CMS Experiment at the LHC, CERN

Experimental Study of the QGP with Jets and Open Heavy Flavor

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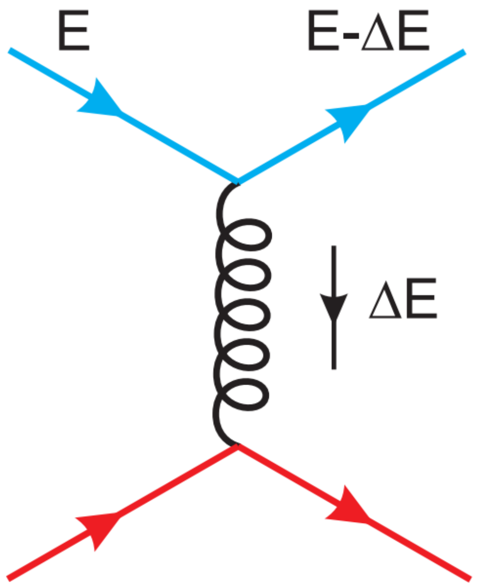
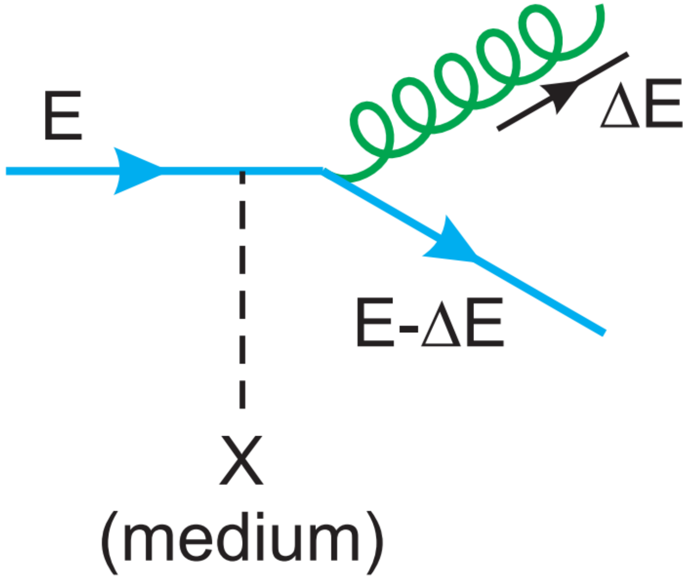
MIT HIG group's work was supported by US DOE-NP

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)

Quenching depends on color factor

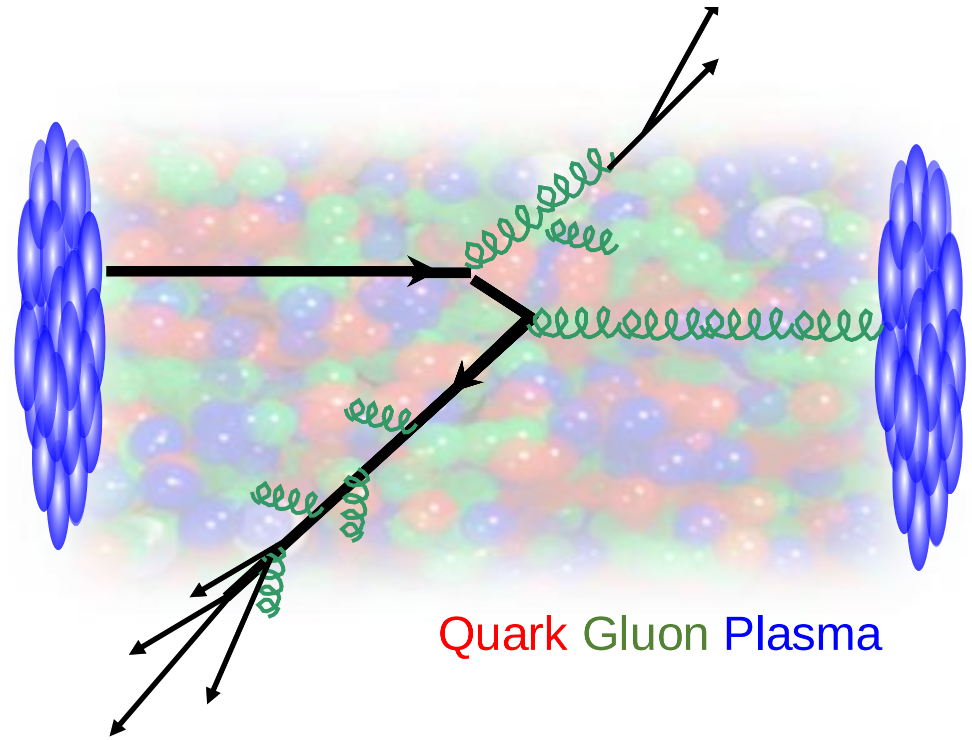
$$C_F = \begin{cases} 3 & \text{gluon jets} \\ 4/3 & \text{quark jets} \end{cases}$$

Jet: a powerful tool for the understanding of QGP

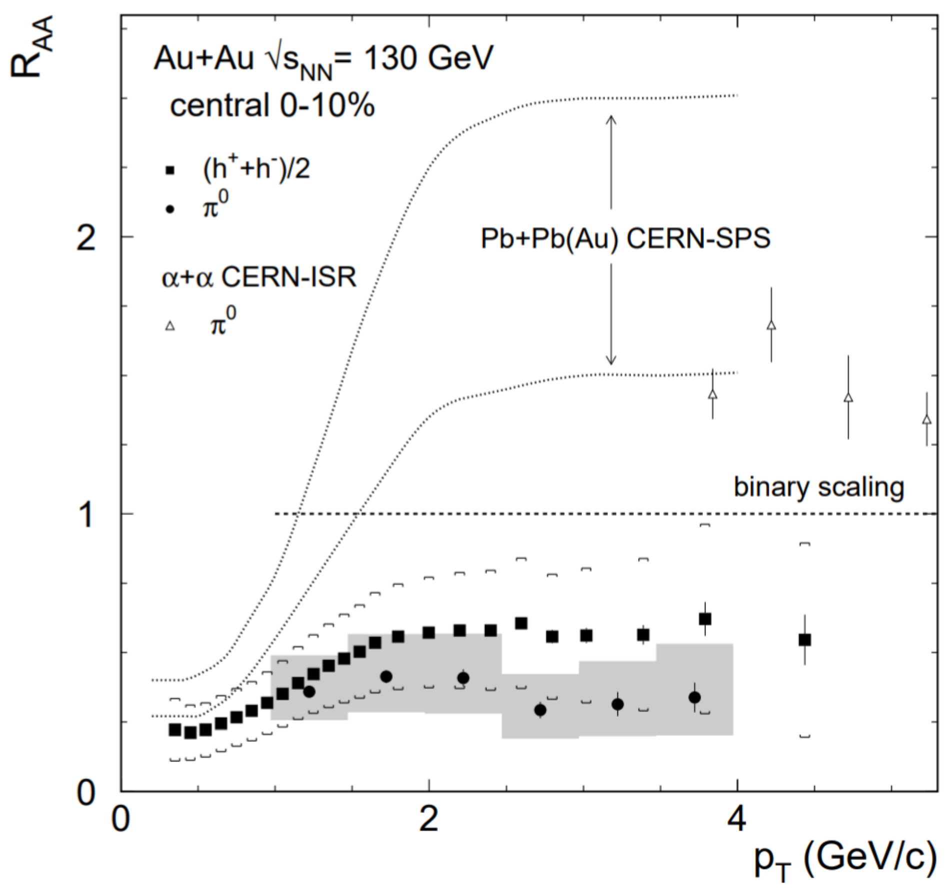
Early Measurements at RHIC (2001-3)

'Nuclear modification factors'

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



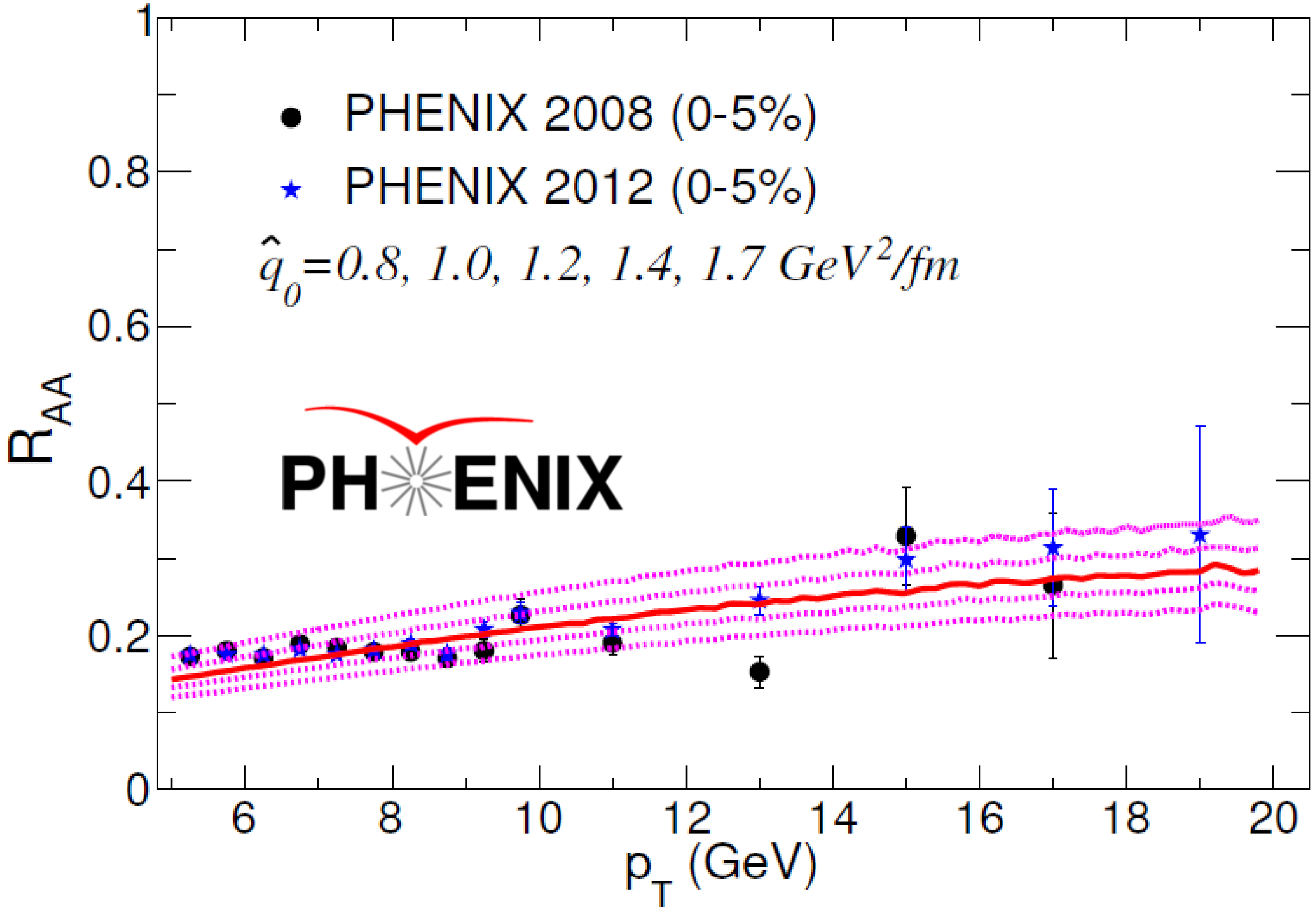
PHENIX PRL 88 (2002) 022301

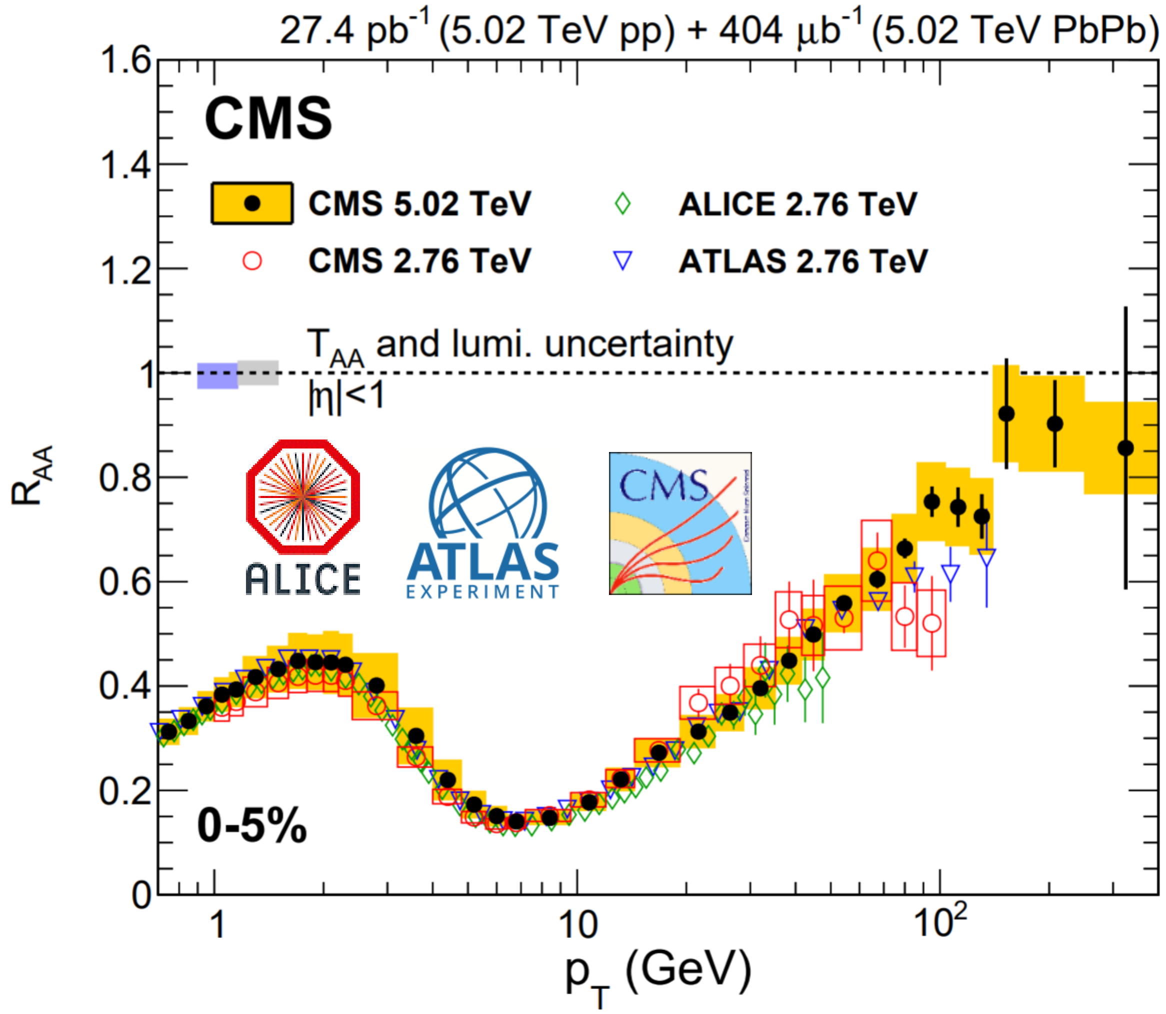


Strong suppression of high p_T hadrons

Modification of the leading fragment

Jet Quenching without Jet: Charged Particle R_{AA}





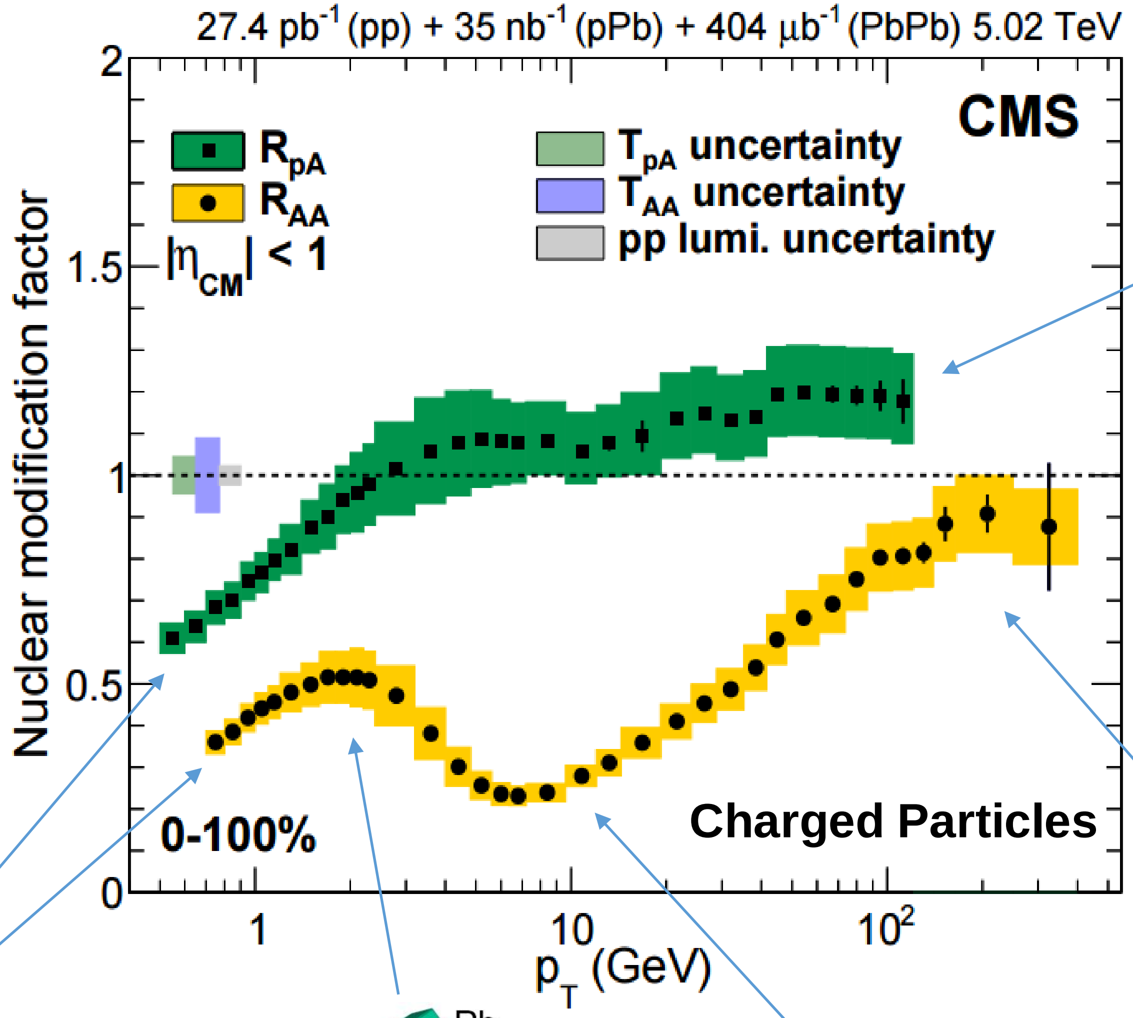
Greatly improved results at RHIC since the first measurement

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

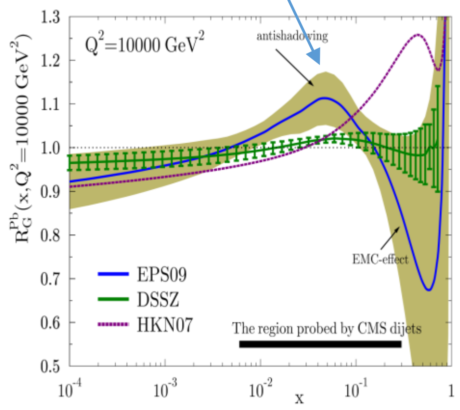
Jet Quenching without Jet

R_{pA} from pPb data

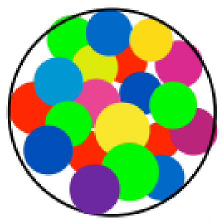
R_{AA} from PbPb data



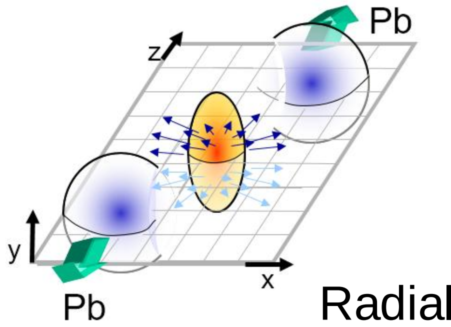
Anti-shadowing for intermediate x partons



Gluon saturation

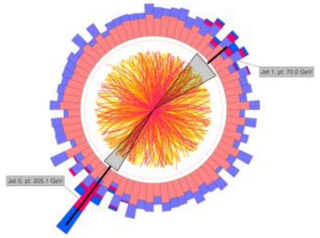


Shadowing



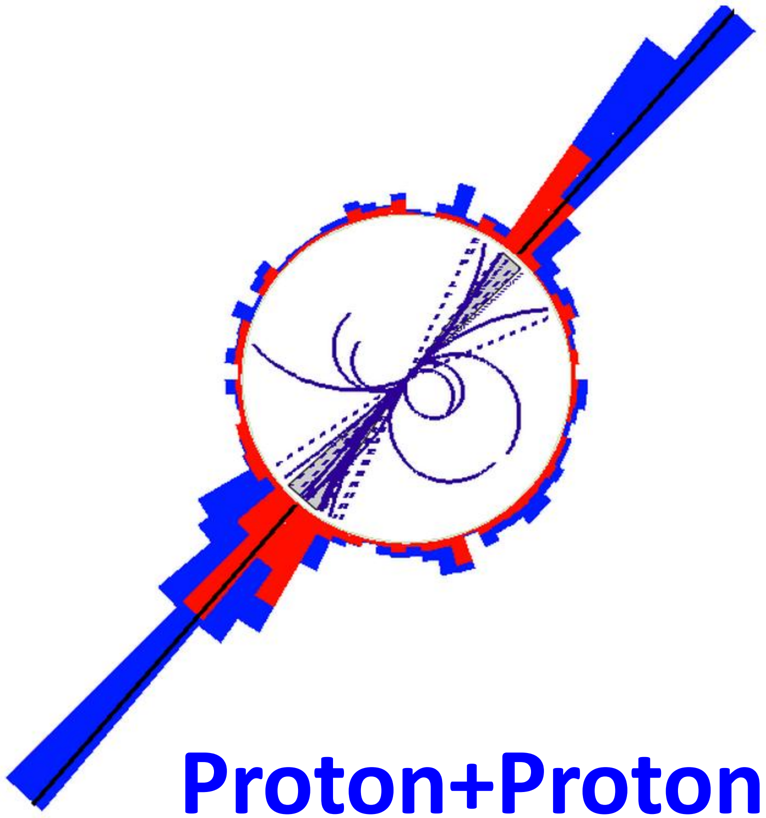
Radial flow

Jet quenching

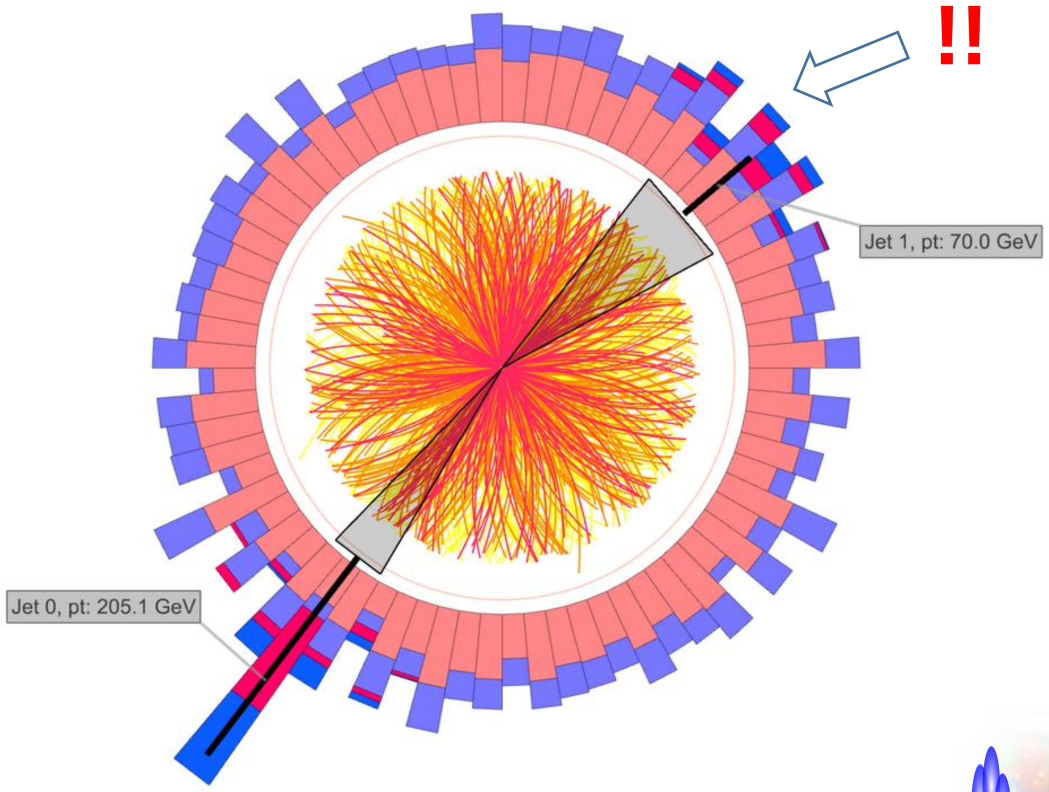


QGP become more transparent to very high p_T particles

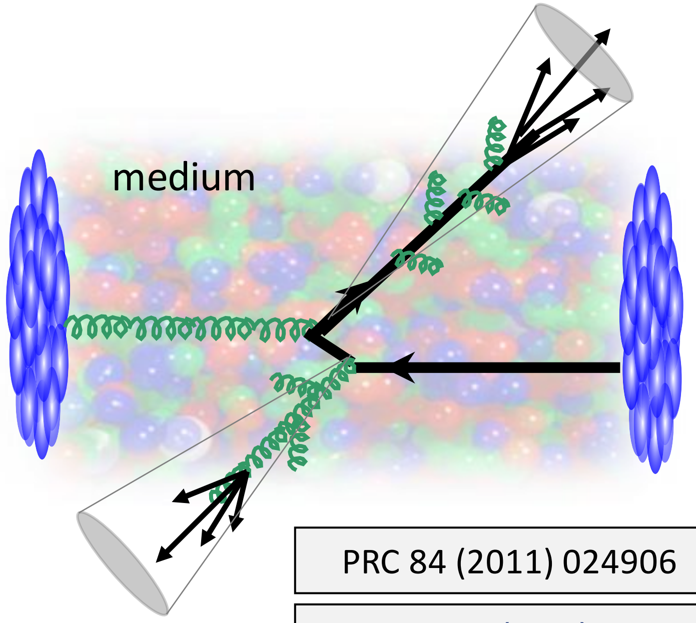
Probe the QGP with High Energy Quarks and Gluons



Proton+Proton



Lead+Lead

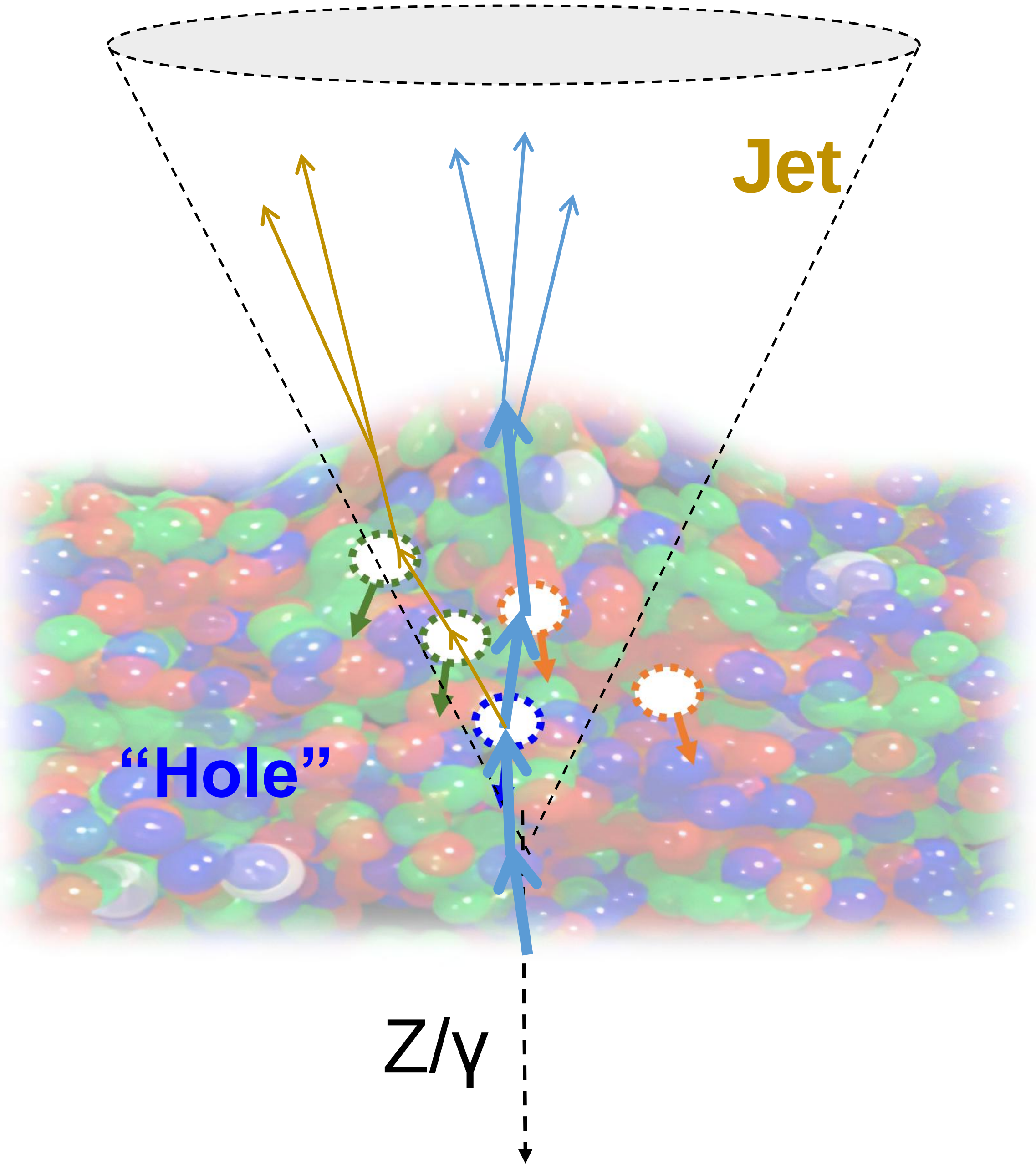


Asymmetric di-jets in Lead+Lead collisions!

PRC 84 (2011) 024906

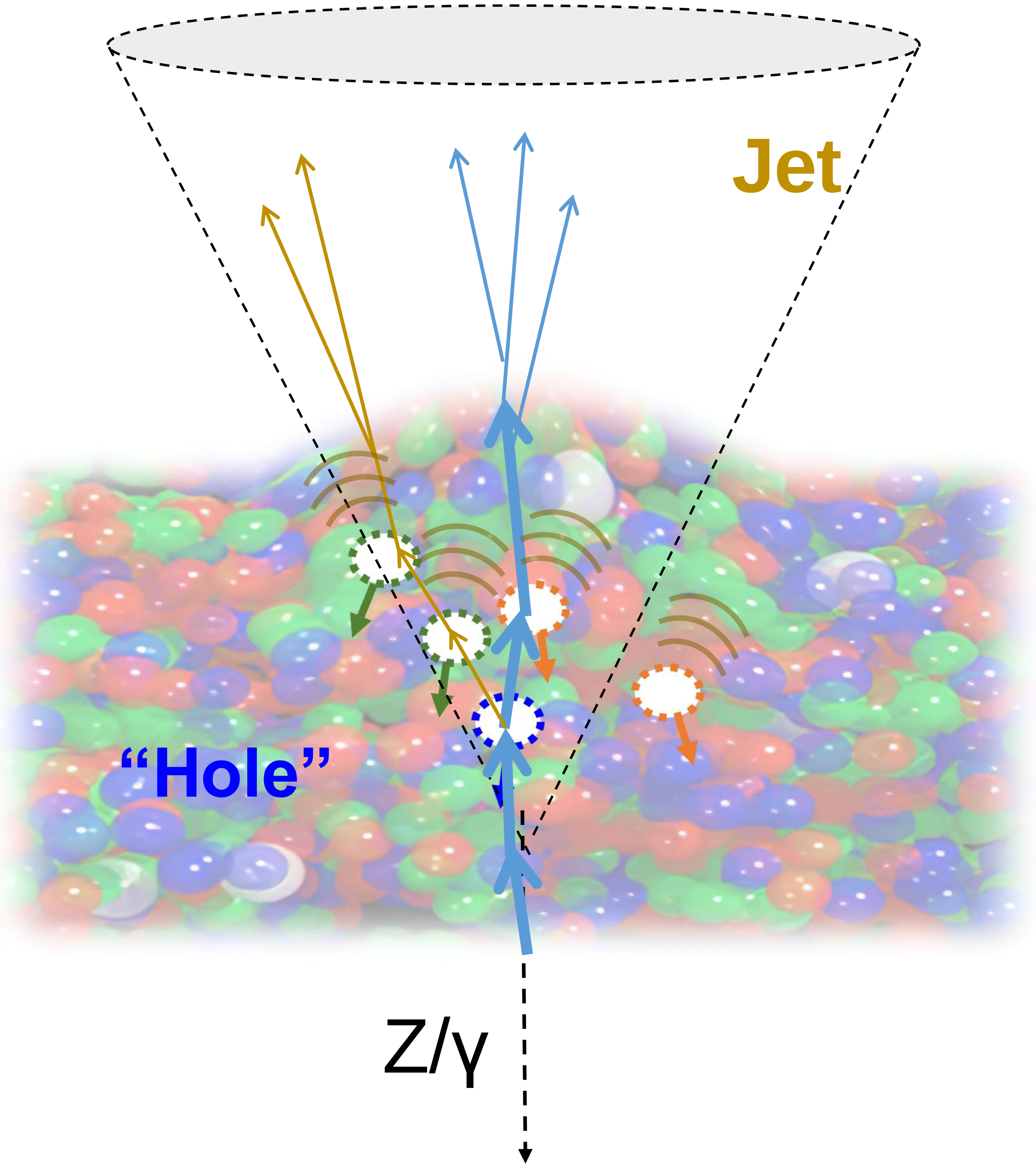
PLB 712 (2012) 176

QGP Transport Properties and Structure with Jets



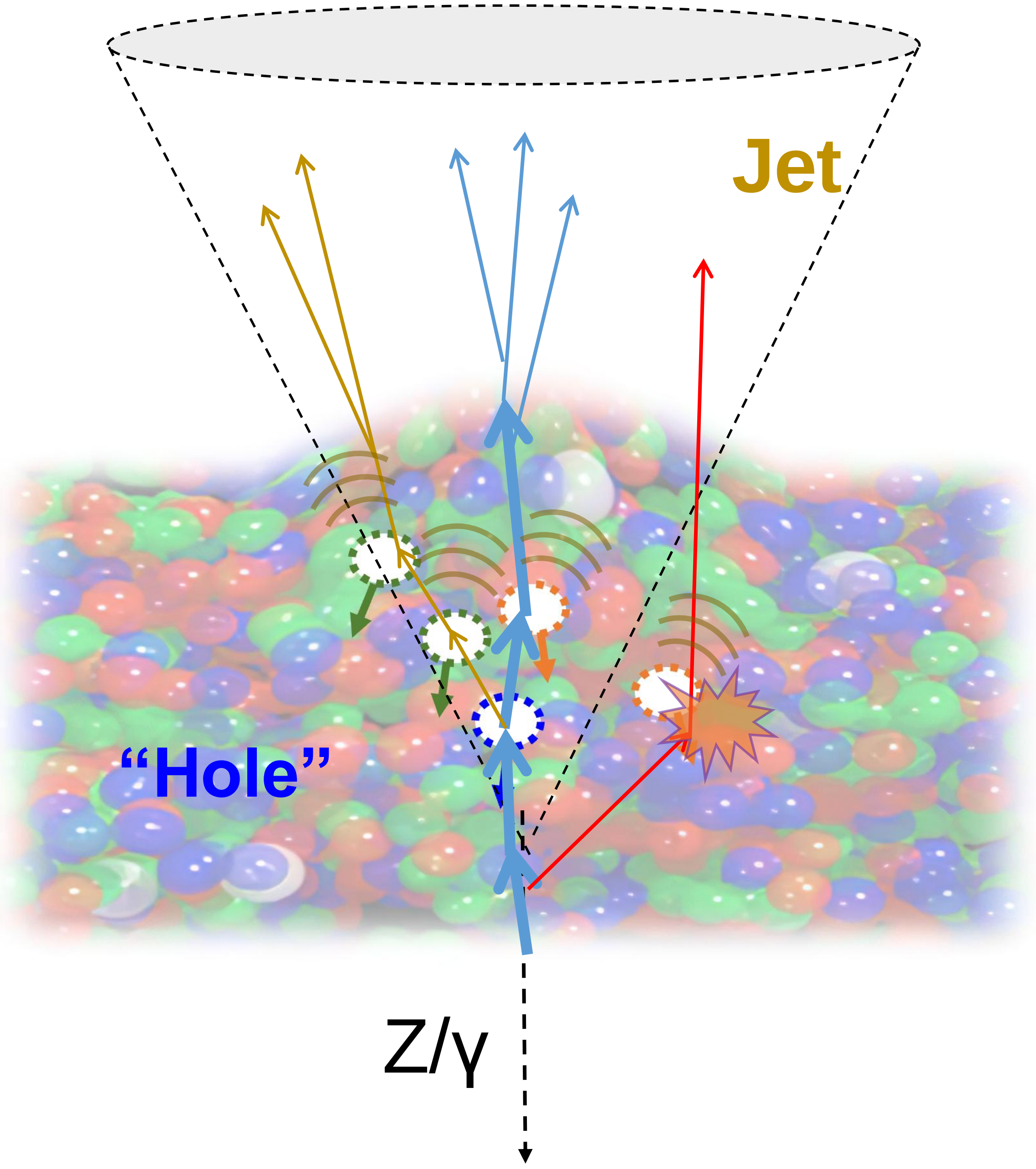
- Jet broadening effects from multiple soft scattering $(\hat{q})$

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)

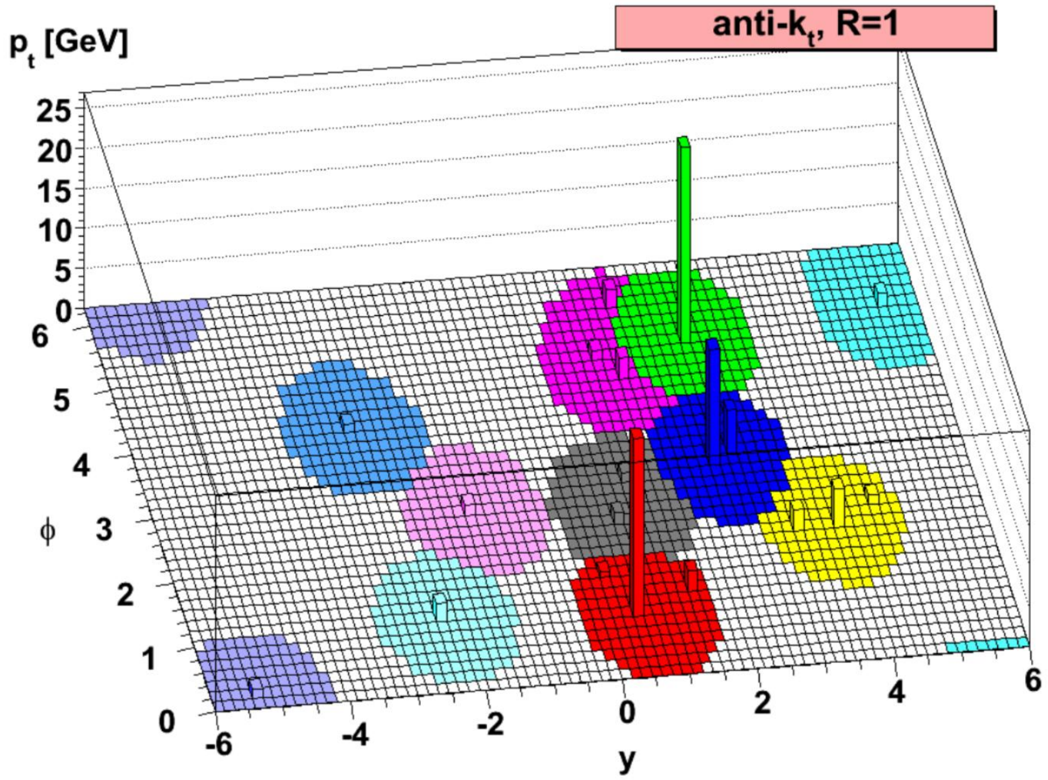
QGP Transport Properties and Structure with Jets



- 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

Jet as a Proxy of Parton: 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**

