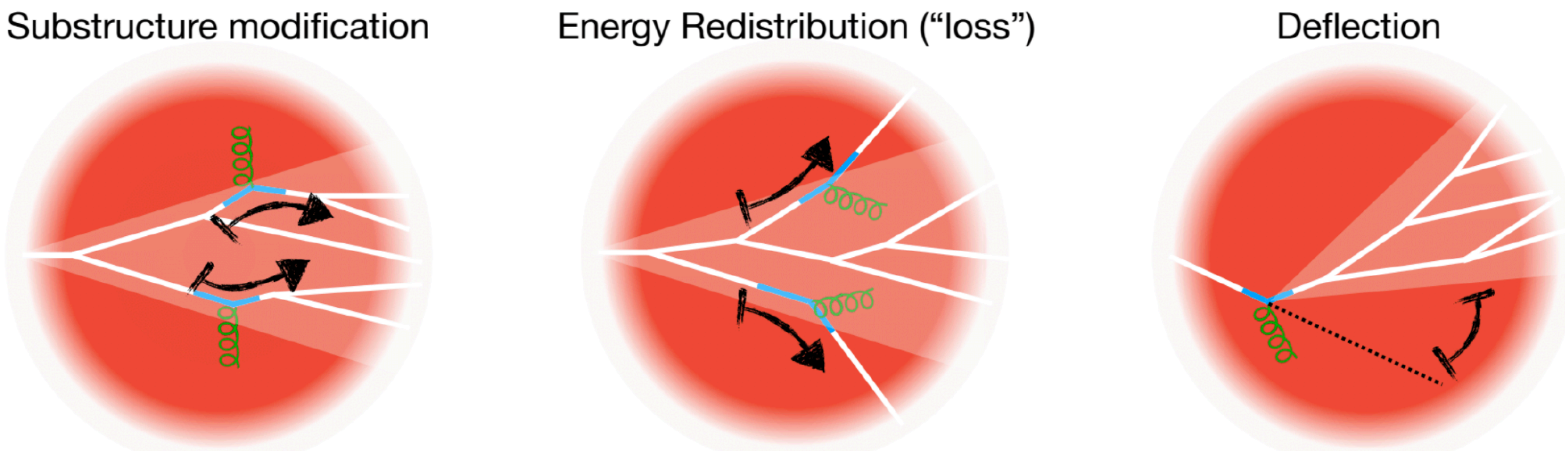
- Study structure of QGP by understanding jet modification from medium interaction (quenching)

- Several types of jet observables

  - Jet yields and constituents → jet suppression and energy redistribution (R_{AA}, I_{AA})

  - Jet reconstruction and declustering → jet substructure (r_g, θ_g) modification

  - Angular correlation → jet deflection ($\Delta\varphi$)

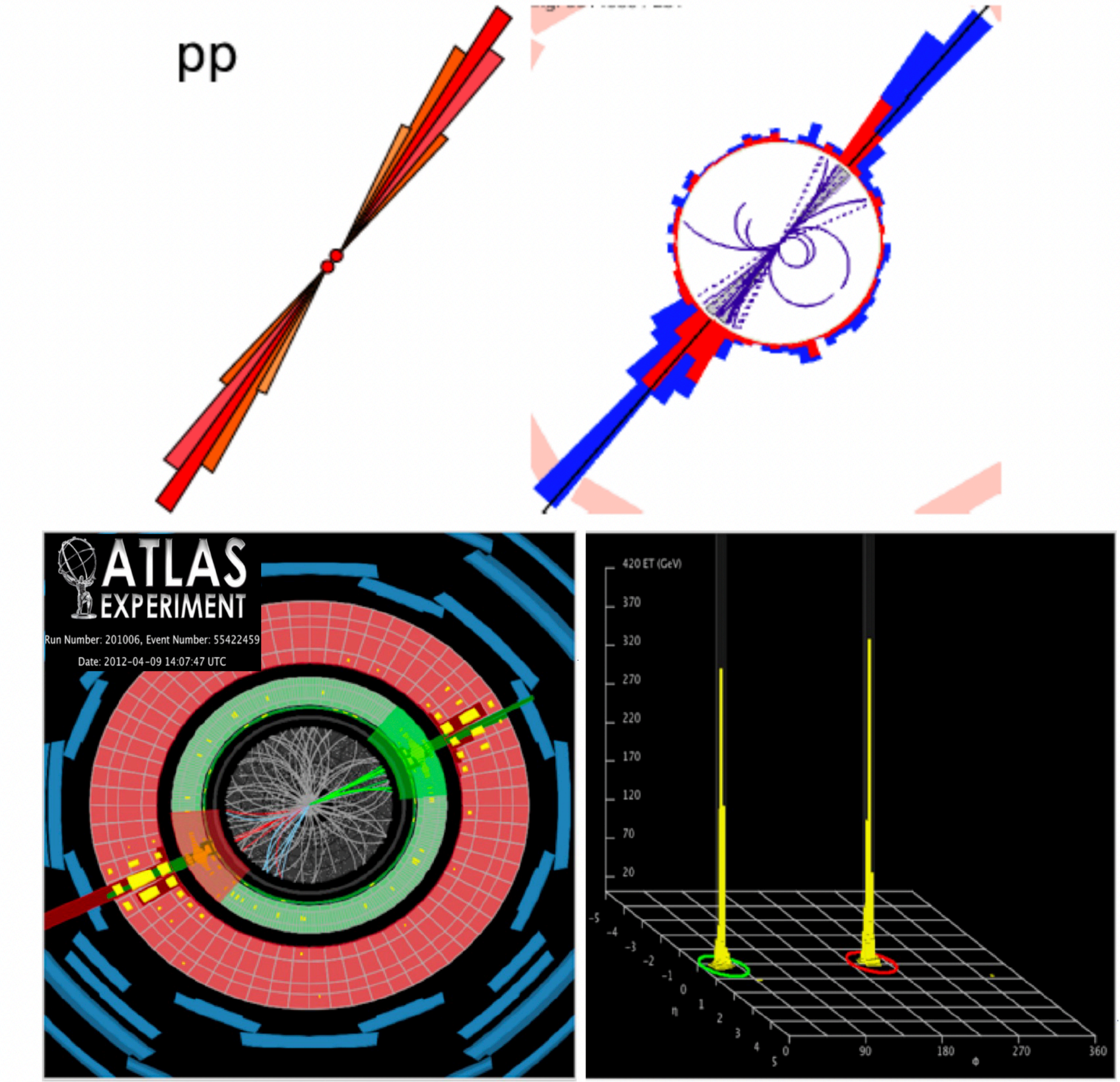


Study of different effects in a complementary way must yield consistent picture

Jets (in vacuum)

In the early stage of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated “sprays” of hadrons

➡ in-vacuum fragmentation

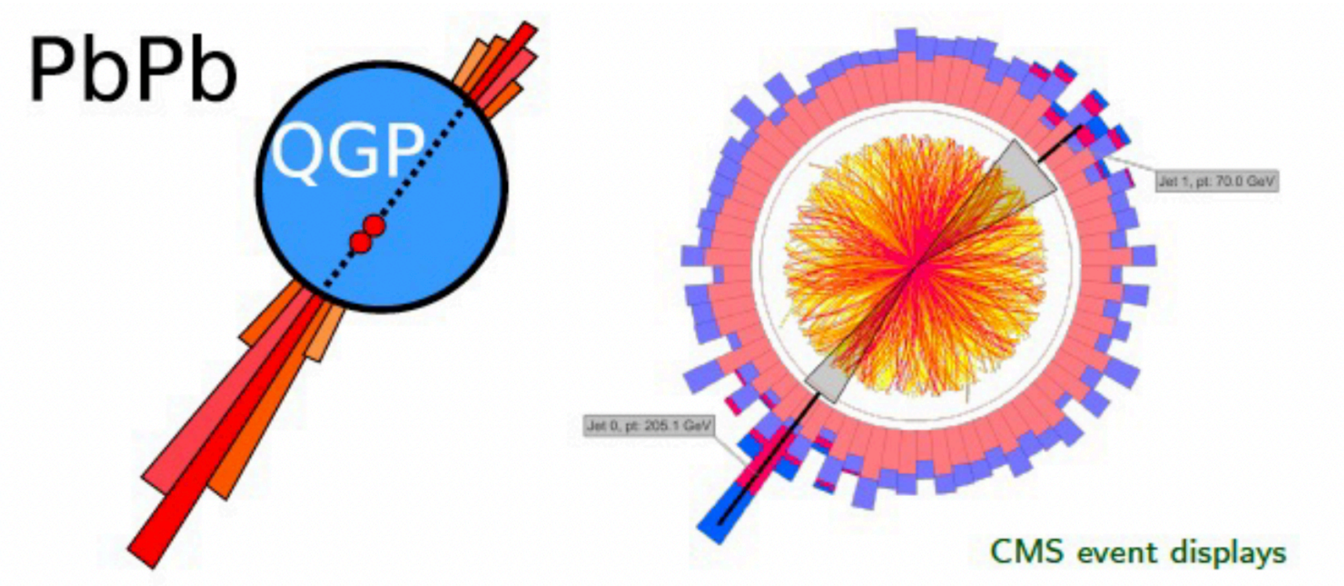


ATLAS, pp collision event display

Jets (in medium)

In the early stage of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated "sprays" of hadrons

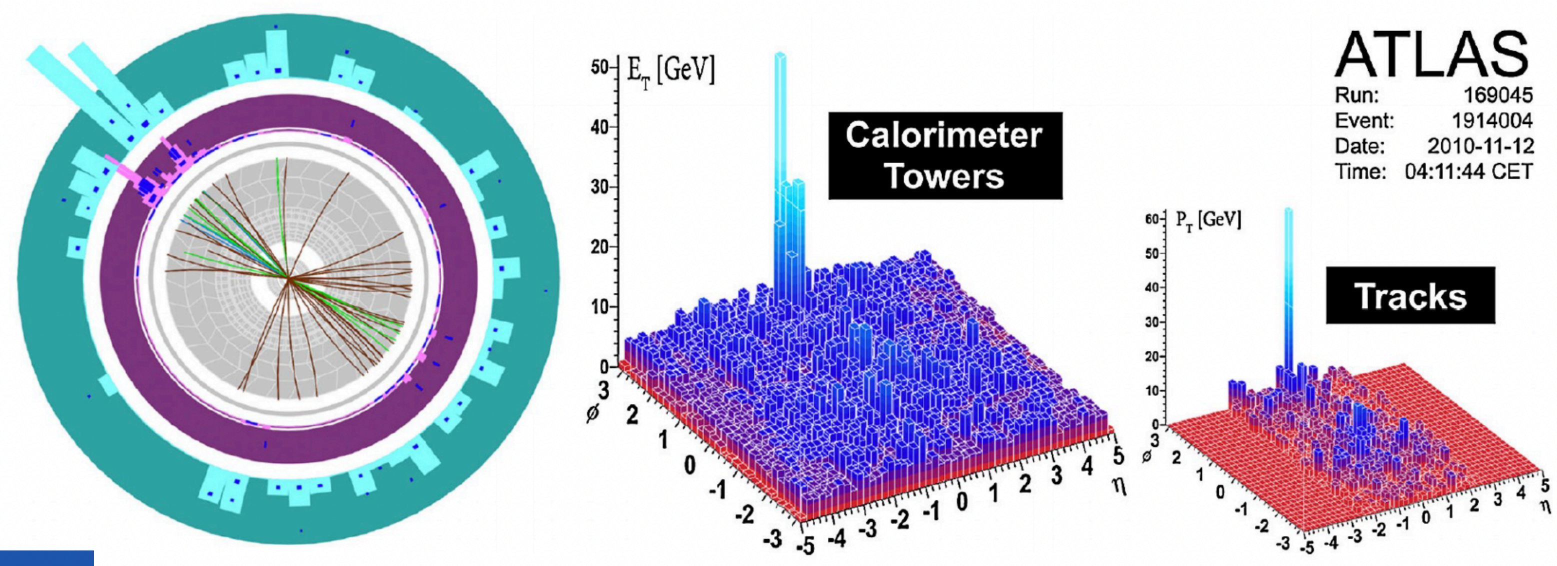
➡ in-vacuum fragmentation



When a QGP is formed, the colored partons traverse and interact with a colored medium

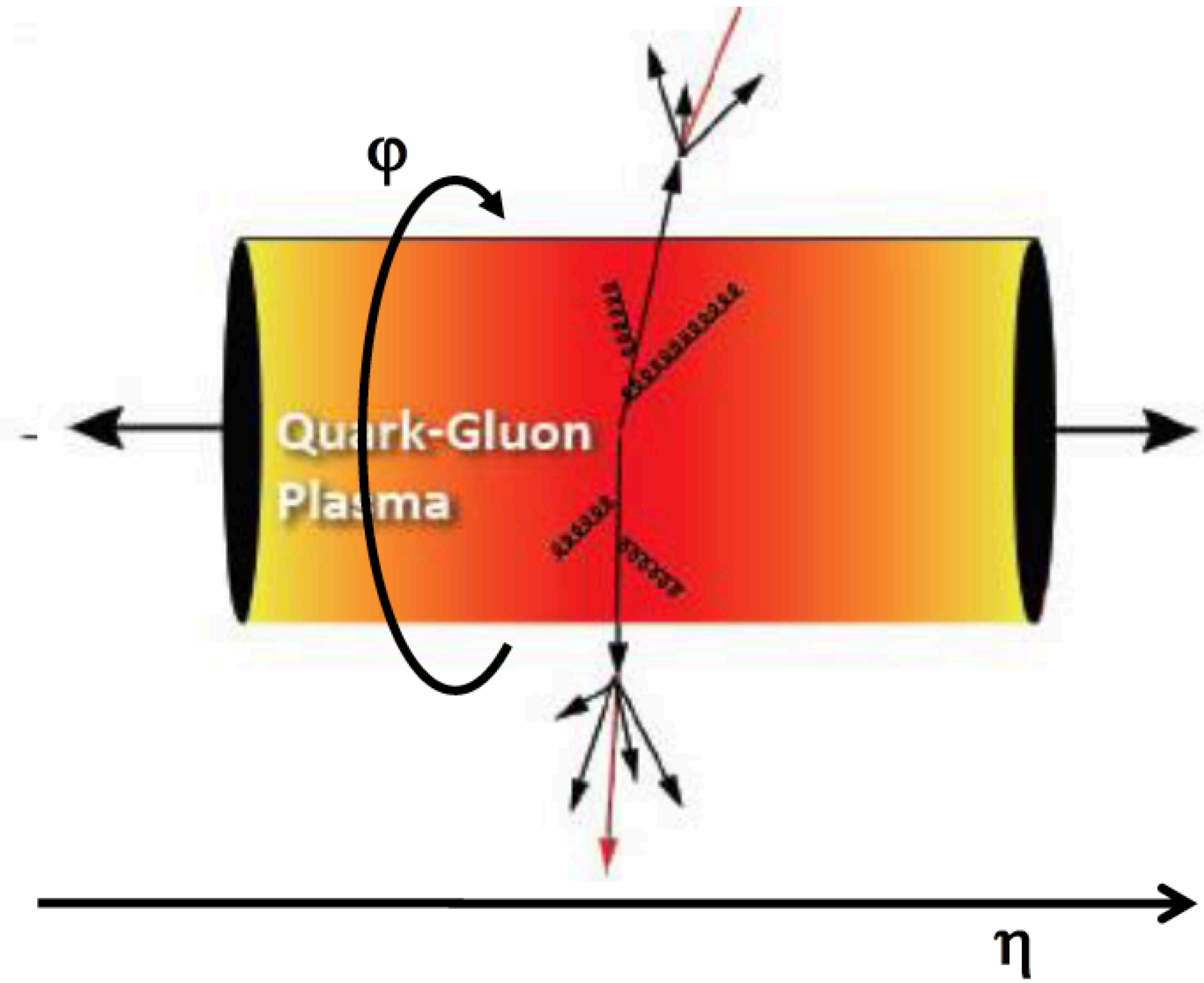
➡ in-medium fragmentation

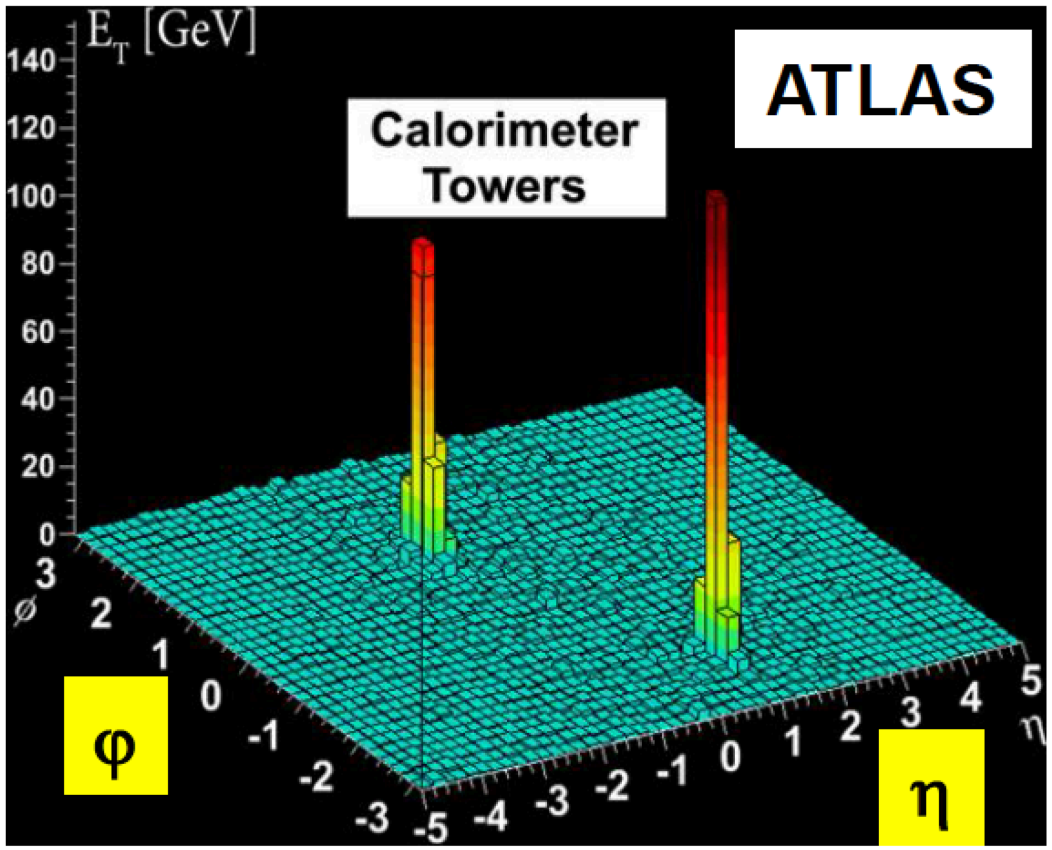
➡ jet "quenching" (energy loss)

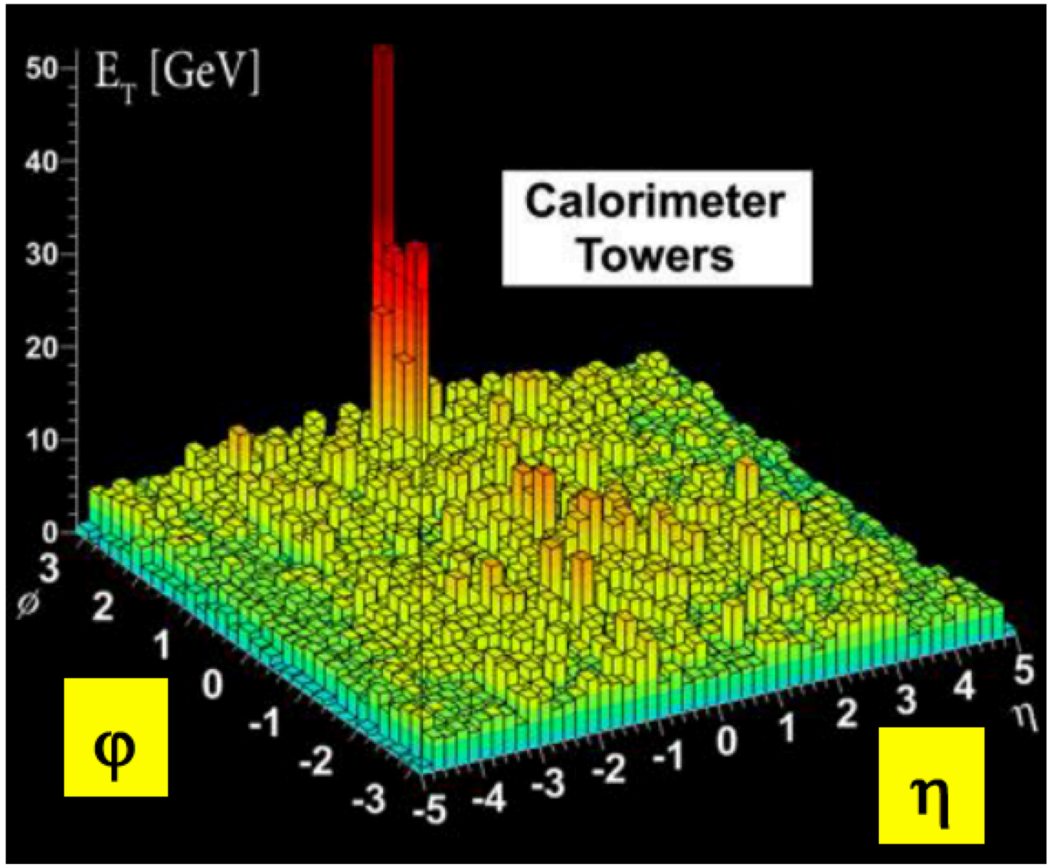


Goal: understand the nature of this energy loss to characterize the strongly-interacting QGP

A Back-to-Back Jet





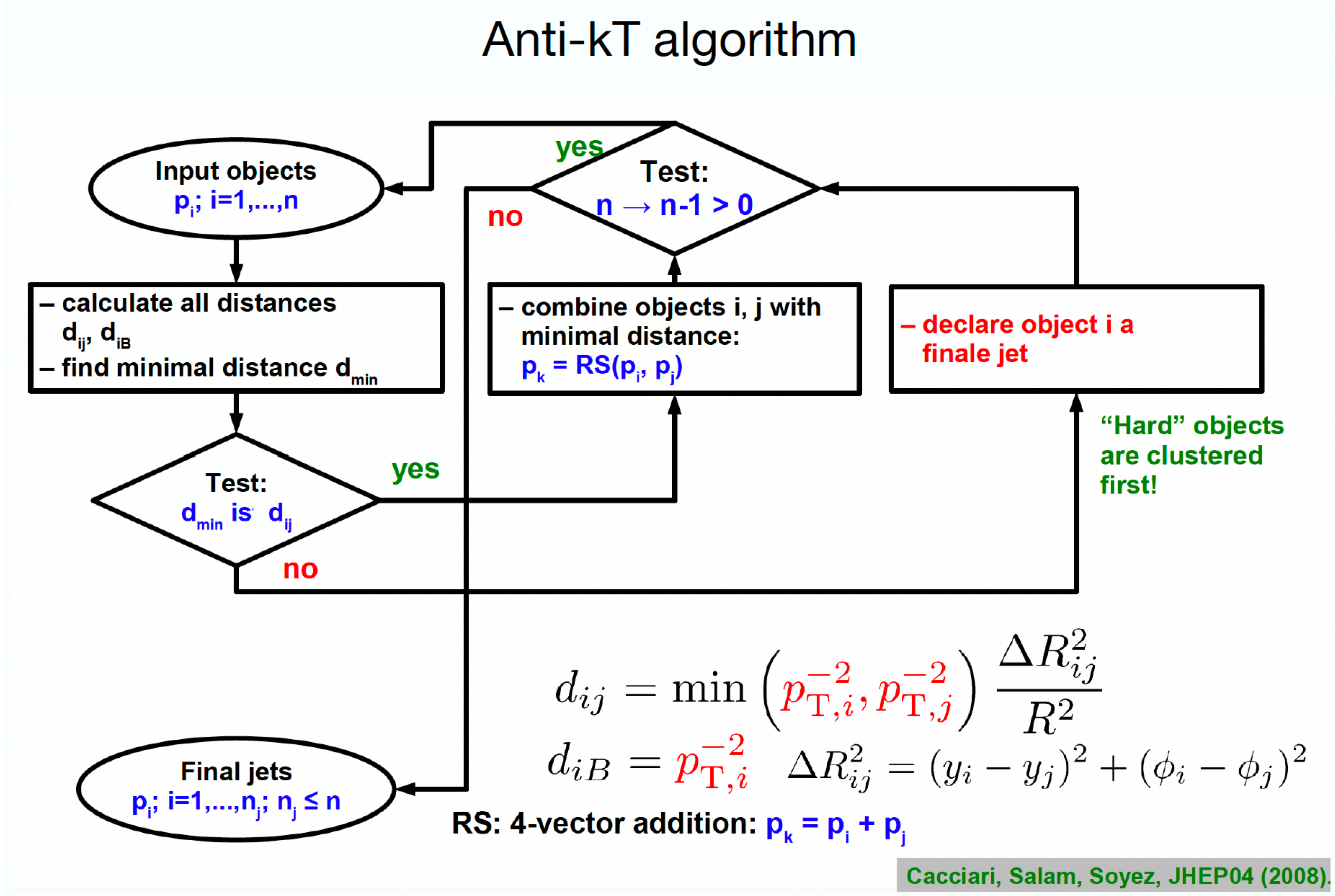


One jet disappears in the QGP
→ "Jet quenching"

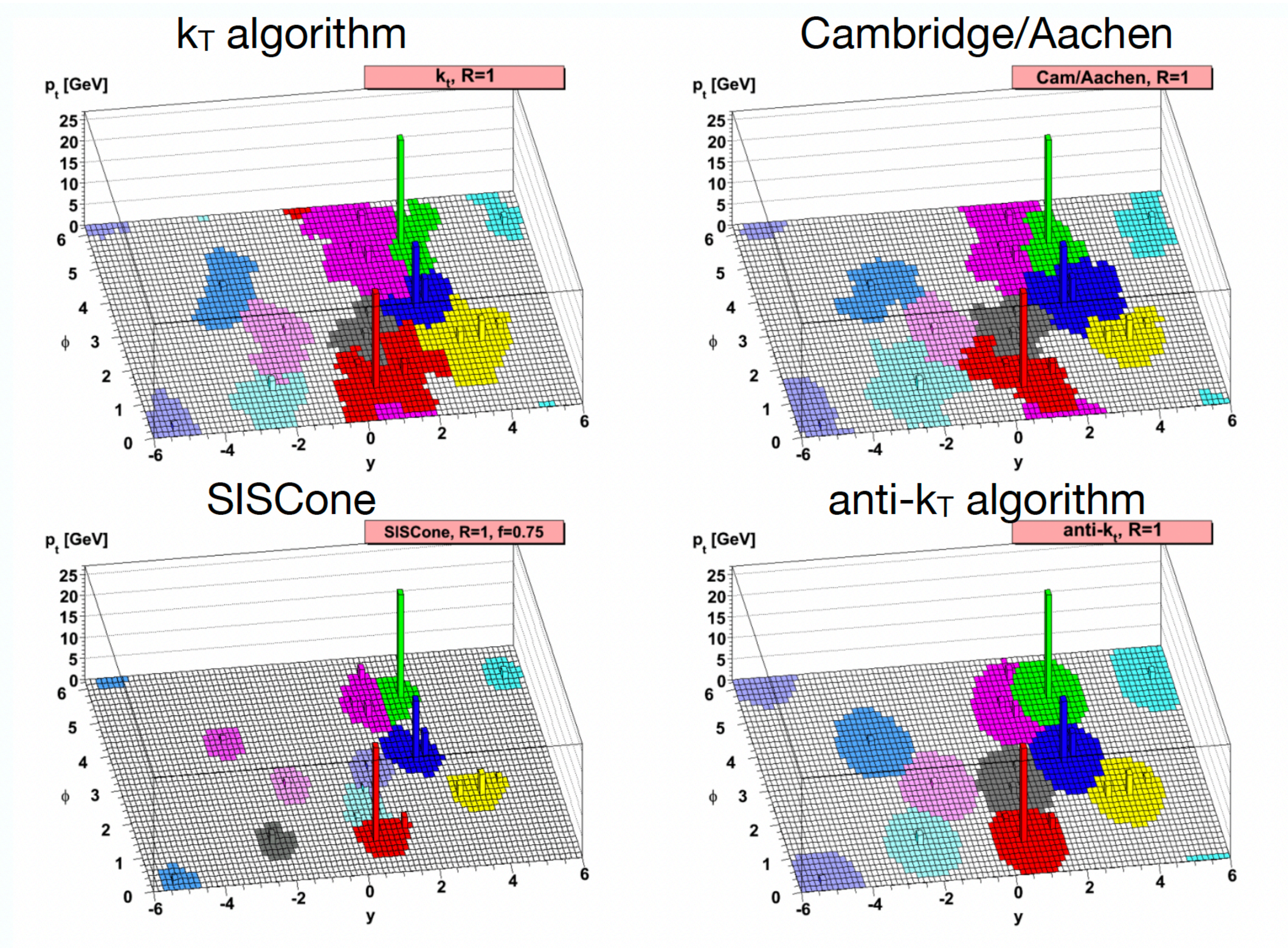
ATLAS, PRL105:252303,2010
Drawing: A. Mischke

Jets at Hadron Collider

- Primary goal is to find correspondence between
  - detector measurements
  - particles in final states
  - hard partons
- Classes of algorithms
  - cone algorithms
  - sequential recombination
- Requirements
  - infrared and collinear safe
  - order independence
  - ease of implementation



Jets at Hadron Collider



$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p} ,$$

p=-1 anti-k_T algorithm
p=0 Cambridge/Aachen
p=1 k_T algorithm

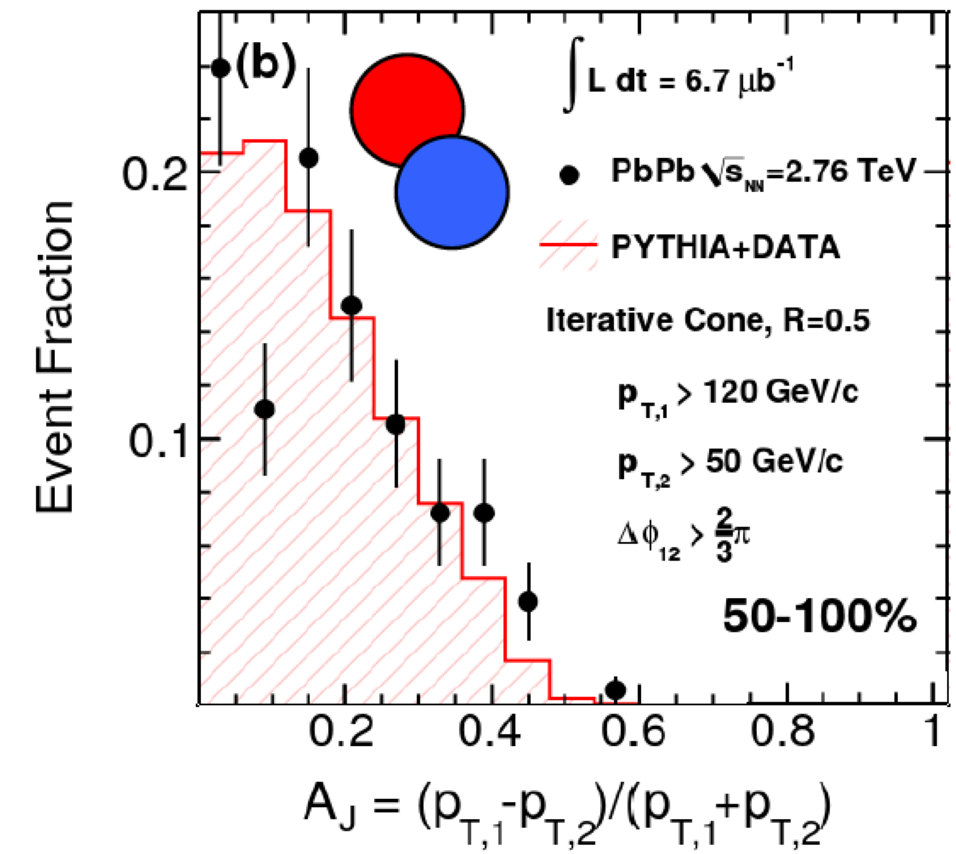
Dijet Asymmetry

- How often do jets lose lot of energy?
- Quantify by dijet asymmetry
- 2 highest energy jets with $\Delta\varphi > 2\pi/3$

$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

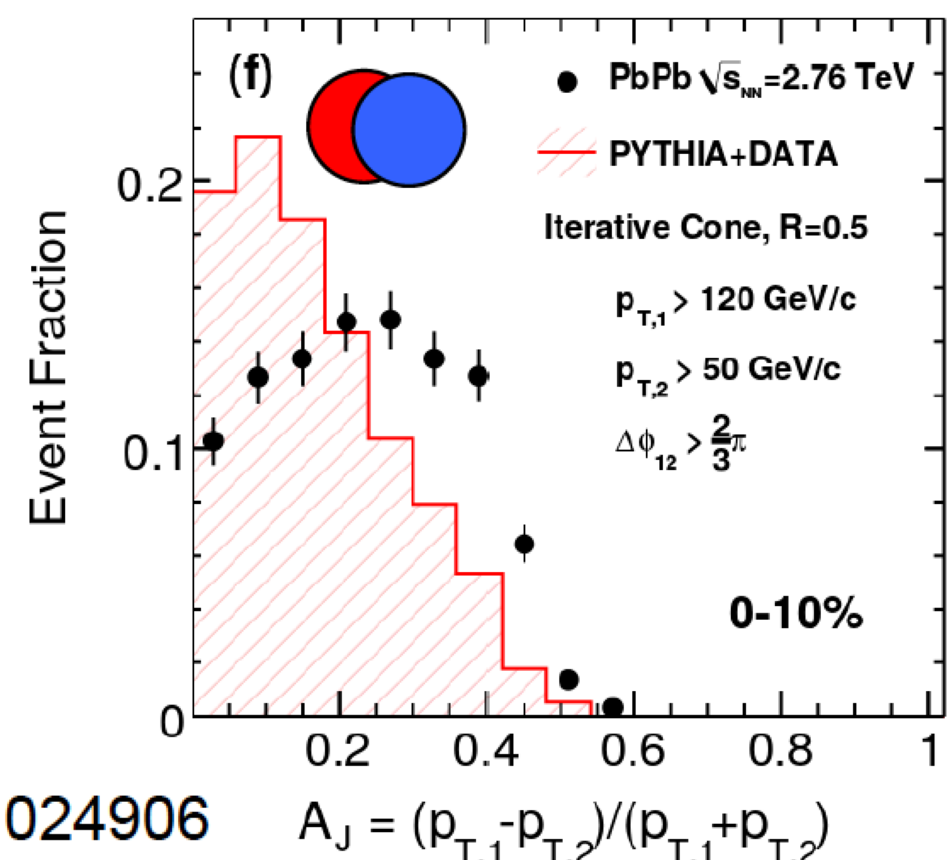
$1/3\ p_{T1} = p_{T2} \rightarrow A_J = 0.5$



- Peripheral collisions: Pb-Pb ~ Pythia
- Central collisions: Significant difference

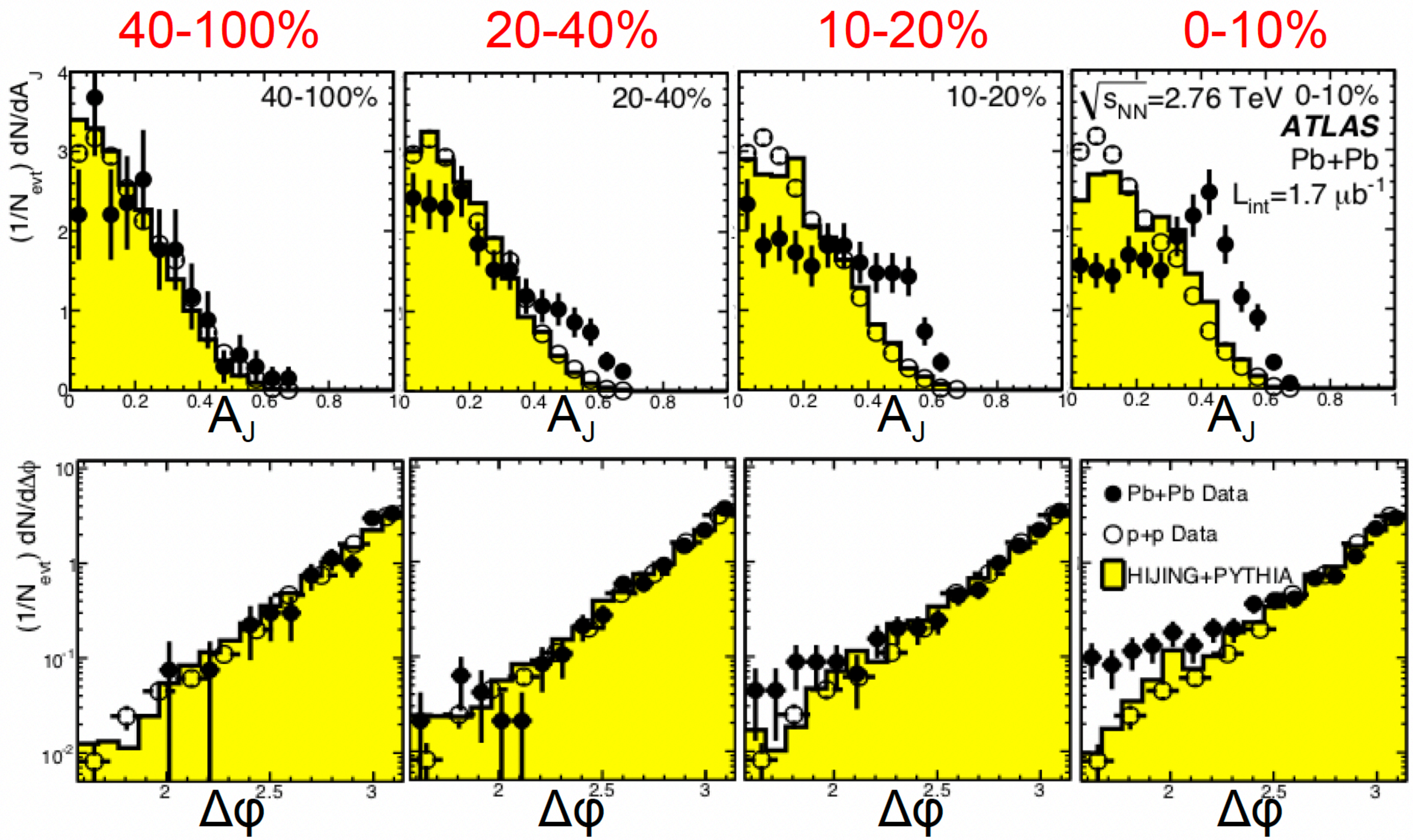
Jets lose up to two thirds of their energy!

→Something significant happening in heavy-ion collisions



PRC 84 (2011) 024906
PRL105:252303,2010

Dijet imbalance: clear signal in PbPb at LHC



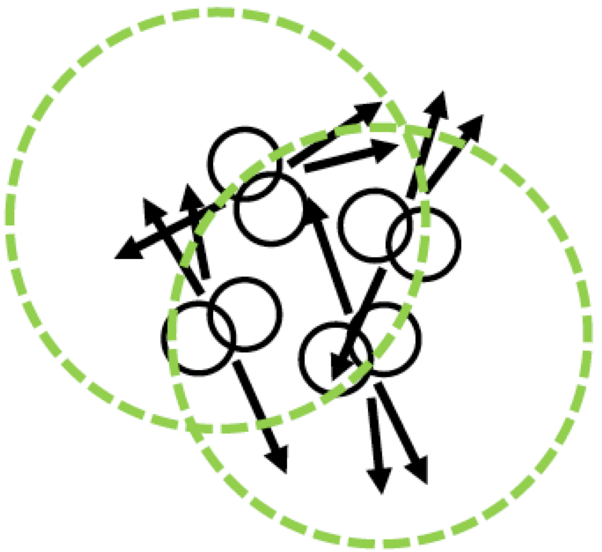
Momentum imbalance wrt to MC (pp) reference increases with increasing centrality.
No (or very little) azimuthal decorrelation.

