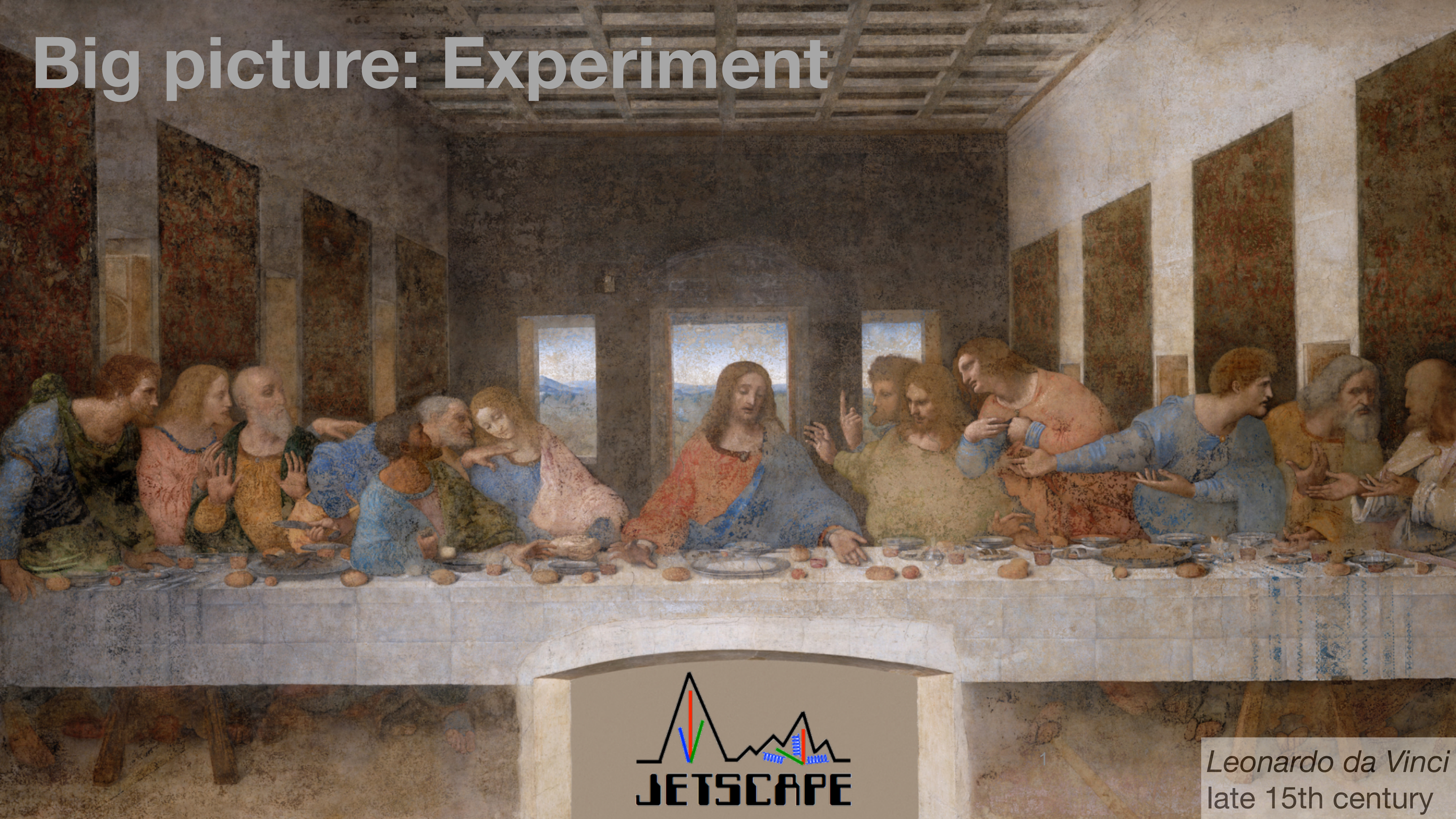
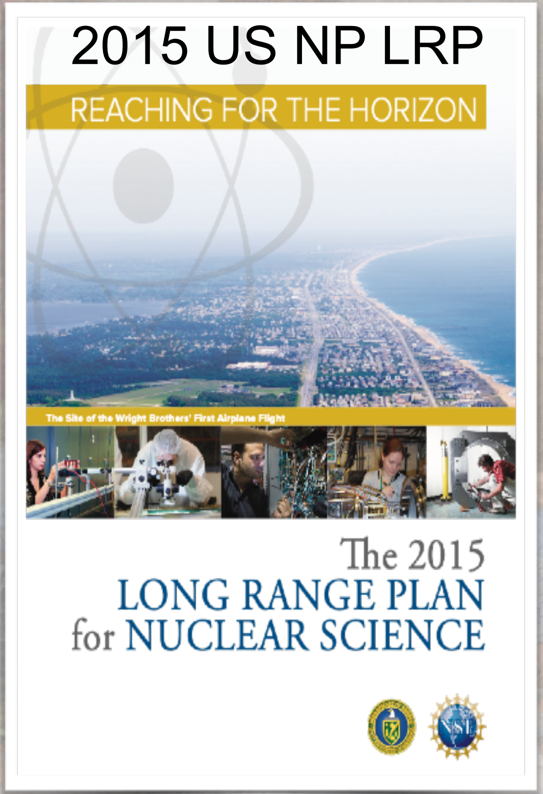
Big picture: Experiment



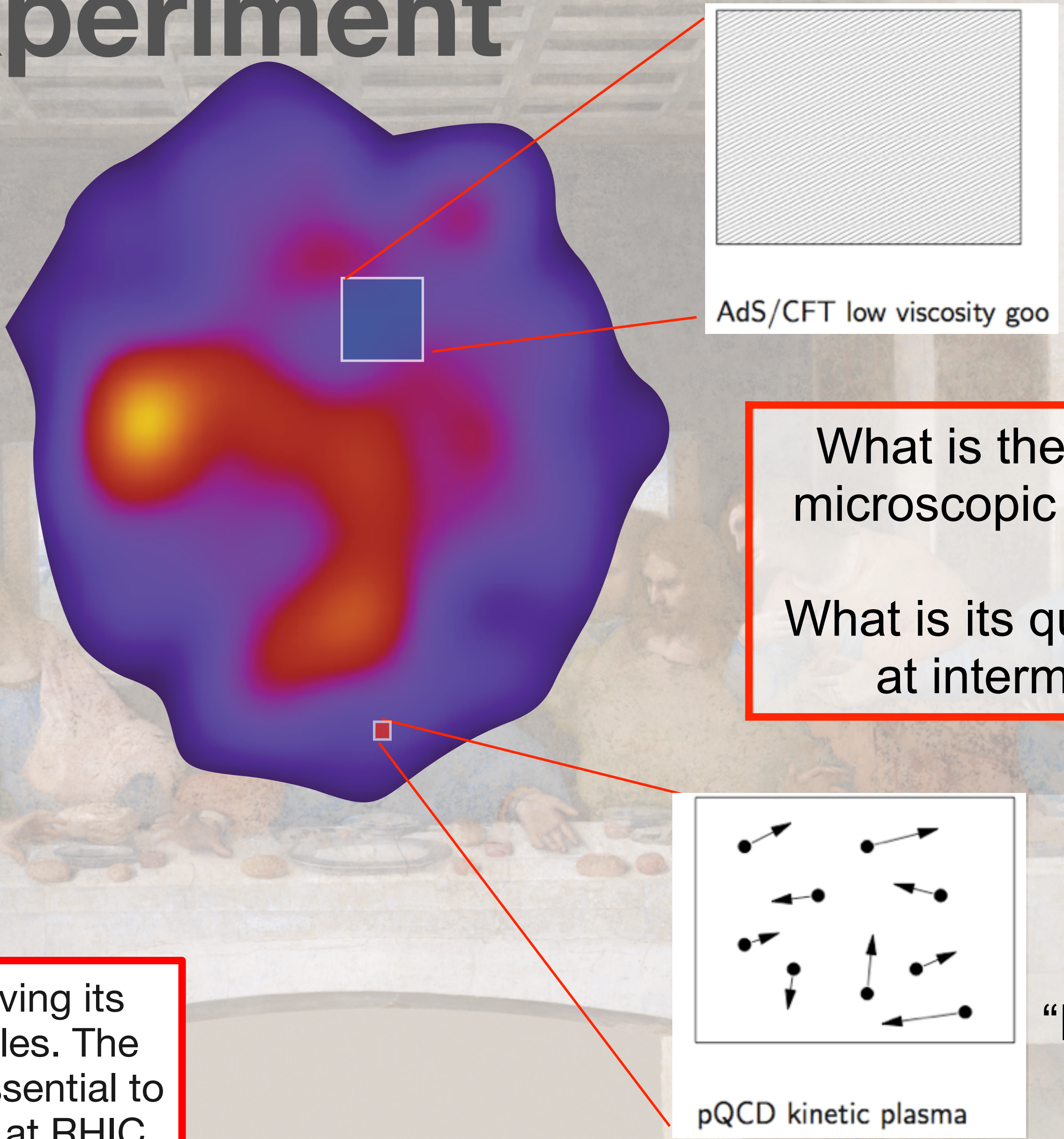
Leonardo da Vinci
late 15th century

Big picture: Experiment

2015 US NP LRP



“Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of [RHIC and the LHC] is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.”



$\Delta x \approx 1\text{fm}$
$\Delta p \lessapprox 200\text{MeV}$

“Perfect Liquid”

What is the scale-dependent microscopic structure of QGP?

What is its quasi-particle nature at intermediate scales?

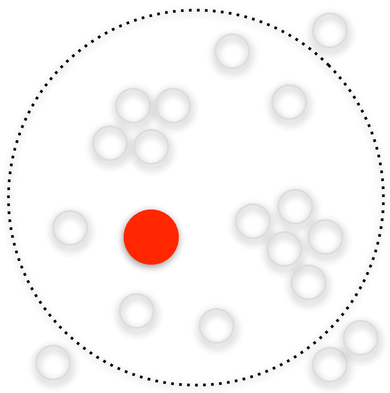
$\Delta x \ll 1\text{fm}$
$\Delta p >> 1\text{GeV}$

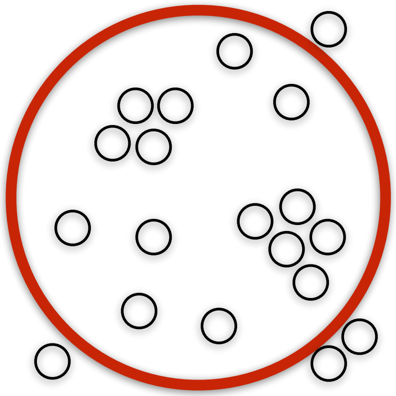
“Free quarks + gluons”

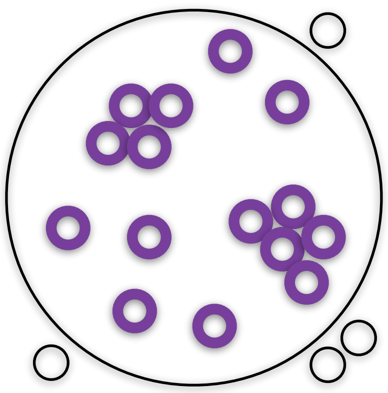
Leonardo da Vinci
late 15th century

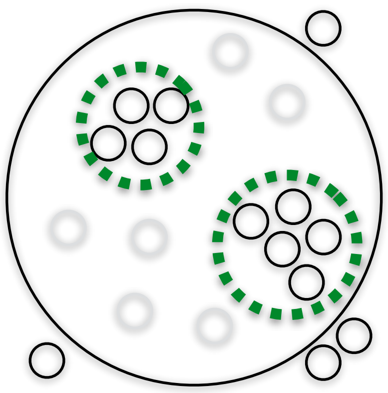
Jet observables in our toolkit (in order of appearance)

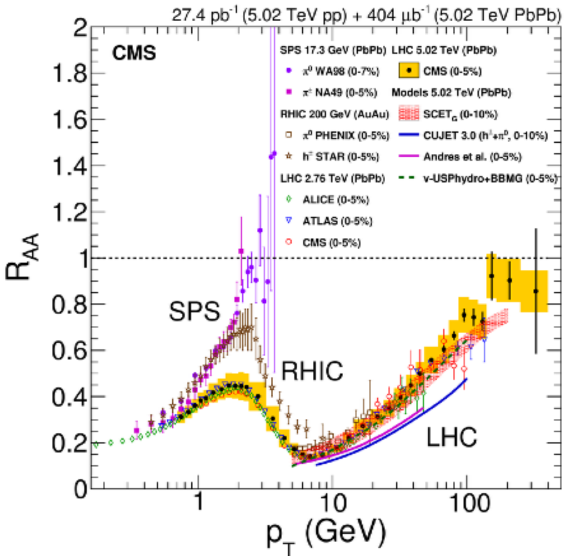
from Yi Chen


Leading Hadron


Full jet

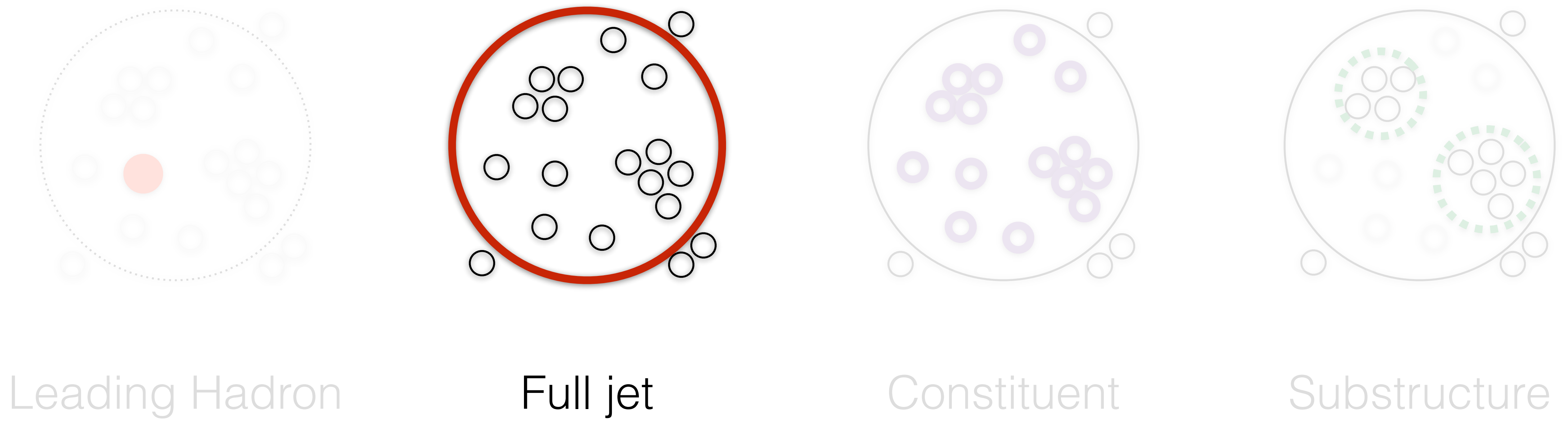

Constituent

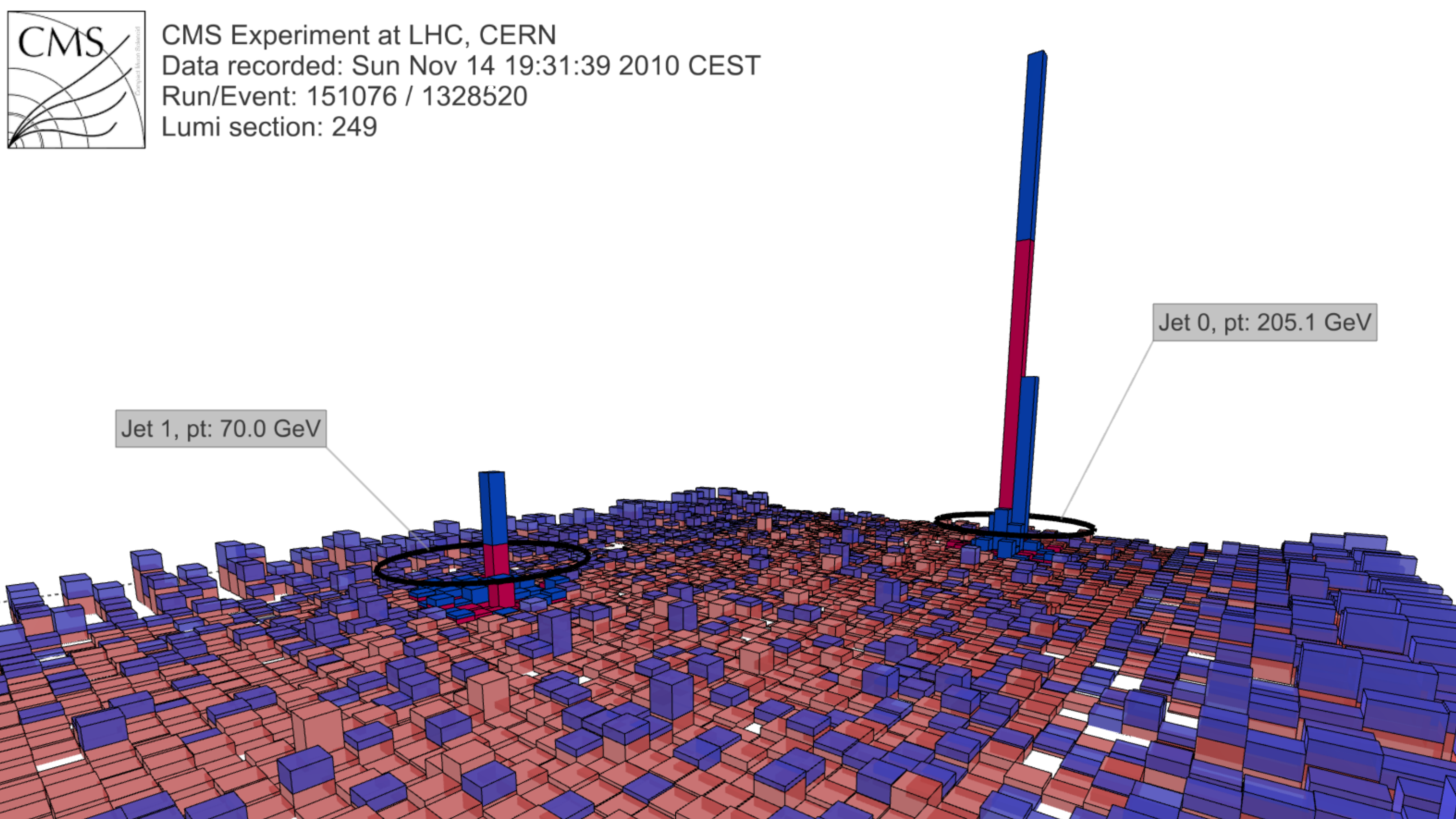

Substructure



Jet physics with jets

from Yi Chen

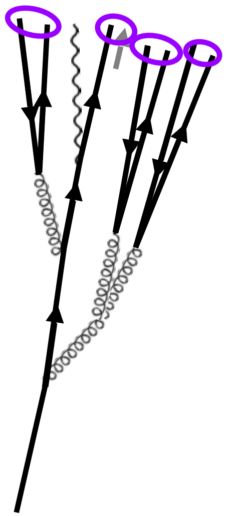



CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

From parton shower to jet

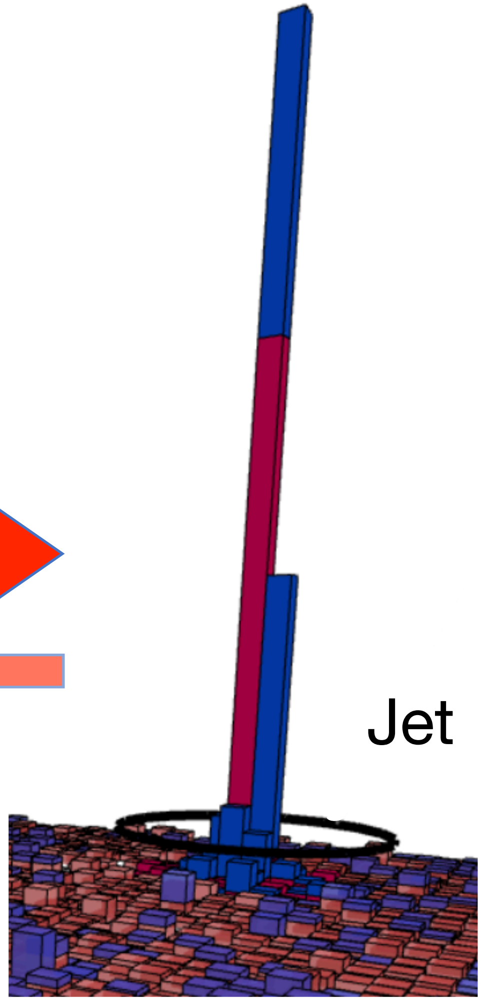
Jet: construct reflecting momentum and angular structure of a parton shower, as well as initial parton flavor/charge

Parton shower



Nature + experiment

Experiment + theory/models



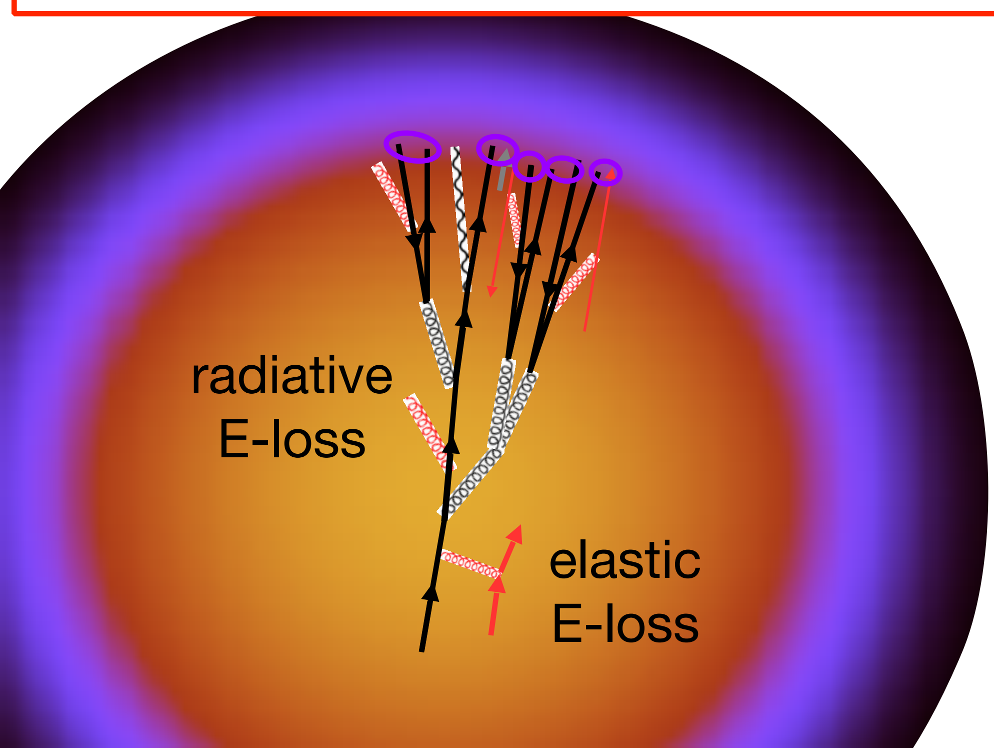
Jet

From parton shower to jet

How is parton shower modified in QGP?

How are modifications related to properties of QGP?

How are modifications/properties related to **nature** of QGP?



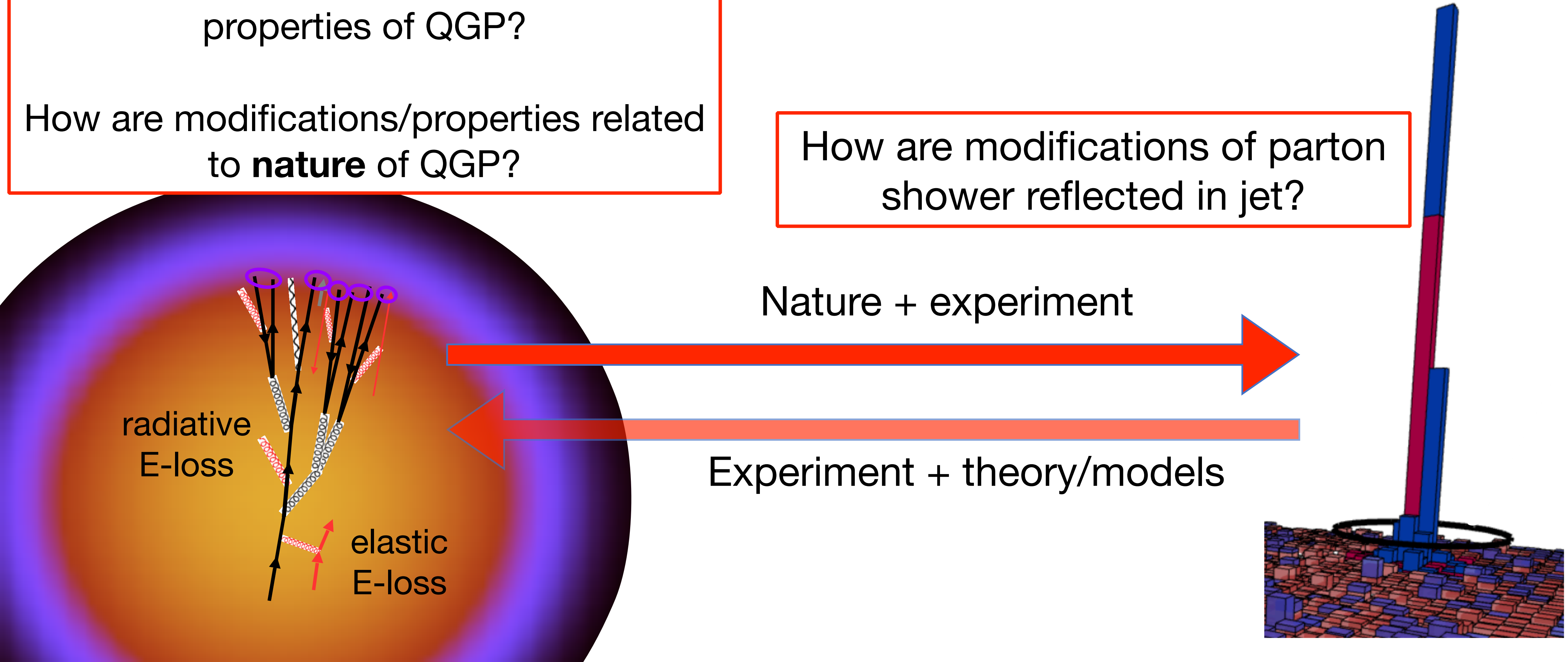
From parton shower to jet

How is parton shower modified in QGP?

How are modifications related to properties of QGP?

How are modifications/properties related to **nature** of QGP?

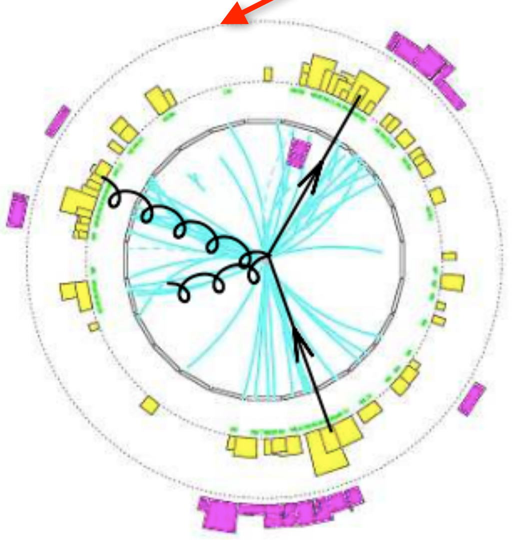
How are modifications of parton shower reflected in jet?



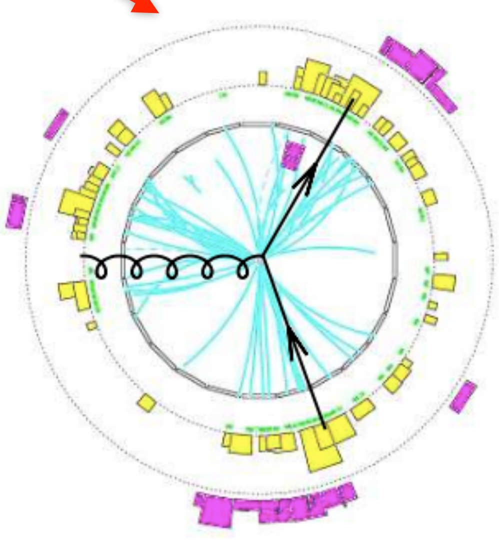
From parton shower to jet: What is a jet?

Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

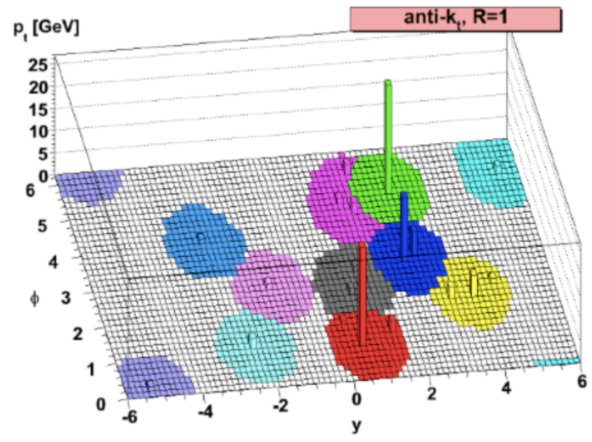
Same pp collision event



or



from Gavin Salam



Need to define algorithm (e.g., anti-k_T) and parameters (i.e., "radius" R)

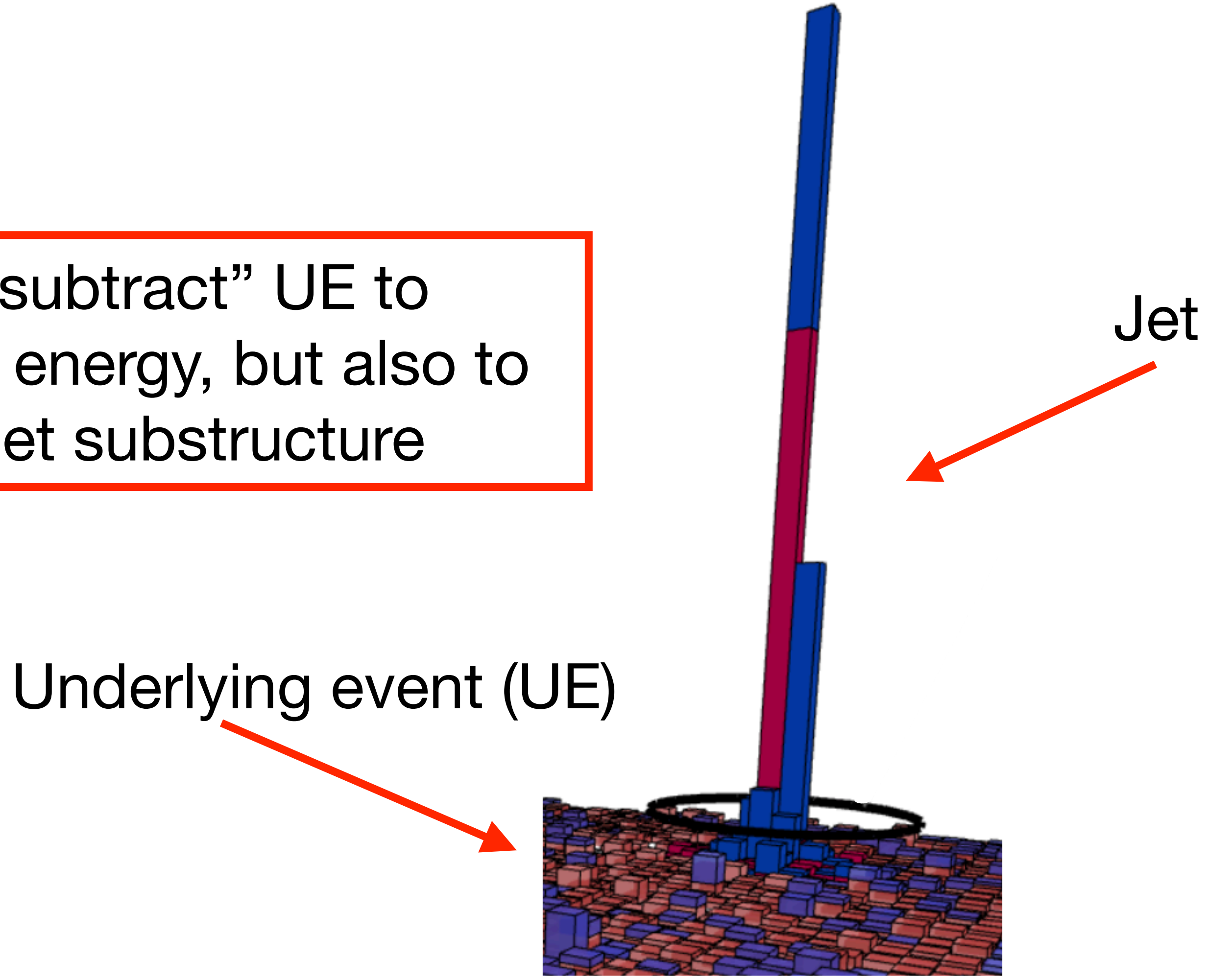
2008: Fastjet revolution

"anti-k_T" became algorithm of choicee:

- conceptually simple
- theoretically sound
  - infrared safe
  - collinear safe
- computationally efficient & robust
- part of Fastjet package

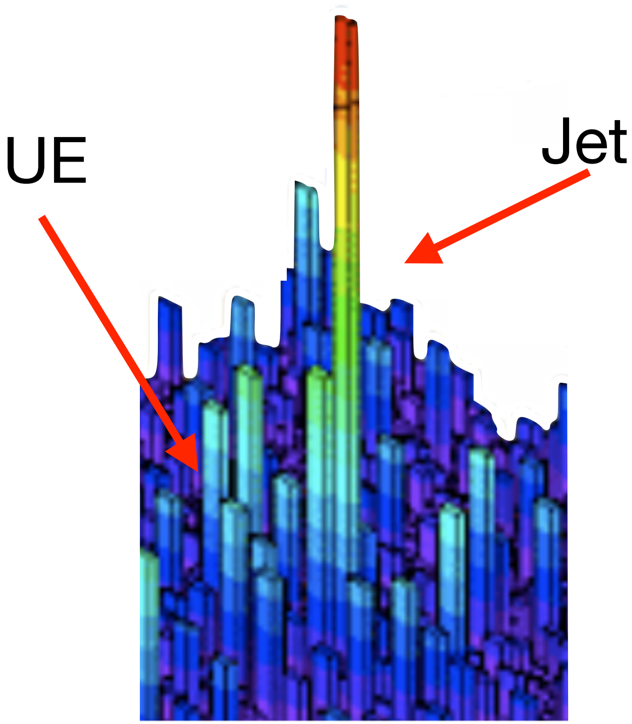
What is a jet in a heavy-ion collision?

Need to “subtract” UE to determine jet energy, but also to examine jet substructure



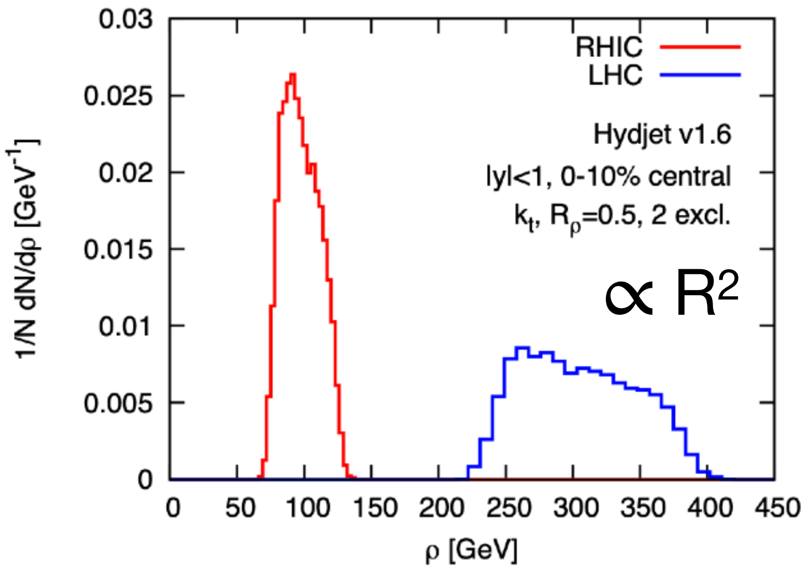
n.b., CMS jet energy correction corrects to E(jet + UE_{pp})

What is a jet in a heavy-ion collision?



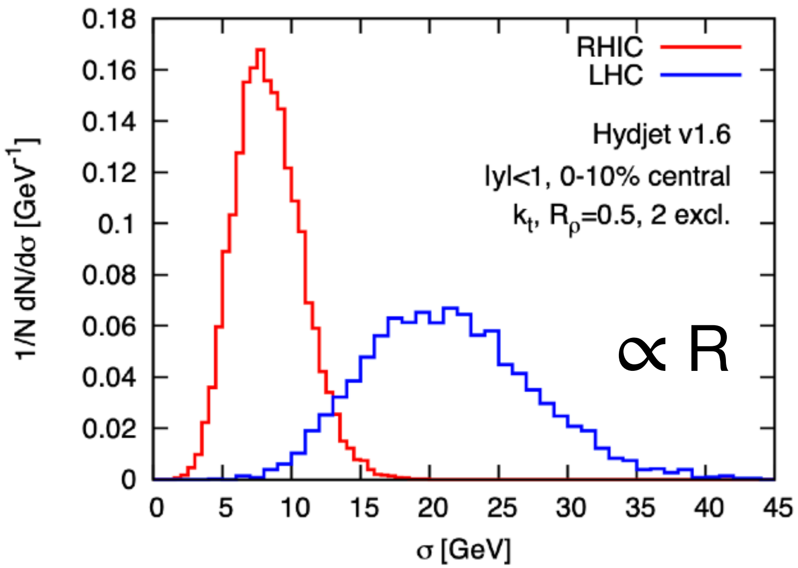
UE subtraction non-trivial for low p_T jets and/or large R

UE energy/area

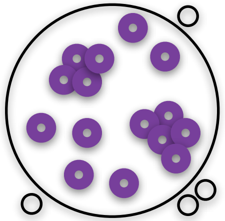


UE fluctuations

Cacciari, Rojo, Salam, Soyez (2010)



- Statistical UE subtraction
  - Correct jet p_T for $\langle \rho \rangle$
  - Unfold distributions for σ
  - Constituent based corrections for substructure measurements
  - **Individual jets: irreducible smearing of jet-by-jet structure**

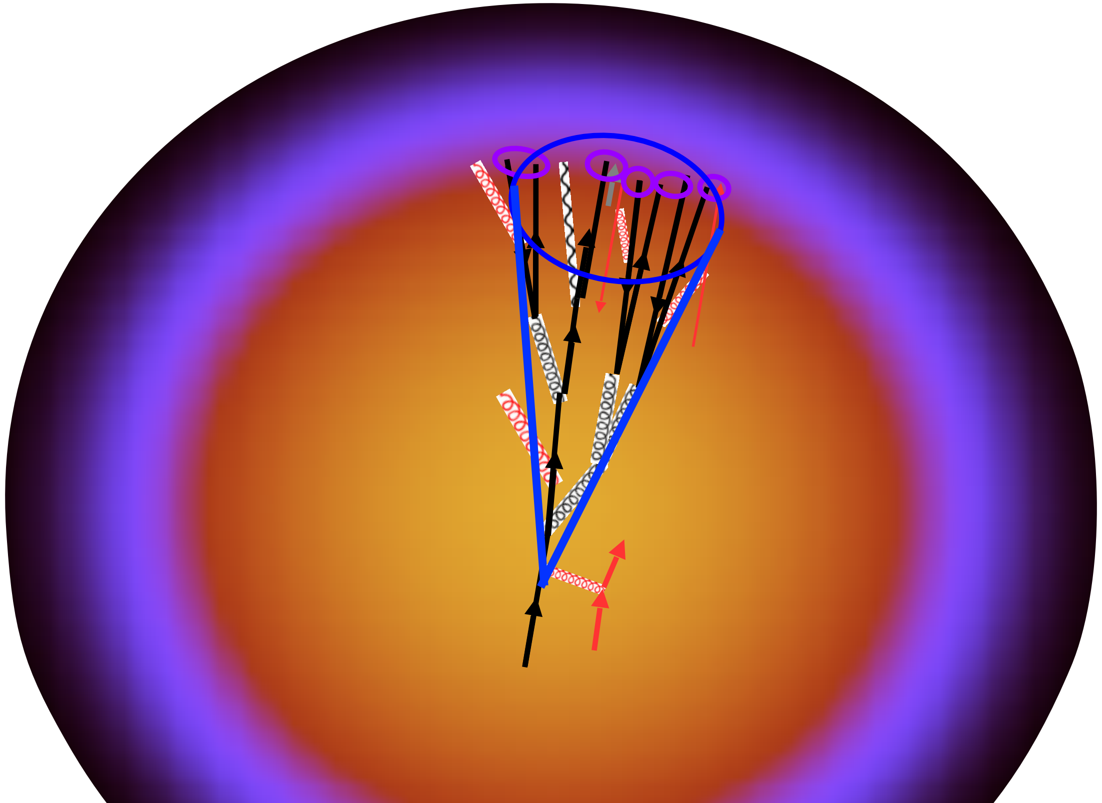


What is a jet in a heavy-ion collision?

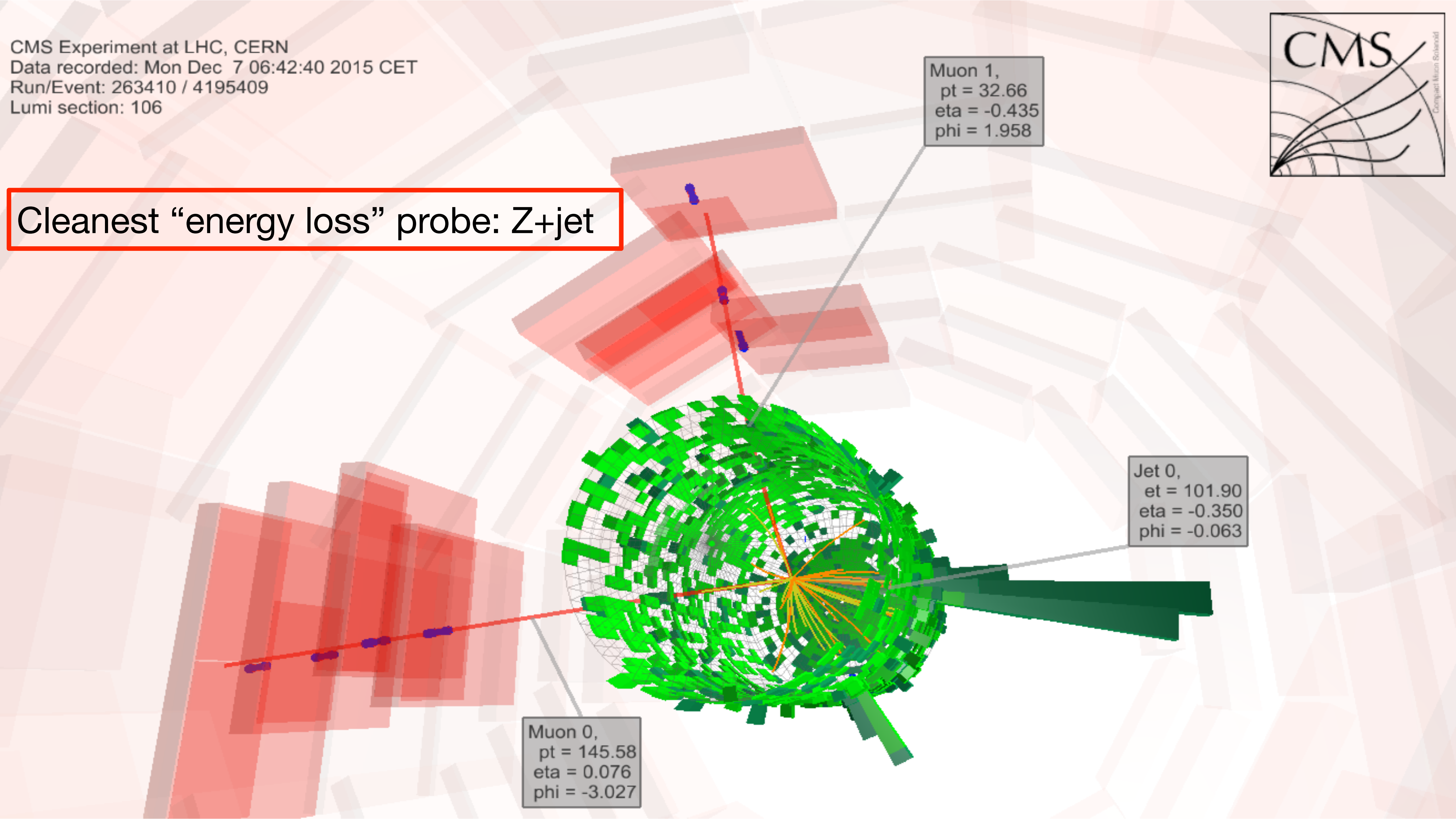
- Operational definition of jets assumes separability of jet and UE
  - Trivially true for high pileup pp collisions (source of many of our techniques)
- HI challenge:
  - Nature gives us jets in medium, but we measure jets on top of medium

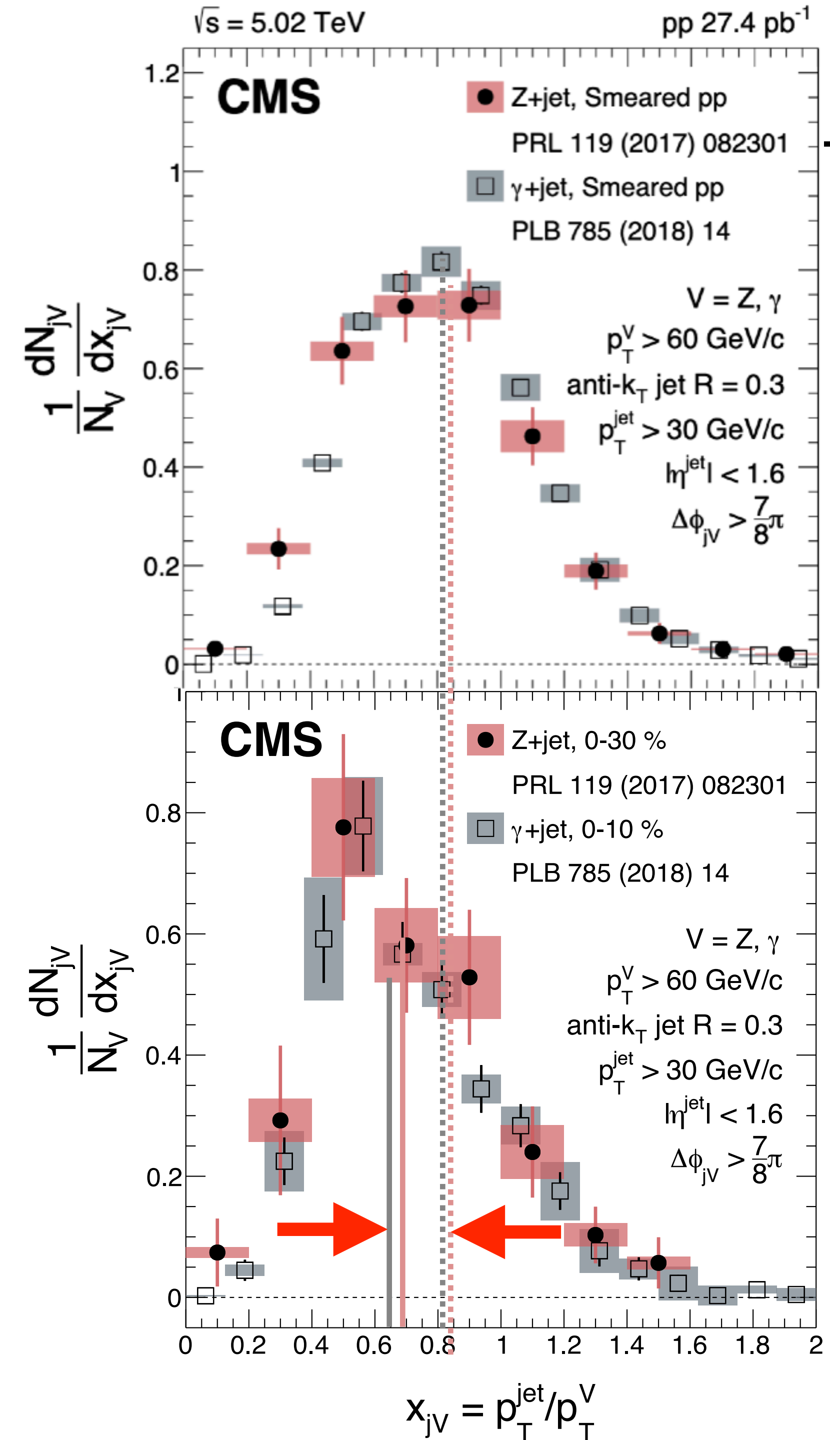
How much energy do jets lose in QGP?

“Energy loss” out-of-cone



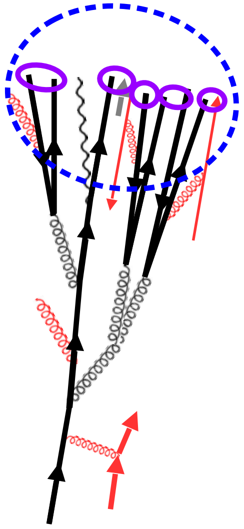
Cleanest “energy loss” probe: Z+jet



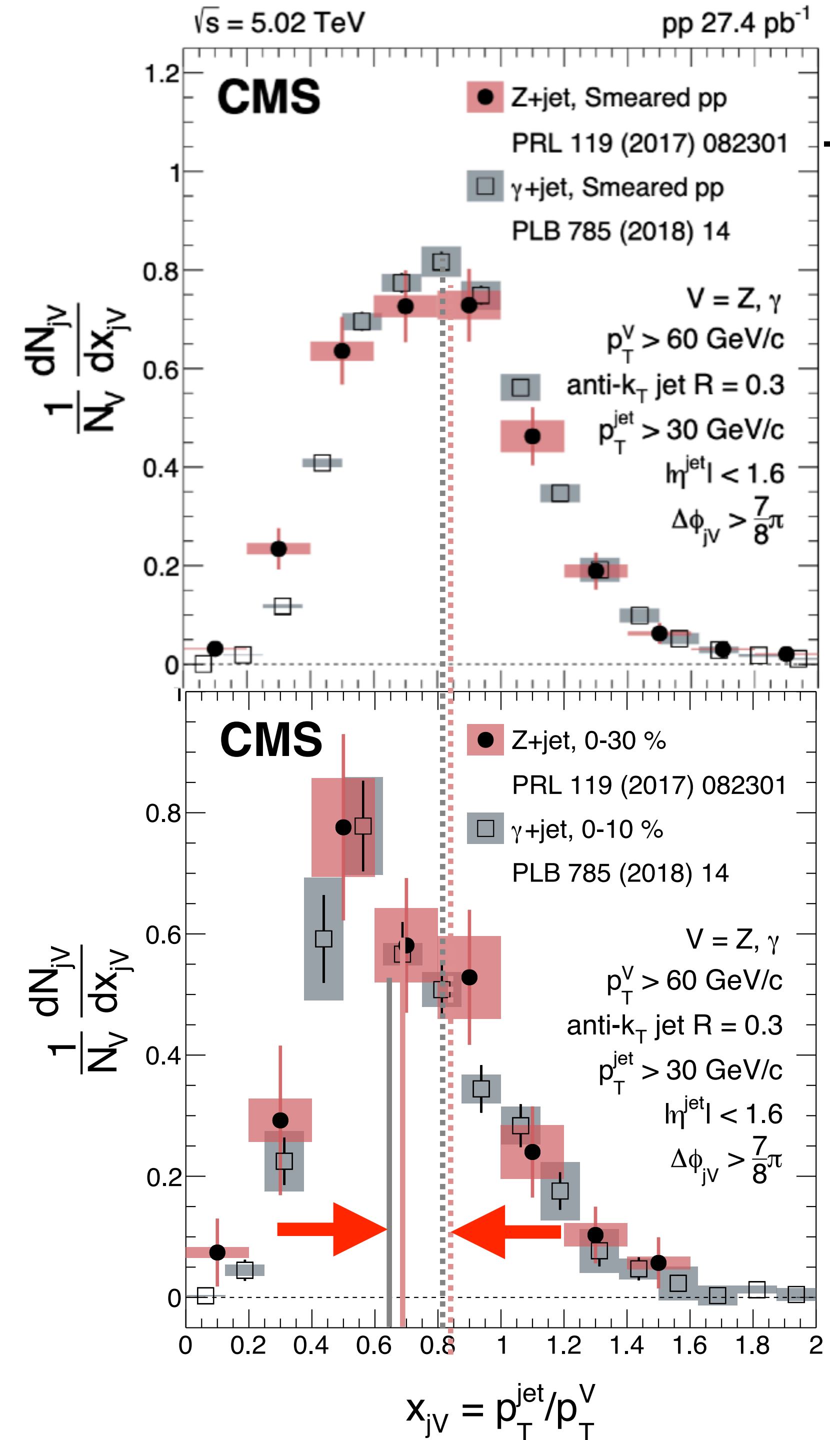


Z(γ) + jet correlations

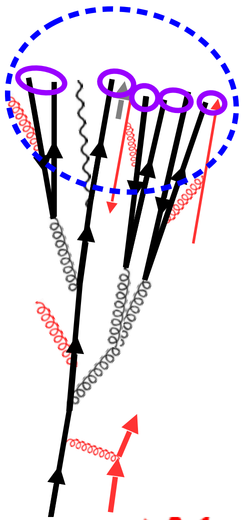
- Observe shift in Z(γ)-jet p_T ratio from pp to PbPb
- Shift in jet energy by 10-15%

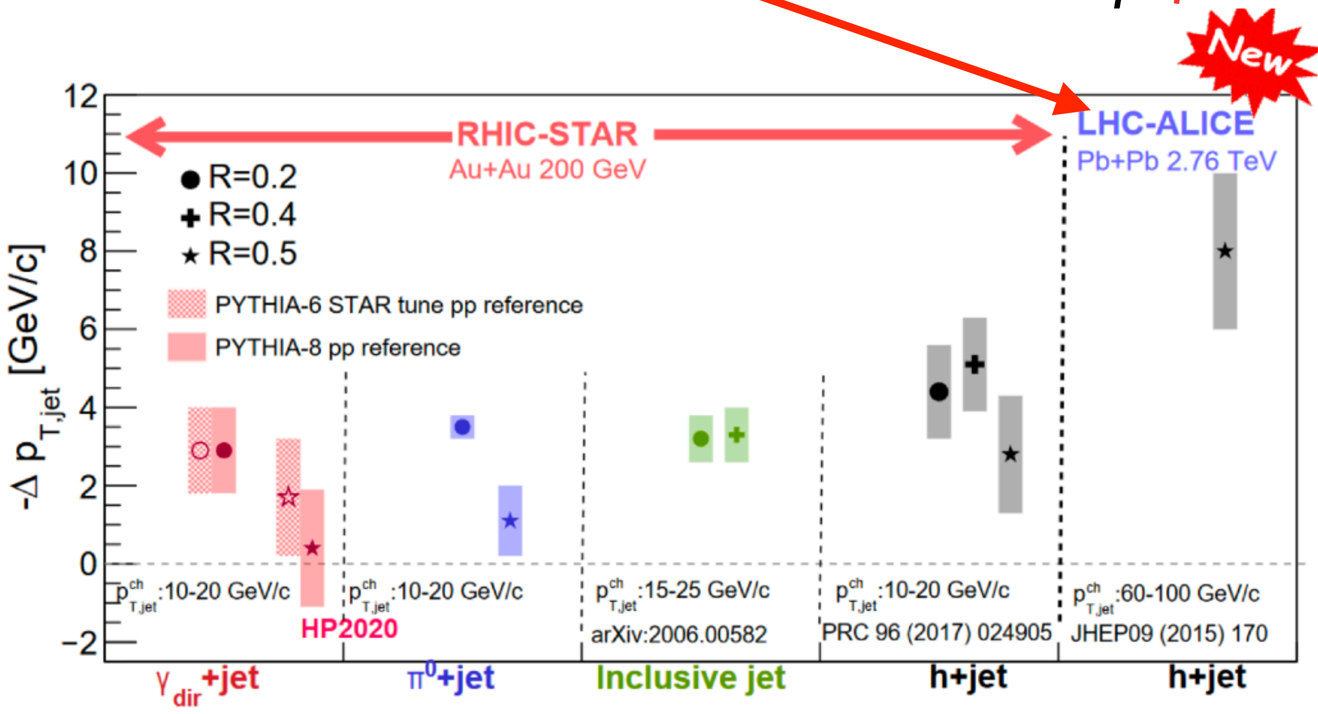


Z(γ) + jet correlations



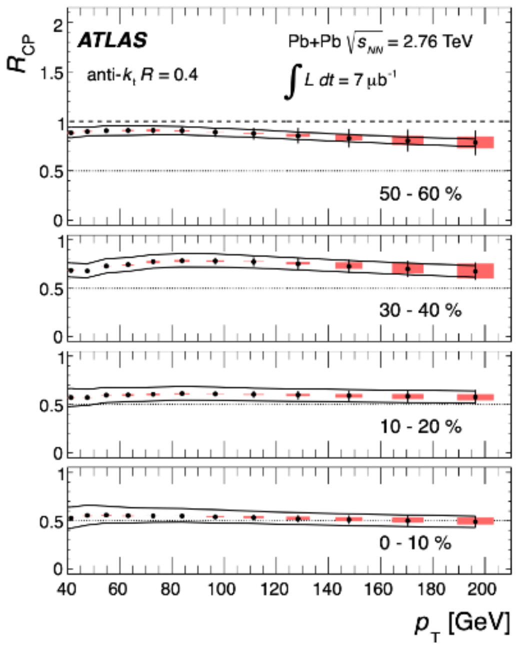
- Observe shift in Z(γ)-jet p_T ratio from pp to PbPb
- Shift in jet energy by 10-15%
- Broadly consistent with ALICE h+jet correlations





Another old friend: jet R_{aa} (ok, R_{CP})

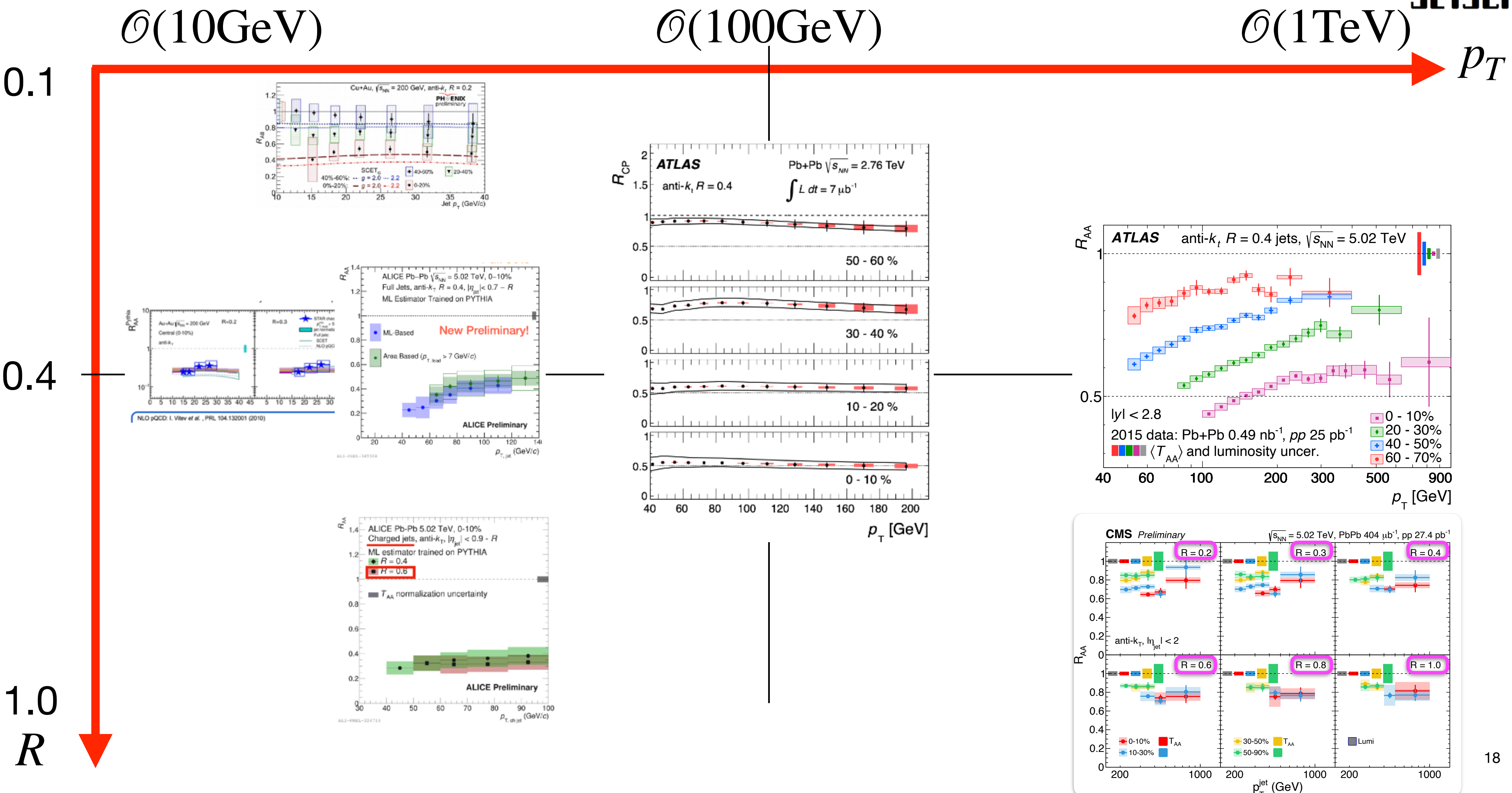
ATLAS (2012)