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

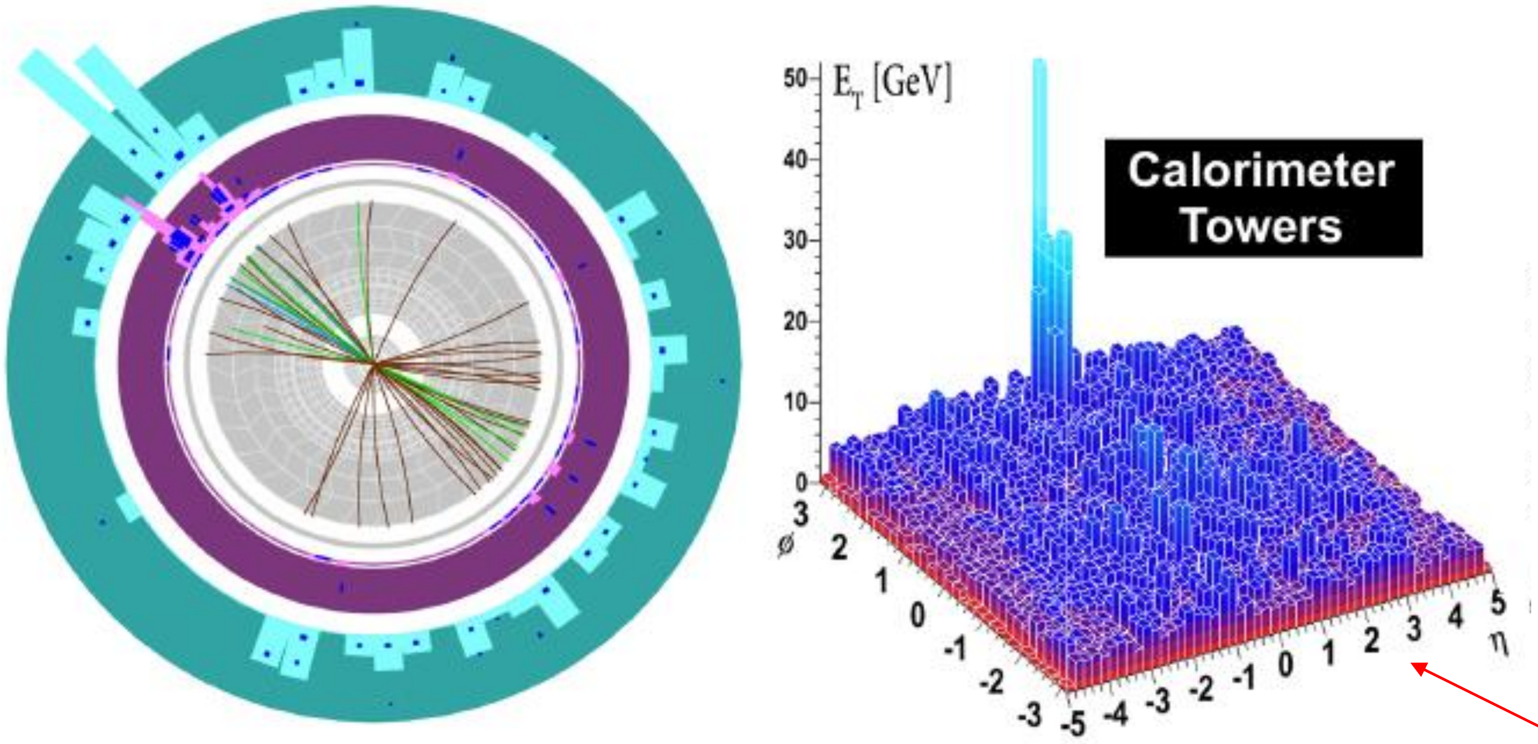
Distance to beam **B**

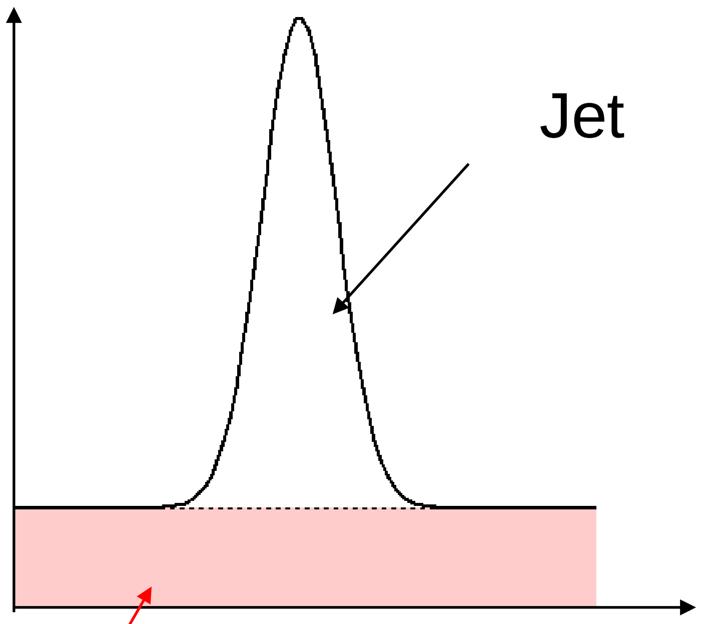
$$d_{iB} = k_{t,i}^{-2}$$

- Give close to **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



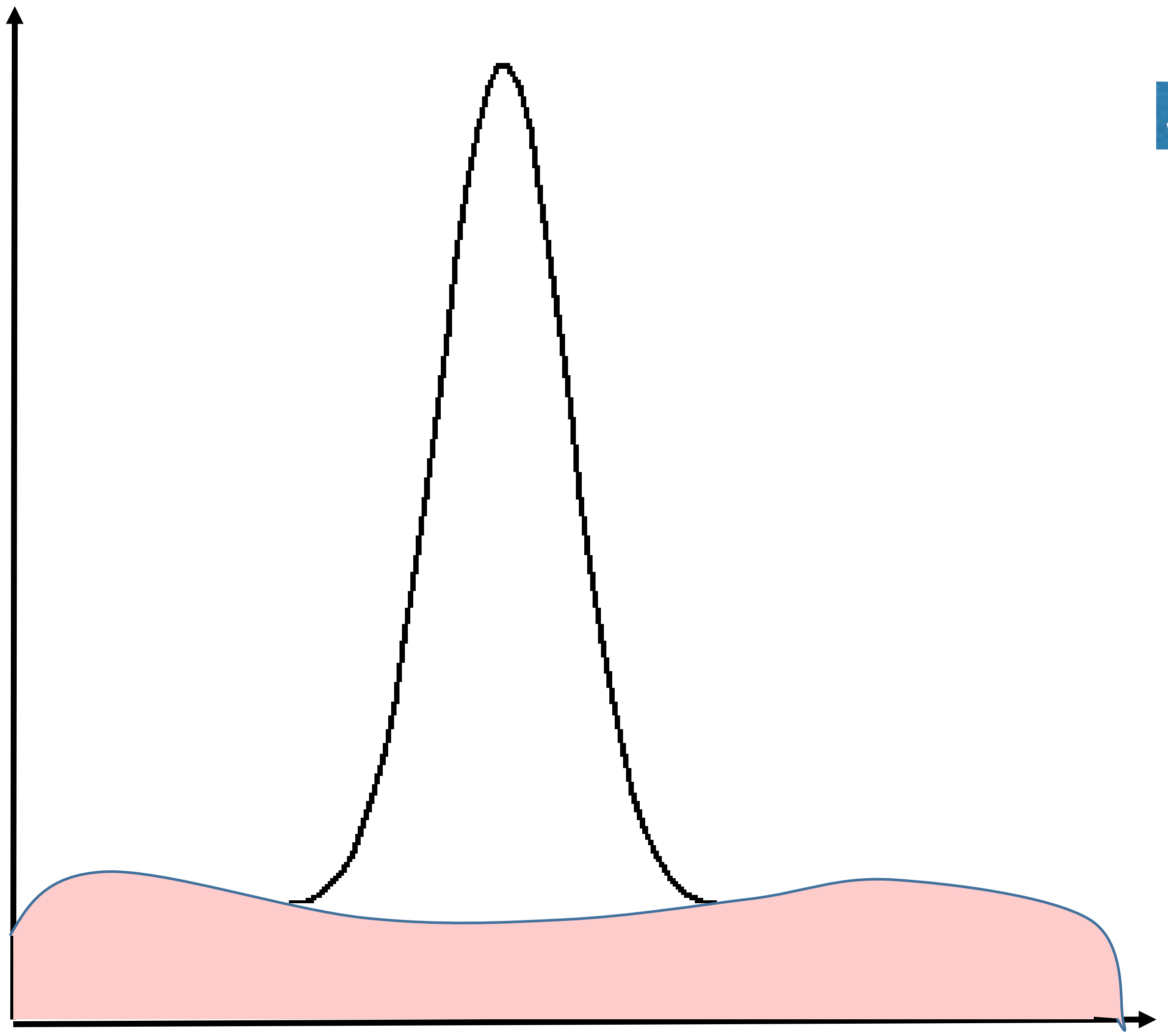


Multiple parton interaction

Large underlying event from soft scattering

💡 Need to subtract the underlying event background

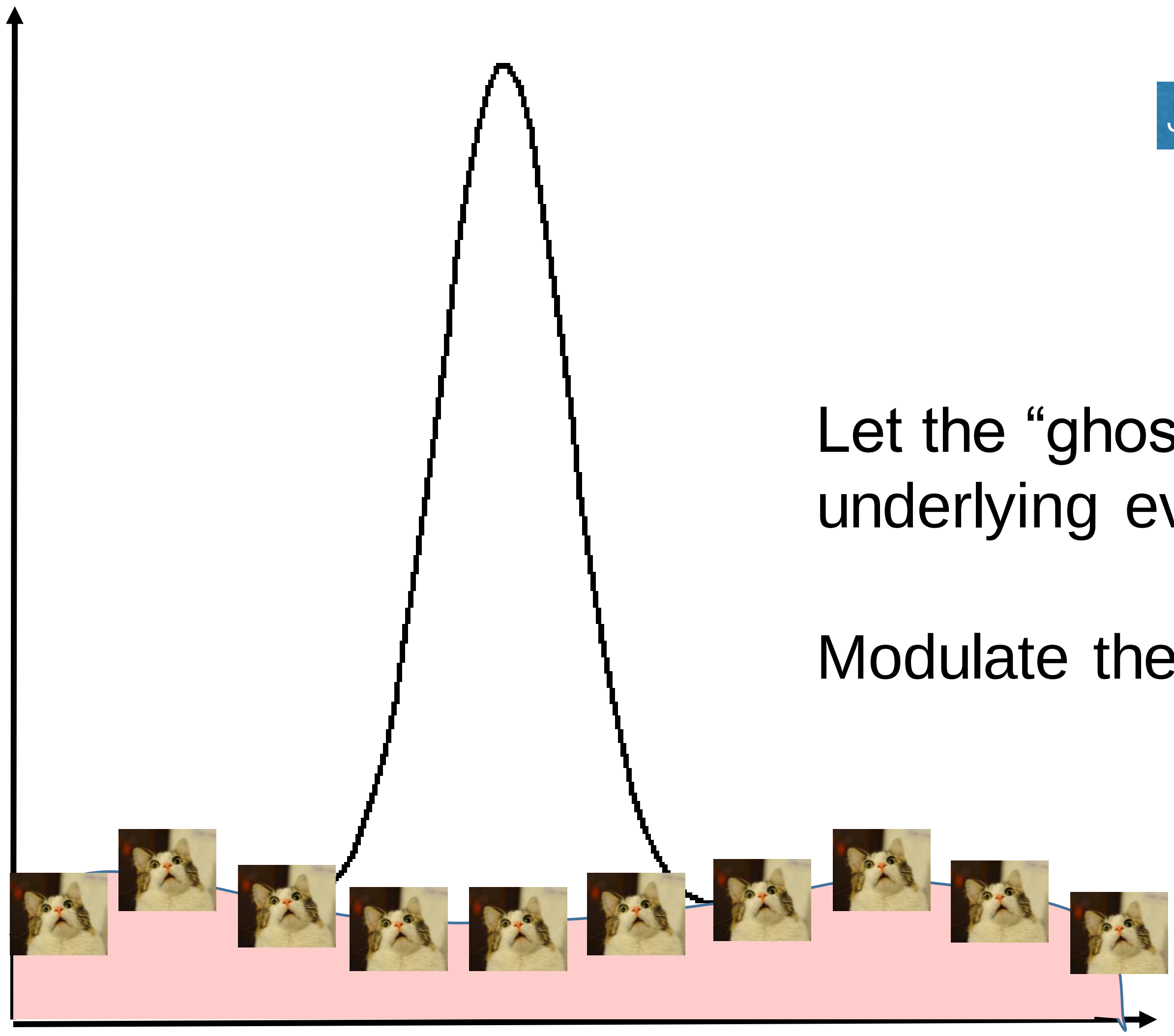
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction **with flow modulation**

Constituent Subtraction



JHEP06 (2014) 092

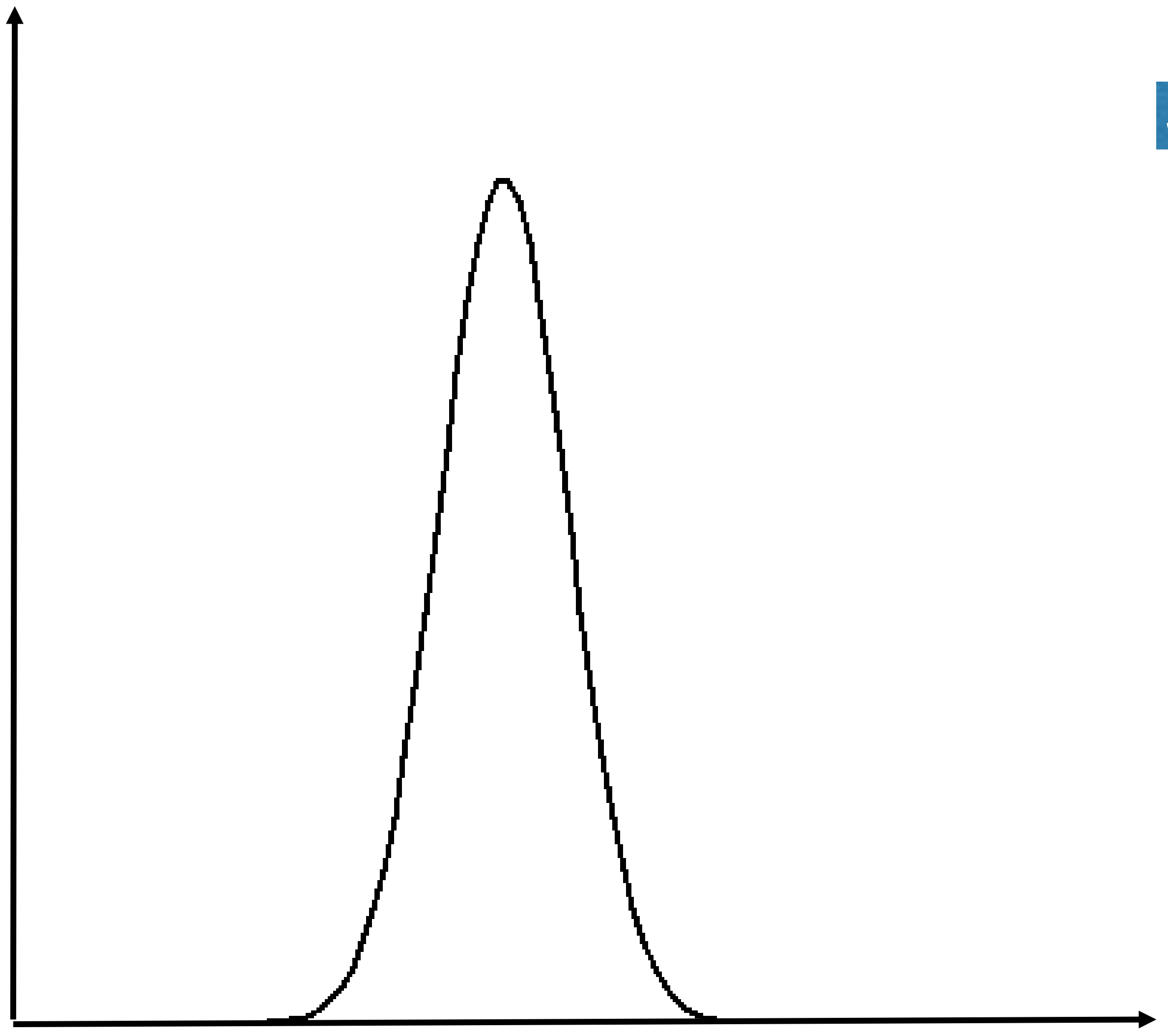
Let the “ghost” remove the underlying event

Modulate the number of ghost!

Constituent subtraction **with flow modulation**

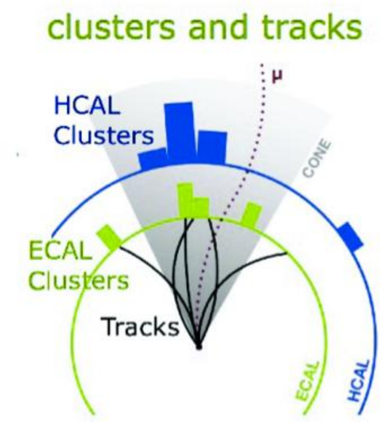
Constituent Subtraction

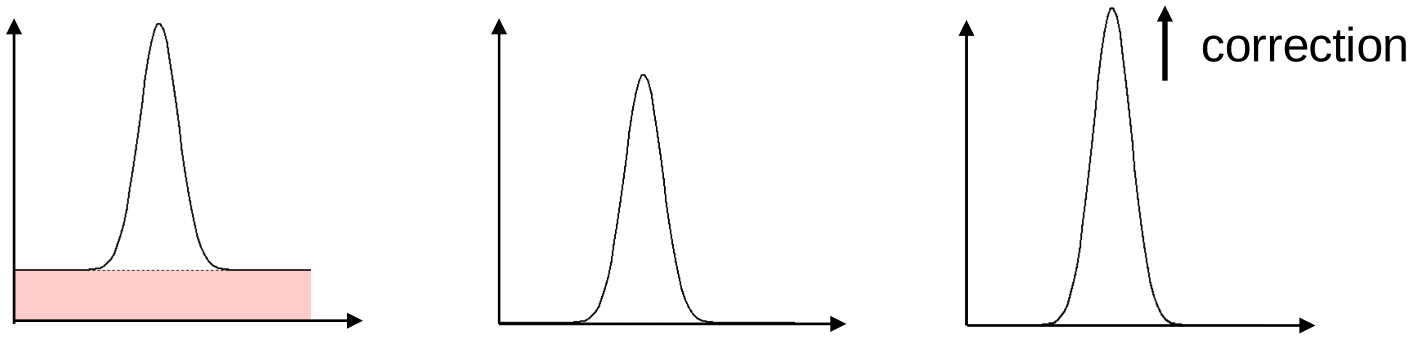
JHEP06 (2014) 092



Constituent subtraction **with flow modulation**

Summary of Jet Reconstruction





Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation PYTHIA

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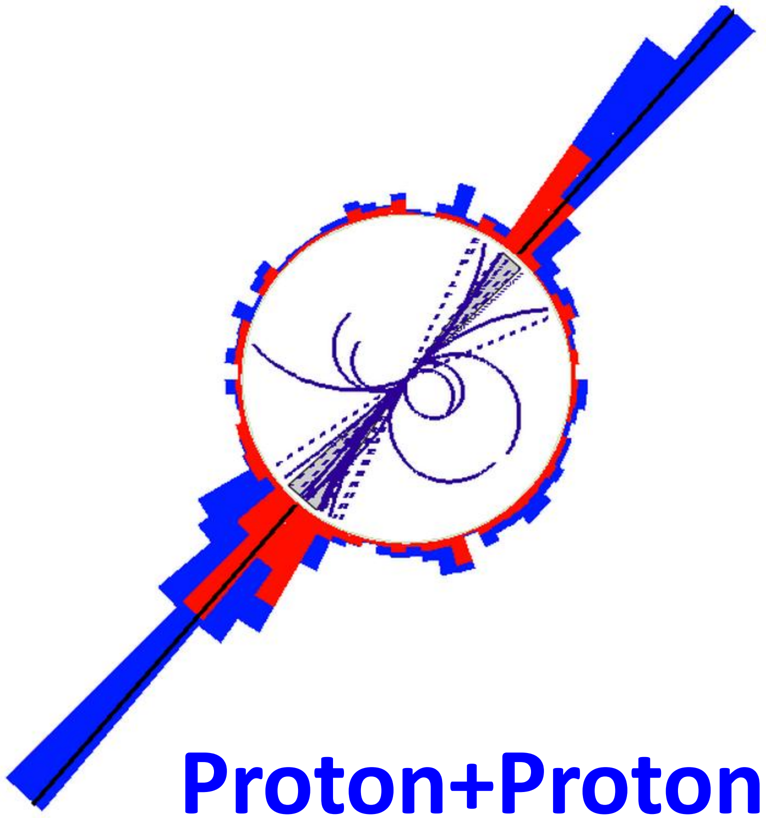
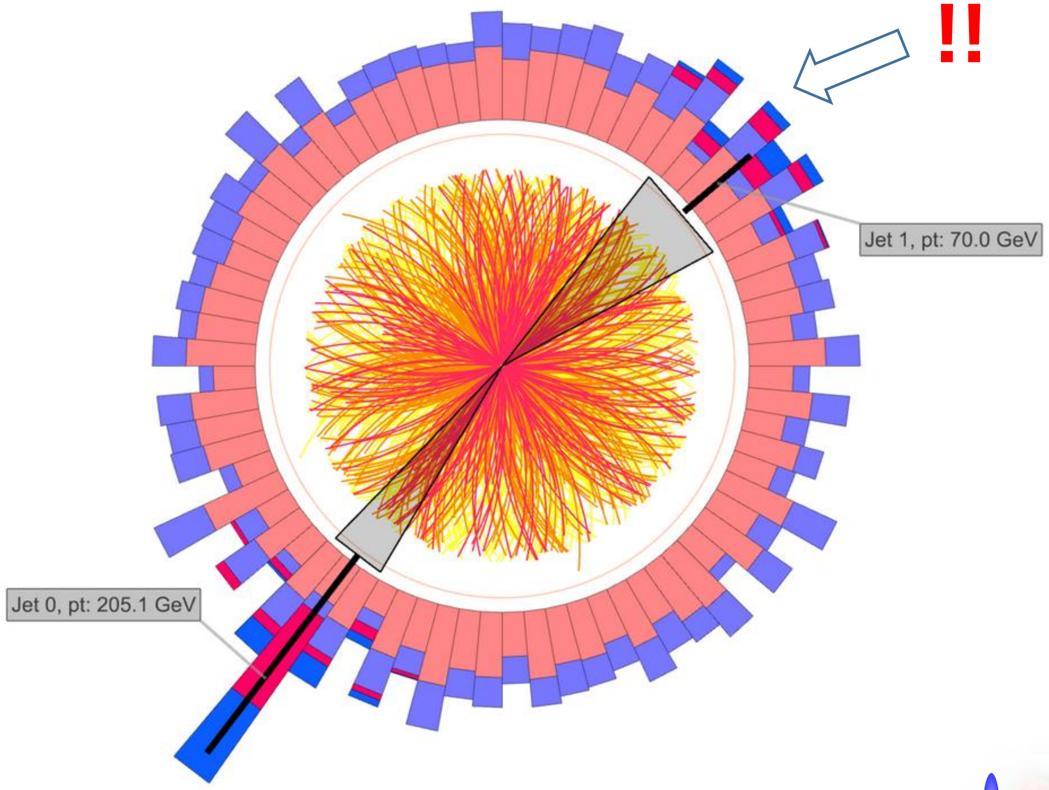
Probe the QGP with High Energy Quarks and Gluons

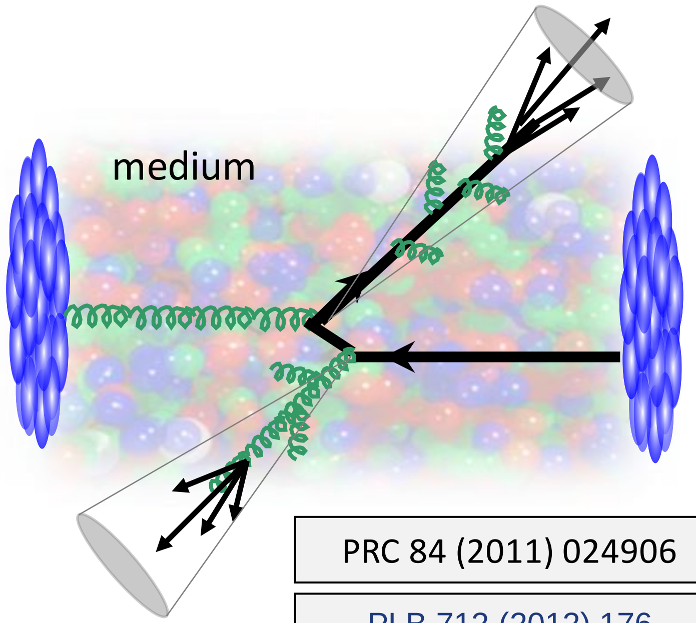


Proton+Proton



!!

Lead+Lead



Asymmetric dijets in Lead+Lead collisions!

PRC 84 (2011) 024906

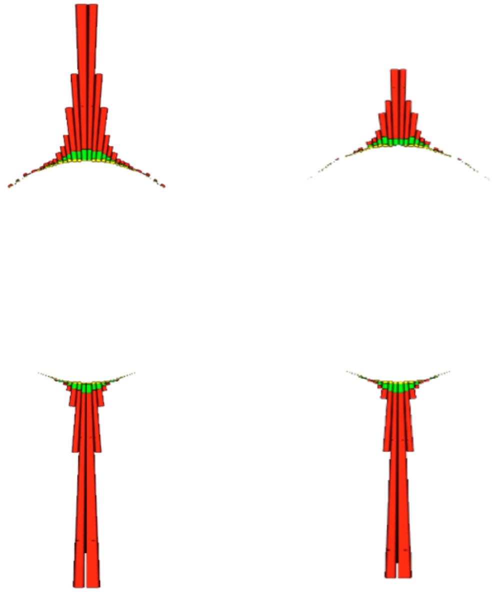
PLB 712 (2012) 176

First Measurement of Full Jets in Pb+Pb at LHC

PRL 105 (2010) 252303

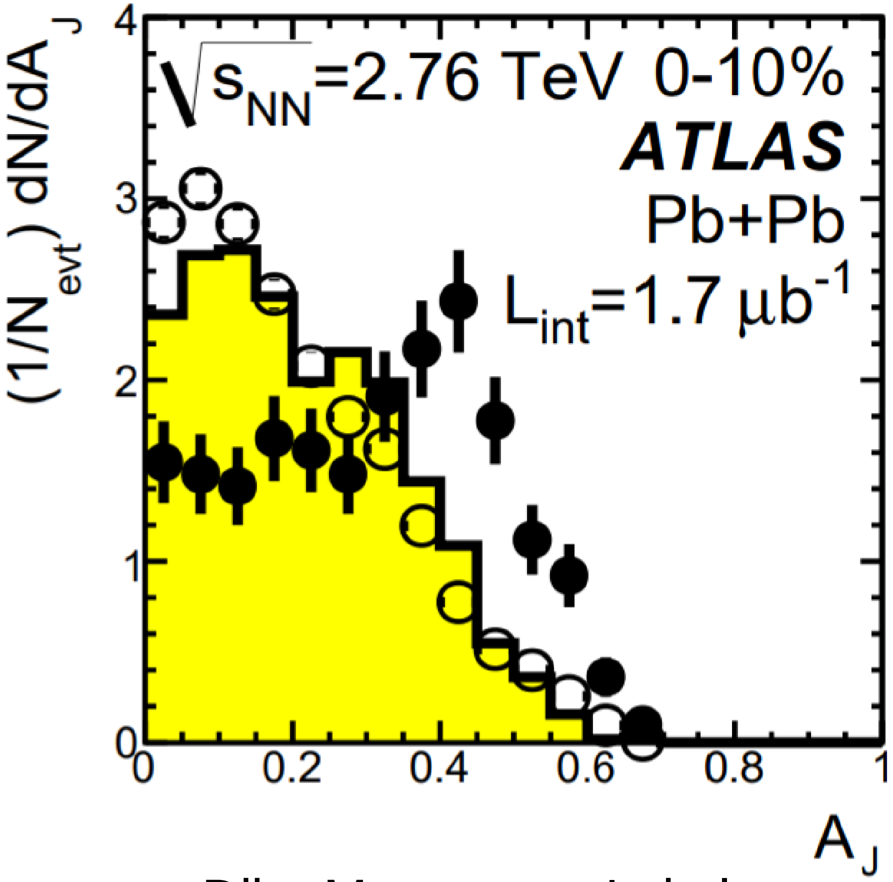
PRC 84 (2011) 024906

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

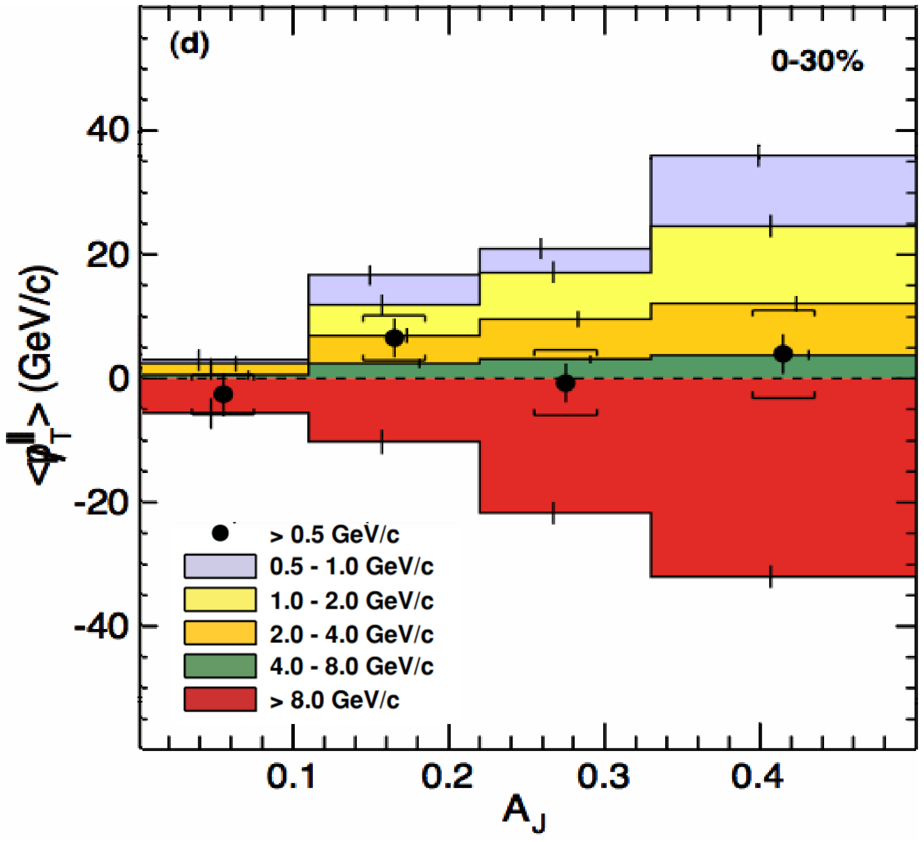


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



Dijet Momentum Imbalance

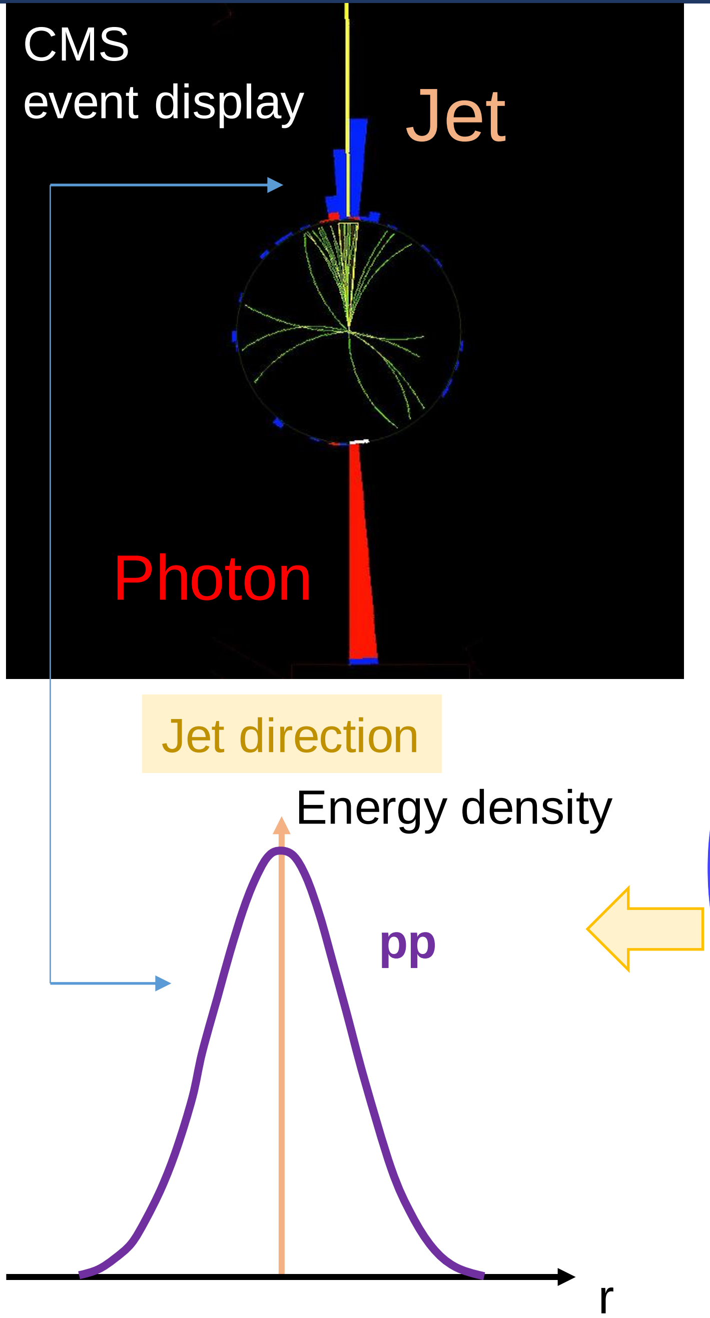


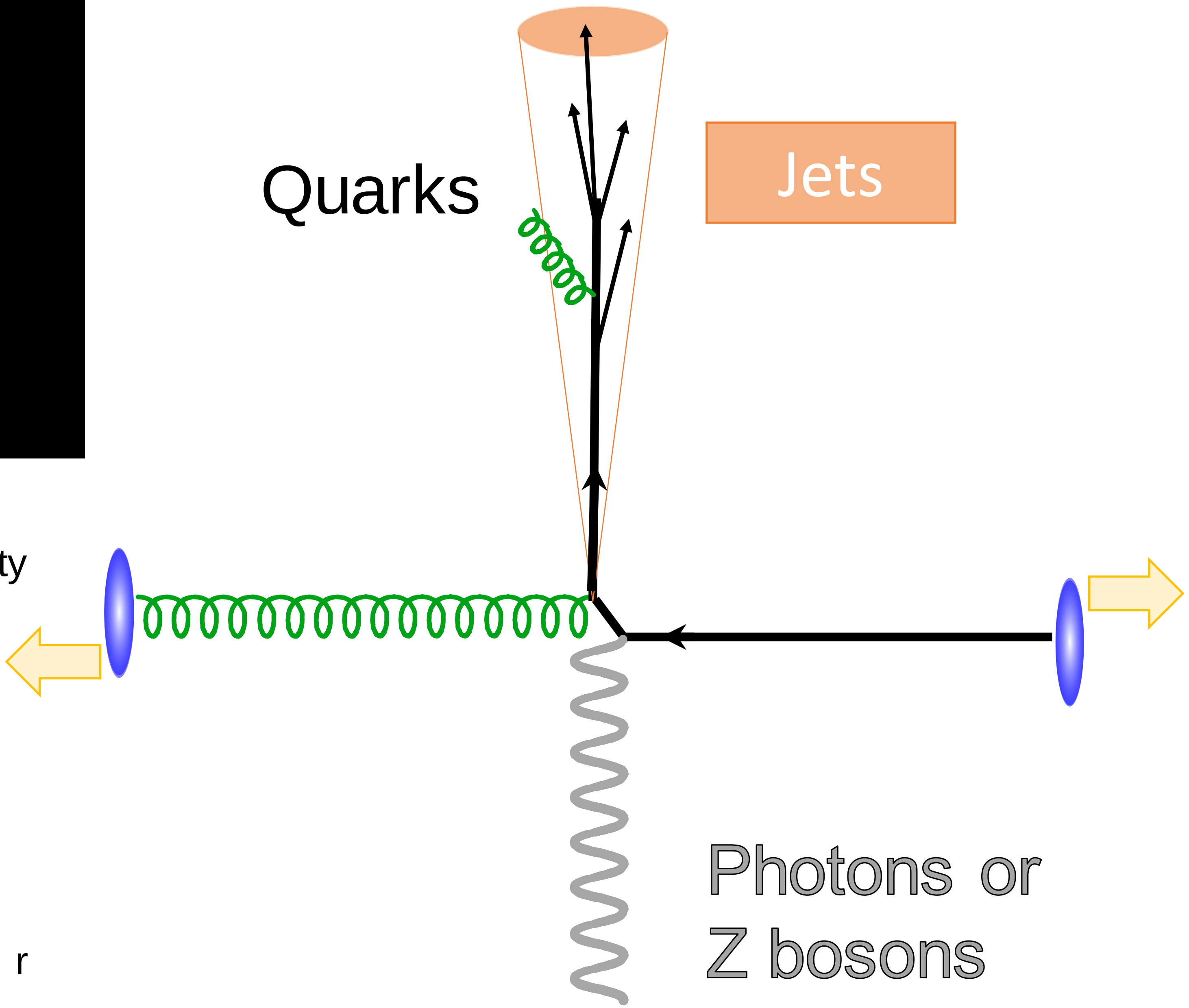
Missing Transverse Momentum

Jet quenching with jet
Energy flow out of the jet cone

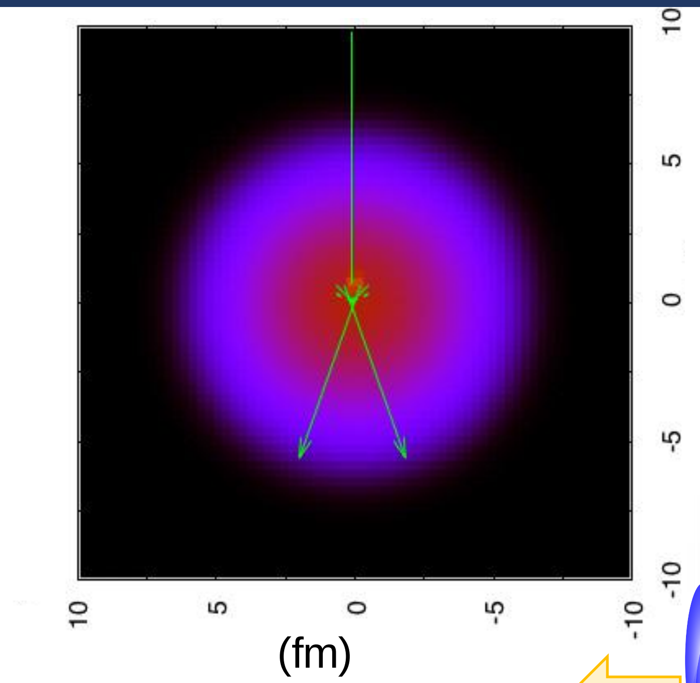
Quenched energy carried by low p_T particle out of the jet cone

High Transverse Momentum Scattering

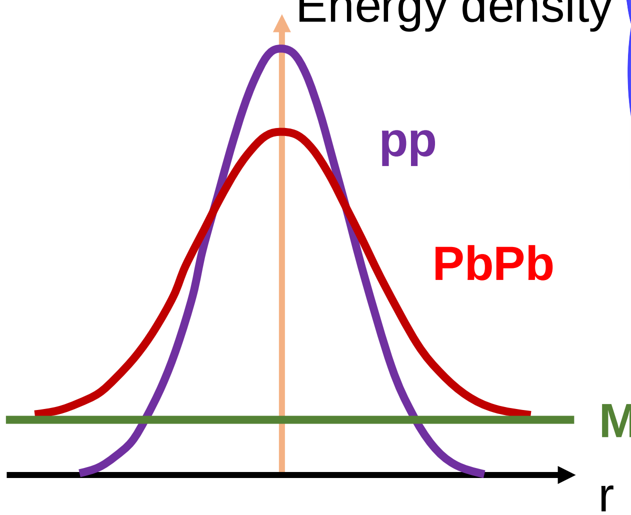


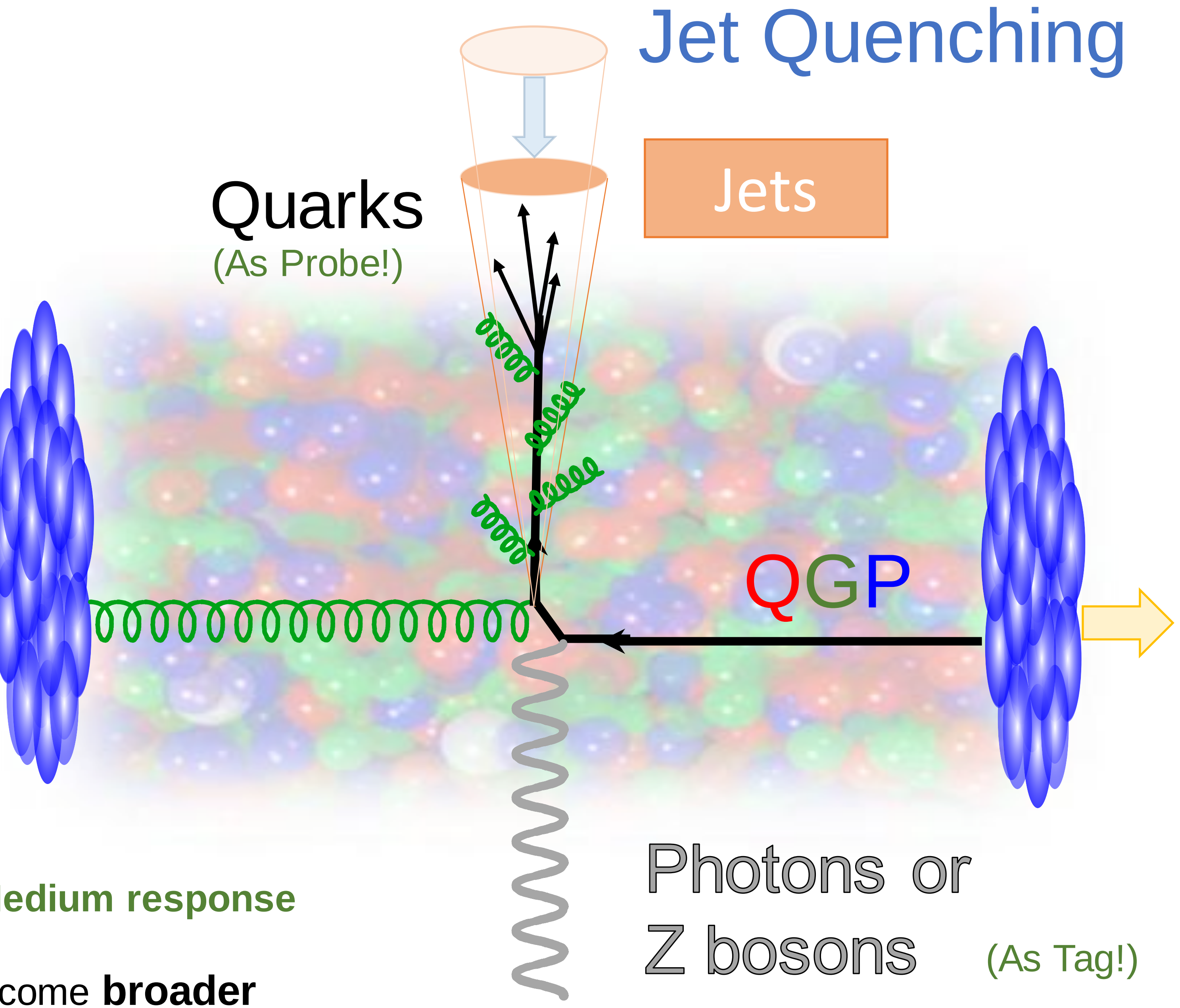


Probes Produced with the QGP



Jet direction

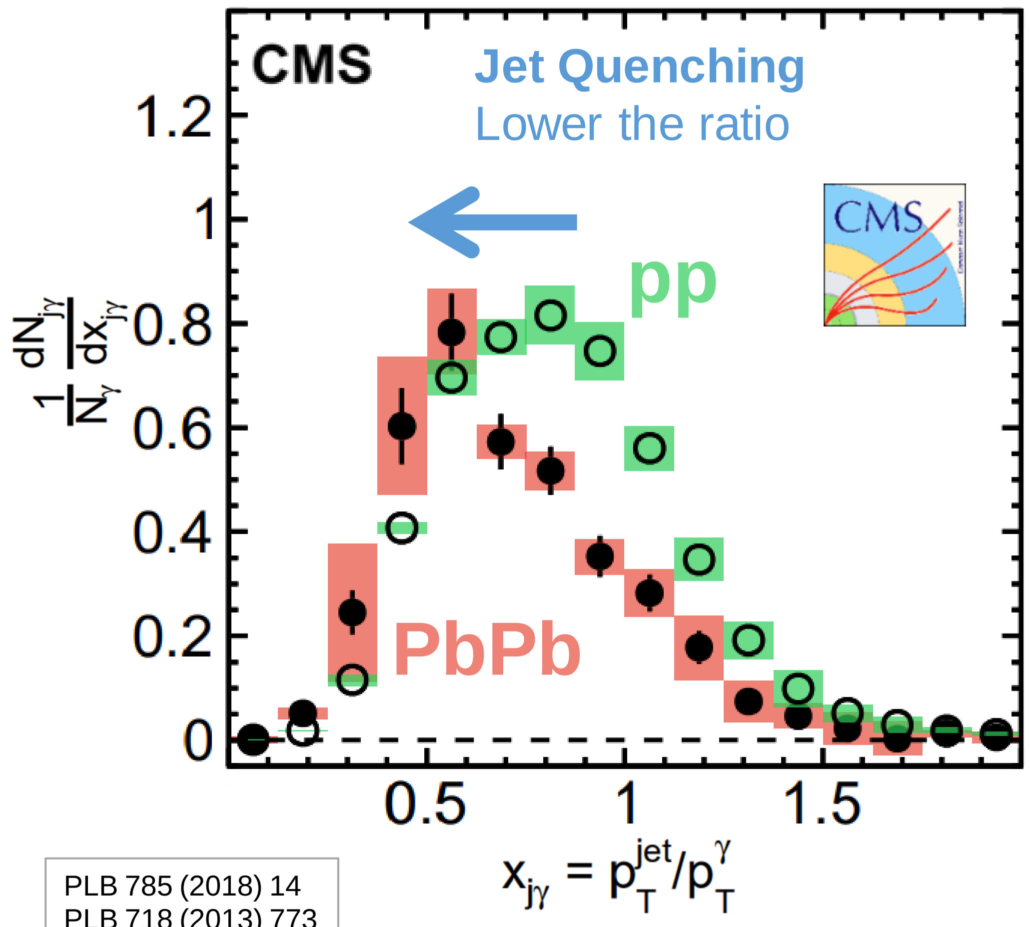




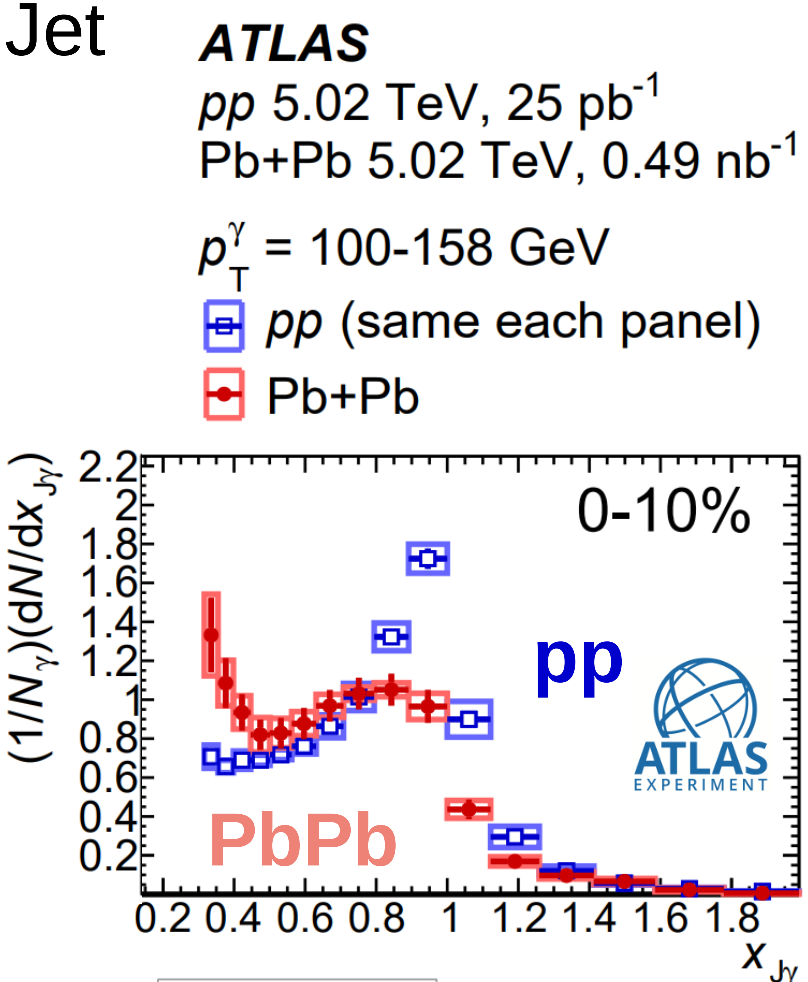
Quark jets in PbPb could become **broader**