ATLAS, PRL 105 (2010) 252303
CMS, PRC 84 (2011) 024906

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

Nuclear-Modification Factor

- Hard processes occur in nucleon-nucleon (NN) collisions
- Heavy-ion collision : many NN collisions
  - Hard process is independent of number of NN collisions
- Without QGP, HI collision is superposition of NN collisions with incoherent fragmentation



$$dN_{AA}/dp_T = \langle N_{coll} \rangle dN_{pp}/dp_T$$

← **any object, e.g. charged particles, jets, J/ψ, D, …**

- Let's turn this into an observable

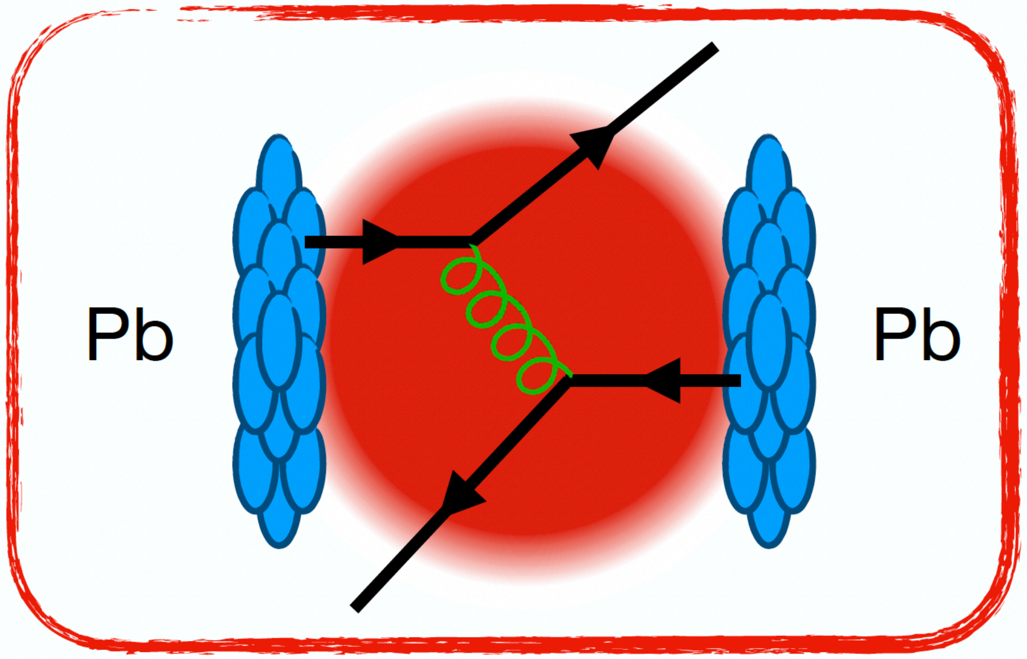
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

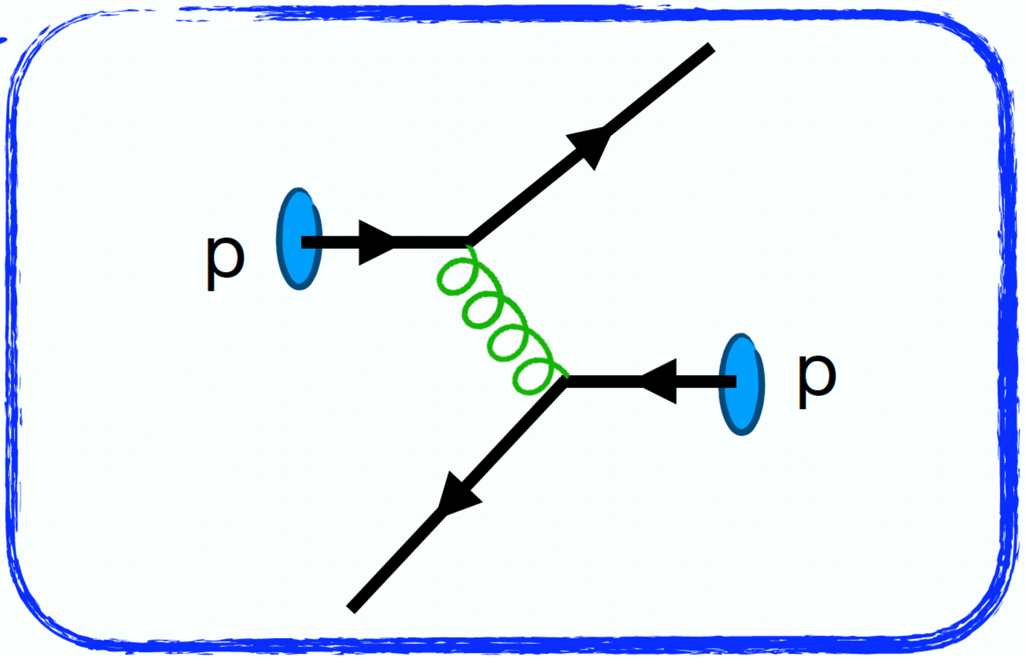
R_{AA} = 1 → no modification

R_{AA} != 1 → medium effects

Nuclear-Modification Factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



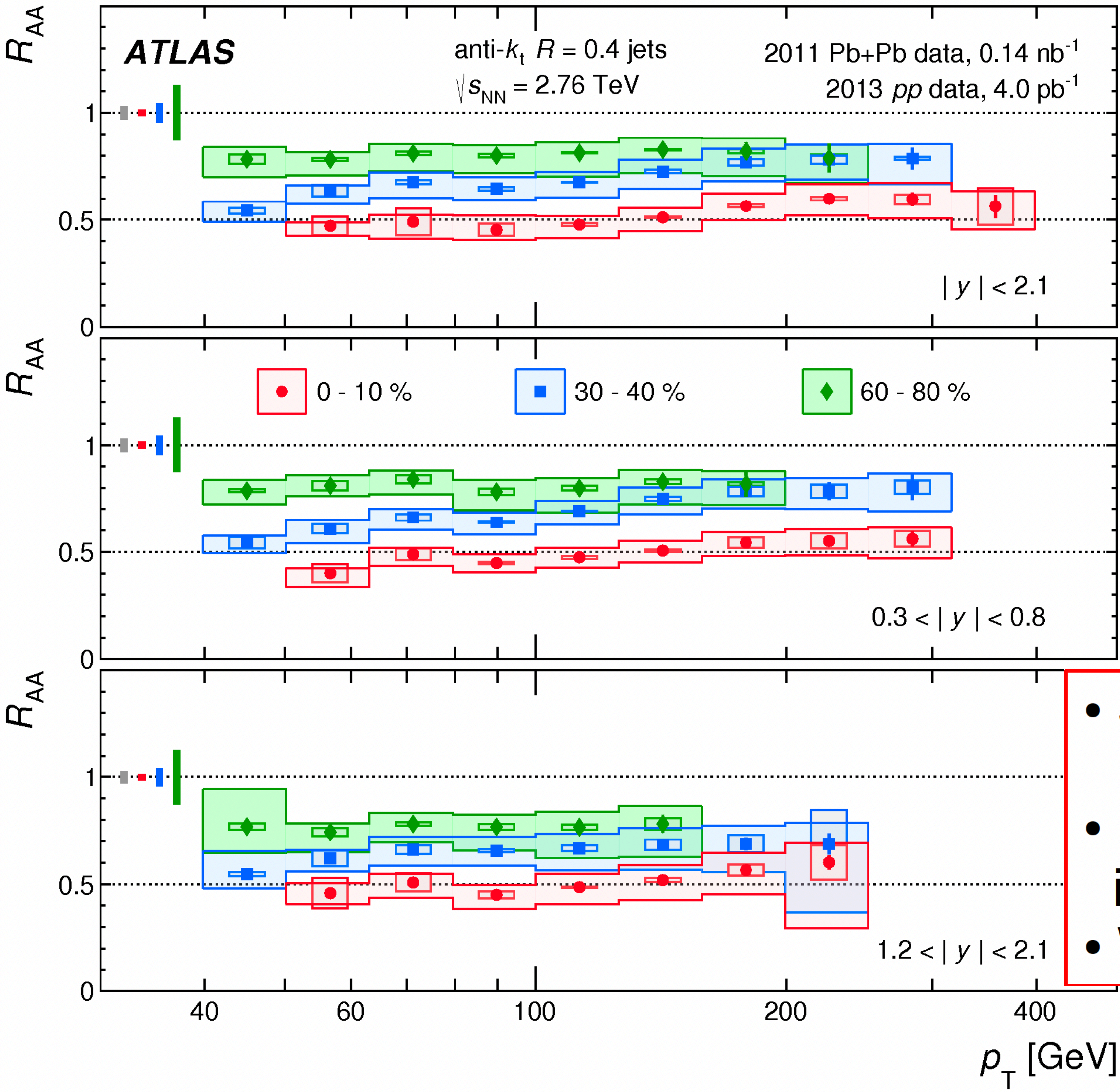


$R_{AA} > 1 \rightarrow$ enhancement

$R_{AA} = 1 \rightarrow$ no medium modification

$R_{AA} < 1 \rightarrow$ supression

Jet R_{AA} up to very high p_T

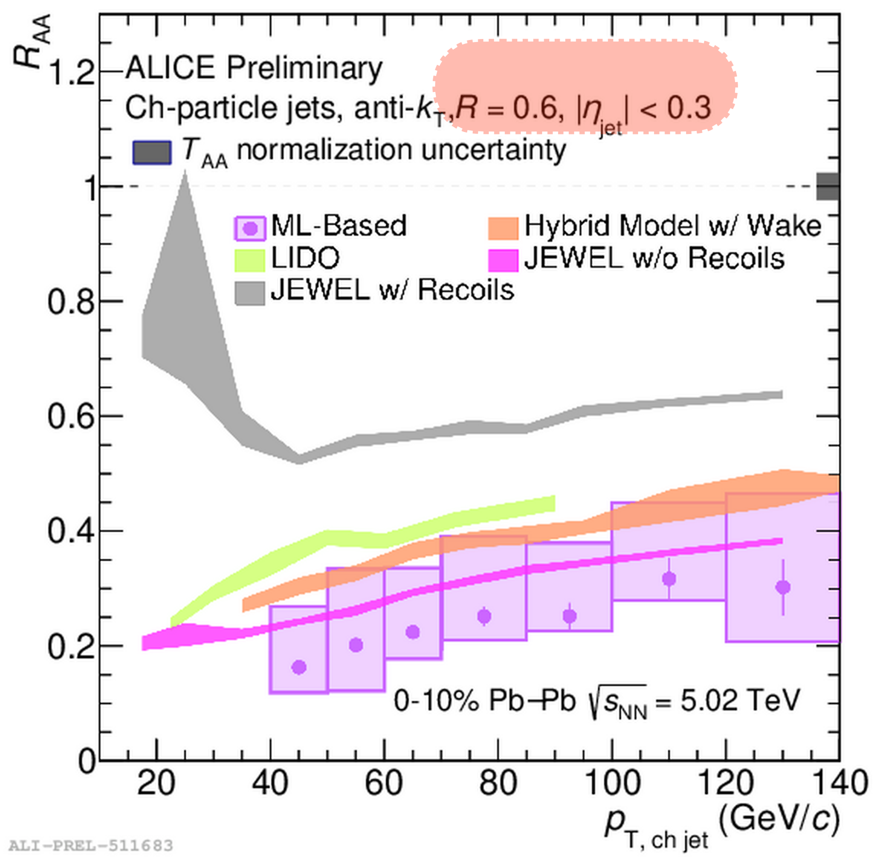


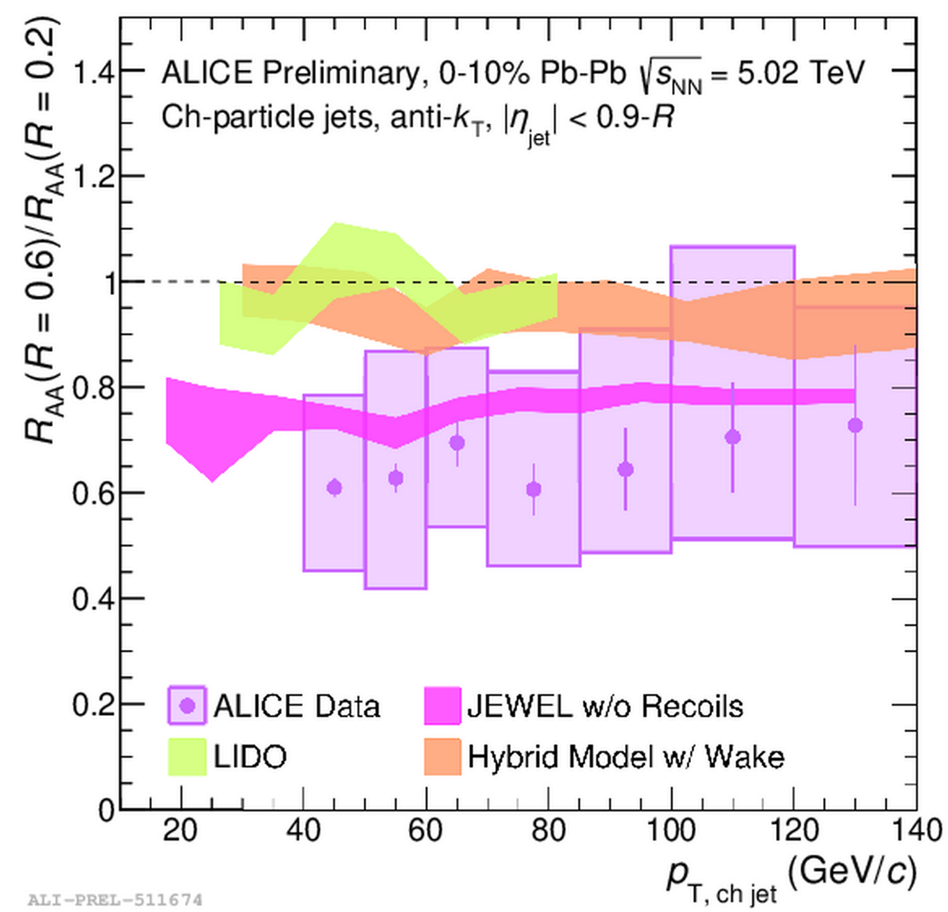
arXiv:1506.08656

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{coll}\, dN_{pp}/dp_T}$$

- Strong jet suppression even at up to 200-300 GeV
- Radiation not captured inside cone R=0.4
- Where does the energy go?

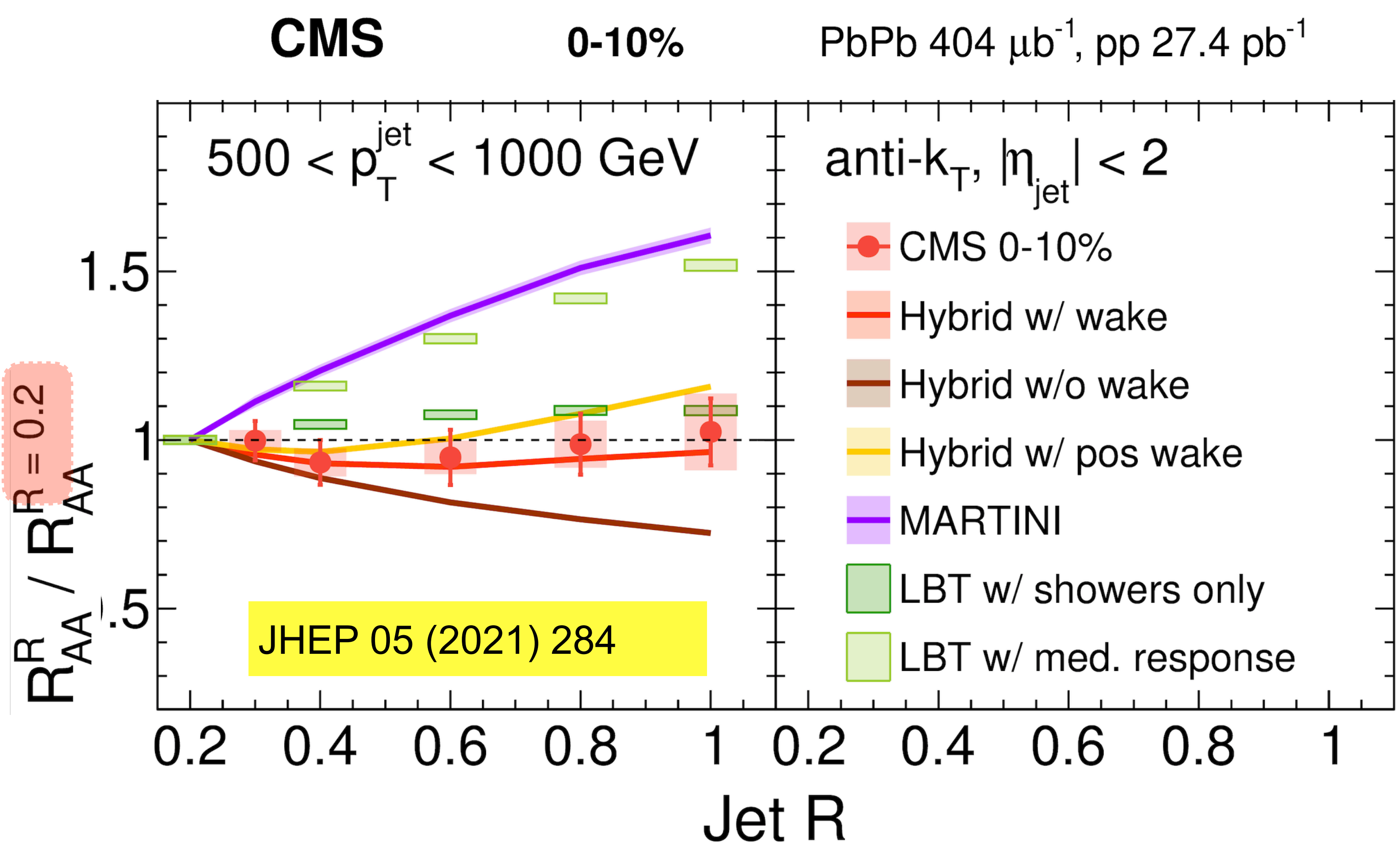
Jet suppression and energy redistribution





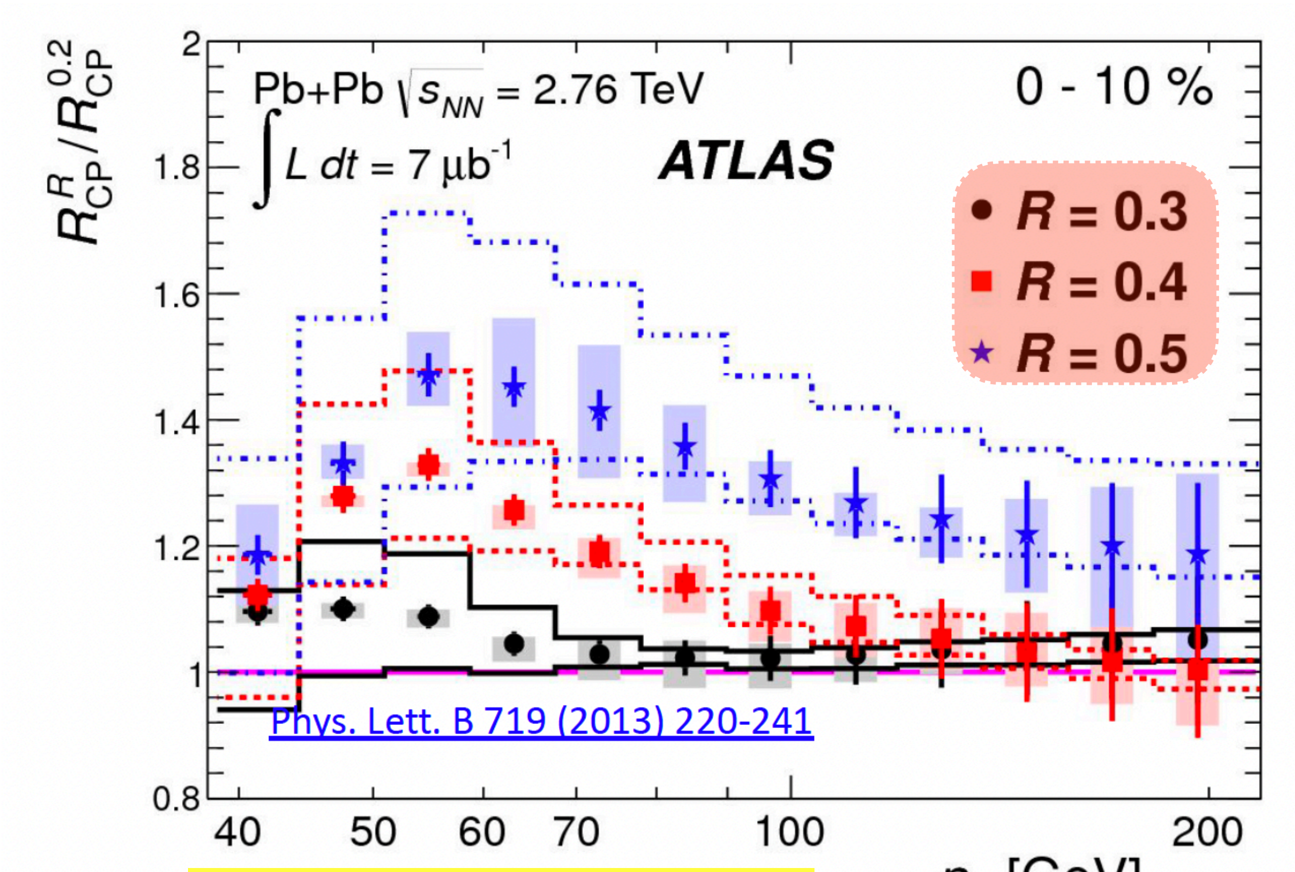
- Jet measurements extended to lower jet p_T and large R using machine learning (ML)
  - improvements on background subtraction and systematics
- Large R (= 0.6) jets indicate a stronger suppression than smaller R (= 0.2) jets
  - suggesting R-dependence of jet energy loss

R dependence of jet R_{AA}

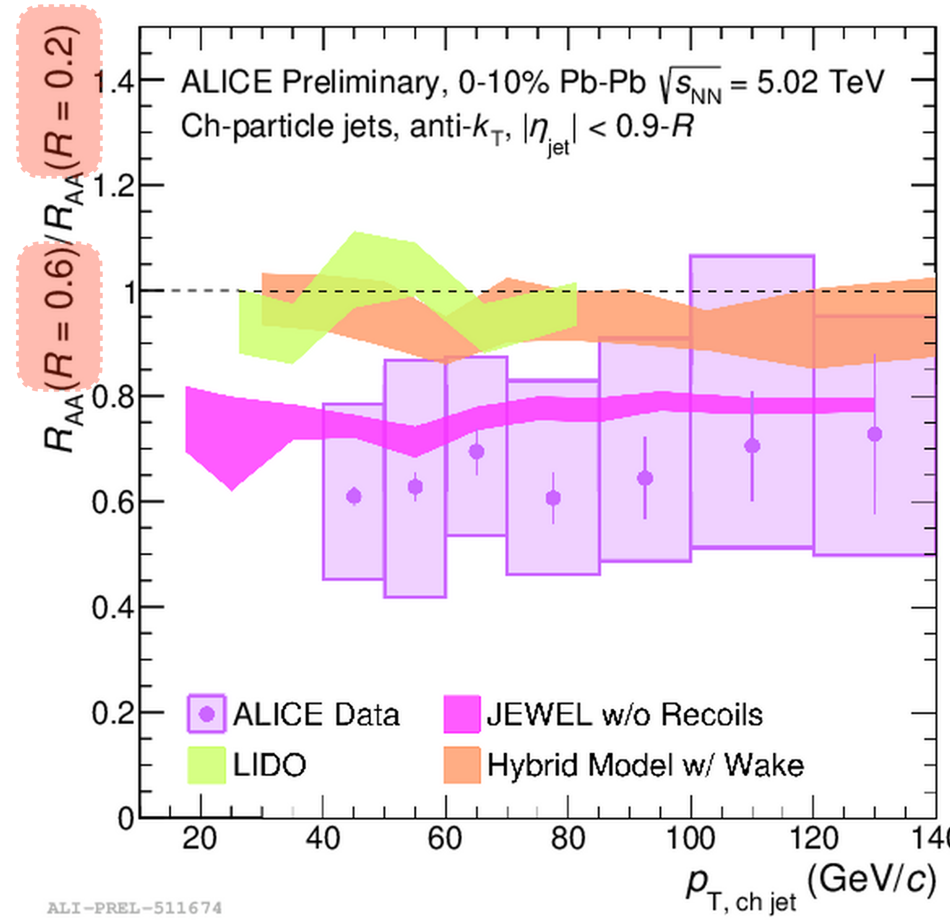


- No strong R dependence of jet R_{AA} for very high p_T jets observed by CMS
- R dependence of jet R_{AA} can help to disentangle energy loss mechanisms
  - competing effect between the amount/how energy redistributed and ability to recover it

Tension with previous ATLAS results



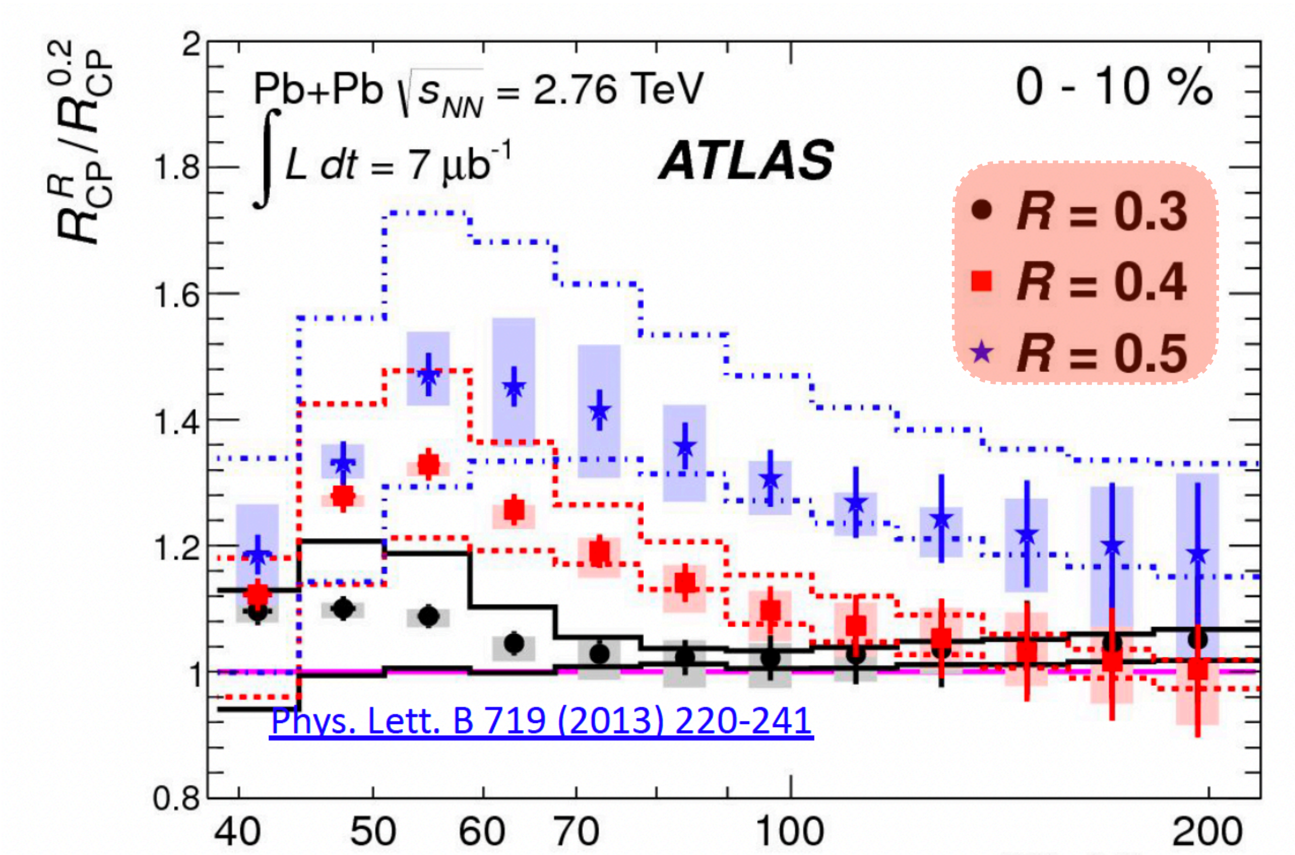
PLB 719 (2013) 220



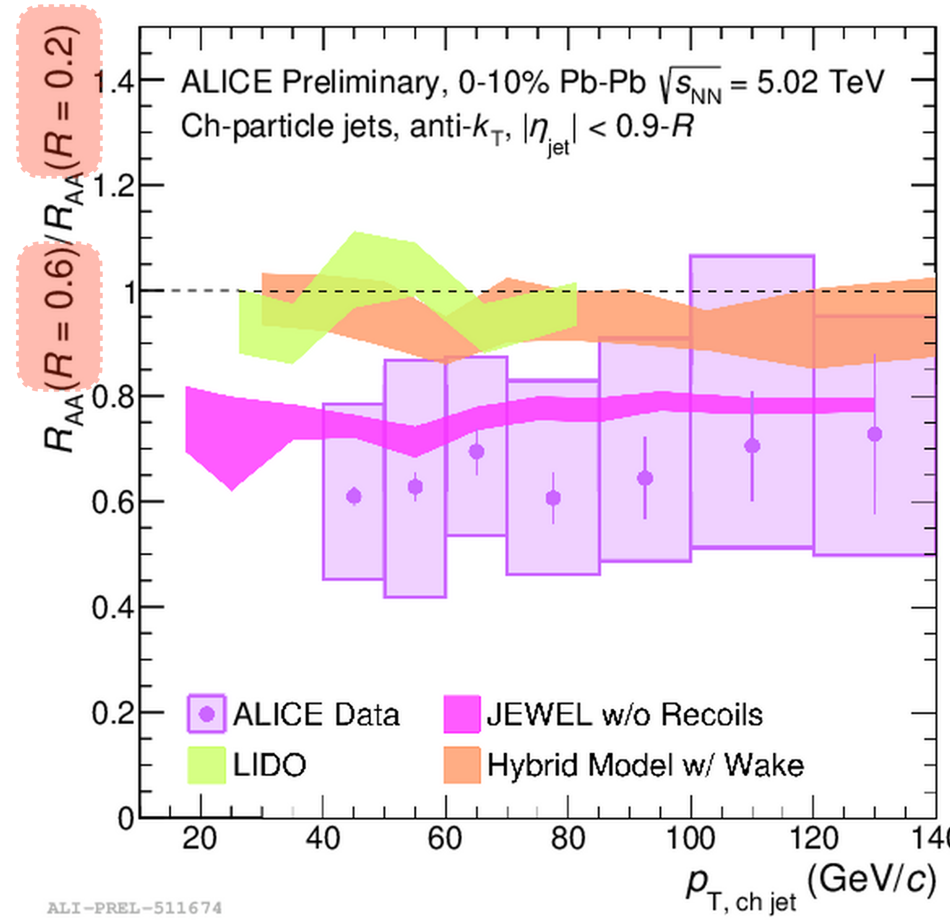
Suggests larger radius **less** suppressed

Suggests larger radius **more** suppressed

Tension with previous ATLAS results



PLB 719 (2013) 220



Suggests larger radius **less** suppressed

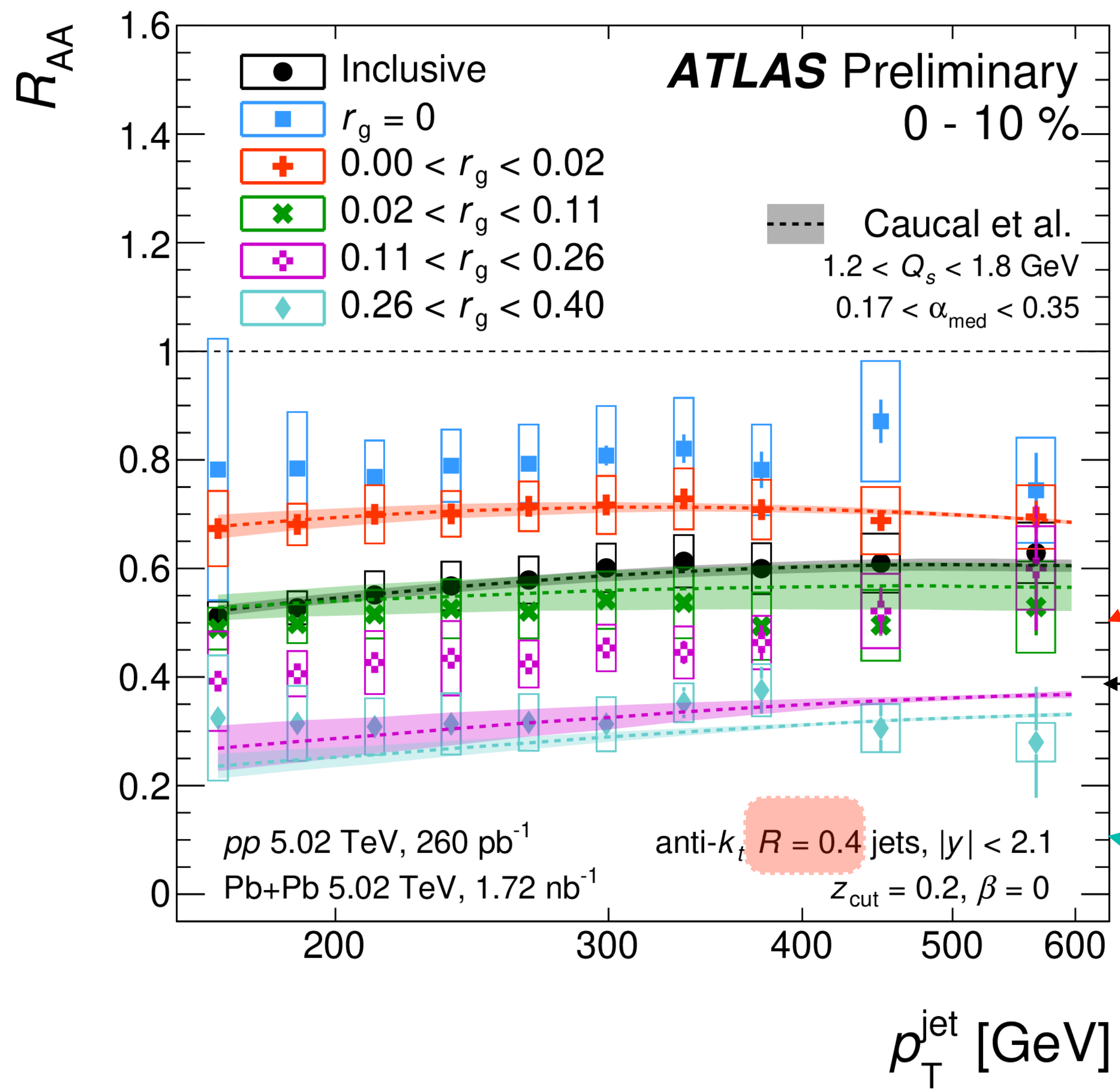
Suggests larger radius **more** suppressed

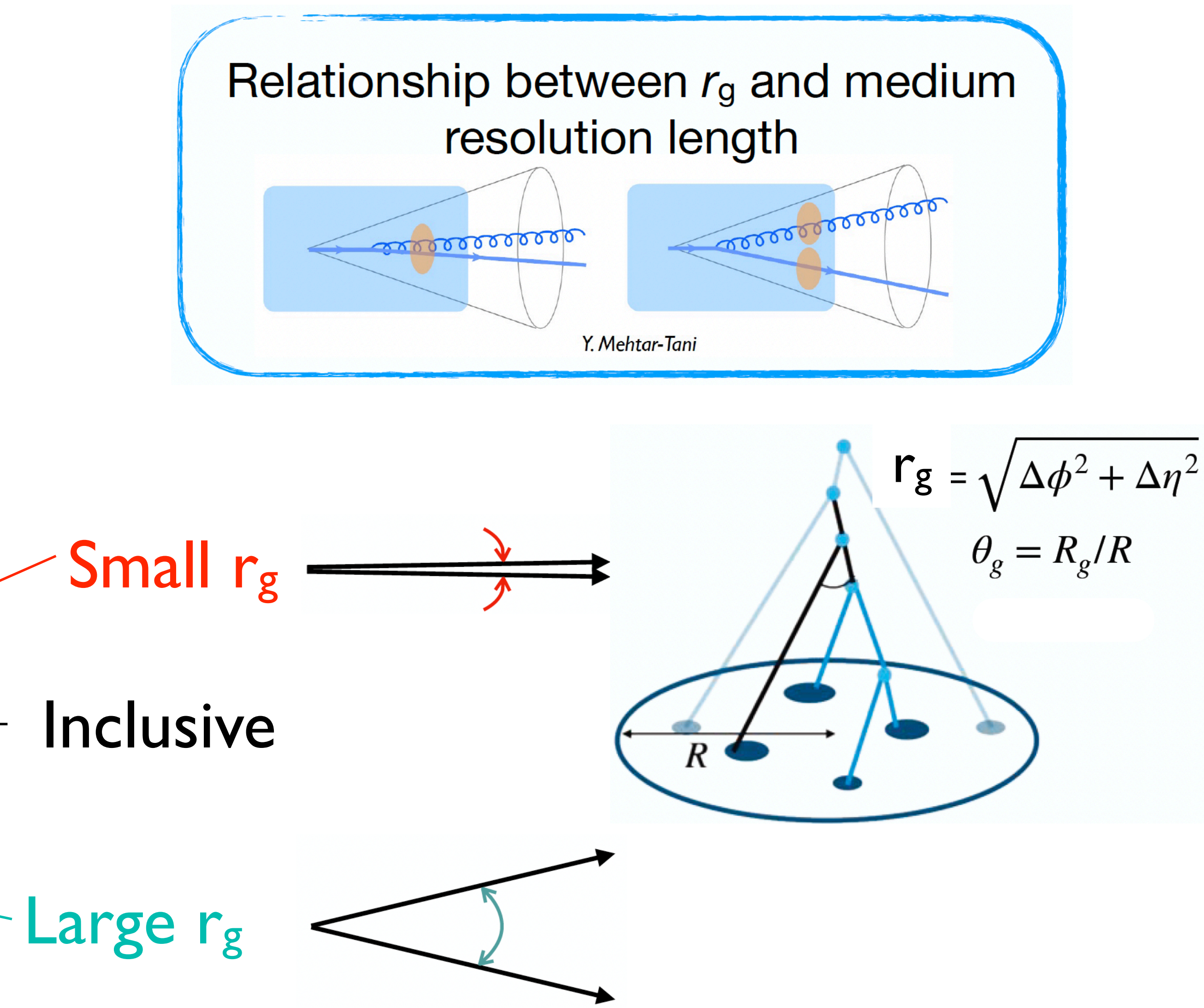
- Not exactly the same observables: R_{cp} vs. R_{AA}
- Different types of jets: full vs. charge
- Different centre-of-mass energy and phase-space
- Larger systematics in ALICE

More detailed comparison and future studies are needed

R_{AA} - substructure interplay

ATLAS-CONF-2022-026

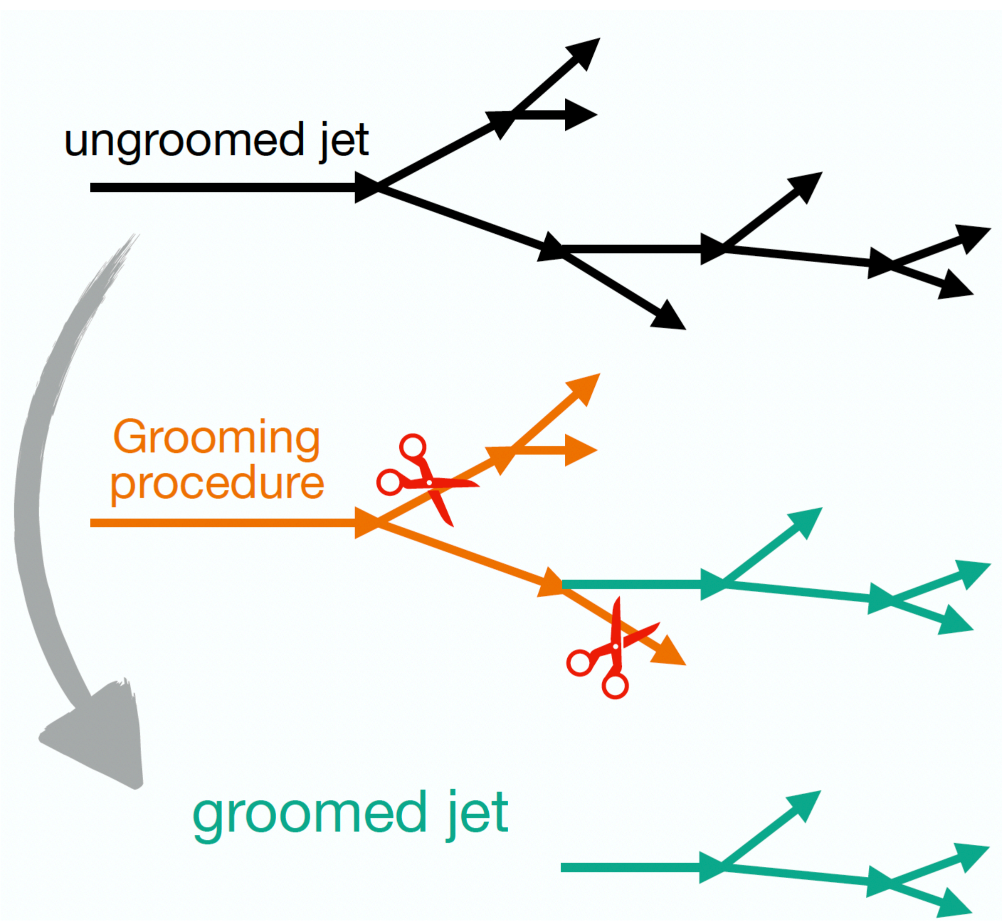




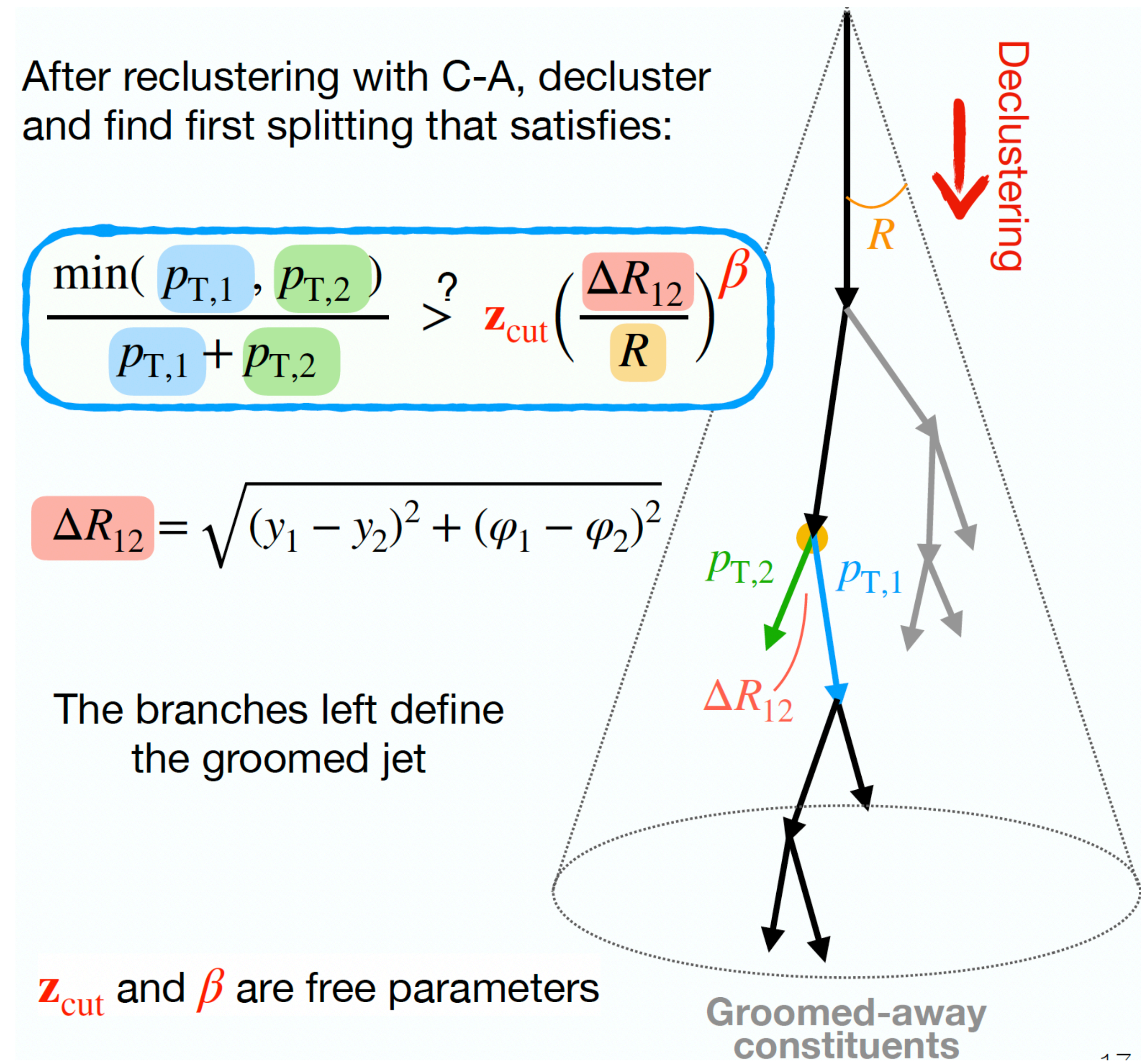
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed

Grooming and Soft Drop

Grooming: systematically removing soft wide-angle radiation from a jet to mitigate effects such as initial- state radiation, multi-carton interactions, and pileup

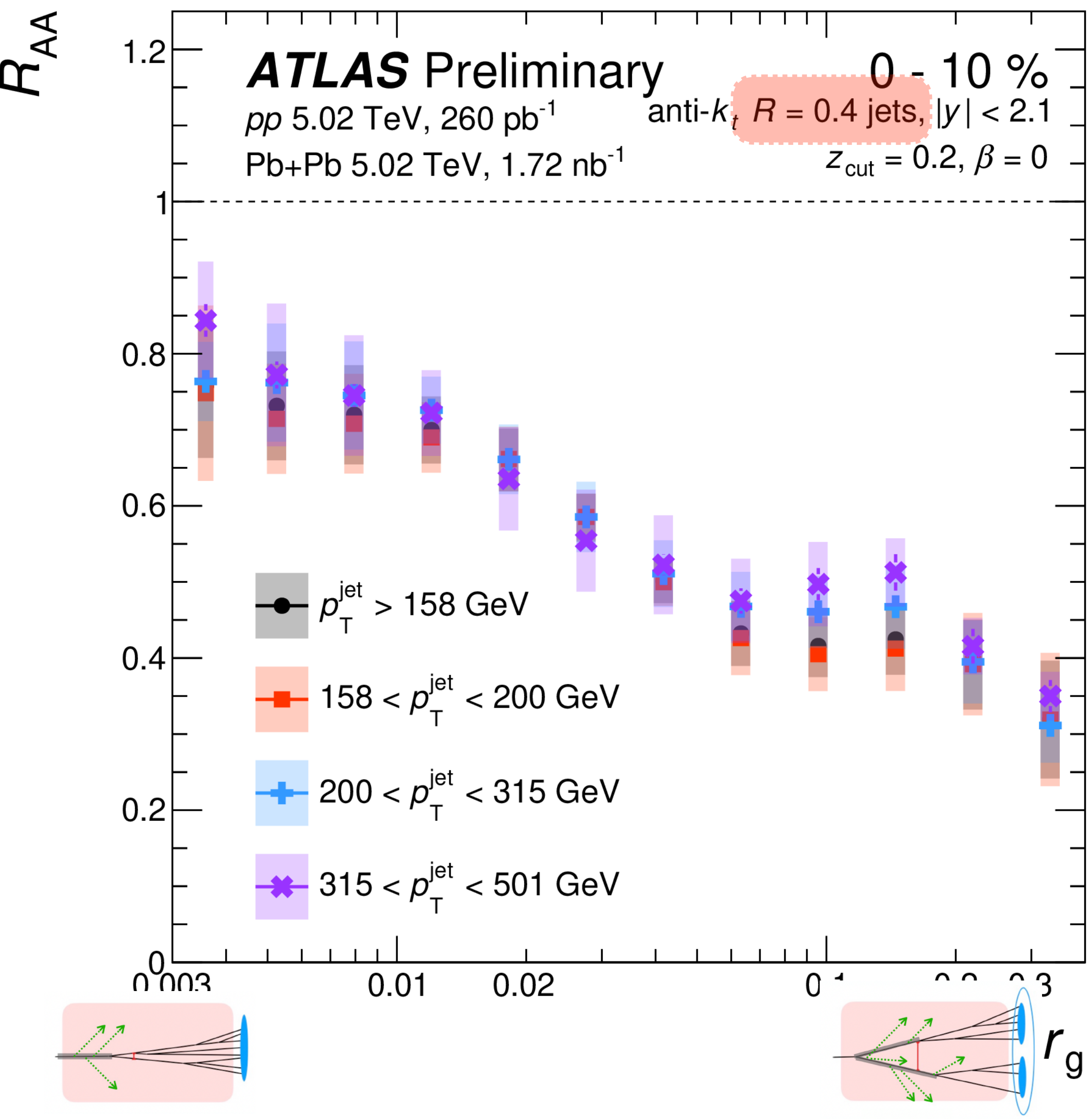


Soft Drop: JHEP 1405 (2014) 146

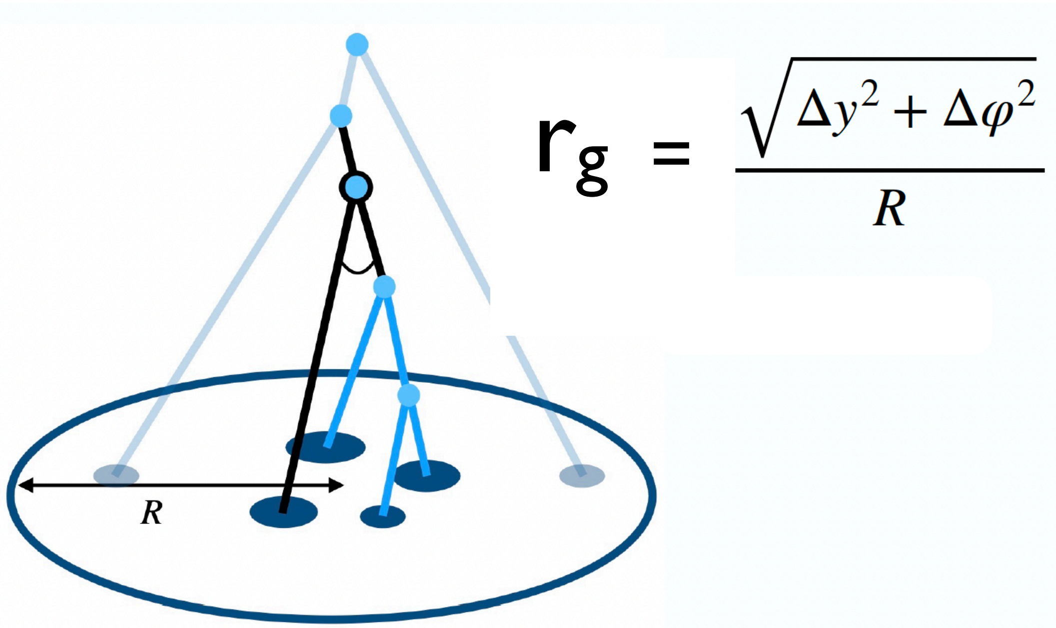


R_{AA} vs groomed jet radius

ATLAS-CONF-2022-026



Absolutely-normalized results

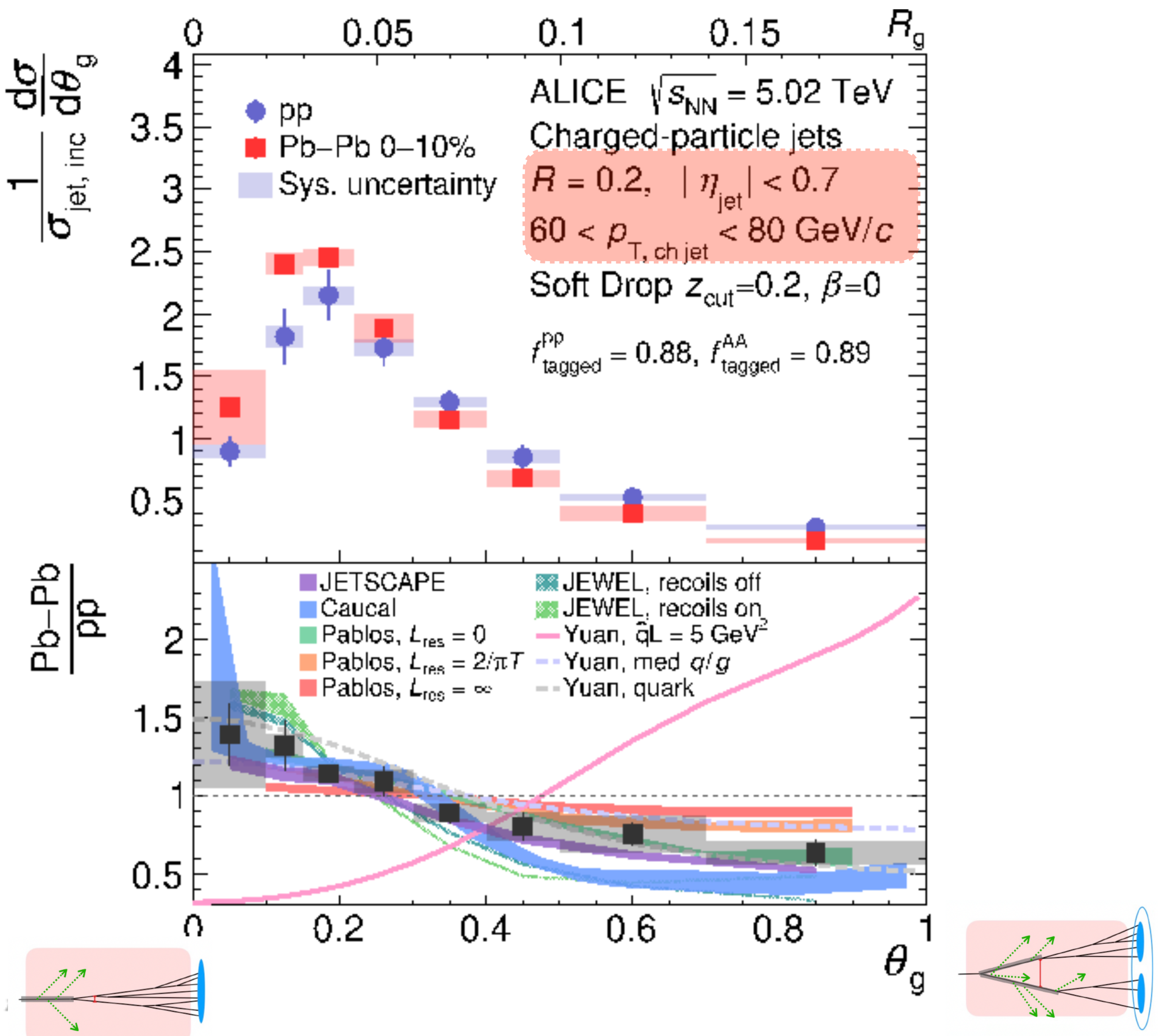


$$r_g = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

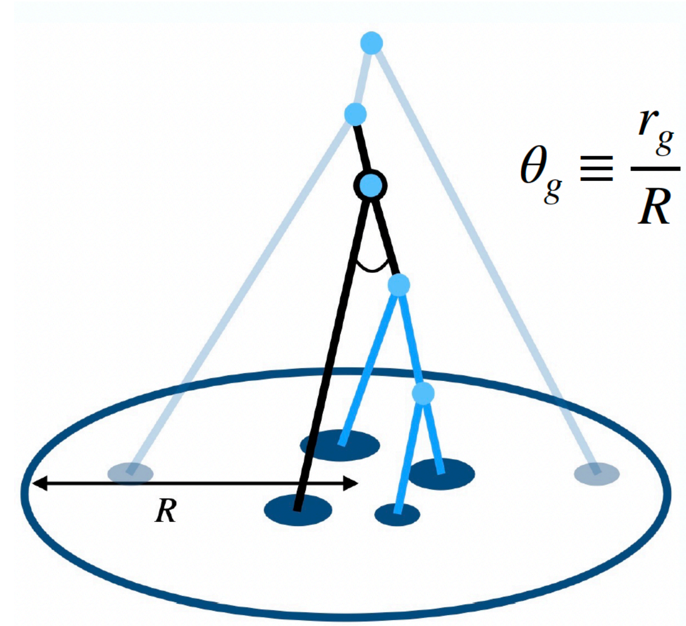
- No significant p_T dependence
- Strong r_g dependence of R_{AA}
  - ➡ Large r_g jets potentially select more active vacuum shower or with more independent prongs that are more quenched in medium

Groomed jet radius

PRL 128 (2022) 102001



Self-normalized results → shapes!

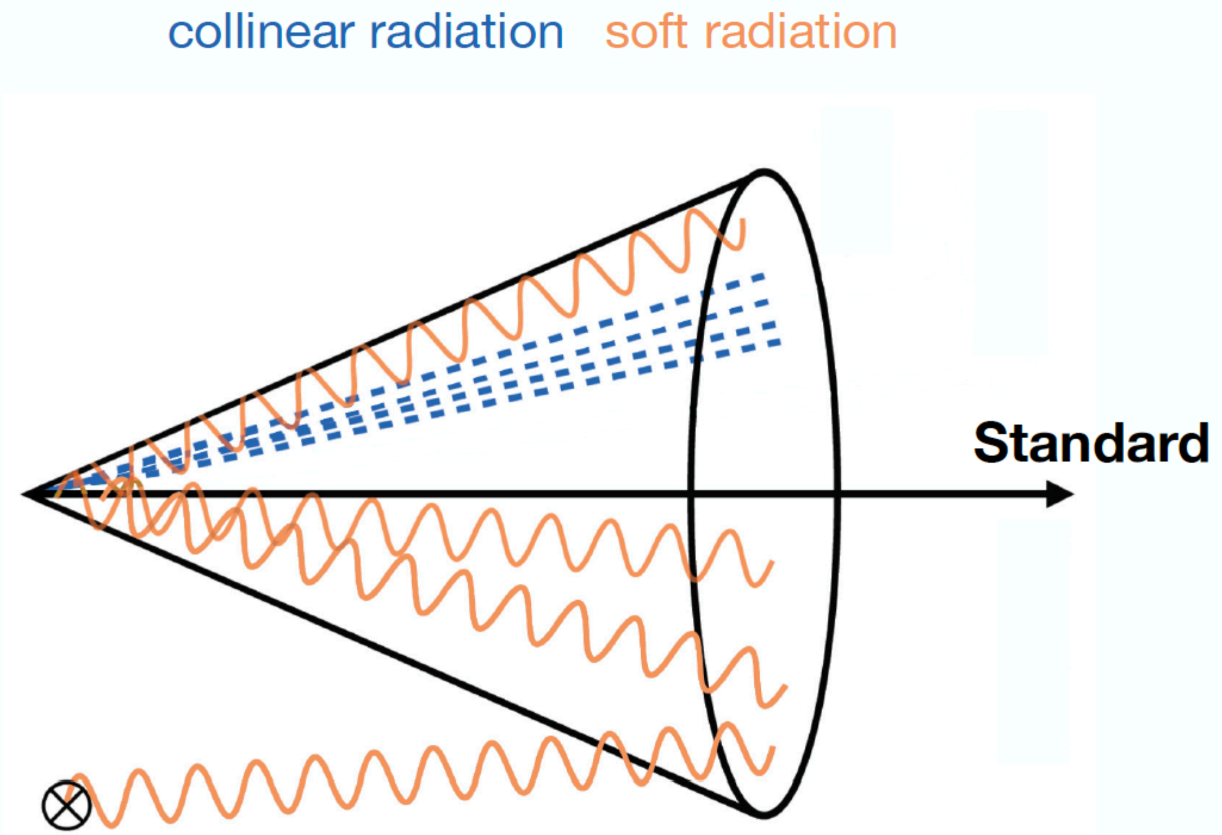


$$\theta_g \equiv \frac{r_g}{R} = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

- Large θ_g jets are more suppressed → narrowing of the Pb-Pb distributions
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

Angle between jet axes

- Standard axis:
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme



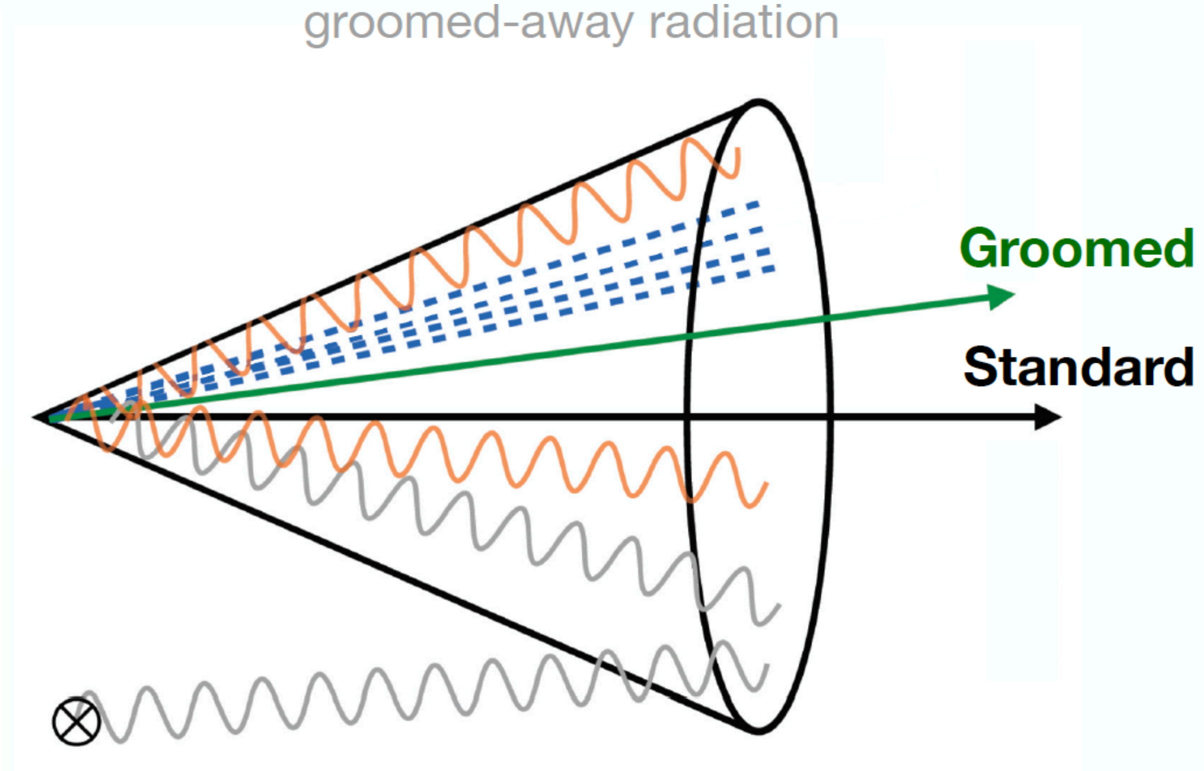
P. Cal et al., JHEP 04 (2020) 211

Substructure observable: $\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$ between two axes

Angle between jet axes

- Standard axis:
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Groomed axis:
  standard axis of groomed (with Soft Drop) jet



P. Cal et al., JHEP 04 (2020) 211

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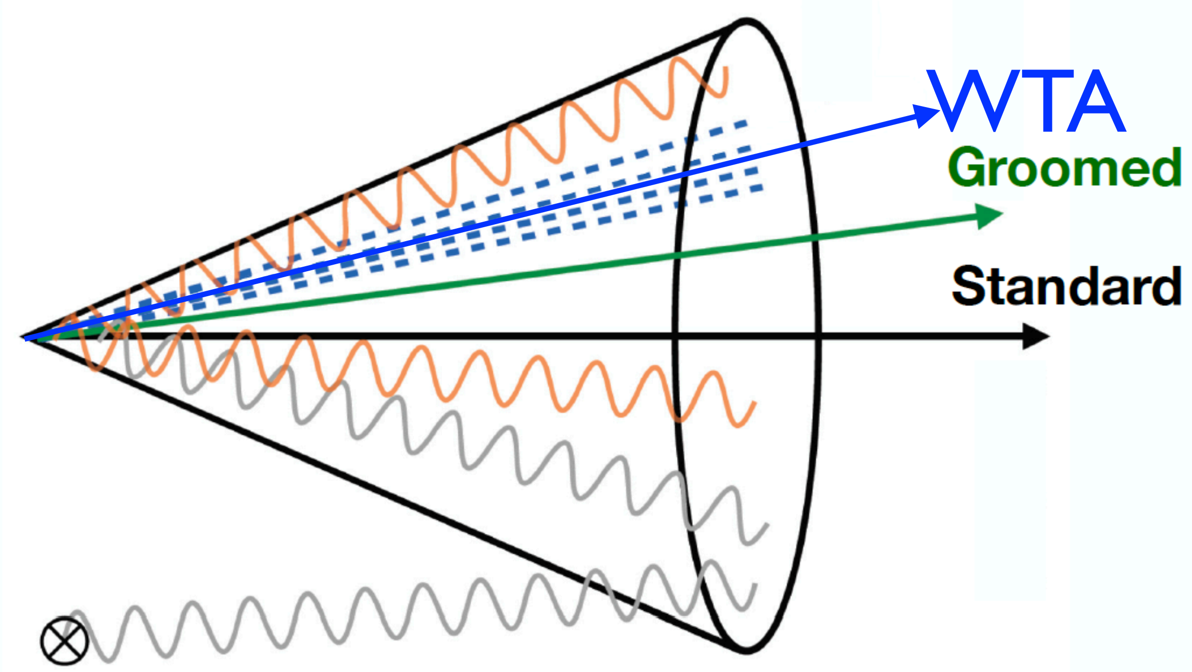
Angle between jet axes

- Standard axis:
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Groomed axis:
  standard axis of groomed (with Soft Drop) jet

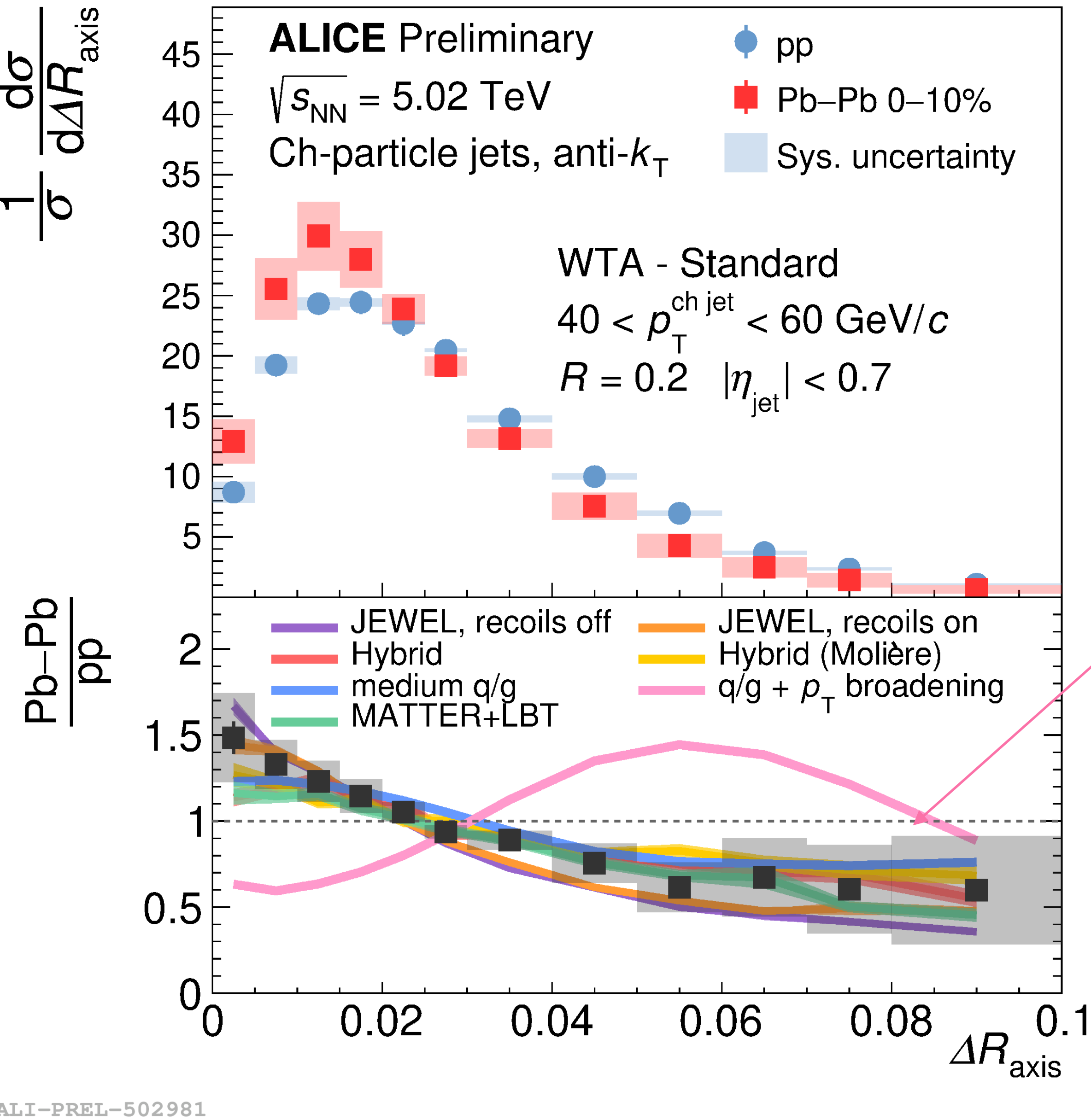
- Winner-Takes-All (WTA) axis:
  - recluster jet with CA algorithm
  - 2 → 1 prong combination by taking direction of harder prong and $p_{T,tot} = p_{T,1} + p_{T,2}$
  - Resulting axis insensitive to soft radiation at leading power



P. Cal et al., JHEP 04 (2020) 211

Substructure observable: $\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$ between two axes

Jet-axis differences



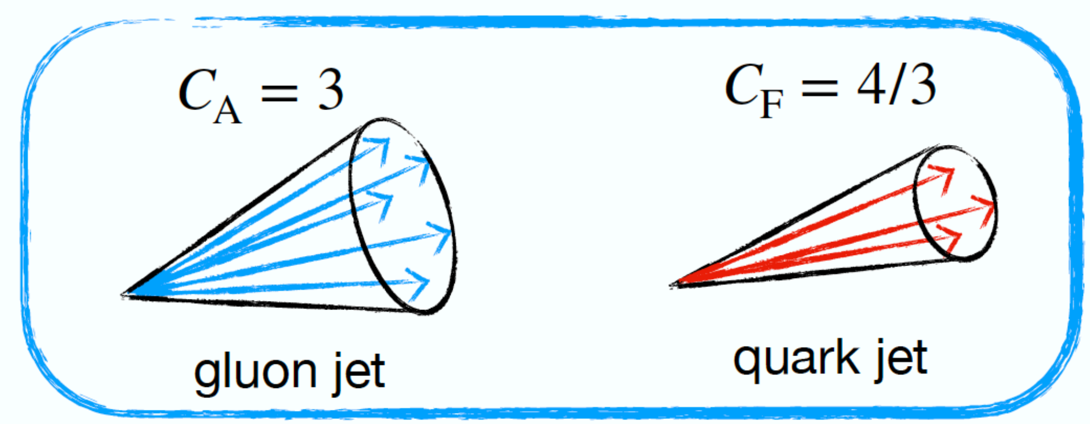
Angle between standard and WTA jet axes

Narrowing of the angular substructure, selection bias?

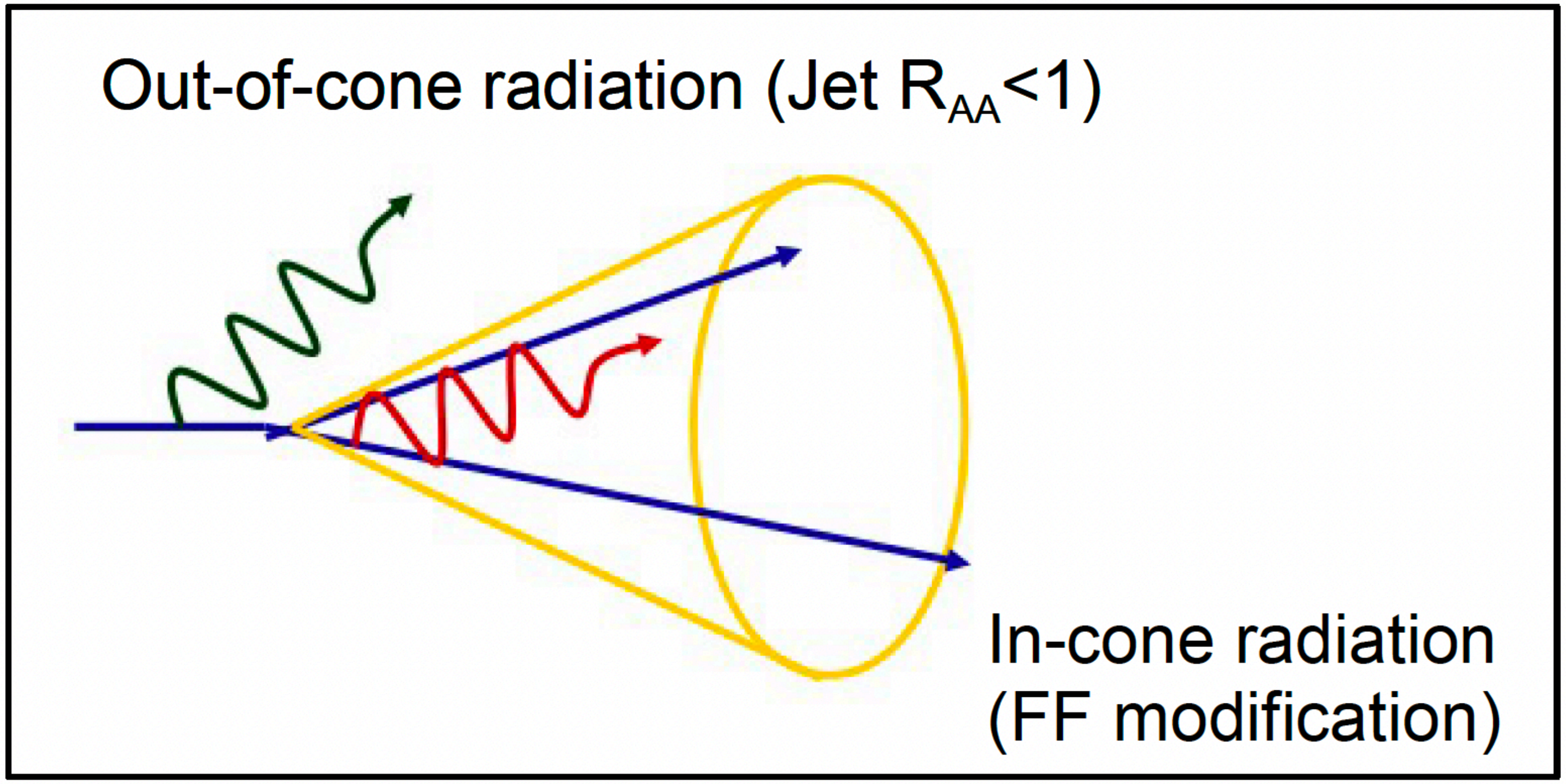
BDMPS-based in-jet p_T broadening

The disagreement seen in here can't be explained by grooming

Quark-jet fraction higher in medium?



Where does the radiated energy go?



Yaxian MAO
Central China Normal University
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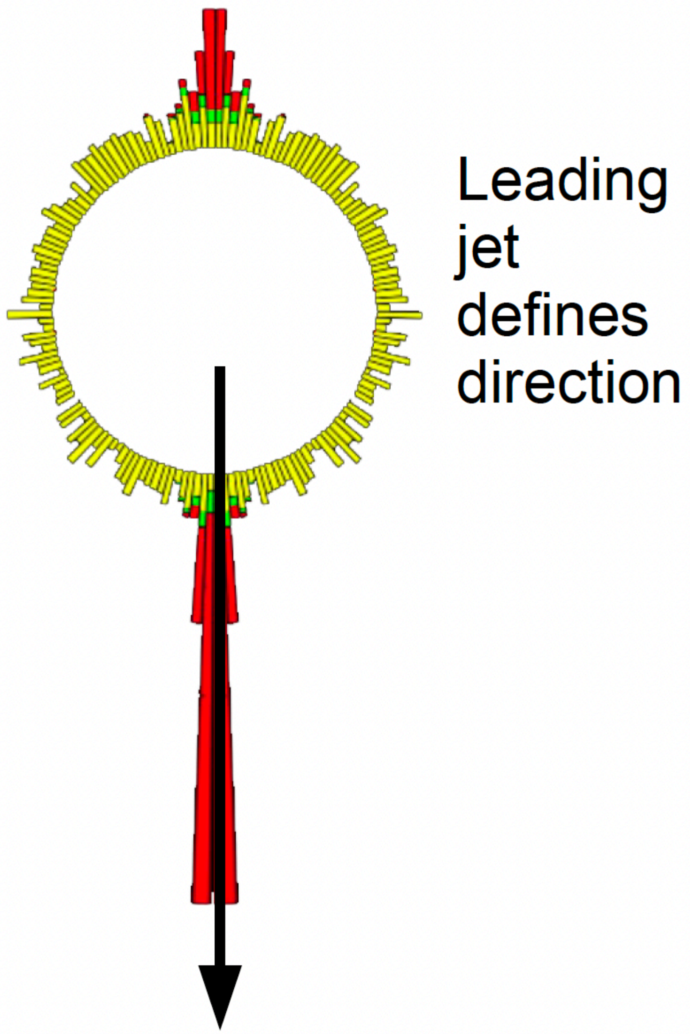
Where does the radiated energy go?

- Calculate projection of p_T on leading jet axis and average over selected tracks with p_T>0.5 GeV/c and |η| < 2.4
- Define missing p_T $$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$
- Averaging over event sample in bins of A_J find missing p_T consistent with zero



PRC 84 (2011) 024906

Where does the radiated energy go?

- Calculate projection of p_T on leading jet axis and average over selected tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$
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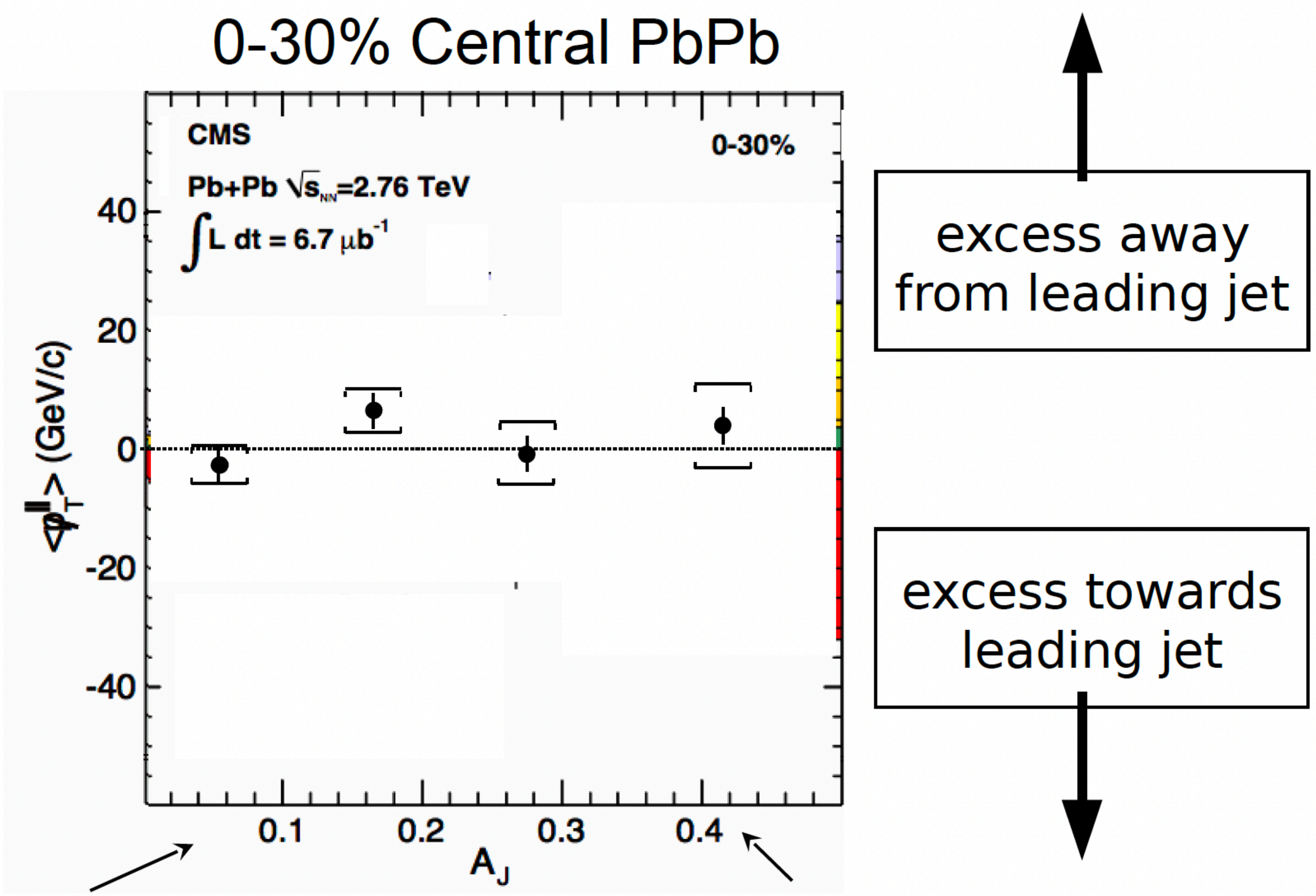
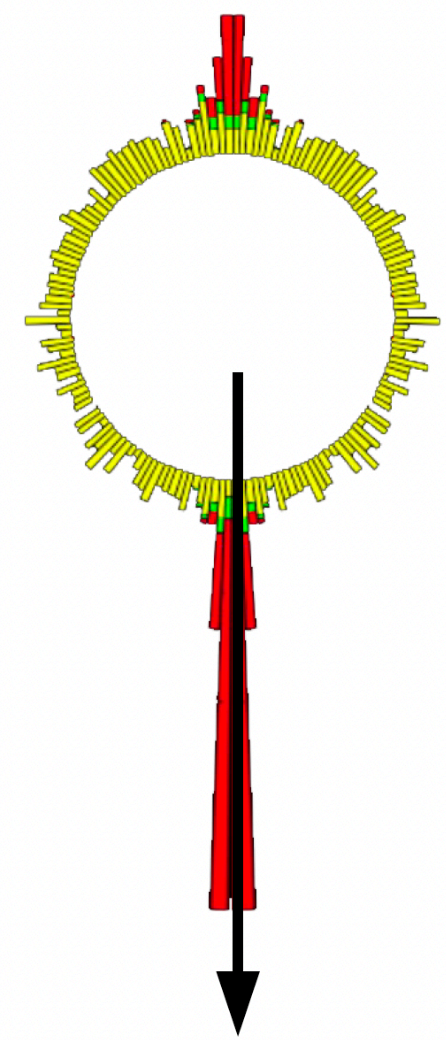


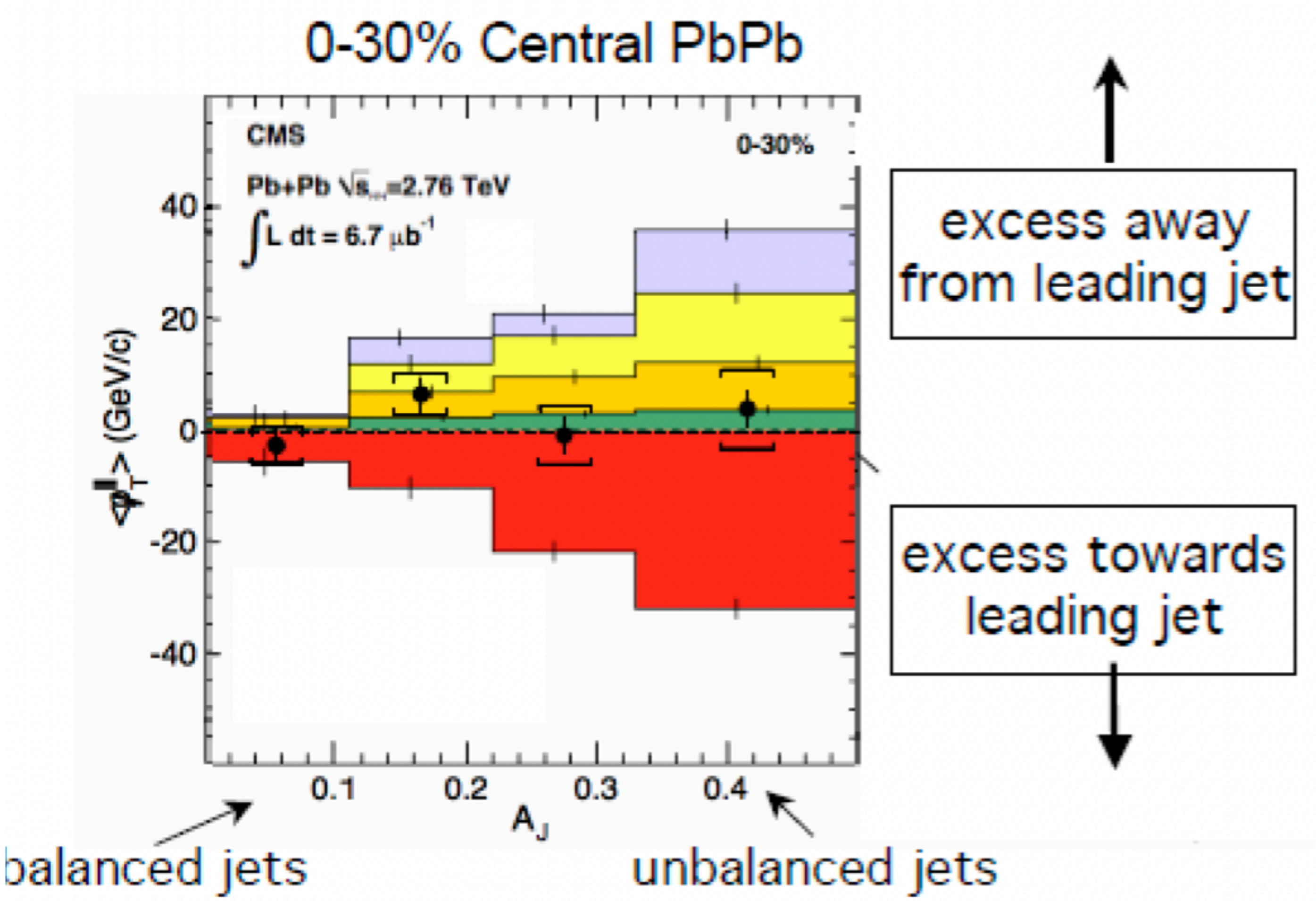
balanced jets unbalanced jets



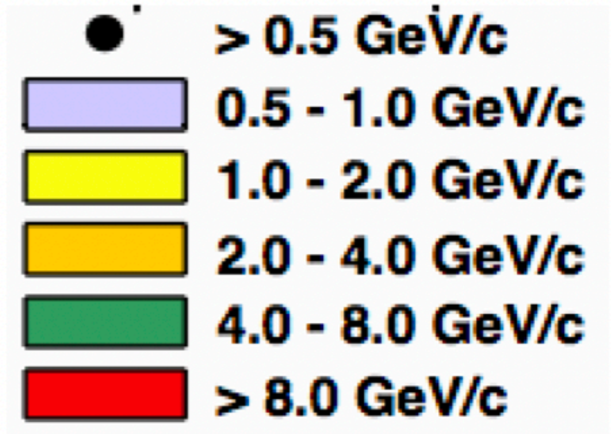
Leading jet defines direction

PRC 84 (2011) 024906

Where does the energy go?