R_{CP} not as bad for jets as for charged hadrons, selection bias for peripheral collisions, but still…

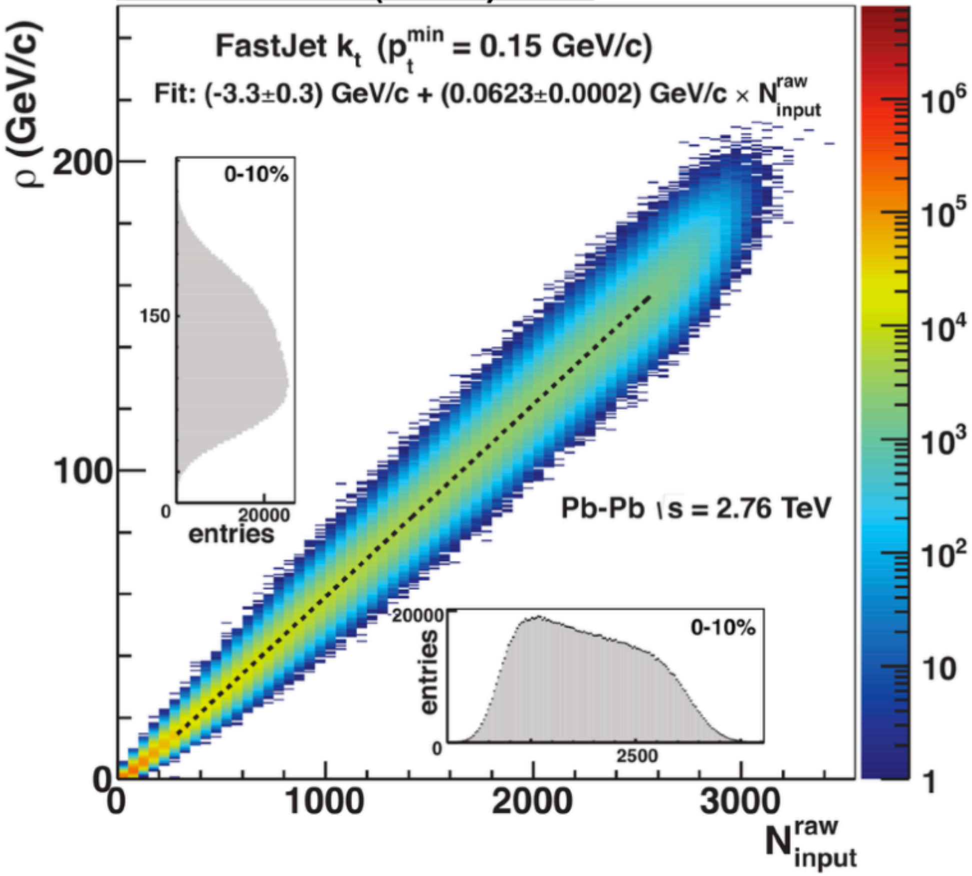
Jet yields in central PbPb suppressed by ~constant factor of 2

Pushing towards low p_T, large R



Low p_T jets at LHC

JHEP 1203 (2012) 053



Challenge for low p_T jets results from large UE fluctuations

- Can produce "fake" jets
- Loss of control over JES

Limits inclusive jets to $p_T \gtrsim$ 60GeV

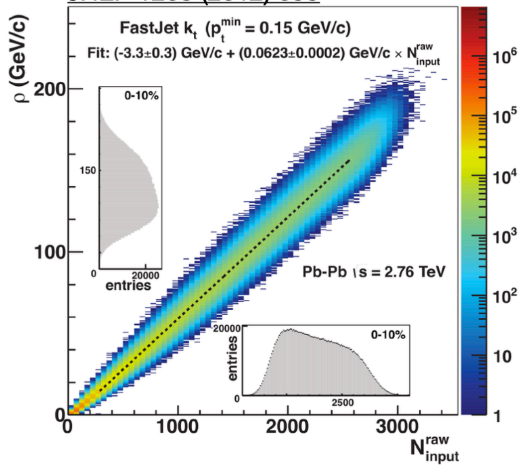
Limits tagged jets (e.g., γ + jet) to $p_T \gtrsim$ 25GeV

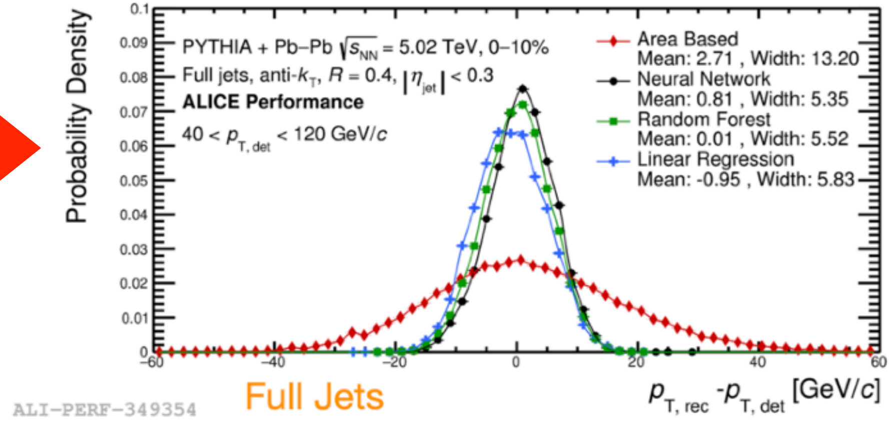
Remedies:

- Small R (physics compromise)
- Require high p_T constituent (bias)

Low p_T jets at LHC: p_T estimation using ML

JHEP 1203 (2012) 053





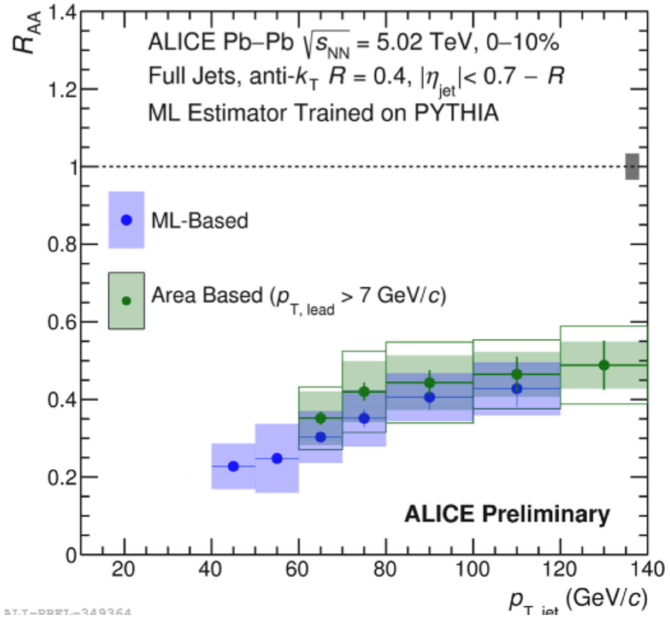
The novel background estimator introduced in this paper follows a different approach. Instead of calculating the background once for an event, the background correction is applied completely on a jet-by-jet basis. The main idea behind this is that the properties of background particles and those belonging to the jet process are very different. While the background is dominated by low-p_T particles, the jet signal should contain sizable higher momentum contributions. The

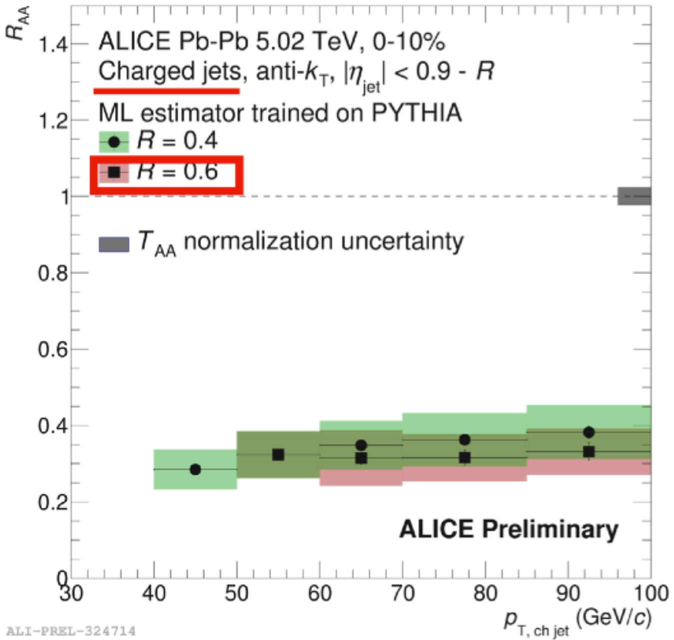
- Use ML estimator, trained on PYTHIA + UE, to determine jet energy (vs. "area-based" UE subtraction)
- Uses a set of jet-by-jet features as input to ANN
- Significantly improved momentum estimation on (PYTHIA+UE) test sample

TABLE II. Random forest feature importances. A higher score corresponds to a higher importance of the feature. $p^i_{T,\,const}$ is the transverse momentum of the ith-hardest particles. The four most important features are marked in bold face.

Feature	Score	Feature	Score
Jet p_T (no corr.)	**0.1355**	$p^1_{T,\,const}$	0.0012
Jet mass	0.0007	$p^2_{T,\,const}$	**0.0039**
Jet area	0.0005	$p^3_{T,\,const}$	0.0015
Jet p_T (area-based corr.)	**0.7876**	$p^4_{T,\,const}$	0.0011
LeSub	0.0004	$p^5_{T,\,const}$	0.0009
Radial moment	0.0005	$p^6_{T,\,const}$	0.0009
Momentum dispersion	0.0007	$p^7_{T,\,const}$	0.0008
Number of constituents	0.0008	$p^8_{T,\,const}$	0.0007
Mean of const. p_T	**0.0585**	$p^9_{T,\,const}$	0.0006
Median of const. p_T	0.0023	$p^{10}_{T,\,const}$	0.0007

Low p_T jets at LHC: p_T estimation using ML

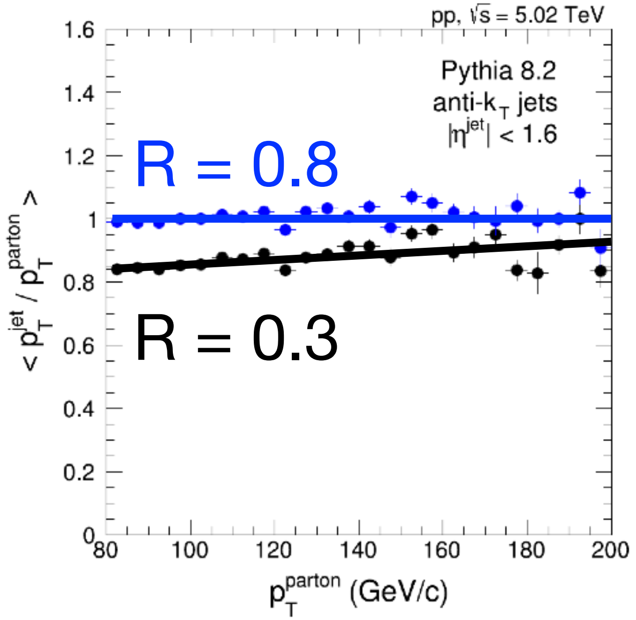




- Allows significant extension of p_T range, large R ≈ 0.6
  - n.b., charged jet $p_T \neq$ full jet p_T
- Caveats:
  - PYTHIA fragmentation barely describes pp; PbPb further modified (some studies shown, but more work needed)
  - How does this work? UE fluctuations are real.
  - My interpretation:
    - Improvement possible by overweighting core high S/B region at expense of low S/B periphery
    - Reduced sensitivity to UE noise, but also jet modifications
    - Different jet definition vs HI definition of “jets on top of UE”
    - Need to be very careful when going beyond inclusive jets
- Promising direction, but handle with care!

Large R jets at LHC

from Kaya Tatar



Fraction of energy captured increases vs R

(n.b., would not matter for R_{AA} if fragmentation unmodified)

$$-\pi < \phi < \pi$$

$$-2.5 < \eta < 2.5$$

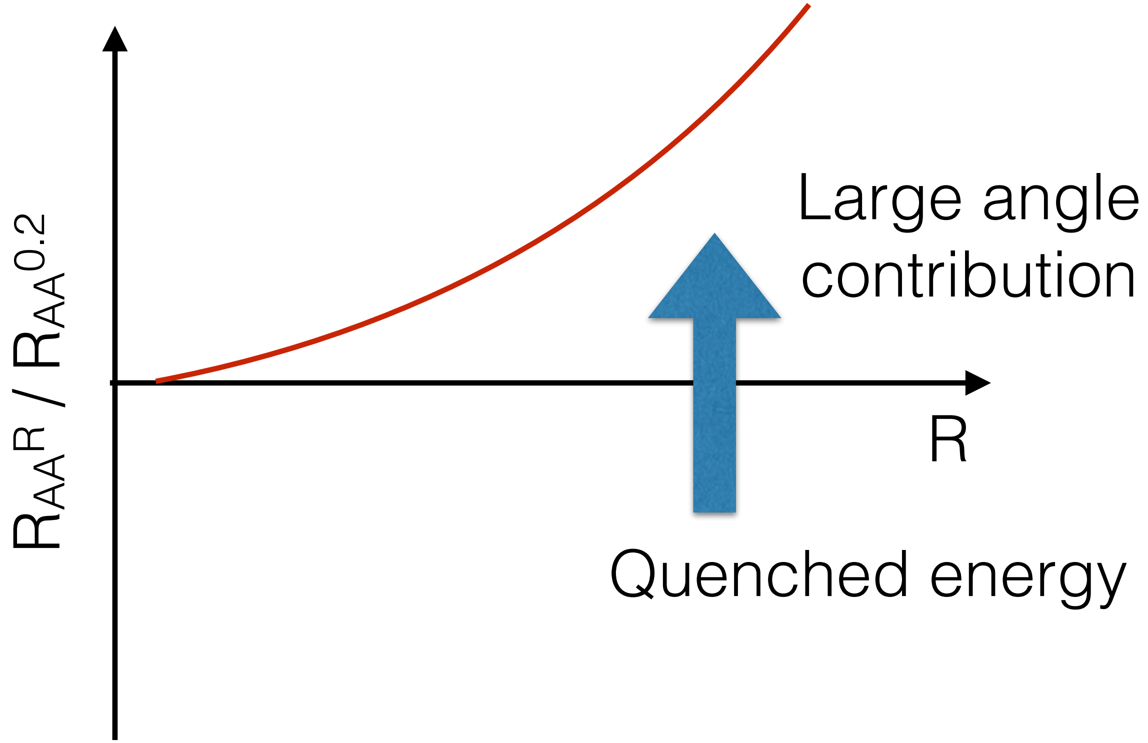
Large: R = 1

Small: R=0.2

Jet clustering provides excess energy over UE in $\mathcal{O}(\pi R^2)$ region

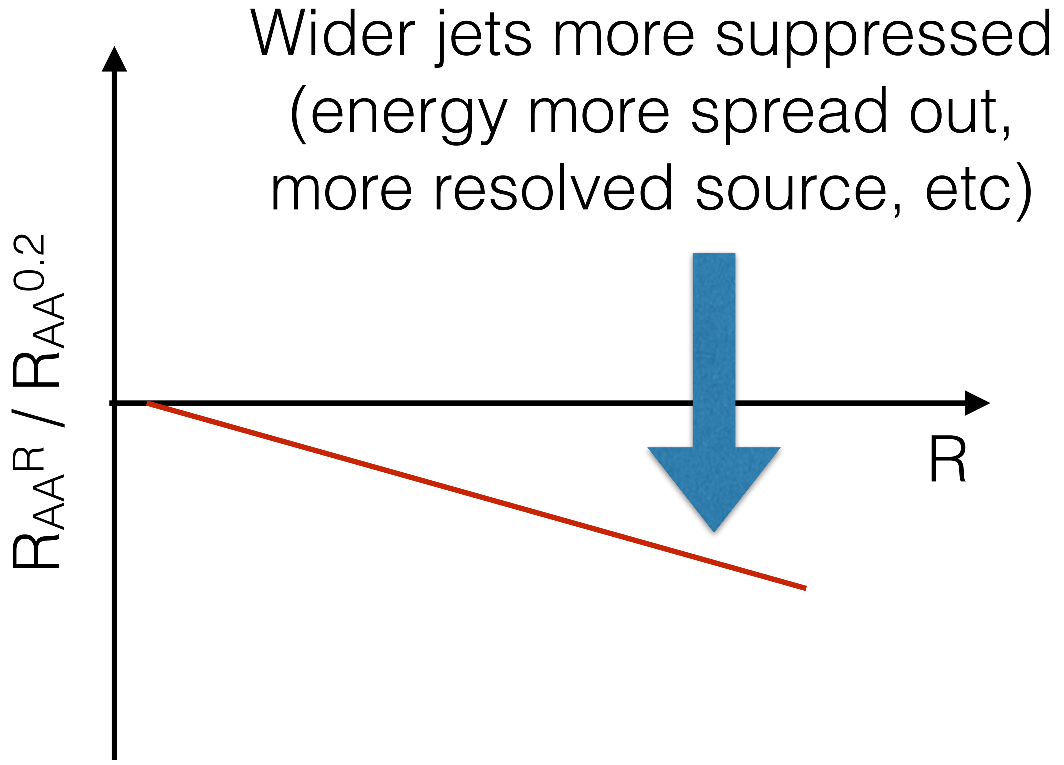
R-dependence: Balance of competing effects

R-dependence: Balance of competing effects



from Yi Chen

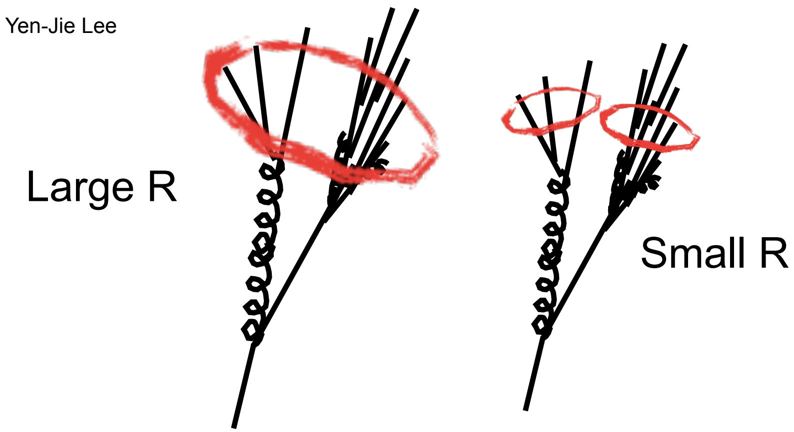
R-dependence: Balance of competing effects



from Yi Chen

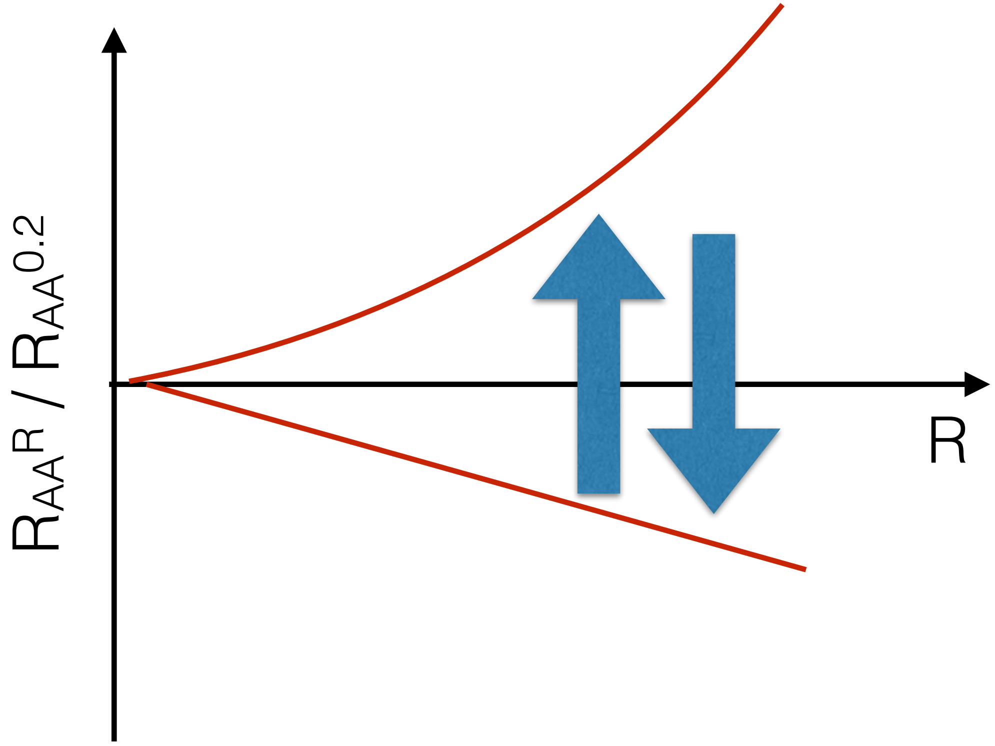
R-dependence: Balance of competing effects

from Yen-Jie Lee



But also: different jet populations!

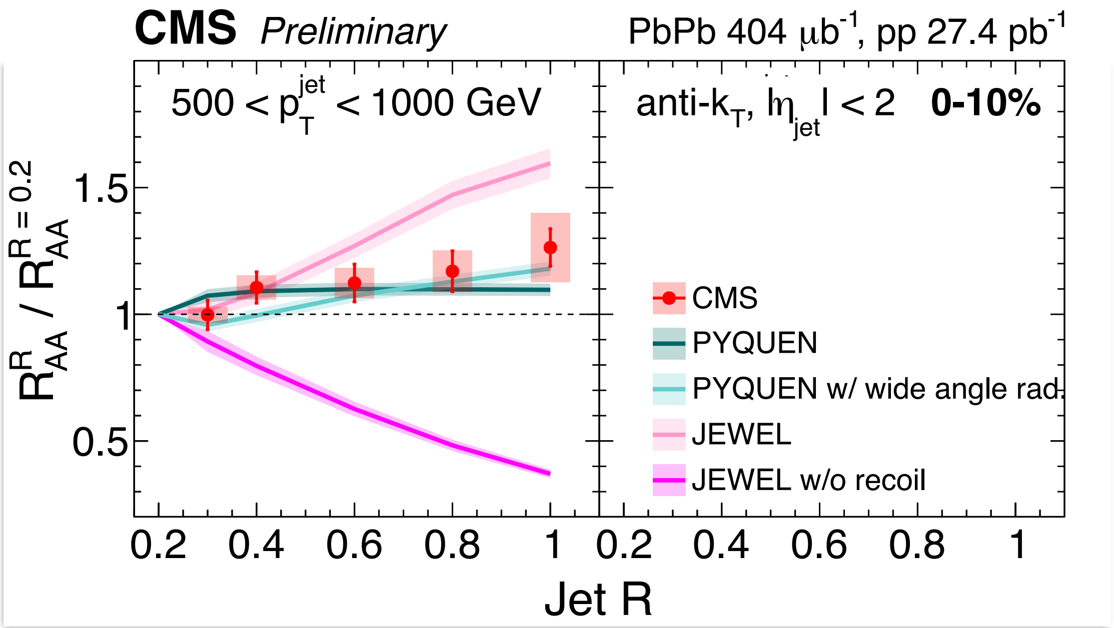
not every R=0.2 jet is found as R=1 jet and vice versa

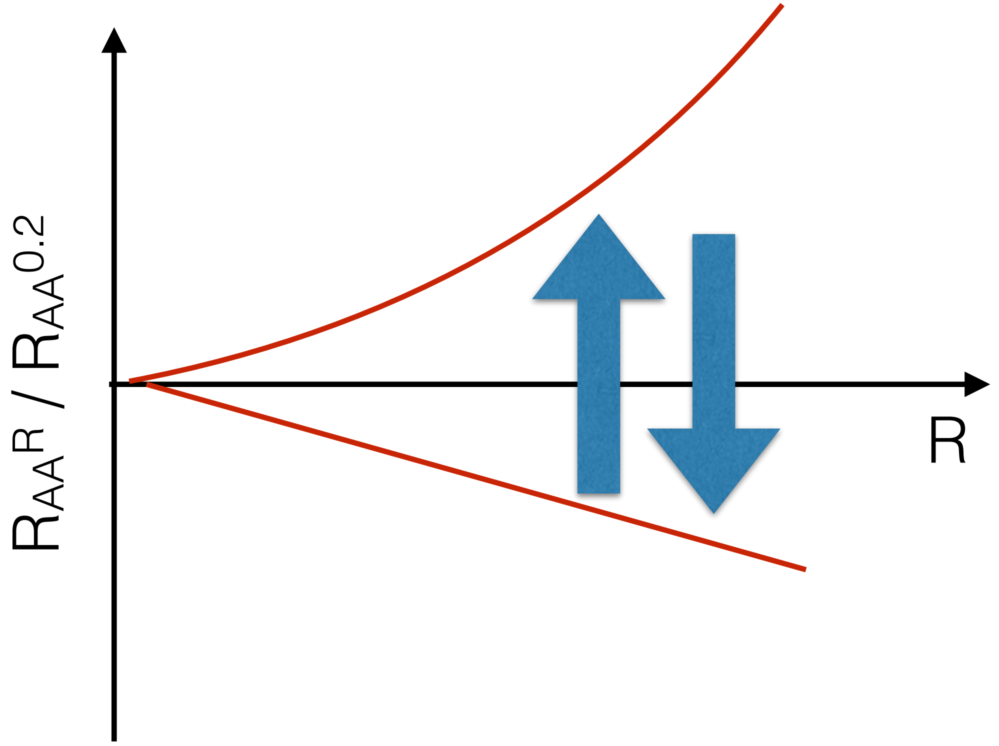


To describe R dependence, models need to get many aspects of jet modifications ~ right

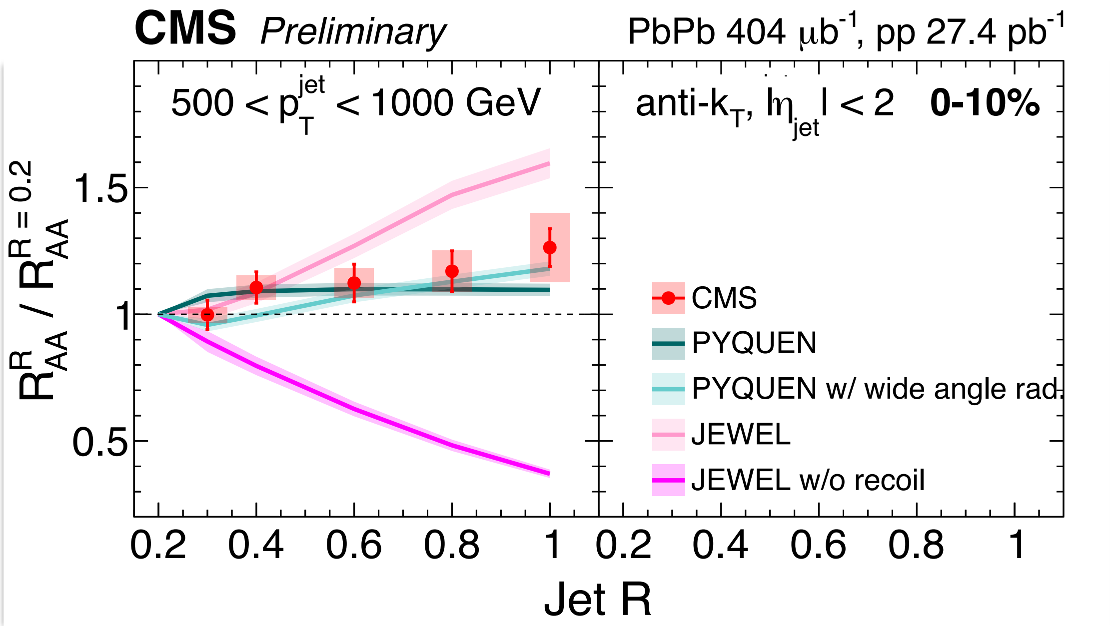
from Yi Chen

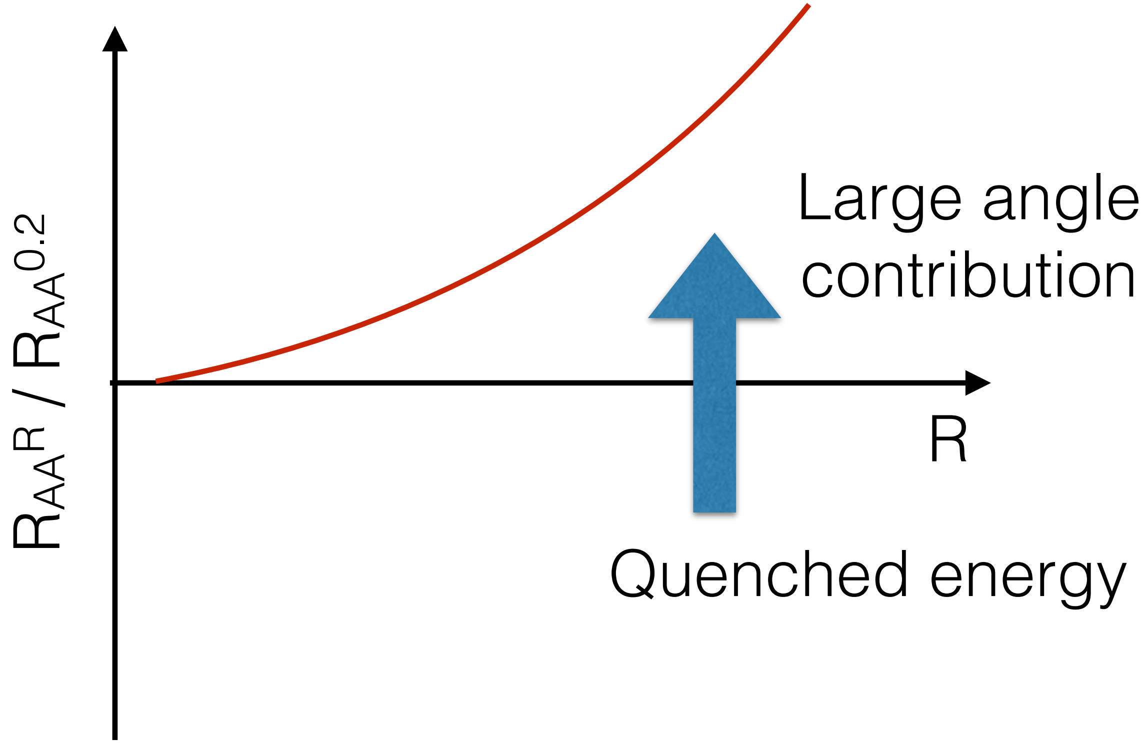
R-dependence: Balance of competing effects





