CMS Experiment at the LHC, CERN

Heavy-Ion Physics (II)

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Student Lecture

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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?

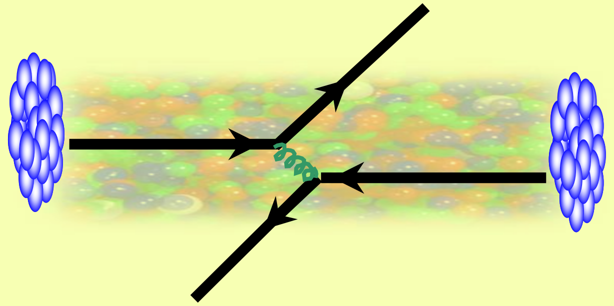
Study how Colored Probes are modified by QGP
Study how QGP respond to Colored Probes

How do we extract the medium effect in A+A collisions?

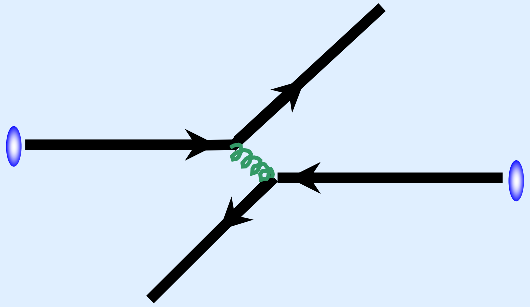
See for instance review form
D. d'Enterria and C. Loizides
Ann.Rev.Nucl.Part.Sci. 71 (2021) 315-44

One typical way is to compare A+A data to pp reference measurement

A+A measurements



pp reference



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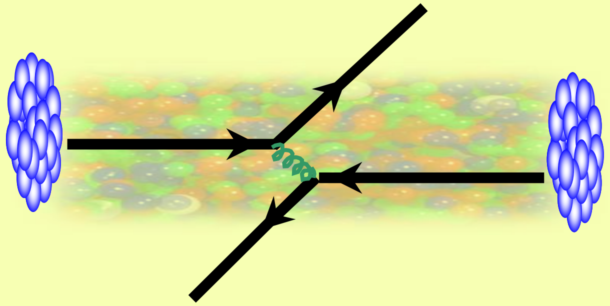
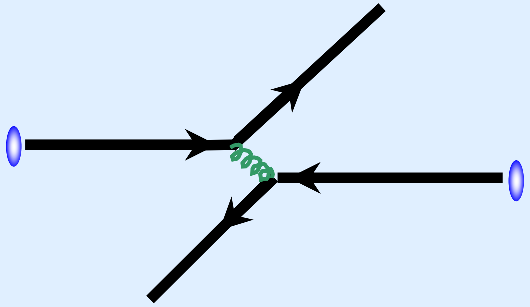
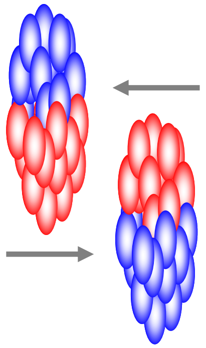


pp reference

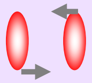
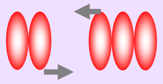




N_{part} → Number of participating nucleons

N_{coll} → Number of binary scatterings

Example:

	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$

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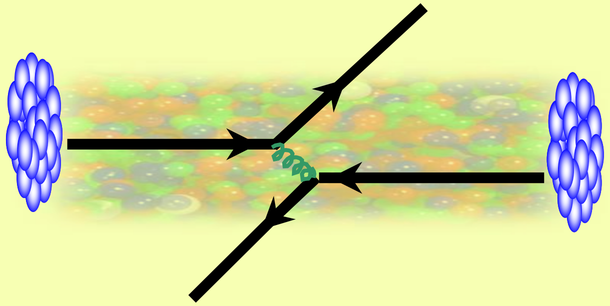
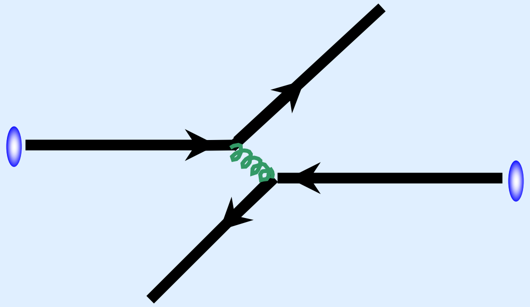
A+A measurements



pp reference



'Nuclear modification factors'

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

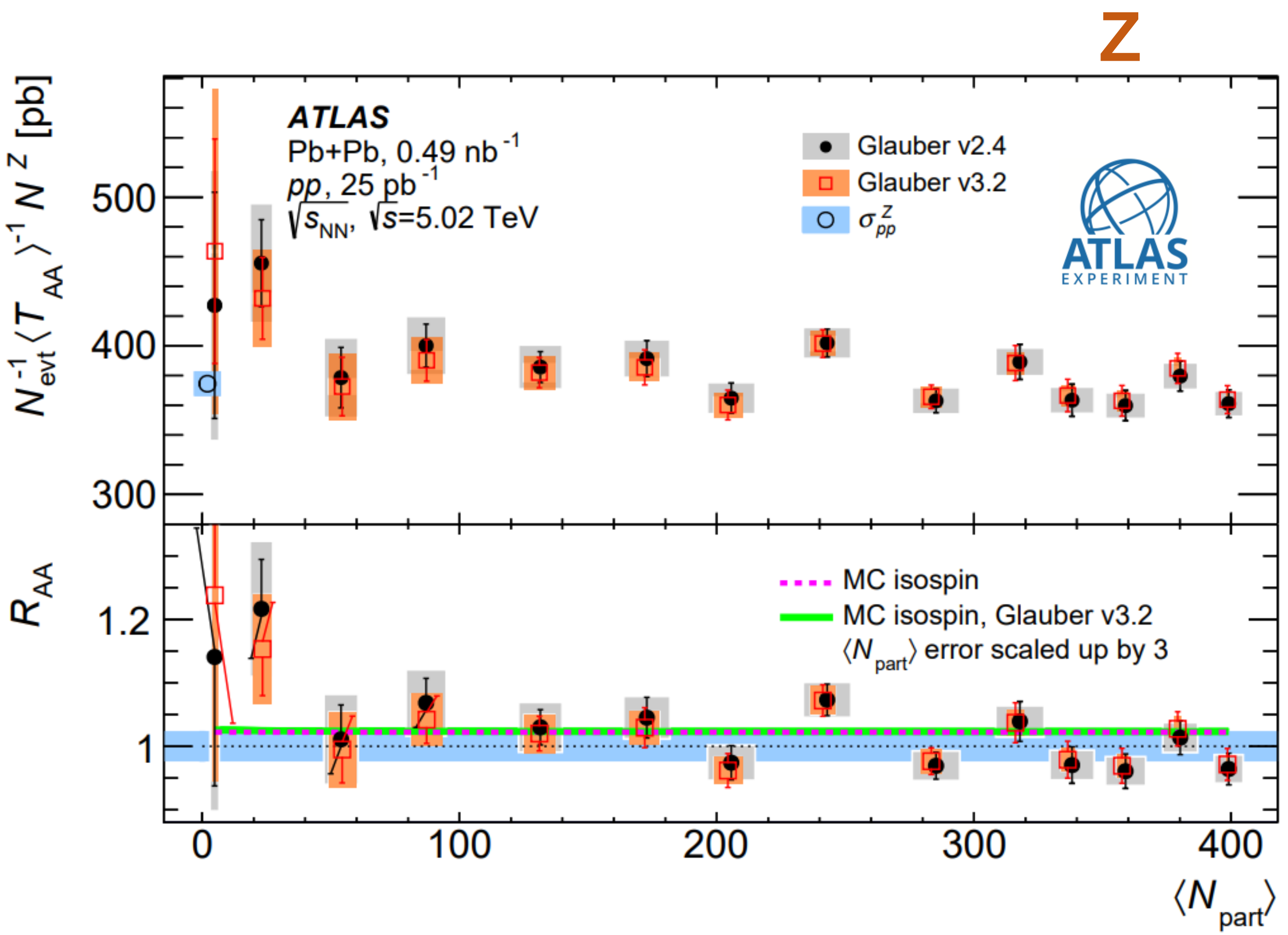
N_{coll} → Averaged number of binary scattering

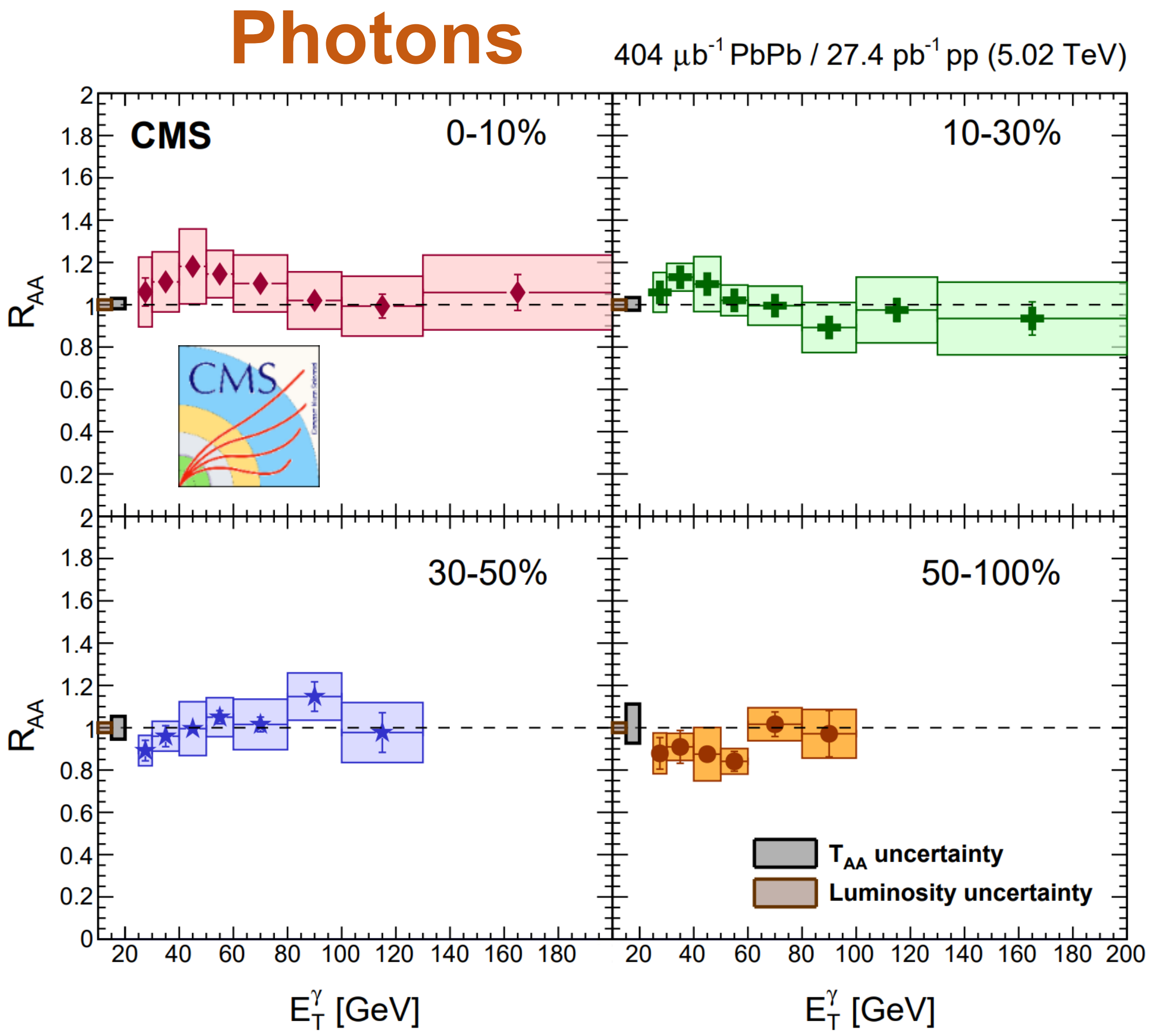
Questions: How do we know the Glauber model calculation of N_{coll} is correct?

Is the nuclear PDF modified with respect to nucleon PDF?

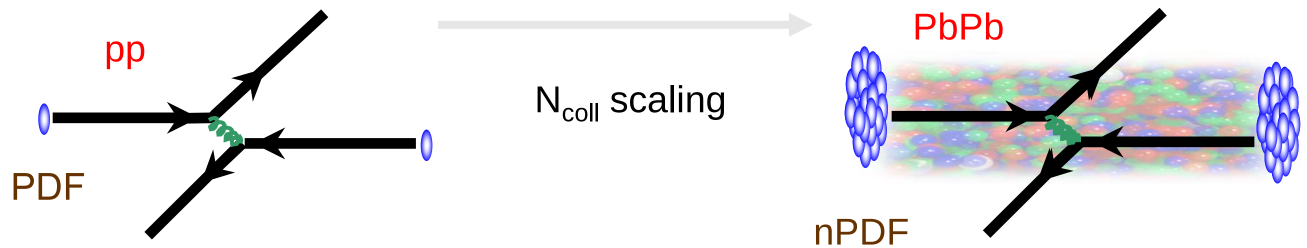
→ Motivates the studies of electroweak probes

Example: Photon R_{AA}



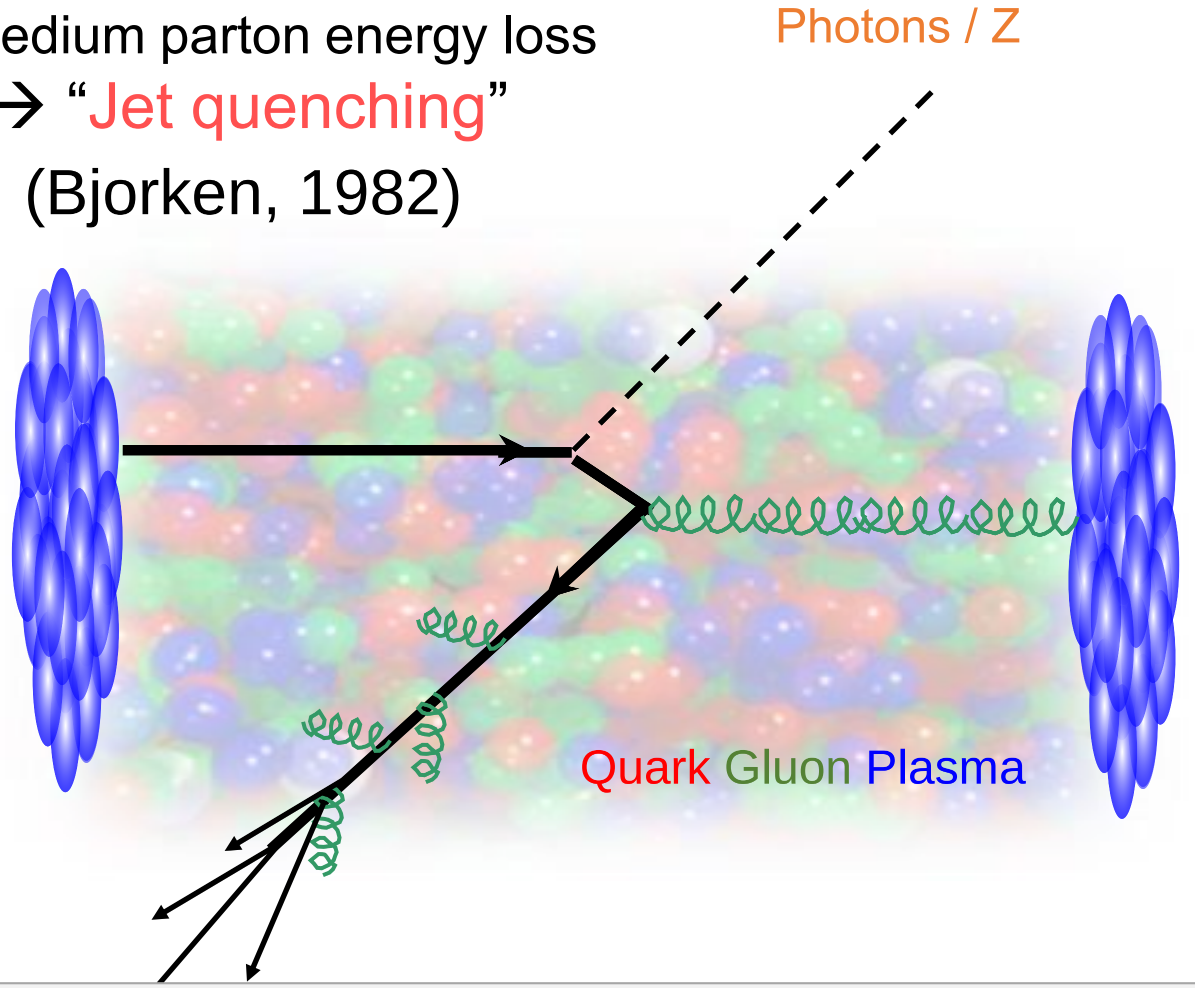


- Electroweak probes are unmodified
- Confirm N_{coll} scaling of hard scattering
- High precision W, Z and isolated photon measurements: constraint nPDF



Colorless and Colored Hard Probes

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



Colorless Probes

Photons, electroweak bosons
Validation
Tag the initial state

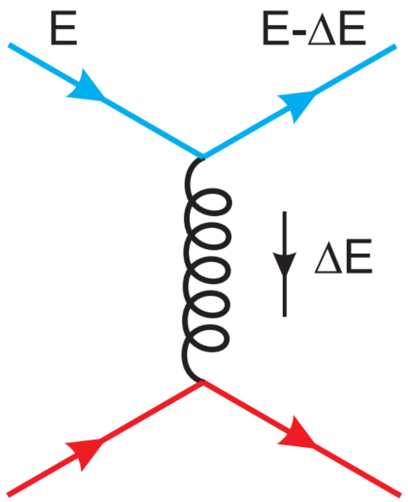
Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

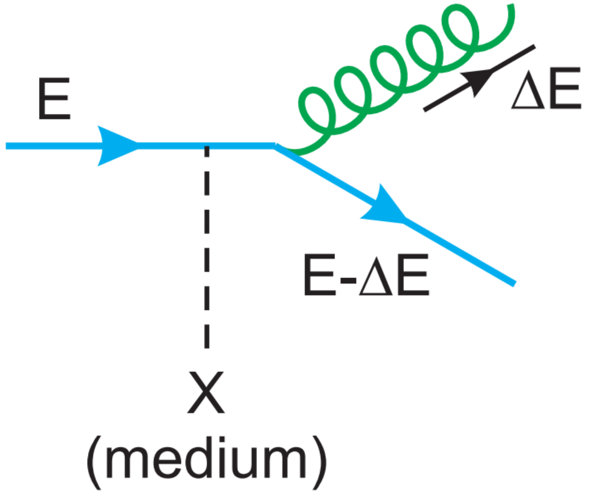
Colored Probes:

Fast-moving high energy quarks and gluons,
Heavy quarks

Studies of the medium properties

Mechanism of In-medium Energy Loss





Landolt-Bornstein 23 (2010) 471

For mean free path λ << medium size *L* we are in the LPM regime

$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

L^2 instead of *L*, due to destructive interference between scattering centers (LPM effect)

Jet: a powerful tool for the understanding of QGP

Jet quenching parameter: $\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$

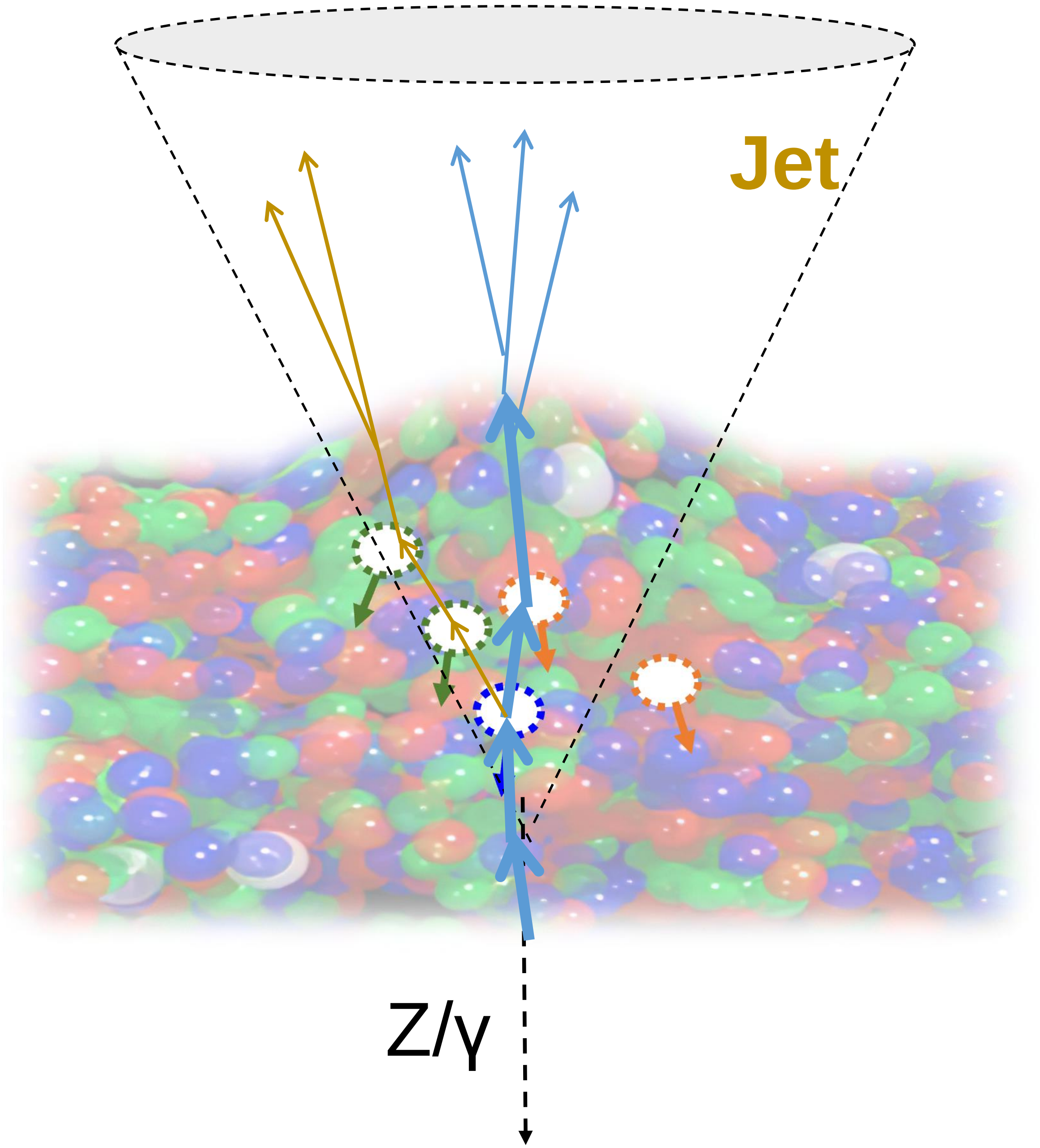
And it is the first moment of the Fourier Transform of the elastic cross-section to momentum space

$$\hat{q} = \rho_N \int d^2\mathbf{q}\, \mathbf{q}^2 \frac{d\sigma}{d^2\mathbf{q}}$$

Quenching depends on color factor

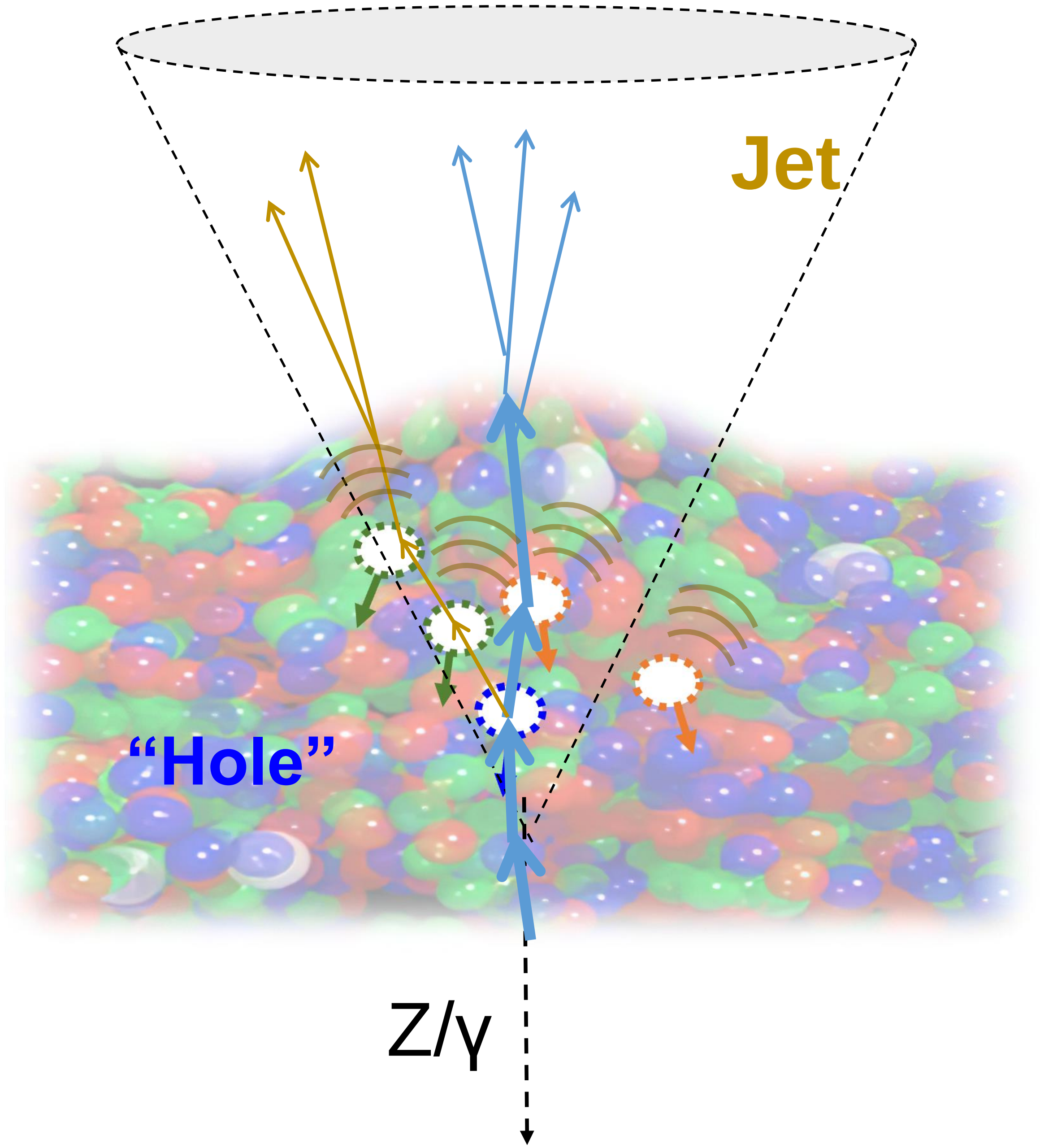
$$C_F = \begin{cases} 3 & \text{gluon jets} \\ 4/3 & \text{quark jets} \end{cases}$$

QGP Transport Properties and Structure with Jets



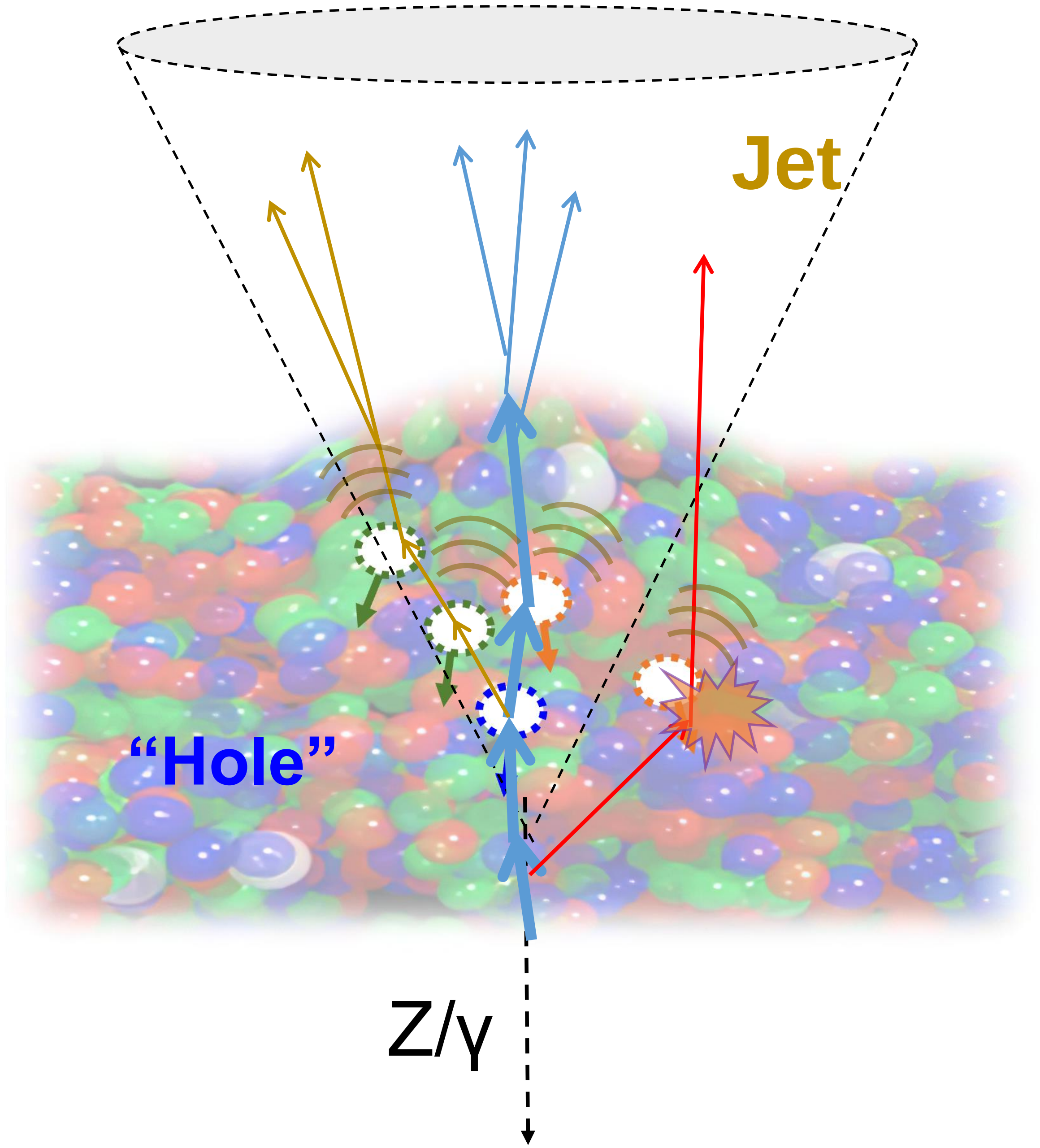
- Jet broadening effects from multiple soft scattering $(\hat{q})$

QGP Transport Properties and Structure with Jets



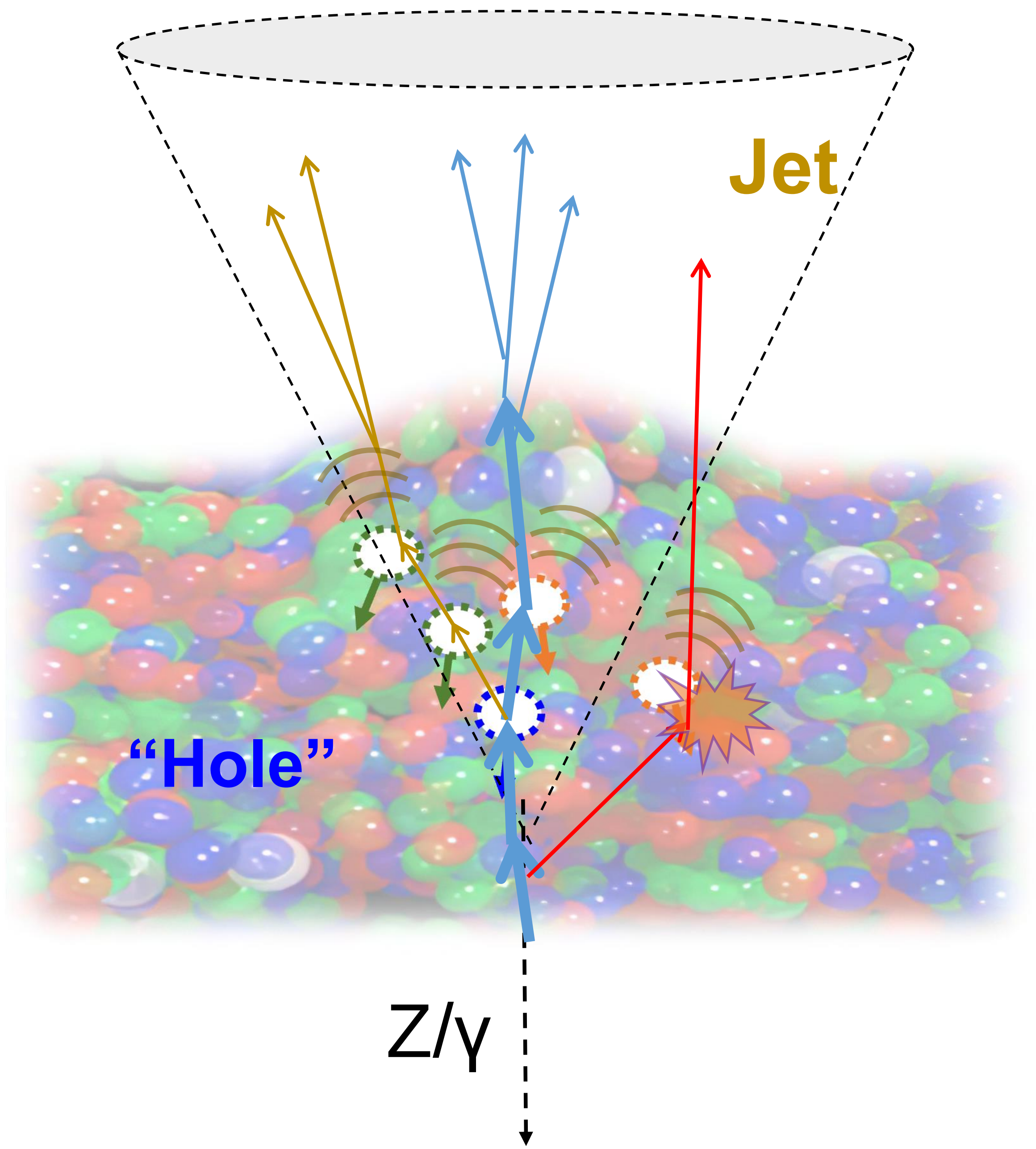
- Jet broadening effects from multiple soft scattering $(\hat{q})$
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes) 

QGP Transport Properties and Structure with Jets

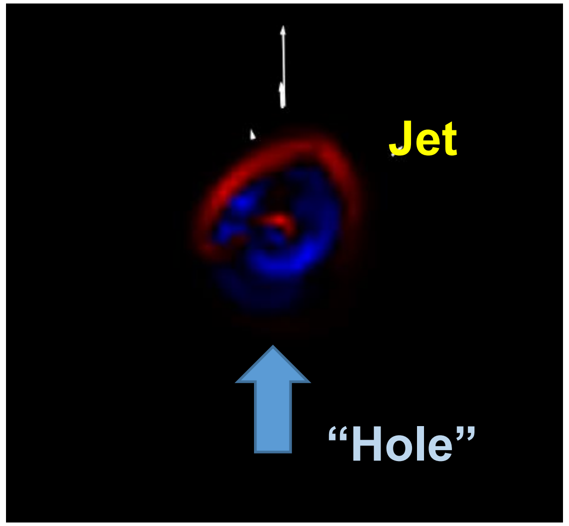


- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

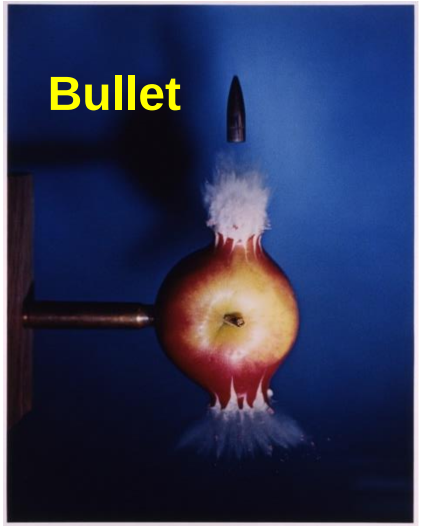
QGP Transport Properties and Structure with Jets



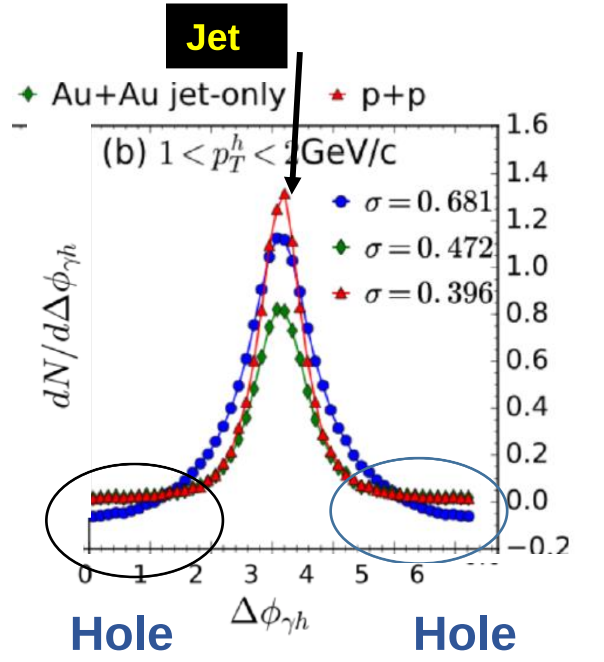
Tan Luo, Xin-Nian Wang (CoLBT)



wake



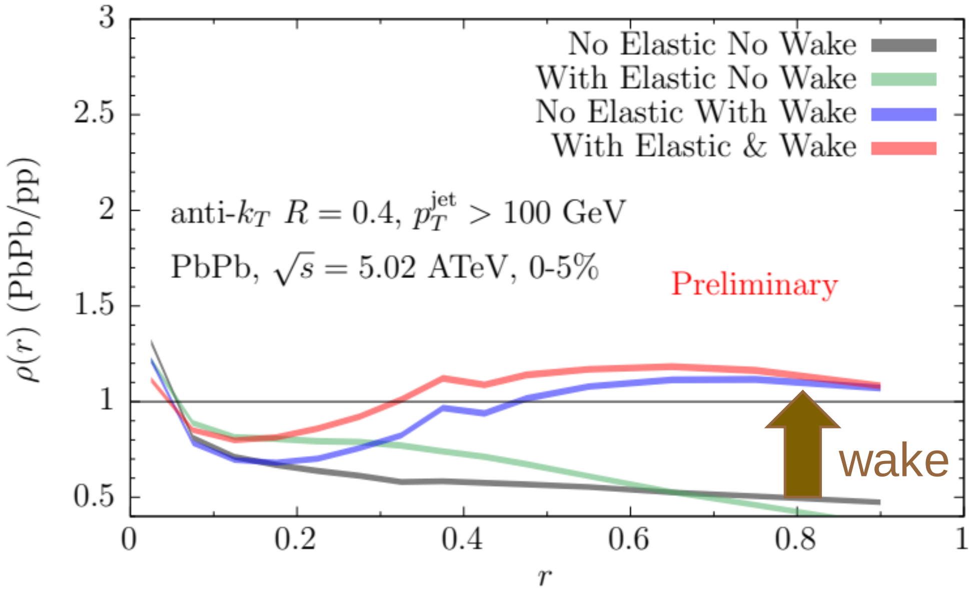
Hole



medium response / wake

Low p_T particles at large angle

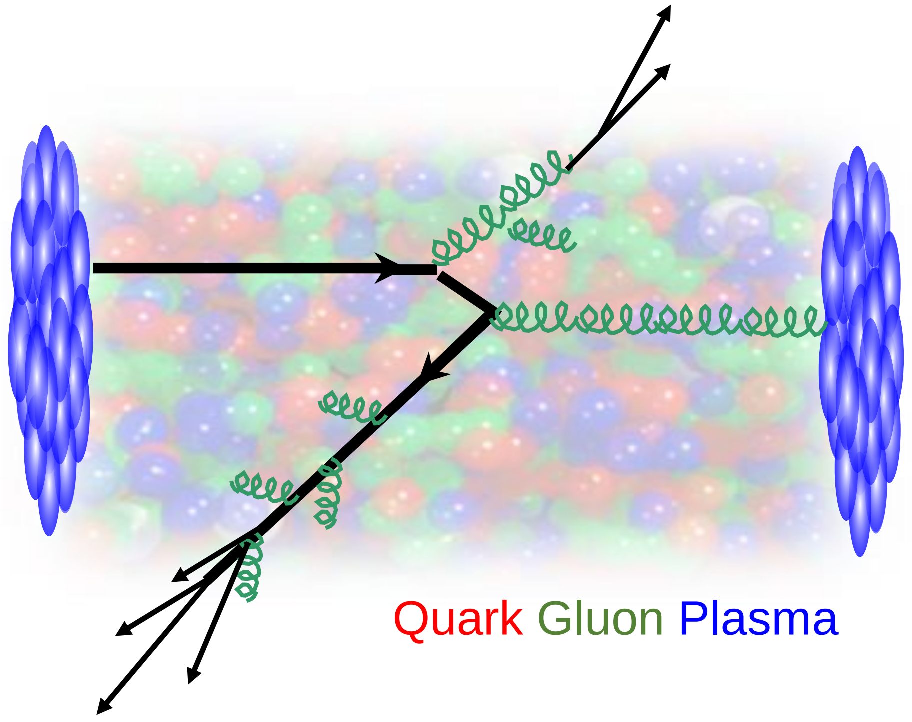
arXiv:2208.13593
Hulcher, Pablos, Rajagopal



Parton Energy Loss with Final State Particles

- Ideally, we would like to measure Quarks and Gluons directly

- In reality, we could only measure **final state particles** which are coming from hard scattered partons



Quark Gluon Plasma

Early Measurements at RHIC (2001-3)

Reminder:

‘Nuclear modification factors’

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

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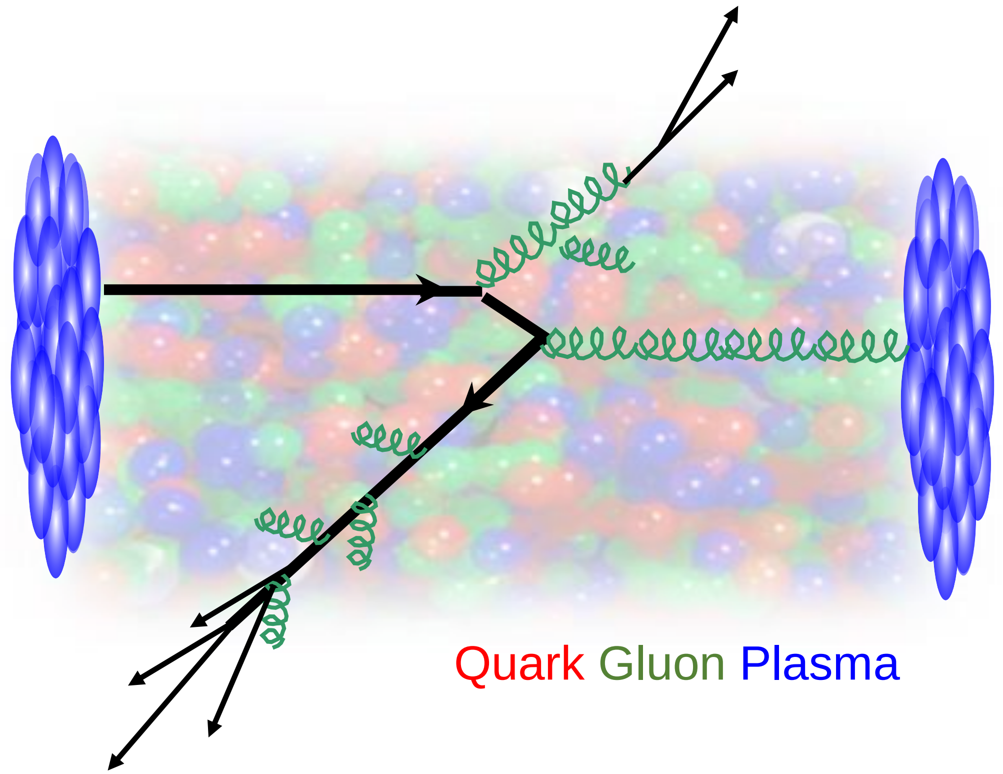
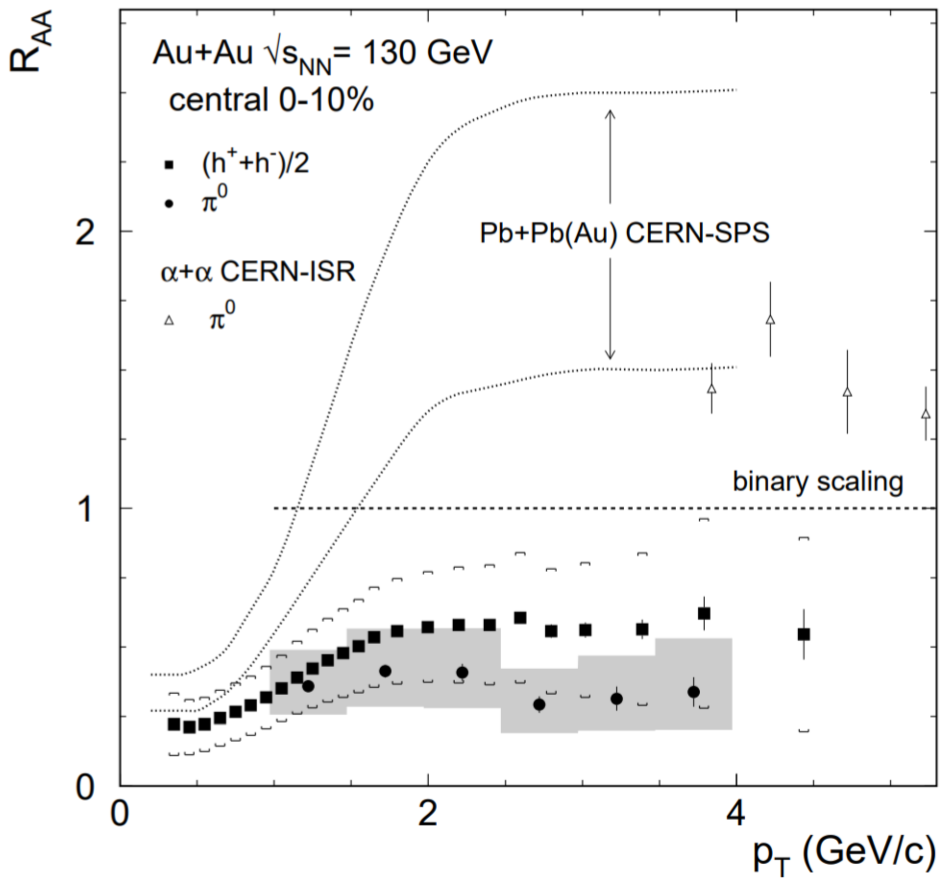


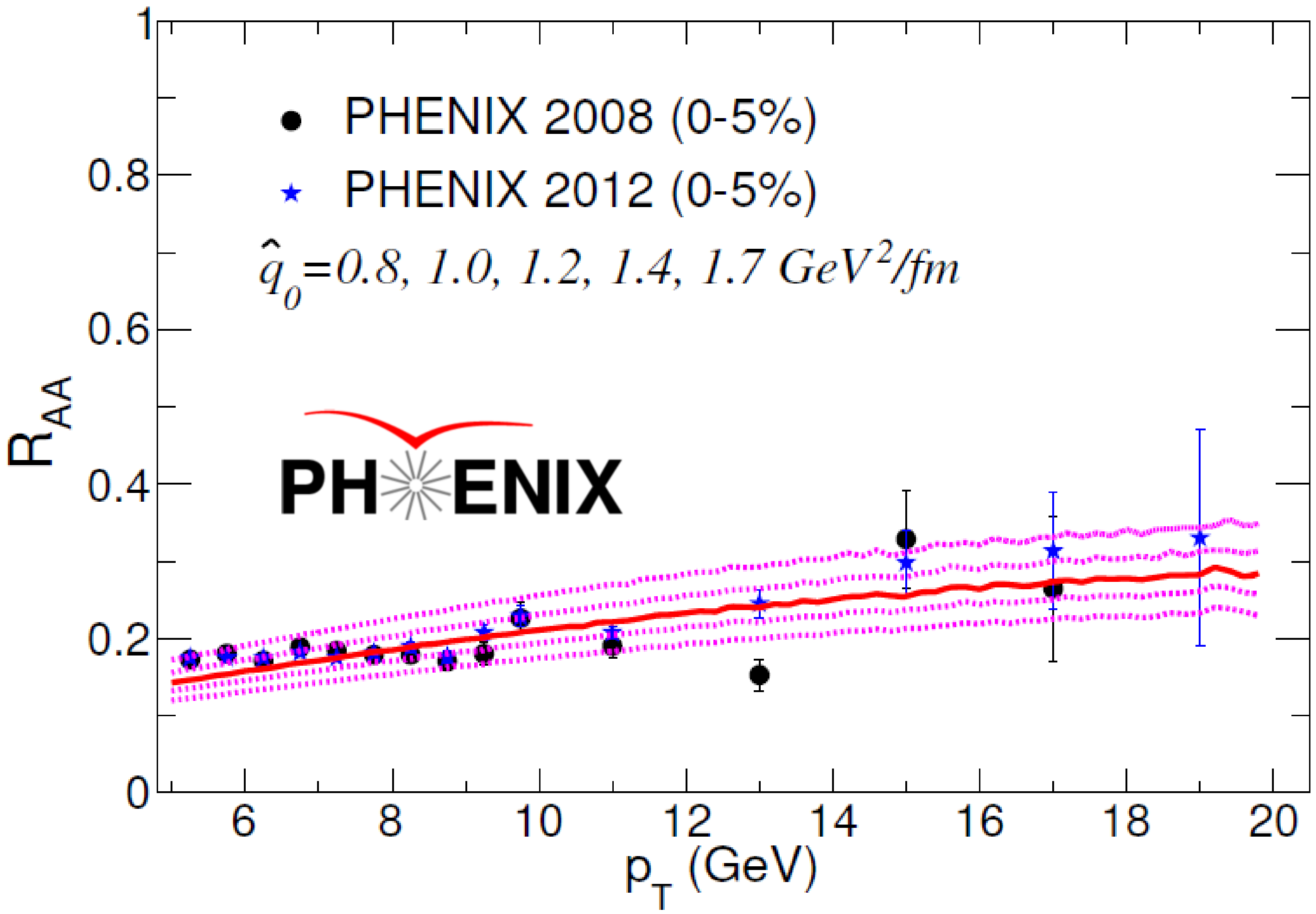
PHENIX PRL 88 (2002) 022301

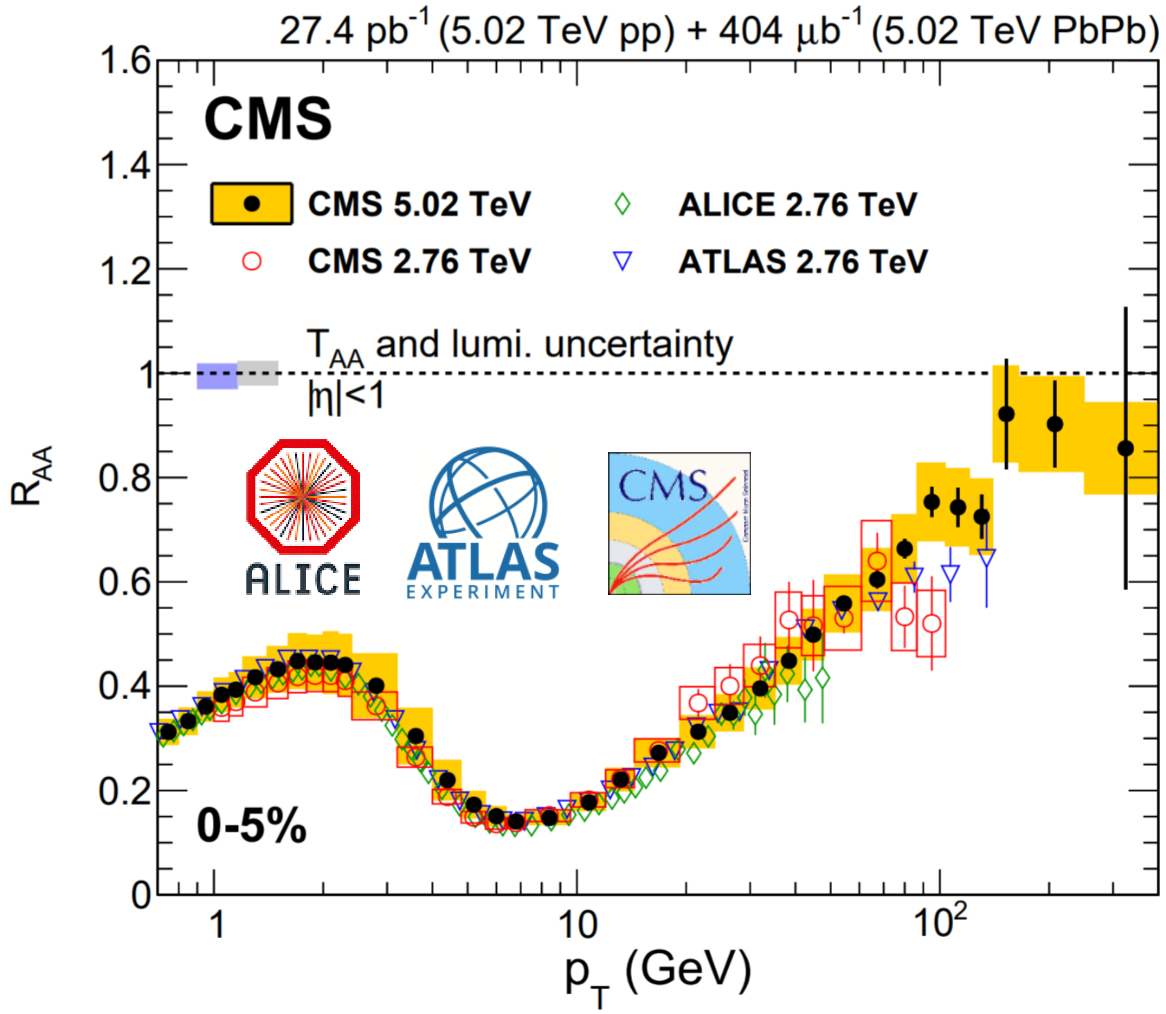


Strong suppression of high p_T hadrons

Modification of the leading fragment

Jet Quenching without Jet: Charged Particle R_{AA}





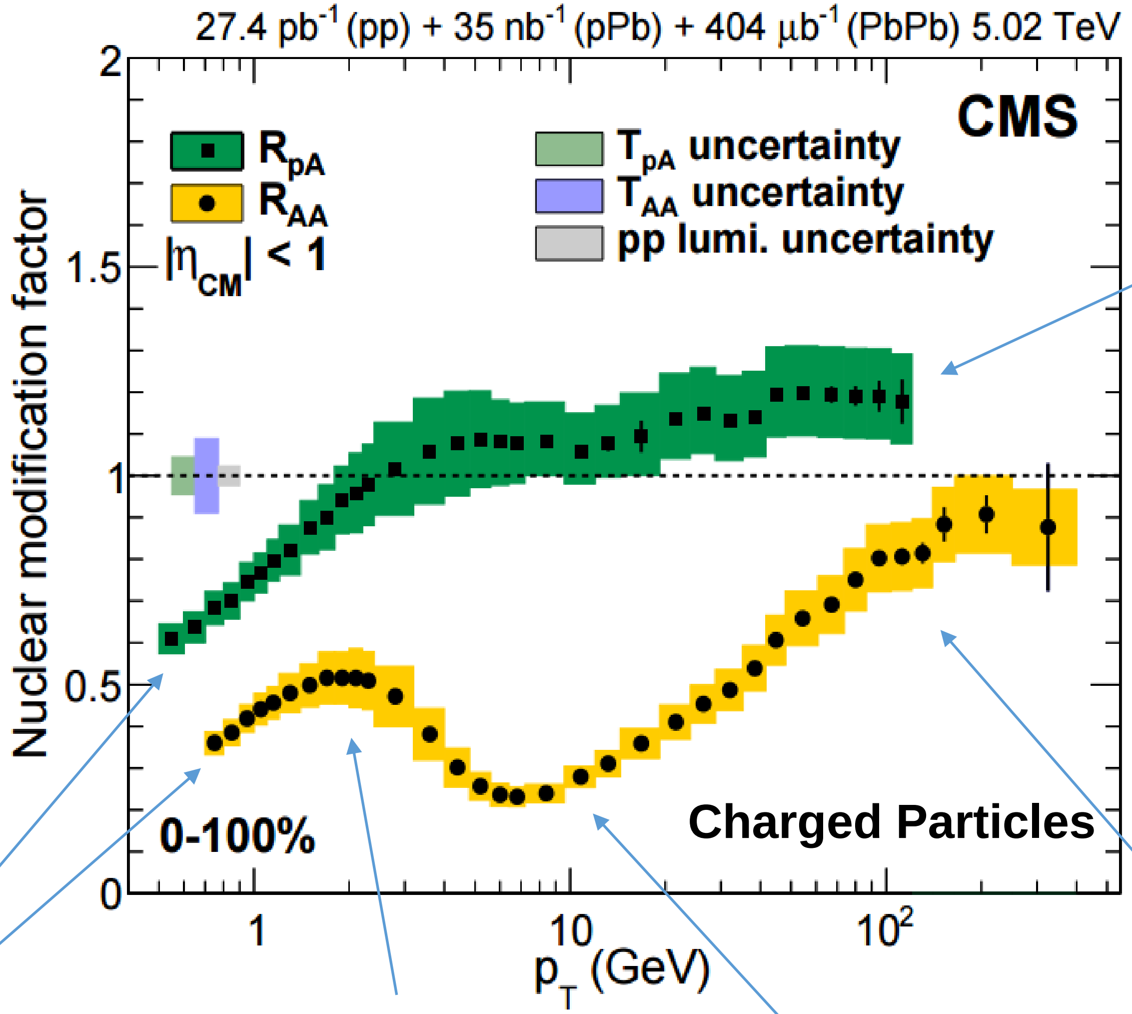
Greatly improved results at RHIC since the first measurement