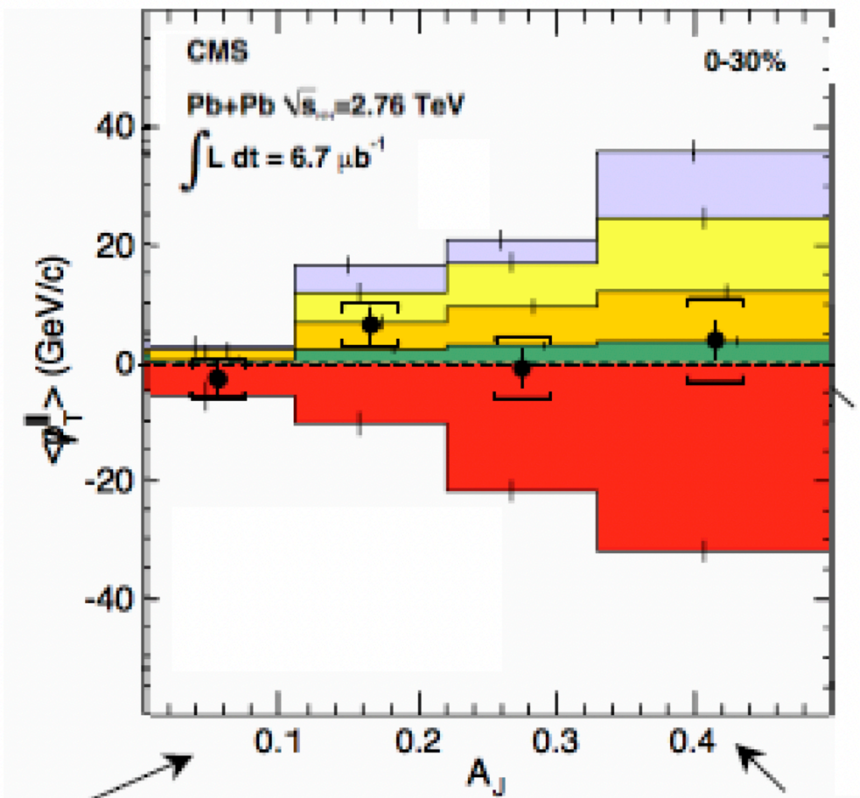
Calculate missing p_T in bins of track p_T



The momentum difference in the leading jet is compensated by low p_T particles

Where does the energy go?

0-30% Central PbPb



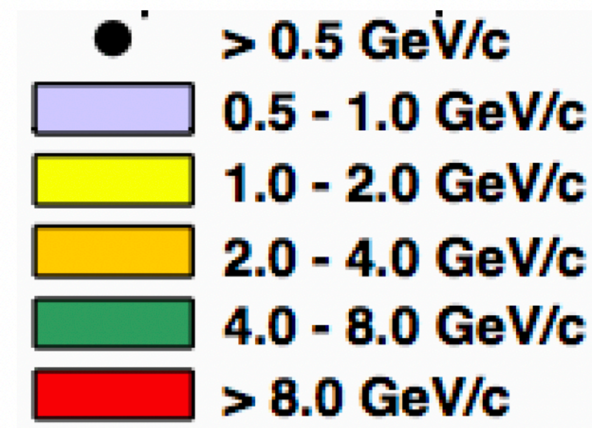
excess away from leading jet

excess towards leading jet

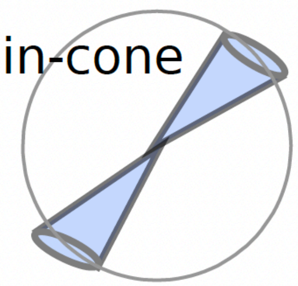
balanced jets

unbalanced jets

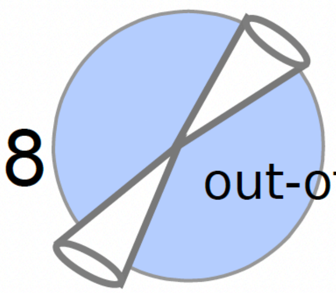
Calculate missing p_T in bins of track p_T



in-cone

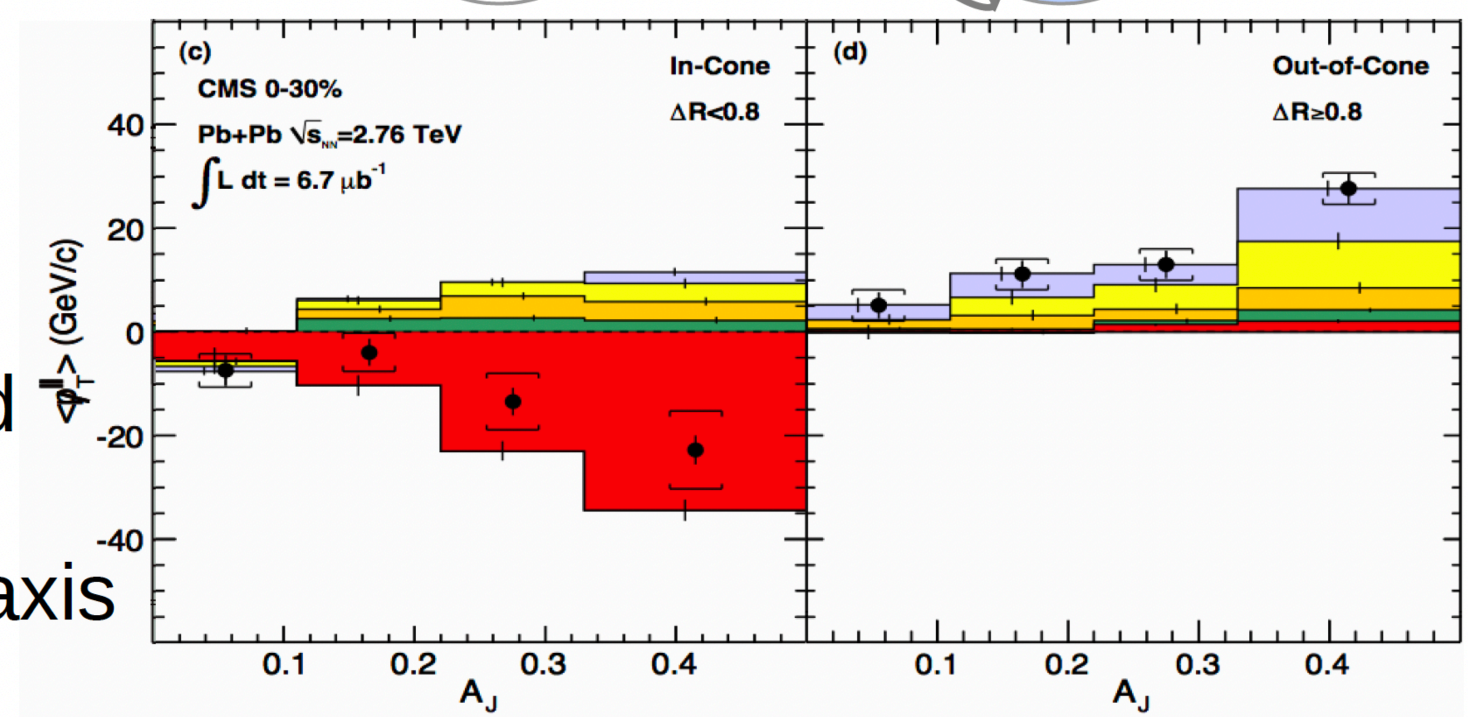


$\Delta R = 0.8$

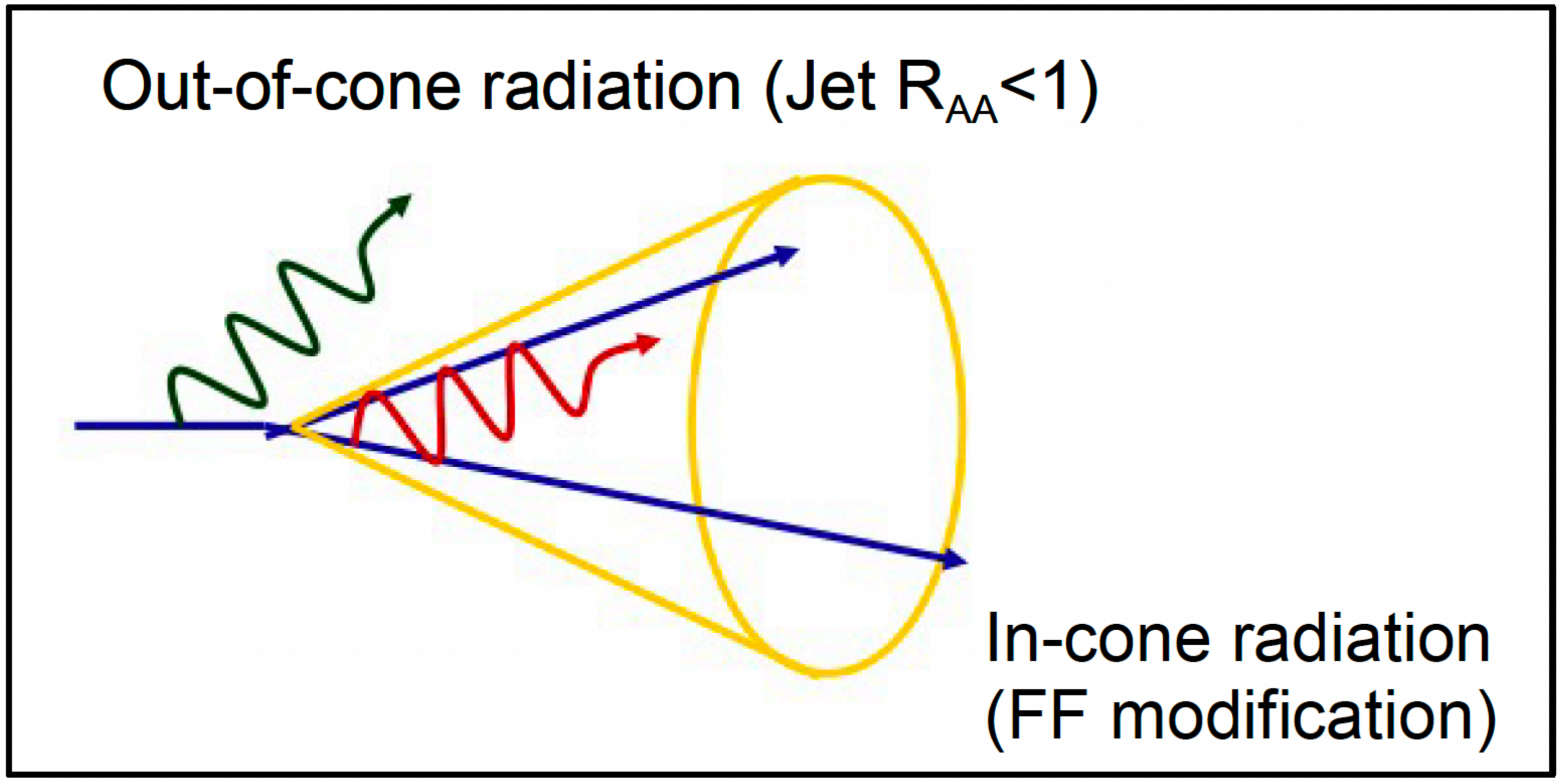


out-of-cone

The momentum difference in the leading jet is compensated by low p_T particles at large angles with respect to the jet axis



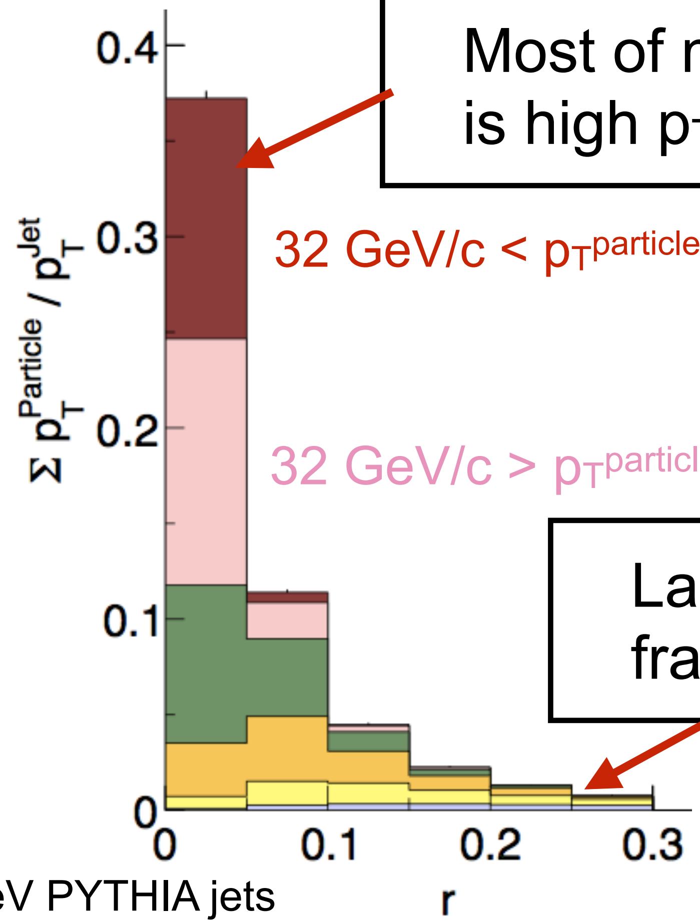
Where does the radiated energy go?



Is there an observable difference in the jet cone?

Jet anatomy

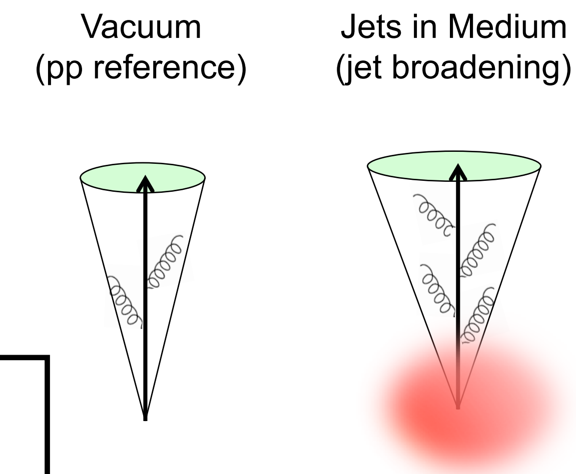
Most of momentum found close to jet axis is high p_T particles ($p_T > O(10\ GeV)$)



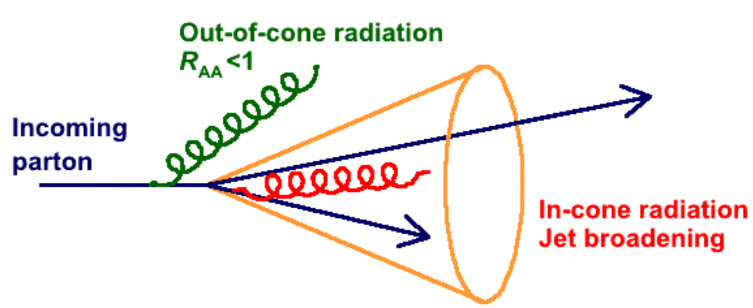
Large angle component of jet contains small fraction of jet p_T in soft particles ($p_T > O(1GeV)$)

100 GeV PYTHIA jets

- **> 32 GeV/c**
- **16-32 GeV/c**
- **8-16 GeV/c**
- **4-8 GeV/c**
- **2-4 GeV/c**
- **1-2 GeV/c**



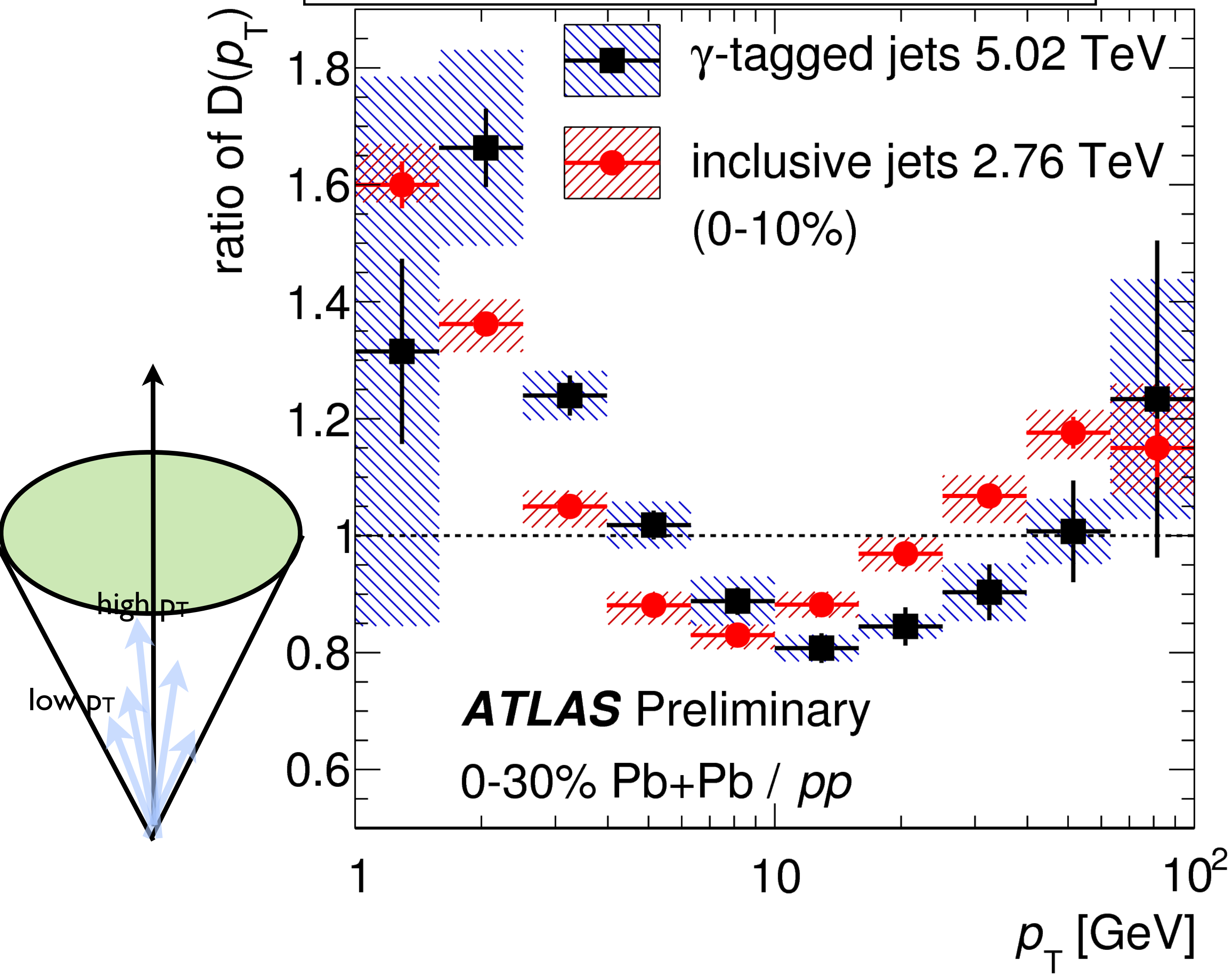
$r = \sqrt{(\eta_{jet}-\eta_{ch})^2+(\varphi_{jet}-\varphi_{ch})^2}$

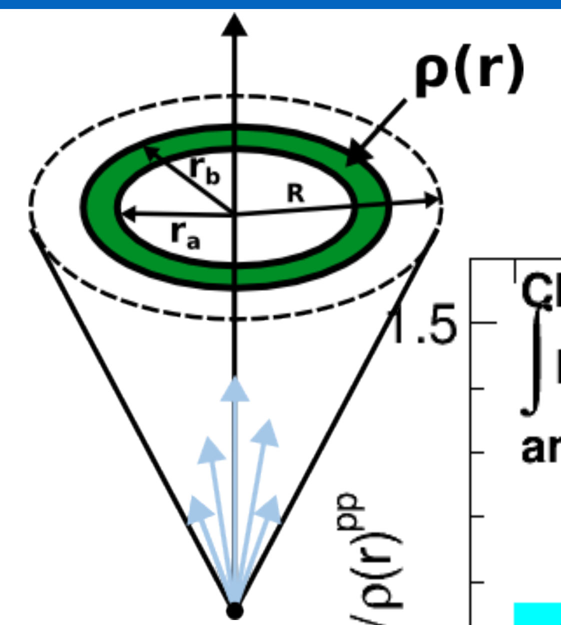


- How the parton shower modified?
- What is the mechanism modifying the shower?
- Can we relate to shower modifications to medium properties?

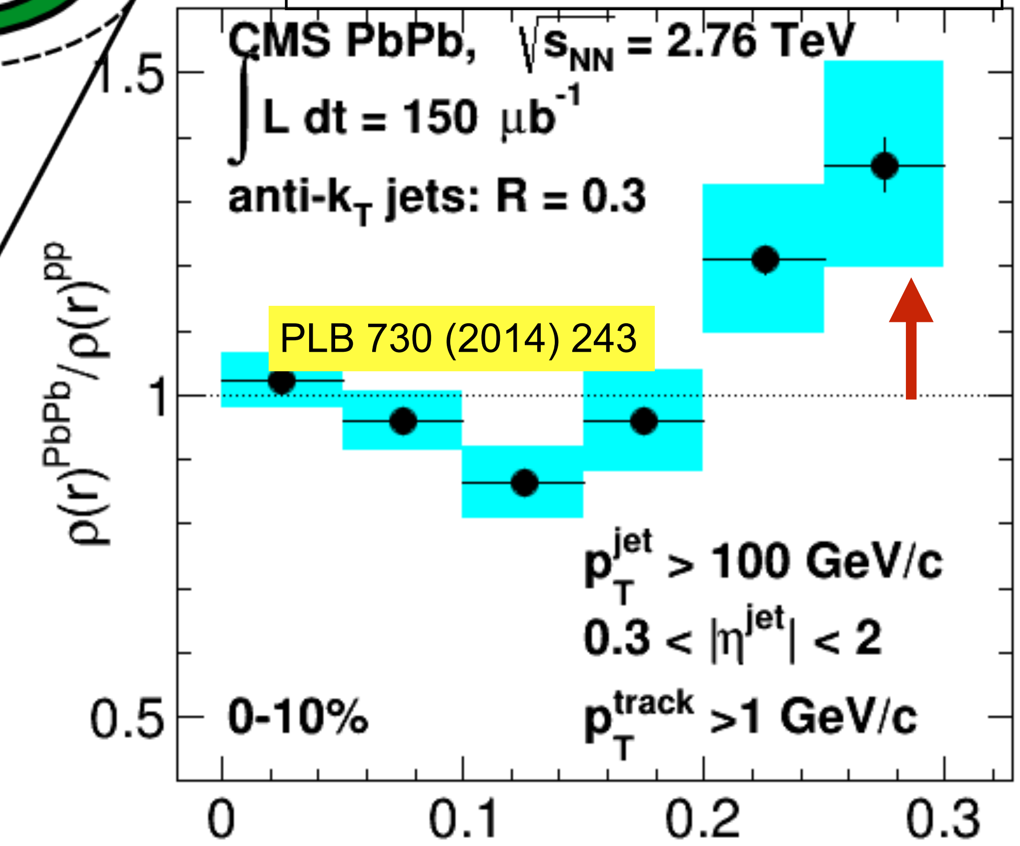
Modification of jet fragmentation patterns

jet FF: momentum redistribution





radial profile:
energy flow redistribution

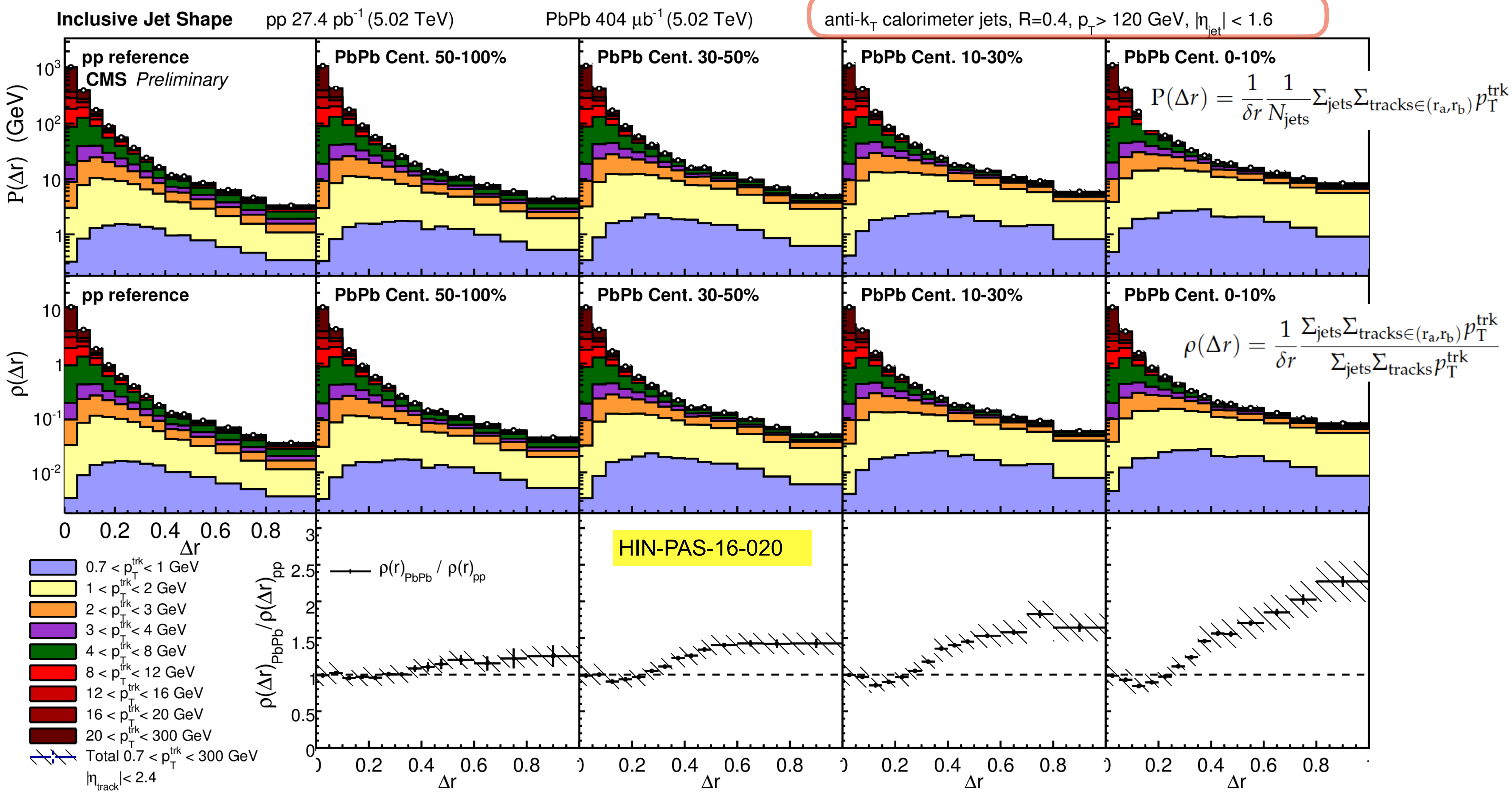


$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}},$$

- Excess at low p_T and large angular distance → jet broadening
- Suppression in intermediate p_T and radii → jet quenching

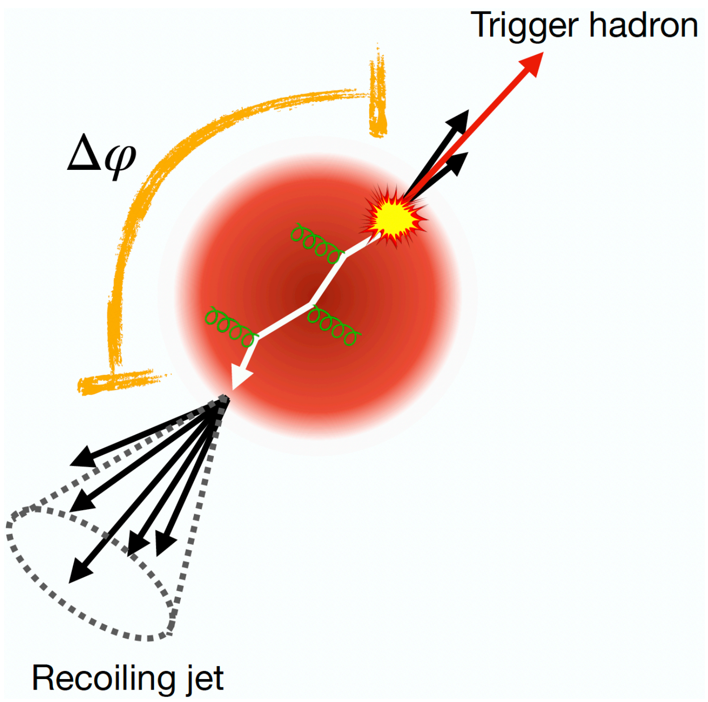
➡ Investigate low p_T jet fragmentation patterns with ALICE

Jet shape measurements to larger distance

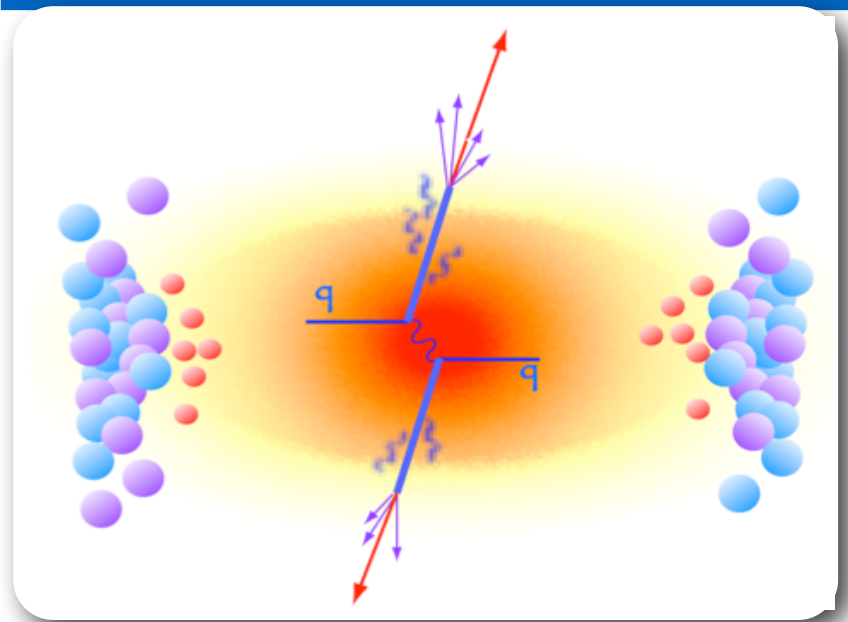


- Extend jet shape analysis to large R using 2-d correlation methods
- Large angle broadening becomes stronger

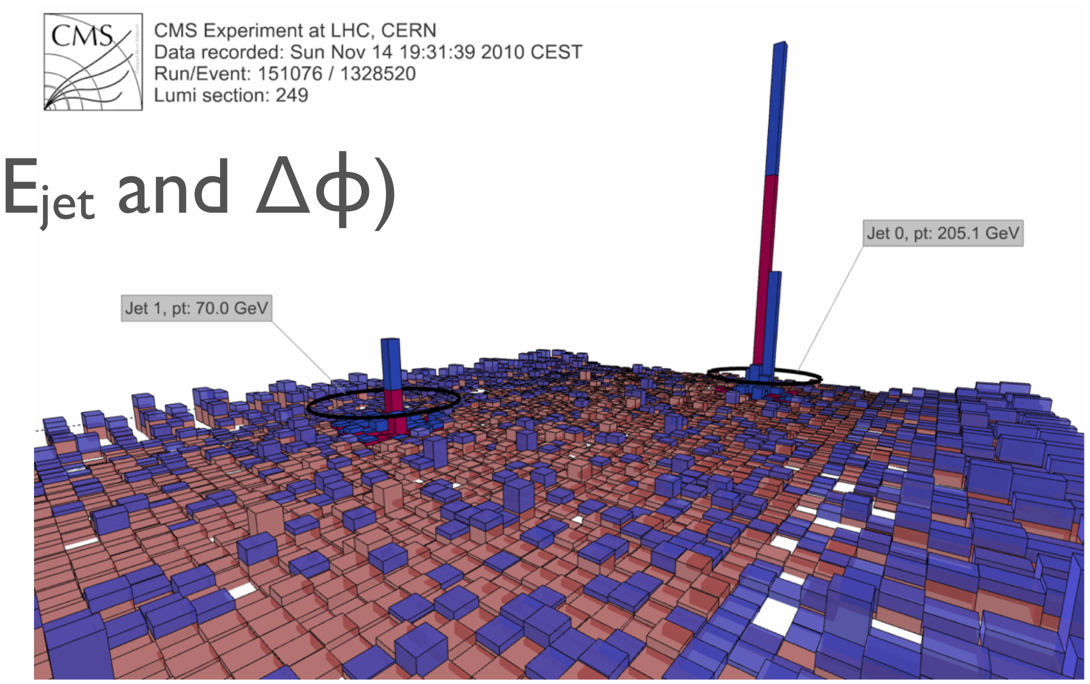
Correlations with high-p_T hadrons



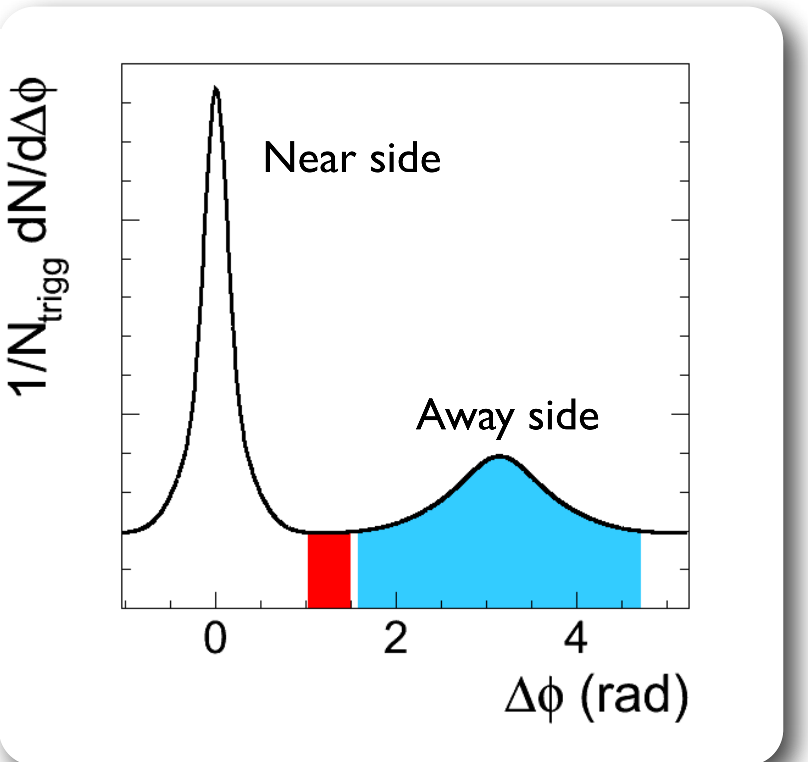
Di-jet and di-hadron correlations



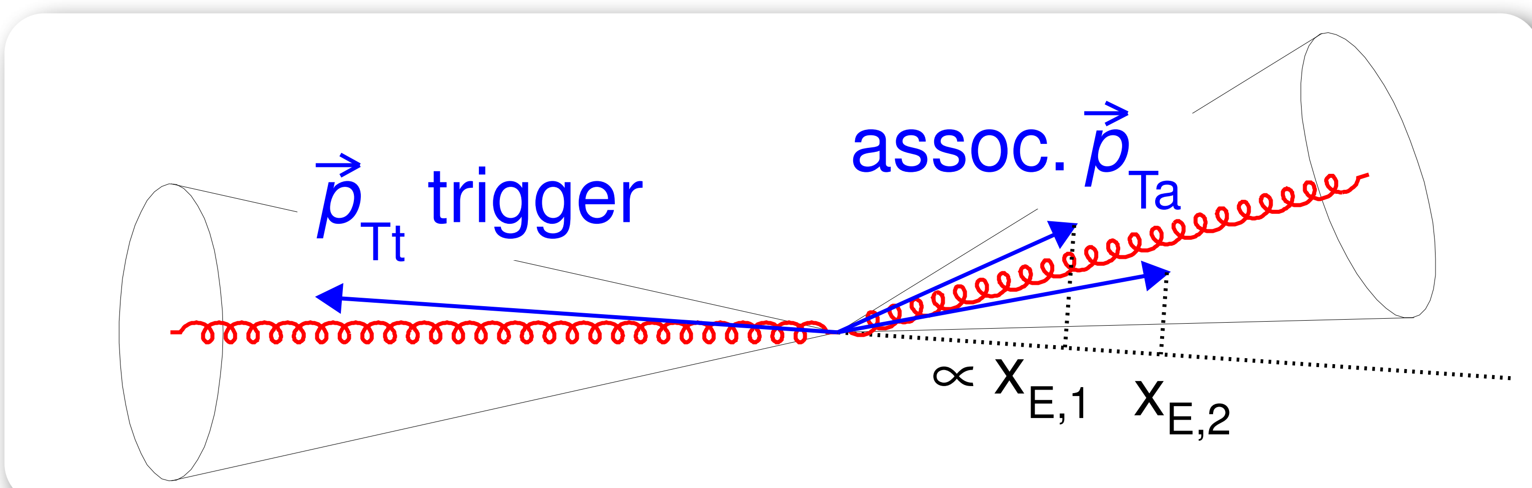
- hard scattered parton looses energy while traversing the medium



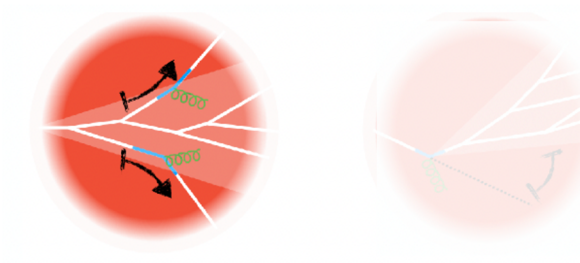
- di-jet (im)balance (E_{jet} and $\Delta\phi$)



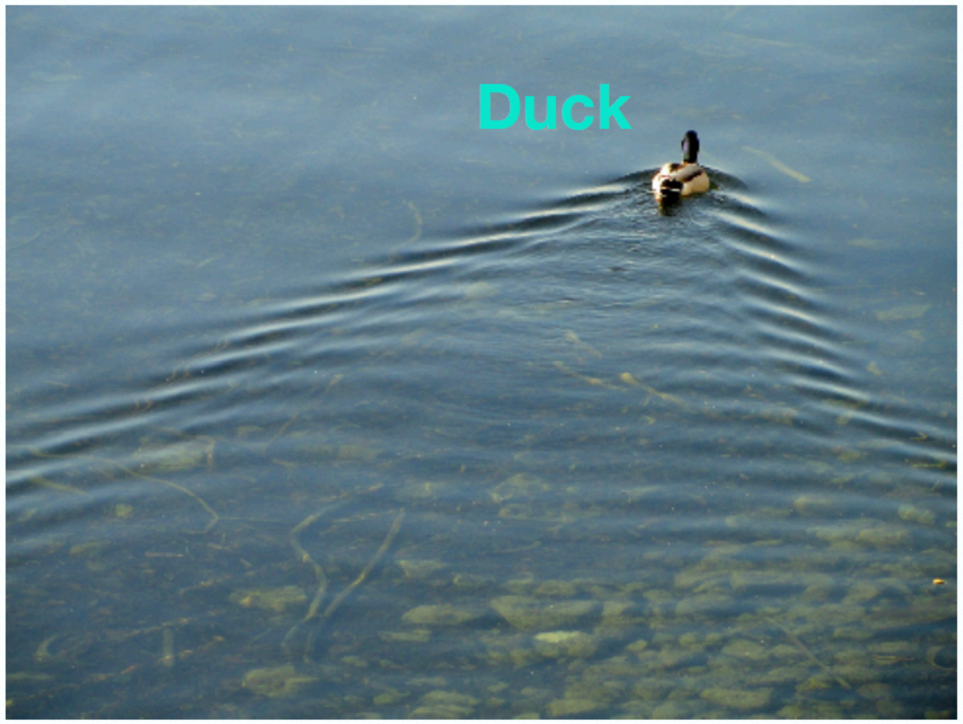
- di-hadron correlation pattern
  - Inter-jet properties ($\Delta\phi$, away side x_E)



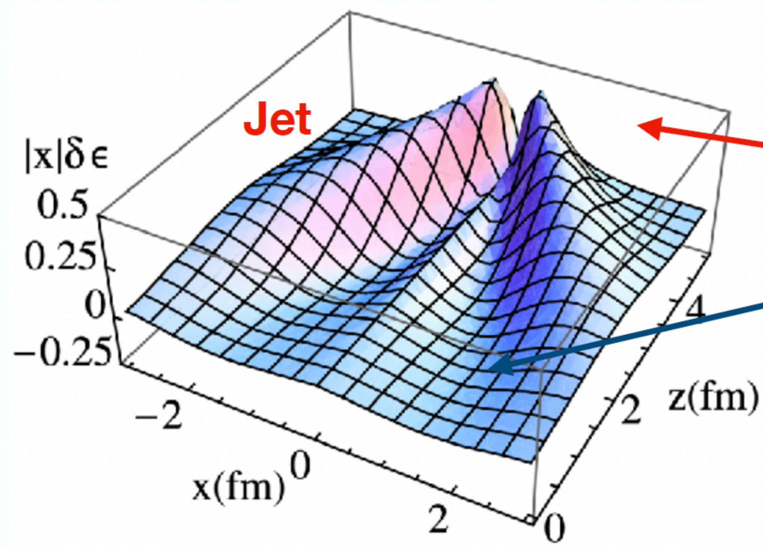
Medium response to propagating parton



- Jet lose energy due to interaction with medium
  - ➡ medium modified by jets



G.-Y. Qin, A. Majumder, H. Song, and U. Heinz, Phys. Rev. Lett. 103, 152303 (2009)



Expectation: 'wake' effects:

Enhancement around jet

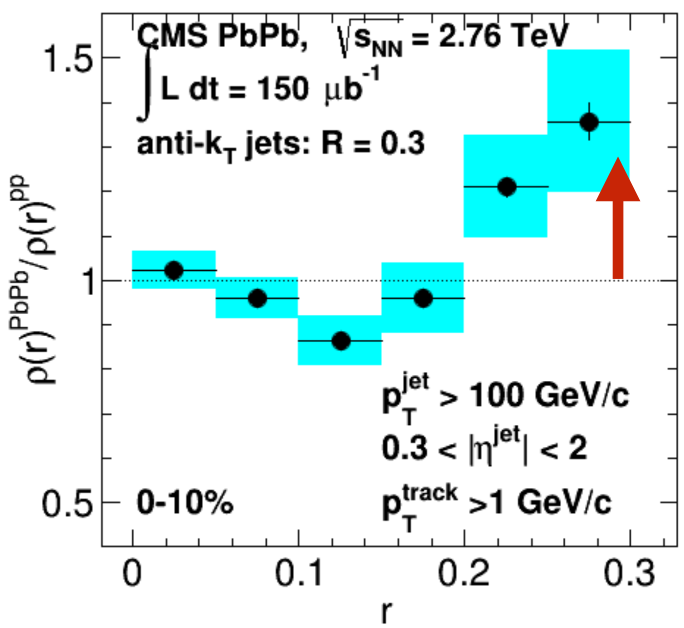
Deletion opposite jet

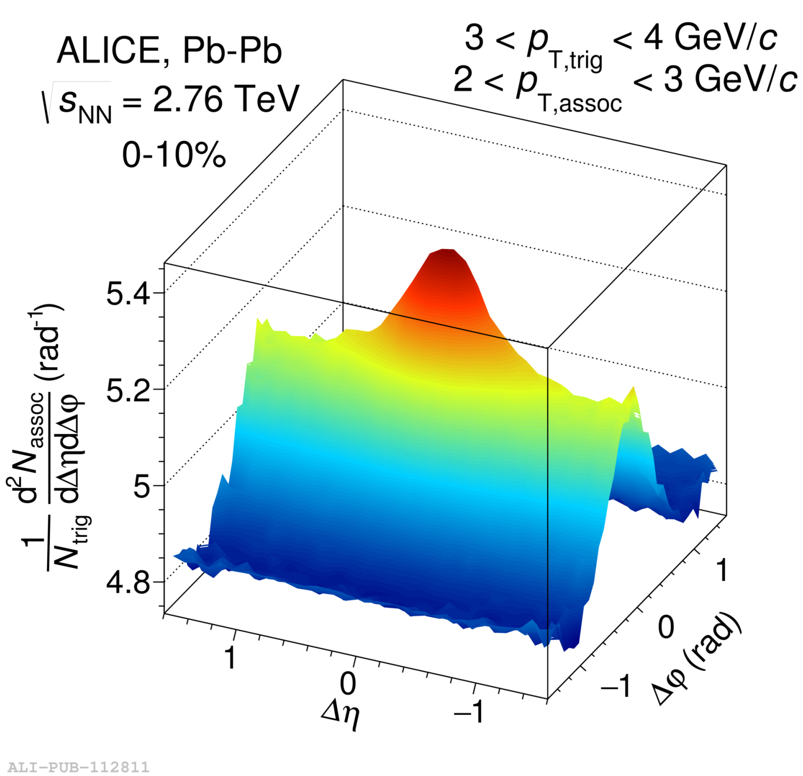
Sonic boom - $v_{\rm jet} > c_s \sim 0.5c$

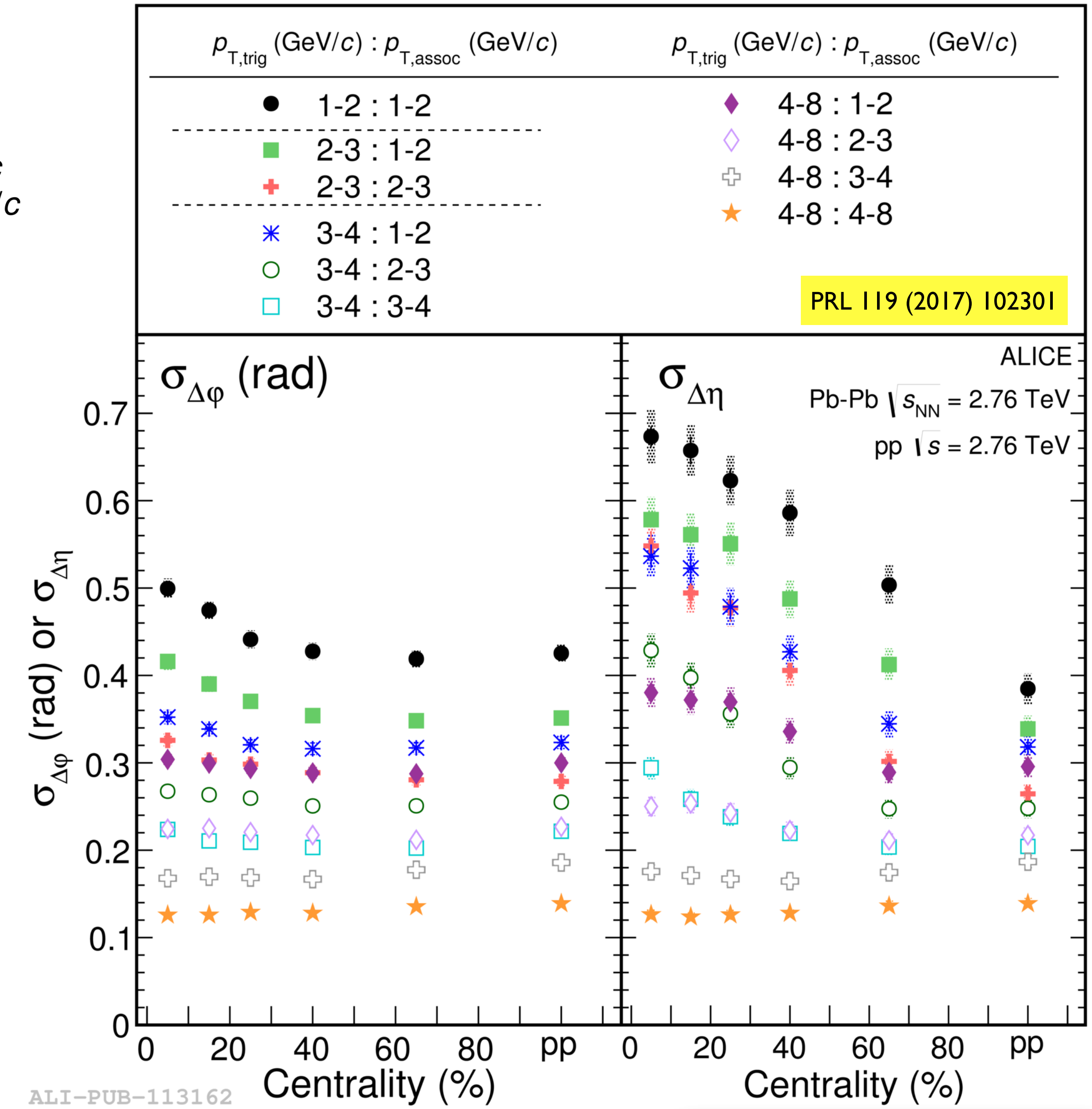
- Insert out-of-equilibrium probe — see how medium responds
  - ➡ transport coefficients, equation of state

Broadening observed in two particle correlations

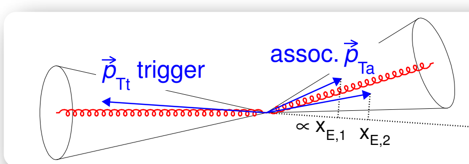
PLB 730 (2014) 243





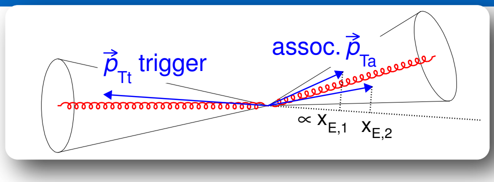


$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{jet}},$$

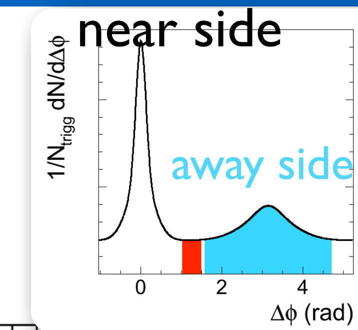


- Excess at large angular distance → jet broadening
- Jet broadening quantified using two particle correlations:
  - ➡ Small broadening in Δφ, significant broadening in Δη ($p_{T,trig}$ ↑, width ↓)

Low p_T broadening observed in π^0-h correlations



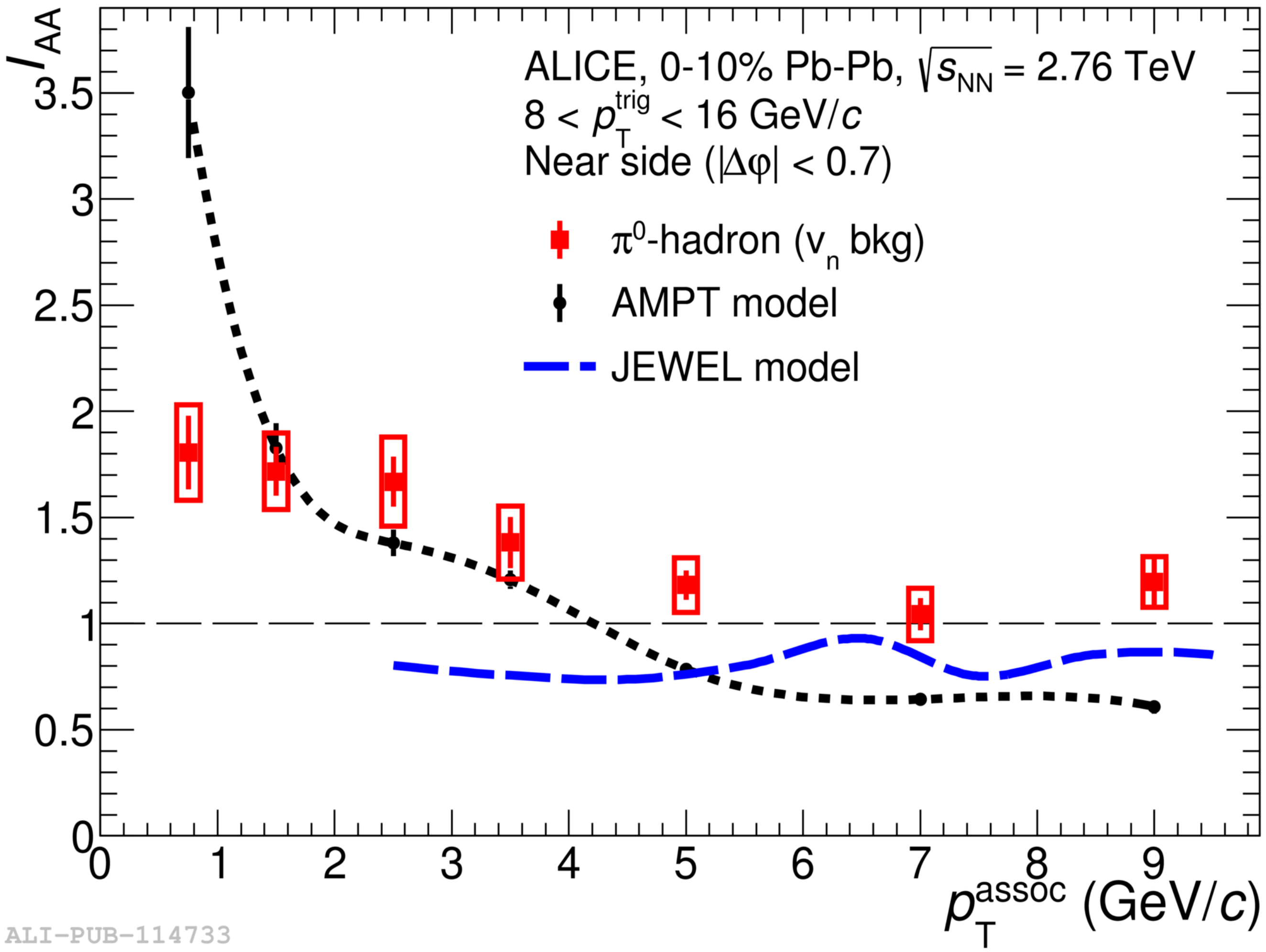
$$I_{AA} = \frac{Y_{\text{Pb-Pb}}}{Y_{\text{pp}}} \qquad Y = \int \frac{dN_{assoc}}{d\Delta\varphi} d\Delta\varphi$$

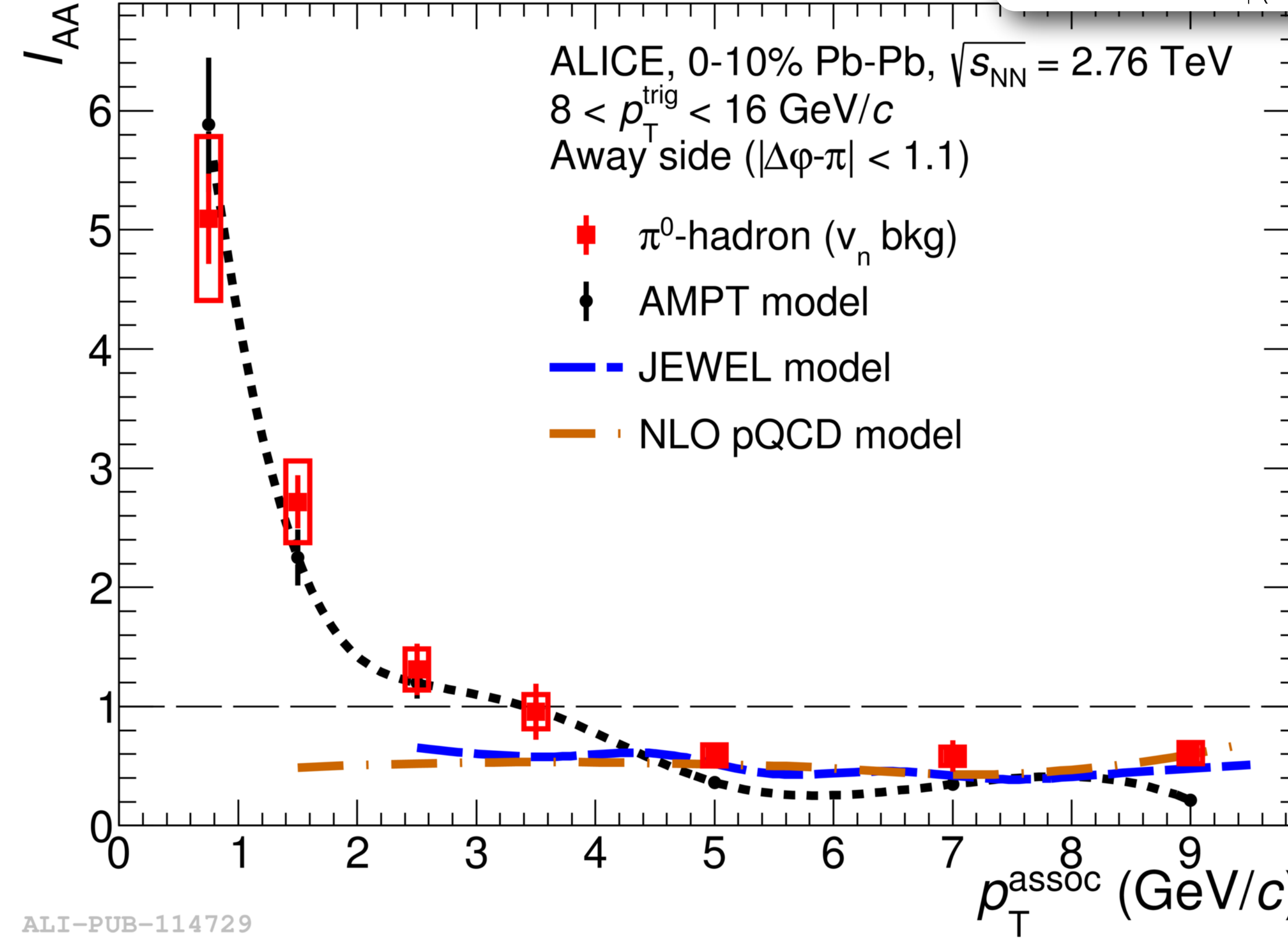


near side

PLB 763 (2016) 238

away side

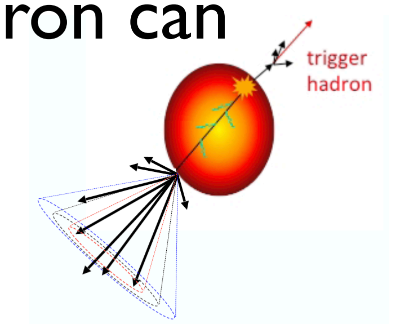




- Enhancement at very low p_T, indicating extra particles excess → consistent with low p_T broadening (soften of fragmentation functions? excited by medium?)
- Suppression on the away side for high p_T → consistent with jet quenching

Semi-inclusive yield of jets recoiling from high-p_T hadron

- Measurements of semi-inclusive yield of jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening

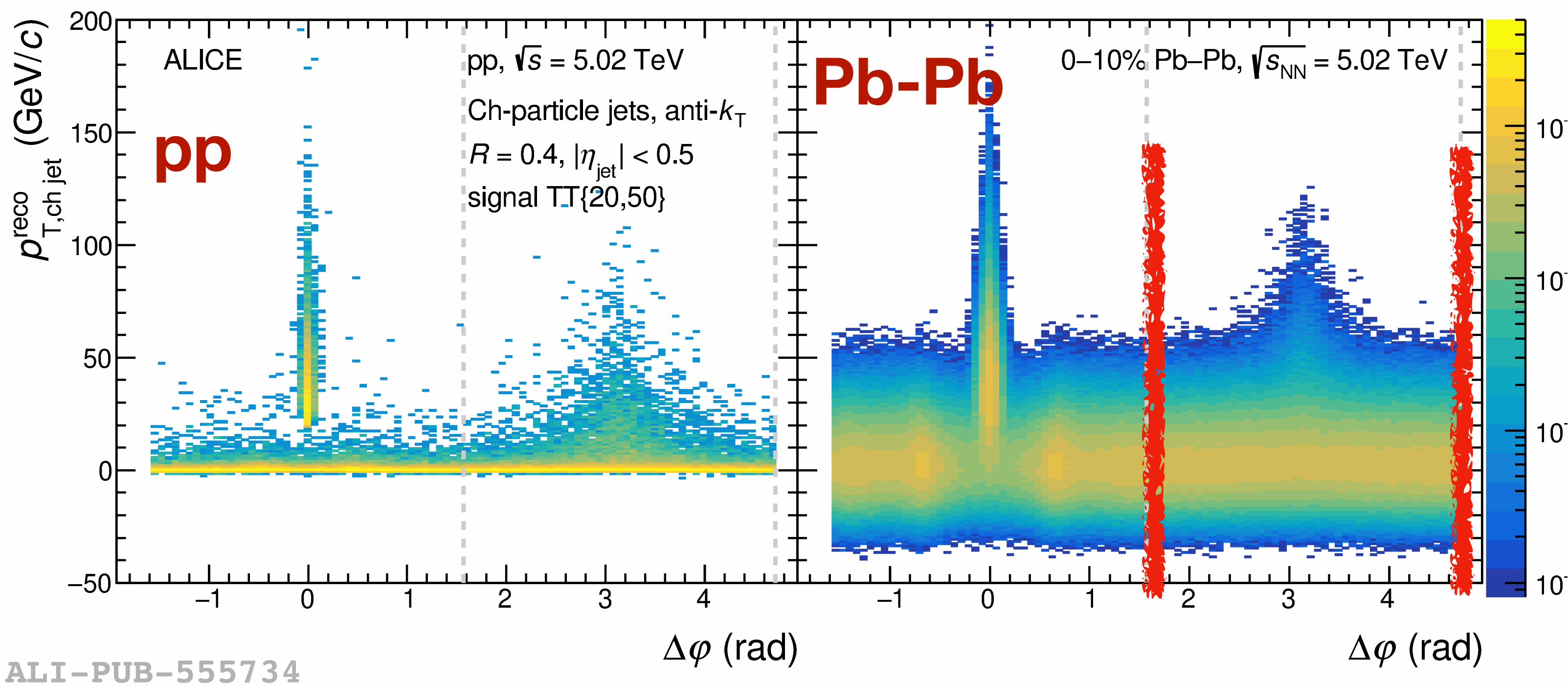


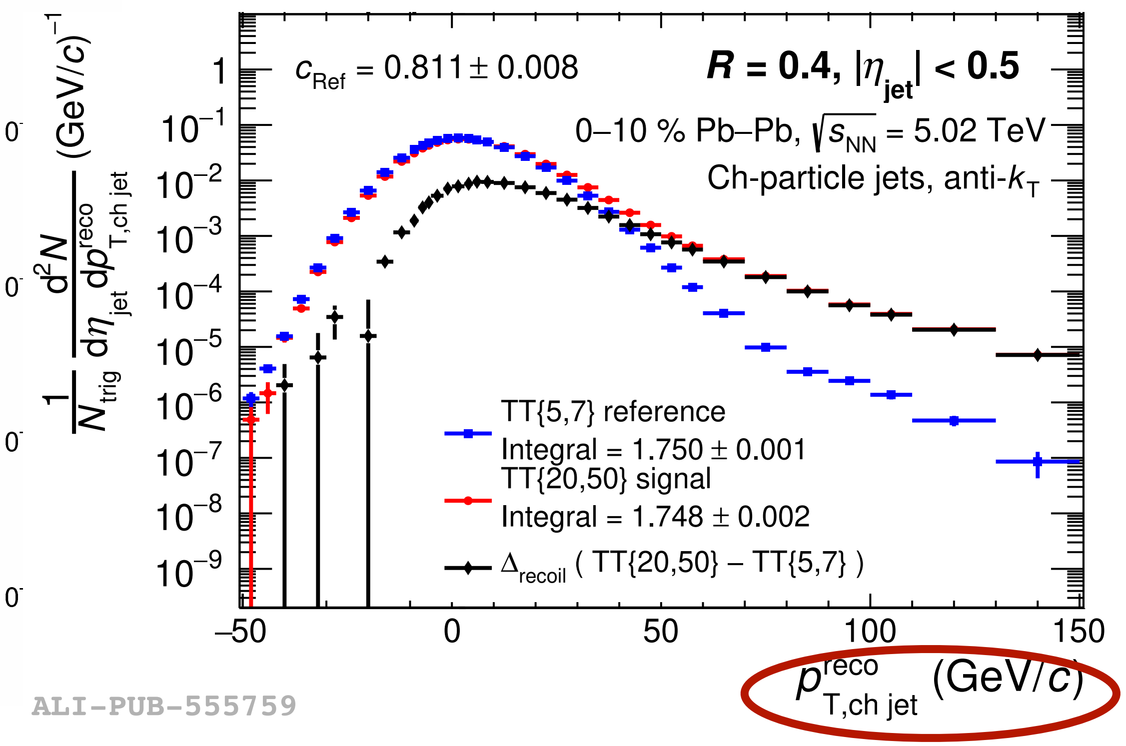
- Subtract uncorrelated background: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

TT$_{sig}$: $20 < p_{T,trig} < 50$ GeV/c

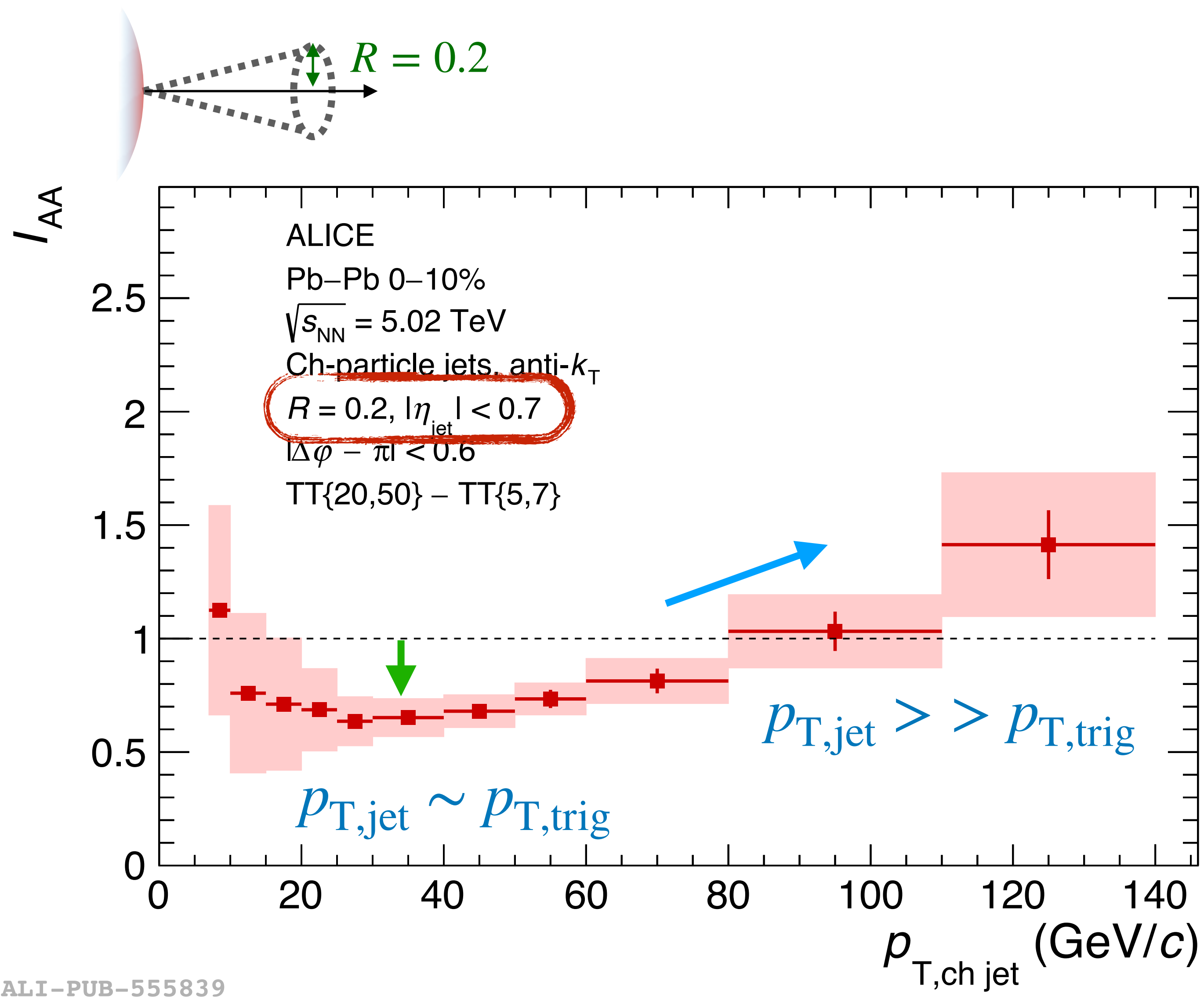
TT$_{ref}$: $5 < p_{T,trig} < 7$ GeV/c

$$\Delta_{recoil} = \frac{1}{N^{AA}_{trig}} \frac{d^3N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\Delta\varphi\, d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref}\cdot \frac{1}{N^{AA}_{trig}} \frac{d^3N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\Delta\varphi\, d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Ref}}$$

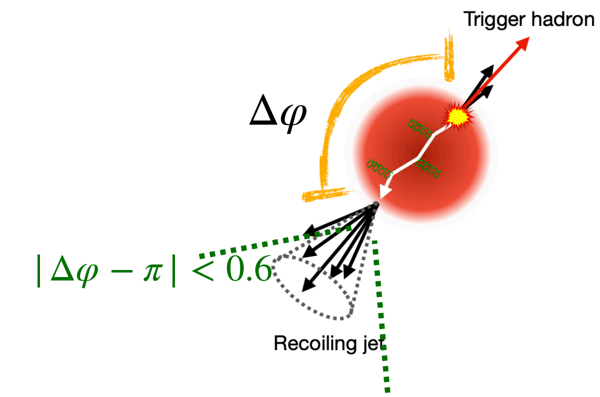




Recoil jet yield modifications: R = 0.2

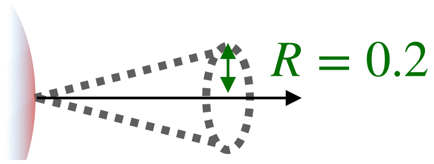


$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

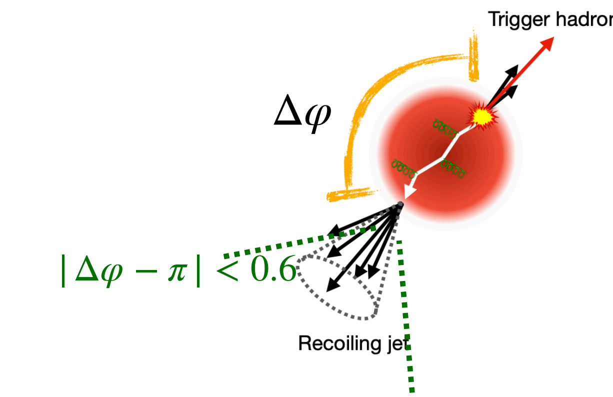


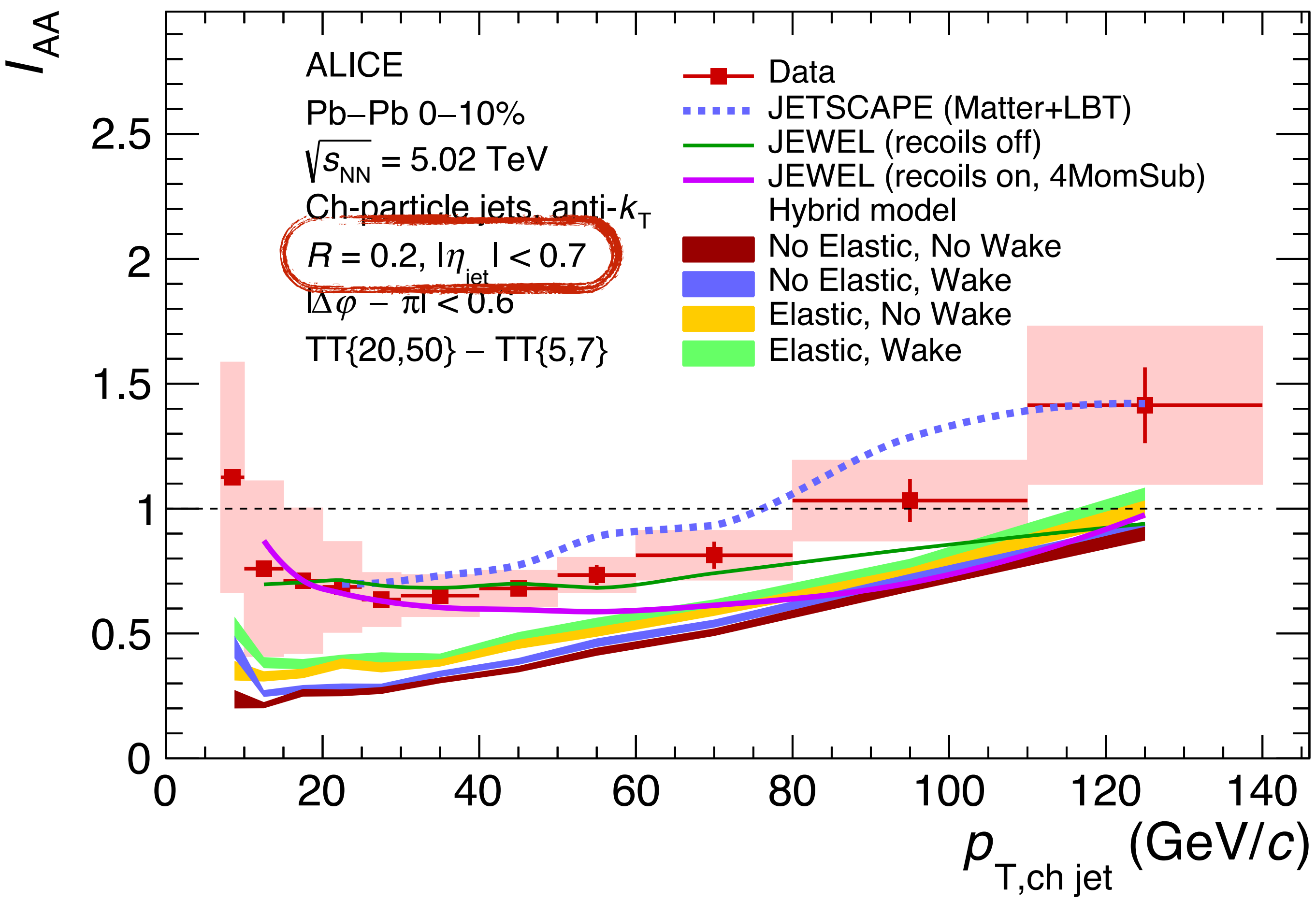
- **Suppression** at 20 < $p_{T,ch\ jet}$ < 80 GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\ jet}$**
  → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,jet} > > p_{T,trig}$?

Recoil jet yield modifications: model comparison



$$I_{AA} = \frac{\Delta_{recoil}(\mathrm{Pb-Pb})}{\Delta_{recoil}(\mathrm{pp})}$$





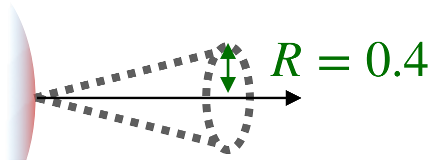
- **Suppression** at $20 < p_{T,\mathrm{ch\,jet}} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$**
  → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,\mathrm{jet}} >> p_{T,\mathrm{trig}}$?
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low $p_{T,\mathrm{jet}}$ I_{AA}

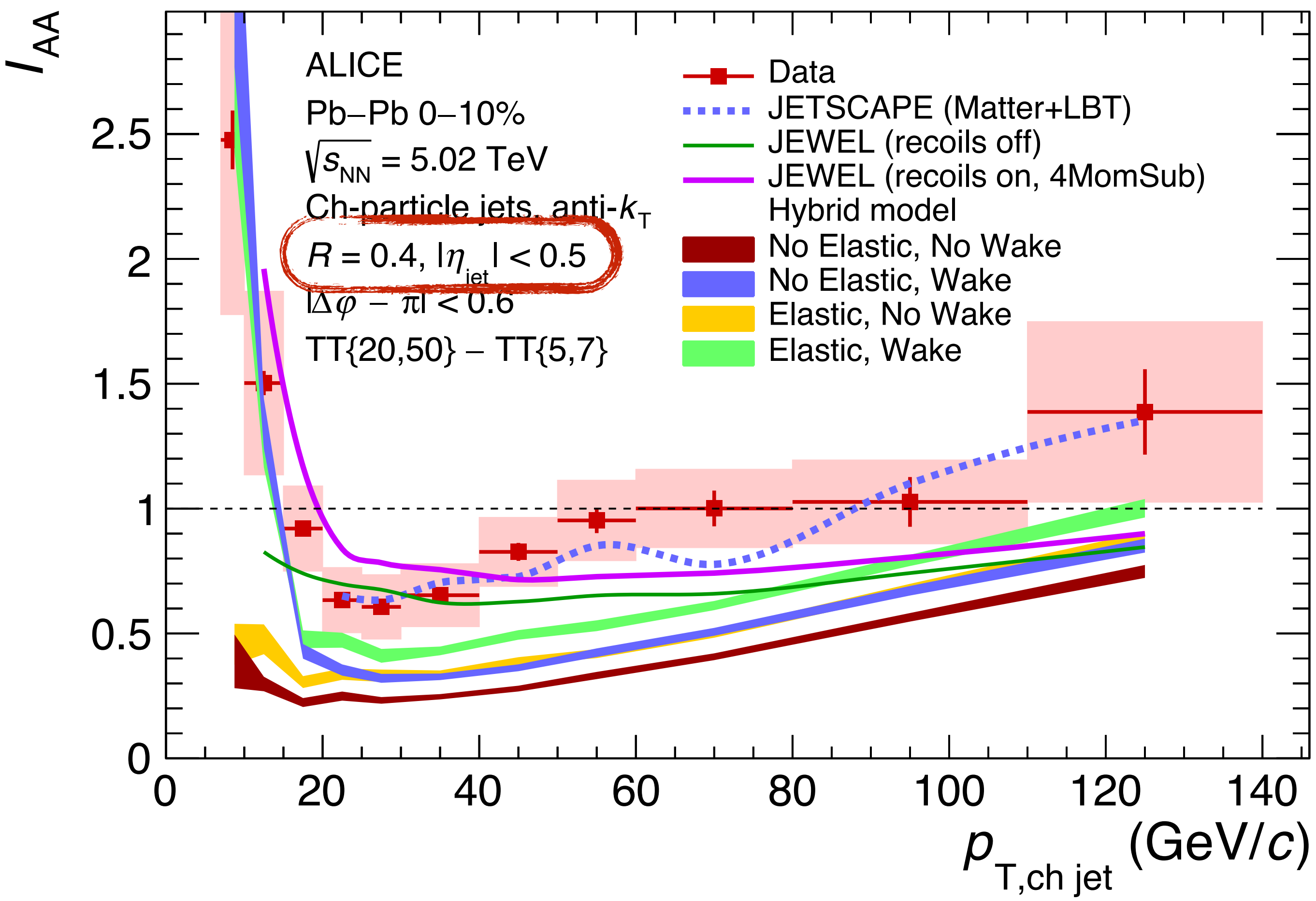
Hybrid Model: elastic (Moliére) scatterings and wake (medium response) included
F. d'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

JETSCAPE: energy loss based on MATTER (high virtuality) and LBT (low virtuality)
JETSCAPE, Phys. Rev. C 107, 034911

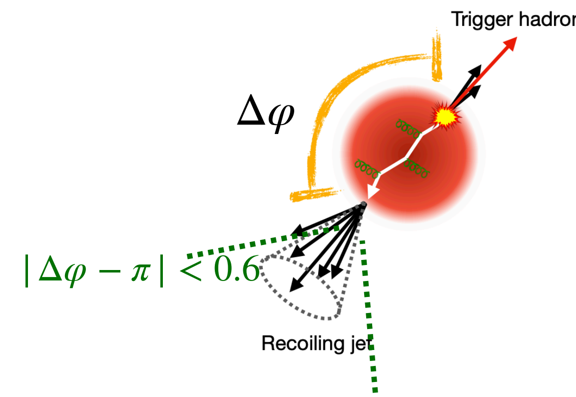
JEWEL: medium response effects via treatment of 'recoils'
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Recoil jet yield modifications: large R





$$I_{AA} = \frac{\Delta_{recoil}(\mathrm{Pb-Pb})}{\Delta_{recoil}(\mathrm{pp})}$$



- **Suppression** at $20 < p_{T,\mathrm{ch\,jet}} < 80$ GeV/c → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$** → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,\mathrm{jet}} >> p_{T,\mathrm{trig}}$?
- **Rise at low $p_{T,\,jet}$** → energy recovery? Reproduced by models including medium response

Hybrid Model: elastic (Moliére) scatterings and wake (medium response) included
F. d'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172
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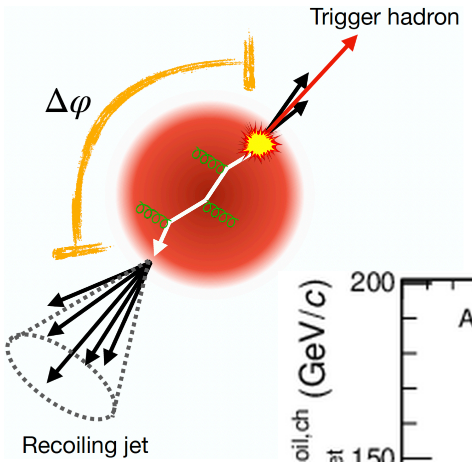
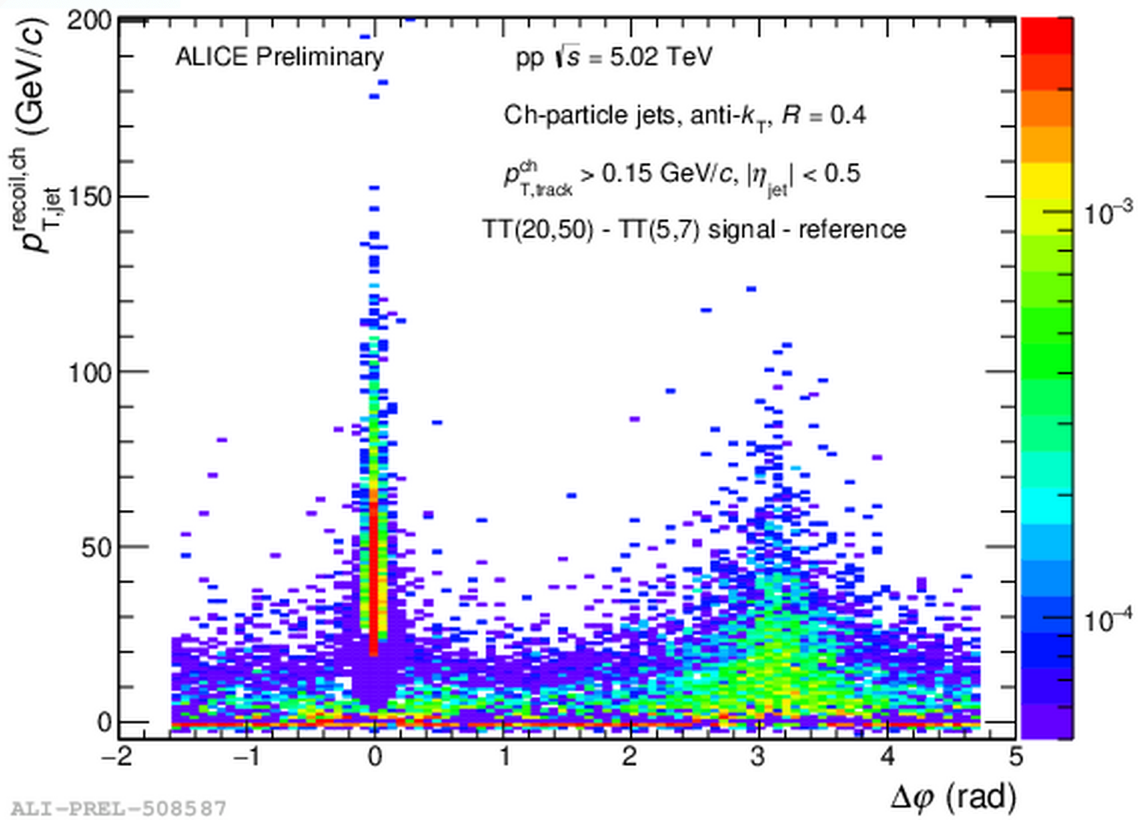
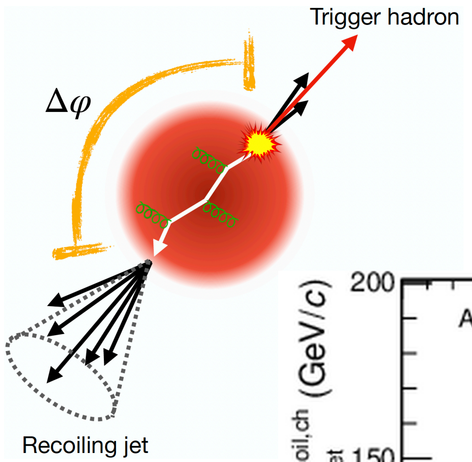
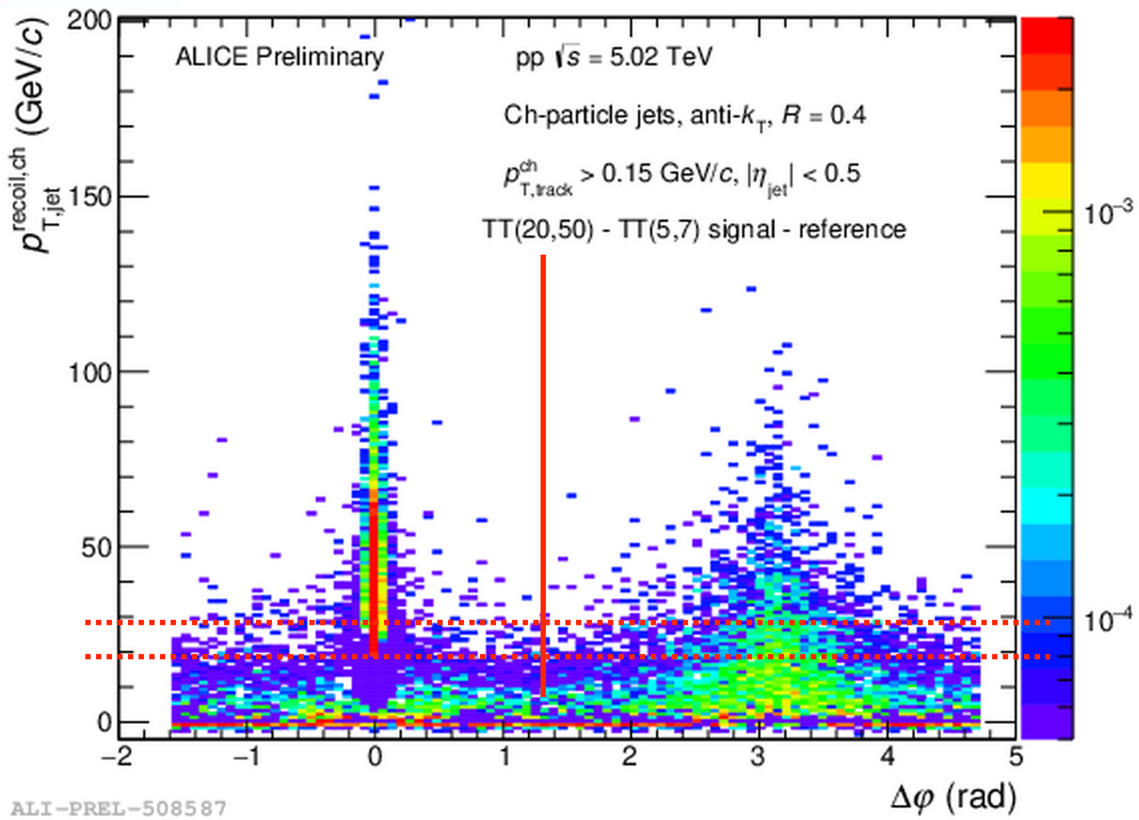
Δφ results - angular deflections



