Studies of Jet Quenching and the Induced Medium Excitation with the CMS detector

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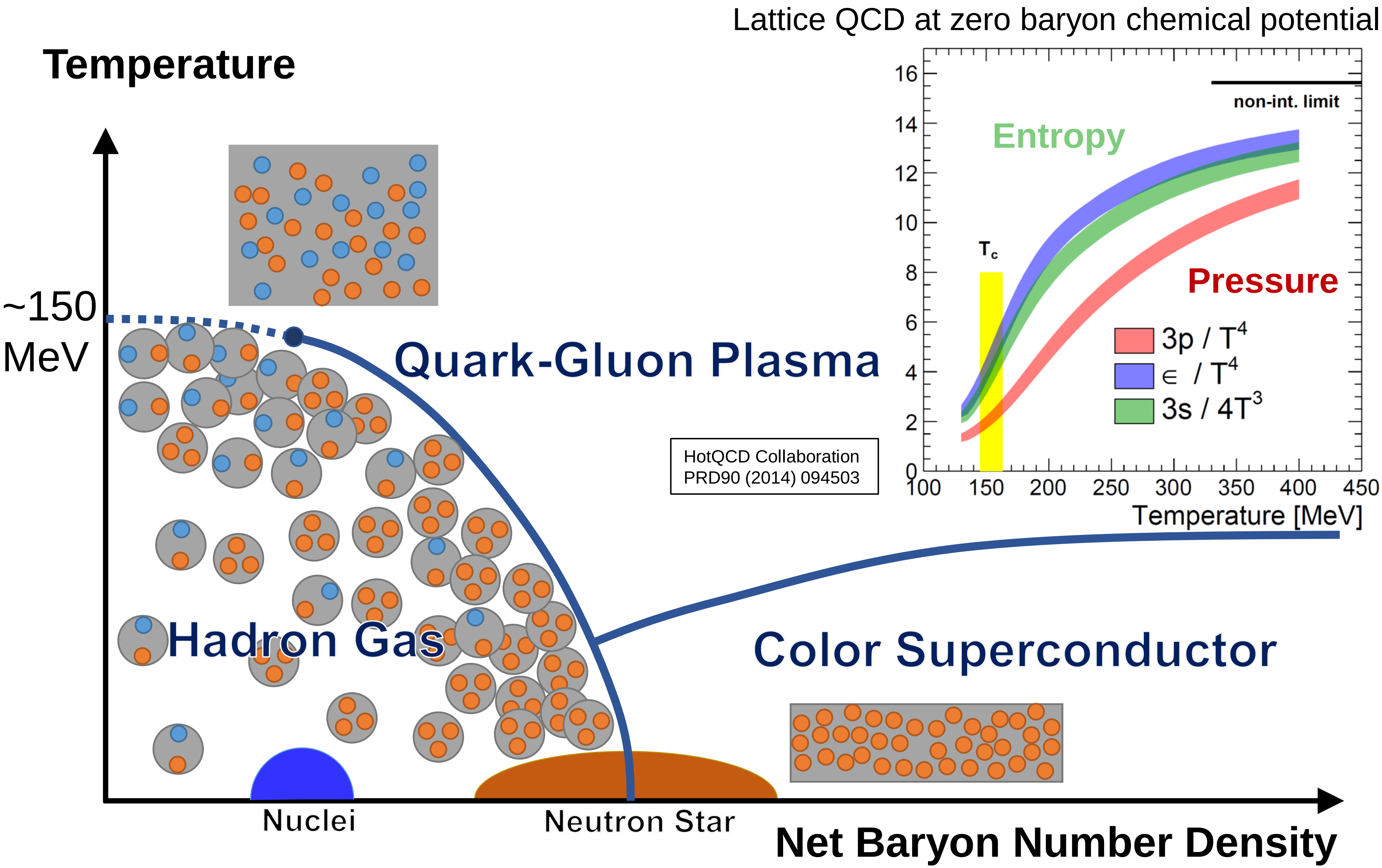
HENPIC Online Seminar

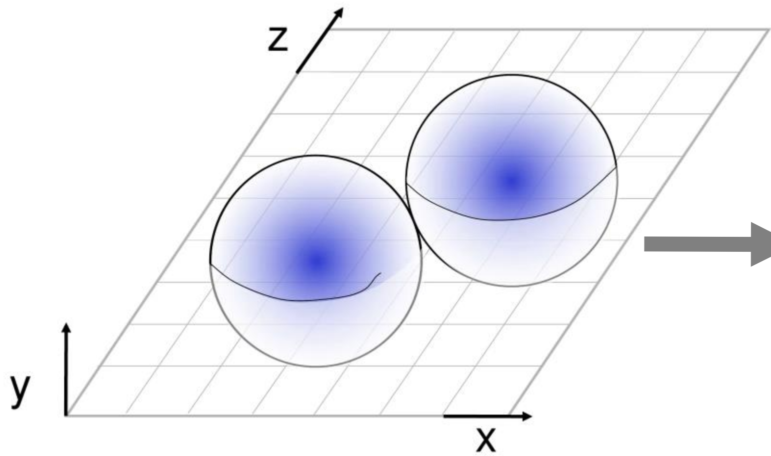
November 26, 2020

MIT HIG group's work was supported by US DOE-NP

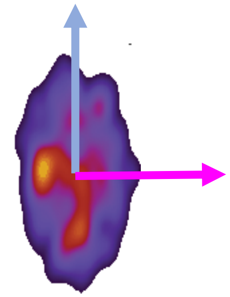
QCD Phase Diagram



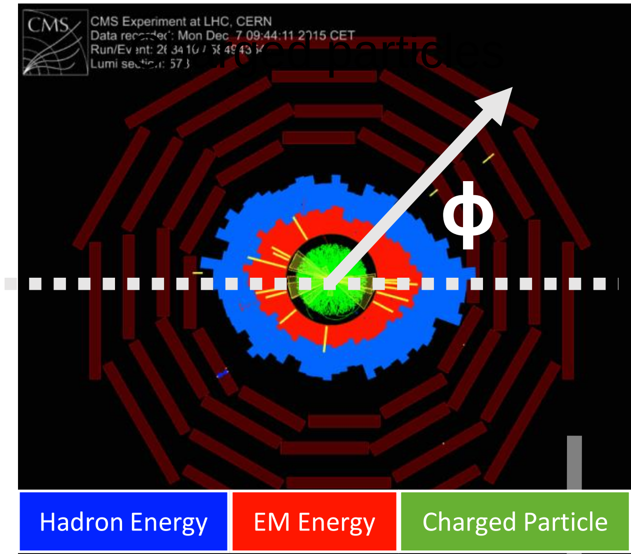
Pressure Driven Expansion of the Quark Soup



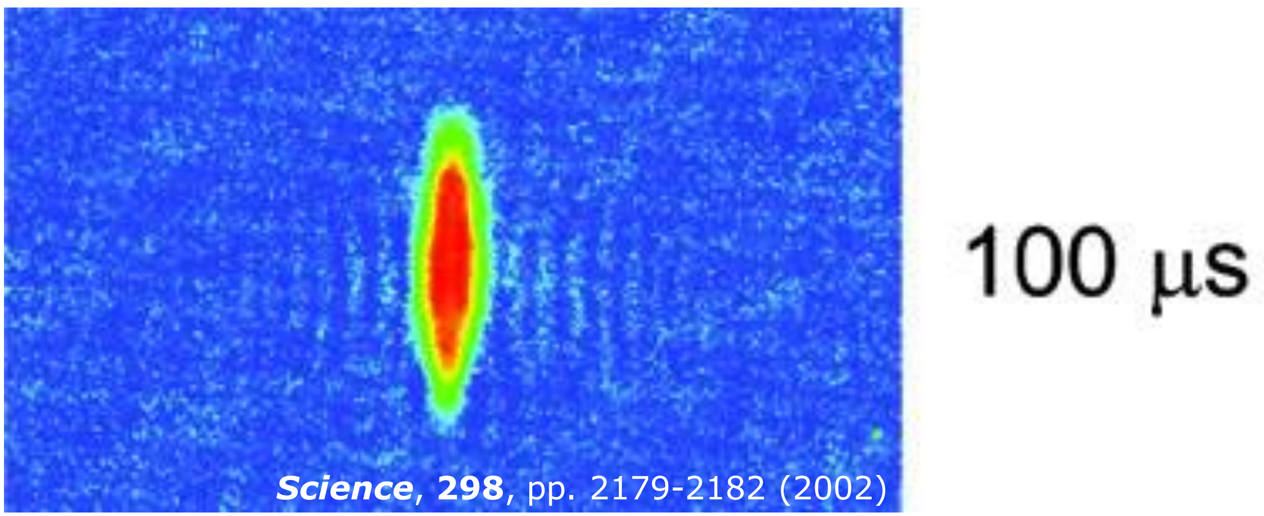
Small pressure gradient

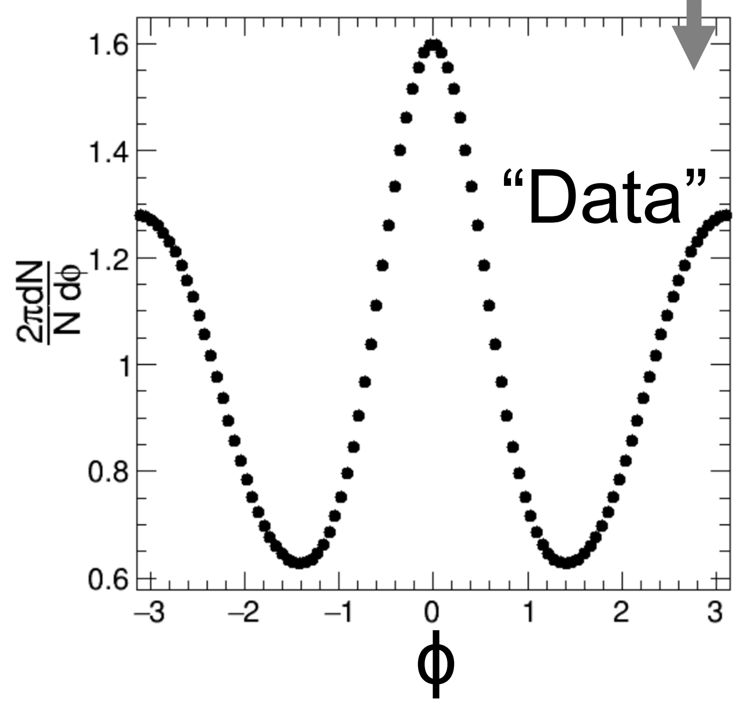


Large pressure gradient



Expansion of **Ultra-cold atoms (Li-6)** released from laser trap





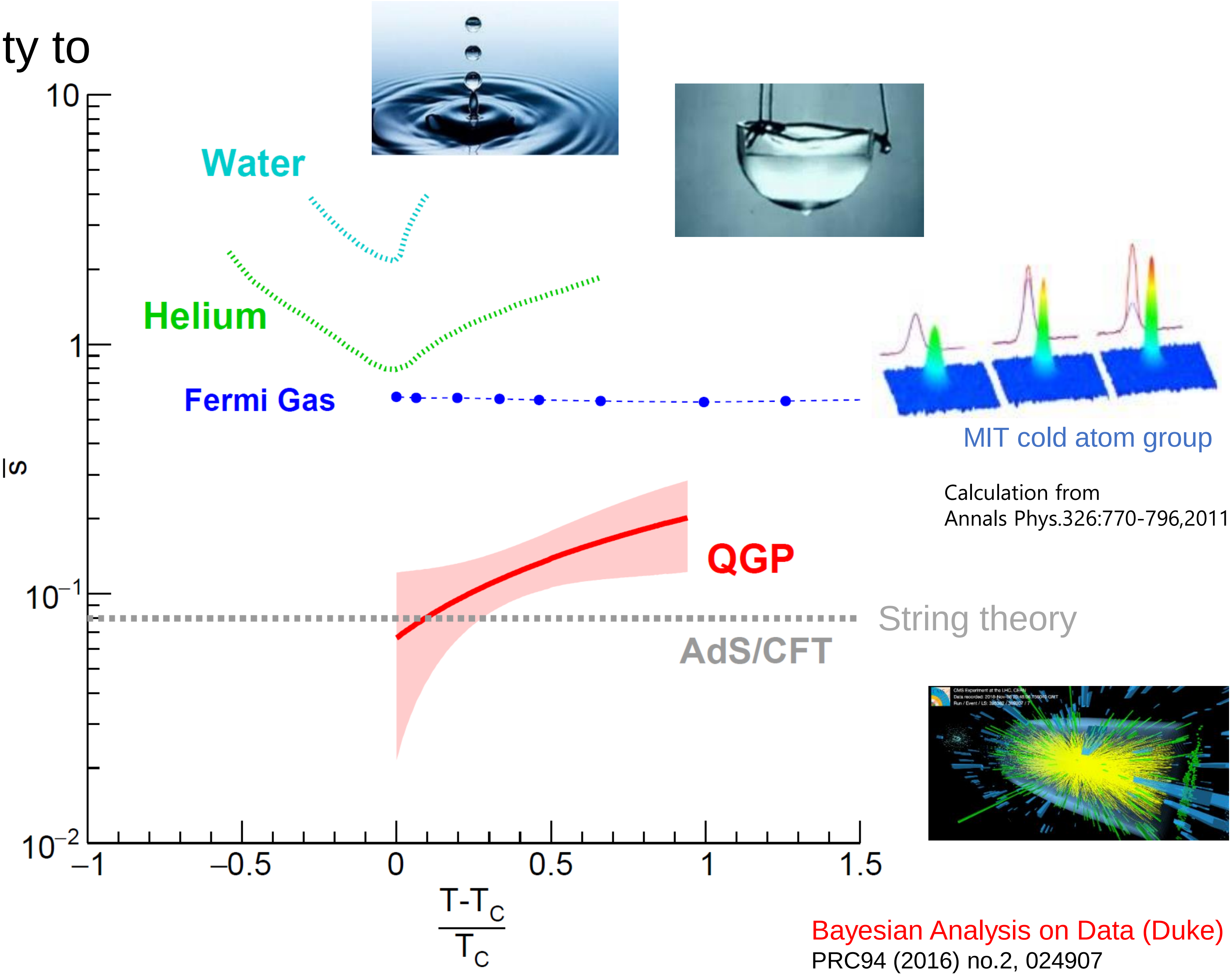
Particle Azimuth Angle Distribution

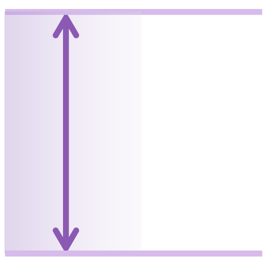
Collective motion is observed

→ **Early hydrodynamization!**

Near Perfect Fluid

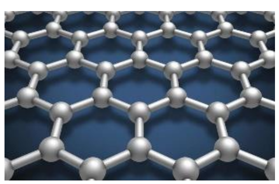
Shear viscosity to entropy ratio





Electron fluid in Graphene

PRL103,025301 (2019)

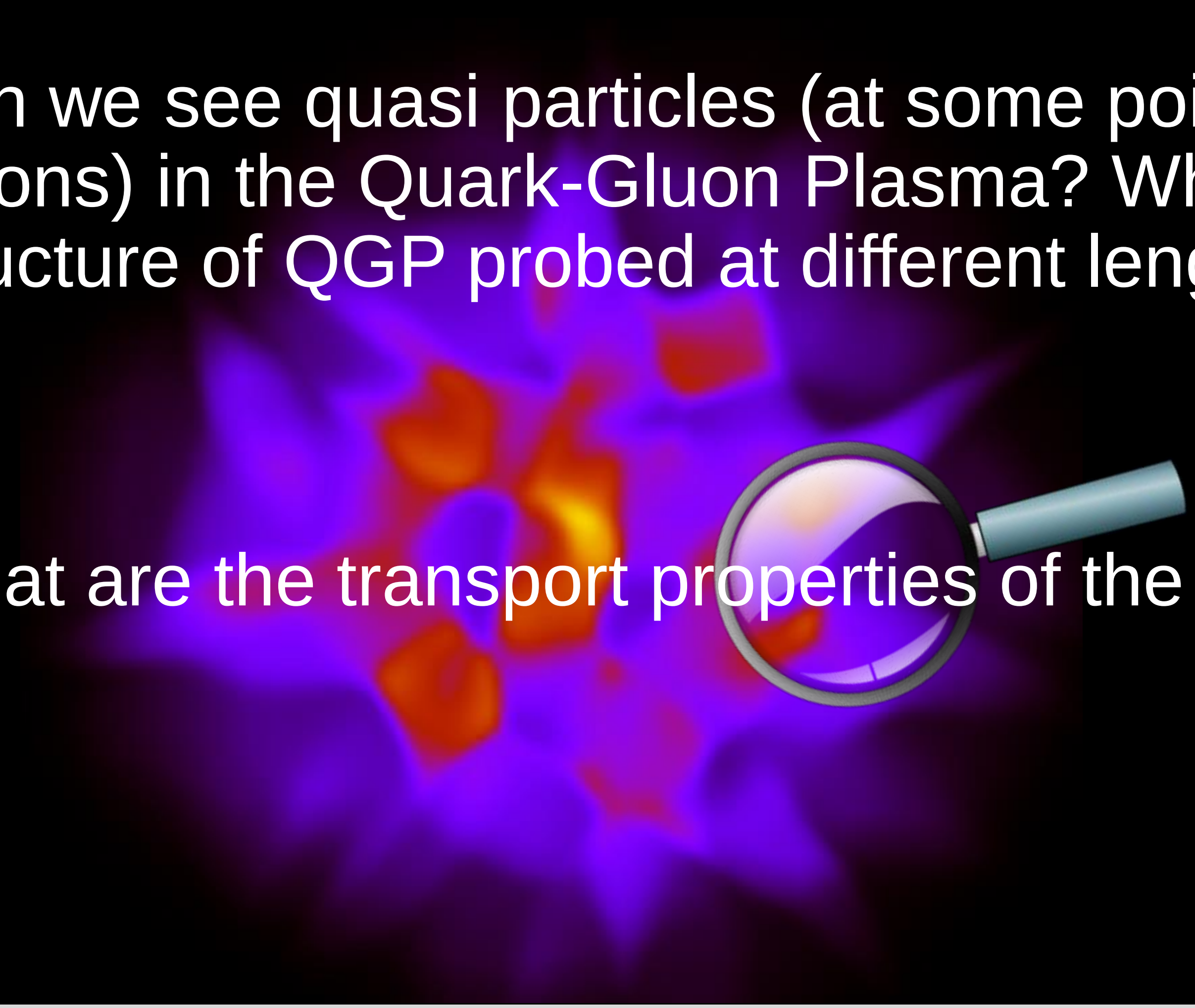


Beyond the Analysis of the Debris

- How does the strongly interacting medium emerge from an asymptotic free theory?

- Can we see quasi particles (at some point, quarks and gluons) in the Quark-Gluon Plasma? What is the structure of QGP probed at different length scales?

- What are the transport properties of the medium?



Probe the Quark Soup!

- How does the strongly interacting medium emerge from an asymptotic free theory?

Start from "un-thermalized" objects and see how they are thermalized in the Quark Soup

- Can we see quasi particles (at some point, quarks and gluons) in the Quark-Gluon Plasma? What is the structure of QGP probed at different length scales?

"QGP Rutherford Experiment"

- What are the transport properties of the medium?

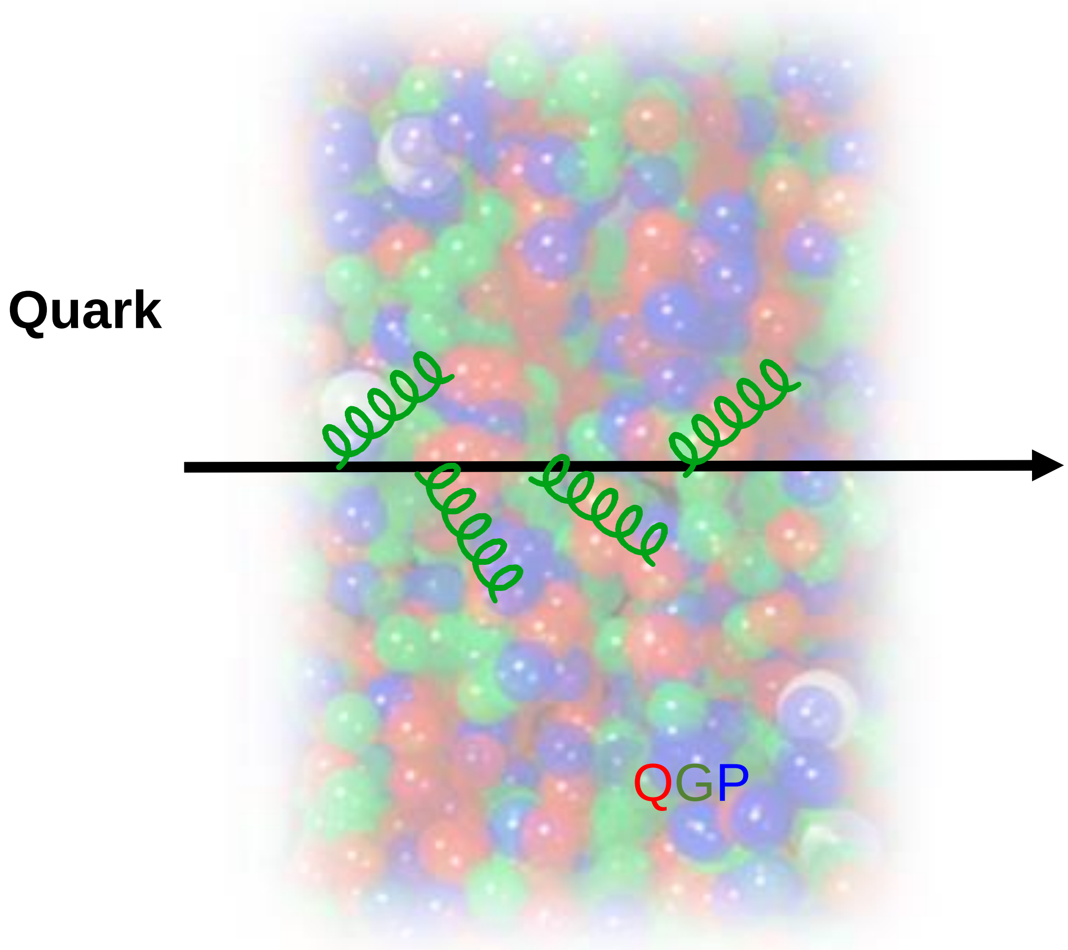
Study how Colored Probes are modified by QGP
Study how QGP respond to Colored Probes

Jetting through the Quark Soup

James Bjorken (1982)

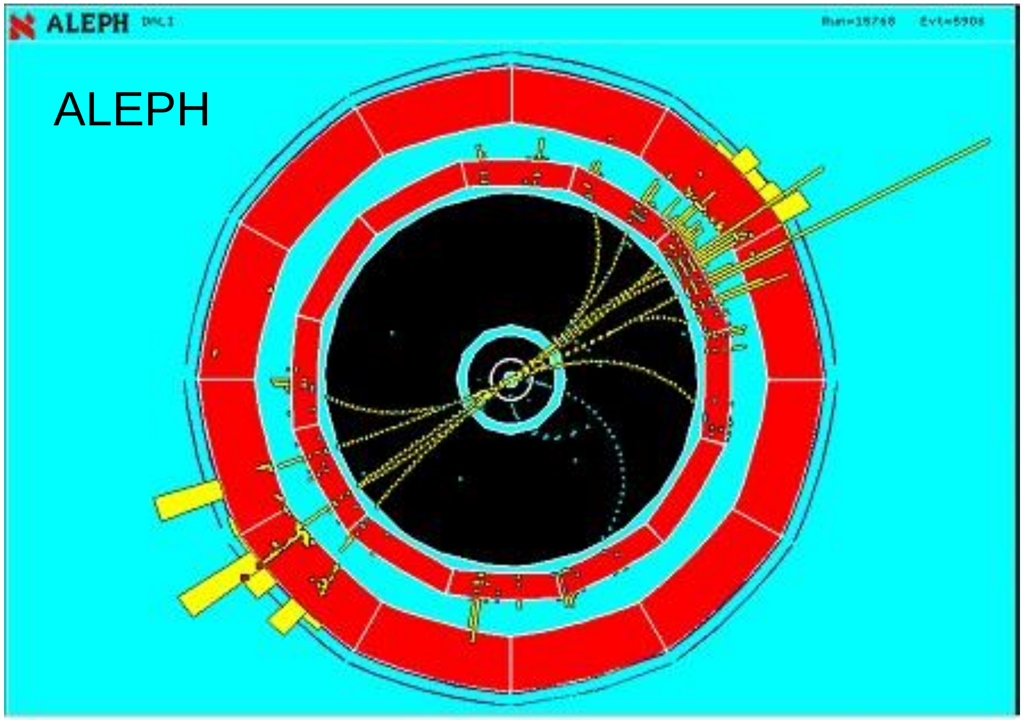
Jet Quenching

Lifetime O(10^{-24}s)



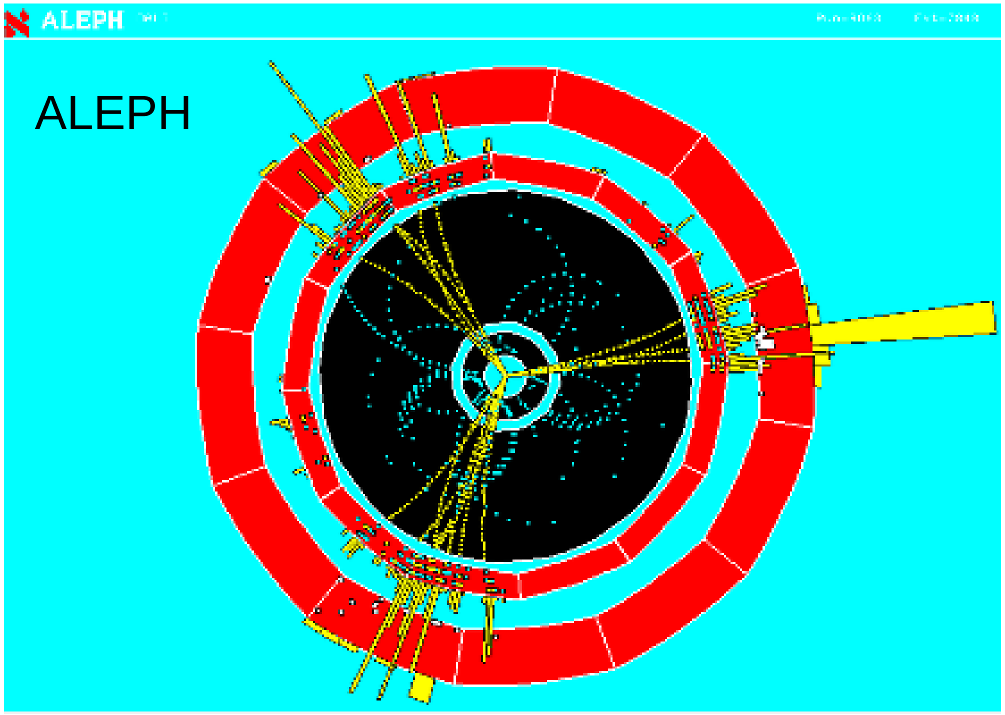
Detecting Quarks and Gluons

Dijet event



$$e^+ + e^- \to q + \bar{q}$$

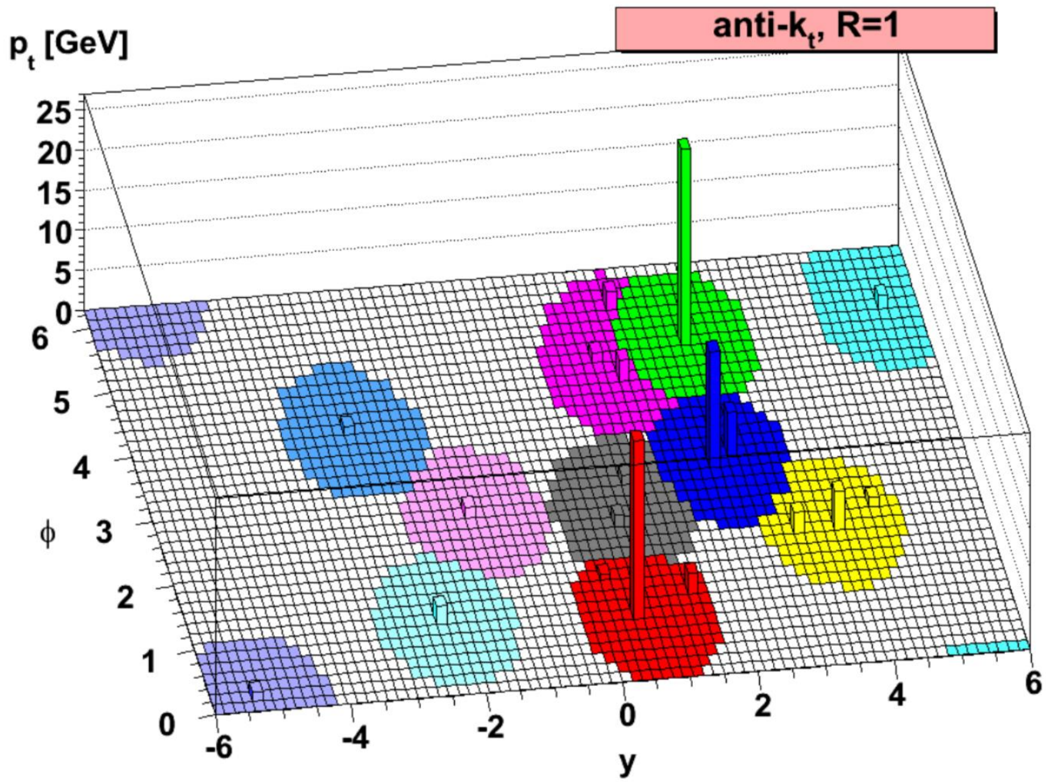
Trijet event



$$e^+ + e^- \to q + \bar{q} + g$$

Jets (defined by jet clustering algorithm) are used as a proxy of quarks and gluons

Jet Clustering Algorithm



Anti-k_t algorithm

Cluster smallest distance d_{ab} pair first

$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}$$

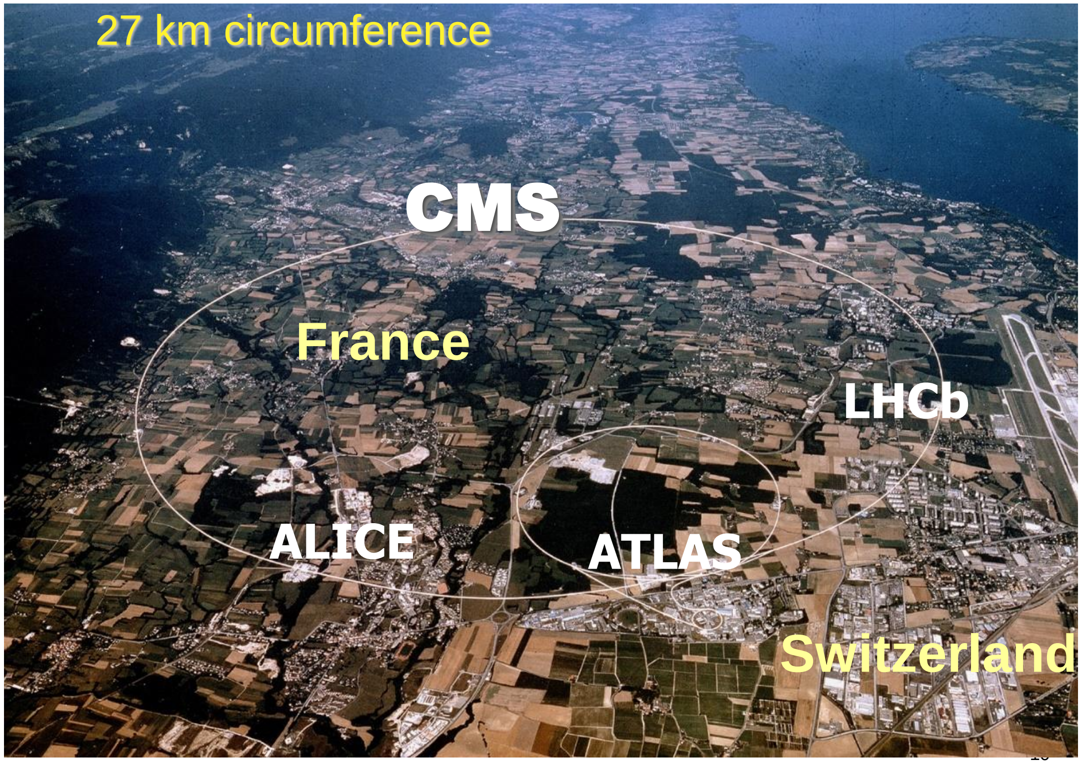
$$d_{iB} = k_{t,i}^{-2}$$

R: distance parameter

- Give circular jet, cluster high momentum particles first
  - Circular with a radius of roughly **R**
- Most popular algorithm used in pp and heavy ion collisions

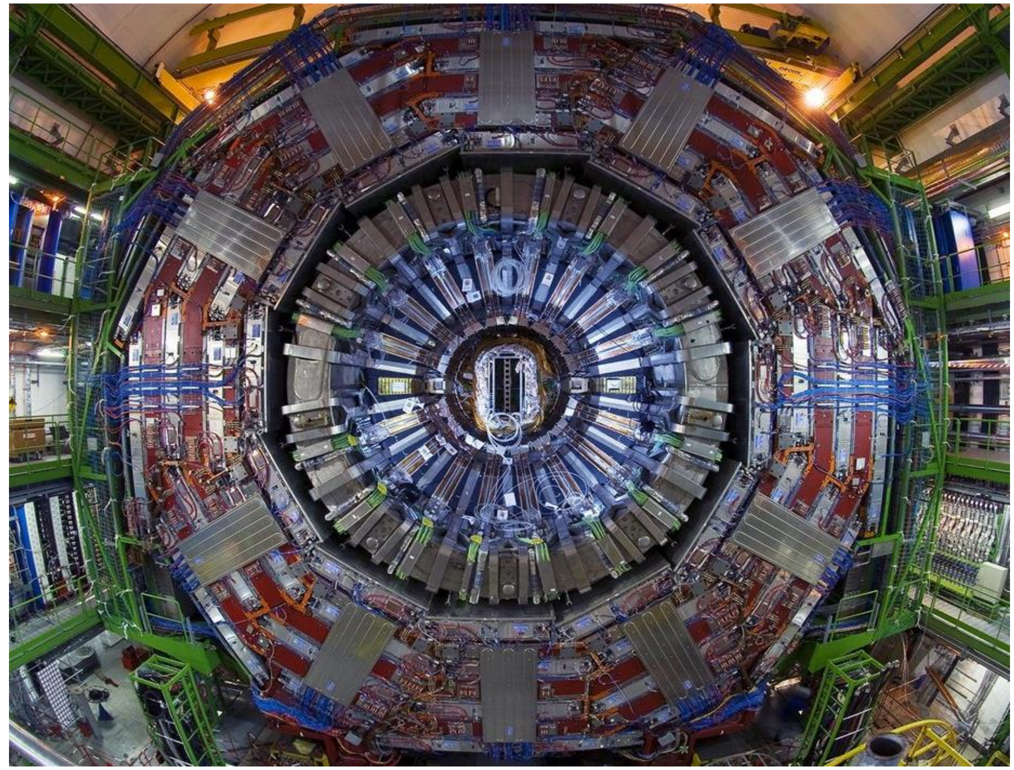
High Energy (Temperature) Frontier

Large Hadron Collider



Lead+Lead (PbPb) collisions
2010-11: 2.76 TeV 0.16/nb
2015-18: 5.02 TeV 2.1/nb

Compact Muon Solenoid

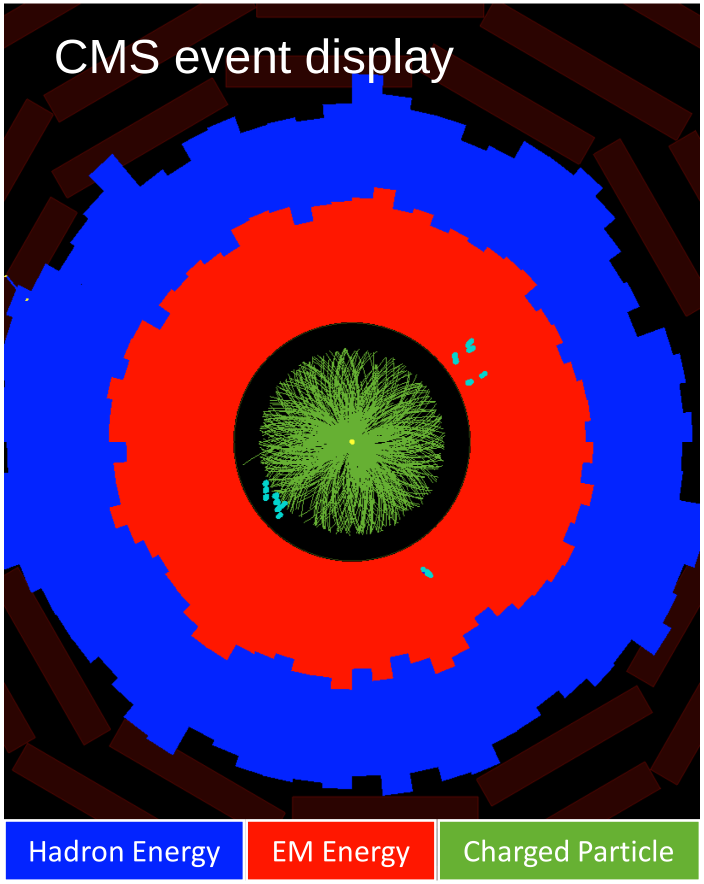


Also smaller system data:
p+Pb at 5.02 & 8.16 TeV
Xe+Xe at 5.44 TeV

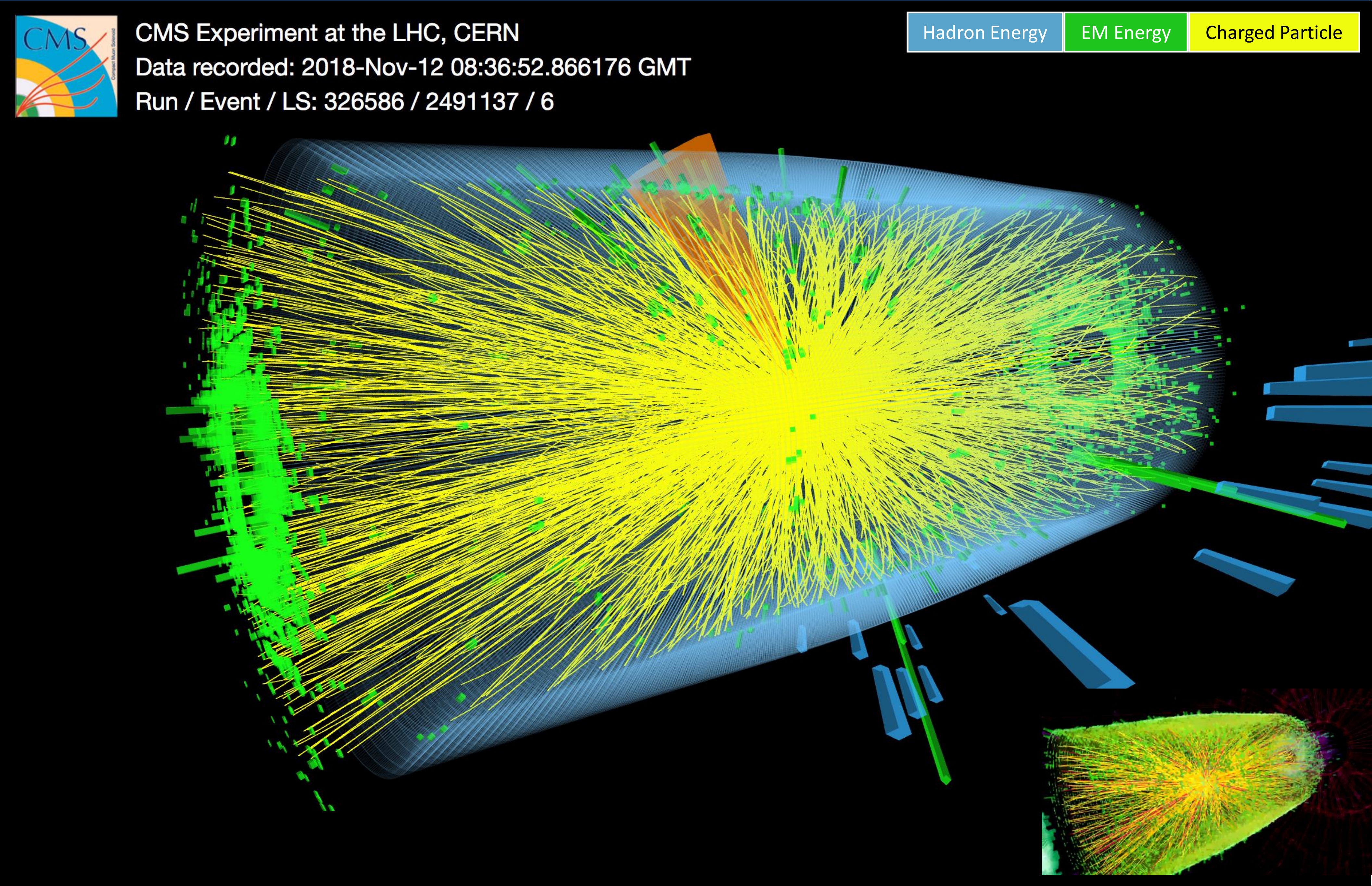
A flying mosquito has about 2 trillion electronvolts **(2TeV)** of kinematic energy

CMS Data Taking

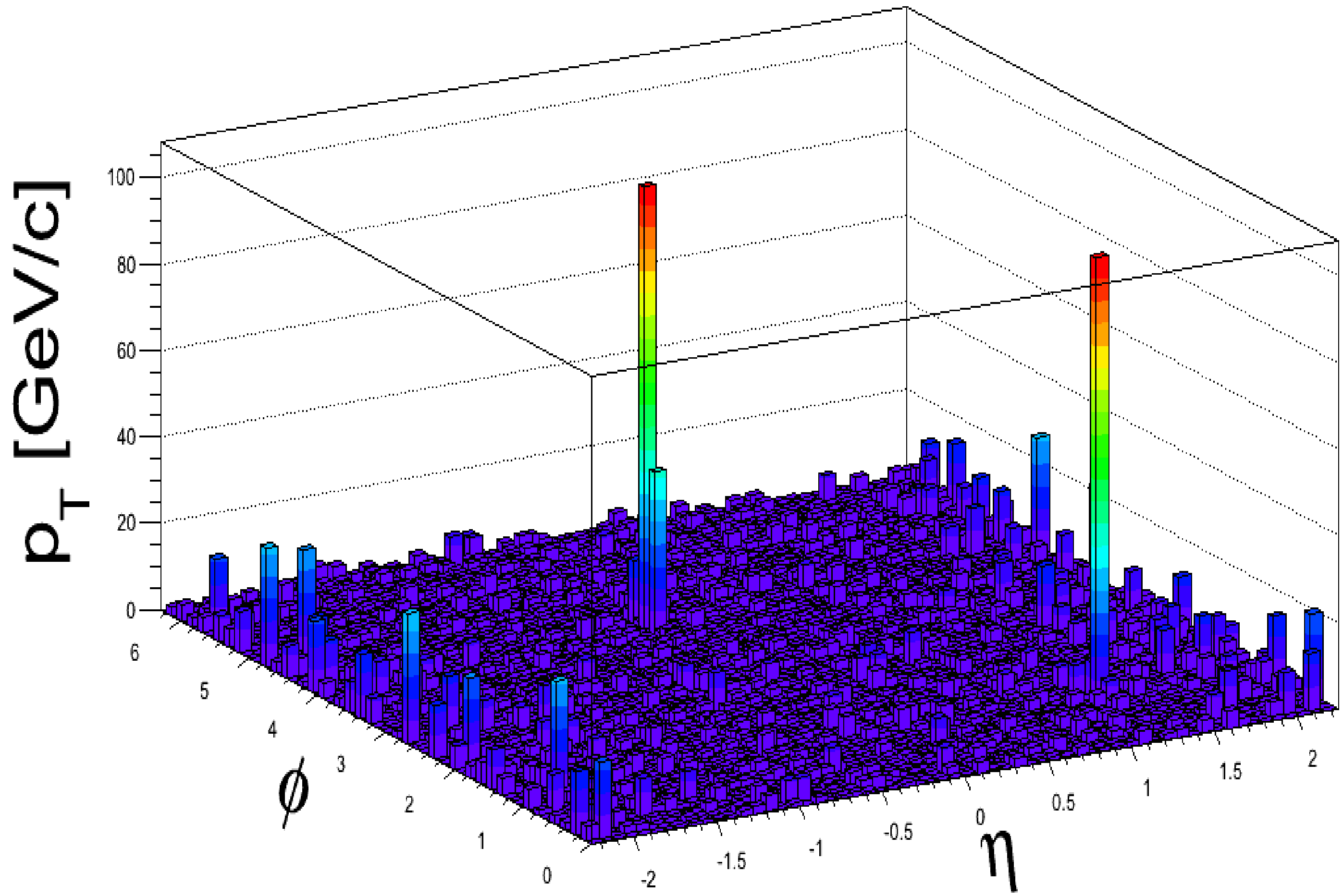
- LHC delivers heavy ion collisions for one month per year
- 2018: CMS PbPb collision data rate up 50 kHz; peak data throughput 9 GB/s



Lead-Lead Collision Recorded by CMS (2018)



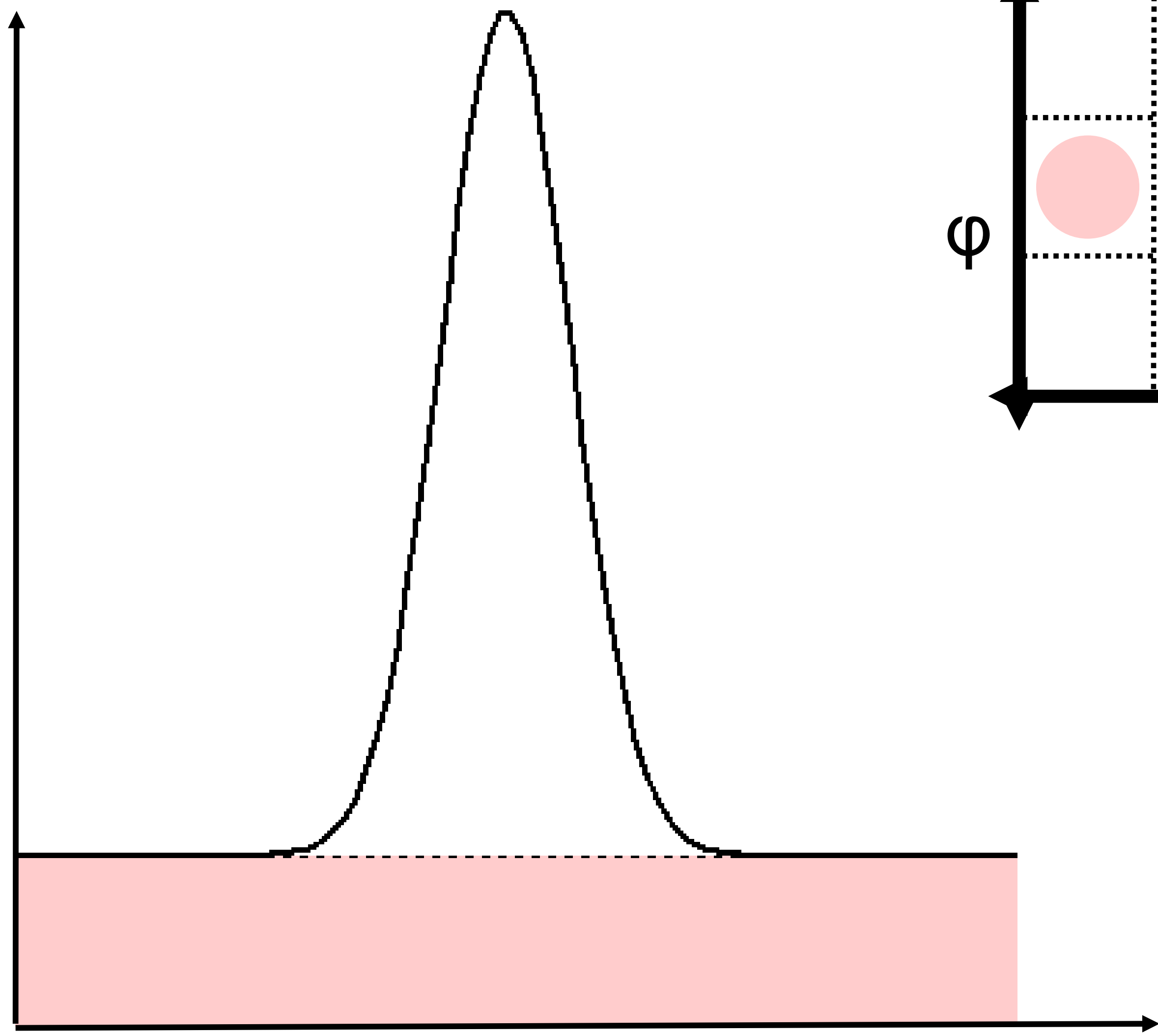
A jet event in PbPb collision

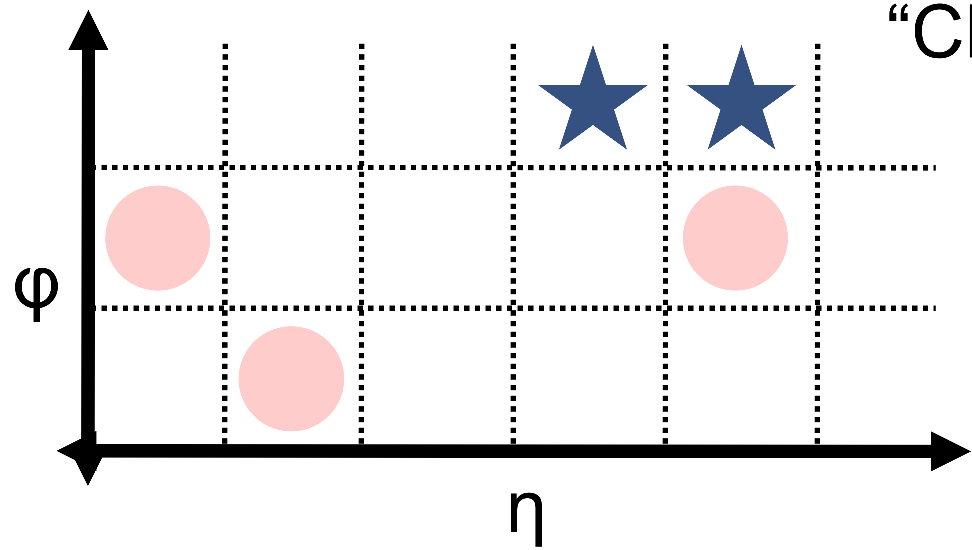


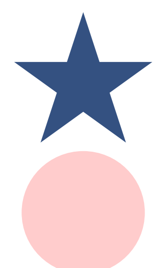
- Background changes with η due to particle density and detector geometry
- An **iterative background subtraction** algo is used in most of the CMS papers
- However the algorithm limits the resolution of subjet