Transverse Momentum Ratio of Quark-enriched Jet and Boson

Photon + Jet

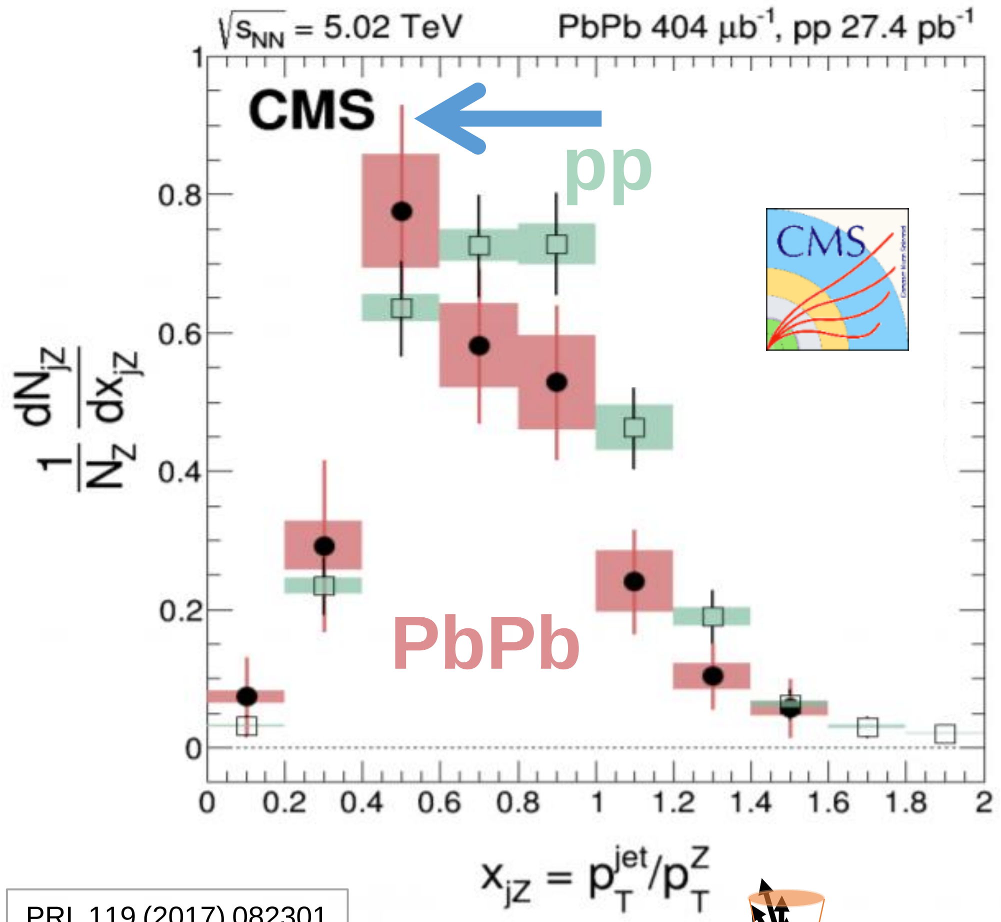


PLB 785 (2018) 14
PLB 718 (2013) 773

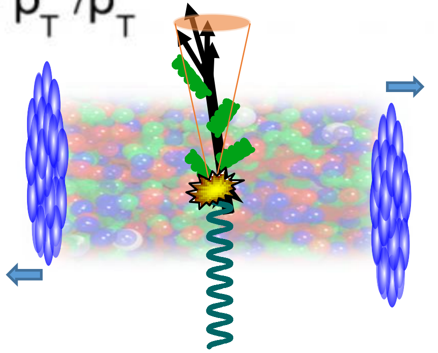


PLB 789 (2019) 167

Z^0 boson + Jet



PRL 119 (2017) 082301



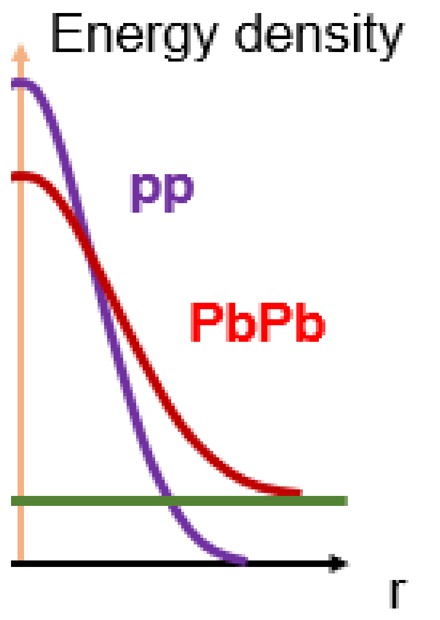
- Initial transverse momentum ~ 0
- Photons and Z bosons are not affected by QGP

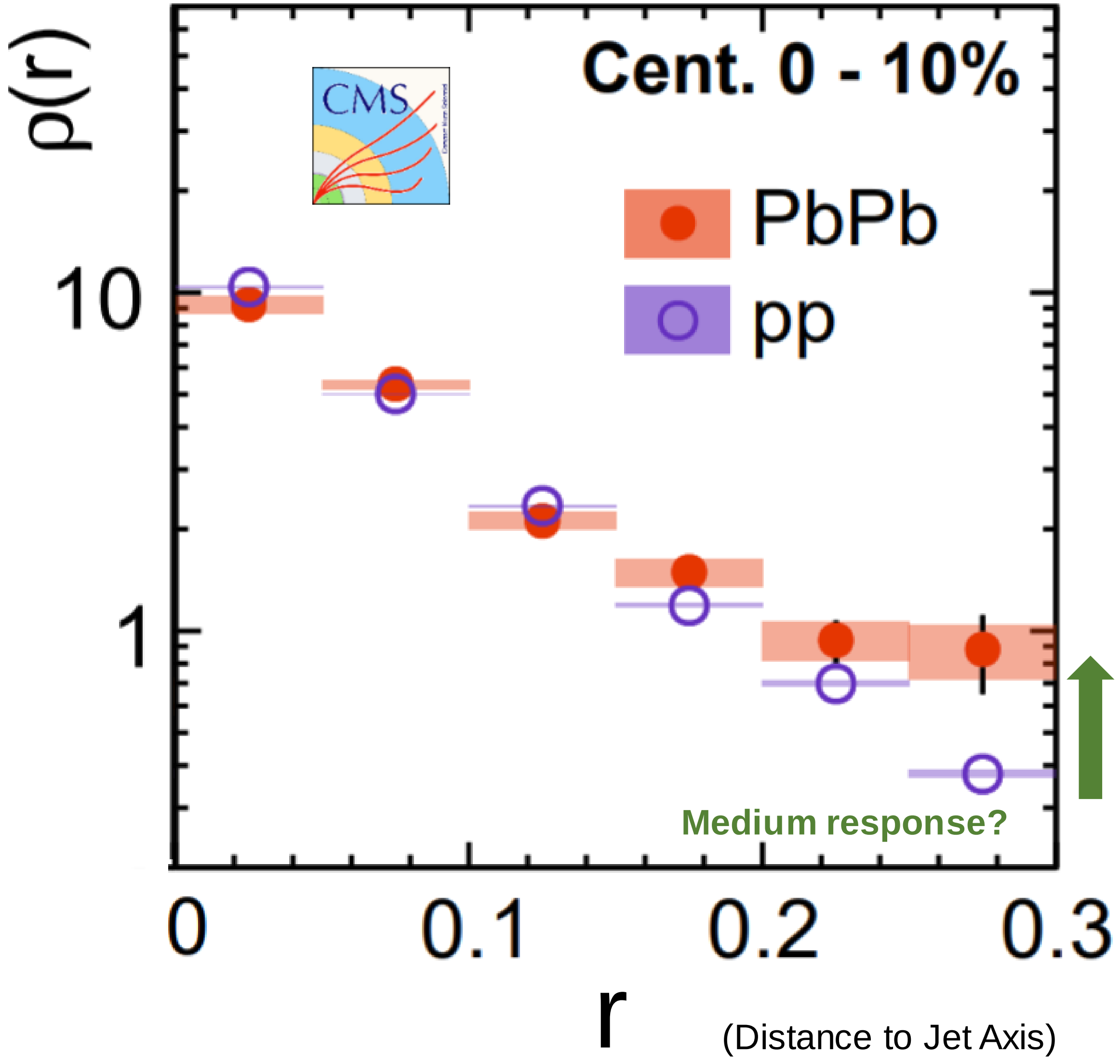
Quark-enriched jet (70% quark) to boson momentum ratio lowered

Quark Jet Shape and Fragmentation Modification

PRL 122 (2019) 152001

Radial Shape



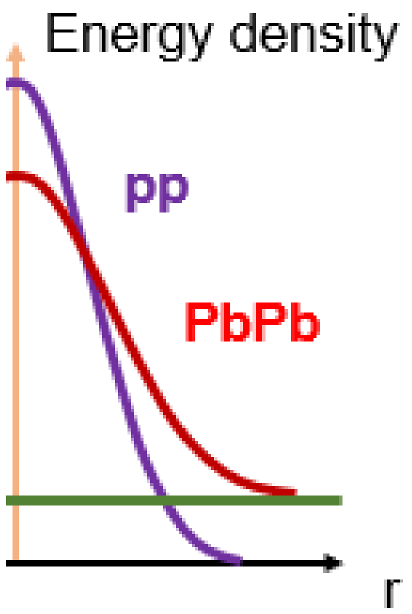


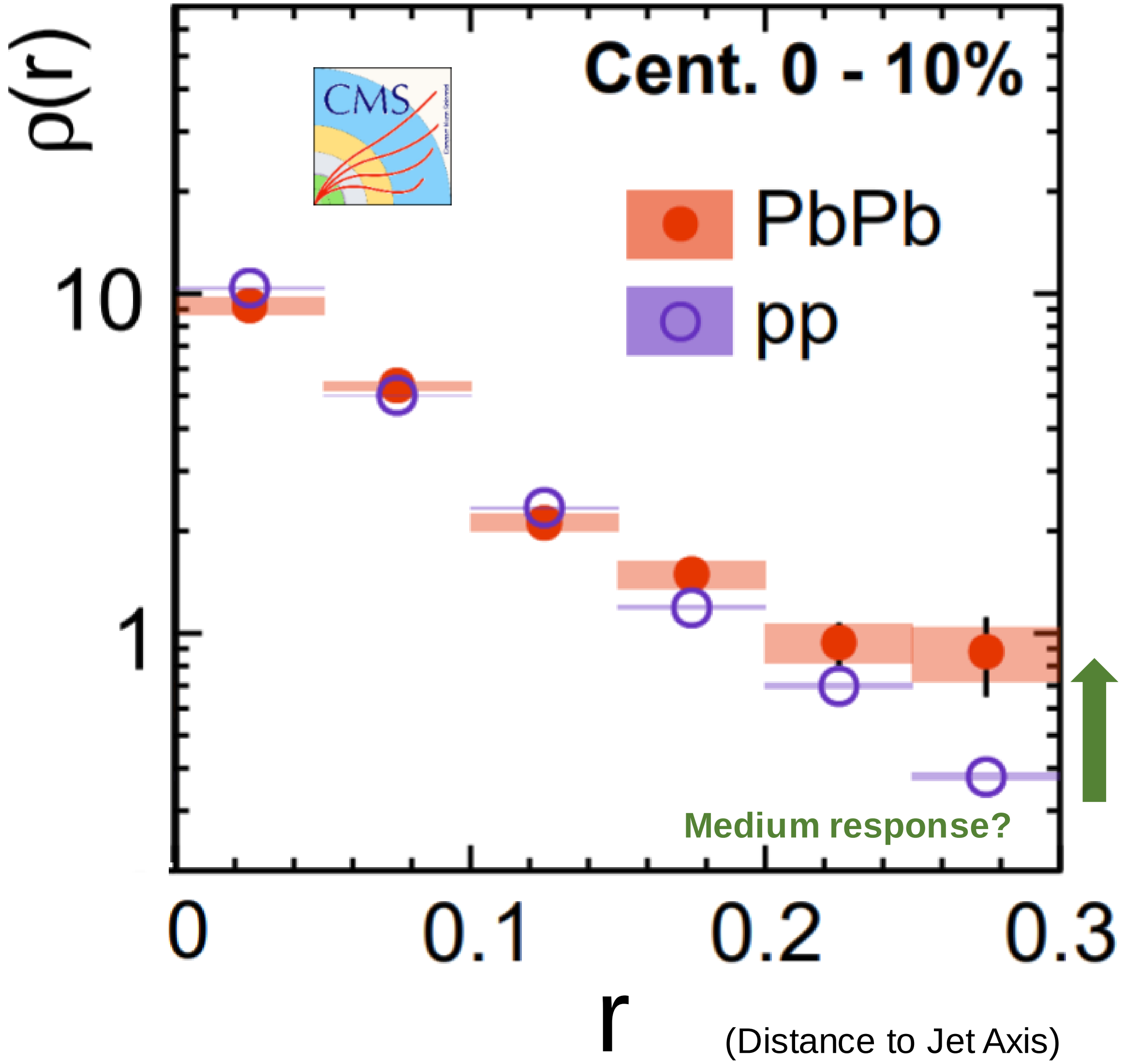
- **Broadening** of the quark-enriched jets

Quark Jet Shape and Fragmentation Modification

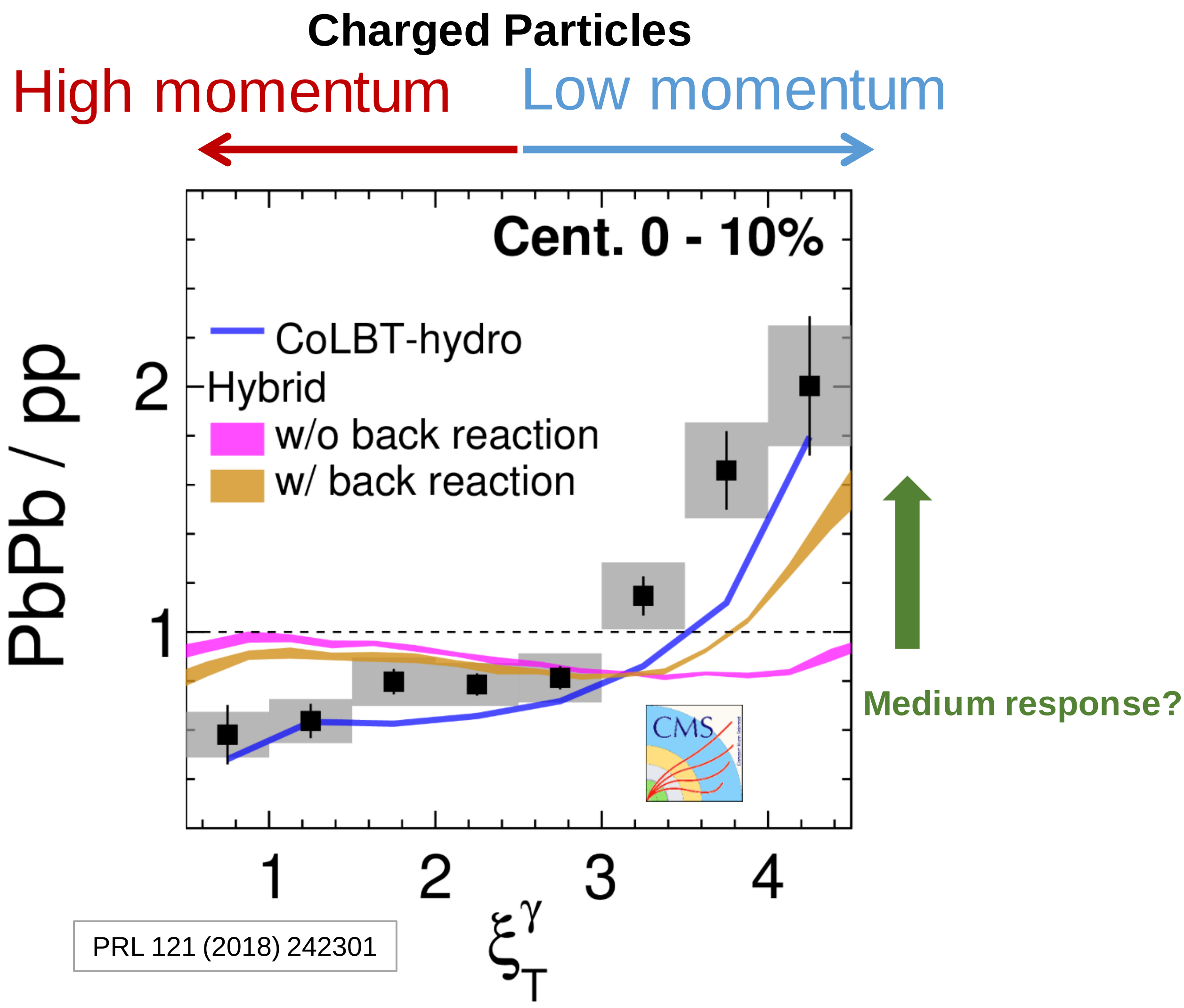
PRL 122 (2019) 152001

Radial Shape





Constituent Momentum Spectrum



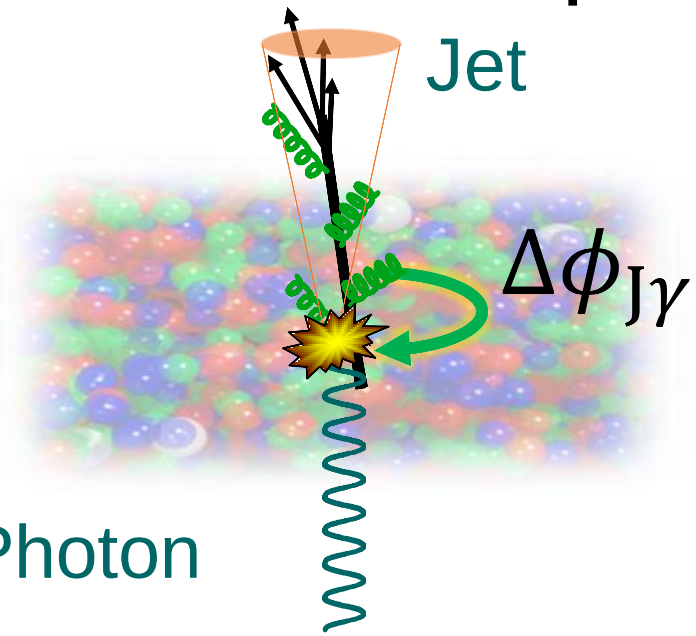
PRL 121 (2018) 242301

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

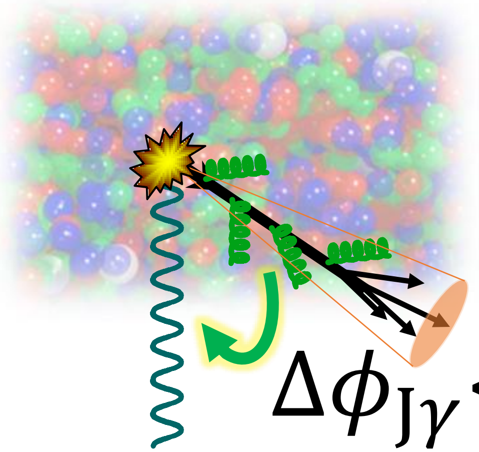
- **Broadening** of the quark-enriched jets, enhancement of **low momentum particles**
- Strong indication of QGP **medium response**!

Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"

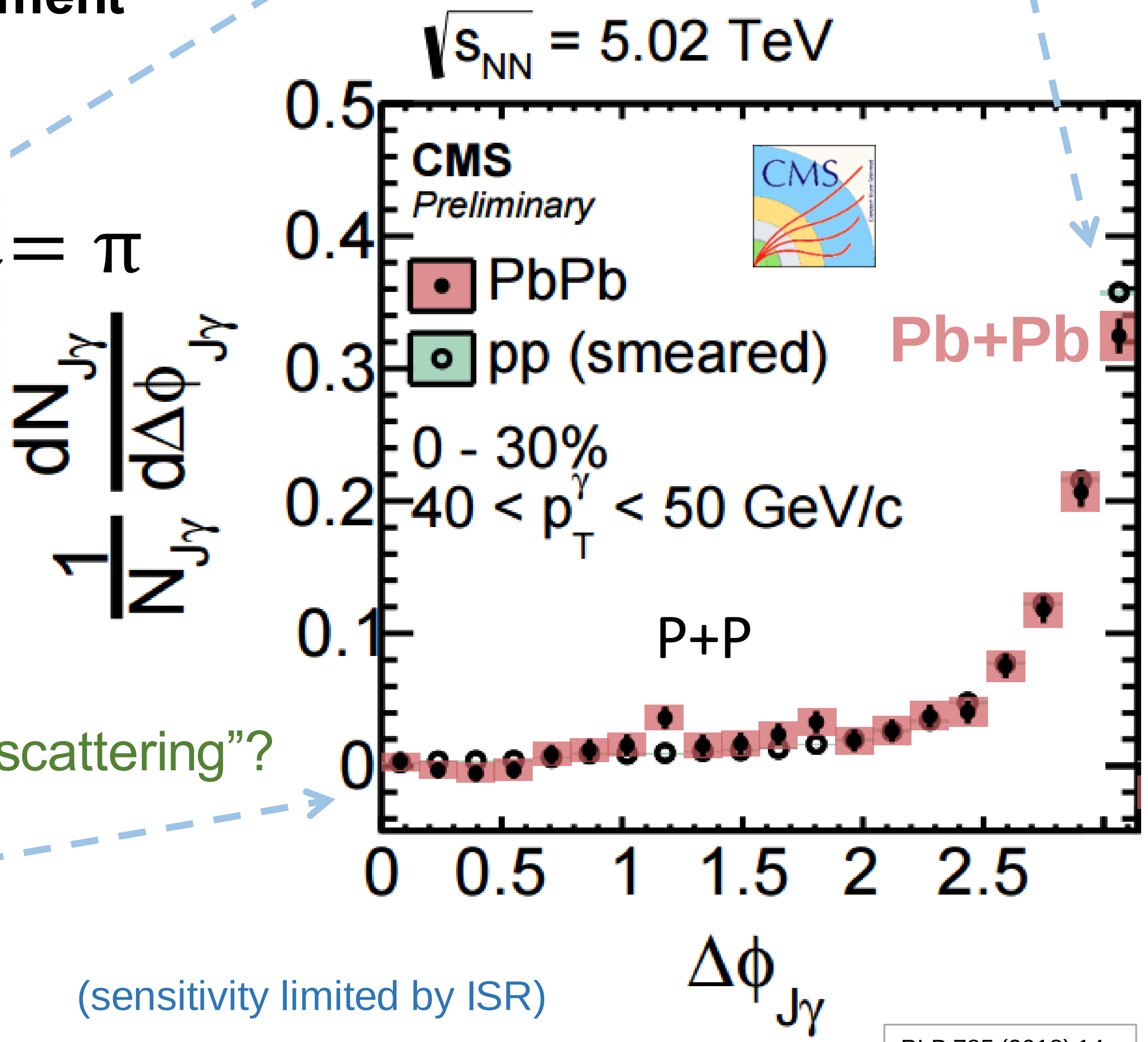


$\Delta\phi_{J\gamma} = \pi$

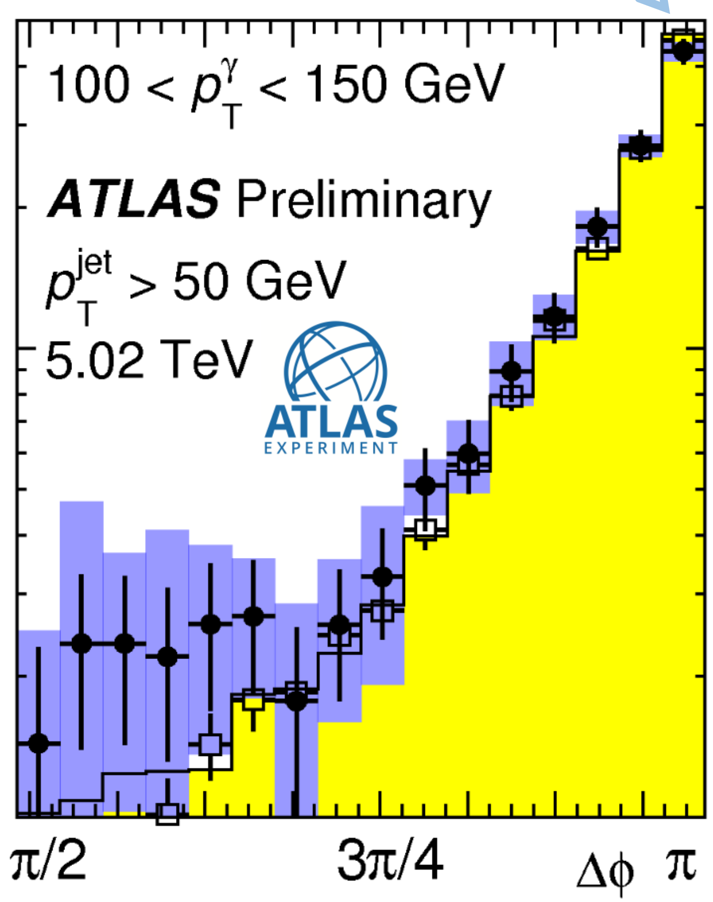


$\Delta\phi_{J\gamma} < \frac{\pi}{2}$

"Backscattering"?



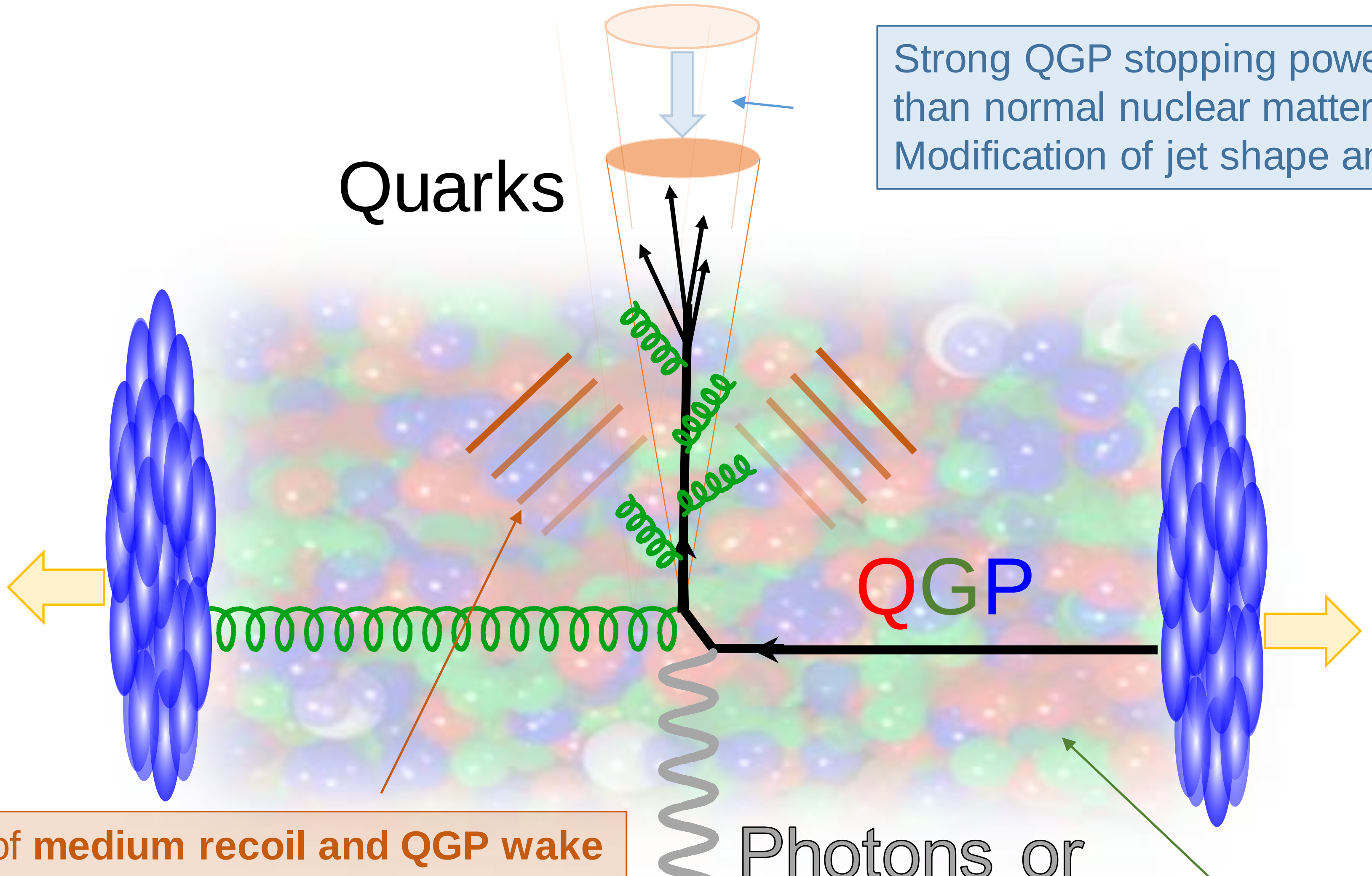
(sensitivity limited by ISR)



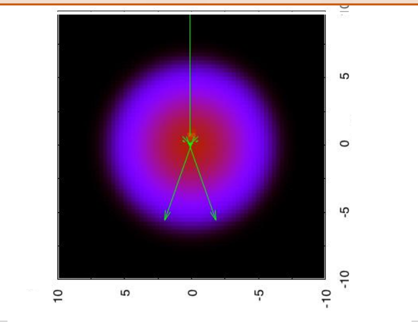
PLB 785 (2018) 14
PLB 718 (2013) 773

Lessons from Jet Spectra and Structure

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

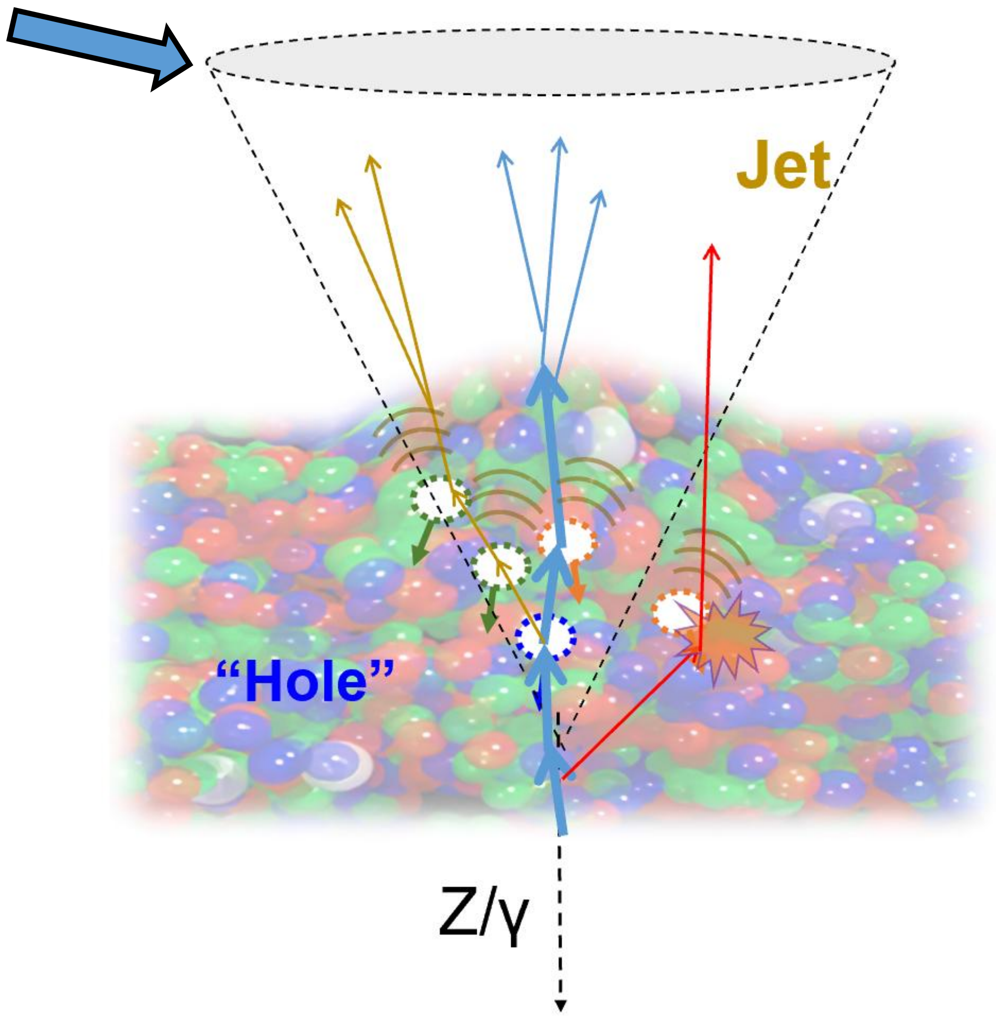


Evidence of **medium recoil and QGP wake**



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

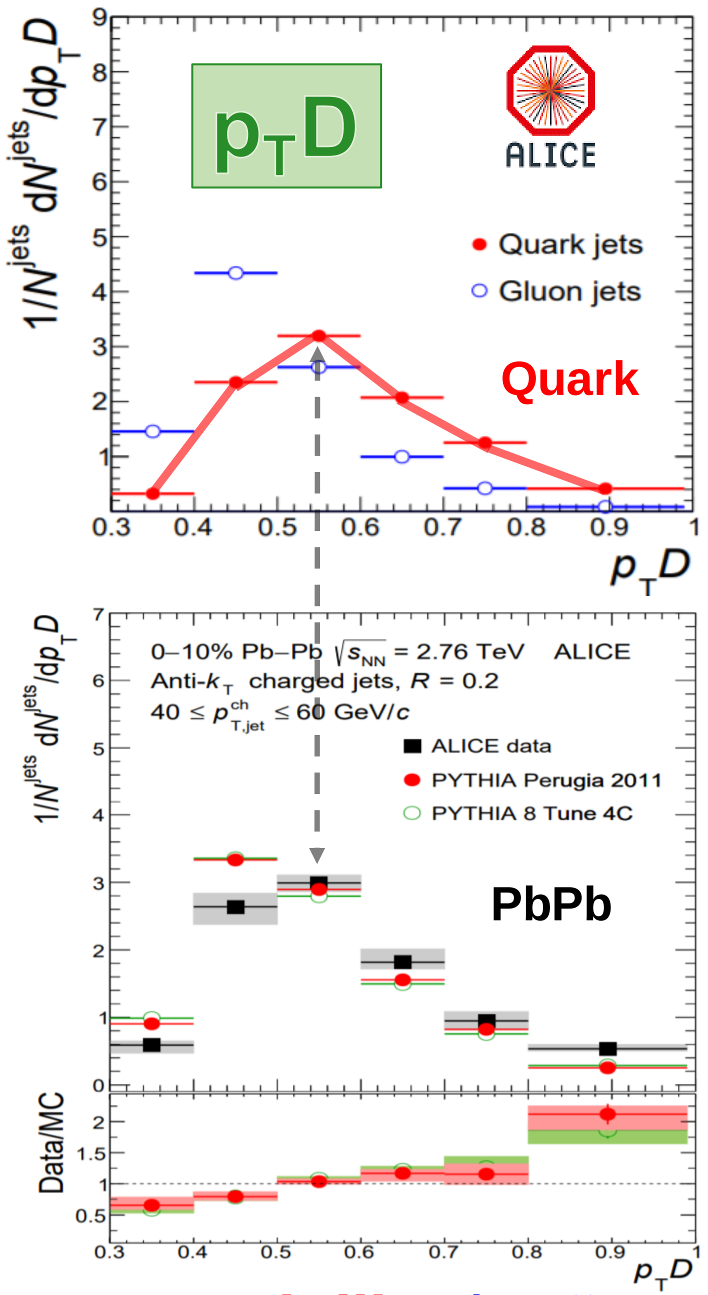
JHEP 10 (2018) 13

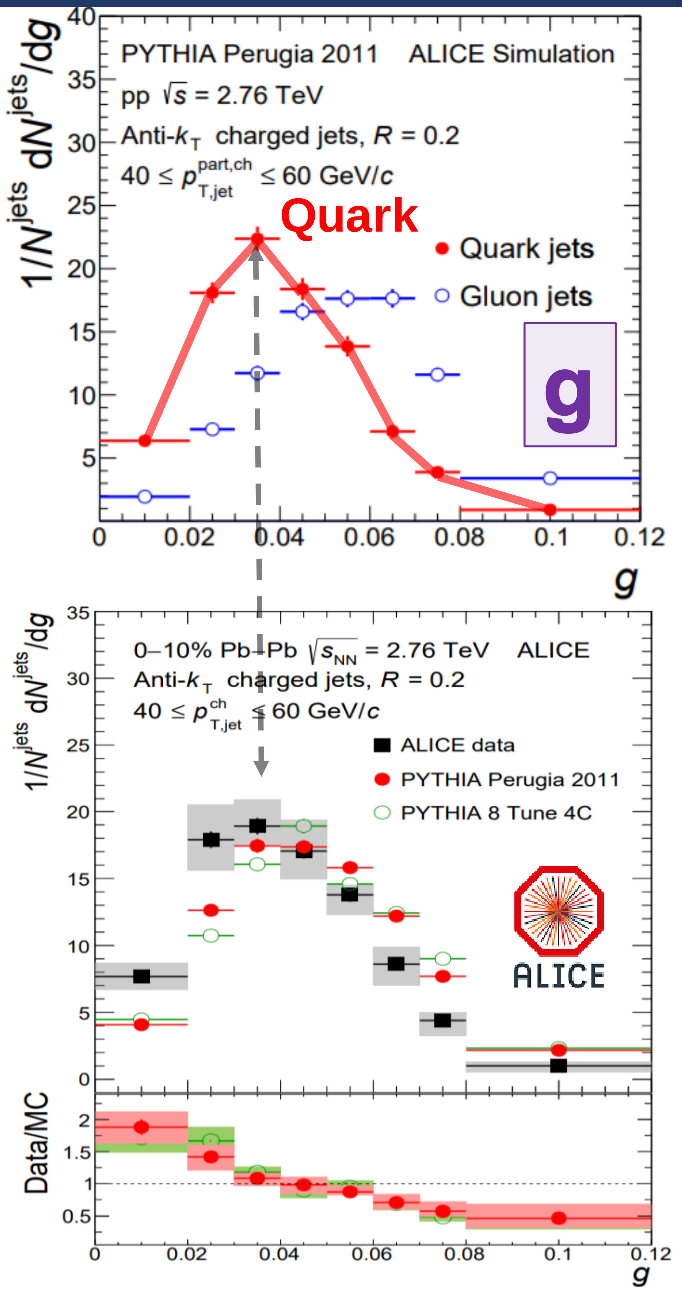
ALICE Simulation

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

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

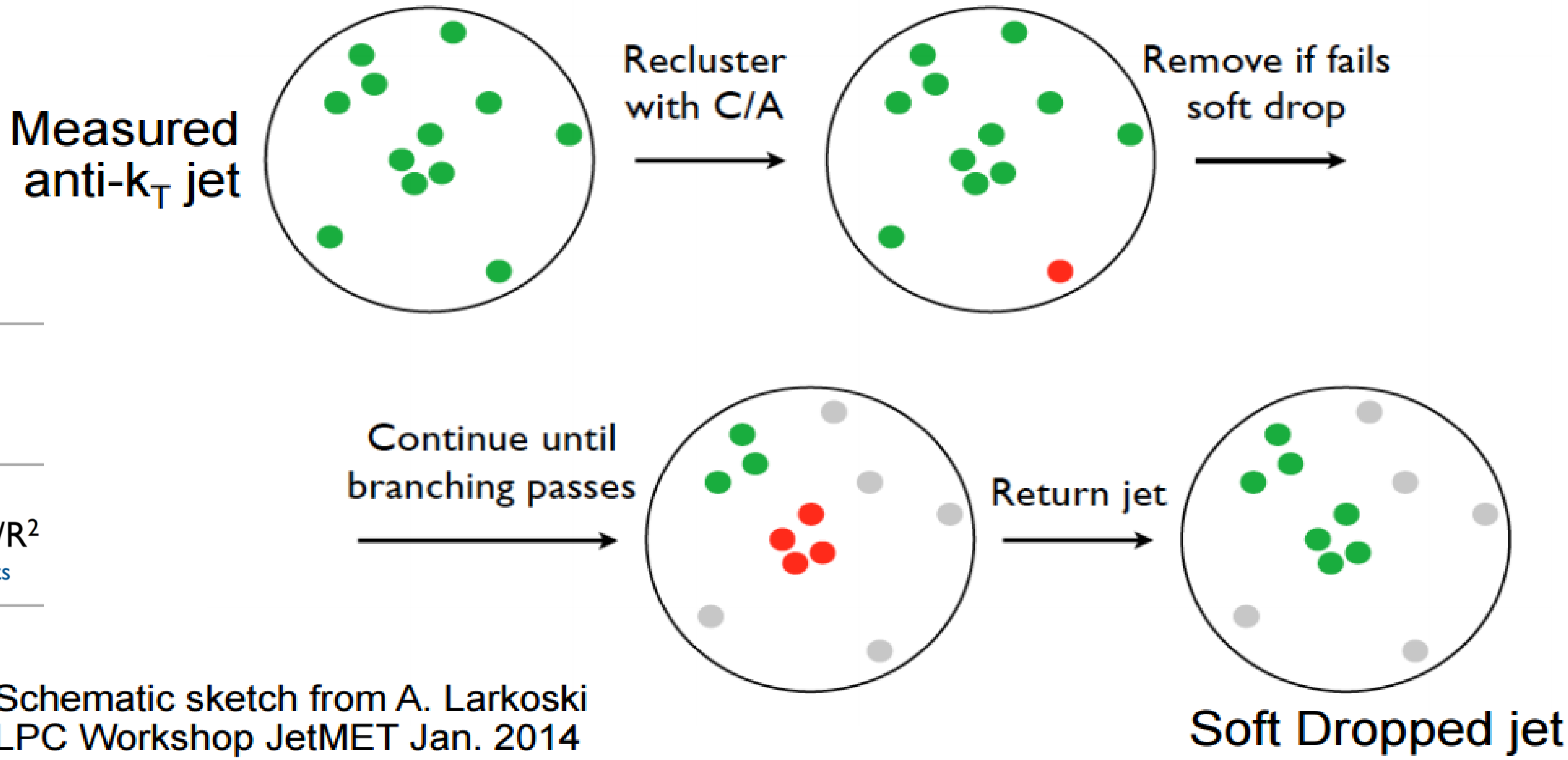
ALICE Data





- 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

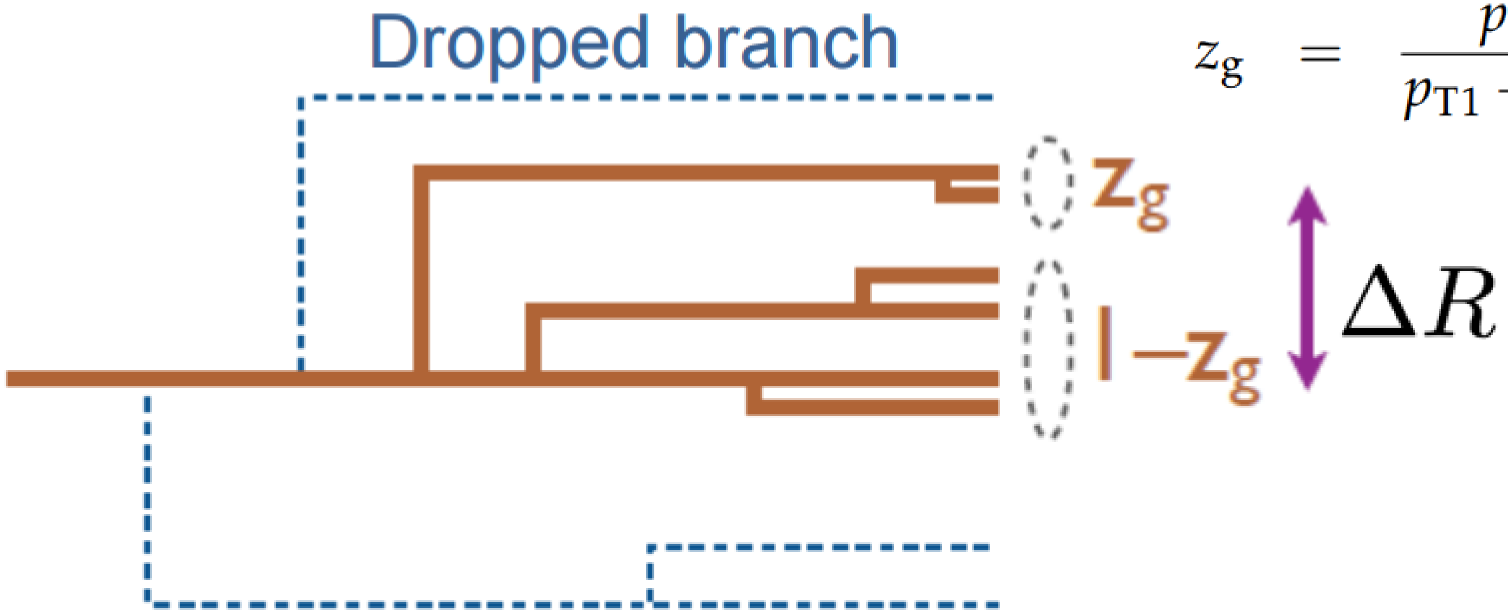
Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets

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

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



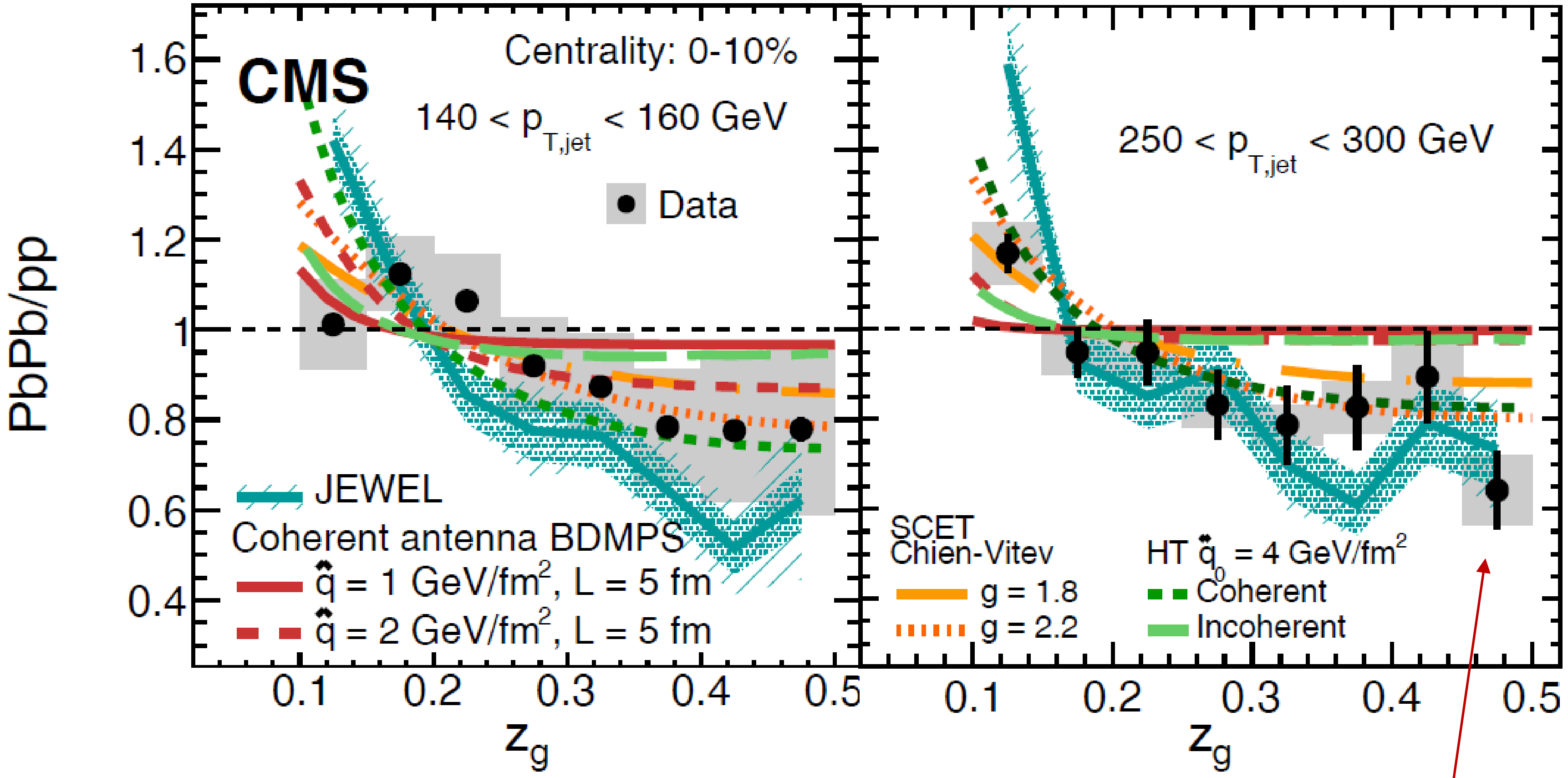
$$z_g = \frac{p_{T2}}{p_{T1}+p_{T2}}$$

Reminder of jet algorithms

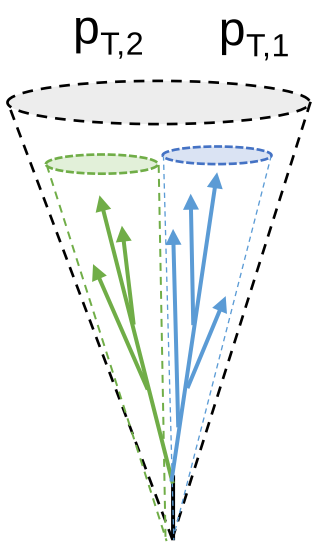
Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets

Andrew Larkoski, et al
JHEP 1405 (2014) 1465

Momentum Sharing of Subjets



arXiv:1708.09429
PRL 120 (2018) 142302
PRL Synopsis



Two hard subjets
$Z_g \sim 0.5$

Quark and gluon Z_g distributions are very similar in pp

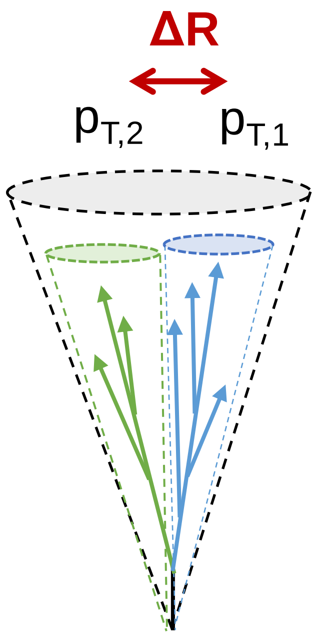
Jets with **two hard subjets** (large Z_g) **"relatively"** more suppressed!

Interpretation:

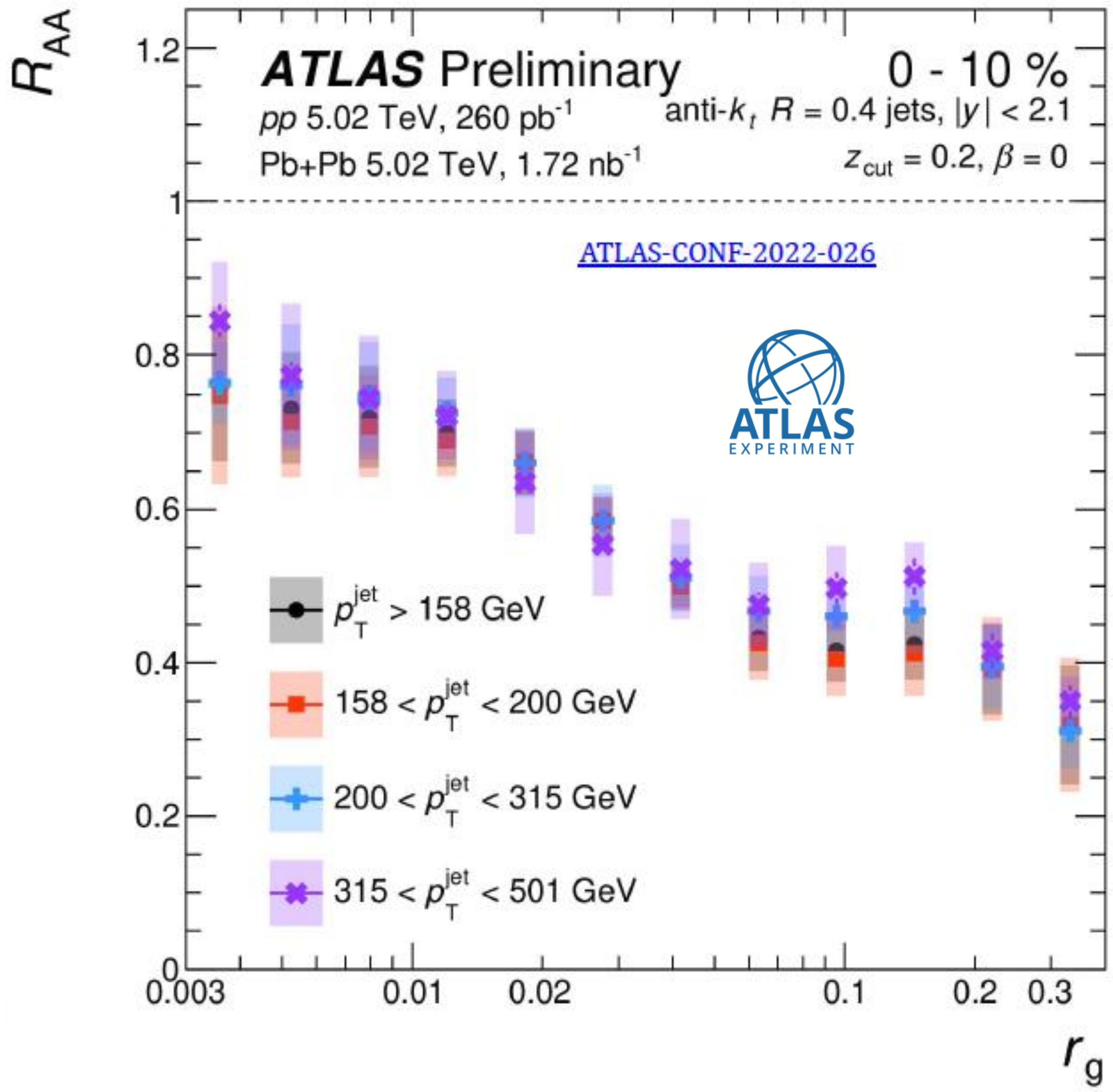
- **JEWEL**: enhancement of low Z_g jets (due to **medium recoil**)
- **$SCET_G$**: modification due to medium induced splitting function
- HT & Coherent antenna BDMPS: Data prefer coherent energy loss

Groomed Subjet Opening Angles

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

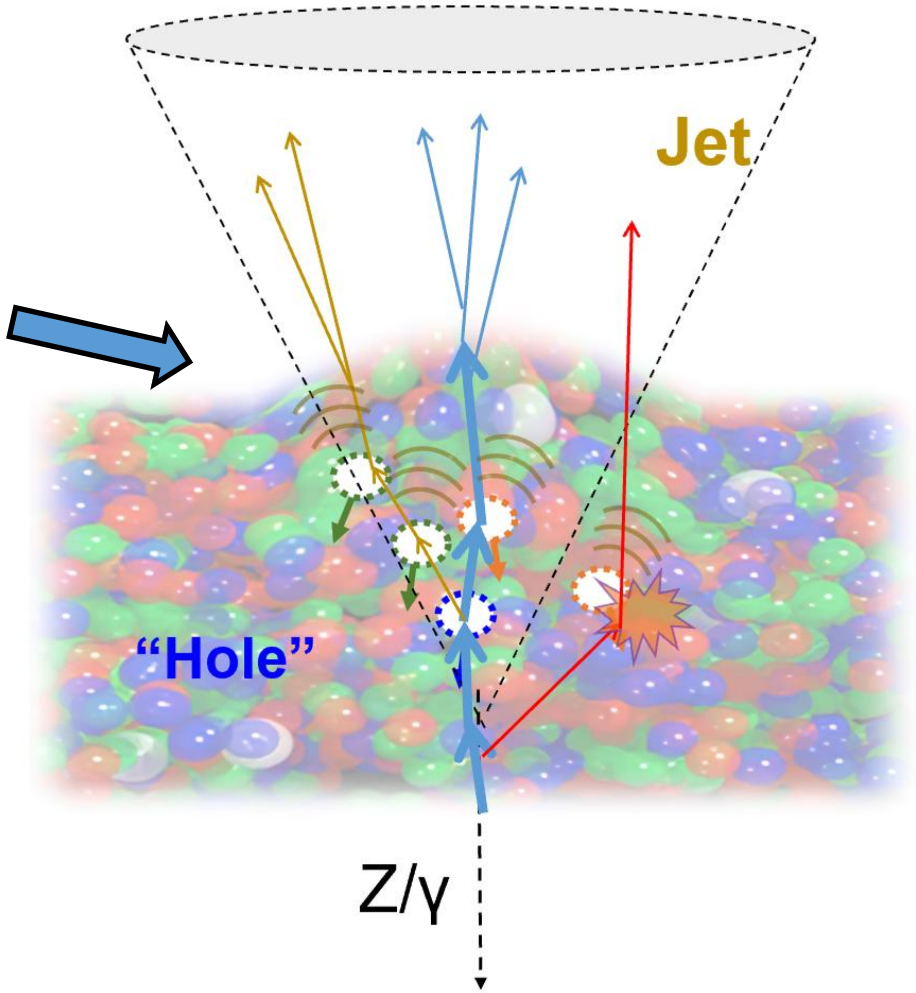


Two hard subjets



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

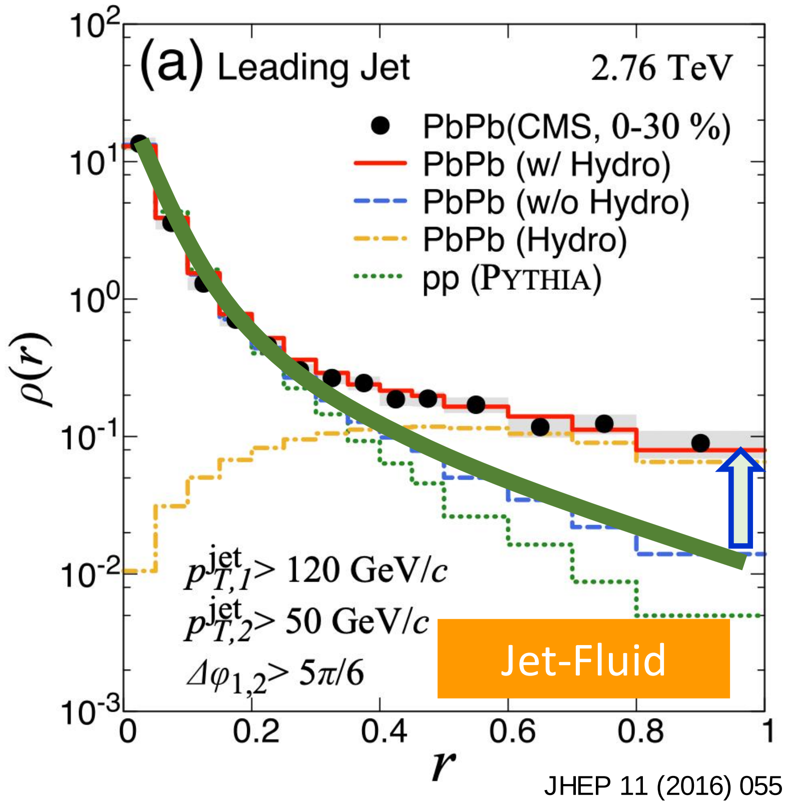
Focus on the Medium Response



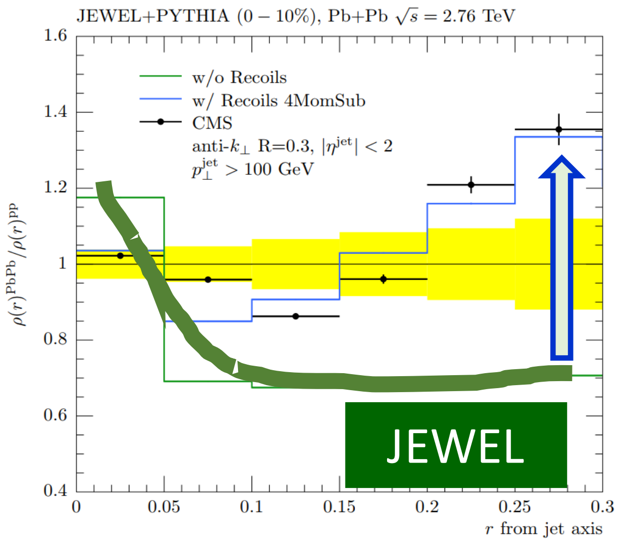
Have we observed the medium response to hard probes?

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

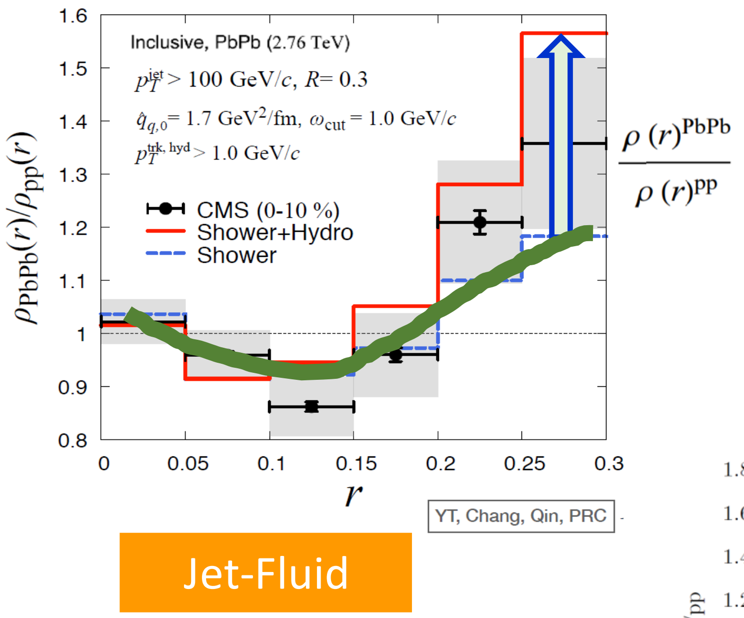
Interpretation of the CMS Jet Shape

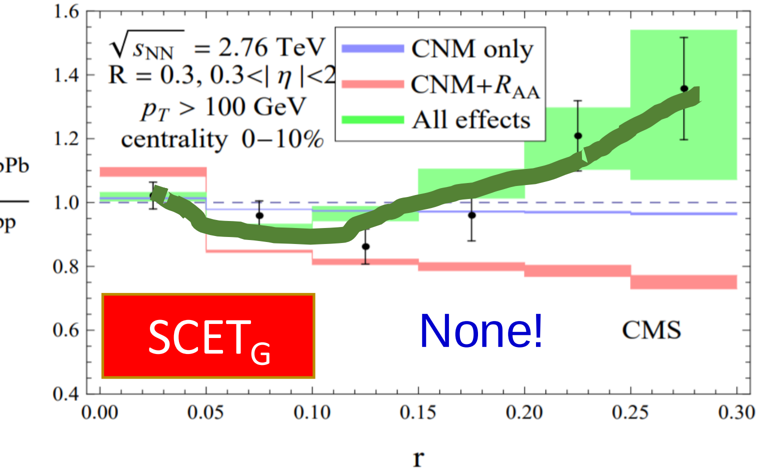


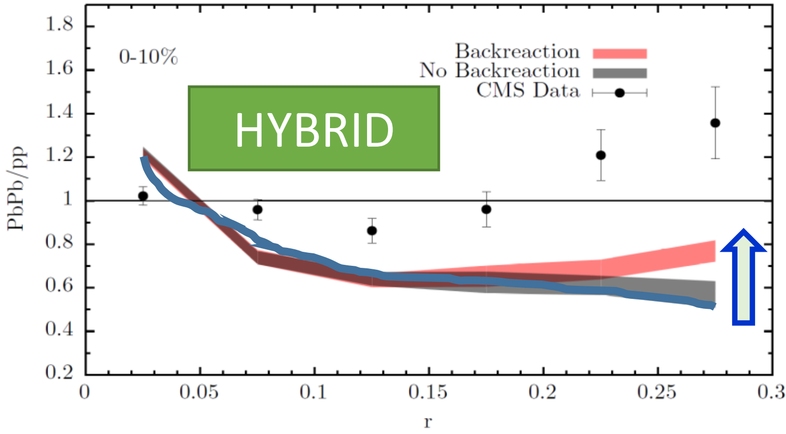
JHEP 11 (2016) 055
PRC 95 (2017) 4, 044909



JHEP 07 (2017) 141

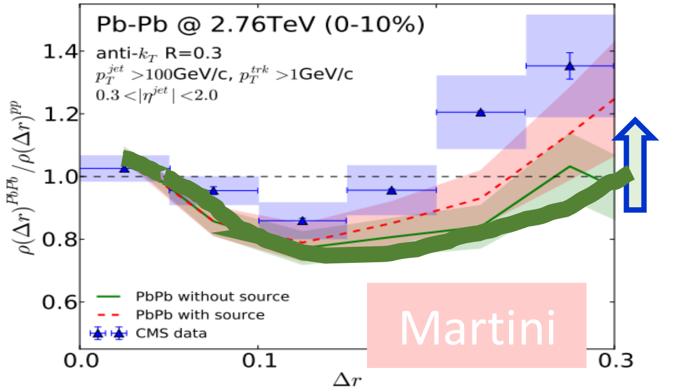






Modifications of the shower

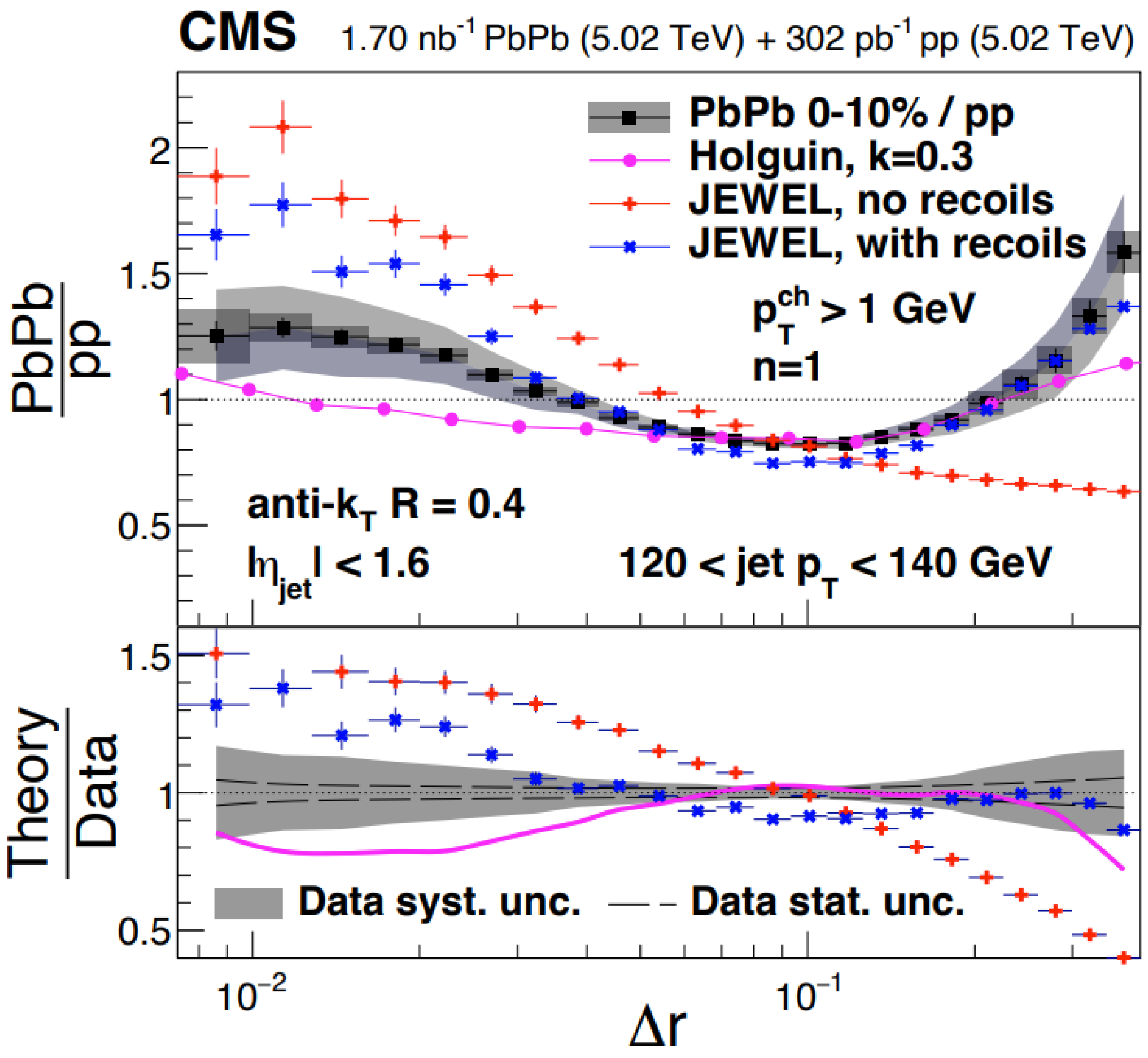
Medium Recoil and Response

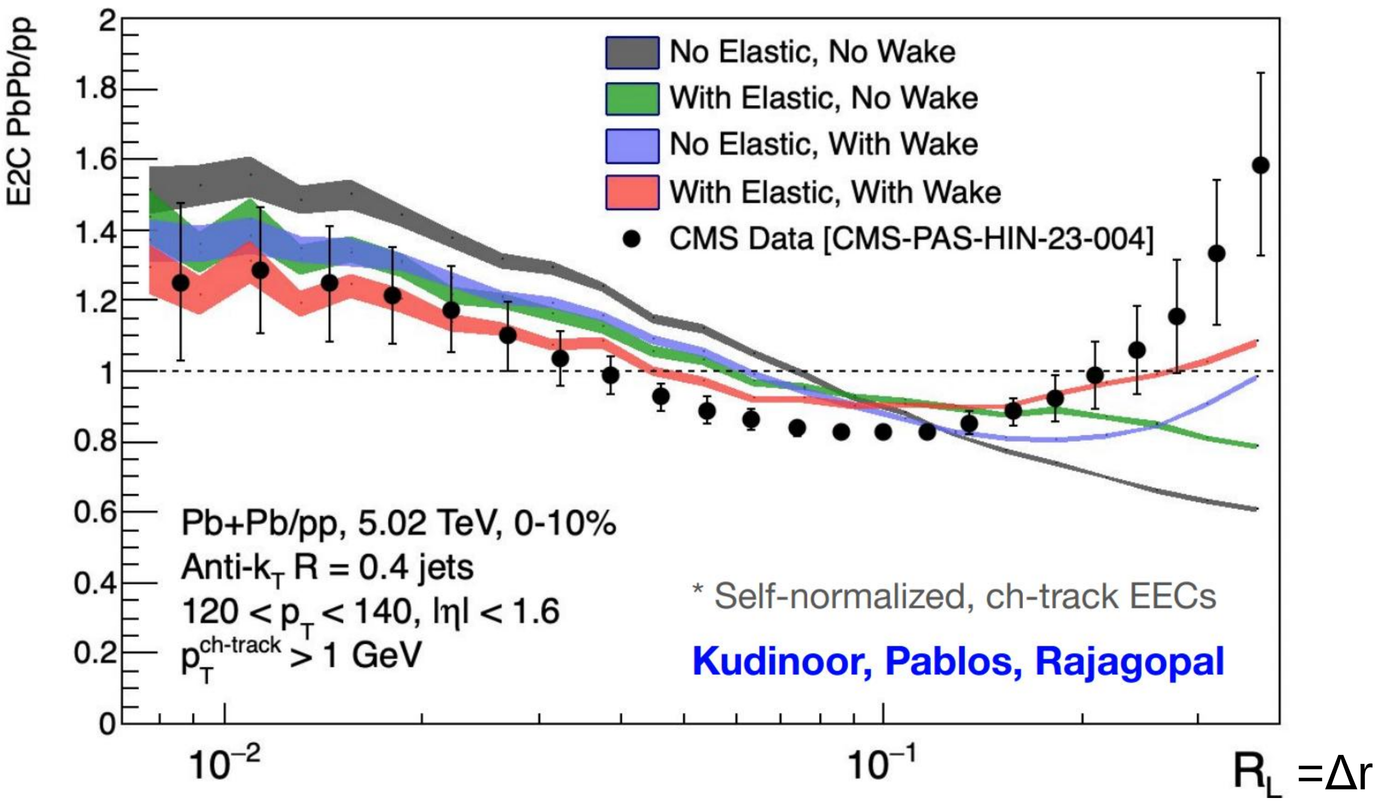


Models with **different mechanisms** give reasonable description of the inclusive jet shape and many other observables

How do we make more progress?

Inclusive Jet EEC PbPb/pp Ratio





Exciting new PbPb / pp ratio measurement!

- Features a **U shape**
- Selection bias: narrows the jet core

Enhancement at **large Δr** could be explained by

- Medium response / recoil
- Elastic scattering
- Medium induced radiation

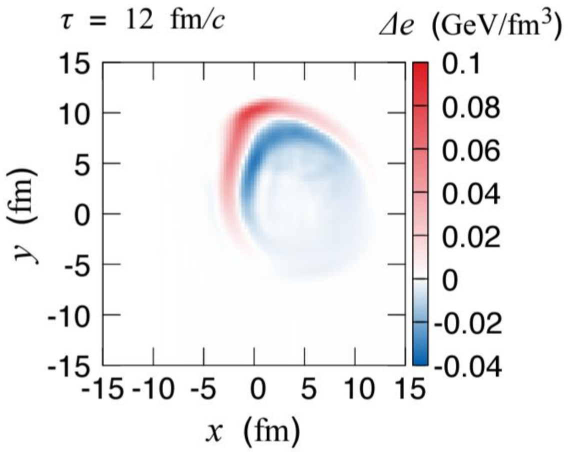
One can read the QGP quenching power directly
https://arxiv.org/pdf/2409.07514

Medium Response to Hard Probes in QGP

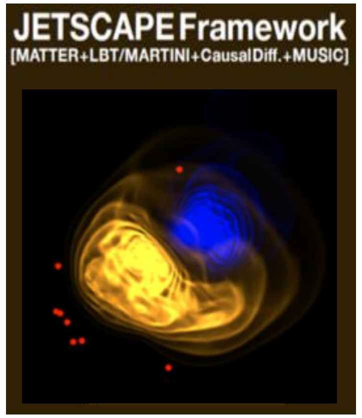
Duck swimming through water

More water going in the duck direction

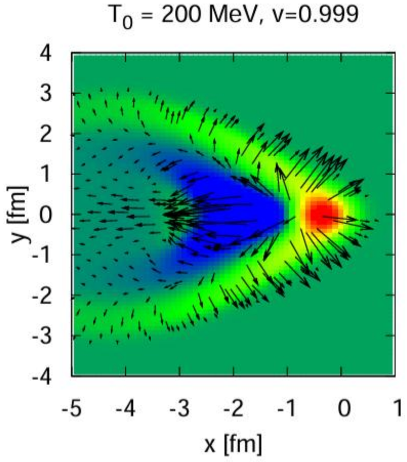
Quark plowing through the QGP

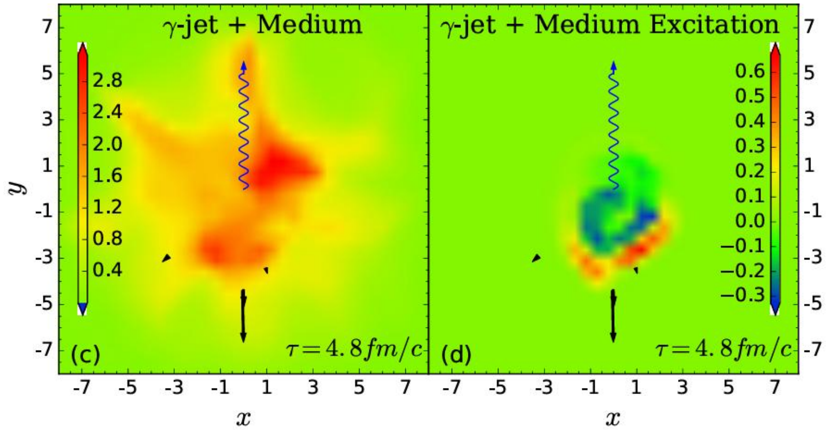


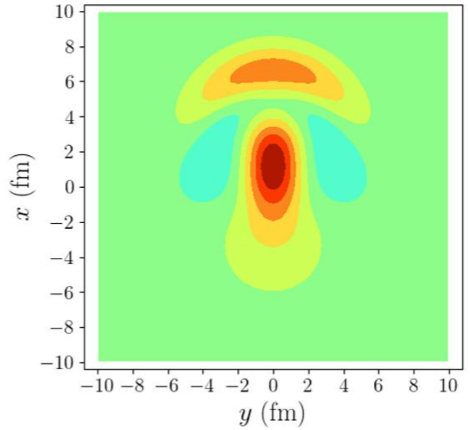
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



JETSCAPE framework
Tachibana, Shen, Majumder
PRC 106 (2022), L021902







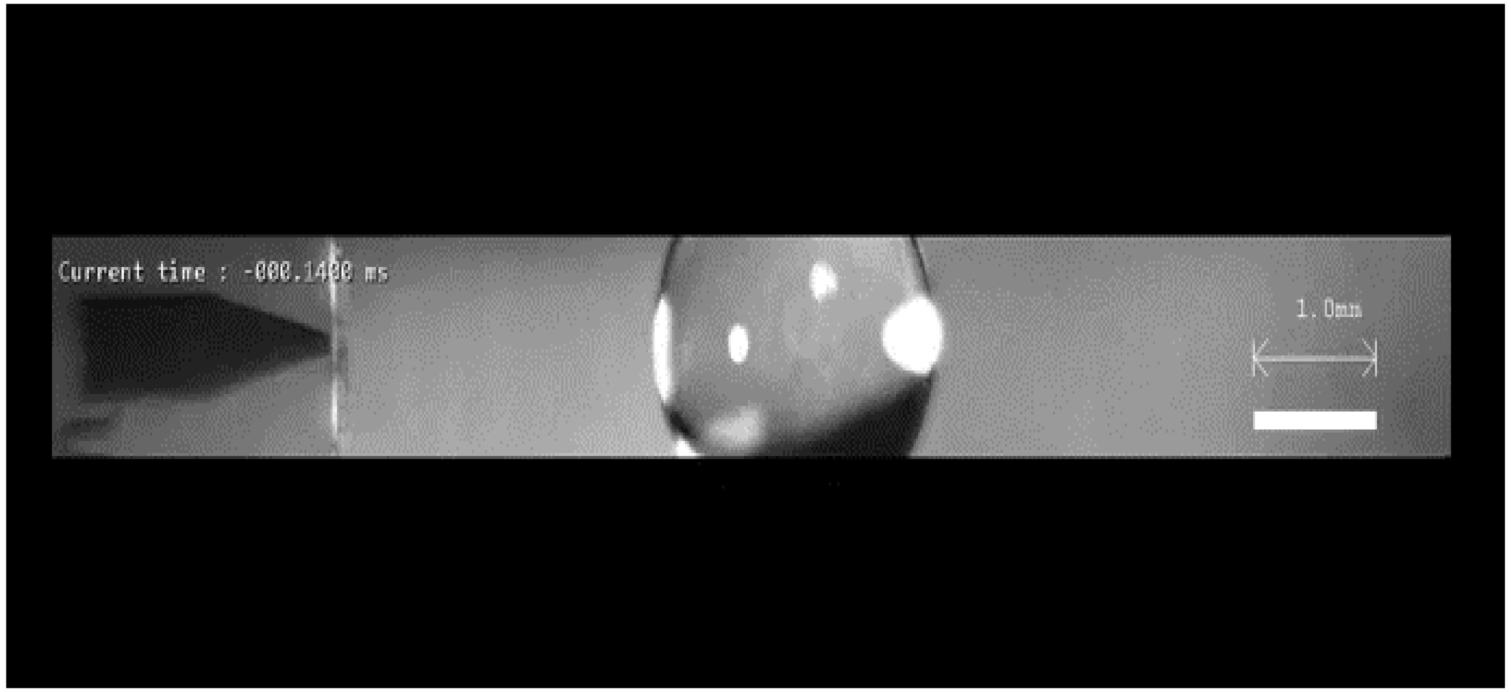
CoLBT Chen, Cao, Luo, Pang, Wang
PLB 777 (2018) 86-90

More QGP going in the jet direction

In Position Space

Medium Response to Hard Probes

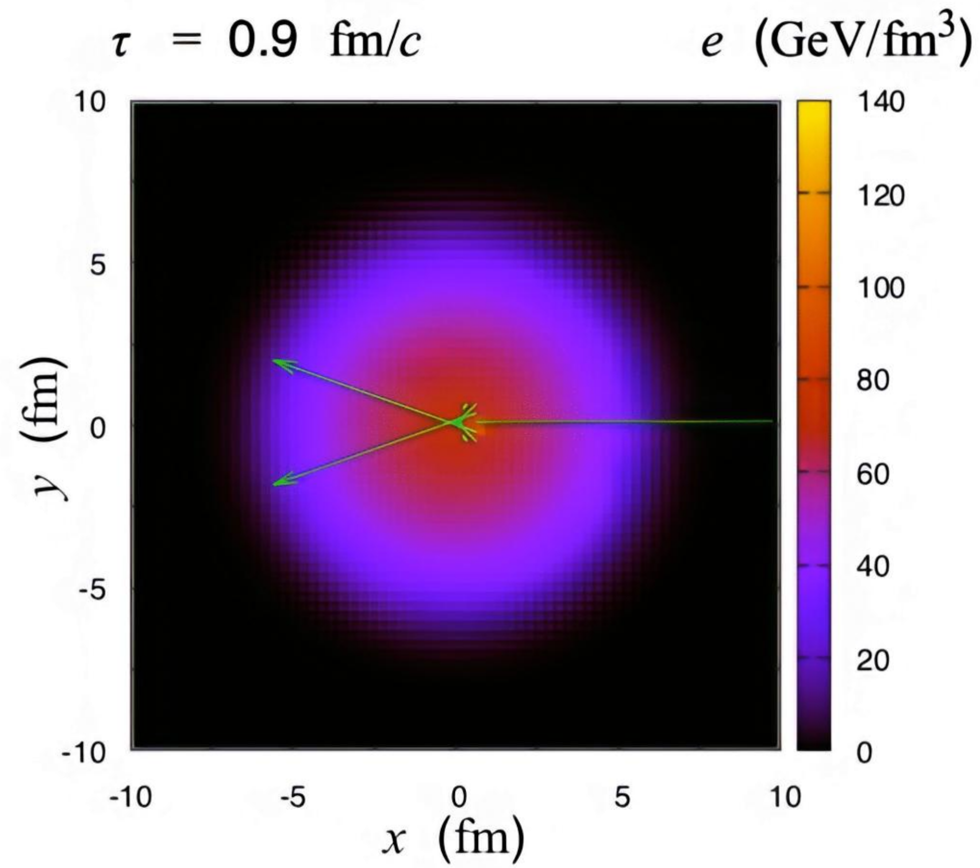
Microfluidic Jet against **viscoelastic droplet**



David Fernandez
https://www.youtube.com/watch?v=TPRur72FGyk

More **water** going in the jet direction

Quark plowing through the **QGP**



LBT Model

More **QGP** going in the jet direction

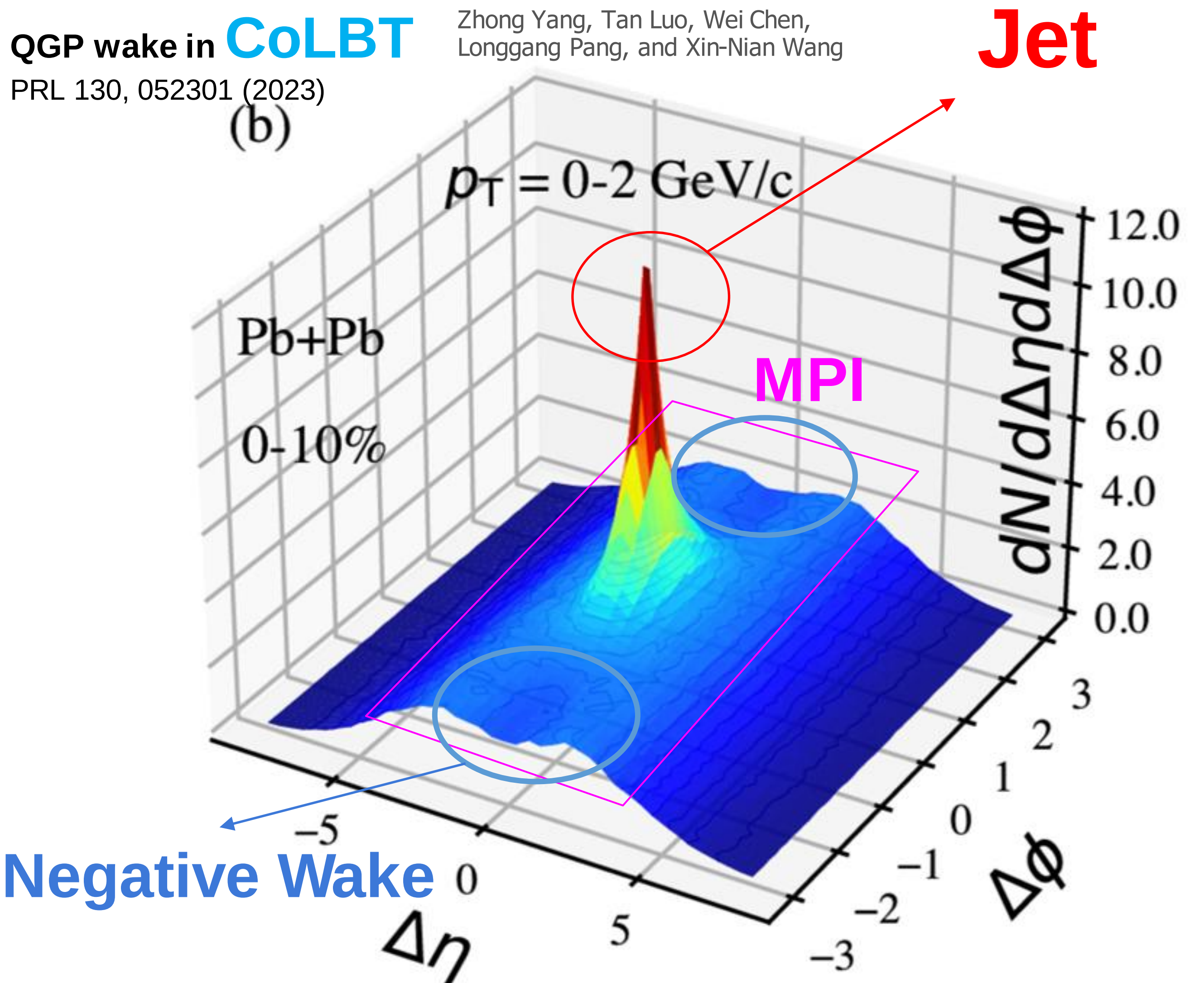
In Position Space

Measure the "Depletion" due to Medium Recoil

Jet and **Hadron** correlation in **Photon-Jet event**

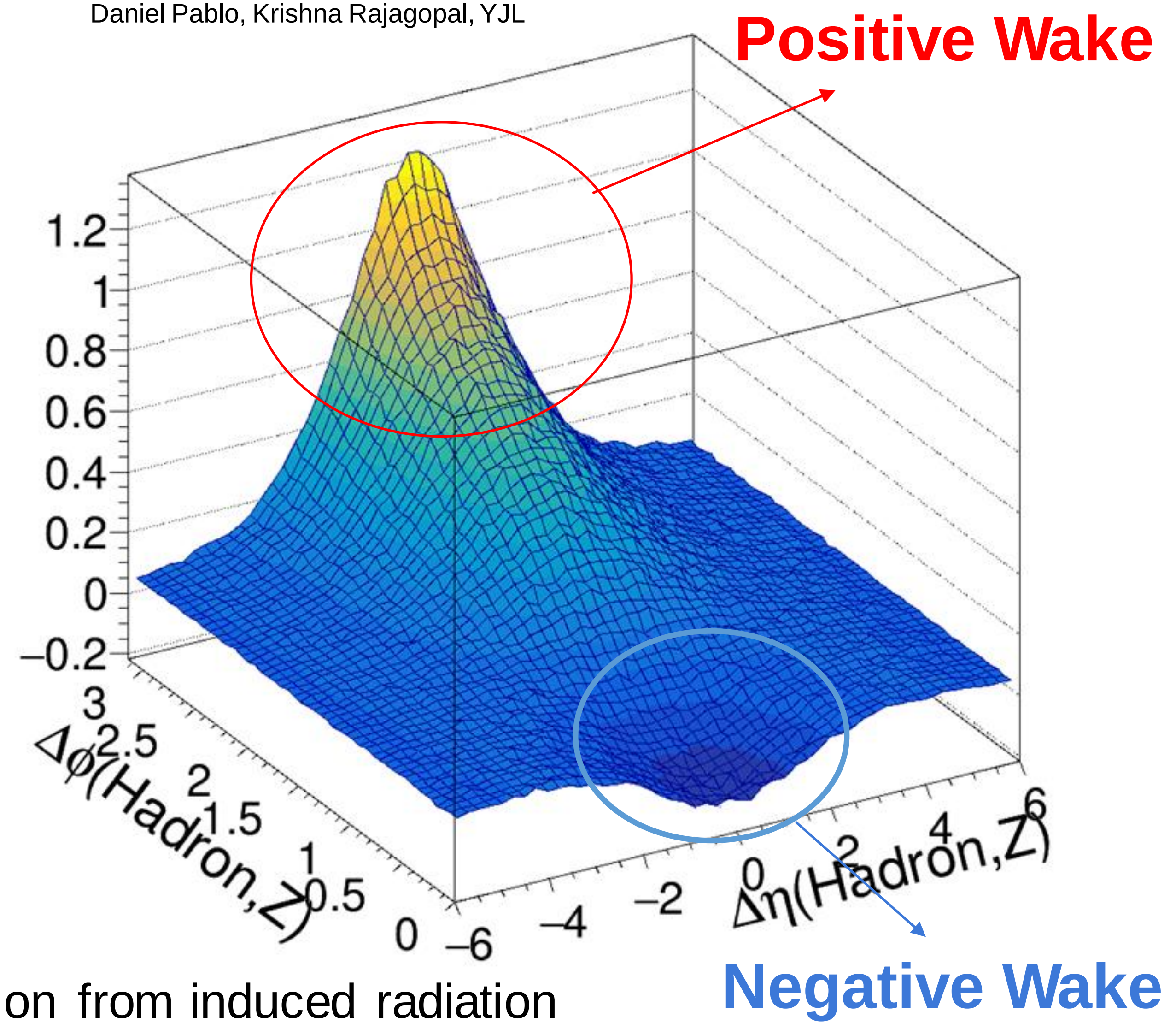
QGP wake in CoLBT Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

PRL 130, 052301 (2023)



Z⁰ and **Wake Hadron** correlation in **Hybrid** model

Daniel Pablo, Krishna Rajagopal, YJL



More QGP going in the jet direction, however, with complication from induced radiation

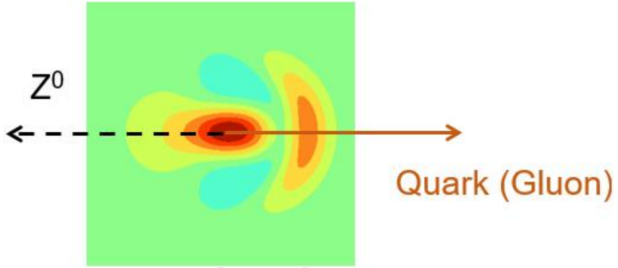
Less QGP left behind in the opposite direction of the jet!!!