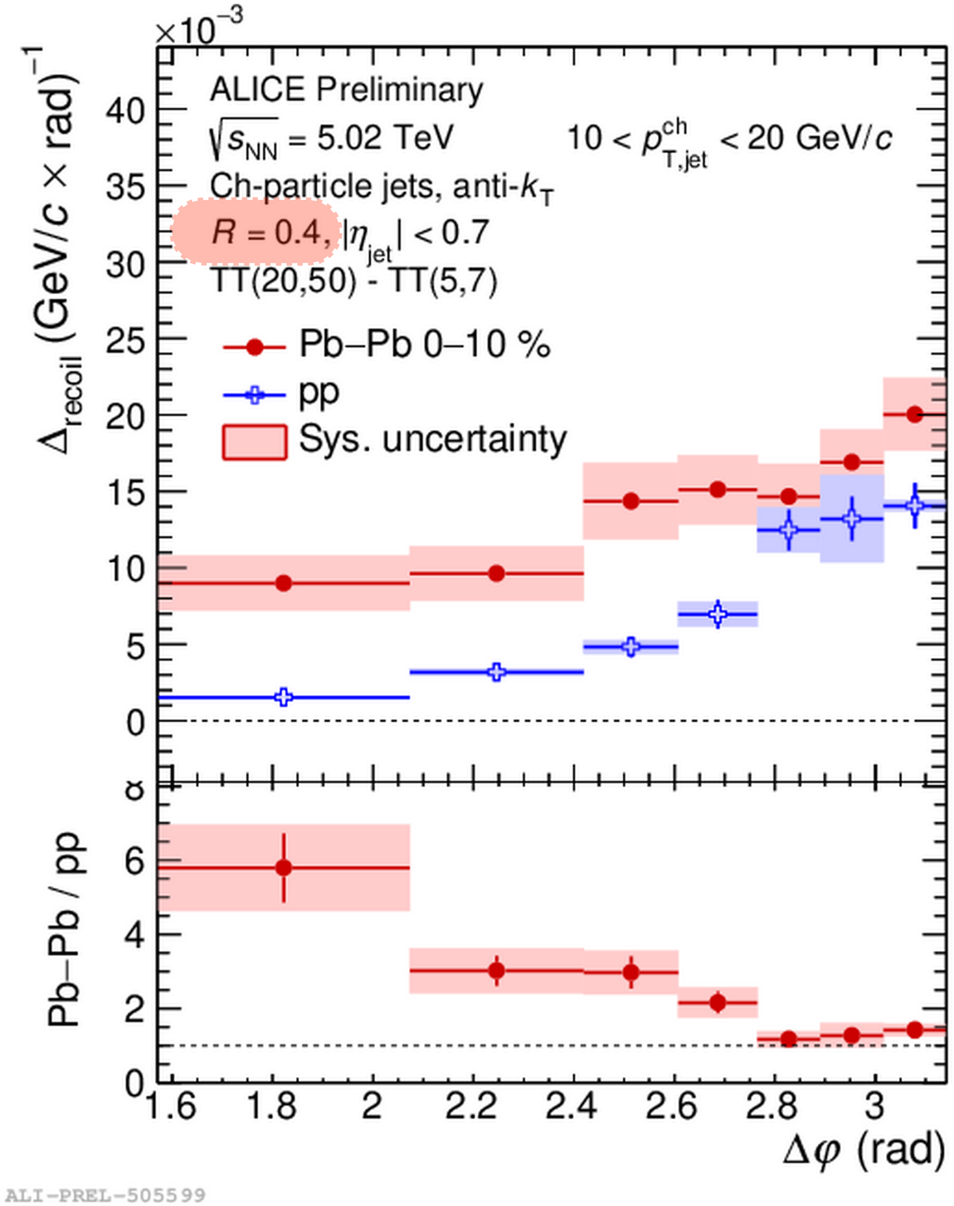


$\Delta\varphi$ results - angular deflections

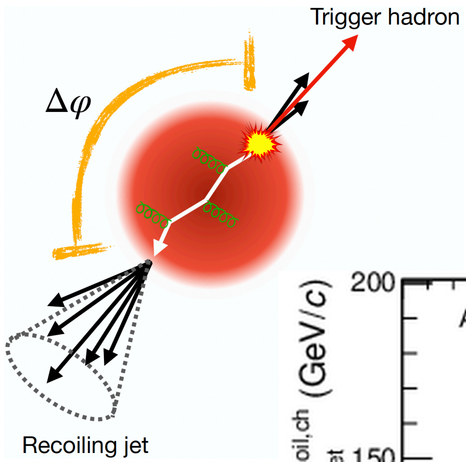


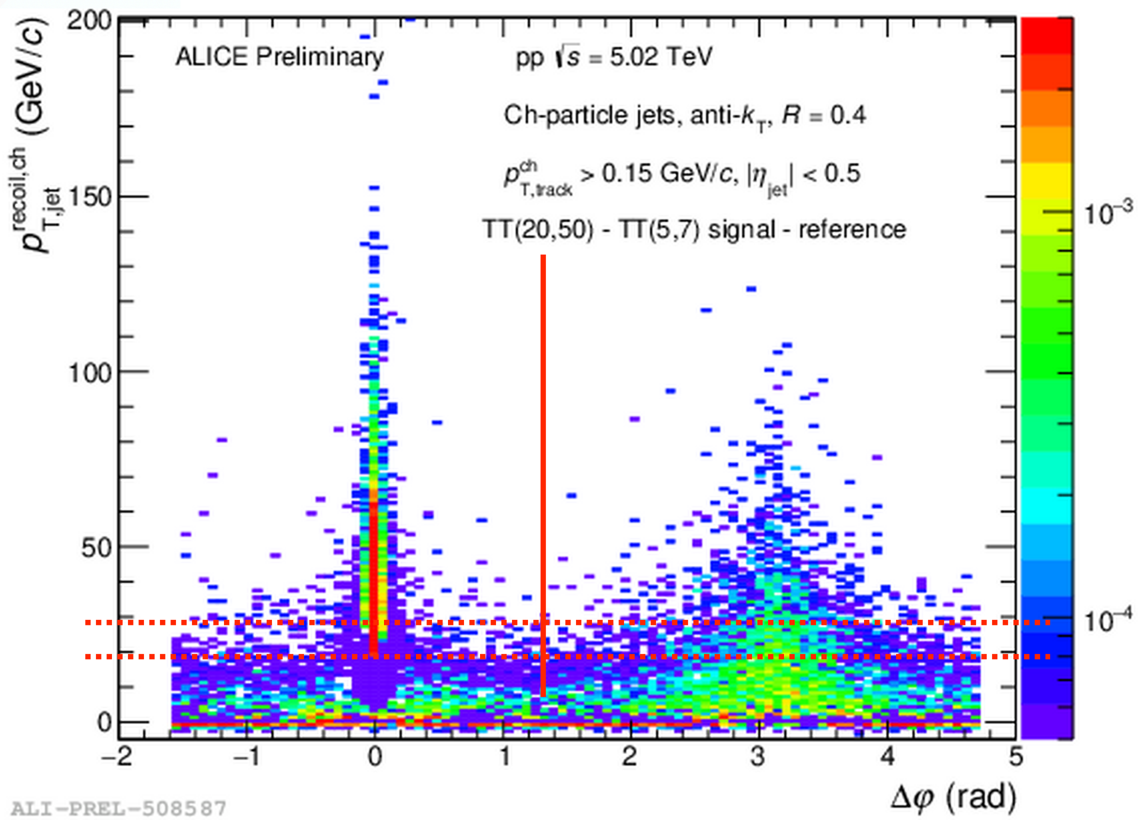


10 < $p_{T,\text{jet}}$ < 20 GeV/c

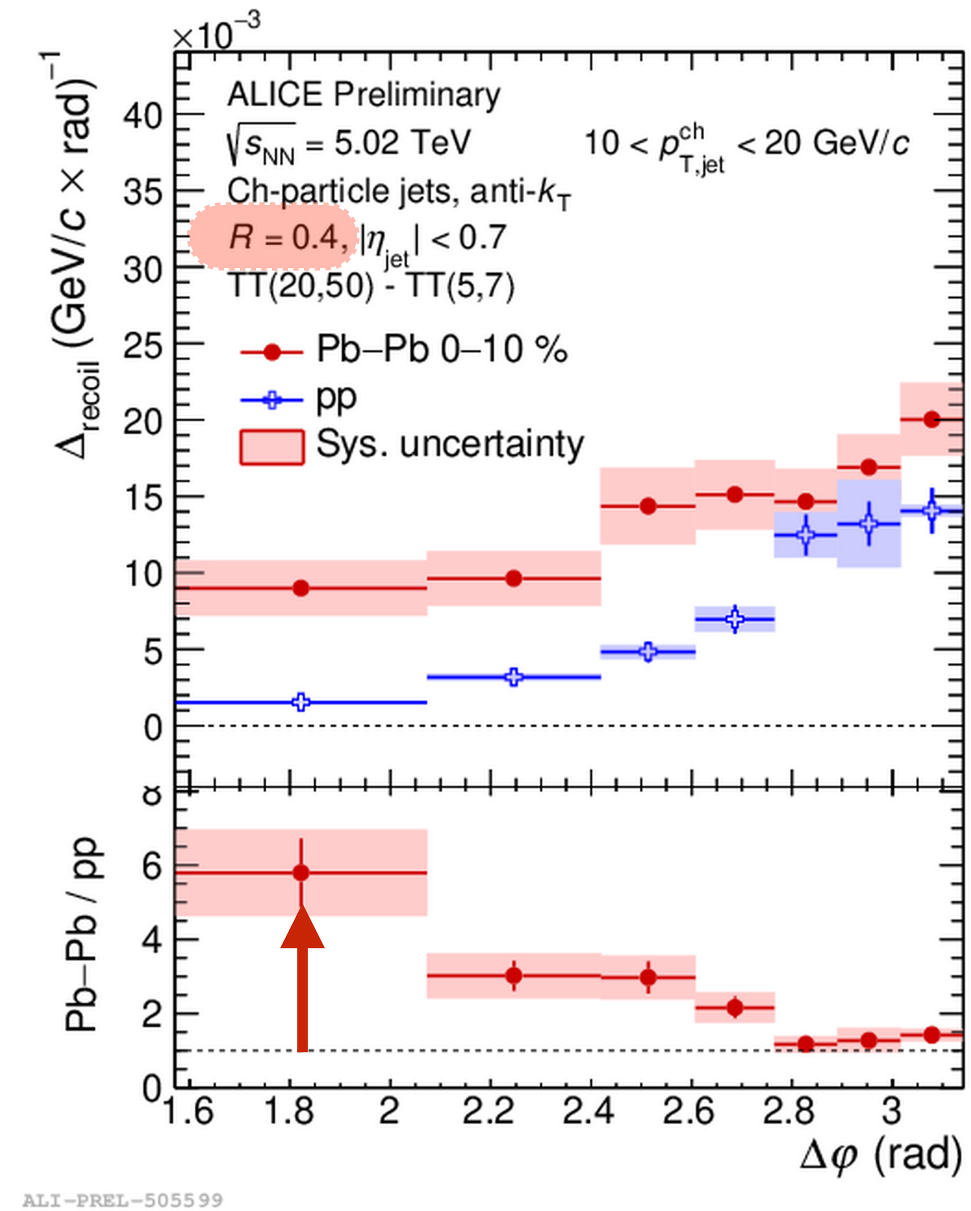


Δφ results - angular deflections



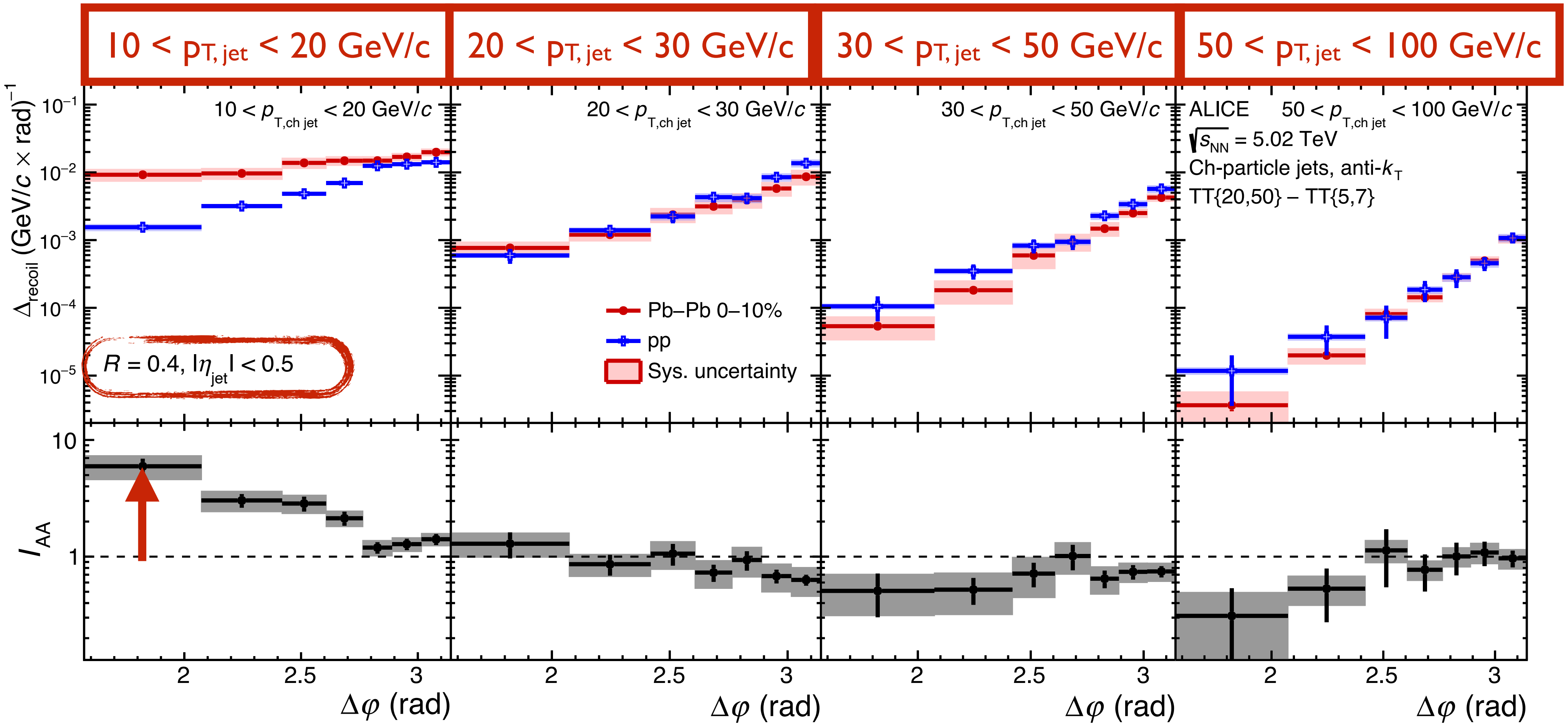


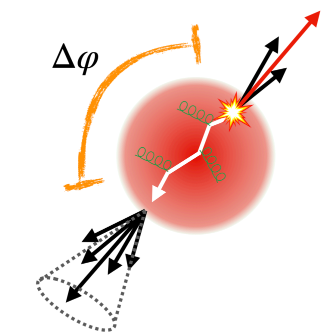
10 < $p_{T,jet}$ < 20 GeV/c



- First evidence of broadening of h-jet azimuthal correlations for soft jets

Recoil jet azimuthal modifications: R = 0.4



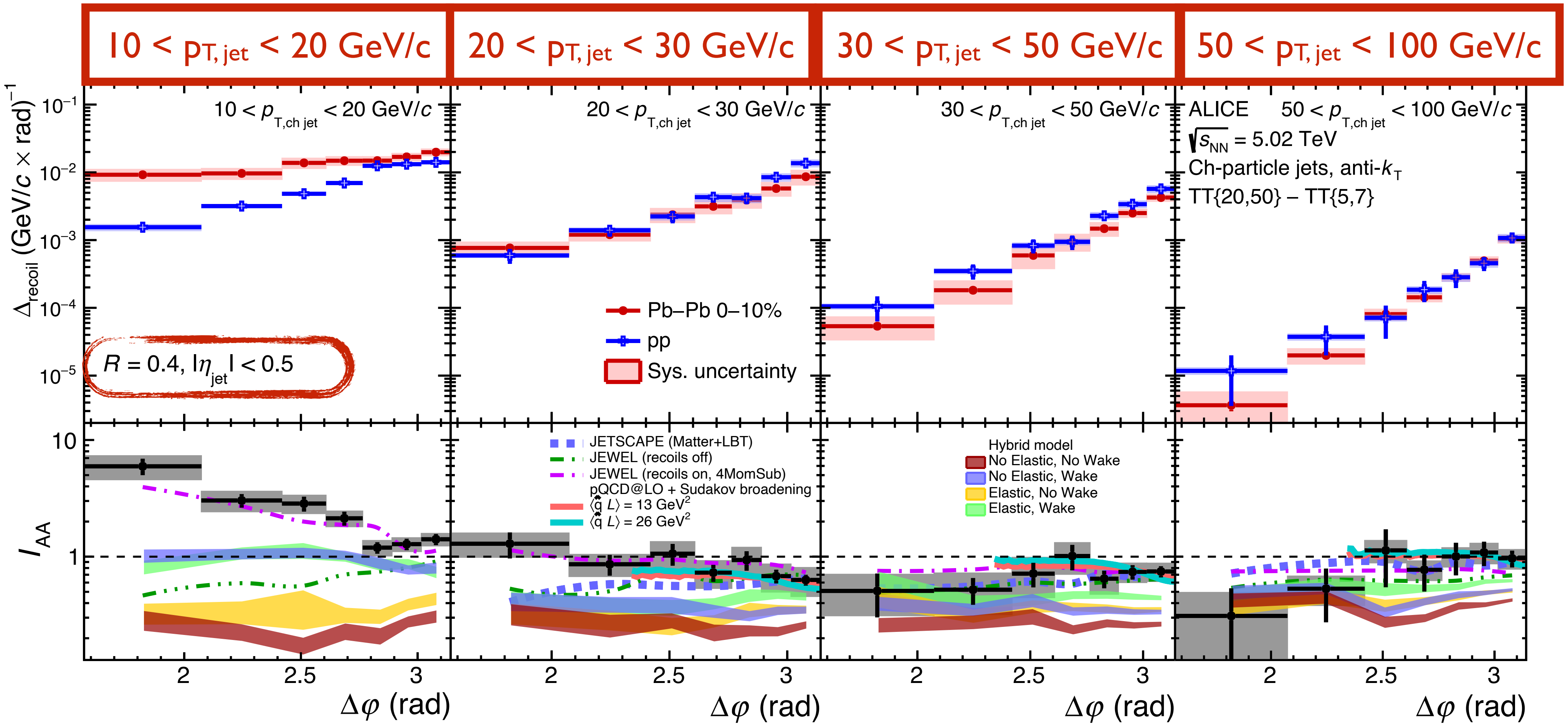


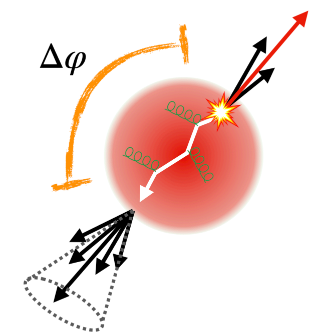
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

- No broadening for [20,100] GeV/c
- Significant broadening for [10,20] GeV/c

(4.7σ deviation of I_{AA} from flat)

Recoil jet azimuthal modifications: model comparison



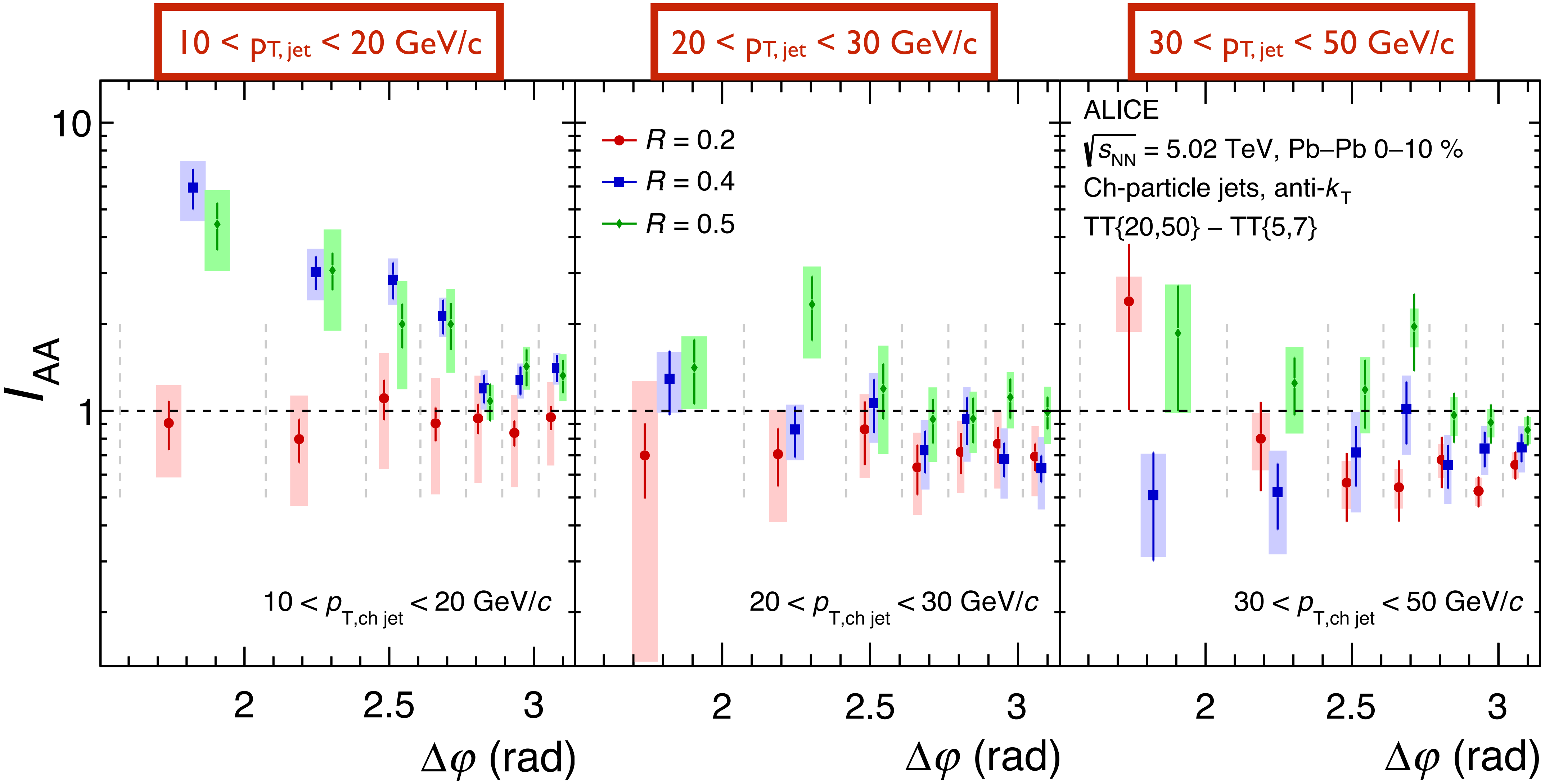


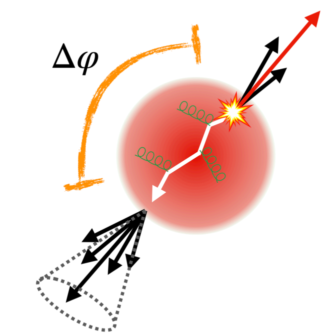
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

pQCD + Sudakov broadening: leading order pQCD, azimuthal broadening via jet transport coefficient
L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676

- Hybrid model w/wake: capture yield enhancement. w/ elastic: negligible broadening
- pQCD w/ broadening via $\hat{q}$: lacking precision to resolve difference between two $\hat{q}$ values
- JEWEL (recoil on): captures all features of data

Recoil jet azimuthal modifications: different R

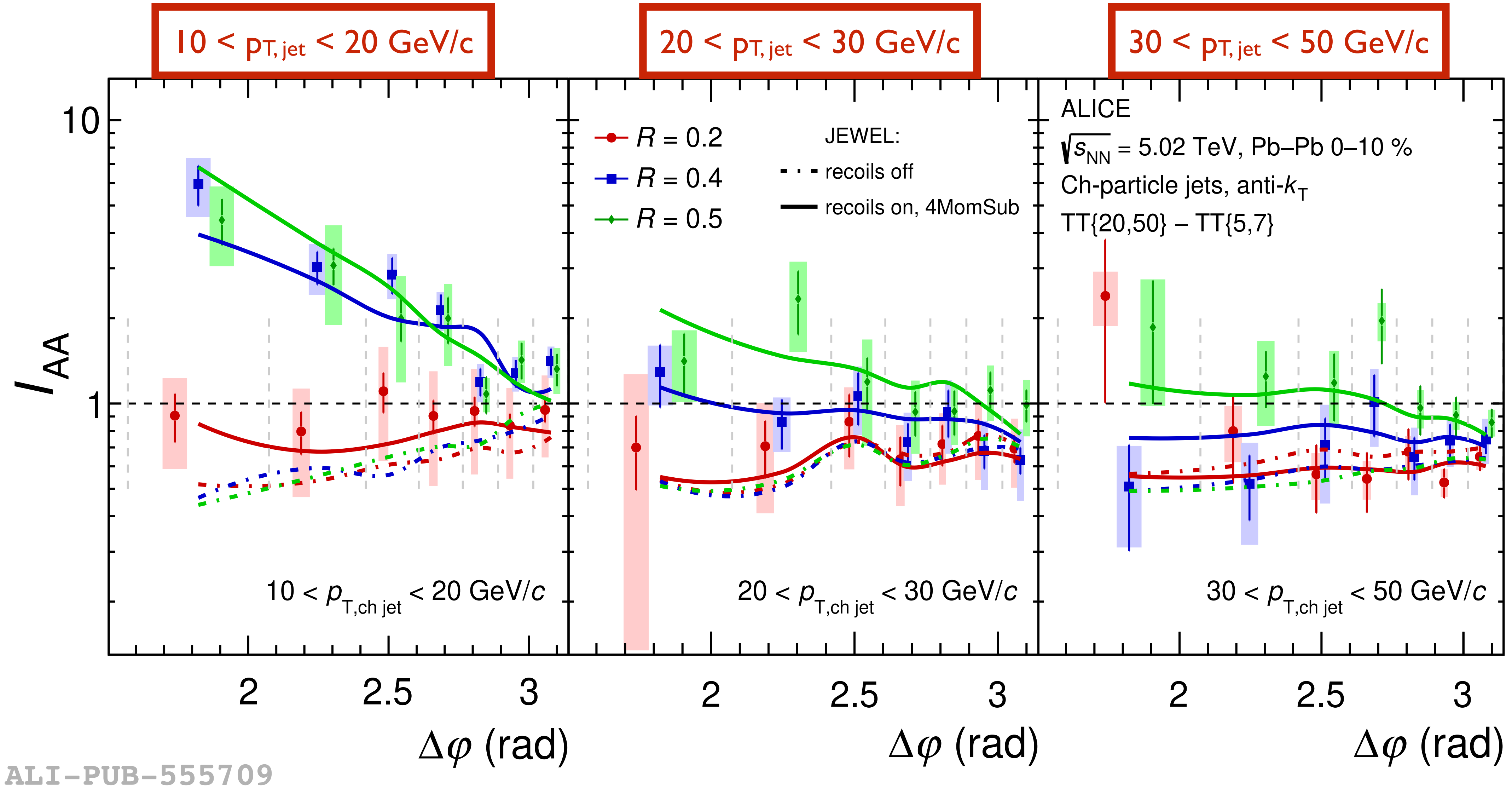


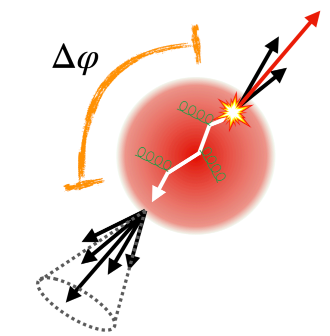


$$I_{AA} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$

- Transition to broadening from R = 0.2 to R = 0.4 for 10 < $p_{\mathrm{T,ch\,jet}}$ < 20 GeV/c
  - soft radiation mimicking a jet may scale with R^2
  - Molière scattering off QGP quasiparticles

Recoil jet azimuthal modifications: JEWEL comparison

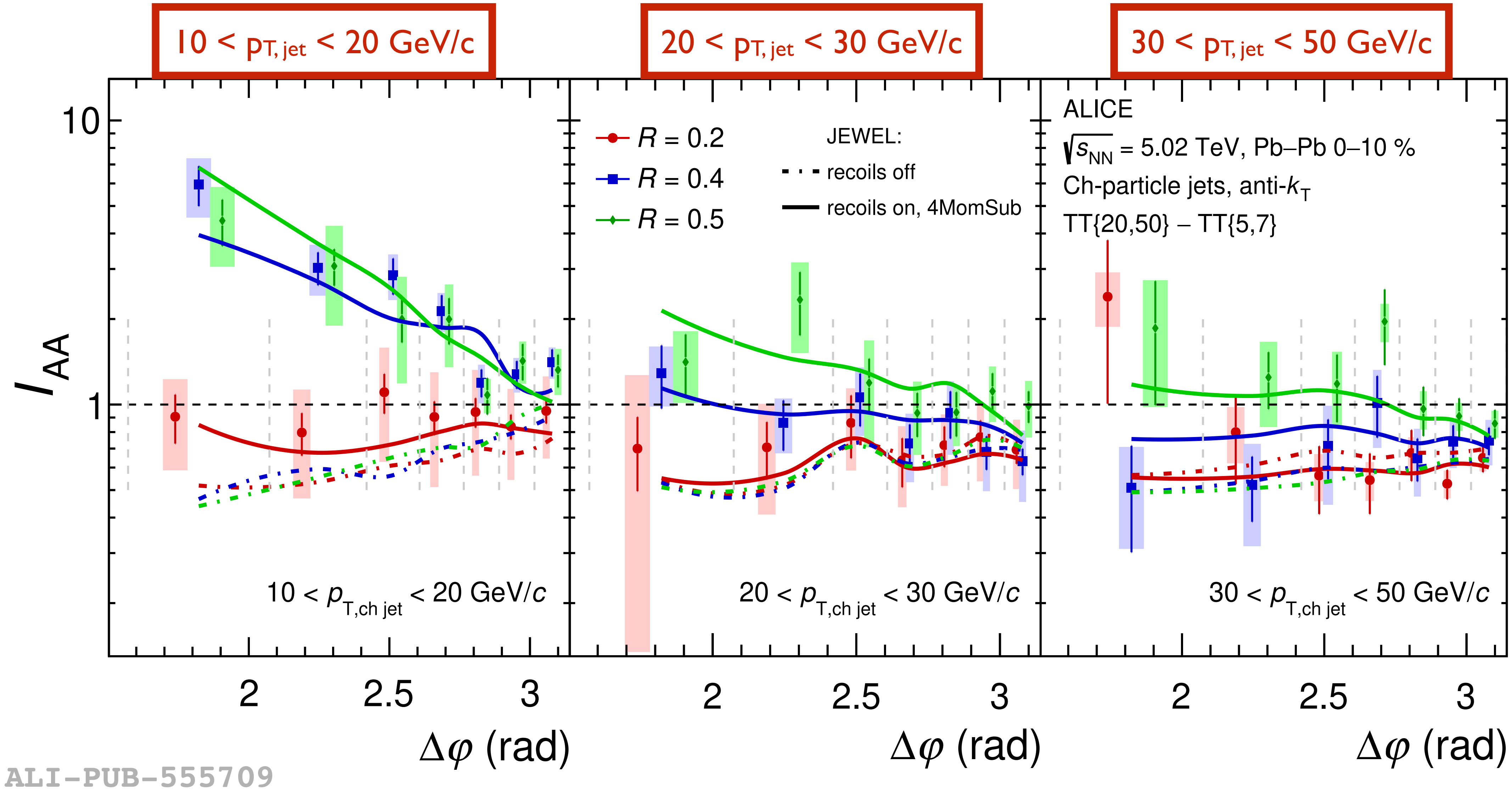


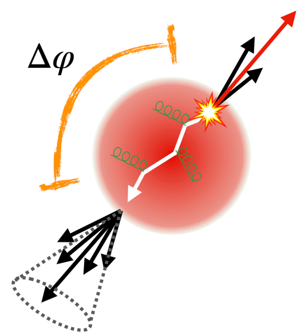


$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

- All features of distribution **reproduced by JEWEL** with recoils on …

Recoil jet azimuthal modifications: JEWEL comparison



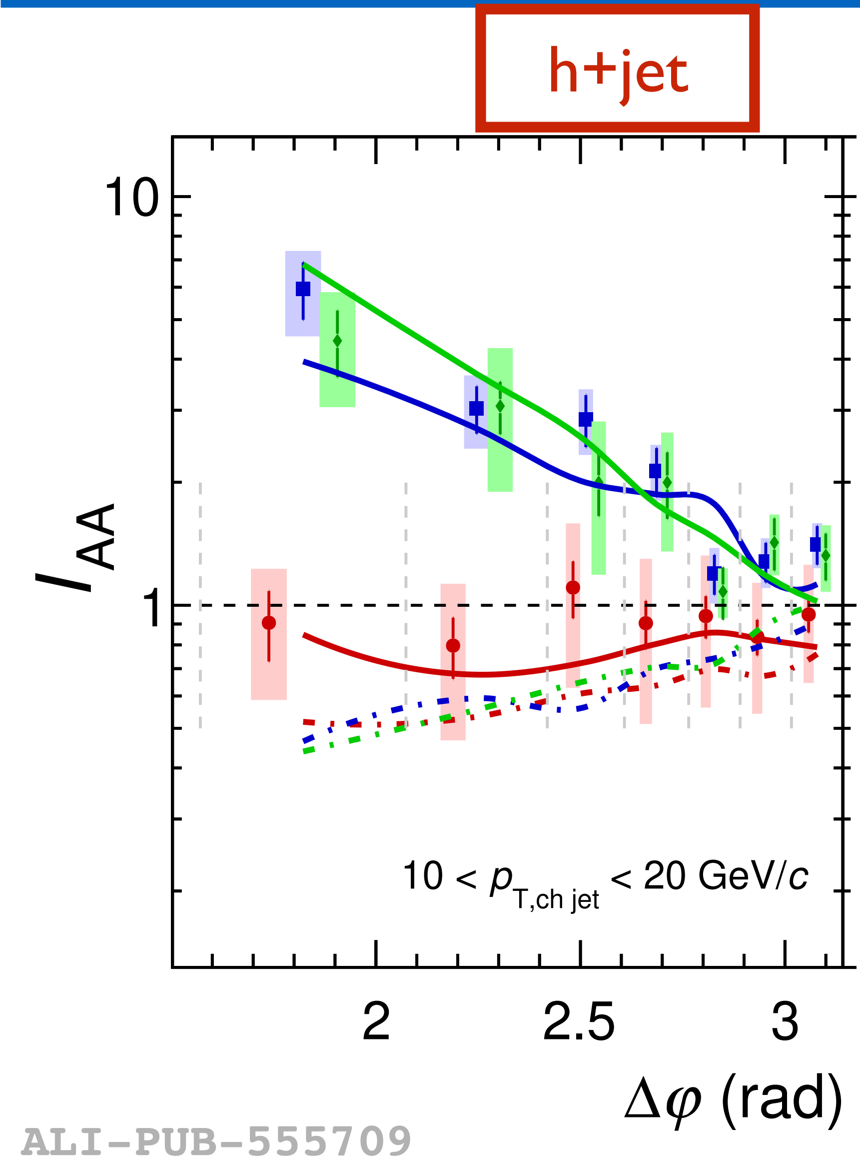


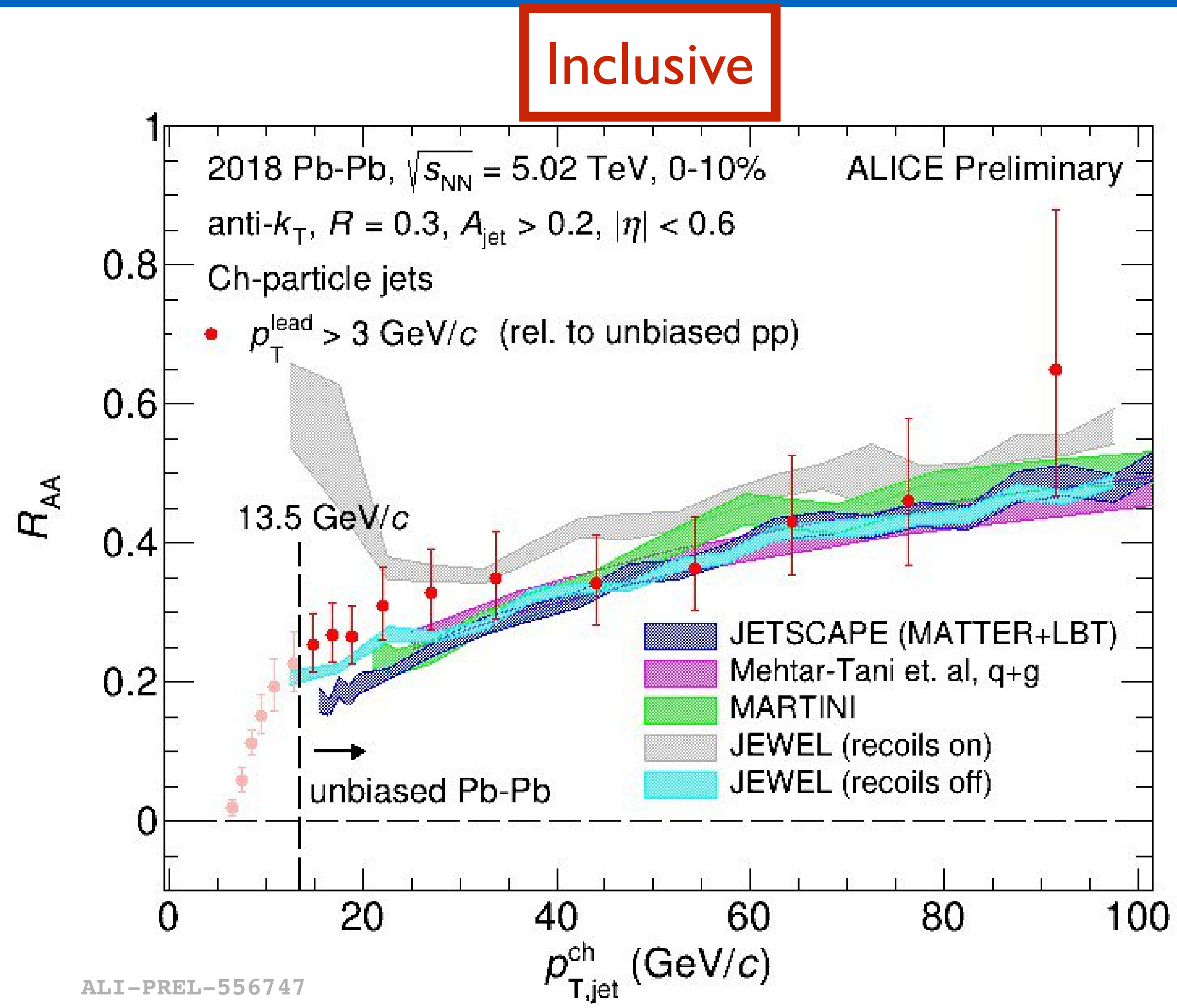
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

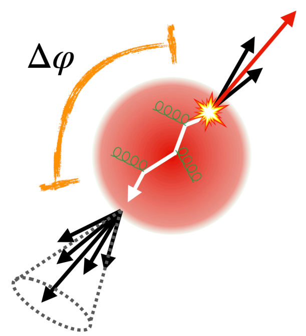
- All features of distribution **reproduced by JEWEL** with recoils on …

→Data favours medium response to jet or medium-induced soft radiation as explanation for observed broadening