EPJC 50 (2007) 117-123

Constituent Subtraction



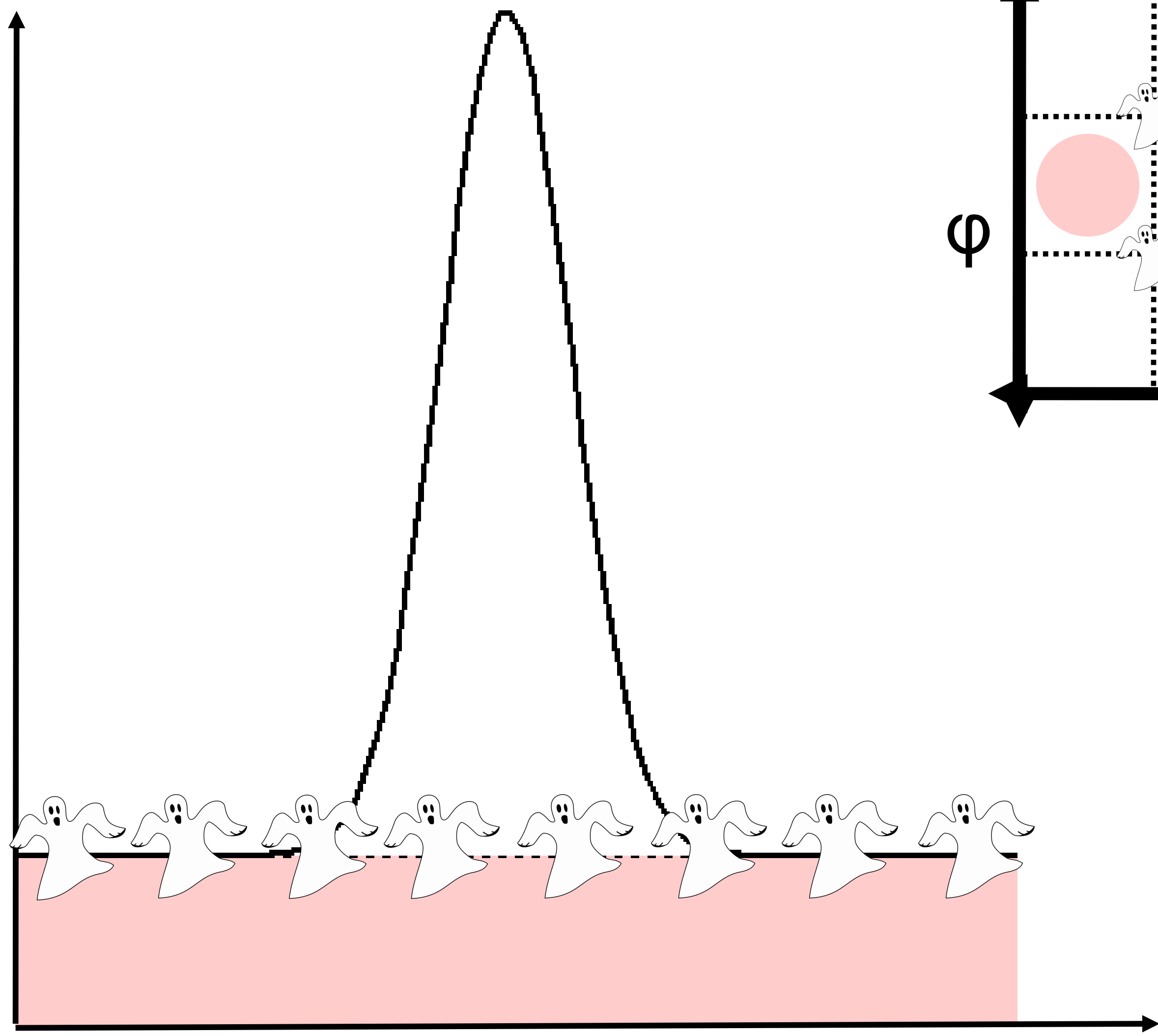


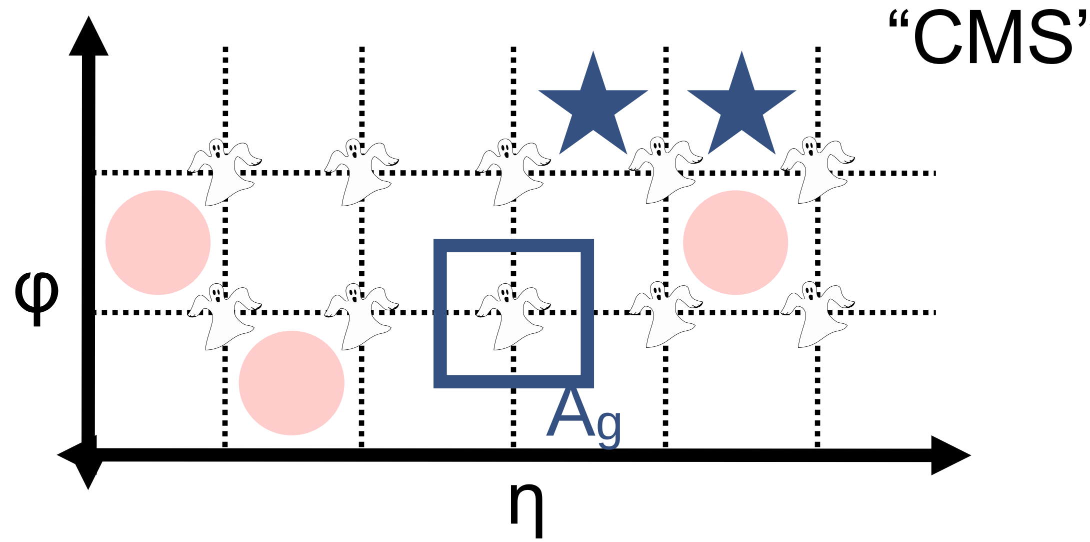


Constituent subtraction

JHEP06 (2014) 092

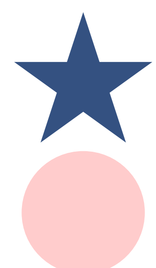
Constituent Subtraction





GHOST: Artificial particles added on an η-φ grid. Given a p_T according to energy density **ρ** times the area it inhabits, A_g

$$p_{\mathrm{T}}^{g} = A_g \cdot \rho,$$
$$m_{\delta}^{g} = A_g \cdot \rho_m$$



SIGNAL

UNDERLYING EVENT

Constituent subtraction

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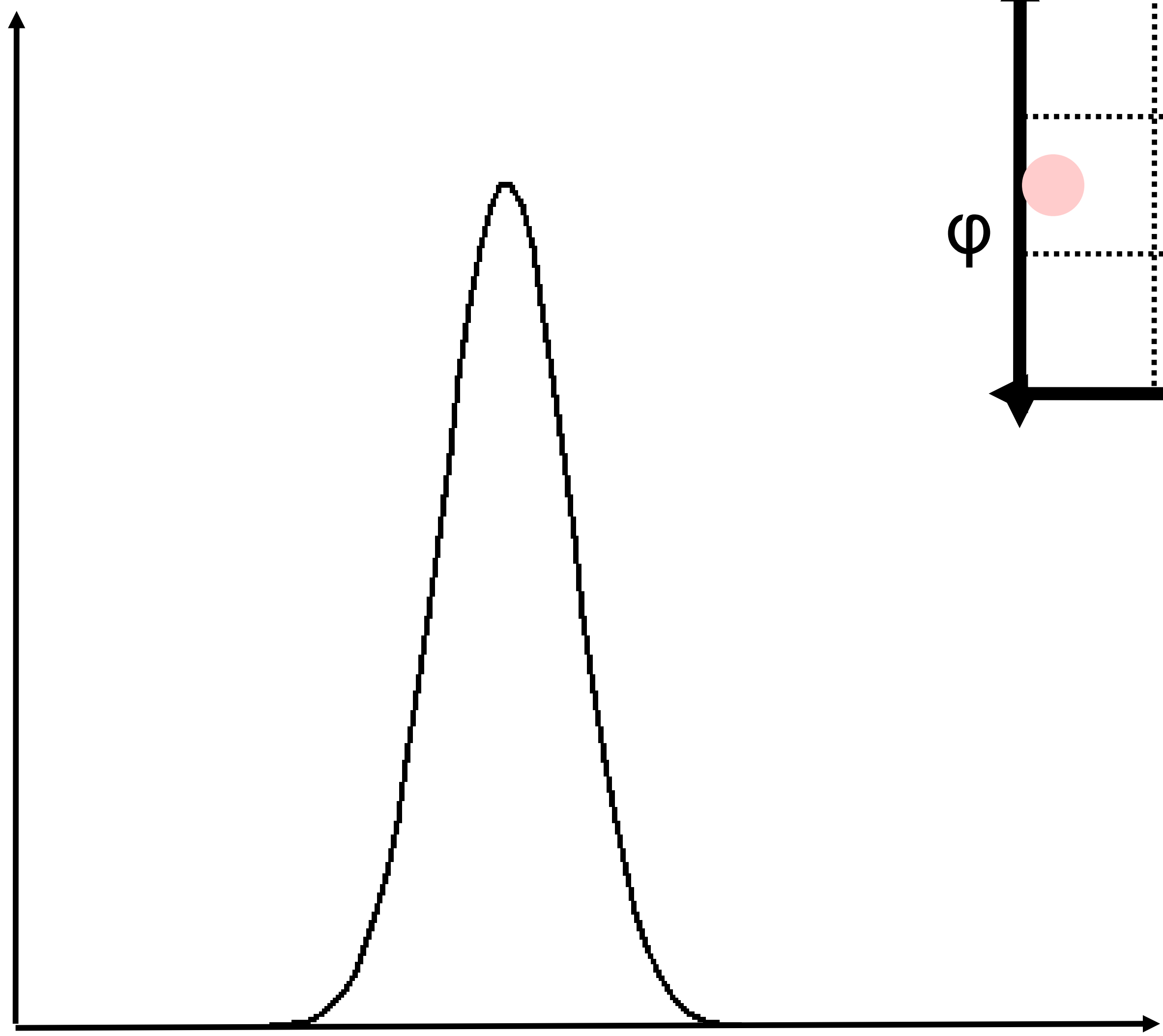
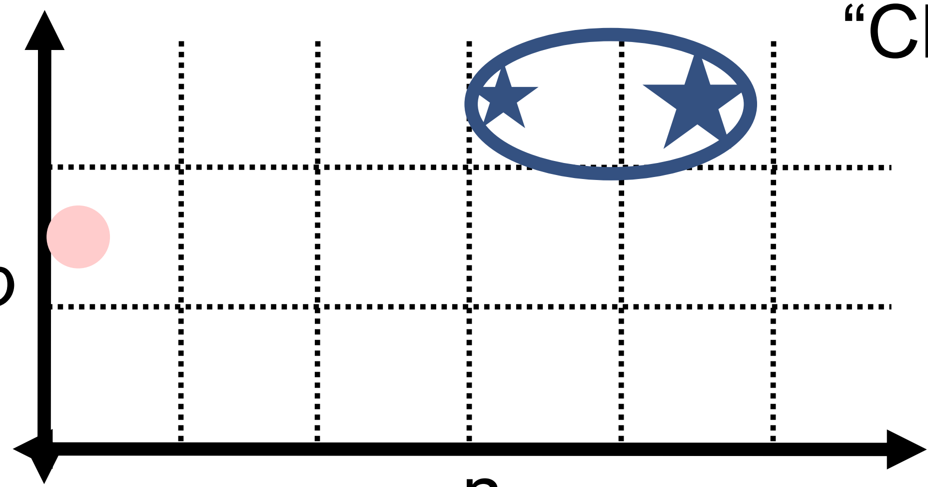
Constituent Subtraction





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SIGNAL

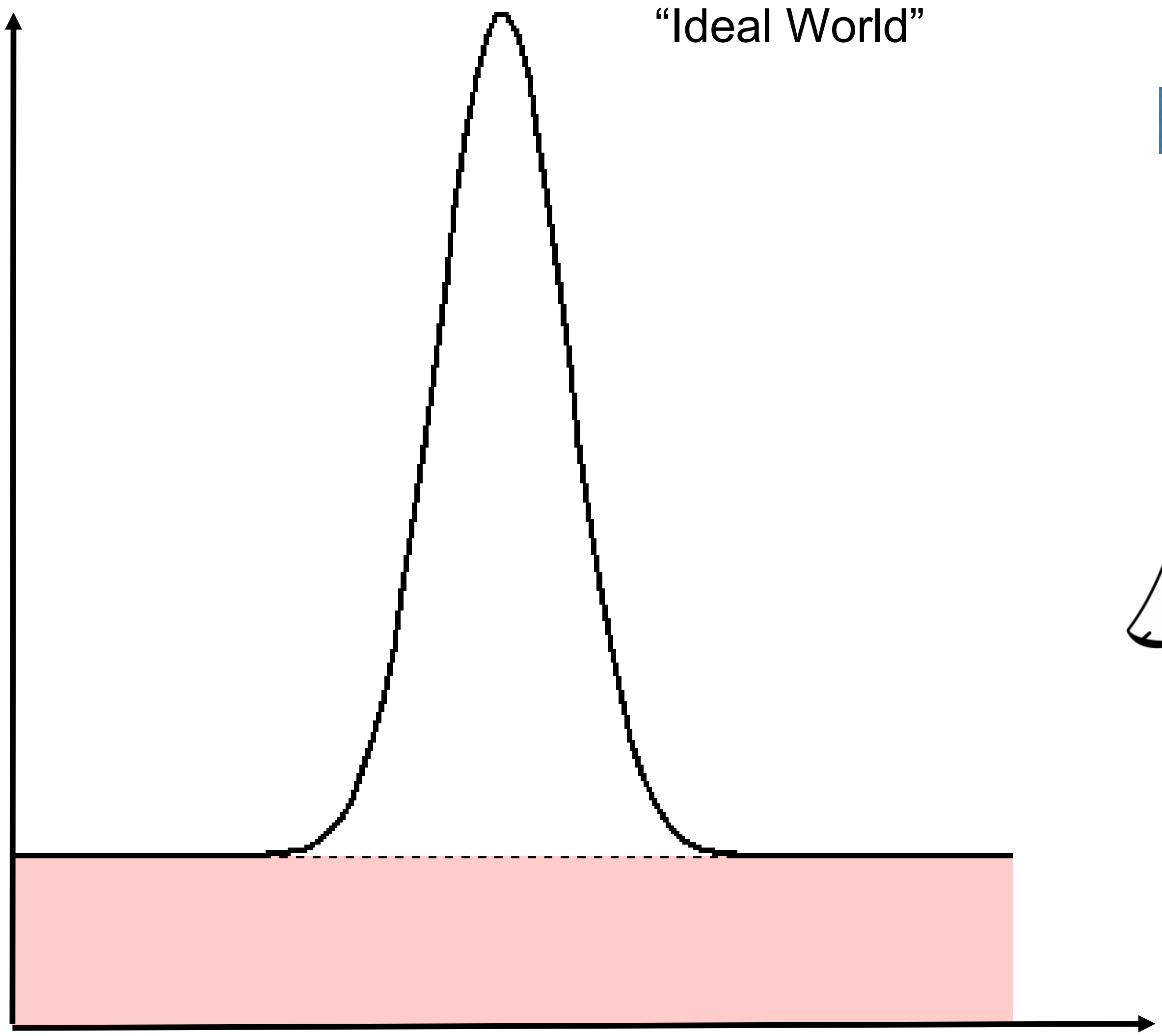
UNDERLYING EVENT

Constituent subtraction

JHEP06 (2014) 092

Used in jet substructure (**Z_g**, **mass**) measurements

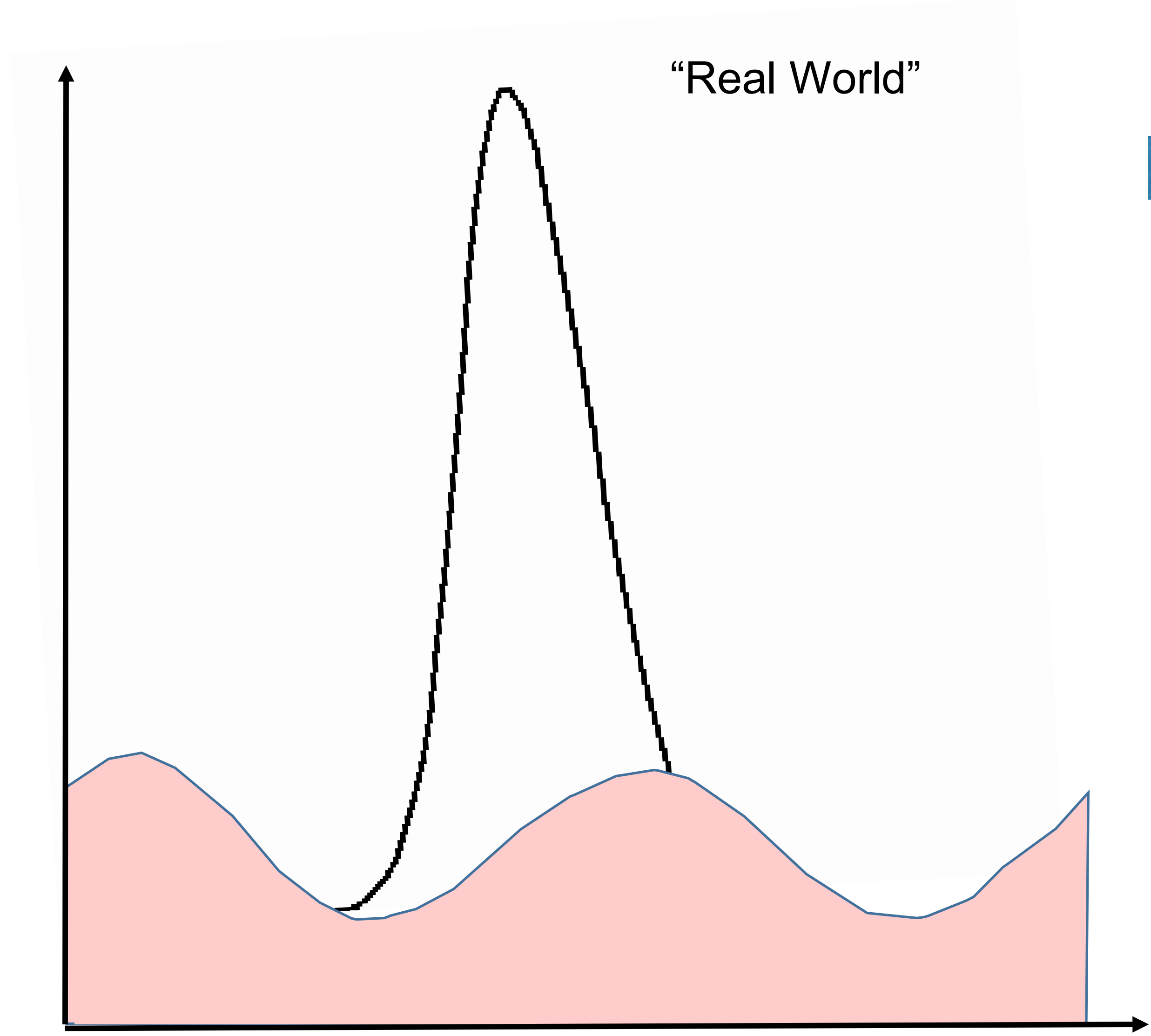
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction

Constituent Subtraction



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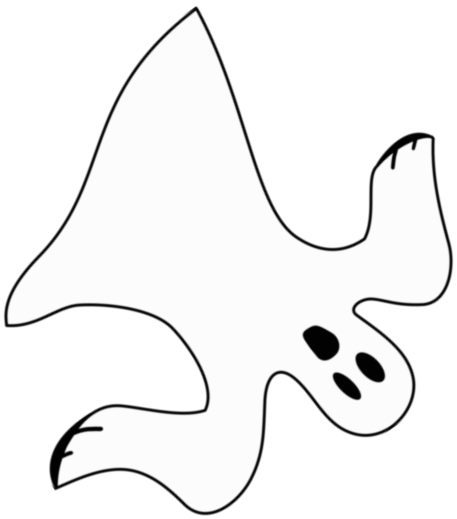
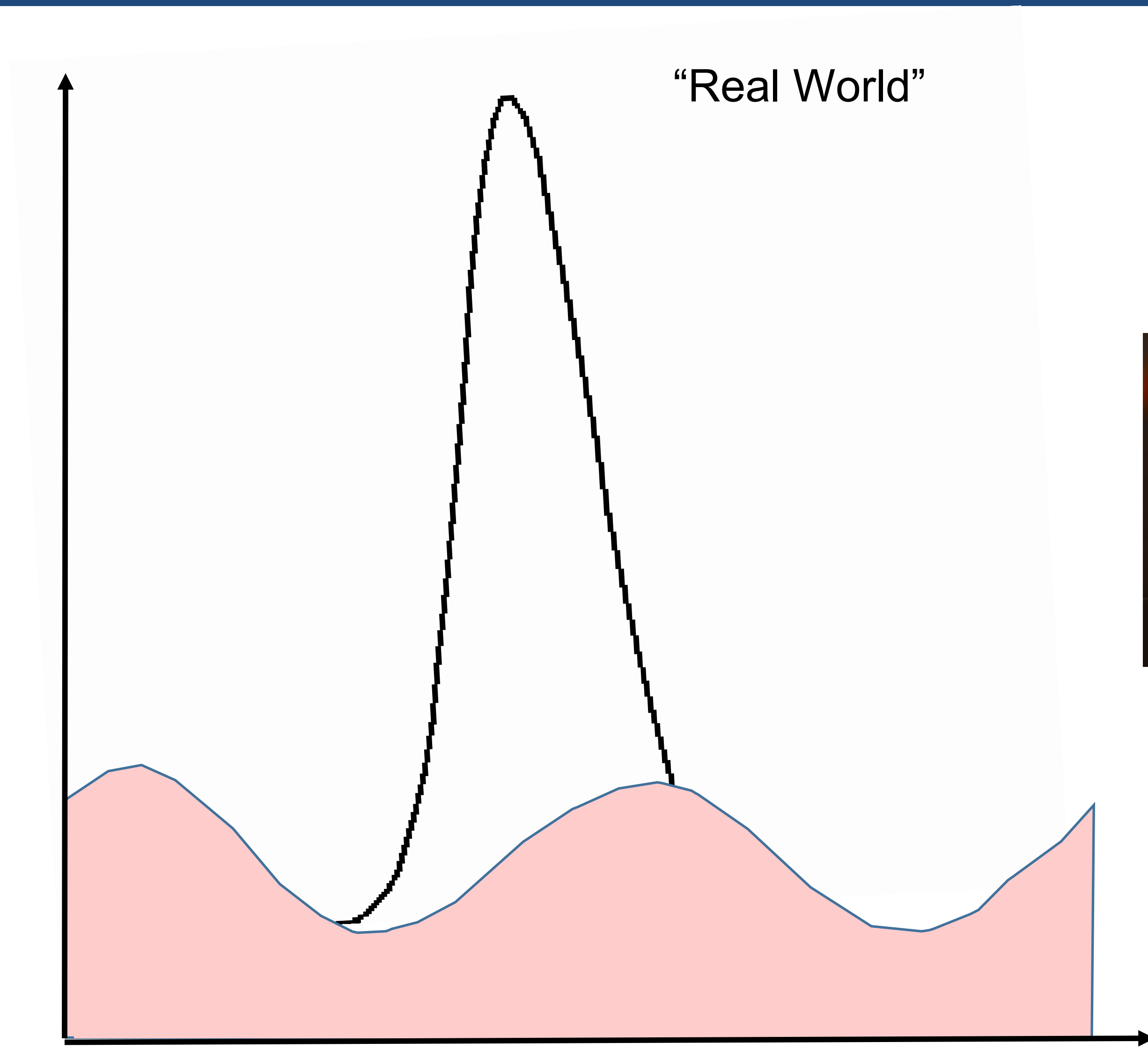


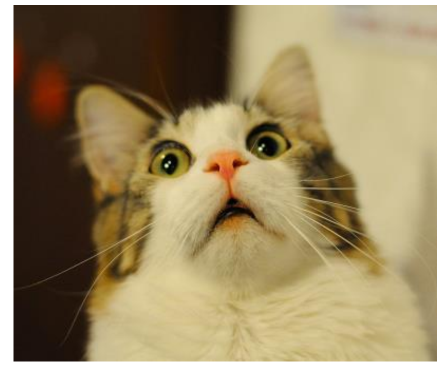
Constituent subtraction

Constituent Subtraction with Flow

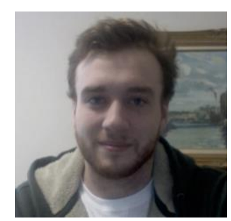


JHEP06 (2014) 092

A smarter ghost



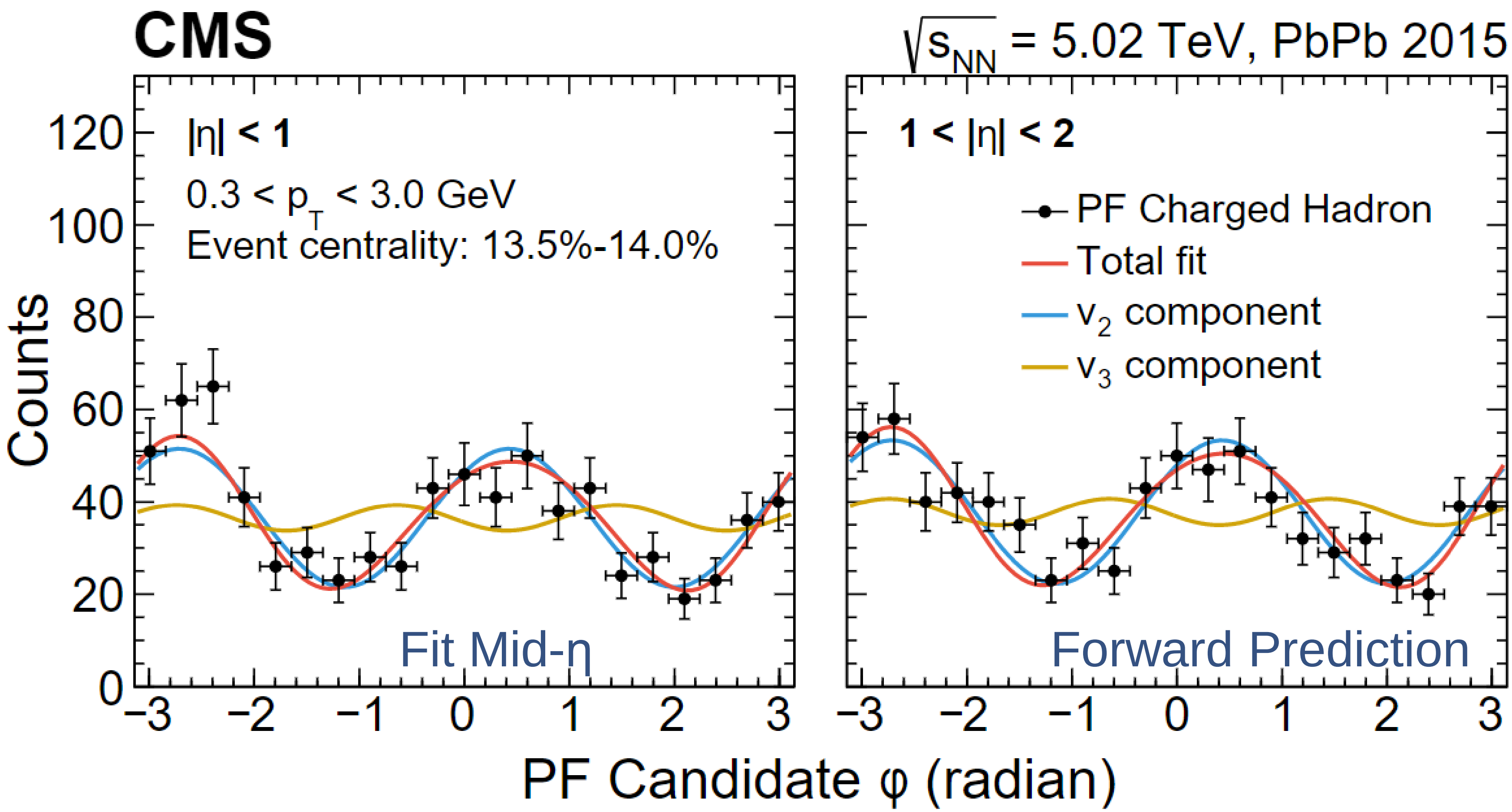
Developed by



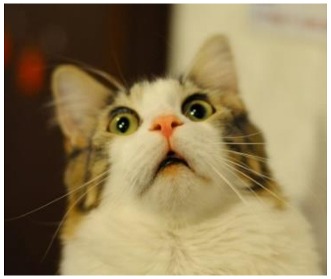
By Chris McGinn

Constituent subtraction **with flow modulation**

Estimating Flow Event-by-Event



A smarter ghost

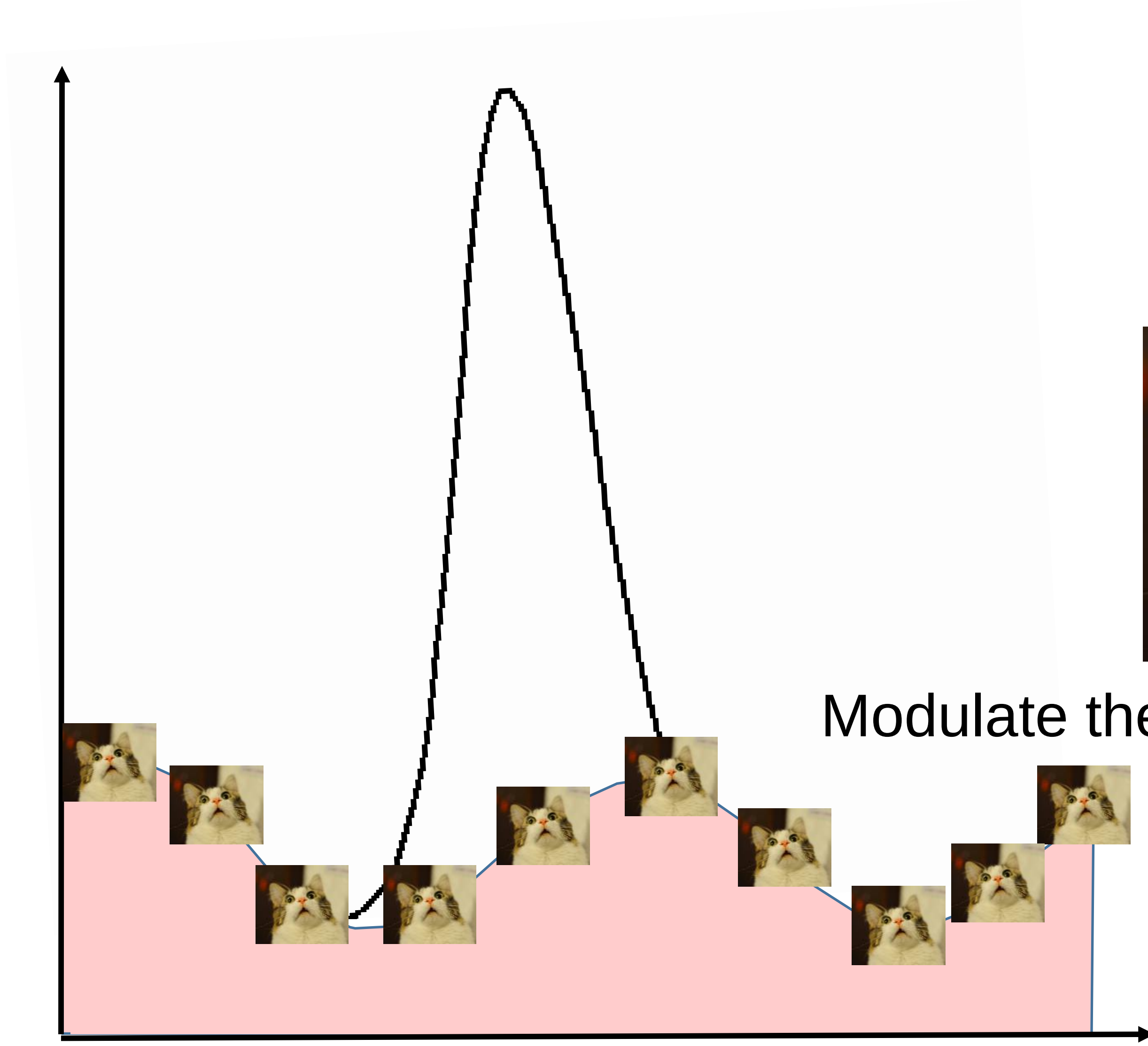


Following Example Of: Phys.Lett. B 753 (2016) 511-525

- Extract an event-by-event v_2 and v_3 by fitting particle flow candidates
  - Charged Hadron candidates, $0.3 < p_T < 3$ and $|\eta| < 1$
  - Fit result on mid-η data is used all η to model flow
- Extracted v_2(v_3) are used to modulate CS ρ to add ghost particles

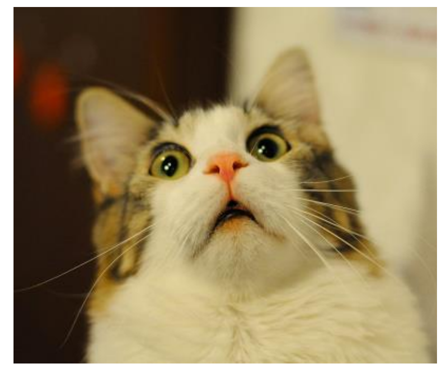
Fig. From: CMS-DP-2018

Constituent Subtraction with Flow



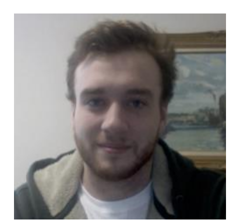
JHEP06 (2014) 092

A smarter ghost



Modulate the energy of ghosts!

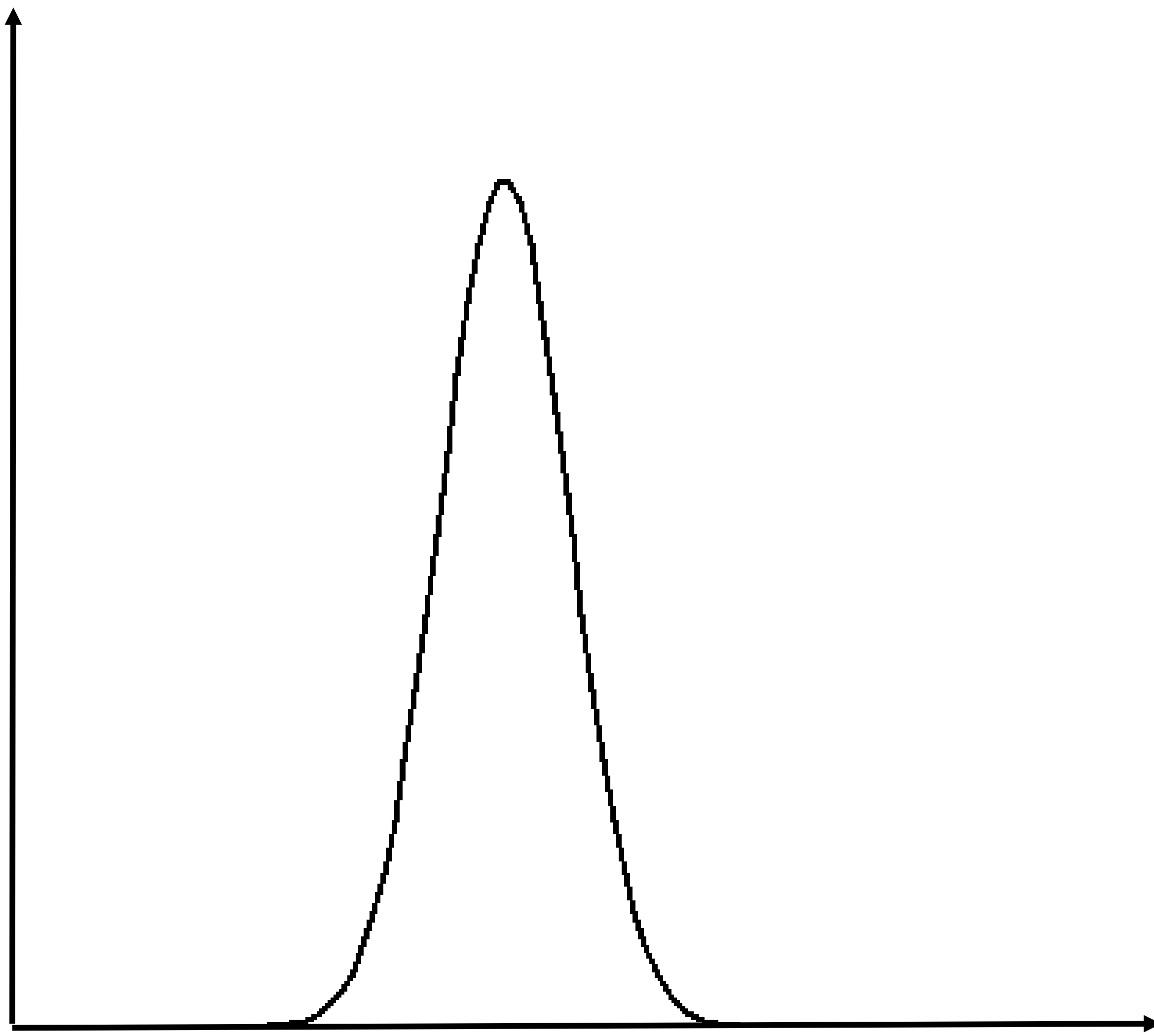
Developed by



By Chris McGinn

Constituent subtraction **with flow modulation**

Constituent Subtraction with Flow



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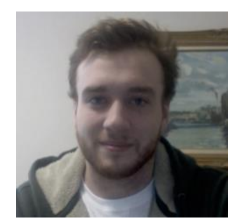
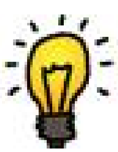
Developed by



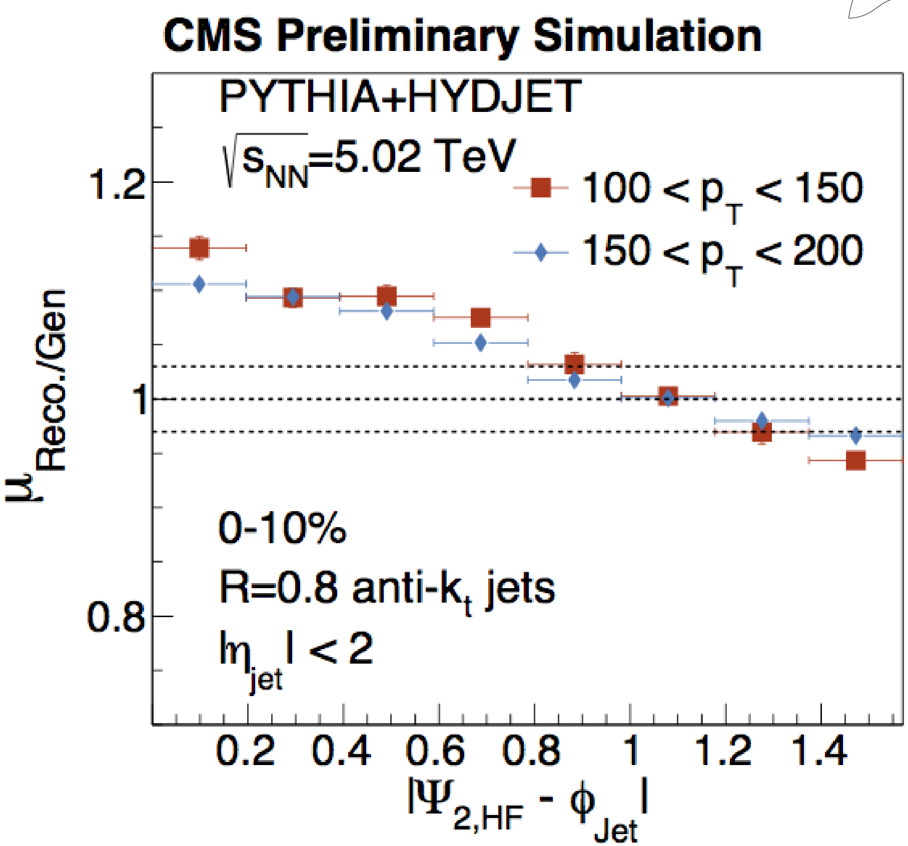
By Chris McGinn



Constituent subtraction **with flow modulation**

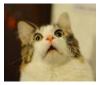
Scale Closure vs. Event Plane (R=0.8)

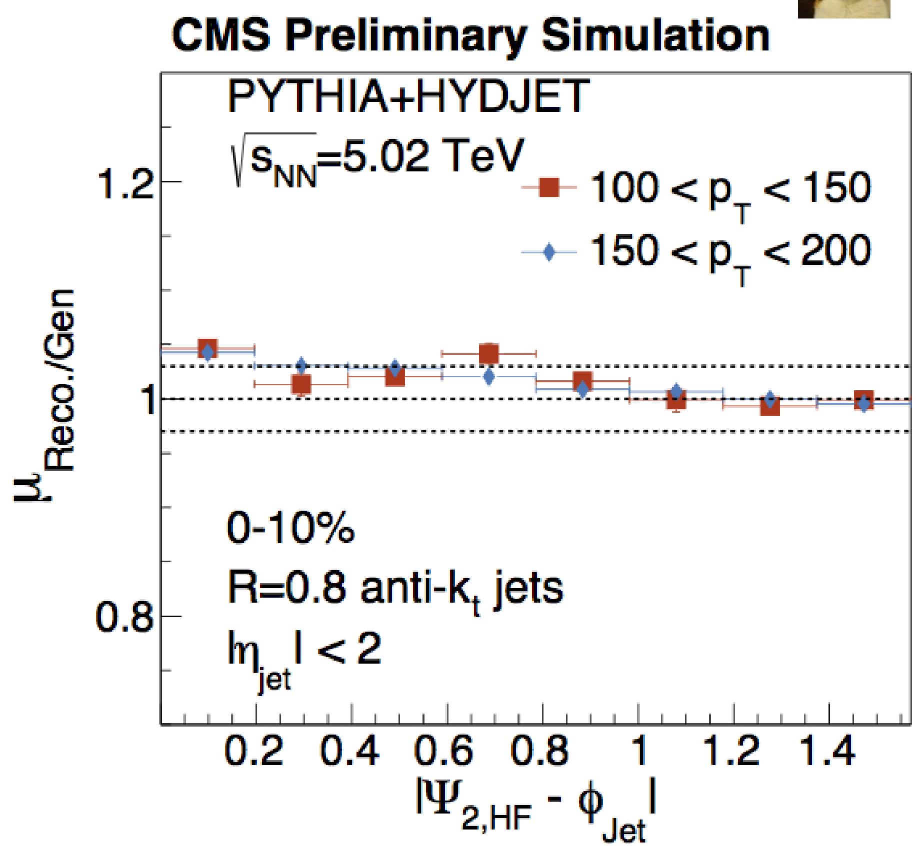
Without flow modulation



Add
Flow
Correction

With flow modulation

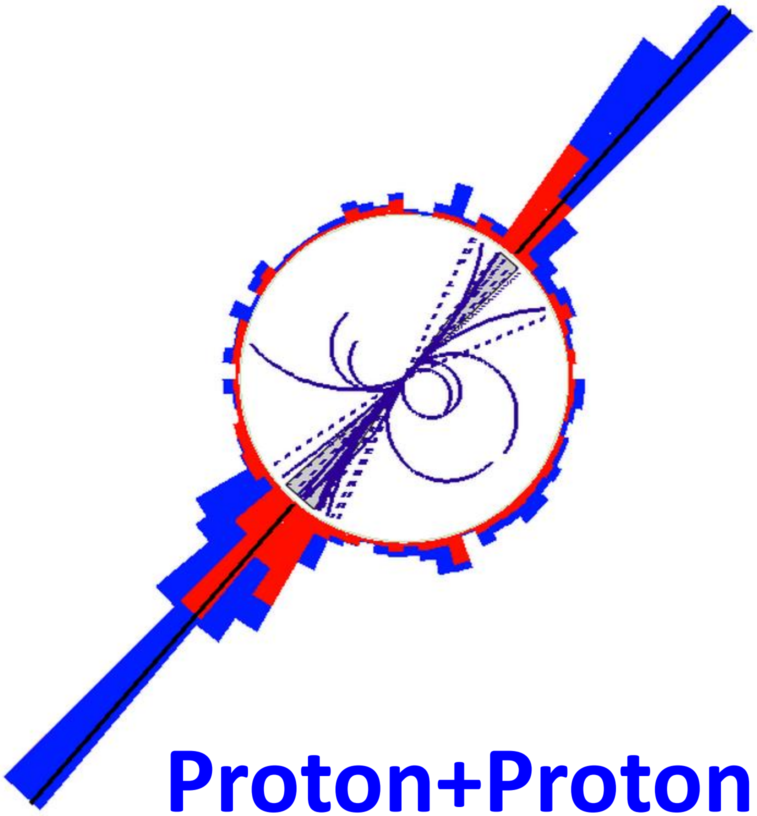




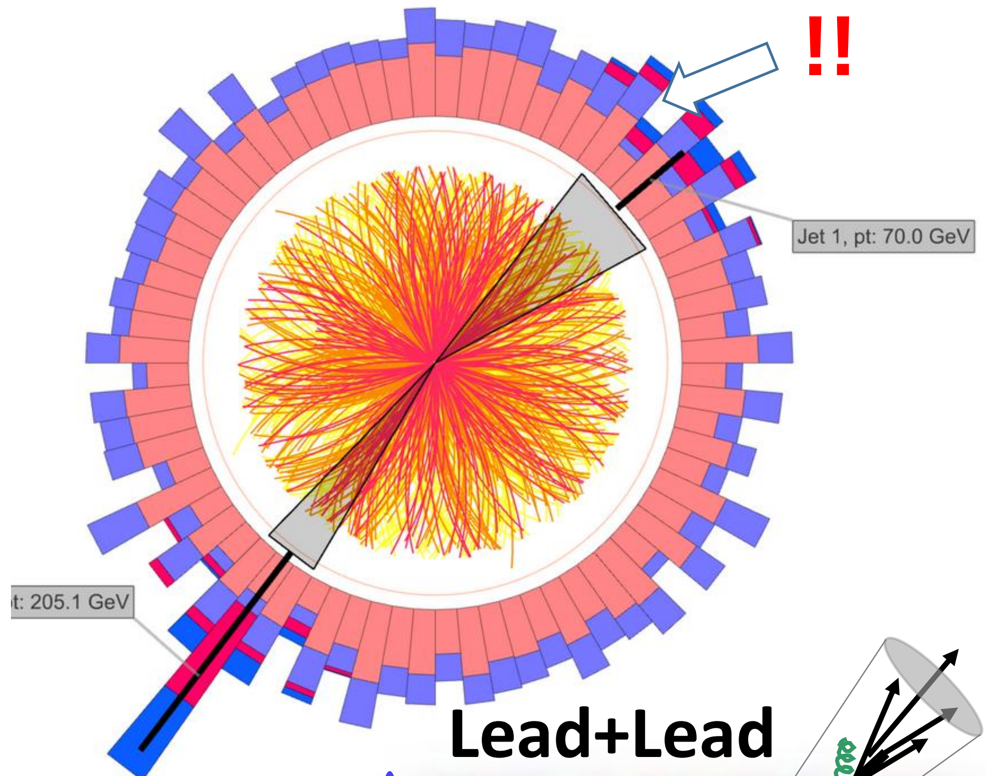
- Jet energy scale closure as function of event plane for R=0.8 w/o flow correction (**Left**) and with flow correction (**Right**)
- Significant flattening of scale translates directly to resolution improvement
- **Opens a door to the large area jet measurements!**