- A prominent “S shape” in charged particle R_{AA}
- Good agreement between experiments at the LHC

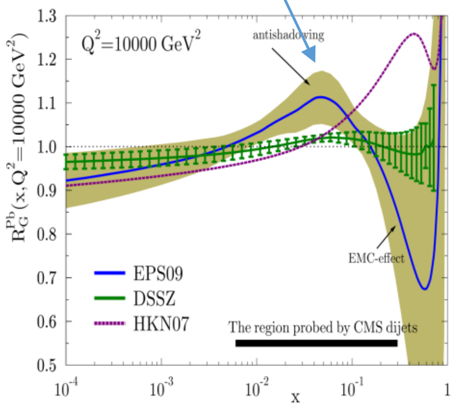
Jet Quenching without Jet: Interpretation

R_{pA} from pPb data

R_{AA} from PbPb data

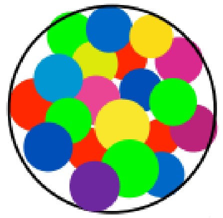


Anti-shadowing for intermediate x partons

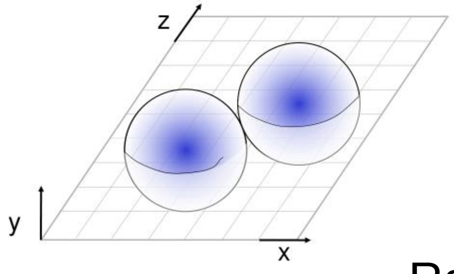


QGP become more transparent to very high p_T particles

Gluon saturation

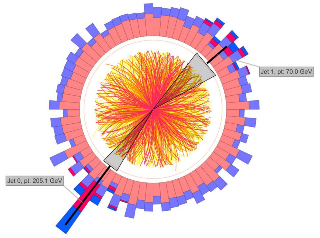


Shadowing



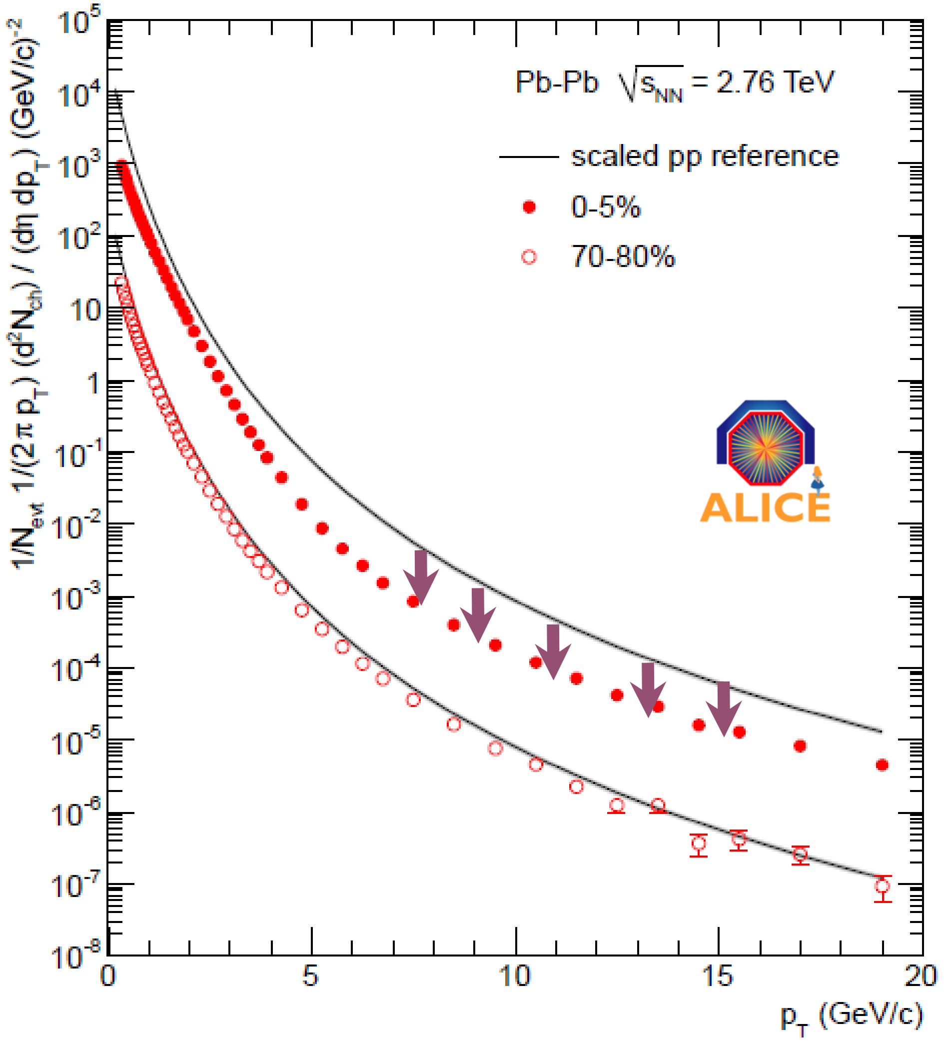
Radial flow

Jet quenching

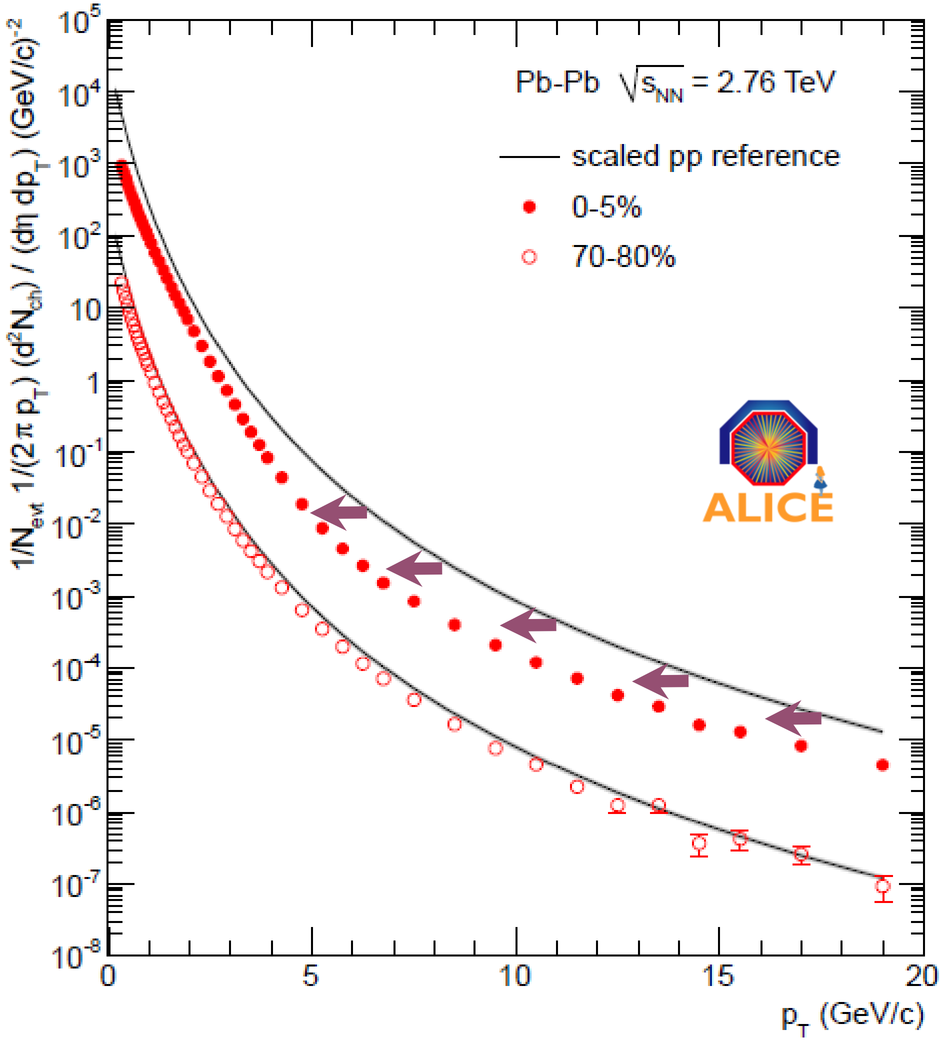


Limitation of Charged Particle Spectra

Absorption?



Energy loss?

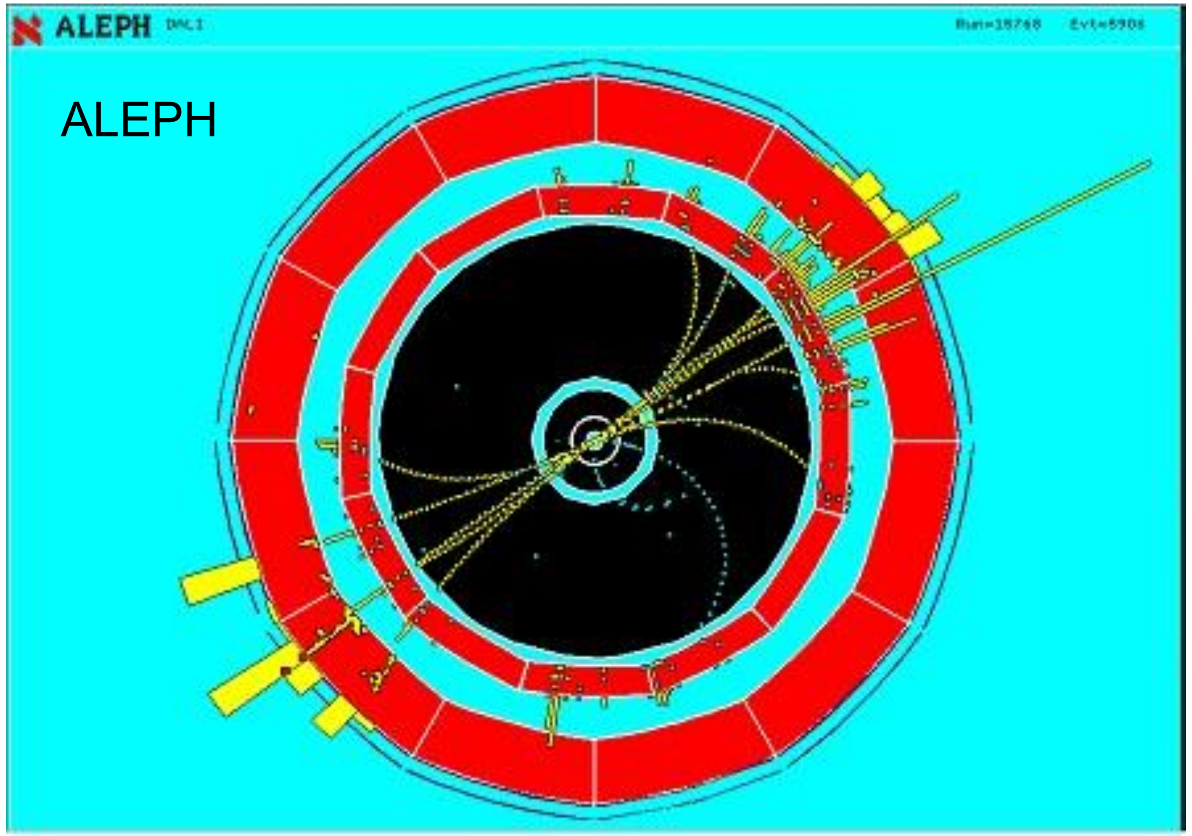


Single hadron spectra itself do not provide details of the underlying mechanism

Need direct jet reconstruction and correlation studies

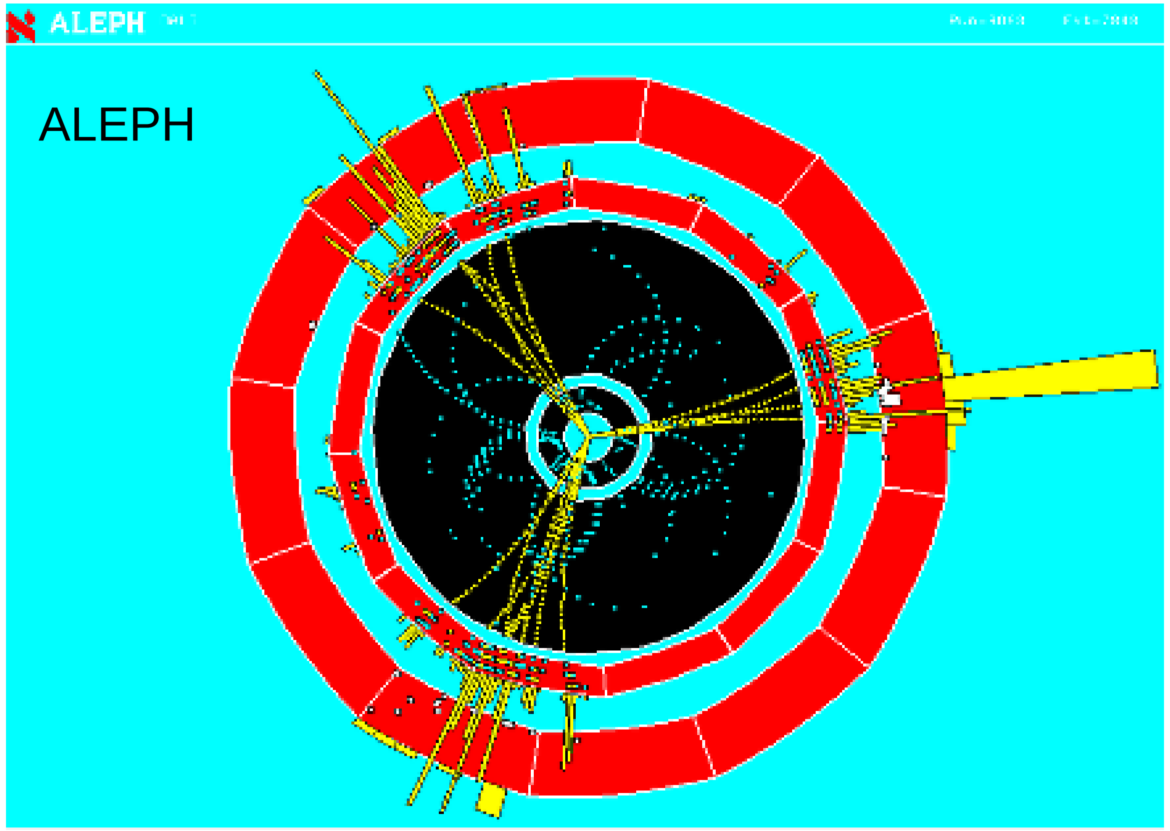
Detecting Quarks and Gluons

Dijet event?



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

Three-jet event?



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

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

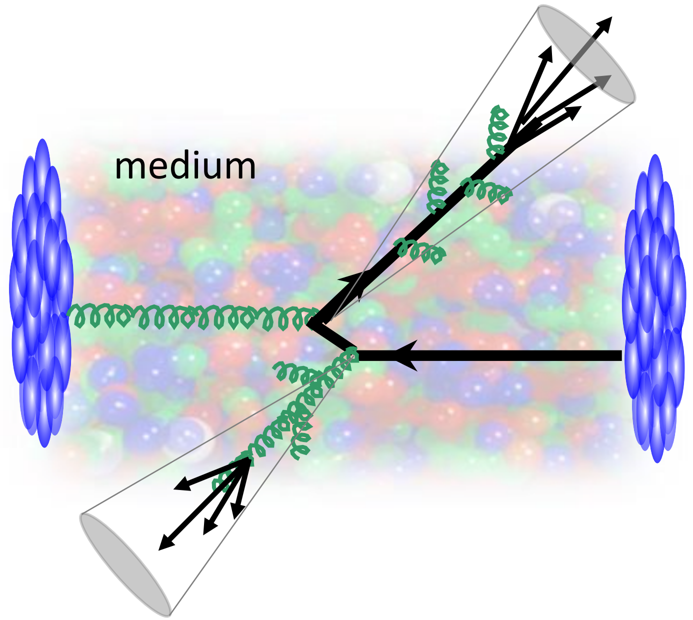
Parton Energy Loss with Jets

- Ideally, we would like to measure quarks and gluons directly
- In reality, we could only measure final state particles which are coming from hard scattered partons

QCD branching:

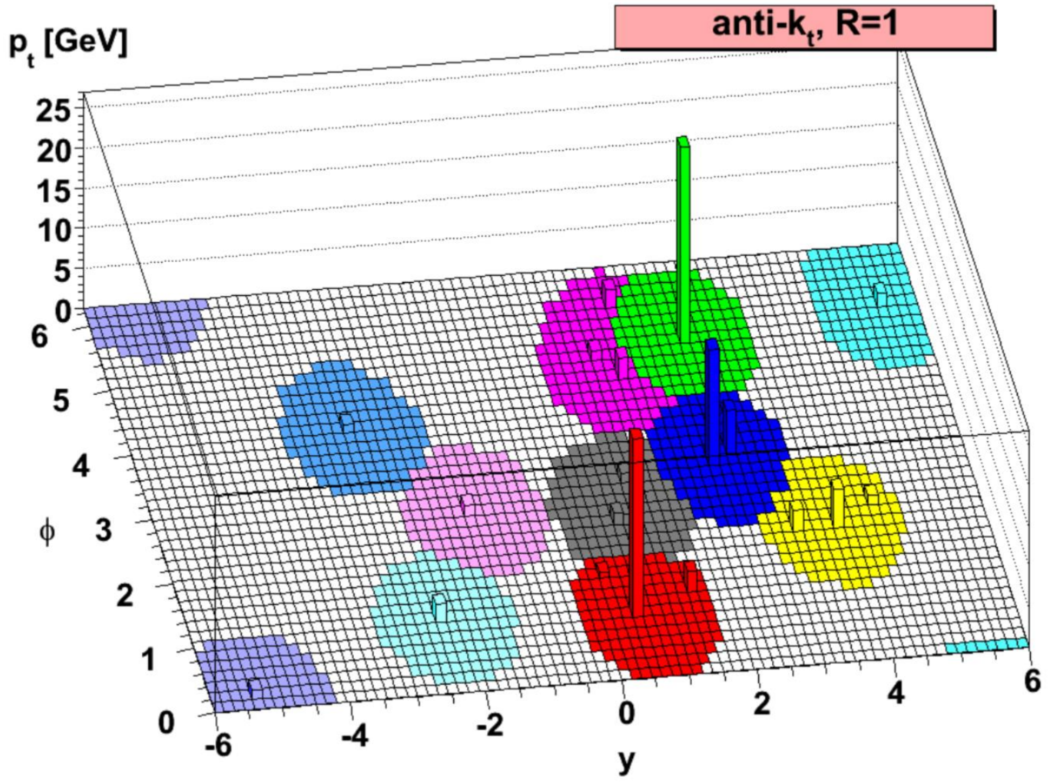
$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi} \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}}{\theta_{ij}}$$

- The attempt to invert this process is called jet reconstruction, defined by **jet algorithms**



Jet Clustering Algorithm

JHEP 0804:063,2008



Anti-k$_T$ algorithm

R: distance parameter

Cluster smallest distance d_{ab} pair first

Distance between pseudo-jets **i** and **j**

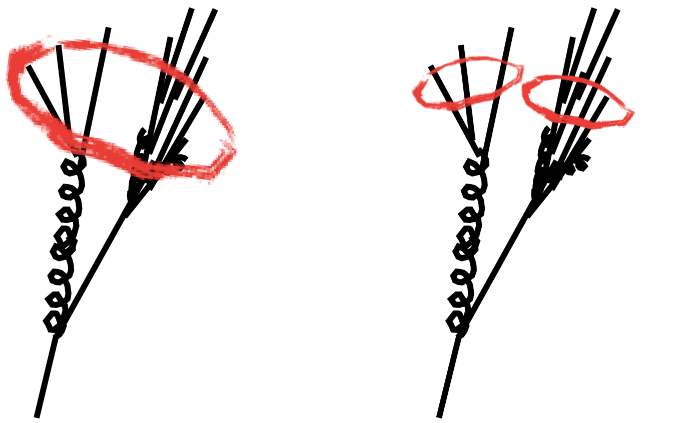
$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}$$

Distance to beam **B**

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

Large **R**

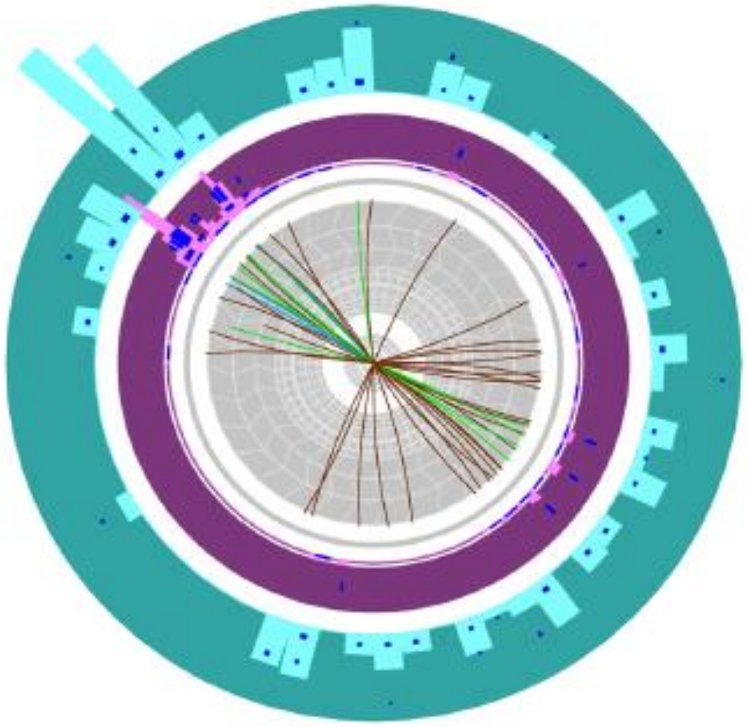
Small **R**
→ jet splitting

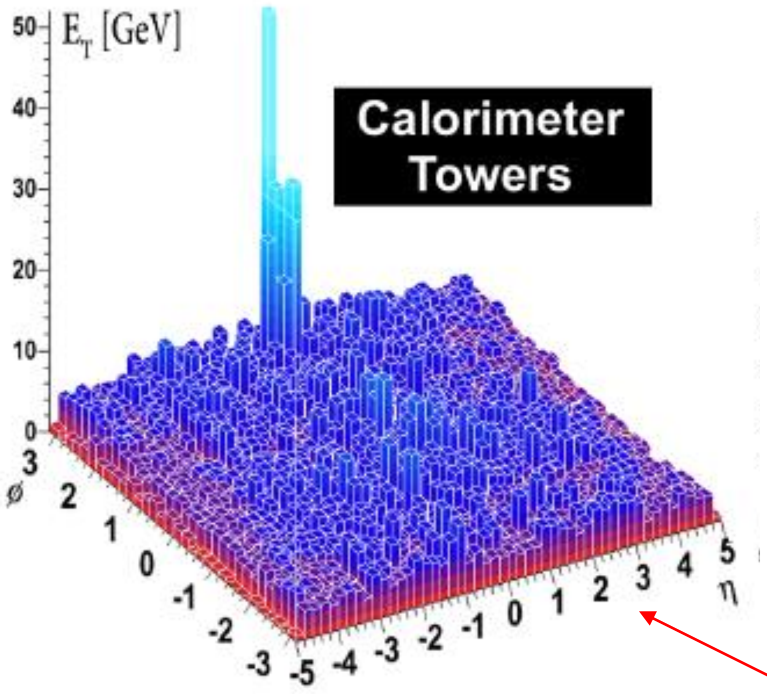


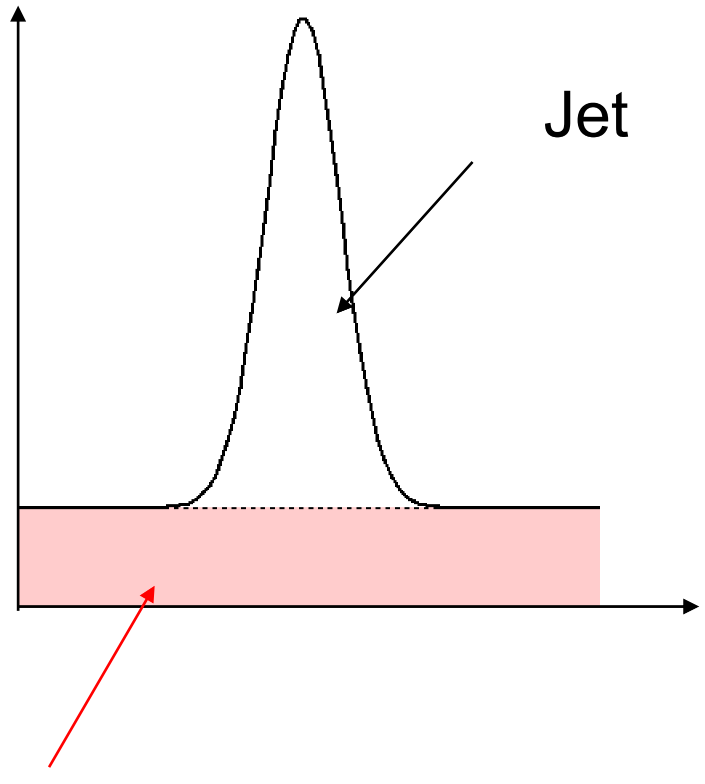
- Give **circular jet**, cluster high momentum particles first
  - Jets with a radius of roughly **R**
- Most popular algorithm used in analyses of pp and heavy-ion collisions

Underlying Event Background

ATLAS





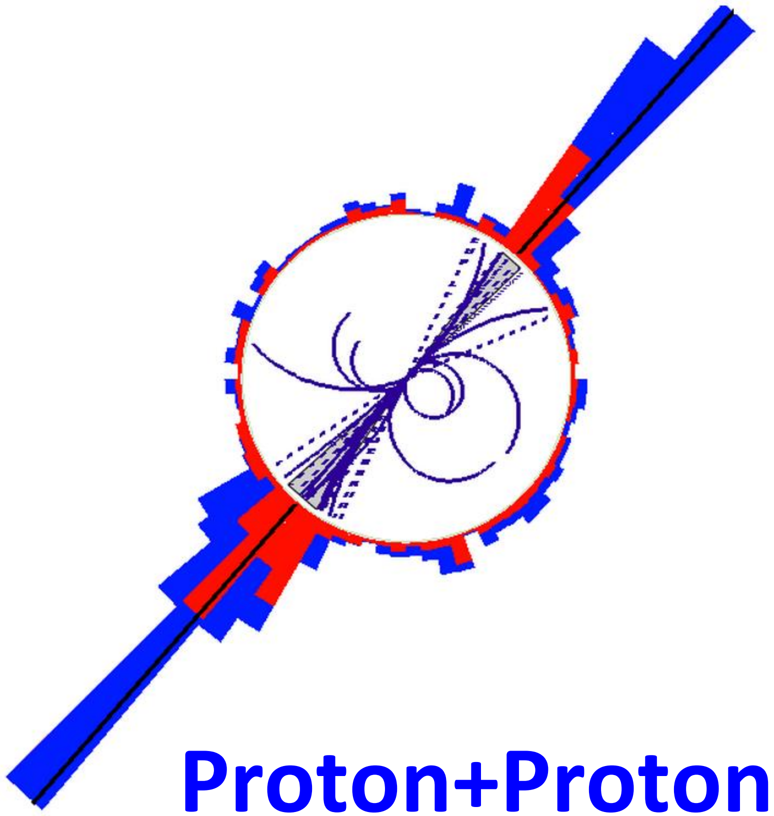


Multiple parton interaction

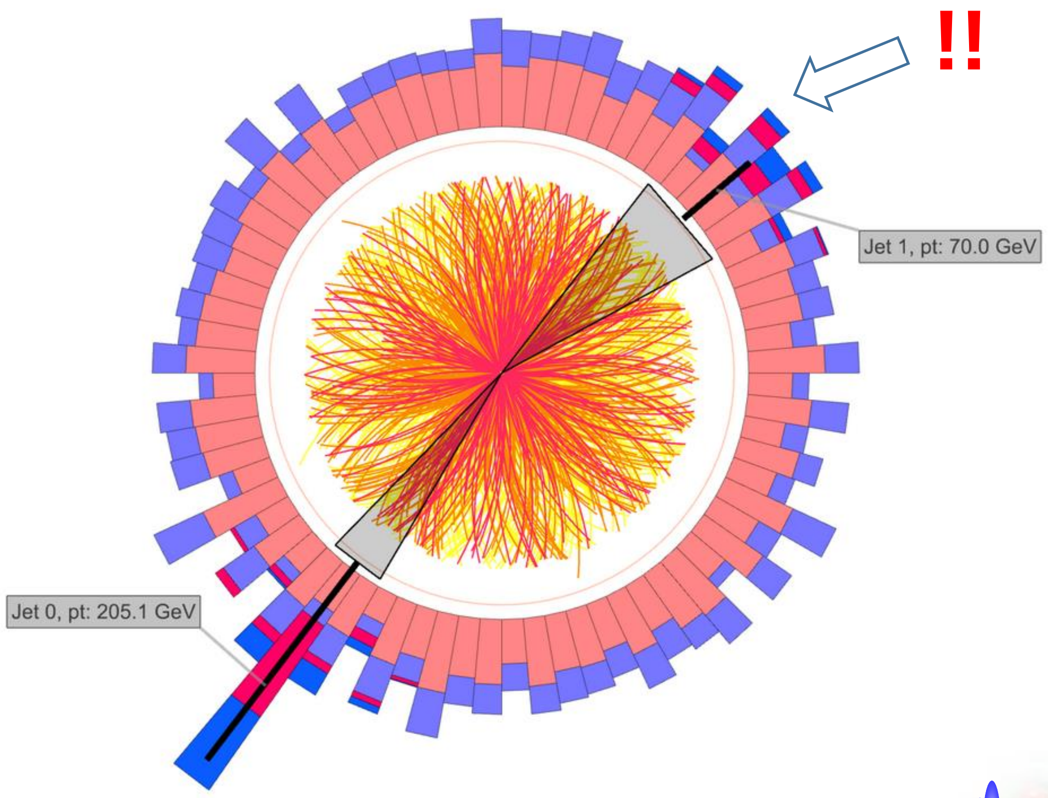
Large underlying event from soft scattering

Need to subtract the underlying event background

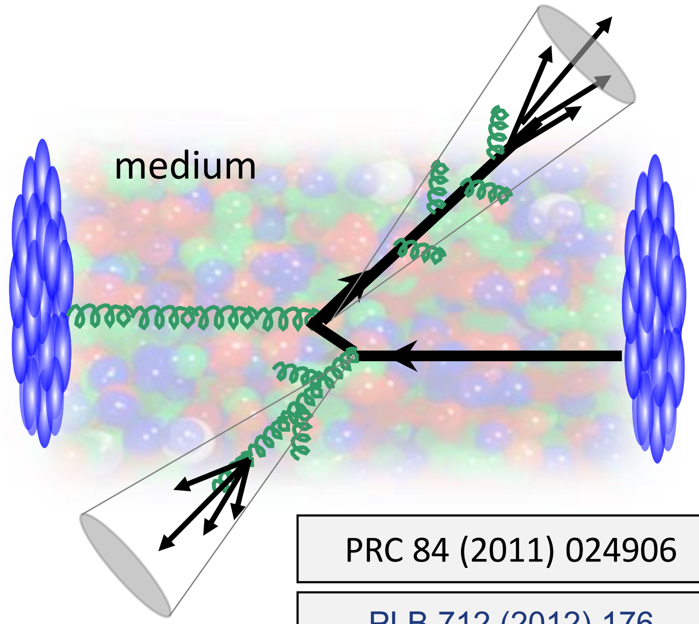
Probe the QGP with High Energy Quarks and Gluons



Proton+Proton



Lead+Lead



Asymmetric dijets in Lead+Lead collisions!

PRC 84 (2011) 024906

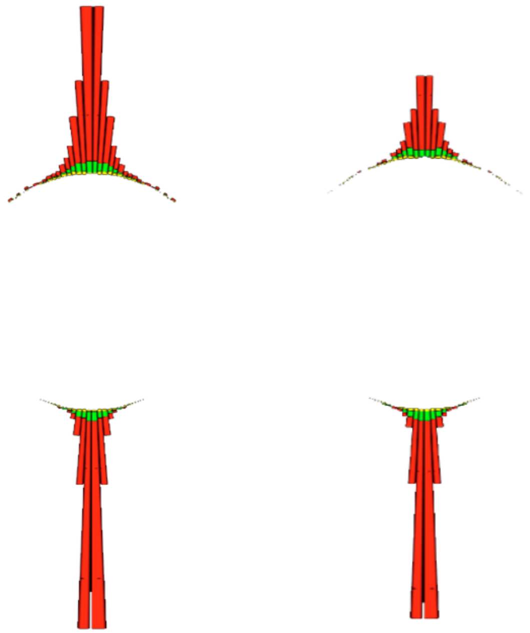
PLB 712 (2012) 176

First Measurement of Full Jets in Pb+Pb at LHC

PRL 105 (2010) 252303

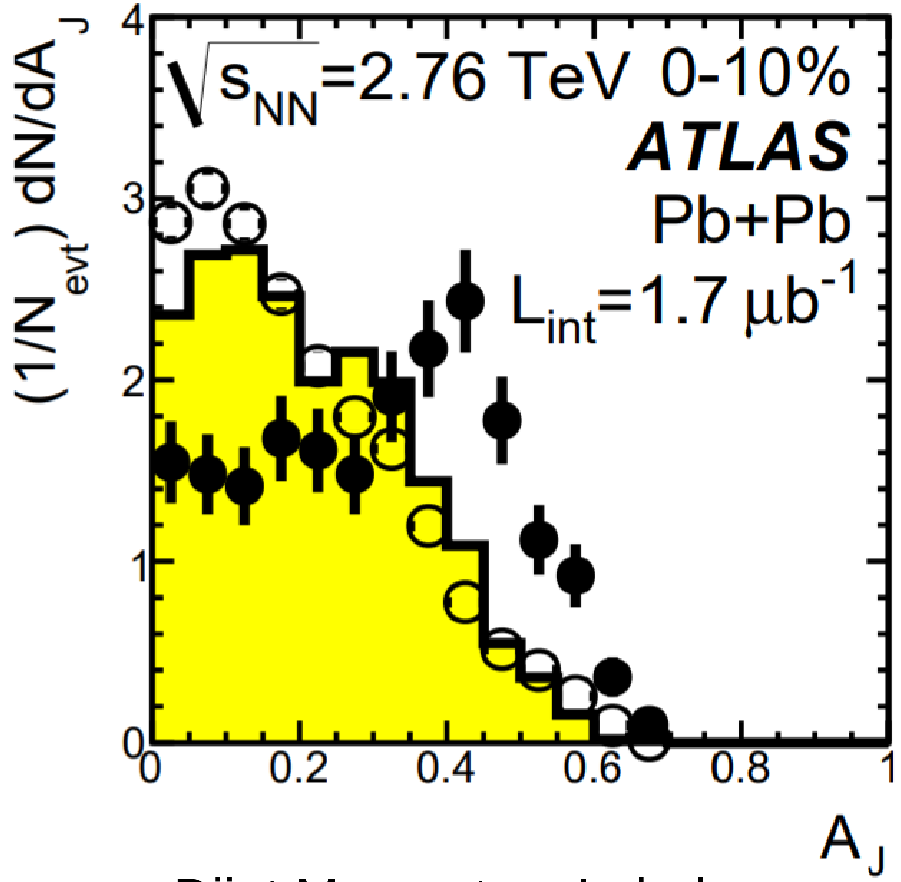
PRC 84 (2011) 024906

$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

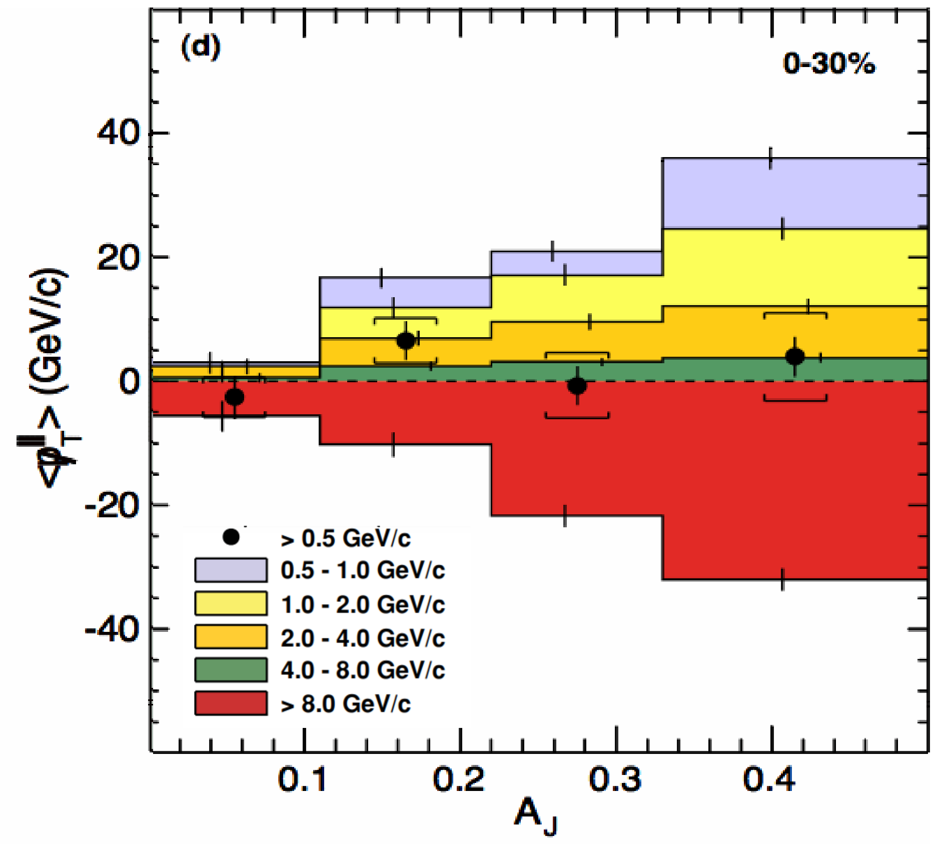


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



Dijet Momentum Imbalance



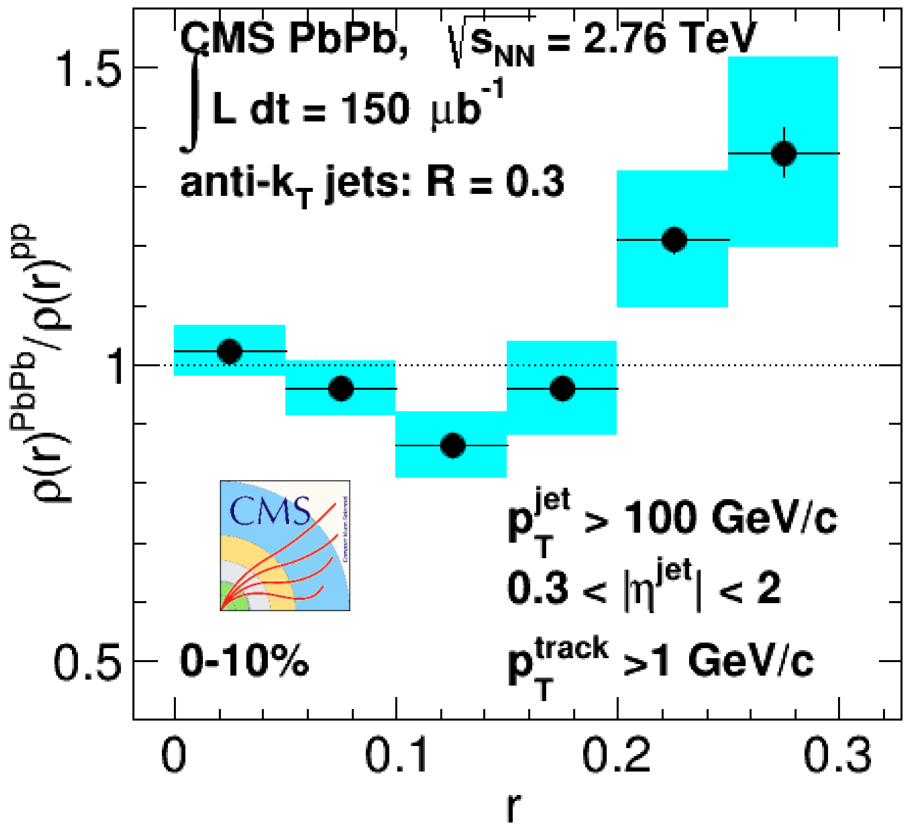
Missing Transverse Momentum

Jet quenching with jet
Energy flow out of the jet cone

Quenched energy carried by low p_T particle out of the jet cone

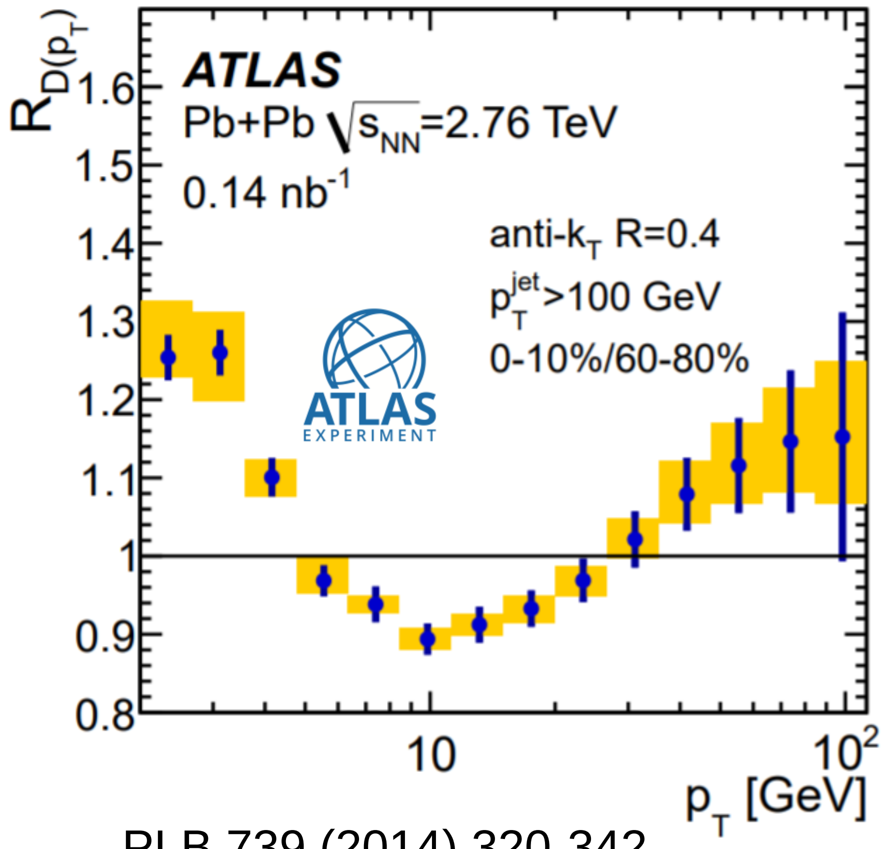
Inclusive Jet Transverse and Longitudinal Structure

Jet Transverse Structure



PLB 730 (2014) 243-263

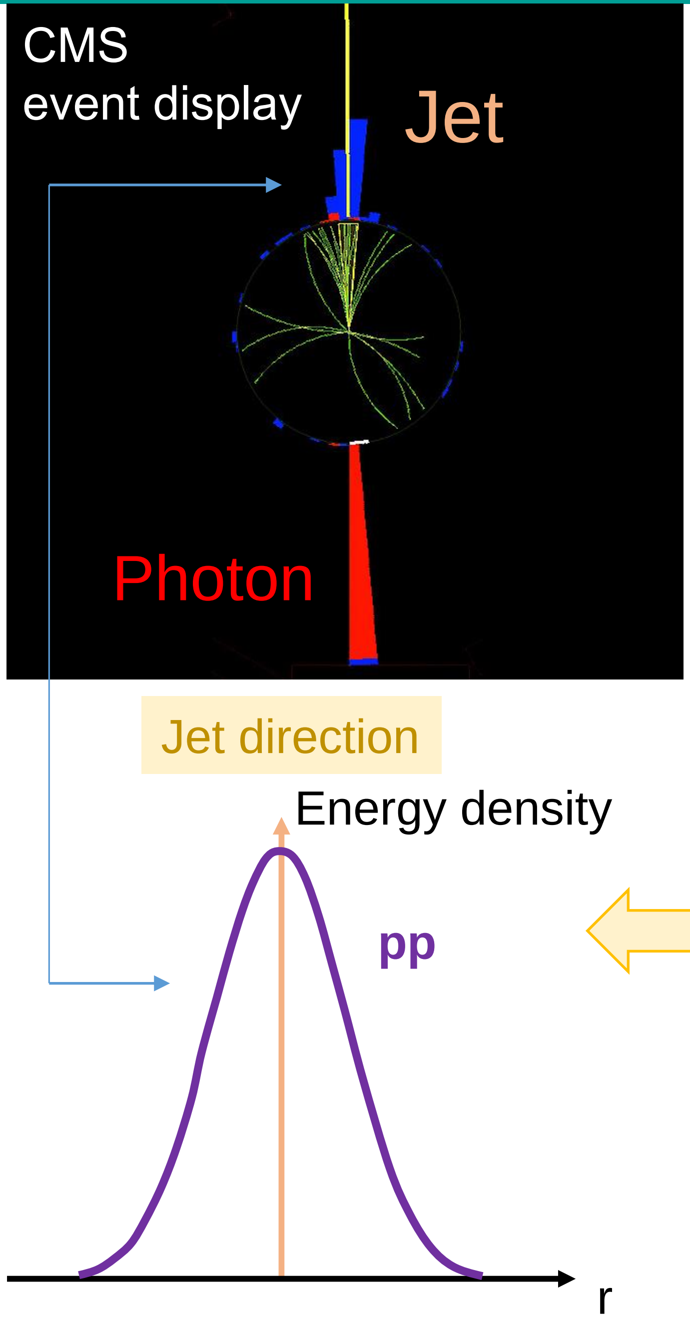
Jet Longitudinal Structure

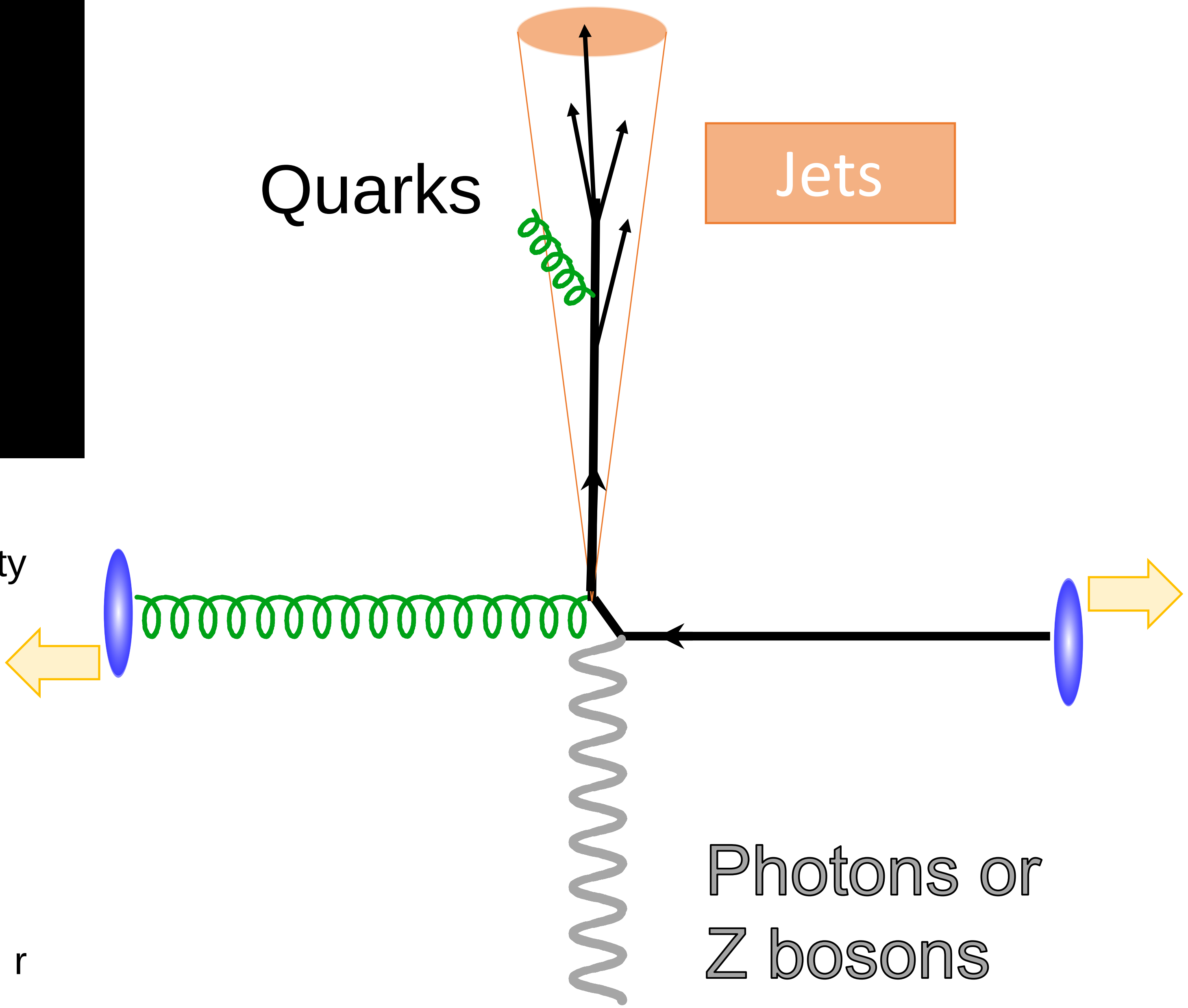


PLB 739 (2014) 320-342

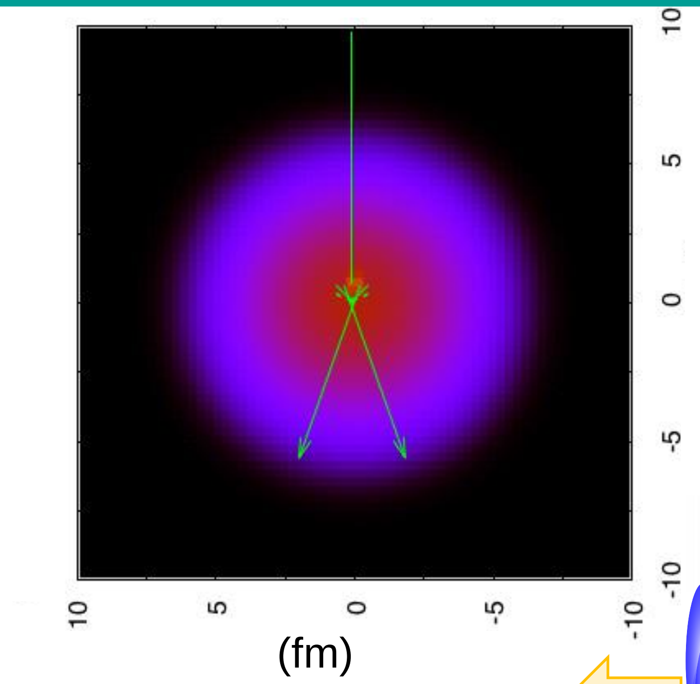
- Modification of average jet structure when compared the jets in PbPb to the pp reference at the same p_T
- Jet structures, defined by clustering and background subtraction algorithms, are modified in PbPb collisions