R-dependence: Balance of competing effects

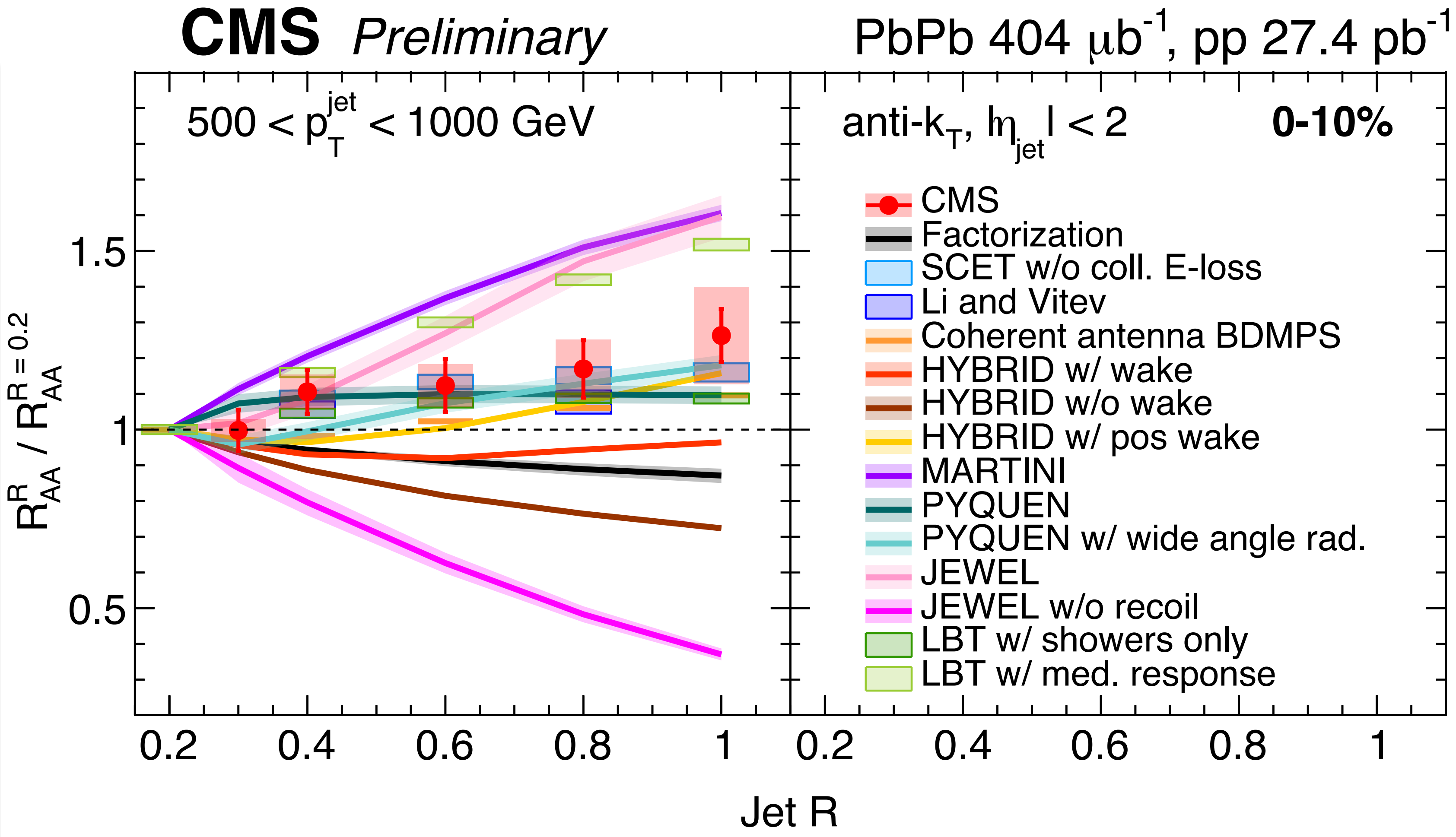




Mild increase of R_{AA} with increasing R

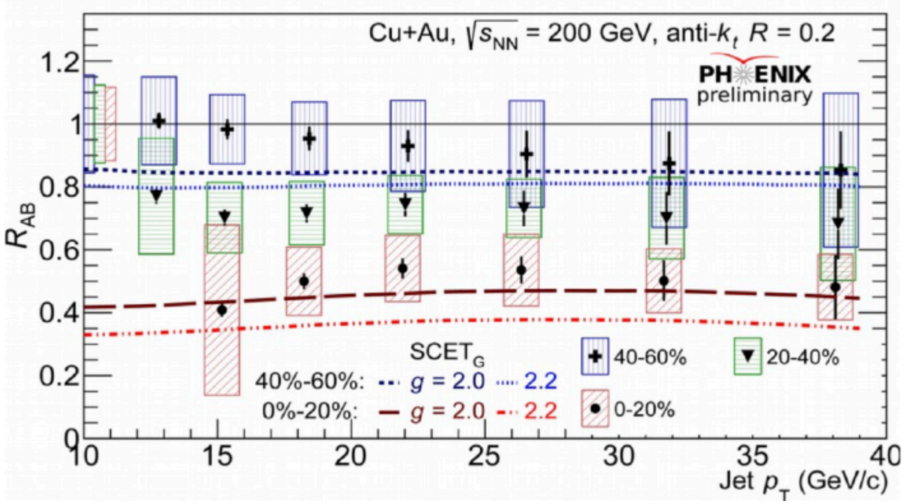
Molly Taylor, Wed.

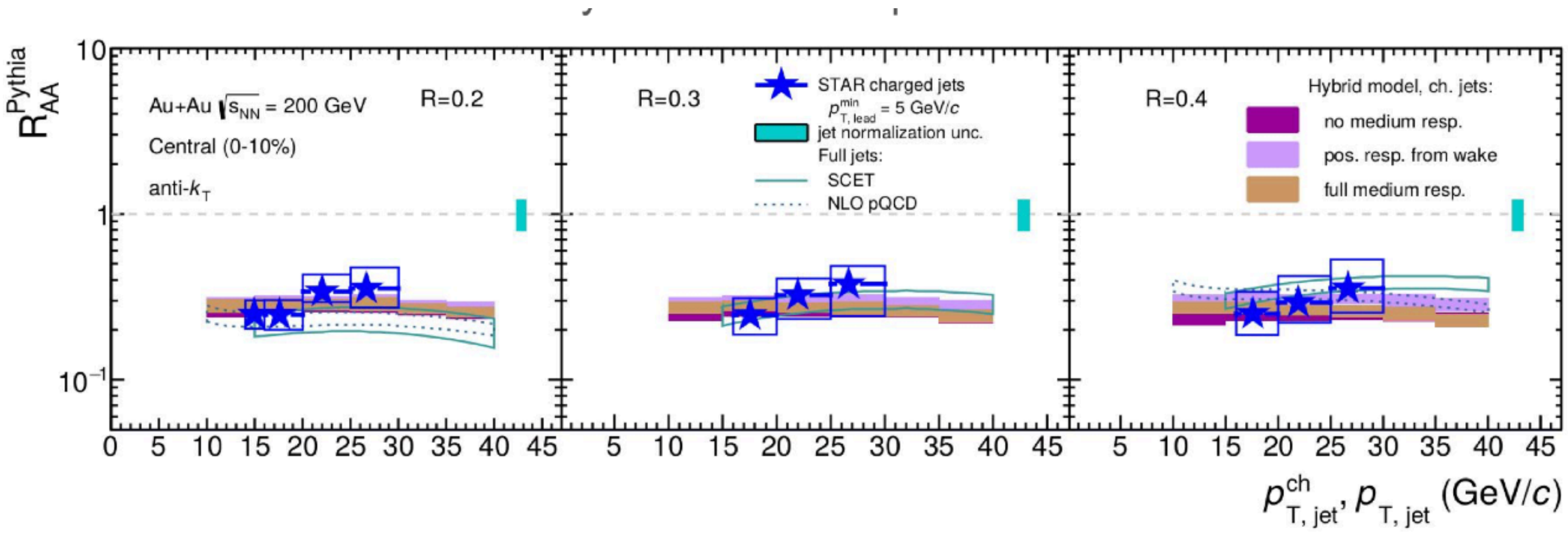
R-dependence



Surprisingly challenging for models
What is the value of comparing at single value of R?

Meanwhile at RHIC





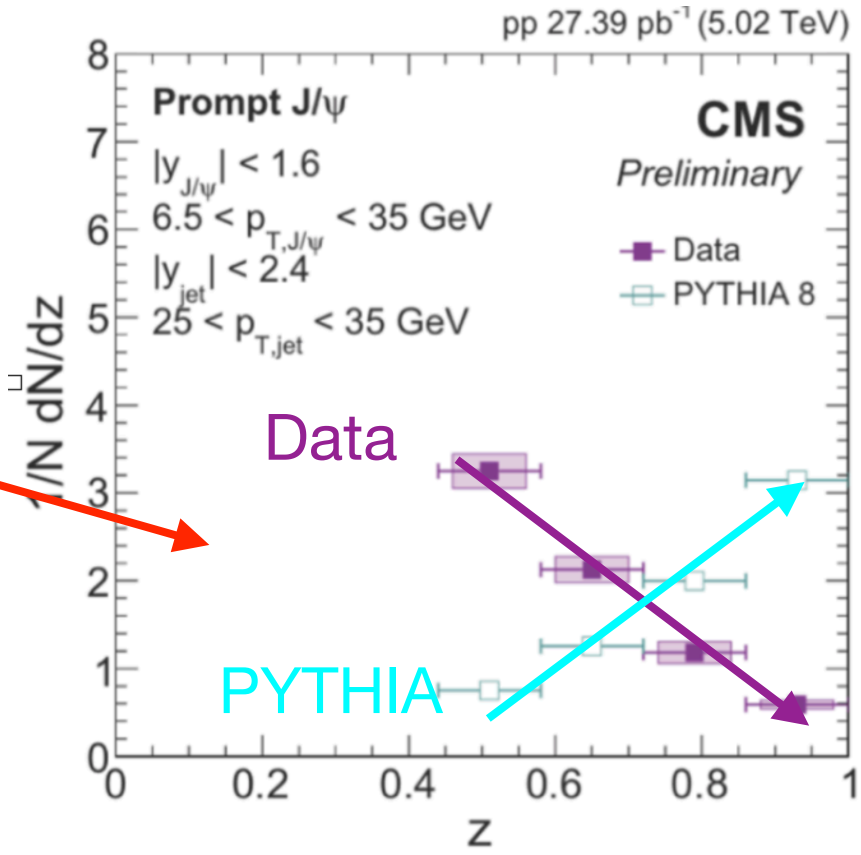
- By necessity, RHIC experiments live in "low p_T" region
  - Control over UE through small R, small systems and/or fragmentation bias requiring hard jet core or high p_T constituent
  - pp statistics remain challenge: R_{CP} or R_{AA}^{PYTHIA}
- Still, recent efforts show results broadly consistent with model predictions and observations at LHC
- Existence proof, demonstrating possibilities at RHIC

PYTHIA as reference (somewhat unfair, I know)

It is important to remember that PYTHIA, when looking at observables or kinematic regions w/o prior constraints from data, can and does get things utterly wrong

In particular, it does not describe fragmentation functions brilliantly in the best of circumstances, and sometimes this happens

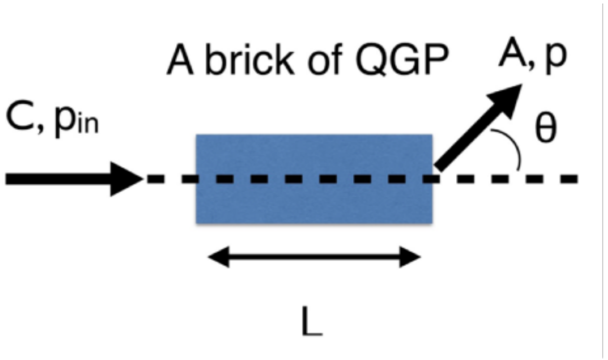
jet $\rightarrow J/\psi$ fragmentation functions in pp (!)

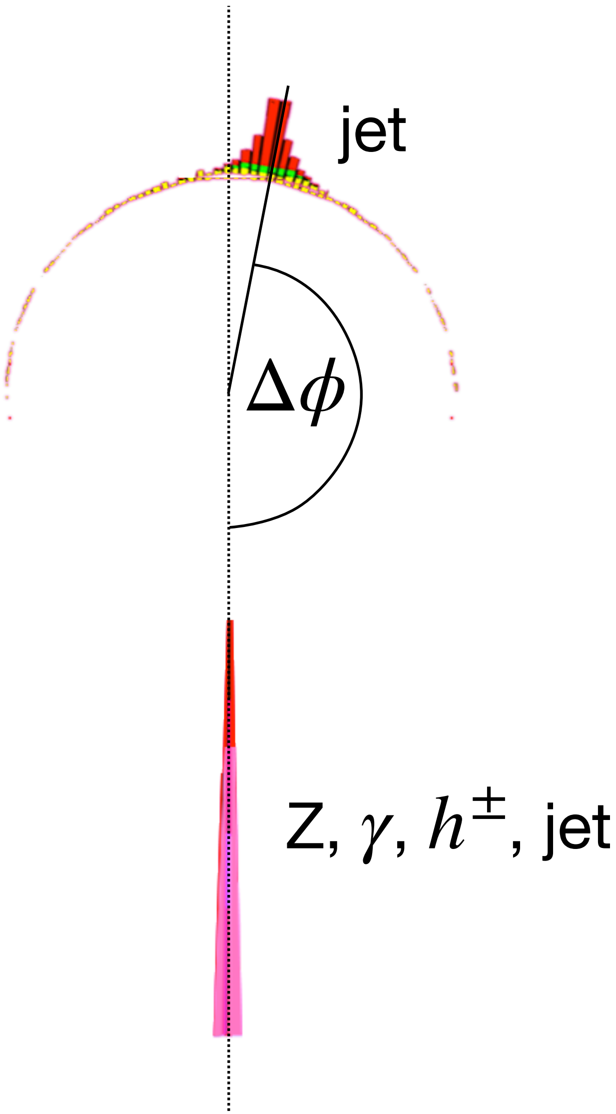


Access QGP structure through jet “Moliere scattering”

Molière Scattering in Quark-Gluon Plasma: Finding Point-Like Scatterers in a Liquid

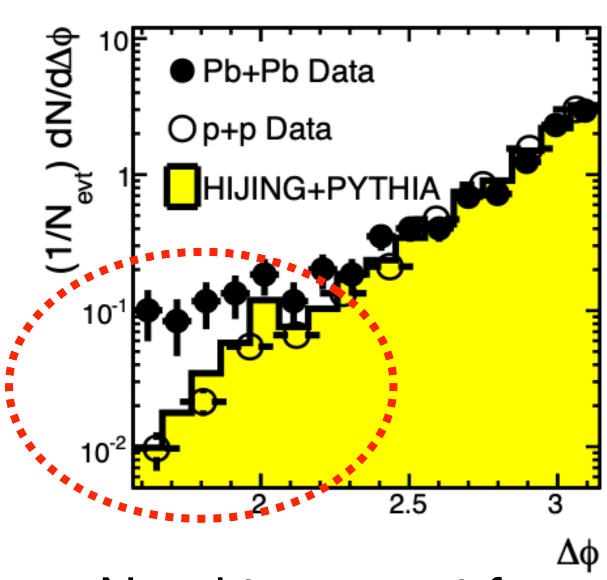
Francesco D'Eramo,[a,b] Krishna Rajagopal,[c] Yi Yin[c]





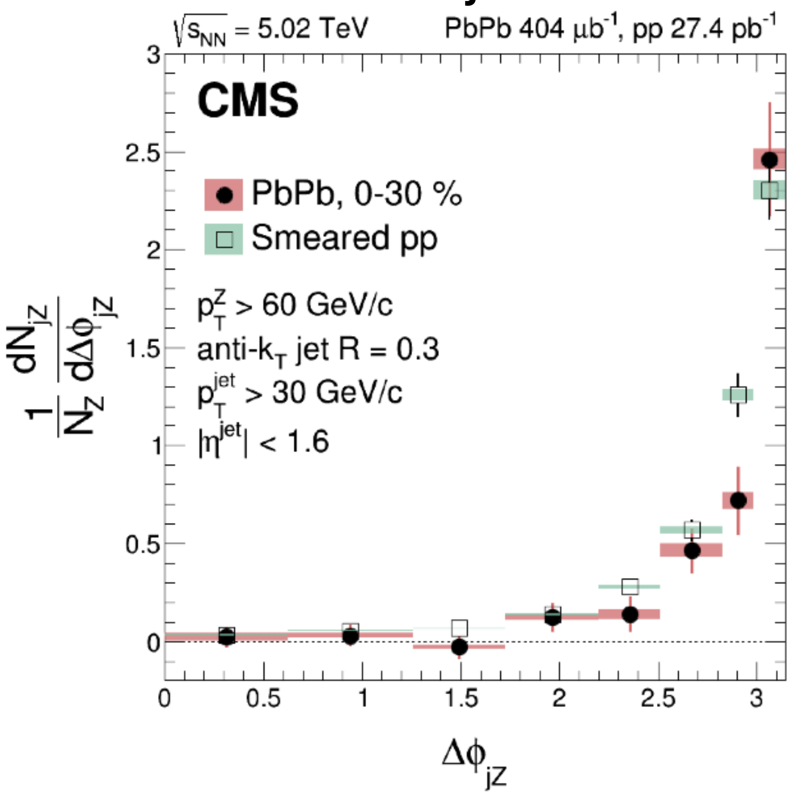
Broadening of back-to-back distributions

Dijet



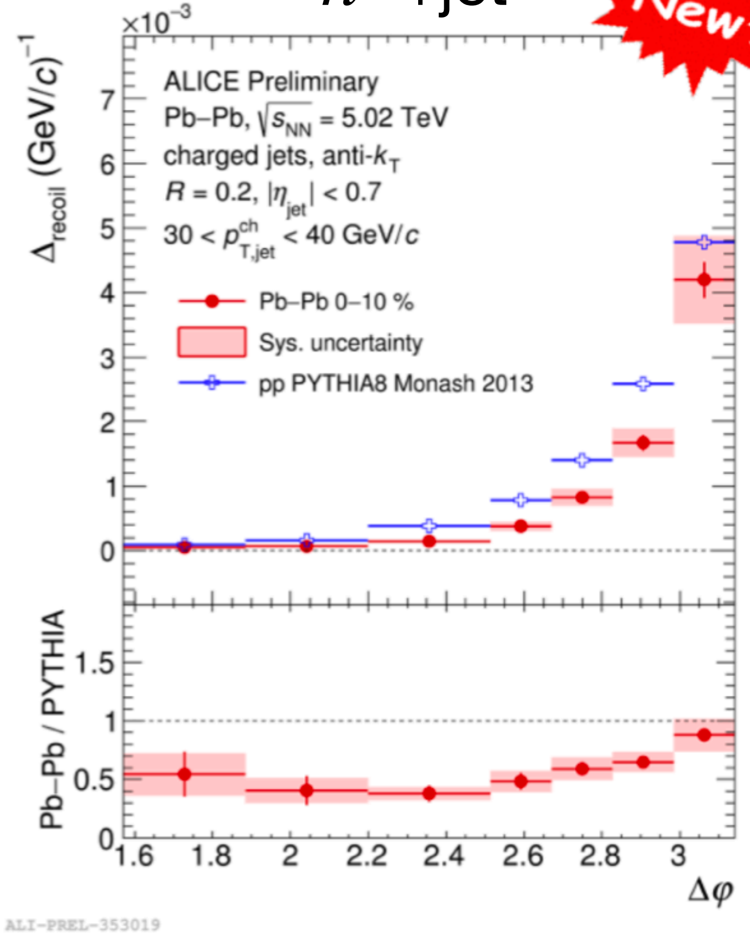
Need to correct for uncorrelated/combinatorial contribution in PbPb

Z+jet



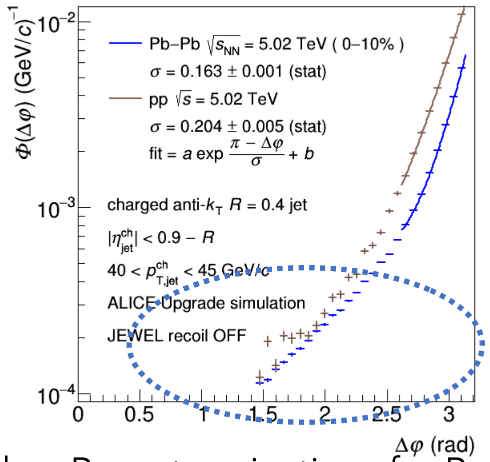
Narrowing in PbPb compared to pp (but $\approx 2\sigma$)

$h^{\pm}$+jet



Narrowing in PbPb compared to pp

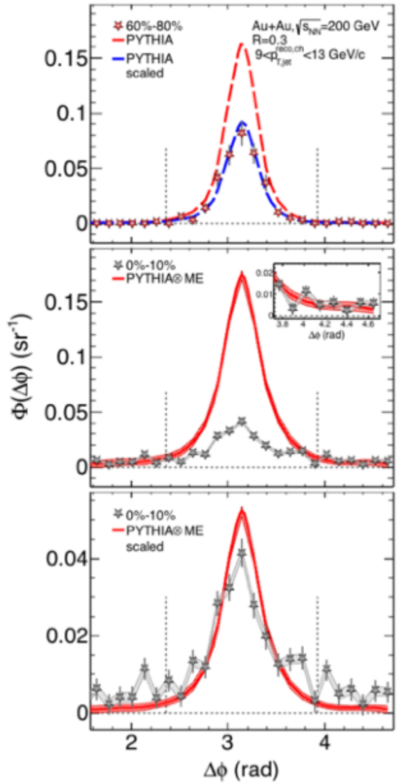
Golden opportunity for RHIC



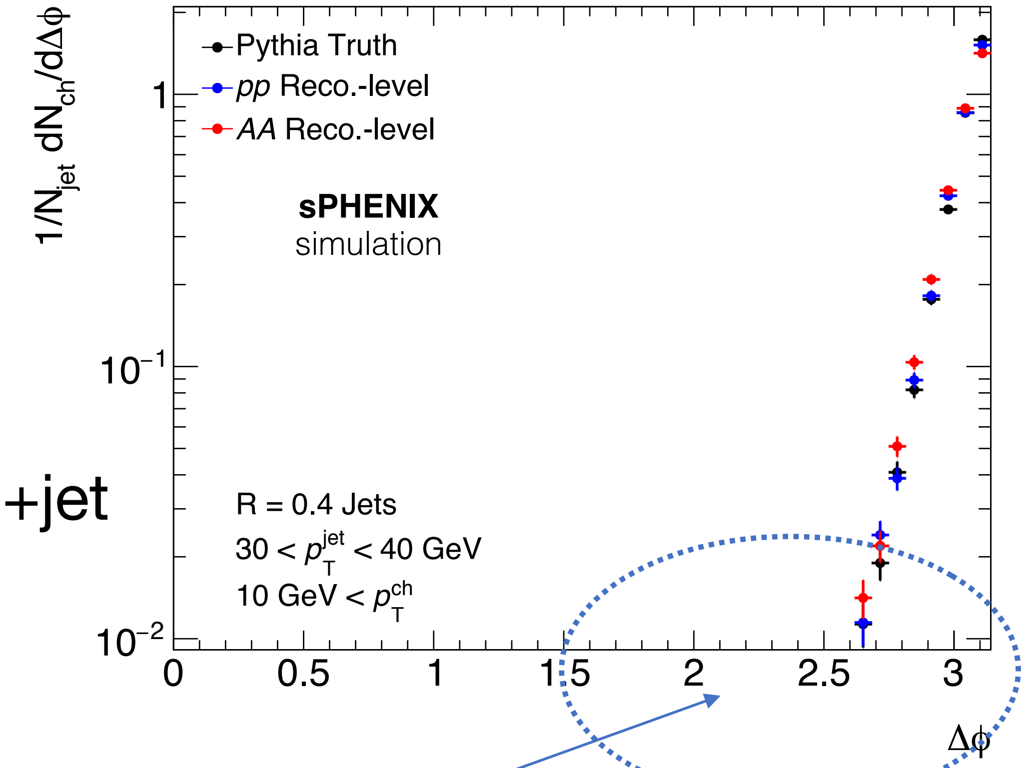
CERN Yellow Report projections for Runs 3, 4

Fig. 31: JEWEL simulation of the angular distribution of charged jet yield in the ALICE acceptance fo $40 < p^{ch}_{T,jet} < 45$ GeV/c and $R = 0.4$ recoiling from a high-p_T reference hadron ($20 < p_{T,trig} < 50$ GeV/c), for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with 10 nb^{-1} int. luminosity, and pp collision at $\sqrt{s} = 5.02$ TeV with 6 pb^{-1} int. luminosity. The recoil jet azimuthal angle $\Delta\varphi$ is defined wit respect to the reference axis. The observable shown is $\Phi(\Delta\varphi)$ which incorporates statistical suppressio of uncorrelated background. Figure from Ref. [1].