Recoil jets verus inclusive jets modification

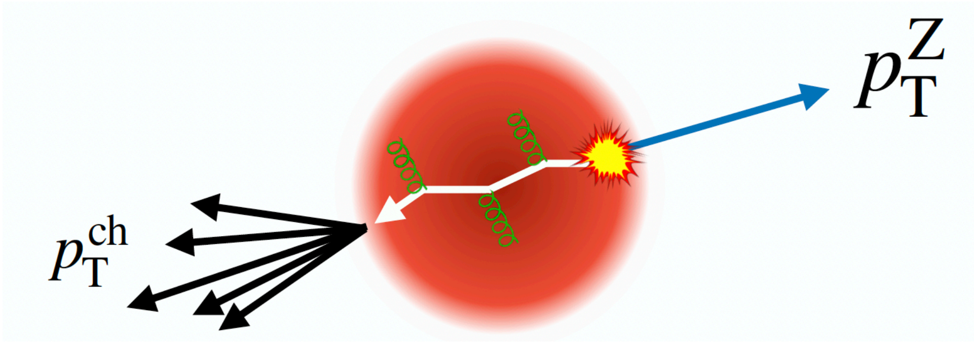






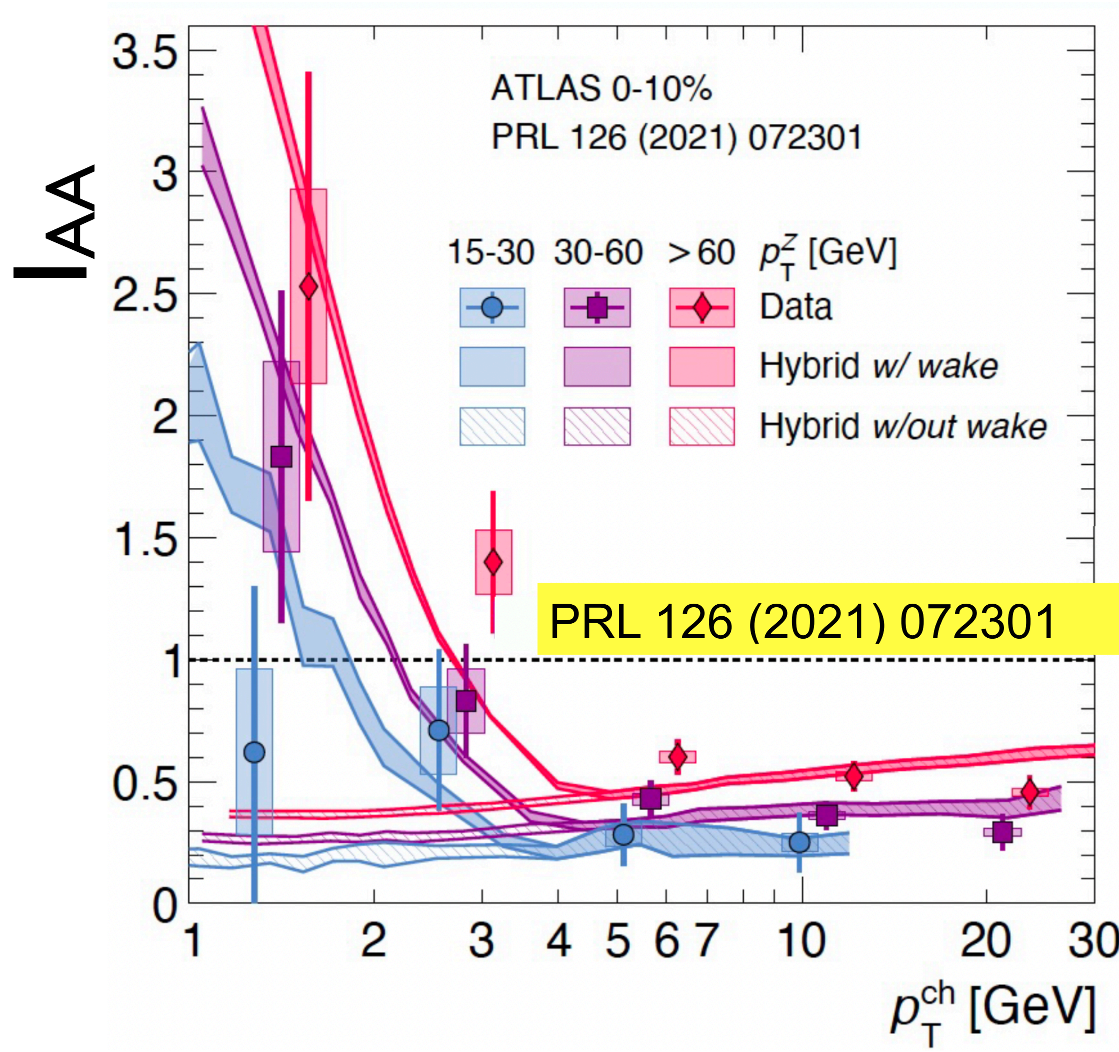
- All features of distribution **reproduced by JEWEL** with recoils on …
- …but no model incorporating medium response describe all measured observables

Charged particle yield recoiling from Z



$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi}$$

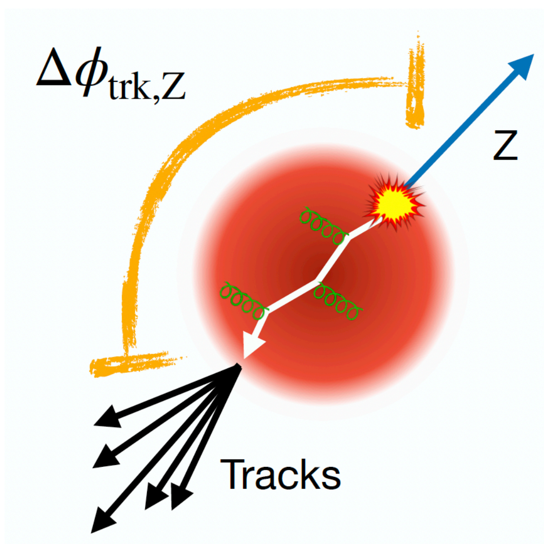
$$I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$

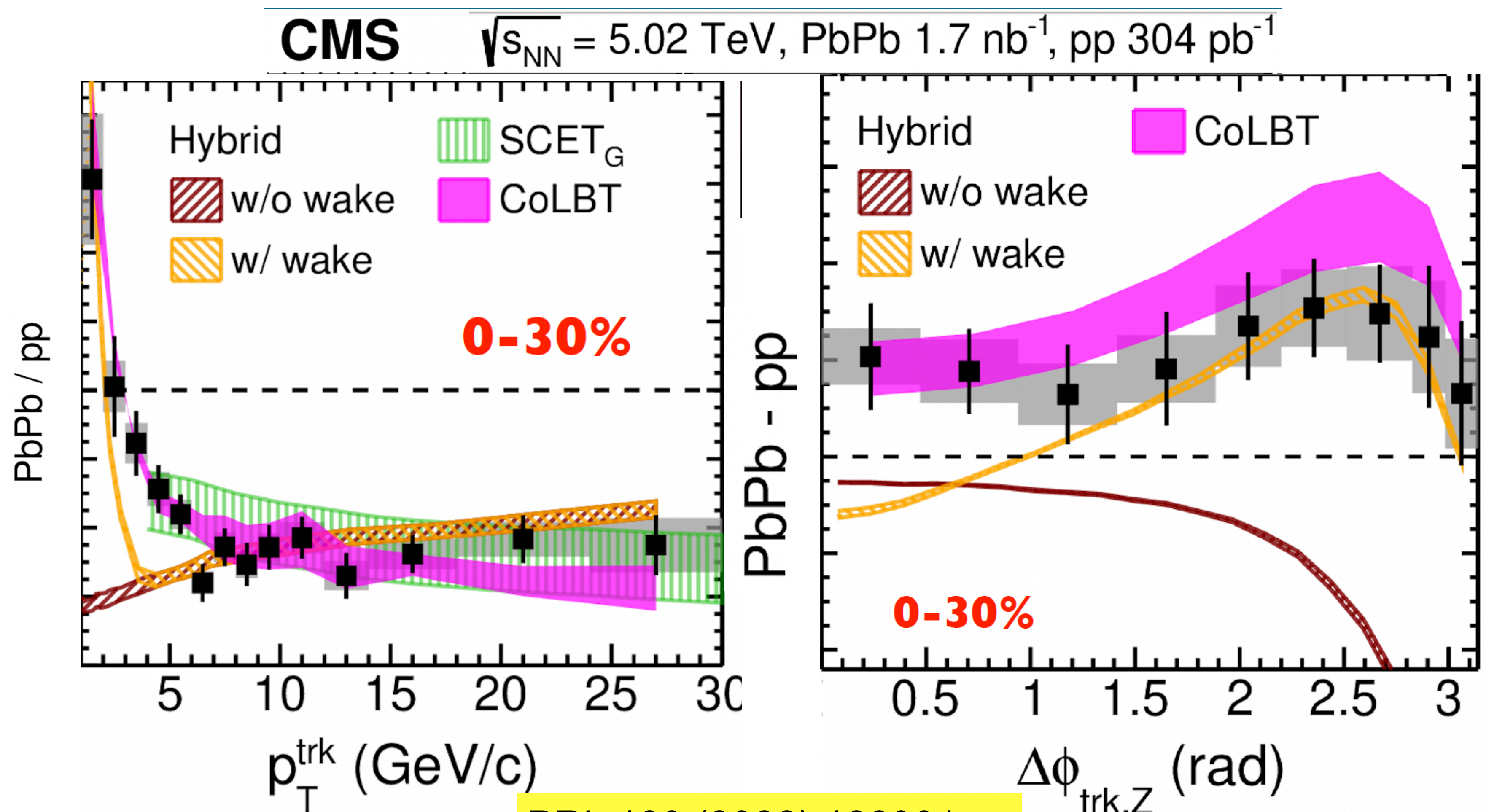


- Study of charged particles opposite to Z without jet reconstruction allows to understand the modification of jet constituents and jet fragmentation functions
  - Colorless Z sets initial scattering proxy, allows probing low p_T range
- Low p_T excess can be described by medium response in hybrid model →energy redistribution due to quenching

Charged particle yield recoiling from Z

$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi}$$



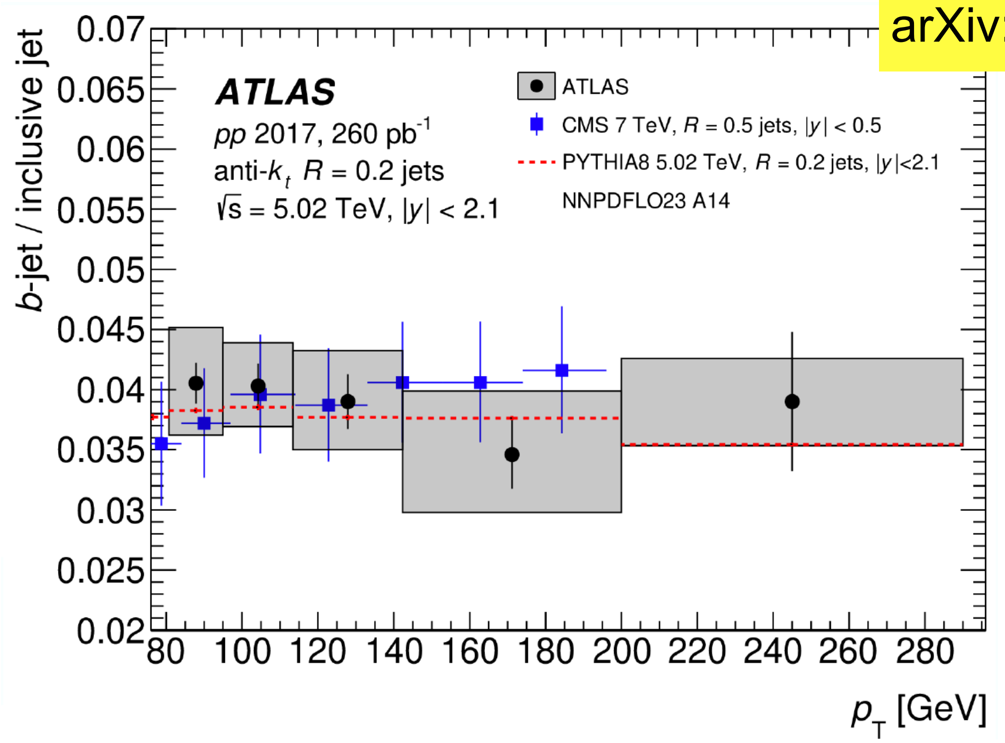


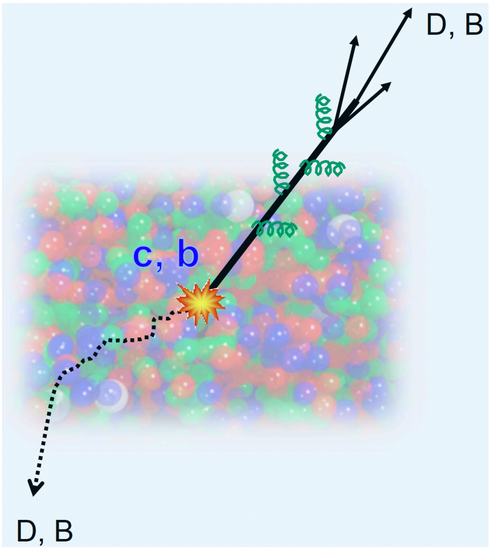
PRL 128 (2022) 122301

- Low p_T excess and high p_T suppression →energy redistribution due to quenching
- Excess of particle yields down to the $\phi^{trk} \approx \phi^{Z}$ in central PbPb collisions
  - quantitative agreement with models including medium response

Flavour dependence of jet suppression

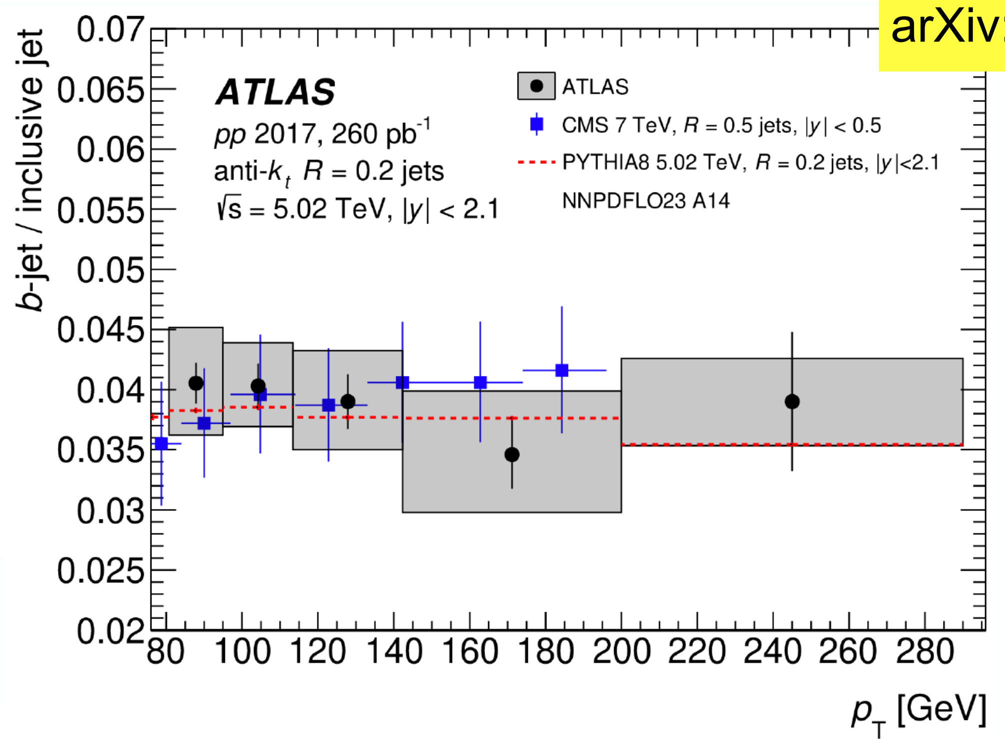
arXiv:2204.13530



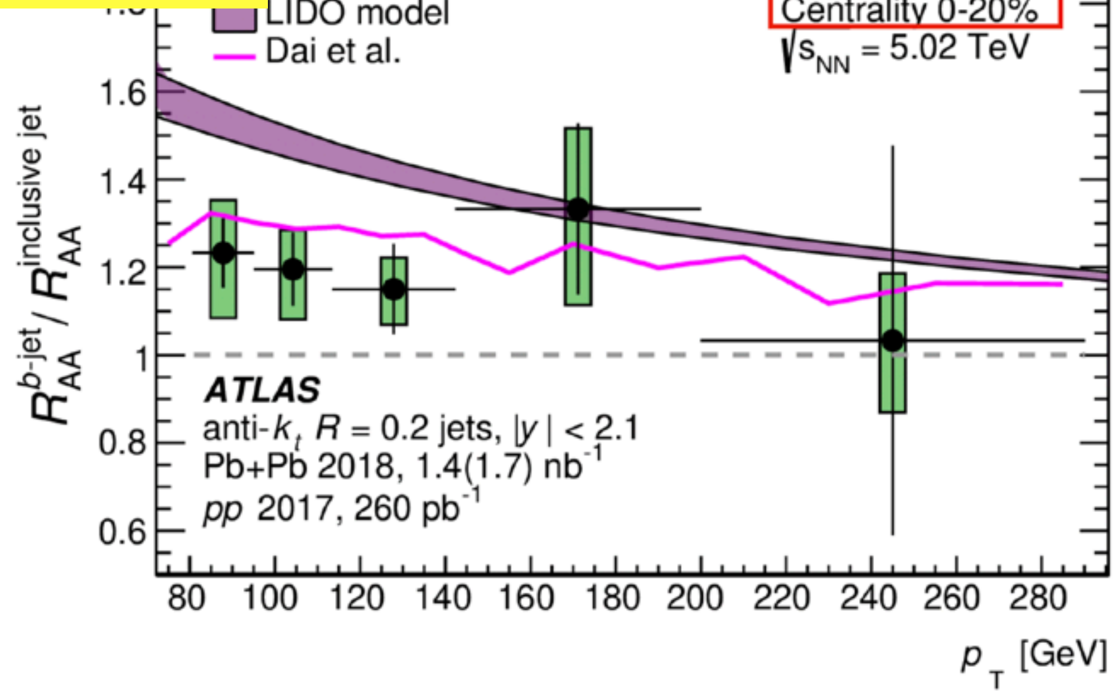


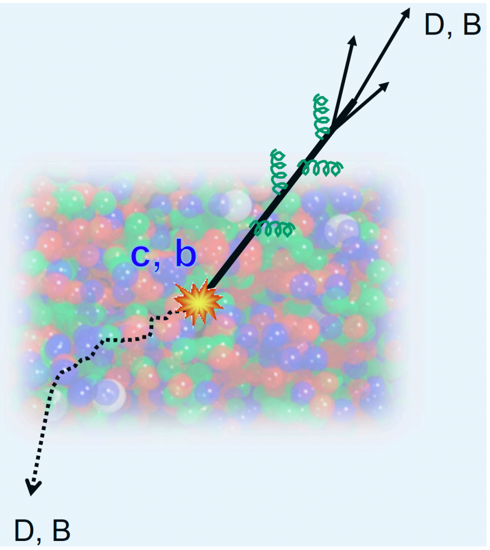
- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation

Flavour dependence of jet suppression



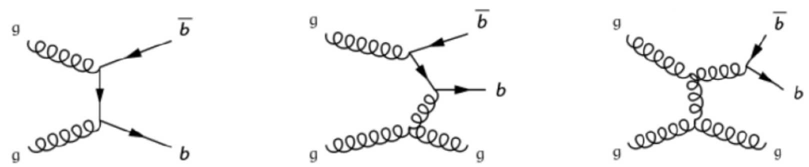
arXiv:2204.13530

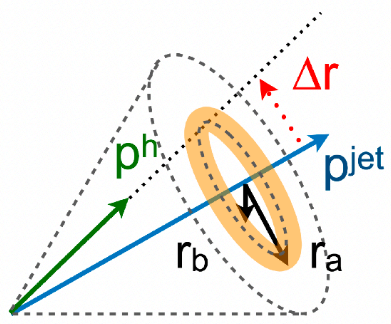




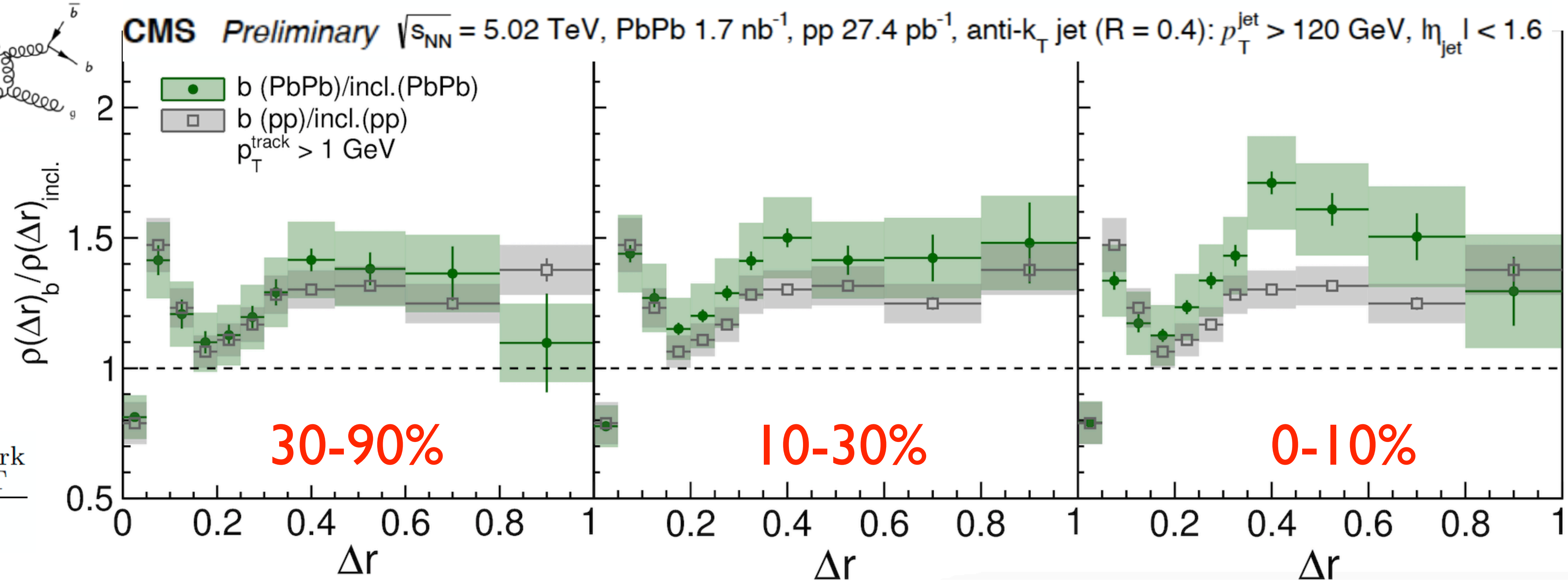
- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation
- Less suppression of b-jets than inclusive jets in most central collisions
  - color charge and mass dependence of energy loss

Mass dependence of jet energy redistribution



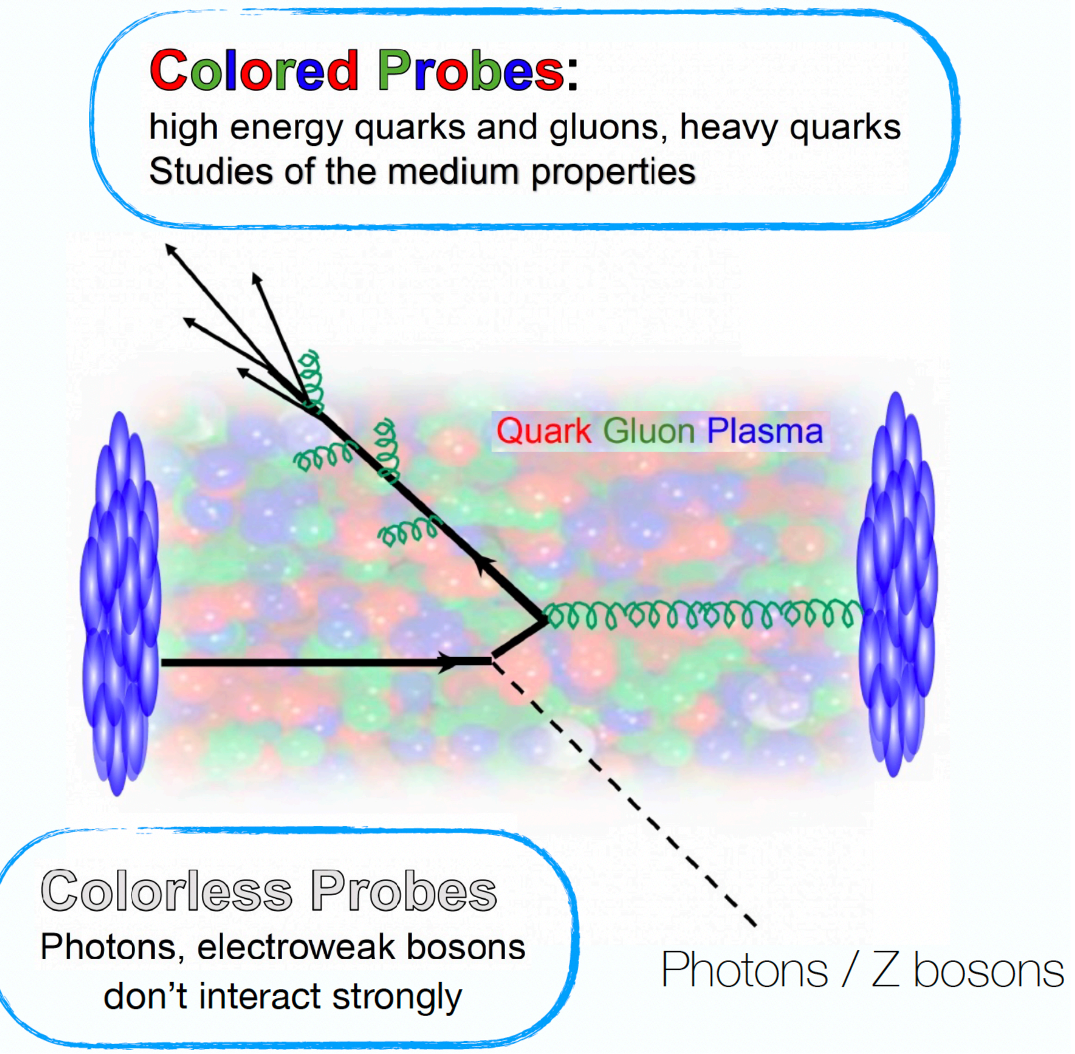


$$\rho(\Delta r) = \frac{1}{\delta r}\frac{\Sigma_{\mathrm{jet}}\Sigma_{\mathrm{trk}\in(\Delta r_a,\Delta r_b)}p_{\mathrm{T}}^{\mathrm{trk}}}{\Sigma_{\mathrm{jet}}\Sigma_{\mathrm{trk}}p_{\mathrm{T}}^{\mathrm{trk}}}$$



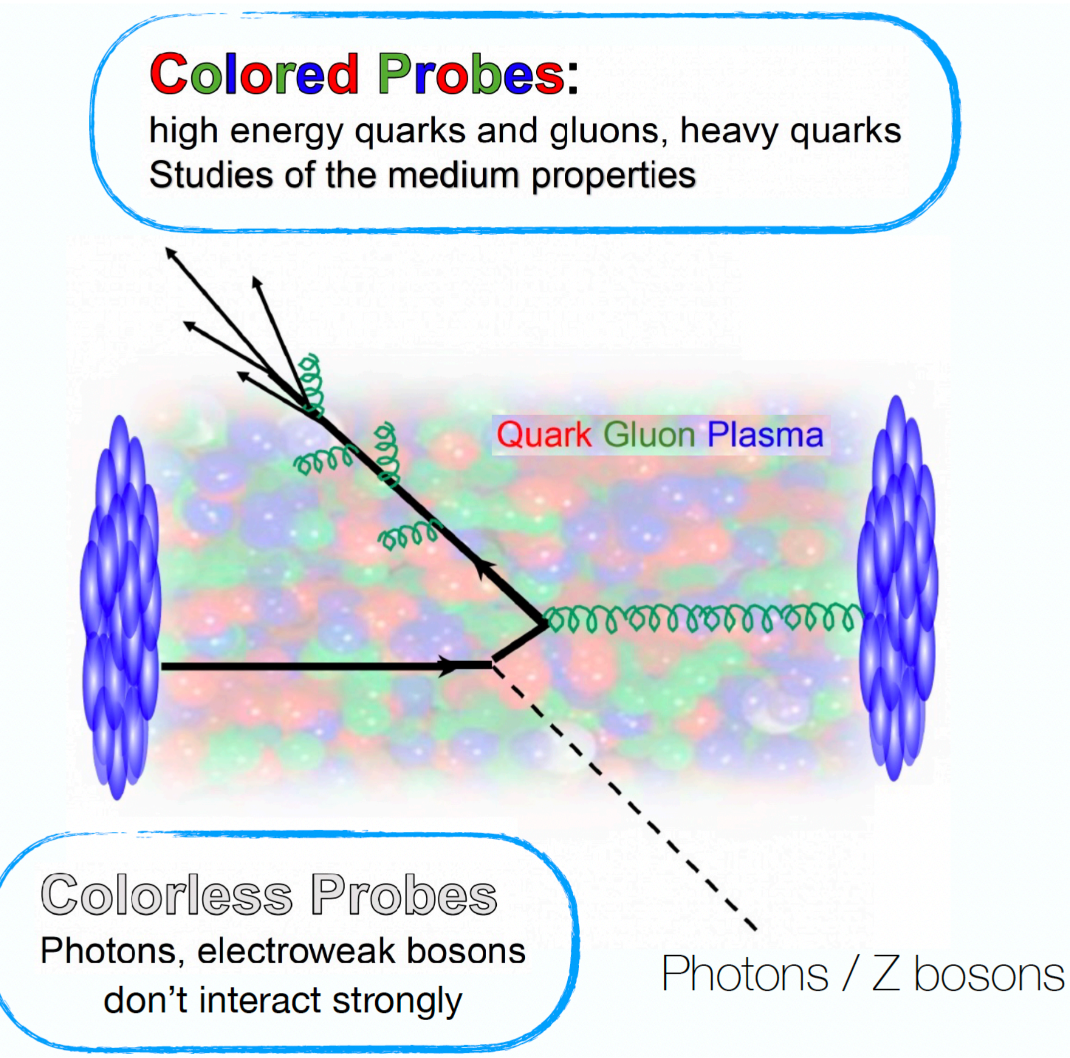
- b-jet shapes are sensitive to production (b-jets from GSP boarder than b jets from other processes) and fragmentation process
- Relative modification between b and inclusive jets at large r region getting larger from peripheral to central collisions
  - Soft p_T accumulation of b-jets are stronger than inclusive jets
- No obvious centrality dependence for small angle depletion