→ Measure the **<u>Boson-side</u> associated yield** with **Z^0-Jet**

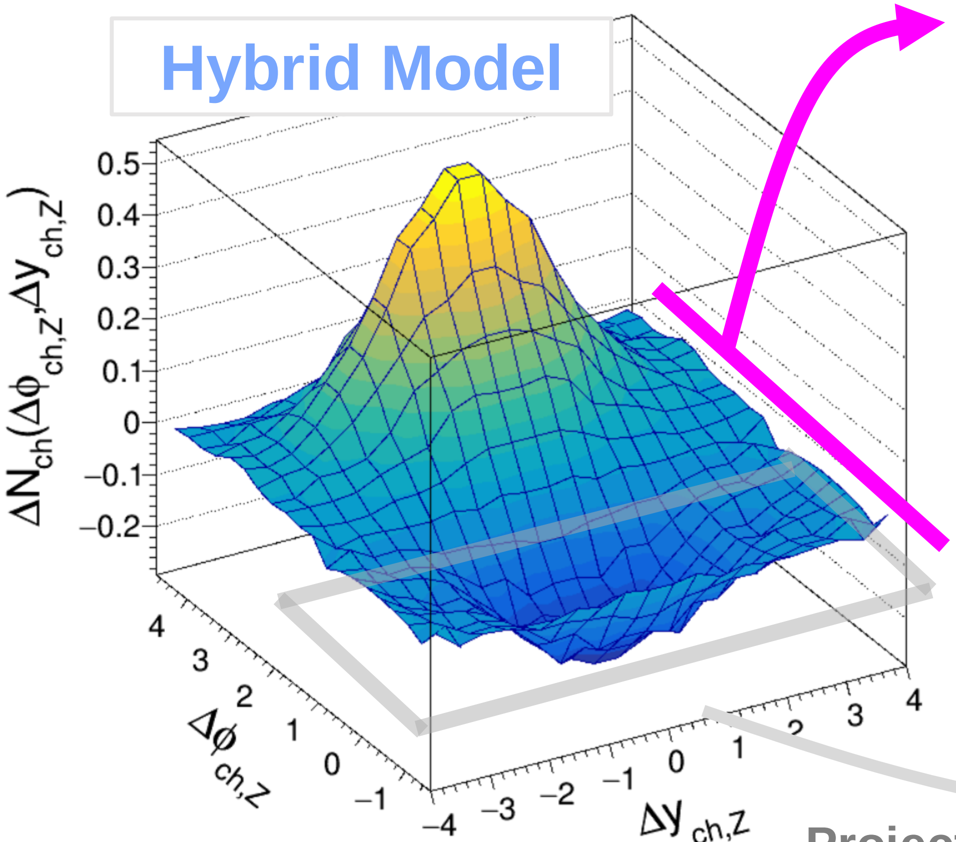
In Momentum Space

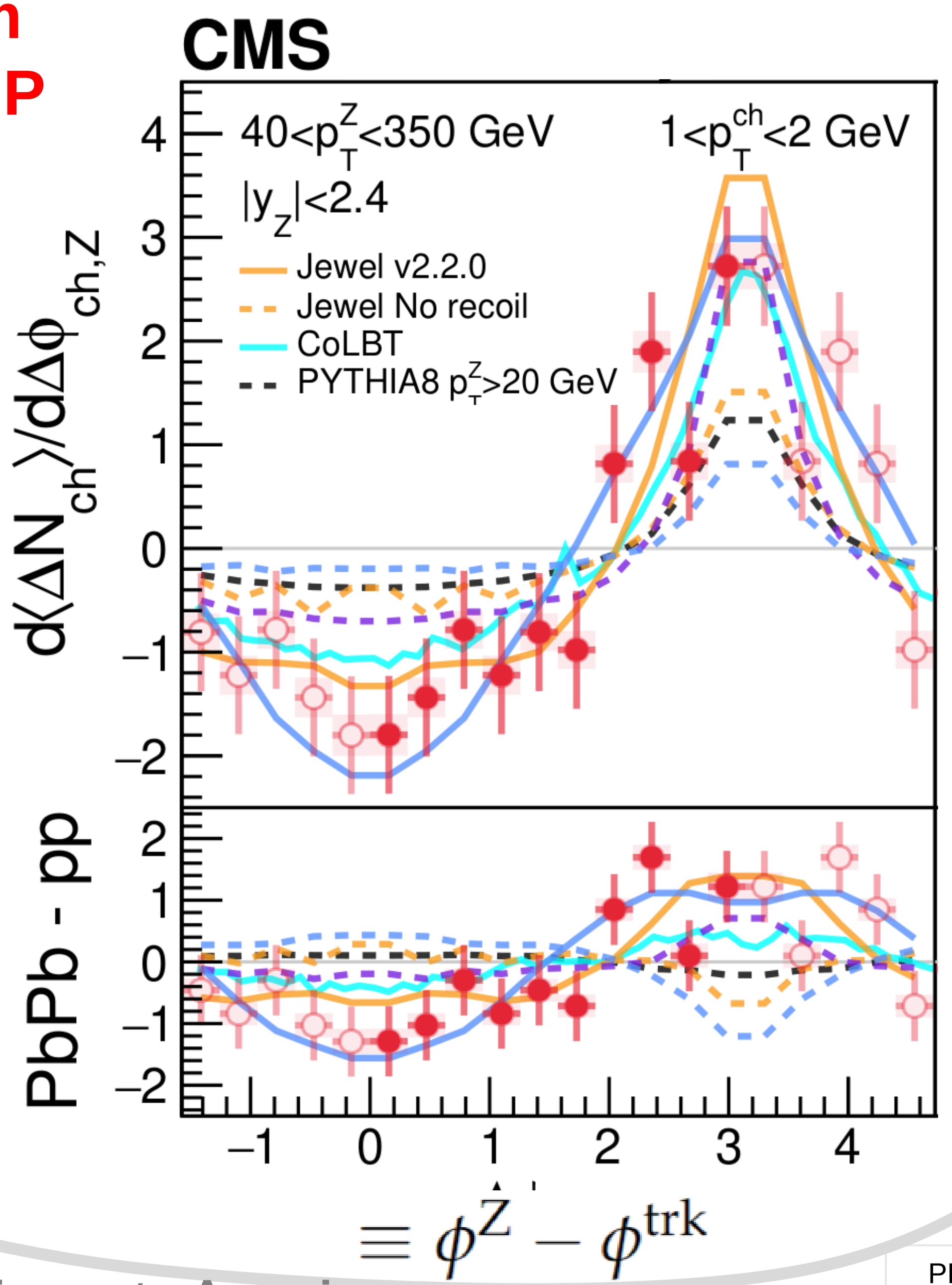
Direct Evidence of Medium Response

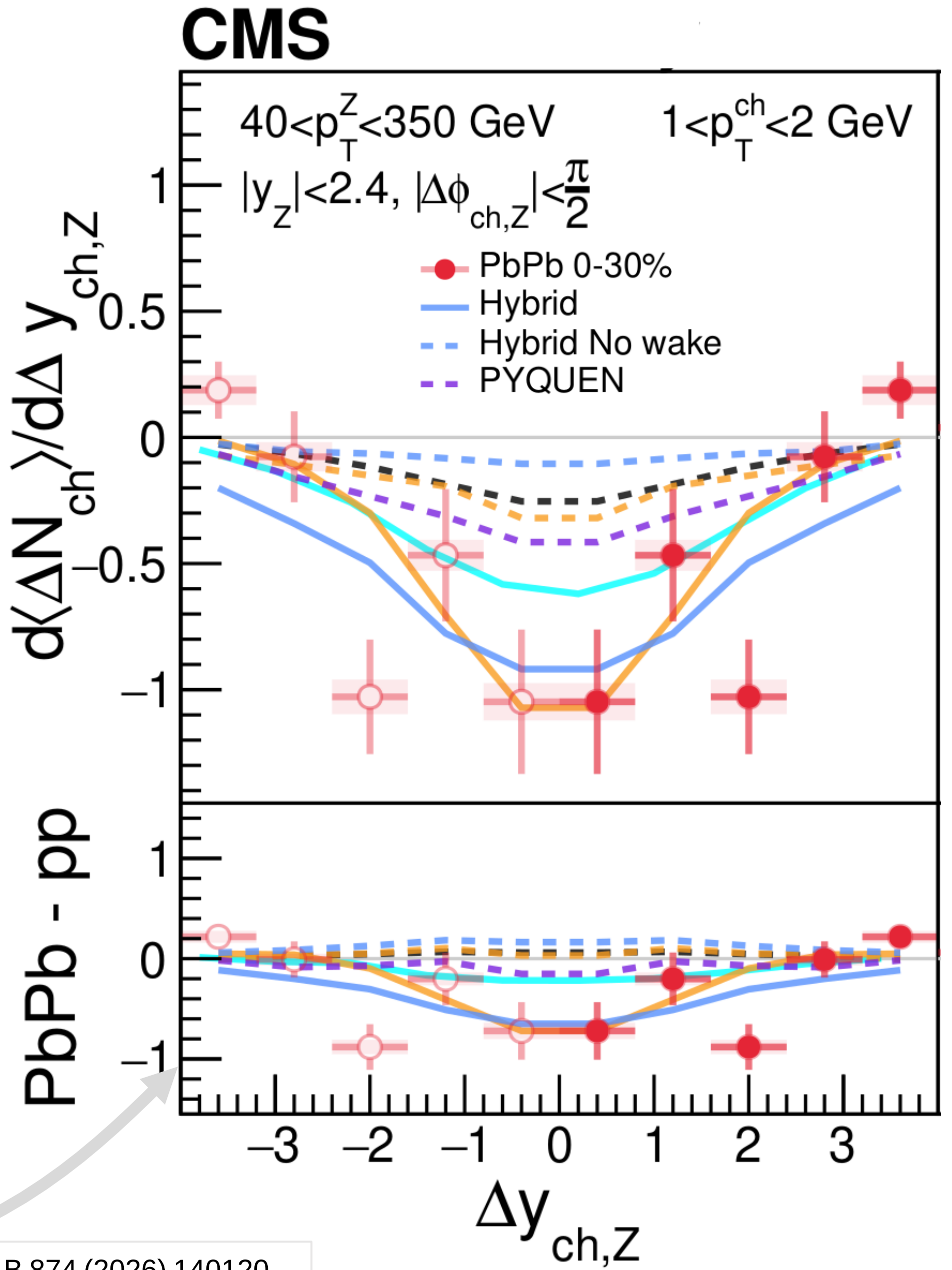
First direct evidence of medium response to hard probes in QGP



Projection onto Δϕ axis







Projection onto Δy axis

PLB 874 (2026) 140120

Summary: Jet

- High p_T partons lose energy in QGP, lost energy is redistributed to soft, wide-angle particles

- 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 momentum imbalance

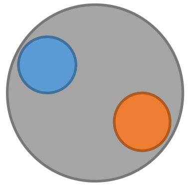
- Size of jet quenching **depends** on parton shower
  - In fact, this is the main reason of dijet momentum imbalance in central PbPb collisions!

- Jet Grooming: a powerful tool for observable design

- Evidence of medium response from Z-hadron correlation

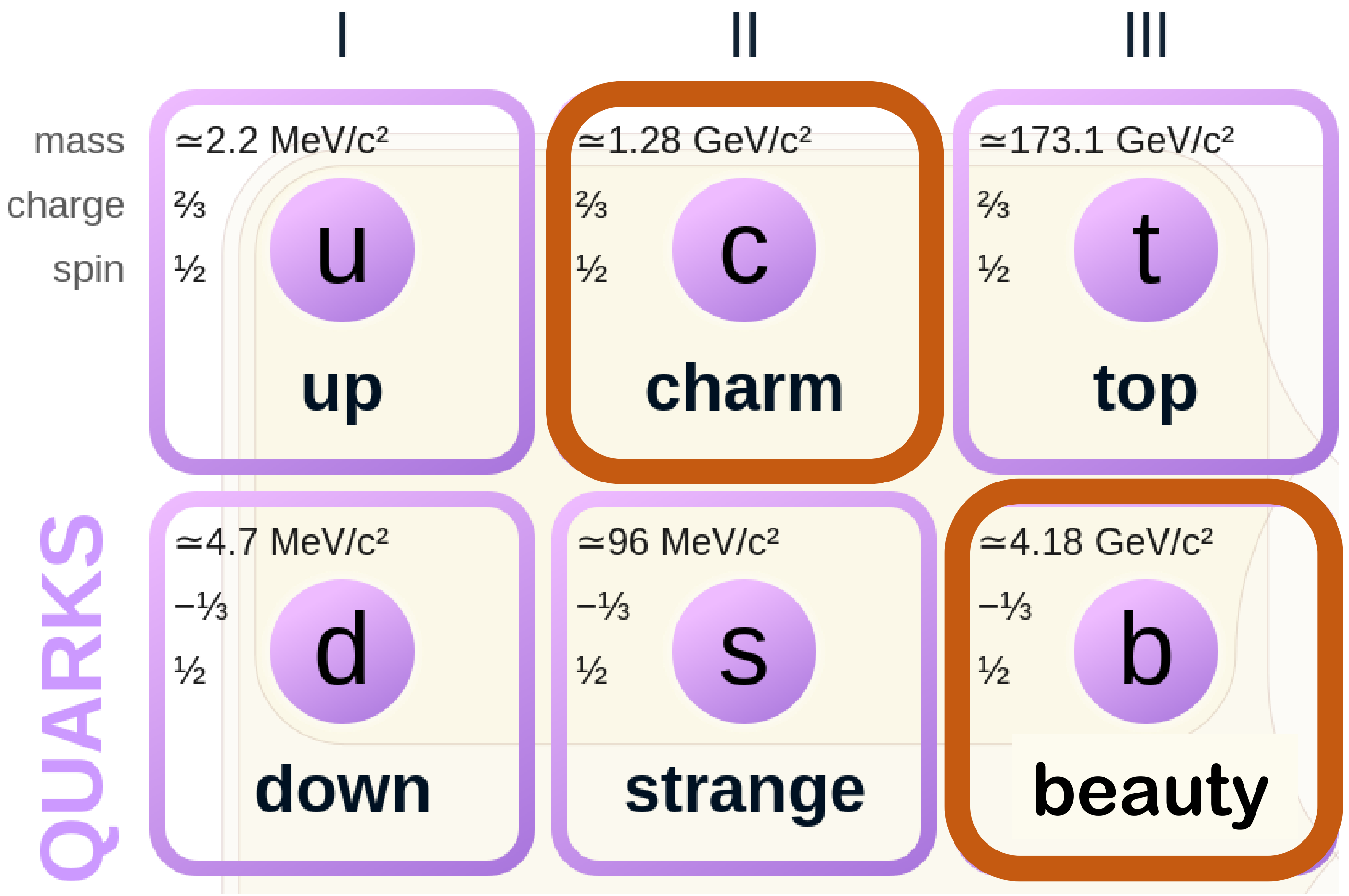
Slow Moving Hard Probe?

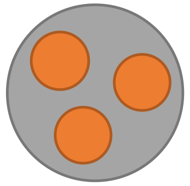
Hadrons: participate in the strong interaction mediated by **gluons**



Mesons
(quark and anti-quark)

Confinement

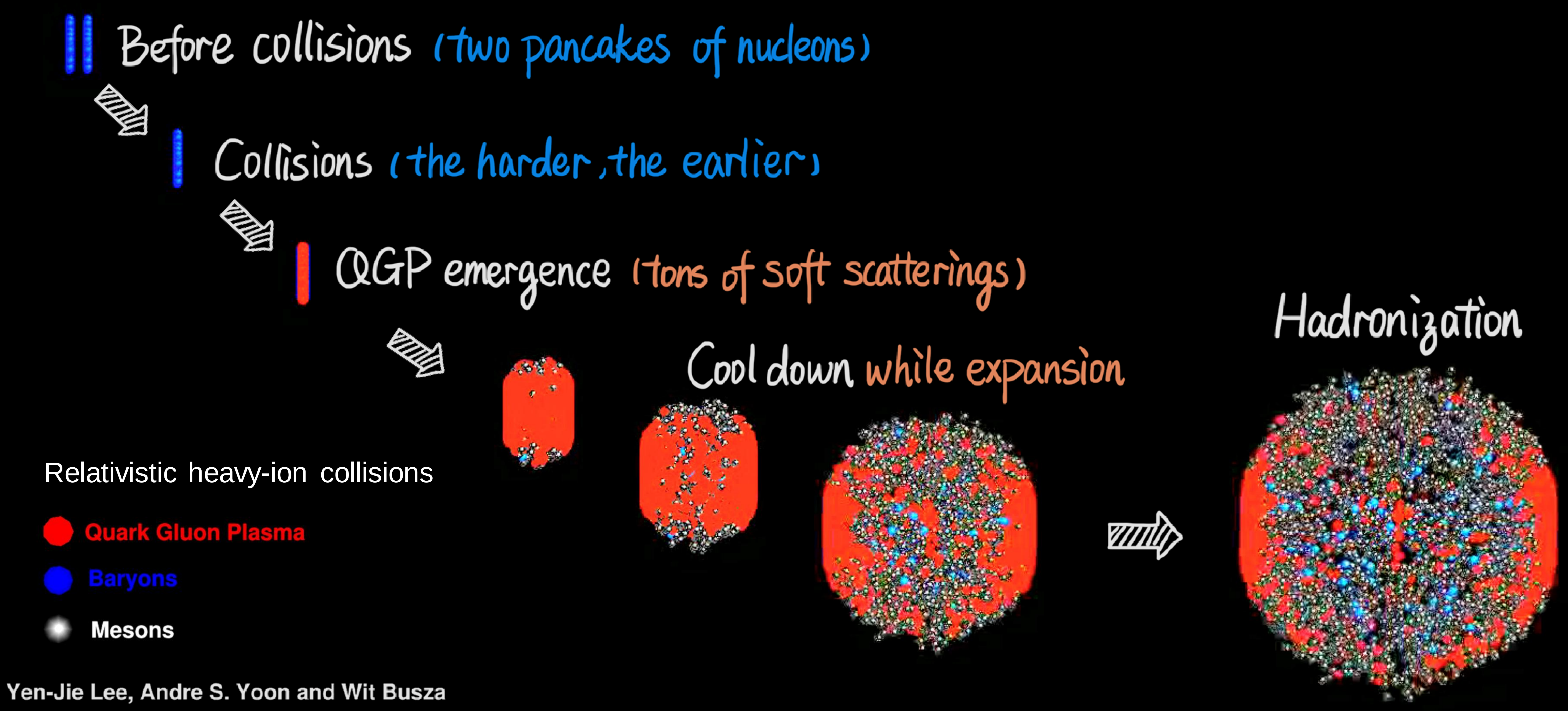




Baryons
(Three quarks)

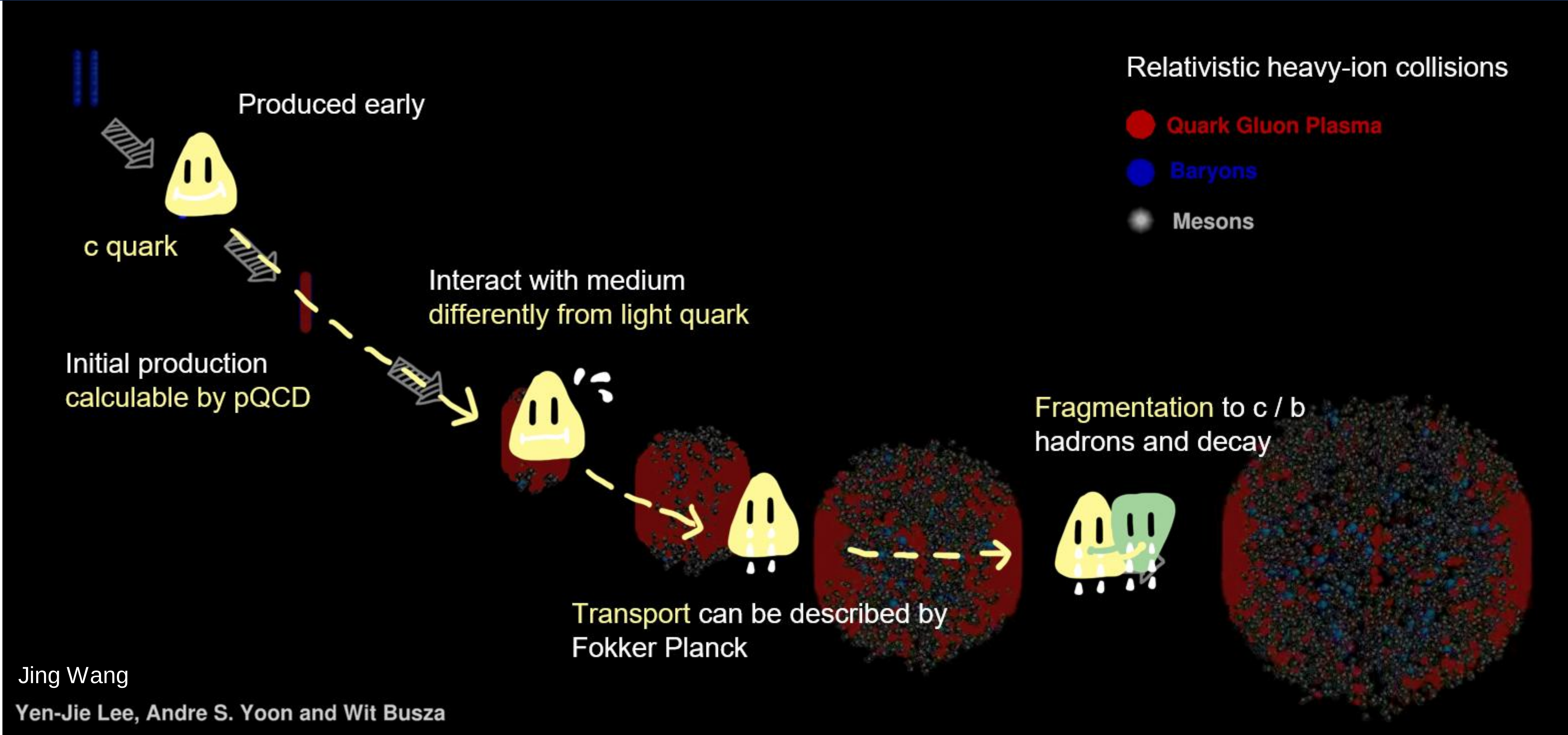
When the quarks form a hadron, the total color charge needs to be neutral

Relativistic Heavy-Ion Collisions



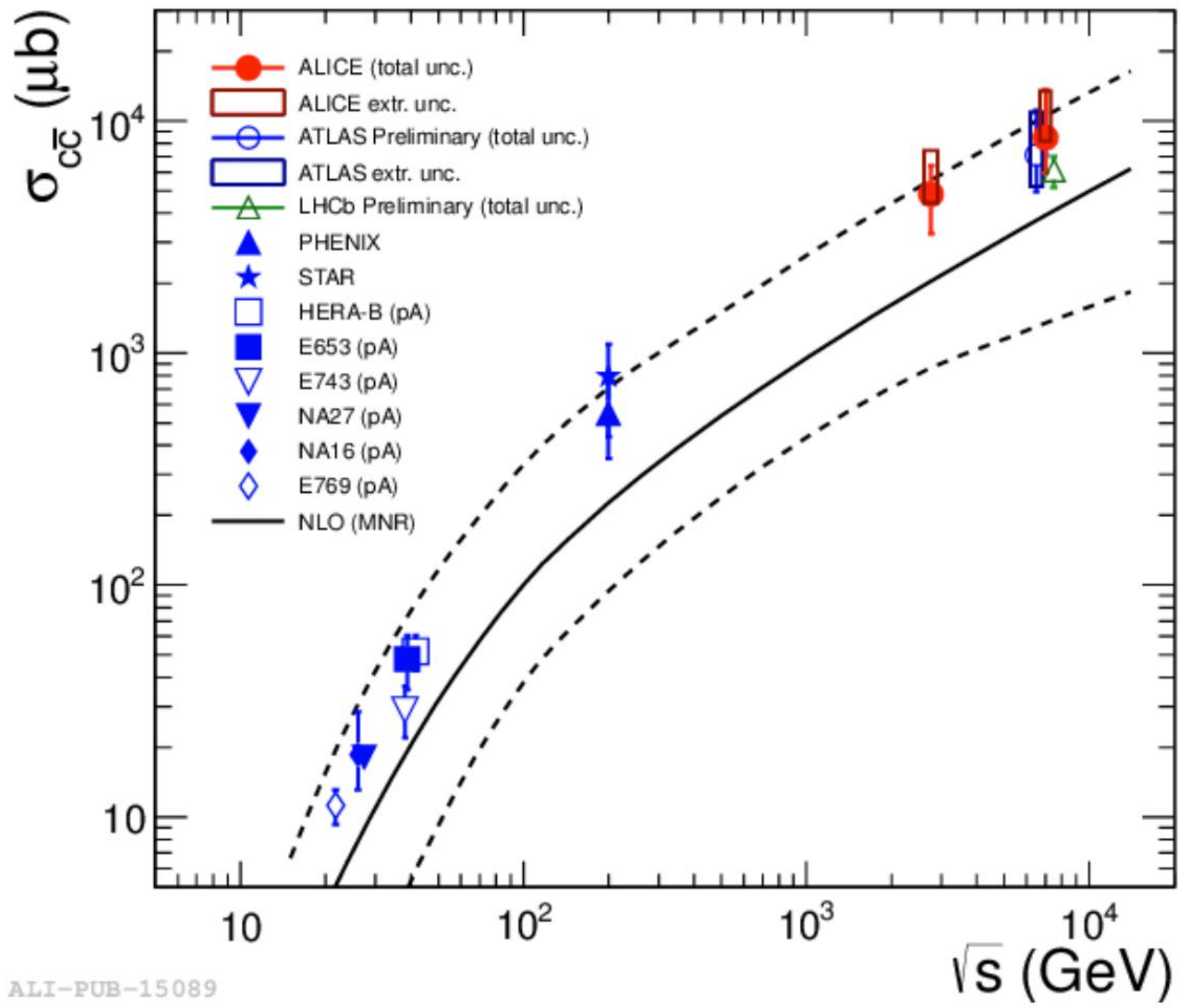
Jing Wang

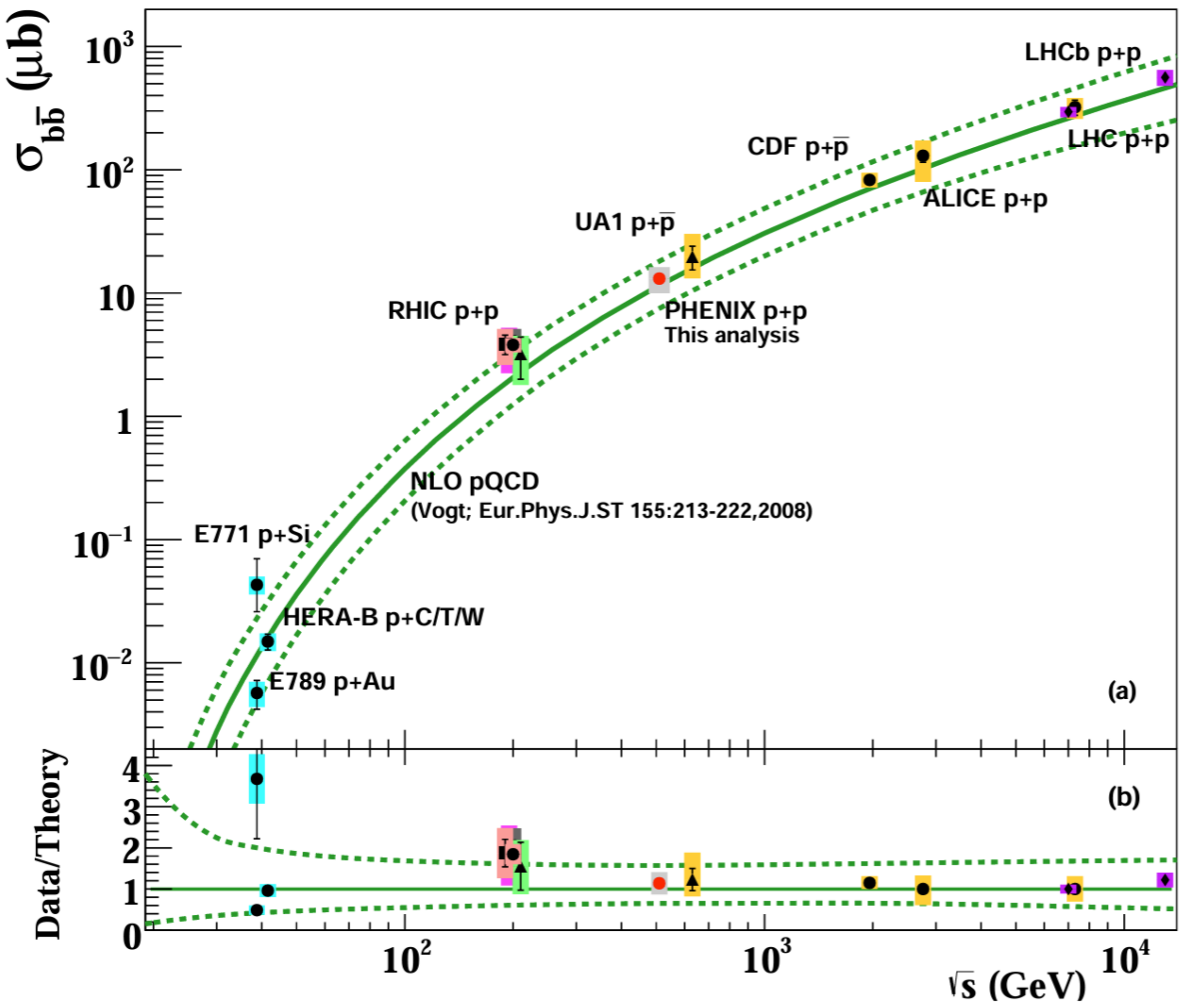
Life of a Heavy Quark in HIC



Jing Wang

How many $c\bar{c}$ and $b\bar{b}$ are produced in 0-5% A+A?





~ 15 pairs of $c\bar{c}$ in 0-5% AuAu at 0.2 TeV
~ 200 pairs of $c\bar{c}$ in 0-5% PbPb at 5 TeV

~ 0.25 pairs of $b\bar{b}$ in 0-5% AuAu at 0.2 TeV
~ 5 pairs of $b\bar{b}$ in central PbPb at 5 TeV

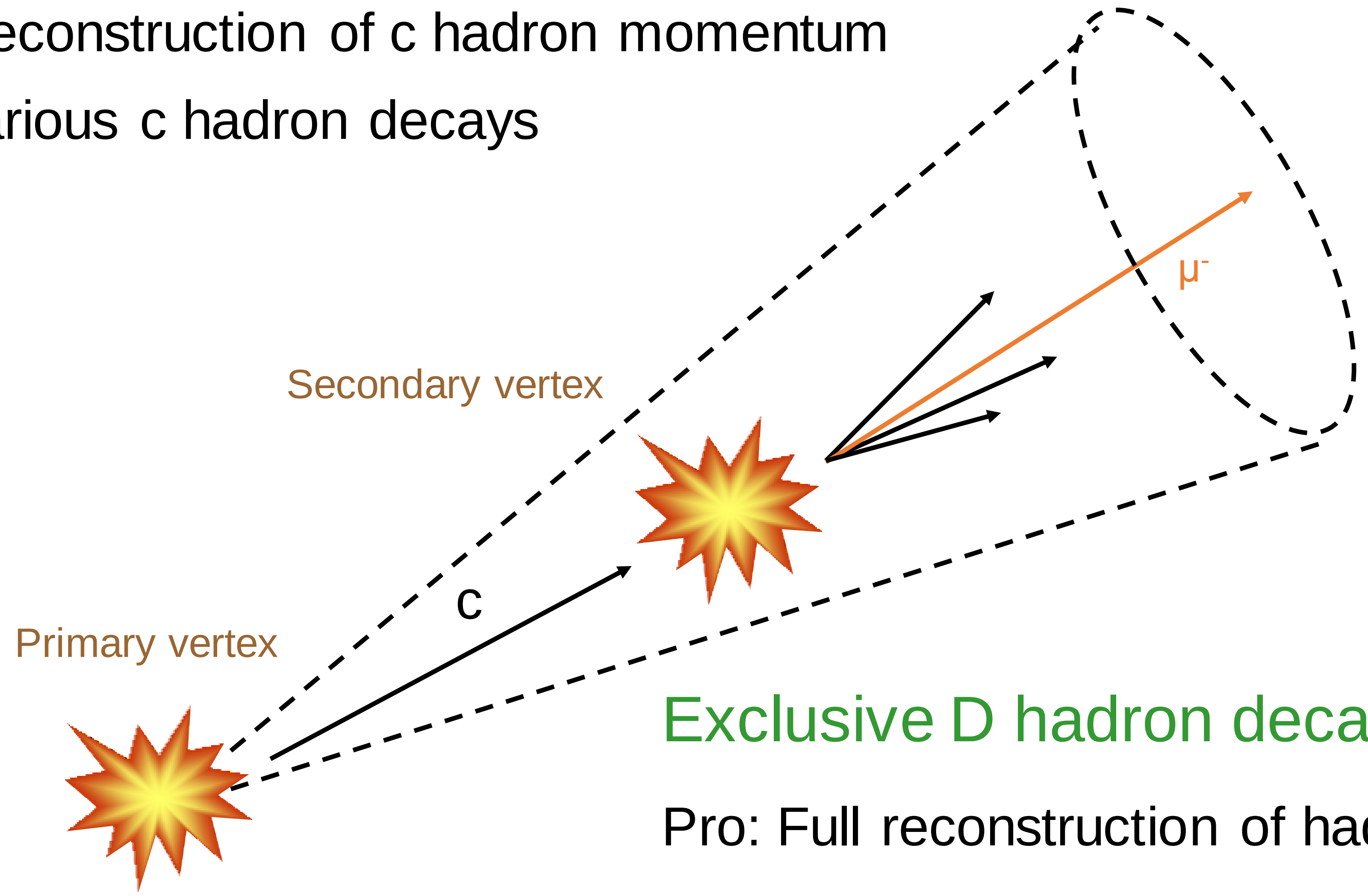
Experimental Measurement of **Charm** Quark

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 and high background

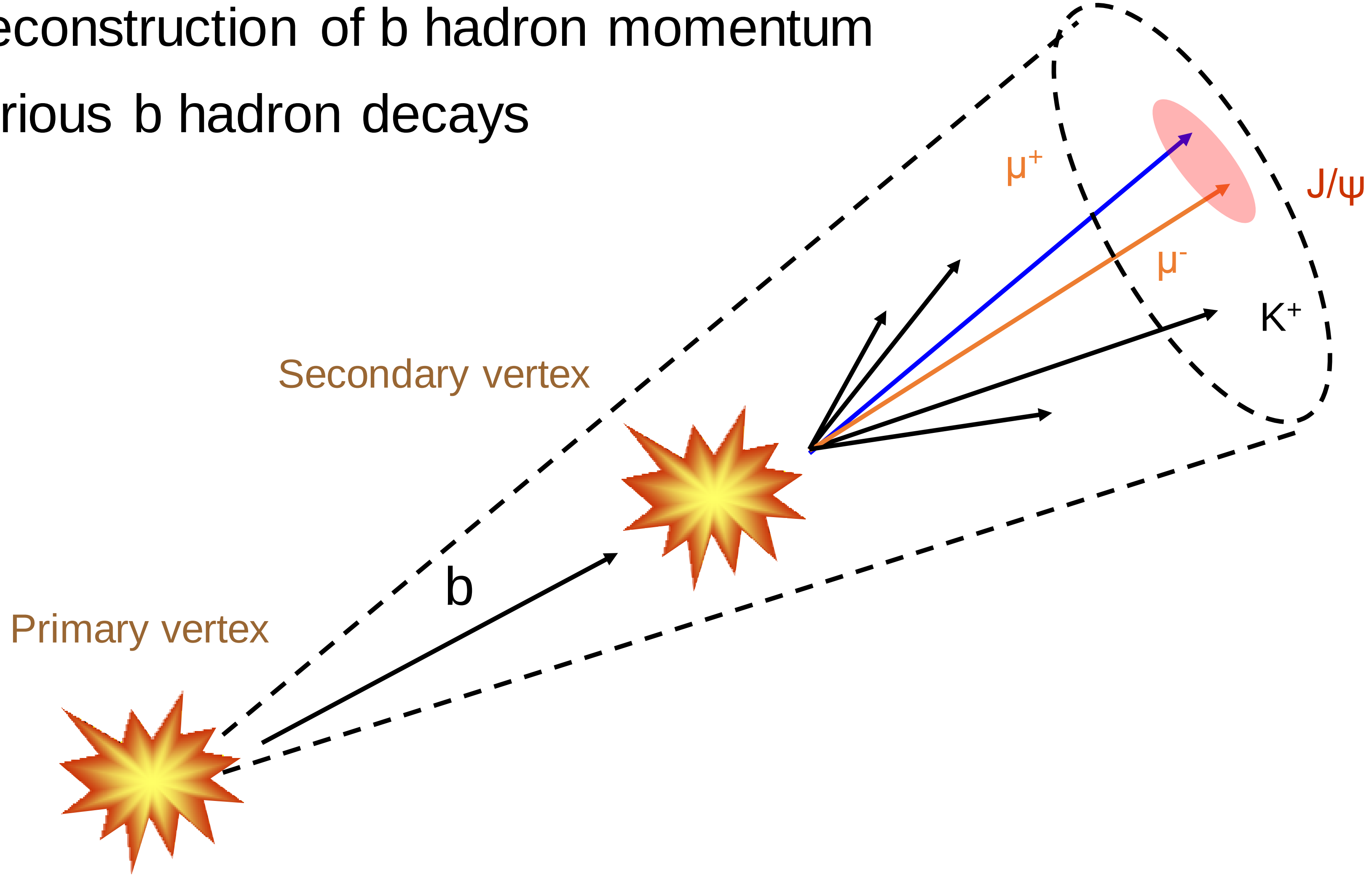
Experimental Measurement of **Beauty** Quark