High Transverse Momentum Scattering

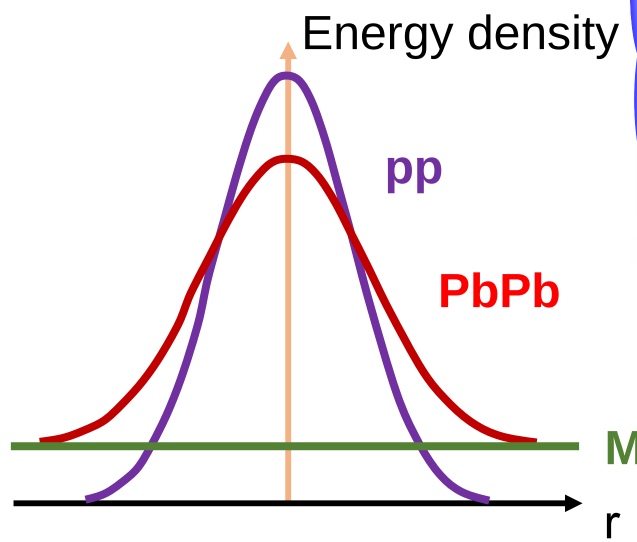




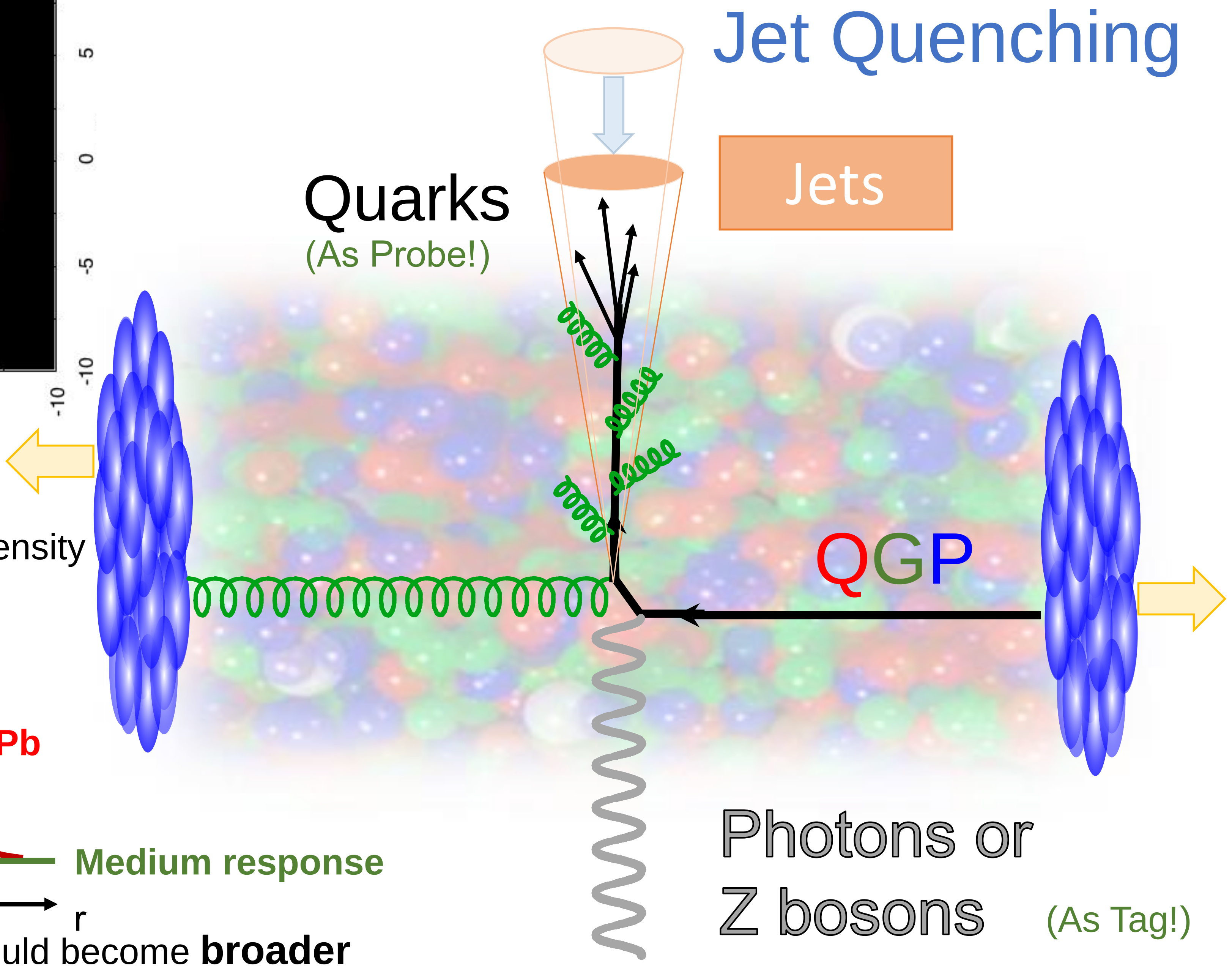
Probes Produced with the QGP



Jet direction

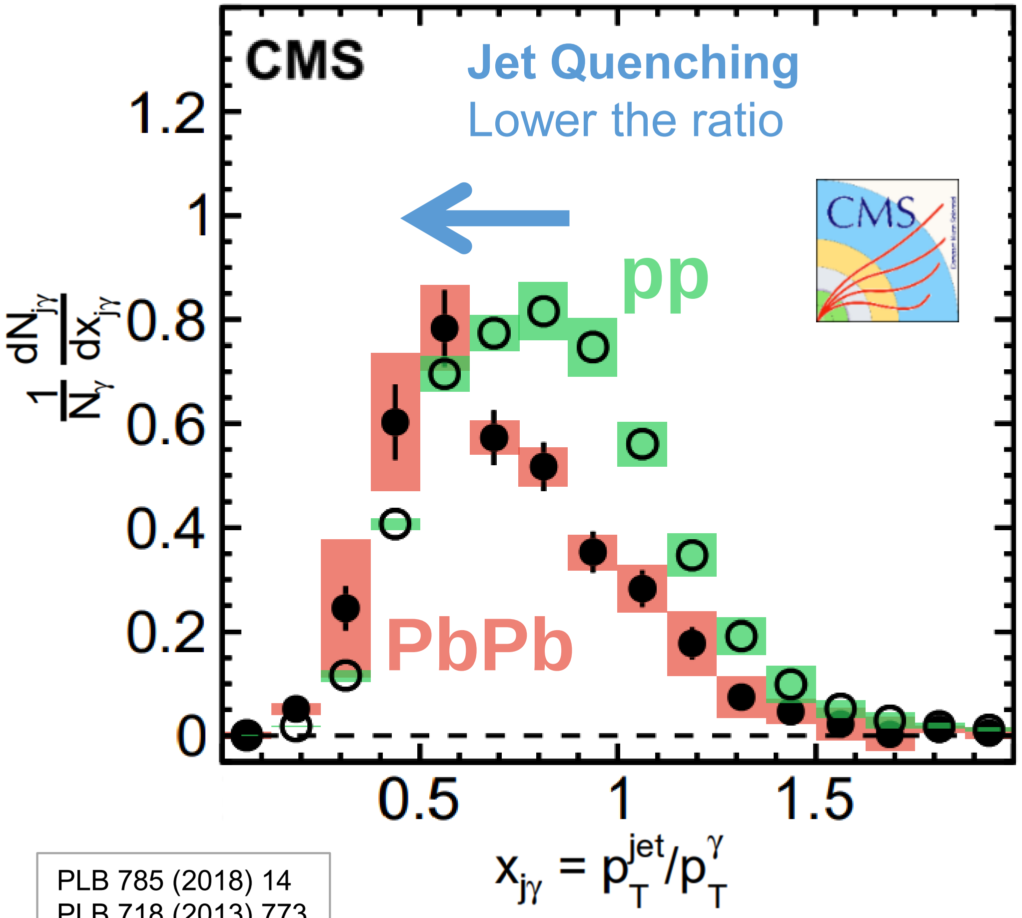


Quark jets in PbPb could become **broader**

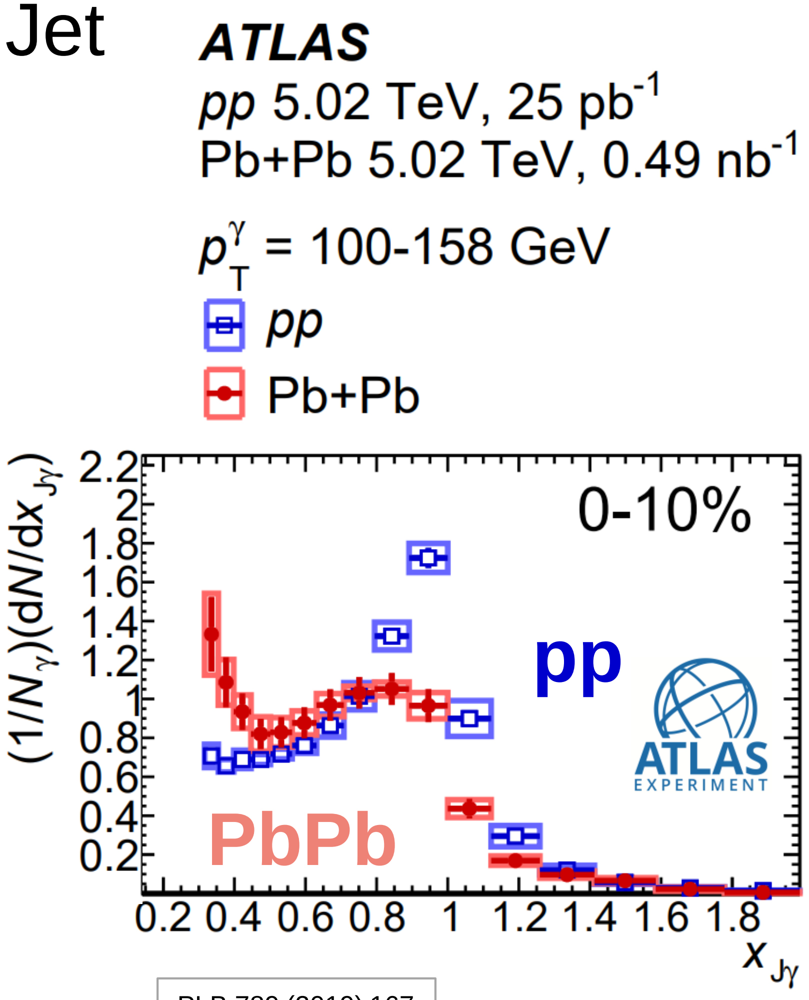


Transverse Momentum Ratio of Quark-enriched Jet and Boson

Photon + Jet

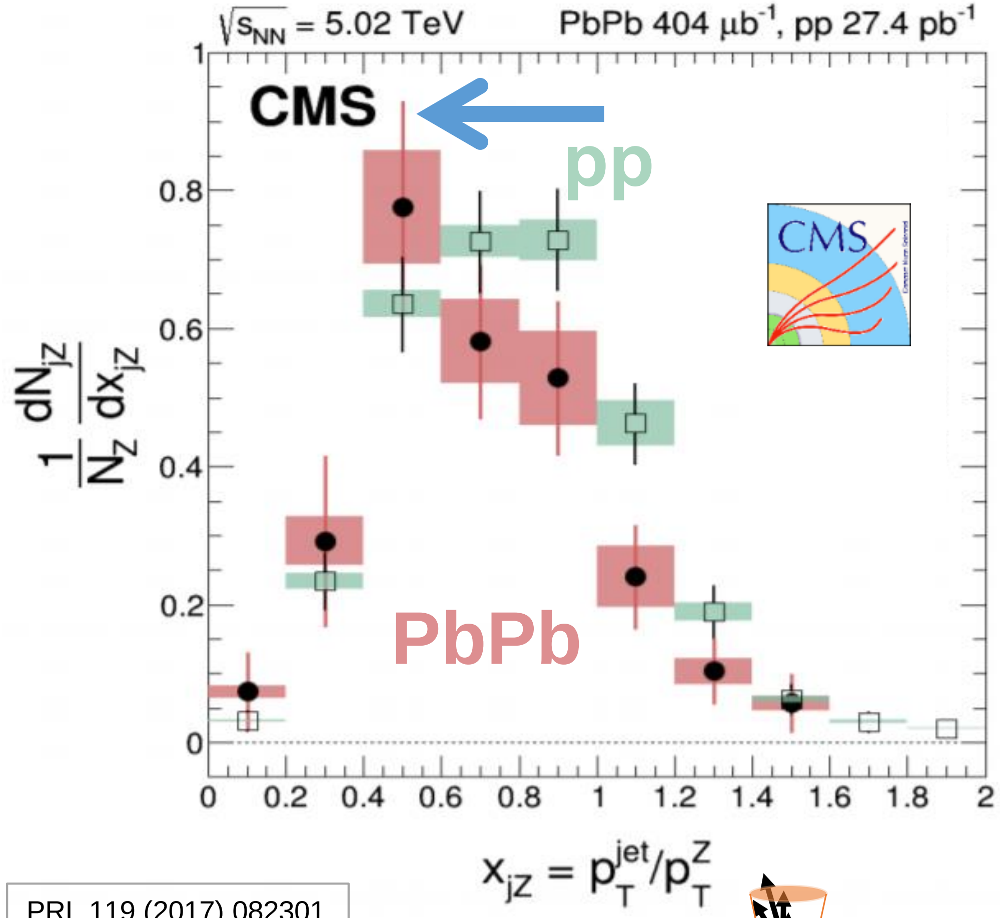


PLB 785 (2018) 14
PLB 718 (2013) 773

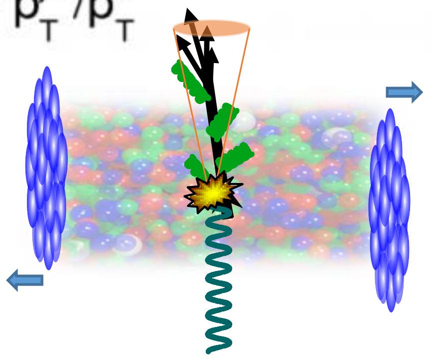


PLB 789 (2019) 167

Z^0 boson + Jet



PRL 119 (2017) 082301

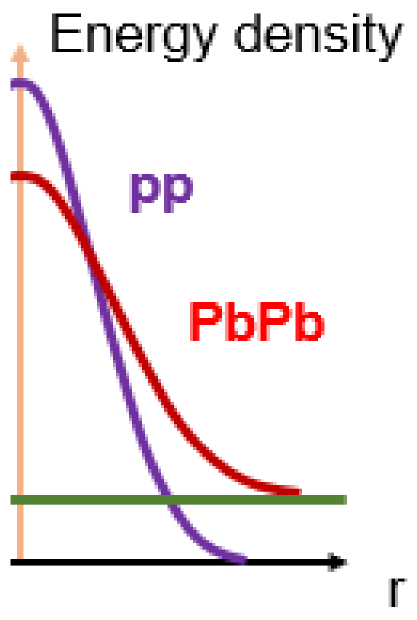


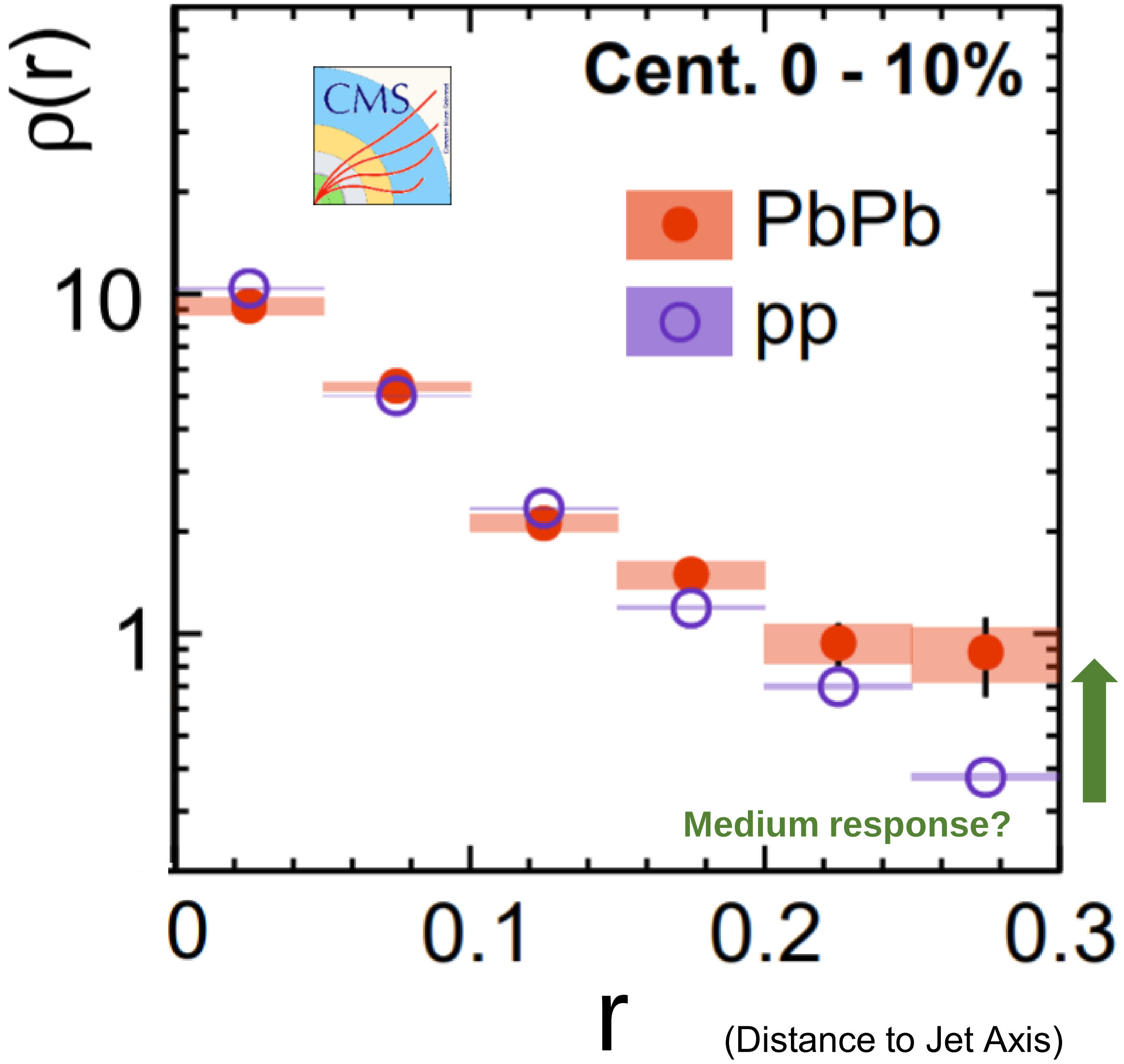
- Initial transverse momentum ~ 0
- Photons and Z bosons are not affected by QGP
  → **Quark-enriched jet (70% quark) to boson momentum ratio lowered**

Quark Jet Shape and Fragmentation Modification

PRL 122 (2019) 152001

Radial Shape



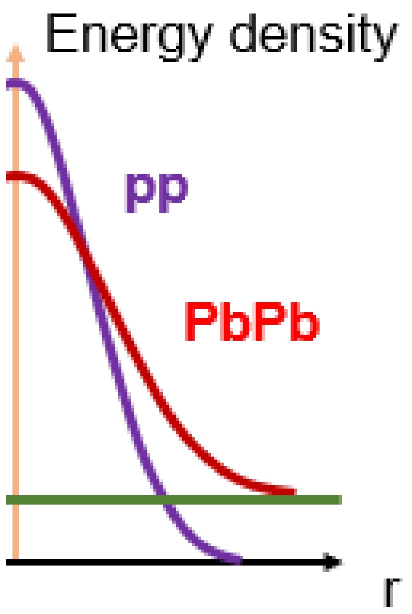


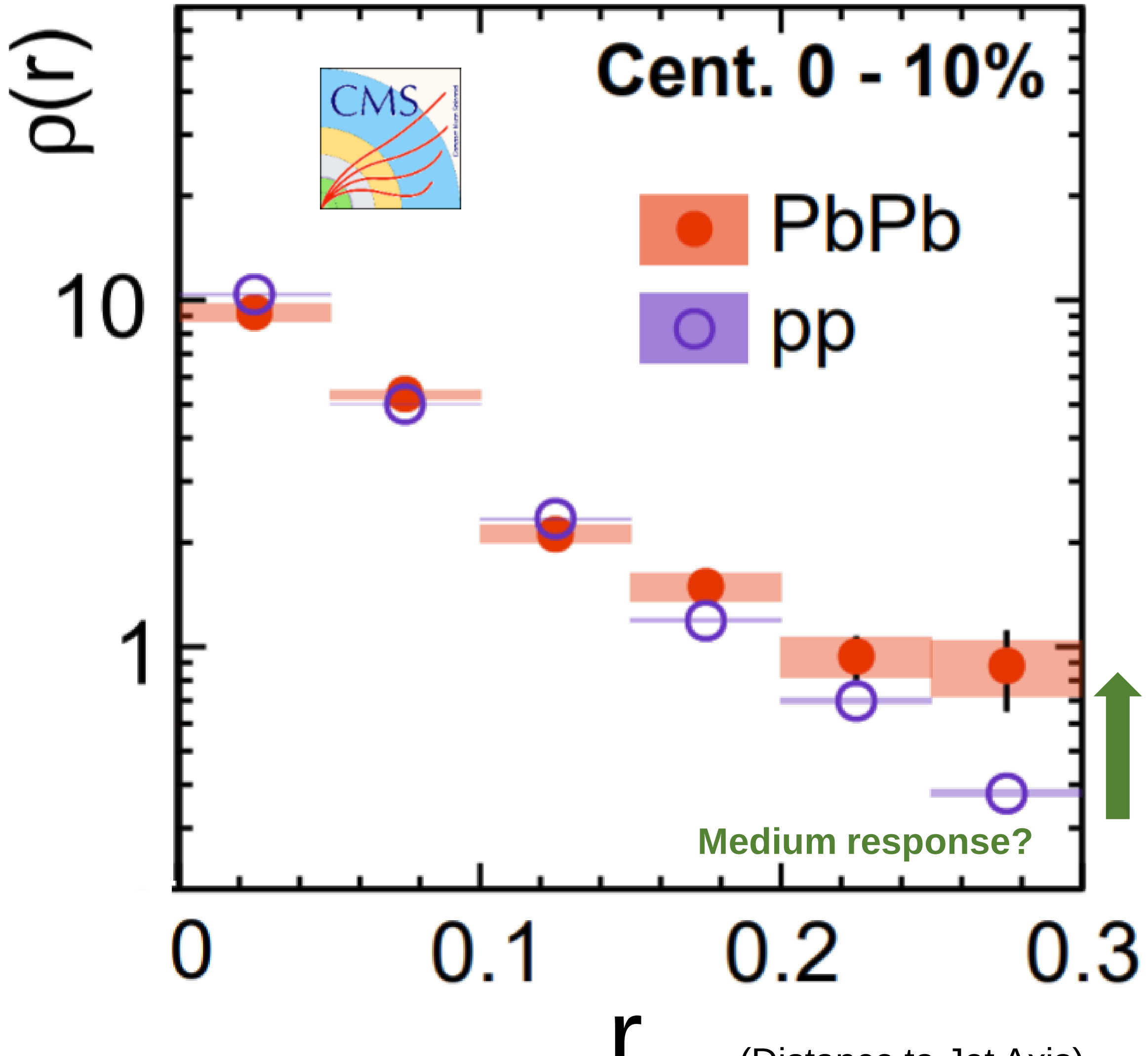
- **Broadening** of the quark-enriched jets

Quark Jet Shape and Fragmentation Modification

PRL 122 (2019) 152001

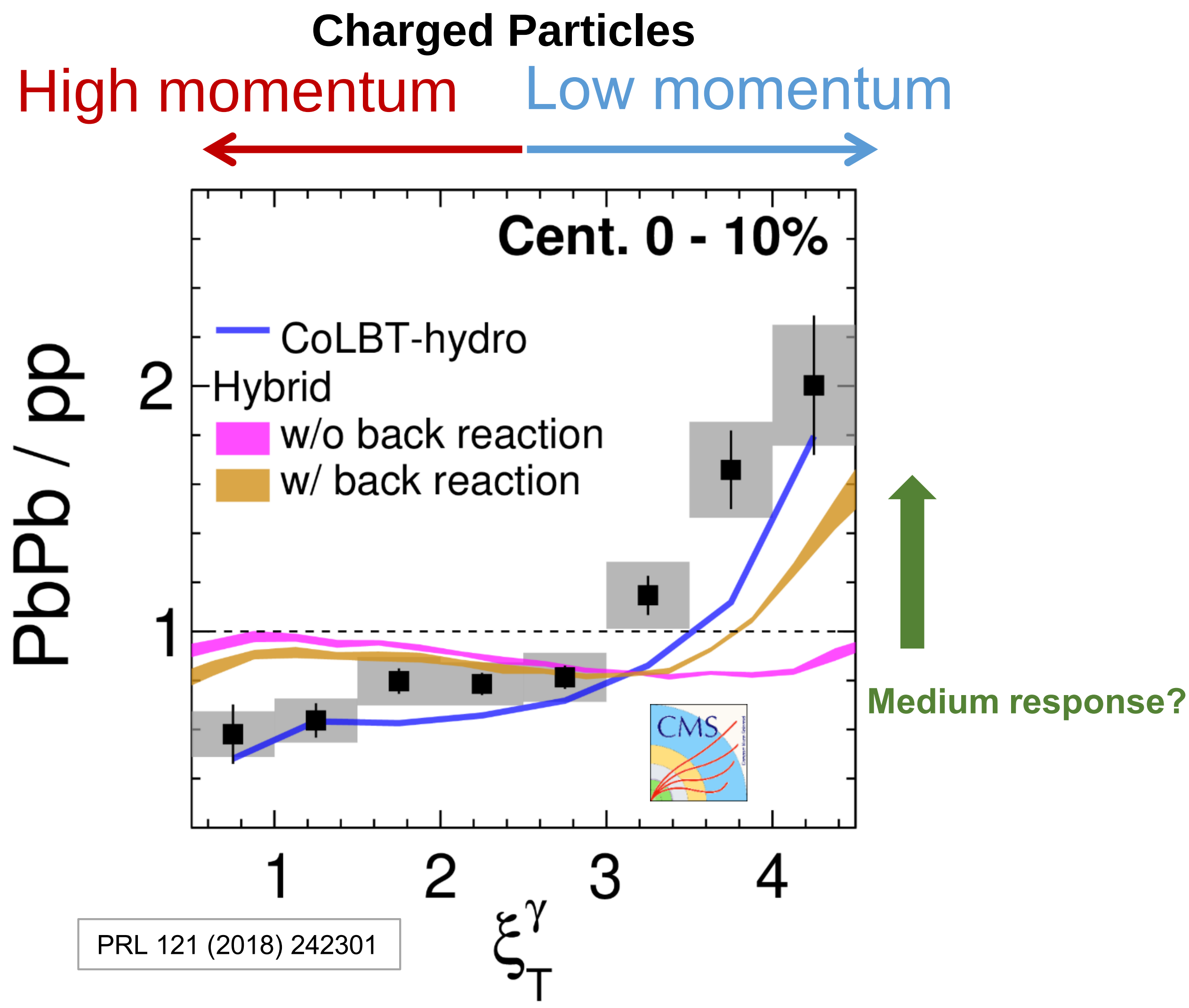
Radial Shape





(Distance to Jet Axis)

Constituent Momentum Spectrum



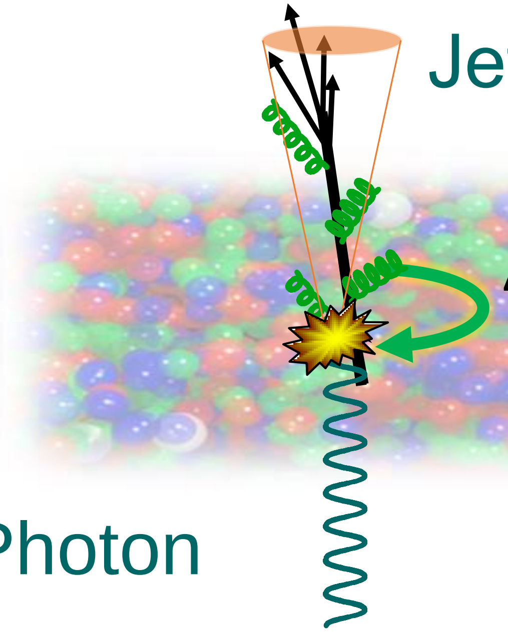
PRL 121 (2018) 242301

$$\xi_T^\gamma = \ln\left[-|\vec{p}_T^{\,\gamma}|^2 / (\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,\gamma})\right]$$

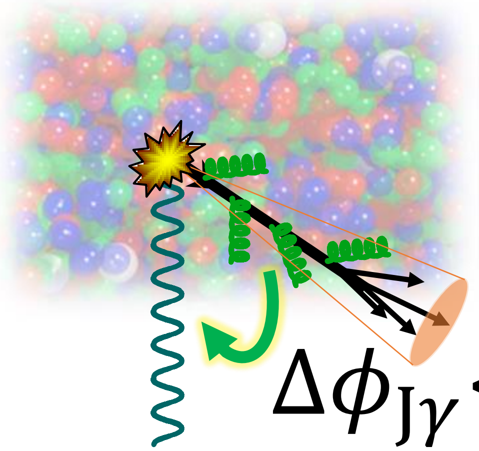
- **Broadening** of the quark-enriched jets, enhancement of **low momentum particles**
- Strong indication of QGP **medium response**!

Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"

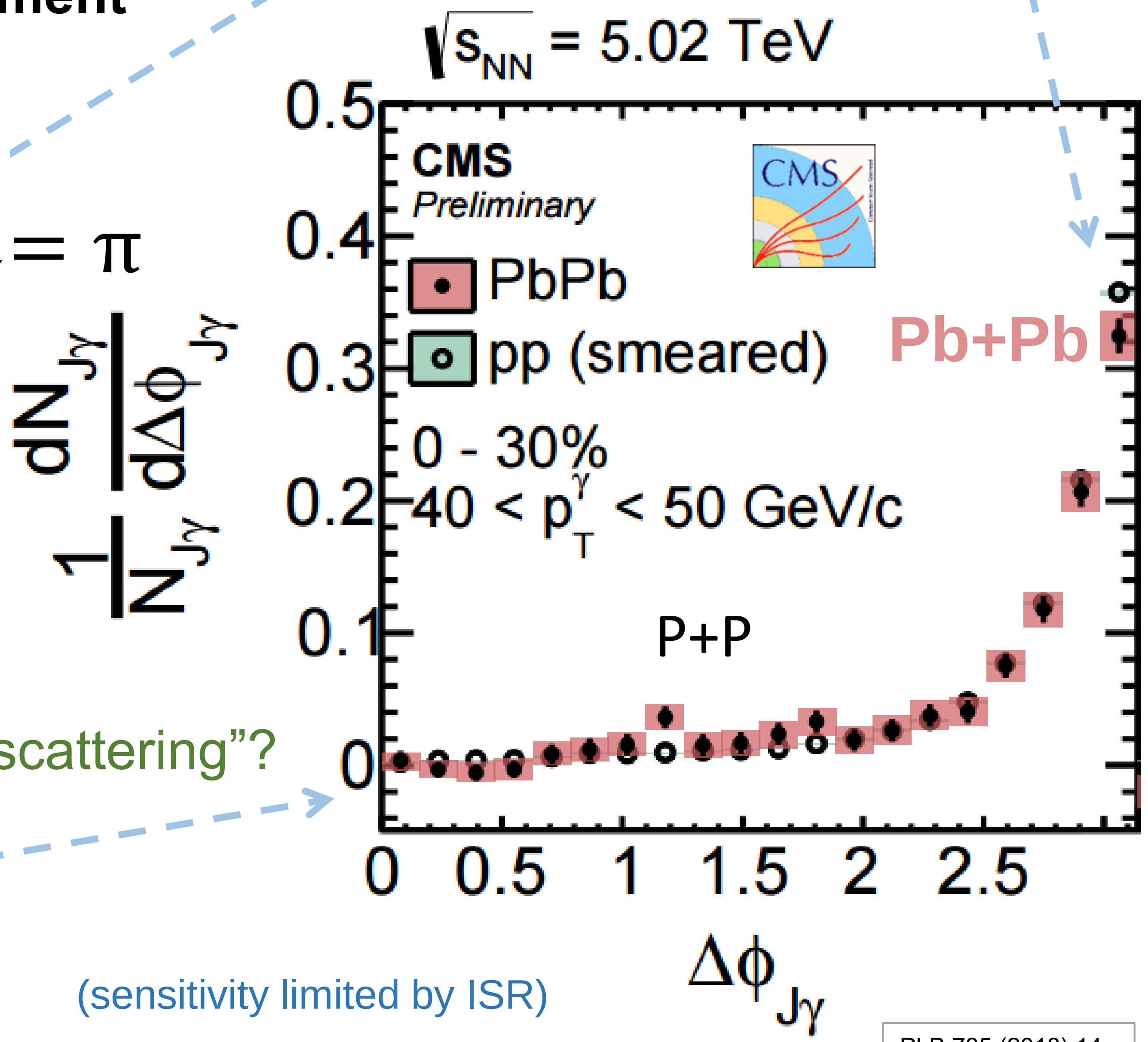


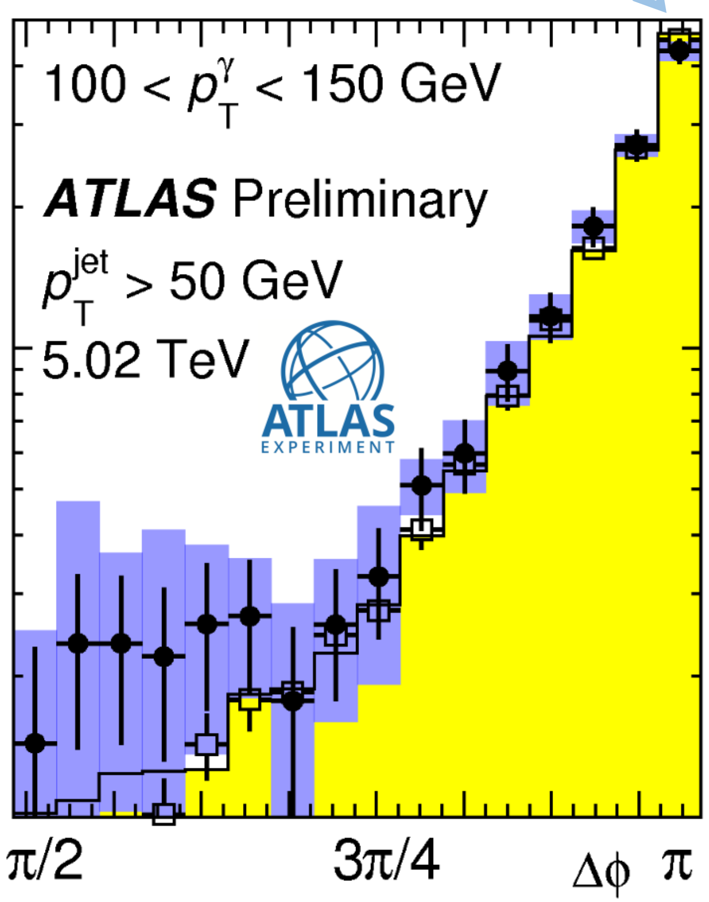
$\Delta\phi_{J\gamma} = \pi$



$\Delta\phi_{J\gamma} < \frac{\pi}{2}$

"Backscattering"?

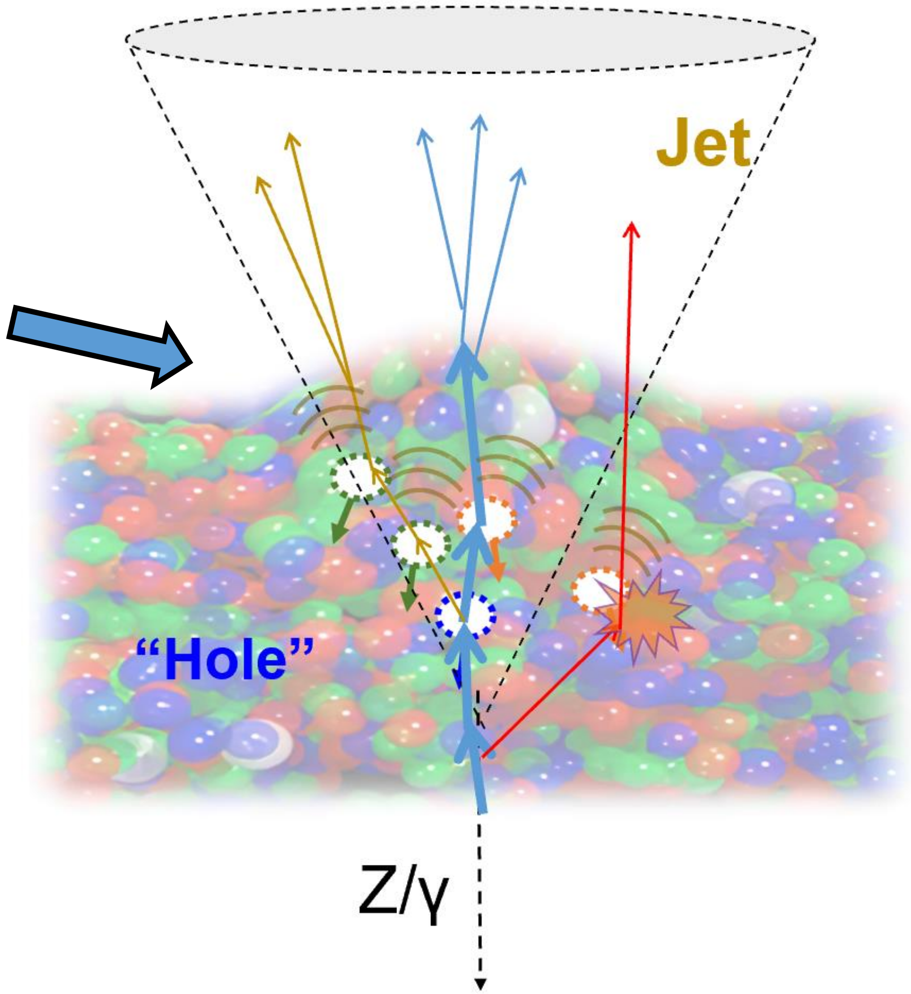


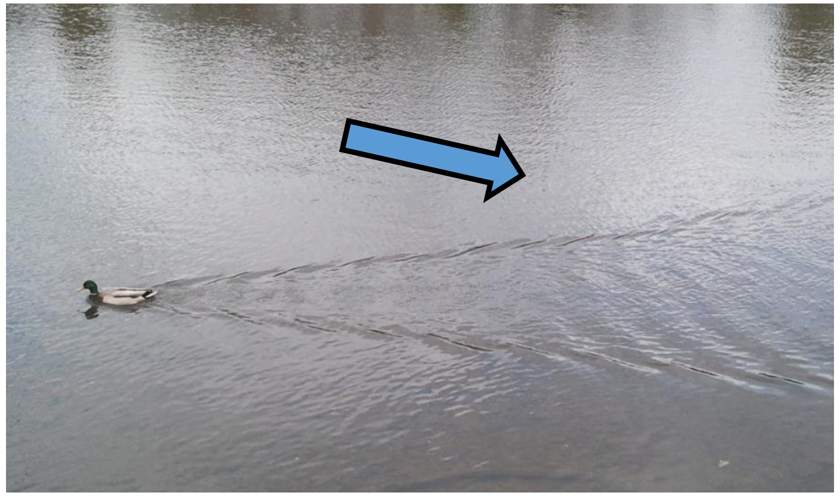


(sensitivity limited by ISR)

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

Focus on the Medium Response





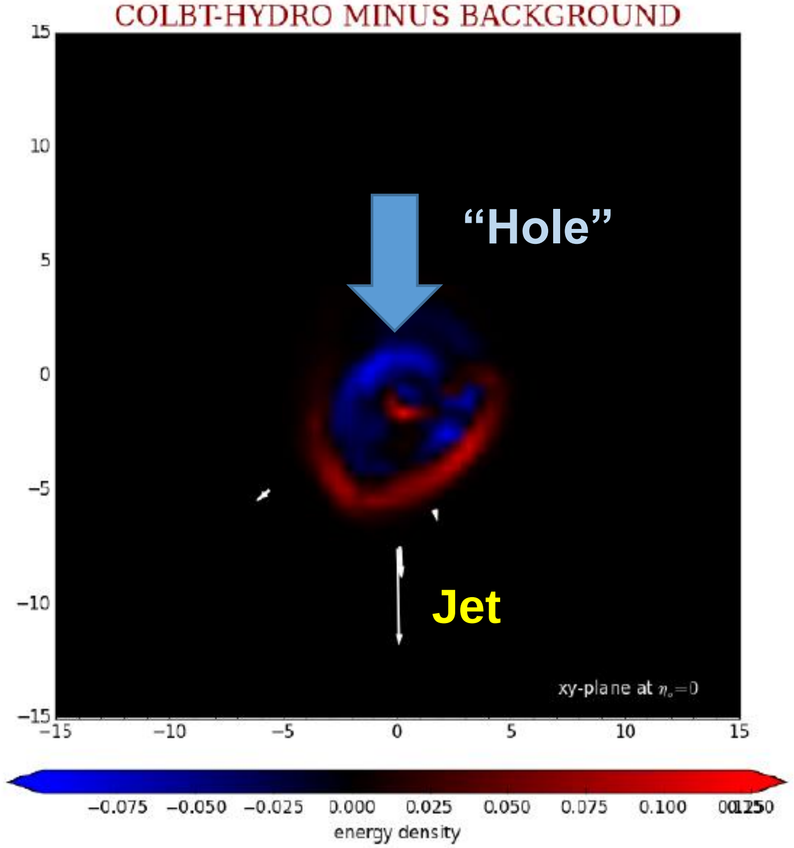
Have we observed the medium response to hard probes?

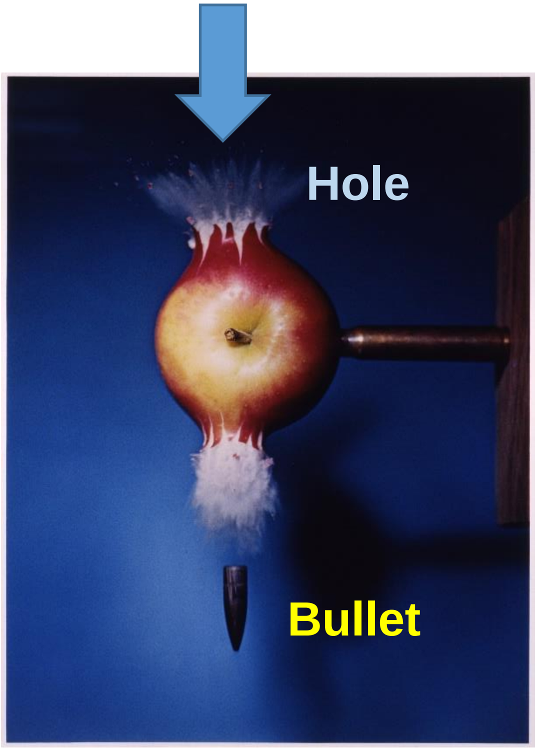
Measure the **boson-side associated yield** with photon-jet and **Z-jet**

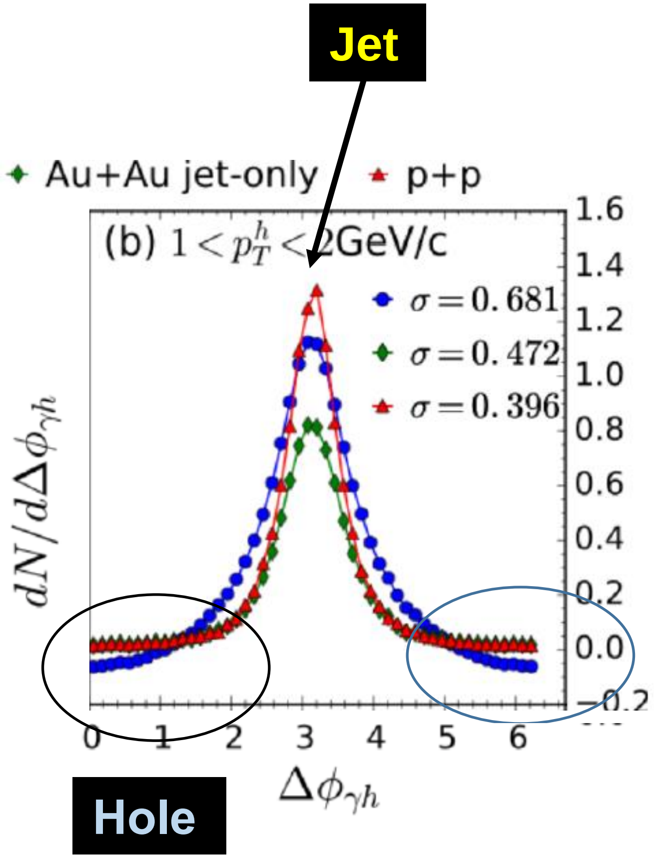
Measure the "Depletion" due to Medium Recoil

CoLBT

Tan Luo, Xin-Nian Wang

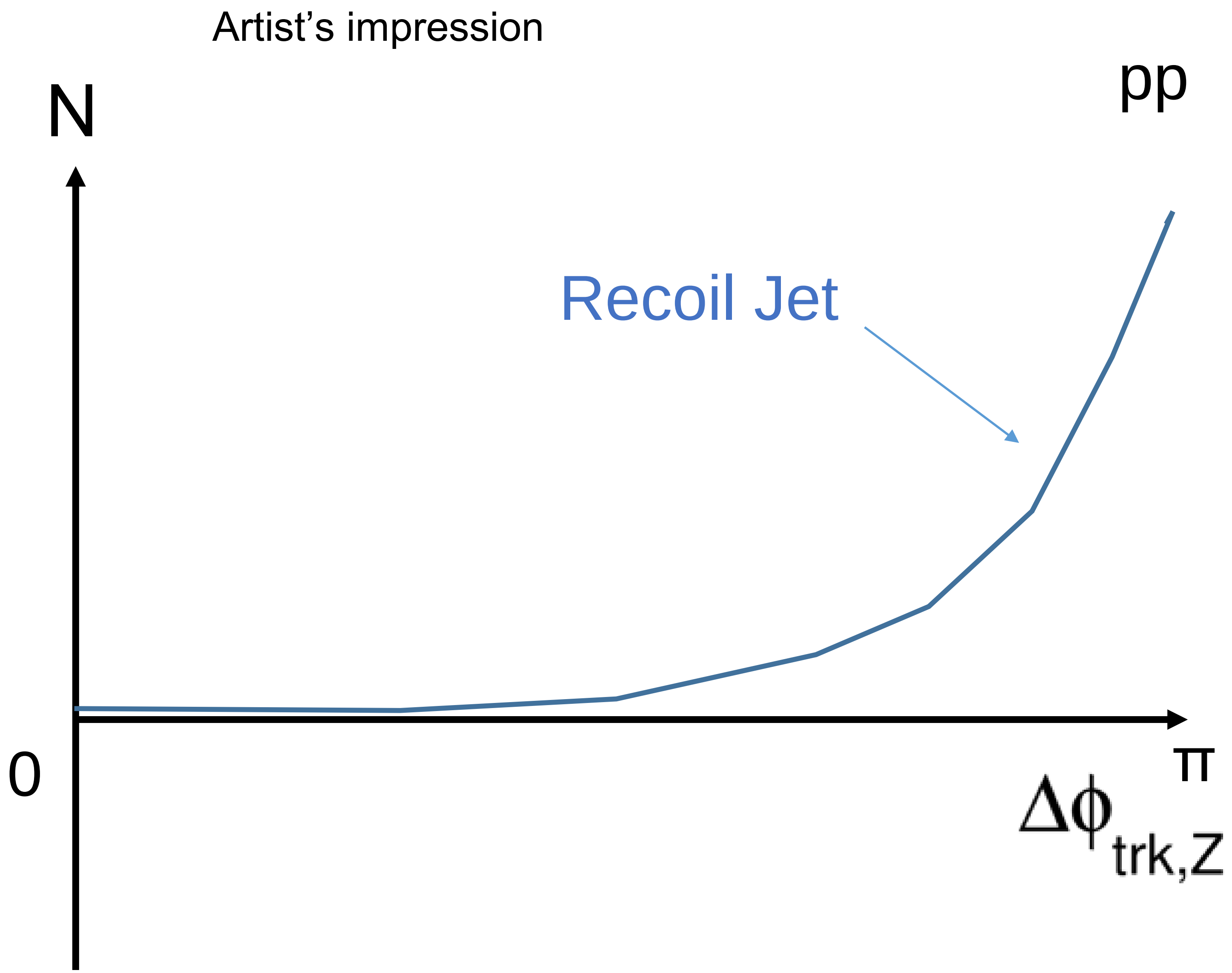


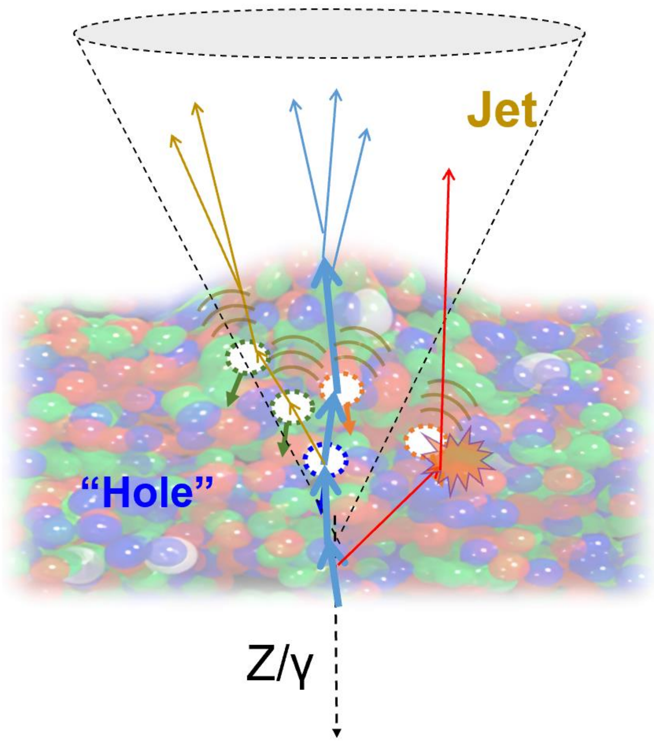




Measure the **boson-side associated yield** with photon-jet and **Z-jet**

Measure the “Depletion” with Z-hadron Correlation

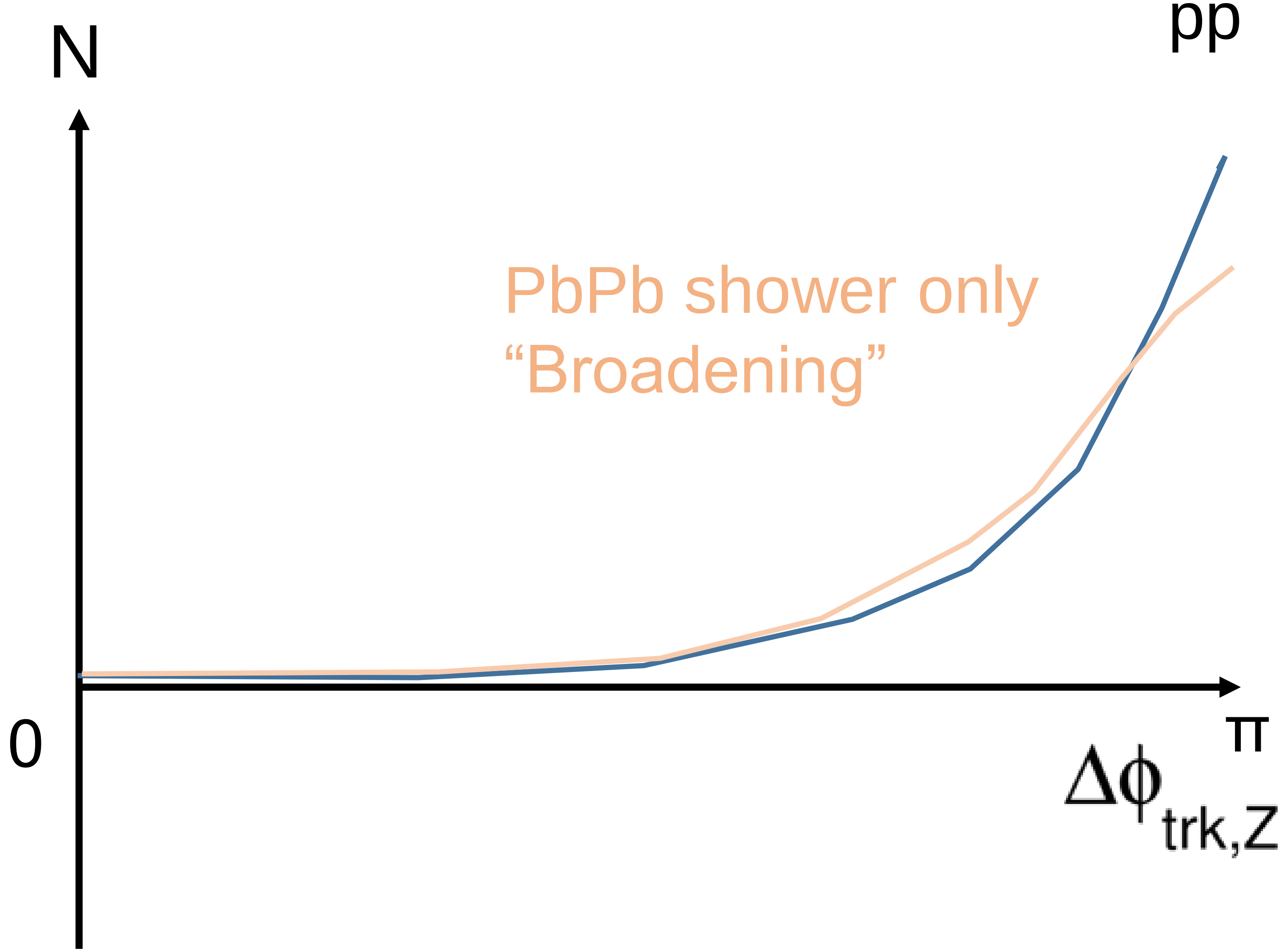


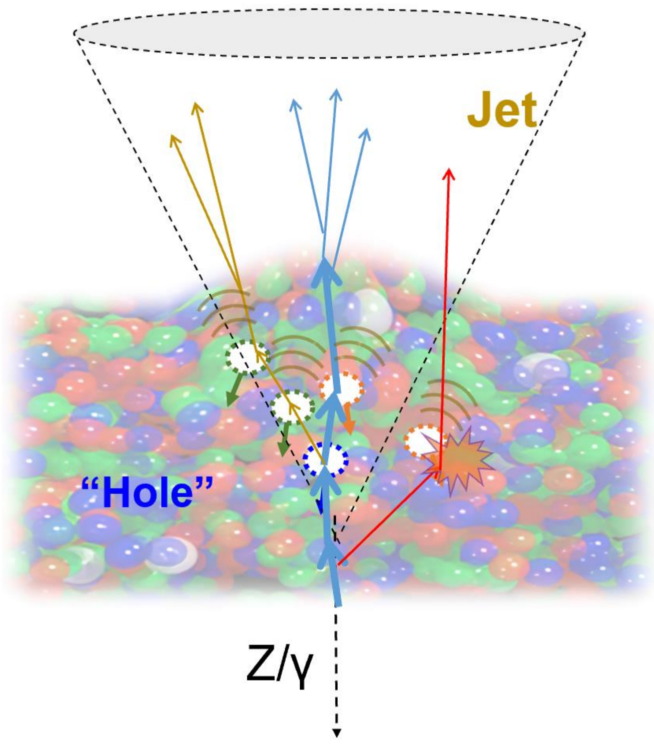


Measure the **boson-side associated yield** with photon-jet and Z-jet

Measure the “Depletion” with Z-hadron Correlation

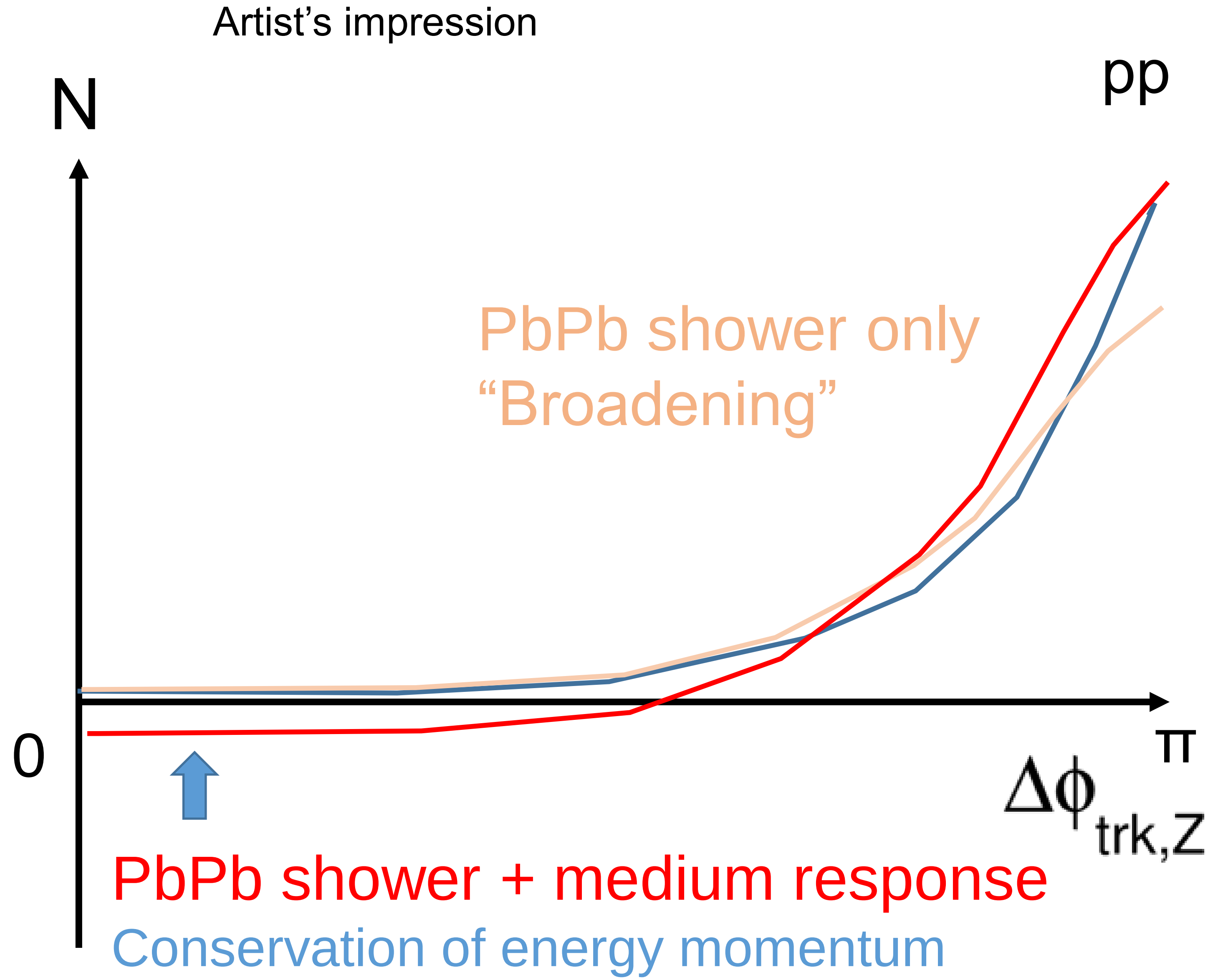
Artist’s impression

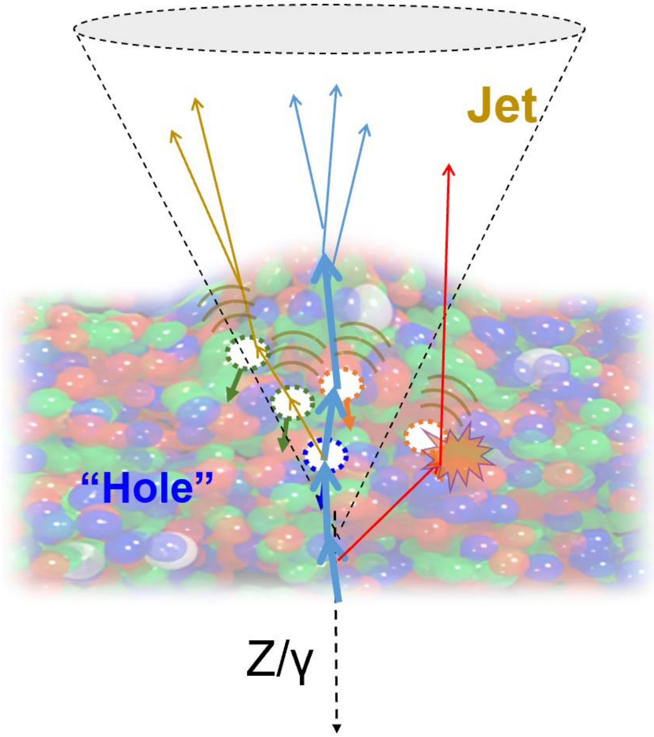




Measure the **boson-side associated yield** with photon-jet and Z-jet

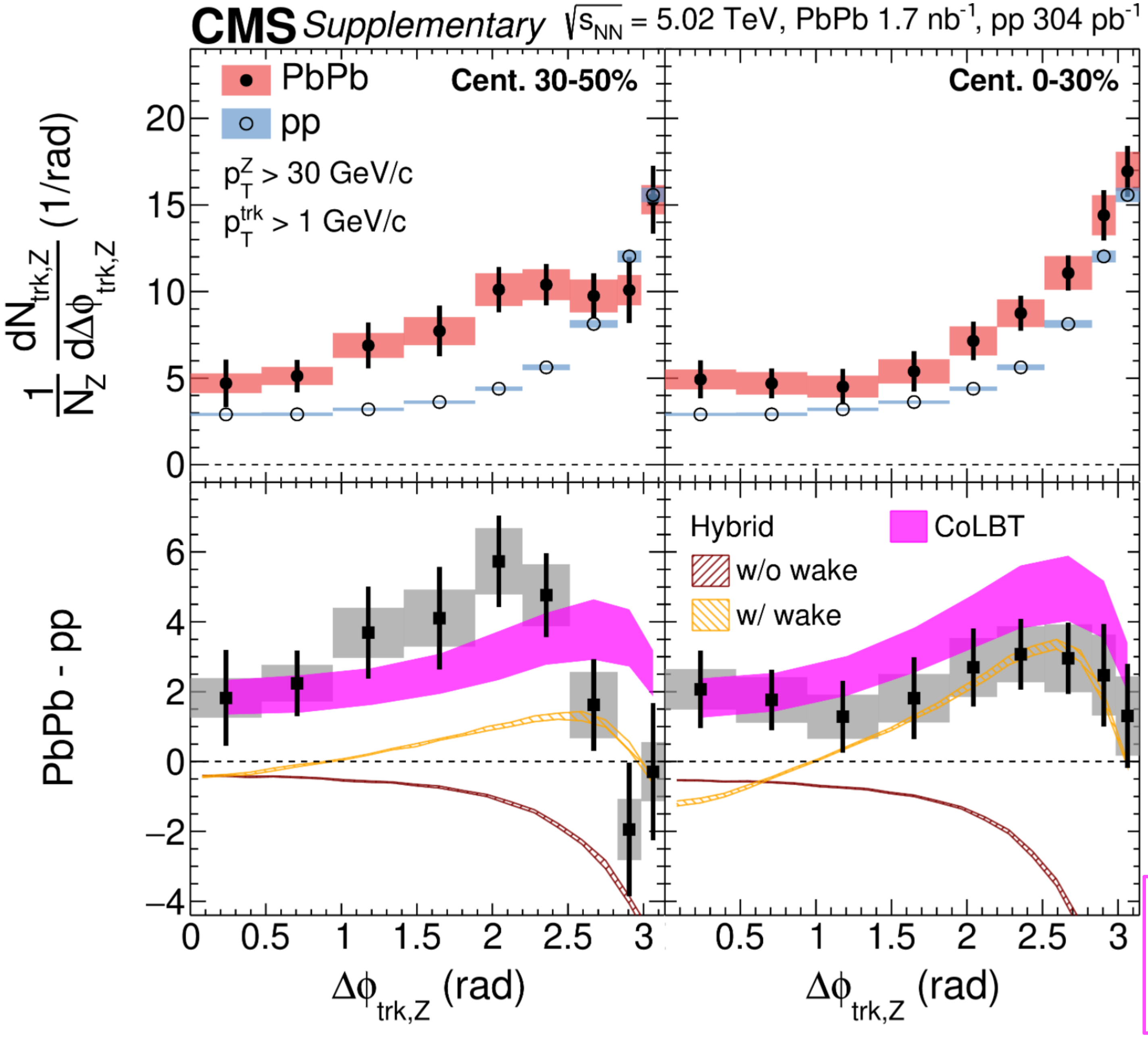
Measure the “Depletion” with Z-hadron Correlation