Fig. From: CMS-DP-2018

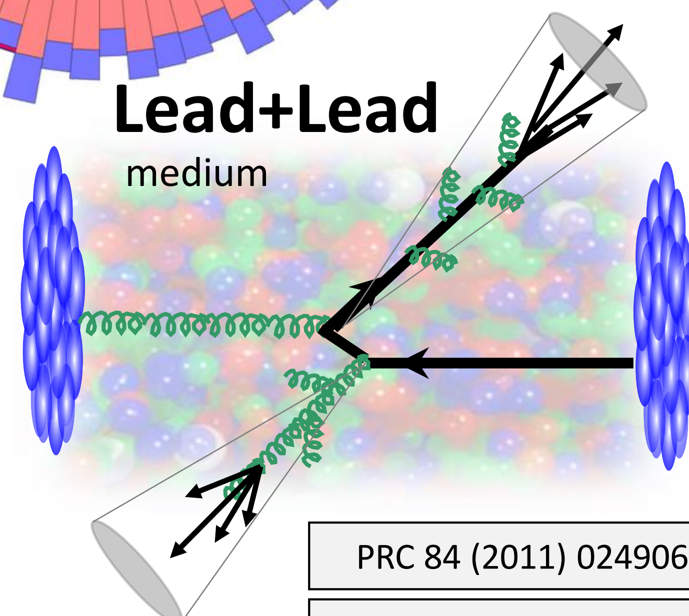
Probe the QGP with High Energy Quarks and Gluons



Proton+Proton



Lead+Lead

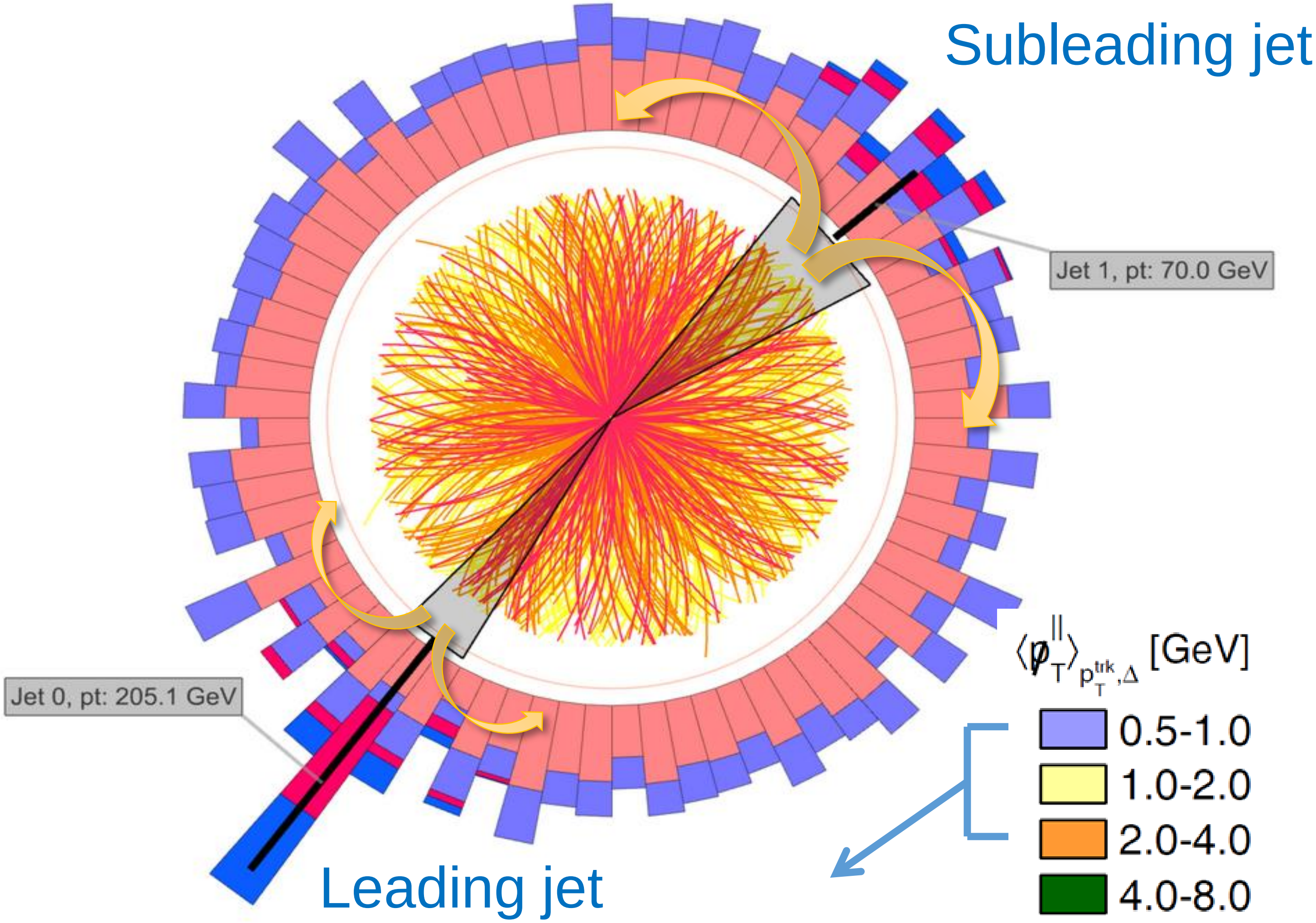


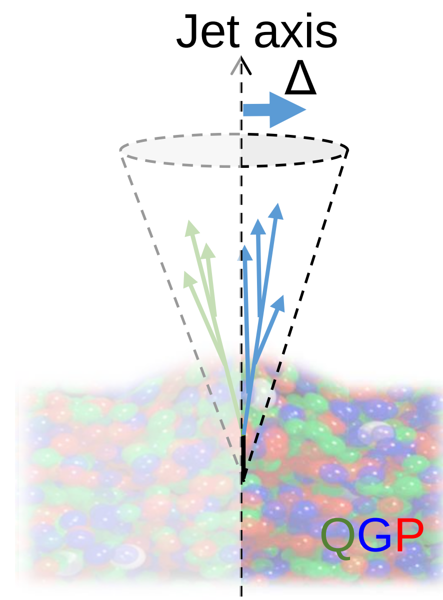
- **Asymmetric** dijets in Lead+Lead collisions
- The stopping power (dE/dx) of the Quark Soup is **Strong** (O(1-10 GeV/fm))

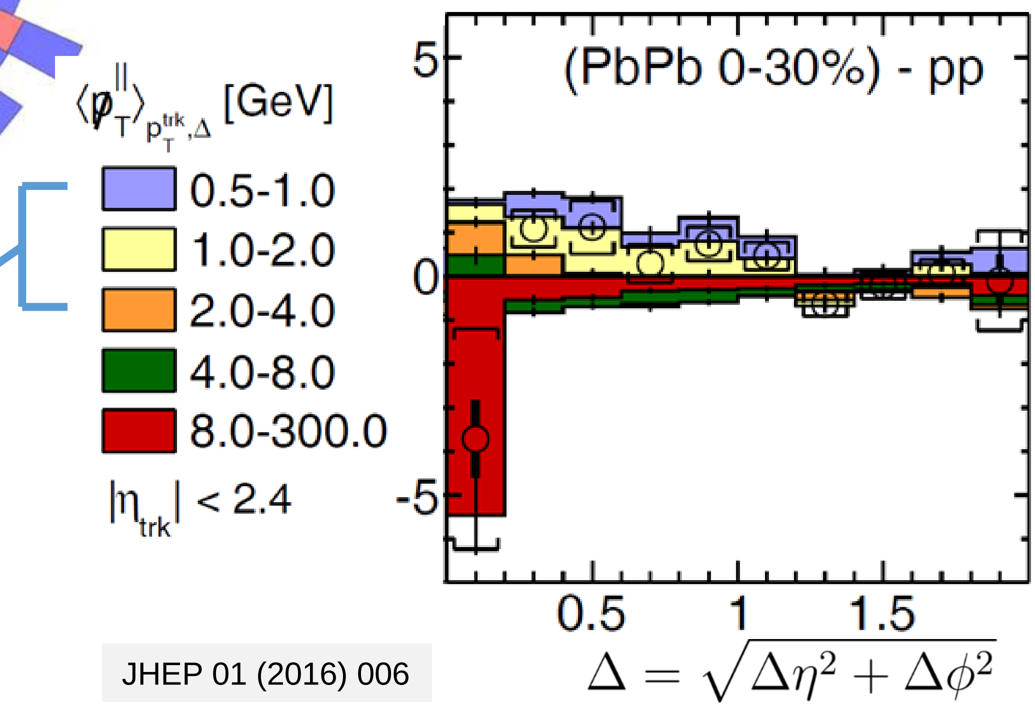
PRC 84 (2011) 024906

PLB 712 (2012) 176

Where does the Quenched Energy Go?



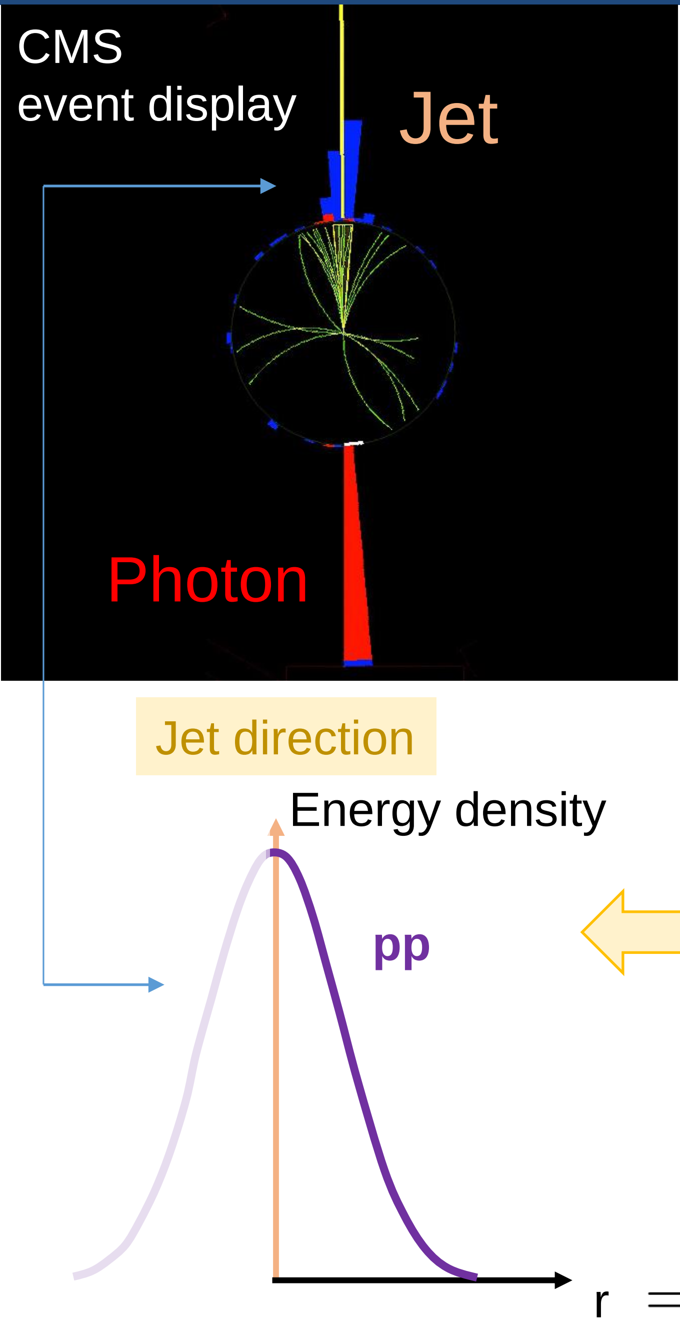




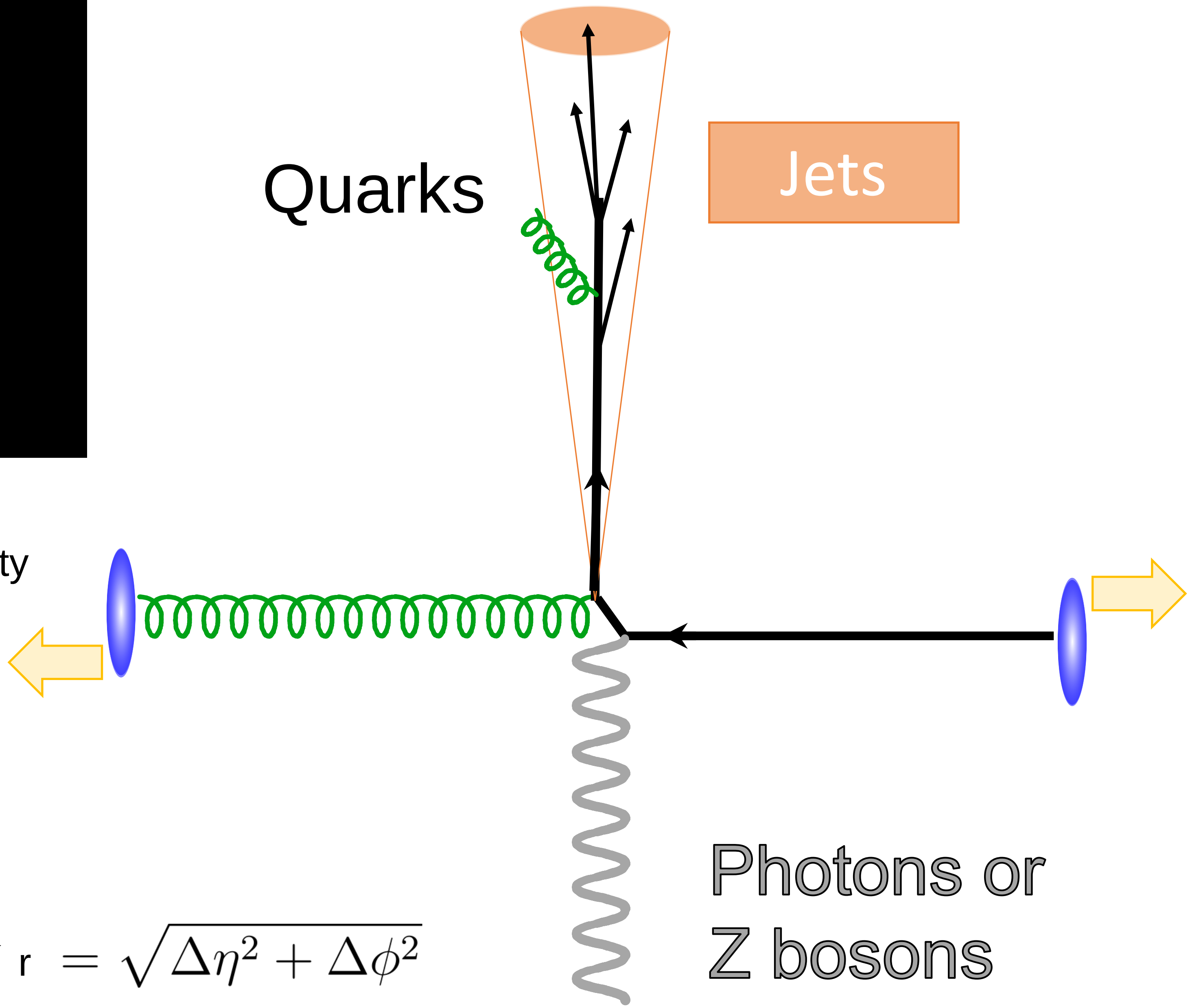
JHEP 01 (2016) 006

- Quenched energy carried by **low momentum particles!**
- Momentum balance recovered with particles up to Δ ~ 2

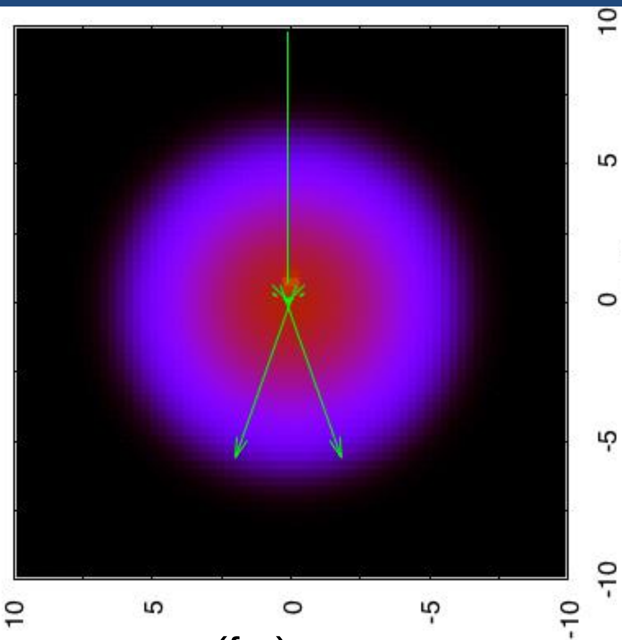
High Transverse Momentum Scattering

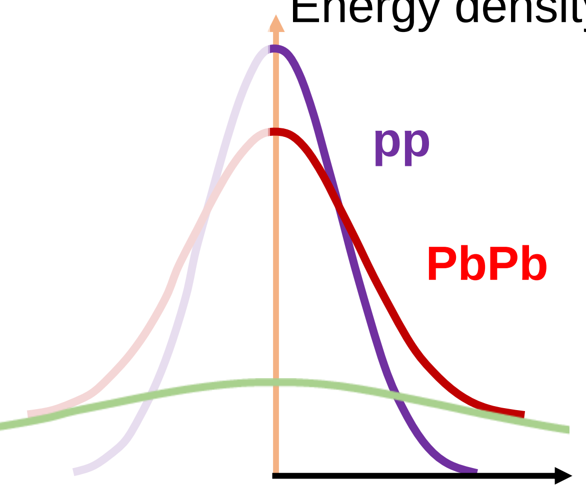


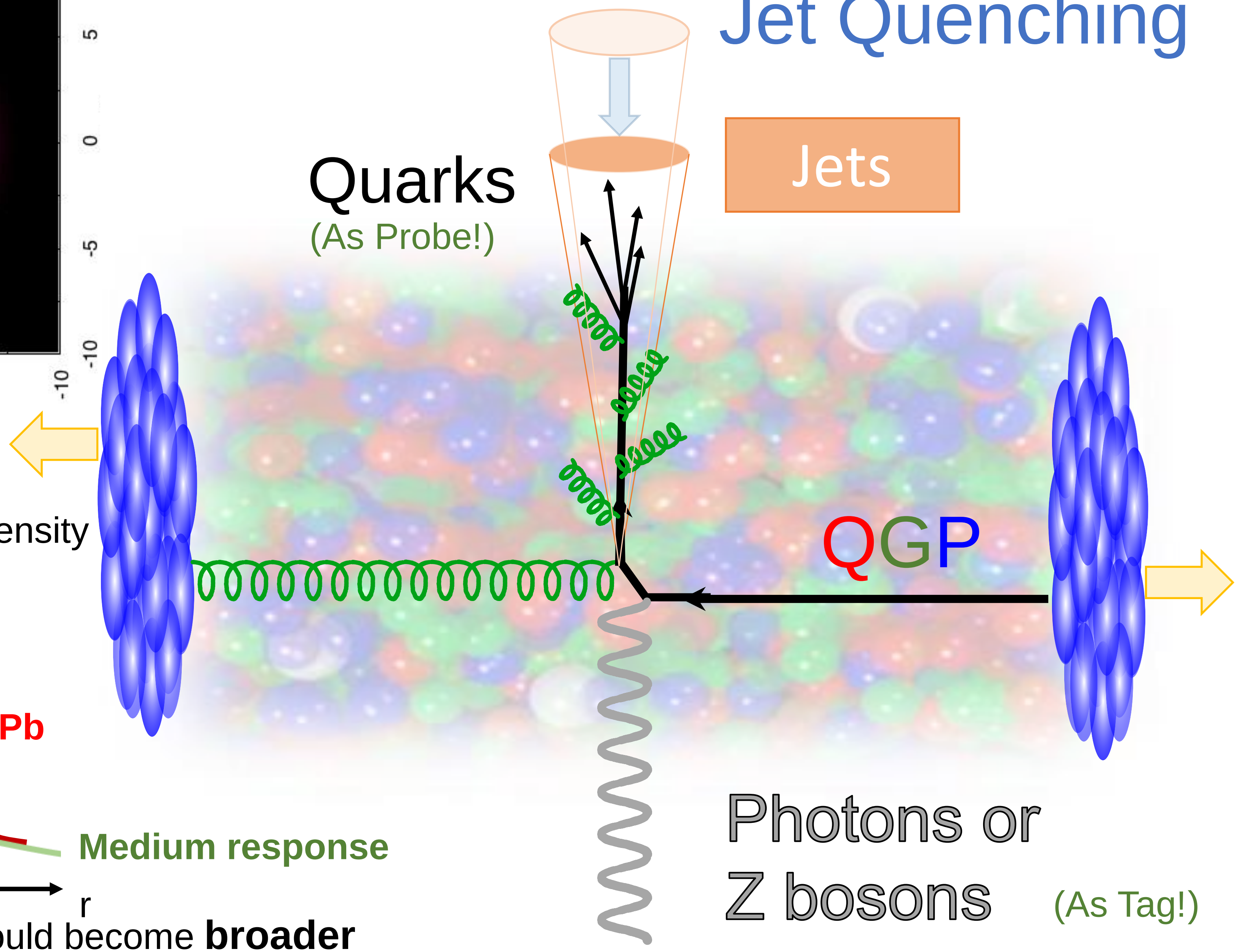
$$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Probes Produced with the QGP



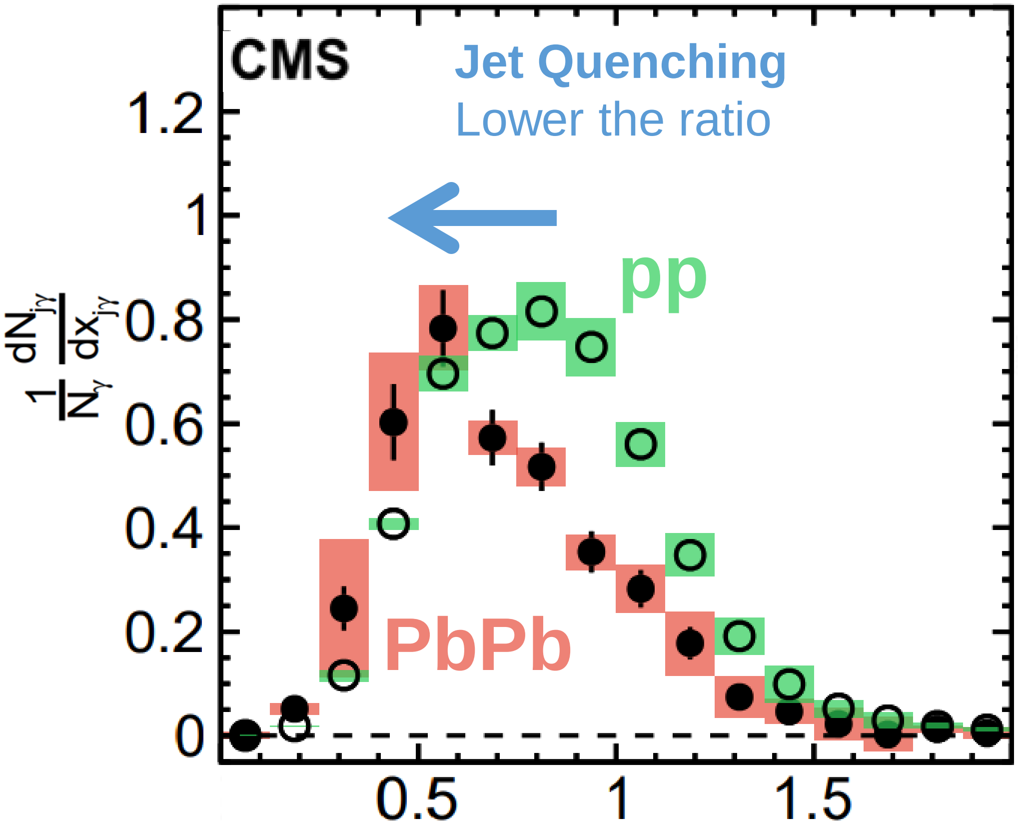




Quark jets in PbPb could become **broader**

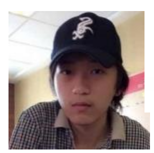
Momentum Ratio of Quark (Jet) and Boson

Photon + Jet



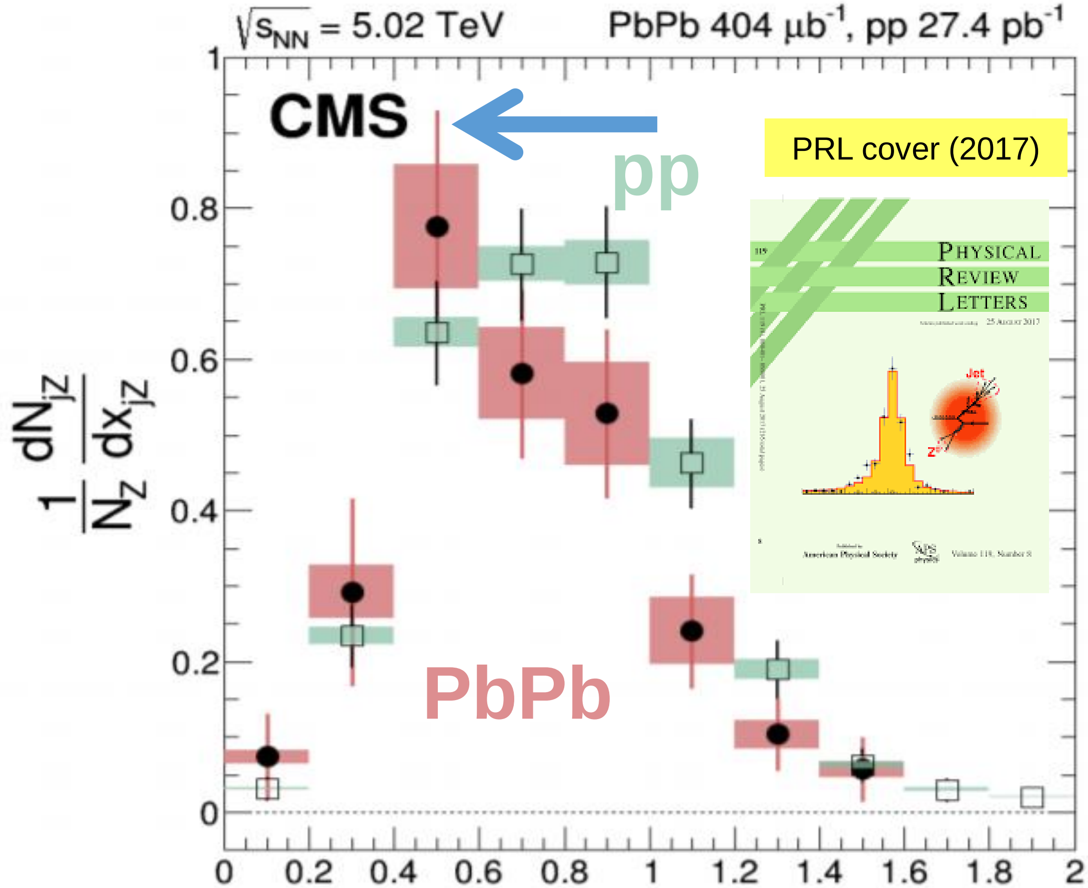
PLB 785 (2018) 14
PLB 718 (2013) 773

$\frac{\text{Jet Momentum}}{\text{Photon Momentum}}$



Ran Bi

Z^0 boson + Jet



PRL 119 (2017) 082301

$\frac{\text{Jet Momentum}}{\text{Z Boson Momentum}}$

Kaya Tatar

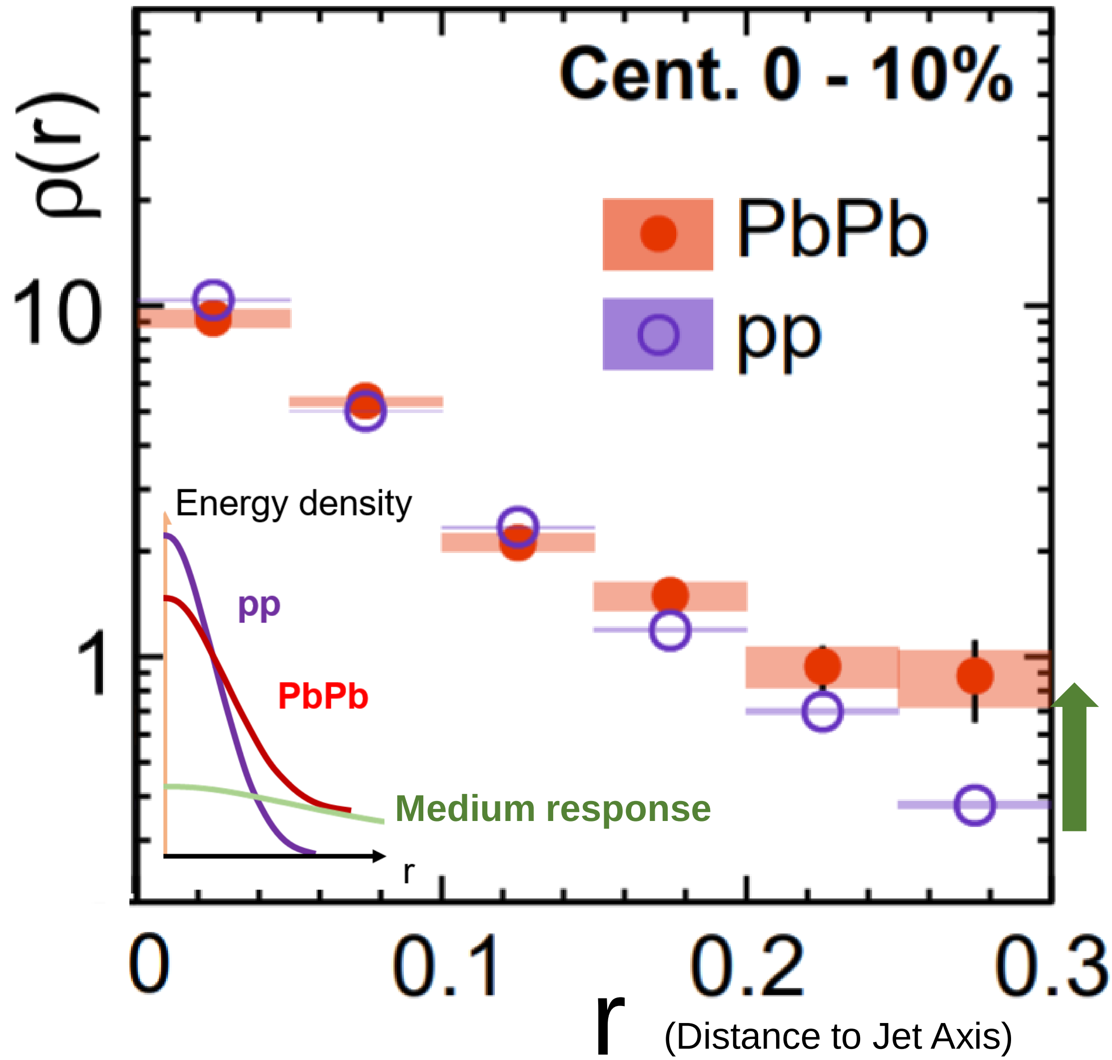
- Quarks met a very large amount of color charges and lose energy!
- Photons and Z bosons are not affected by QGP

→ **Quark jet to boson momentum ratio lowered by around ~ 14% for ~60 GeV jet**

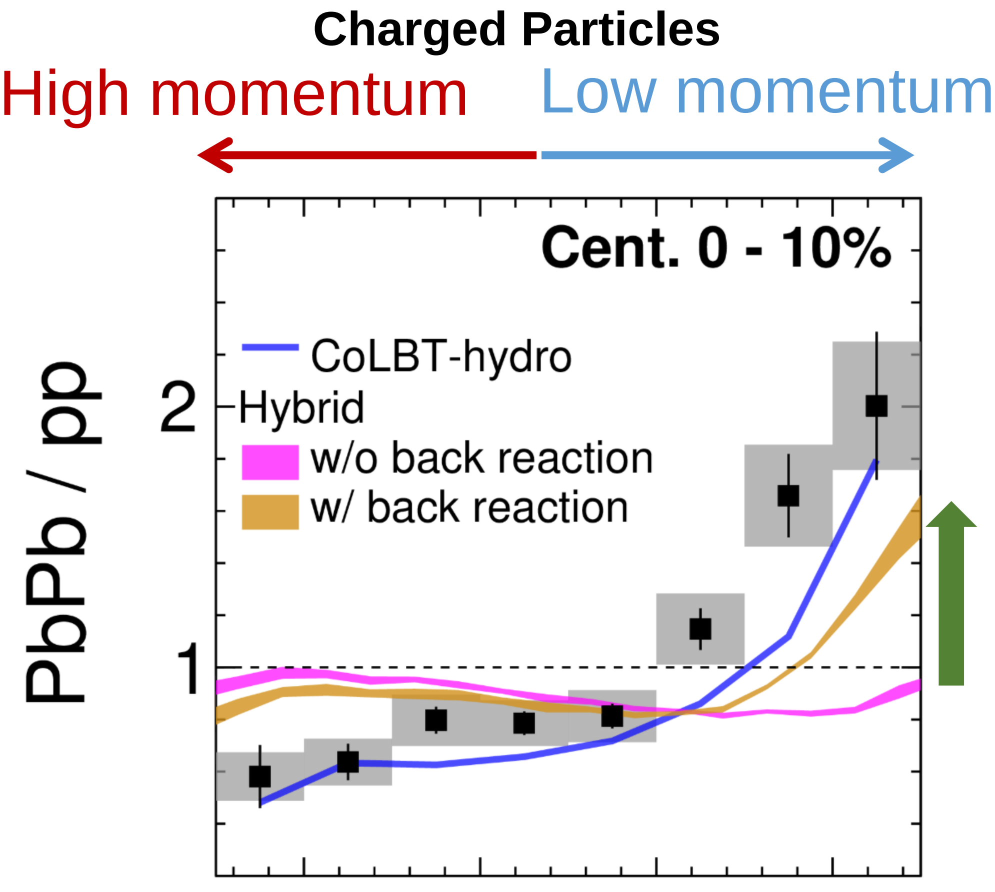
Quark Jet Shape Modification

PRL 122 (2019) 152001

Radial Shape



Constituent Momentum Spectrum



PRL 121 (2018) 242301

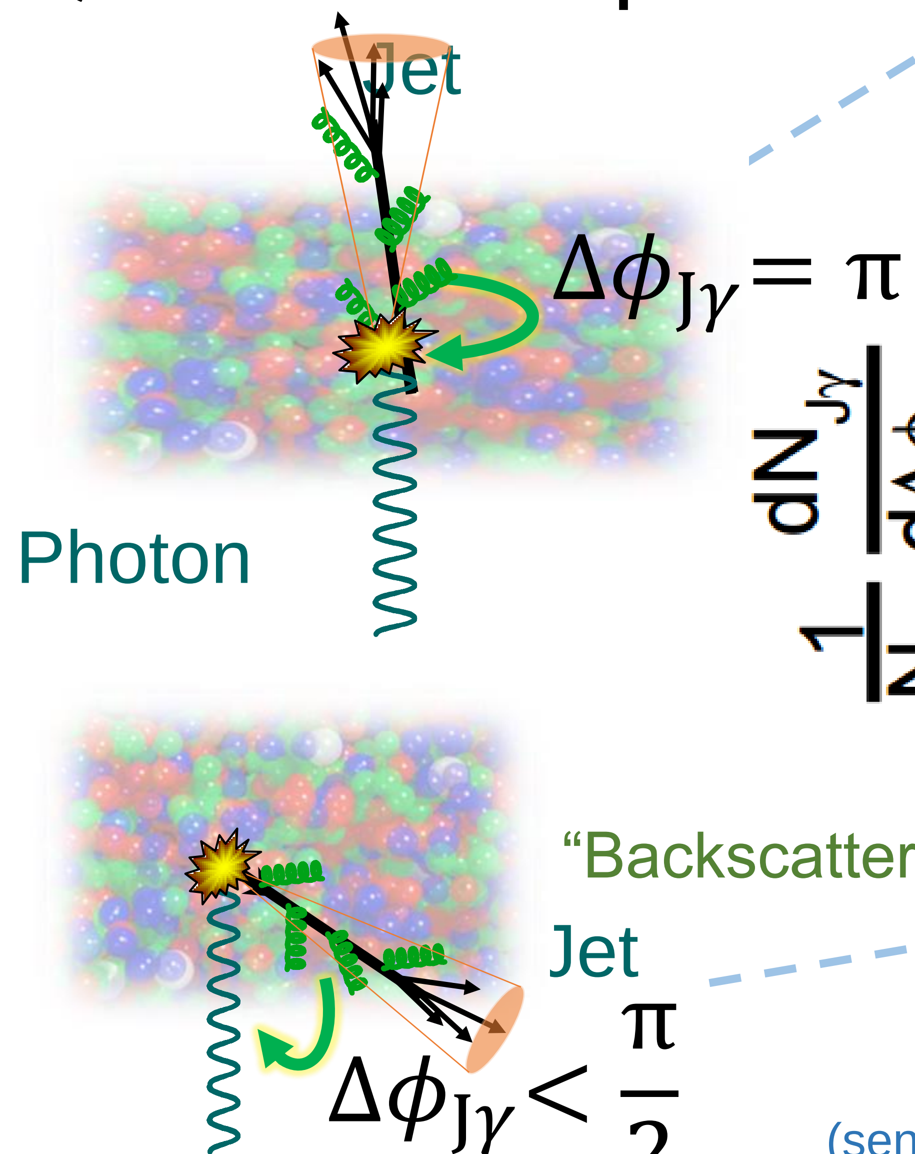
Kaya Tatar

- **Broadening** of the quark jets, enhancement of **low momentum particles** in jet
- Strong indication of QGP **medium response**!

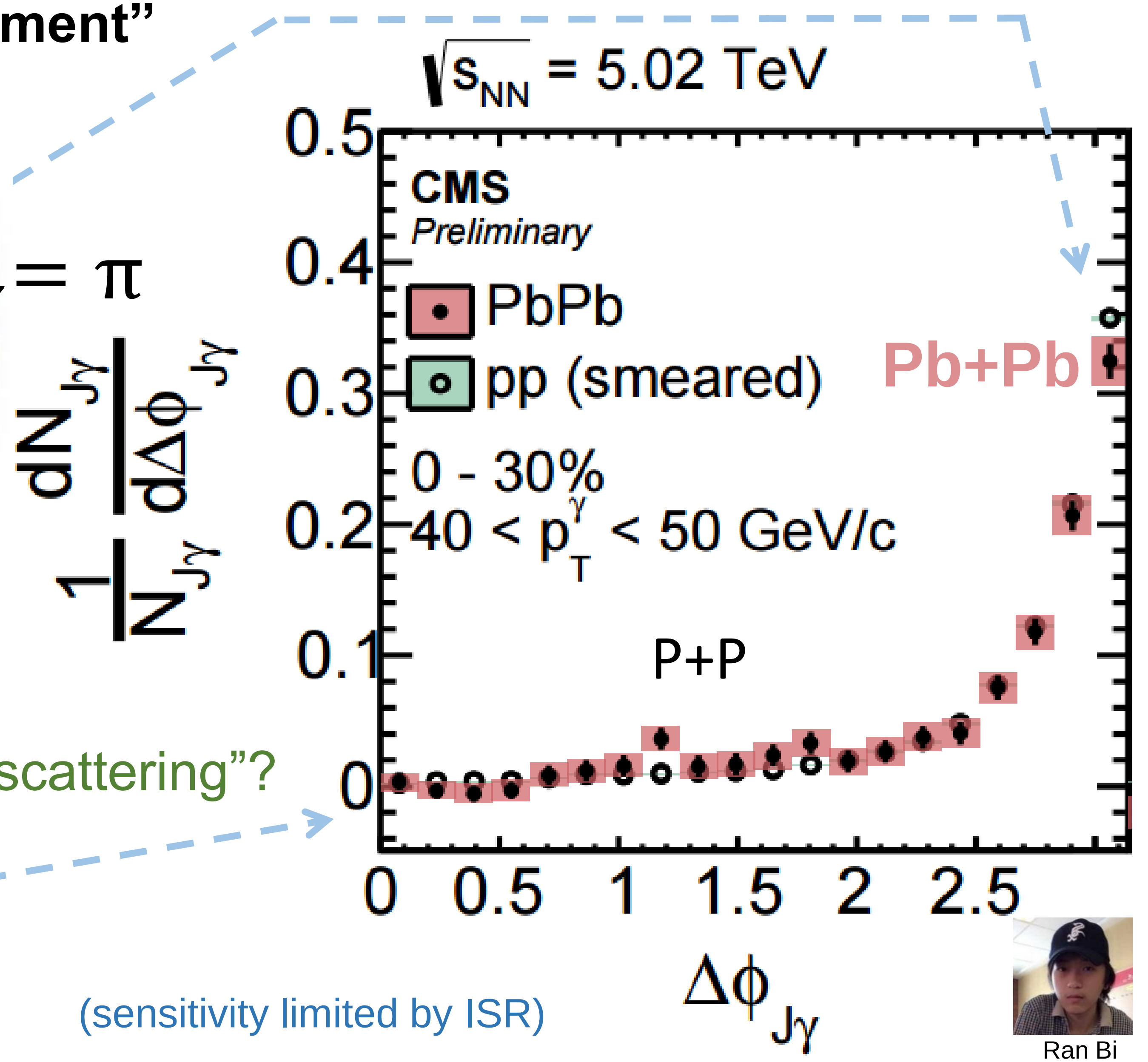
Hybrid Model
Krishna Rajagopal (MIT CTP) et.al

Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"



"Backscattering"?



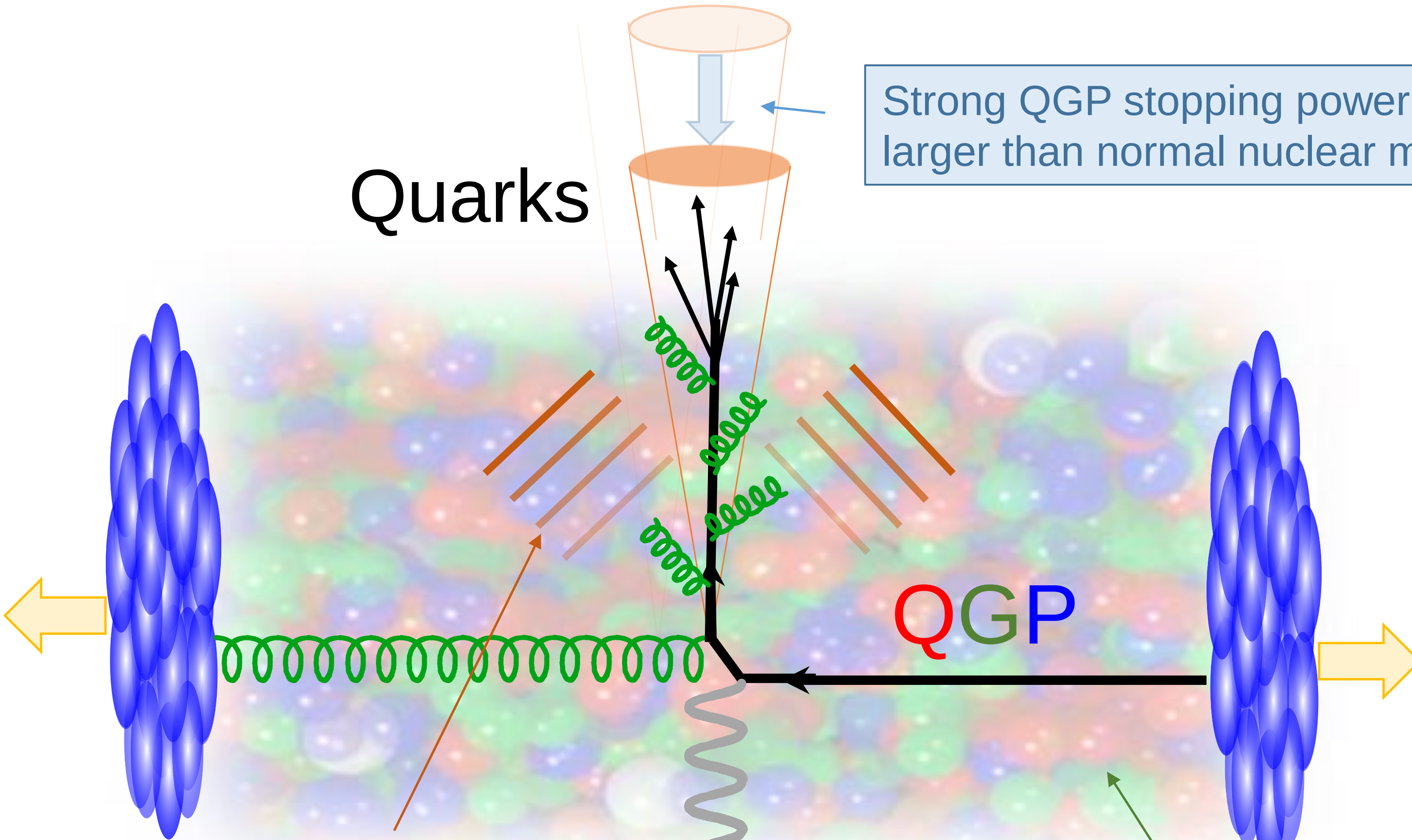
(sensitivity limited by ISR)

Ran Bi

Quark Soup probed is smooth!!

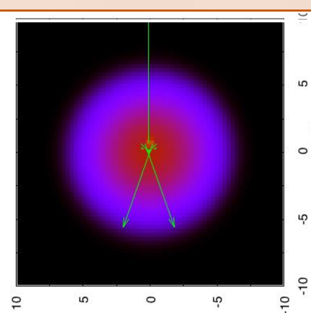
PLB 785 (2018) 14
PLB 718 (2013) 773

Implications from Jet Quenching Measurements



Strong QGP stopping power; O(10x) larger than normal nuclear matter

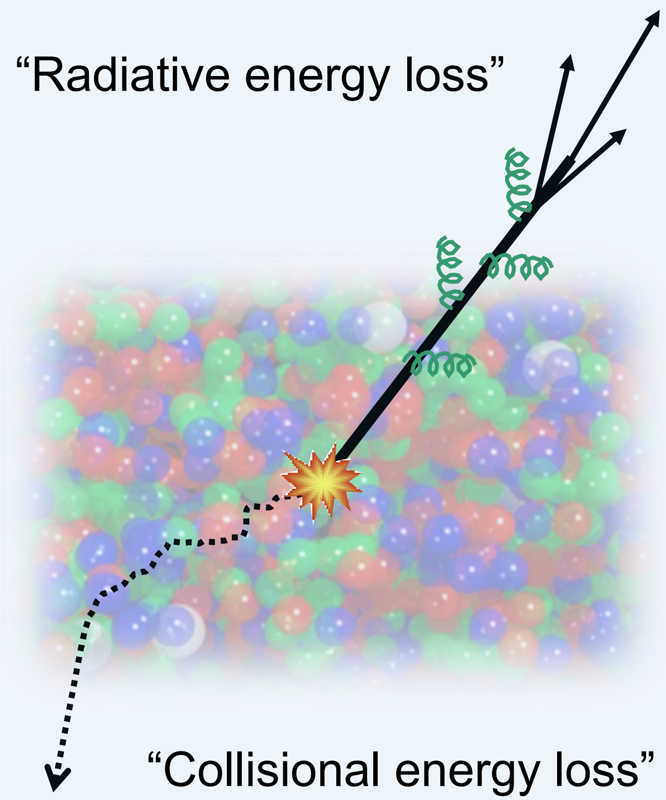
Indication of **medium recoil and QGP wake**



No indication of quasi-particles
QGP is incredibly smooth!!