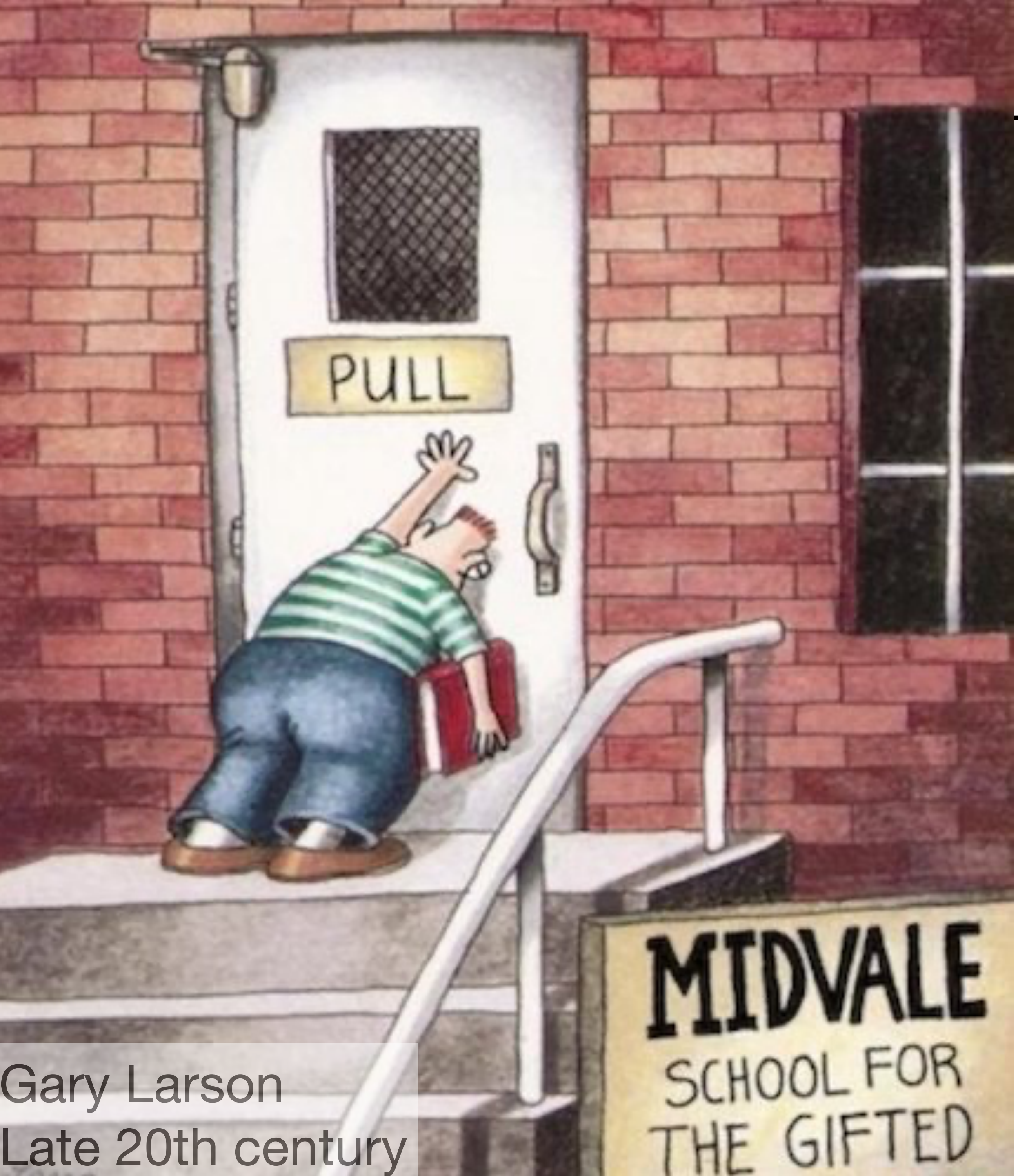
STAR (2017)



$h^{\pm}$+jet

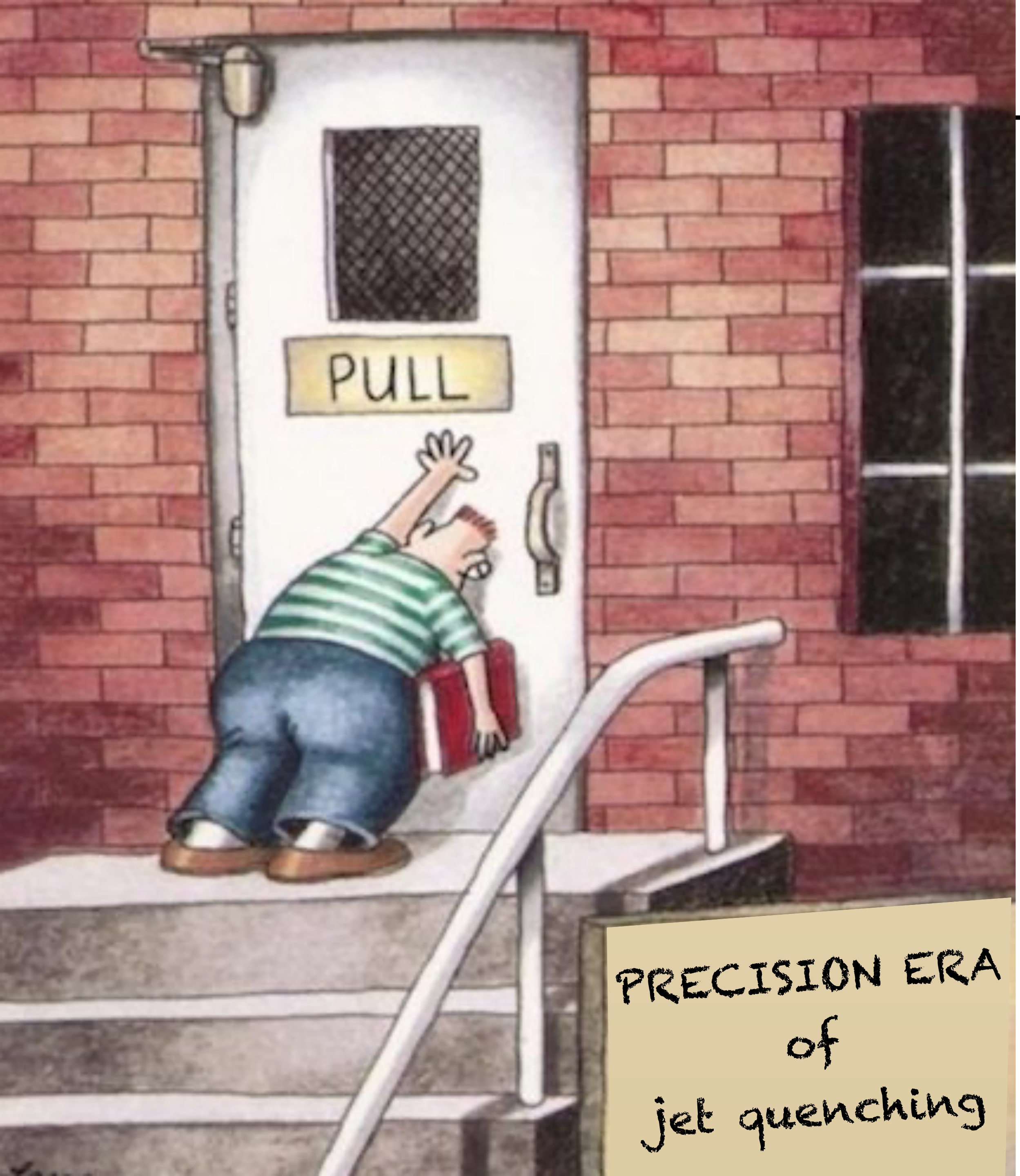


- At comparable jet energies:
    - much smaller contribution from ISR/FSR at RHIC
    - smaller smearing from UE fluctuations
- Also, access to lower p_T jets at RHIC



Gary Larson
Late 20th century

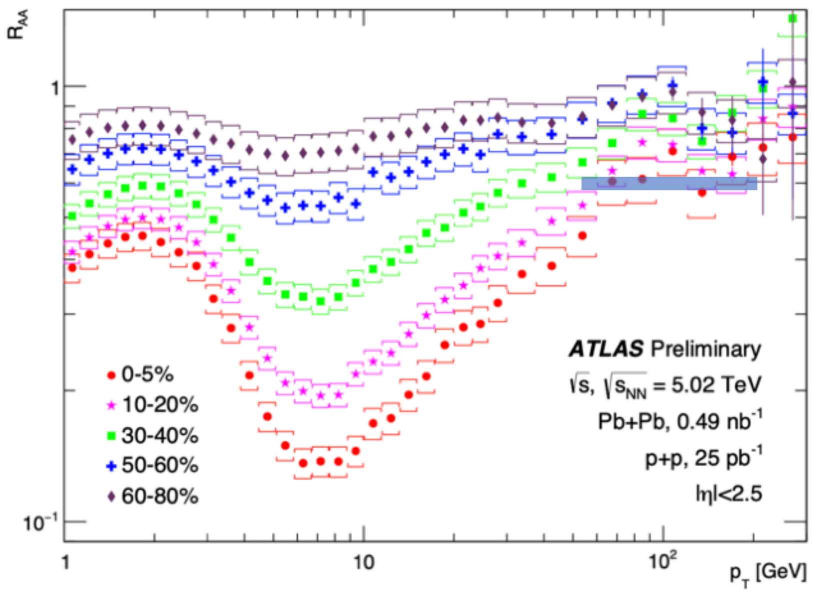
A brief interlude before moving on to constituent based jet measurements…

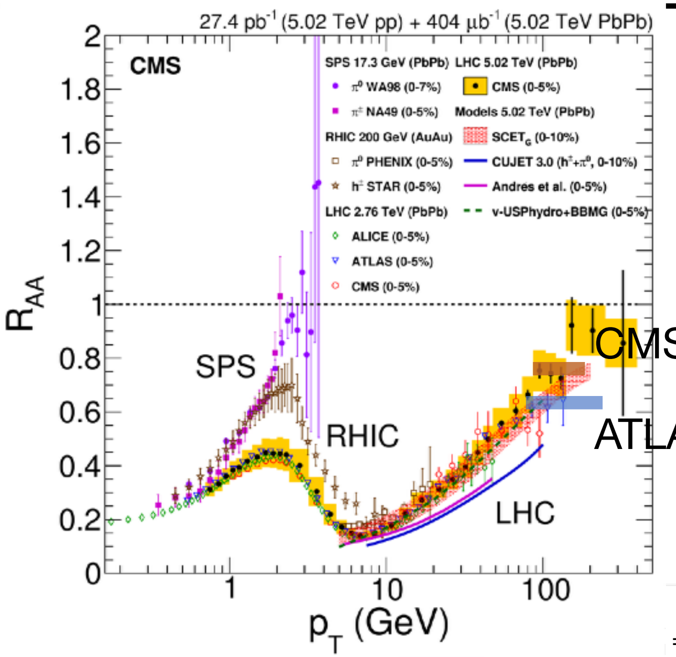


- We have spent the better part of a decade “*entering the precision phase*”
    - go-to phrase for justifying more running/new experiments/more theory resources
- Where do we stand?
- Where should we be going?
- Can we achieve and exploit precision?

n.b. I’m ignoring the distinction between “precision” and “accuracy”, and am really referring to the latter

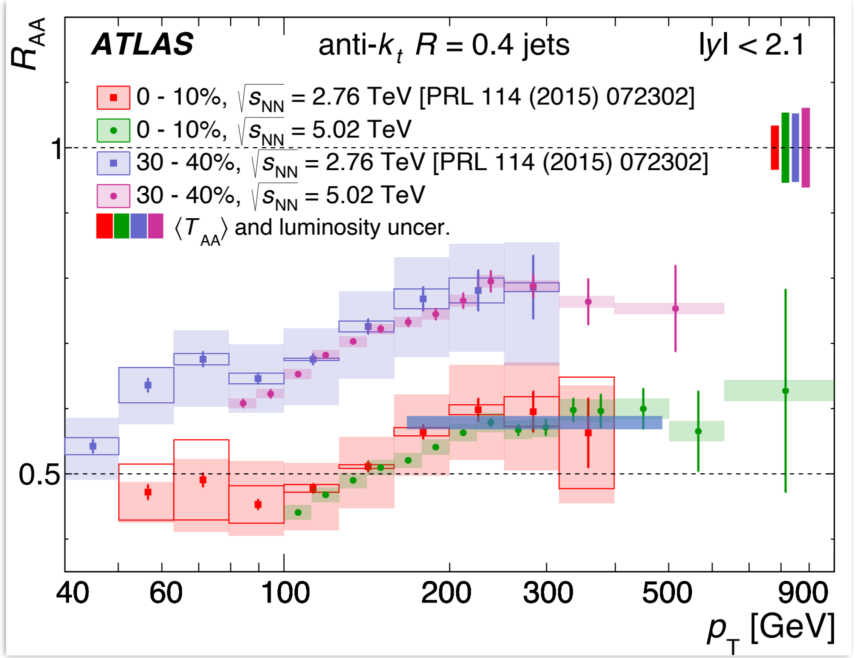
“Precision era”

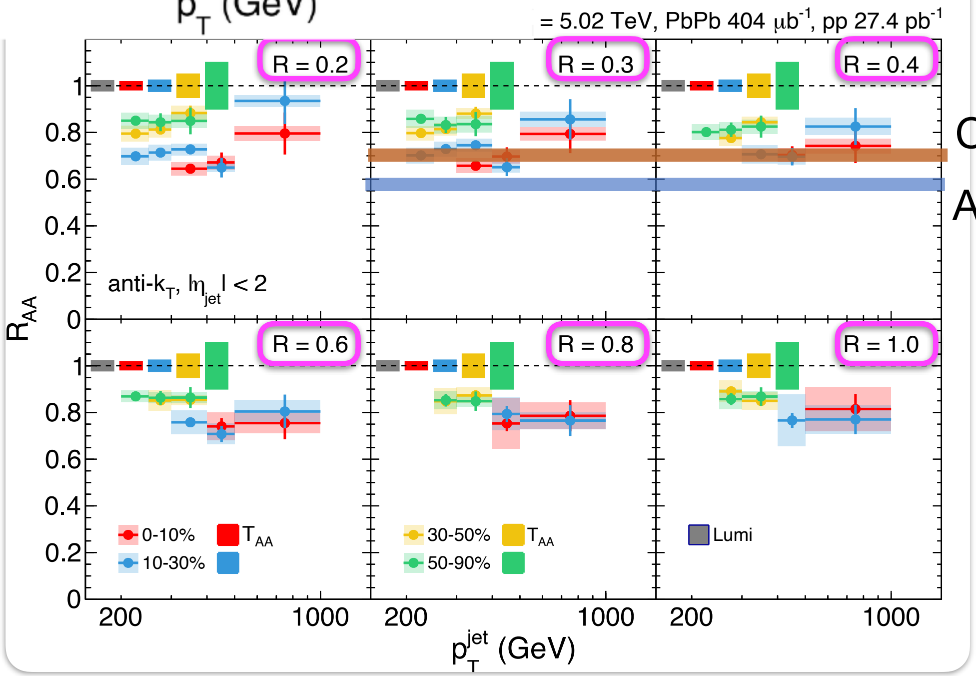




CMS hadrons

ATLAS hadrons

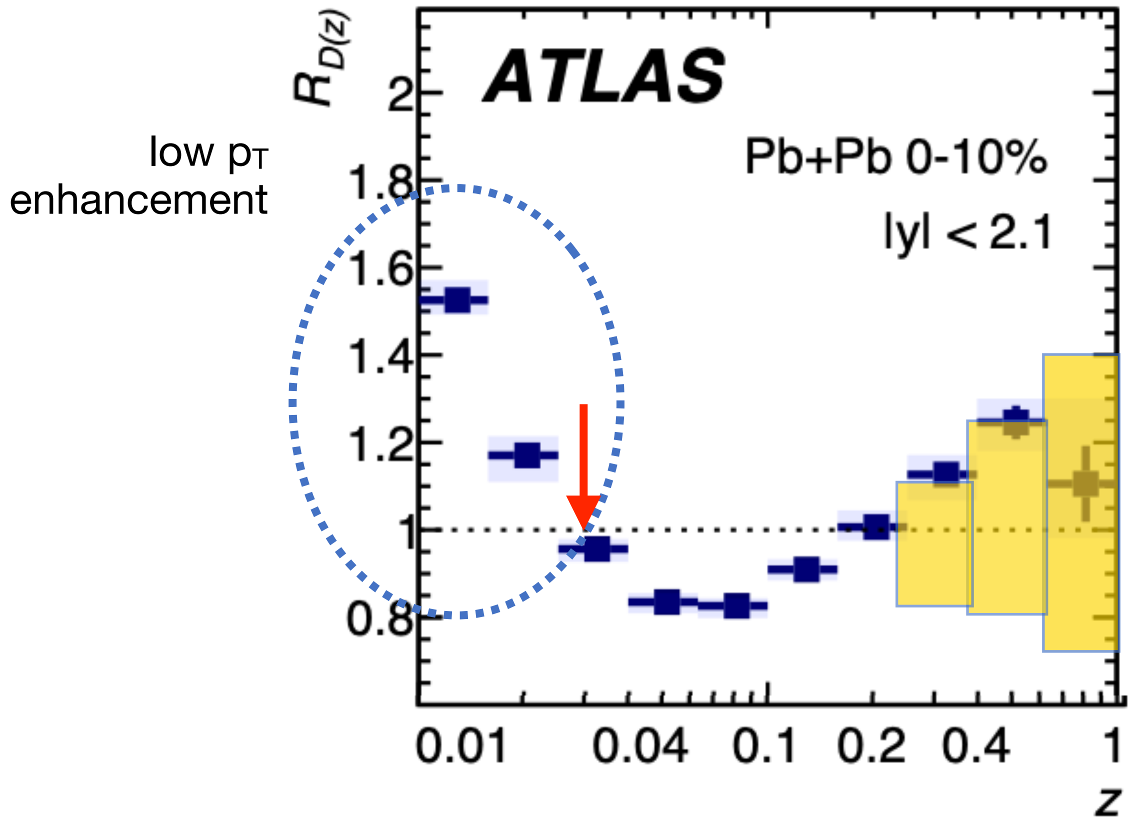


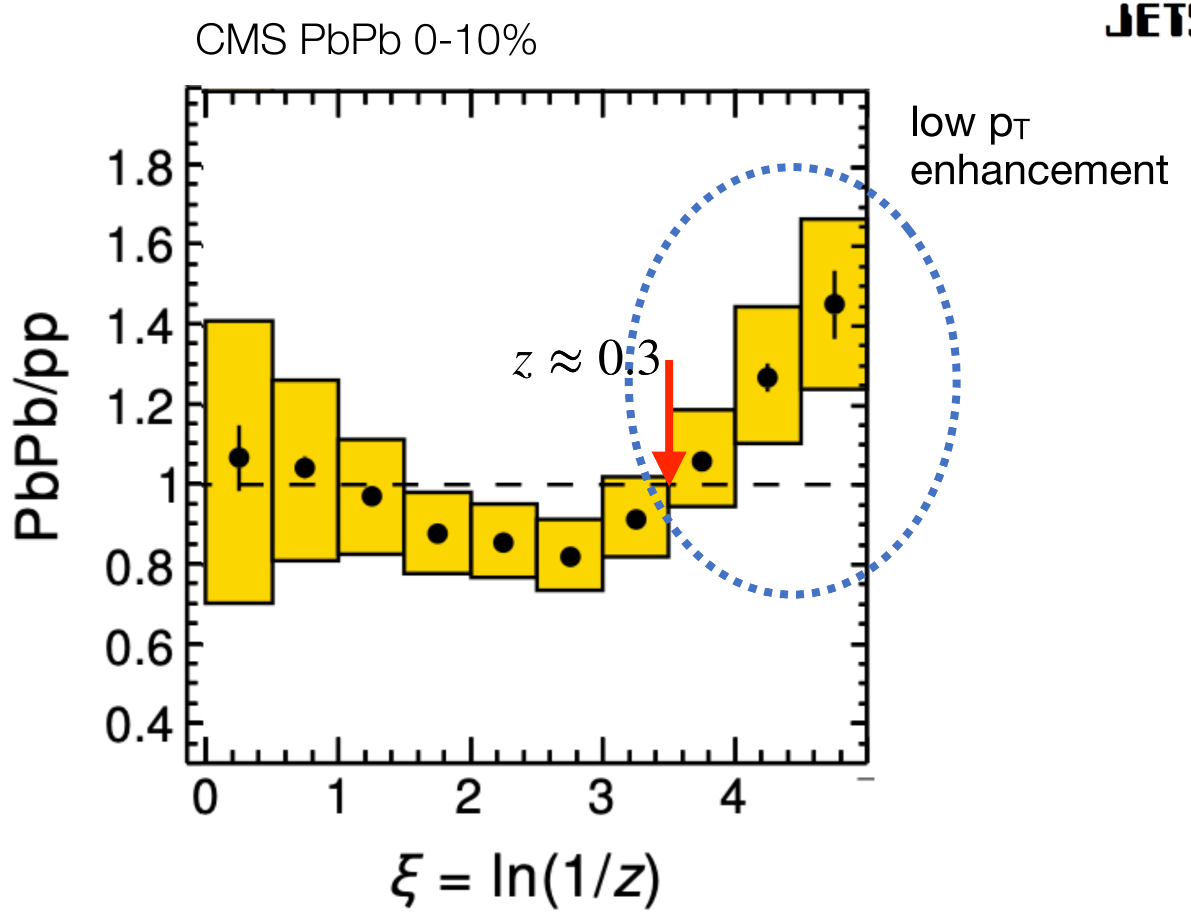


CMS jets

ATLAS jets

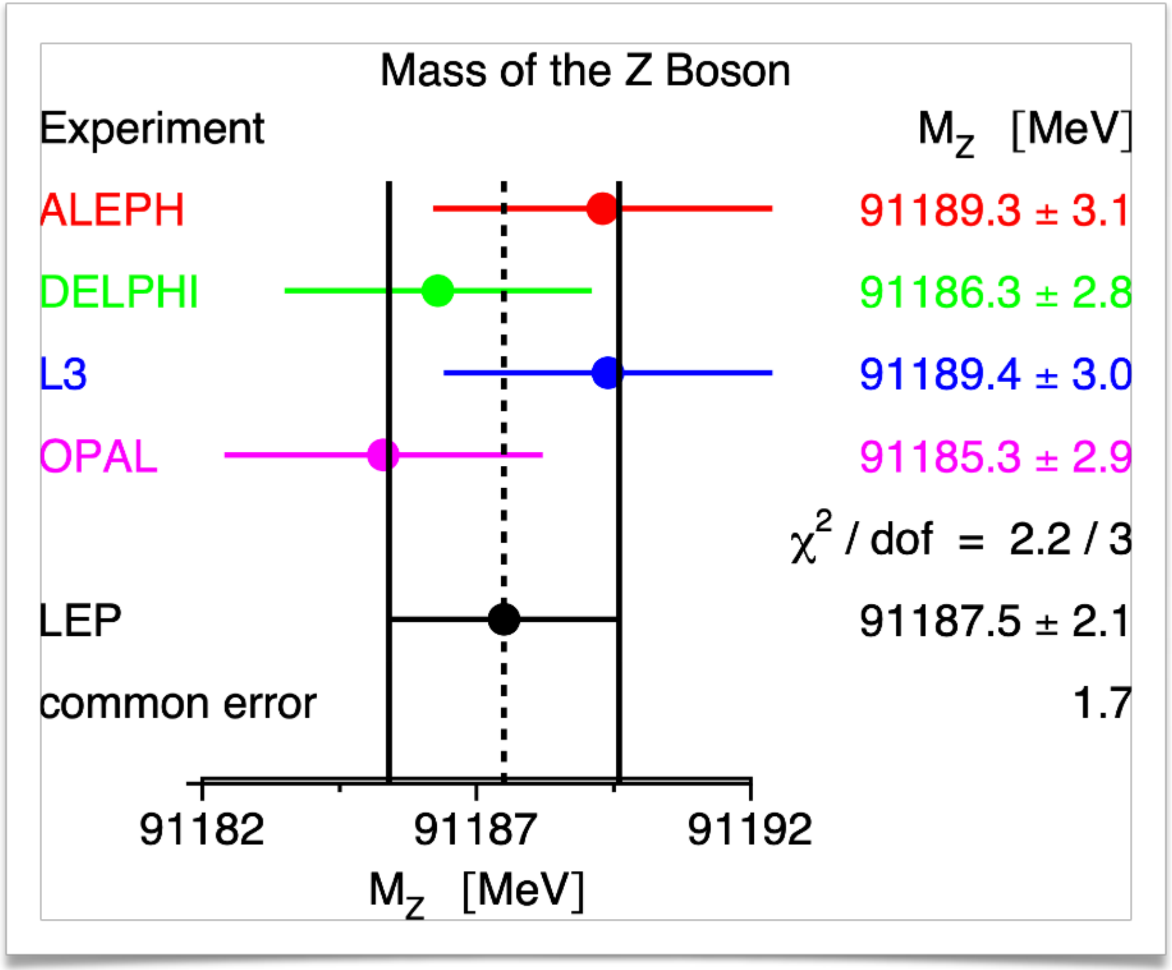
“Precision era”





Fragmentation function comparison at high z saved by large CMS errors

Precision era

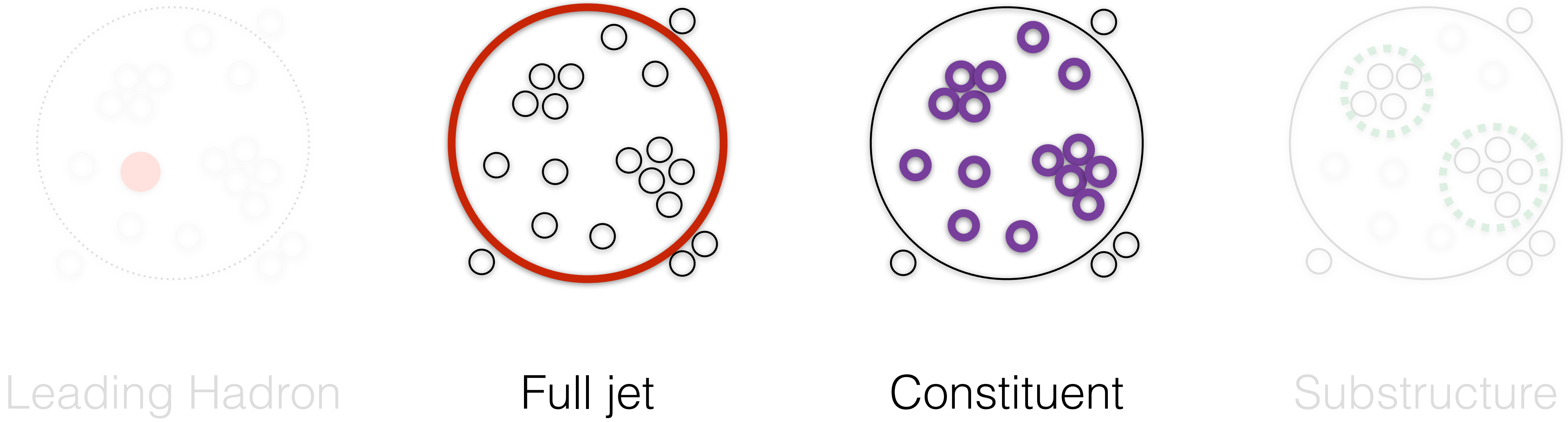


LEP Electroweak working group

- Is it time for a "HI jet" working group?
- Understand inter-experiment discrepancies
- Provide properly compiled/combined results to theory community
- Fit within JETSCAPE structure/ extension of STAT WG effort?

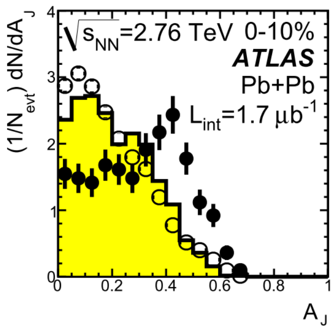
Jet physics with jets and their constituents

from Yi Chen

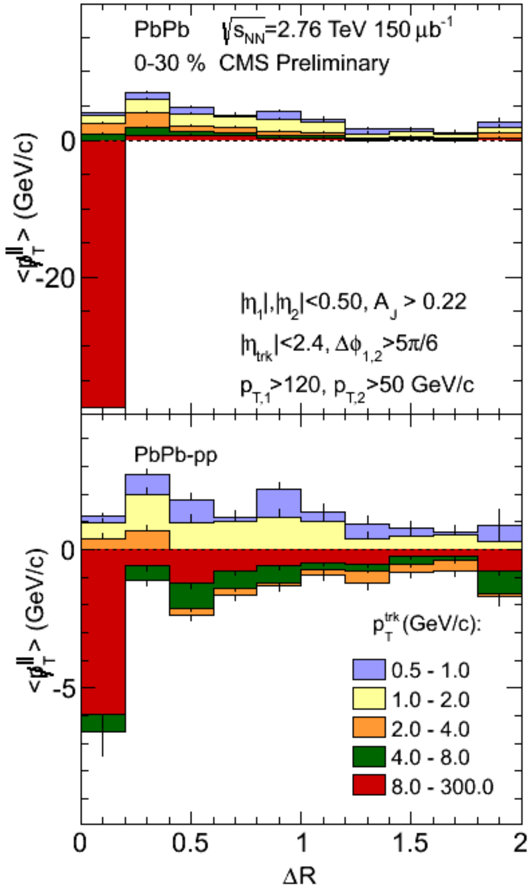


Missing energy has been found

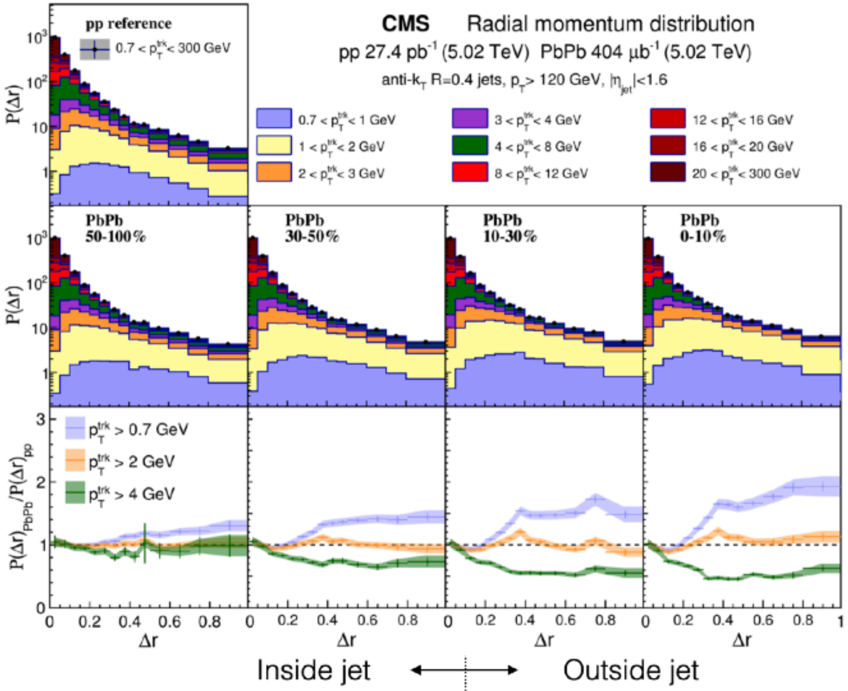
ATLAS 2010



Jets more unbalanced in PbPb
Where does "missing" energy go?