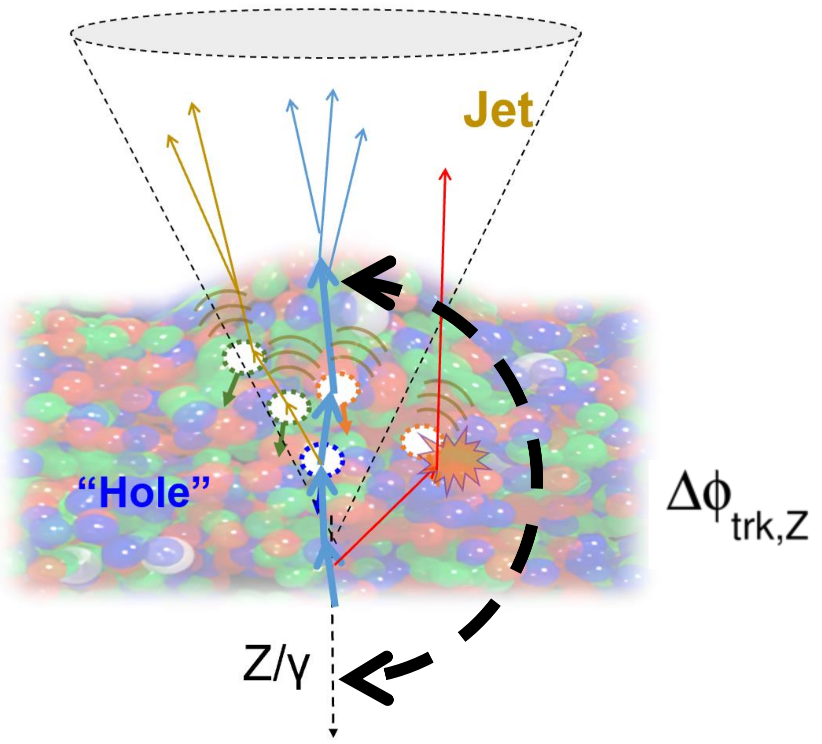


Measure the **boson-side associated yield** with photon-jet and Z-jet

Z-hadron Δφ in PbPb at 5.02 TeV



Phys. Rev. Lett. 128 (2022) 122301

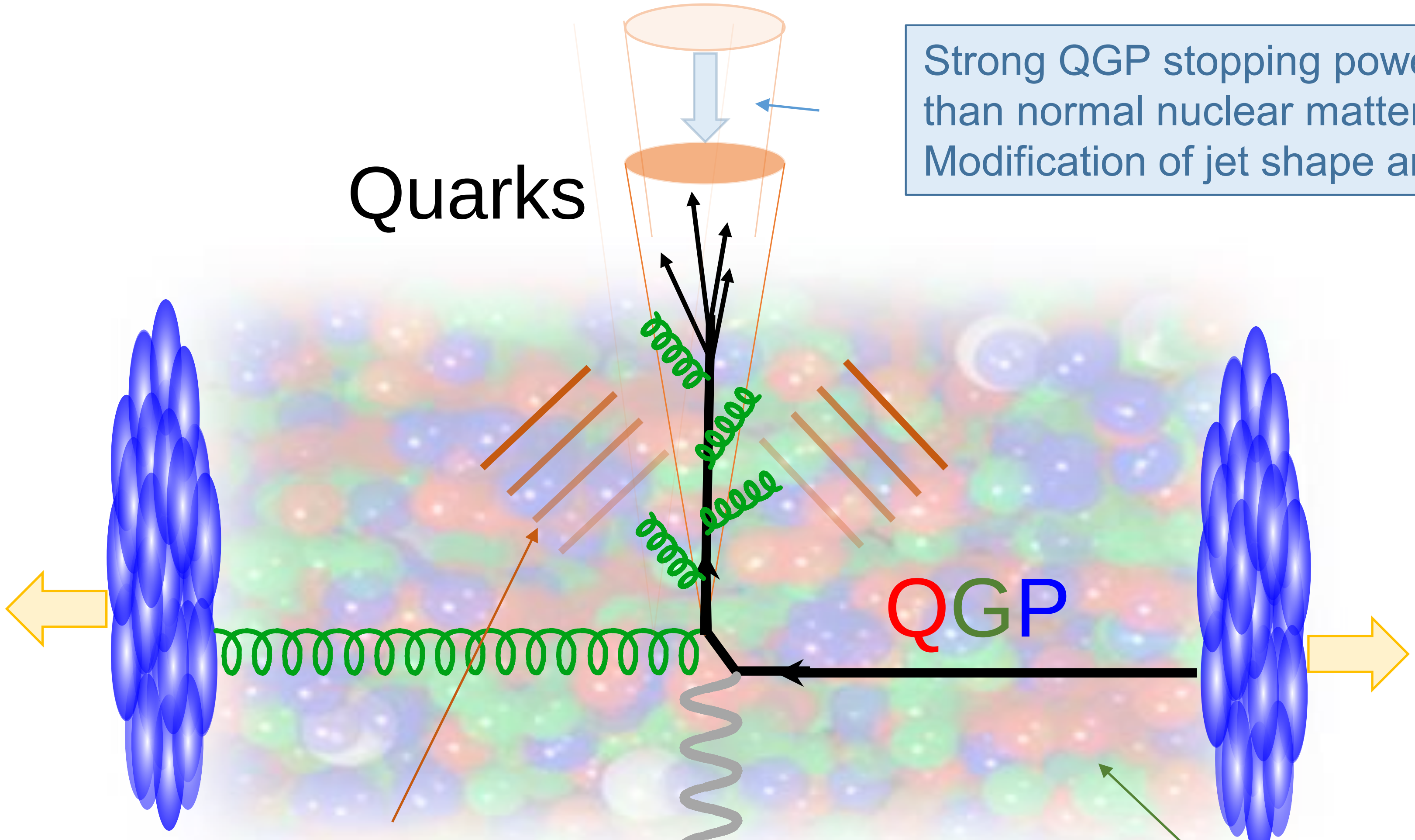


CoLBT:

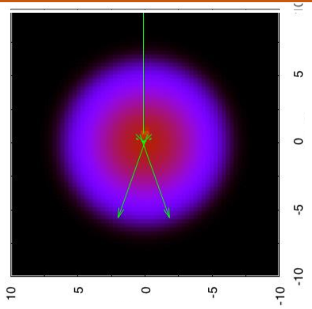
- Good agreement with PbPb data in 30-50%.
- However, MPI jet quenching contributed to small Δφ excess!
- Need to follow up with improved analysis and high statistics data

Lessons from Jet Spectra and Structure

Strong QGP stopping power; O(10x) larger than normal nuclear matter
Modification of jet shape and fragmentation

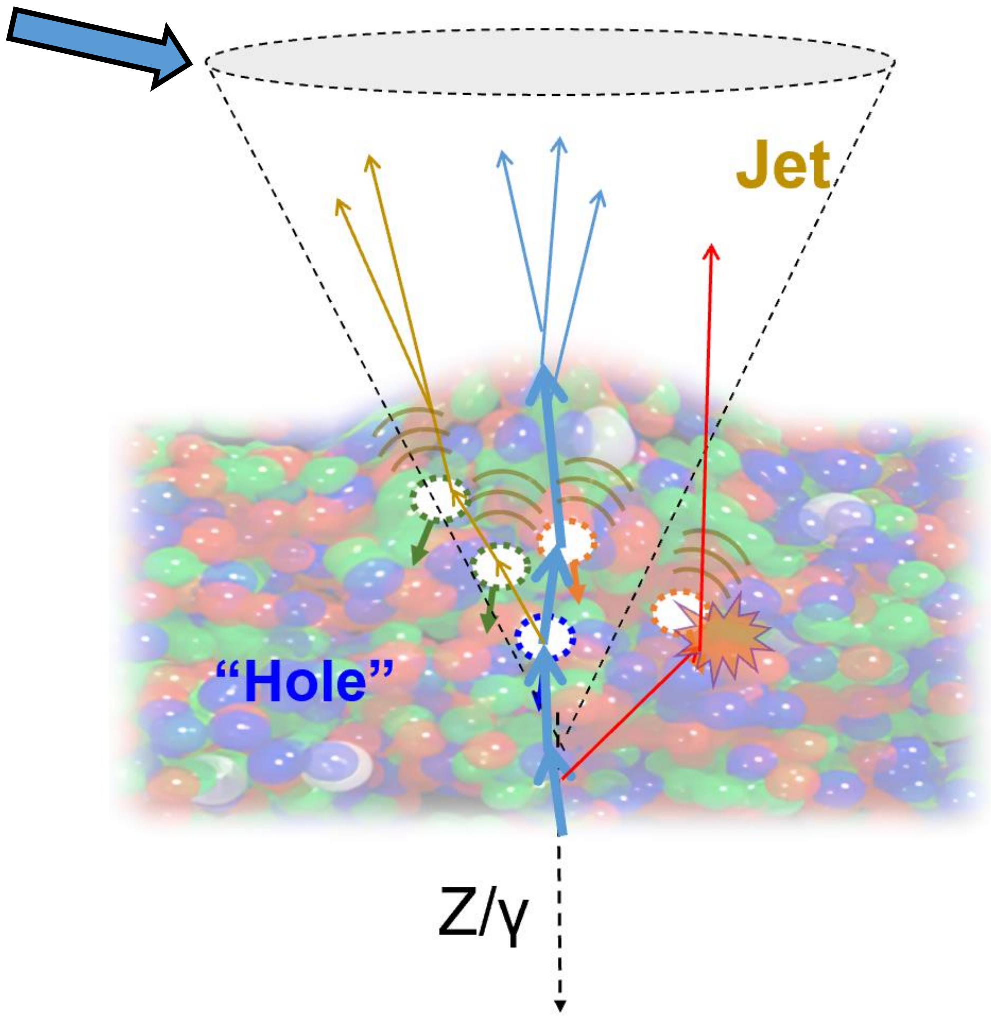


Indication of **medium recoil and QGP wake**



No sign of backscattering effect

Focus on the Hardest Substructure



Does the magnitude of quenching depend on the structure of parton shower?
Shower shape dependence of energy loss!

Charged Jet $p_T D$ (Dispersion) and Jet Girth

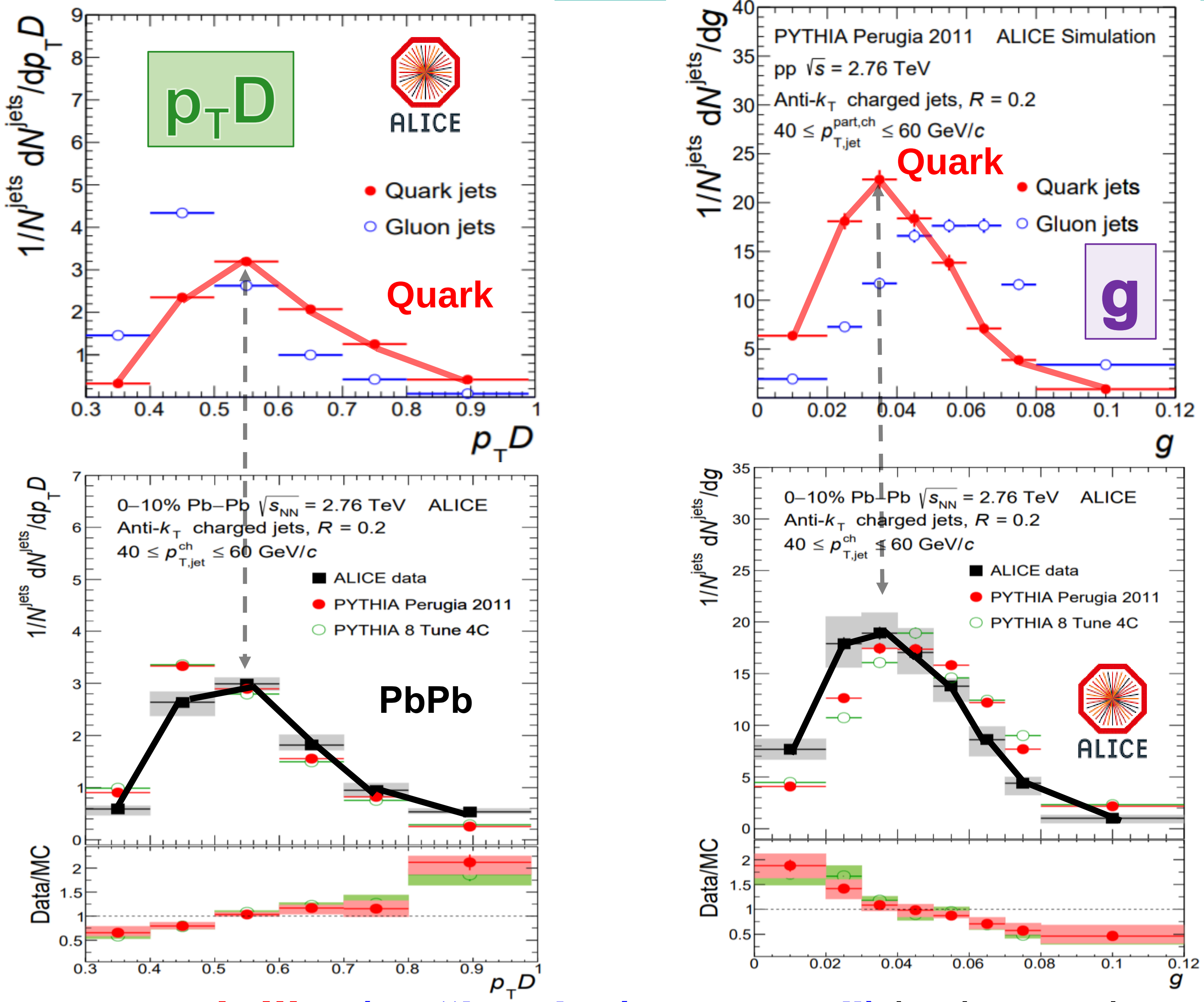
JHEP 10 (2018) 13

ALICE Simulation

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

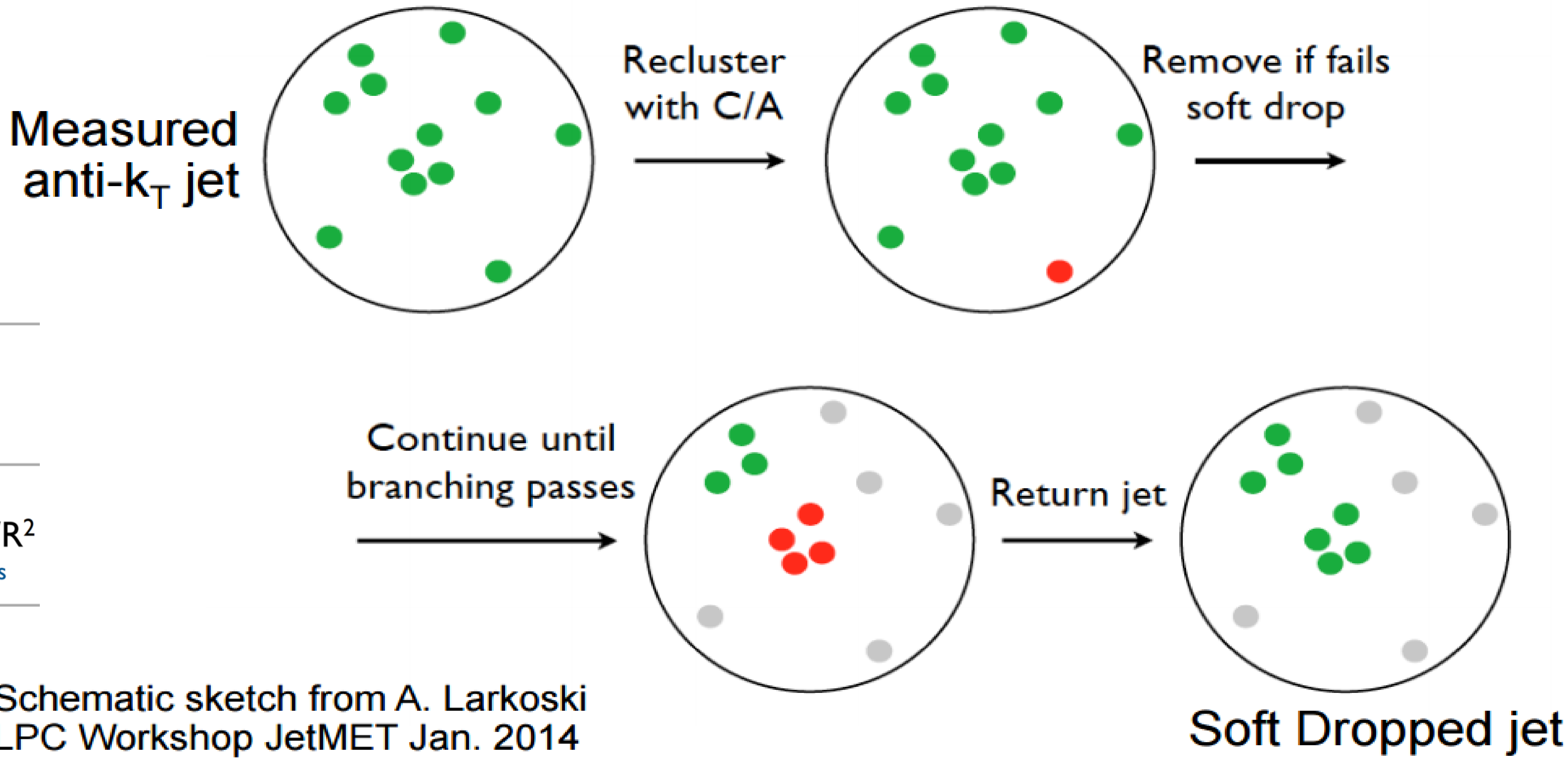
$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|$$

ALICE Data



- Charged jets in PbPb are more **Quark-like** **(or "harder/narrower")** in those observables

Isolate the Jet Core: Jet Grooming



Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

Jet algorithms

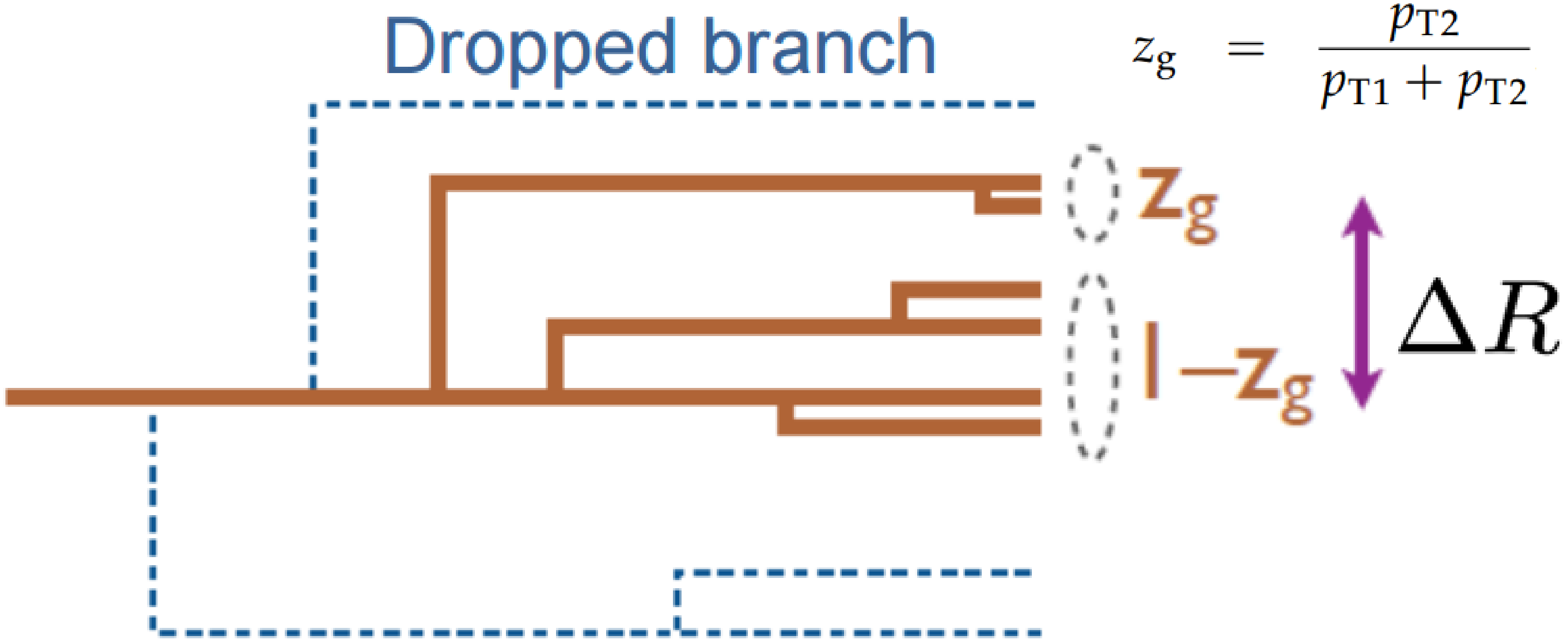
Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets

$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^\beta$$

Andrew Larkoski, et al
JHEP 1405 (2014) 1465

Jet Grooming with Soft Drop

Anti-k_T jet is re-clustered with Cambridge/Aachen (CA)
Then decluster the angular-ordered CA tree
Drop soft branches



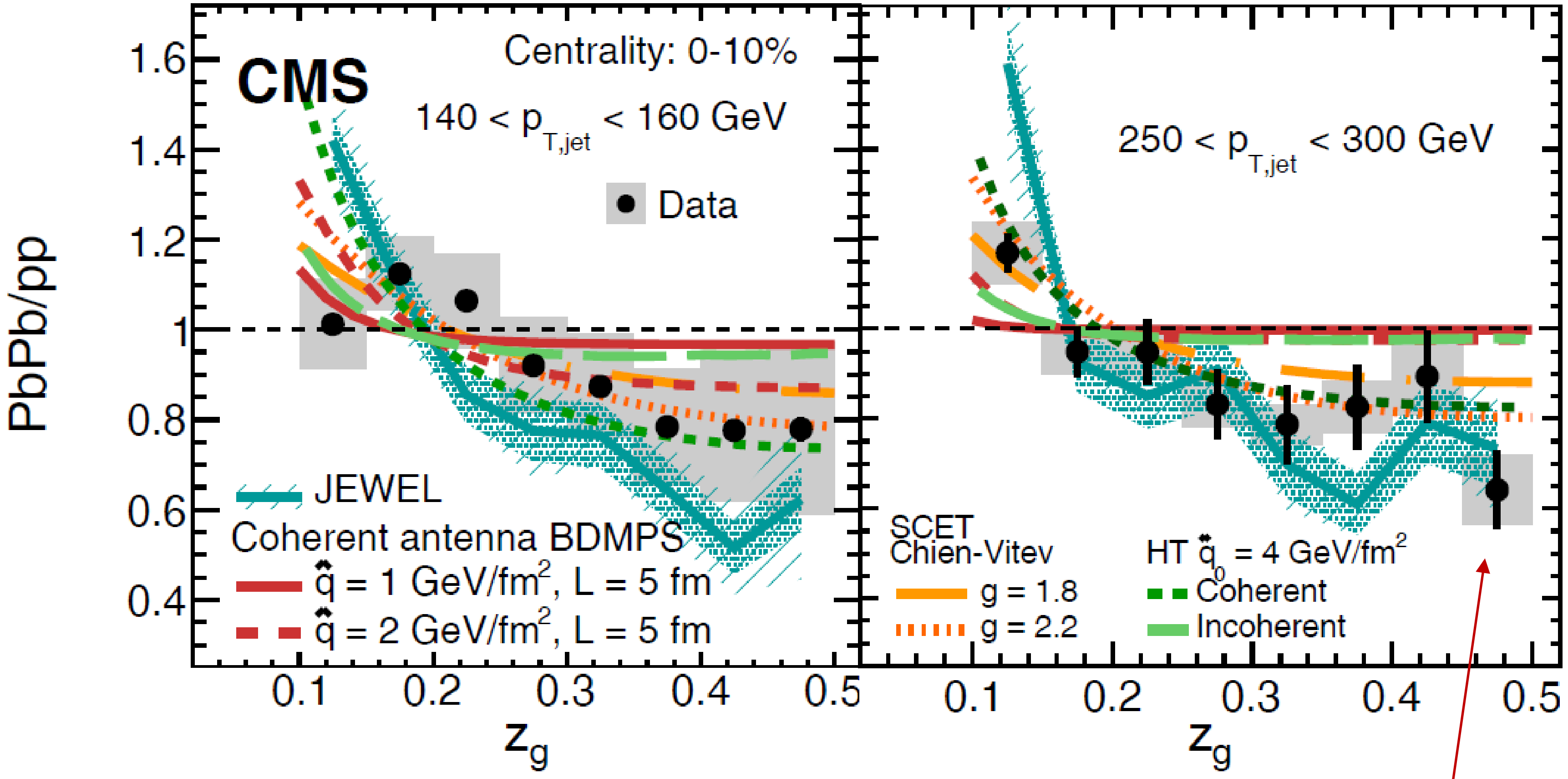
$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

Reminder of jet algorithms

Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets

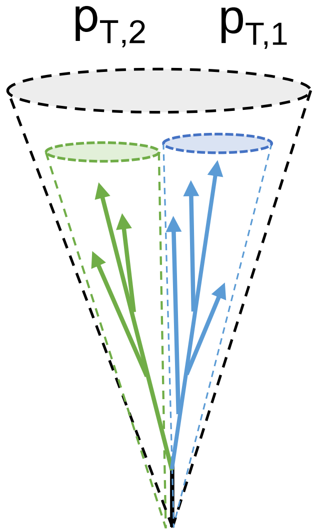
Andrew Larkoski, et al
JHEP 1405 (2014) 1465

Momentum Sharing of Subjets



arXiv:1708.09429
PRL 120 (2018) 142302
PRL Synopsis

$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2}$$



Two hard subjets
$Z_g \sim 0.5$

Quark and gluon Z_g distributions are very similar in pp

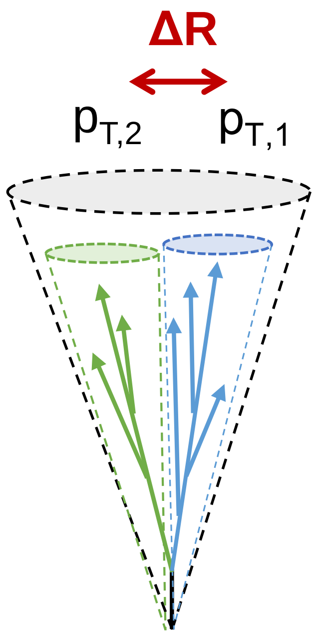
Jets with **two hard subjets** (large Z_g) **“relatively”** more suppressed!

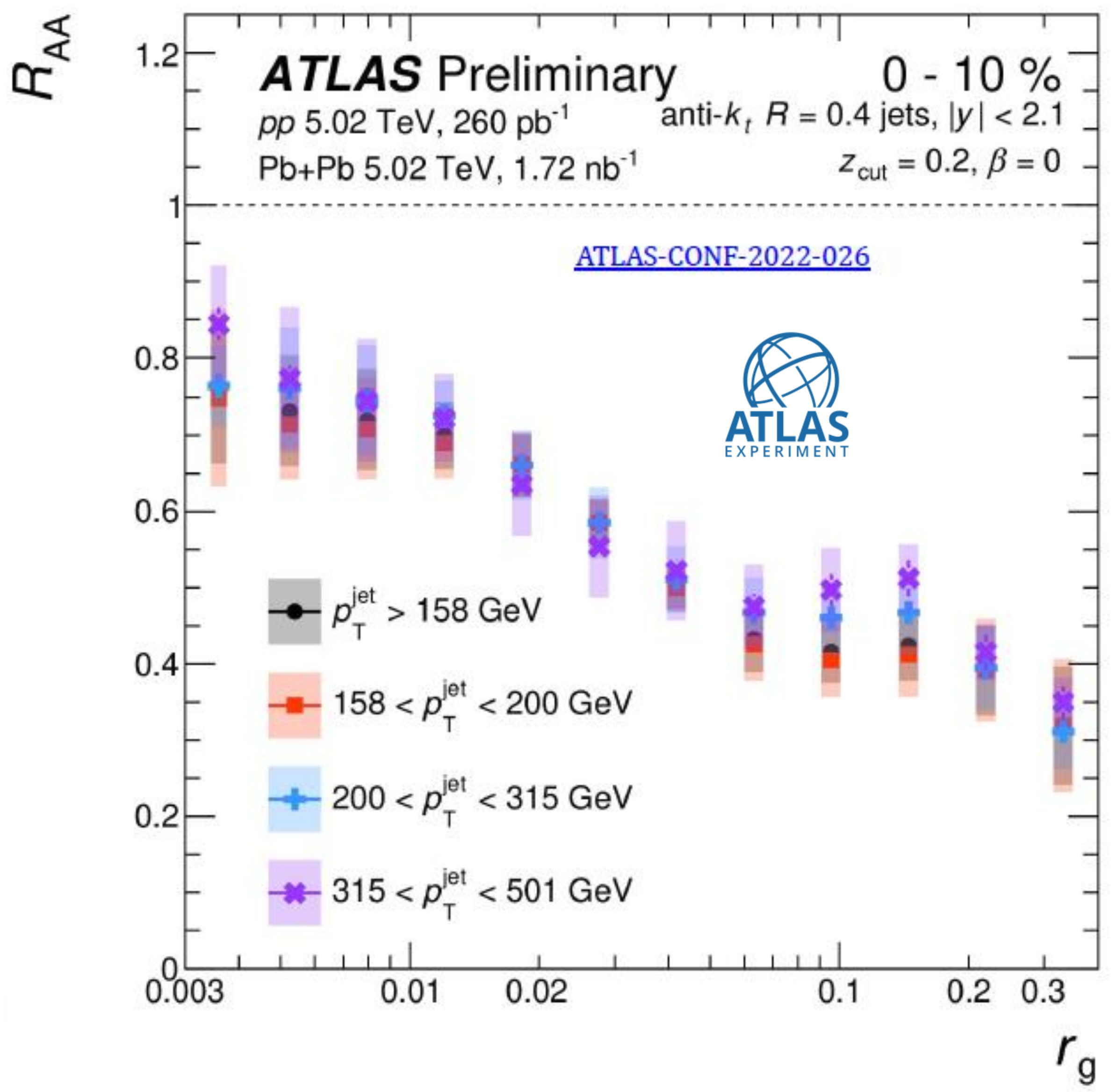
Interpretation:

- **JEWEL**: enhancement of low Z_g jets (due to **medium recoil**)
- **SCET$_G$**: modification due to medium induced splitting function
- HT & Coherent antenna BDMPS: Data prefer coherent energy loss

Groomed Subjet Opening Angles

$$\theta_g = r_g = \frac{\Delta R}{R}$$



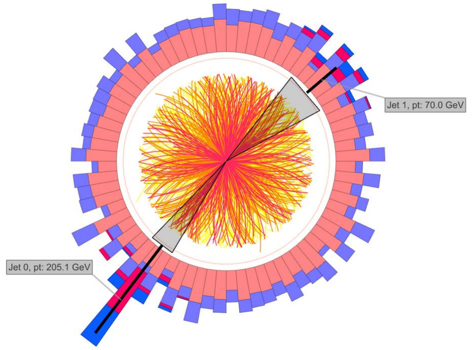


- Progress on absolute normalization:
  - First measurement of R_{AA} vs r_g
  - Jets with small r_g are less suppressed

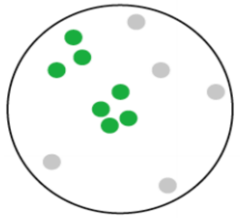
Summary: Jet-by-Jet Substructure Observables

- Inclusive jet substructure:
  - Measurement of jets that **“survived”** the jet p_T selection
  - Those jets tends to be **“harder”** than that in pp collisions
    - Harder fragmentation, narrower, smaller subjet opening angle

- Size of jet quenching **depends** on parton shower
  - In fact, this is the main reason of dijet momentum imbalance in central PbPb collisions!

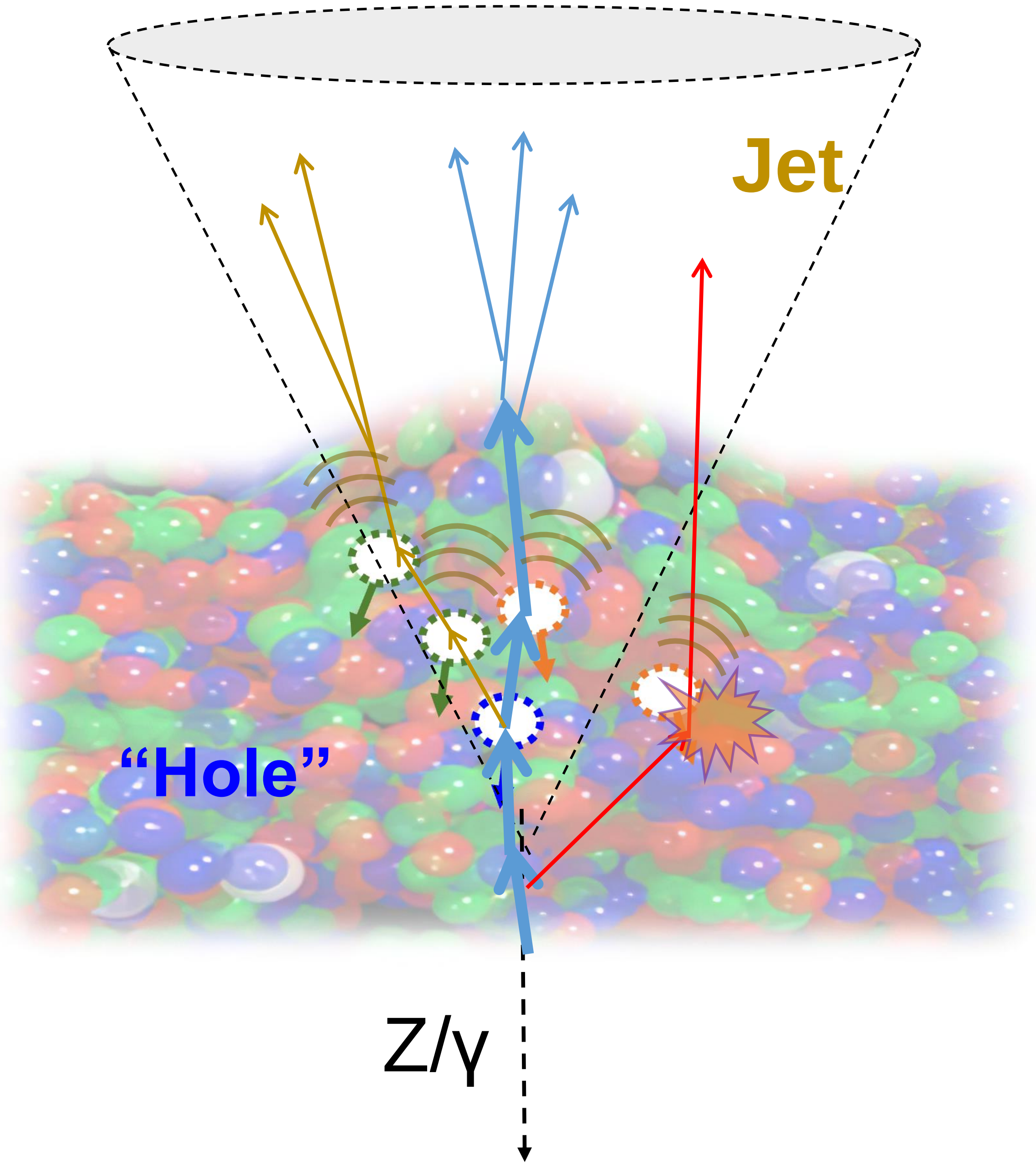


- Jet Grooming: a powerful tool for observable design



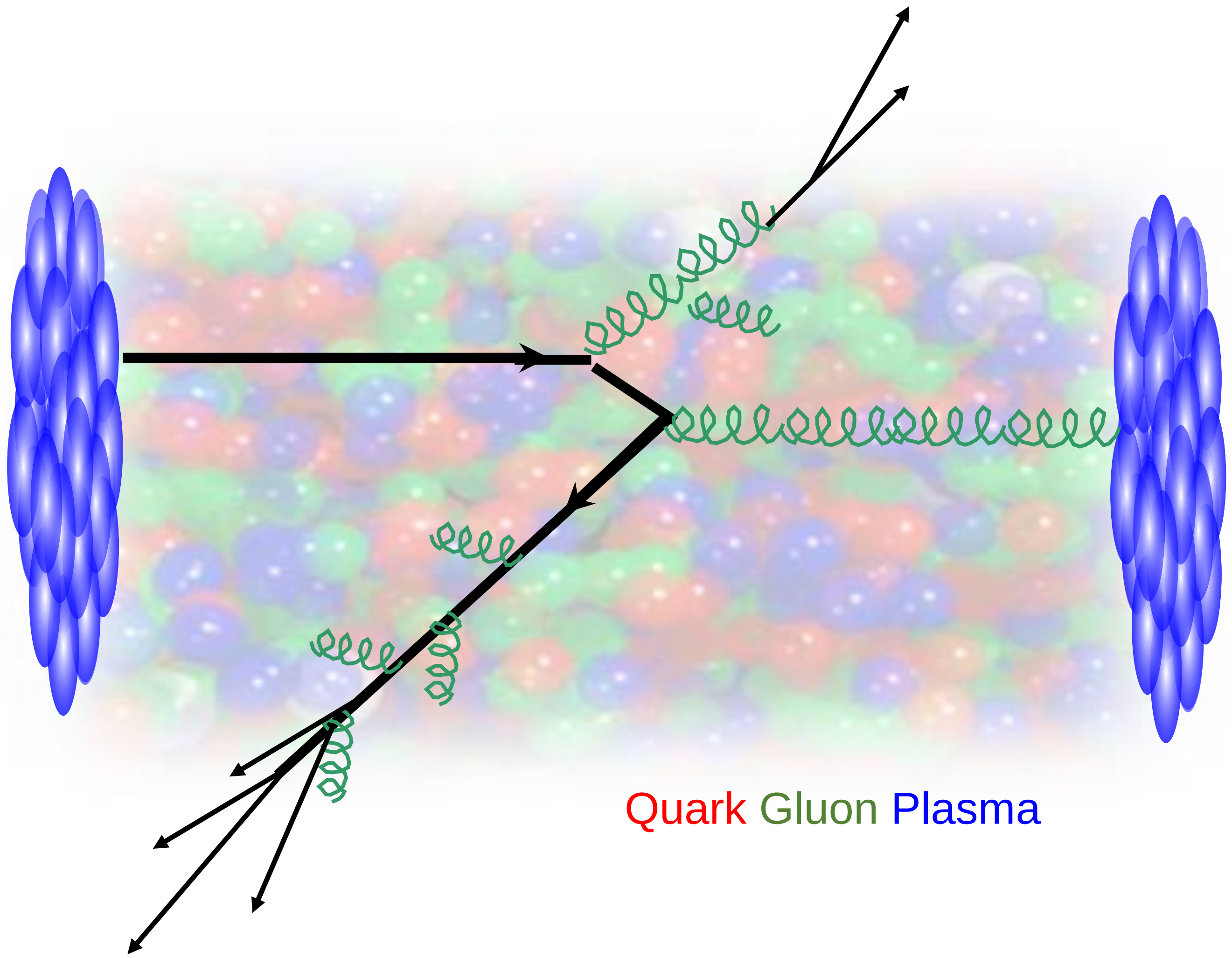
Soft Dropped jet

QGP Transport Properties and Structure with Jets



- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

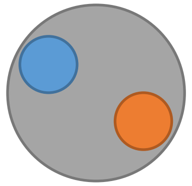
Slow-Moving Hard Probes?



Until now, we focused on the high energy partons

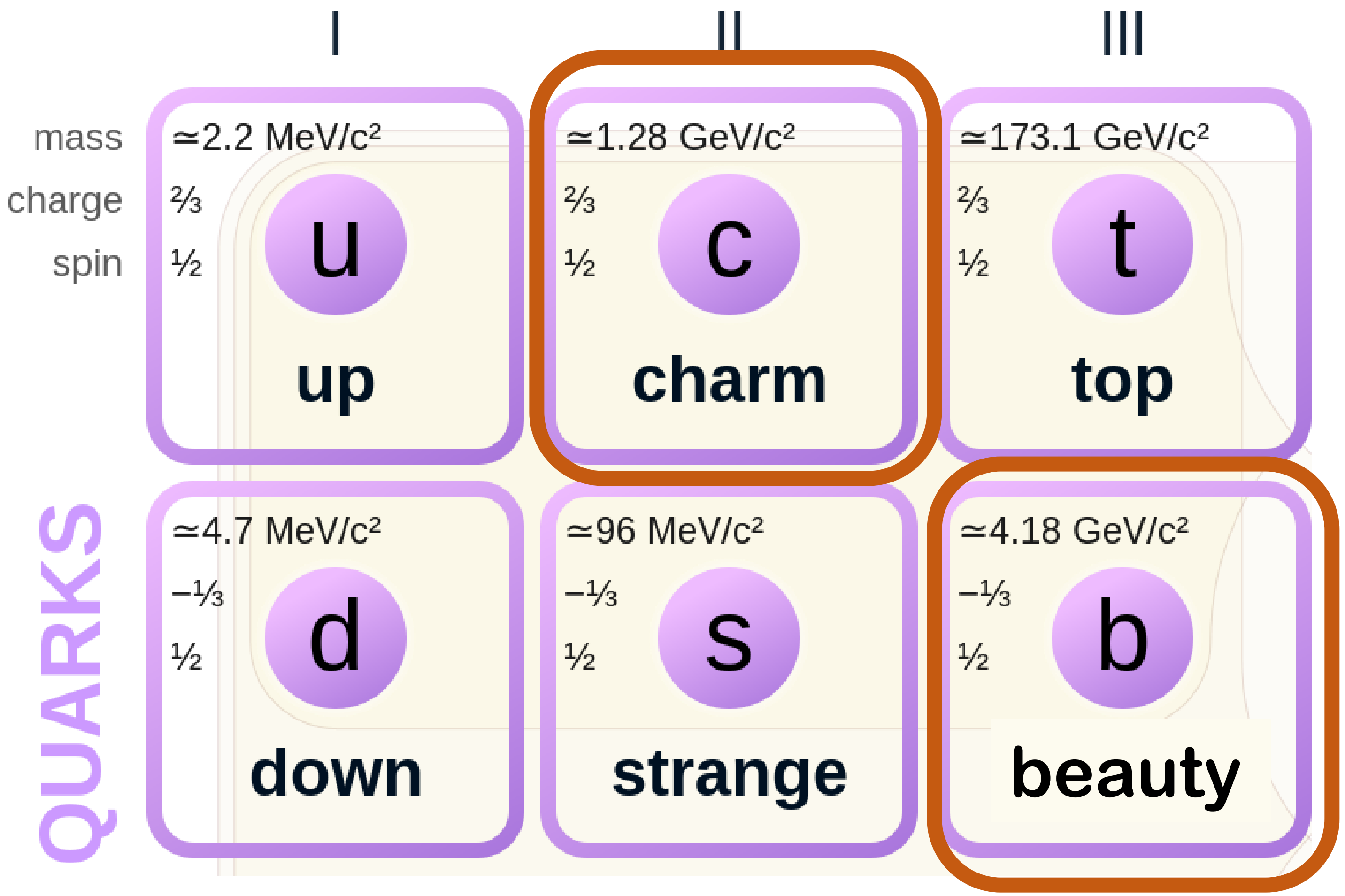
Is there a way to trace a slow-moving parton in QGP?

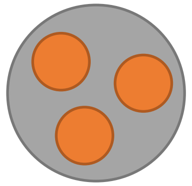
Heavy Quark Hadron and Exotic Hadron



Mesons
(quark and anti-quark)

Confinement



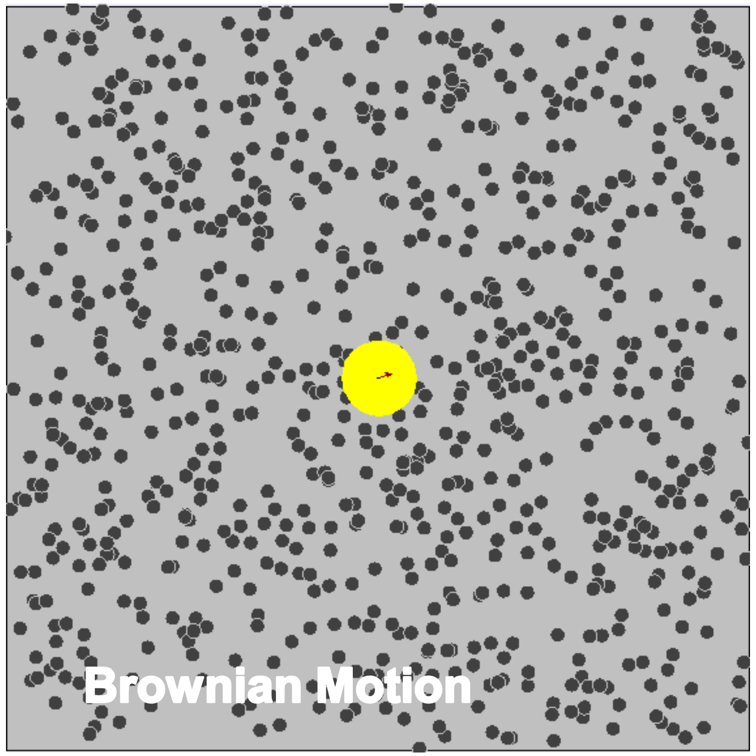


Baryons
(Three quarks)

When the quarks form a hadron, the total color charge needs to be neutral

Heavy Quarks as Probes of Quark Gluon Plasma

- **Charm** and **beauty** quarks (heavy quarks) are produced before QGP formation (<0.2 fm/c)
- An opportunity to study QGP with a "**slow-moving hard probe**"
- Once produced, they **can not be destroyed by strong interaction** (in particular, for beauty)

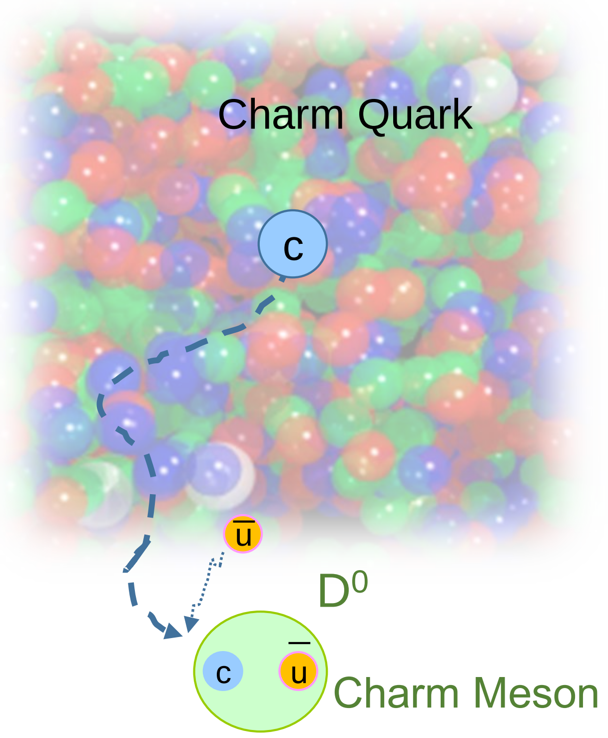


- Low momentum heavy quarks are then "kicked around" by quasi-particles (Brownian Motion) before they hadronized: A direct window to in-medium color force
- Heavy quark diffusion constant can be calculated in phenomenological models or Lattice QCD calculations

Heavy Quarks as Probes of Quark Gluon Plasma

Hadronization of heavy quarks could be modified in QGP, recombination of heavy (and light) quarks from independent hard parton-parton interactions

- Flavor identified heavy flavor hardrons: insights into the hadroization process



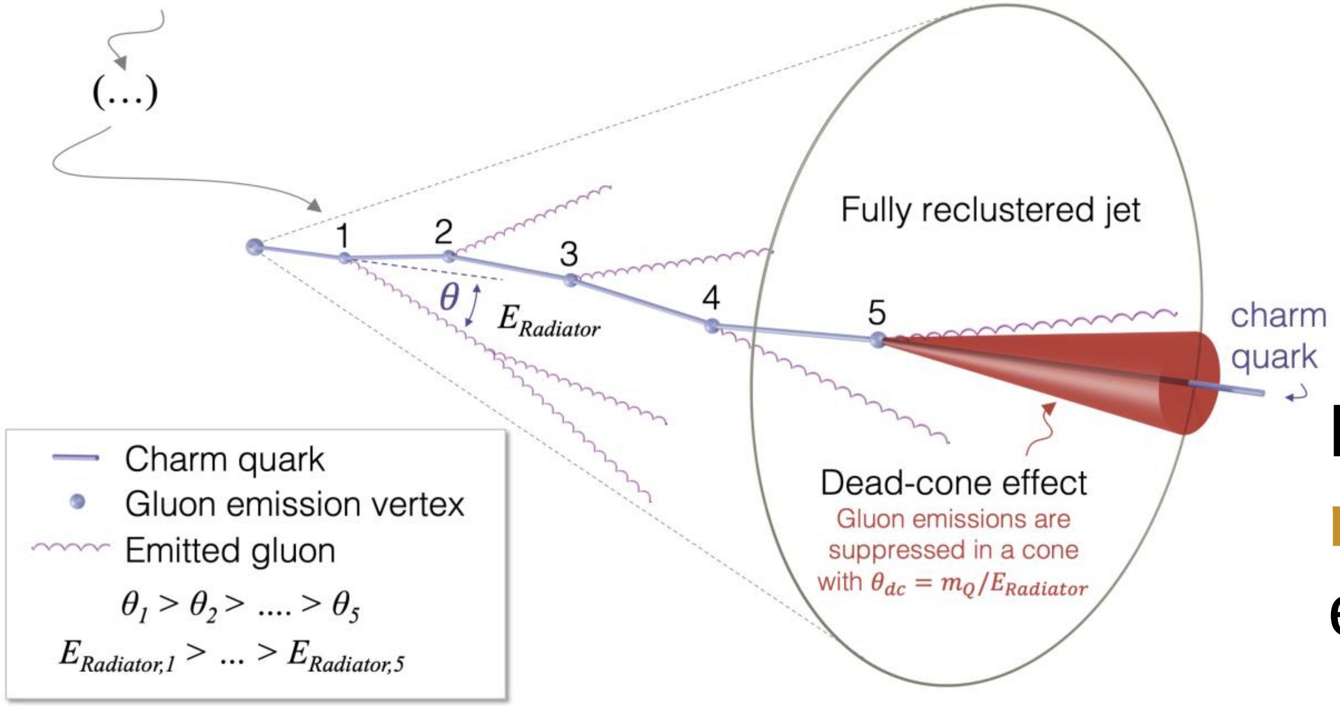


Figure from ALICE publication in Nature 605 (2022) 7910, 440-446

Fast moving heavy quarks: **suppression of radiative energy loss** due to dead-cone effect compared to light quarks

- Parton flavor dependence of jet quenching

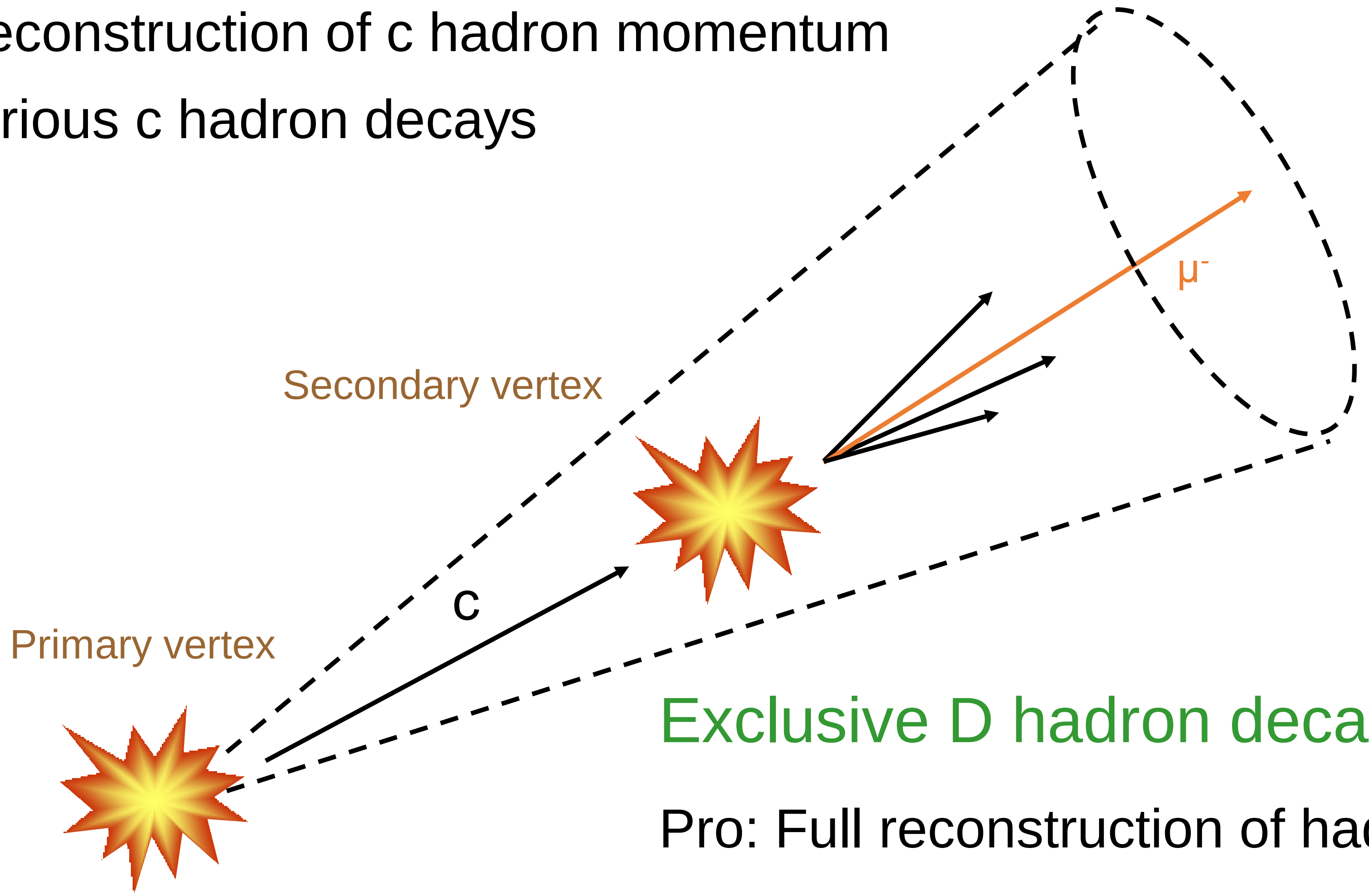
Study of Charm Hadron

Heavy flavor electrons or muons:

Pro: Higher statistics than fully reconstructed c hadron

Con: Partial reconstruction of c hadron momentum

From various c hadron decays



Exclusive D hadron decays

Pro: Full reconstruction of hadron momentum and flavor

Con: low statistics

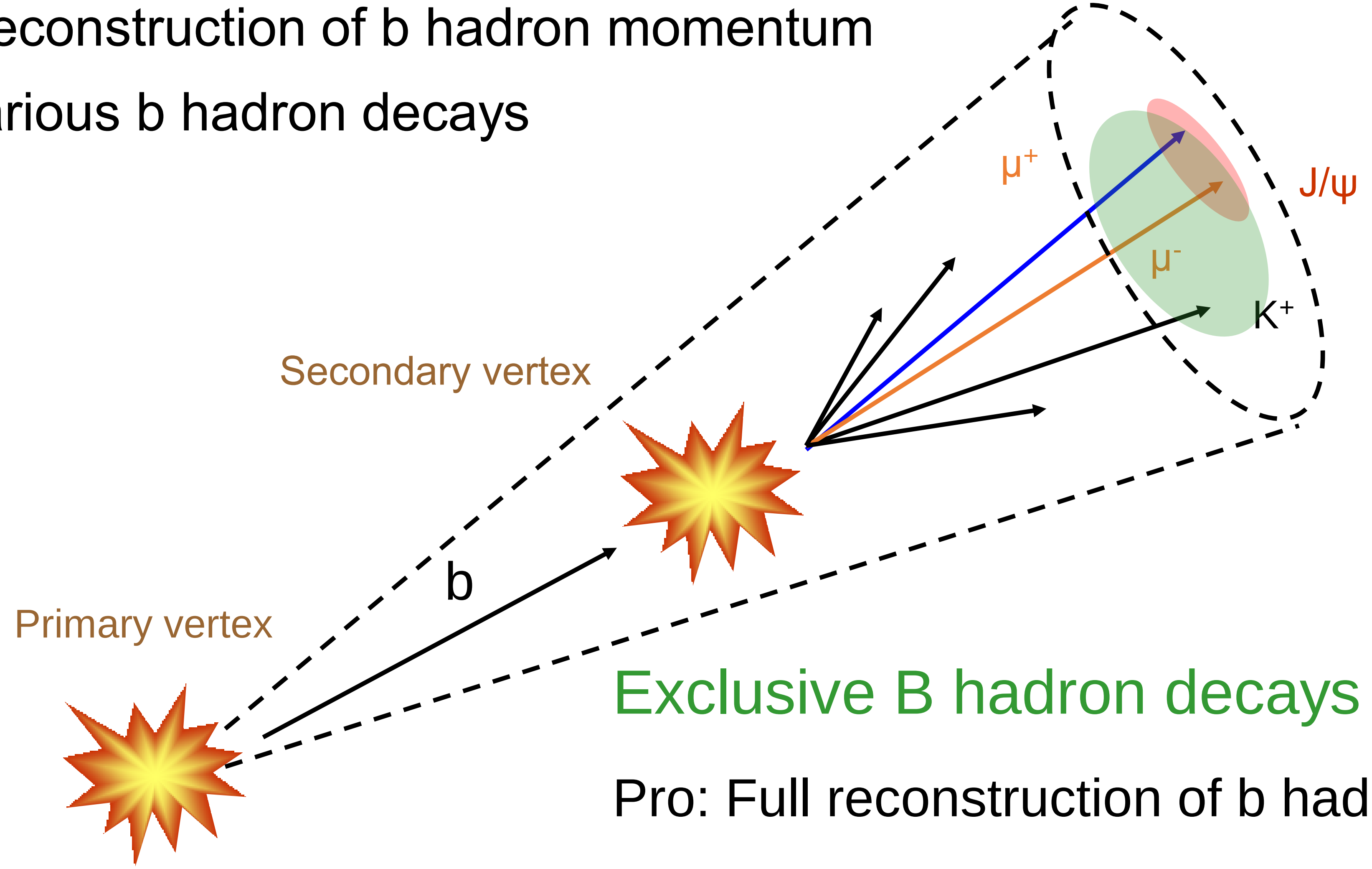
Study of Beauty Hadron

Non-prompt **J/ψ** (or **D^0** or **lepton**):

Pro: Higher statistics than fully reconstructed b hadron

Con: Partial reconstruction of b hadron momentum

From various b hadron decays

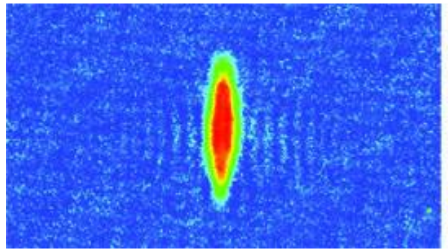


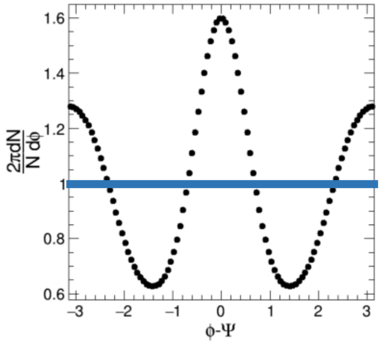
Exclusive B hadron decays

Pro: Full reconstruction of b hadron momentum and flavor

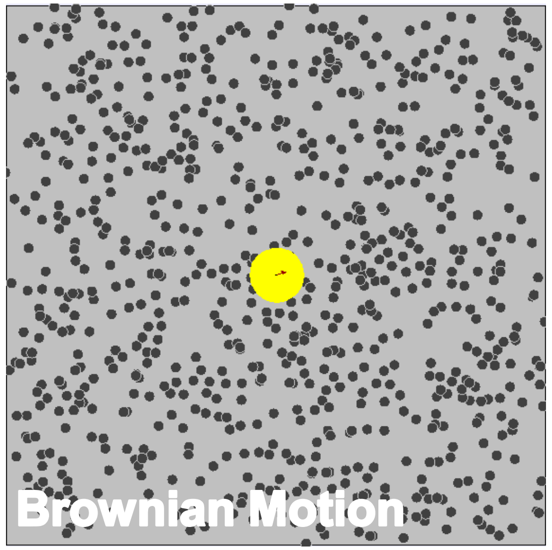
Con: low statistics

Heavy Quark (Charm and Beauty) Diffusion

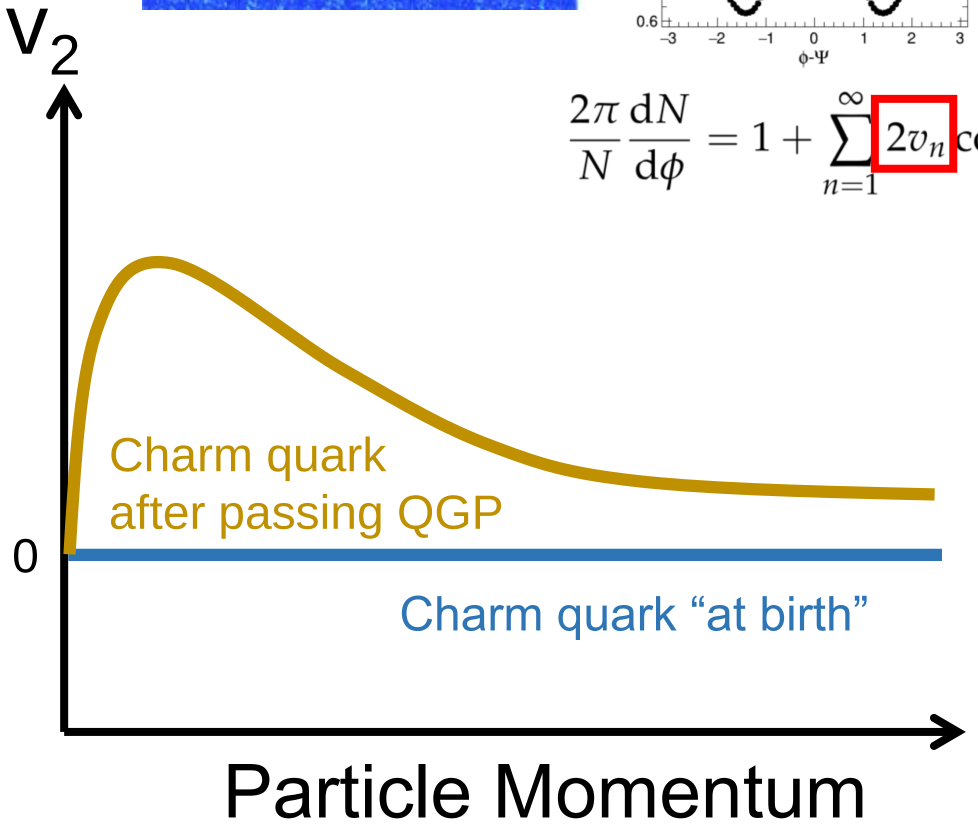




$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



Artist's impression

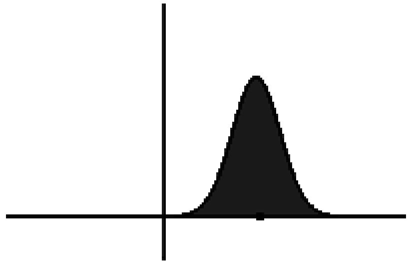


Fokker-Planck equation

$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p} pA(p) f_Q(t,p) + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q(t,p)$$

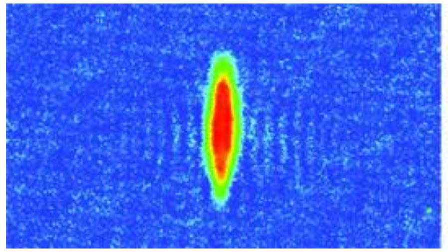
A and B are transport coefficients

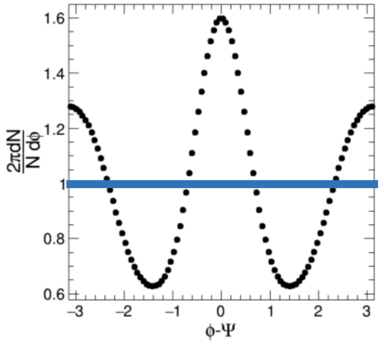
$$\mathcal{D}_s = \frac{T}{m_Q A(p=0)}$$



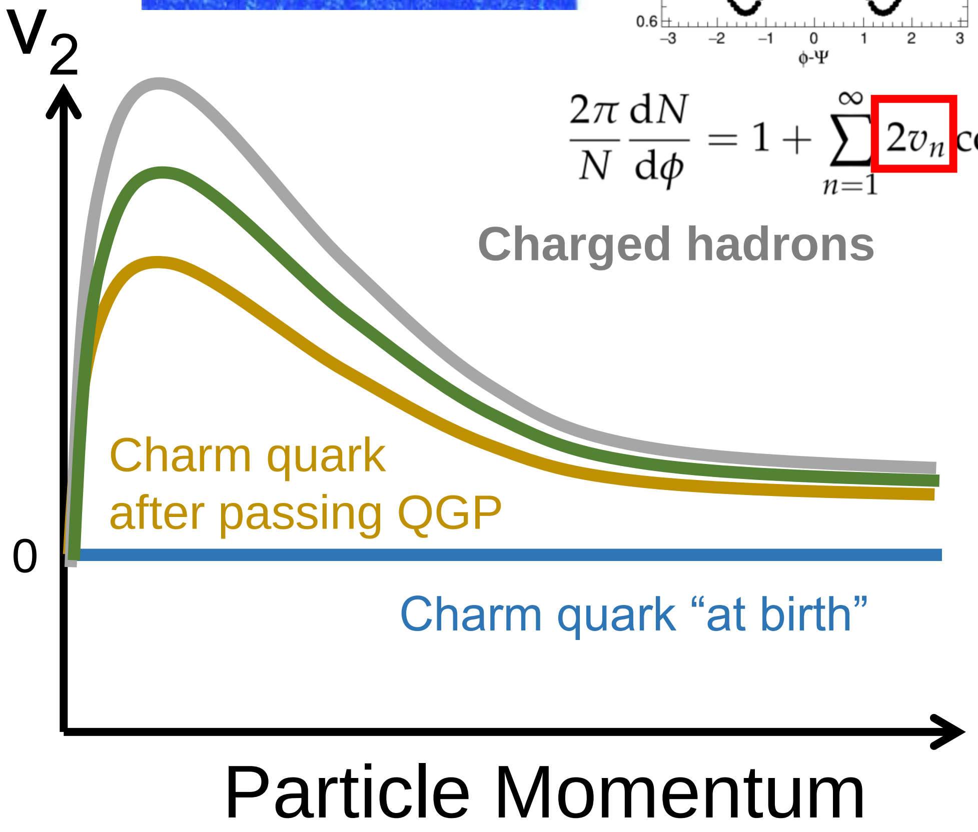
- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!

Heavy Quark (Charm and Beauty) Diffusion

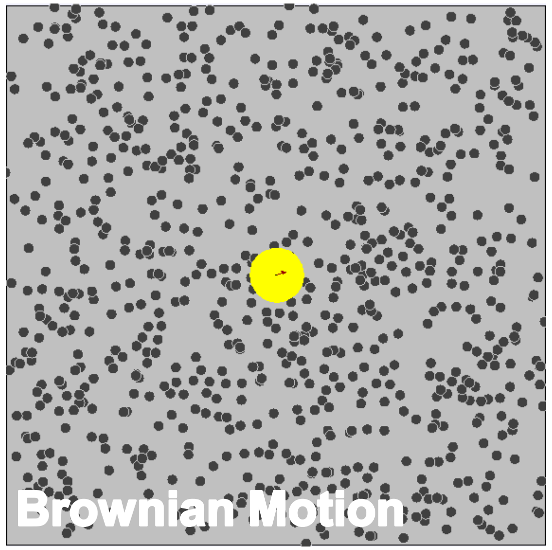


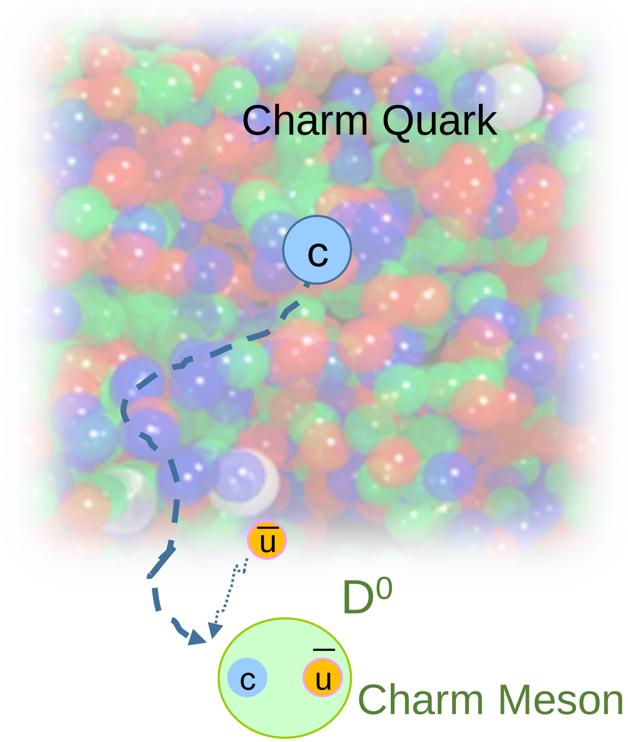


$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



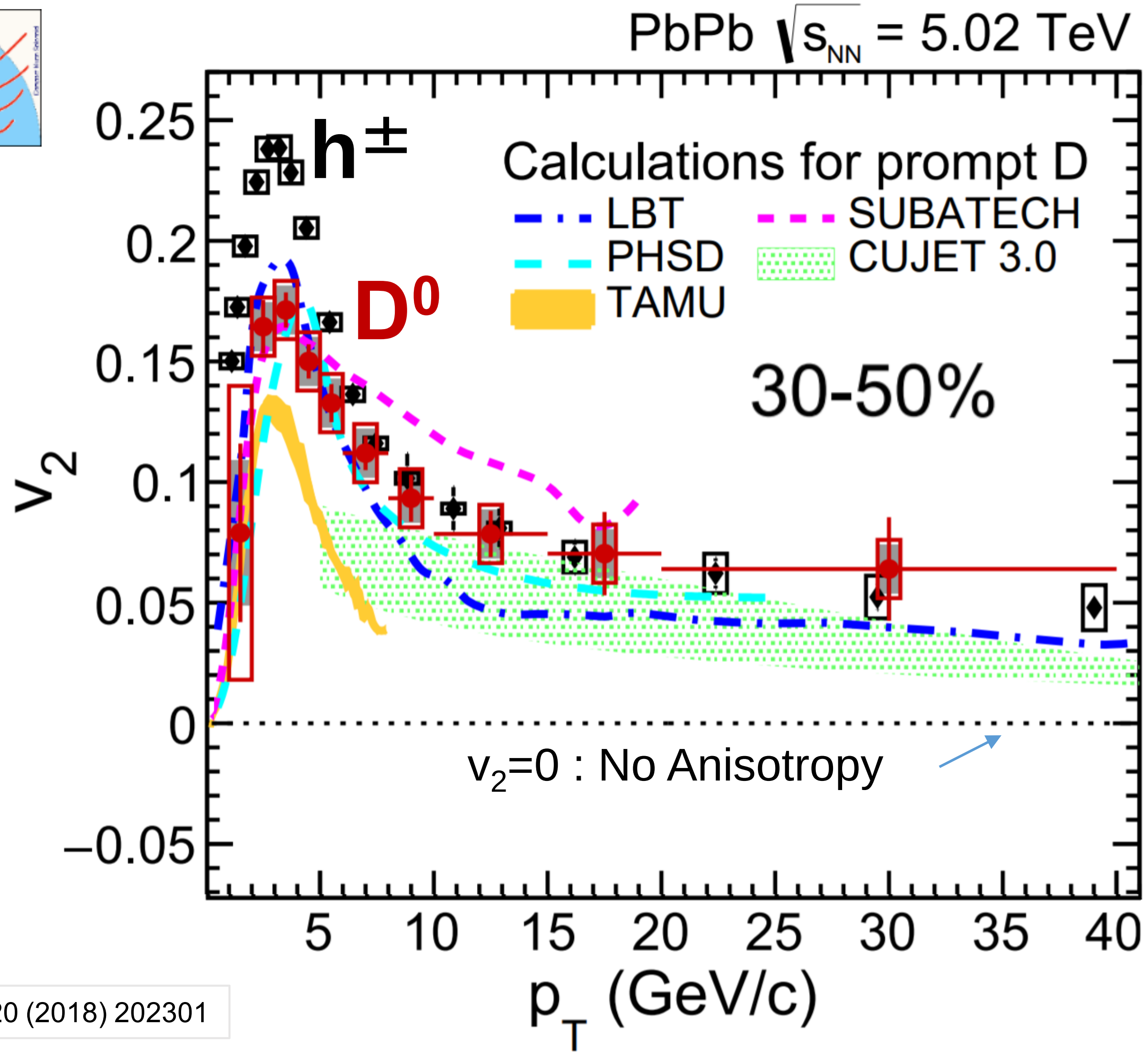
Artist’s impression



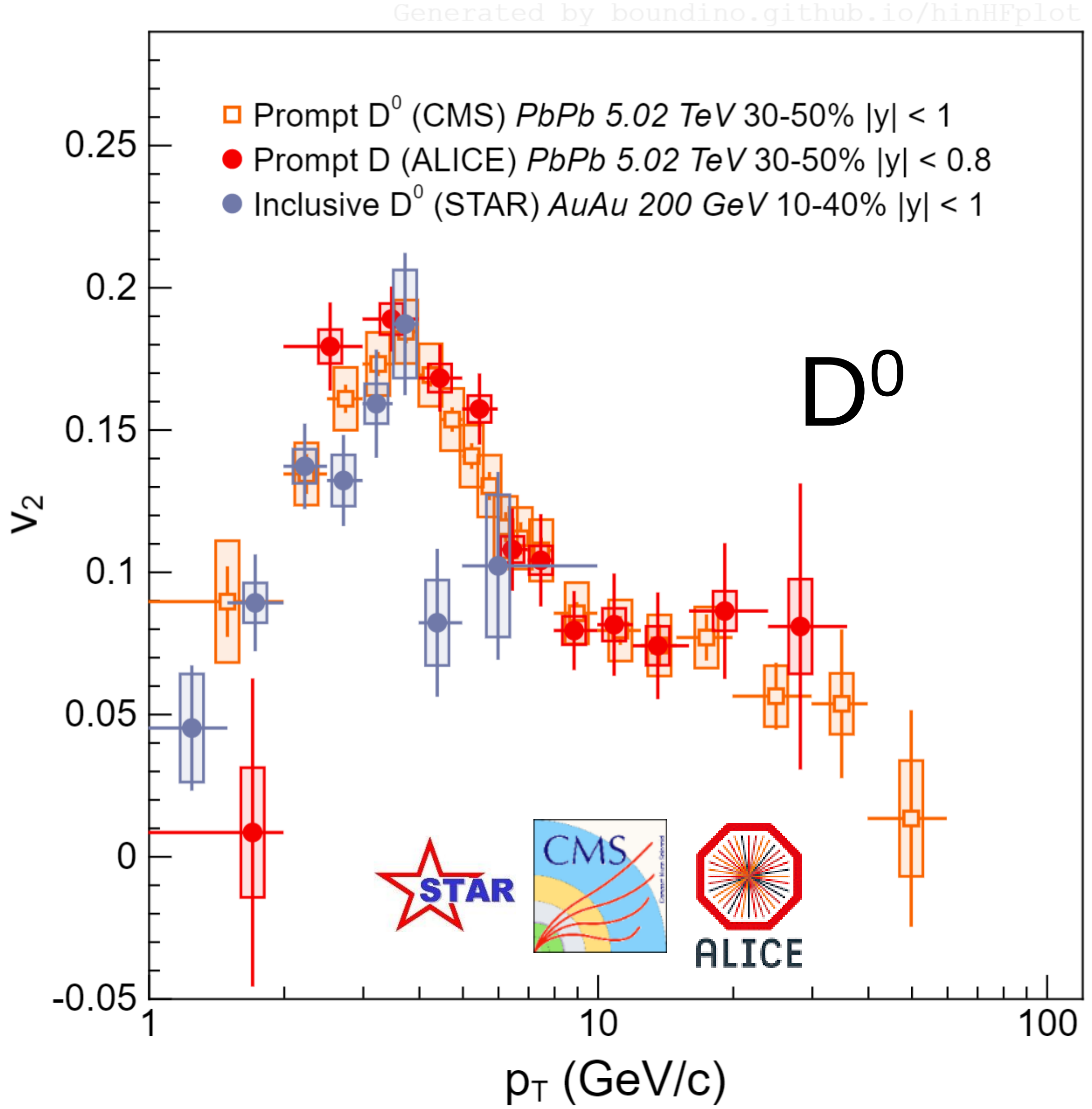


- Since the **QGP is expanding radially**, QCD force (like ‘**wind**’) increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!
- Hadronization effect could change the v_2 of the heavy flavor hadron further

Charm Diffusion



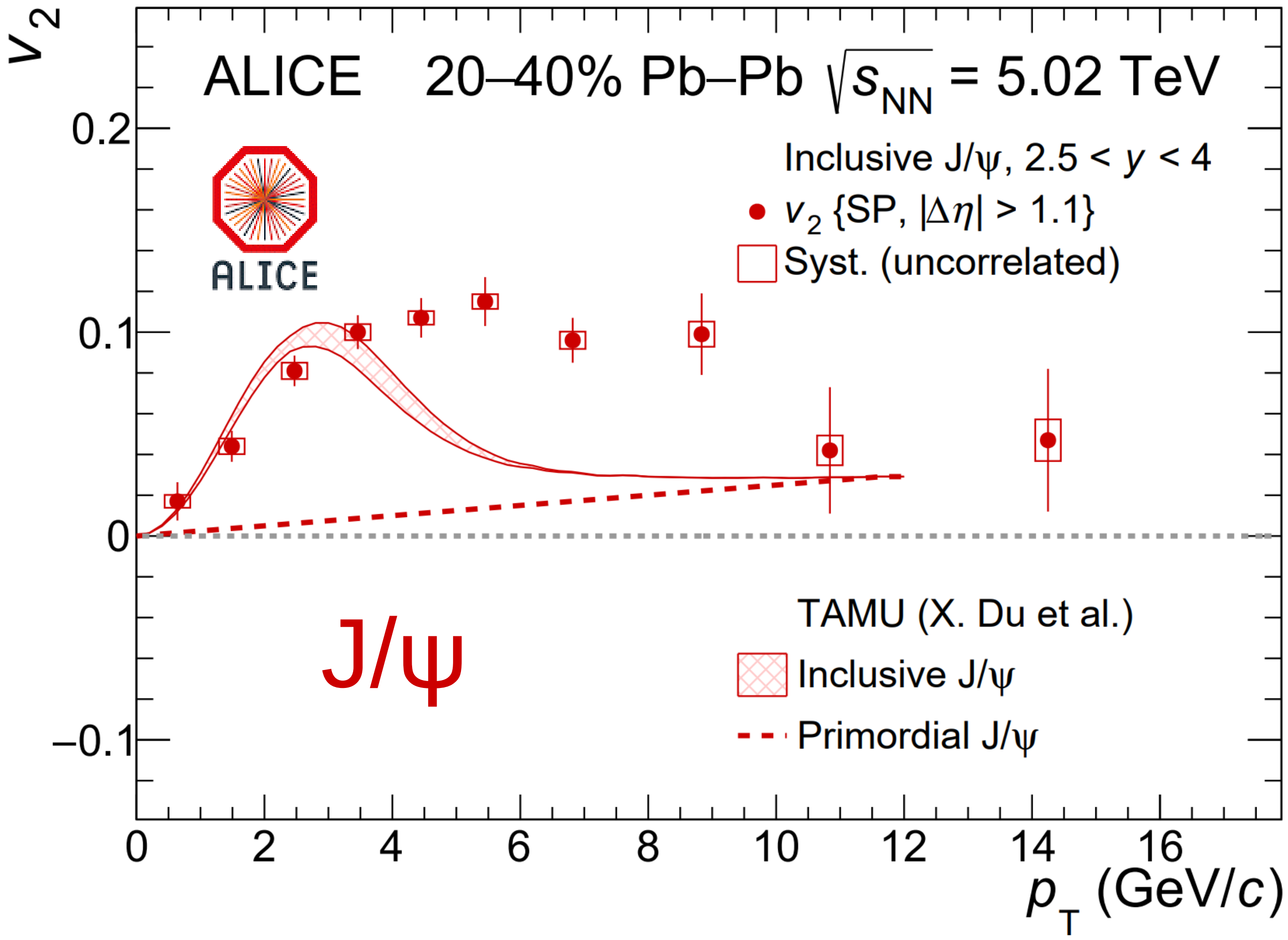
PRL 120 (2018) 202301



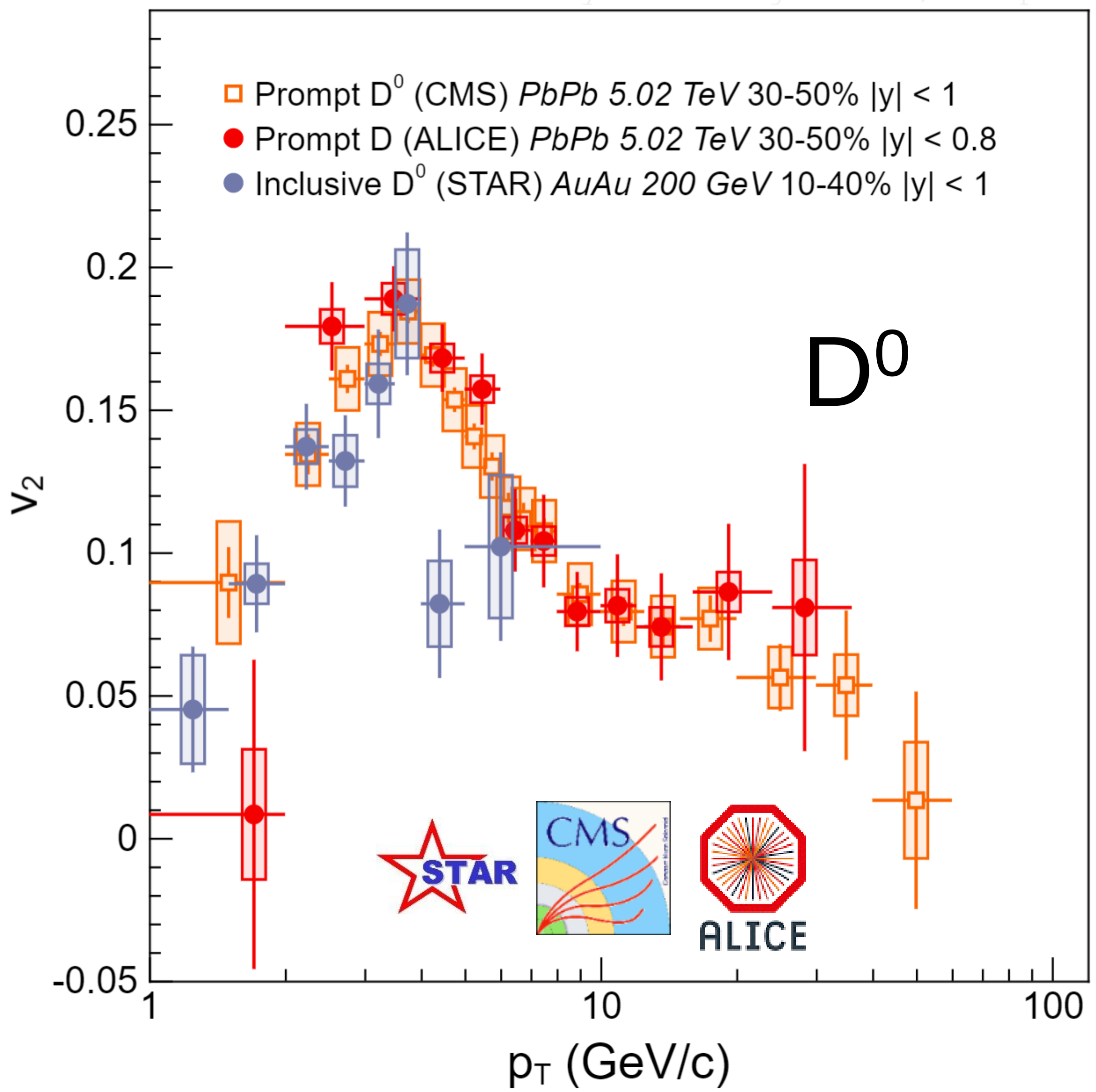
- Observation of charm meson elliptic flow (v_2)
- Charm quarks moving toward thermalization

ALICE PLB 813 (2021) 136054
CMS PLB 816 (2021) 136253
STAR PRL 118 (2017) 212301

Charm Diffusion



JHEP 10 (2020) 141



ALICE PLB 813 (2021) 136054
CMS PLB 816 (2021) 136253
STAR PRL 118 (2017) 212301

- Observation of D^0 and J/ψ elliptic flow (v_2)
- Charm quarks moving toward thermalization

Dead-Cone Effect in QGP?

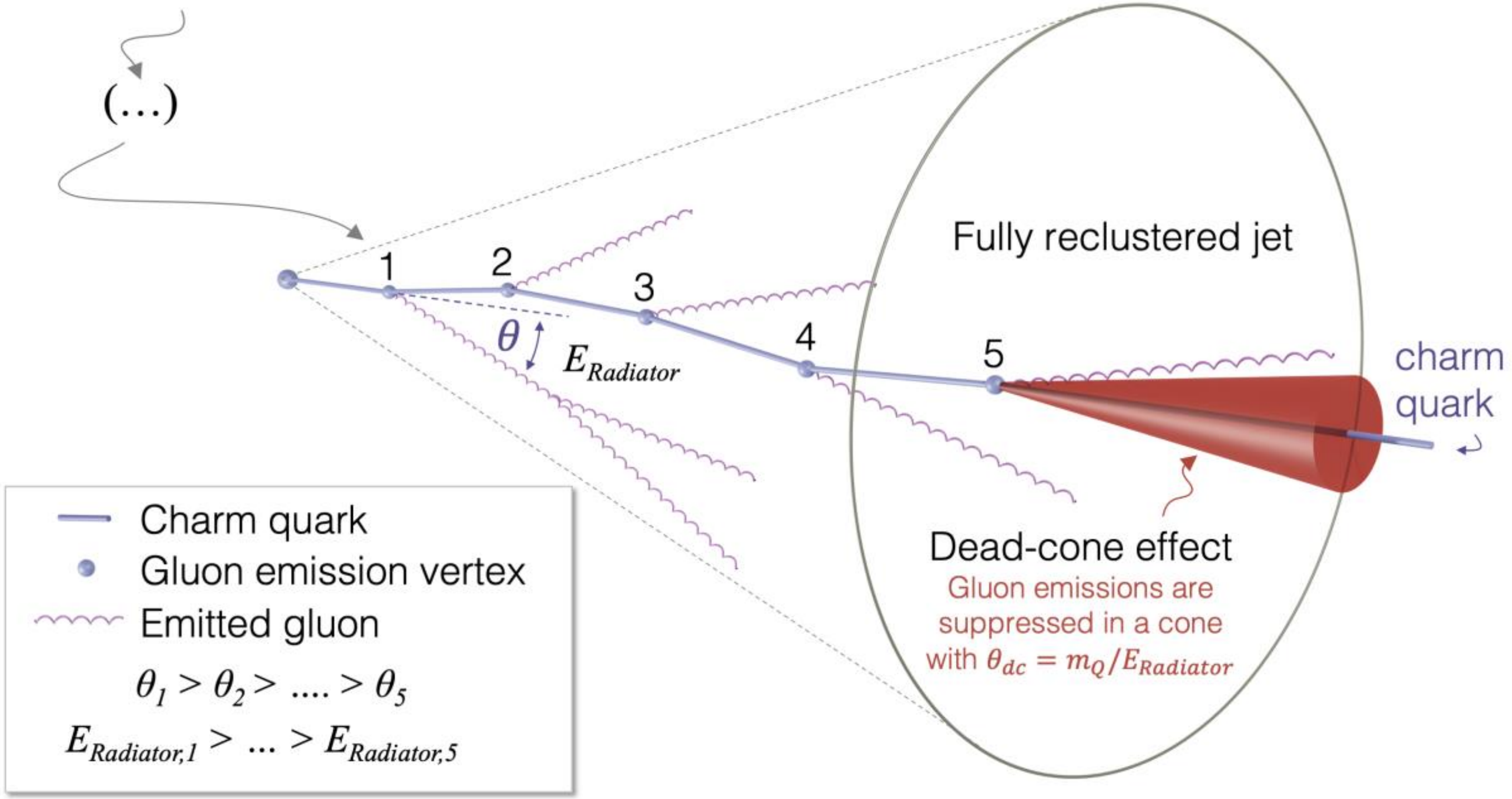
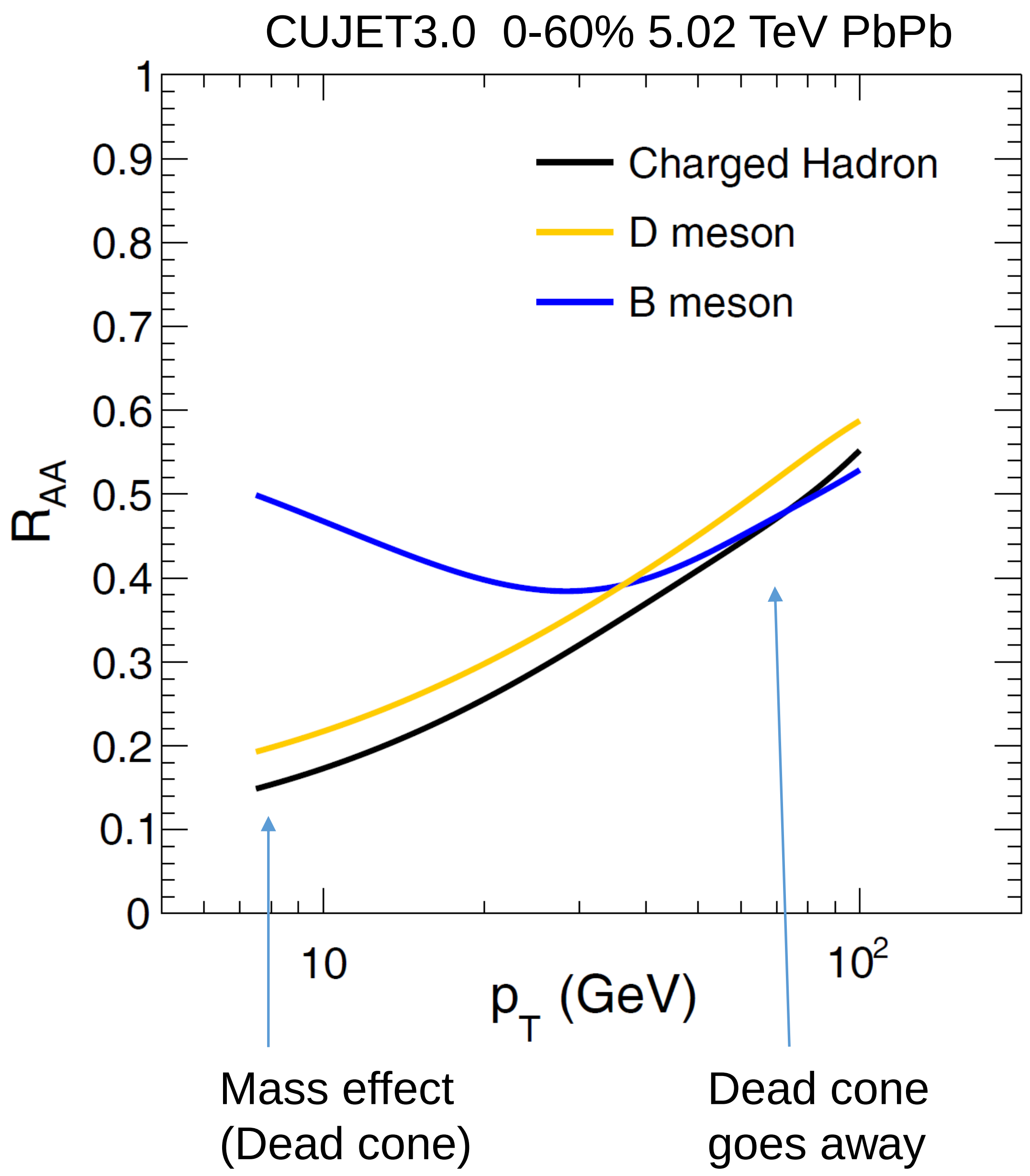
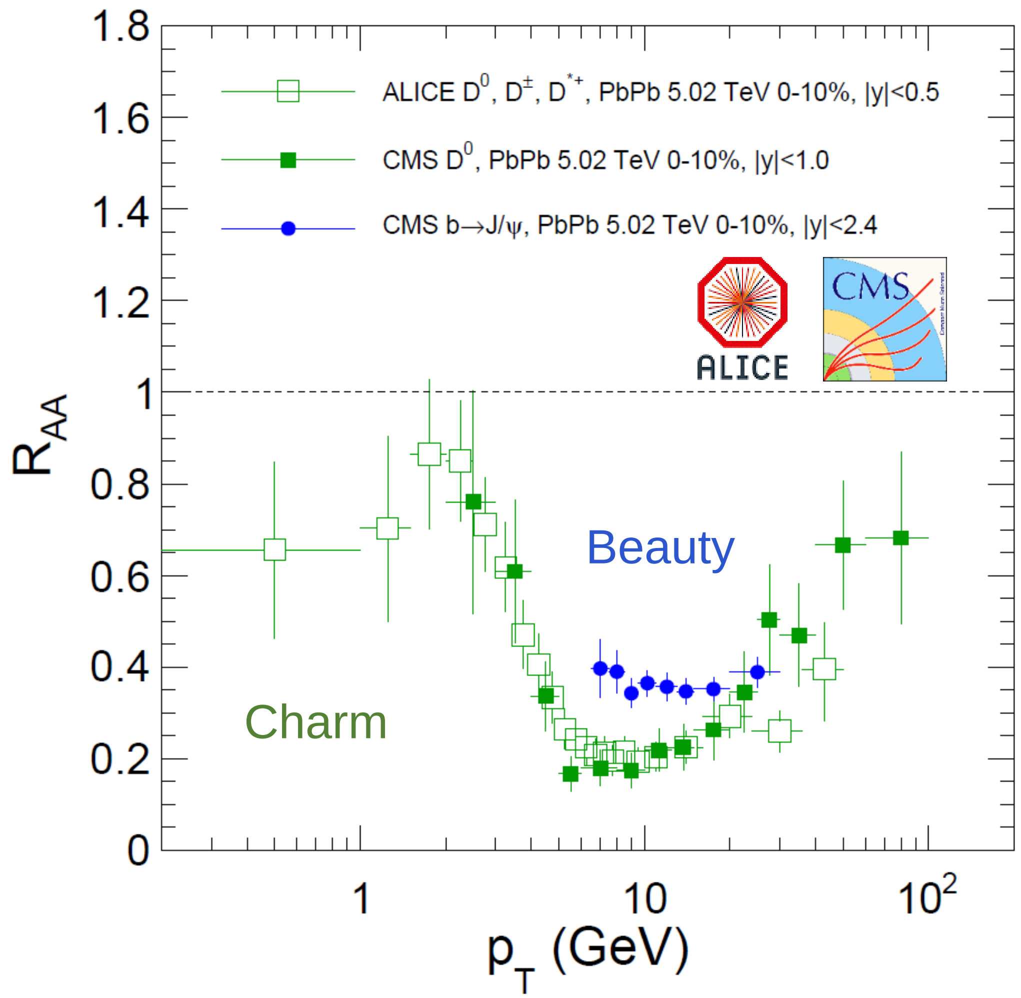
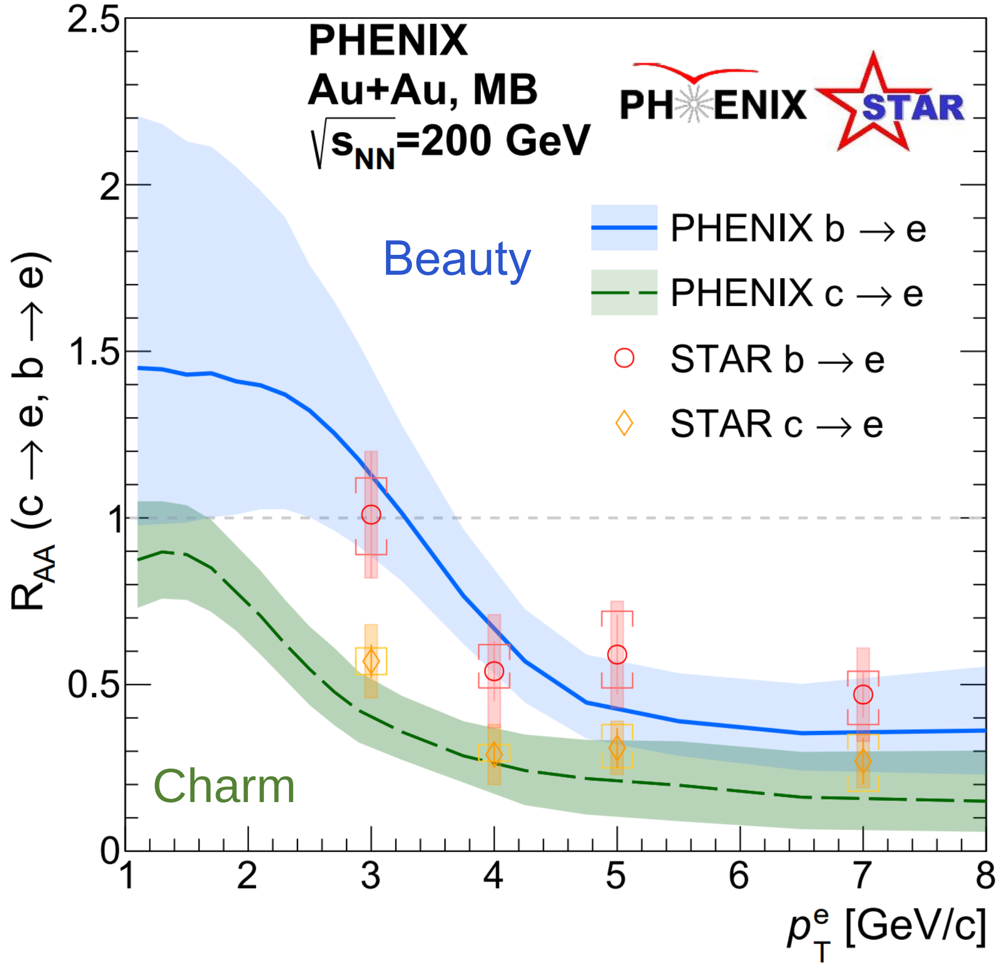


Figure from ALICE publication in Nature 605 (2022) 7910, 440-446



Beauty vs. Charm R_{AA}





- Nuclear modification factors of depends on quark mass:
  - ALICE and CMS data though various fully / partially reconstructed decay channels at LHC
  - STAR and PHENIX HF electron data at RHIC
  - Observation of the mass dependence at low p_T and disappearance at high p_T

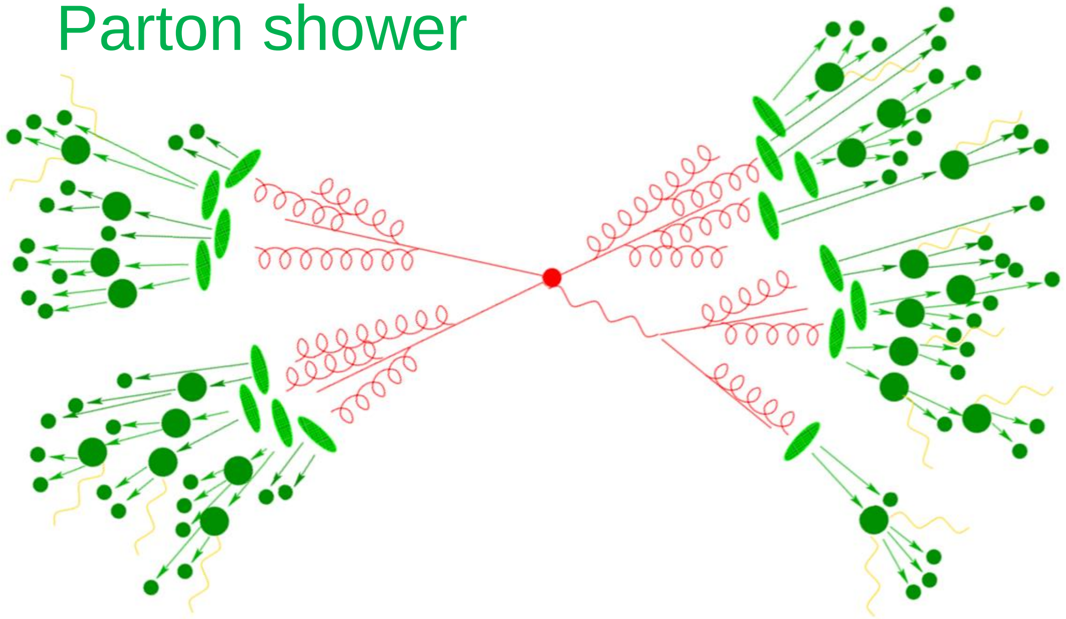
Hadronization of Heavy Quarks in QGP

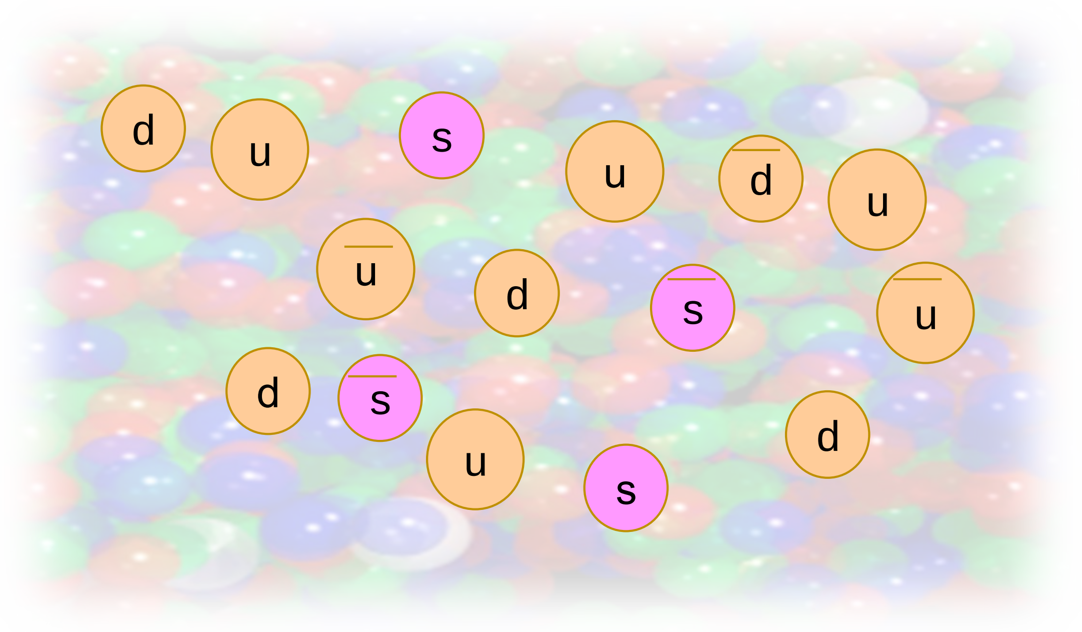
Hadronization: from Quarks to Hadrons

Strange quark content is enhanced in QGP
(Due to the high temperature)
Idea: Probe the partonic QGP by heavy quarks!