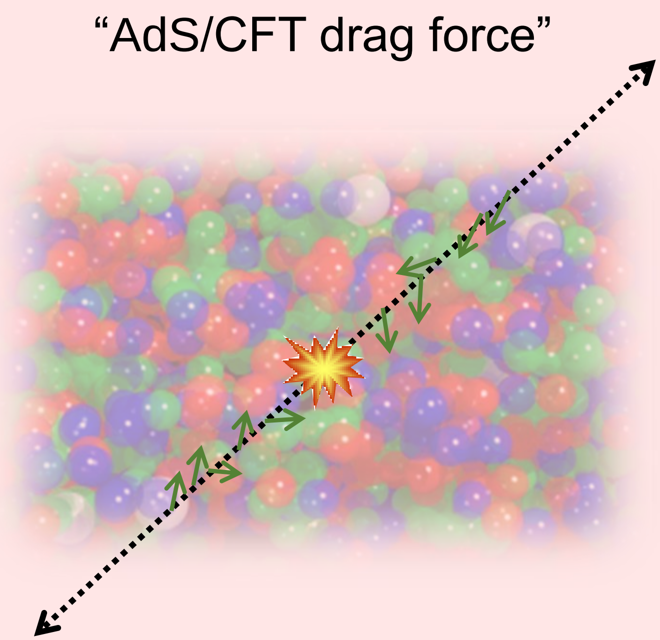
Weak Coupling vs. Strong Coupling Limit

Perturbative QCD
Weak coupling limit



Note: both processes happen simultaneously

Holographic calculation
Strong coupling limit



JETSCAPE

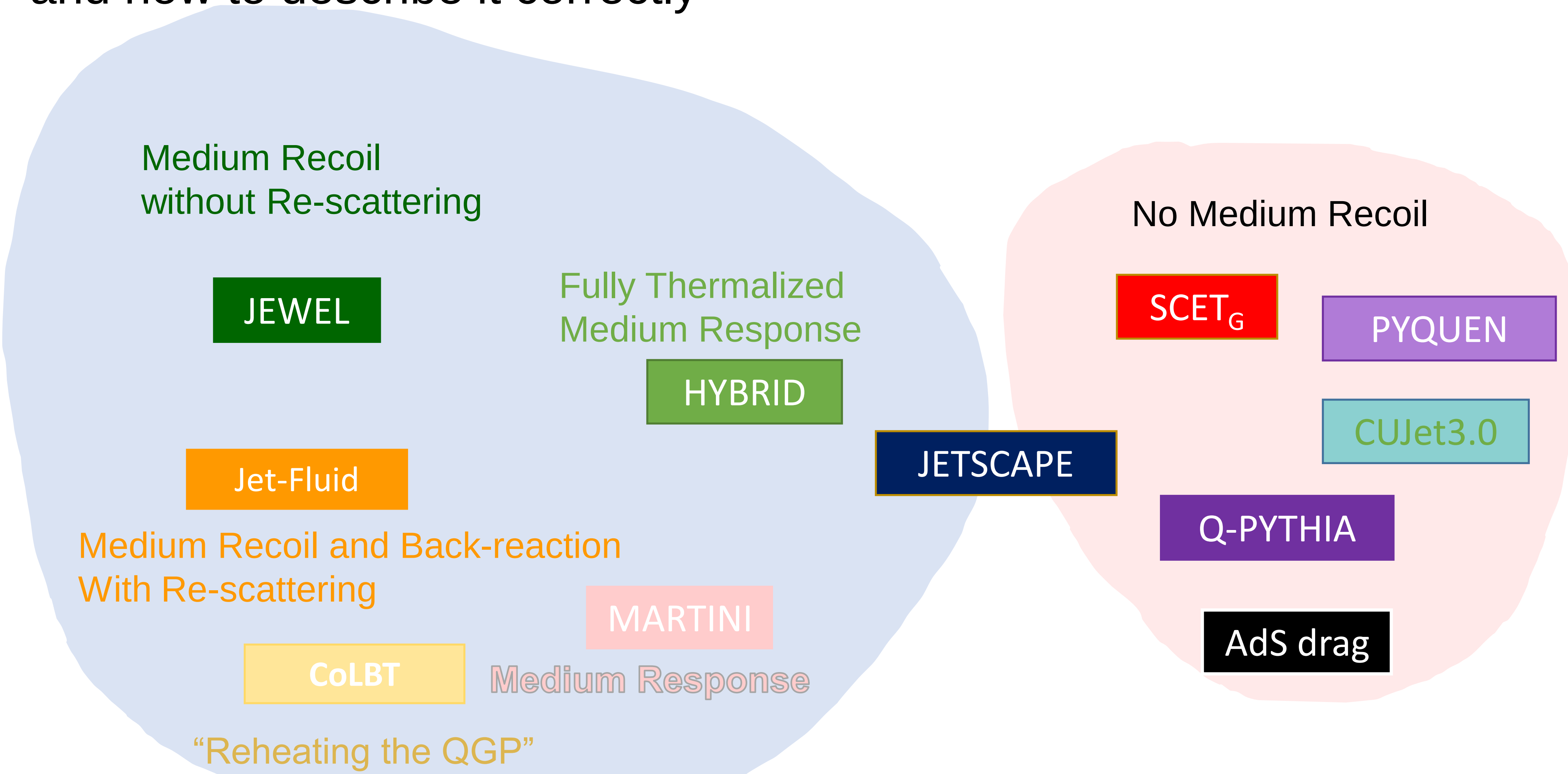
JEWEL | CUJet3.0 | Jet-Fluid | CoLBT | Q-PYTHIA | $SCET_G$ | MARTINI | PYQUEN

AdS drag | HYBRID

Need to understand **jet quenching mechanism** before QGP property extraction

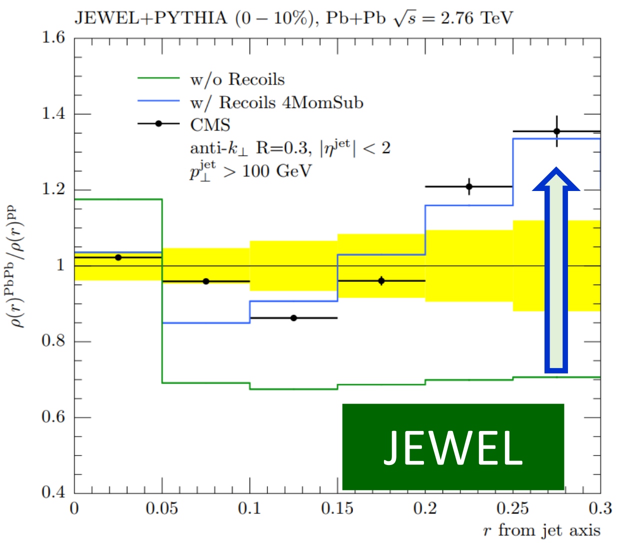
Medium Response

We also don't know **how much** the medium response (recoil) plays a role in the description of the jet quenching observables
and how to describe it correctly

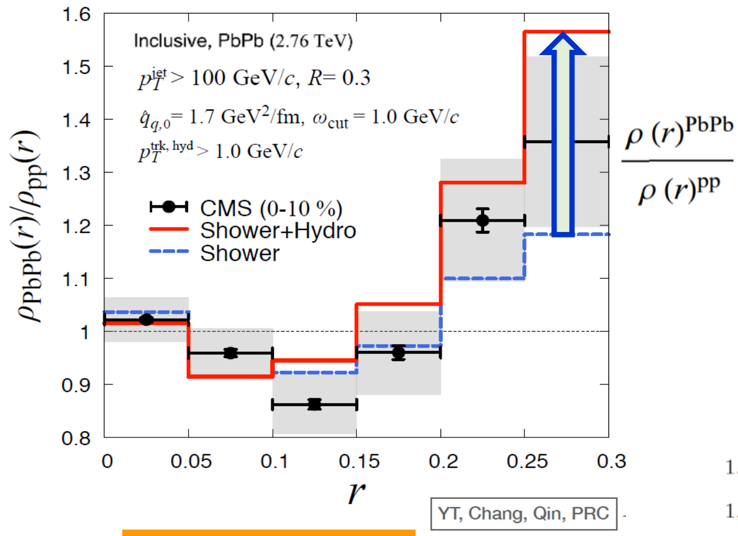


…and the modification of hadronization

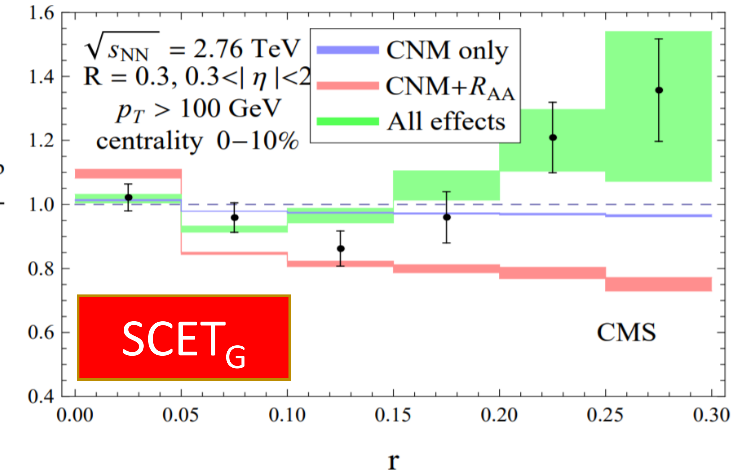
Theoretical Interpretation of the CMS Jet Shape

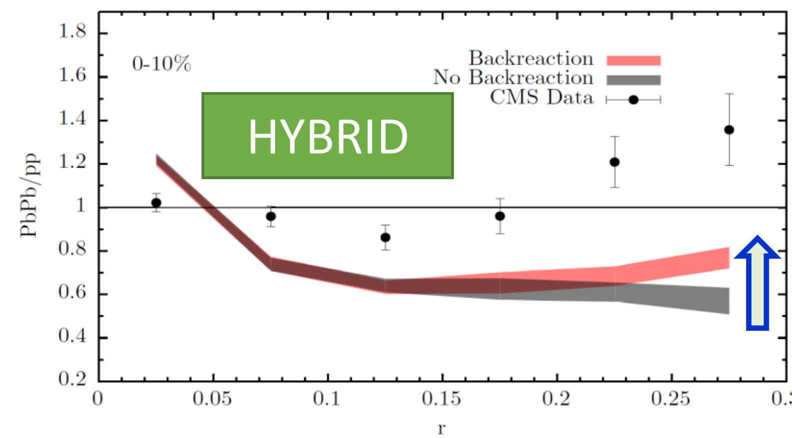


arXiv:1707.01539



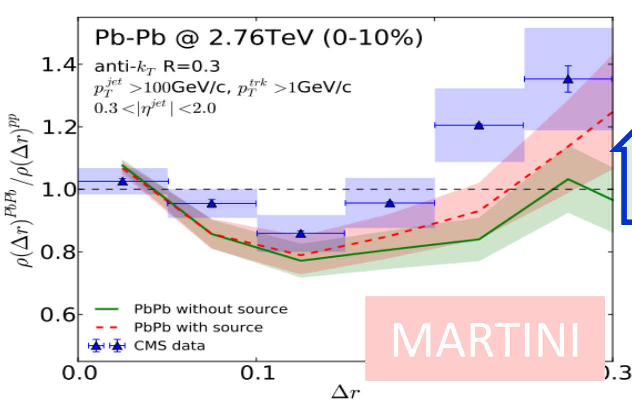
Jet-Fluid



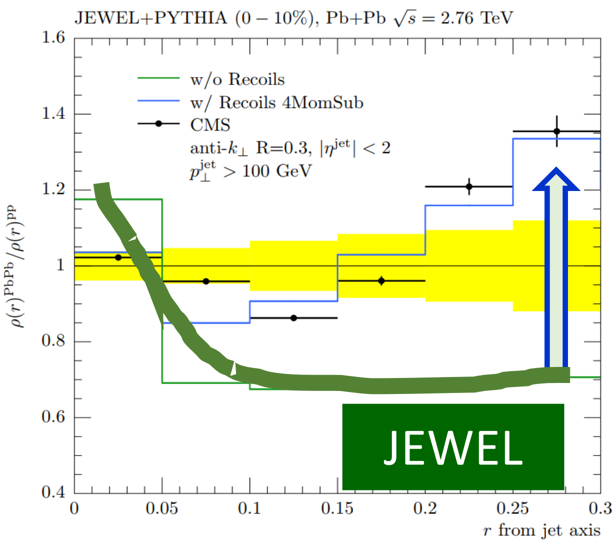


Different explanations of the large angle enhancement in jet shape measurement

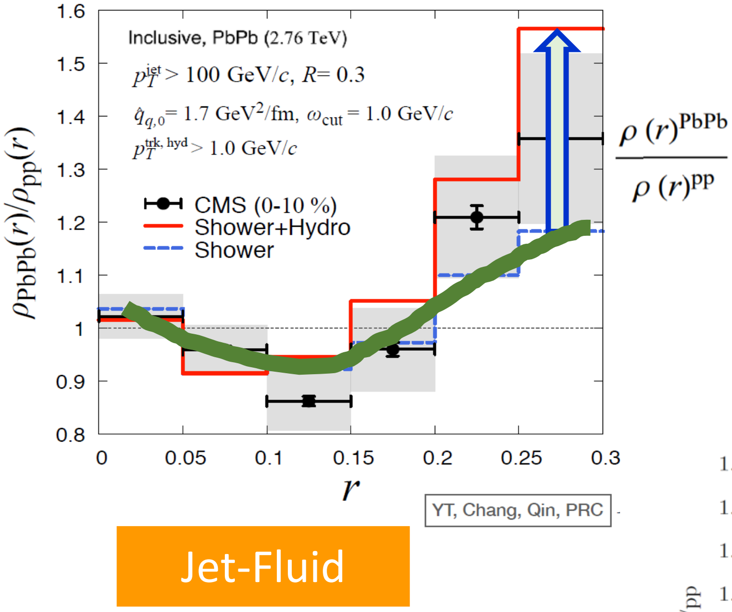
- SCET$_G$: Splitting function (large angle radiation)
- JEWEL & JETSCAPE: medium recoil parton
- Jet-Fluid: recoil parton + hydro dynamical evolution
- HYBRID: fully thermalized medium response
- MARTINI: medium response + shower

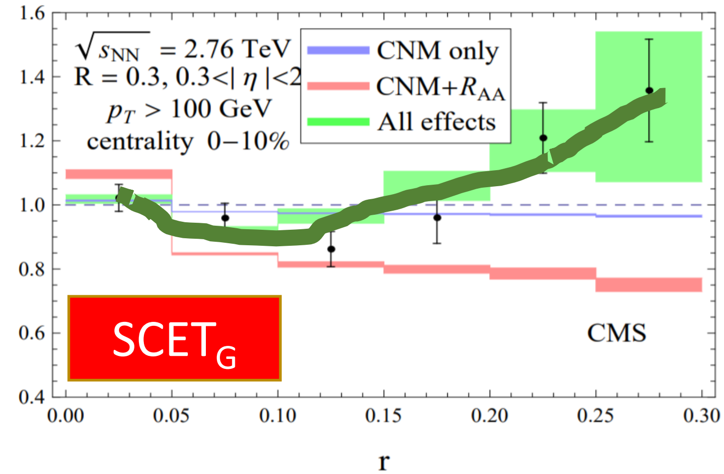


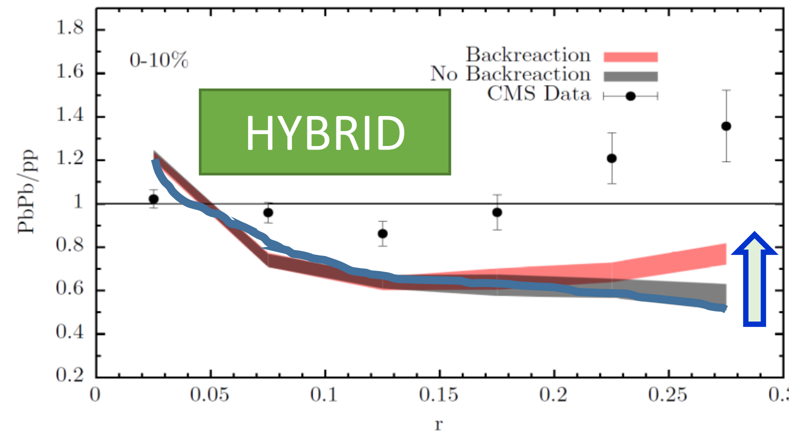
Theoretical Interpretation of the CMS Jet Shape



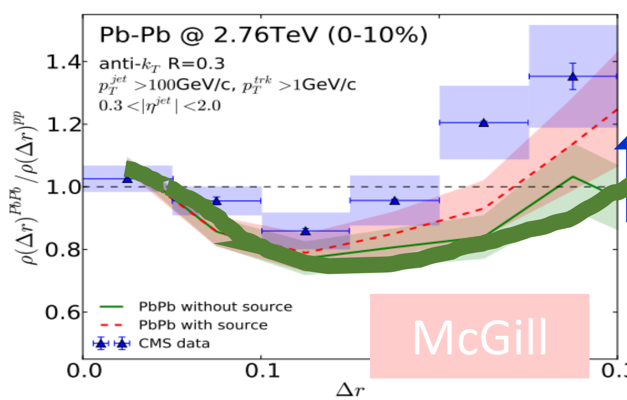
arXiv:1707.01539







Modifications of the shower

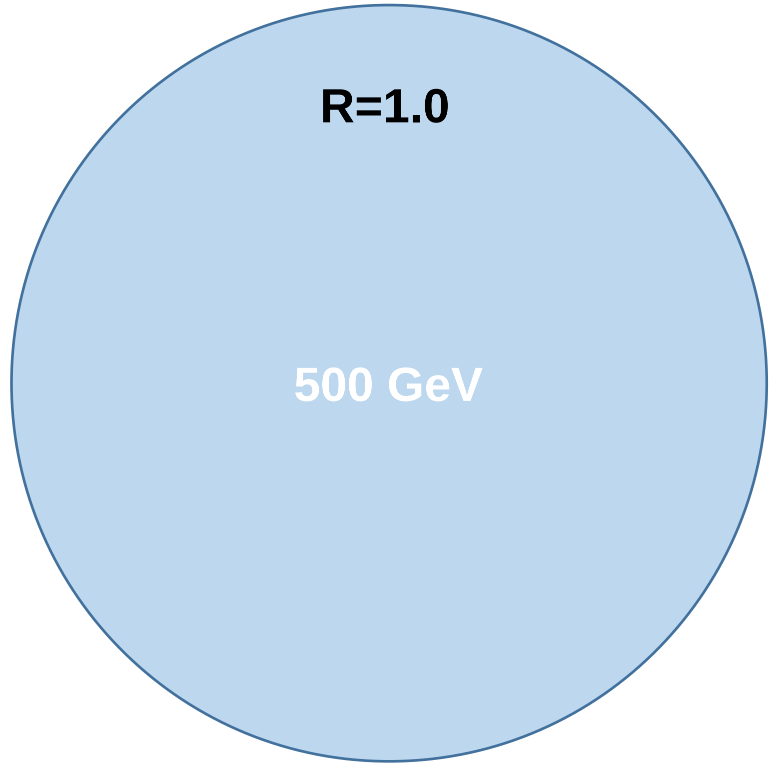


Models with very different underlying mechanisms give reasonable description of the inclusive jet shape!

How do we make progress?

(1) Large Area Jet R_{AA}

R=0.2



Accept **narrow** Jets

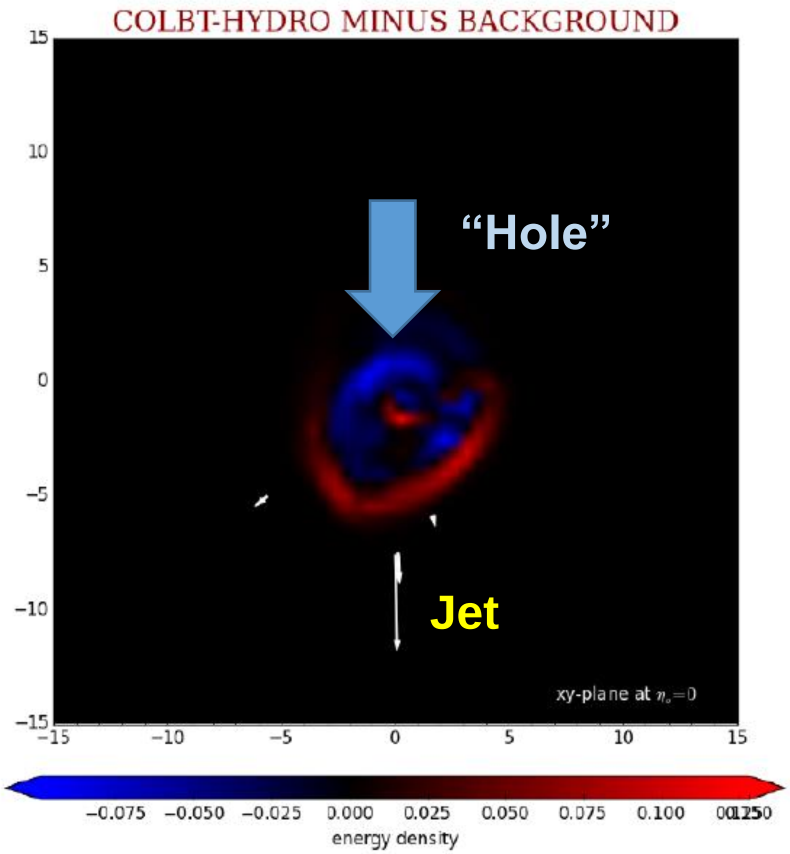
Accept Both **narrow and wide** jet

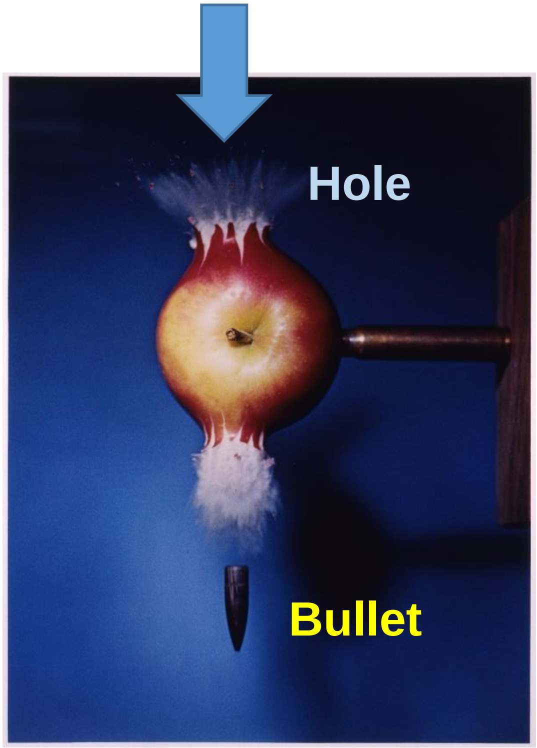
Measure large area jet (include wide parton shower) to provide further test of the jet quenching models

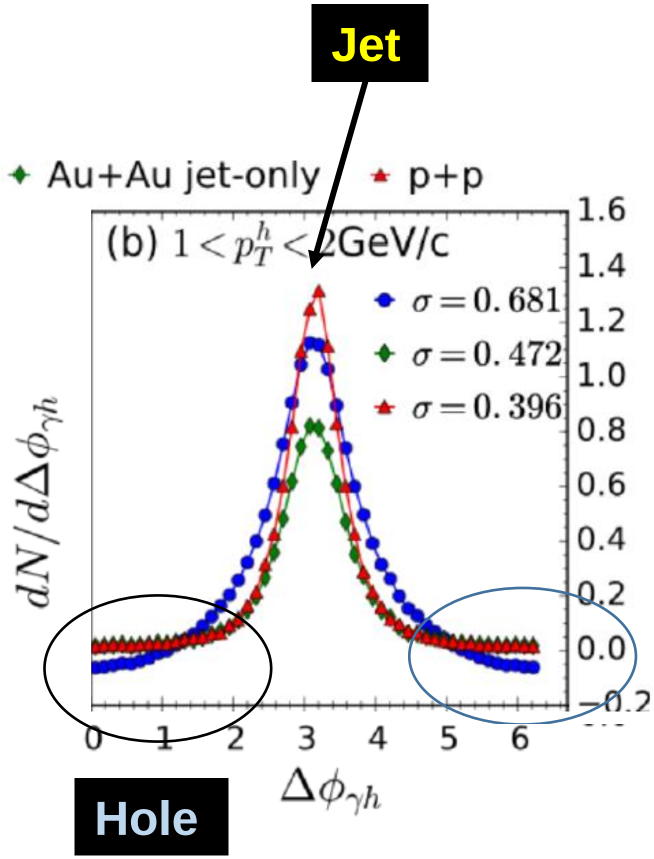
(2) To Measure the “Depletion” due to Medium Recoil

CoLBT

Tan Luo, Xin-Nian Wang

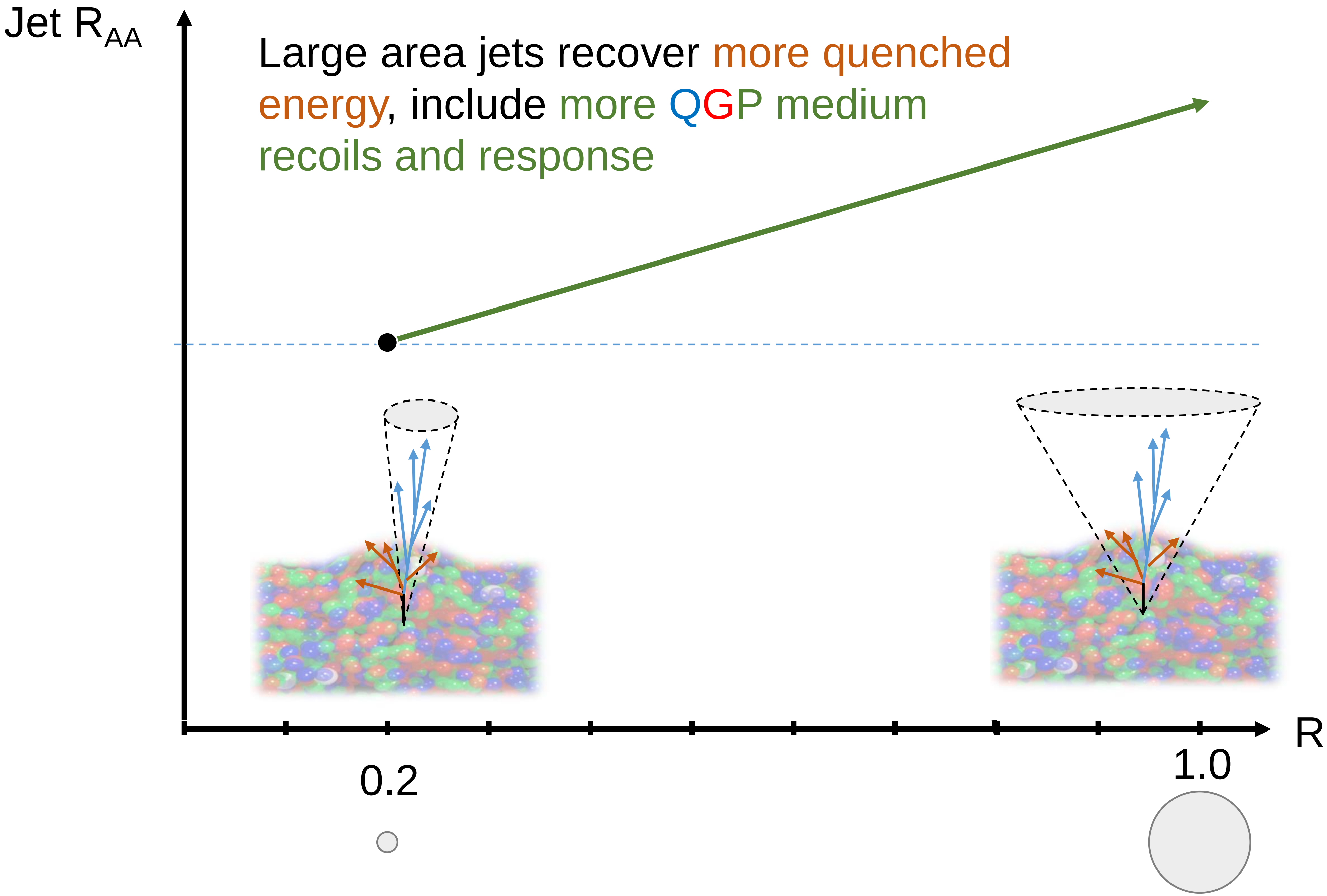




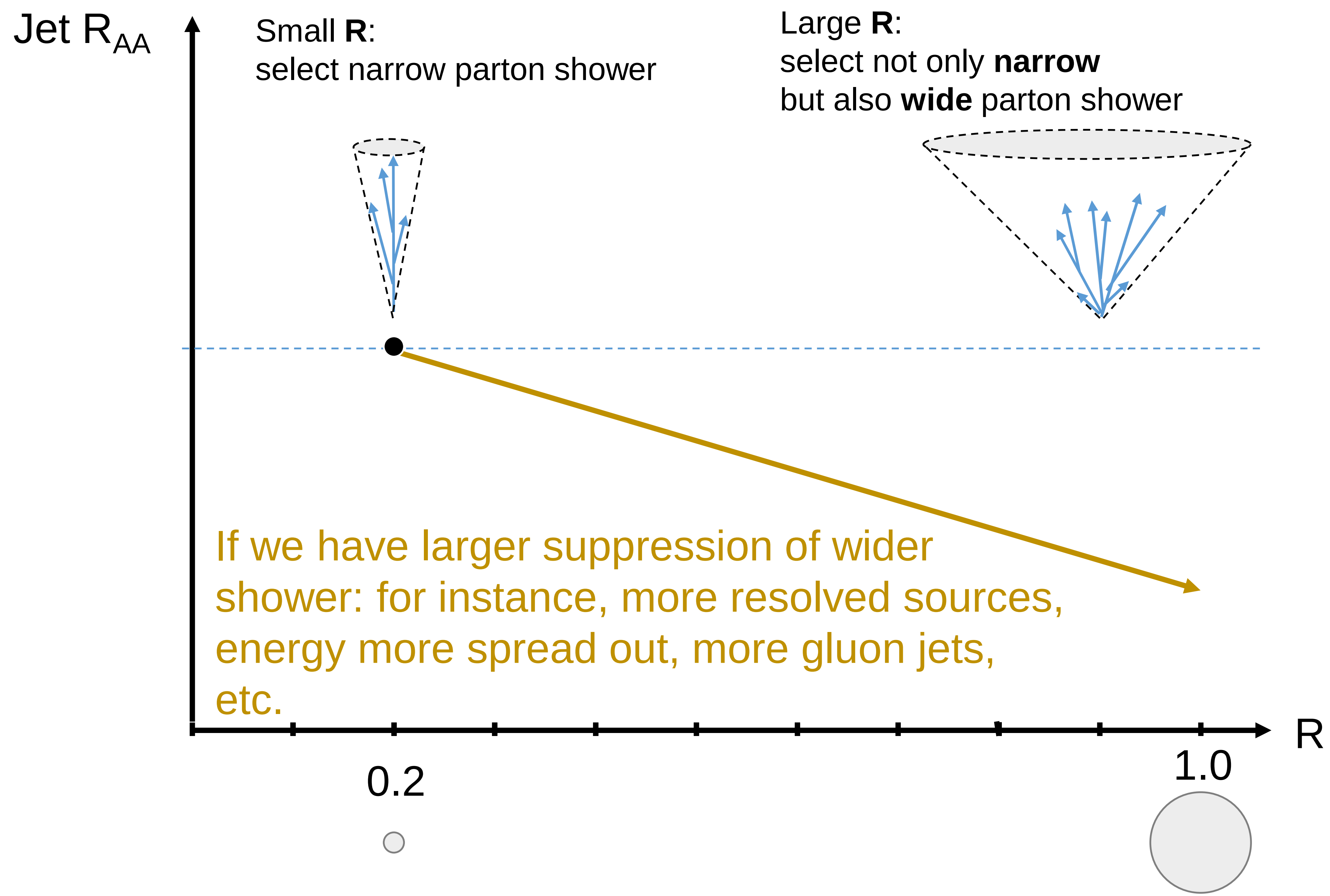


Measure the **boson-side associated yield** with photon-jet and **Z-jet**

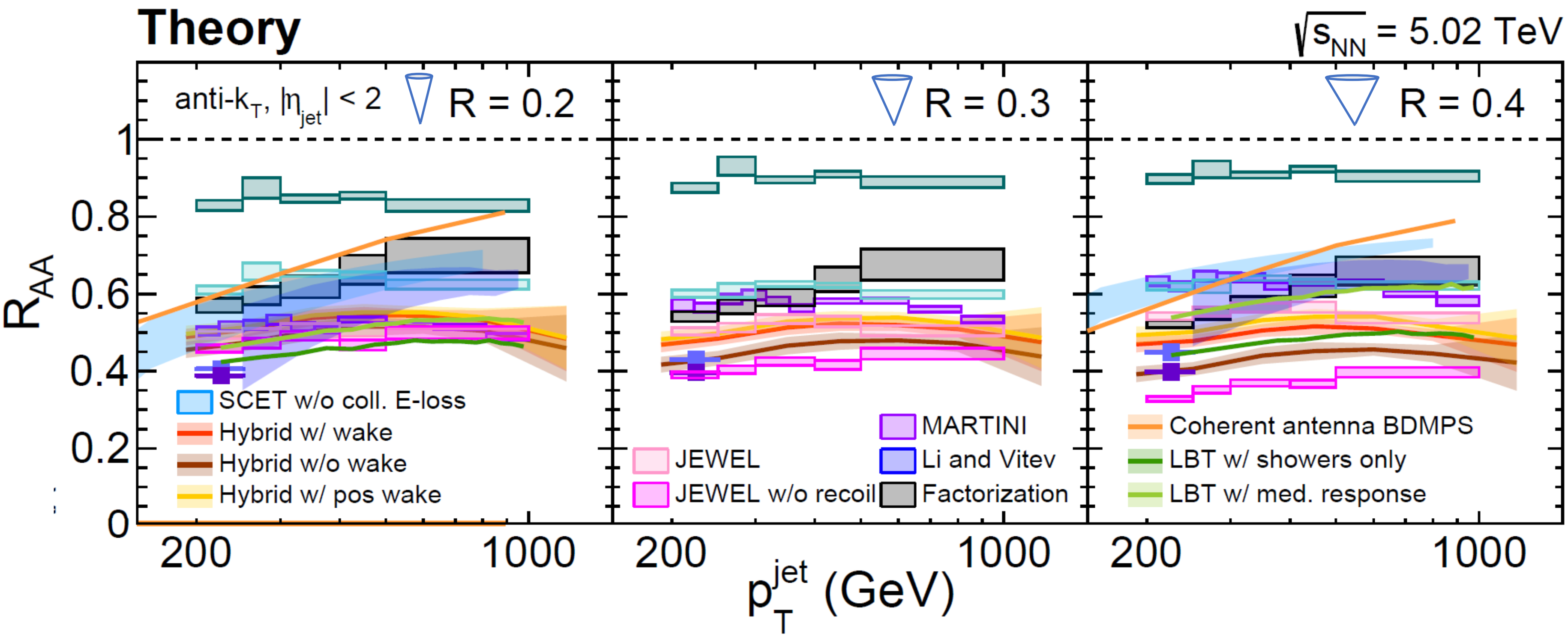
Recovery of Quenched Energy



Fate of Wider Jets



Jet R_{AA} vs. R

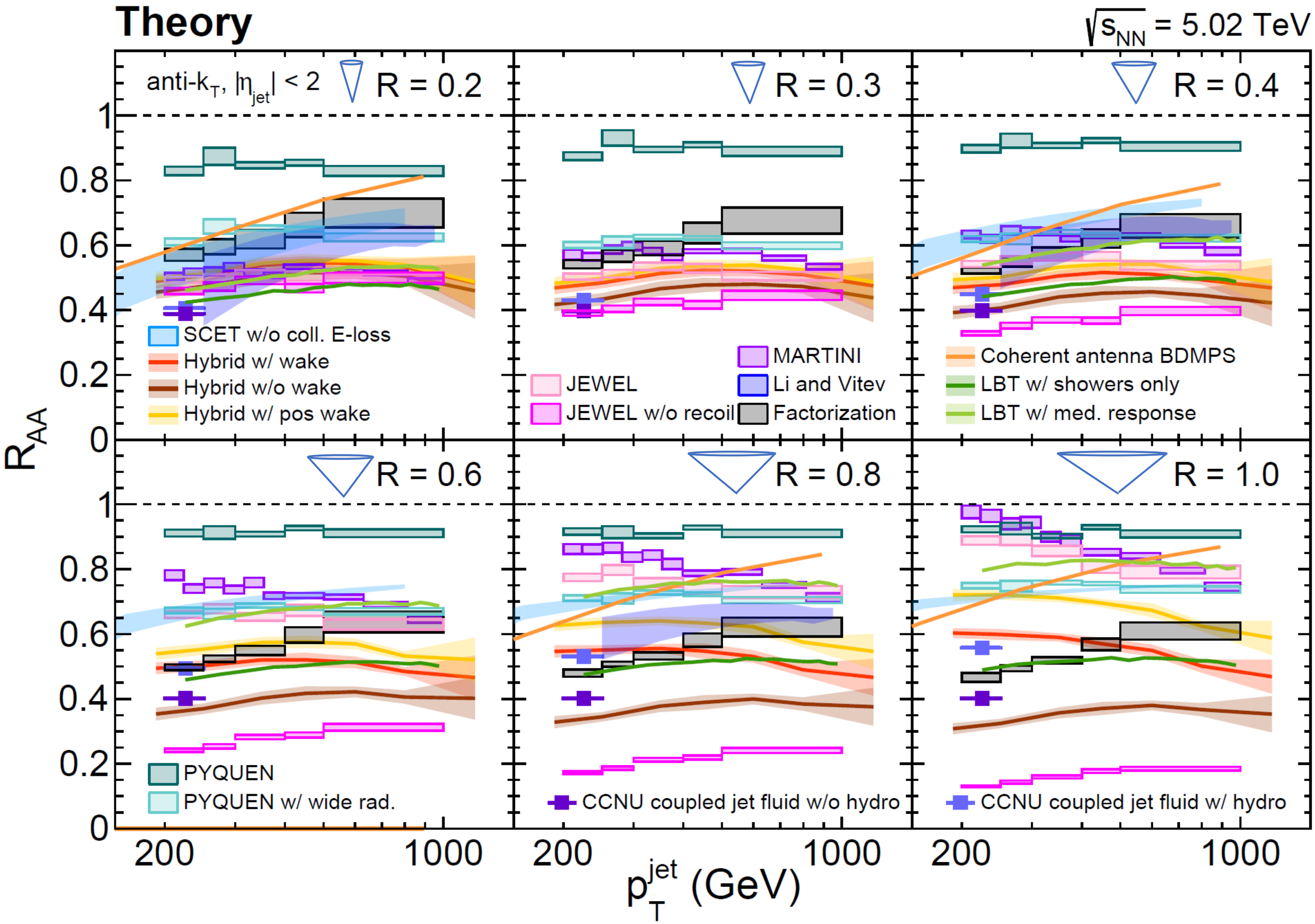


Models tuned by small R data at low p_T, predicts jet R_{AA} ~ 0.4-0.6

Compiled by

Molly Taylor

Jet R_{AA} vs. R

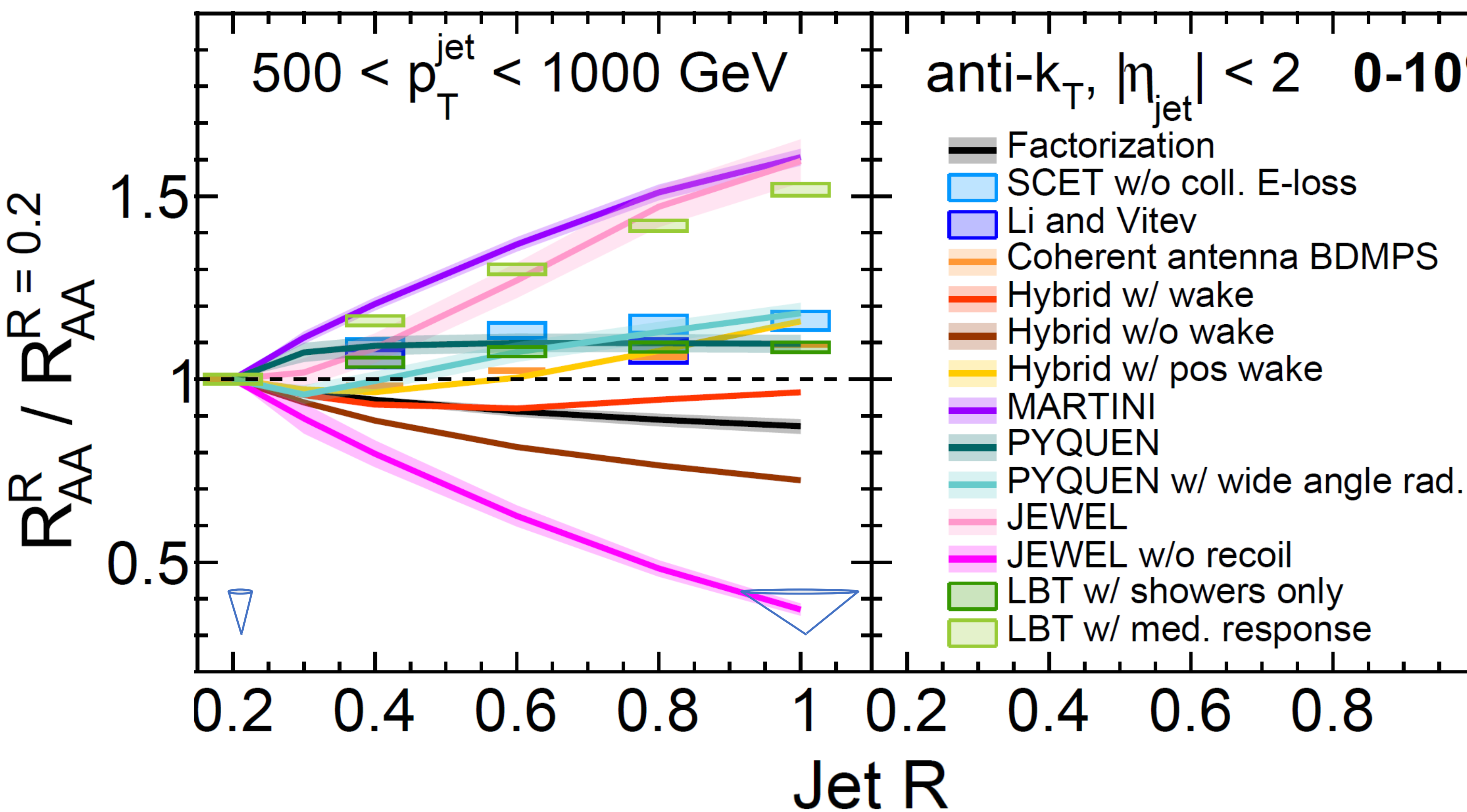


Compiled by

Molly Taylor

Models tuned by small R data **predict very different large area jet R_{AA}!!!**

Jet R_{AA} ratios vs. R in 0-10% PbPb at 5 TeV

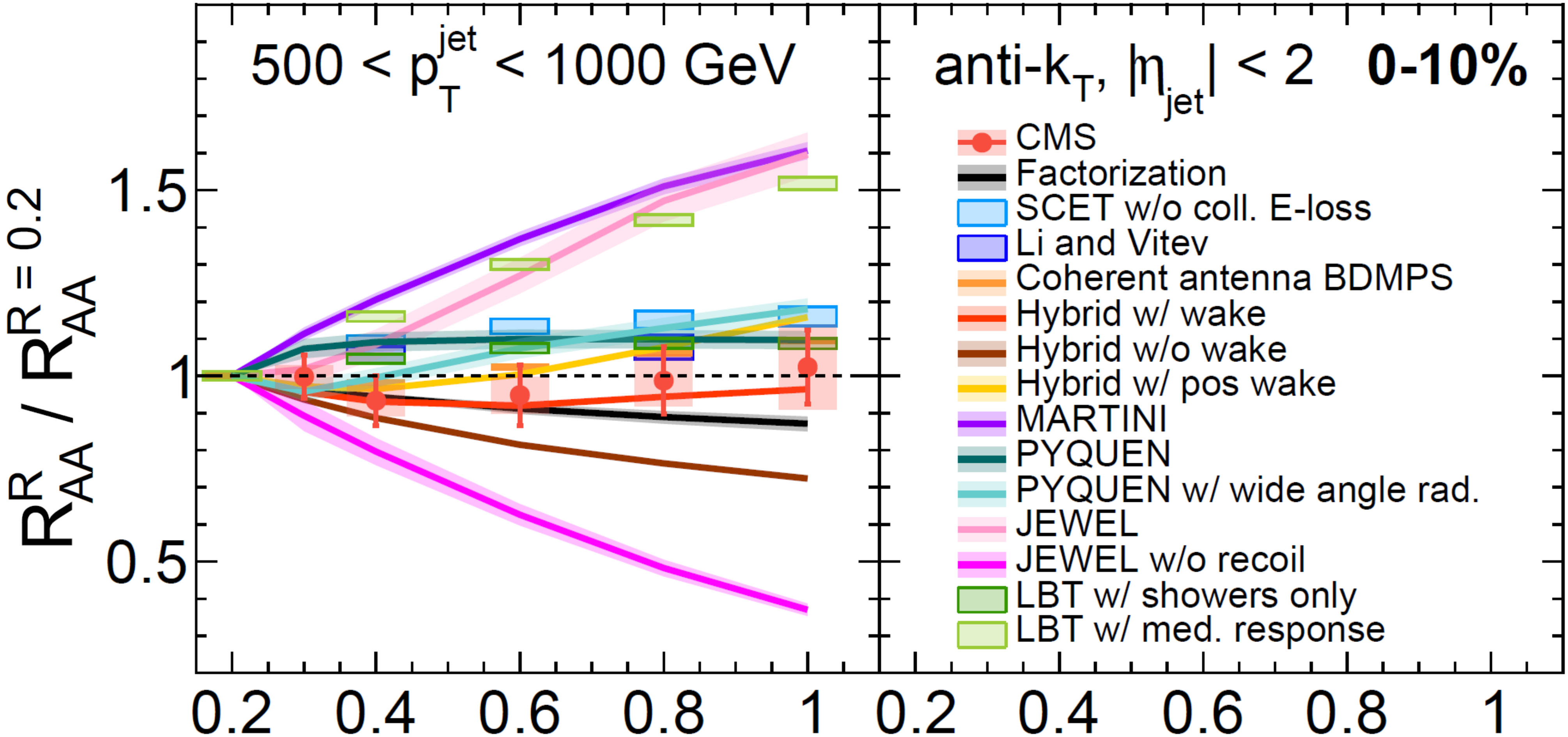


Compiled by

Molly Taylor

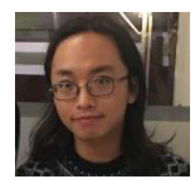
Competition between different mechanisms (collisional and radiative energy loss, pQCD vs. AdS/CFT, including/excluding medium recoil and responds, re-scattering…)

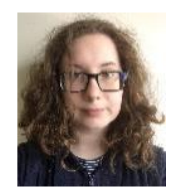
Jet R_{AA} ratios vs. R in 0-10% PbPb at 5 TeV



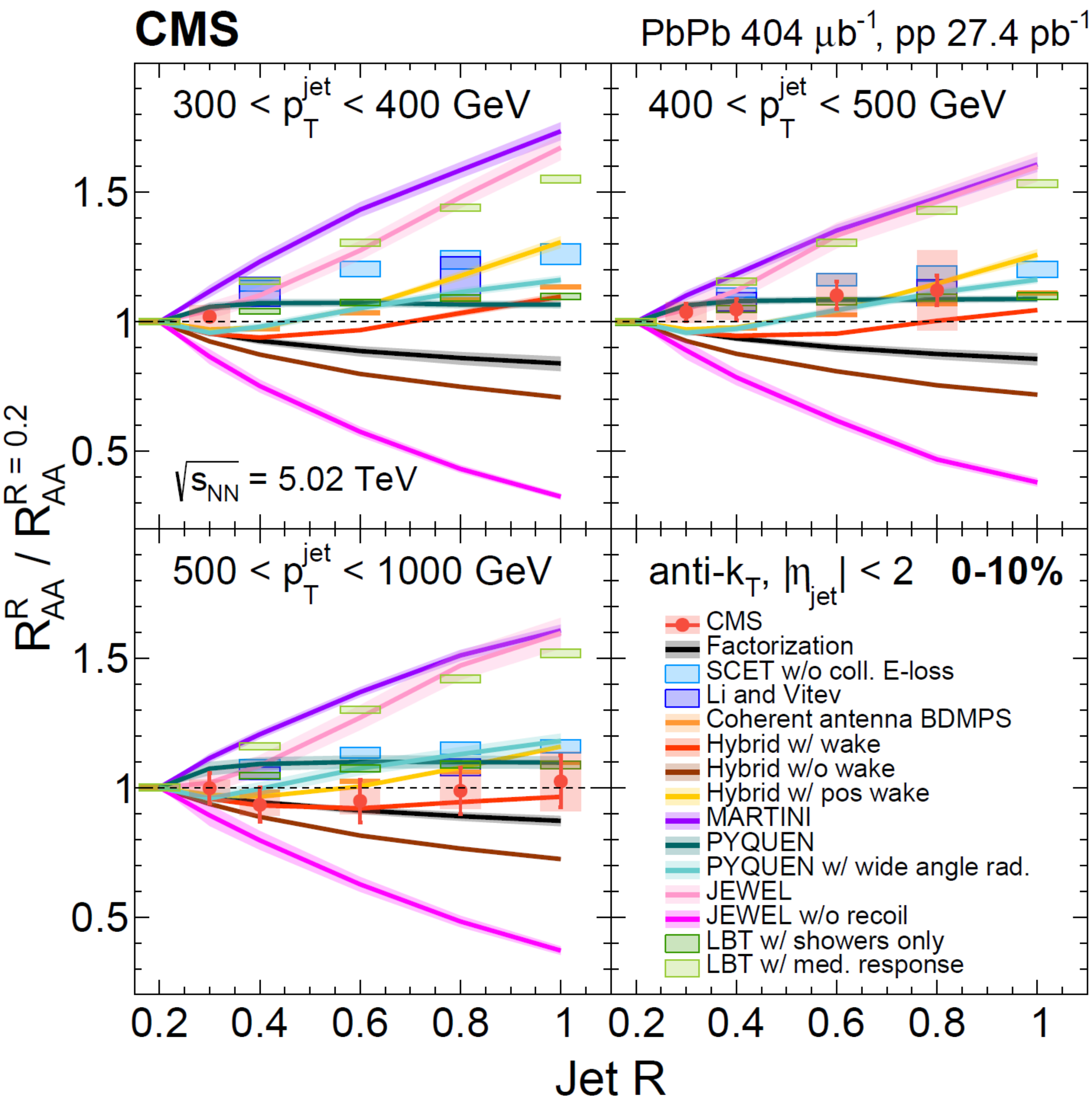
Jet R_{AA} ratios in data are **consistent with 1 up to R=1** !!!