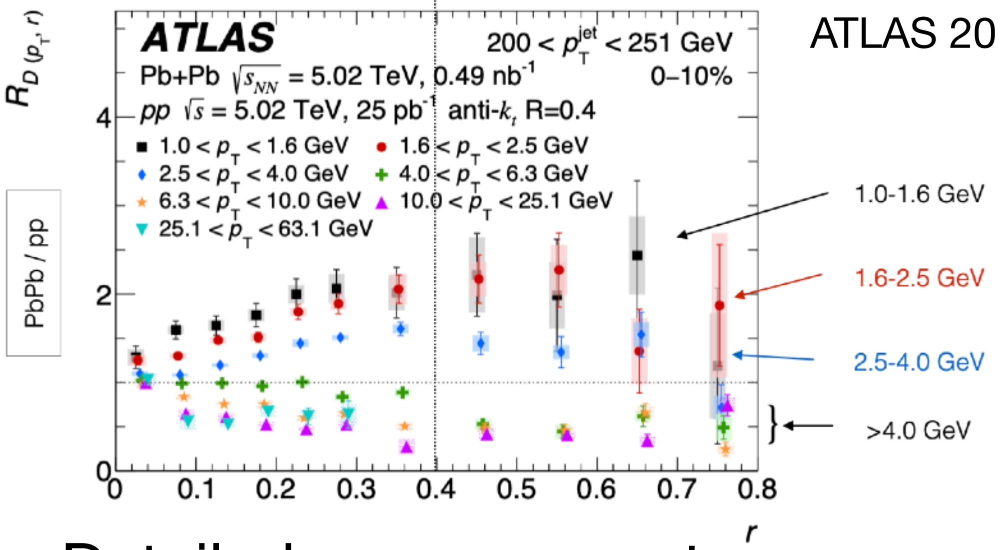


"Missing p_T" (CMS, 2010):
Energy balanced by low p_T tracks out to very large angles, up to $\Delta R \gtrsim 2$



CMS 2016

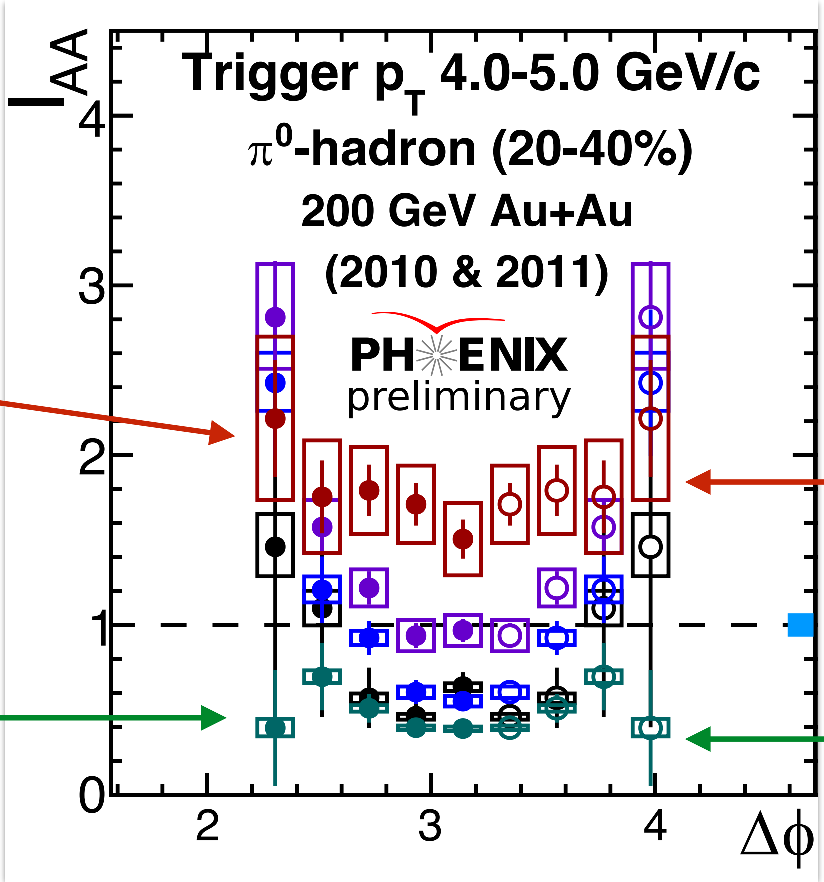
ATLAS 2019

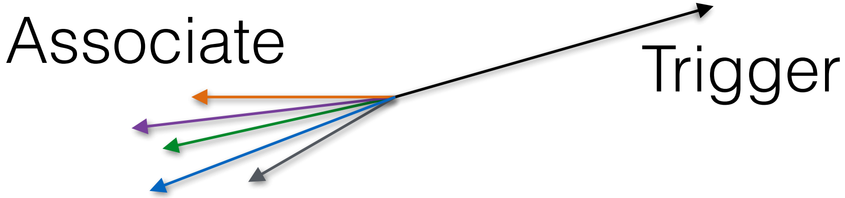


Detailed measurements of jet-track correlations

(Qualitatively) similar observations at RHIC

Track p_T (GeV)
0.5-1.0
1.0-2.0
2.0-3.0
3.0-5.0
5.0-7.0



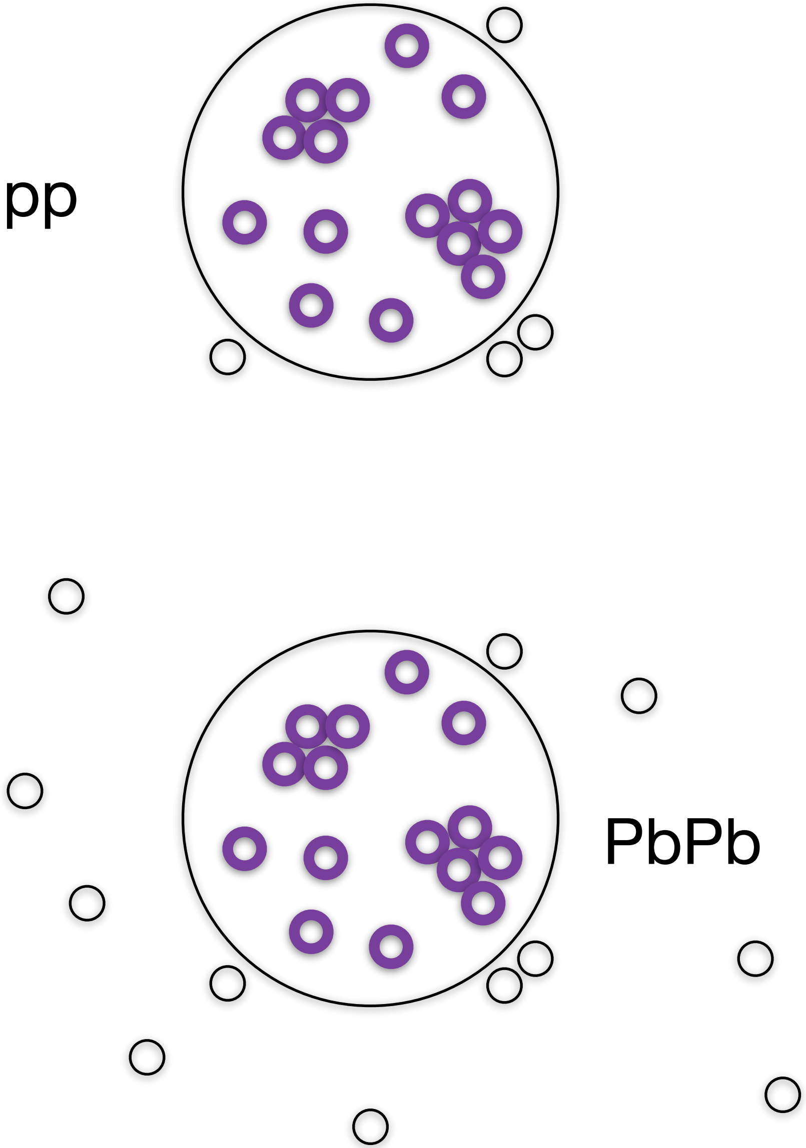


Away-side enhancement of **low p_T**

Away-side suppression of **high p_T**

Quantitative comparison to LHC observations awaits model studies

What is a jet?



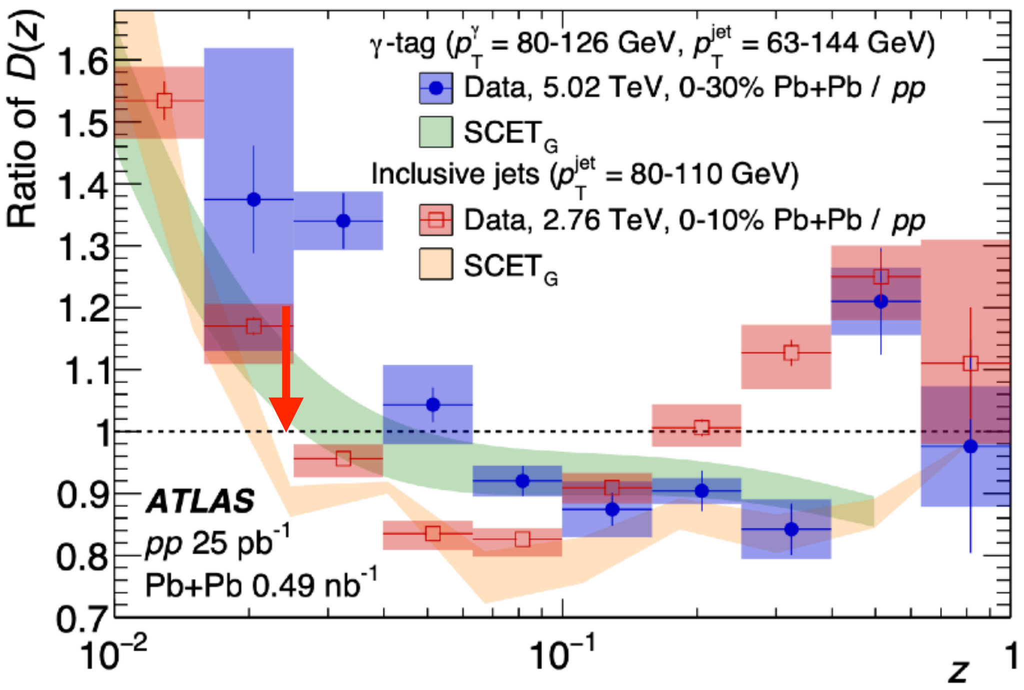
Operational definition of jets in HI based on separation of observed energy flow into "jet" and "UE"

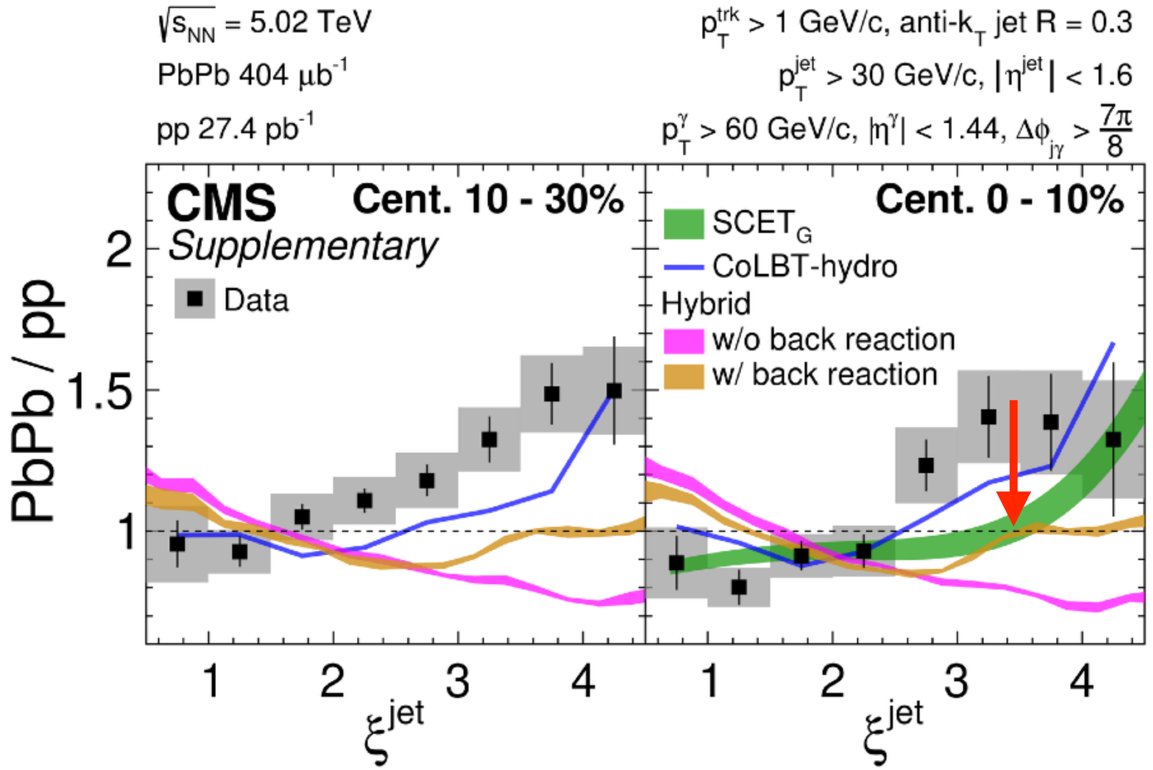
Data show that fraction ($\mathcal{O}(10\%)$) of parton shower related energy gets lumped into UE, predominantly in form of low p_T hadrons

Mechanism?

- Medium transport?
- Modified angular structure of shower?

γ + jet fragmentation functions

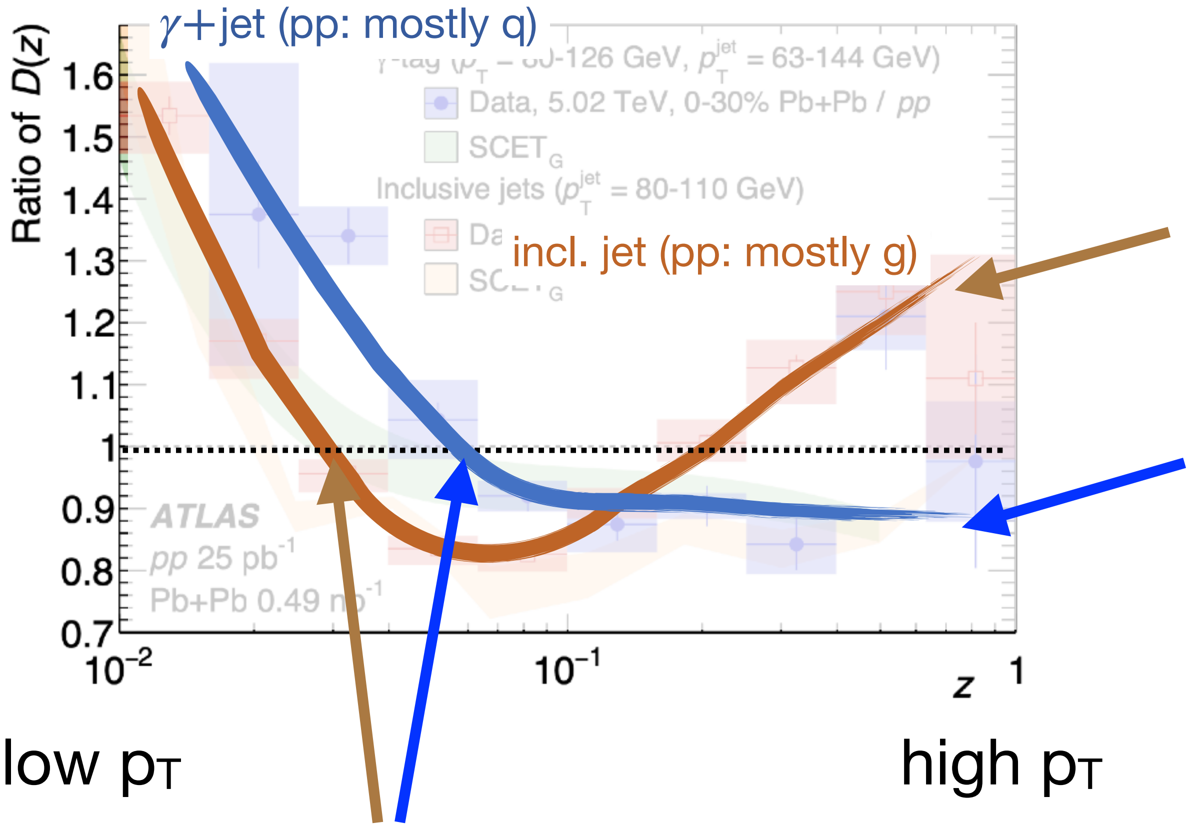




Photon tag changes fragmentation functions wrt inclusive jets:

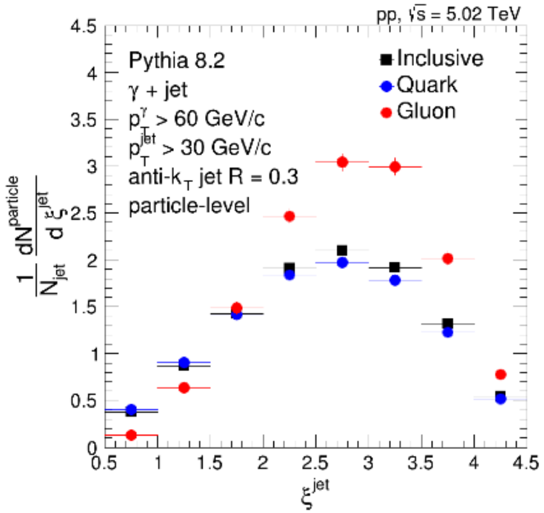
- onset of “low p_T” enhancement shifts to higher z
- depletion extends to highest z (ignoring the z ~0.5 point)

Inclusive jet vs γ-jet fragmentation functions



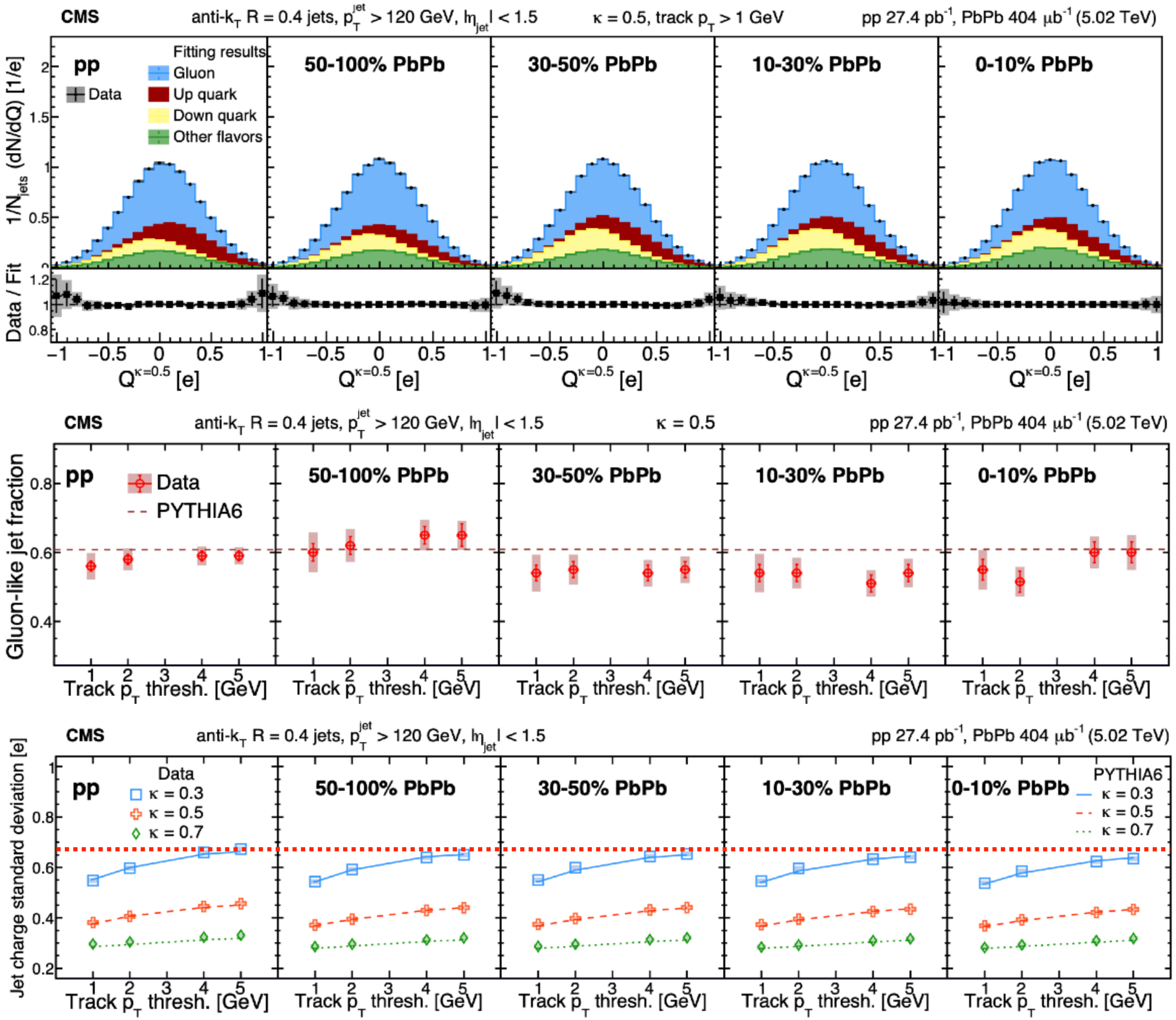
- High z enhancement for inclusive jets
  - “gluon filtering” with surviving quark jets showing harder fragmentation?
- Not seen in γ+jet
  - dominated by q jets also in pp
- Sign of elusive q/g E-loss difference?

- Shift in low p_T crossover
- Origin of shift in medium response interpretation?
- Surface bias of incl. jets vs γ tag?



Harder fragmentation for quark jets vs gluons

Jet charge and q/g ratio



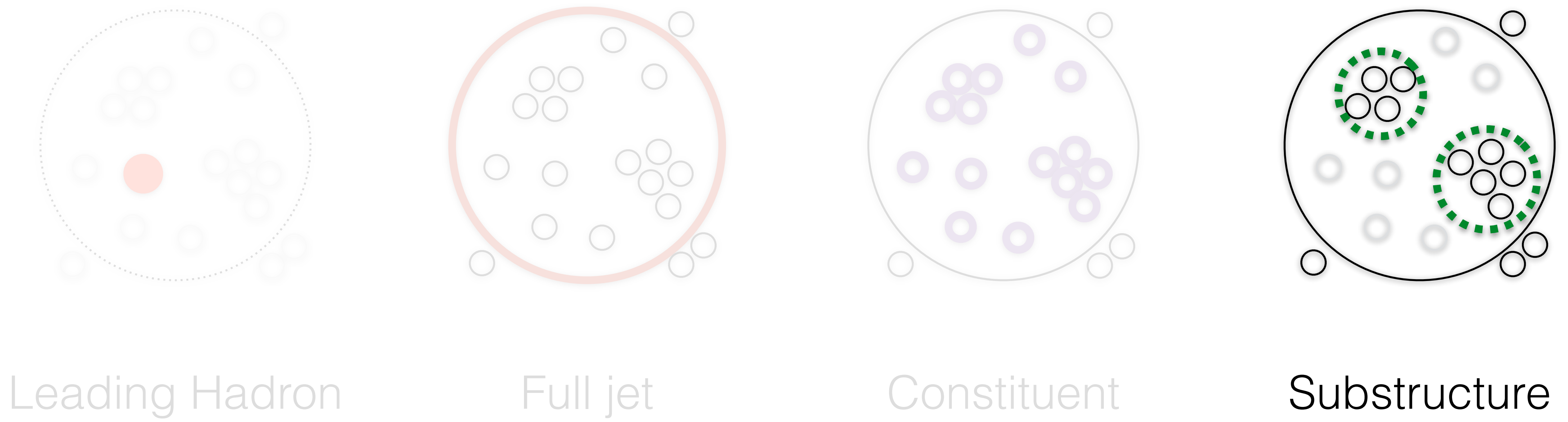
$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_{i \in \mathrm{jet}} q_i p_{\mathrm{T},i}{}^{\kappa}$$

Fit with PYTHIA-based templates does not show expected depletion of gluon-like jets in central PbPb vs pp

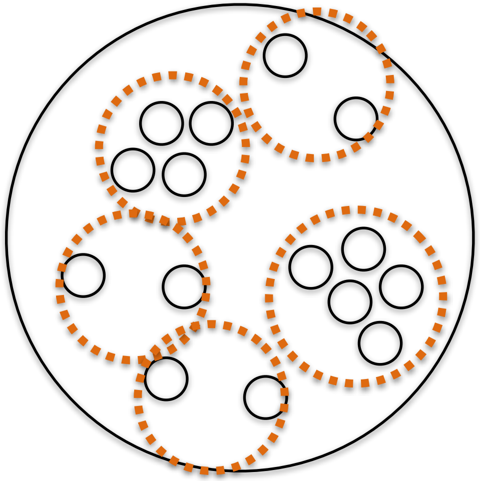
Width of Q distribution (independent of PYTHIA!) shows minimal change from pp to peripheral and central PbPb - compensating effects?

Jet physics with jet substructure

from Yi Chen

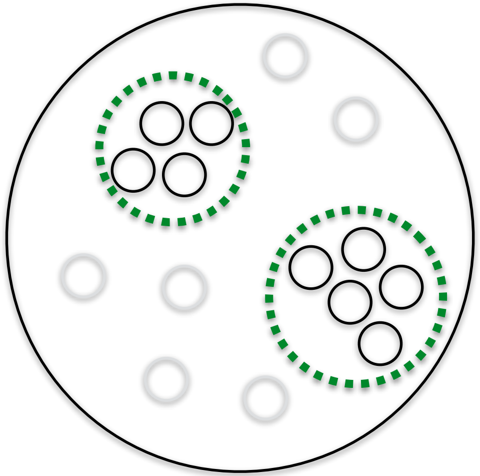


Accessing jet substructure



Reclustering

Recluster constituents into small radius jets



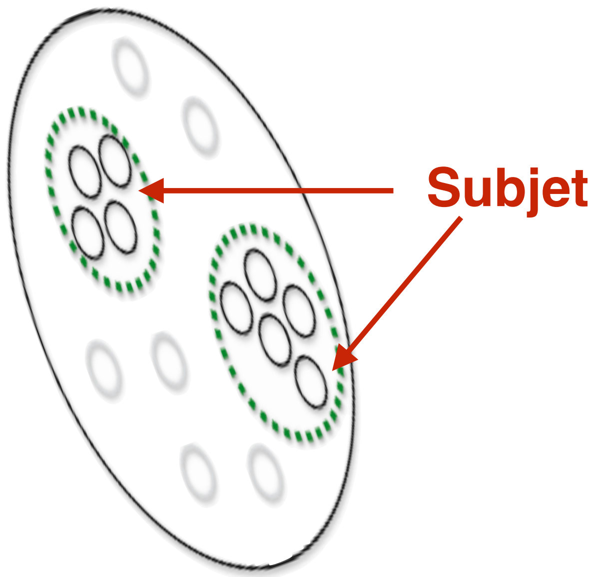
Grooming

Clean up (drop) soft parts of the jet

Typically controlled through momentum cut with angular weight:

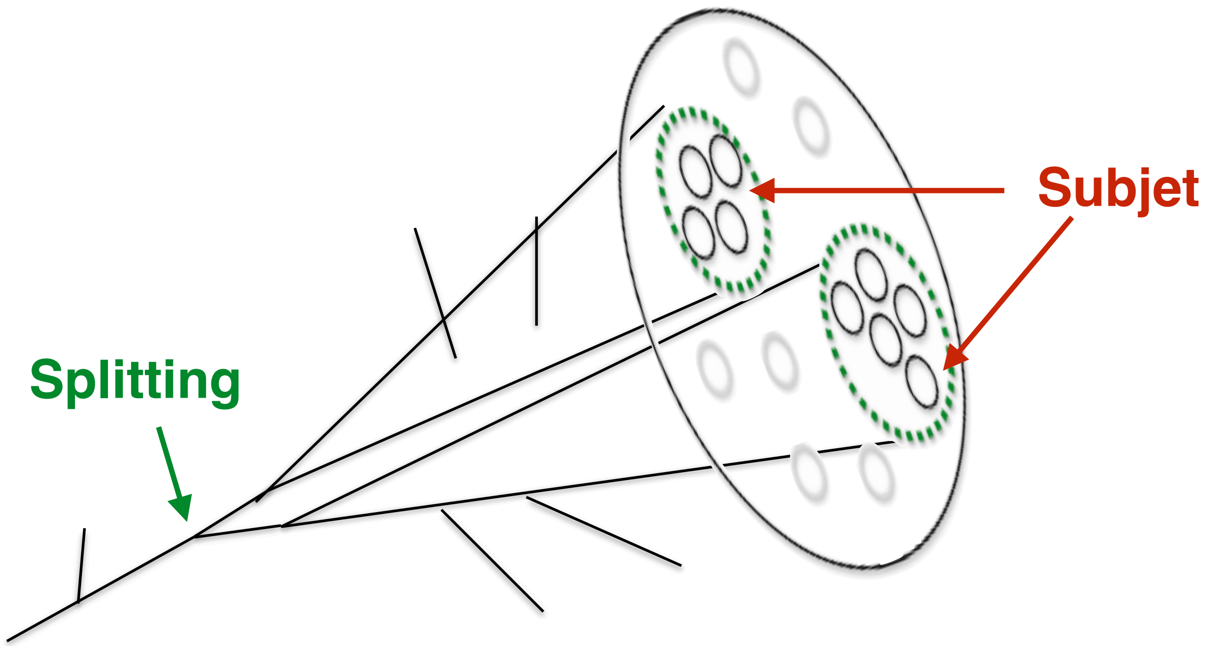
$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}} \theta^{\beta}$$

Why substructure?



Why substructure?