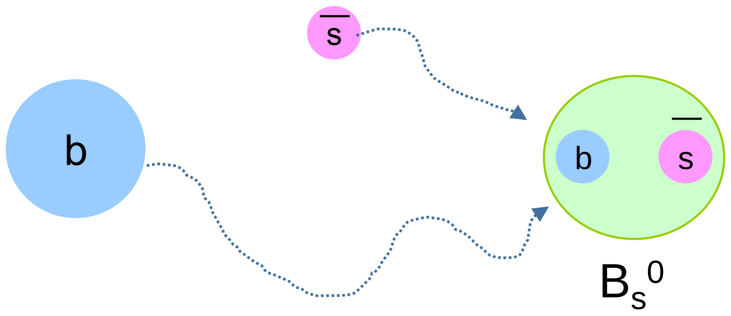
Example: in additional to parton shower,
B_s could be **enhanced via parton coalescence** in QGP

Parton shower

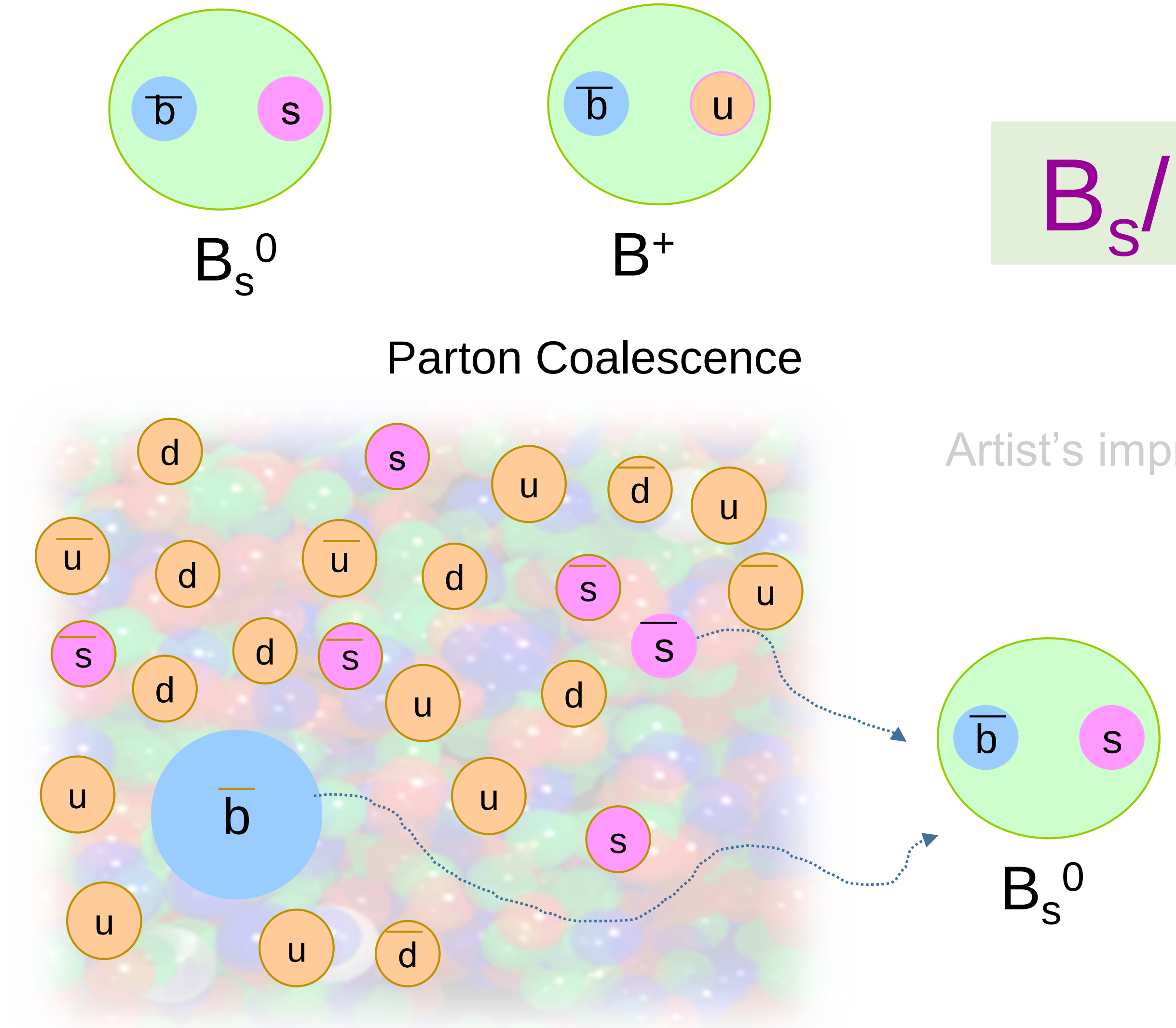




Parton Coalescence

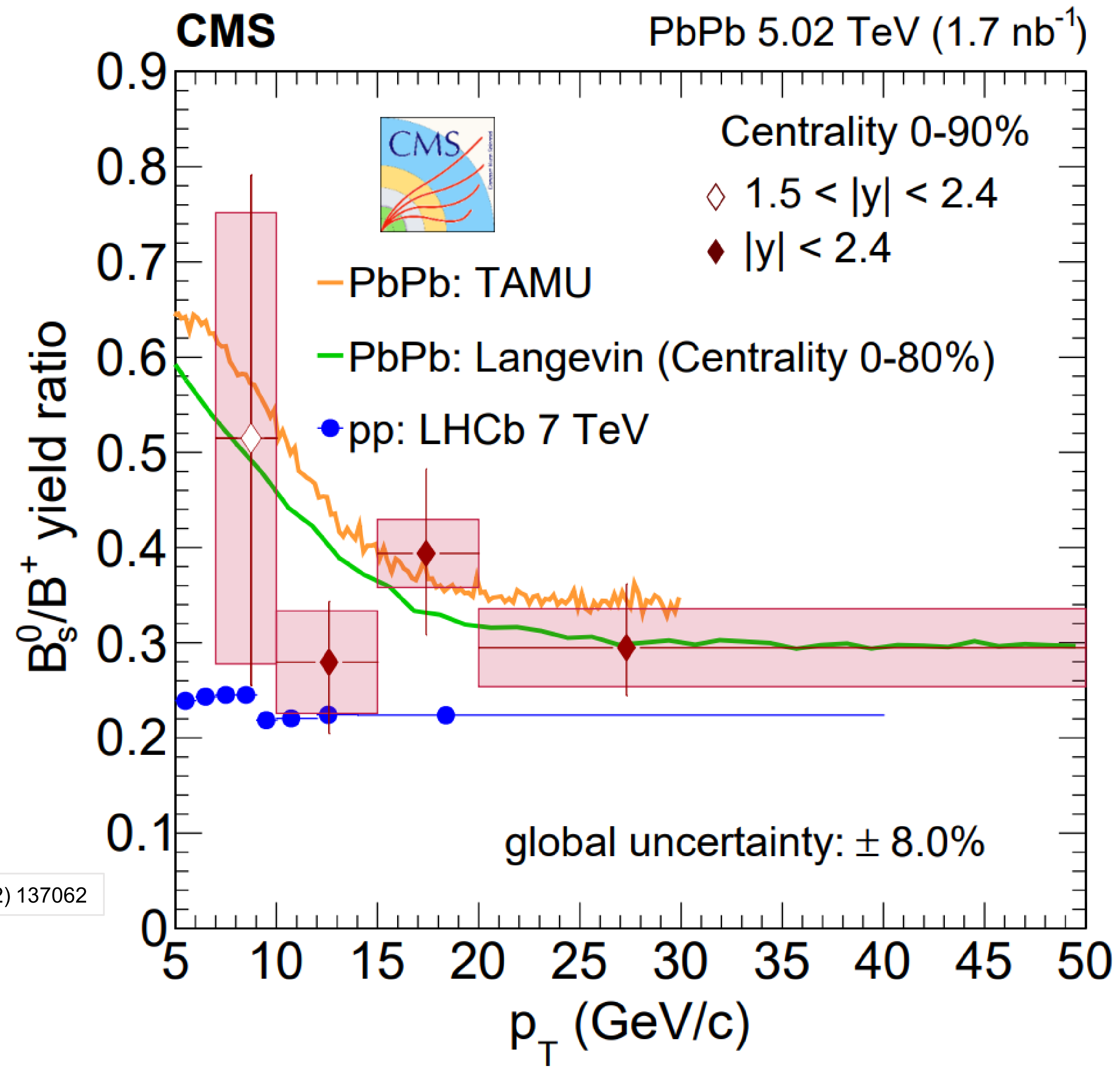


Beauty Quark Hadronization



B_s/B^+

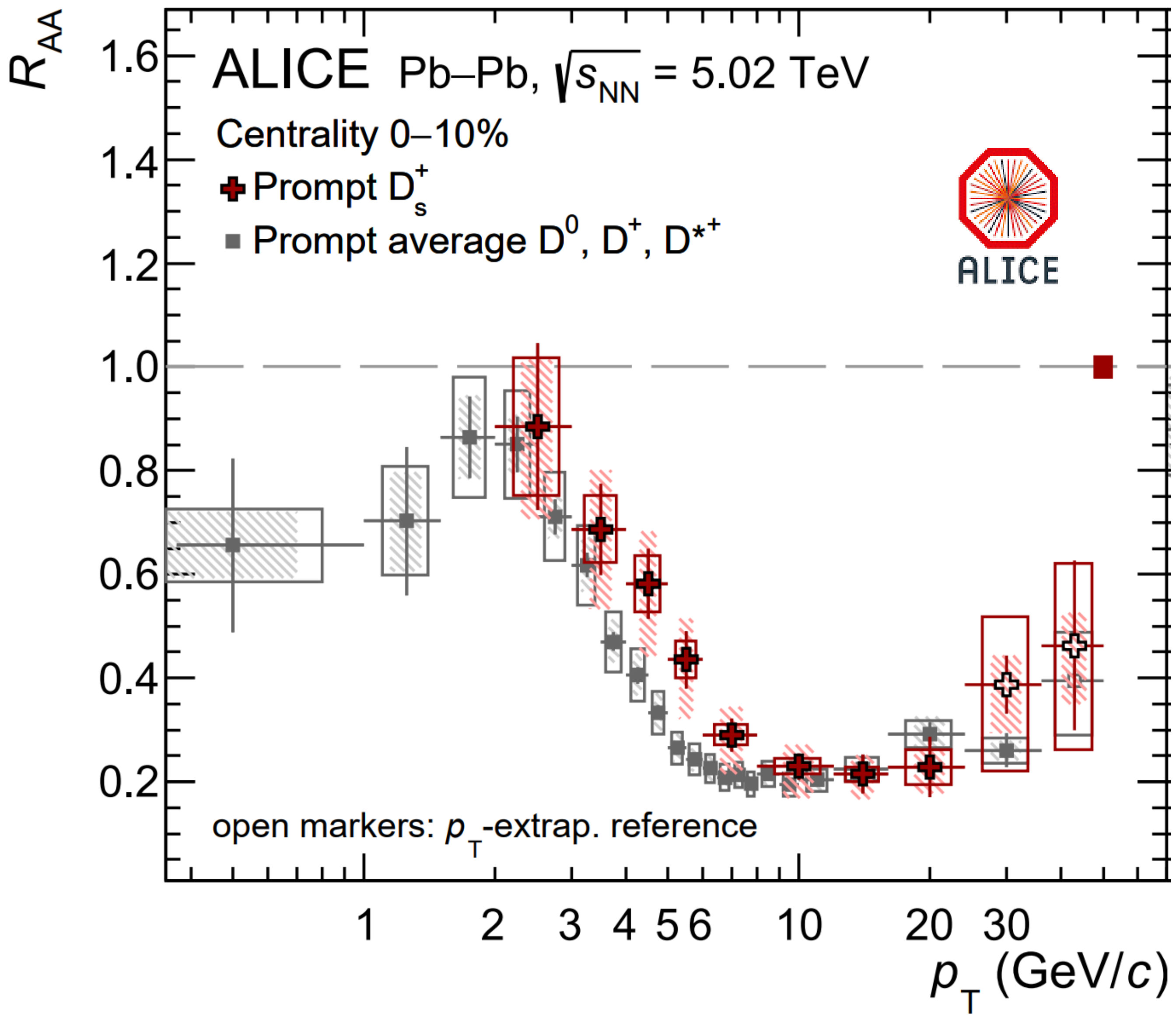
Artist's impression

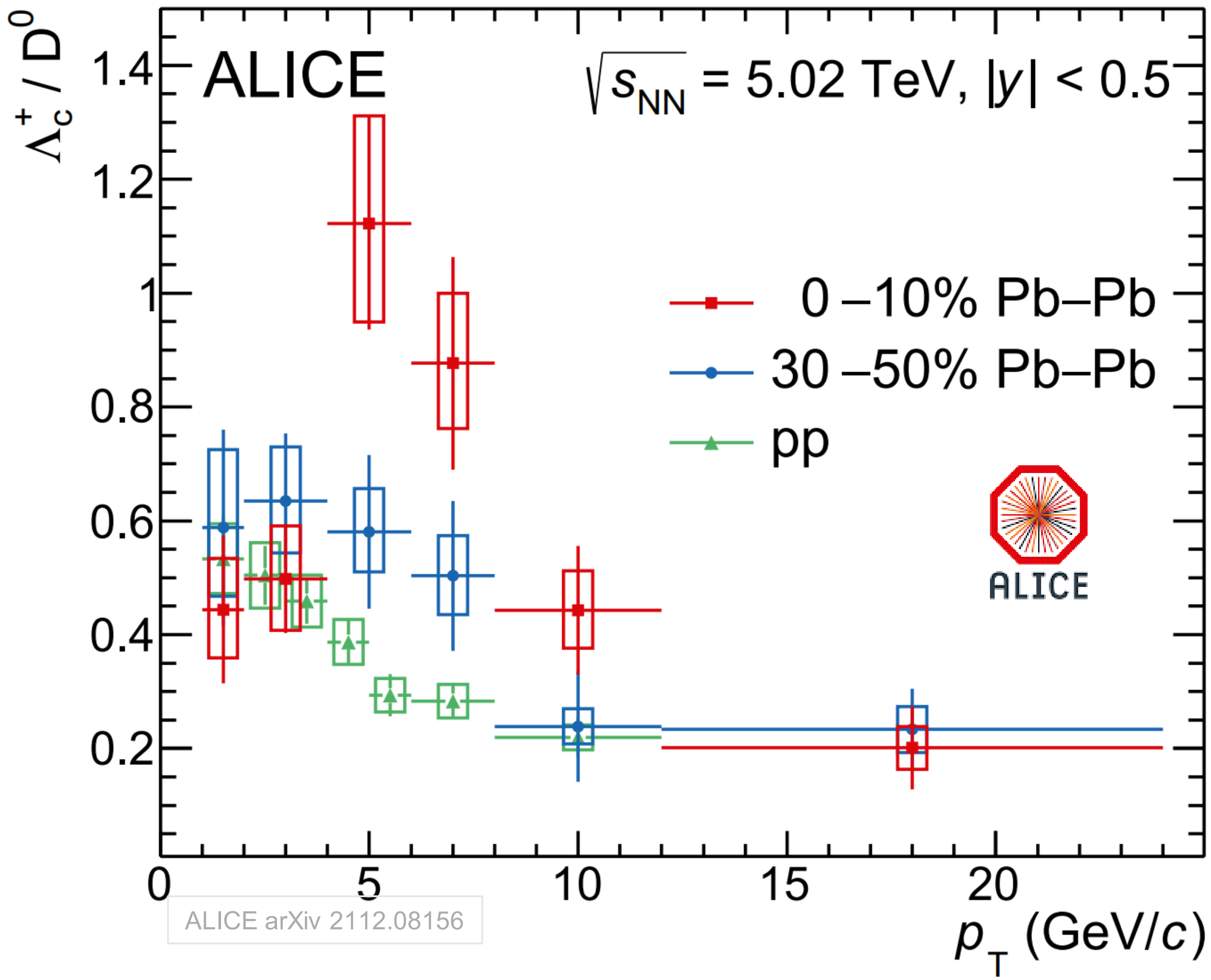


PLB 829 (2022) 137062

- Hint of enhanced production of B_s^0 !
- To be followed up with Run 3+4 data

Charm Quark Hadronization





Indication of enhanced production of D_s (2.3σ) in PbPb collisions!

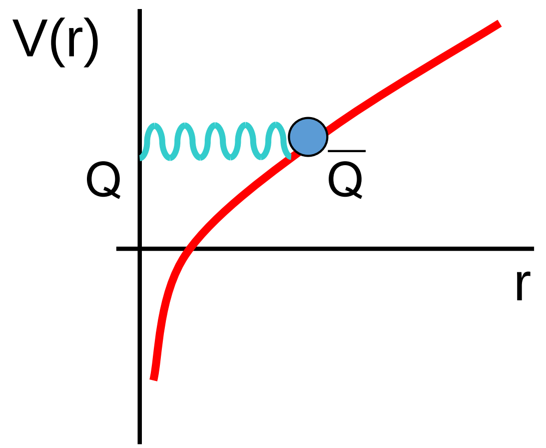
Enhanced production of charmed baryon in PbPb

QGP Temperature

- One interesting tool: the Bottomonium states!
- Bottomonium are rare probes

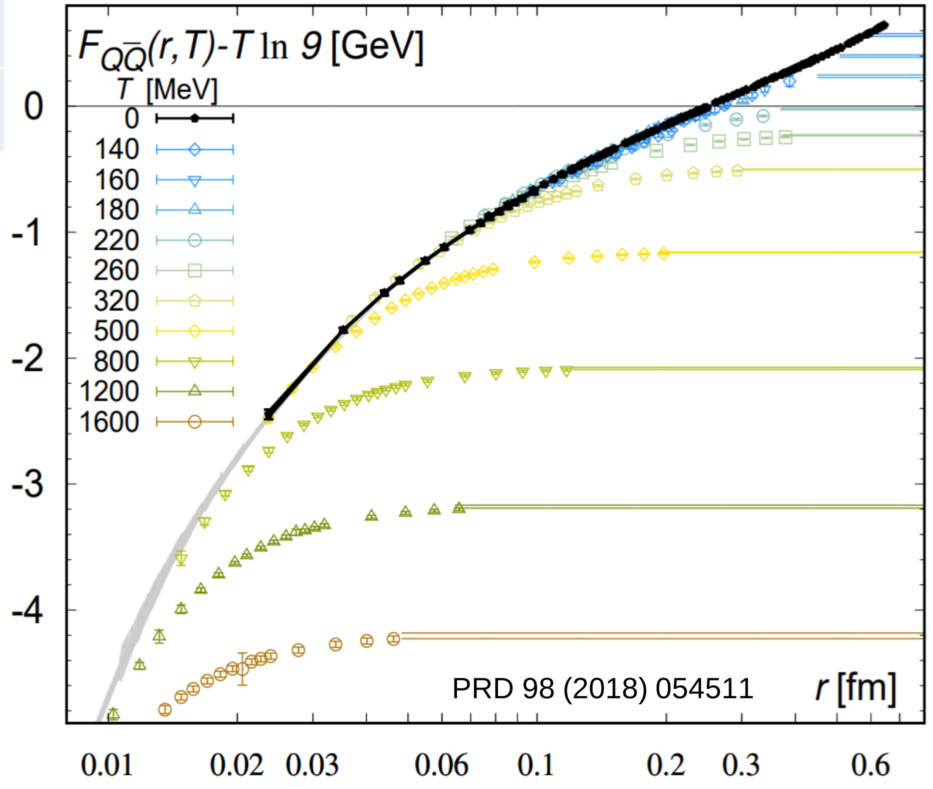
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

- Can be described by non-relativistic Schrödinger Equation



$b\bar{b}$ State	$\Upsilon(1S)$	$\chi_{bJ}(1P)$	$\Upsilon(2S)$	$\chi_{bJ}(2P)$	$\Upsilon(3S)$
Mass [GeV]	9.46	9.99	10.02	10.26	10.36
ΔE to $B\bar{B}$ threshold[GeV]	1.10	0.67	0.54	0.31	0.20
r_0 [fm]	0.28	0.44	0.56	0.68	0.78

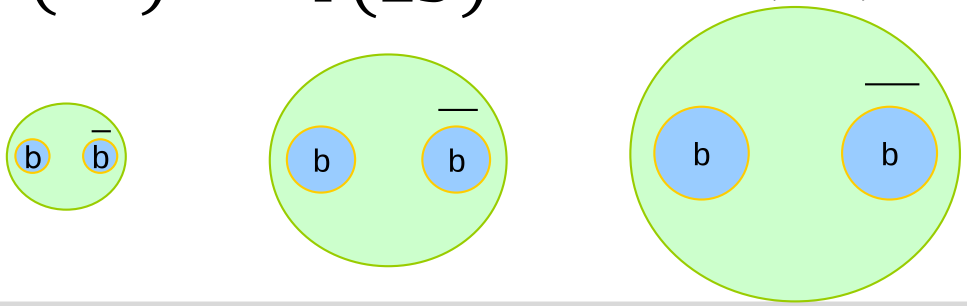
Color Screening from LQCD



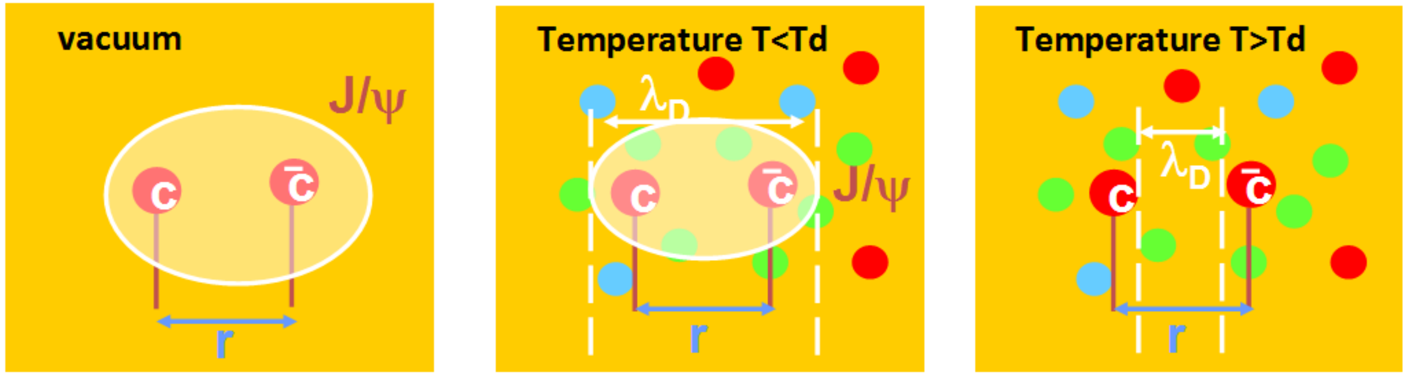
Tightly bound
Small in radius

Loosely bound
Large in radius

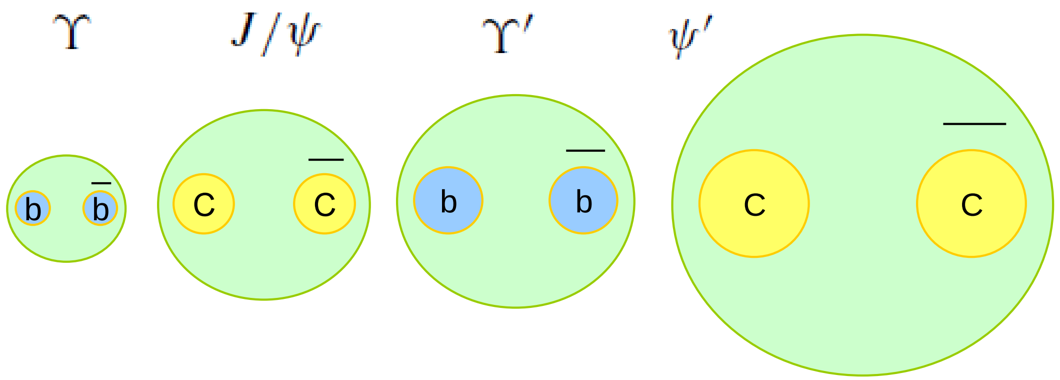
$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

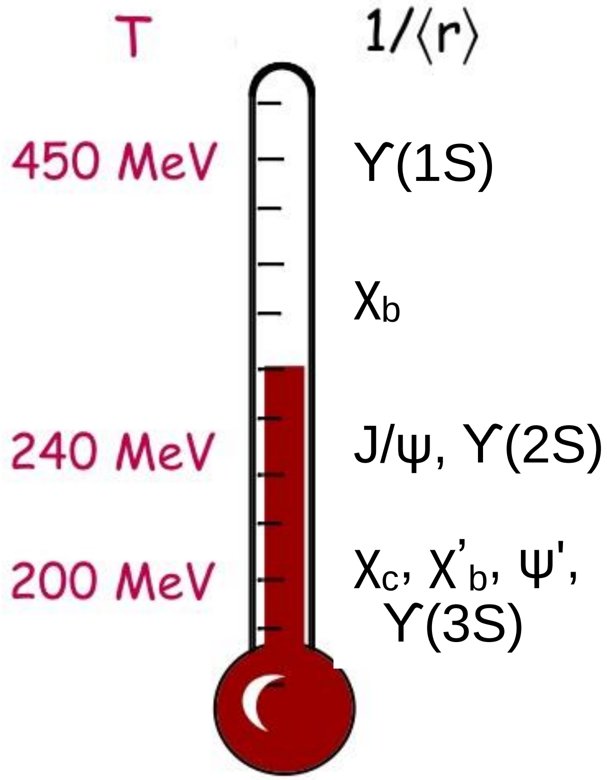


Quarkonia as a Tool to Probe the QGP



Matsui & Satz, PLB168 (1986) 415





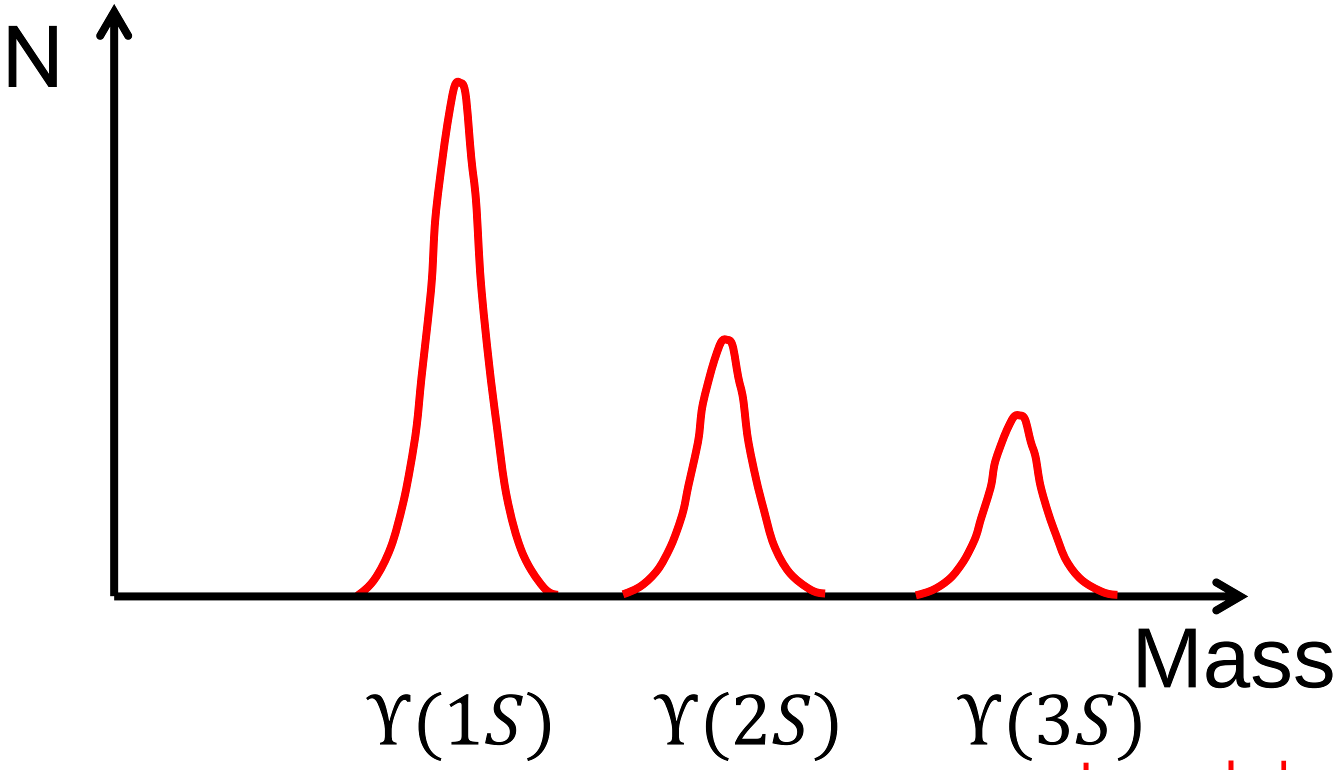
Different states have different binding energies
Loosely bound states melt first!

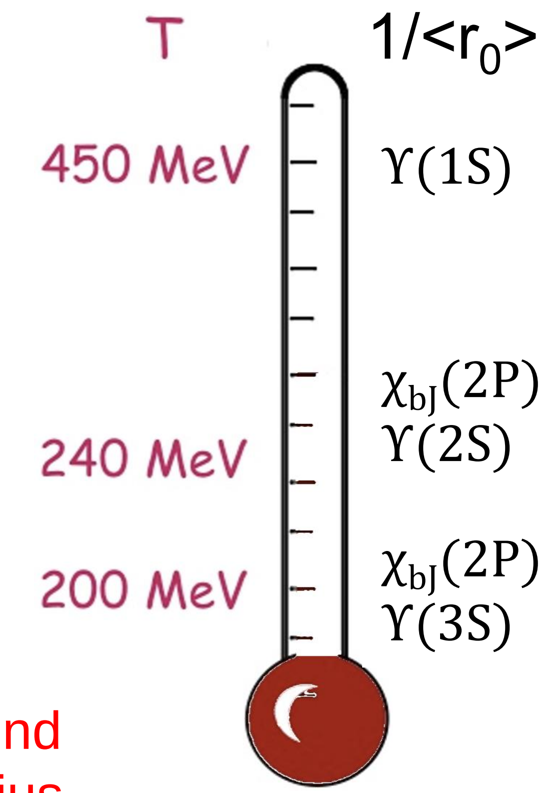
Successive suppression of individual states provides a "thermometer" of the QGP

Mocsy, EPJC61 (2009) 705
BNL workshop in June

In Vacuum (pp)

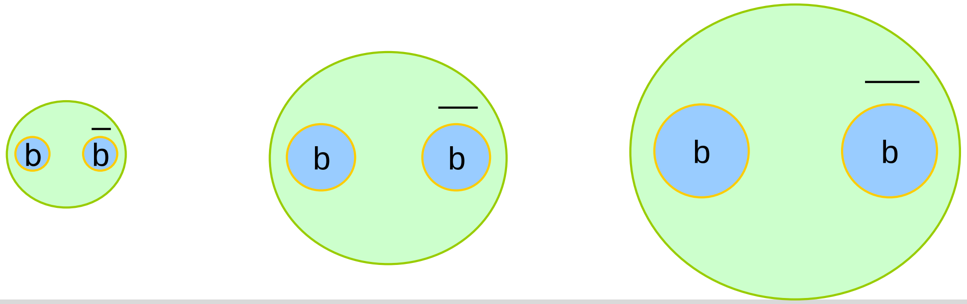
Artist's impression

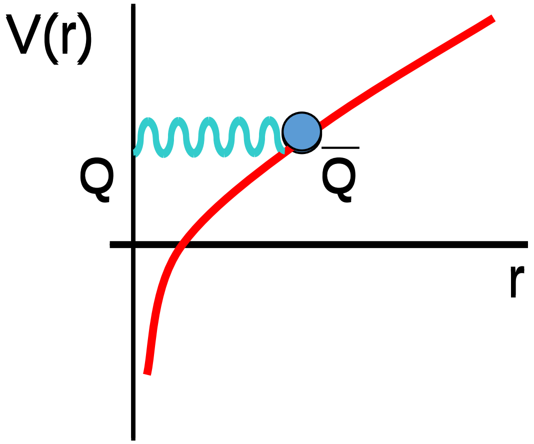




Tightly bound
Small in radius

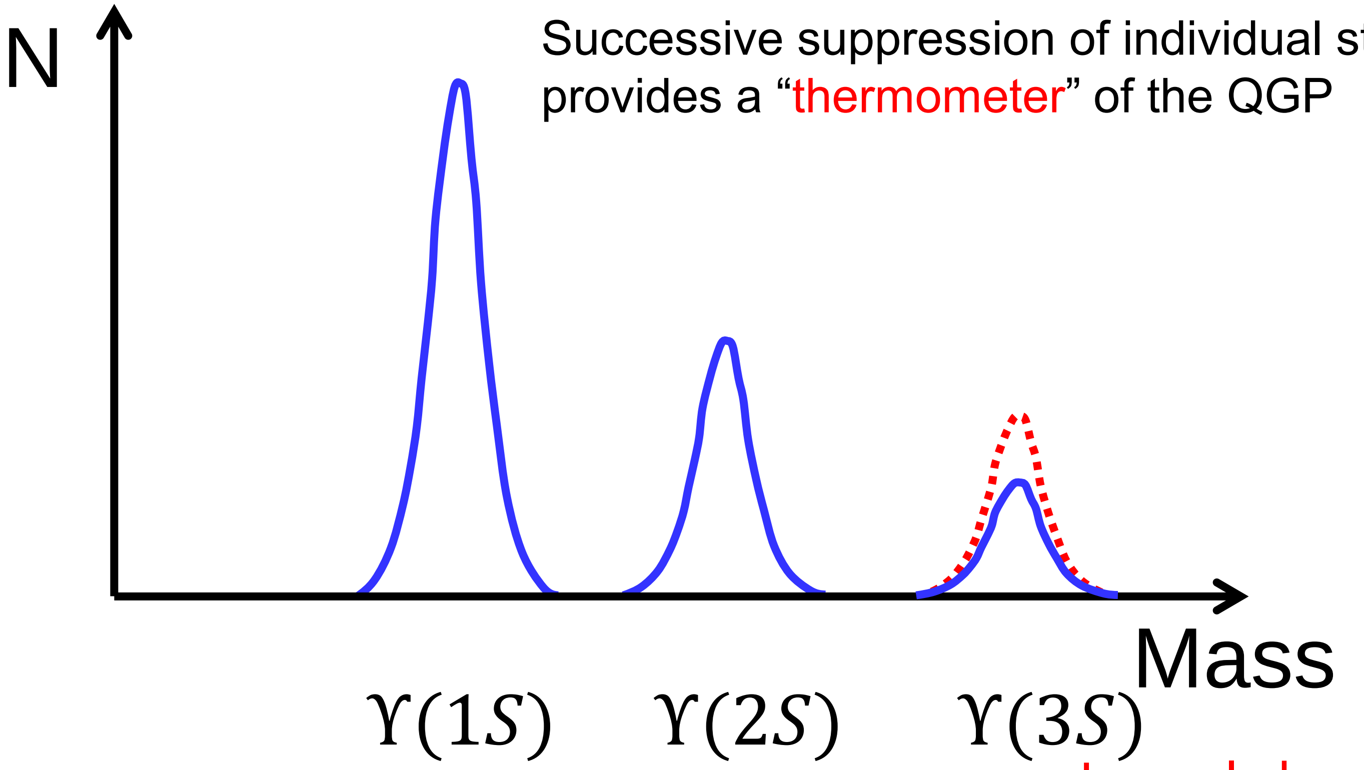
Loosely bound
Small in radius





In QGP (lower Energy AA collisions)

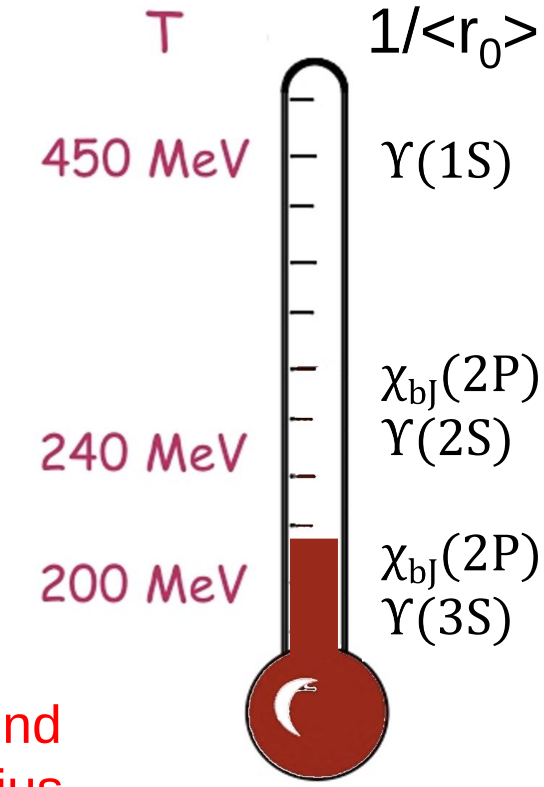
Successive suppression of individual states provides a “thermometer” of the QGP



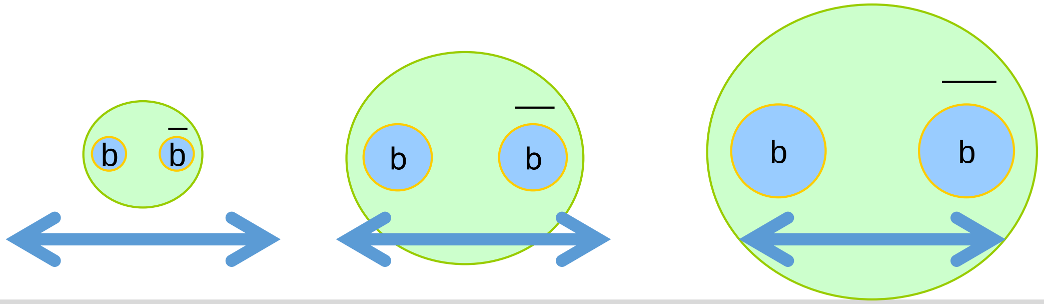
Artist’s impression

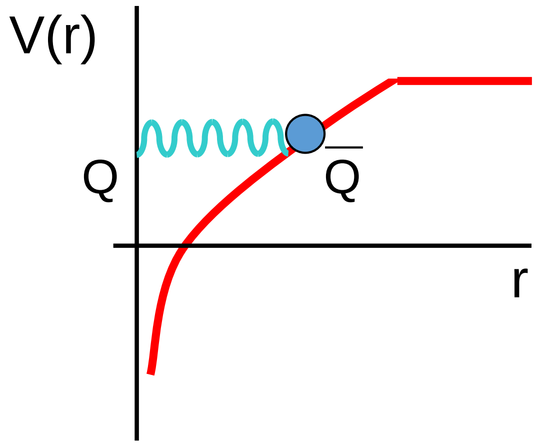
Tightly bound
Small in radius

Loosely bound
Small in radius



Debye Screening Length

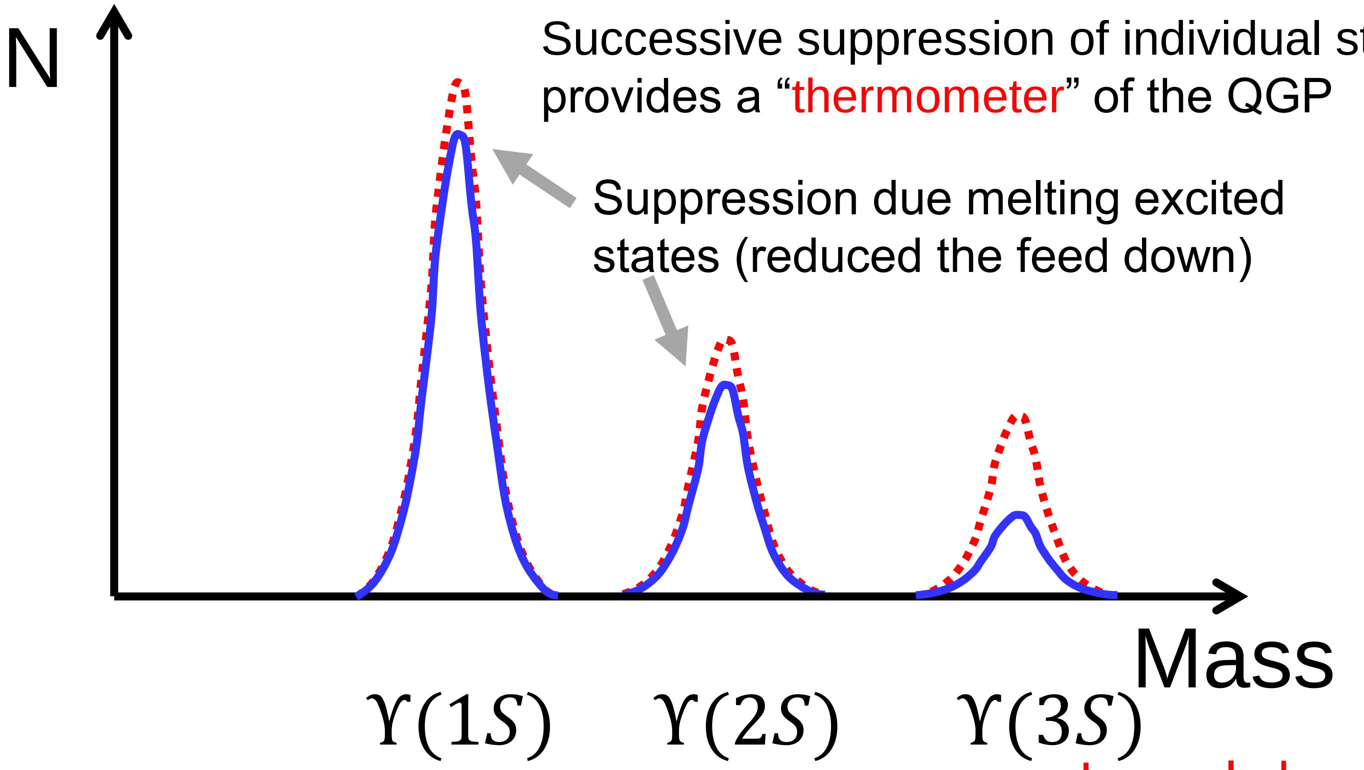




In QGP (AA collisions)

Successive suppression of individual states provides a "thermometer" of the QGP

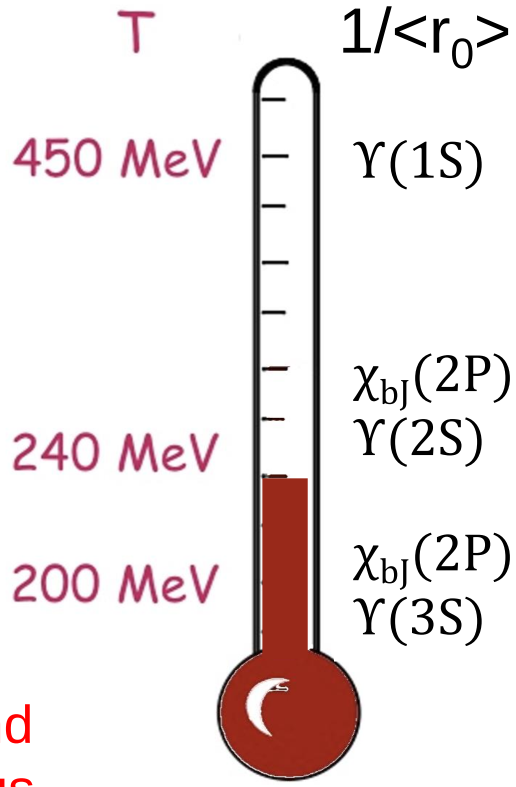
Suppression due melting excited states (reduced the feed down)



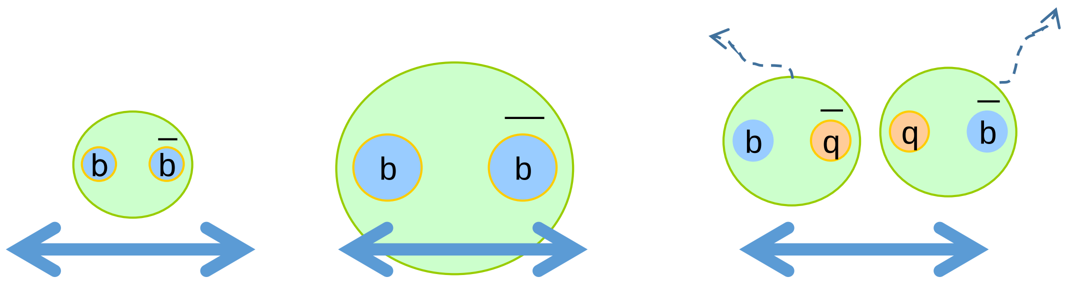
Artist's impression

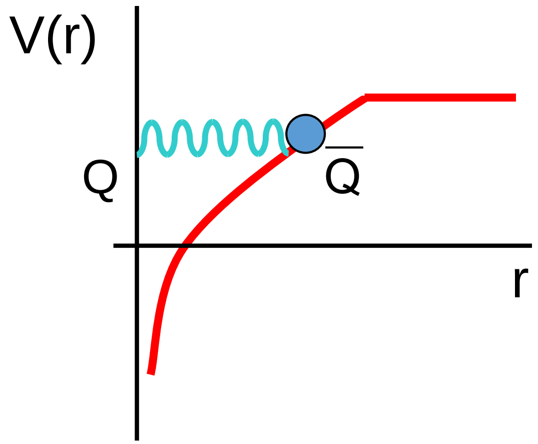
Tightly bound
Small in radius

Loosely bound
Small in radius

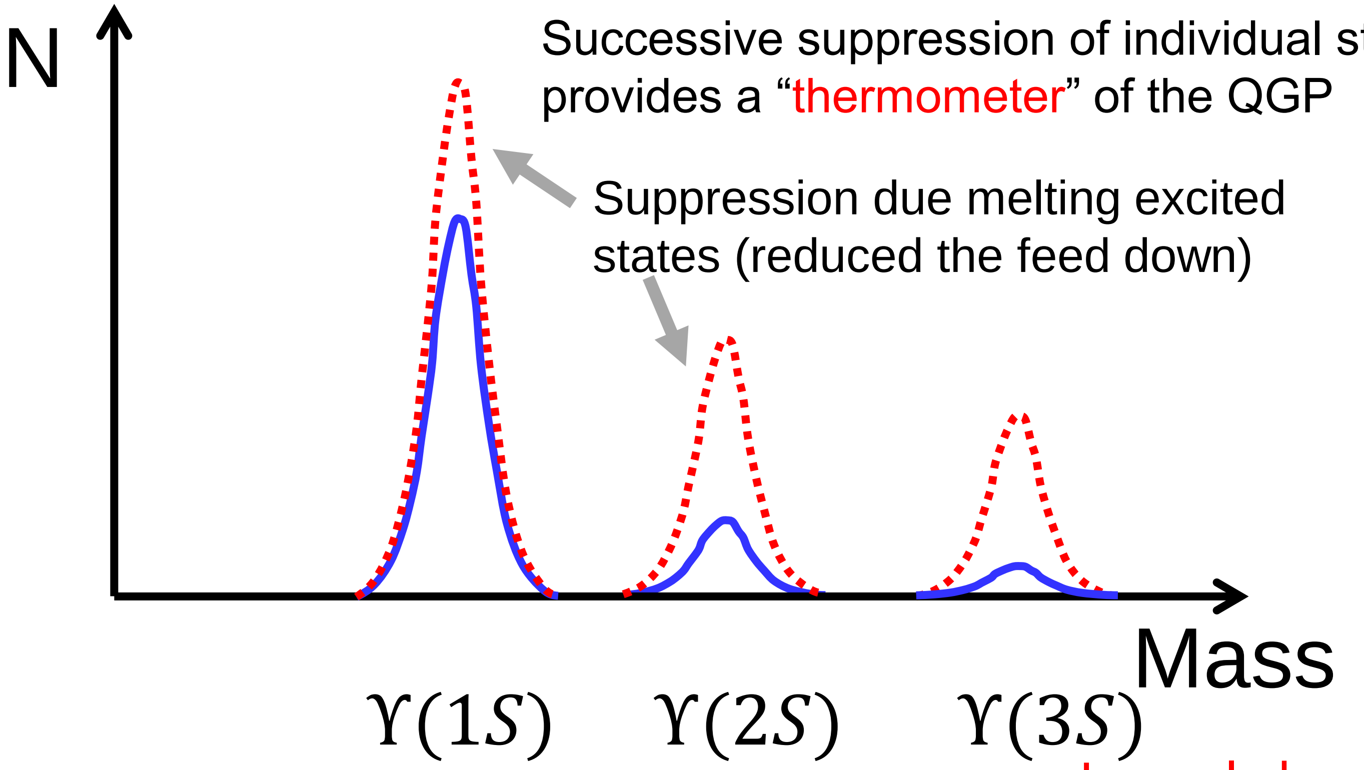


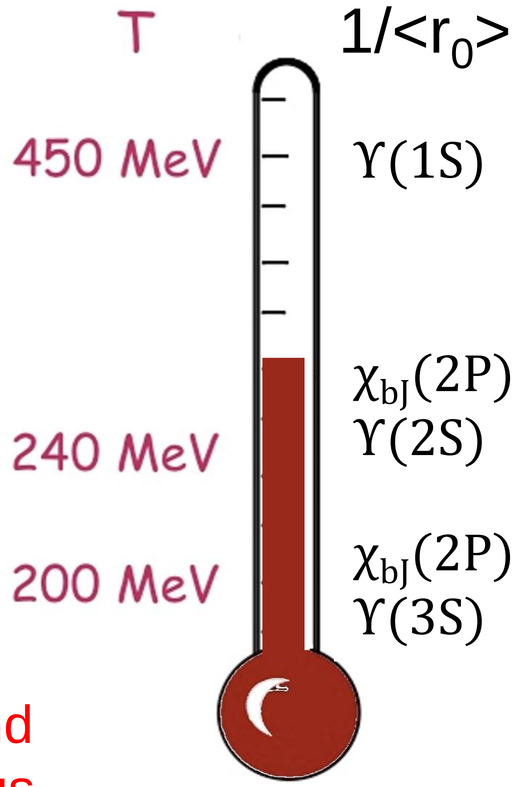
Debye Screening Length





In QGP (AA collisions)



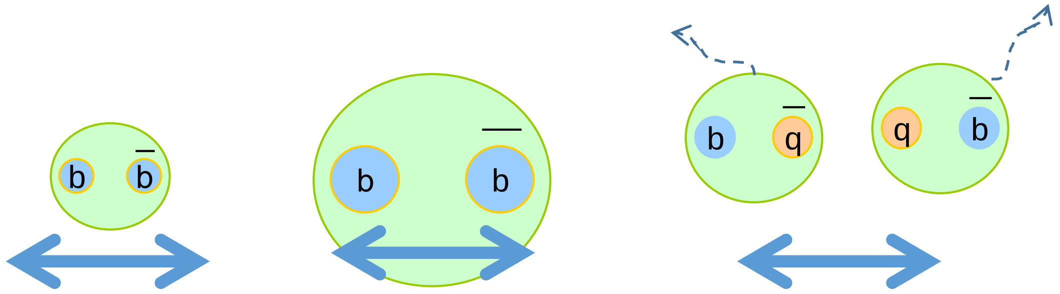


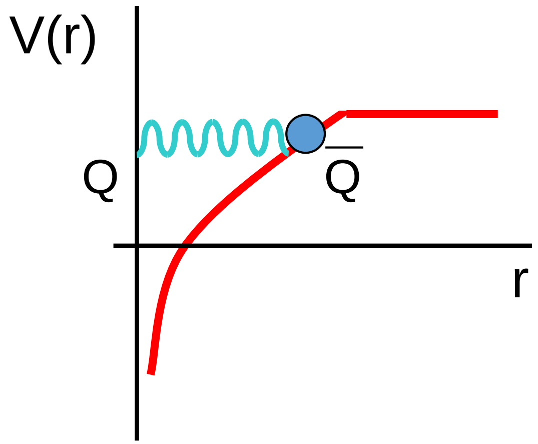
Artist's impression

Tightly bound
Small in radius

Loosely bound
Small in radius

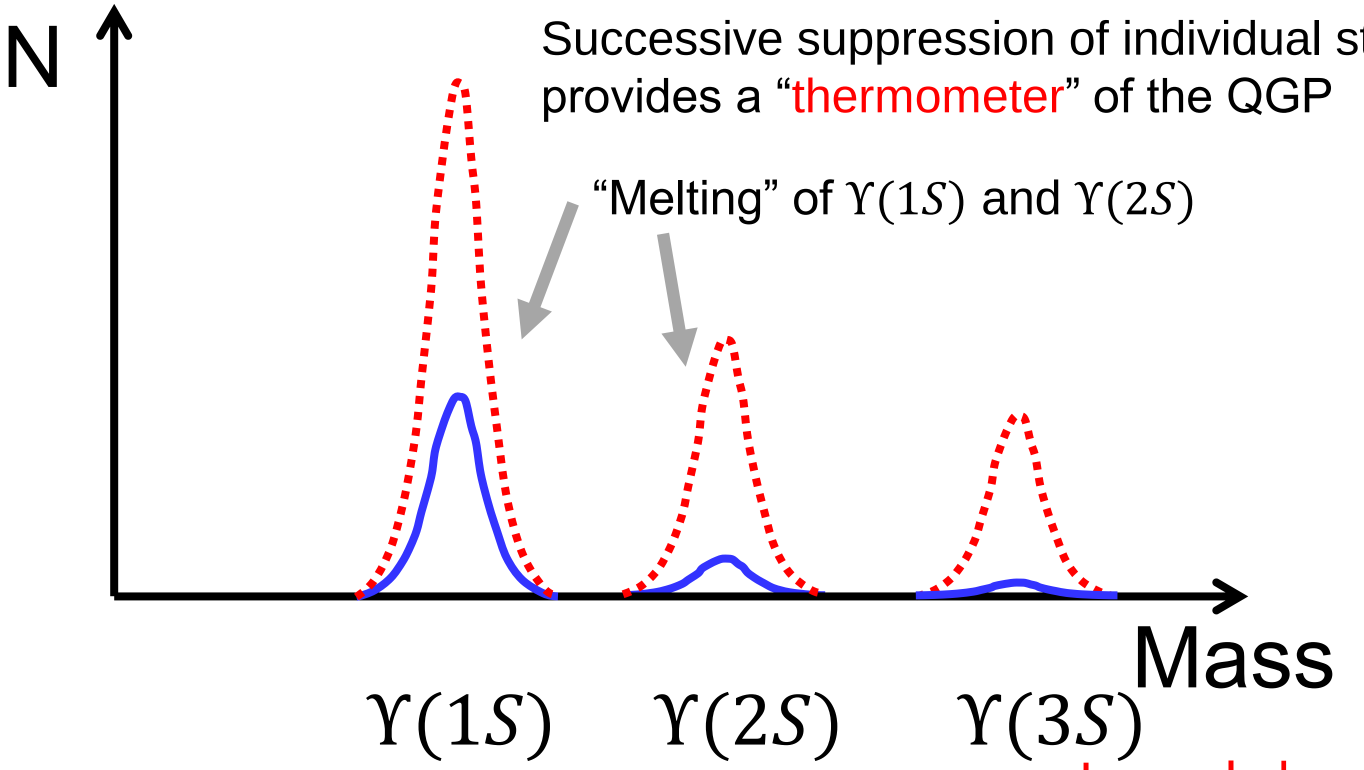
Debye Screening Length



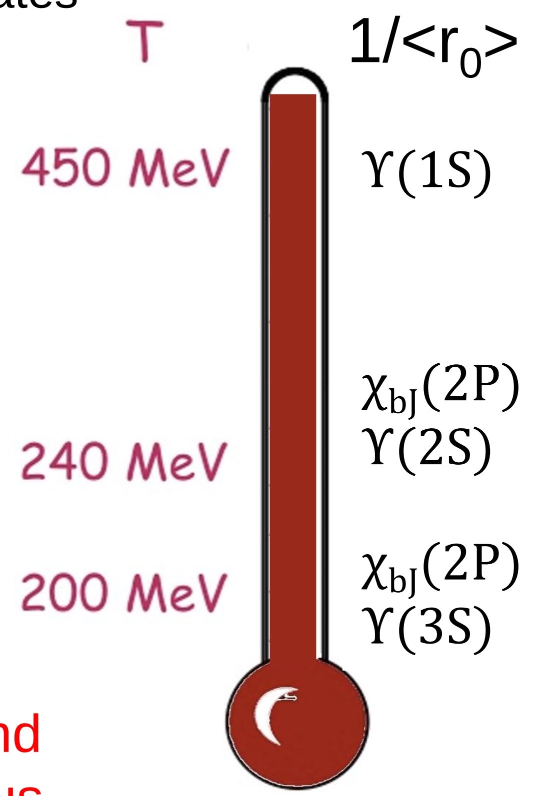


In QGP (AA collisions at LHC)