Chris McGinn (Thesis)


Yi Chen


Molly Taylor

Jet R_{AA} ratios vs. R in 0-10% PbPb at 5 TeV



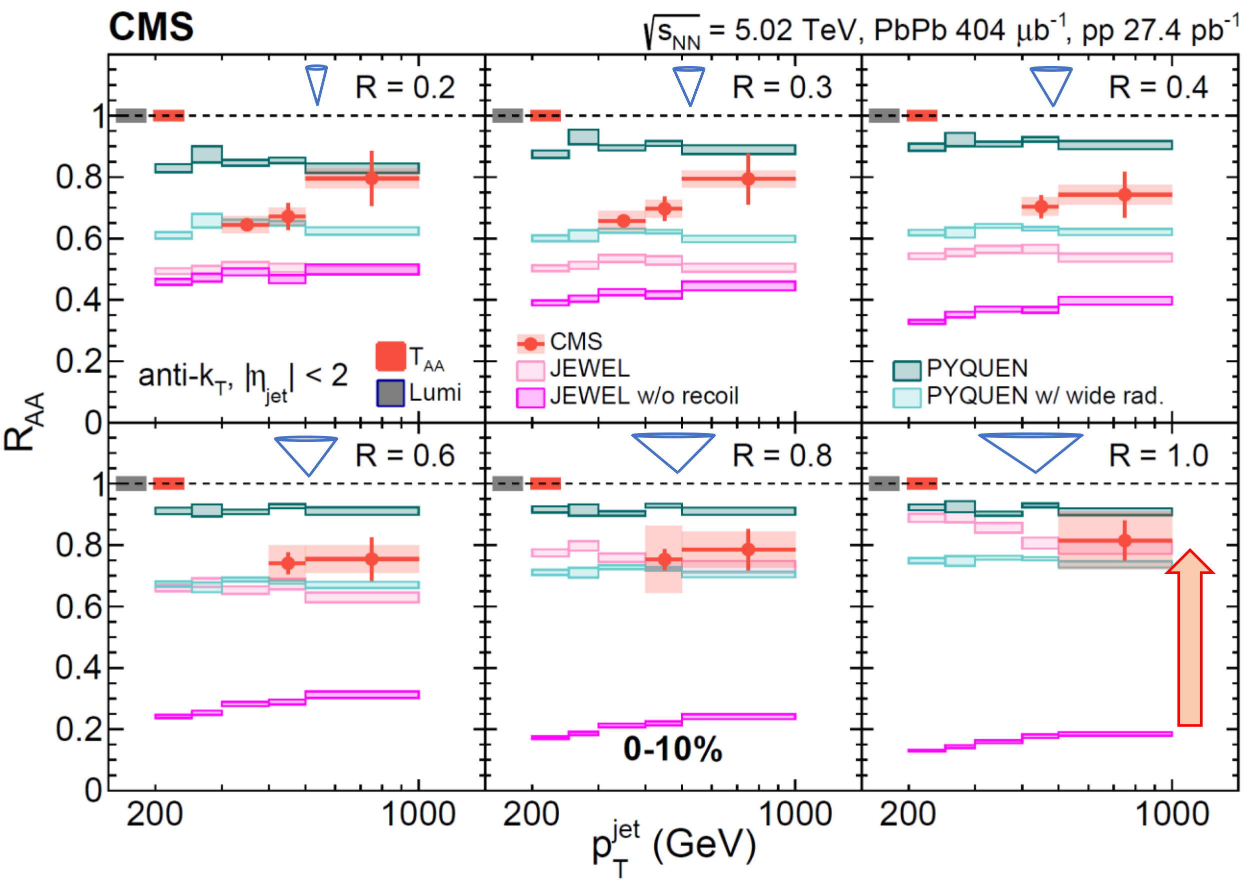
Similar picture in different jet p_T intervals

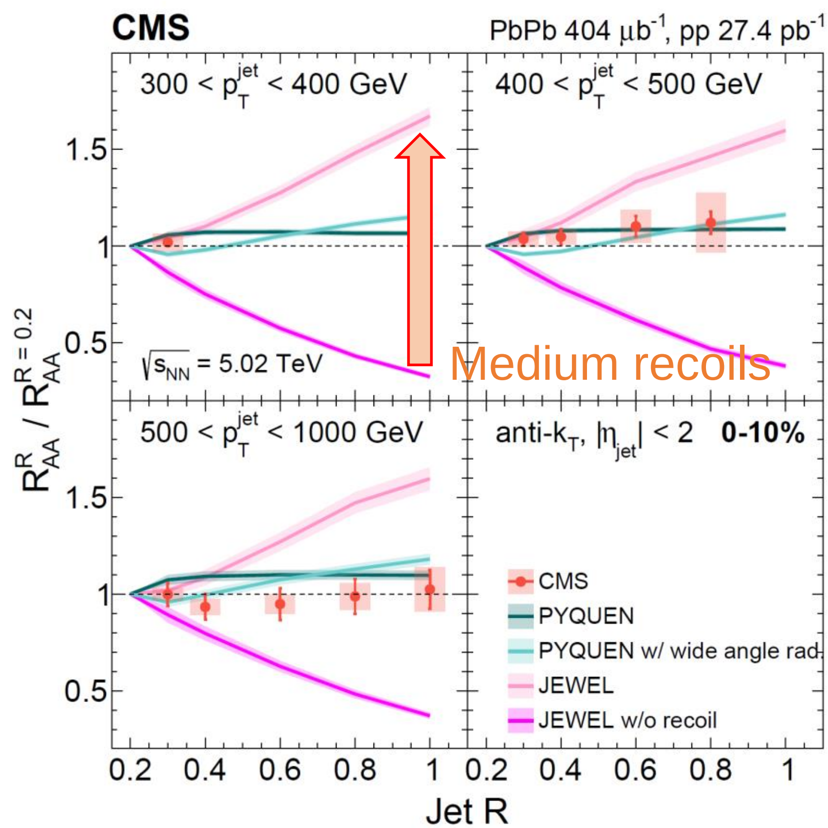
Chris McGinn (Thesis)

Yi Chen

Molly Taylor

Jet R_{AA} vs. Event Generator



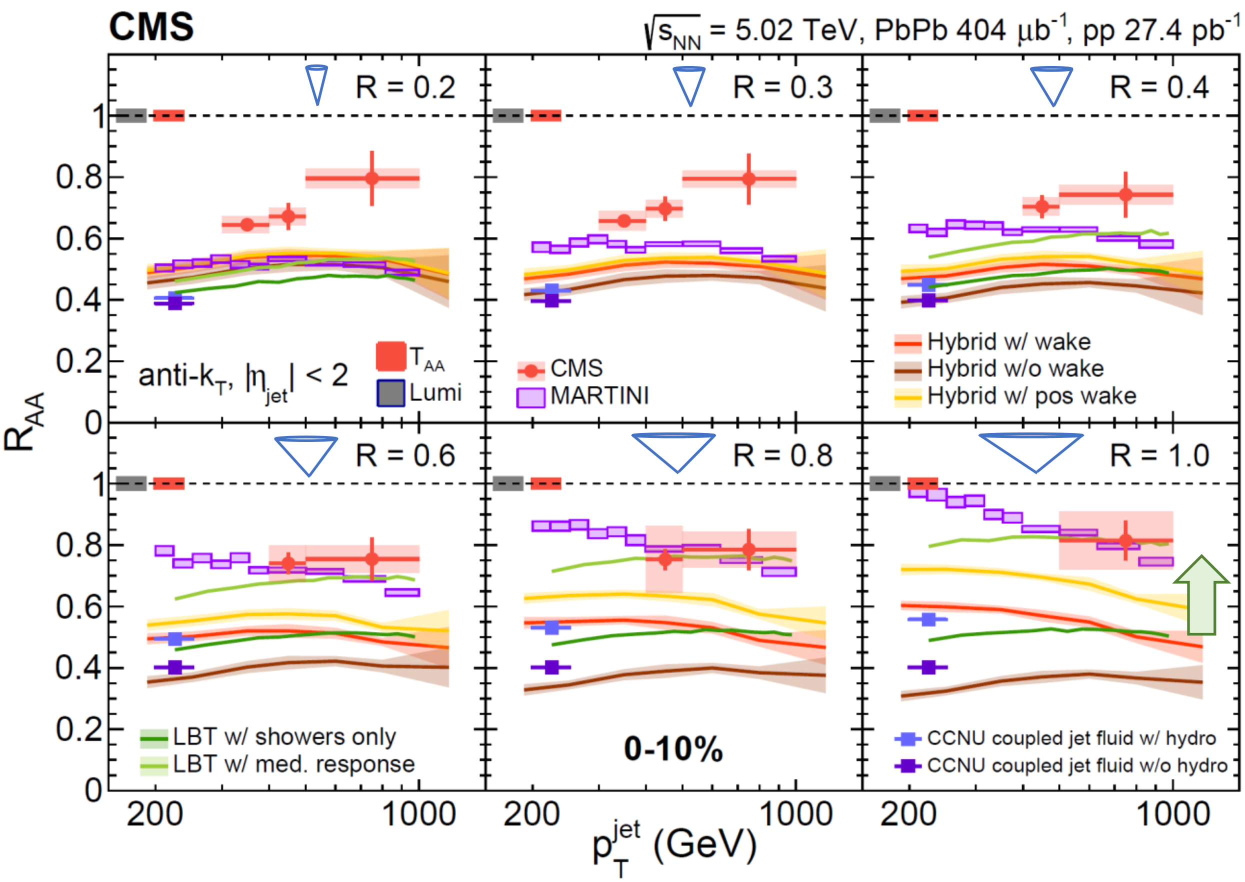


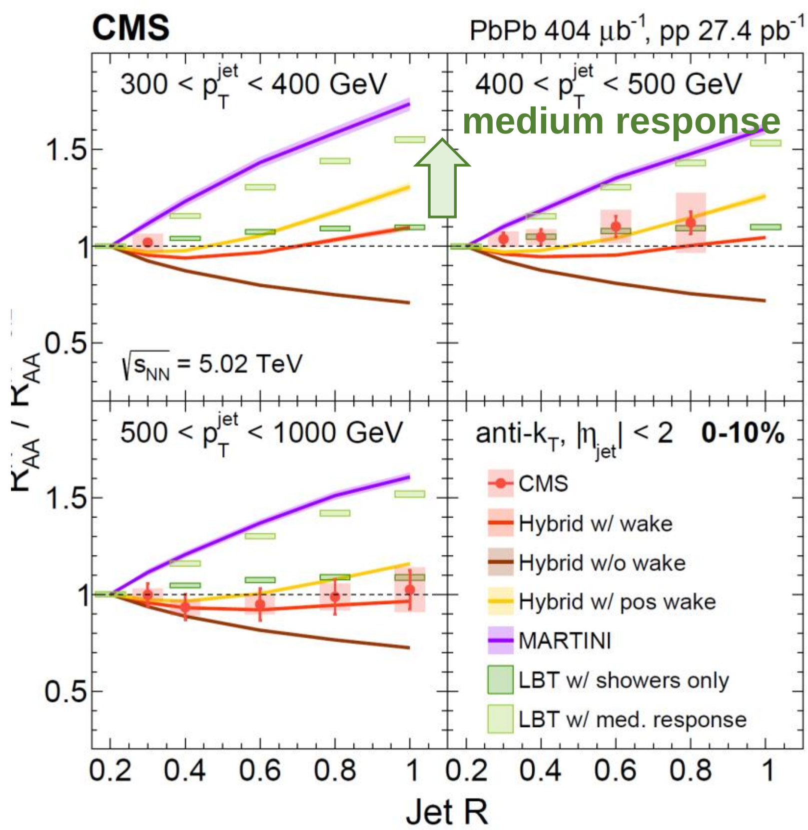
- **JEWEL**: Scattering and radiative energy loss for hard partons. **Medium recoils** that carry energy away. Full model overestimates R dependence
- **PYQUEN**: Hard Partons re-scatter and radiate according to BDMPS. Wide angle radiation push the quenched energy away from the jet axis. Doesn't conserve energy and momentum (no medium response). Decent description of R dependence despite the incomplete modeling of the event.

JEWEL JHEP 1707 (2017) 141

PYQUEN EPJC 16 (2000) 527

Jet R_{AA} vs. Monte Carlo

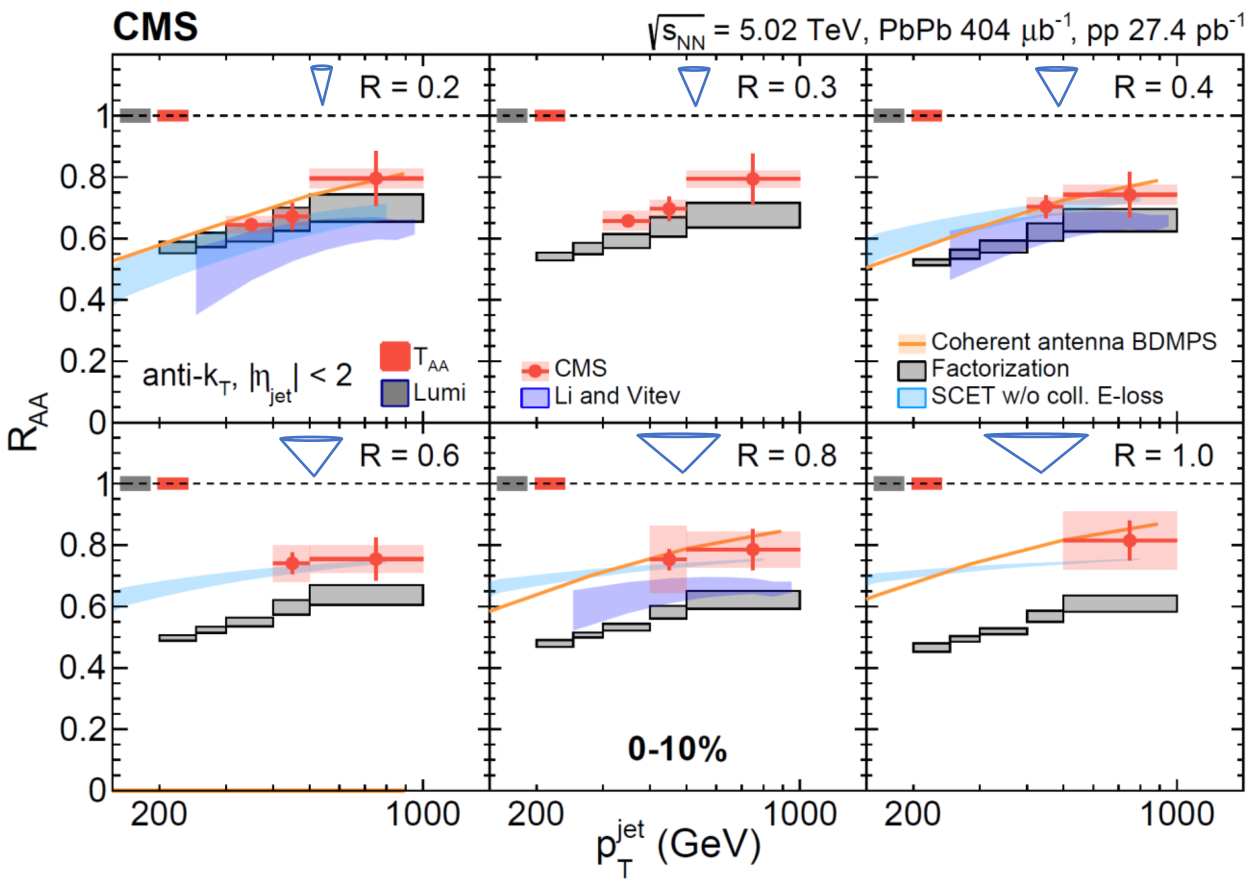


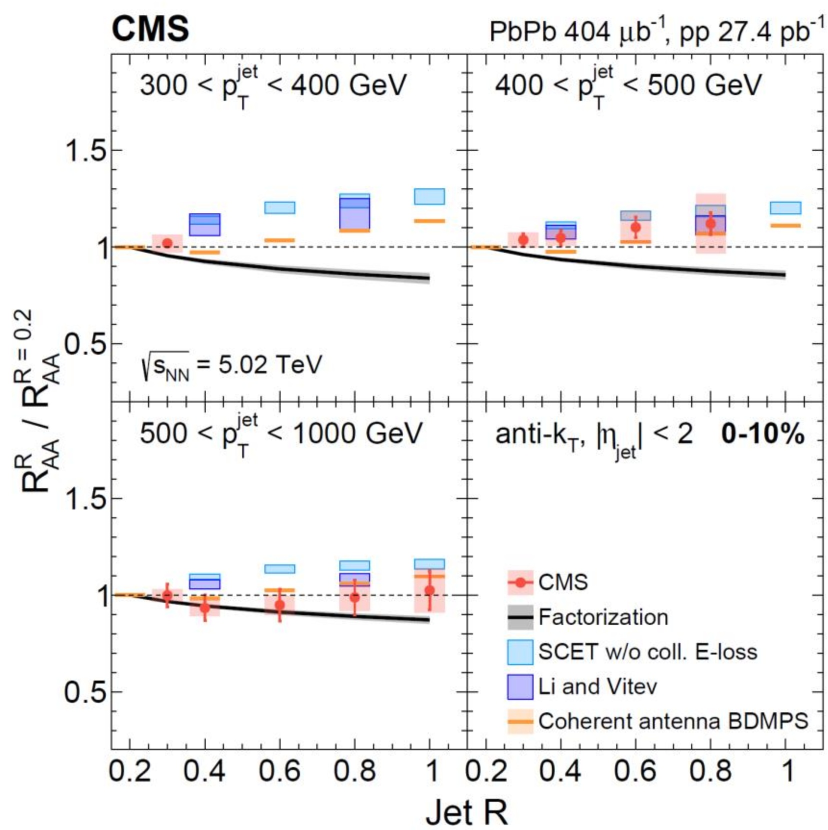


- **MARTINI:** Jet propagate (McGill-AMY) in evolving hydrodynamic medium. Overestimates R dep.
- **LBT:** Recoil thermal partons and their propagation in the dense medium are described by a 3+1D viscous hydro model. Shows the importance of **medium response**. Overestimates R dependence.
- **Hybrid:** A hybrid model of pQCD (for shower generation) and AdS/CFT drag force. Diffusion wake reduces the jet suppression. Overestimate the jet suppression.
- **CCNU jet-fluid:** includes both collisional, splitting and p_T broadening in a viscous hydro medium. Shows the importance of hydrodynamic component increases as a function of R

MARTINI PRC 80 (2019) 054913 | LBT PRC 99 (2019) 054911 | Hybrid JHEP 03 (2017) 135 | CCNU jet-fluid PRC 94 (2016) 024902

Jet R_{AA} vs. Calculations

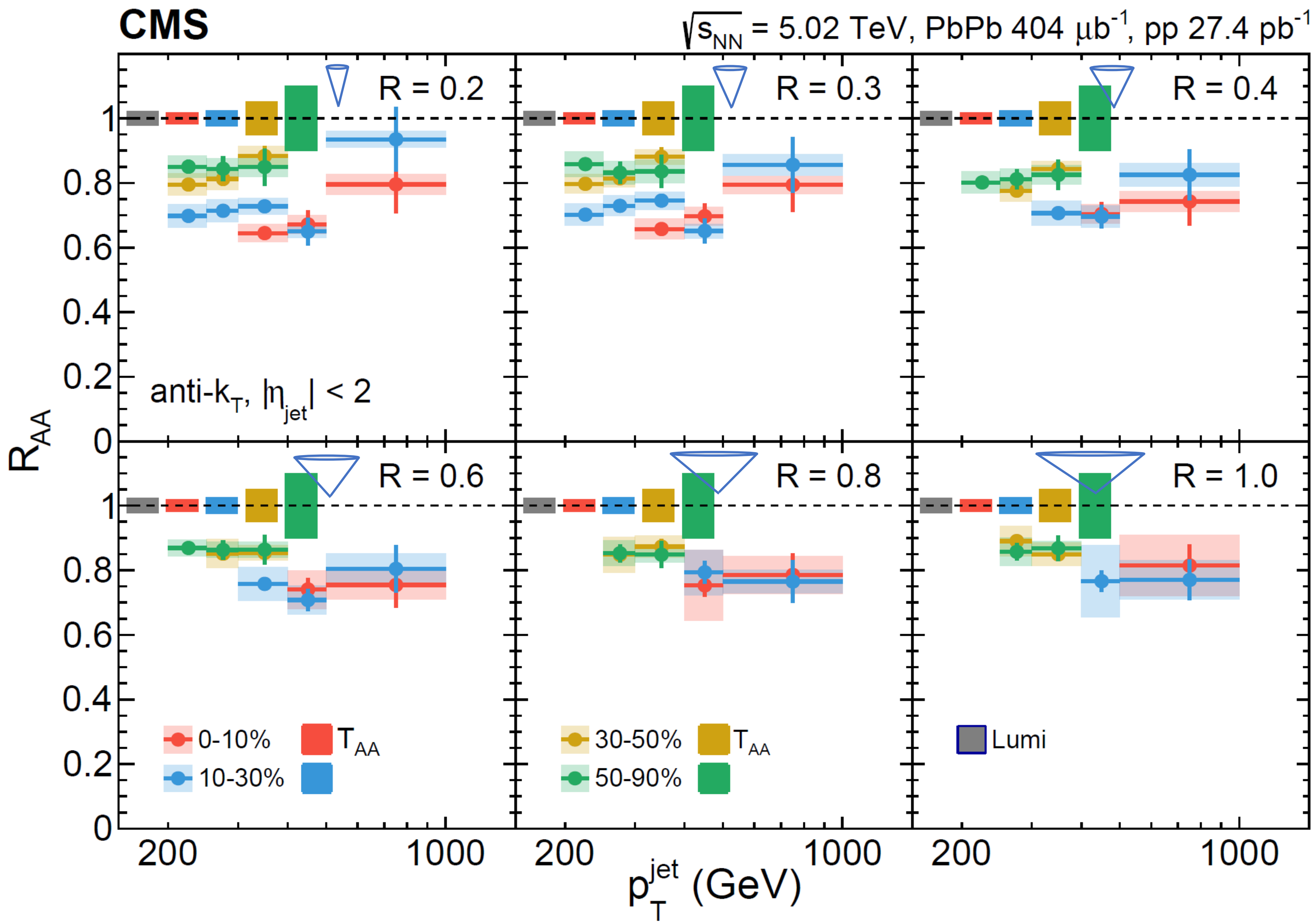




- **Factorization:** Factorization of jet cross sections. Medium-modified jet functions extracted from jet R_{AA} at R=0.2 & 0.4. Underestimates R dependence: **factorization breaks down for large area jet?**
- **$SCET_G$:** without collision energy loss, soft-collinear effective theory based method coupled with a Glauber gluon medium. Good agreement with the data.
- **Li and Vitev:** $SCET_G$ with collision energy loss and cold nuclear matter effect. Slightly underestimate R_{AA}
- **Coherent Antenna BDMPS**: an analytical approach that resums multiple emissions to leading logarithmic accuracy including radiative energy loss and color coherence effects. General agreement with data

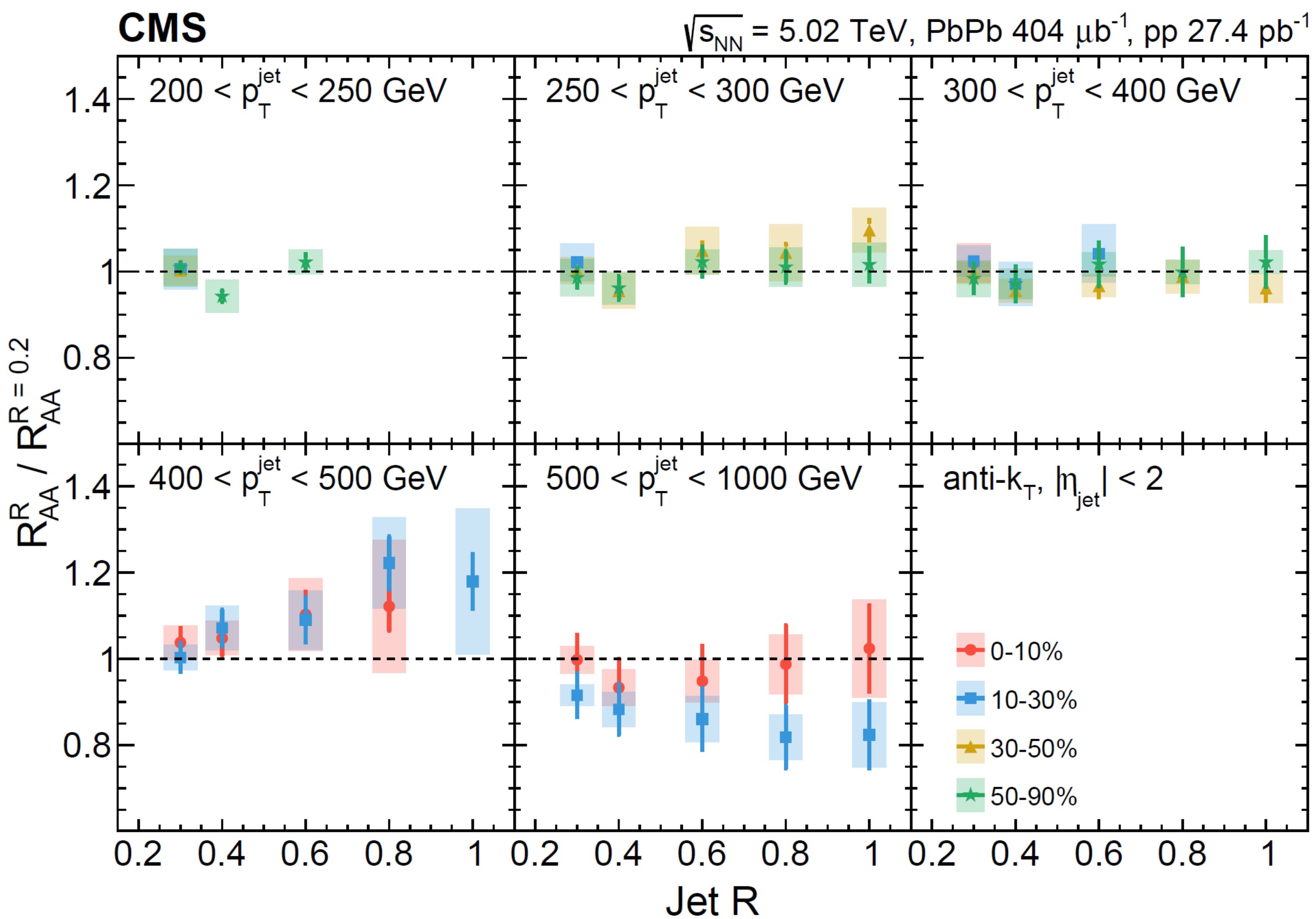
Factorization PRL 122 (2019) 252301 | Li and Vitev JHEP 1907 (2019) 148 | $SCET_G$ w/o coll E. loss: JHEP 1905 (2016) 023 | Coherent antenna BDMPS: PRD 98 (2018) 051501

Jet R_{AA} in Different Centrality Bins



- Large radius jets at high p_T are **suppressed by a factor of around 20-30%**
- Less suppression in the peripheral events

Jet R_{AA} Ratios in Different Centrality Bins

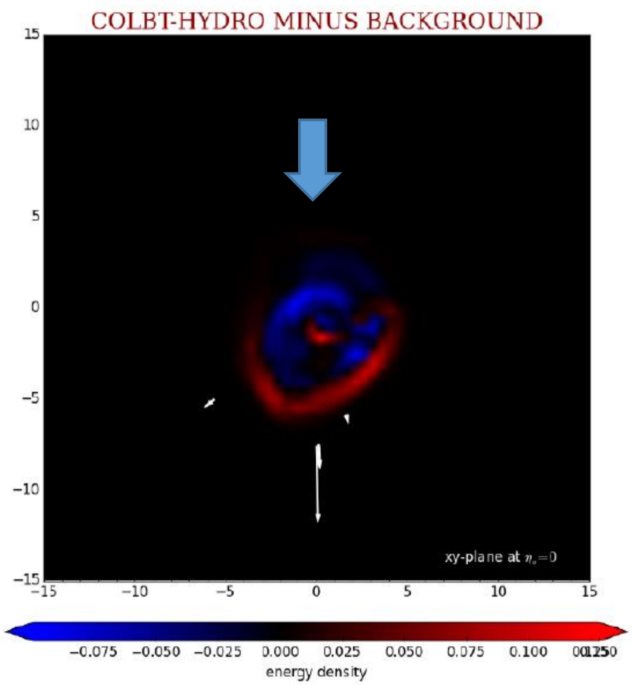


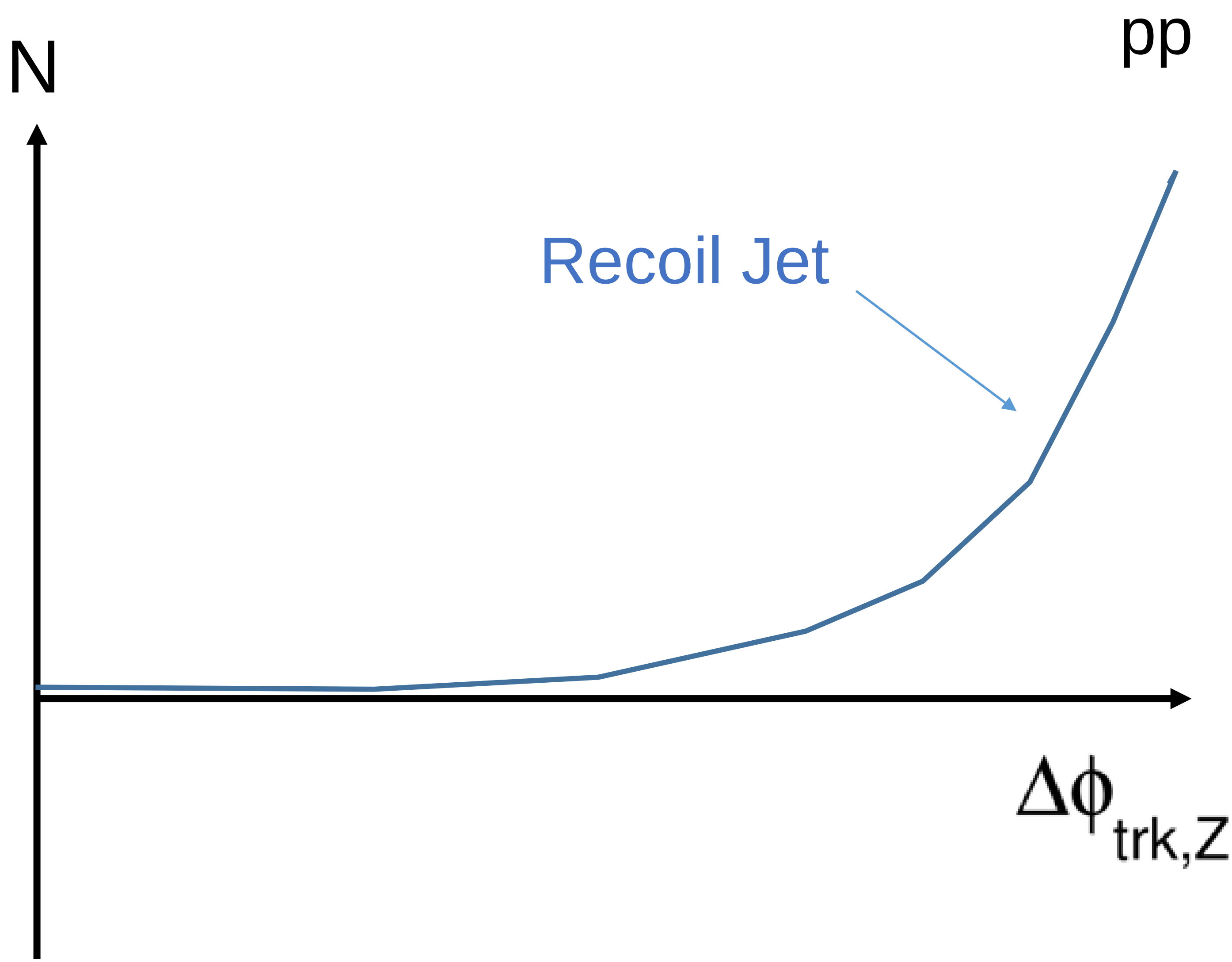
R_{AA} ratios are close to 1 (except 10-30%)

(2) To Measure the "Depletion" with Z-hadron Correlation

CoLBT

Tan Luo, Xin-Nian Wang





Measure the **boson-side associated yield** with photon-jet and Z-jet

(2) To Measure the “Depletion” with Z-hadron Correlation

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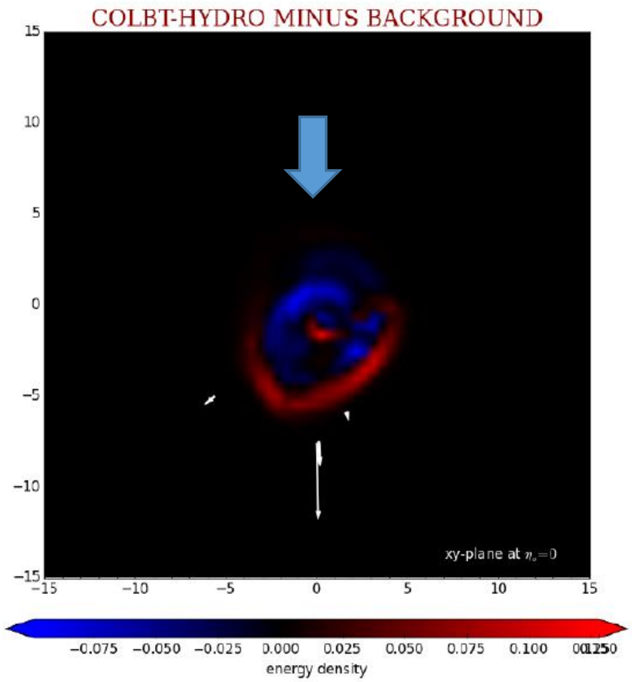

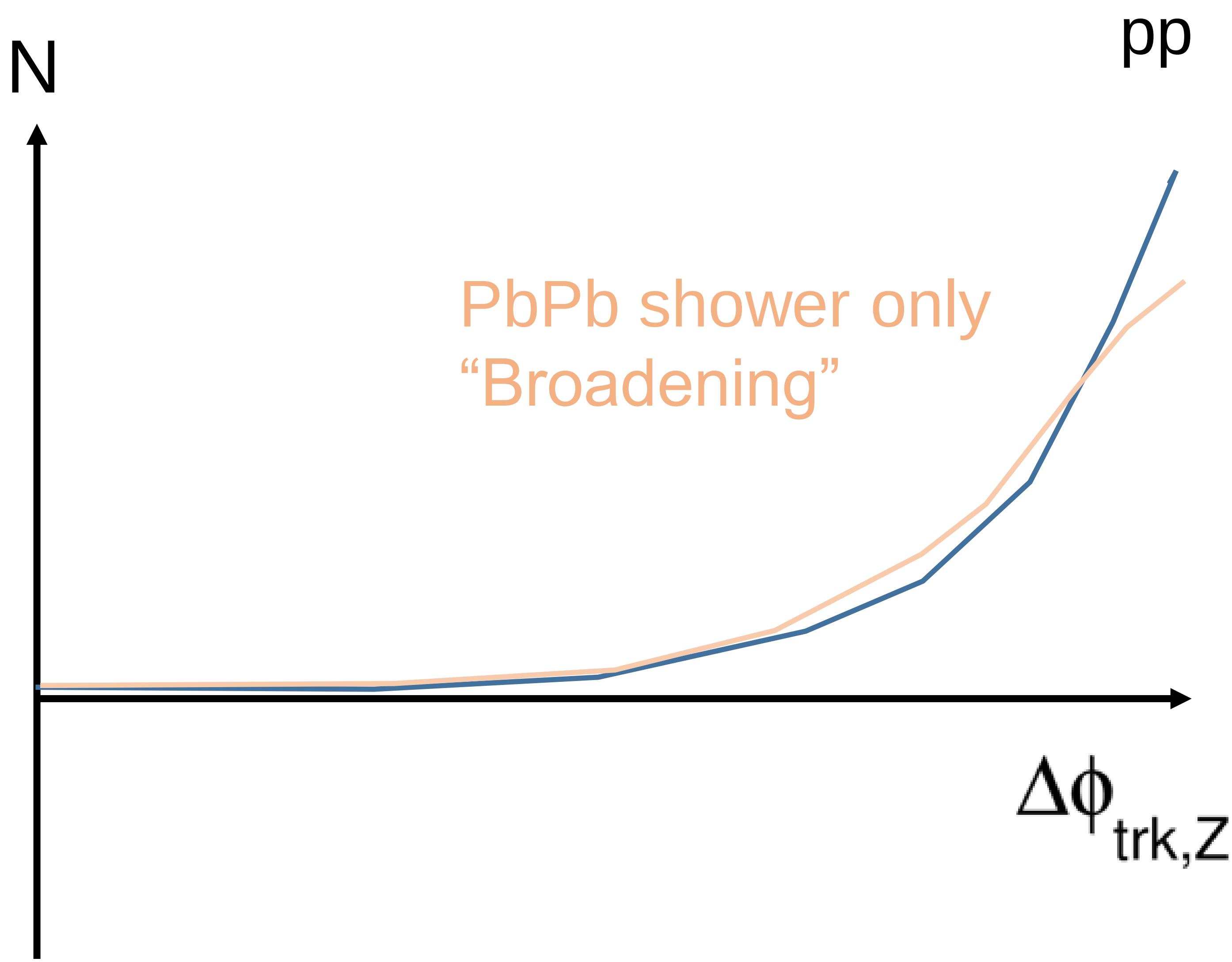

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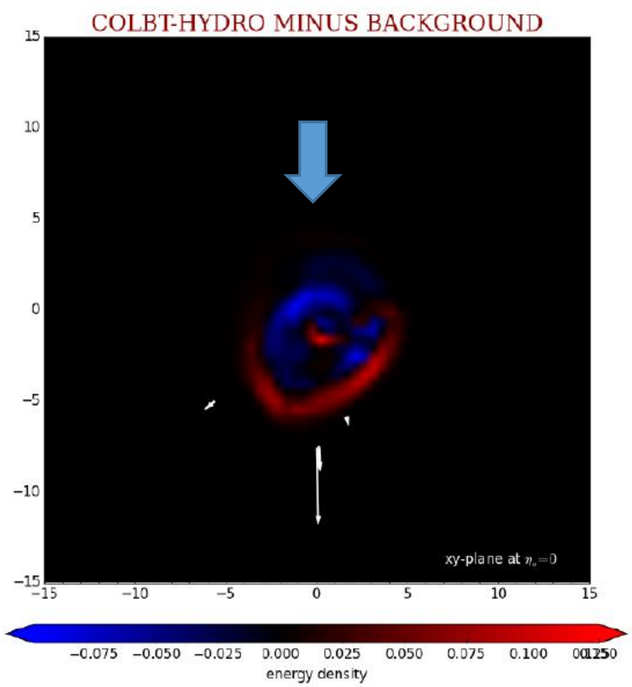
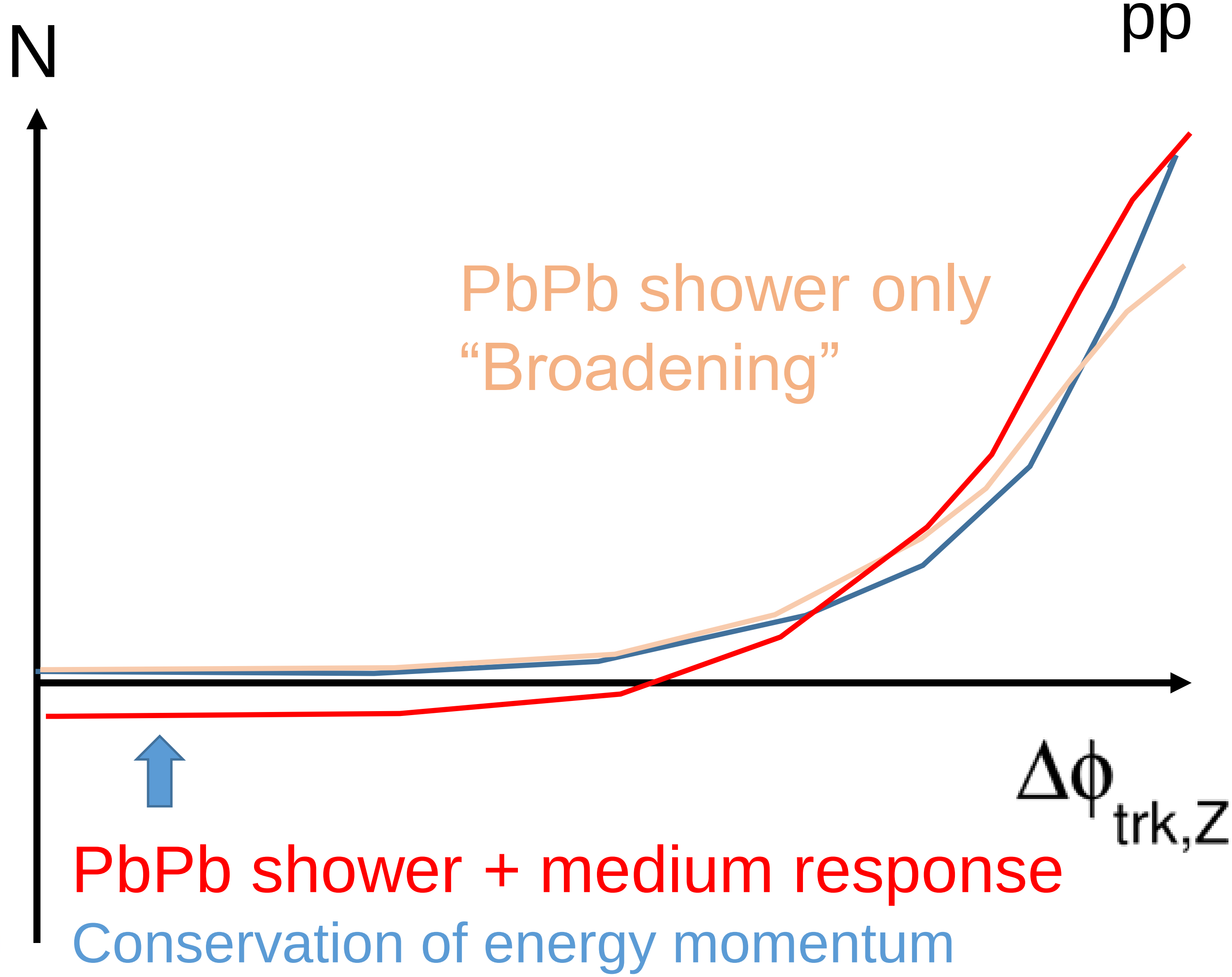
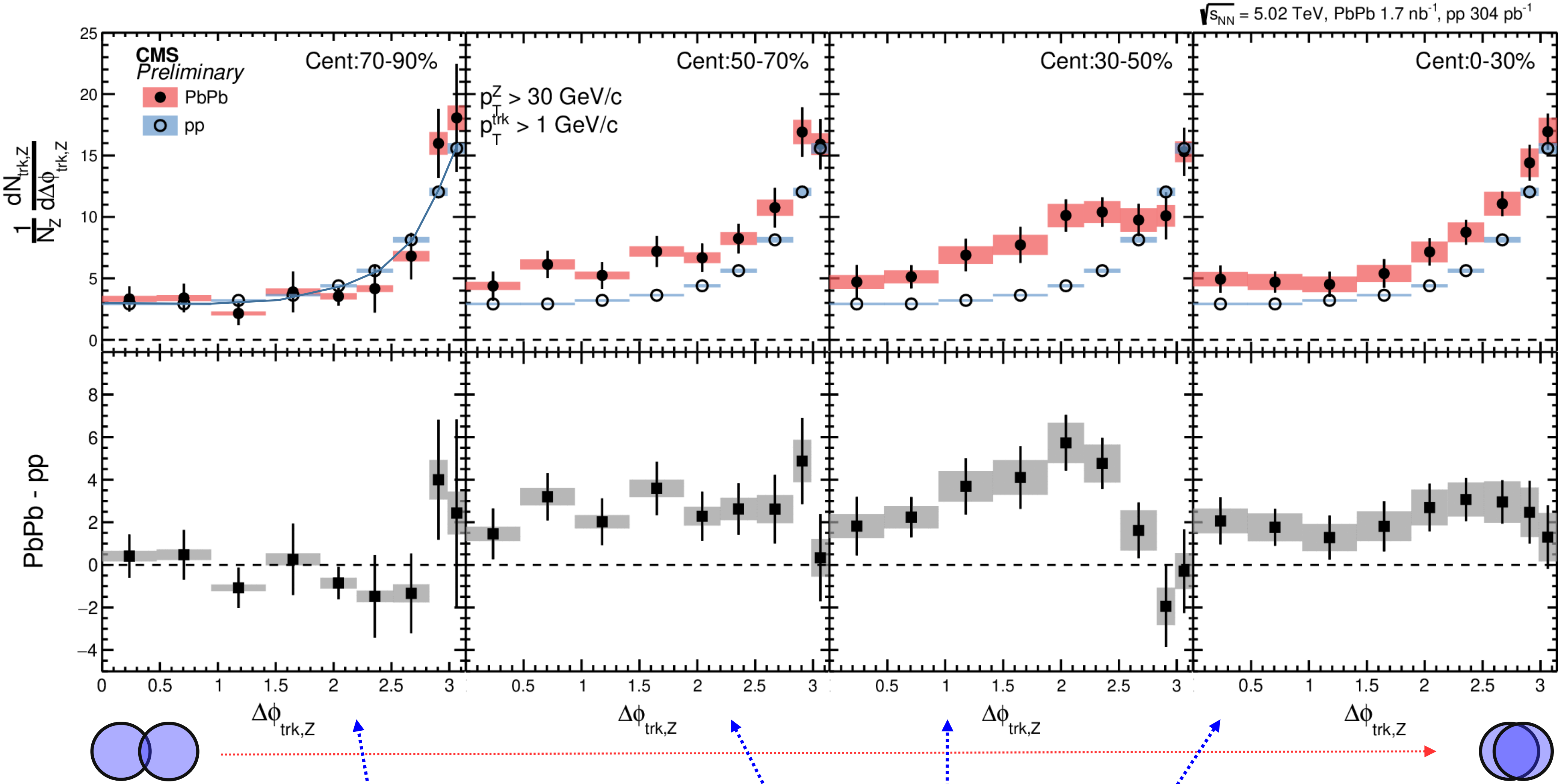




Measure the **boson-side associated yield** with photon-jet and Z-jet

Results: Z-hadron Δφ

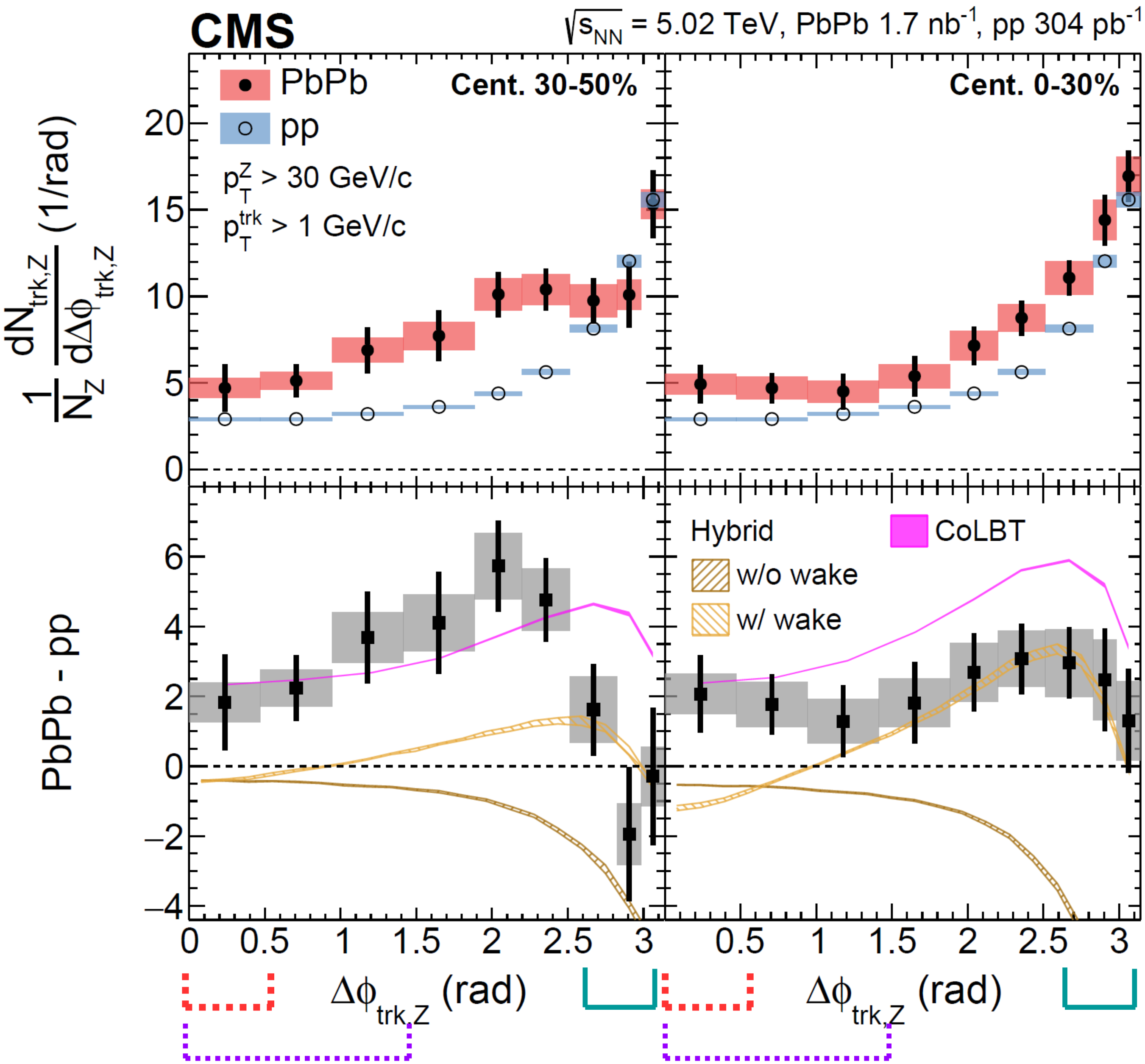


PbPb consistent with pp

Excess of particle yield in PbPb!!
Quenched 2nd jet?