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



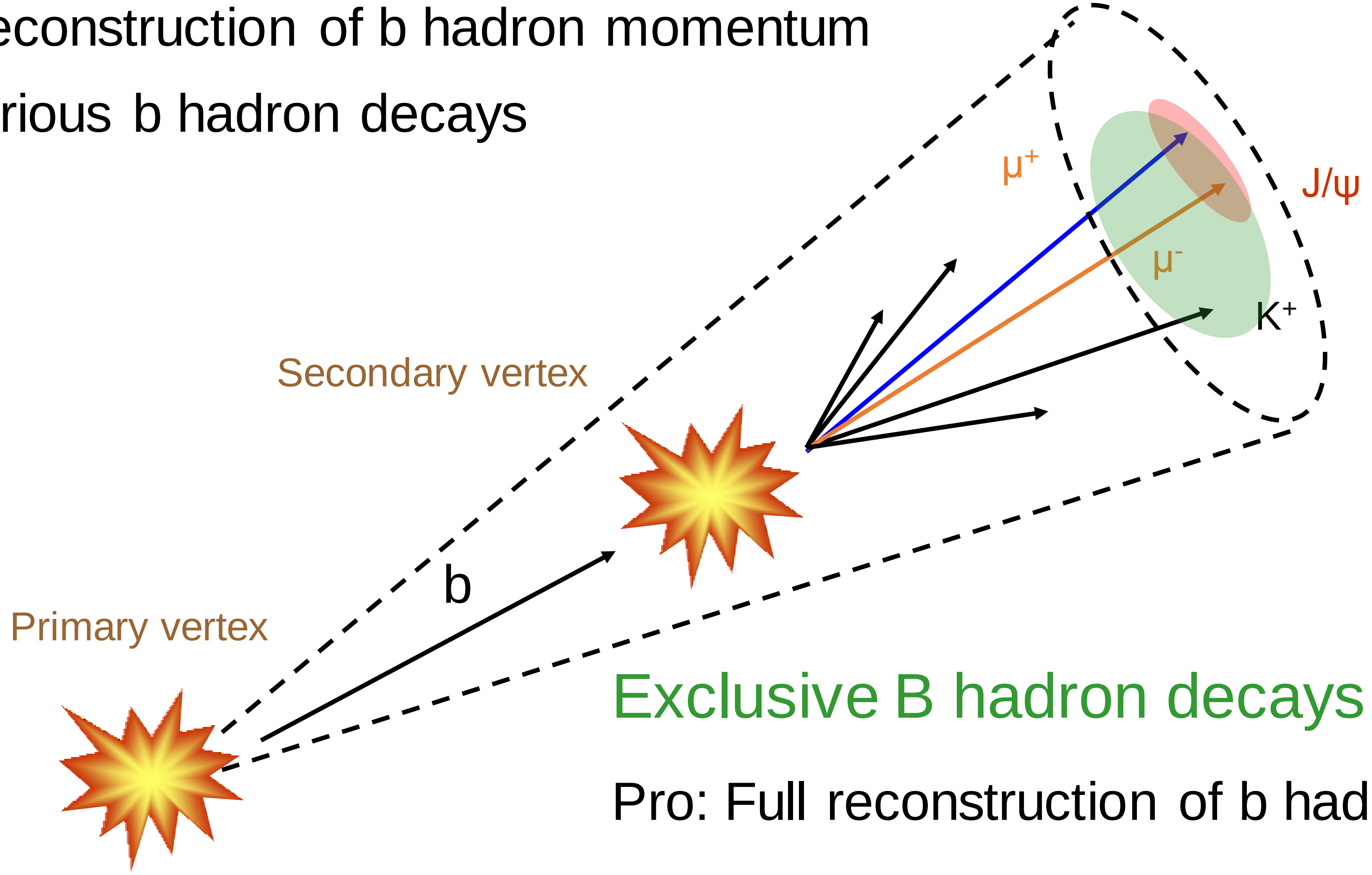
Experimental Measurement of **Beauty** Quark

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



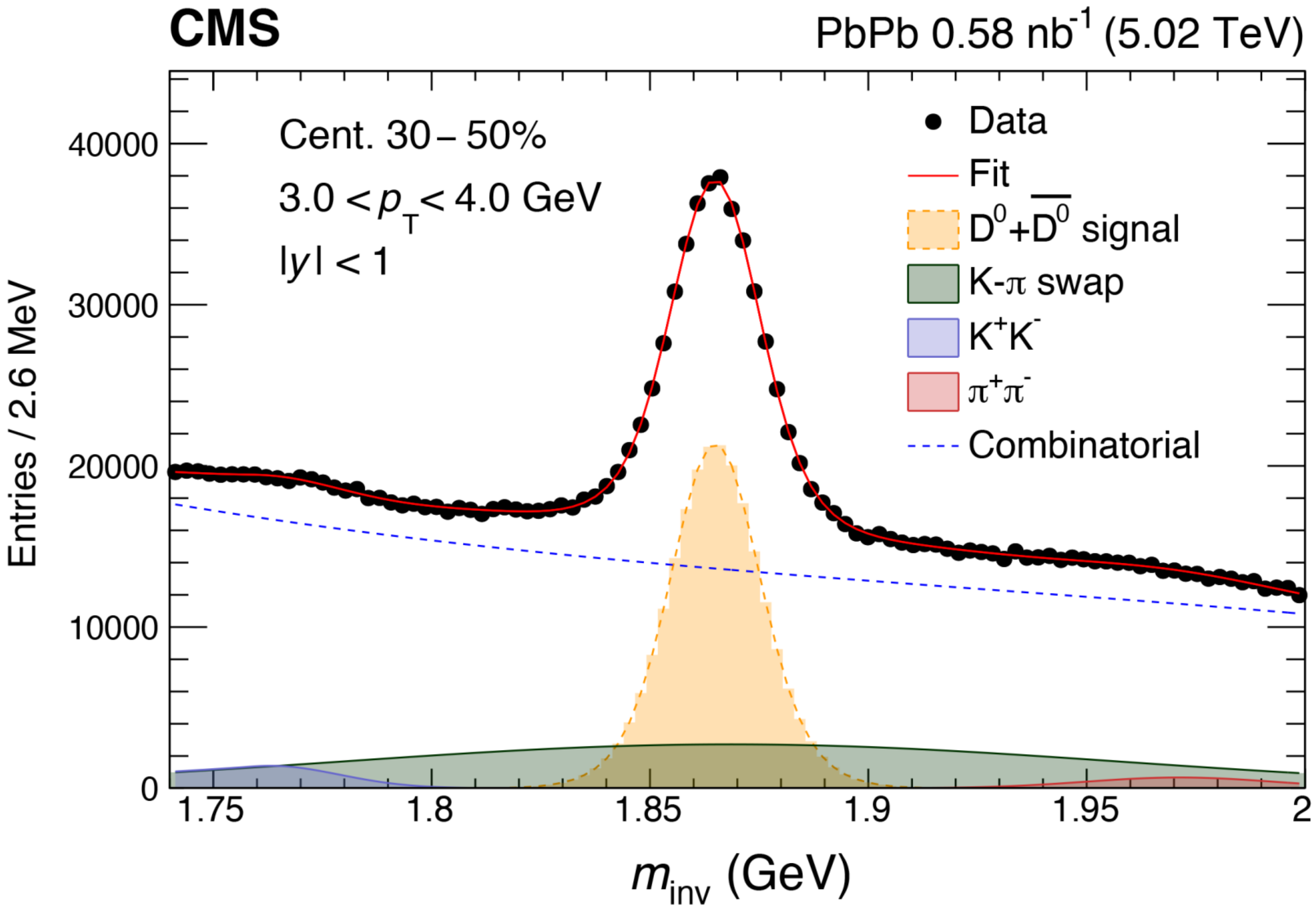
Exclusive B hadron decays

Pro: Full reconstruction of b hadron momentum and flavor

Con: low statistics

Invariant Mass Fit $D^0 \to K\pi$ as an Example

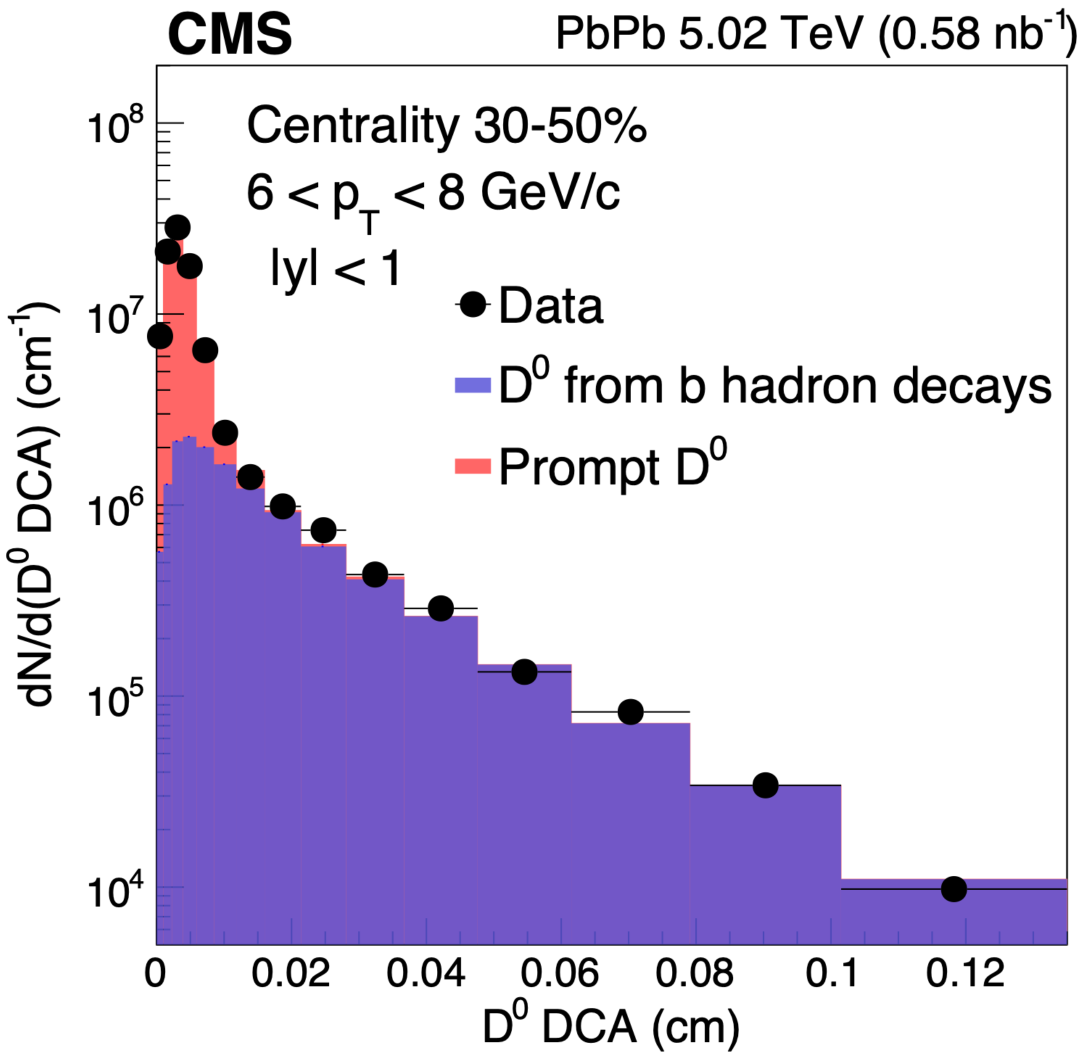
[PRL 129 (2022) 022001]



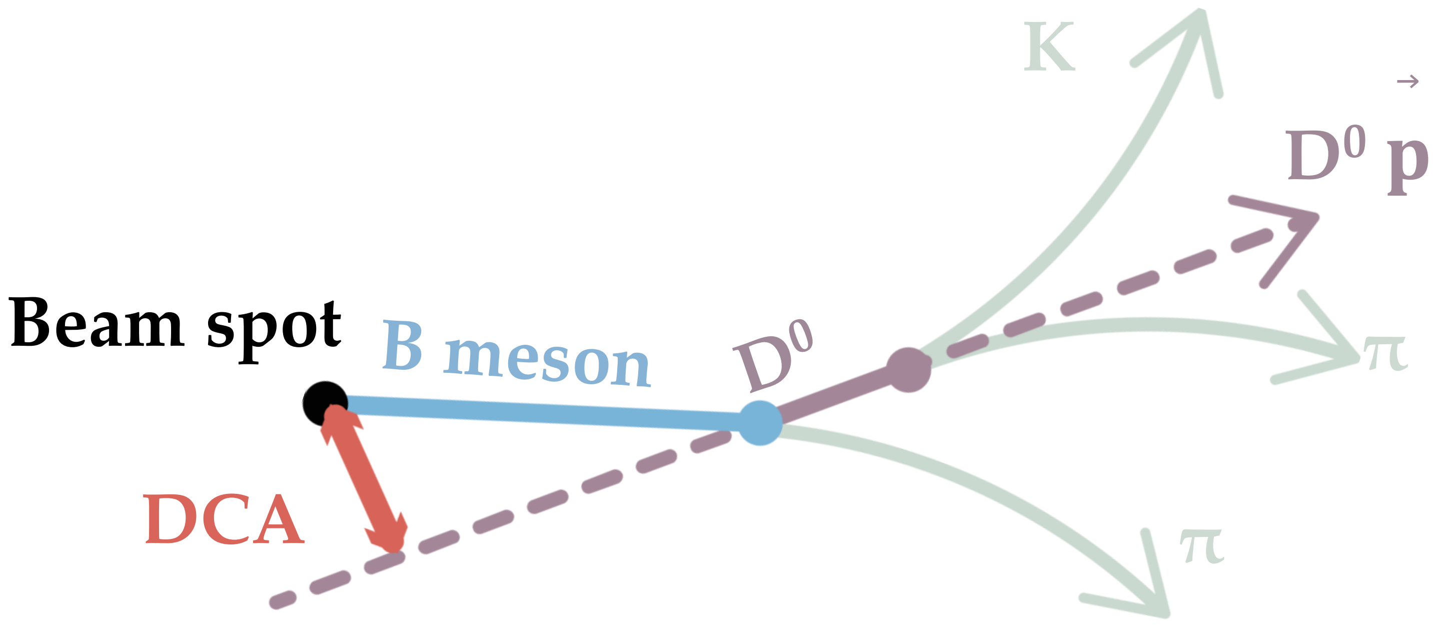
- Signal shape width reflects track momentum resolution
- Combinatorial randomly pairing two opposite-sign tracks
  - Likelihood ratio test degree of freedom needs to balance fitting performance and overfitting
- Peaking background
  - K-π swap $D^0 \to K\pi$ is reco-ed but the mass assignment is swapped
  - KK and ππ $D^0 \to KK/\pi\pi$ is reco-ed as $D^0 \to K\pi$

Separate Prompt and Nonprompt D mesons

[PLB 850 (2024) 138389]

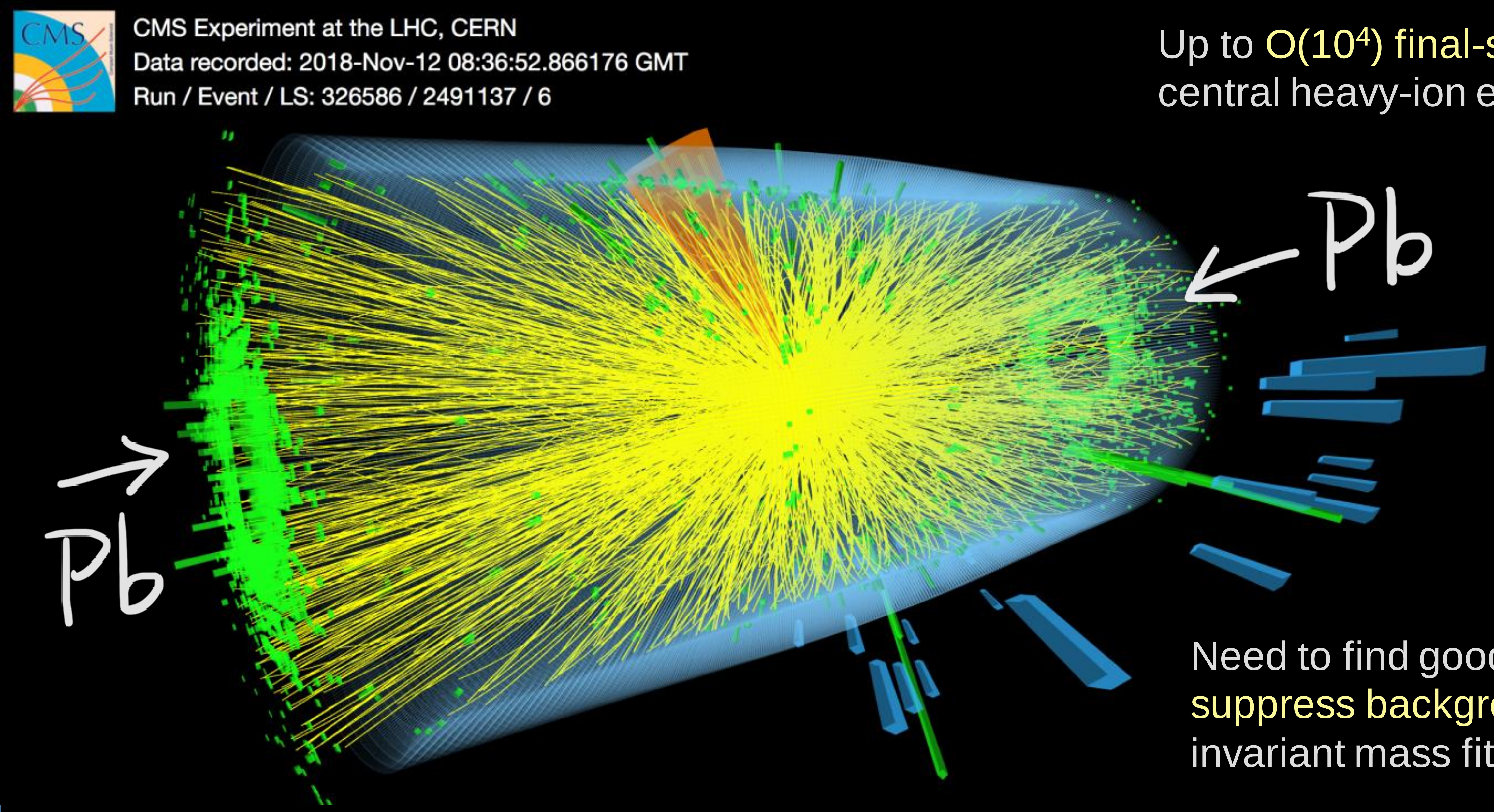


- Template fits on D meson DCA
  - DCA ~ 0 for prompt D
  - Large DCA for nonprompt D



DCA of nonprompt D

Huge Combinatorial Background in HIC

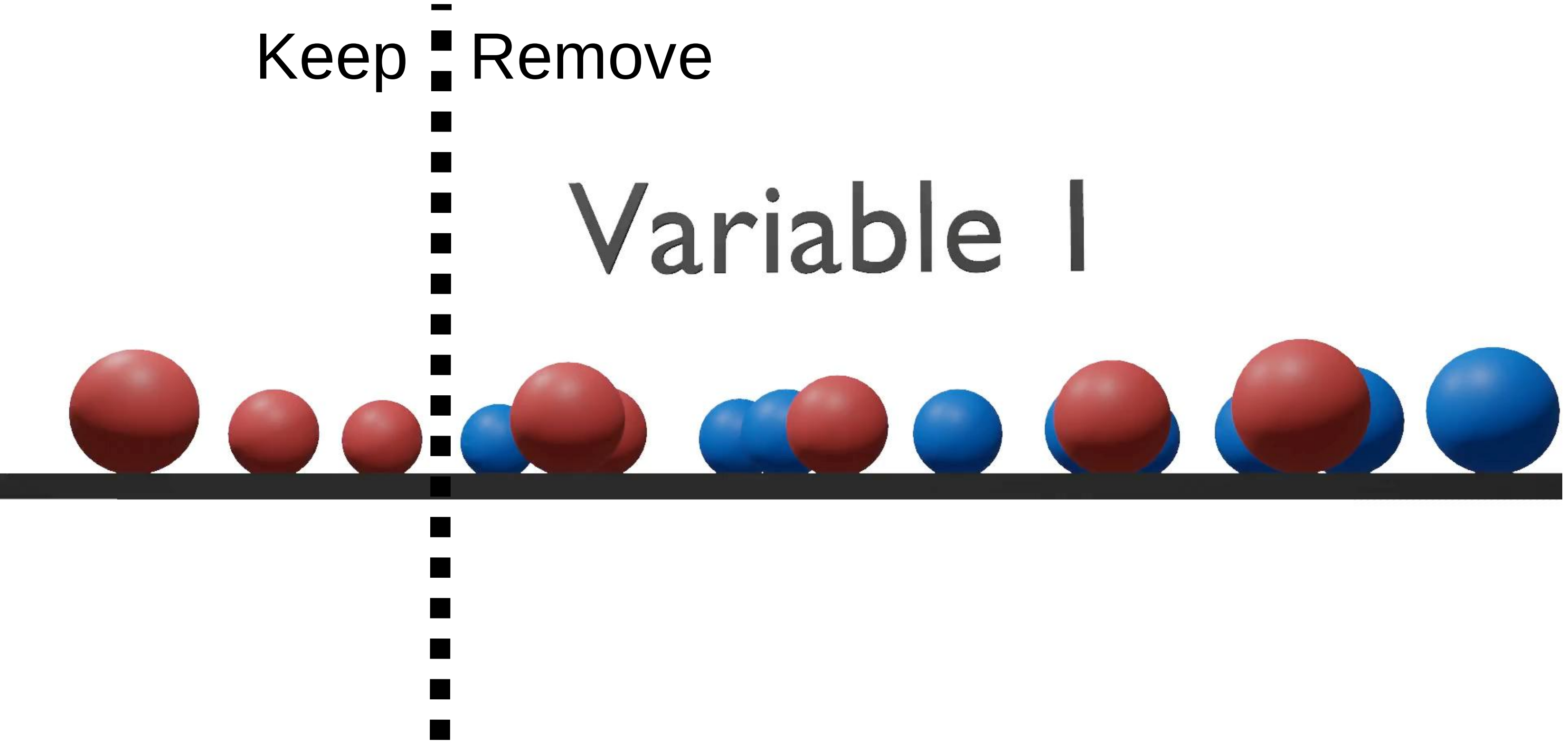


Up to O(10^4) final-state particles in a central heavy-ion event

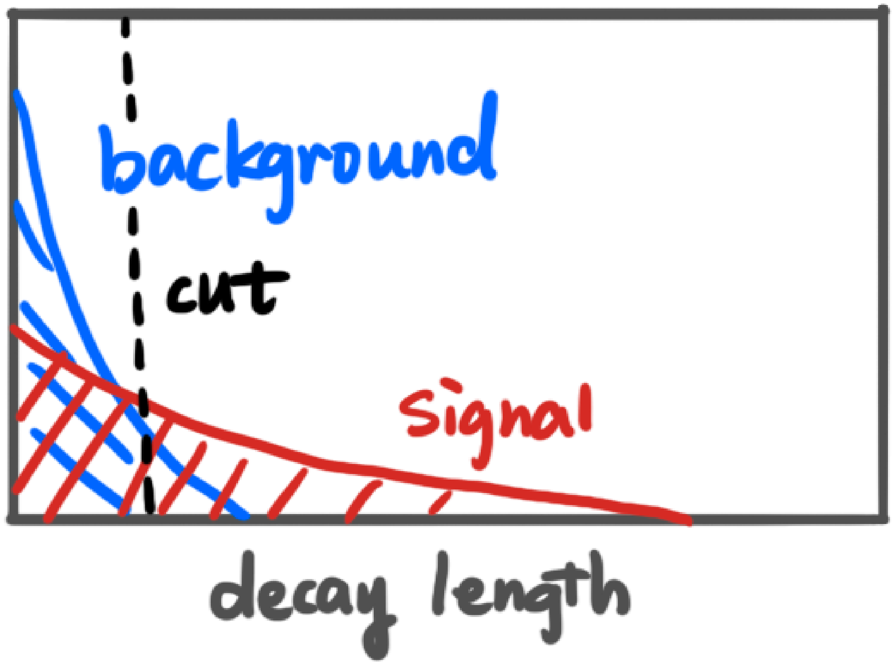
Need to find good selections to suppress backgrounds first before invariant mass fits

Suppress Background: Multivariate Classification

If want to keep red and remove blue balls…



Animation from Jing Wang



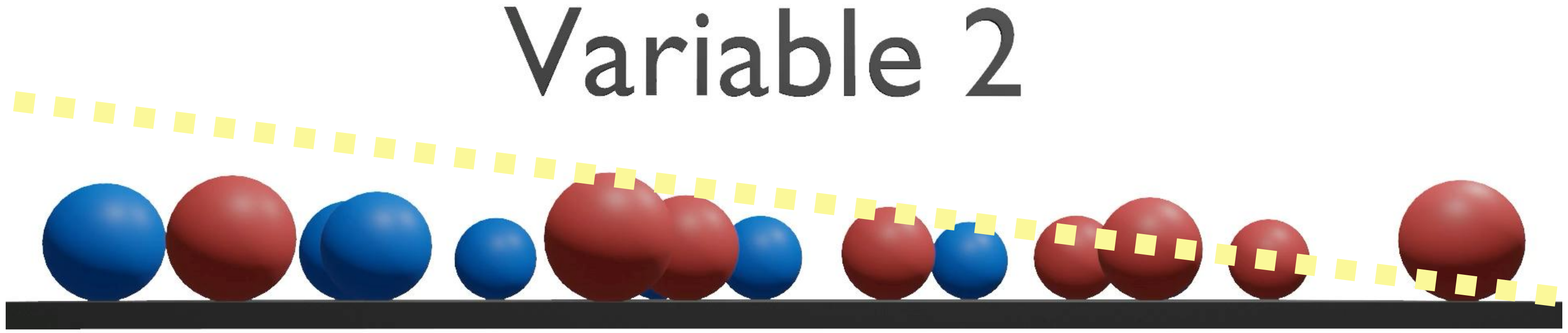
Some variables can separate signals and backgrounds to a certain extent

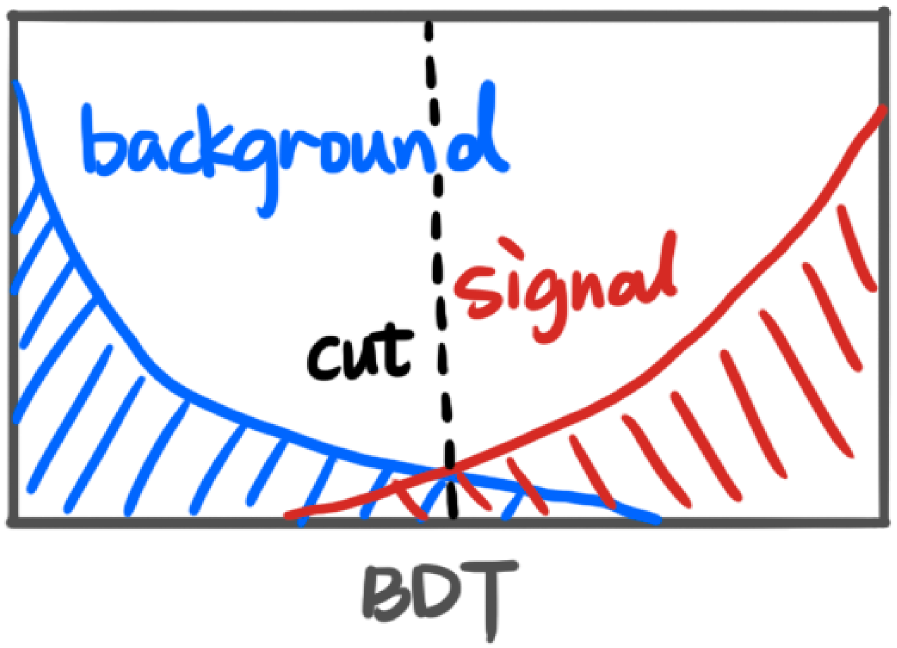
- Decay length significance
- Secondary vertex probability
- Pointing angles
- …

[Animation]

Suppress Background: Multivariate Classification

If want to keep red and remove blue balls…





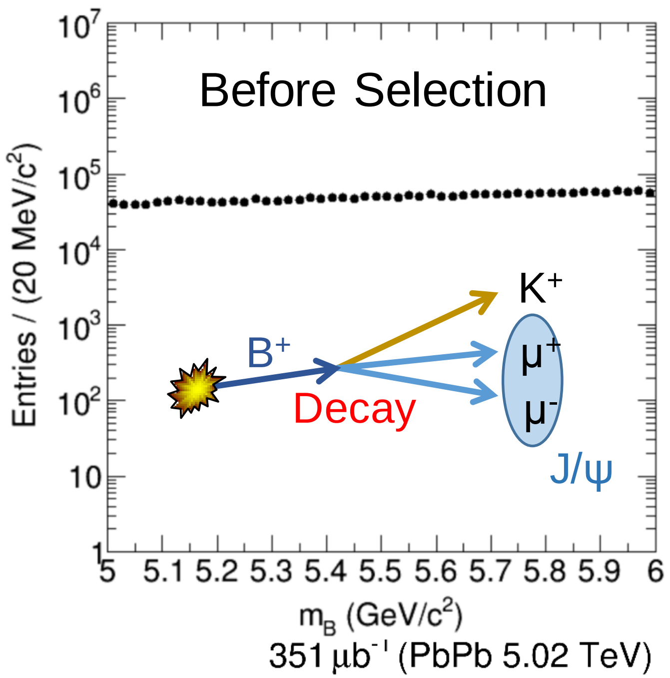
Combining multi variables in a smart way separate backgrounds and signals better
→ where ML can help

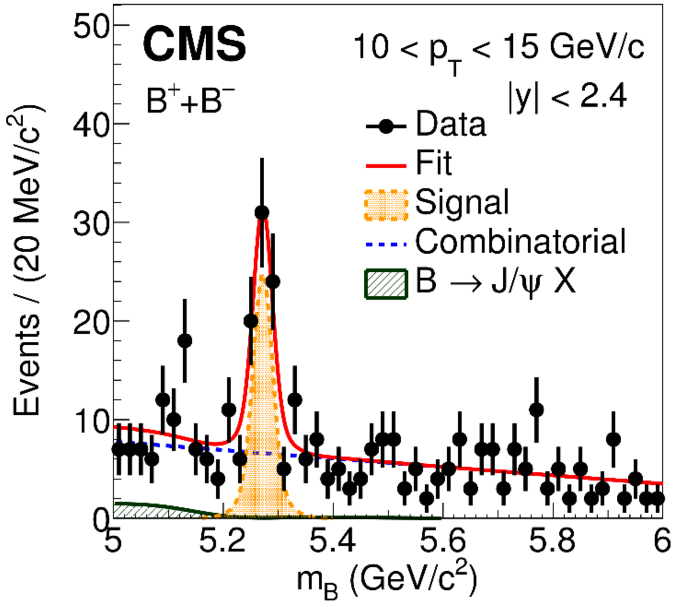
Animation from Jing Wang

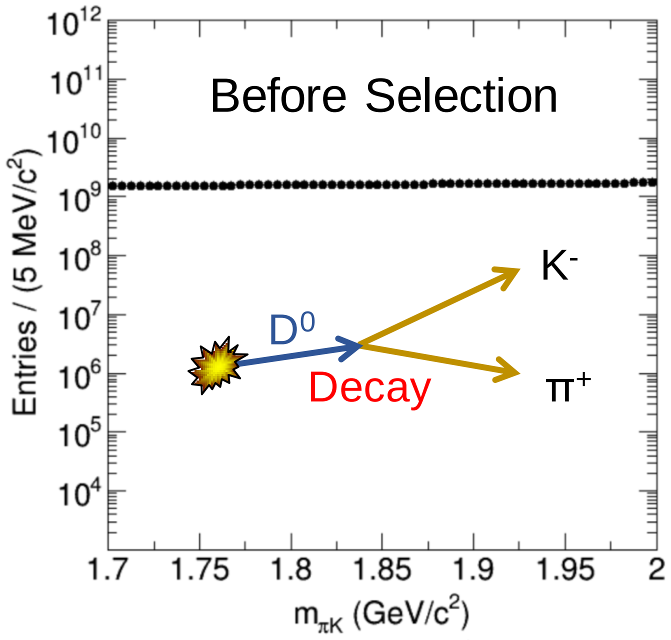
[Animation]

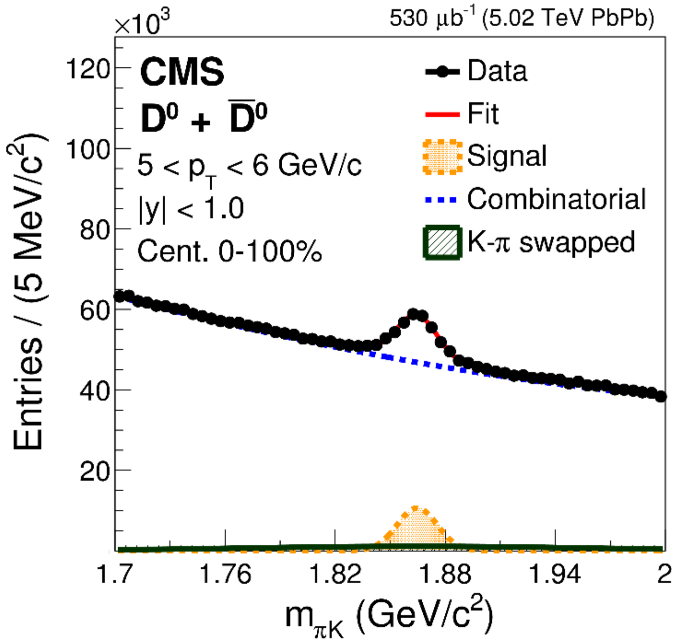
Example: Background Suppression in PbPb with CMS

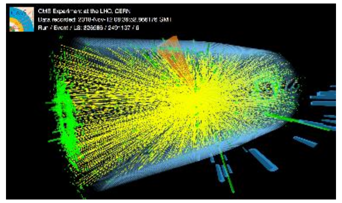
Background reduction by a factor of 10^3-10^4











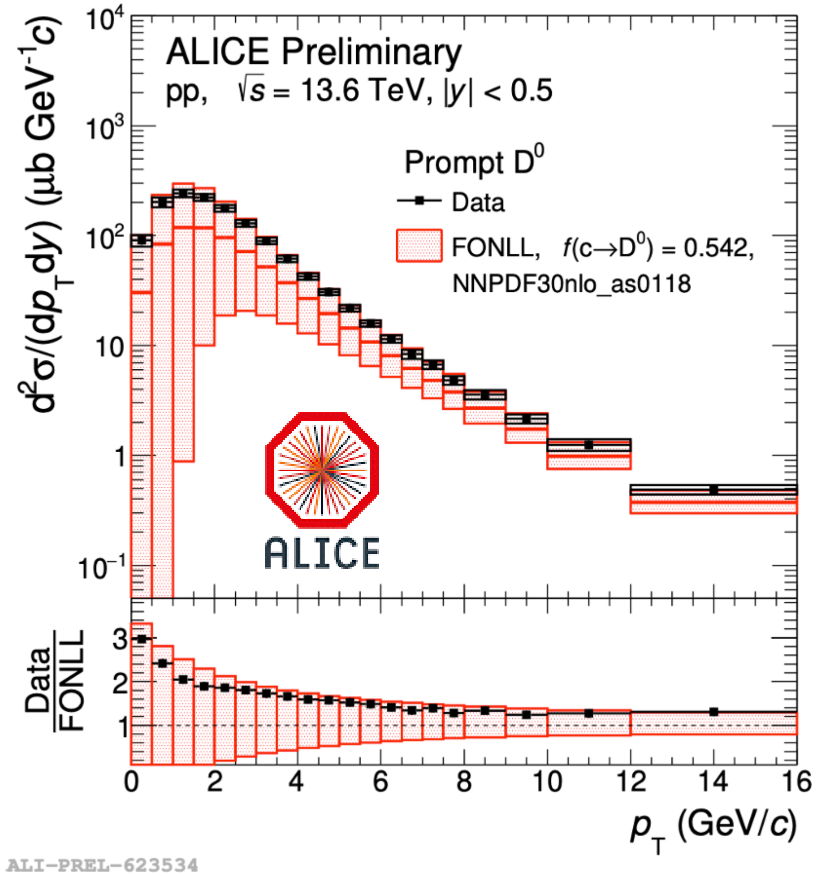
Background reduction by a factor of 4×10^4-10^8

PRL 116 (2016) 032301
PRL 119 (2017) 152301
PLB 796 (2019) 168

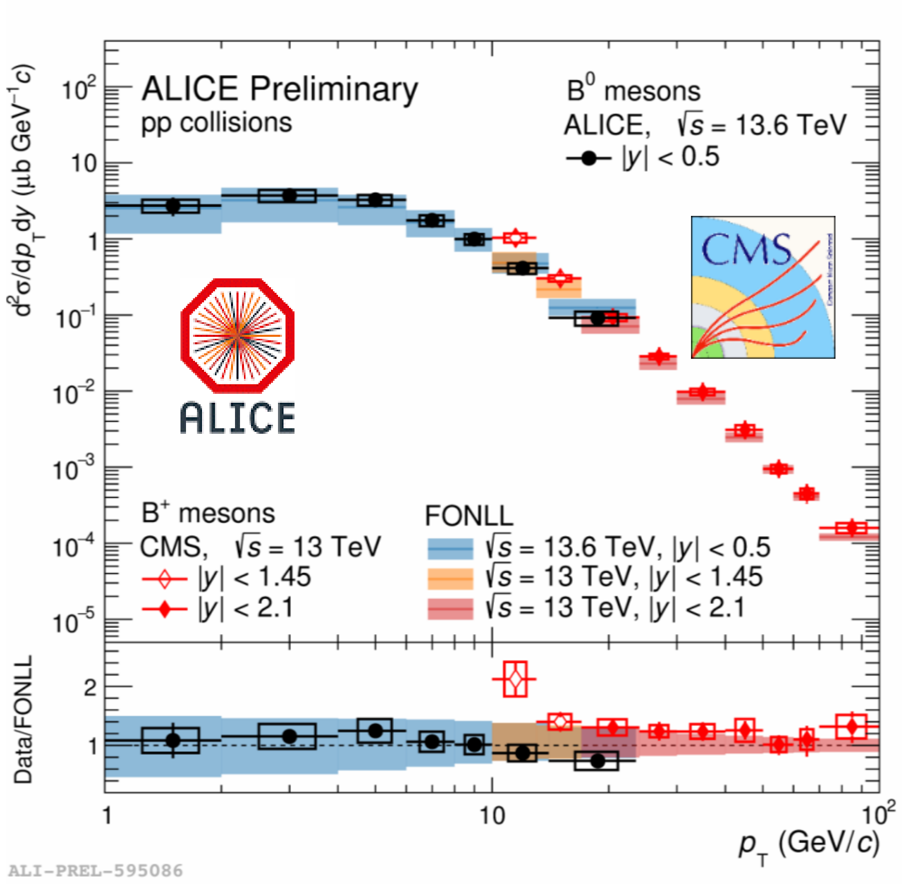
PLB 782 (2018) 474
PRL 120 (2018) 202301

Heavy Flavor Meson Production in pp

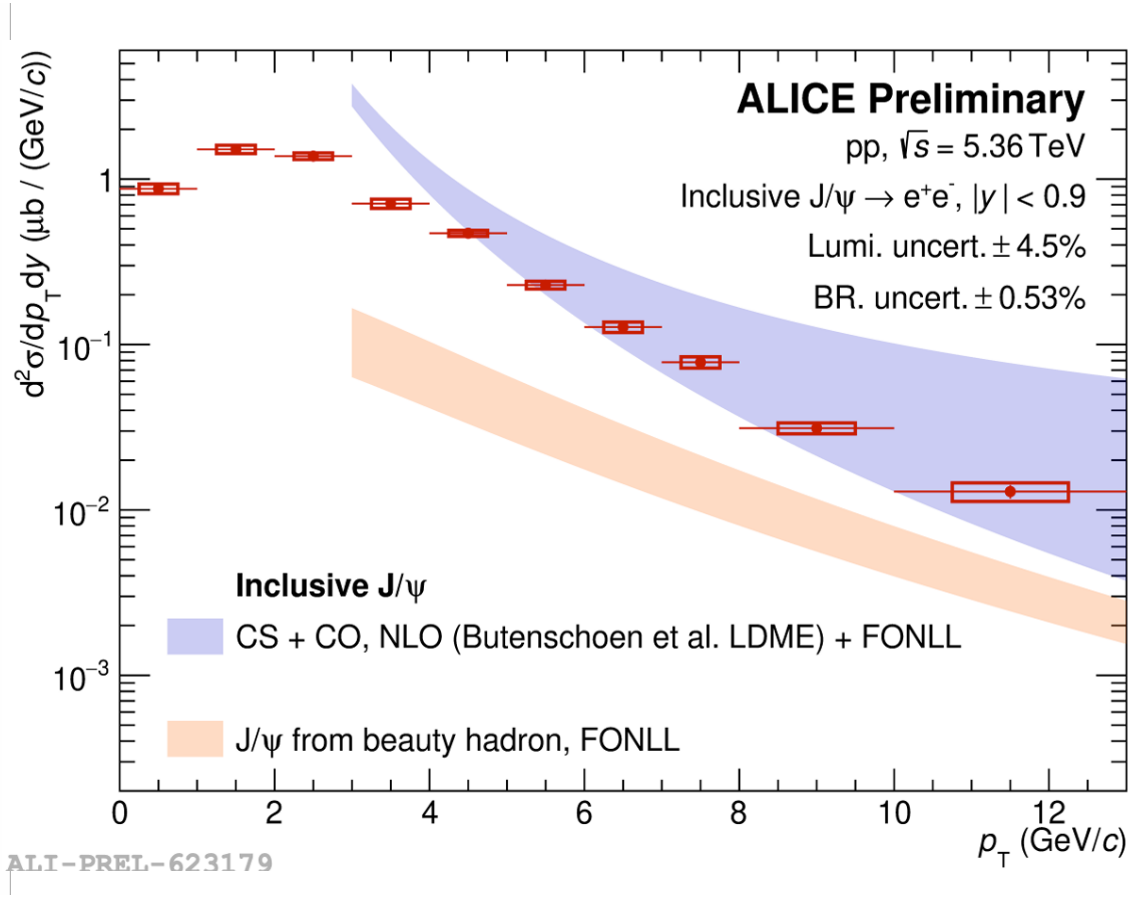
D^0



B^+



J/ψ



- D^0 and B^+ meson p_T spectra can be described by pQCD calculations
- ALICE showed 5.36 TeV inclusive J/ψ result