Successive suppression of individual states provides a “thermometer” of the QGP



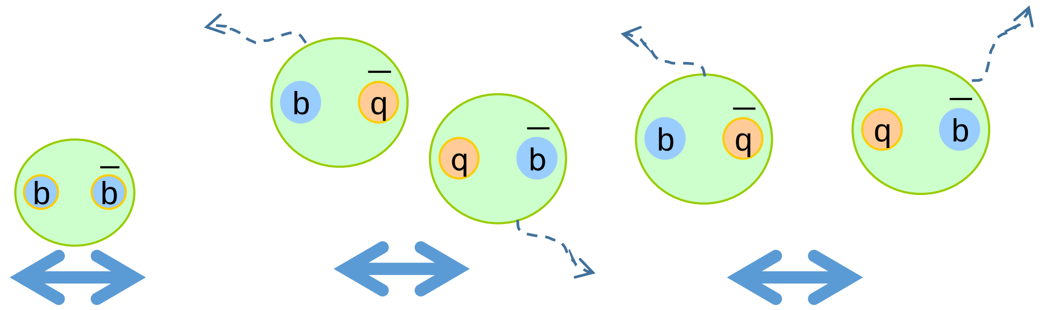
Artist’s impression

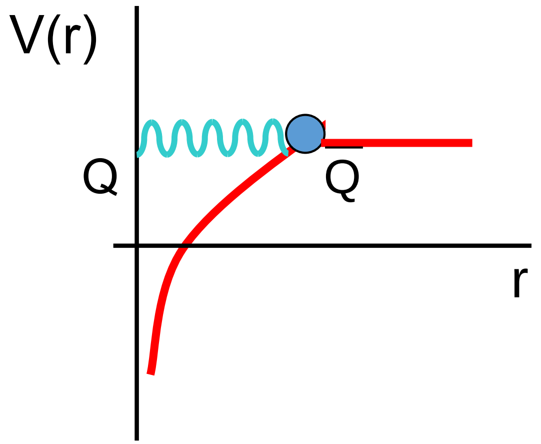


Tightly bound
Small in radius

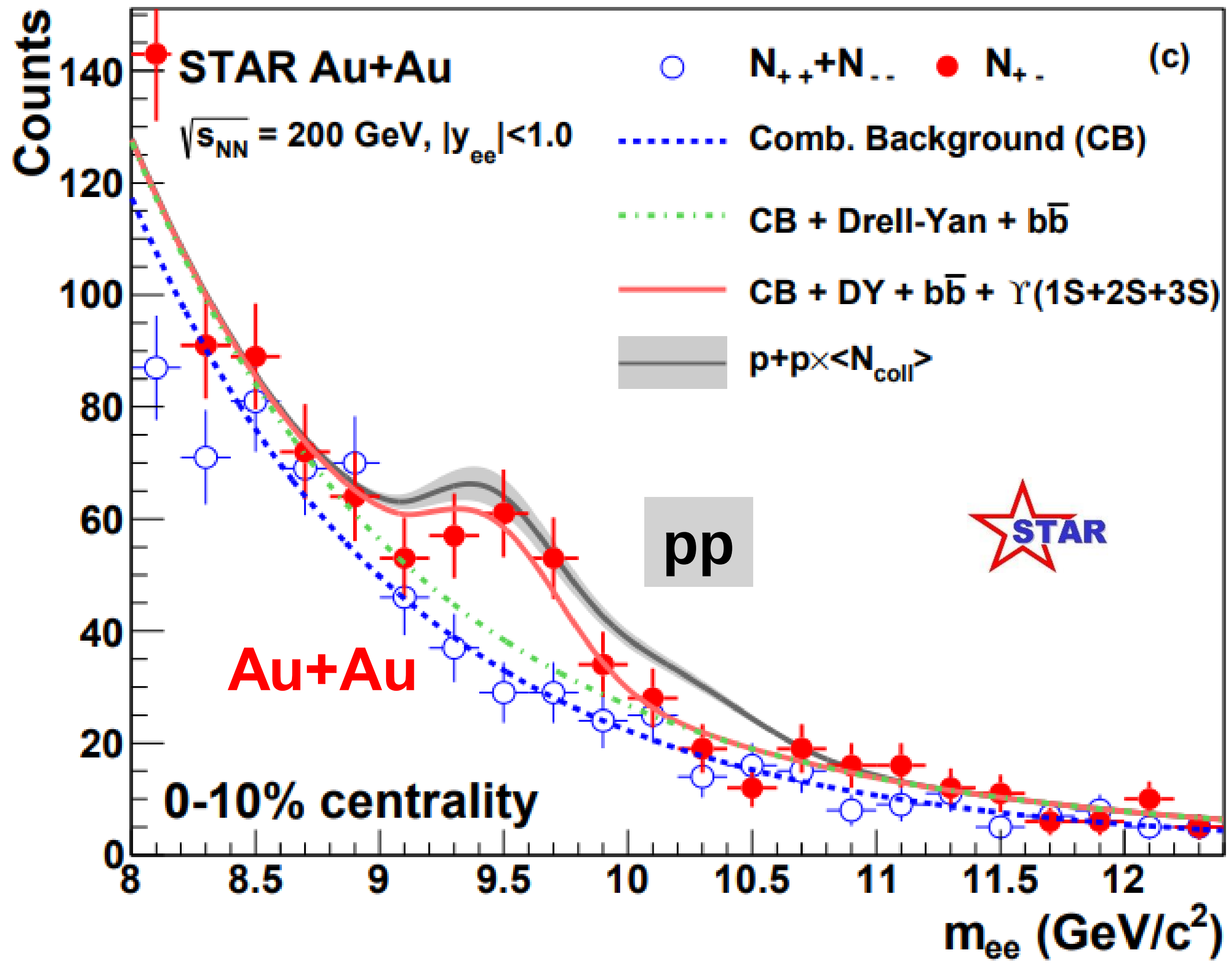
Loosely bound
Small in radius

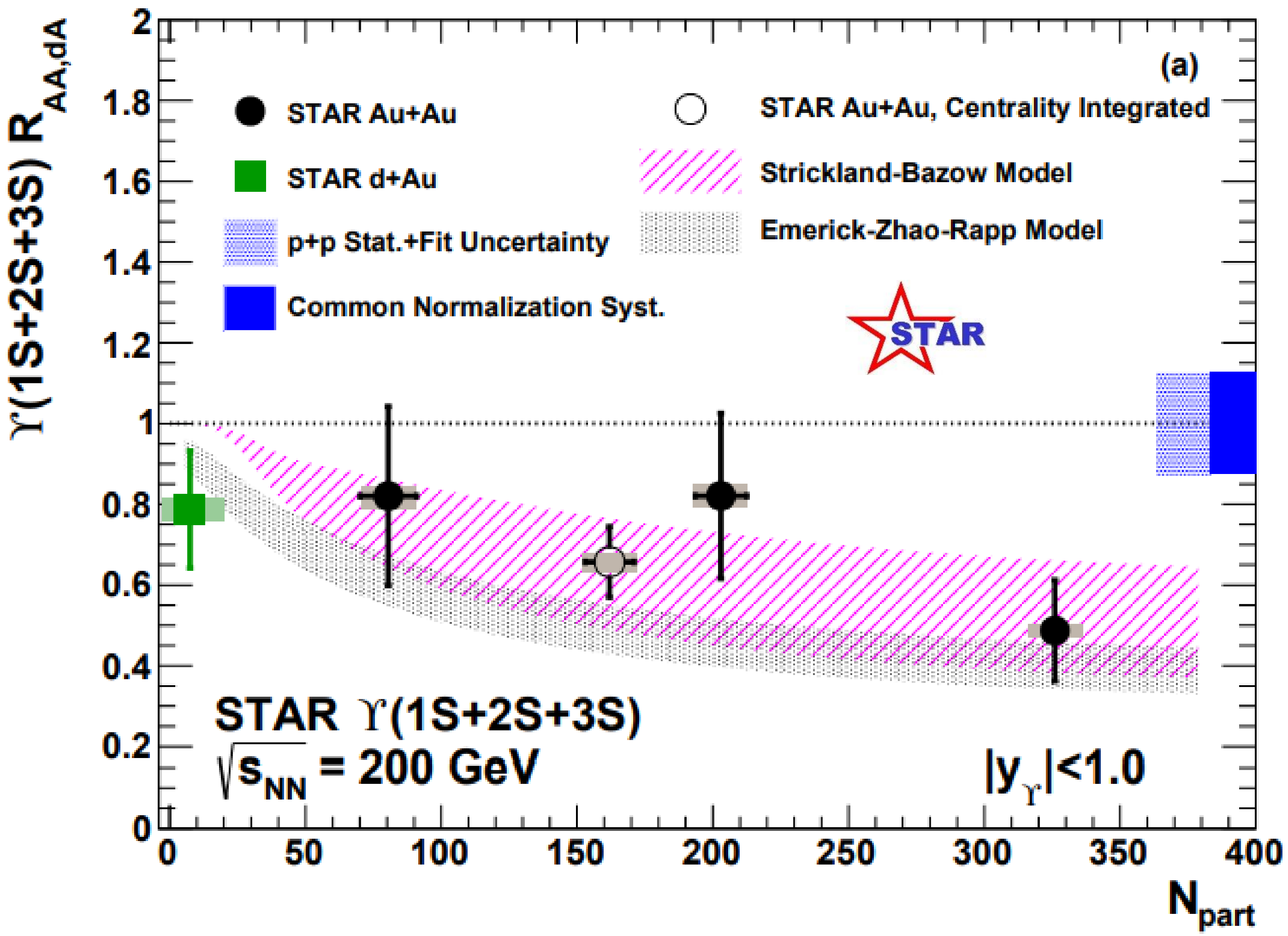
Debye Screening Length





Inclusive Upsilon Spectra at RHIC

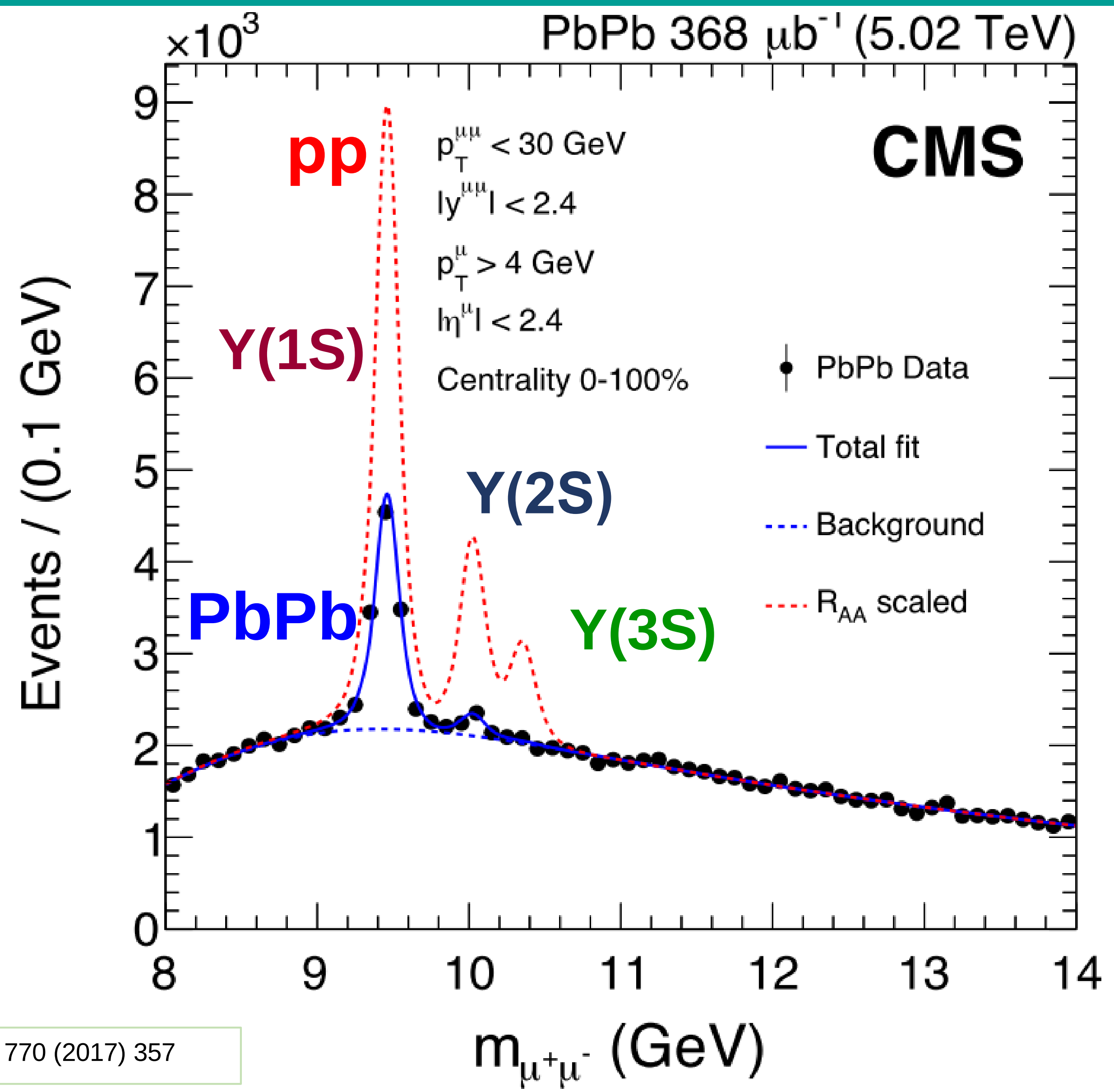




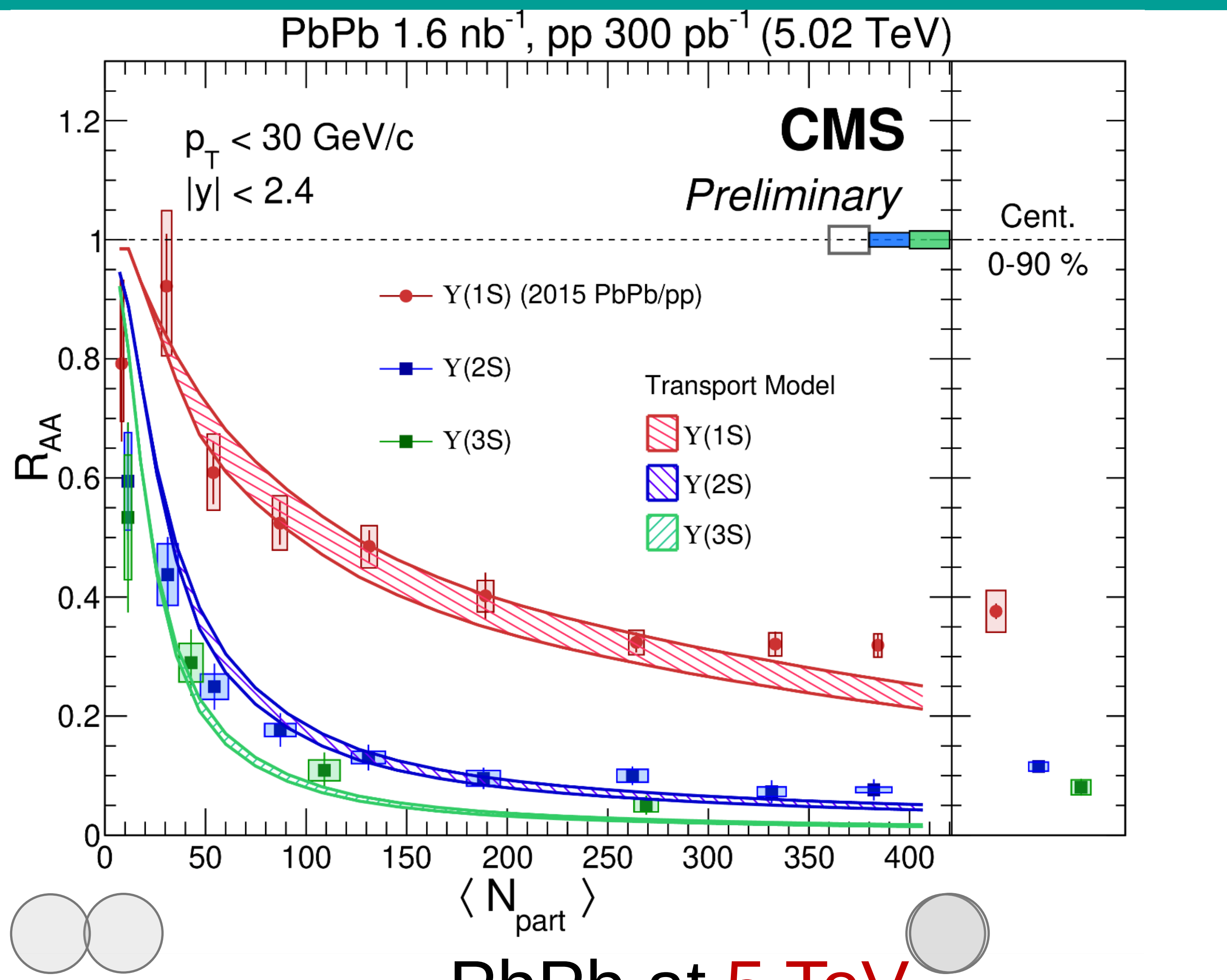
Au+Au at 200 GeV

- Significant suppression of the Upsilon states in central Au+Au collisions
- Extracted initial medium temperature **330 - 442 MeV** based on the models

Inclusive Upsilon Spectra at LHC



PLB 770 (2017) 357



PbPb at 5 TeV

CMS-PAS-HIN-21-007

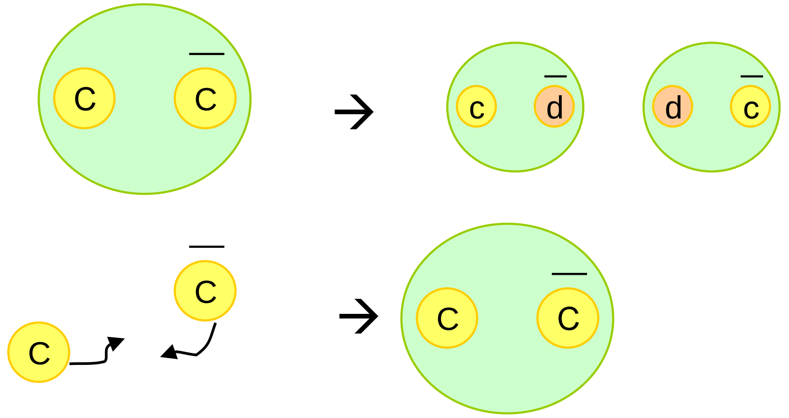
- Consistent with models **with Υ(1S) melting** and (with or without) Υ regeneration
- Extracted initial medium temperature **550 - 800 MeV** based on models

Quarkonia in Heavy Ion Collisions

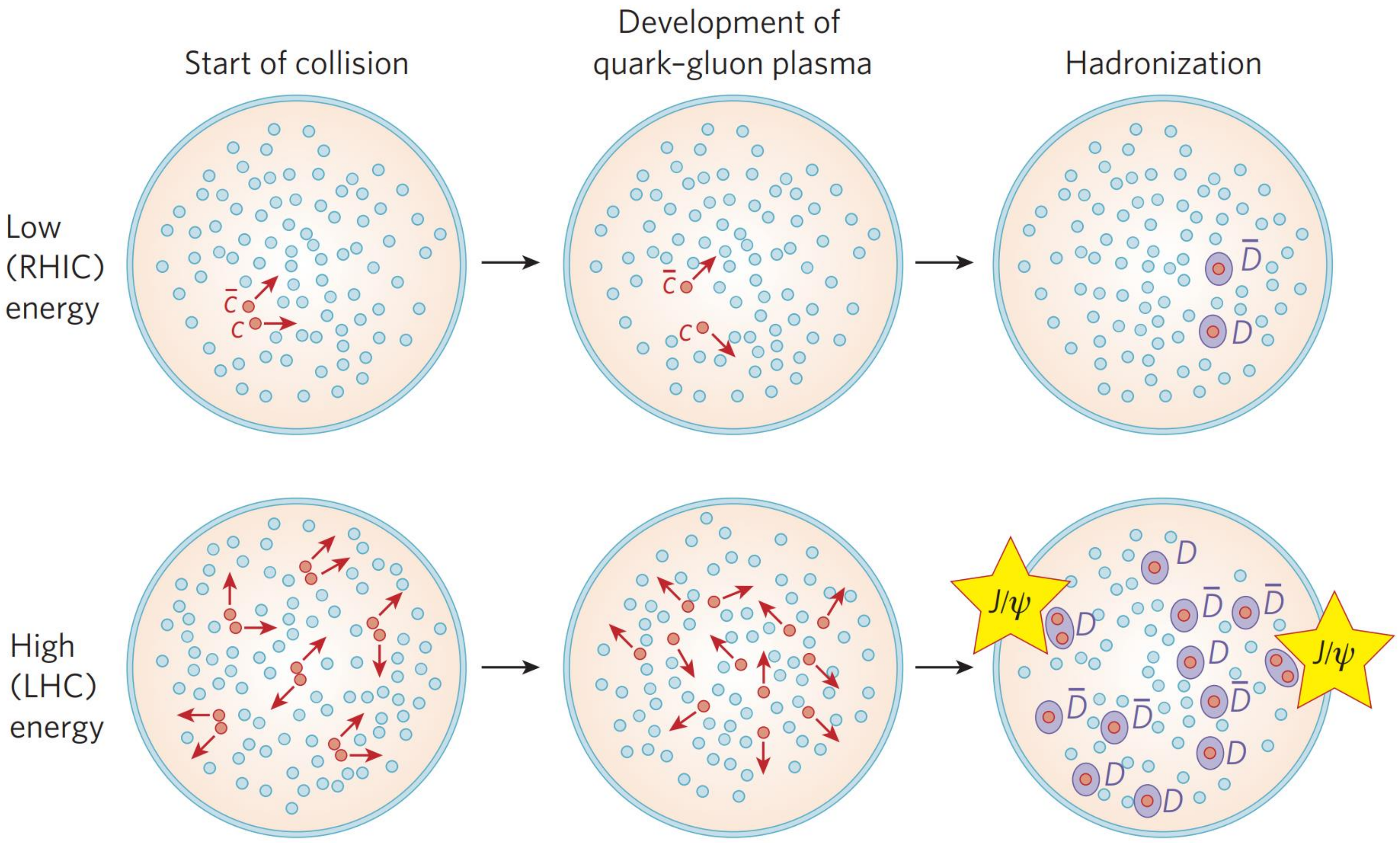
Good picture for guiding the discussion! However, the story is far more complicated…

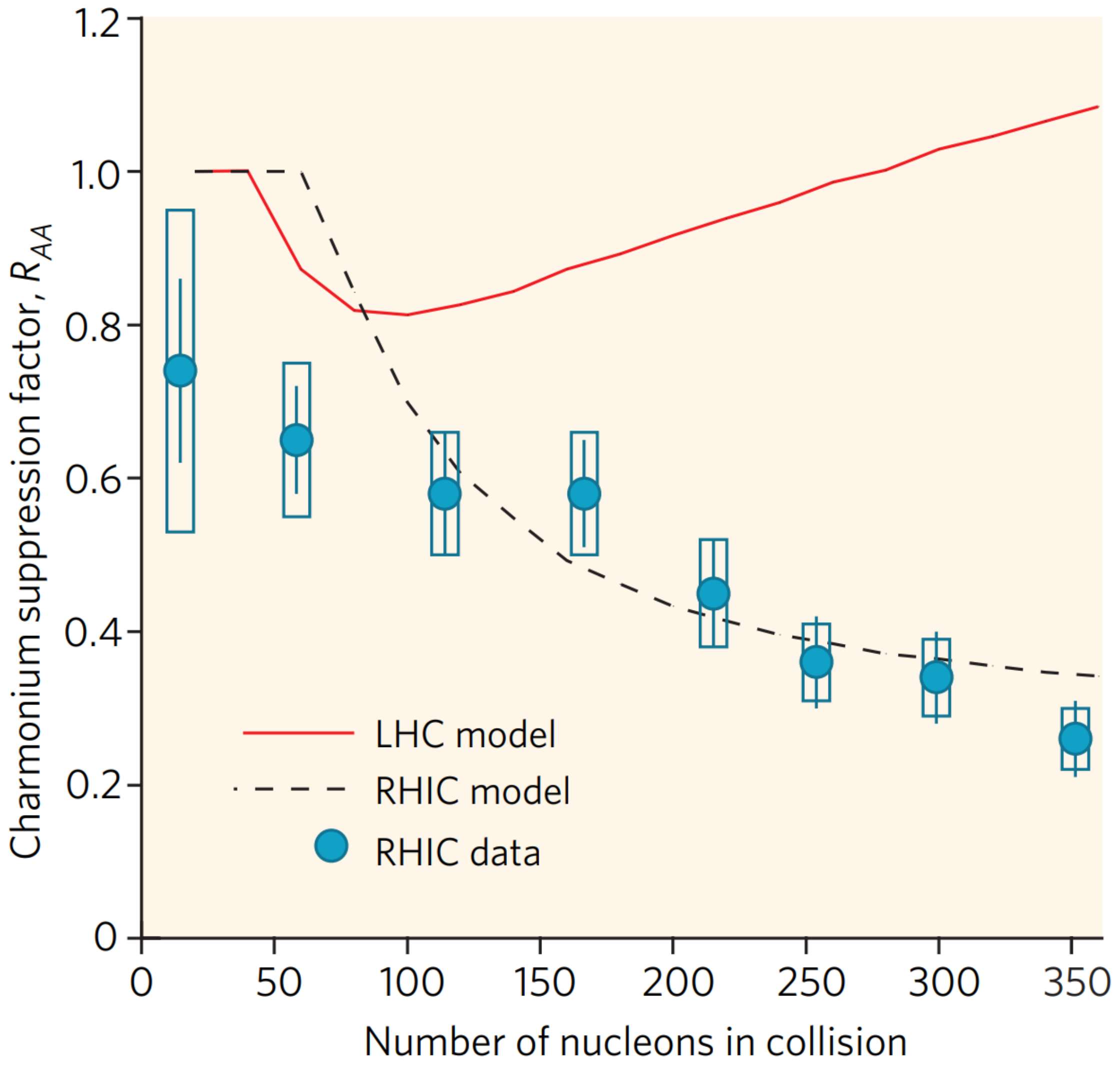
- **Cold effects:**
  - Shadowing effect (nPDF vs. PDF)
  - Nuclear absorption (multiple scattering of QQbar within nucleus)
  - Hadronic co-mover (dissociation in the dense hadonic medium)
  - …

- **Hot effects**:
  - Sequential suppression
    - Medium temperature is not uniform in QGP
  - **Quarkonia (re-)generation contribution**



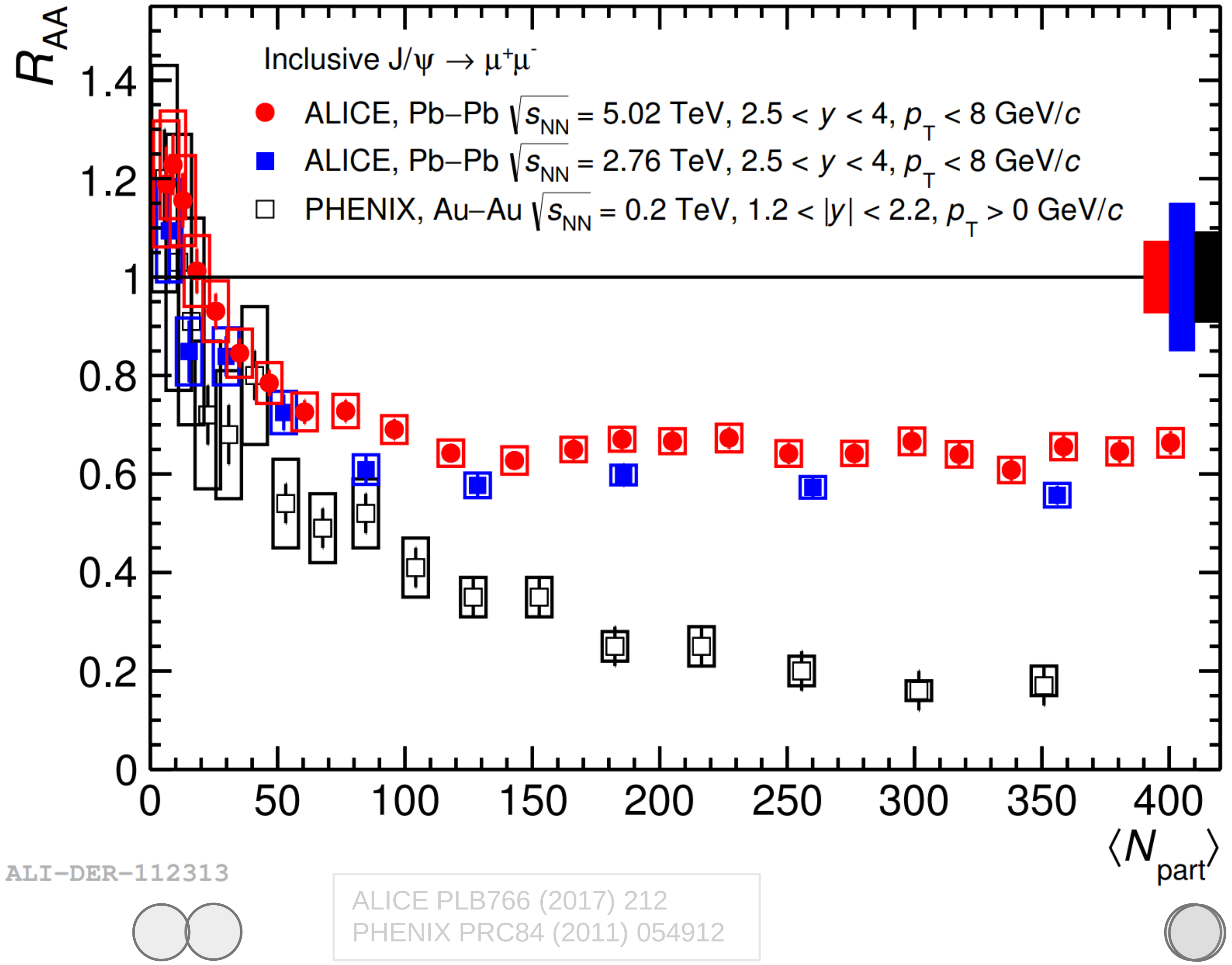
Collision Energy Dependence of Charmonium Production

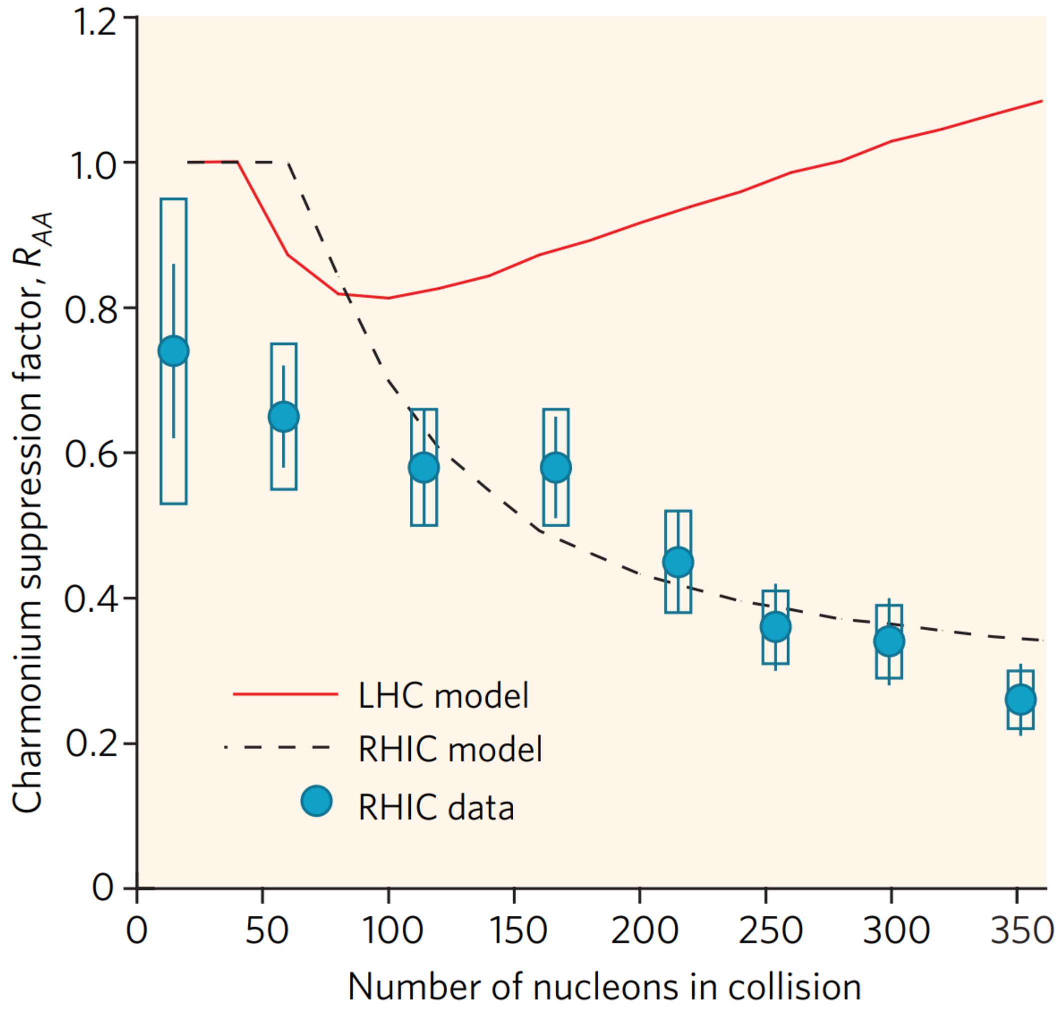


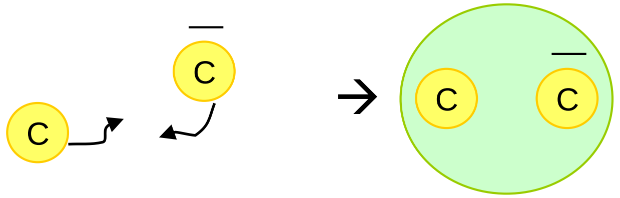


Nature 448, 302–309 (2007)

Inclusive J/ψ R_{AA}

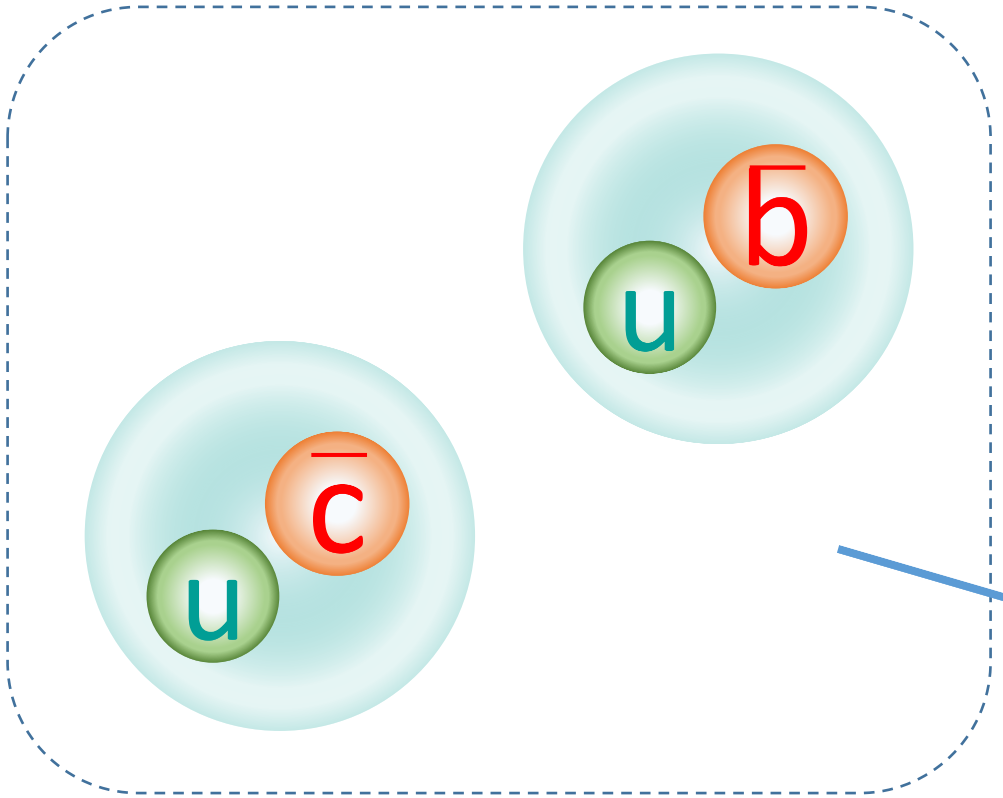


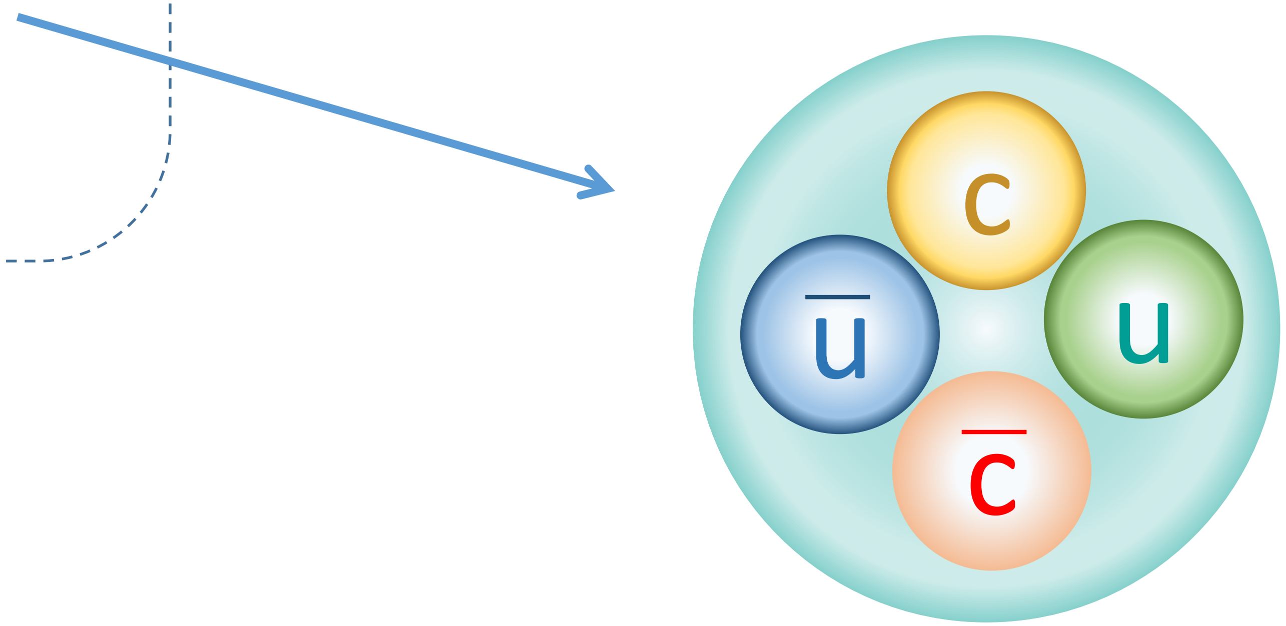




- At RHIC: large J/ψ suppression in central collisions
- At LHC where the ccbar cross-section is a lot larger:
  - Reduced suppression at low p_T

Beyond the Studies of HF Mesons: X(3872)





Increase the number
of valence quarks!!

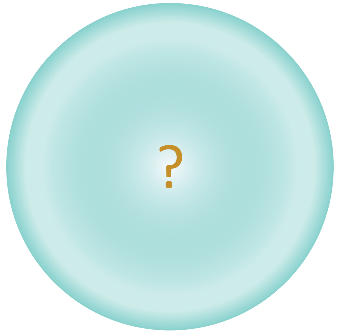
X(3872)

X(3872): Observed by Belle (2003), its internal structure is still under debate

- Quantum number determined by CDF and LHCb data: **J^{PC}=1^{++}**
- **Charmonium** interpretation: **abandoned**, predict wrong mass with J^{PC}=1^{++}
- Remaining possibilities:
  - D-$\overline{D}^*$ hadron molecule: mass X(3872) ≈ D(1875)$\overline{D}^*$(2007), large & extended state
  - **Tetraquark:** a compact four quark state
  - **Hybrid**: mixed molecule-charmonium state

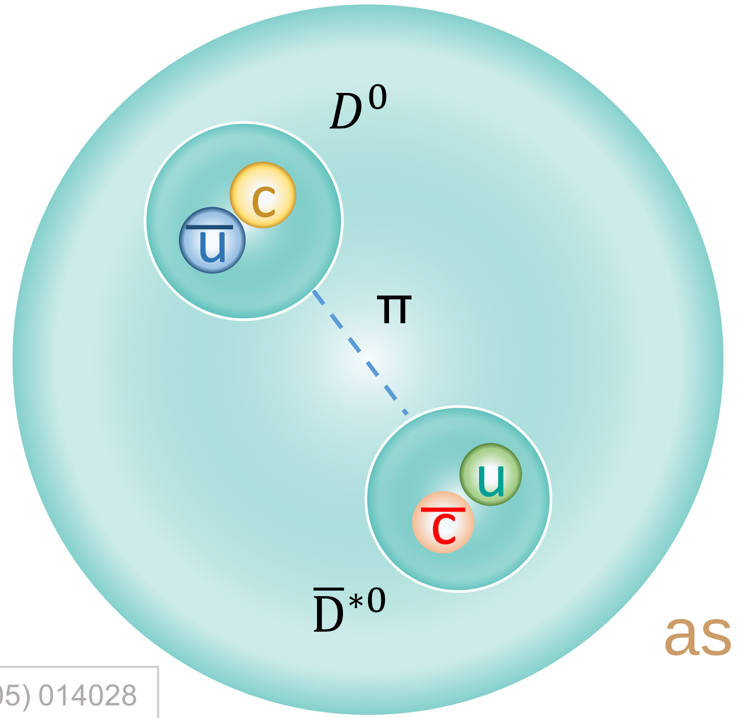
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



EPJA47 (2011) 101

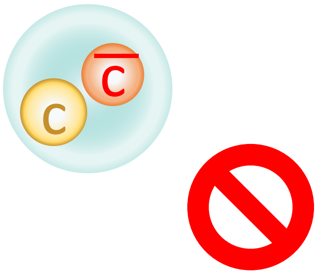
$D^0 - \overline{D}^{*0}$ molecule



$r_{molecule}$ as large as 5 fm

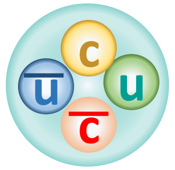
PRD71 (2005) 014028

Charmonium



PLB 590 209-215 (2004)

Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

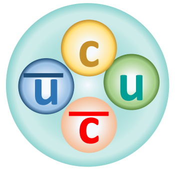
PRD 71 (2005) 014028

Probe the Nature of X(3872)

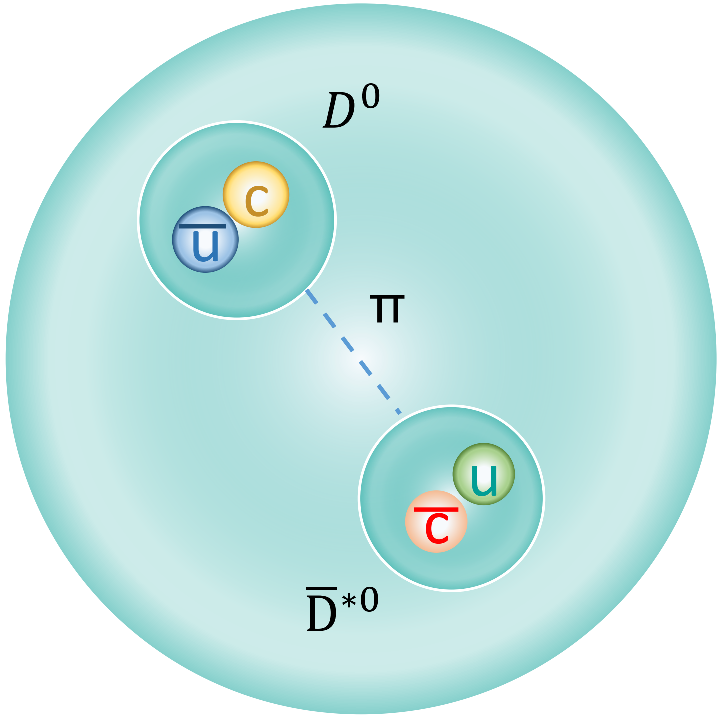
Tightly bound

Loosely bound

Tetraquark (4q)



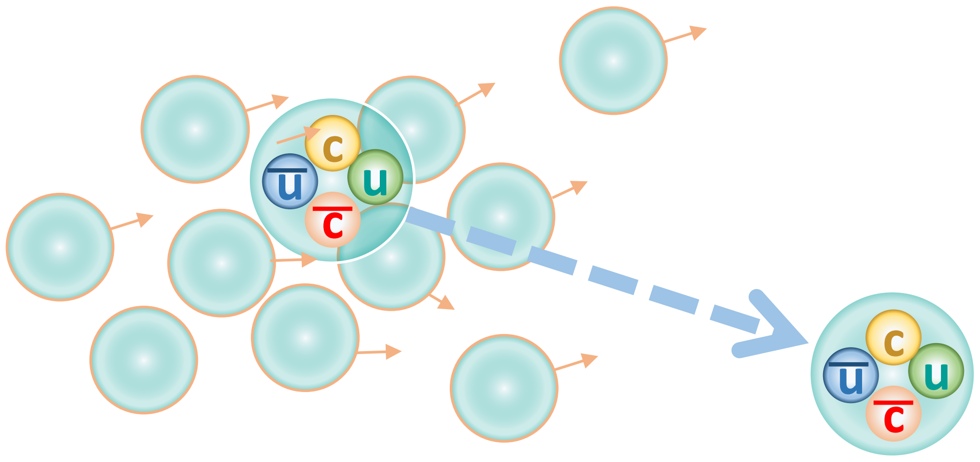
$D^0 - \bar{D}^{*0}$ molecule



- However, the lifetime of X(3872) is extremely short!

Tightly bound

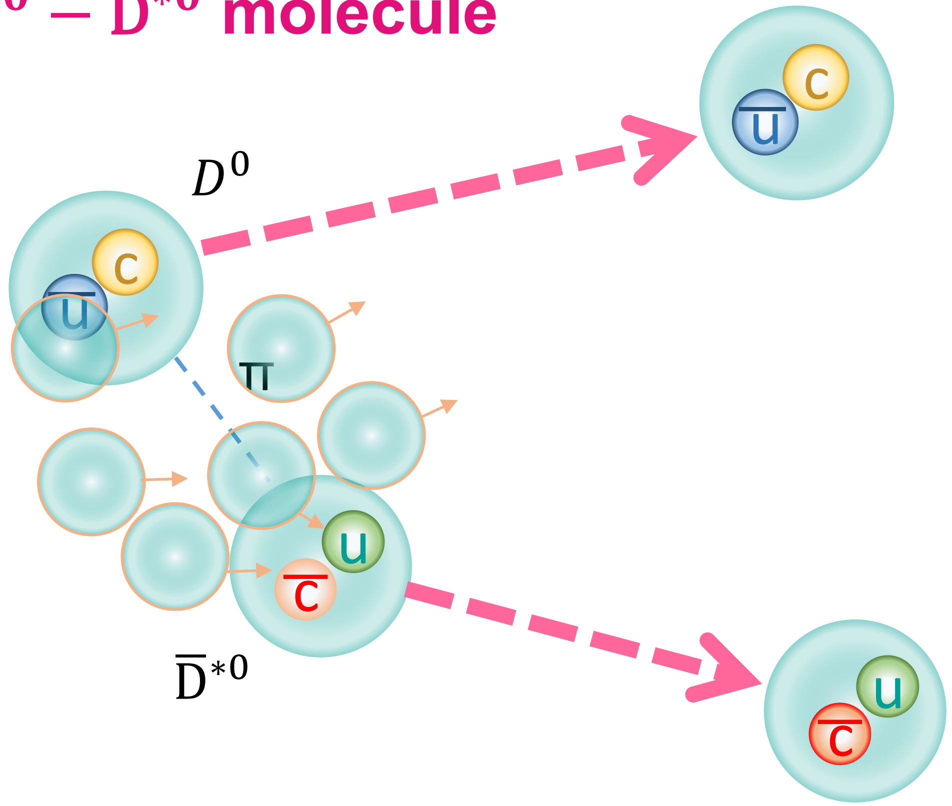
Tetraquark (4q)



Comoving particles

Loosely bound

$D^0 - \overline{D}^{*0}$ molecule



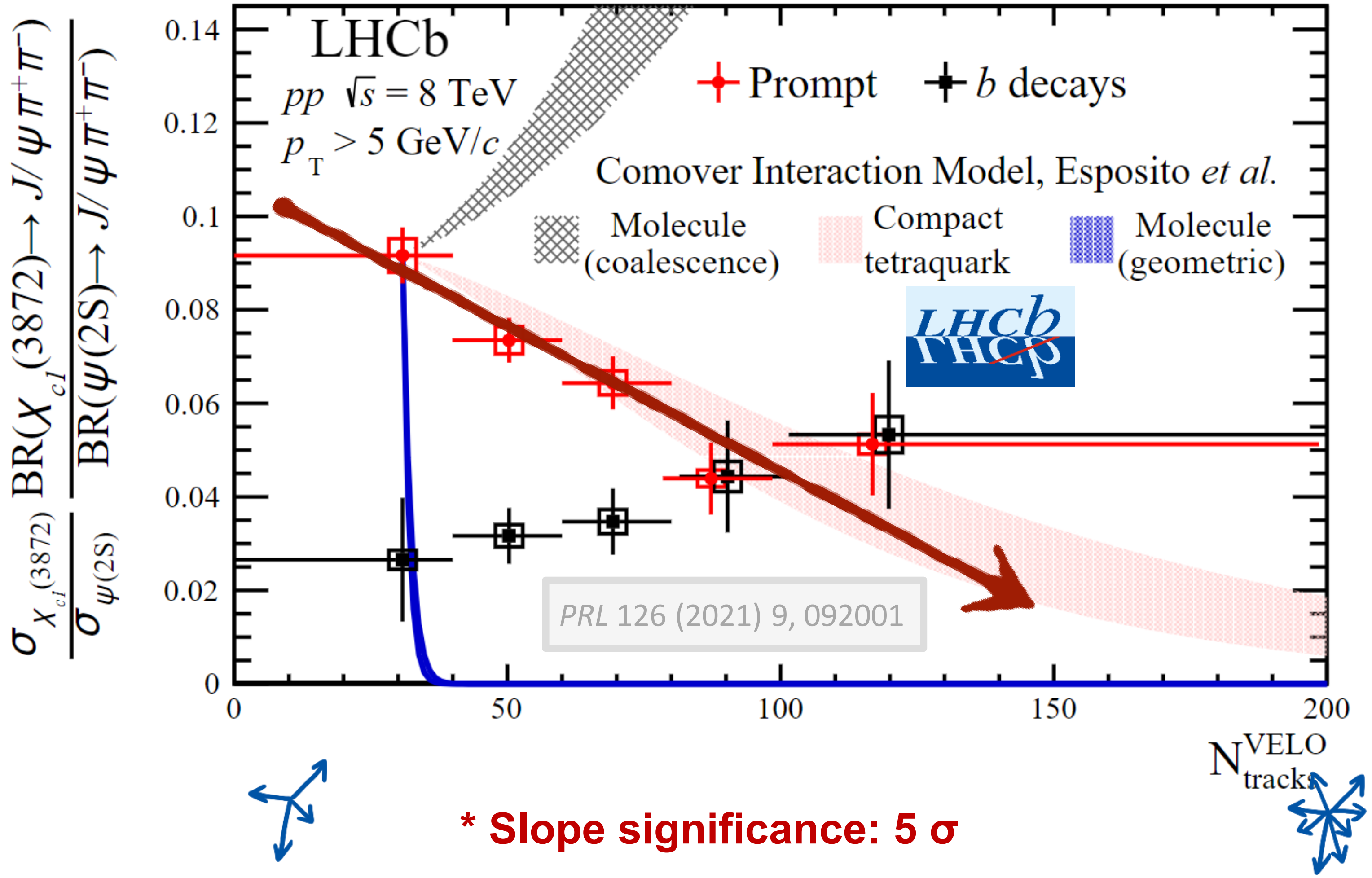
Smaller dissociation probability

Larger dissociation probability

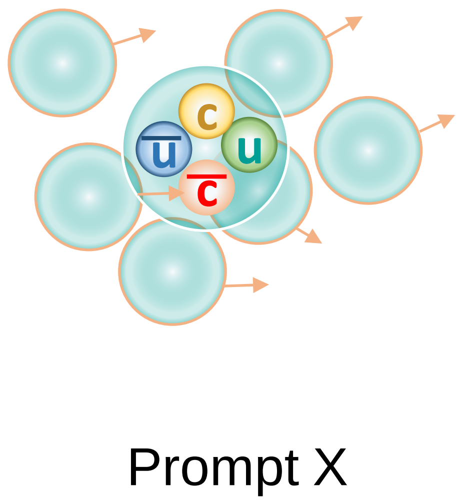
Esposito et al, arXiv: 2006.15044

X(3872) in High Multiplicity pp from LHCb

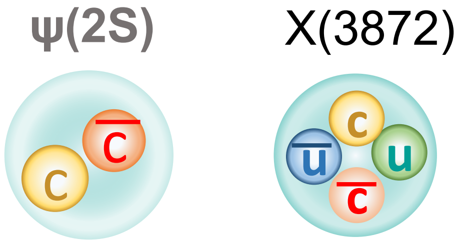
Prompt X(3872)/ψ(2S) vs. multiplicity in pp



* **Slope significance: 5 σ**

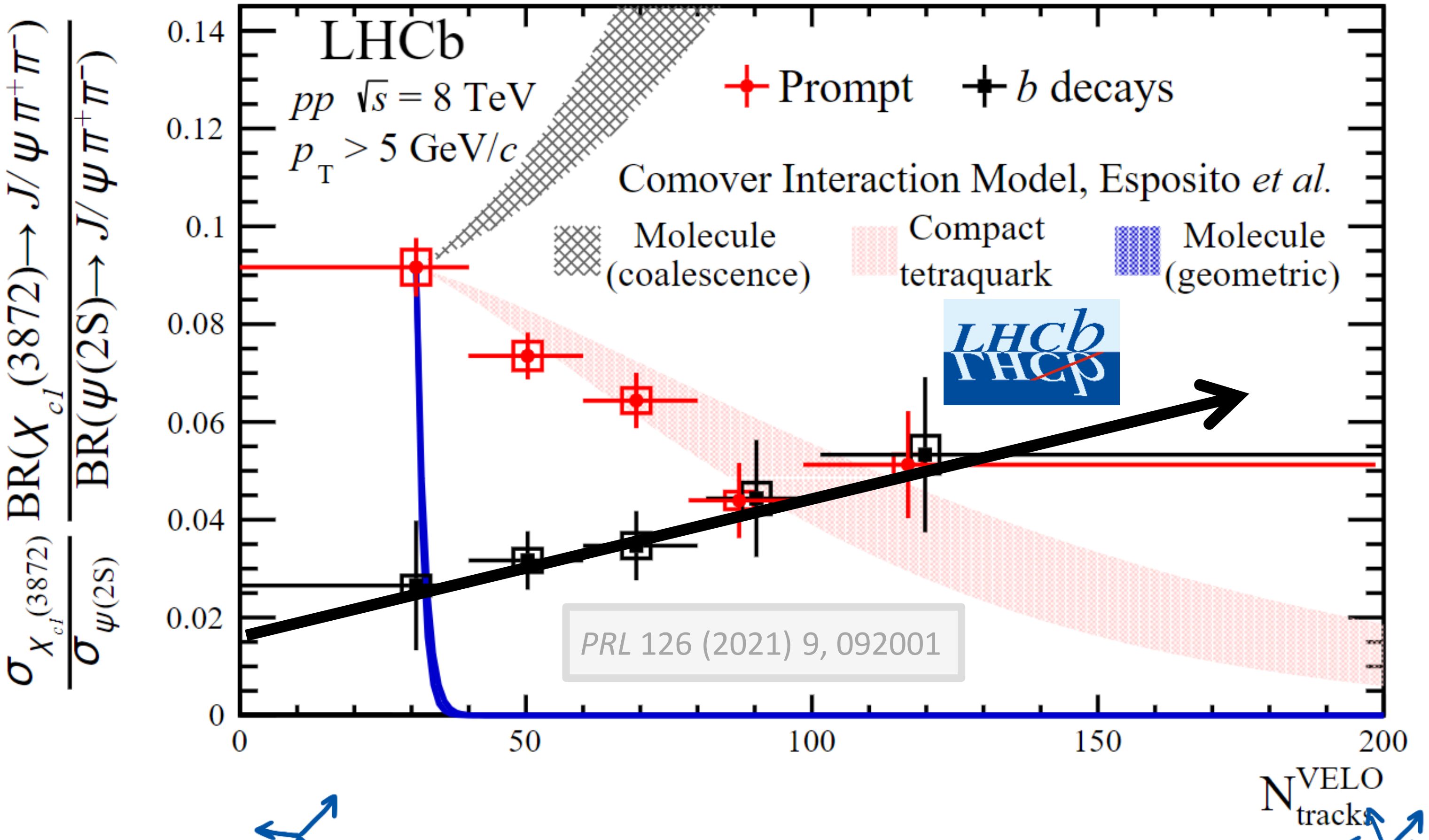


- Destroyed by interactions with other hadrons due to smaller binding energy?