Kaya Tatar
(Thesis)

Theory Comparison: Z-hadron Δφ



Hybrid Model:

$\Delta\varphi_{trk,Z}$ ~ π trend similar when **including** medium response

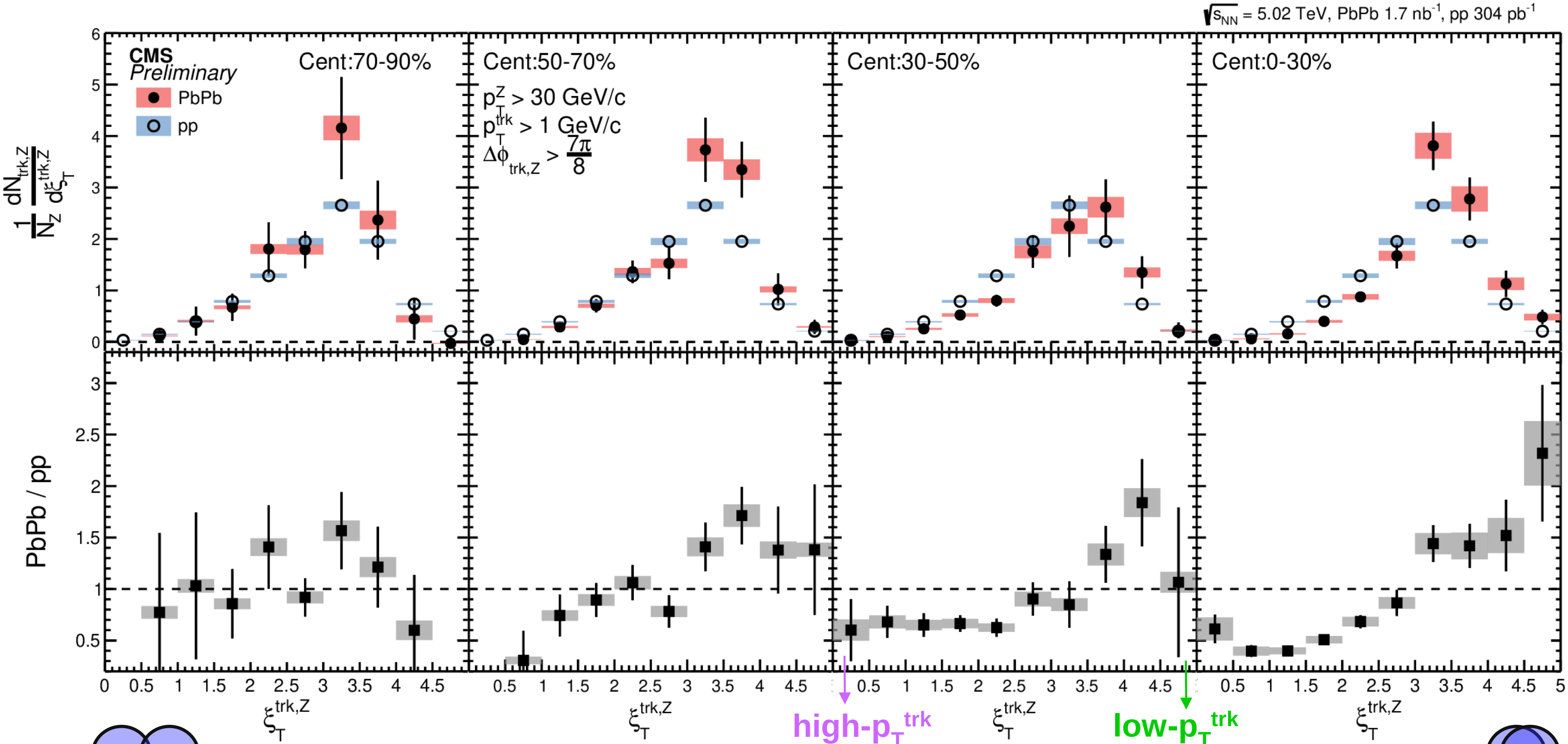
$\Delta\varphi_{trk,Z}$ < π/2 underestimated by Hybrid

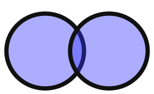
Full wake negative at **$\Delta\varphi_{trk,Z}$ ~ 0** **(w/ diffusion) in Hybrid model**
Medium response treatment may be too simple.

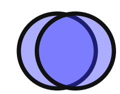
CoLBT:

- Good agreement with PbPb data in 30-50%.
- Slightly overestimate the associated yield in 0-30%

"Fragmentation function": $\xi_T^{trk,Z}$







$$\xi_T^{trk,Z} = \ln \frac{-|\vec{p}_T^{\,Z}|^2}{\vec{p}_T^{\,trk}\cdot\vec{p}_T^{\,Z}}$$

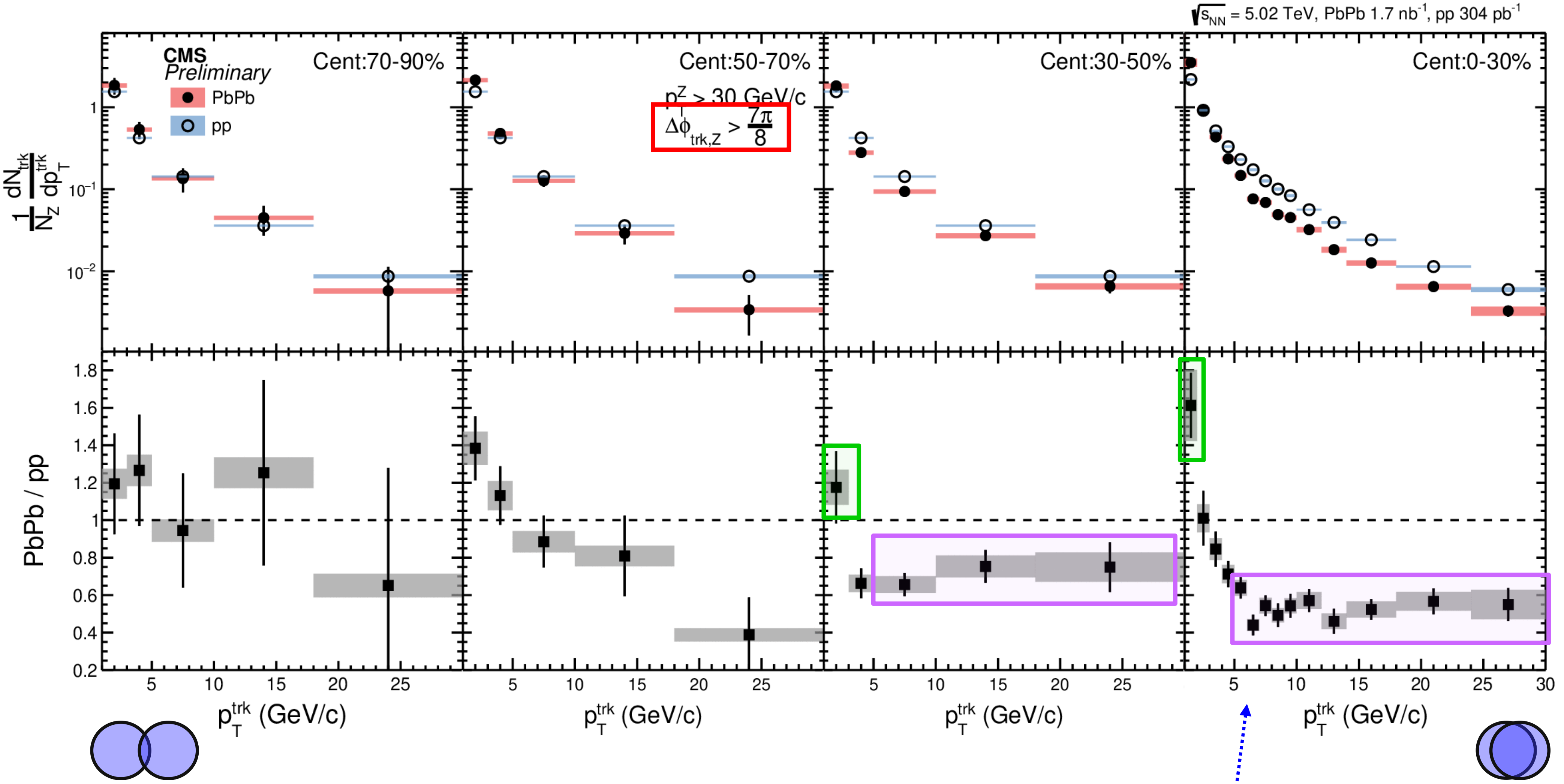
$\vec{p}_T^{\,Z}$: transverse mom. vector of the Z

$\vec{p}_T^{\,trk}$: transverse mom. vector of the track

Peripheral PbPb consistent with pp

Kaya Tatar (Thesis)

Z-tagged charged particle p_T spectra

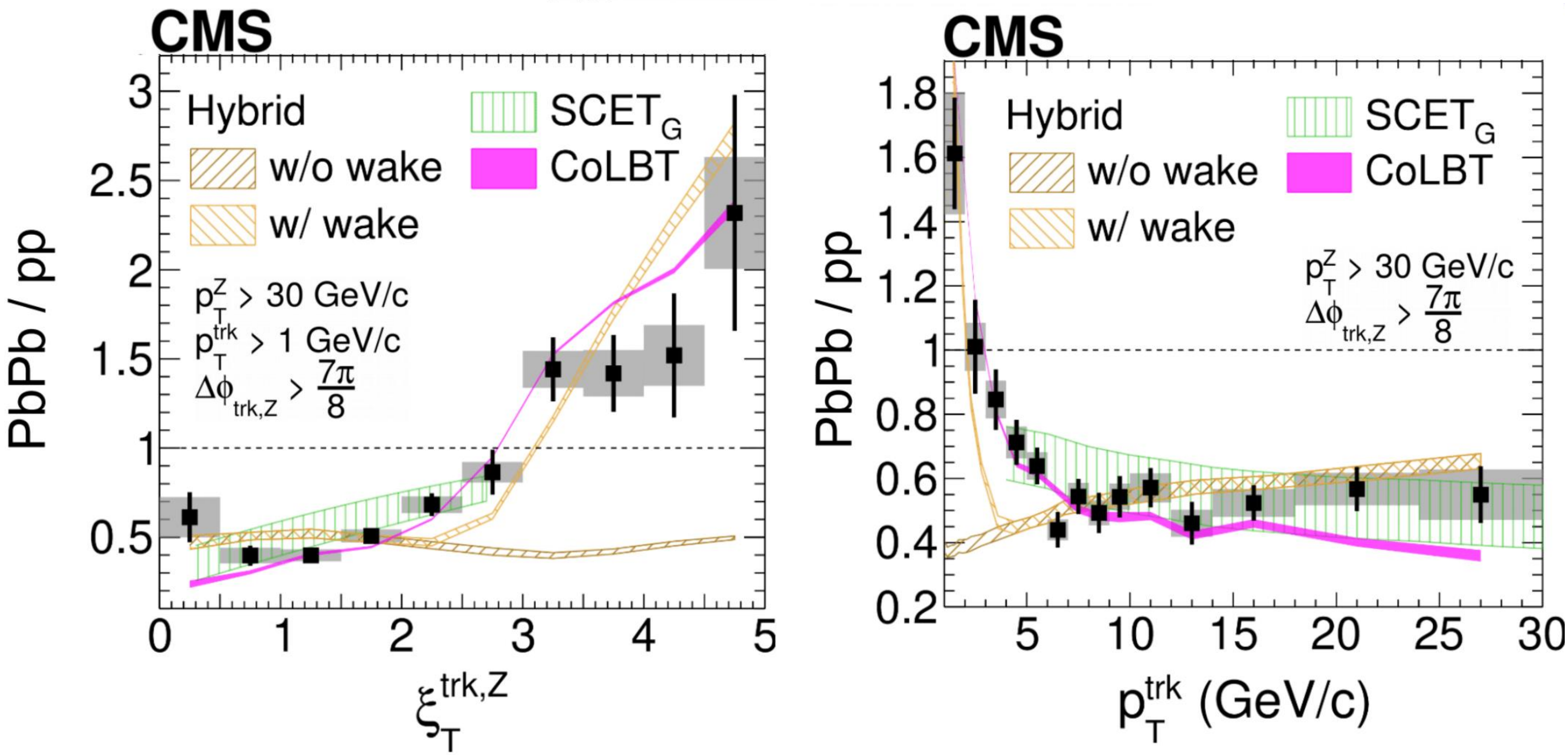


Peripheral PbPb consistent with pp

PbPb / pp ($1 < p_T^{trk} < 2$ GeV) ~ 1.6
($p_T^{trk} > 5$ GeV) ~ 0.4 - 0.6

Theory Comparison: particle spectra in the jet side

Z-tagged FF $\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 1.7 nb^{-1}, pp 304 pb^{-1} **recoil p_T^{trk}**



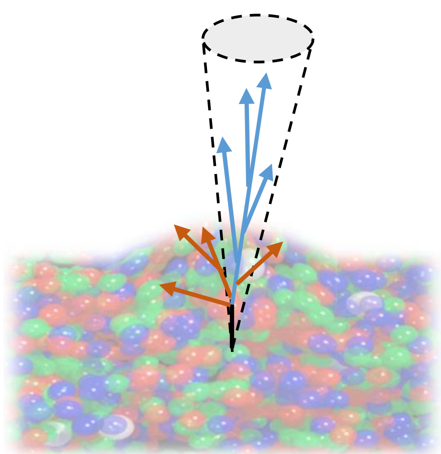
- Good description of the high p_T part by **SCET$_G$**, **CoLBT** and **Hybrid**
- Low p_T particle enhancement: wake contribution in **Hybrid**; very good description by **CoLBT** which include hydro medium response

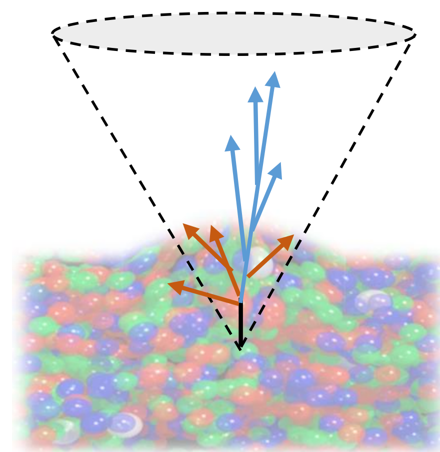
Discussion

- Large area jet spectrum provided new constraints on jet quenching due to the inclusion of particles at large angle and the inclusion of wide parton shower
- Most models which were extremely successful for the description of small area jet failed to describe the data

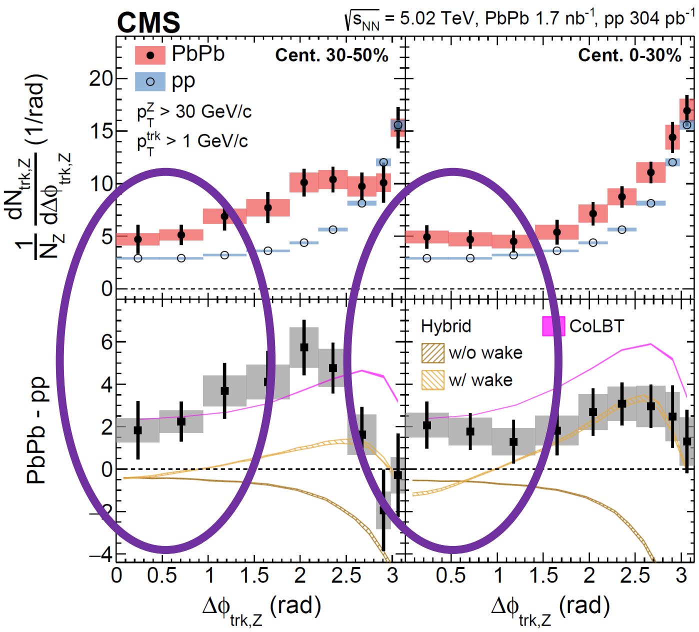
Discussion

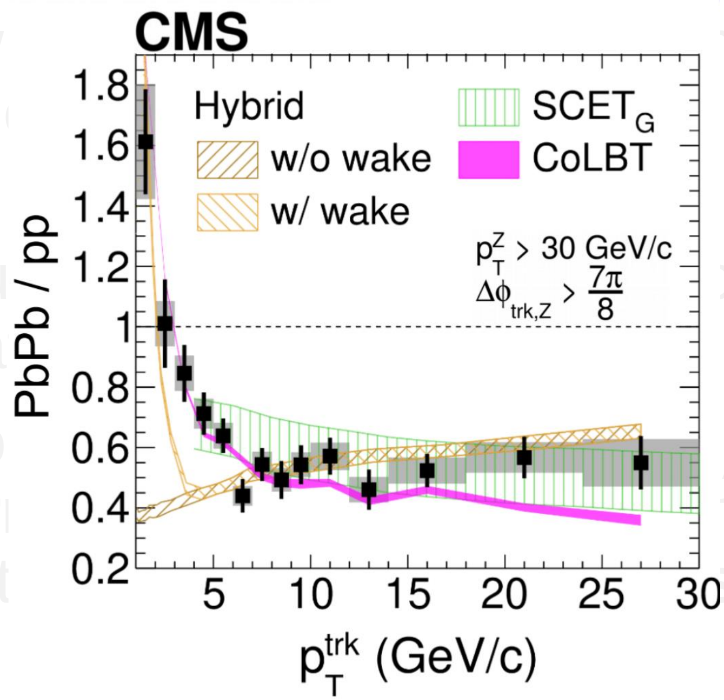
- Large area jet spectrum provided new constraints on jet quenching due to the inclusion of particles at large angle and the inclusion of wide parton shower
- Most models which were extremely successful for the description of small area jet failed to describe the data
- Models with medium response tend to overshoot the large jet R_{AA} data which may indicate **too tight correlation** between medium response and the mother parton direction or **too small suppression of the wide parton shower**





Discussion



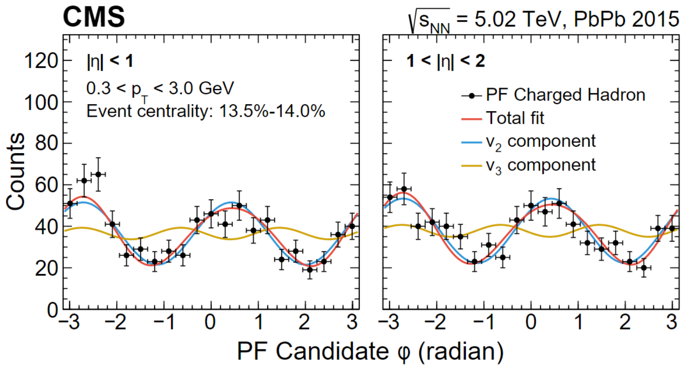


- On the other hand, calculations which don't have detailed QGP modeling or medium are in better agreement with the data.
- Z-tagged hadron spectra showed new signal of associated particles near the color-neutral Z boson ("**jetless" jet quenching analysis**, therefore, include all kinds of parton showers)
- Models / calculations are relatively more successful in the description of Z-tagged hadron spectra in the jet side.

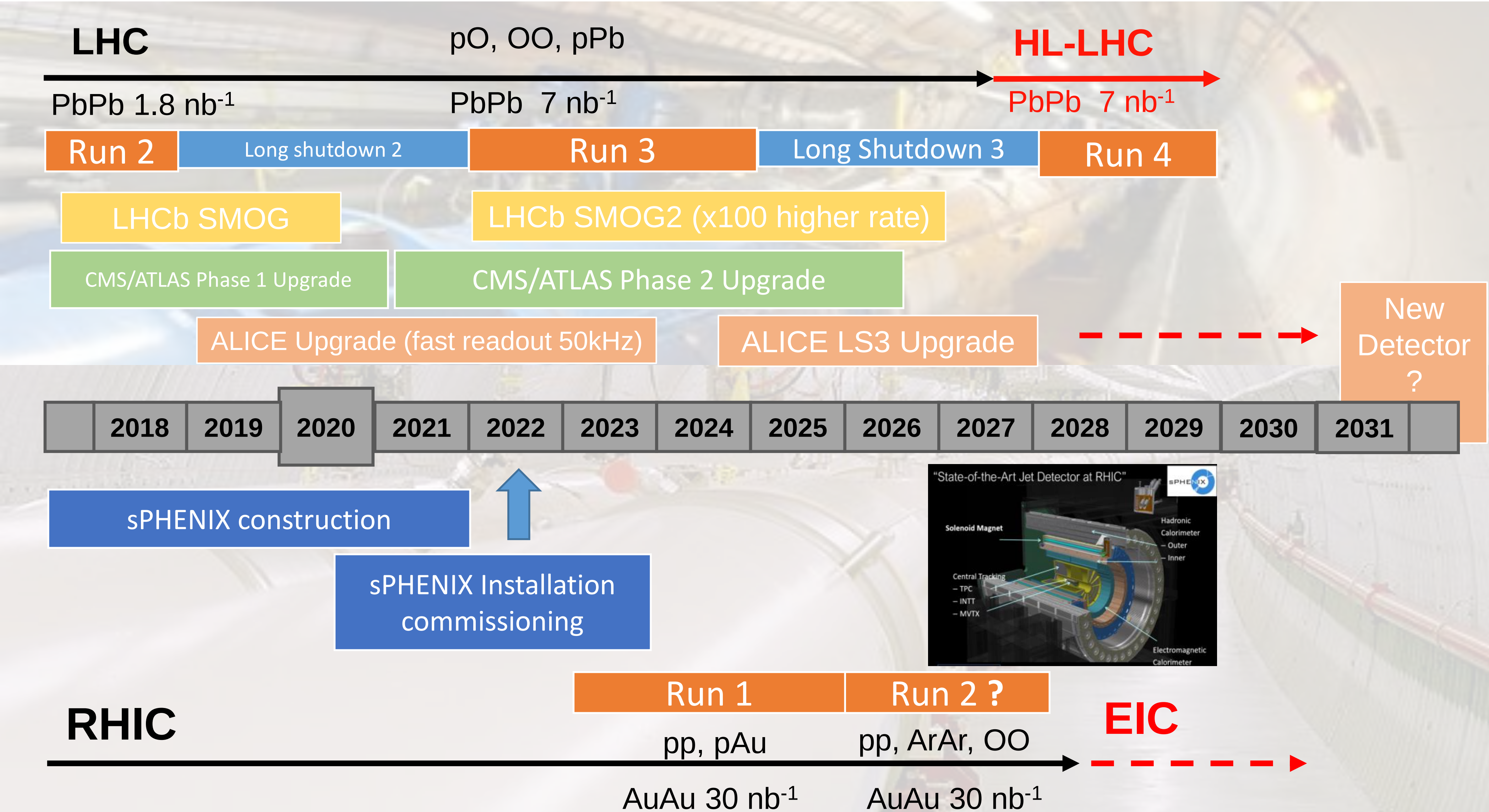
Discussion and Plan

- Plan to provide direct experimental results on the parton shower shape dependence of jet quenching:
  - Update the large area jet results with 2018 data (ongoing)
  - Groomed jet substructure dependence of jet R_{AA}
  - Large area jet shape and fragmentation function

- Facilitate communication between theorists and experimentalists on the background subtraction method
  - Theorists did not perform the same background subtraction as the experimentalists
  - Experimentalists also need to do a better job documenting the algorithms
  - The worry is that part of the medium response signal could be partially suppressed due to the background subtraction method introduced by the experimentalist



Summary

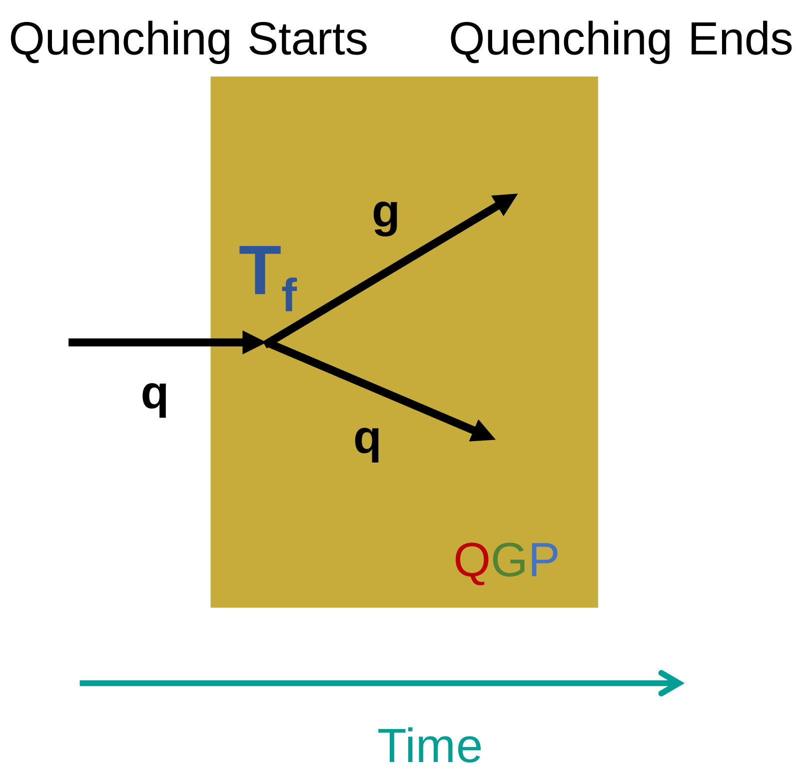


Exciting future jet physics program in the next 10 years and beyond!

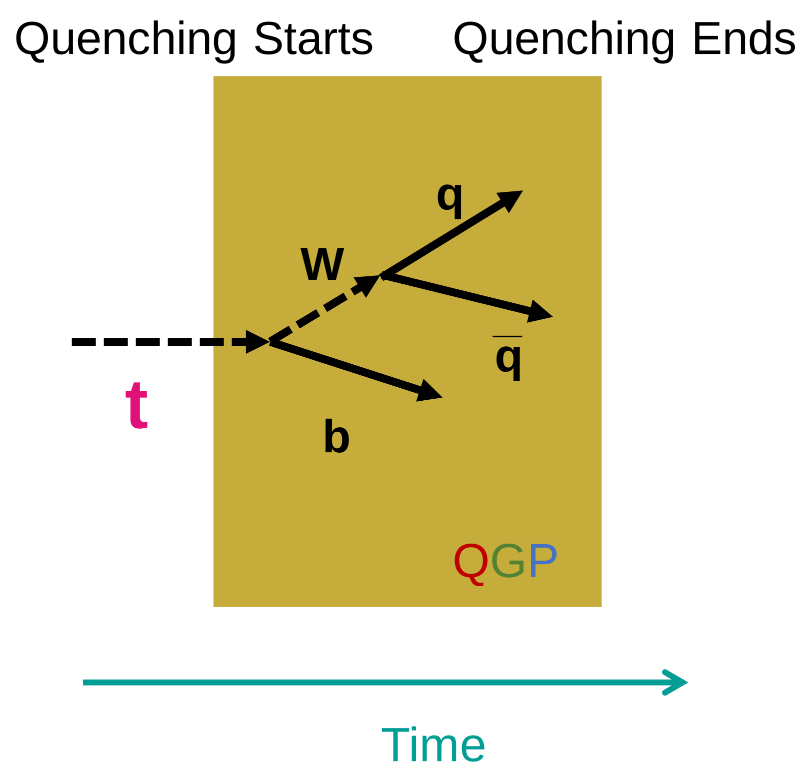
Backup slides

Probing the QGP Evolution

Formation Time (T_f) Tagging



Boosted Top



Probing the QGP Evolution

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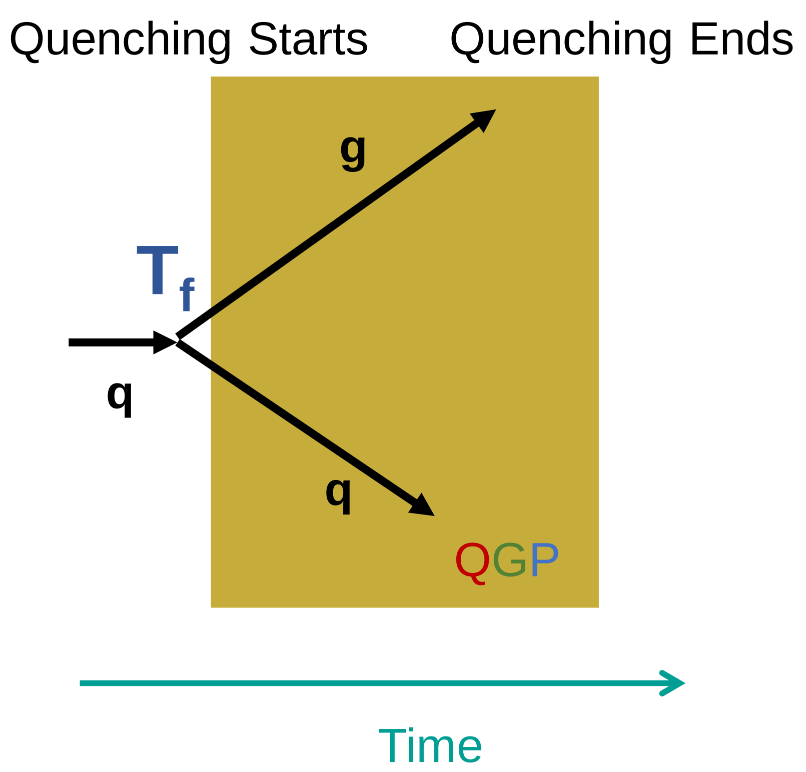
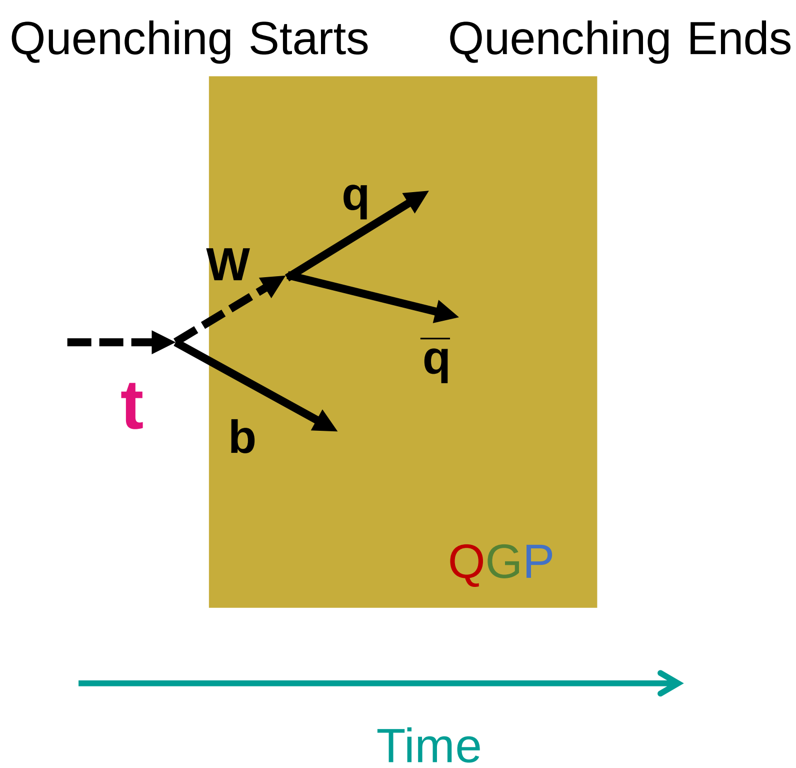


Short formation time

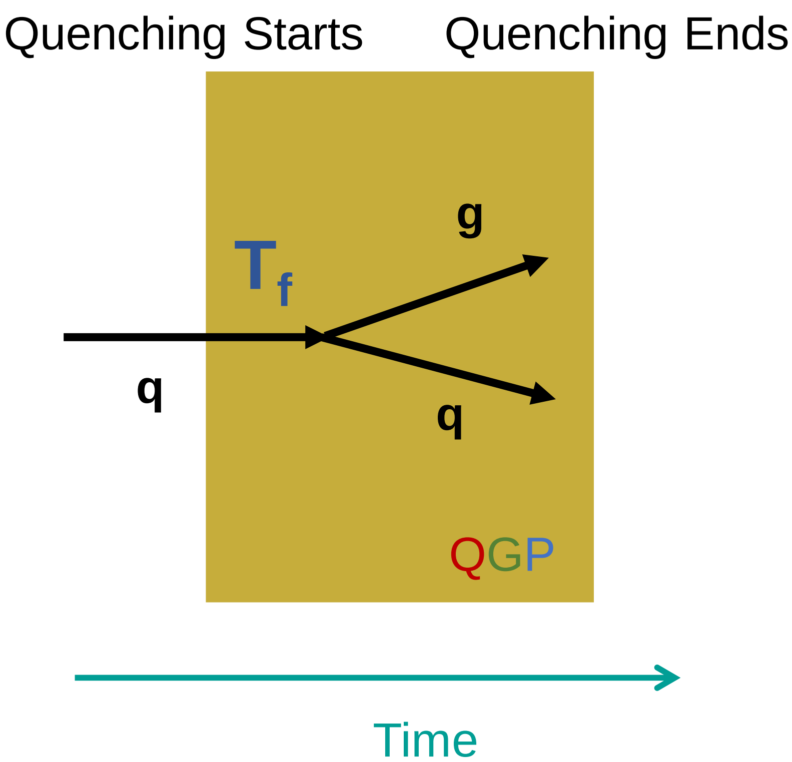
Boosted Top



Low p_T top

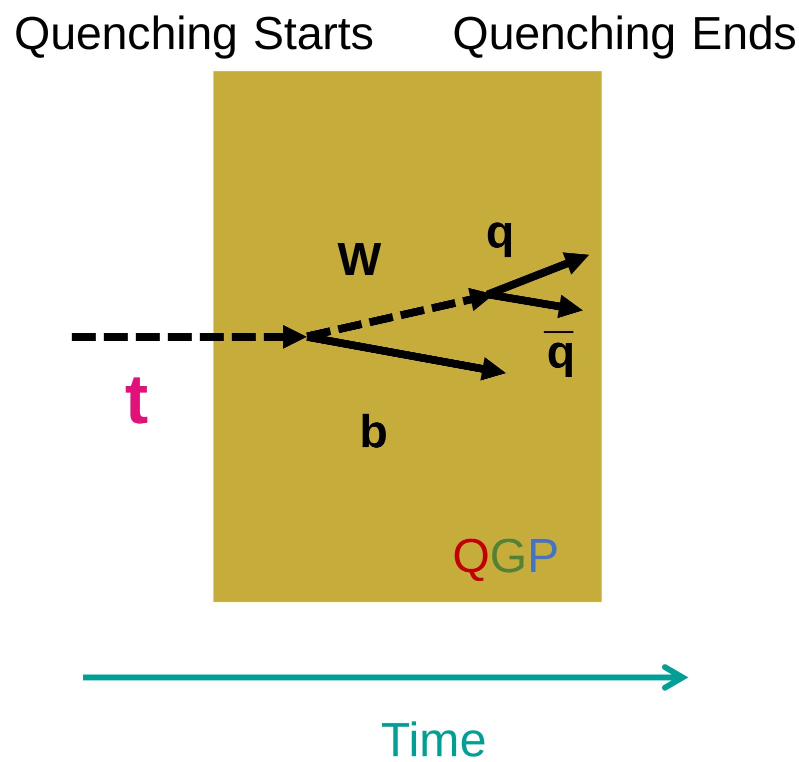
Probing the QGP Evolution

Formation Time (T_f) Tagging



Long formation time

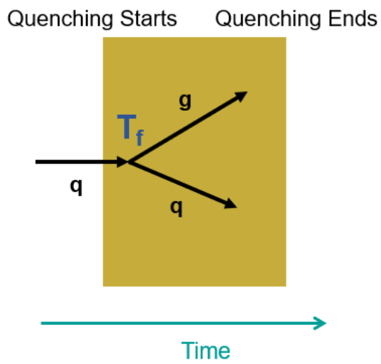
Boosted Top

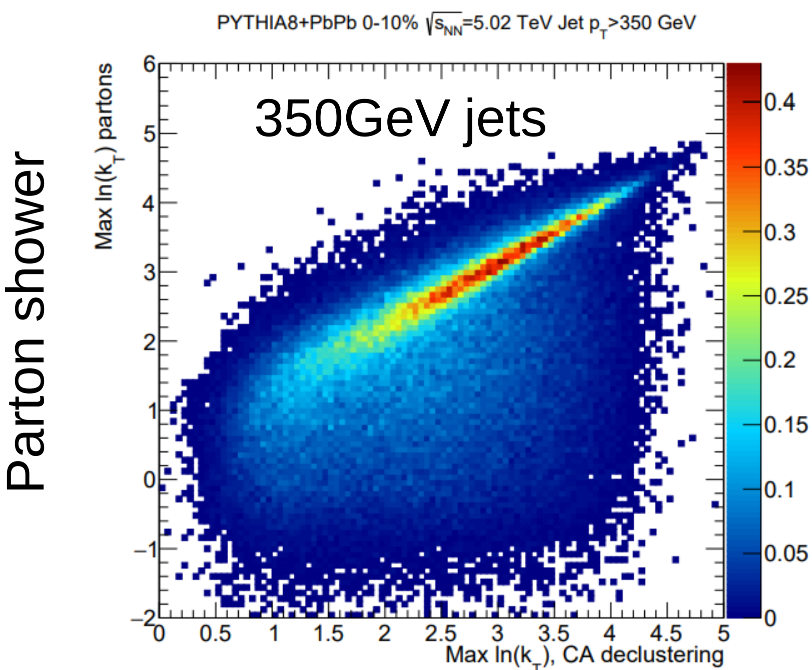


High p_T top

Time Dependent Evolution of QGP

Formation Time (T_f) Tagging

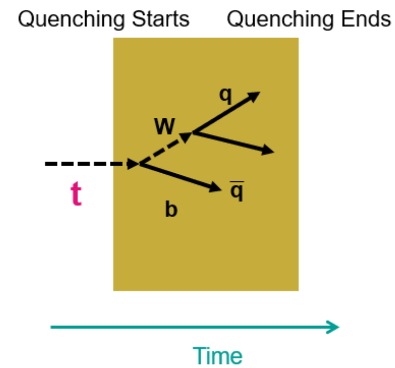


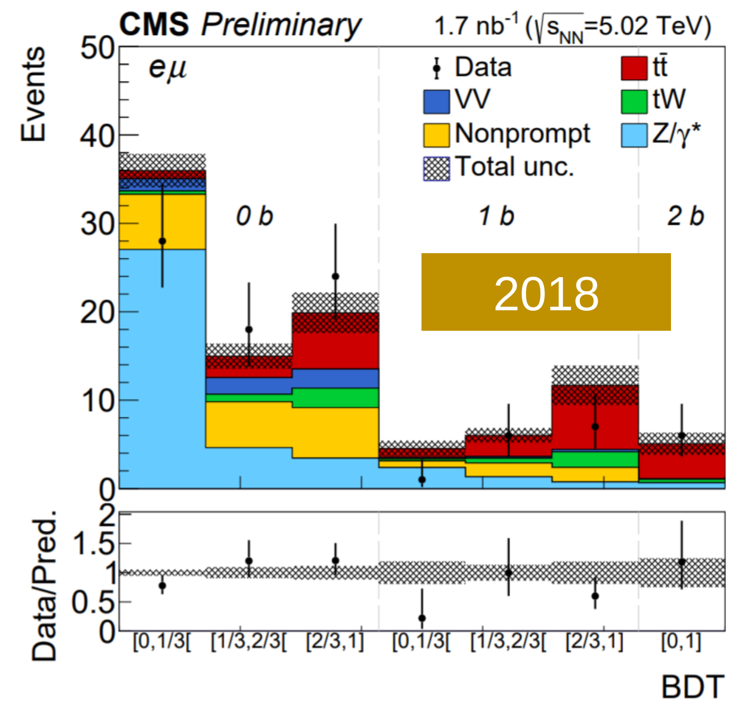


Hadron level (C-A declustering)

Modification of jet structure and correlations through interactions with QGP constituents ("Moliere scattering")