Quark Mass Dependence of the Hadron Suppression

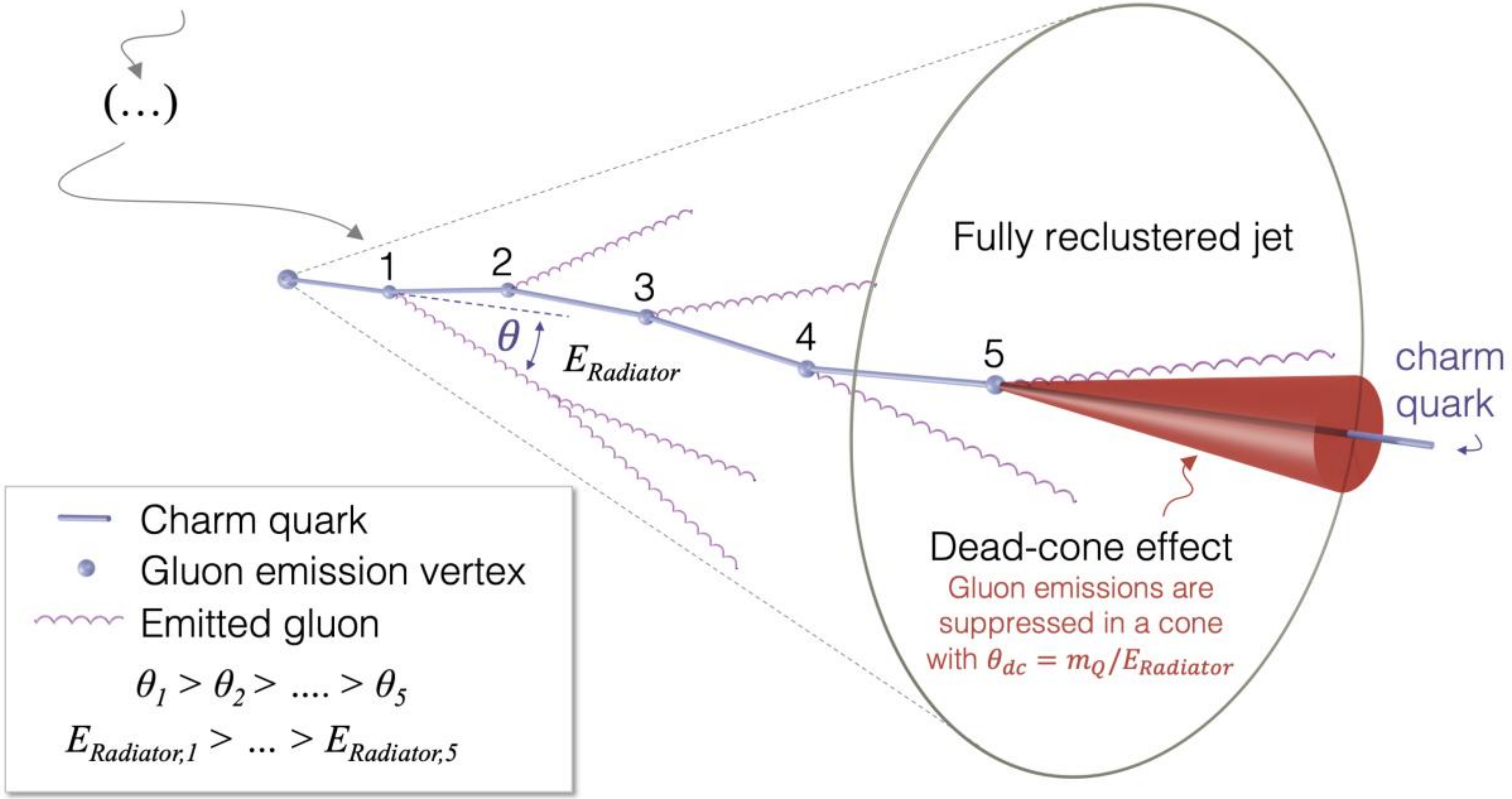
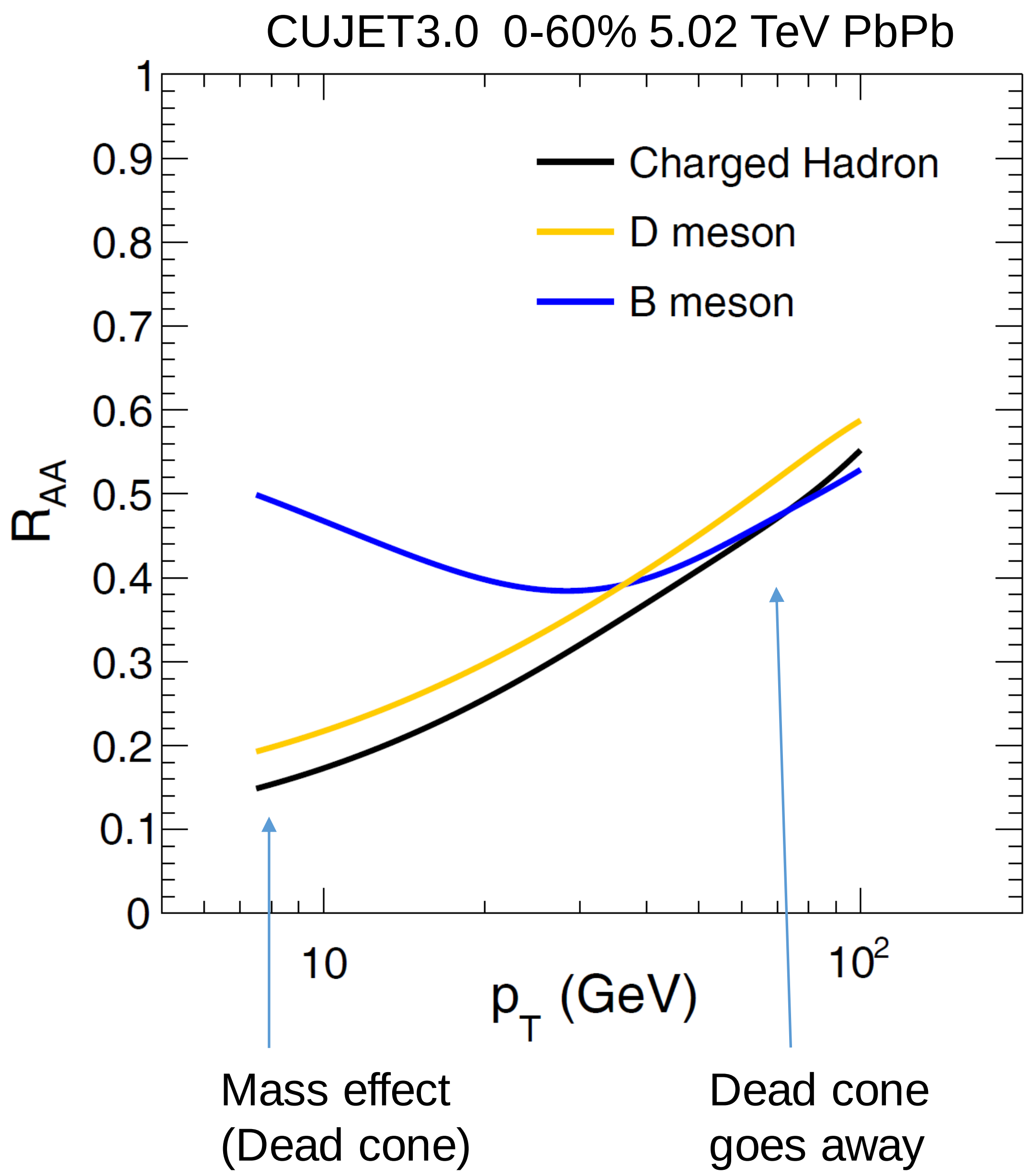
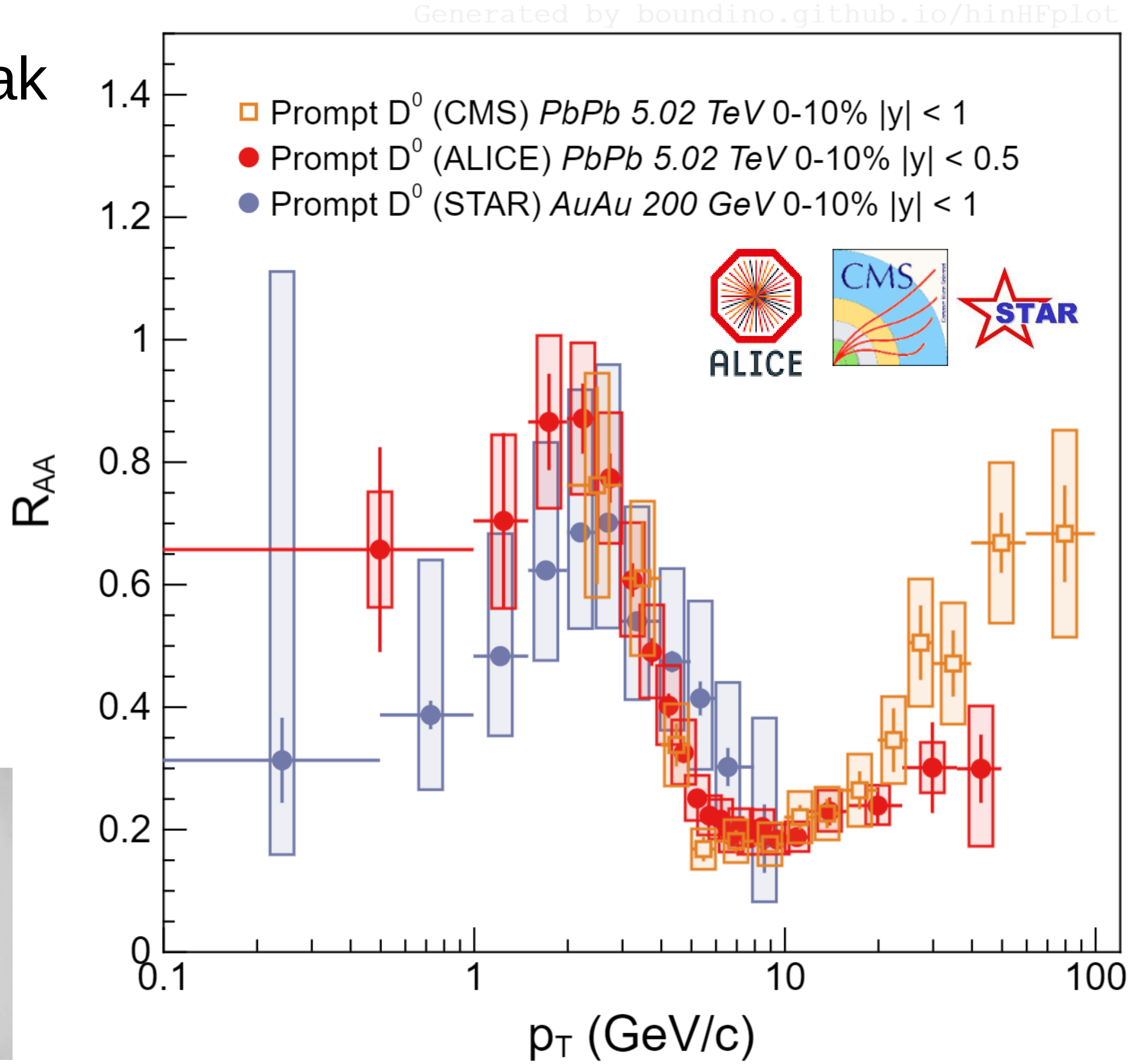


Figure from ALICE publication in Nature 605 (2022) 7910, 440-446



D^0 R_{AA} in 0-10% A+A Collisions

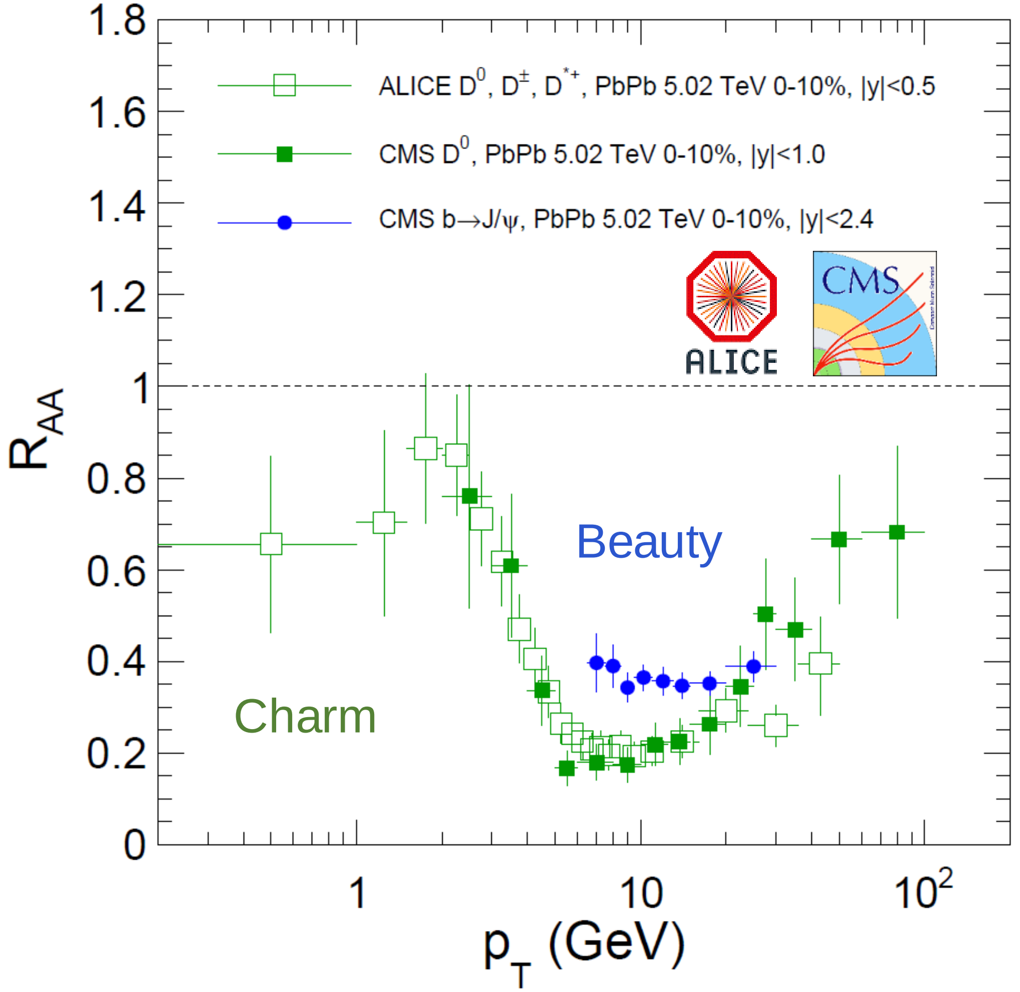
- R_{AA} first increases with p_T, reaching a peak value at p_T ~ 1 - 4 GeV, then decreases
- Minimum of R_{AA} is at around 10 GeV
- R_{AA} increases with p_T at p_T > 20 GeV
- The results from RHIC and LHC are similar at the low p_T

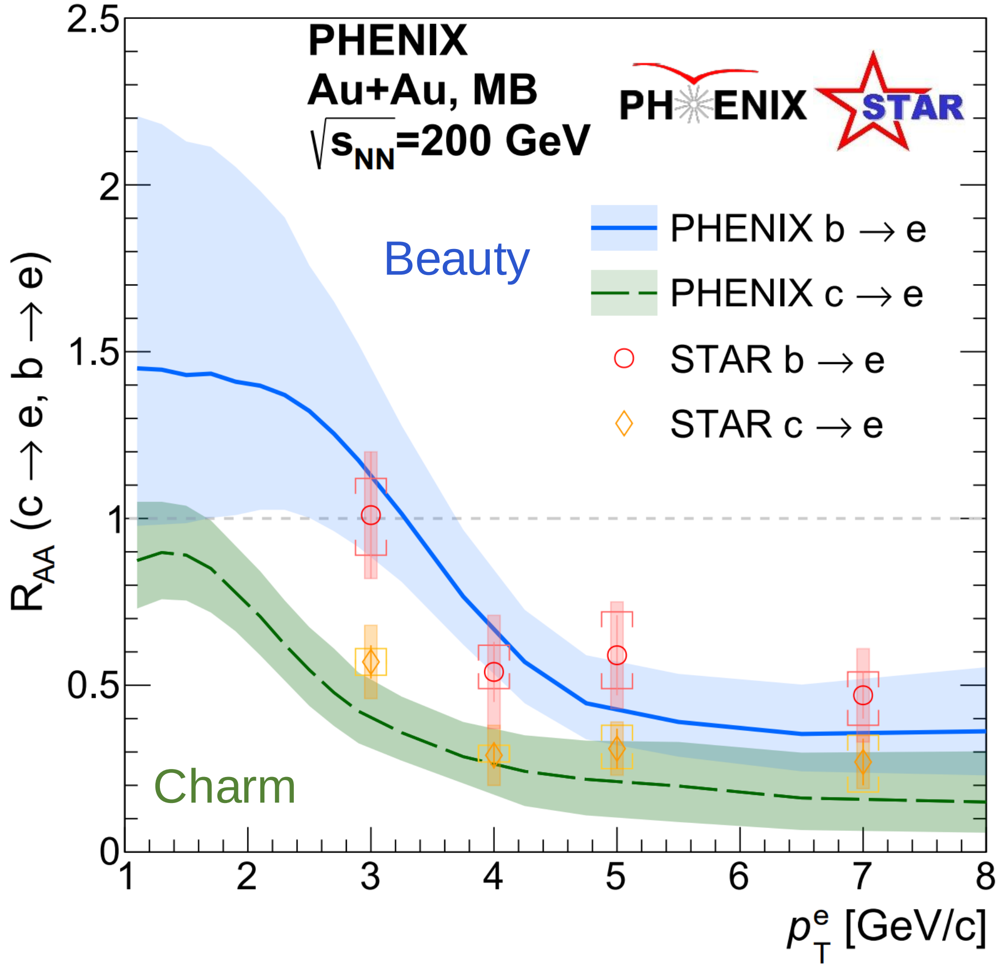



Bullet in gelatin block

ALICE JHEP 01 (2022) 174
CMS PLB (2018) 474
STAR PRC 99 (2019) 034908

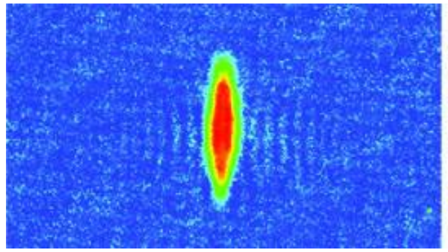
Beauty vs. Charm R_{AA}

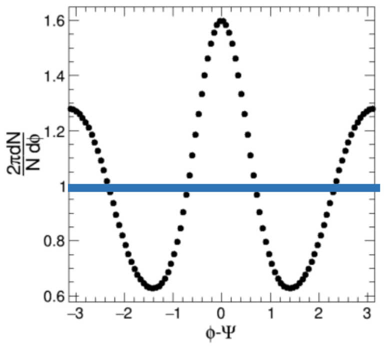




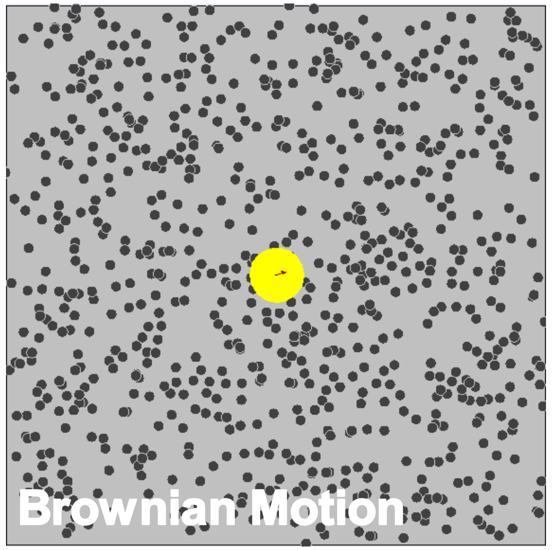
- Nuclear modification factors of depends on quark mass:
  - ALICE and CMS data though various fully / partially reconstructed decay channels at LHC
  - STAR and PHENIX HF electron data at RHIC
  - Observation of the mass dependence at low p_T and disappearance at high p_T

Heavy Quark (Charm and Beauty) Diffusion

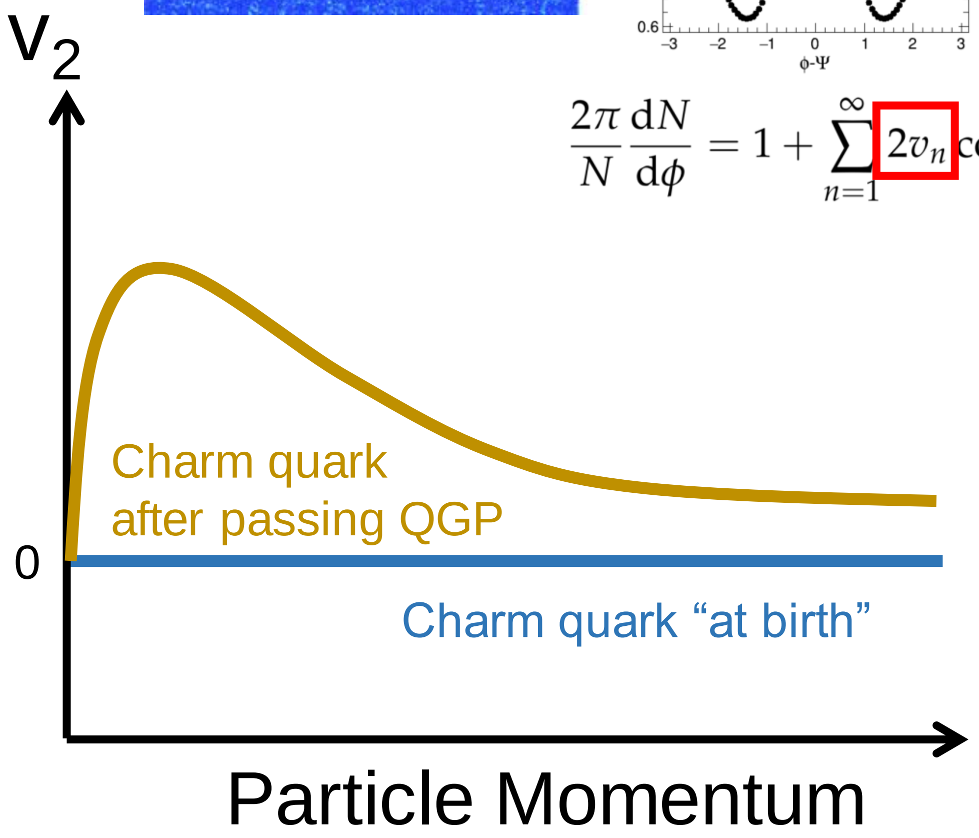




$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



Artist's impression



Fokker-Planck equation

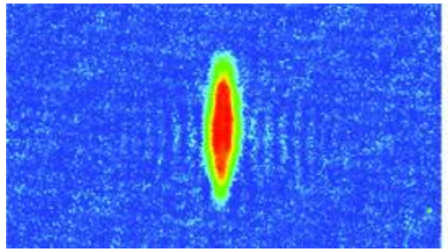
$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p} pA(p) f_Q(t,p) + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q(t,p)$$

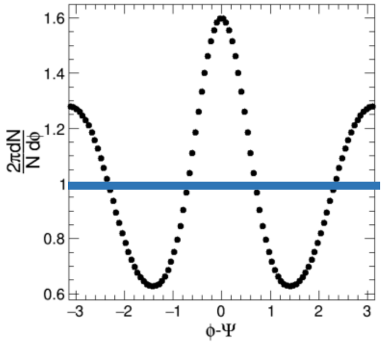
A and B are transport coefficients

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

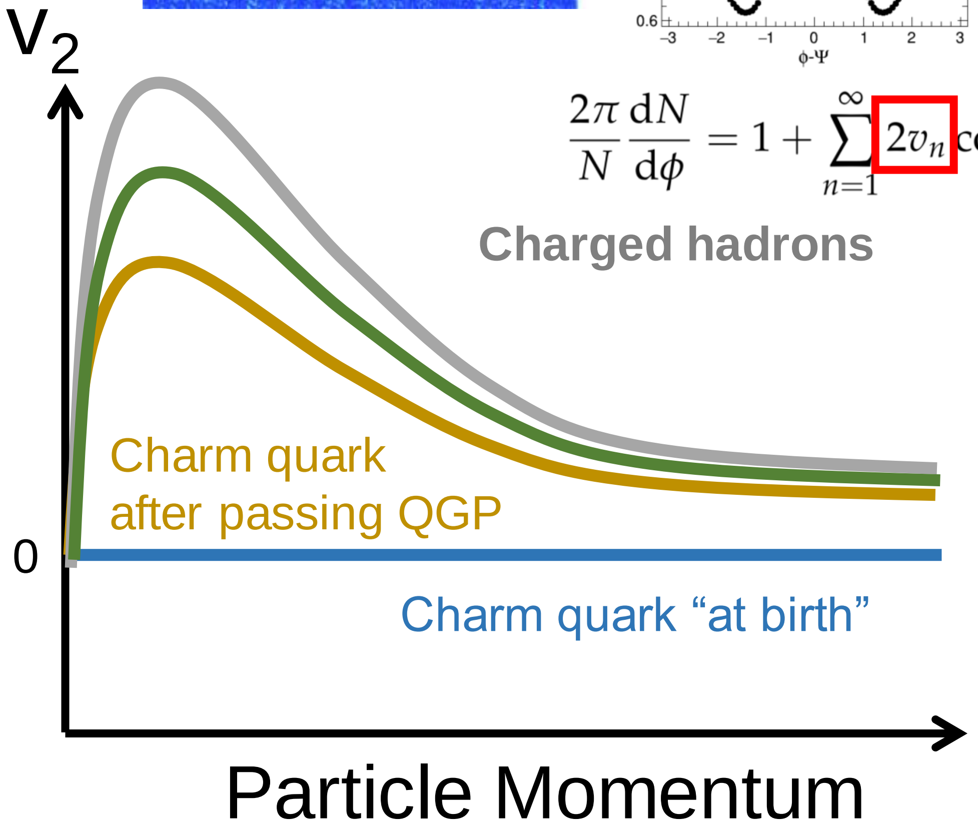
- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!

Heavy Quark (Charm and Beauty) Diffusion

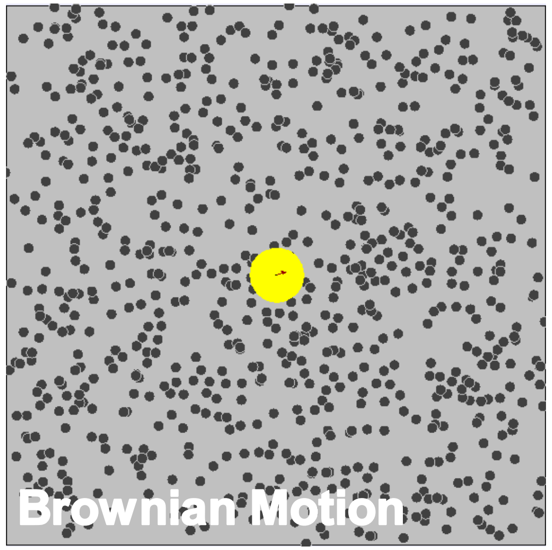


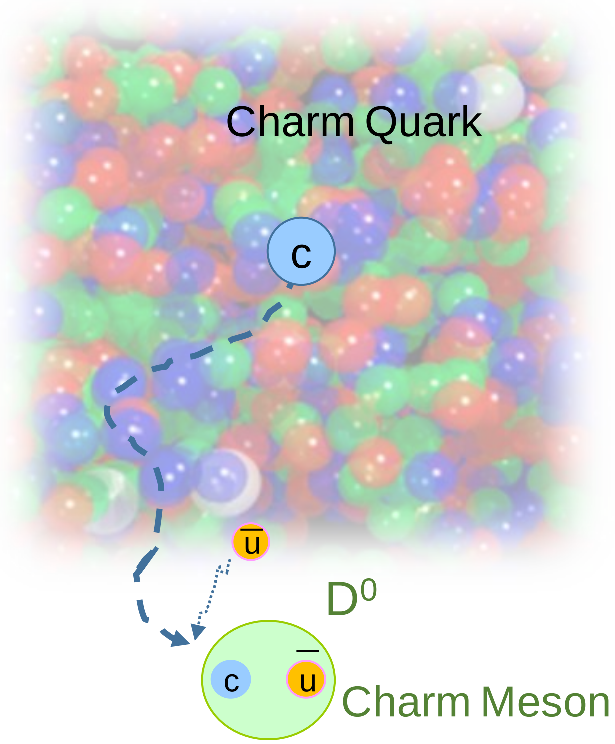


$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



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

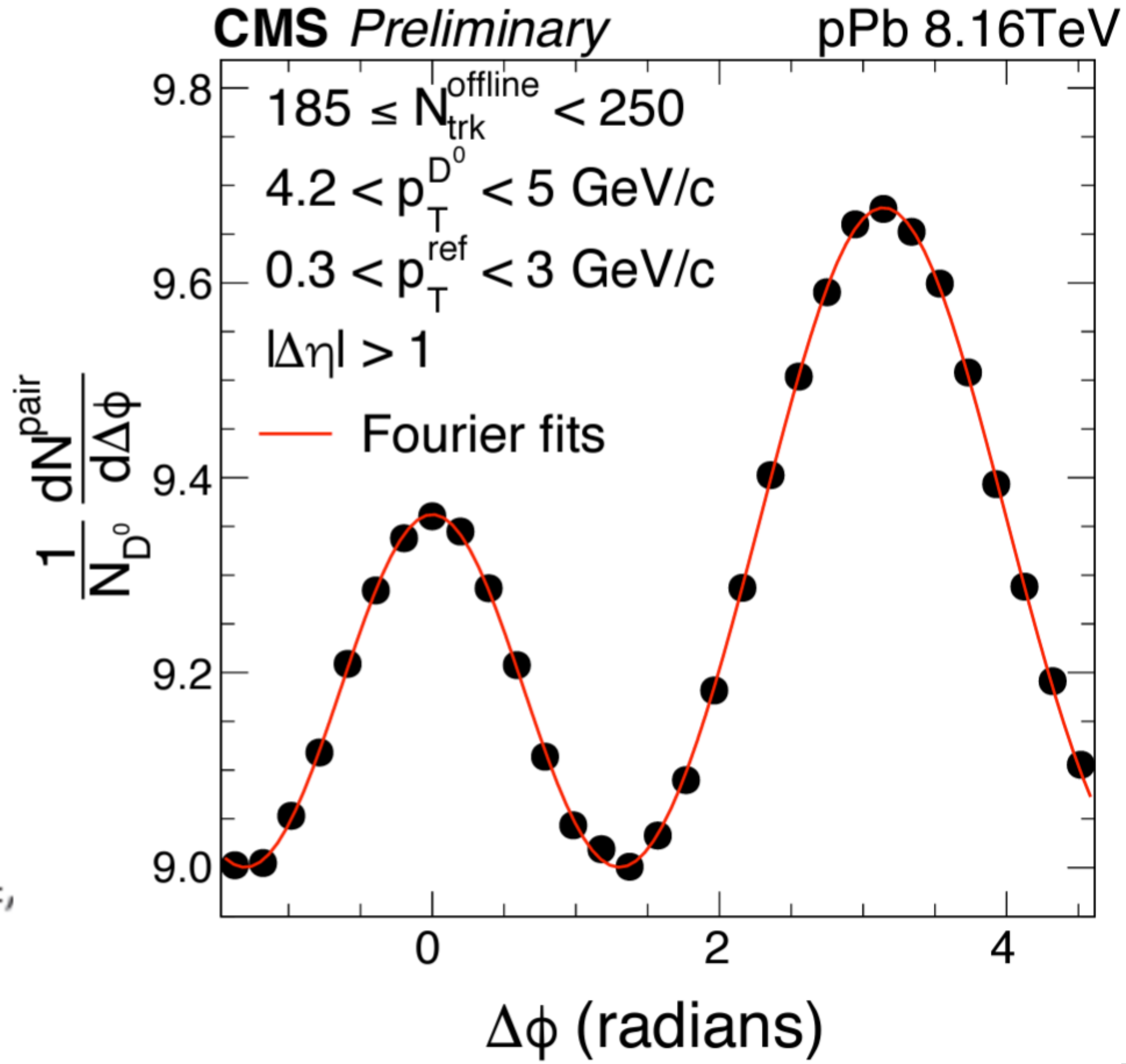
Extraction of D^0 v_2 with Two-Particle Correlation Function

- Projection in long-range ($|\Delta\eta| > 1$)
- Fit by Fourier decomposition to get $V_{n\Delta}$

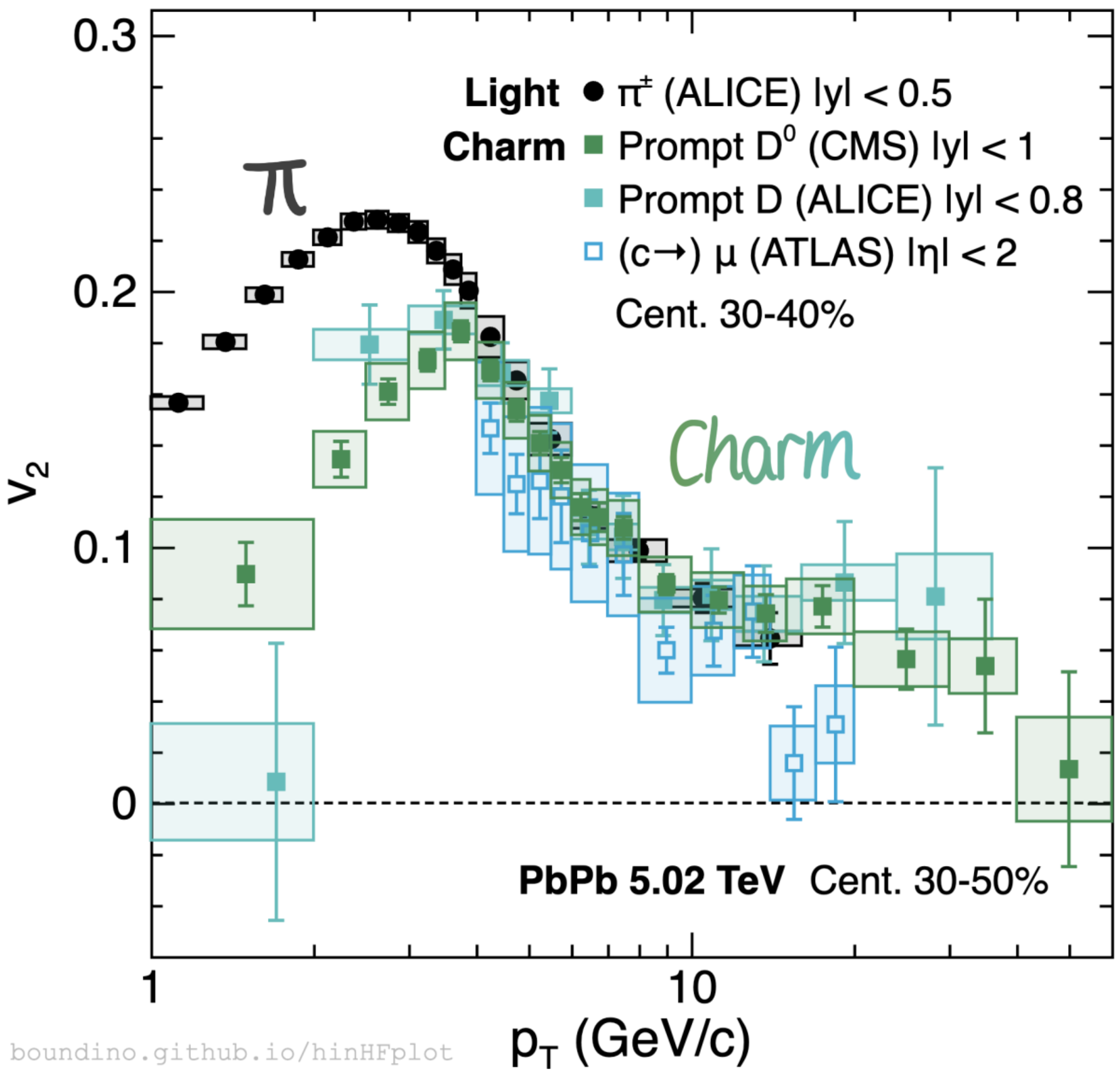
$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right\},$$

- Anisotropic harmonics extracted by

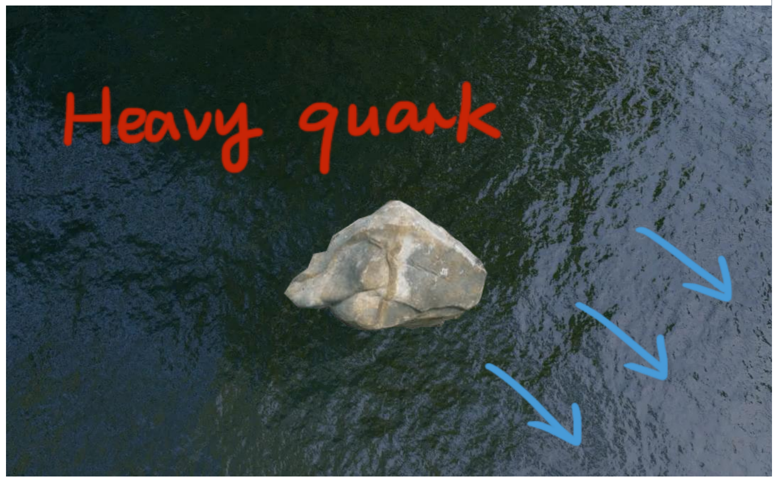
$$v_n\{2, |\Delta\eta| > 2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{\mathrm{ref}})}{\sqrt{V_{n\Delta}(p_T^{\mathrm{ref}}, p_T^{\mathrm{ref}})}},$$



Collective Flow Open Charm



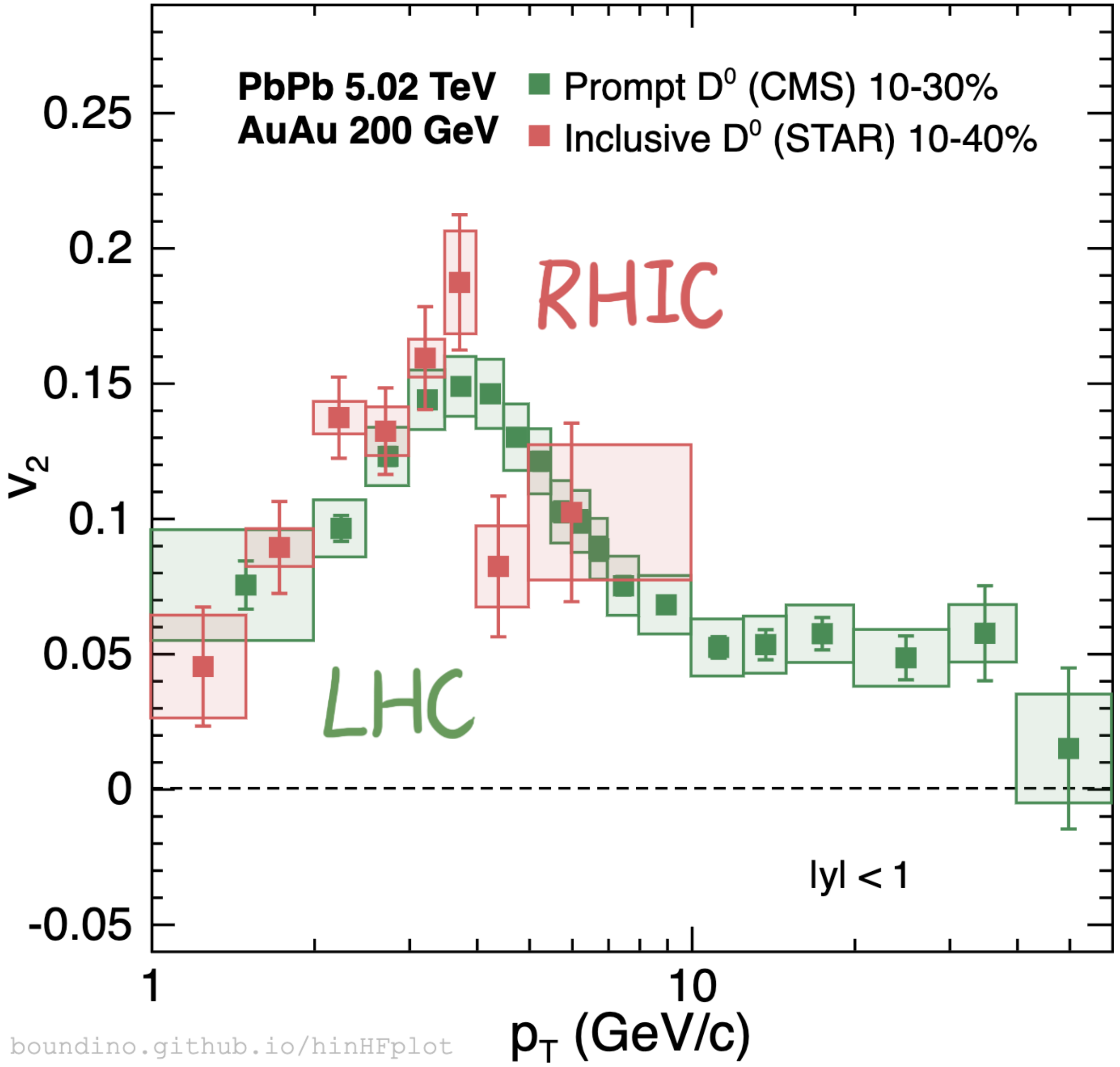
- Significant non-zero open charm flow signal
  - Smaller v_2 than light hadrons at low p_T
  - Magnitude reflects thermalization degree



- Consistent between LHC results
  - (c→) μ seems to shift to lower p_T

PLB 816 (2021) 136253 PLB 813 (2021) 136054 PLB 807 (2020) 135595

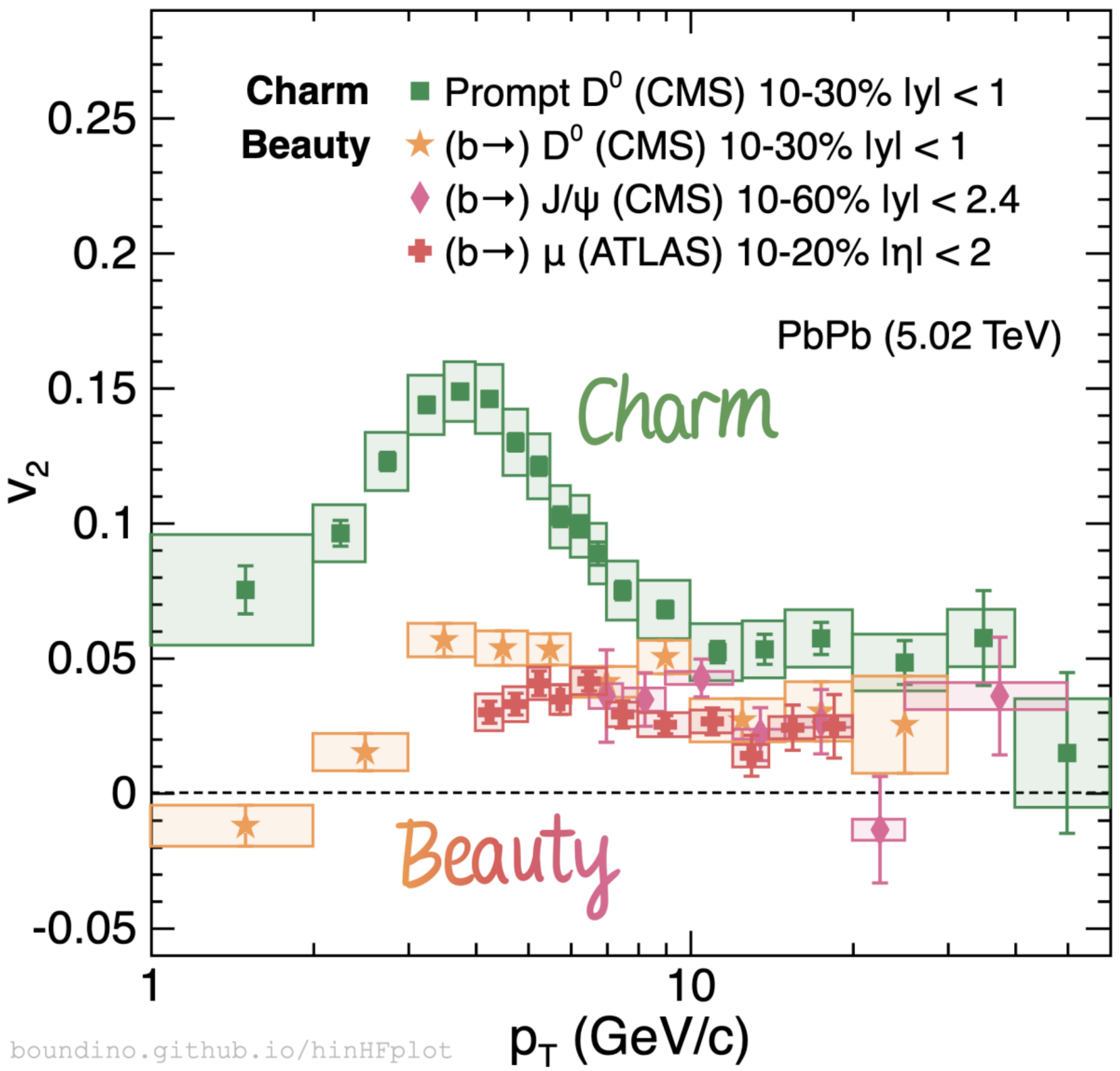
Open Charm Flow LHC vs RHIC



PLB 816 (2021) 136253 PRL 118 (2017) 212301

- Similar D v_2 between LHC PbPb 5 TeV and RHIC AuAu 200 GeV
  - despite different temperature & size?
  - decisive precision at sPHENIX