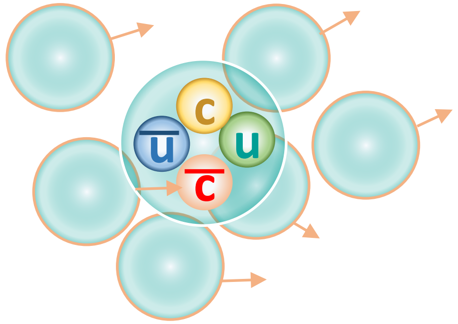
Non-prompt X(3872) in pp from LHCb

Prompt X(3872)/ψ(2S) vs. multiplicity in pp

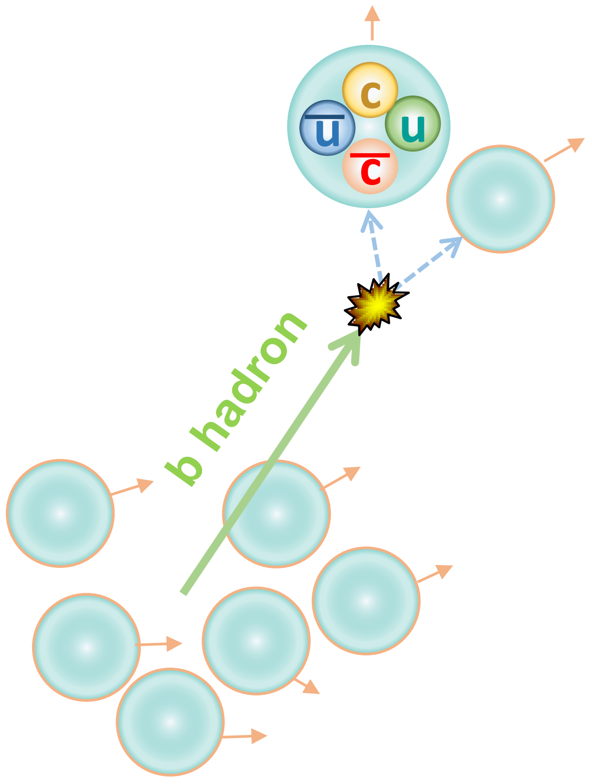


* **Slope significance: 1.6 σ**

- X(3872) from b decays seems to follow a different trend

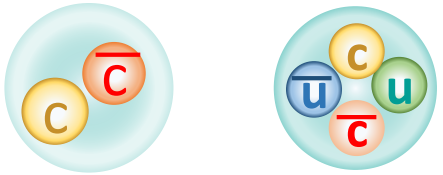


Prompt X



b hadron → X + hadrons

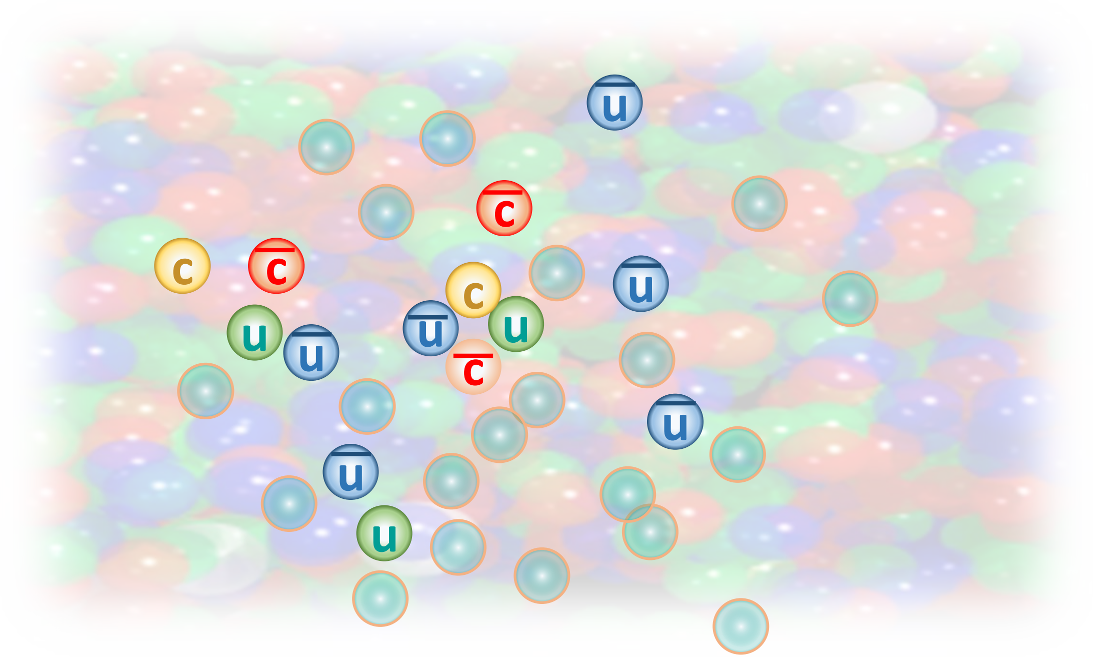
ψ(2S) X(3872)



Production of X(3872) in Heavy Ion Collisions

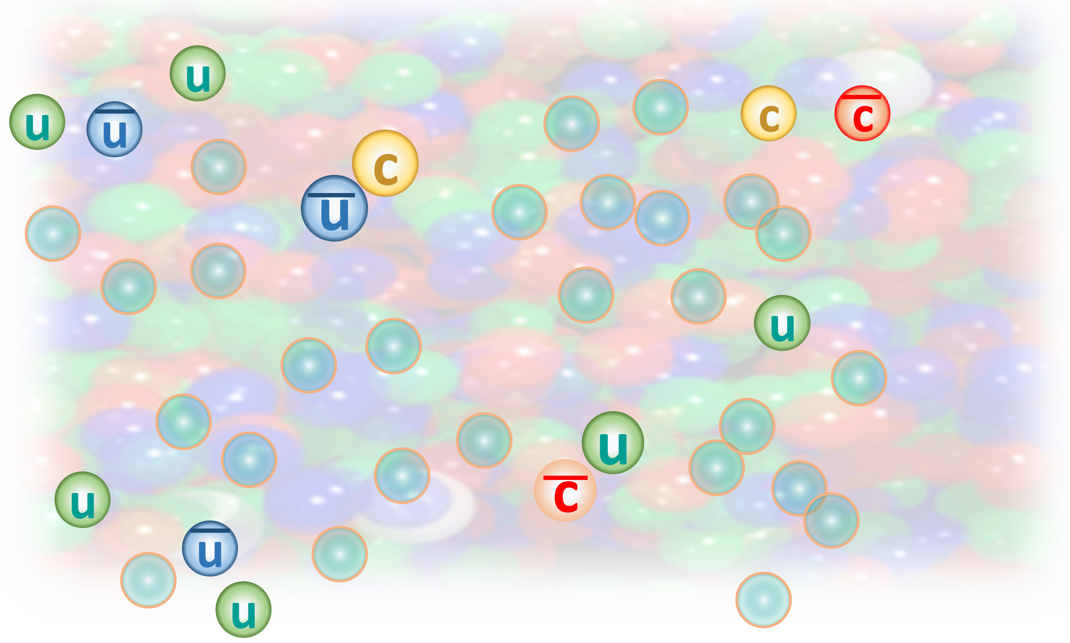
Tightly bound

Tetraquark (4q)



Loosely bound

$D^0 - \bar{D}^{*0}$ molecule

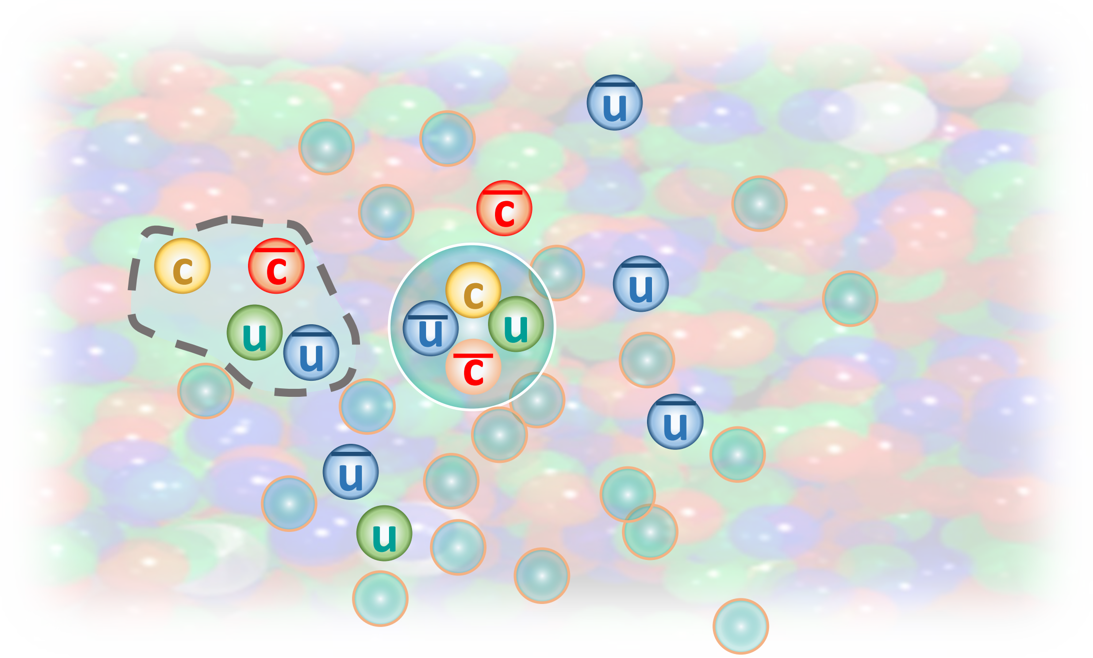


Production of X(3872) in Heavy Ion Collisions

Jinfeng Liao + collaborators
PRL 126 (2021) 1, 012301

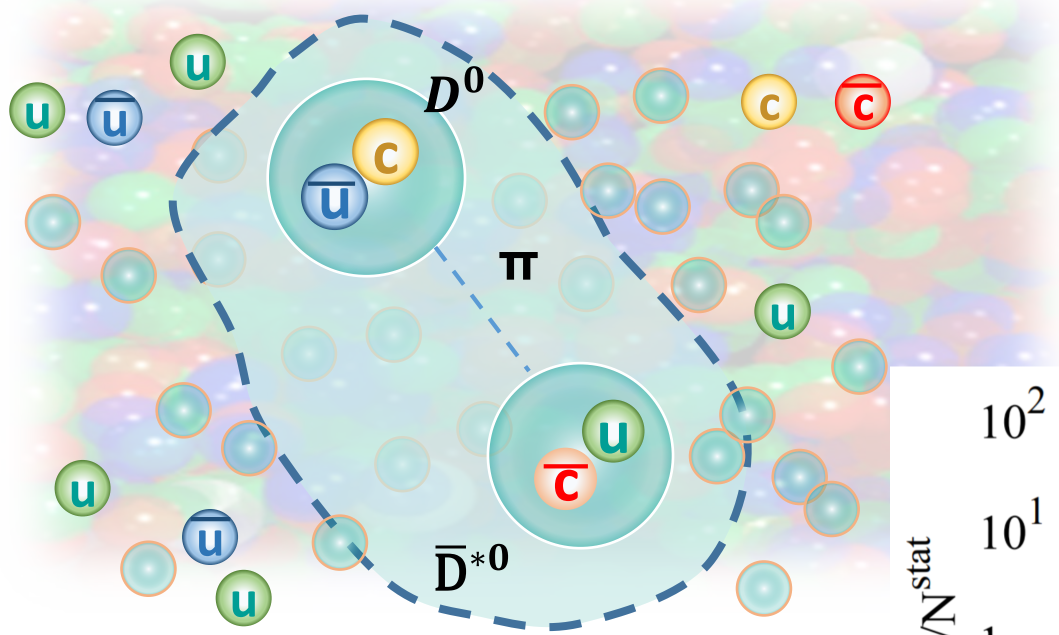
Tightly bound

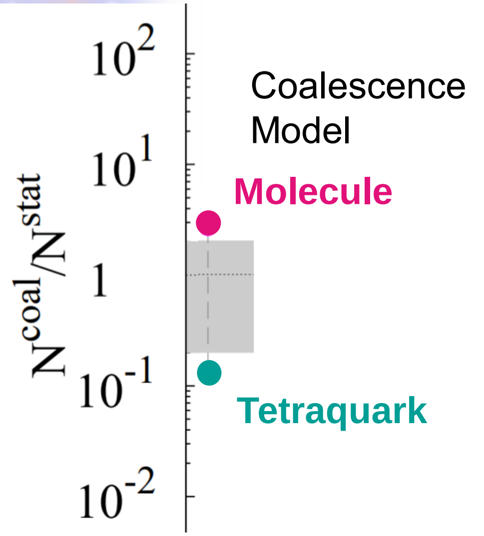
Tetraquark (4q)



Loosely bound

$D^0 - \bar{D}^{*0}$ molecule



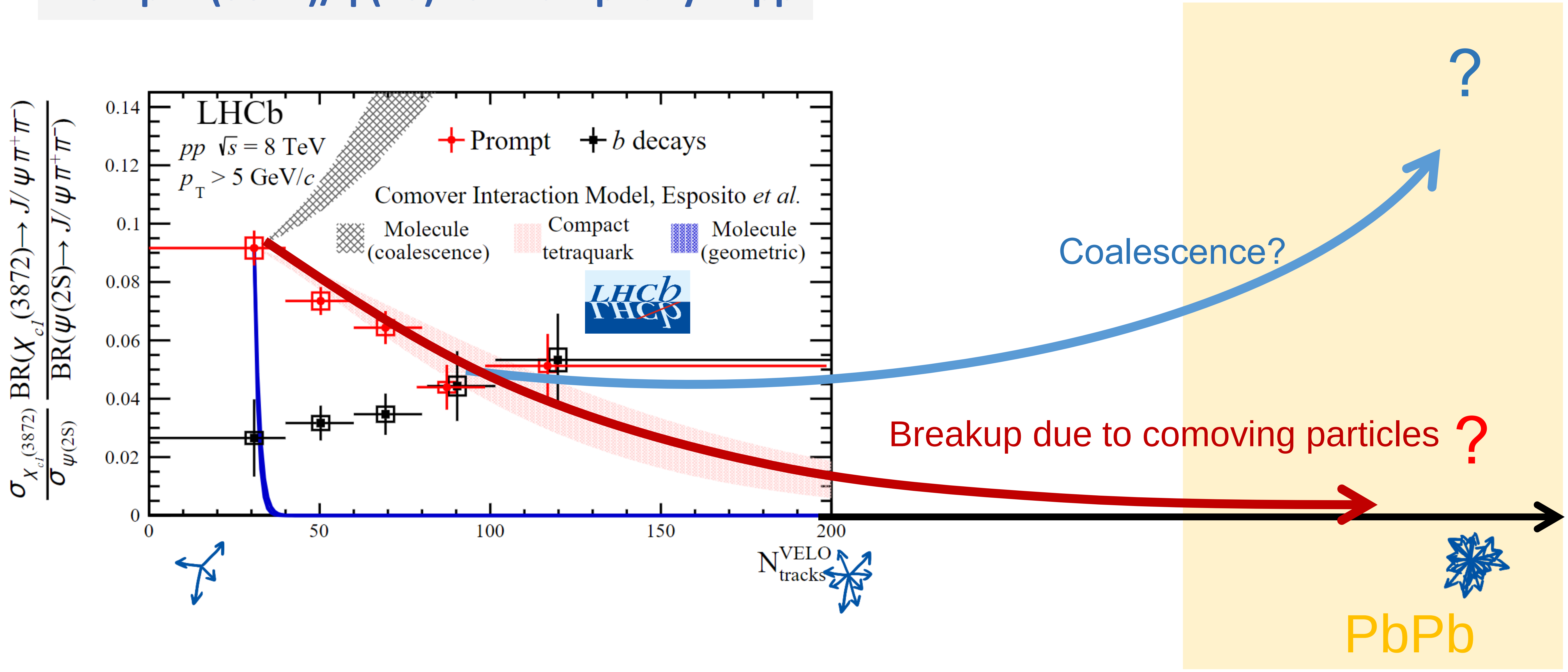


ExHIC Collaboration
PRL 106 (2011) 212001

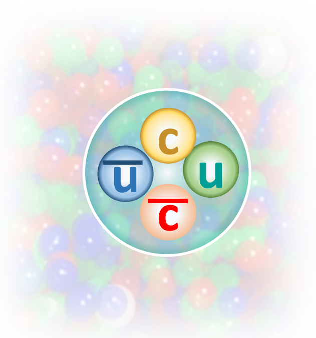
Sample the X(3872) wave function from the QGP
→X(3872) production could be significantly modified in Heavy Ion Collisions!!

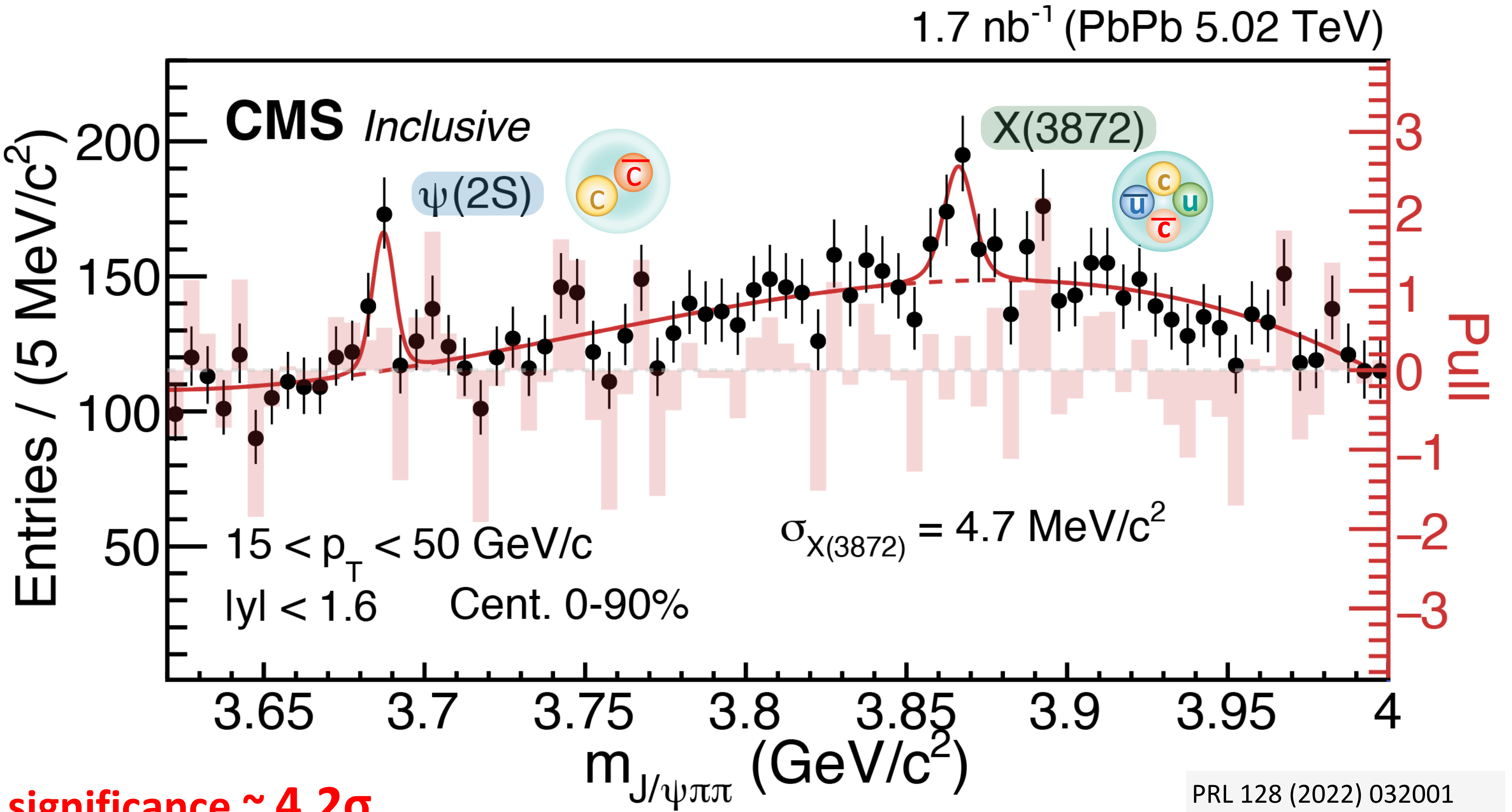
X(3872) in Lead-Lead Collision?

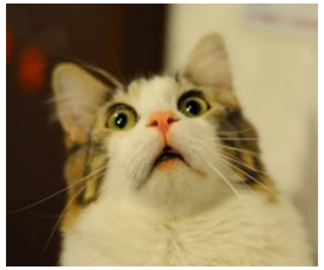
Prompt X(3872)/ψ(2S) vs. multiplicity in pp



The First Evidence of X(3872) in PbPb Collision







PRL 128 (2022) 032001

Statistical significance ~ 4.2σ

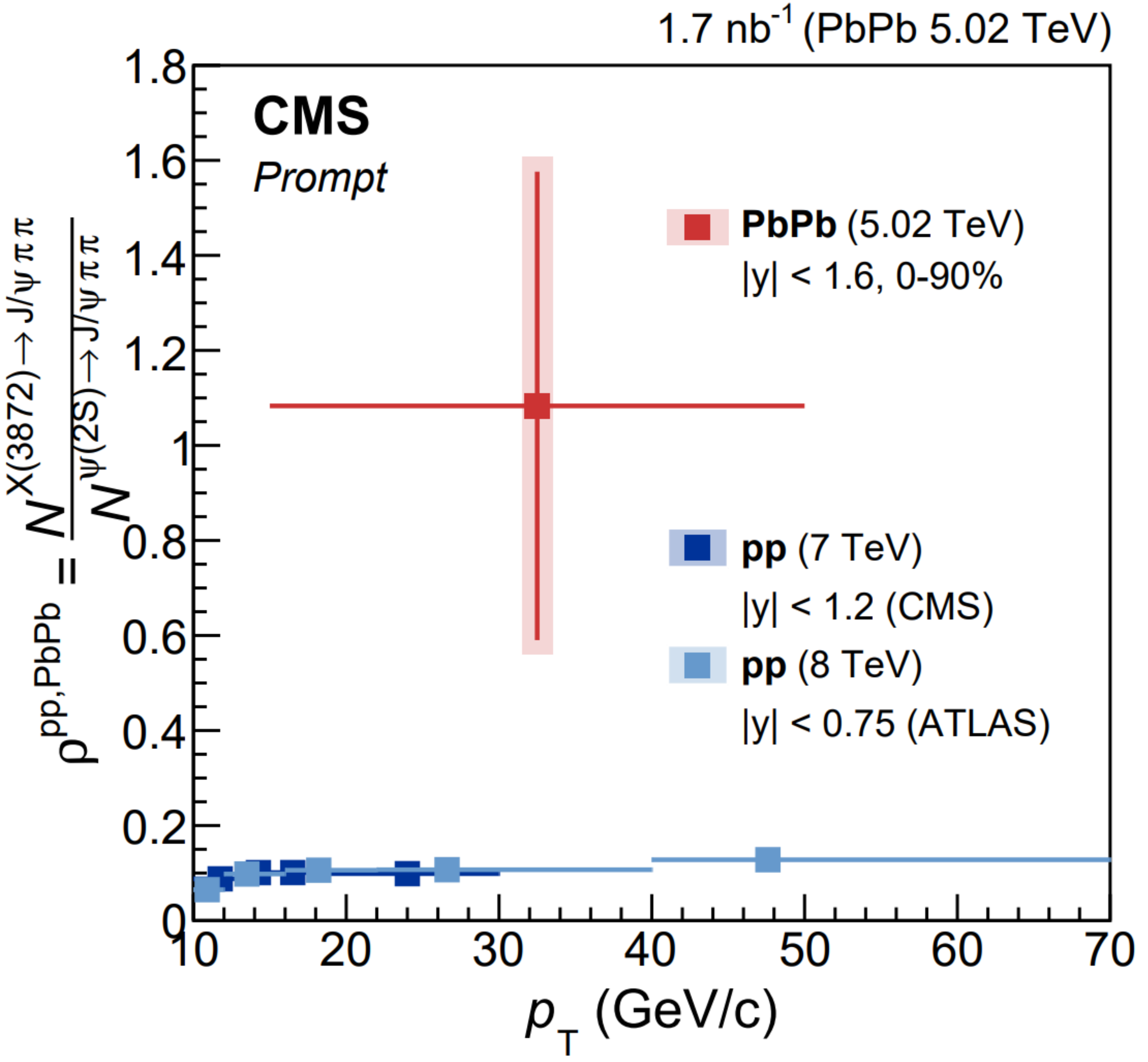
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

$$\rho = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

In Lead-Lead collisions:

$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$

Indication of ρ enhancement in Lead-Lead collisions with respect to **proton-proton collisions** (large uncertainty)

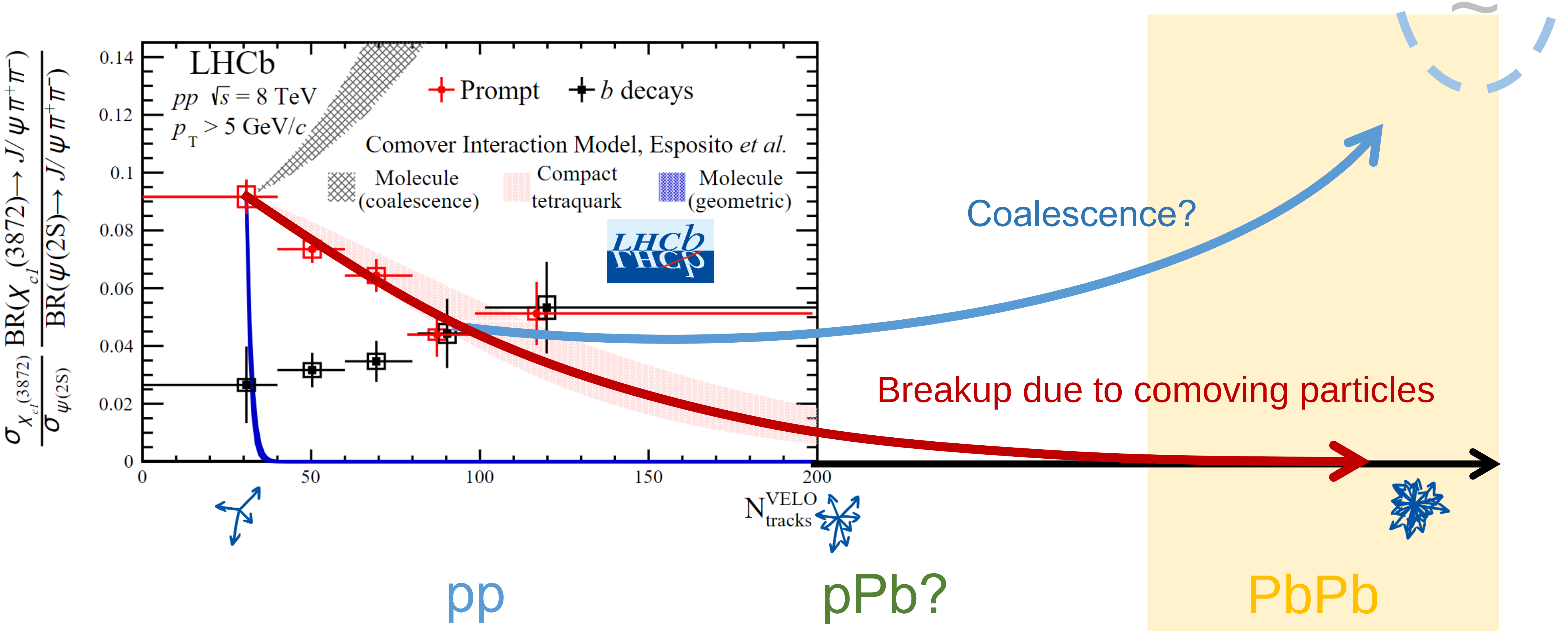


PRL 128 (2022) 032001

Studies of X(3872) in Heavy Ion Collisions

CMS PbPb

$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$



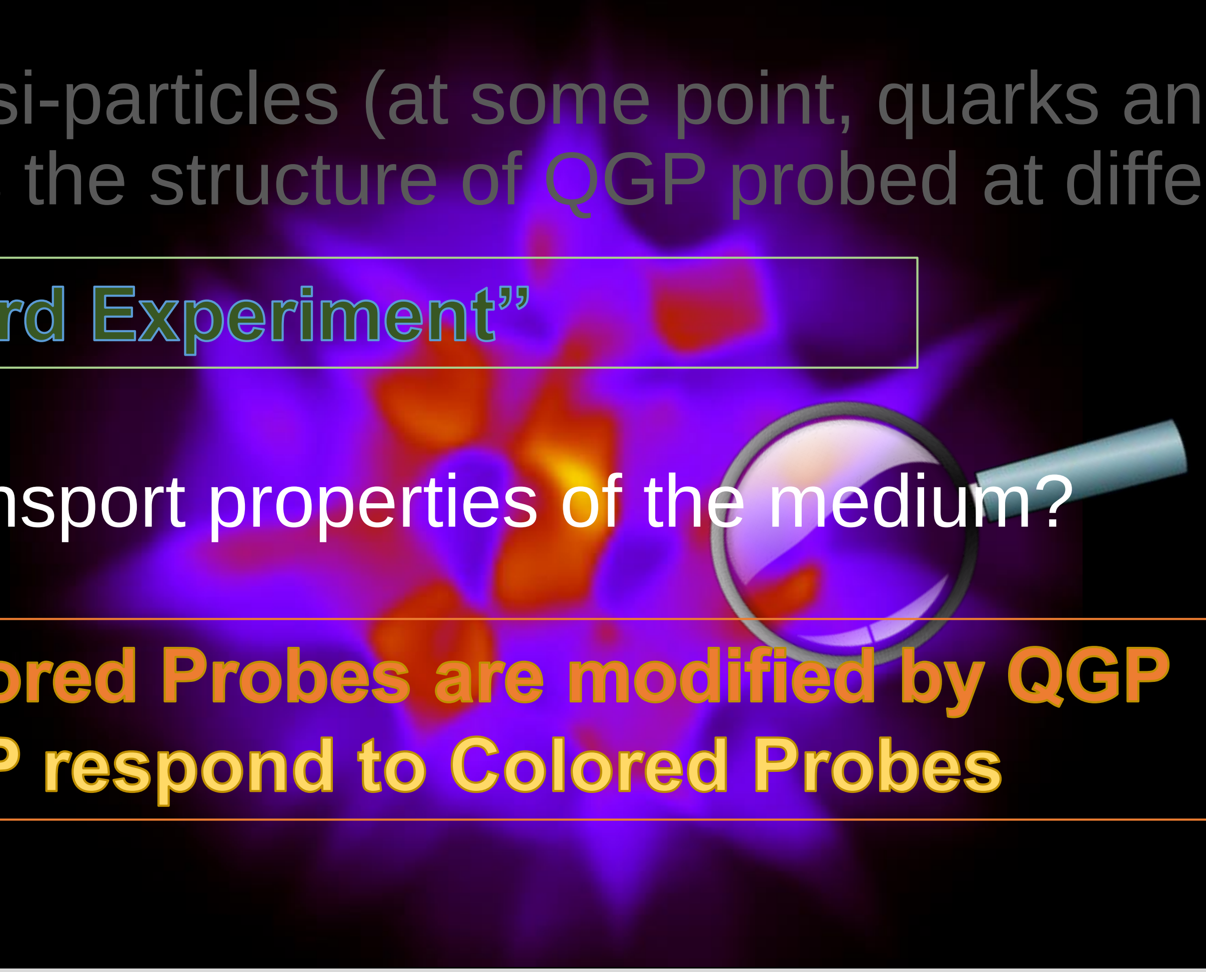
Probe the Quark Soup!

- 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?

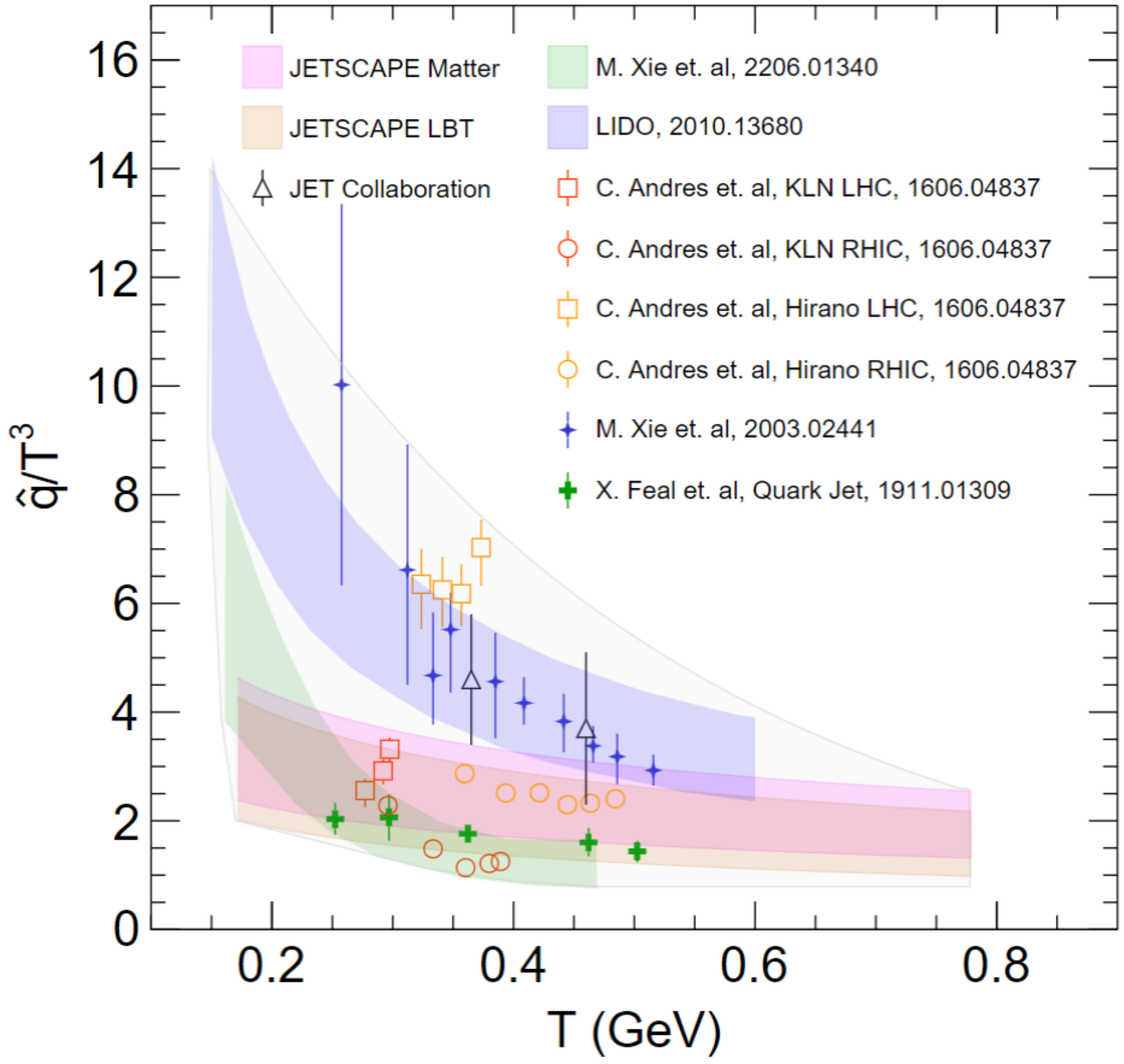
"QGP Rutherford Experiment"



- What are the transport properties of the medium?

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

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

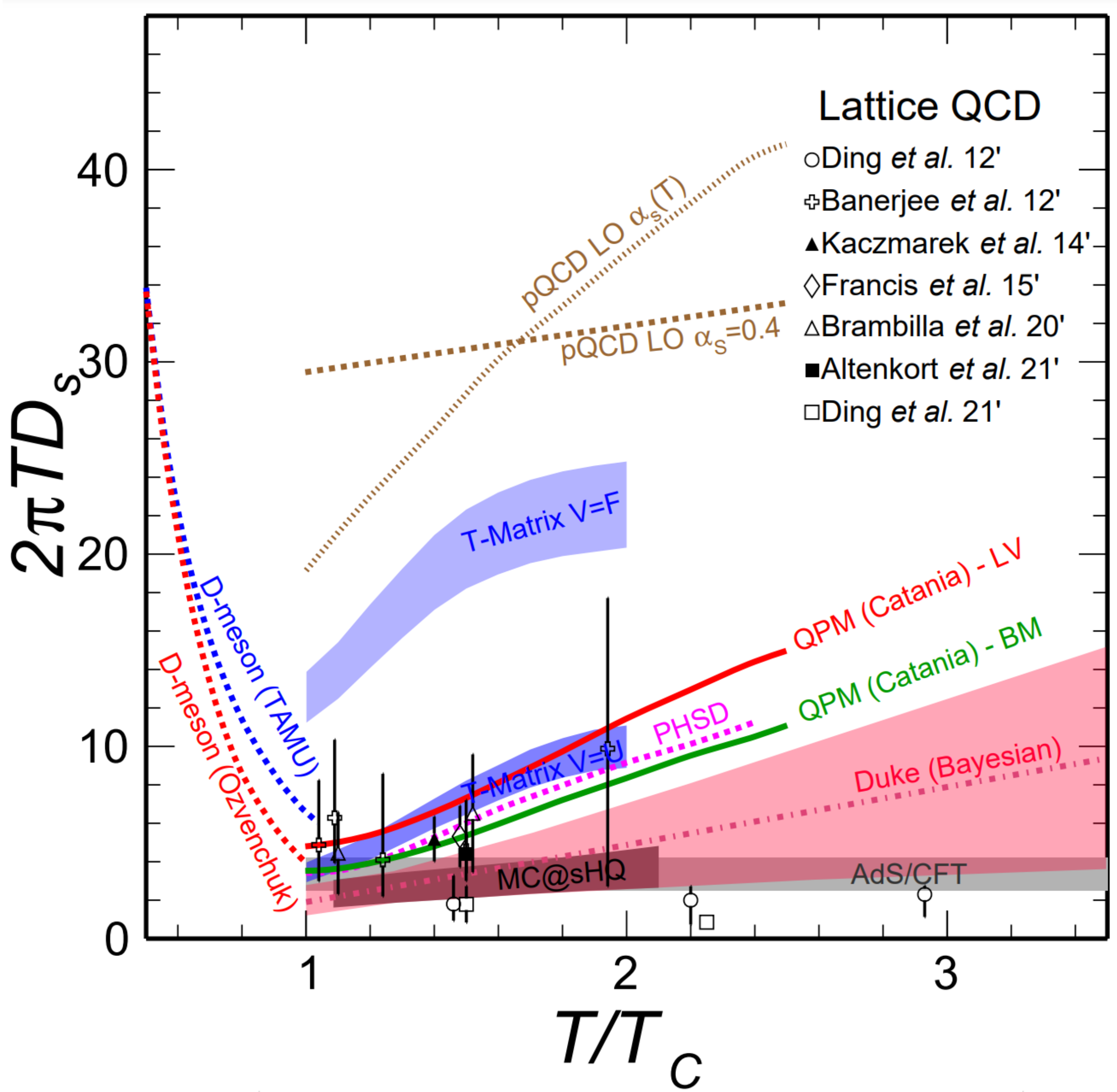
Jet Quenching Parameter $\hat{q}$

- Extracted mainly from charged hadron spectra R_{AA} data
  - Some analyses included γ-hadron and di-hadron data
- $\hat{q}/T^3$: decreasing trend vs. T,
  O(10x) larger than that in cold nuclear matter
- Extracted values differ by up to a factor of 7

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in calculations
- Hadron re-scattering in the hadron gas phase
- Hadronization of fast moving partons

QGP Transport Properties with RHIC and LHC Run 2 Data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

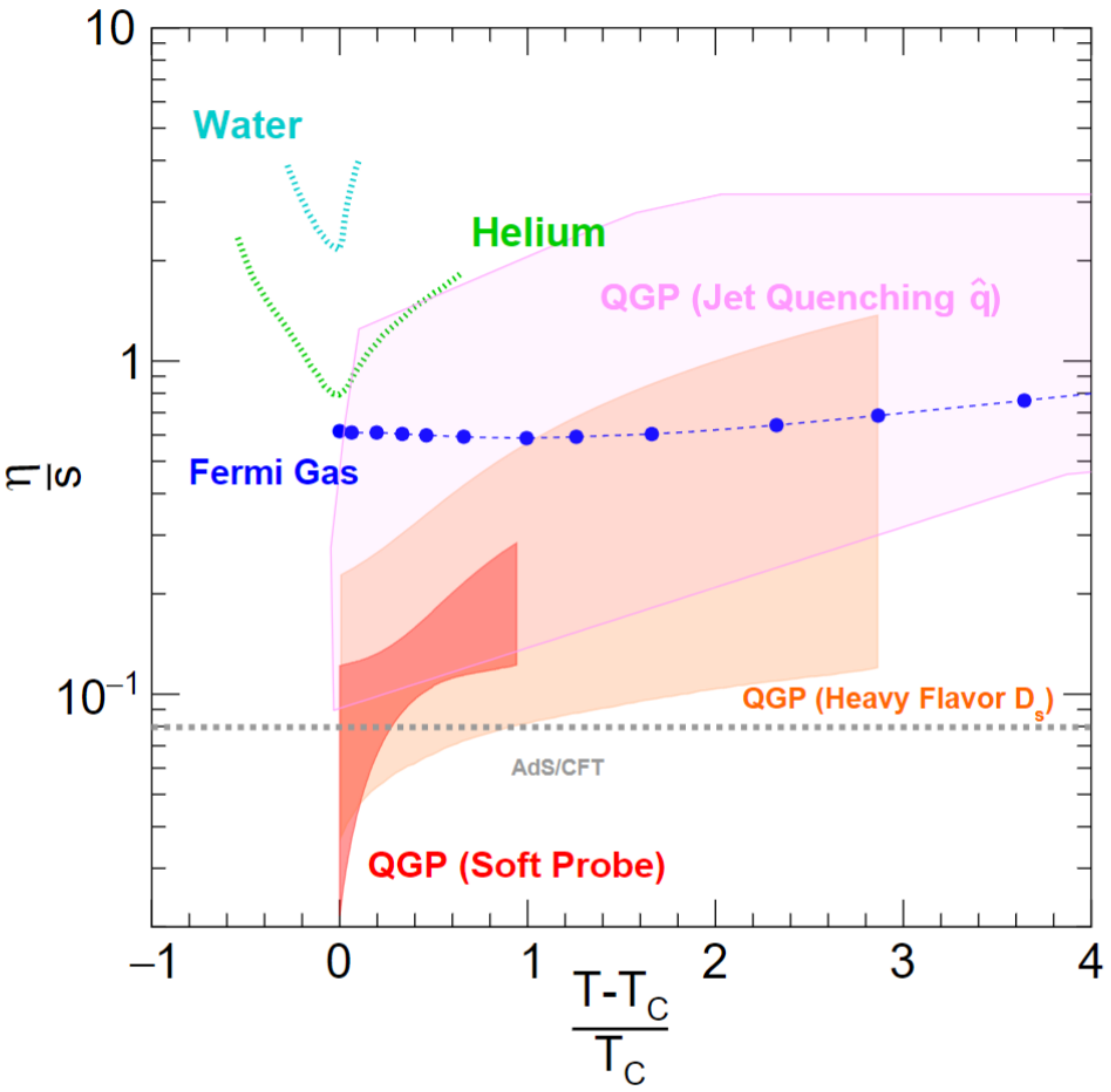
Charm diffusion coefficient D_s

- Bayesian analysis from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $2\pi TD_s$ vs. T in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- Different QGP media used in various calculations
- Precision of the experimental data

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

Where the scale factor C is varied between 1.25 and 2.5

A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**, but within rather large uncertainties

Probe the Quark Soup: Status

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

We see evidence of charm quarks and hard scatter partons moving toward thermalization.

- 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?

We find no evidence of backscattering from with photon-jet. Investigation continues with lower p_T jets, and subjet multiplicity with high statistics data.

- What are the transport properties of the medium?

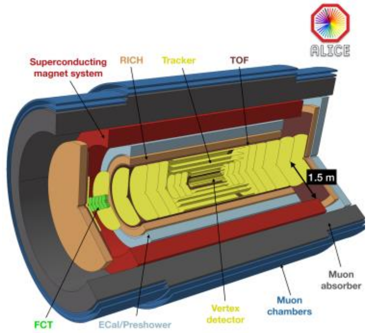
Based on theoretical models:
Extracted initial T, jet quenching parameters $\hat{q}$, heavy quark diffusion constant D_s
We see a consistent picture between soft and hard probes within large uncertainties.
We see an indication of medium response to hard probes.

LHC Timeline and CMS/ATLAS Upgrade

Phase 1 Upgrade | CMS/ATLAS Phase 2 Upgrade | CMS/ATLAS Phase 3 Upgrade

ALICE Upgrade | ALICE 3 Upgrade

LHCb SMOG | LHCb SMOG2 (x100 higher rate)



LHC → **HL-LHC**

PbPb 2 nb^{-1}

PbPb 7 nb^{-1}, pPb, pO, OO

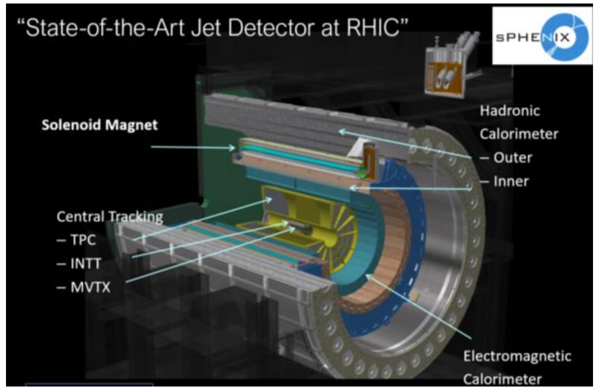
PbPb 7 nb^{-1}, pPb

AA, small systems?

Run 2	Long shutdown 2	Run 3	Long Shutdown 3	Run 4	LS4	Run 5

	2018	2019	2020	2021	**2022**	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038

sPHENIX construction | Installation commission | Run 1

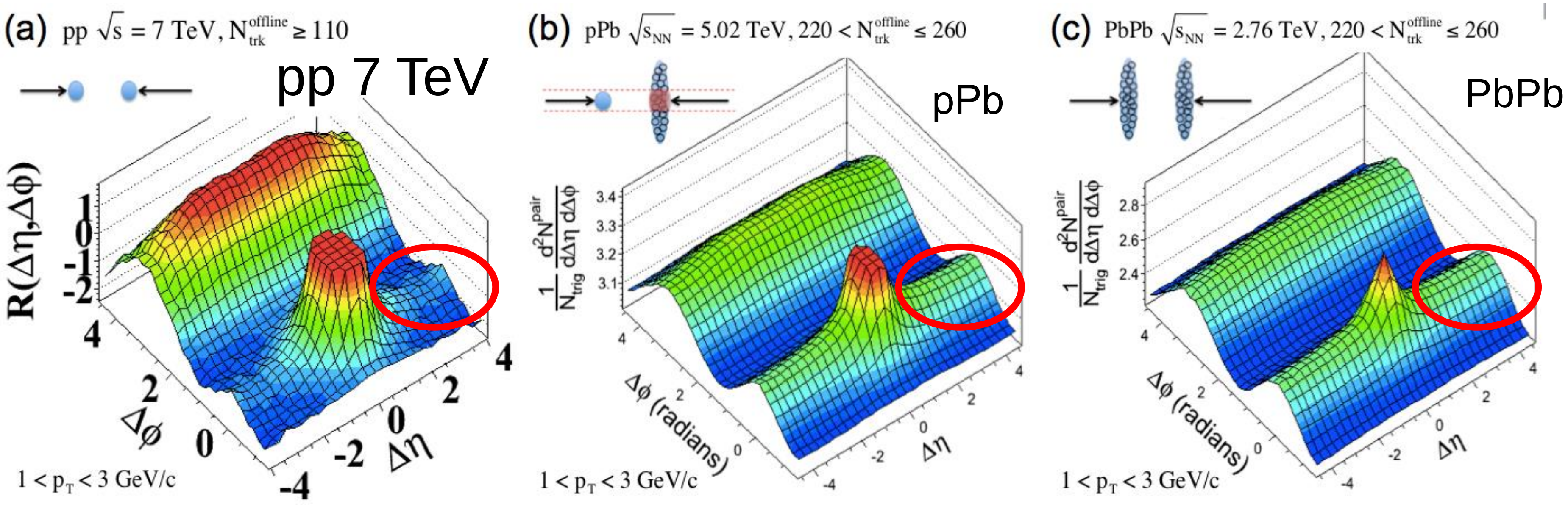


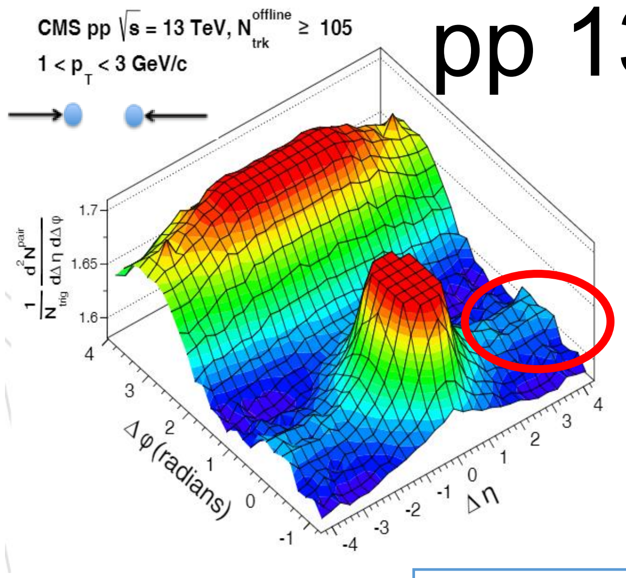
RHIC → **EIC**

AuAu 30 nb^{-1}

Bonus Material

"Ridge" in pp, pPb and PbPb





pp 13 TeV

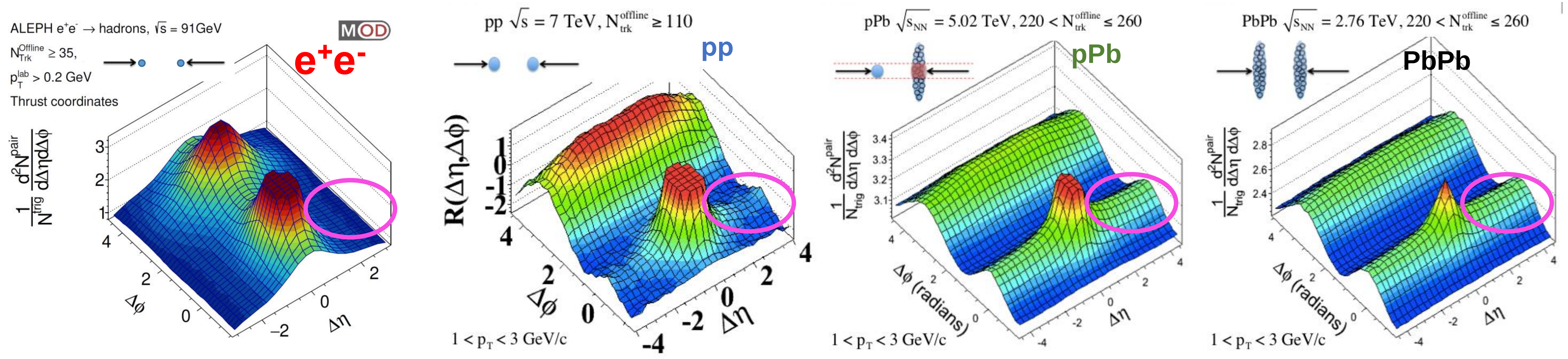
CMS-FSQ-15-002

Big Surprise at the LHC: the ridge was also observed in pp and pPb collisions!!

Indication of mini-QGP production in pp and pPb?

What about e^+e^-???

Small System



PRL 123 (2019) 21, 212002

JHEP 09 (2010) 091

PLB 718 (2013) 795

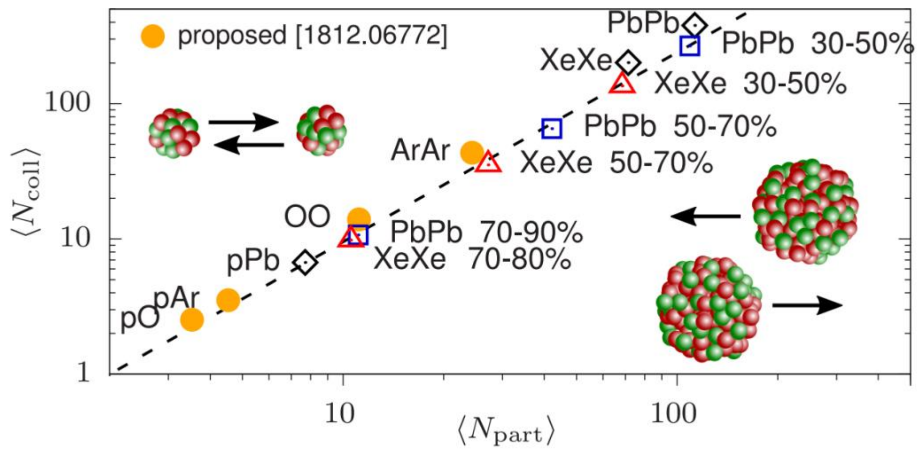
- Flow-like phenomena in high multiplicity pp and pPb collisions, not yet observed in e^+e^- and ep

- Strangeness enhancement from ALICE

- OO: provide unique opportunity to smoothly connect pPb and PbPb

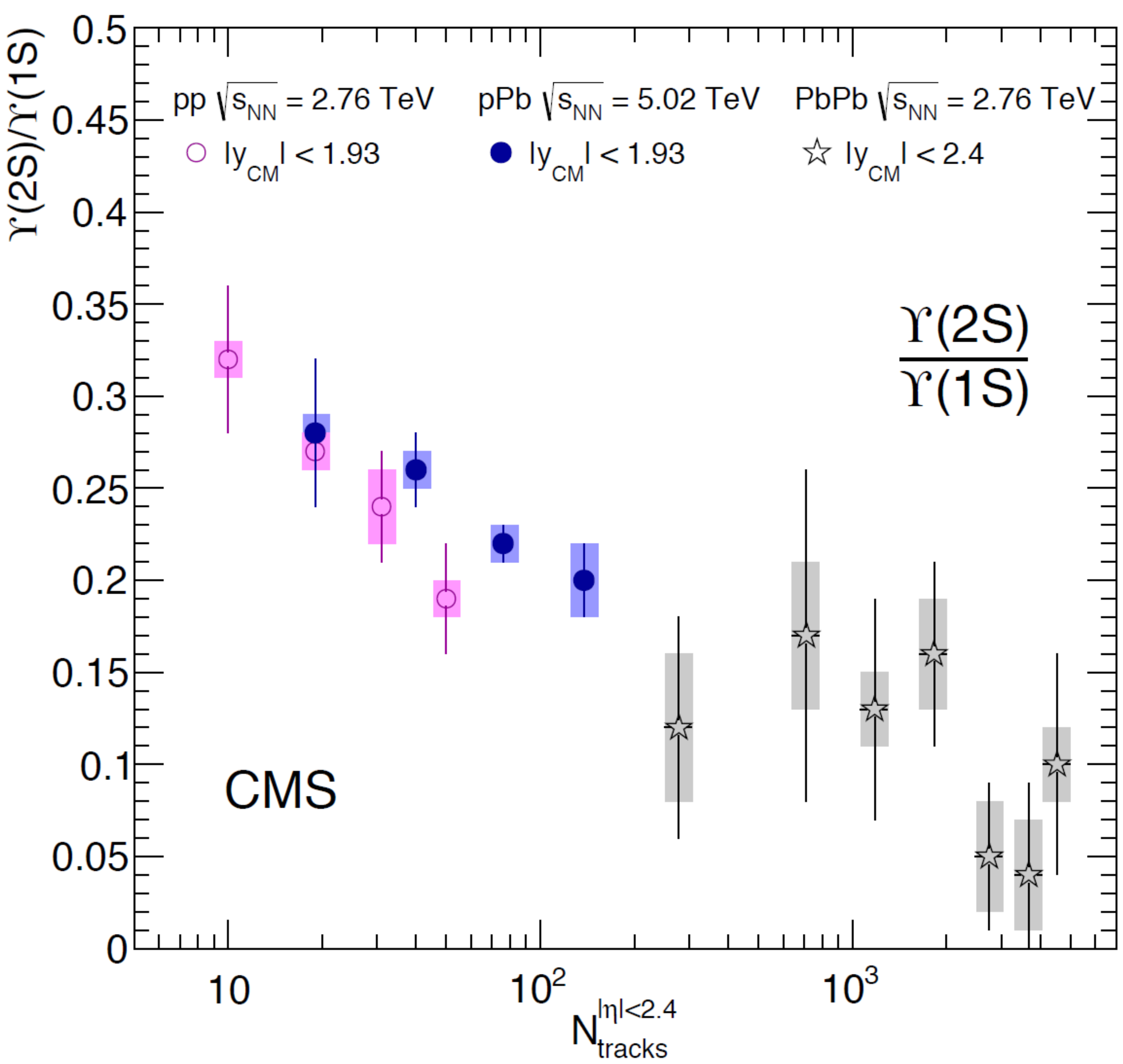
e+e-:
ALEPH LEP1: YJL+ PRL 123 (2019) 21, 212002
Belle: Y.-C. Chen+ PRL 128 (2022) 14, 142005
ep:
ZEUS I. Abt+ JHEP 04 (2020) 070

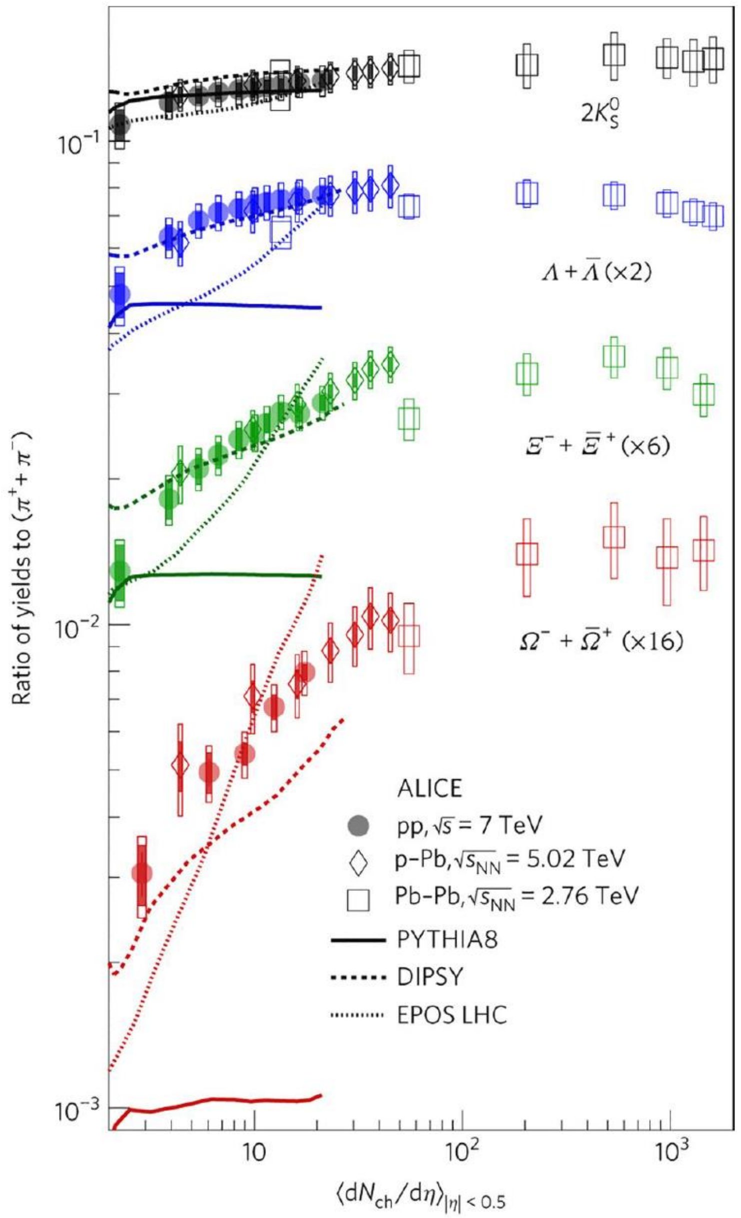
A. Huss et al, PRL 126 (2021) 19,192301



AEPSHEP 2022

Quarkonia and Strangeness Enhancement in Small System



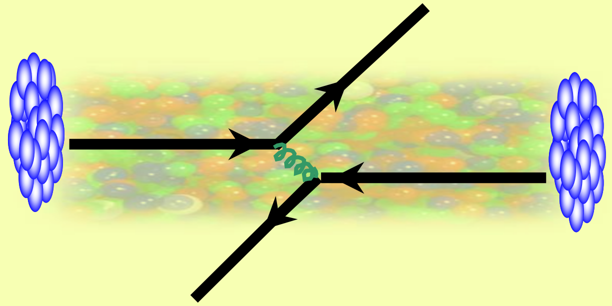


How do we extract the medium effect in A+A collisions?

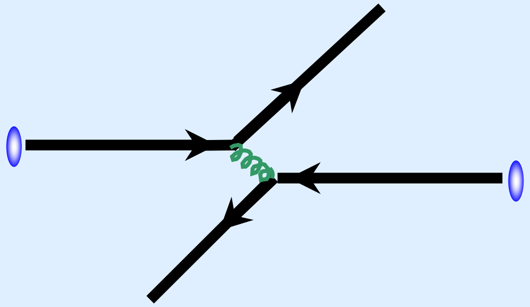
One typical way is to compare A+A data to pp reference measurement

See for instance review form
D. d'Enterria and C. Loizides
Ann.Rev.Nucl.Part.Sci. 71 (2021) 315-44

A+A measurements



pp reference



'Nuclear modification factors'

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

$N_{coll} \rightarrow$ Averaged number of binary scattering

Can also be written as $1/T_{AA}$

$$T_{AA} = \frac{N_{coll}}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per A+A collision"
Reduces the uncertainty from pp inclusive cross-section