Boosted Top

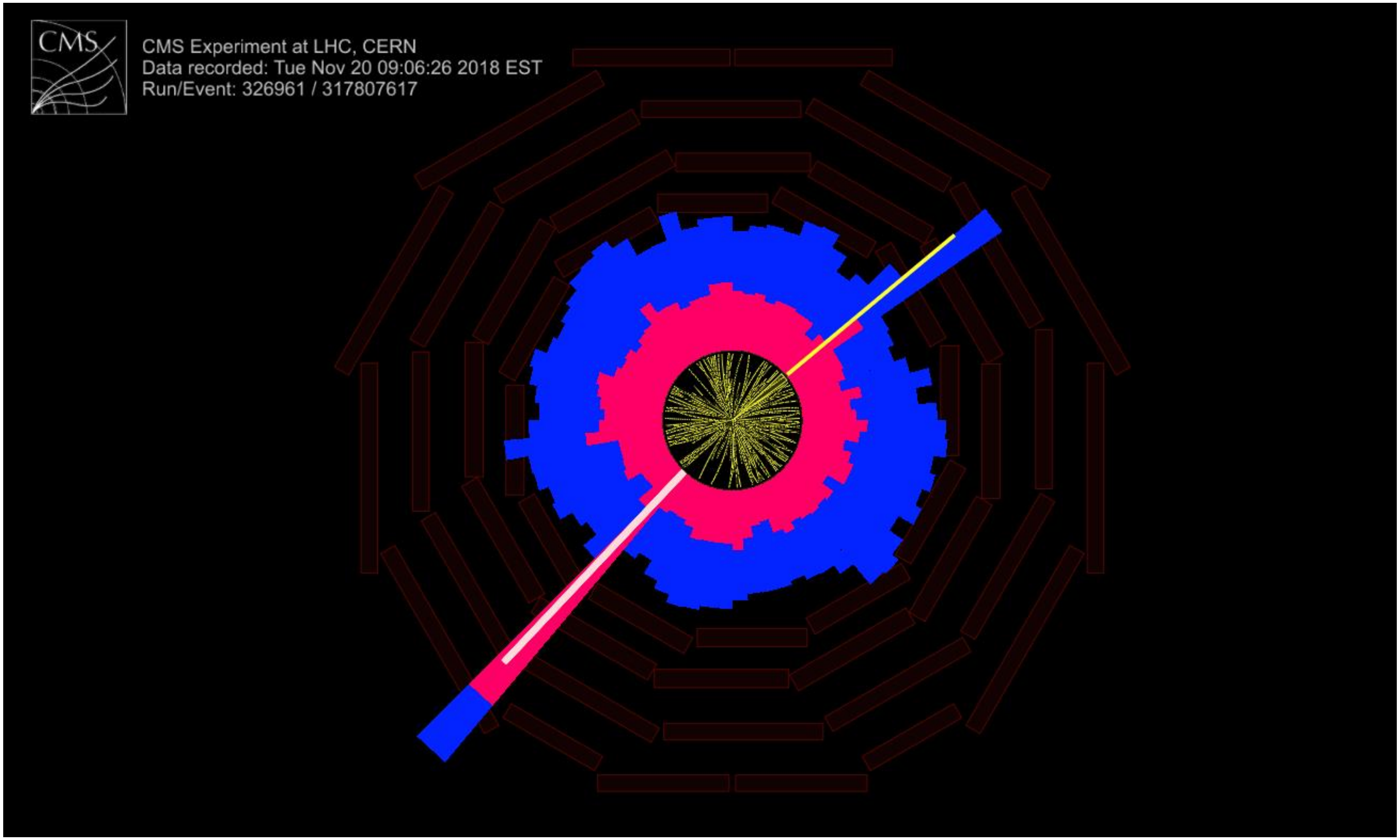




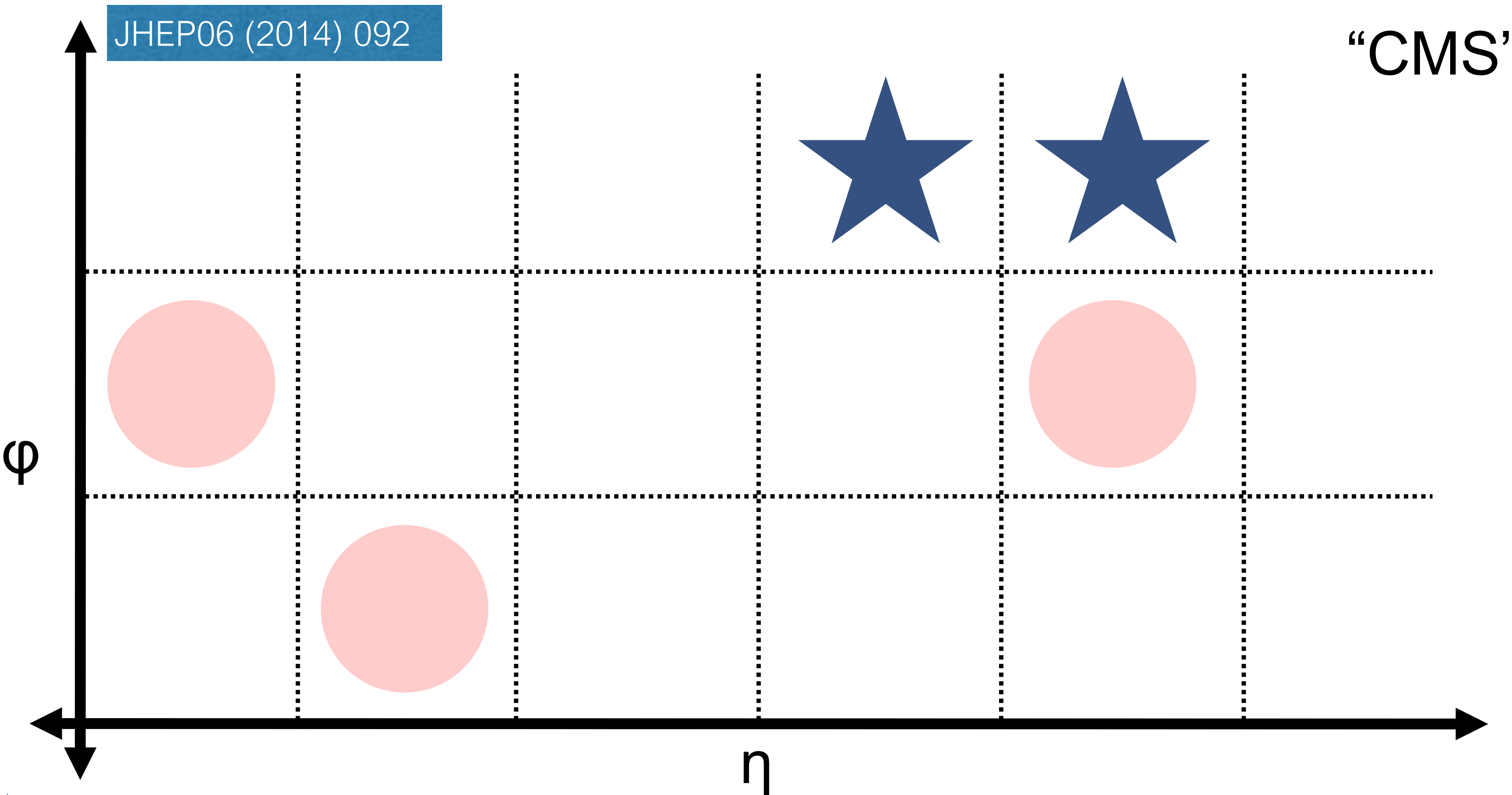
2018 data: 3.8σ

Observation of Top production in Run 3

Photon-Jet Event



(iii) Constituent Subtraction

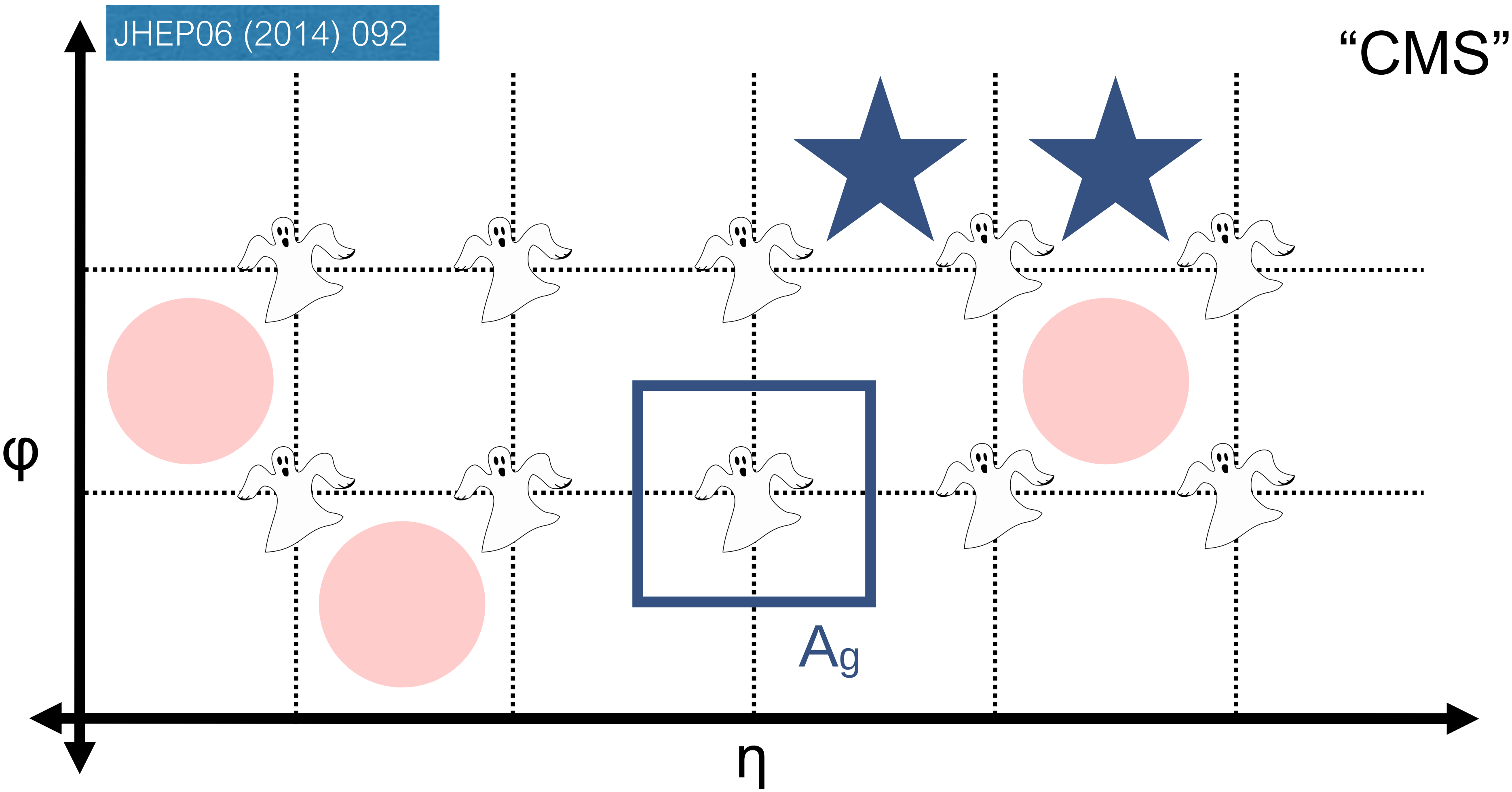


★ SIGNAL: Hard-scattering in PbPb collision producing jets

● UNDERLYING EVENT: Uncorrelated particles from other parton-parton interactions

From Chris McGinn

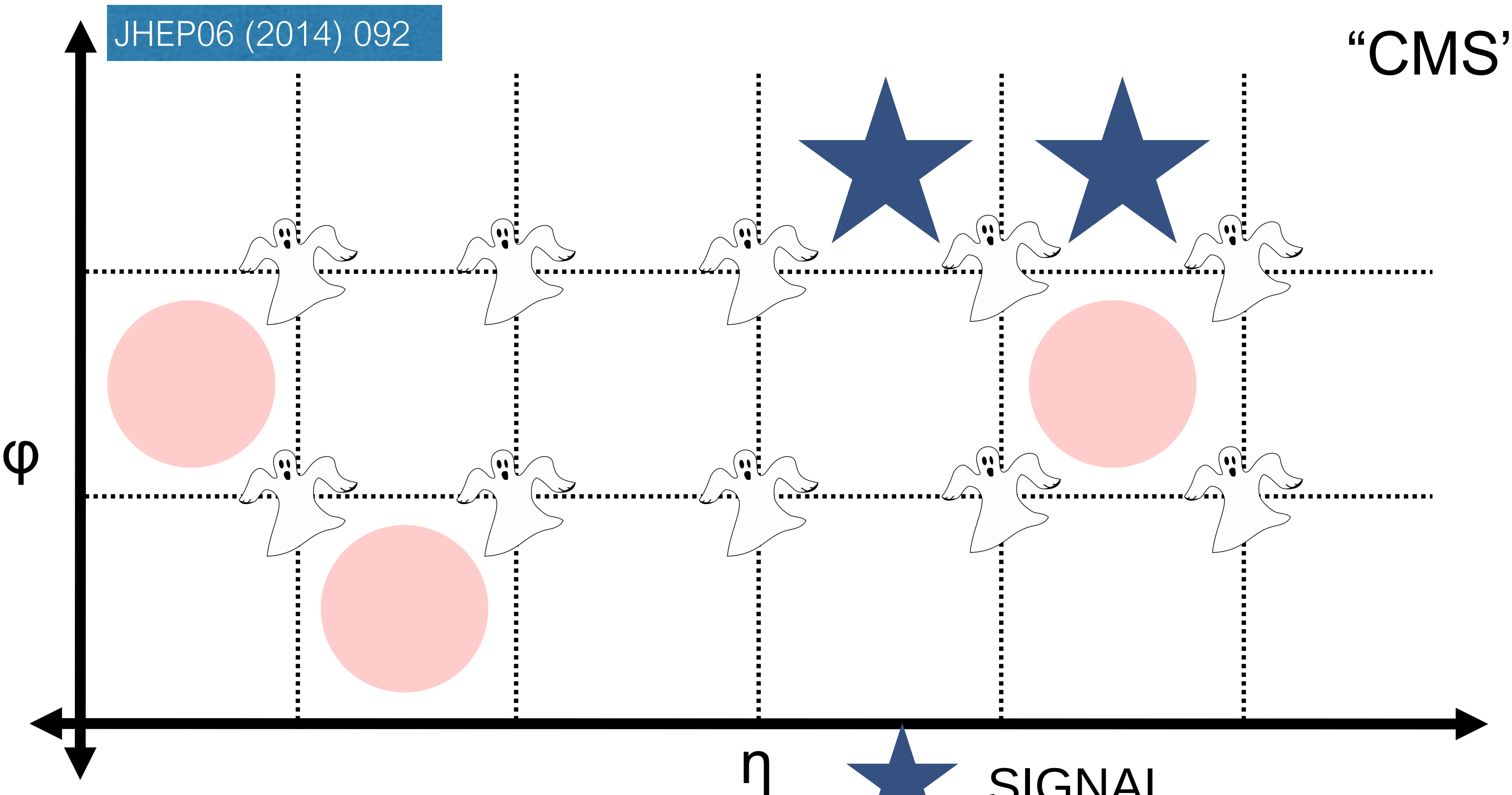
(iii) Constituent Subtraction

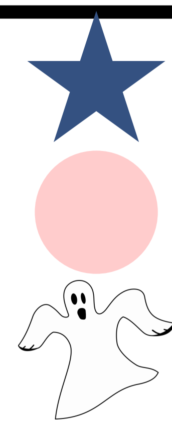


GHOST PARTICLES: Artificial particles added to the event on an η-φ grid. Ghosts are given a p_T according to ρ times the area the inhabit, A_g

From Chris McGinn

(iii) Constituent Subtraction



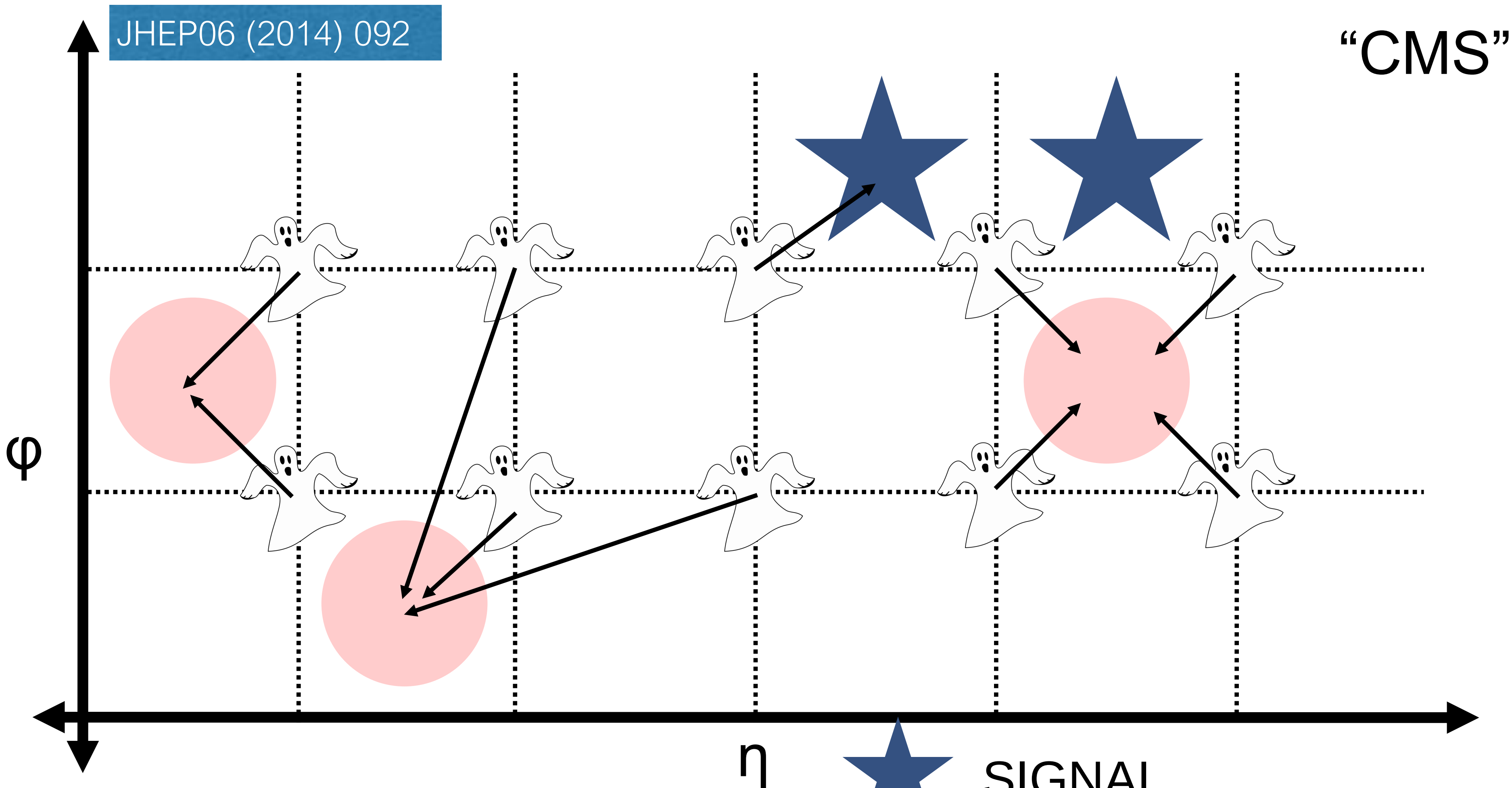


- Add “ghost” particles on η-φ grid a to:

$$p_{\mathrm{T}}^{g} = A_g \cdot \rho,$$

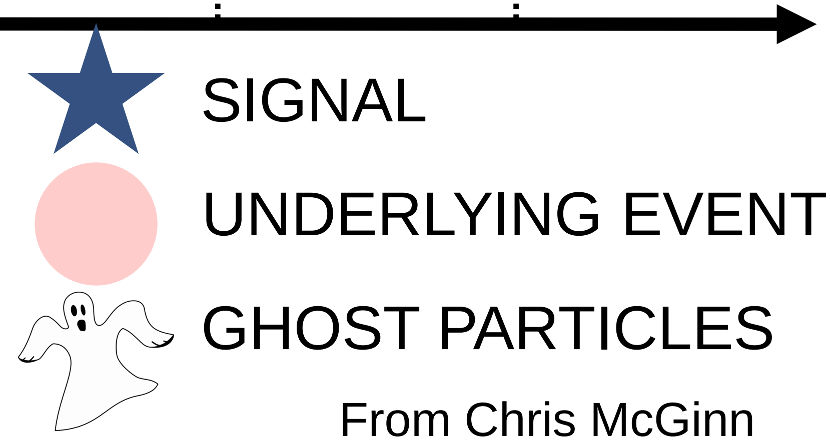
$$m_{\delta}^{g} = A_g \cdot \rho_m$$

(iii) Constituent Subtraction



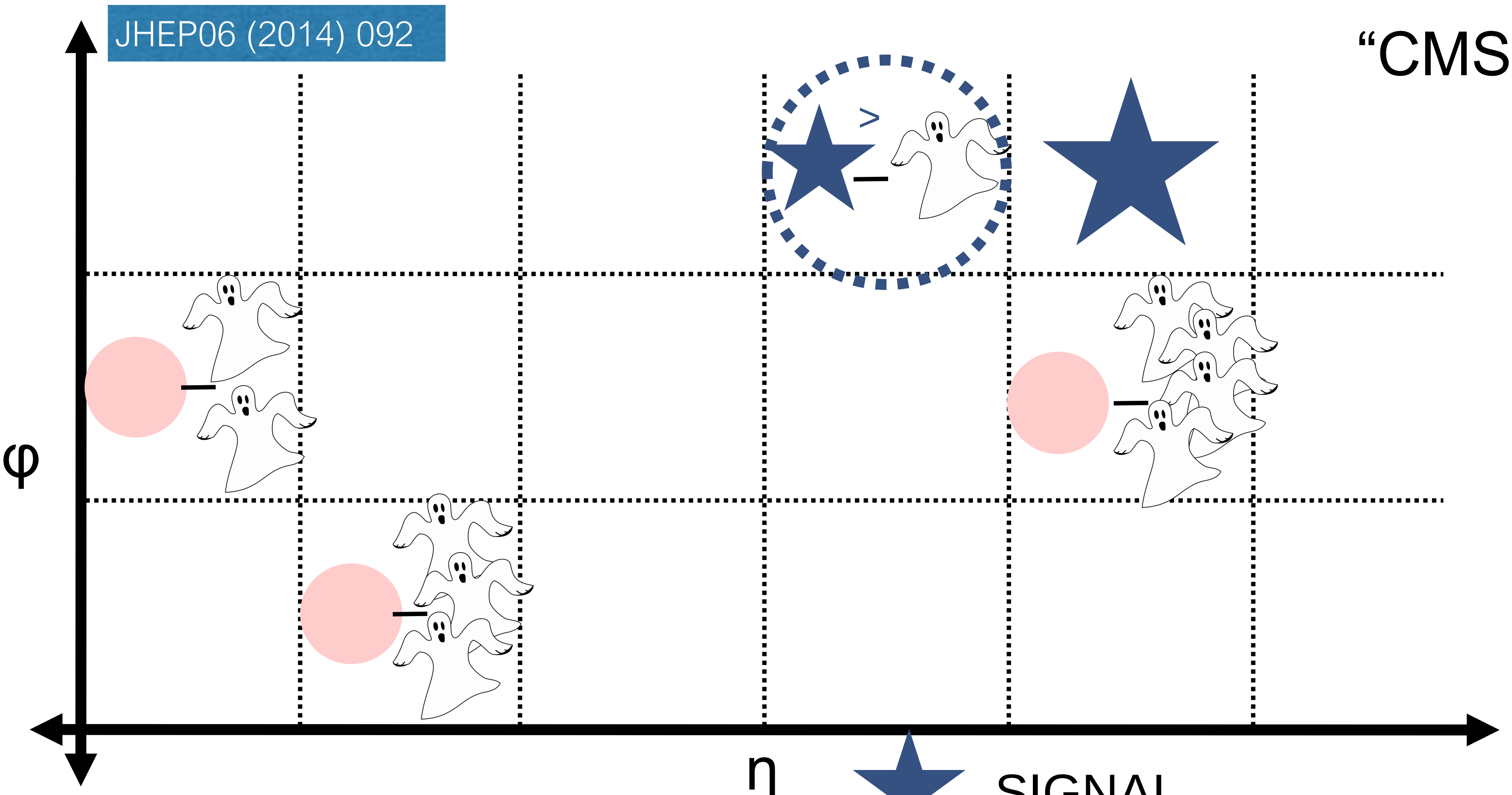
- Combine iteratively with real particles by minimizing metric:

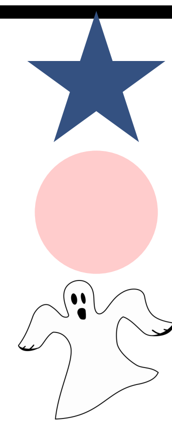
$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{\left(y_i - y_k^g\right)^2 + \left(\phi_i - \phi_k^g\right)^2}$$



From Chris McGinn

(iii) Constituent Subtraction

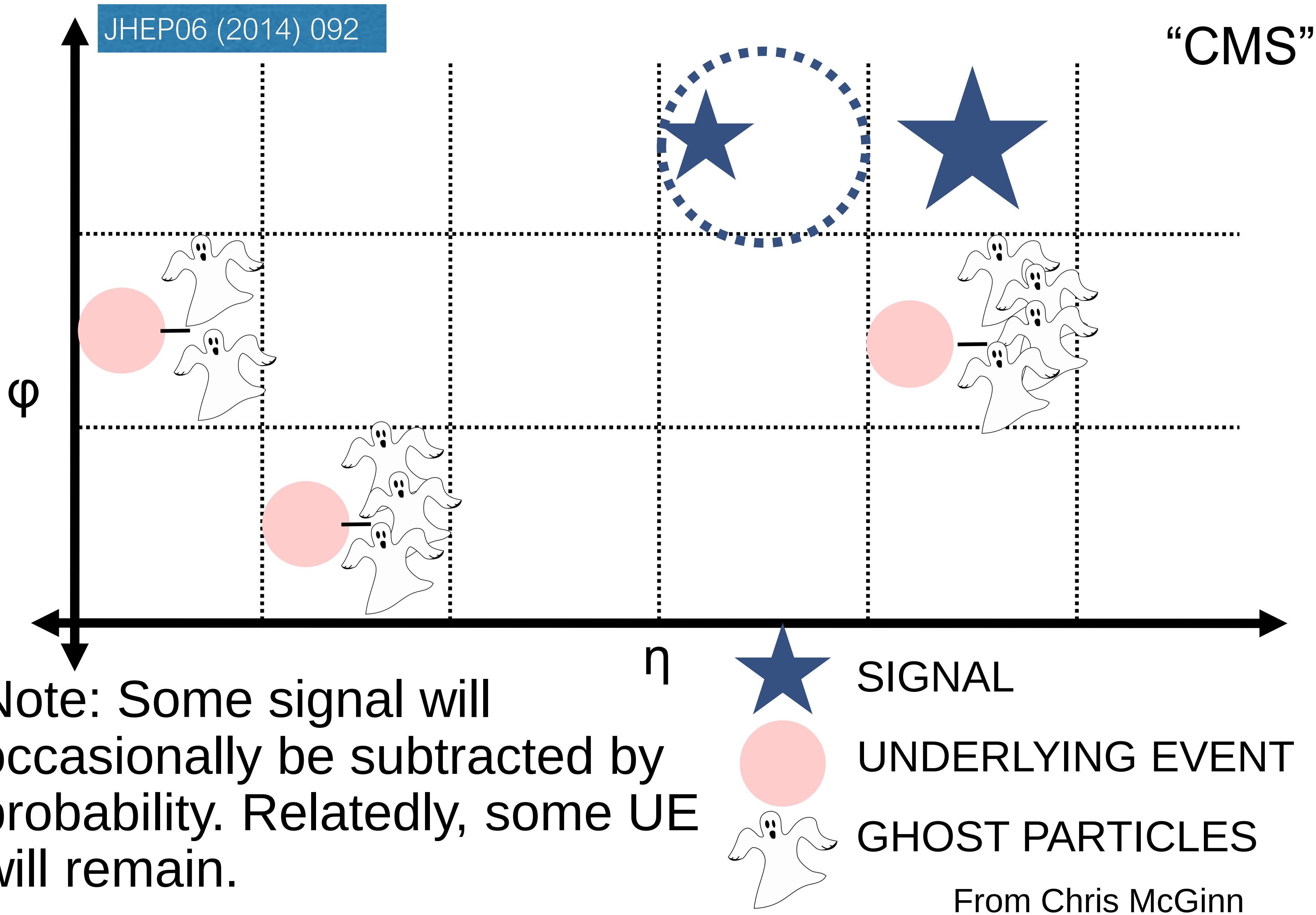




- Particle p_T > Ghost p_T
  - Ghost p_T = 0
  - Particle p_T -= Ghost p_T

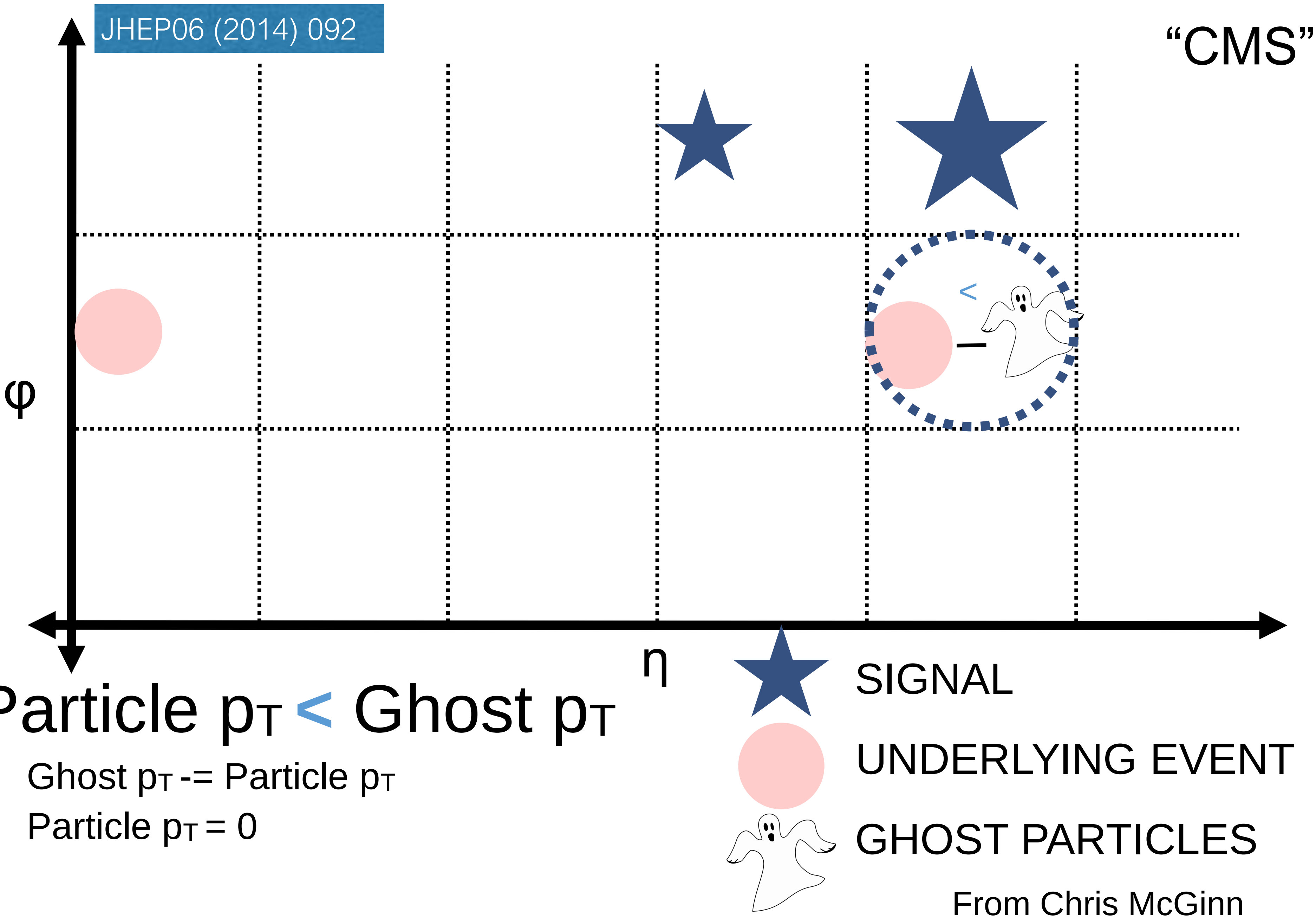
From Chris McGinn

(iii) Constituent Subtraction



- Note: Some signal will occasionally be subtracted by probability. Relatedly, some UE will remain.

(iii) Constituent Subtraction



- Particle p_T < Ghost p_T
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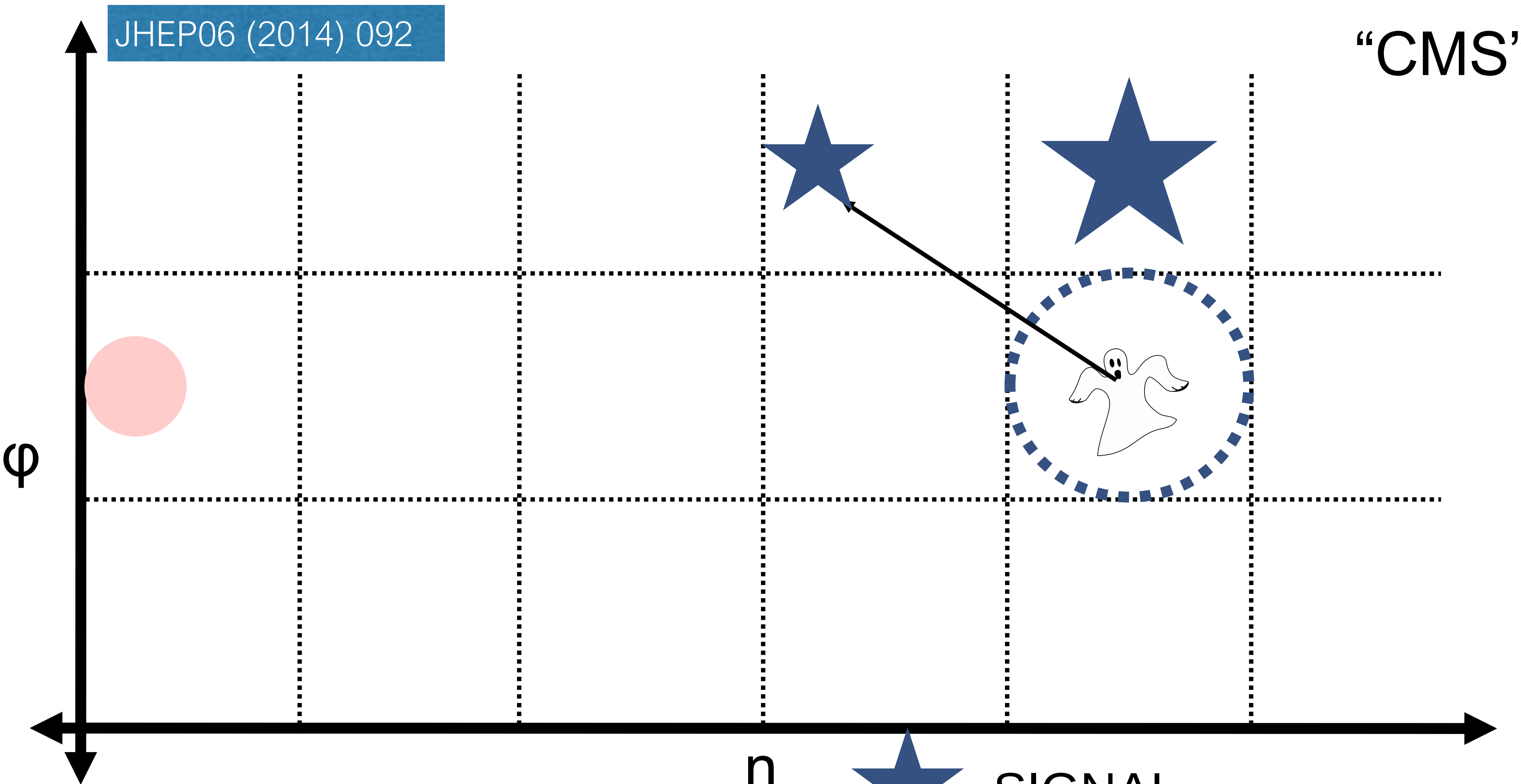
  - Particle $p_T = 0$

From Chris McGinn

(iii) Constituent Subtraction



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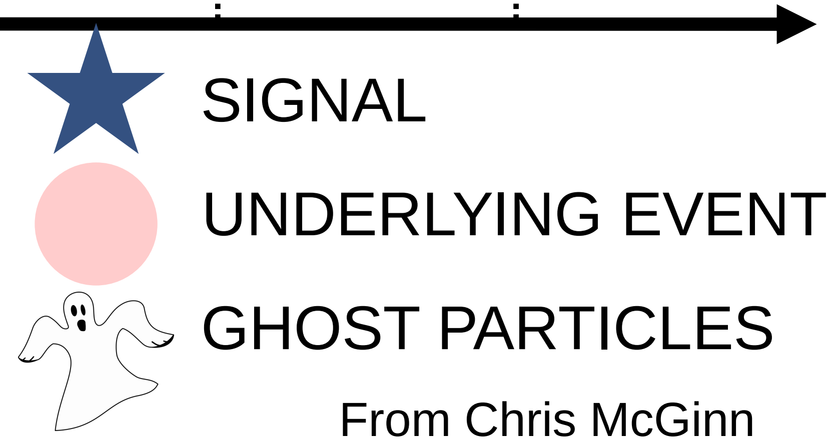
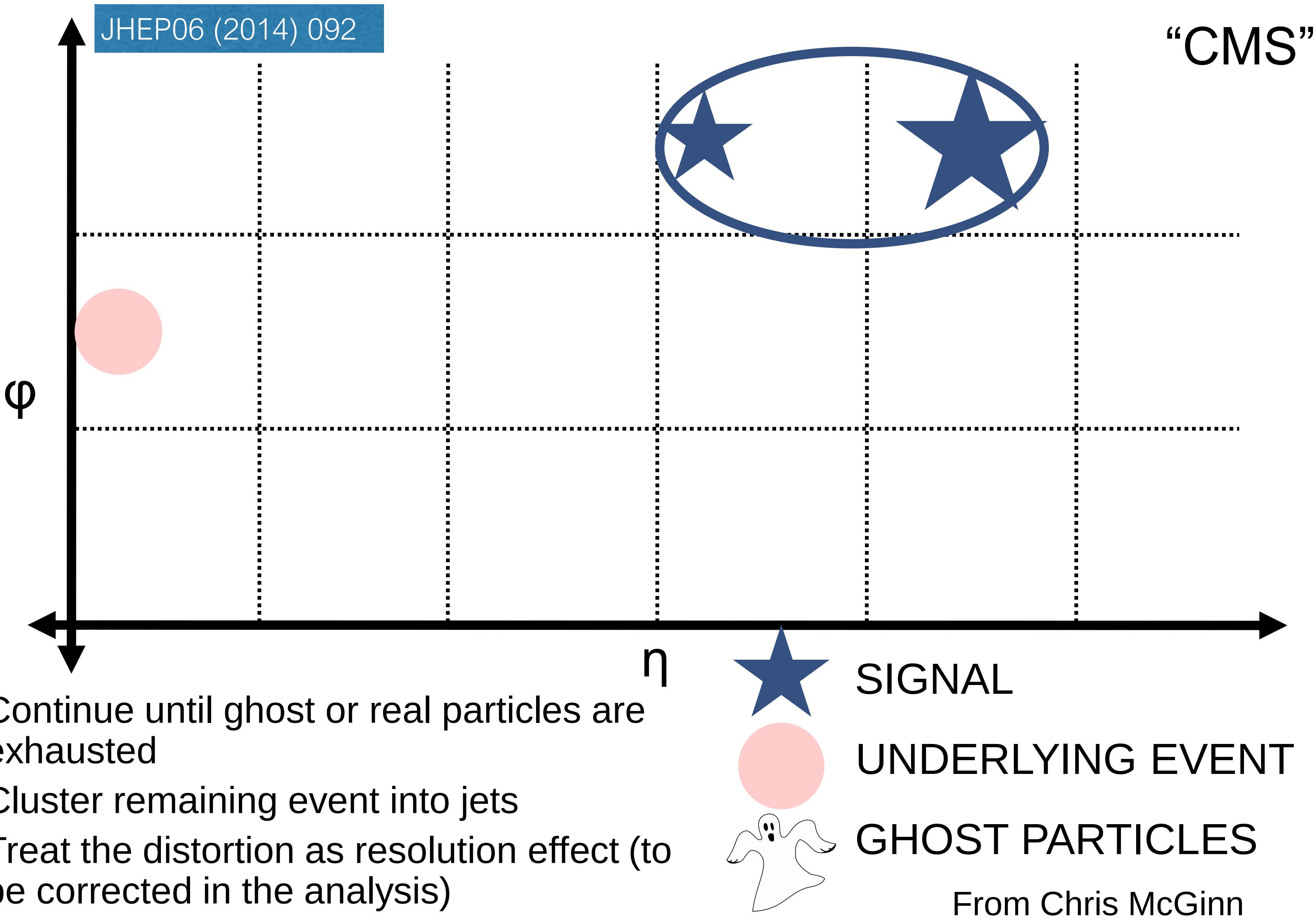


From Chris McGinn

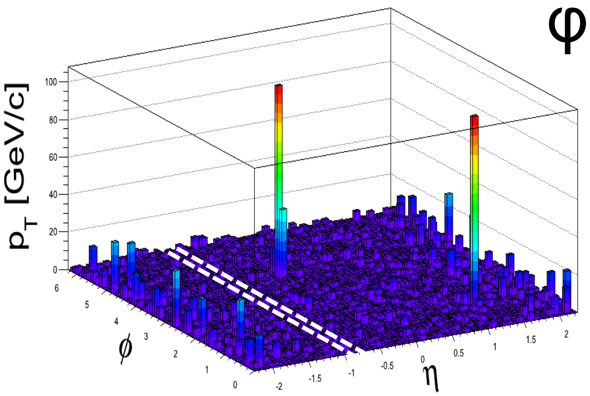
(iii) Constituent Subtraction

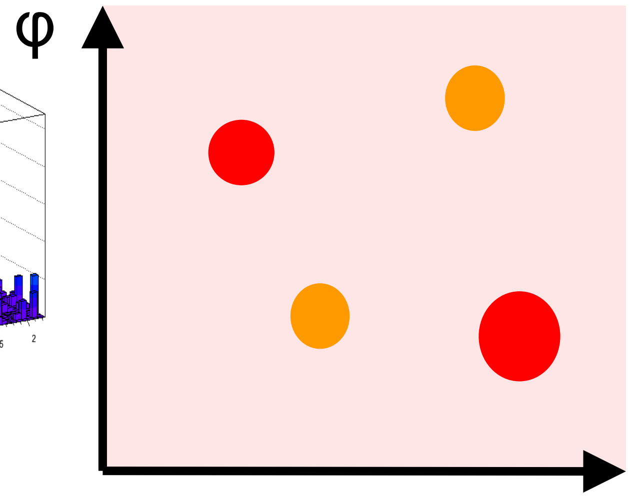


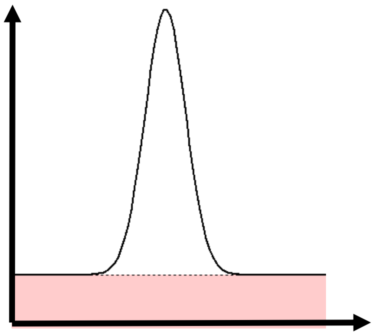
- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets
- Treat the distortion as resolution effect (to be corrected in the analysis)

From Chris McGinn

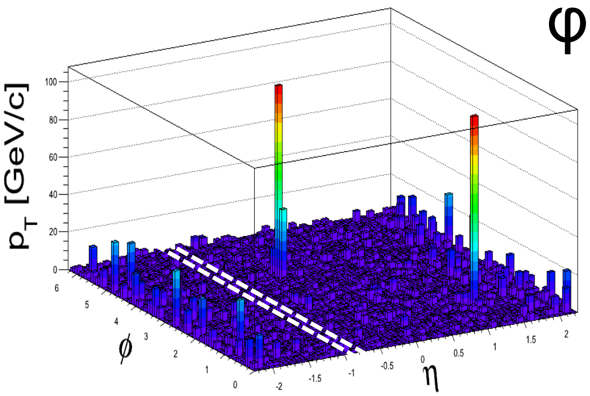
Iterative Background Subtraction

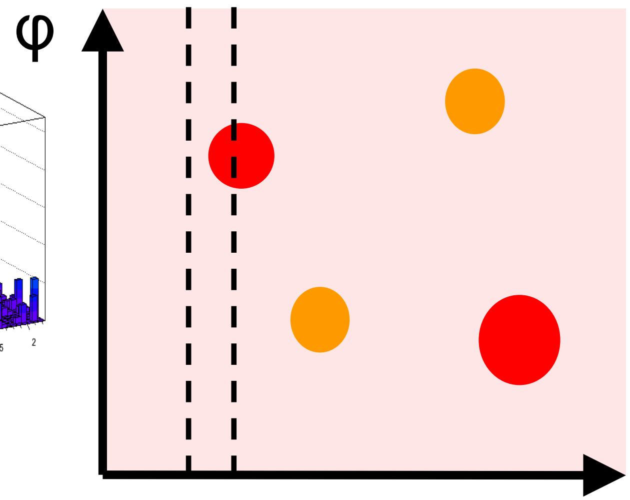




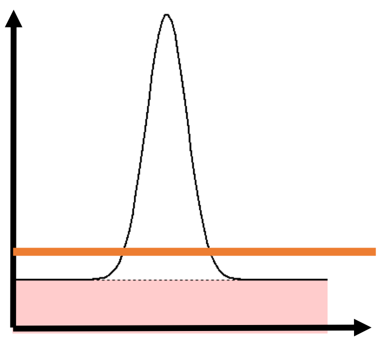


Iterative Background Subtraction





1. Background energy per tower calculated in strips of η. Pedestal subtraction

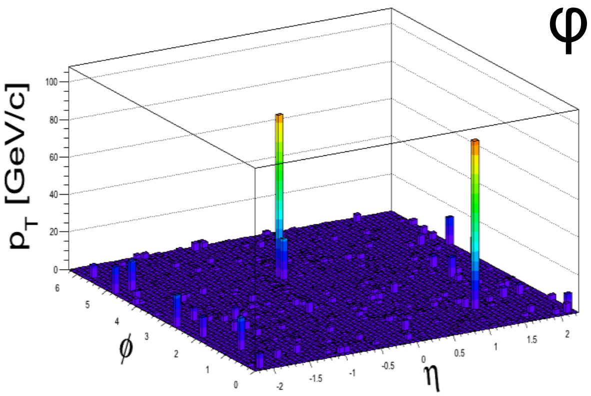


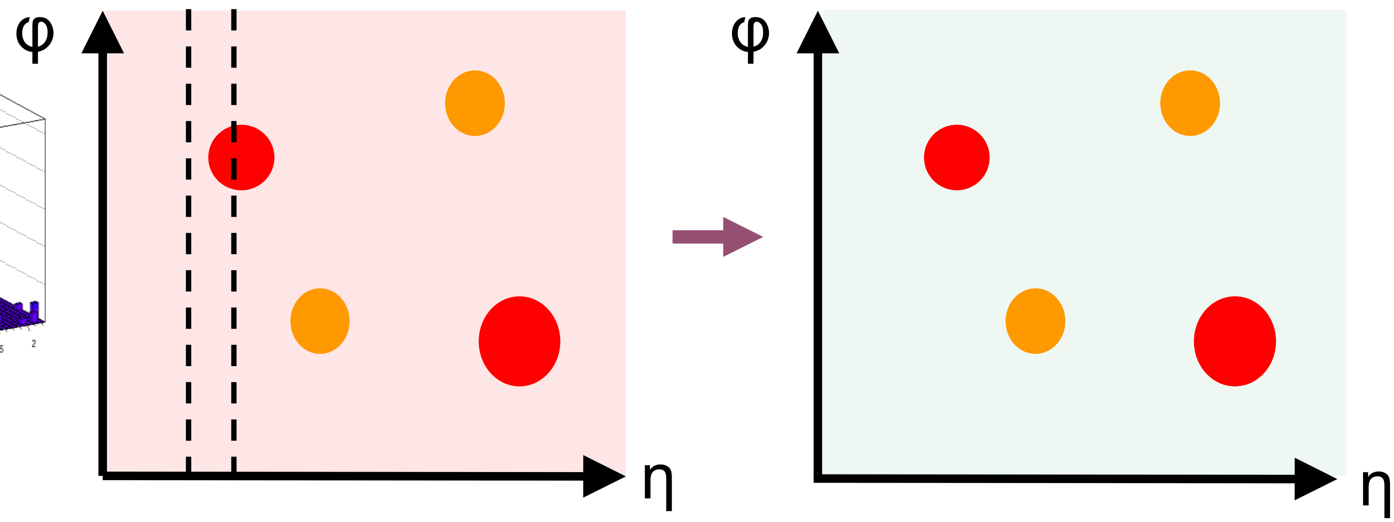
Background level

Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle$ + n $\sigma(p_T)$

- Captures dN/dη of background
- n $\sigma(p_T)$: noise suppression. n is a real number
- Misses ϕ modulation – to be improved

Iterative Background Subtraction





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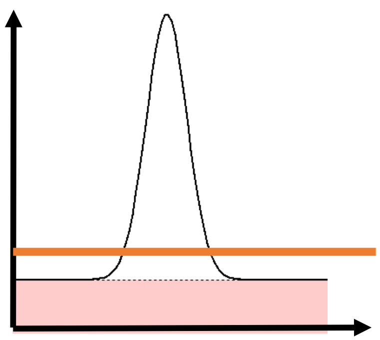
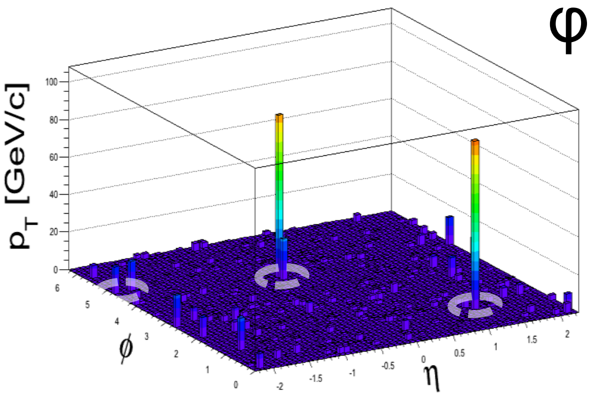
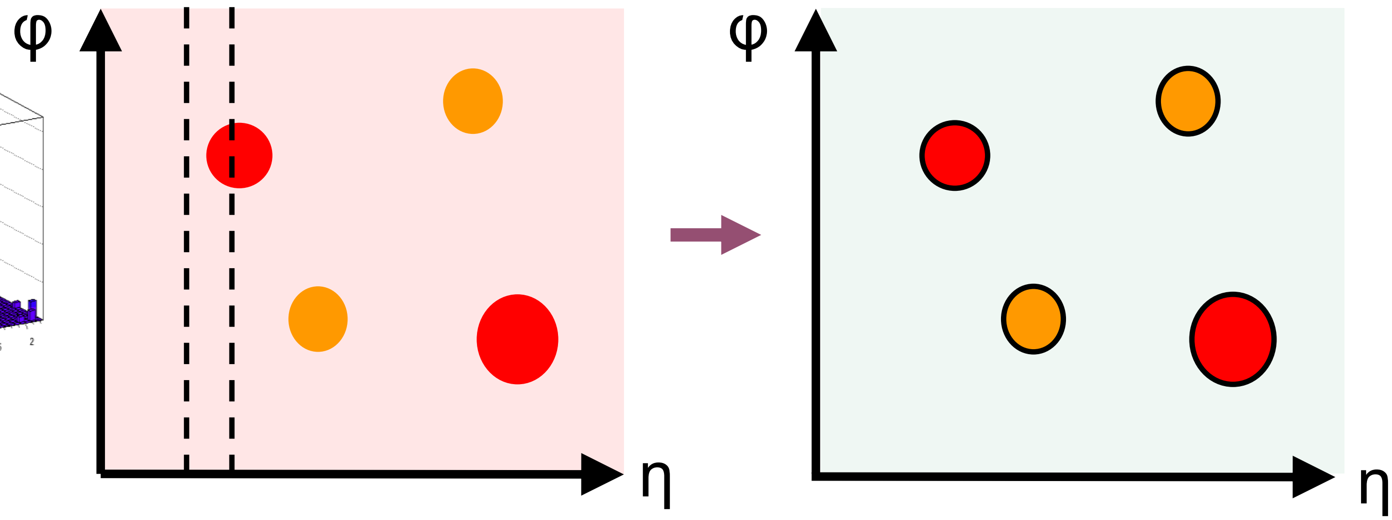


Background level

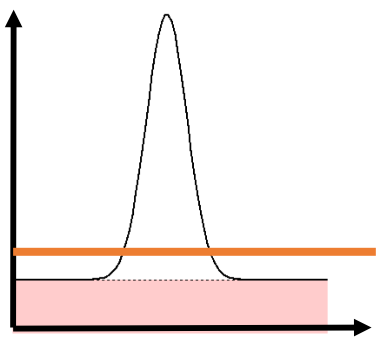
Iterative Background Subtraction





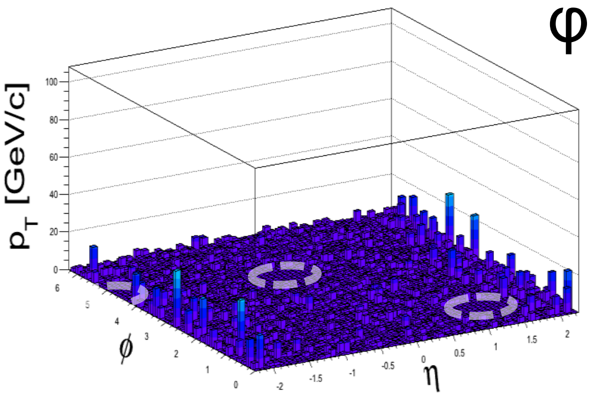
1. Background energy per tower calculated in strips of η. Pedestal subtraction

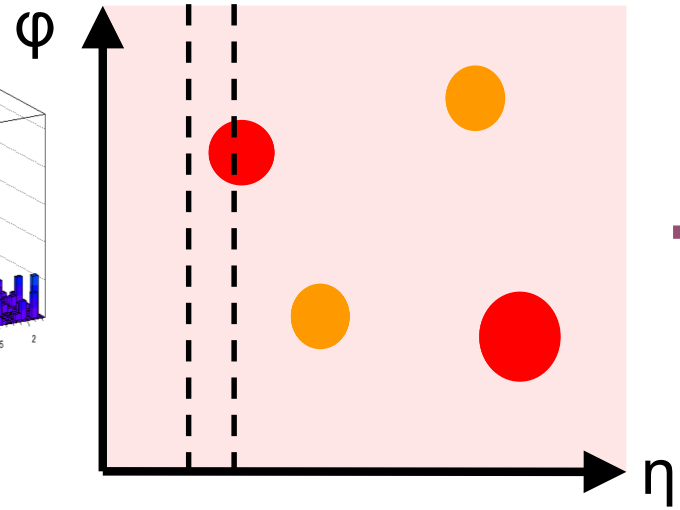
2. Run anti k_T algorithm on background subtracted towers