Subjet: proxy for the
hardest shower splitting

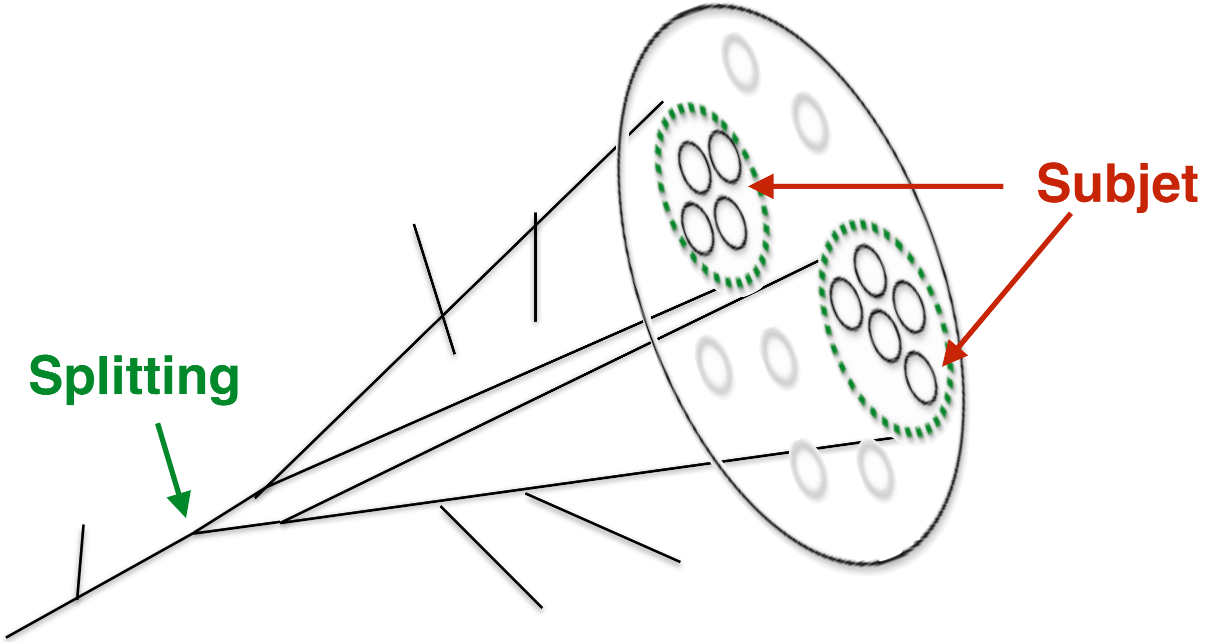


Subjets may provide window into
evolution of parton shower

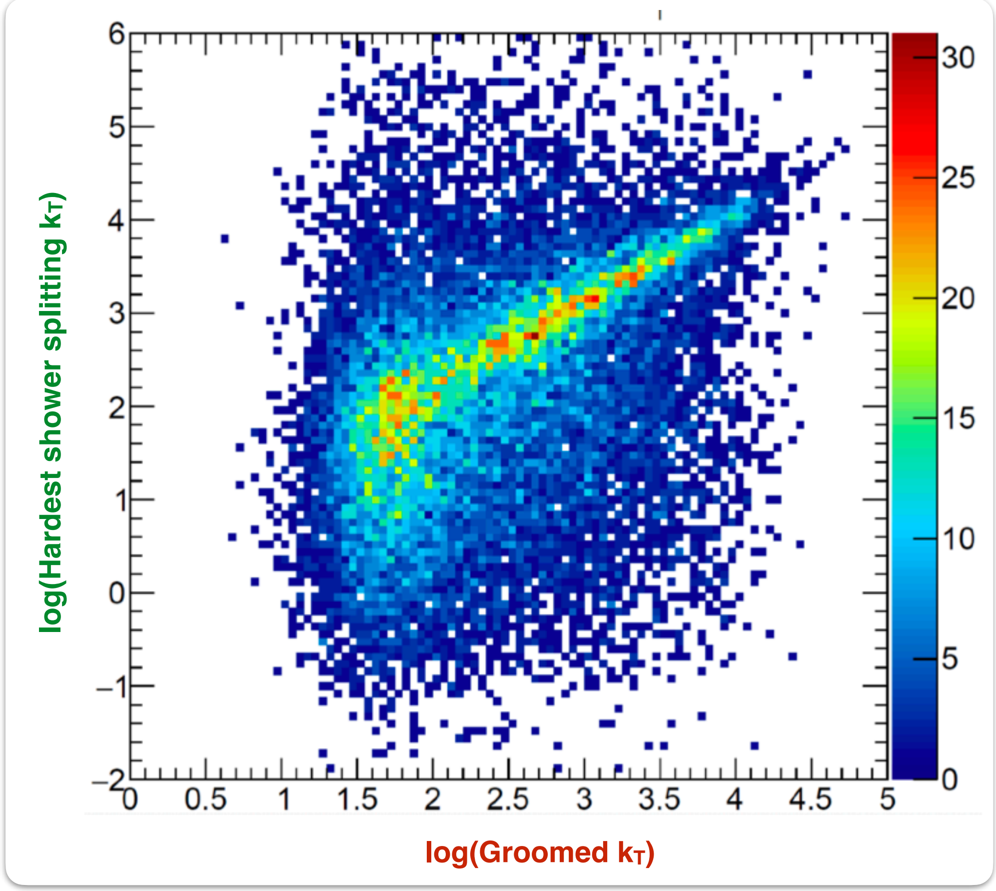
Why substructure?

EMMI RRTF Jet Workshop 2019

Subjet: proxy for the hardest shower splitting

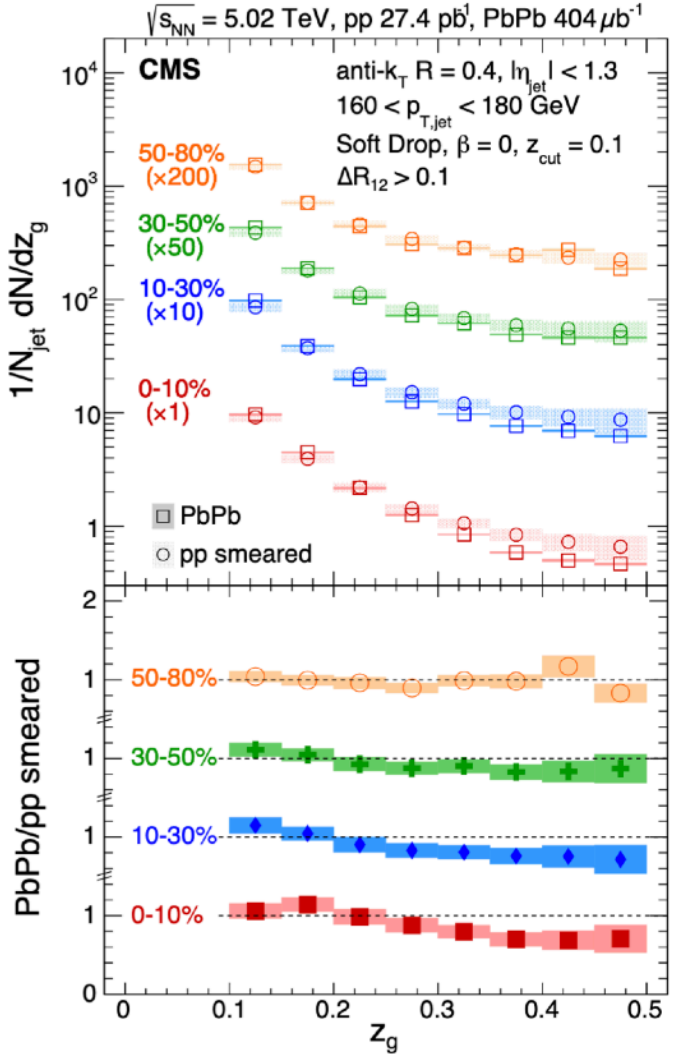


Subjets may provide window into evolution of parton shower



Indication that (some) shower information survives hadronization and experimental procedure

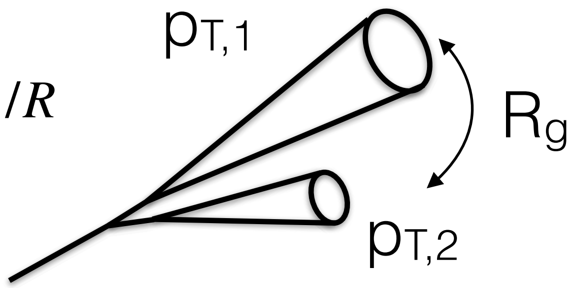
Can medium resolve subjets?



Larkoski, Marzani, Thaler (2015)

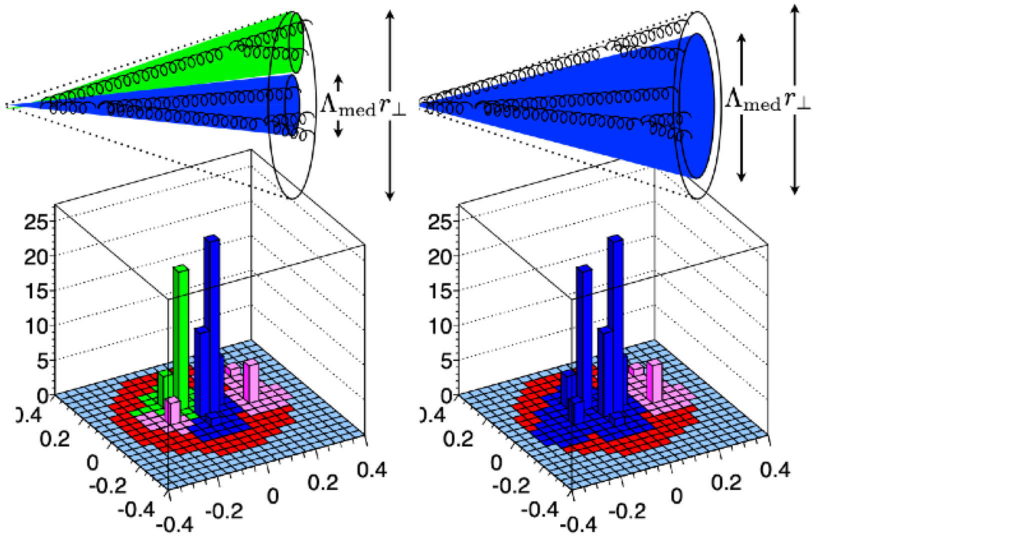
$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} > z_{cut}\theta^{\beta}, \theta_g = R_g/R$$

z_g: p_T fraction carried by softer subjet



R_g limited to $\gtrsim 0.1$ by CMS calorimeter granularity

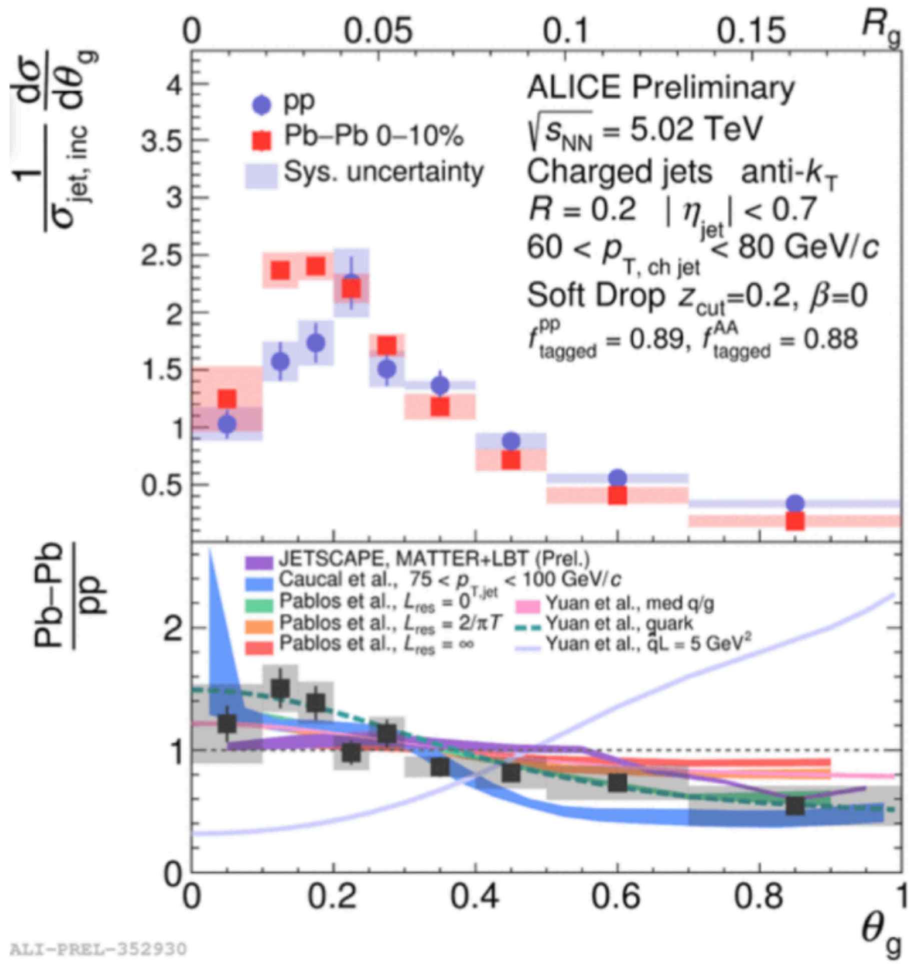
Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk (2012)

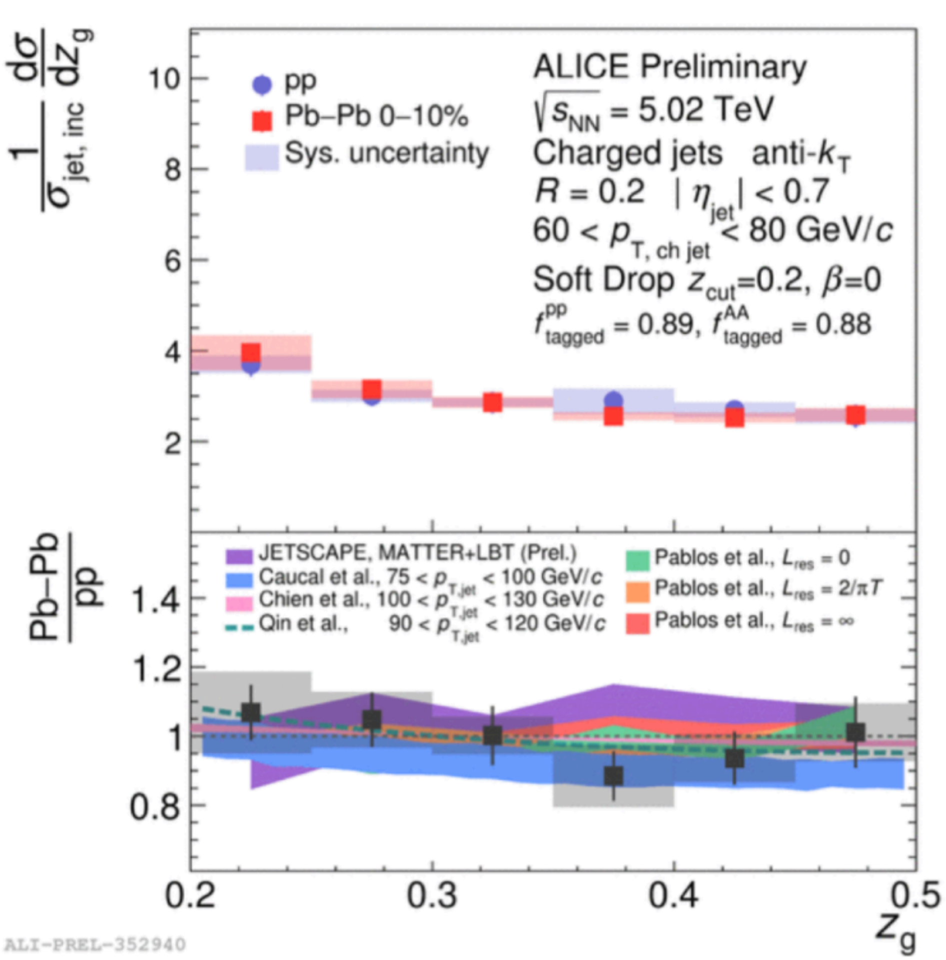


Relative suppression of balanced ($z_g \approx 0.5$) configurations

Relate to the role of color coherence in jet quenching

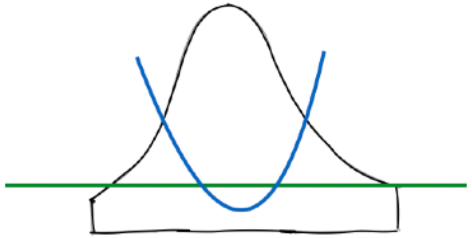
PbPb/pp subjets vs $\theta_g(R_g)$ and z_g





$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\theta^{\beta}, \theta_g = R_g/R$$

Groomed jet mass



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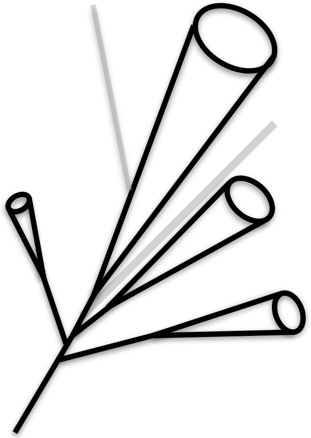
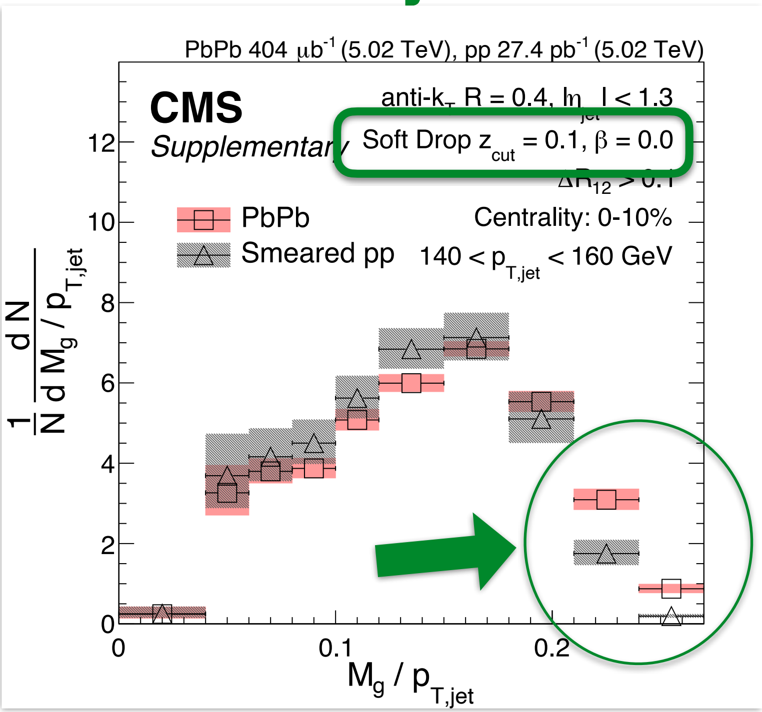
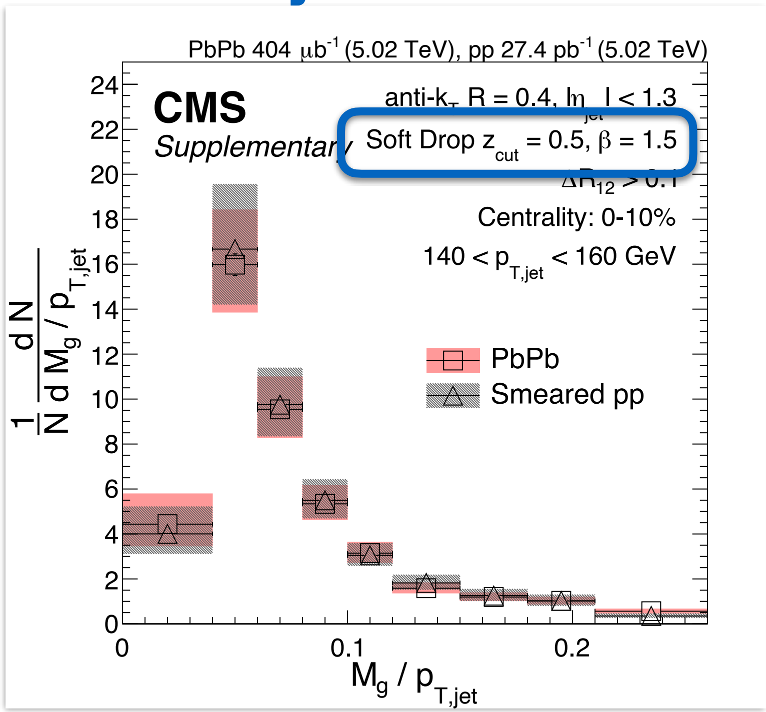
full jet

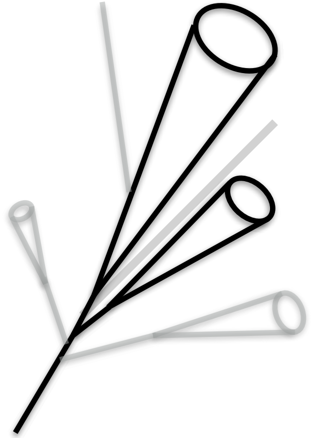




Small modification at large mass

jet core

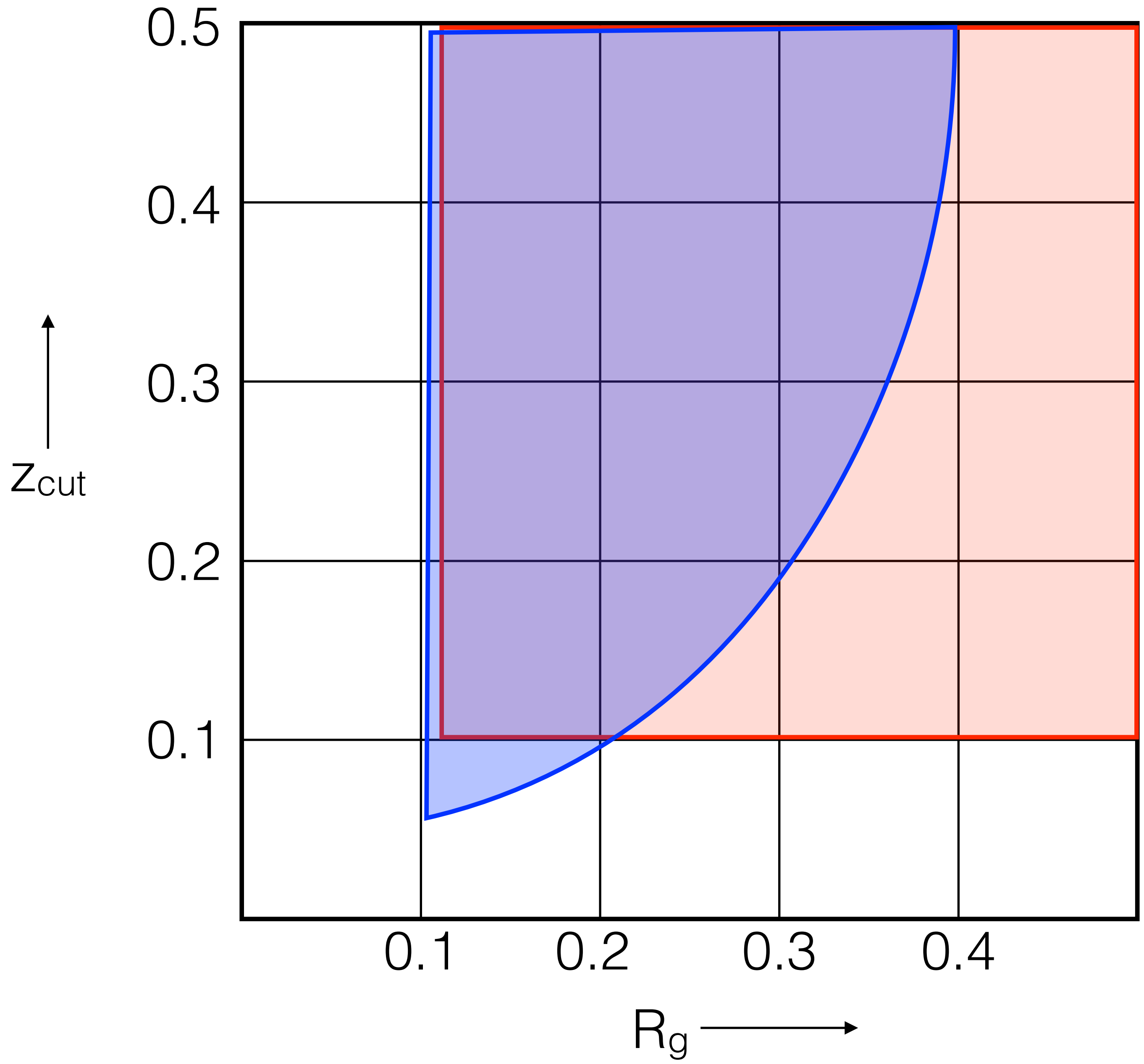




No modification seen

Related to modification of jet structure in large angle range

Jet modification in grooming space

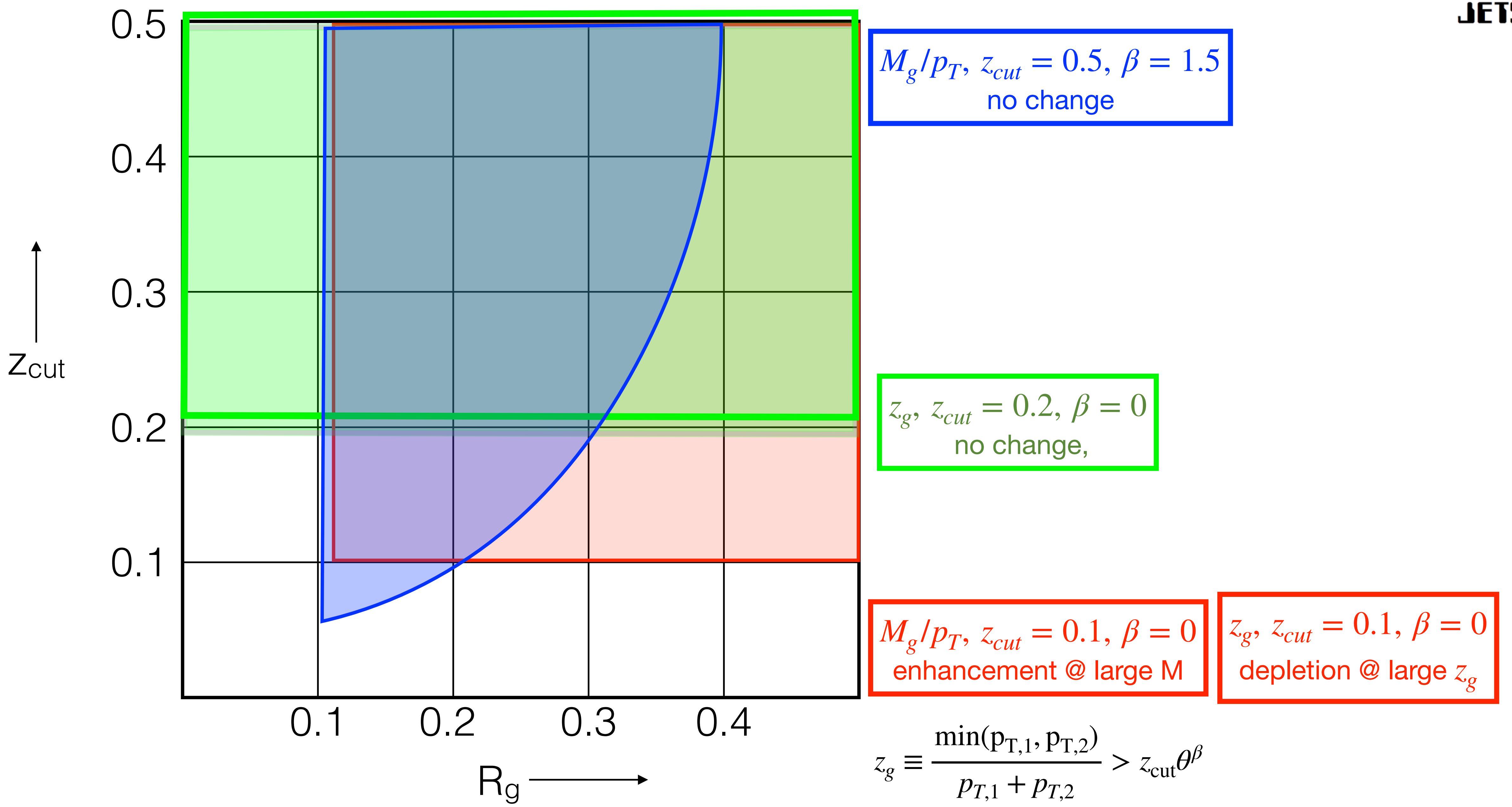


$M_g/p_T,\ z_{cut} = 0.5,\ \beta = 1.5$
no change

$M_g/p_T,\ z_{cut} = 0.1,\ \beta = 0$
enhancement @ large M

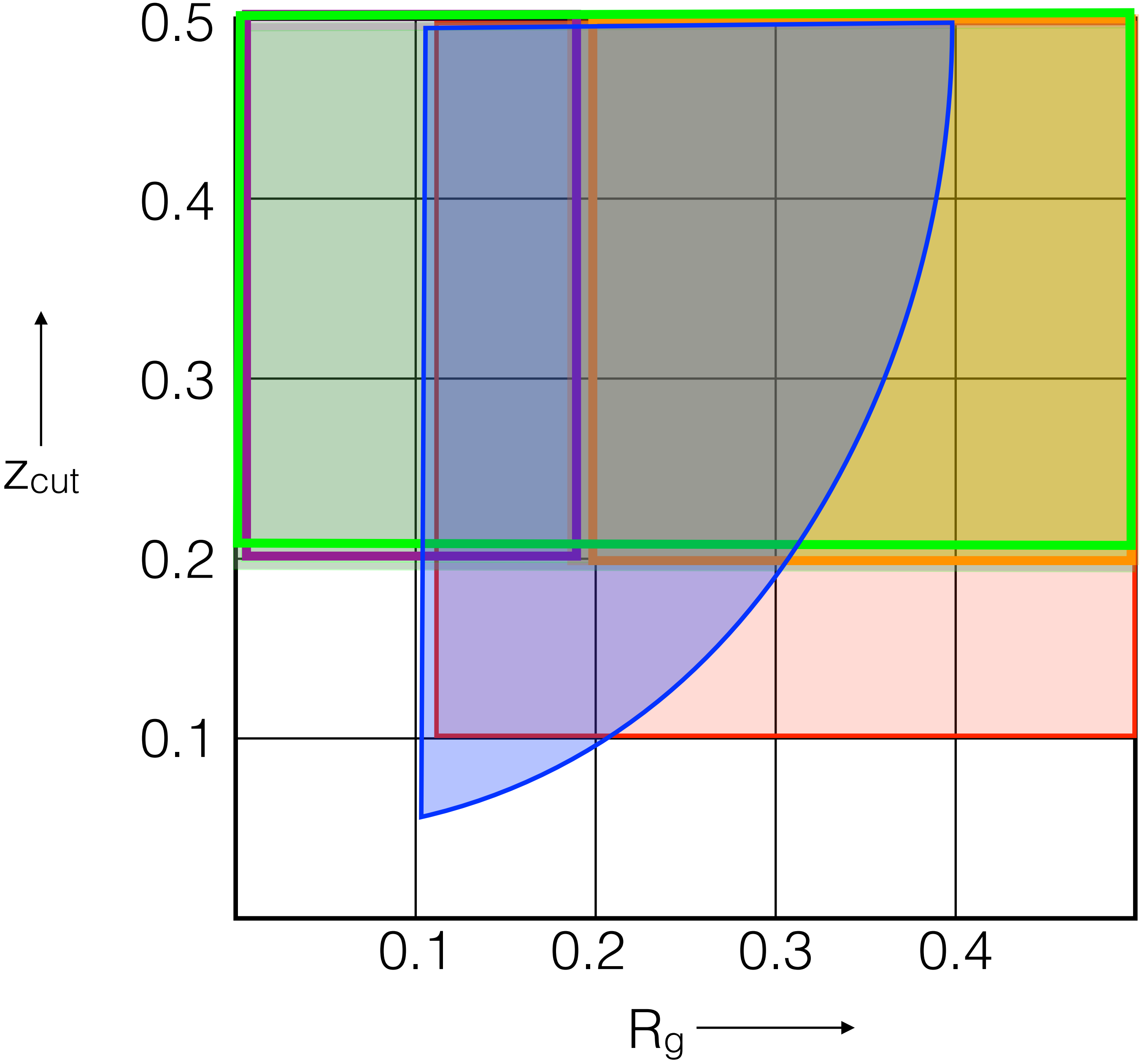
$$z_g \equiv \frac{\min(\mathrm{p_{T,1}}, \mathrm{p_{T,2}})}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}}\theta^{\beta}$$