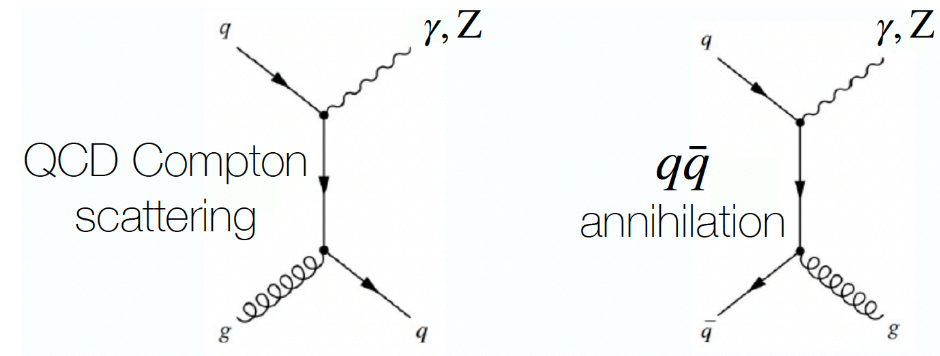
Colorless probes

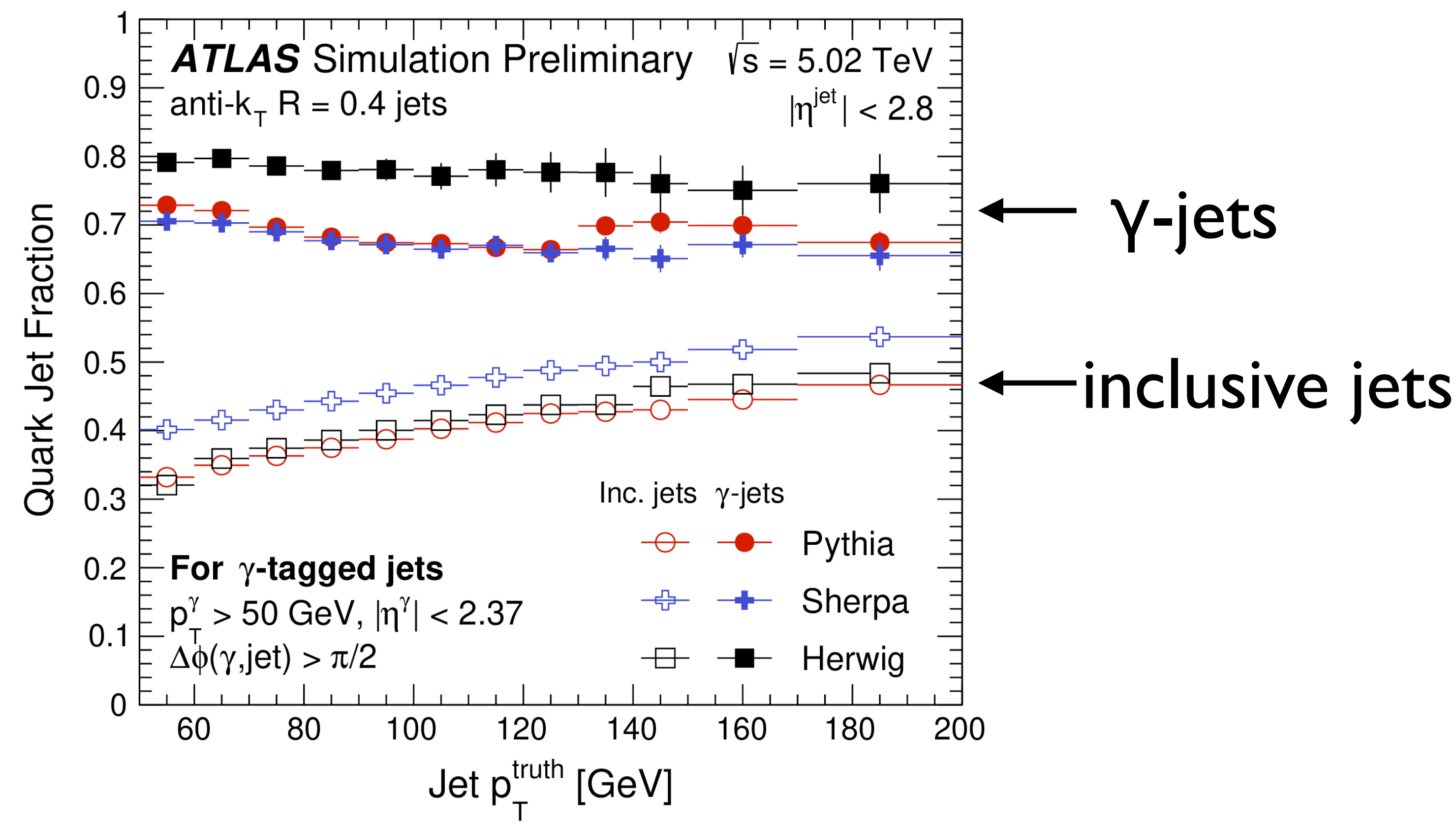


Tagging initial jet energy

Colorless probes





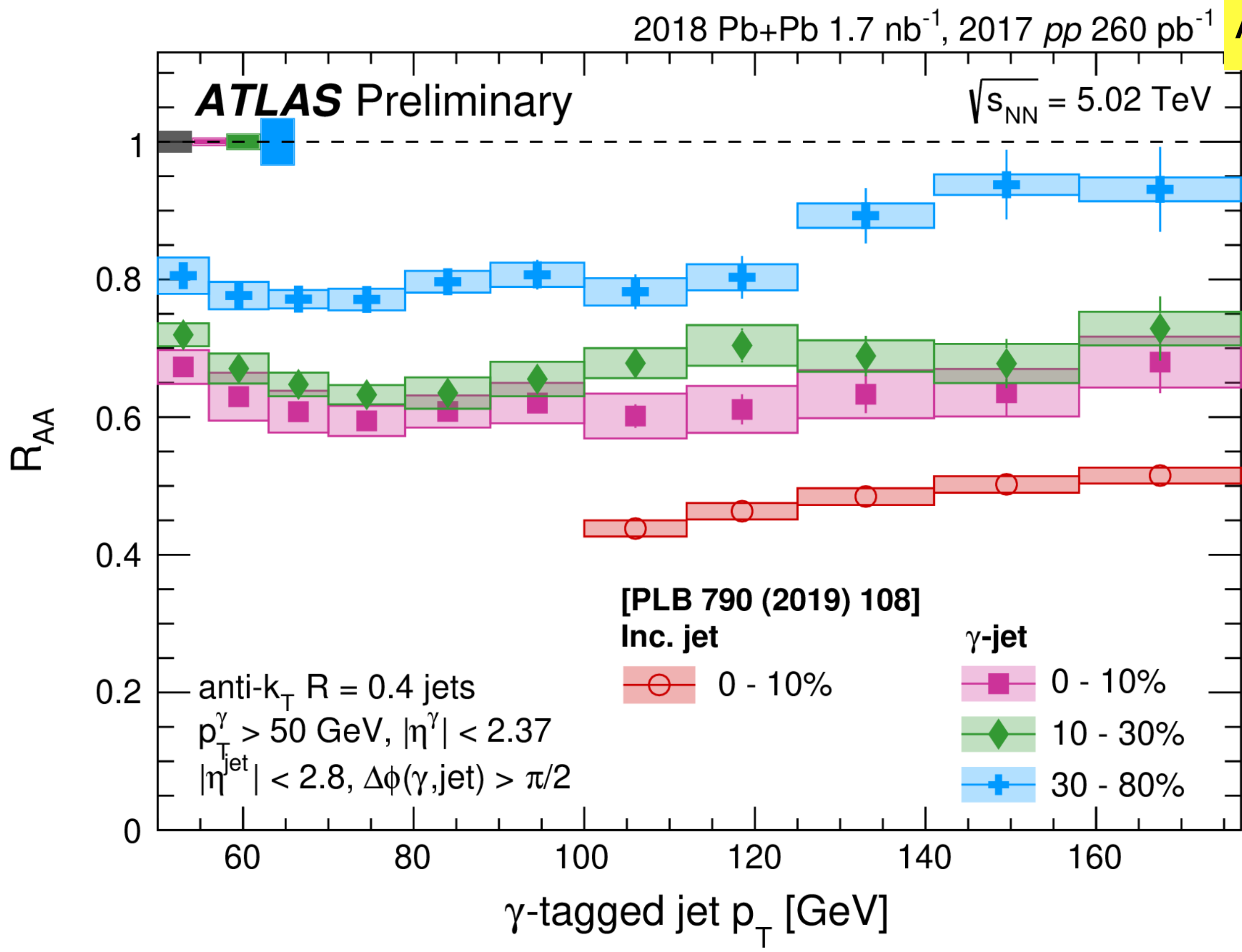


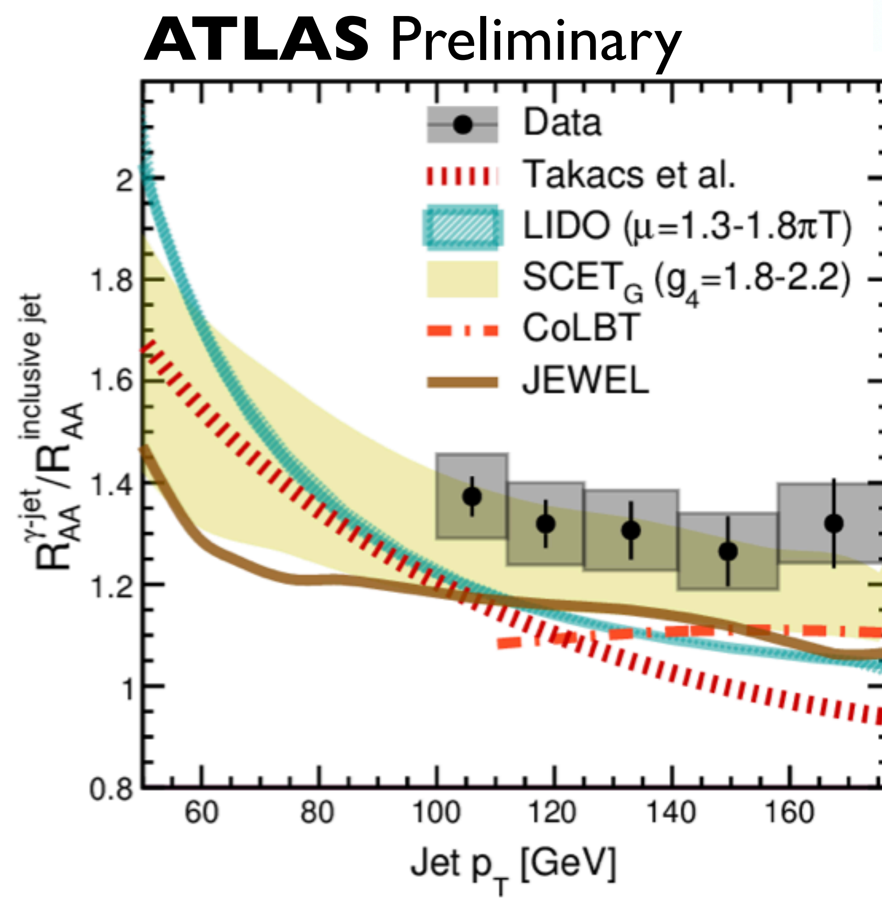
Tagging initial jet energy

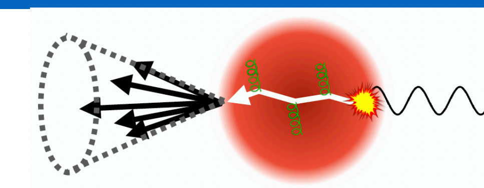
Increasing quark-jet fraction

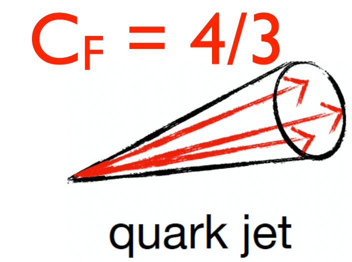
Color-charge dependence of R_{AA}

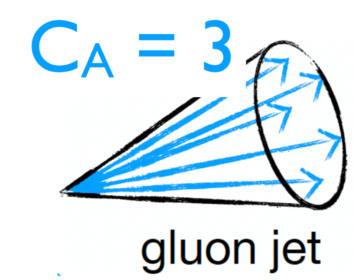
ATLAS-CONF-2022-019





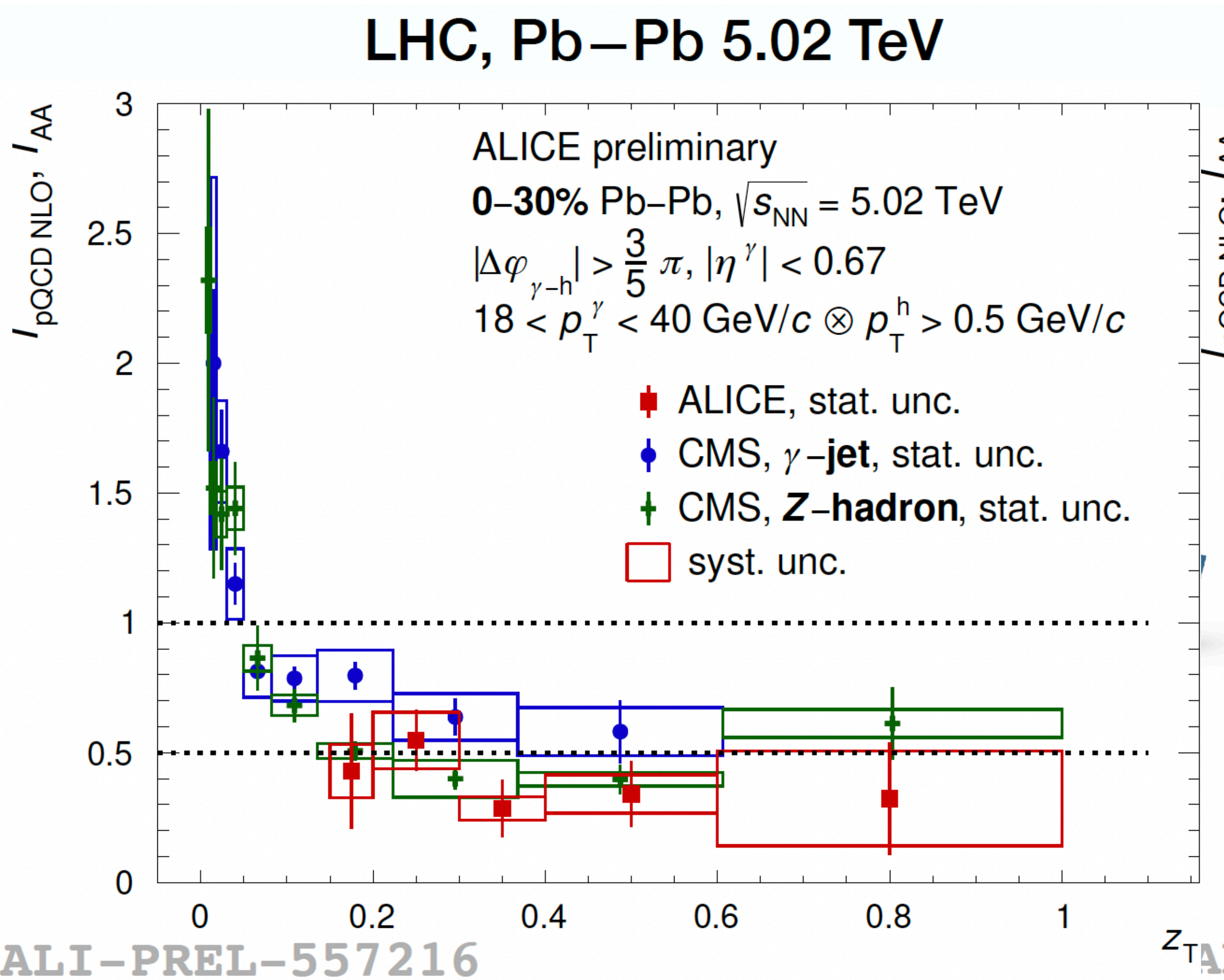


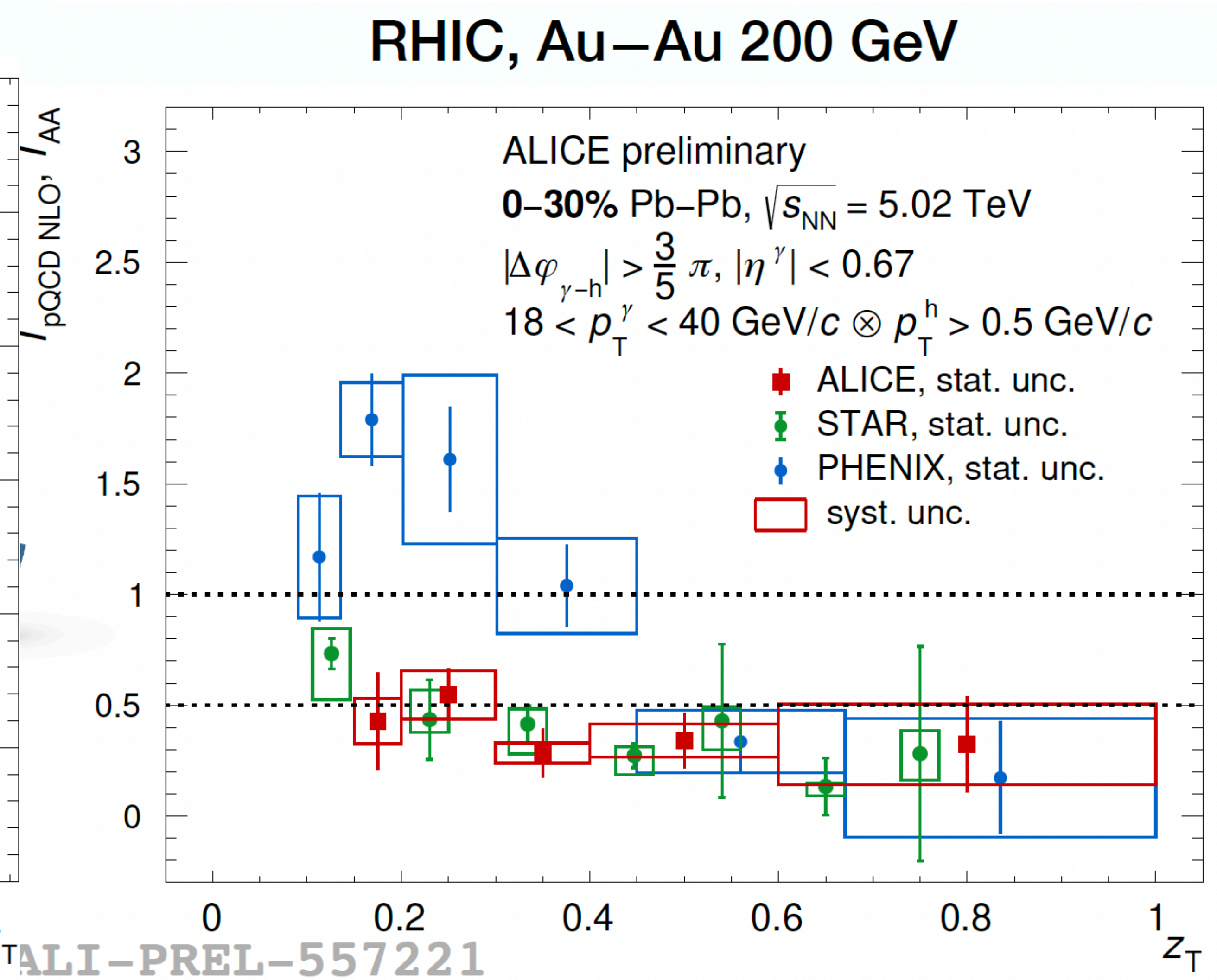




- Photon-tagged (quark-enhanced) jets being significantly less suppressed than inclusive jets
  - quark jets less active in medium, fewer radiating prongs → color factor dependence of parton-medium interaction

Correlations with isolated photons





CMS, γ—jet, 0-10% Phys. Rev. Lett. 121, 242301

CMS, Z—hadron, 0-30% Phys. Rev. Lett. 128, 122301

- same $\sqrt{s_{NN}}$ and system
- different selections and measurements

STAR: γ—hadron, 0-12% Phys.Lett.B 760 (2016) 689-696

PHENIX: γ—hadron, 0-40% Phys. Rev. Lett. 111, 032301

- same measurement
- different $\sqrt{s_{NN}}$, system and selections

Similar behavior as observed at LHC and RHIC experiments, despite of not completely apple-to-apple comparison

LHC HI program

2010-2012		2015-2018		2022-2024		2028-2030		2032-2034		2036-2039
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

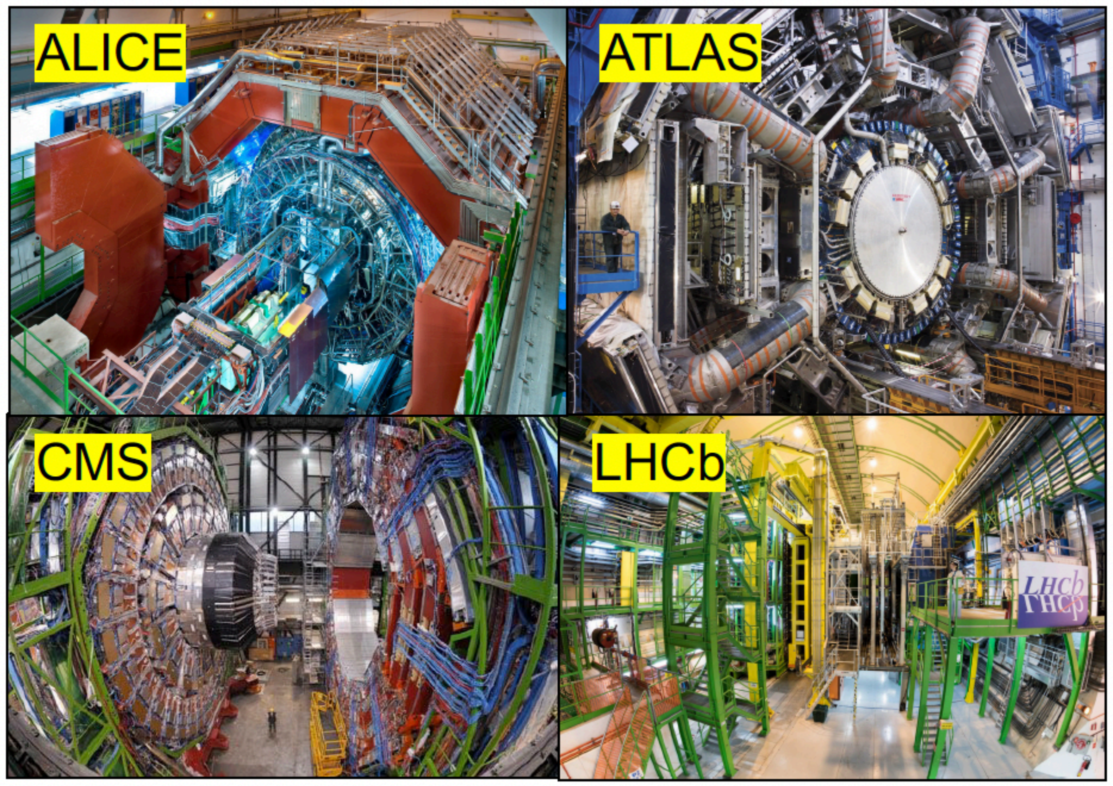
High luminosity LHC

Major upgrades for ALICE and LHCb (LS2)

We are here (Run 3)

ATLAS and CMS phase II
ALICE ITS3 and FoCal (LS3)

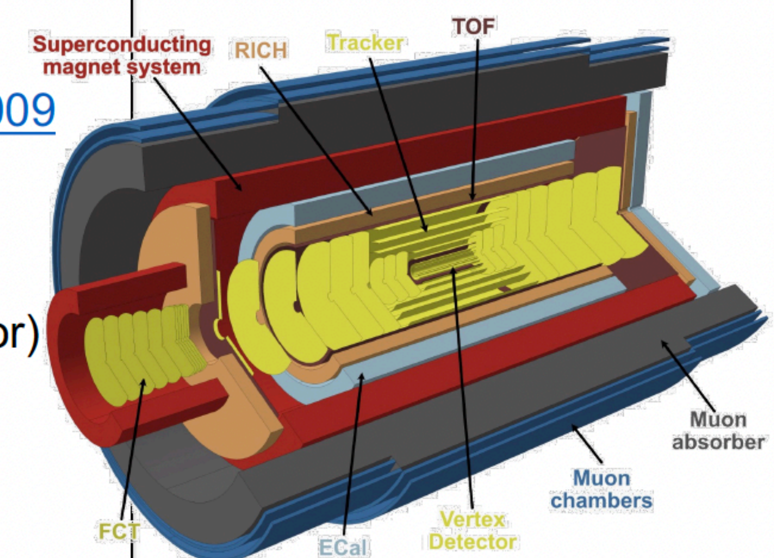
ALICE 3: a whole new dedicated HI detector!
LHCb upgrade II (LS4)



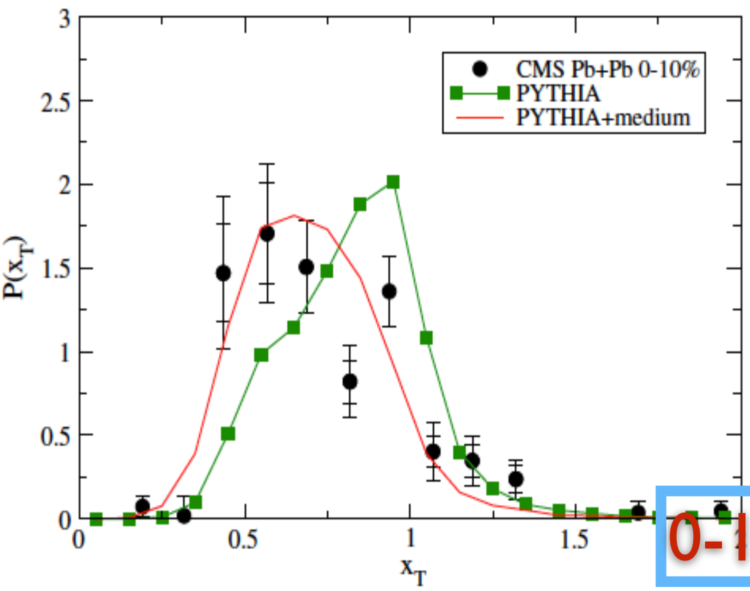
ALICE 3

- Letter of Intent: CERN-LHCC-2022-009
- next-generation HI experiment
- all-Si MAPS tracker
- ultimate vertex detector
- minimal mass (essentially only sensor)
- 5 mm from beam (LHC aperture)

Physics focus:
- low-p_T heavy-flavour
- electromagnetic radiation from QGP

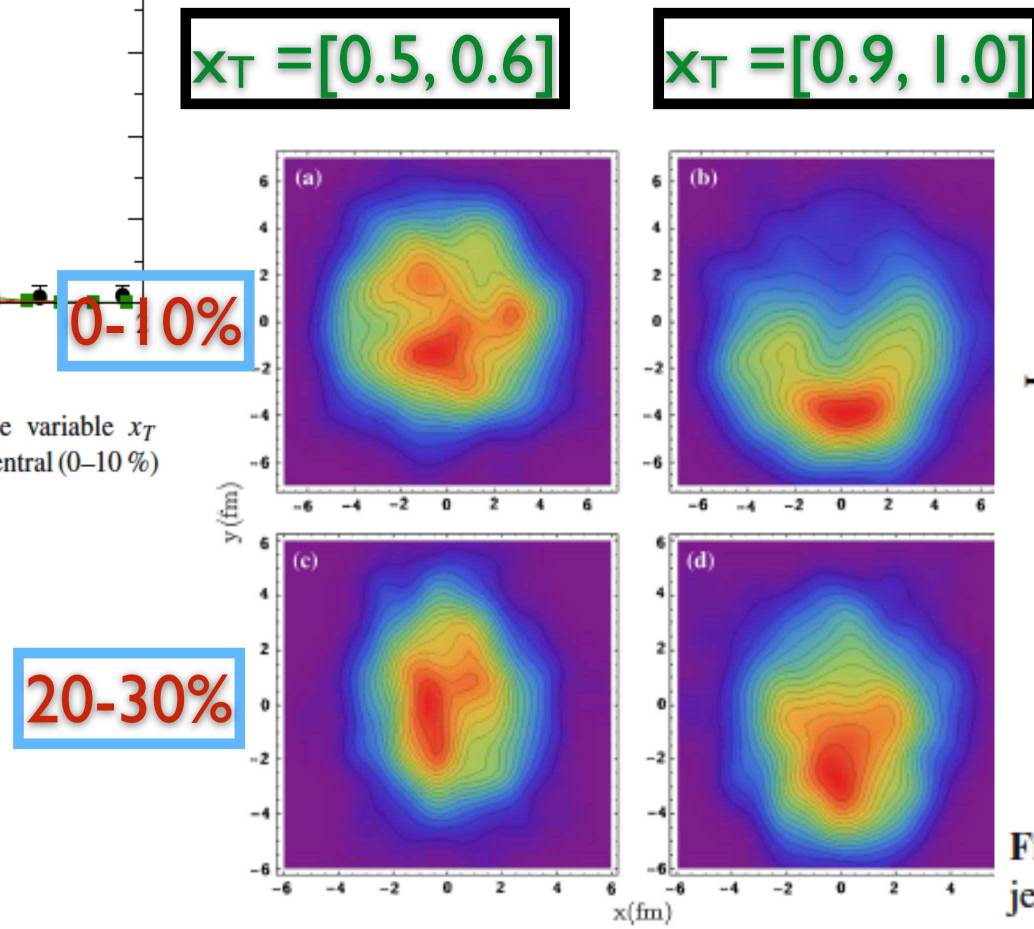


Path length dependent medium effect by tagging



ig. 3 The distribution of the momentum imbalance variable x_T etween triggered photons and associated jets for most central (0–10 %) b+Pb collisions at the LHC. The jet size is $R = 0.3$

Feasible to probe medium density experimentally?



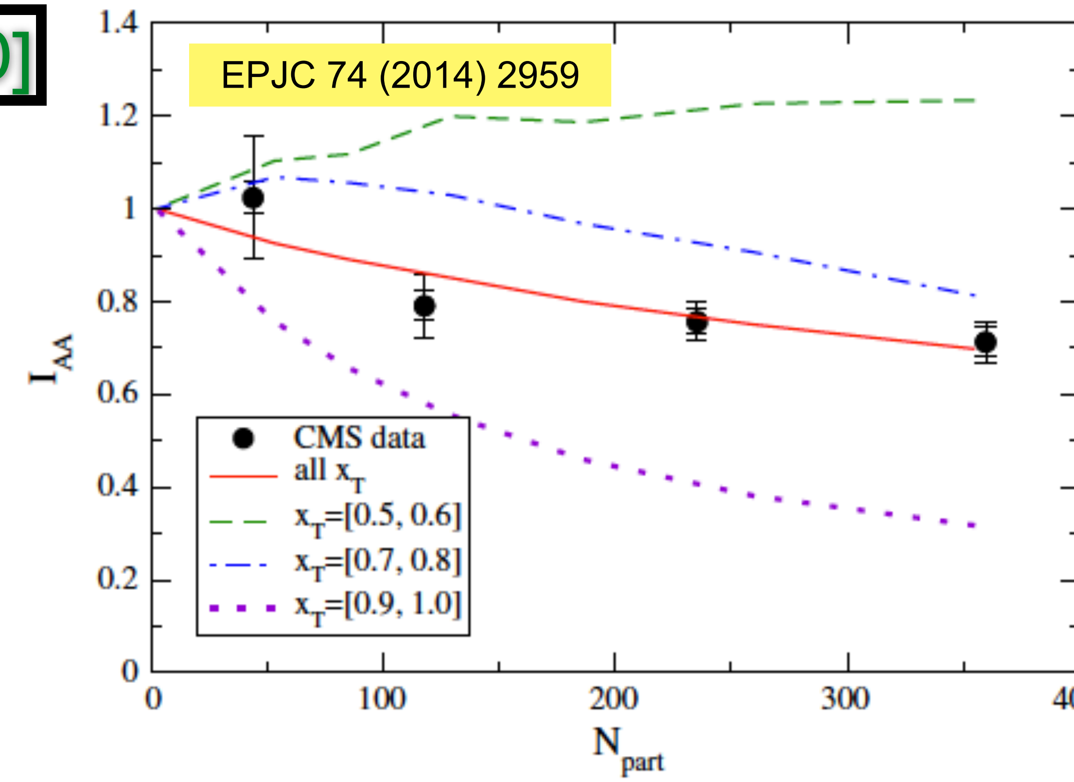


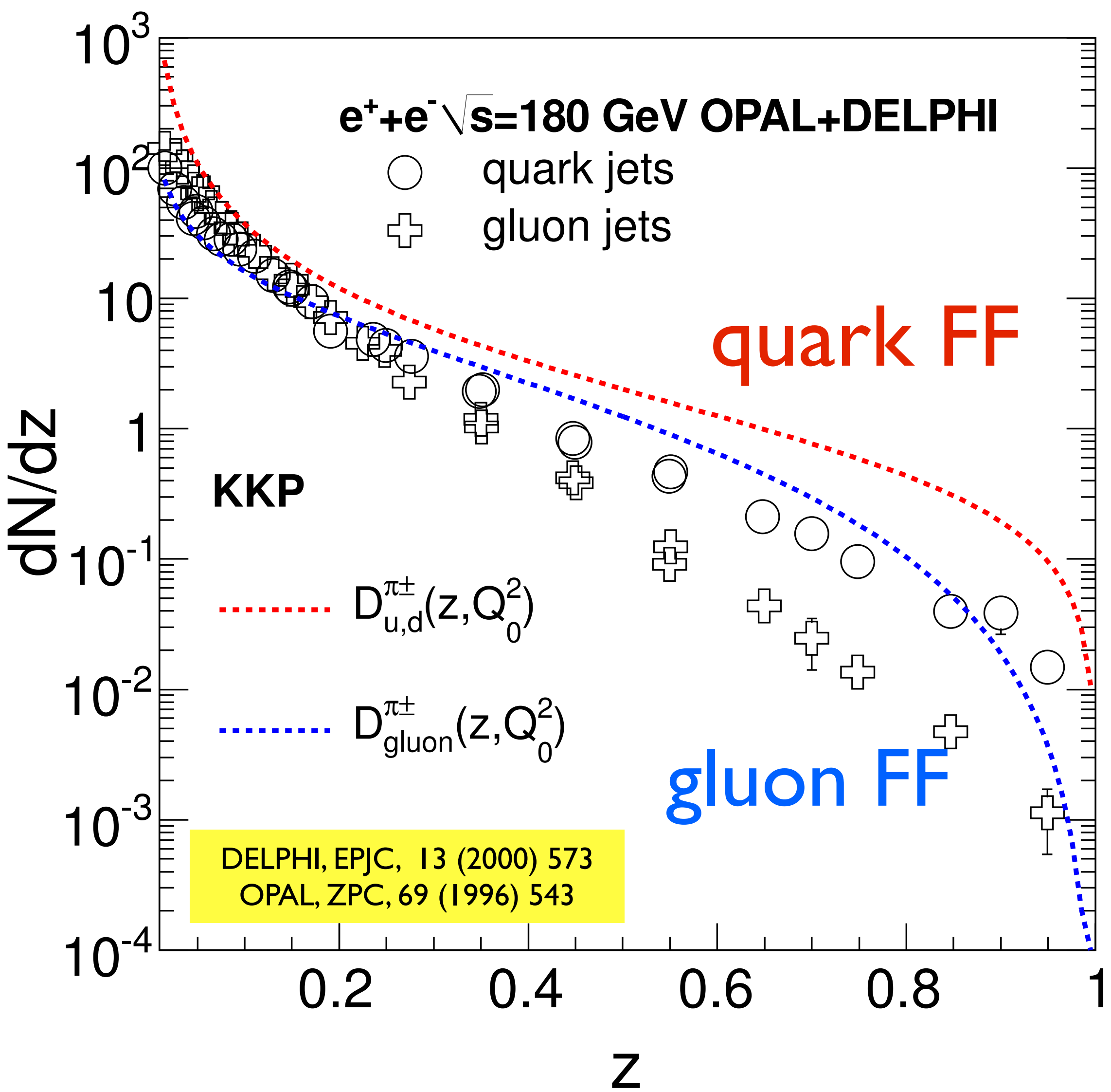
Fig. 8 The nuclear modification factor I_{AA} for the photon-triggered jets as a function of centrality for Pb+Pb collisions at the LHC. The results for different x_T values are compared. The jet size is $R = 0.3$

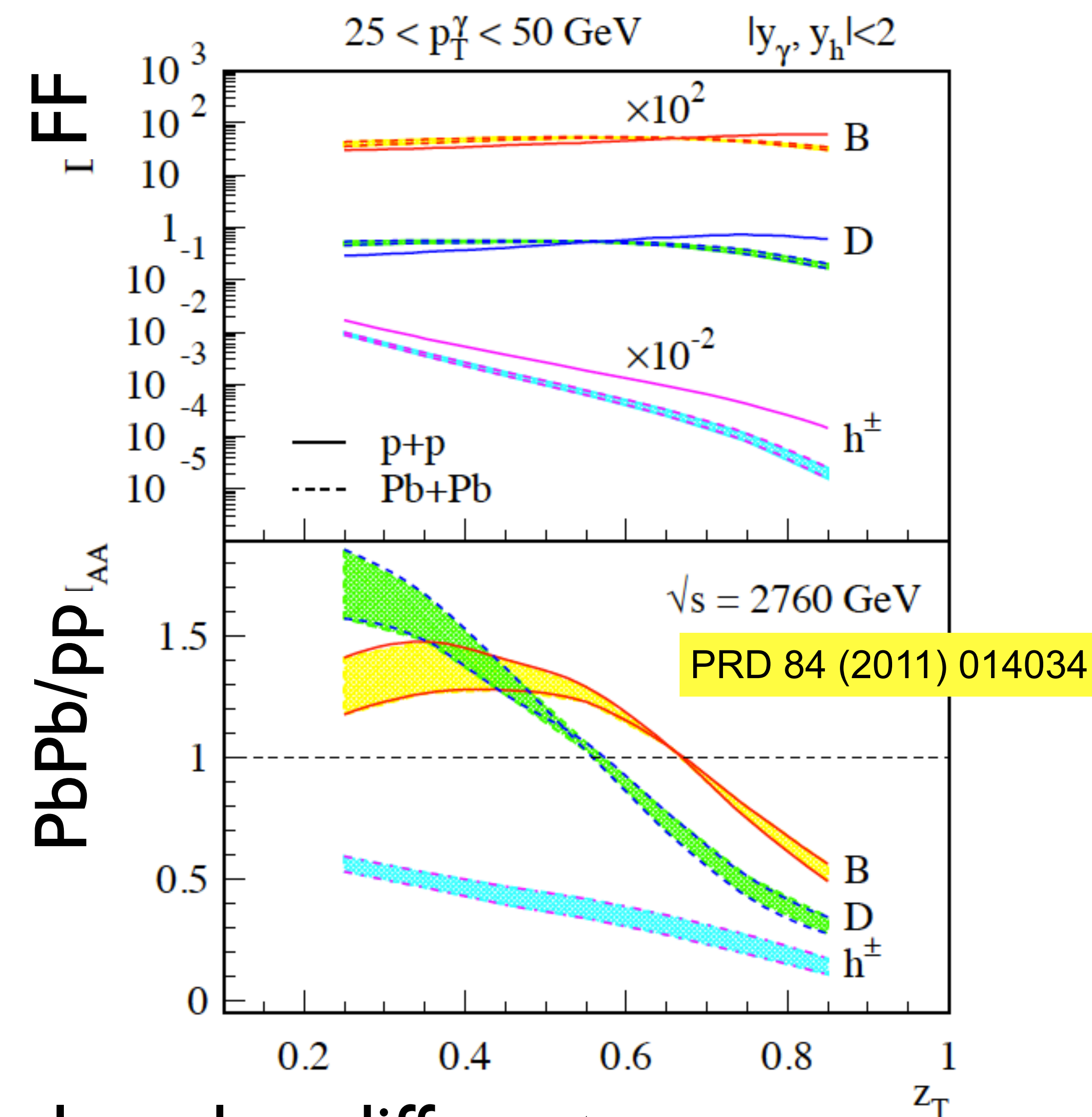
- By selecting jet pair events using different asymmetry (x_T) value (or so called "ESE"), one can probe different medium lengths and density profile, and result different modification patterns

  ➡ can be studied at LHC Run3 and beyond

Color and mass dependence by tagging

Tagging jets by different triggered-particle correlations





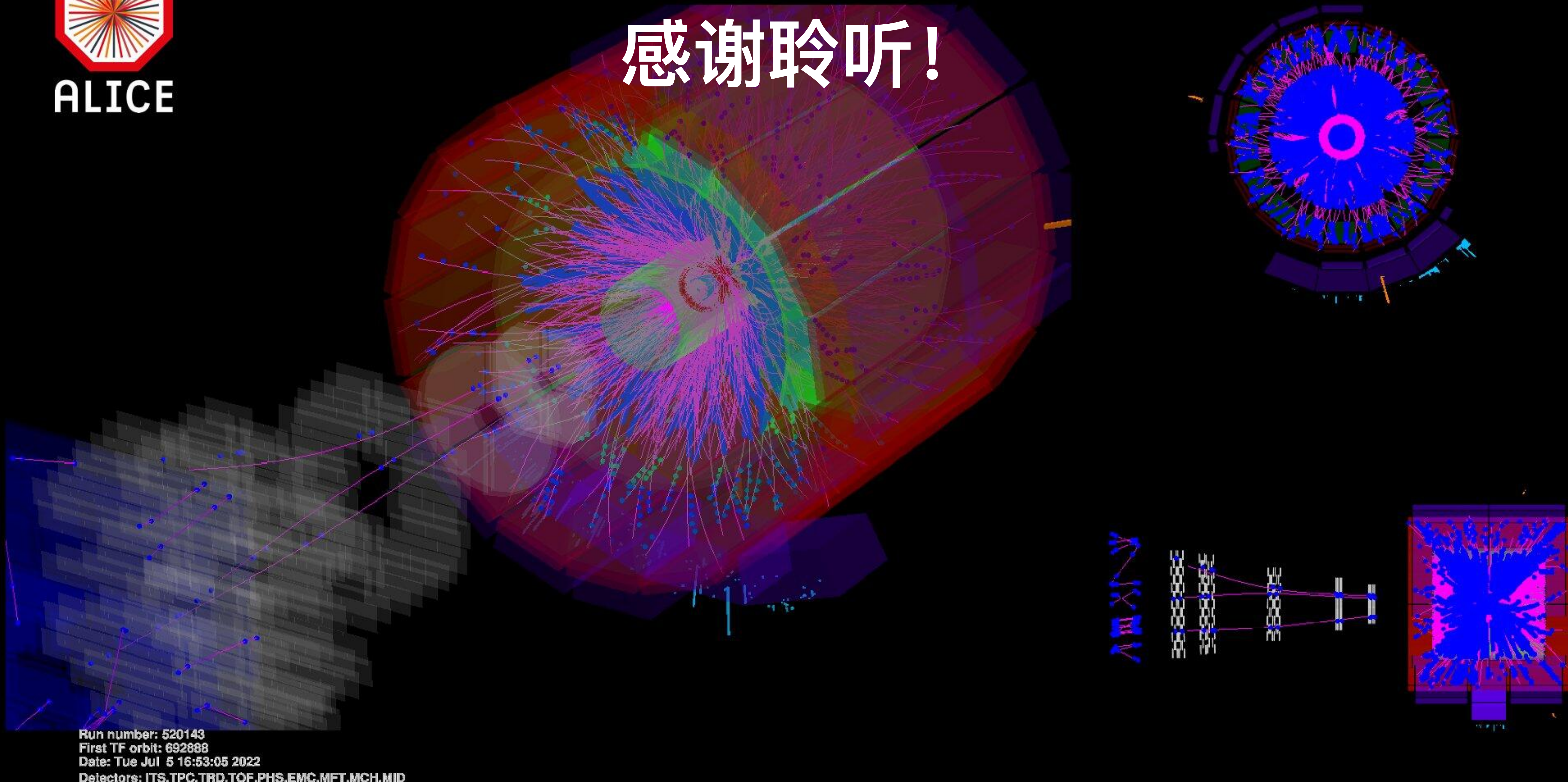
- OPAL and DELPHI measured quark and gluon has different fragmentation pattern in e+e-
- Theory predicted jet fragmentation pattern modified differently for g, q and Q
    - ➡ can be studied at LHC Run3 and beyond

Summary

- Large number of jet results based on full Run 2 LHC data sample (many more not covered here)
  - More precision, extending to low p_{T}/large *R*, more differential, new analysis
- Detailed insights on the QGP properties
  - Color and mass dependent jet energy loss observation
  - Path length dependent jet quenching
  - First evidence of the broadening of the γ-jet and h-jet azimuthal correlations for very soft jets
- Plenty of encouraging and interesting new theoretical/experimental developments with nice results
  - some results are still to be understood → ongoing studies + LHC Run 3!

Thanks for your attention!

感谢聆听！



Literature

- 参考书：
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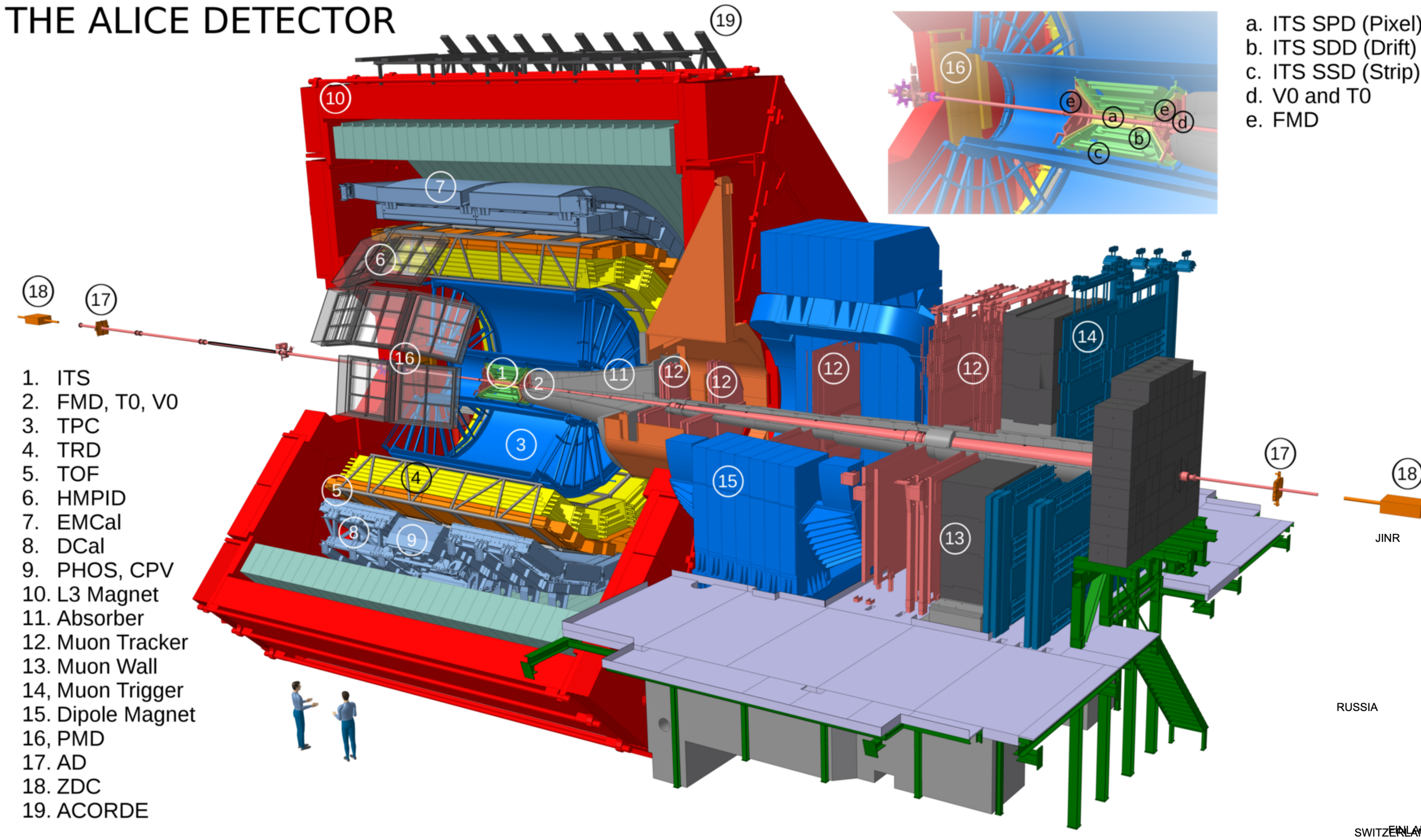
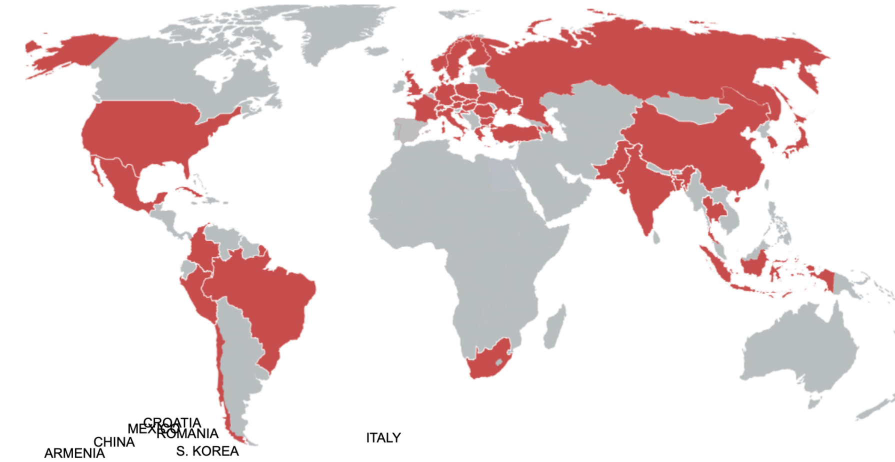
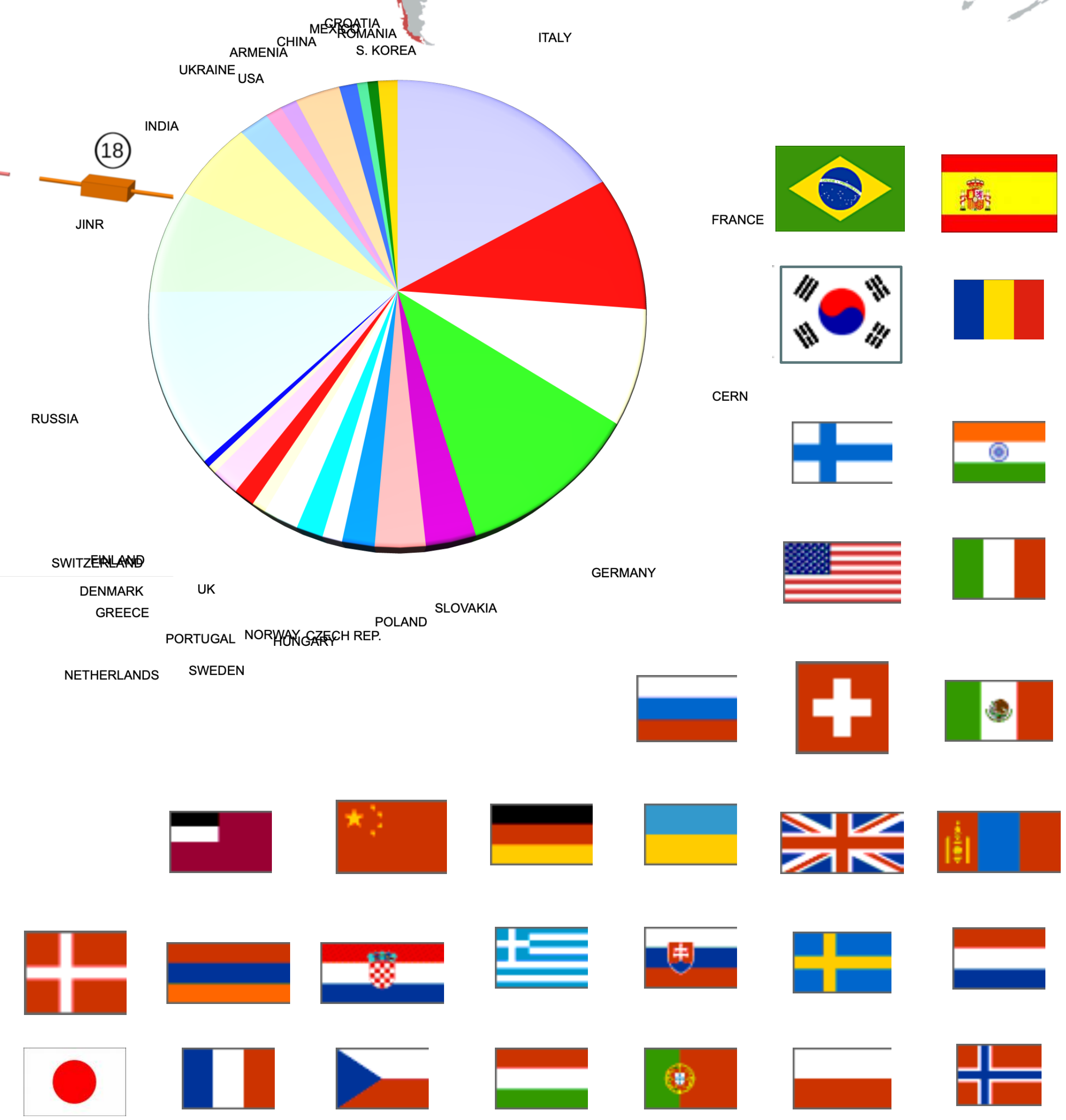
  - 《Introduction to high-energy heavy- ion collisions》, C.Y. Wong, World Scientific
    汉译版：《高能重离子碰撞导论》，[美]黄卓然 著，张卫宁 译，哈尔滨工业大学出版社
  - 《Quark-Gluon Plasma》, K. Yagi, T. Hatsuda, and Y. Miake, Cambridge University Press
    汉译本：《夸克胶子等离子体：从大爆炸到小爆炸》，王群，马余刚，庄鹏飞，中国科学技术出版社
  - 《Introduction to relativistic heavy ion collisions》, L. P. Csernai (free to download link)
  - 《The physics of the quark-gluon plasma》, S. Arkar, H. Satz and B. Sinha, Lecture notes in physics, Volumn 785, 2010 (free to download link)
  - 《Ultrarelativistic Heavy-ion Collisions》, R. Vogt, Elsevier
  - 《Phenomenology of Ultra-Relativistic Heavy-Ion Collisions》, W. Florkowski, World Scientific
  - 《The Physics of Quark-Gluon Plasma》, Berndt Mueller, Springer-Verlag
- Lectures：
  - Quark Matter
  - CERN Summer Students Program
  - Summer schools (video record available in many schools)

ALICE: A Large Ion Collider Experiment

40 countries, 170 institutes, 1999 members







- 耗资1.8亿瑞士法郎
- 历时17年设计、建造
- 探测器高16米、长26米、重达1万吨
- 位于地下50 – 100米

Heavy ion collisions seen at LHC