Background level

Iterative Background Subtraction





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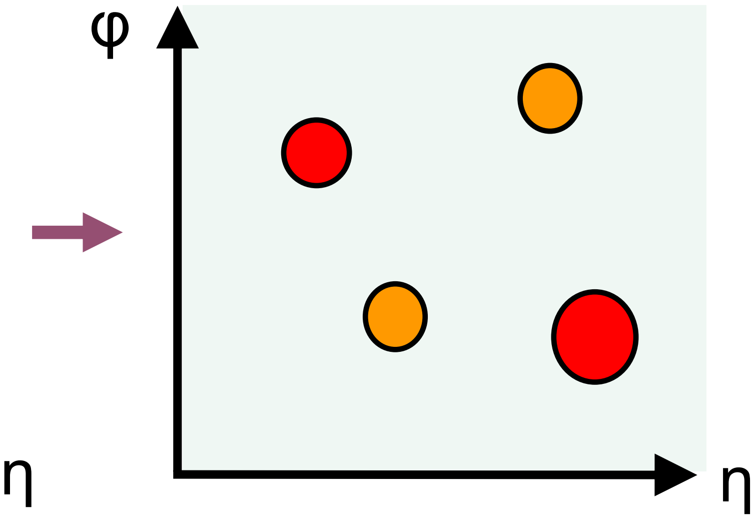
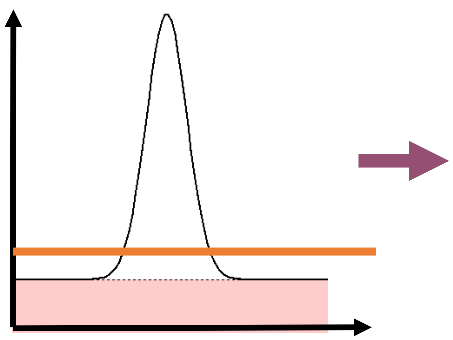
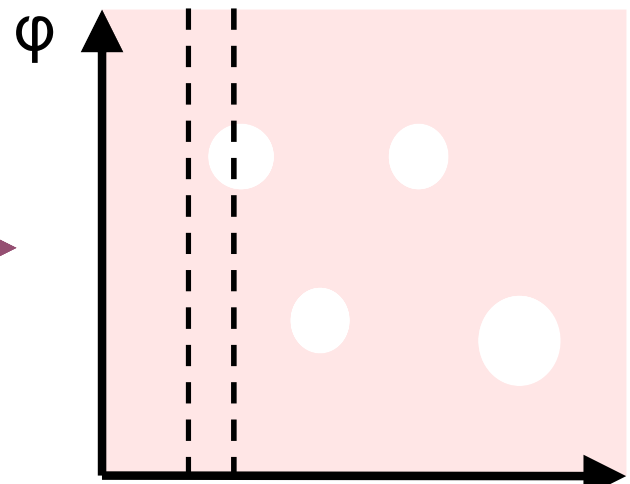


2. Run anti k_T algorithm on background subtracted towers

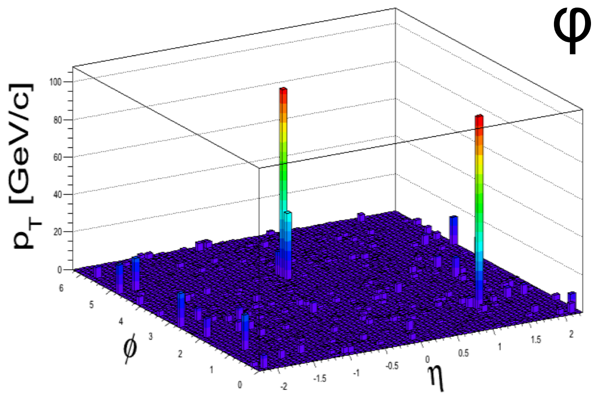


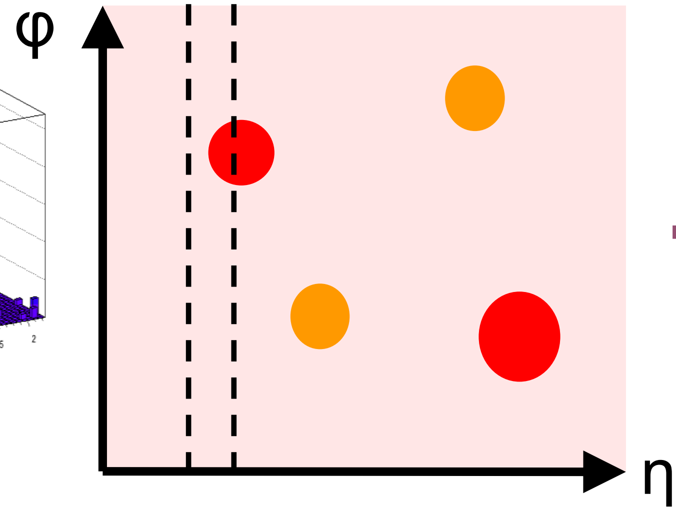
Background level



3. Exclude reconstructed jets > p_T^{cut}

Iterative Background Subtraction





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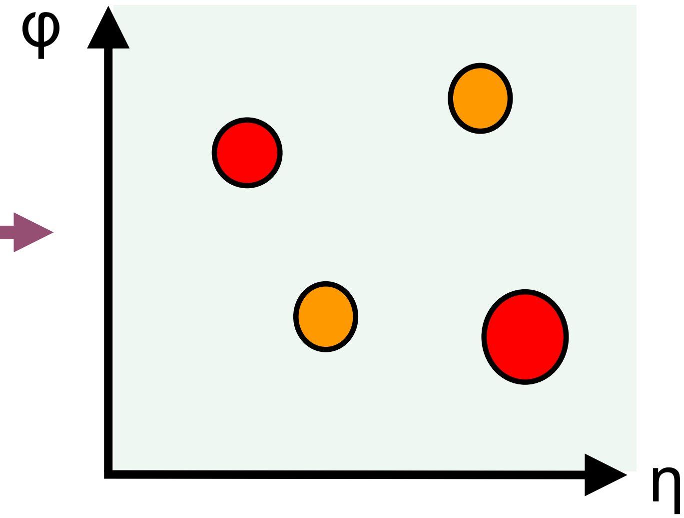
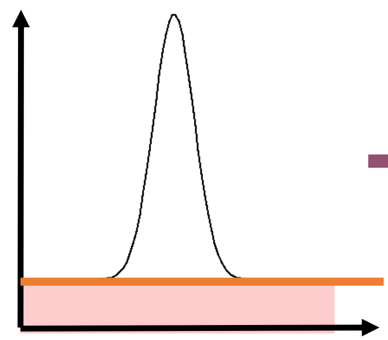
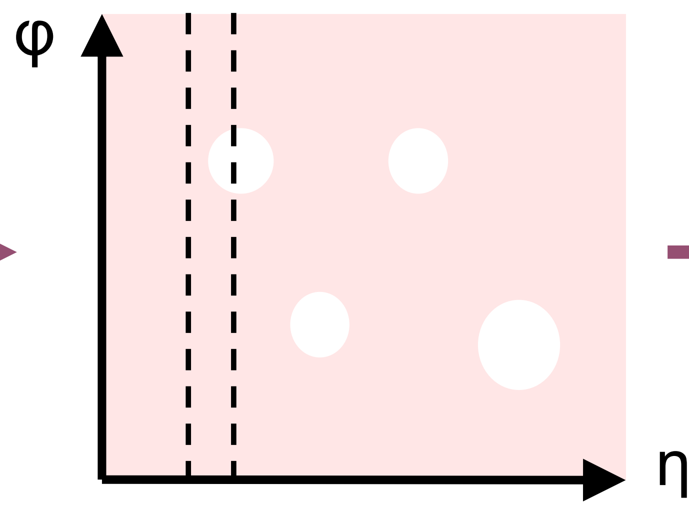


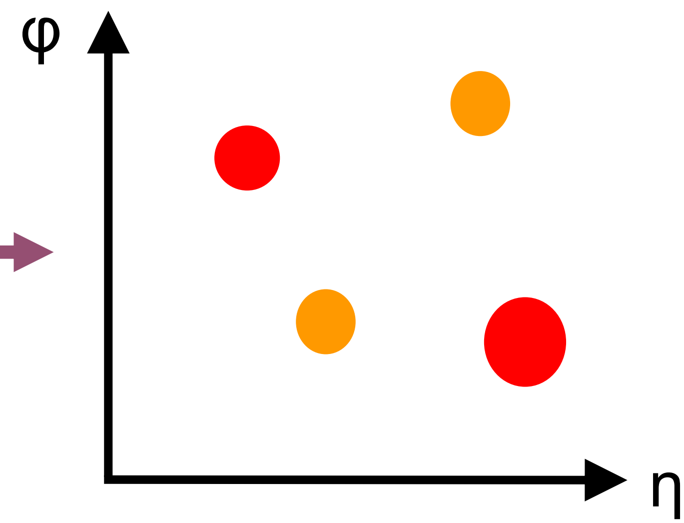
2. Run anti k_T algorithm on background subtracted towers



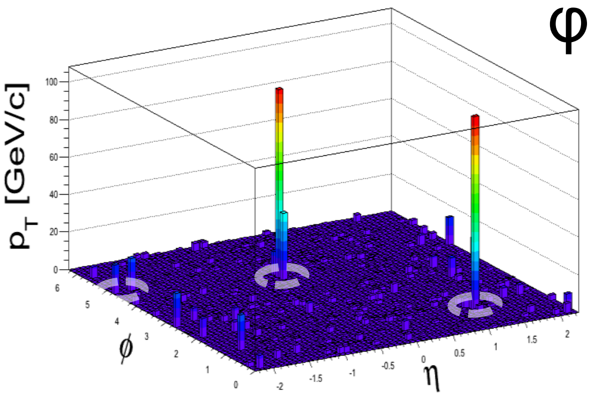
Background level

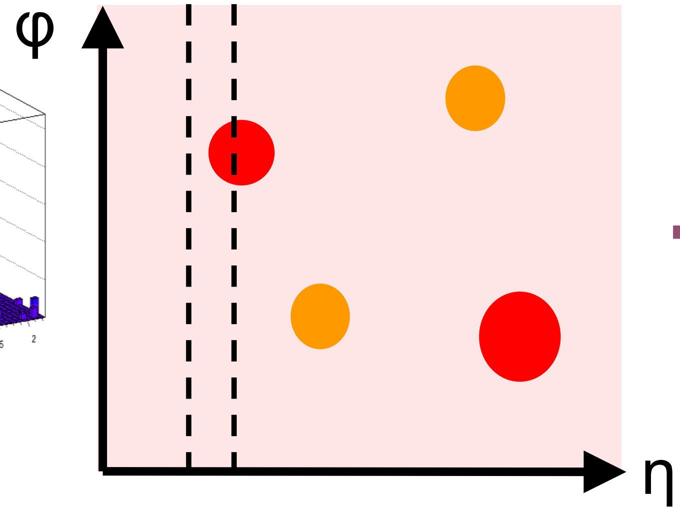


3. Exclude reconstructed jets > p_T^{cut}
Recalculate the background energy

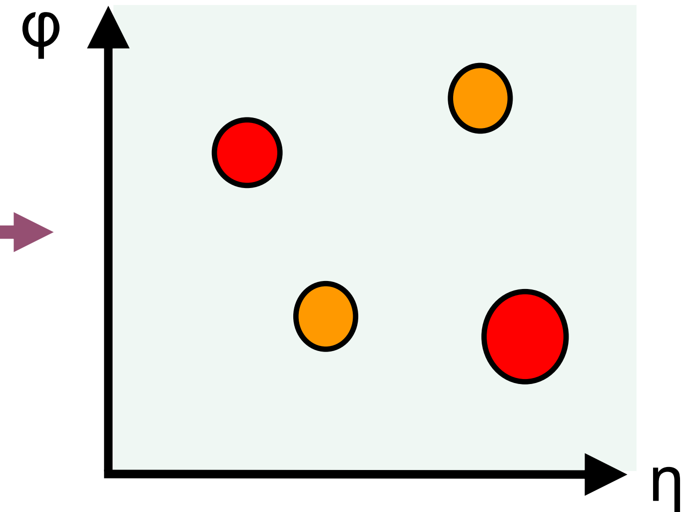


Iterative Background Subtraction

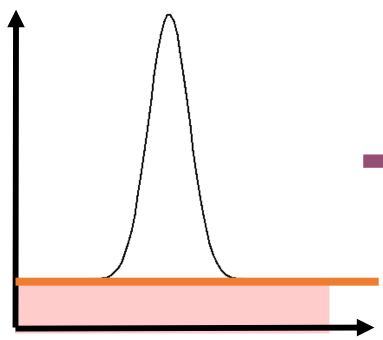




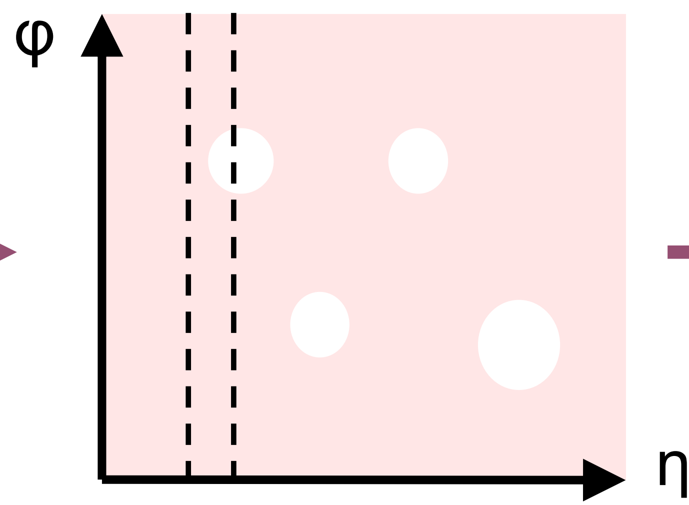
1. Background energy per tower calculated in strips of η. Pedestal subtraction



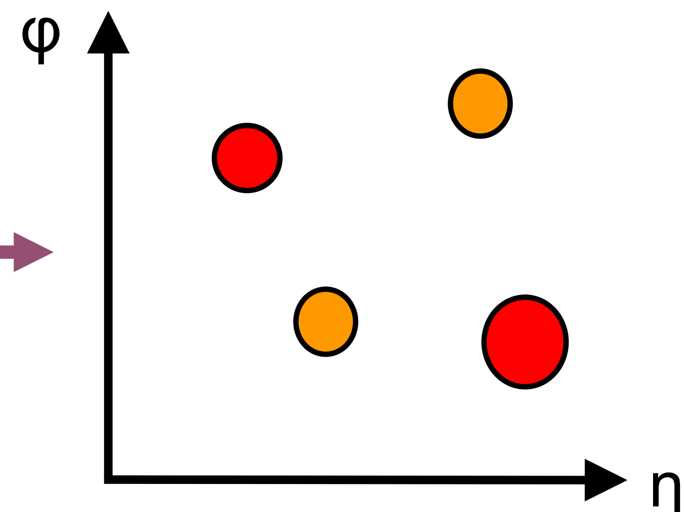
2. Run anti k_T algorithm on background subtracted towers



Background level



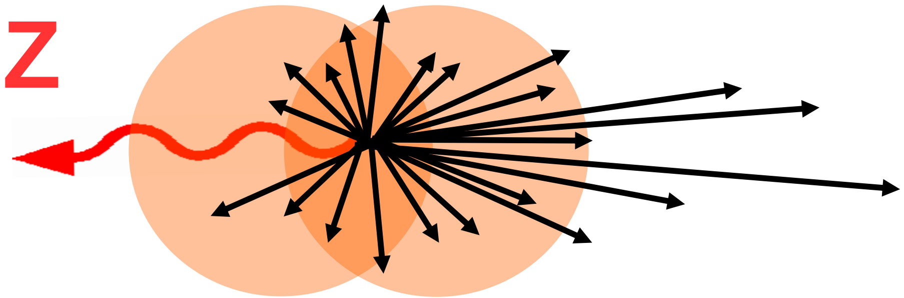
3. Exclude reconstructed jets > p_T^{cut}
Recalculate the background energy



4. Run anti k_T algorithm on background subtracted towers to get final jets

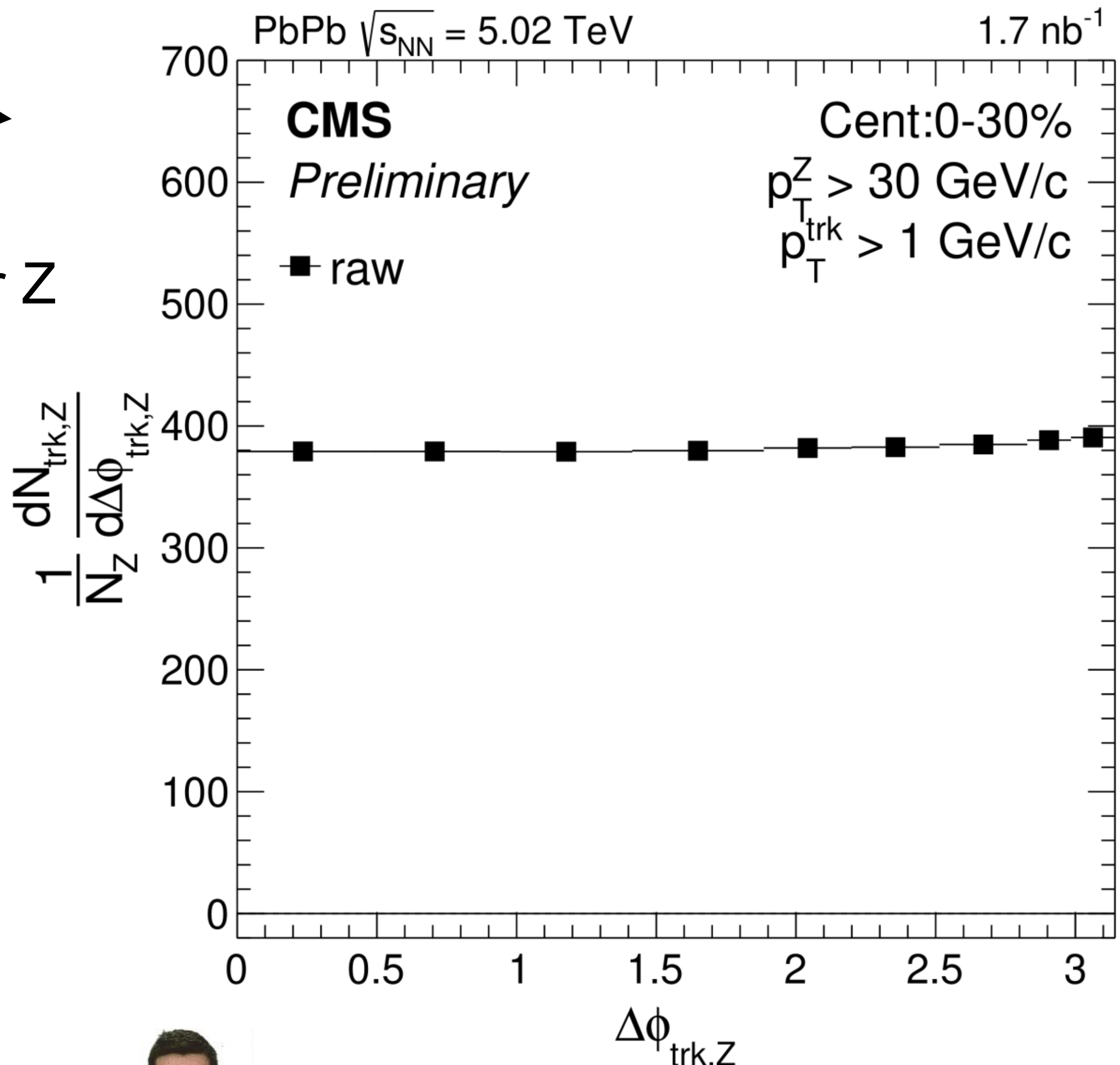
Z+track pairs in PbPb

CMS-PAS-HIN-19-006



A huge yield → ~ 1000 particles per Z

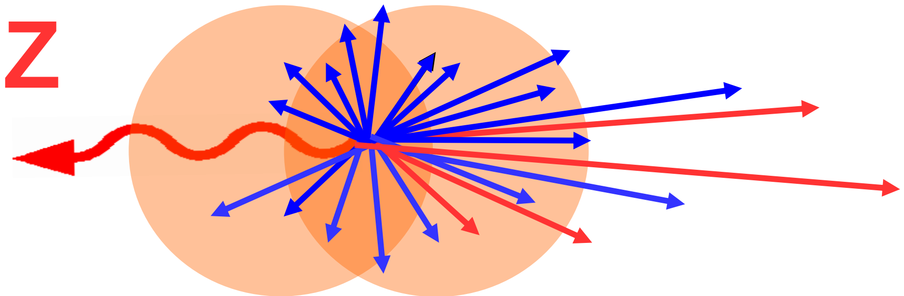
Recall : No particle tagging via jets



Kaya Tatar

Z+track pairs in PbPb

CMS-PAS-HIN-19-006



A huge yield composed of

1.) Signal

The NN collision producing the Z

2.) Background from PbPb UE

Other NN collisions

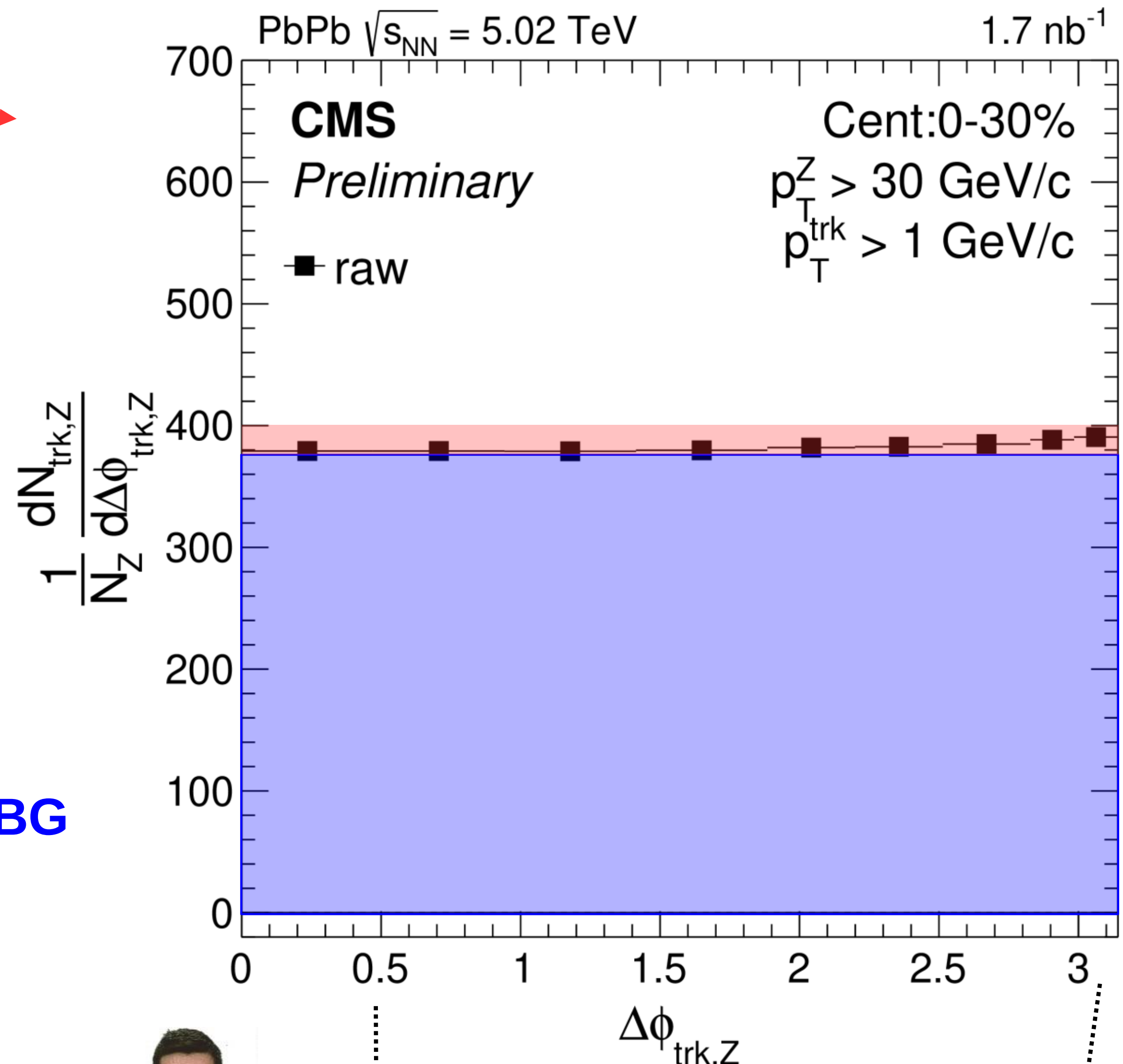
How to estimate the **BG** precisely?

Assumption :

The energy in forward rap. ($3 < |\eta| < 5$)

composed of **UE from Z process** and **BG**

i.e. $\mathbf{E}^{\mathbf{HF}} = \mathbf{E}^{\mathbf{HF,\,Z}} + \mathbf{E}^{\mathbf{HF,\,BG}}$

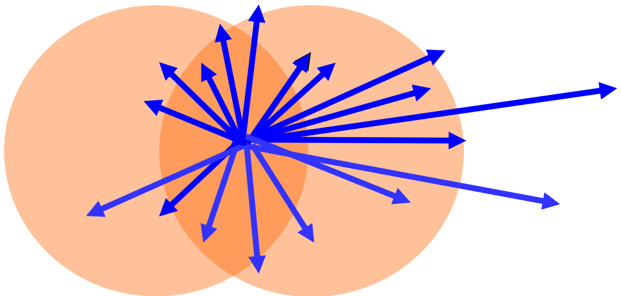


Kaya Tatar

S/B ≈ 1%

S/B ≈ 5%

Z+track pairs in PbPb



A huge yield composed of

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2.) Background from PbPb UE

Other NN collisions

How to estimate the **BG** precisely?

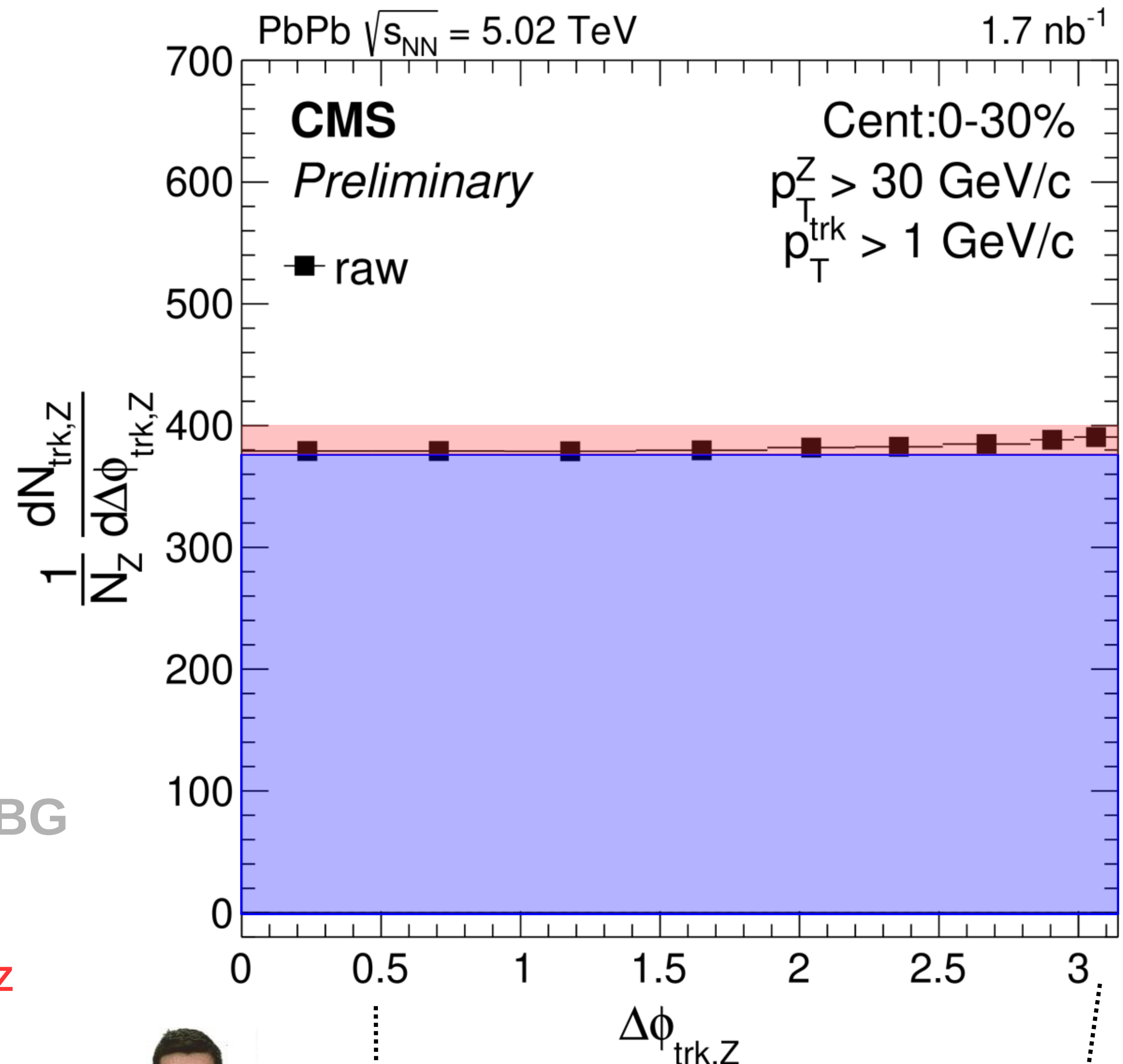
Assumption :

The energy in forward rap. ($3 < |\eta| < 5$) composed of **UE from Z process** and **BG**

i.e. $\mathbf{E^{HF}} = \mathbf{E^{HF,\,Z}} + \mathbf{E^{HF,\,BG}}$

Subtract **BG** using MB events matched with forward energy $\mathbf{E^{HF,\,MB}} = \mathbf{E^{HF}} - \mathbf{E^{HF,\,Z}}$

CMS-PAS-HIN-19-006



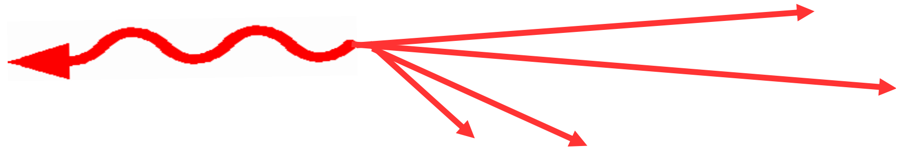
Kaya Tatar

S/B ≈ 1%

S/B ≈ 5%

[CMS-PAS-HIN-19-006](CMS-PAS-HIN-19-006)

Z



A huge yield composed of

1.) Signal

The NN collision producing the Z

2.) Background from PbPb UE

Other NN collisions

How to estimate the **BG** precisely?

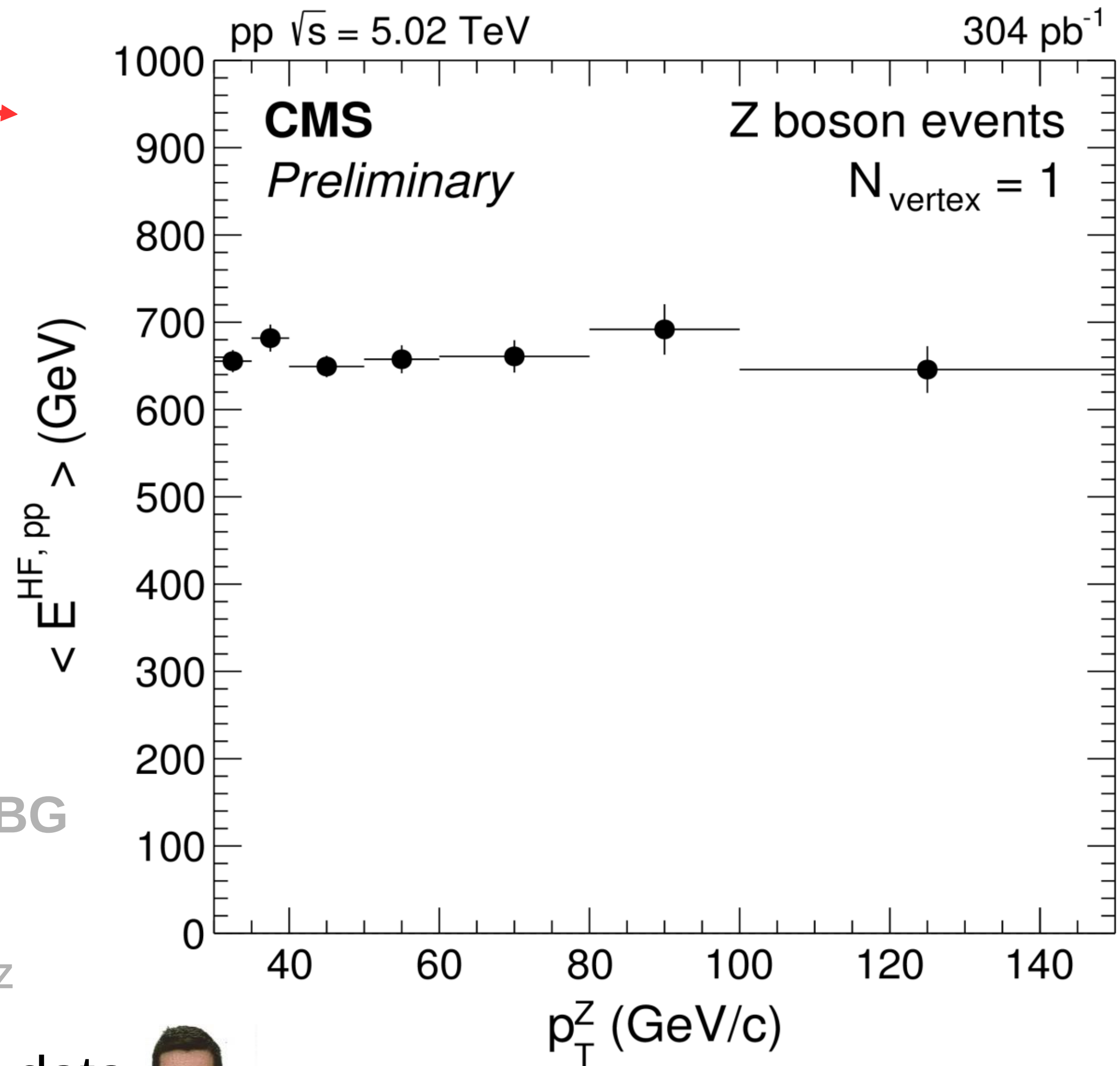
Assumption :

The energy in forward rap. ($3 < |\eta| < 5$) composed of **UE from Z process** and **BG**

i.e. $E^{HF} = E^{HF, Z} + E^{HF, BG}$

Subtract **BG** using MB events matched with forward energy $E^{HF, MB} = E^{HF} - E^{HF, Z}$

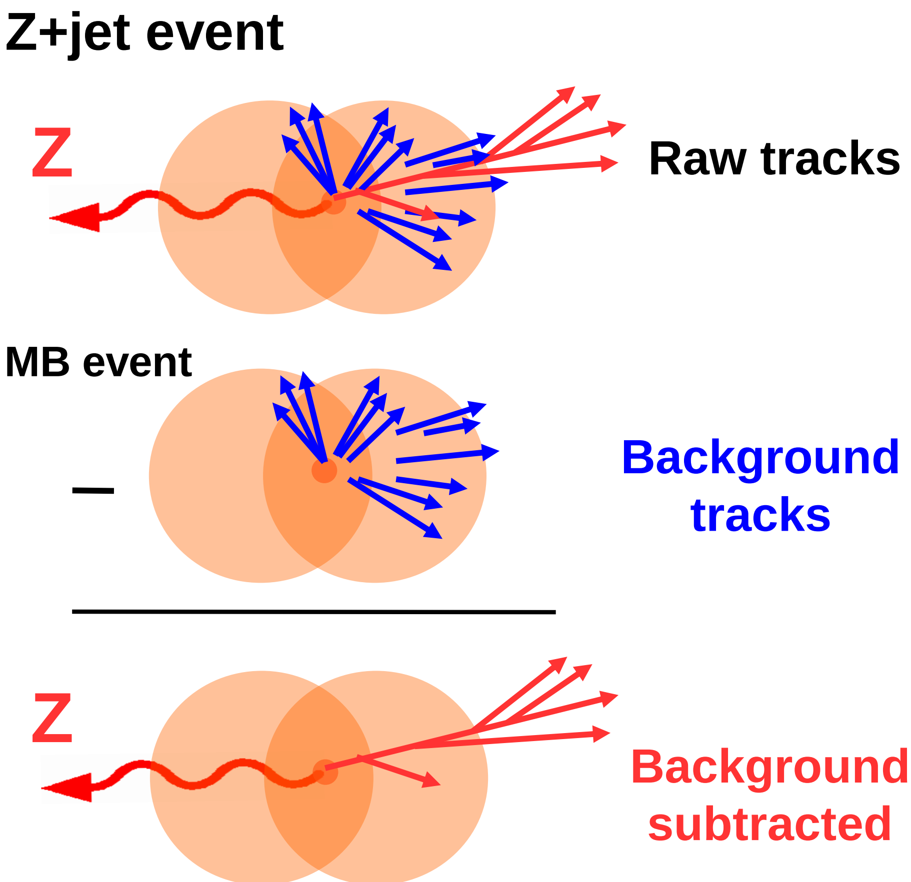
$E^{HF, Z}$ estimated from Z events in pp data

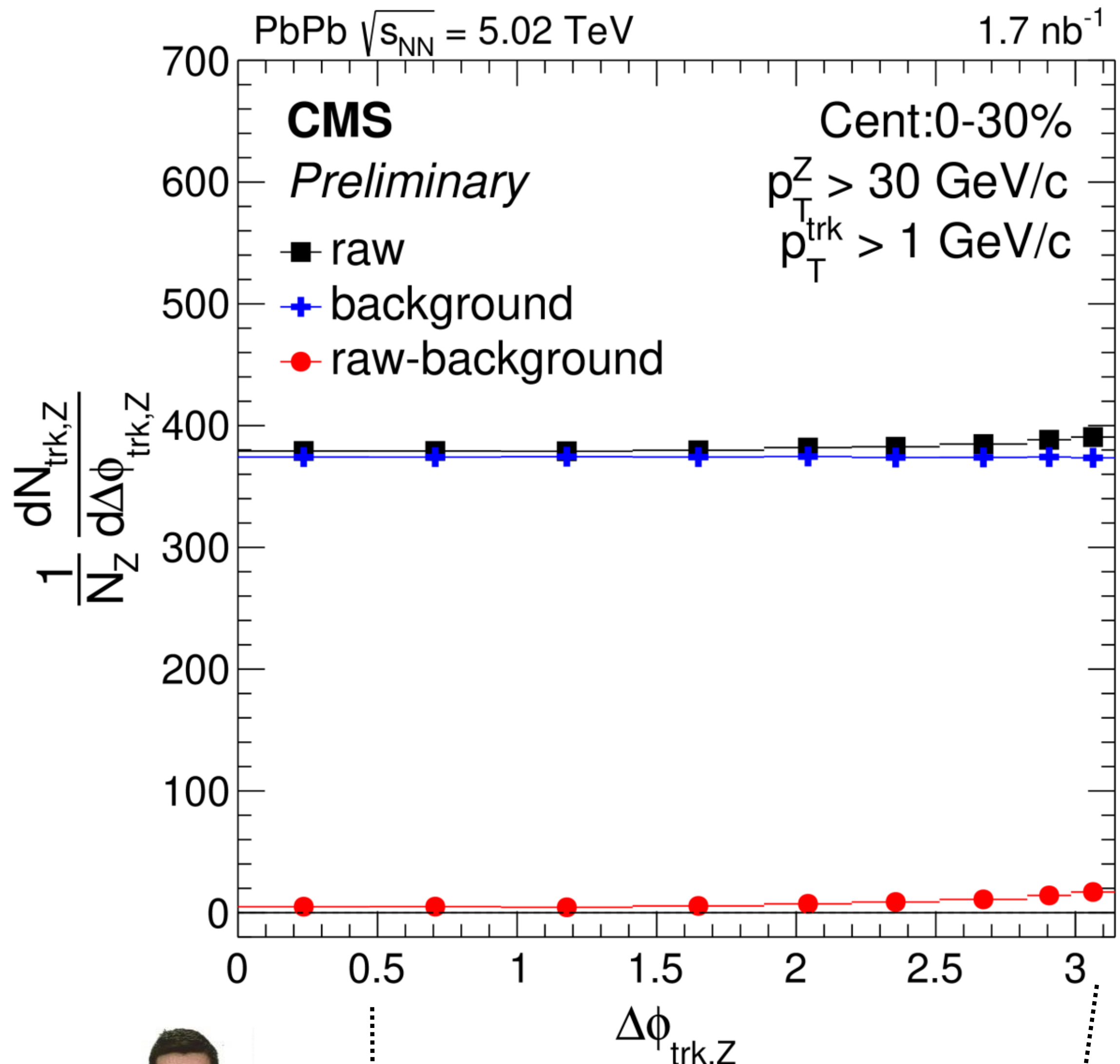


Kaya Tatar

Background subtraction for tracks

CMS-PAS-HIN-19-006





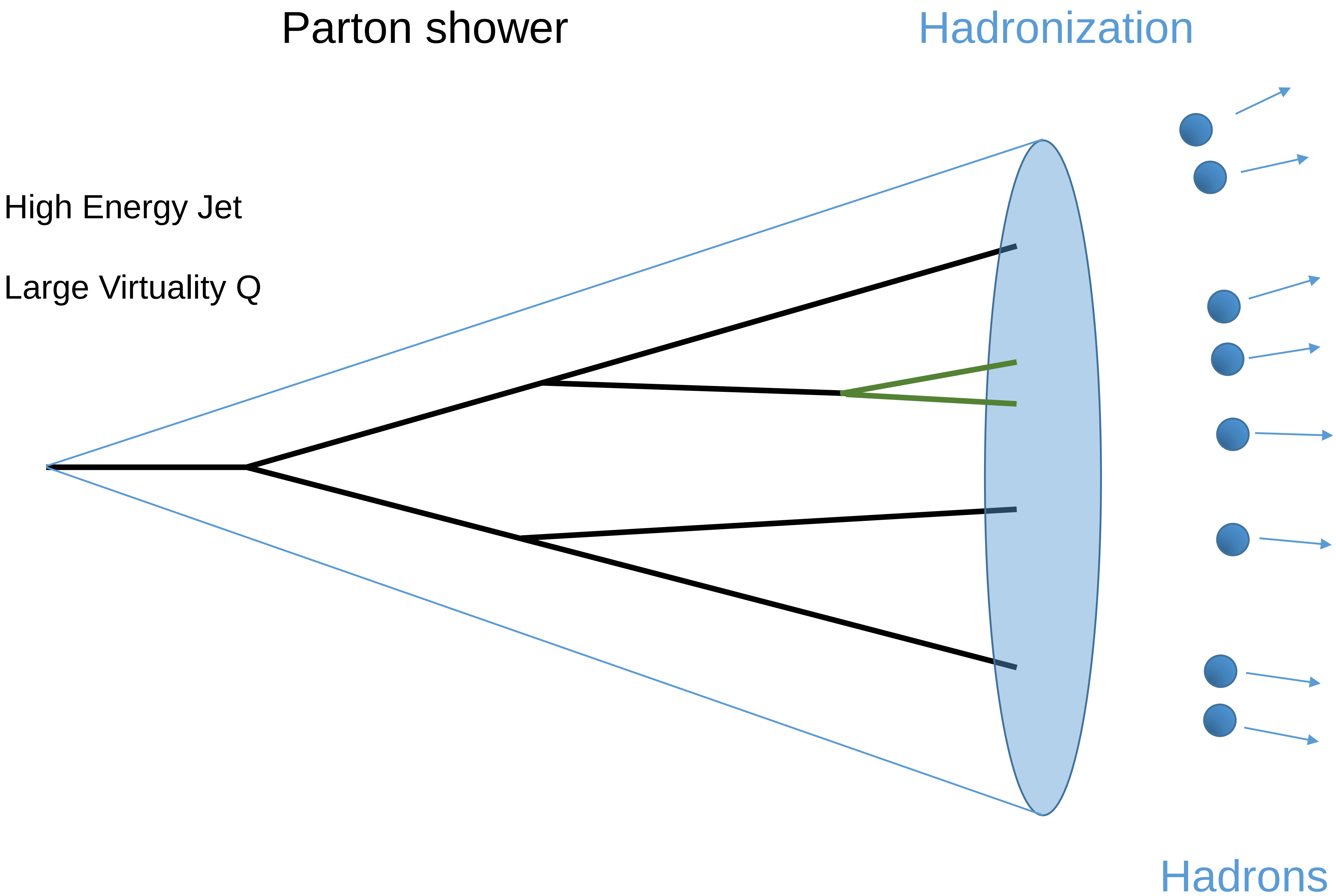
Kaya Tatar

S/B≈ 1%

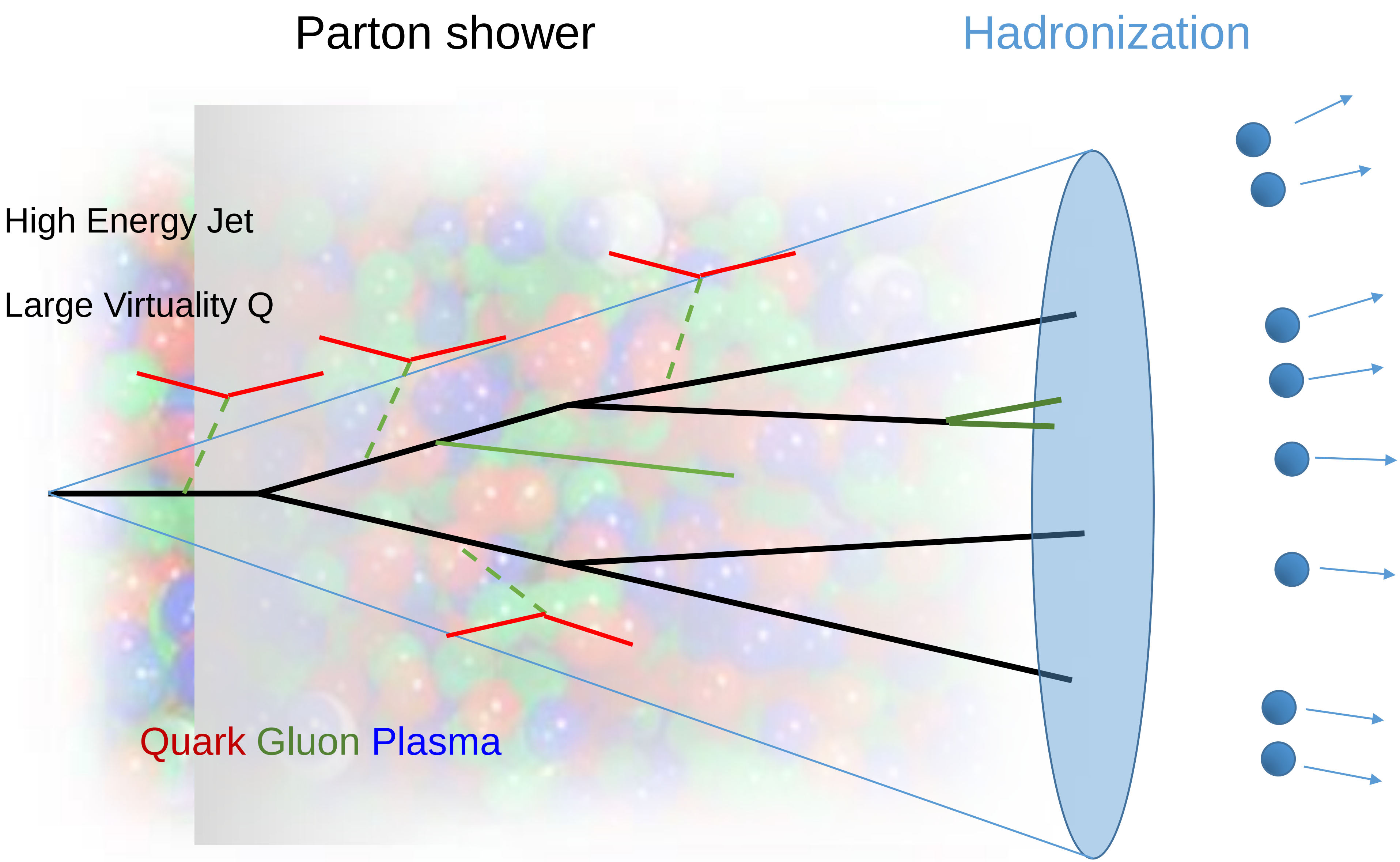
S/B≈ 5%

Background subtraction verified via Pythia+Hydjet simulation

Parton Cascade in Vacuum



Parton Cascade in the Quark Soup



Medium Changes vs. Time

Space-time information is also important in heavy ion environment

Photon-tagged Jet Shape vs. Theory