Jet modification in grooming space



$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\theta^{\beta}$$

Jet modification in grooming space



M_g/p_T, $z_{cut} = 0.5$, $\beta = 1.5$
no change

θ_g, $z_{cut} = 0.2$, $\beta = 0$
θ_g enhancement

θ_g, $z_{cut} = 0.2$, $\beta = 0$
θ_g depletion

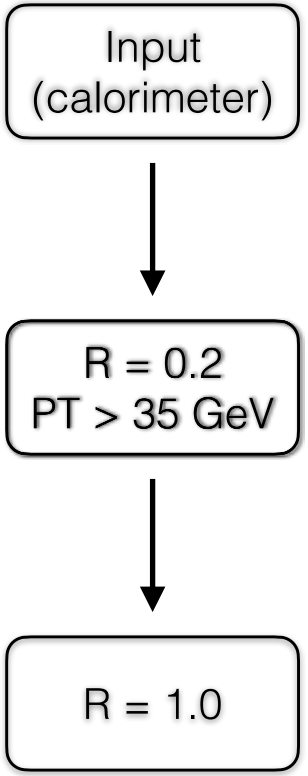
z_g, $z_{cut} = 0.2$, $\beta = 0$
no change,

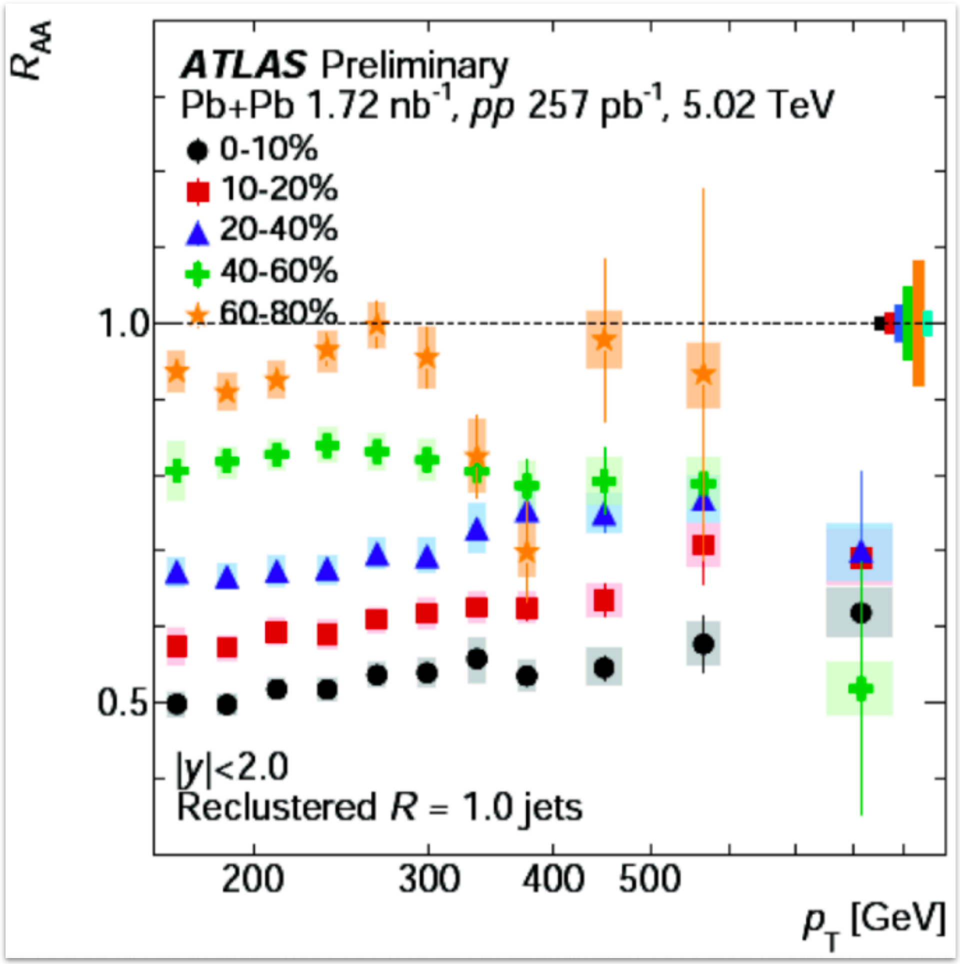
M_g/p_T, $z_{cut} = 0.1$, $\beta = 0$
enhancement @ large M

z_g, $z_{cut} = 0.1$, $\beta = 0$
depletion @ large z_g

$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\theta^{\beta}$$

Two-step jet clustering





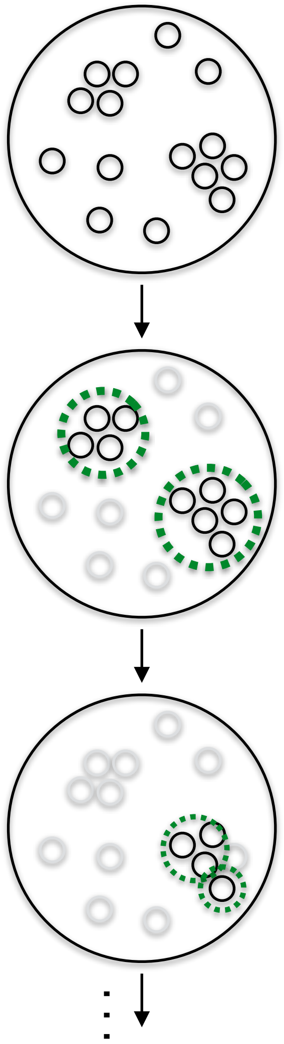
Probes a **special jet population** of R = 1.0, made up of R = 0.2 constituents of >35 GeV each

“Cleaned” jets — soft part removed

Similar R_{AA} as inclusive R = 0.4

Without the soft part, no R_{AA} increase

Grooming multiplicity (nSD)

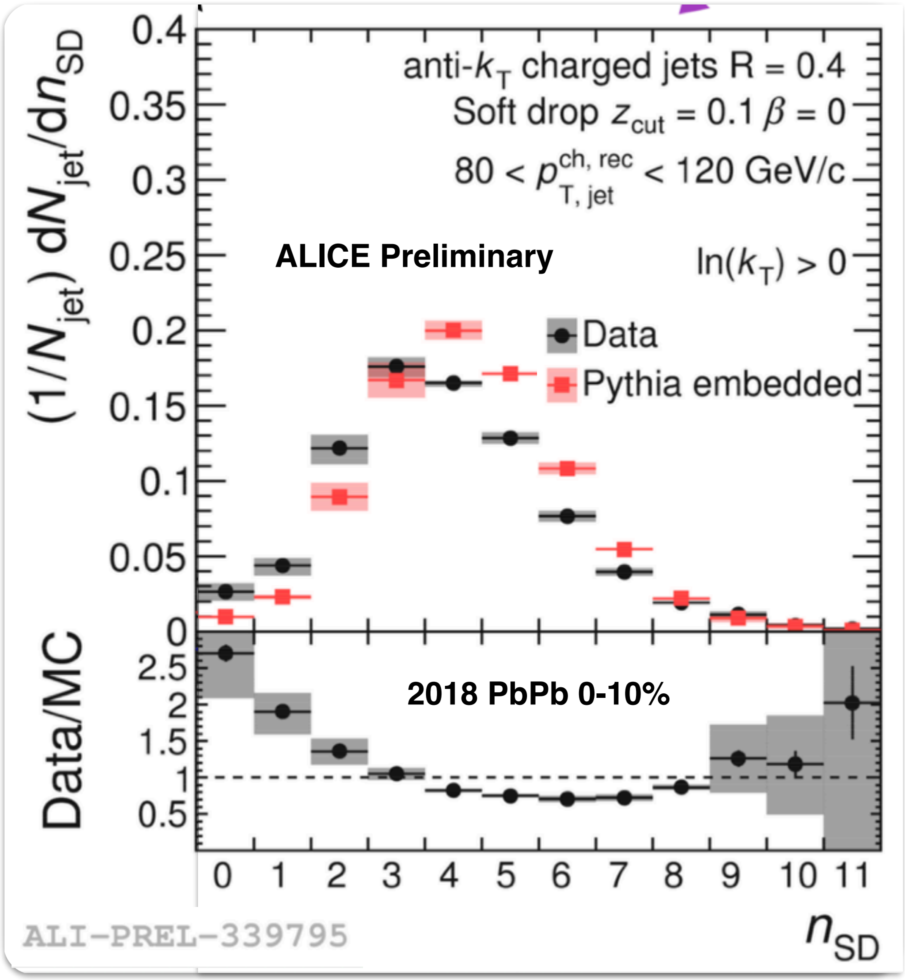


Repeatedly apply grooming algorithm on the stronger subjet

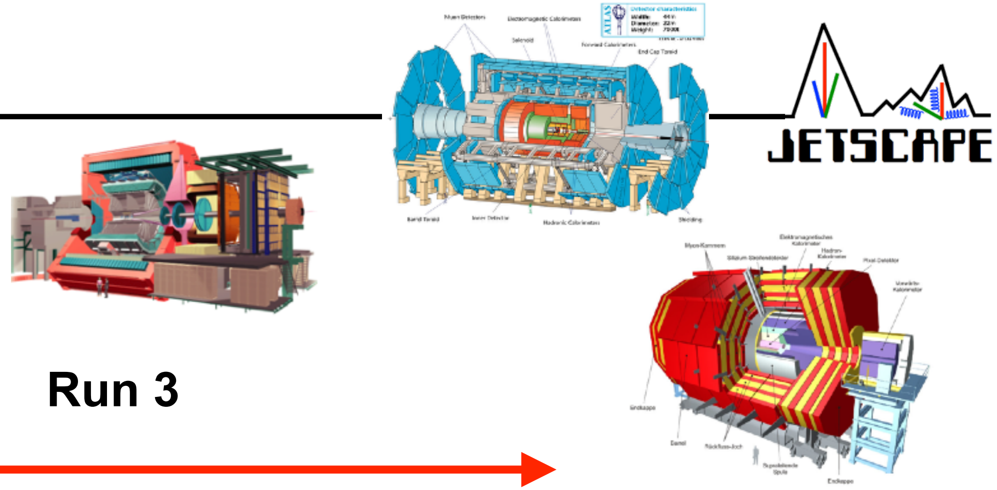
In vacuum n_{SD} is **correlated with number of shower splittings**

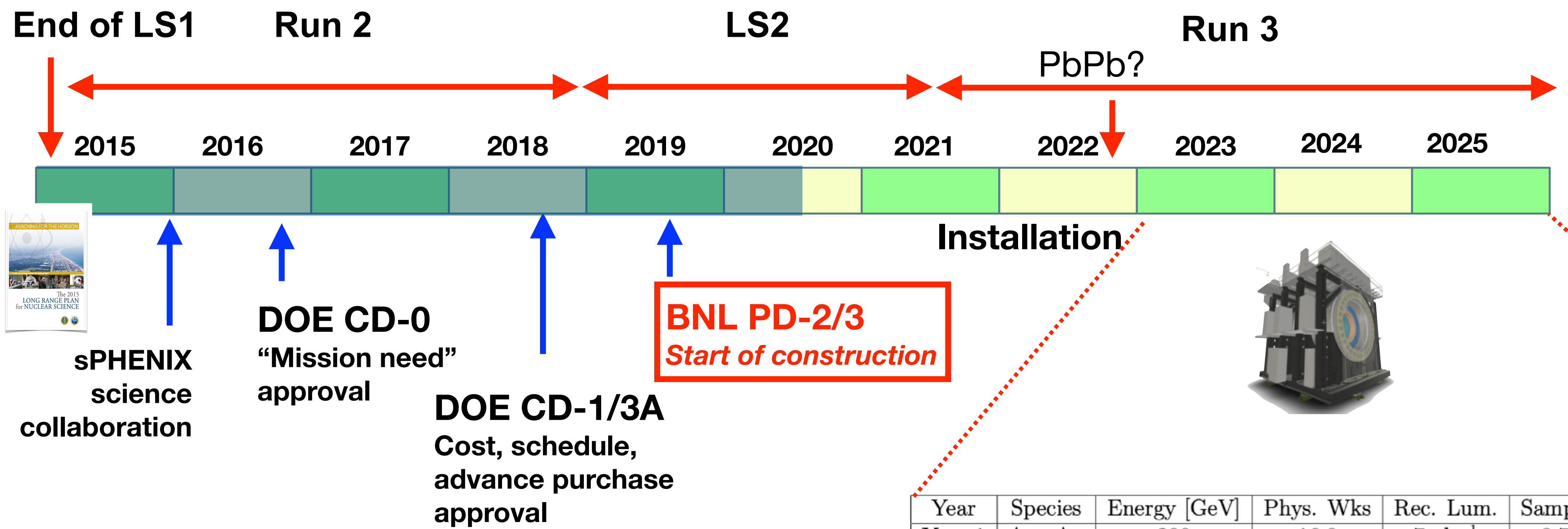
Smaller n_{SD} in PbPb

Consistent with z_g observations where jets are softened



Exciting future ahead



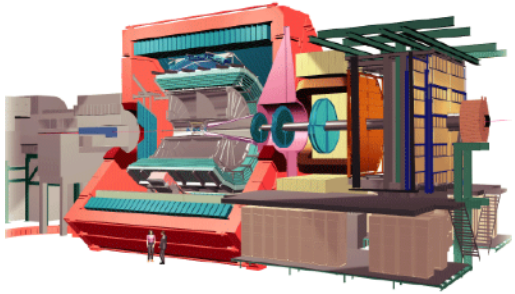


Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}

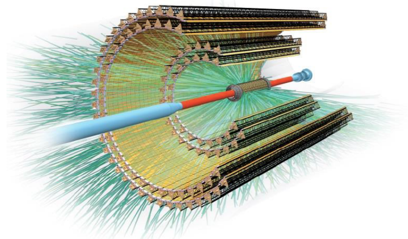
https://indico.bnl.gov/event/4788/attachments/19066/24594/sph-trg-000_06142018.pdf

LHC Phase-1 Upgrades

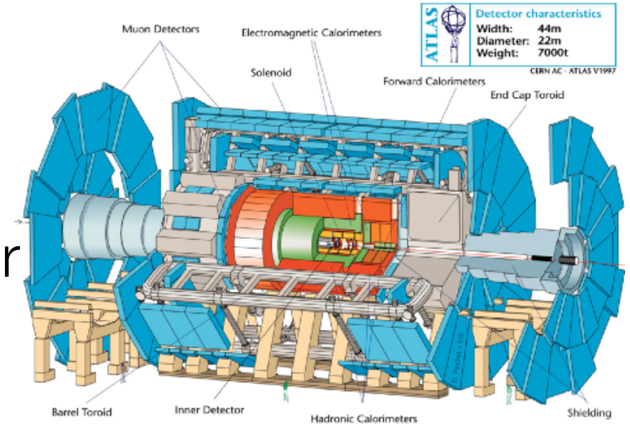
ALICE



Expanded calorimetry
Continuos readout TPC
MAPS-based inner tracker
Improved data acquisition rate (full PbPb lumi)

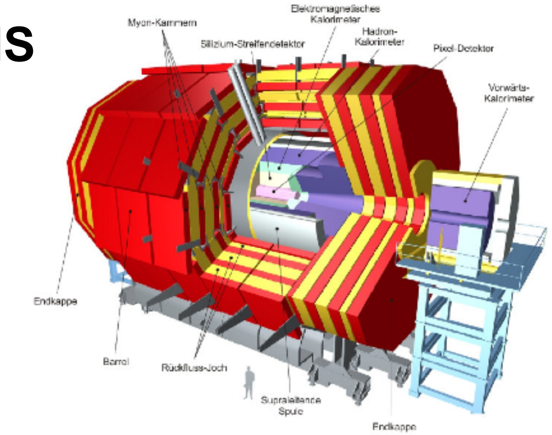


ATLAS



Improved trigger system
New/extended inner tracker

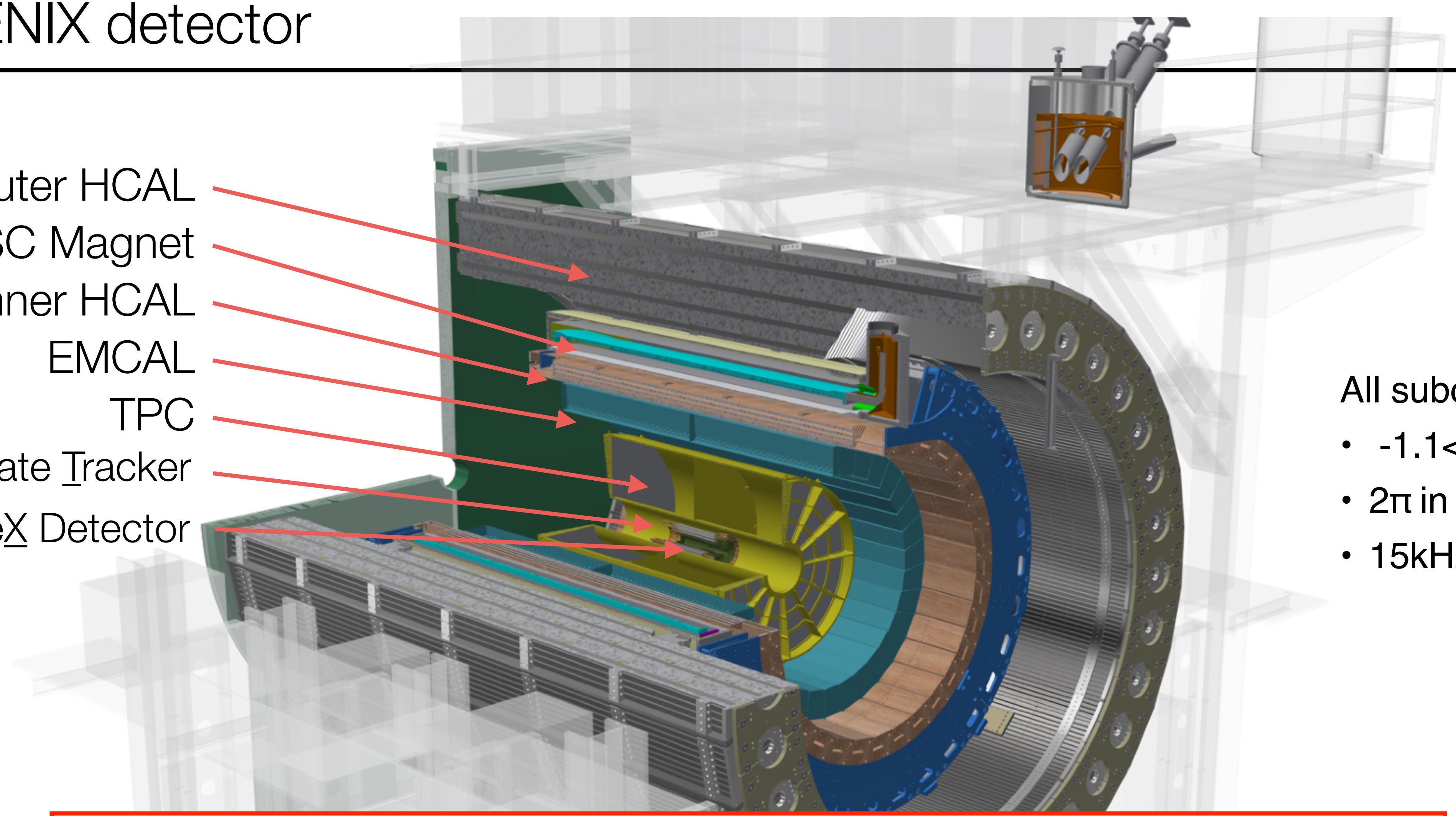
CMS



Improved trigger system
New/extended inner tracker

n.b. more extensive phase-II upgrades for
ATLAS/CMS for LHC Run IV, 2026-2030

sPHENIX detector



All subdetectors:

- $-1.1<\eta<1.1$
- 2π in azimuth
- 15kHz readout rate

Qualitative improvement on 20 years of studies at RHIC through higher statistics (x10+), full calorimetry and higher precision tracking

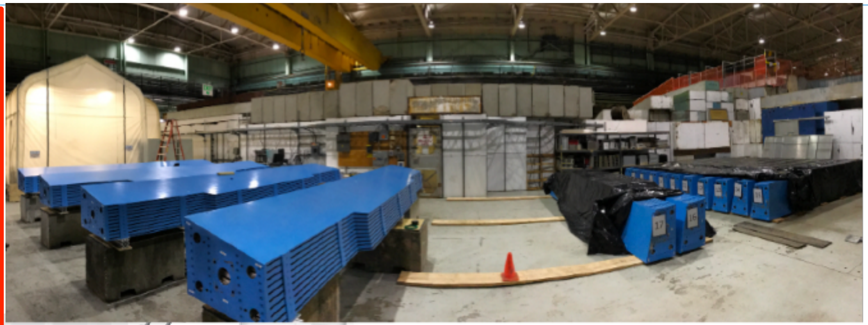
Employ proven and cost-effective detector technology

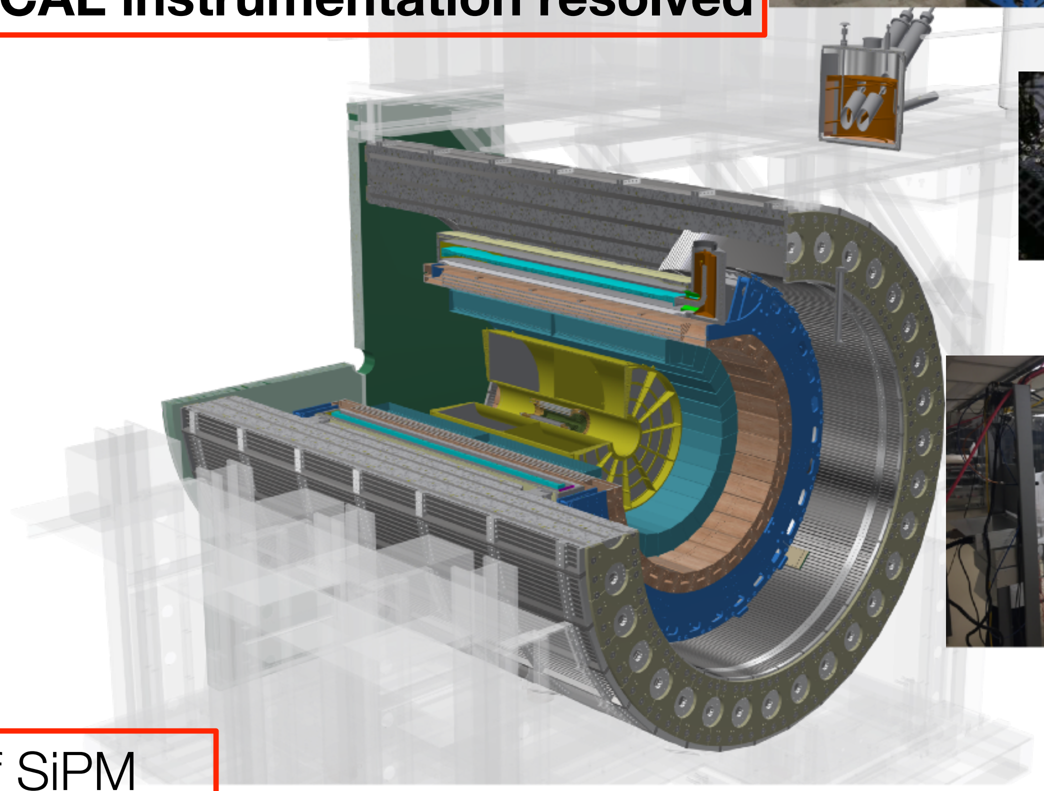
Construction proceeding on all subsystems

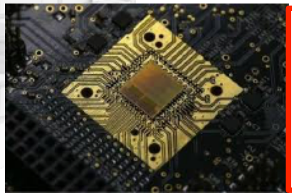
All oHCAL sectors at BNL

Scintillating tile production proceeding at Uniplast

iHCAL instrumentation resolved





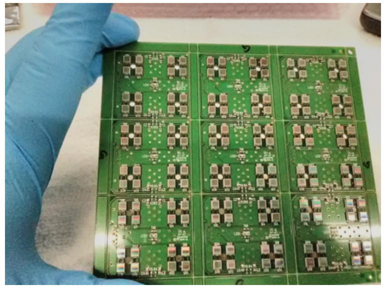


SAMPA v5 TPC FE chip successfully produced and qualified (USP/Lund)

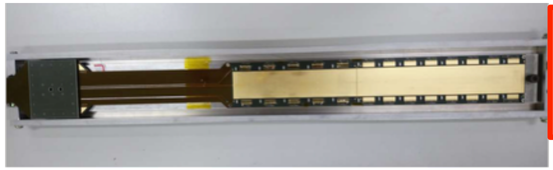
EMCAL "sector 0" prototype produced

Block production has **resumed** at UIUC

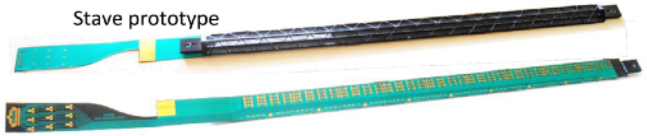
GEM factories starting up (Temple, VU, WSU)



50% of SiPM daughterboards received

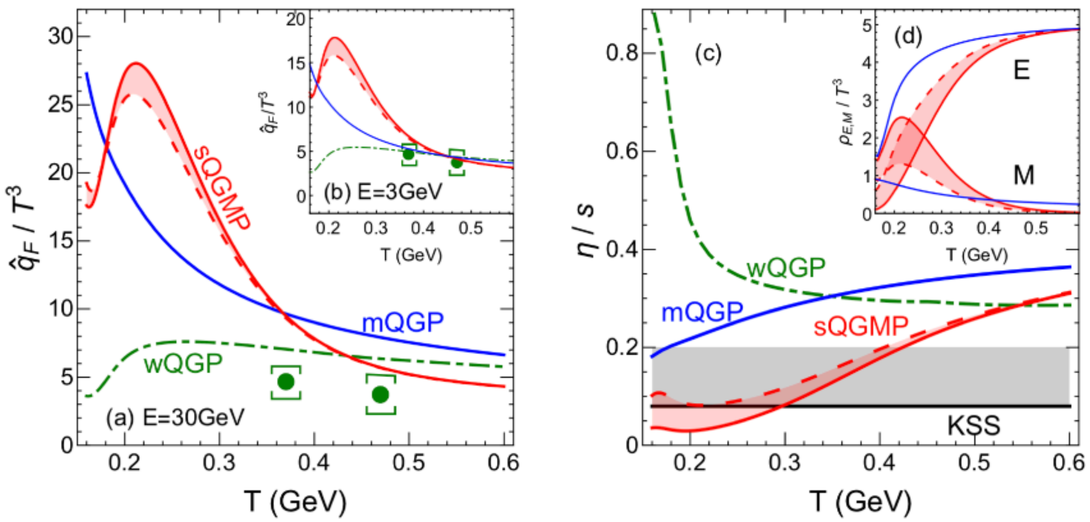


First INTT module assembled (NCU)

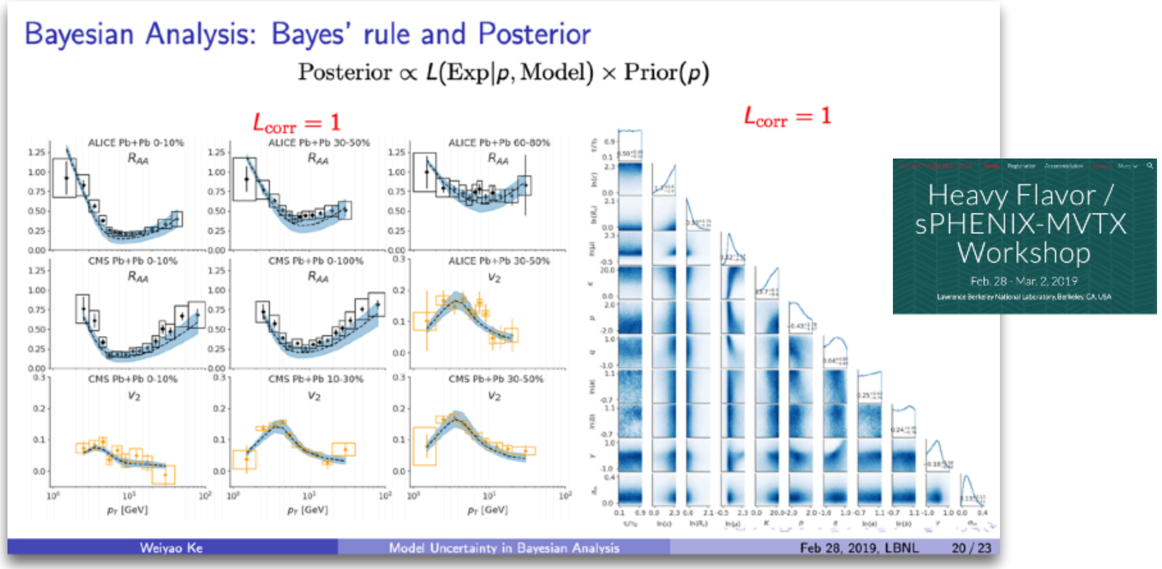


First sPHENIX MVTX staves produced at CERN

Key approach: Transport coefficients vs T



T-dependence of QGP structure, as reflected e.g. in transport coefficients has been sPHENIX focus since beginning



Bayesian inference key approach for both HF and jet sector (started in soft sector)

Data from two energy regimes, RHIC & LHC, essential to constrain T dependence

Many points of contact between sPHENIX and theory/LHC communities (e.g., LBNL HF workshop, work with Duke group, JETSCAPE collaboration).

Summary

- **Key goal of Hot QCD: Understand microscopic structure of QGP and the emergence of its unique long-wavelength properties**
- Toolkit of jet observables plays essential role
- Enormous growth in quantity and depth of jet measurements
- Growth comes with some growing pain
  - Need careful evaluation of experimental consistency and relation between different observables
  - It is not always clear whether we can exploit increased breadth/precision
  - Pressing problem as Run 3/sPHENIX are approaching
- JETSCAPE should play an essential role at theory/experiment interface
- **Much effort required to make connection to QGP microscopic structure**