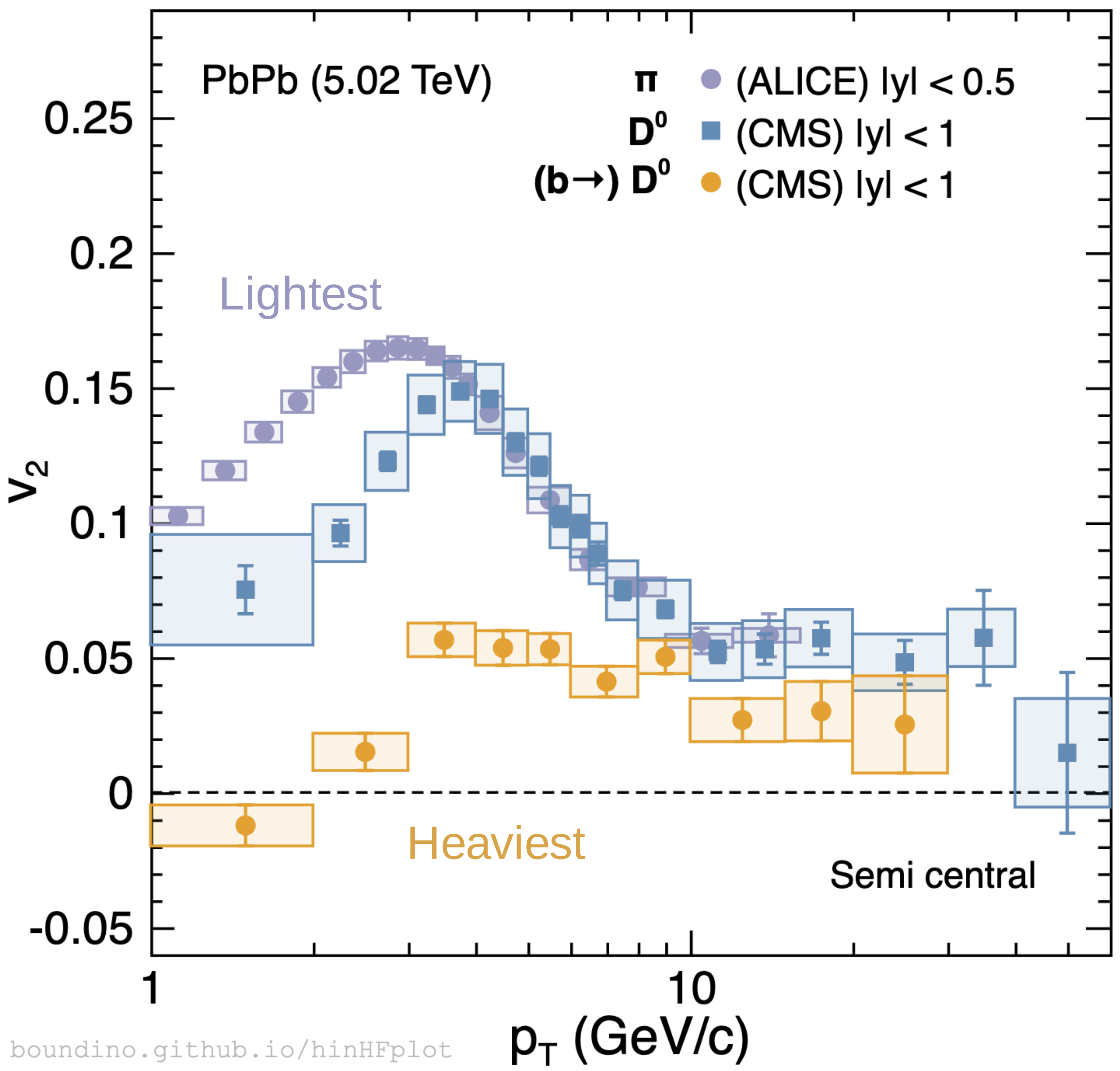
Collective Flow: Charm vs Beauty



- Significant non-zero open beauty flow signal
  - Smaller v_2 than charm hadrons at low p_T
    - Weaker collective flow behavior
  - Similar v_2 with open charm at high p_T
    - Path length dependence of energy loss

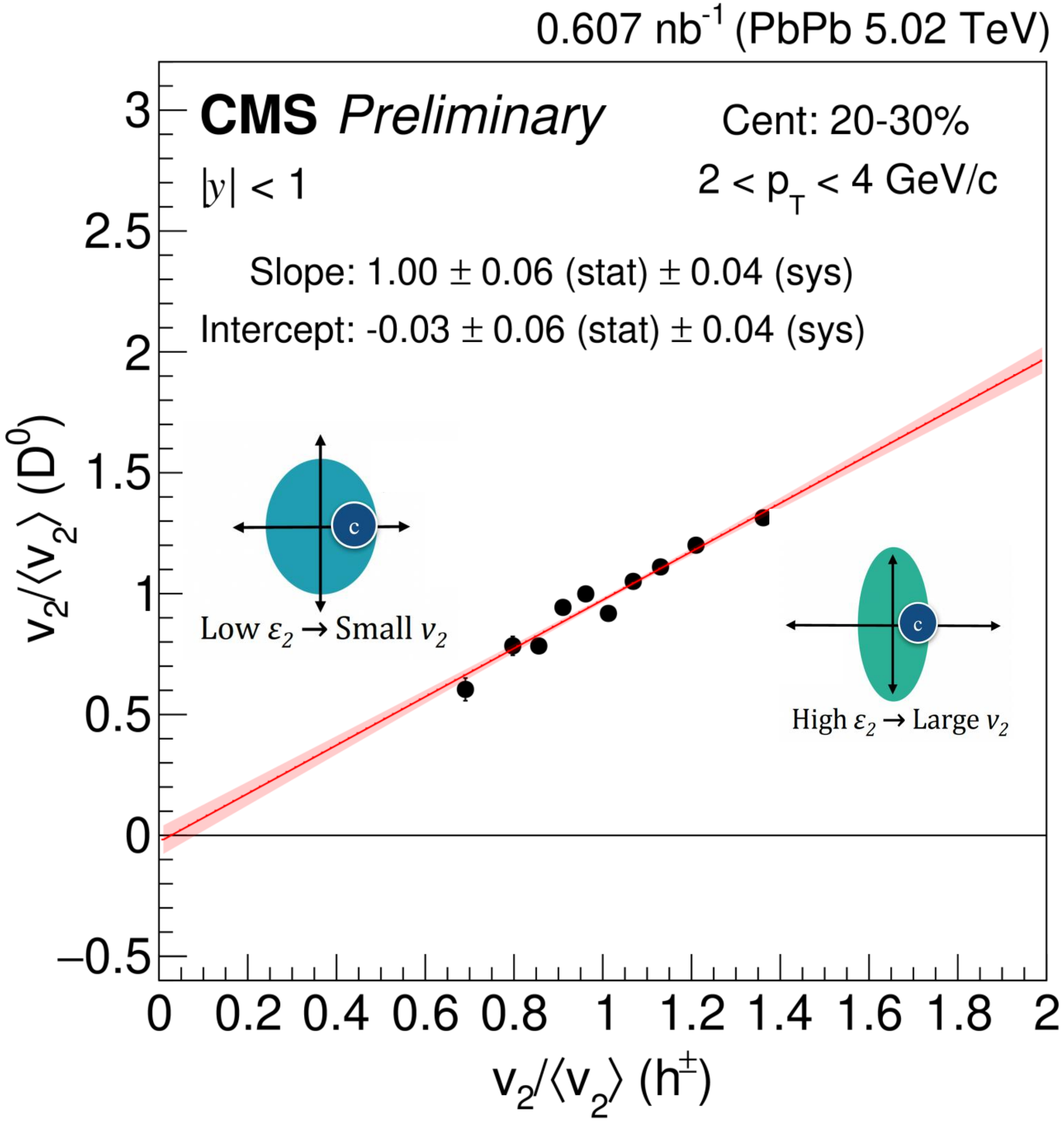
PLB 850 (2024) 138389 JHEP 10 (2023) 115 PLB 807 (2020) 135595

Collective Flow: Mass Hierarchy



- v_2 hierarchy from lightest to heaviest hadrons

Charm Quark v_2 vs. Light Flavor v_2

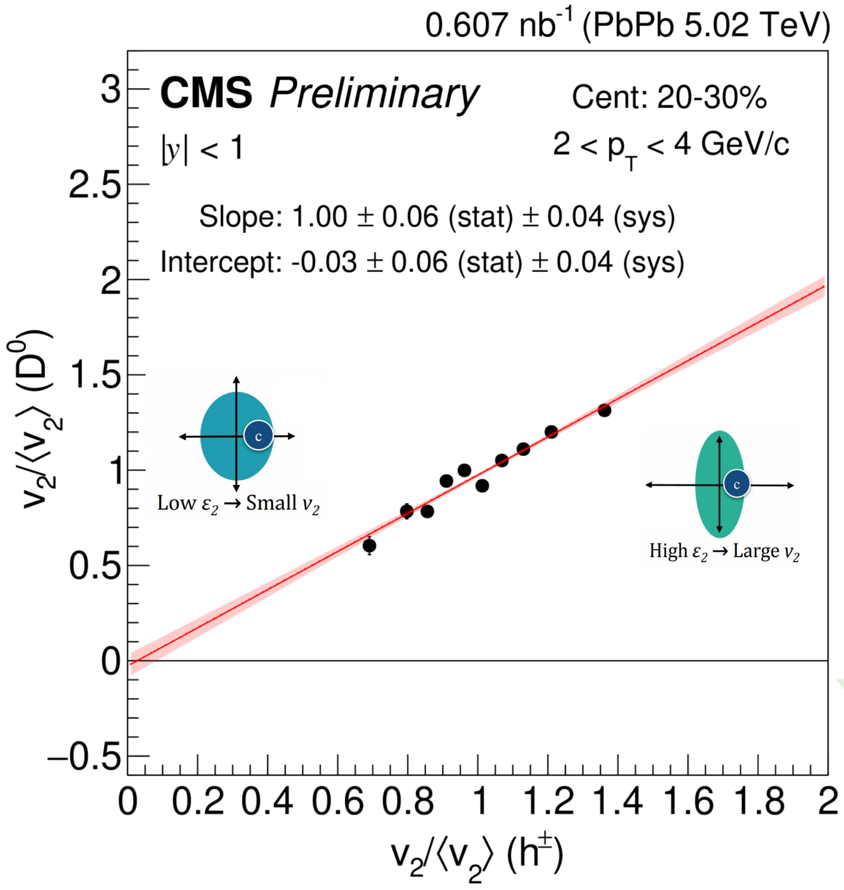


Do charm quarks develop elliptic flow through interactions with the light partons in the QGP?

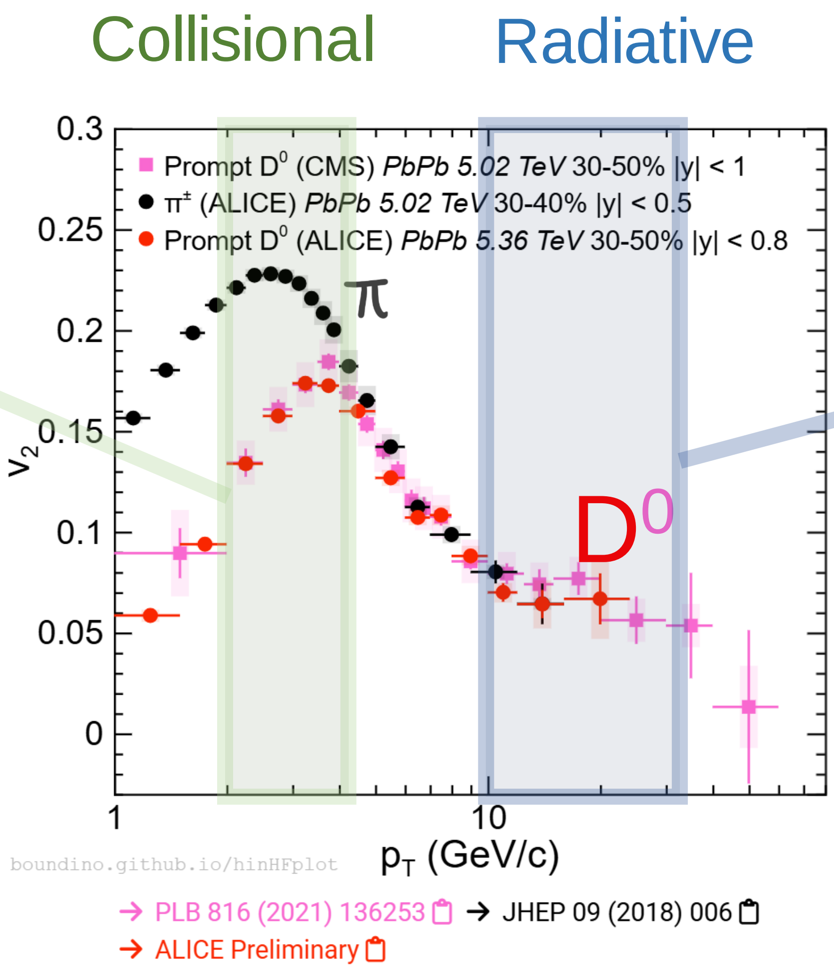
Vary initial eccentricity by Event Shape Engineering q_2 while **keeping the same centrality**

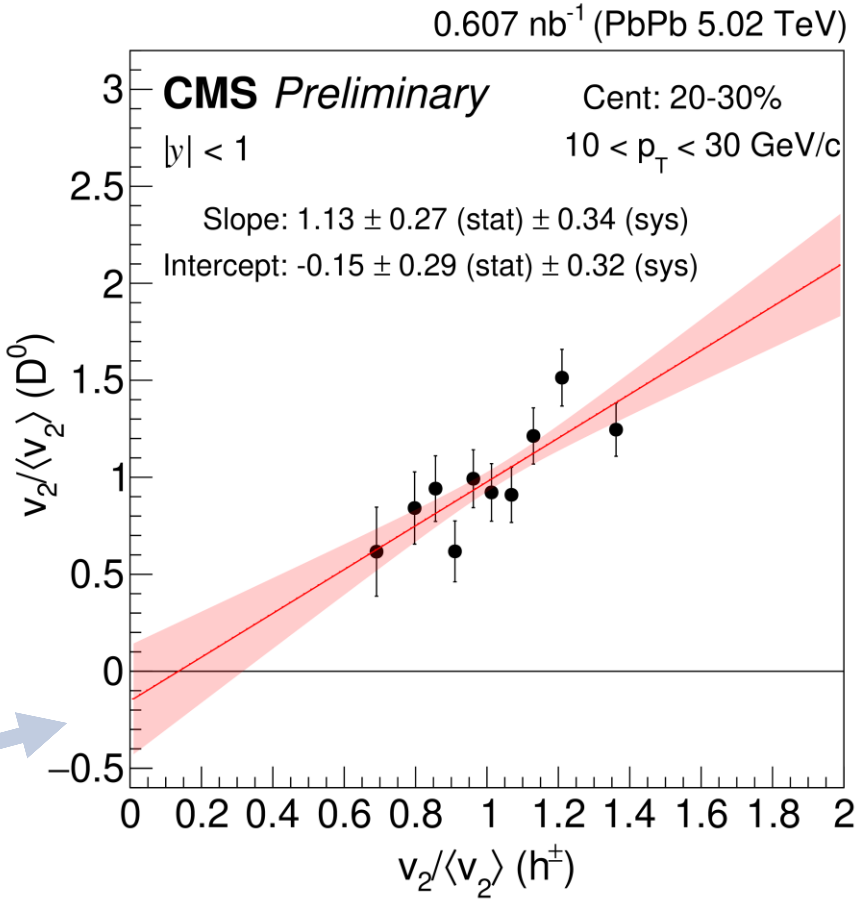
- D^0 v_2 significantly increases with q_2
- **Linear correlation** between D^0 v_2 and light hadron v_2
- Slope is consistent with 1
- This shows D^0 v_2 is driven by initial shape, similar to light flavors

Charm Quark v_2 vs. Light Flavor v_2



Linear correlation observed in both p_T ranges





D^0 v_2 is driven by initial shape, similar to light flavors at low p_T

Also true at high p_T, regardless of the underlying mechanism

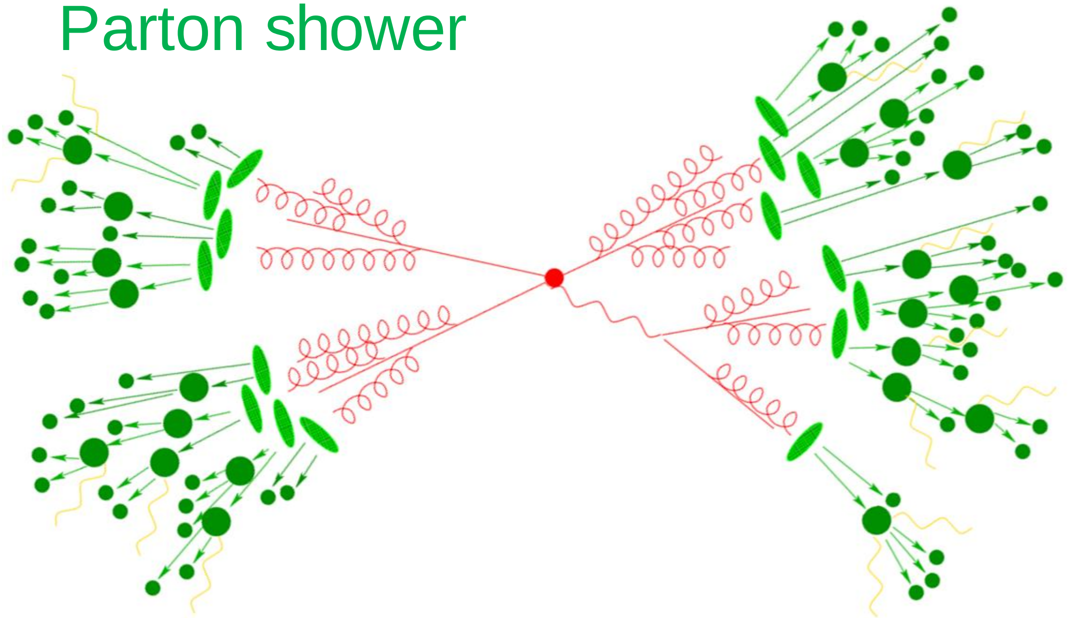
Hadronization of Heavy Quarks in QGP

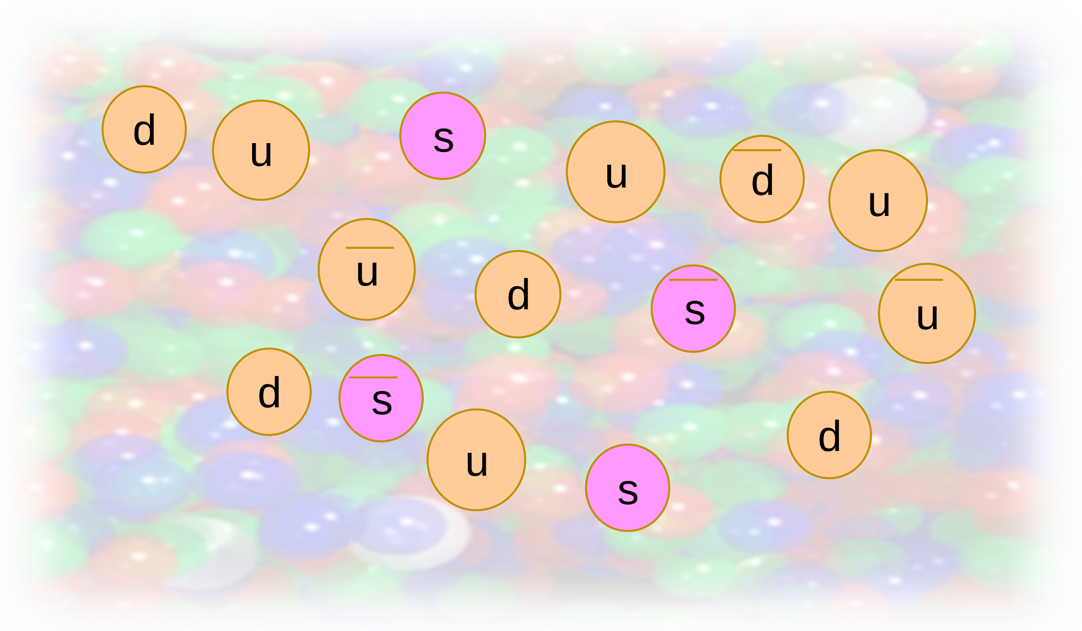
Hadronization: from Quarks to Hadrons

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

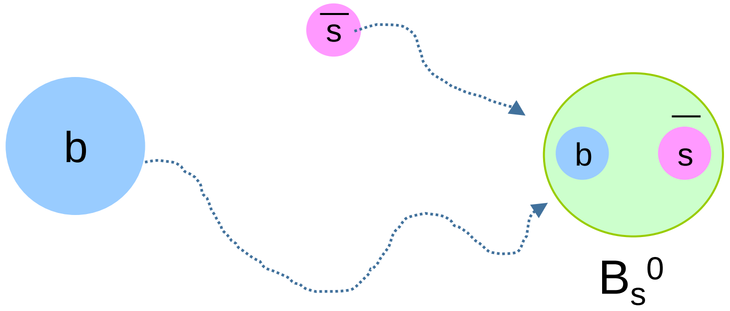
Example: in additional to parton shower,
B_s could be **enhanced via parton coalescence** in QGP

Parton shower

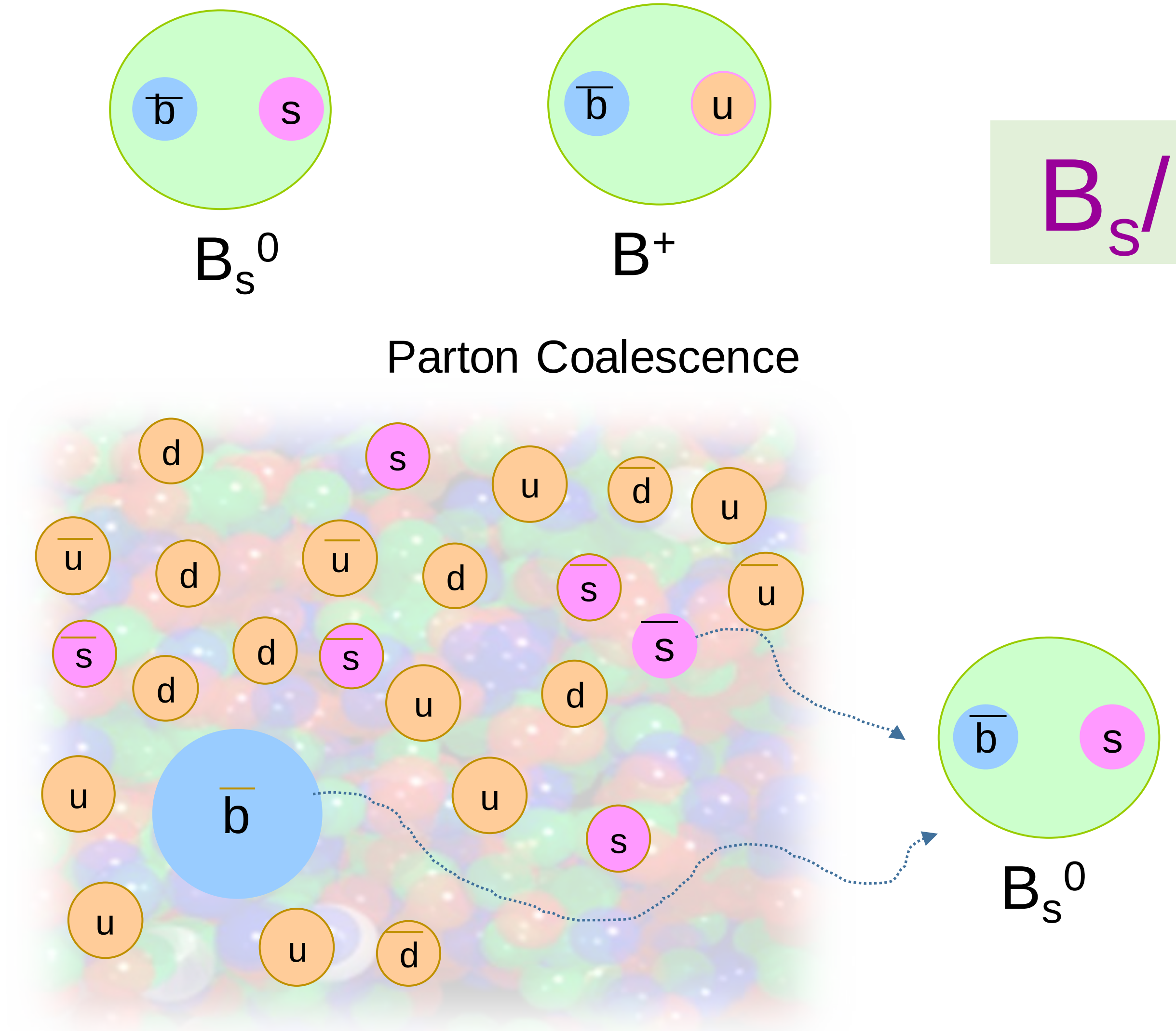




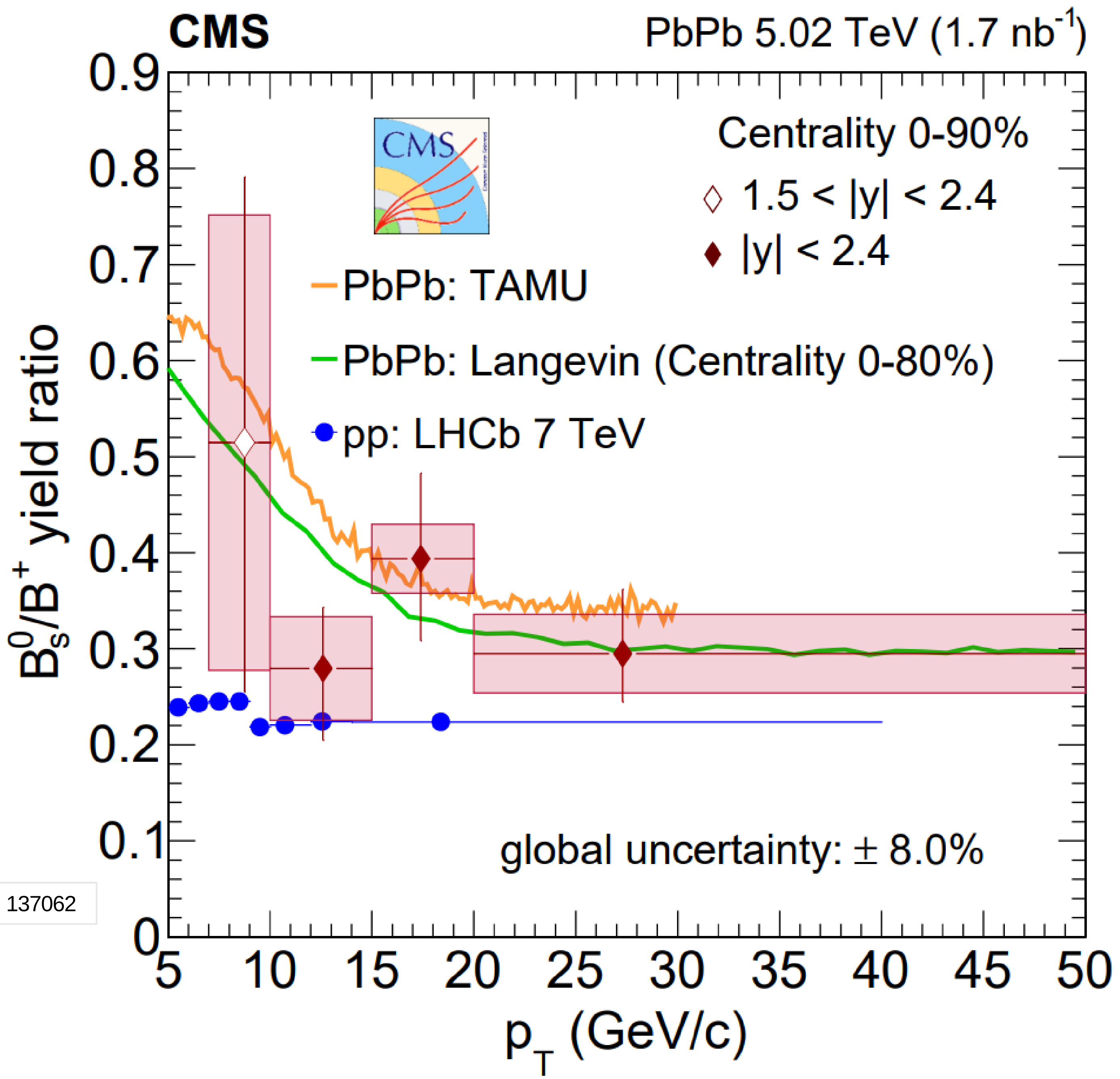
Parton Coalescence



Beauty Quark Hadronization



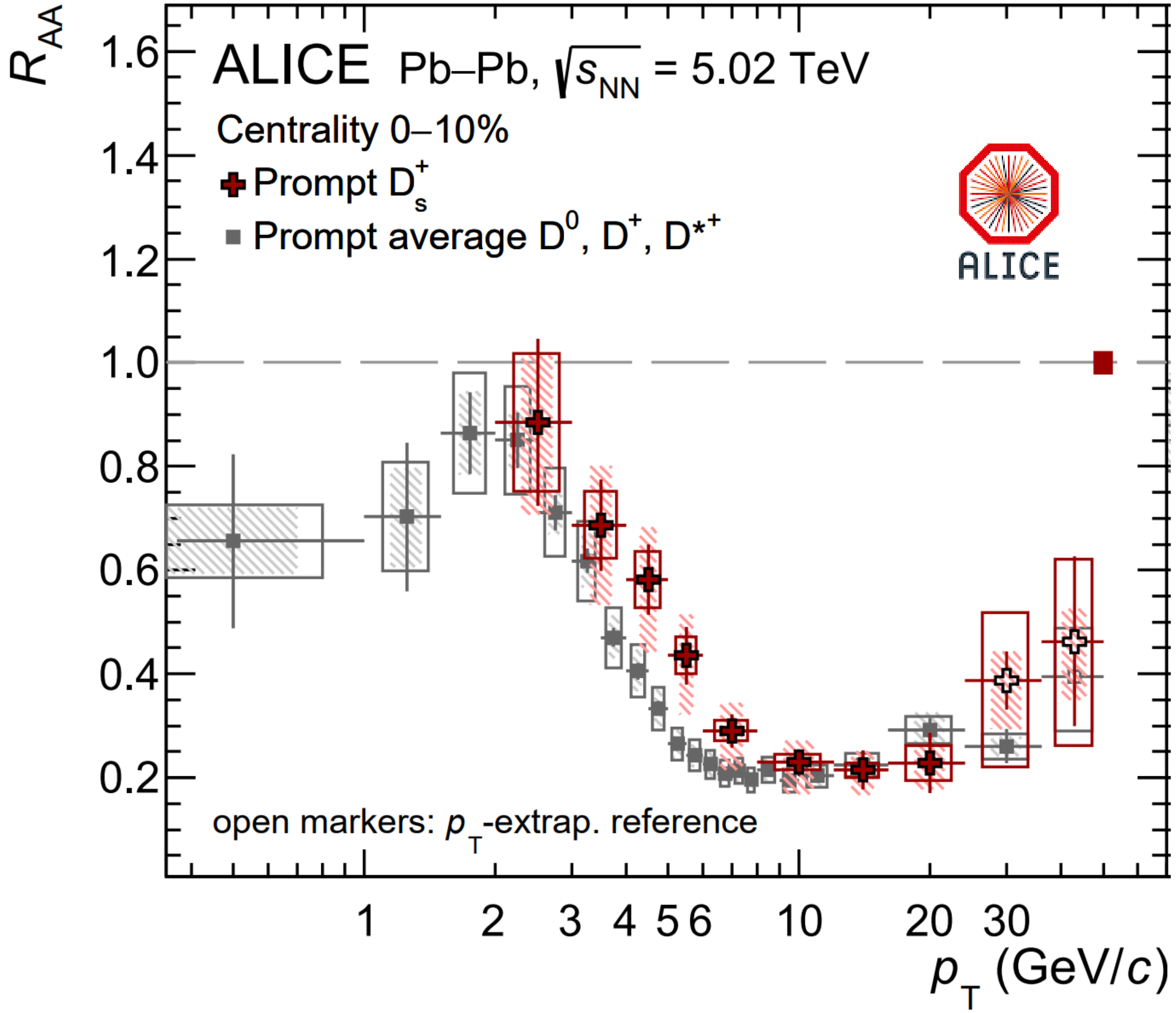
B_s/B^+



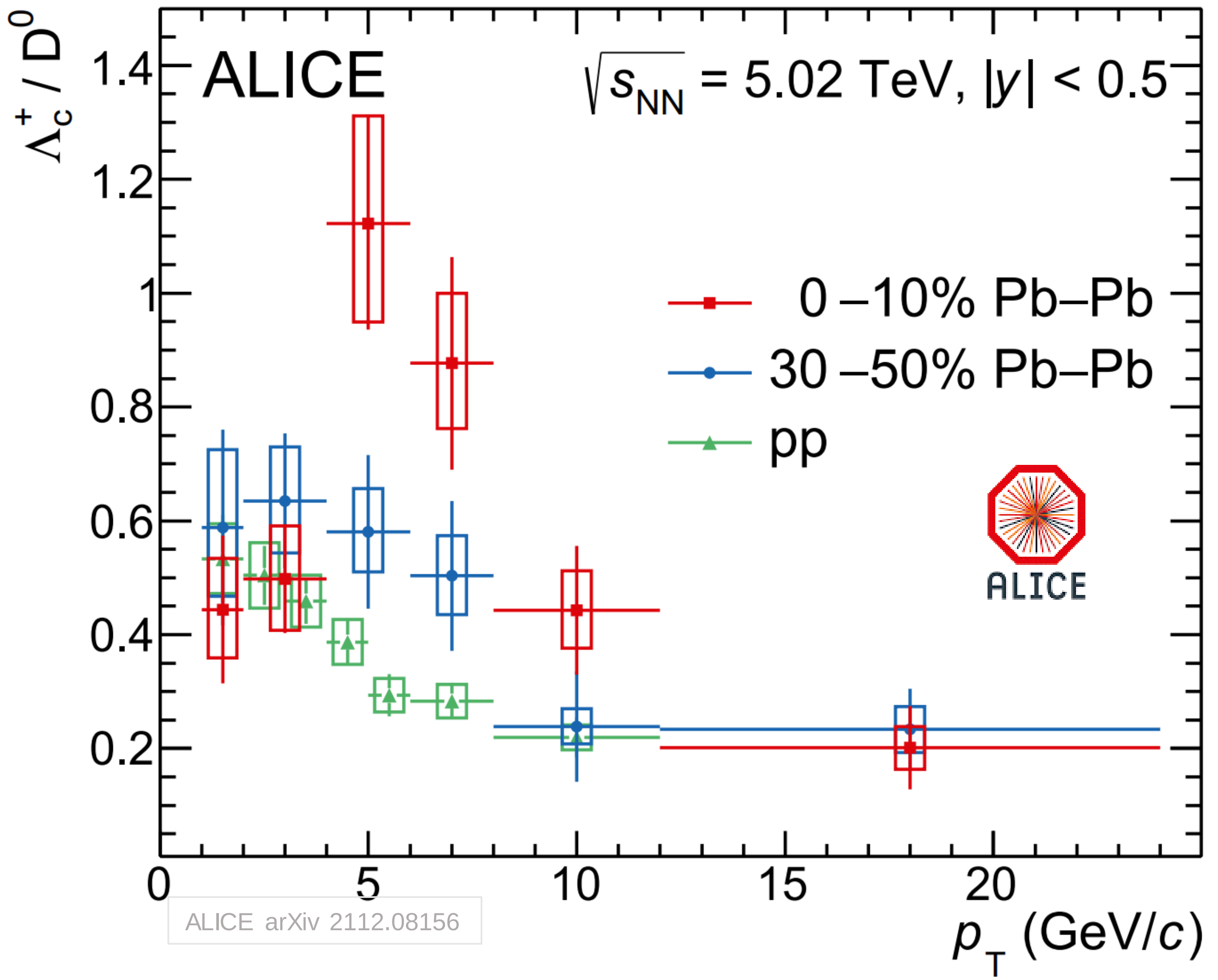
PLB 829 (2022) 137062

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

Charm Quark Hadronization



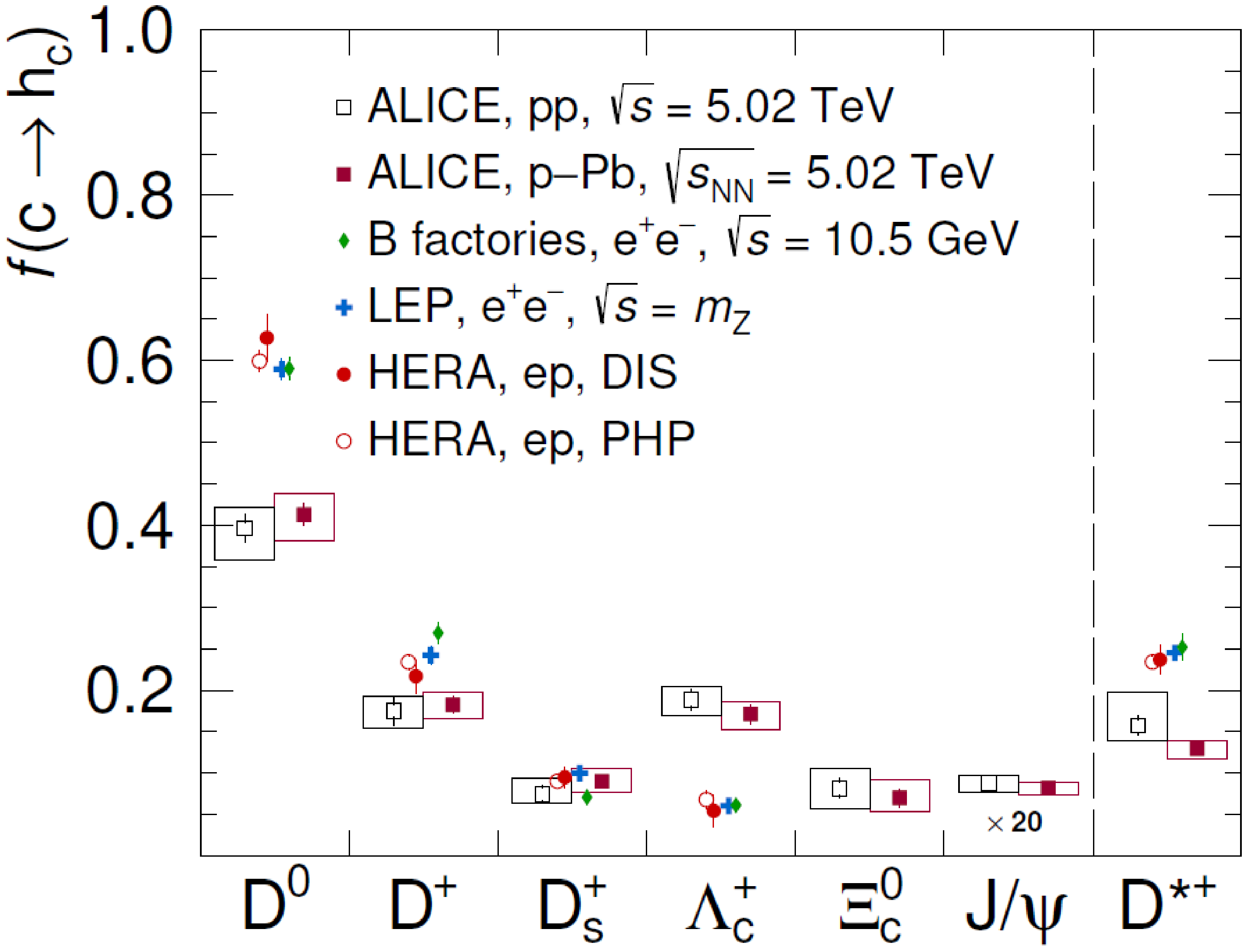
Indication of enhanced production of D_s (2.3σ) in PbPb collisions!



Enhanced production of charmed baryon in PbPb

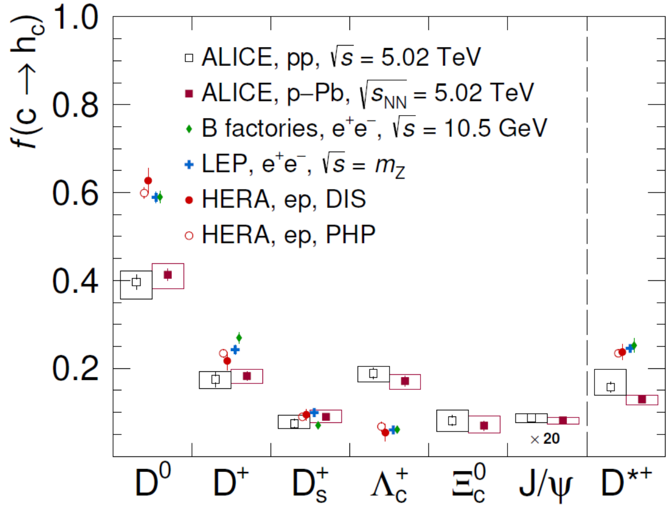
Charm Hadronization in ee, ep, pp and pPb

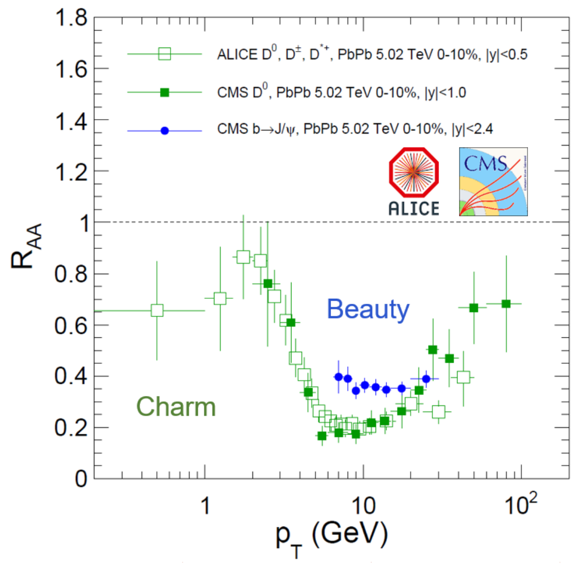
- Charm hadronization is already modified in pp collisions!
- Suppression of D^0, D^+, and D^{*+}
- Enhancement of Λ_c
- Challenge to the “universal” fragmentation function in theoretical calculations

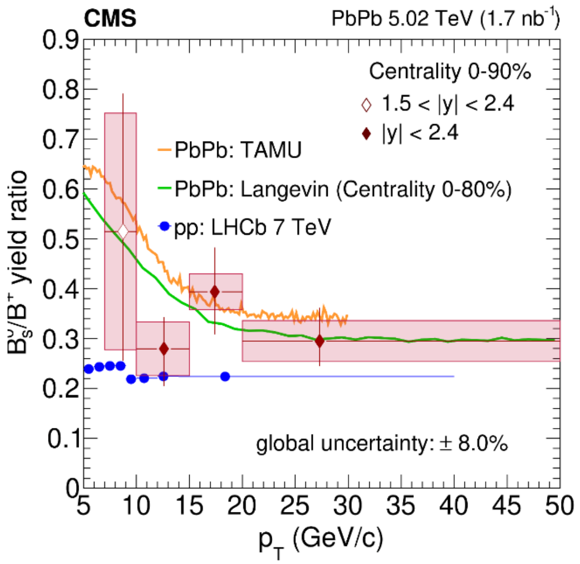


Summary: Open Heavy Flavor

- Charm production has been studied extensively with various experimental techniques
- Large elliptic flow and triangular flow signal
- Mass dependence of open heavy flavor hadron R_{AA}
- Large difference between charm hadronization in ee and pp
- Indication of further modifications of charm and beauty hadronization in AA collisions
- Next lecture: Quarkonia and small systems





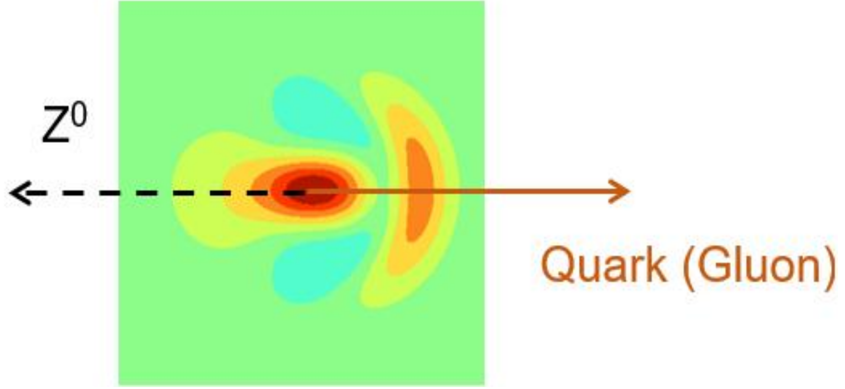


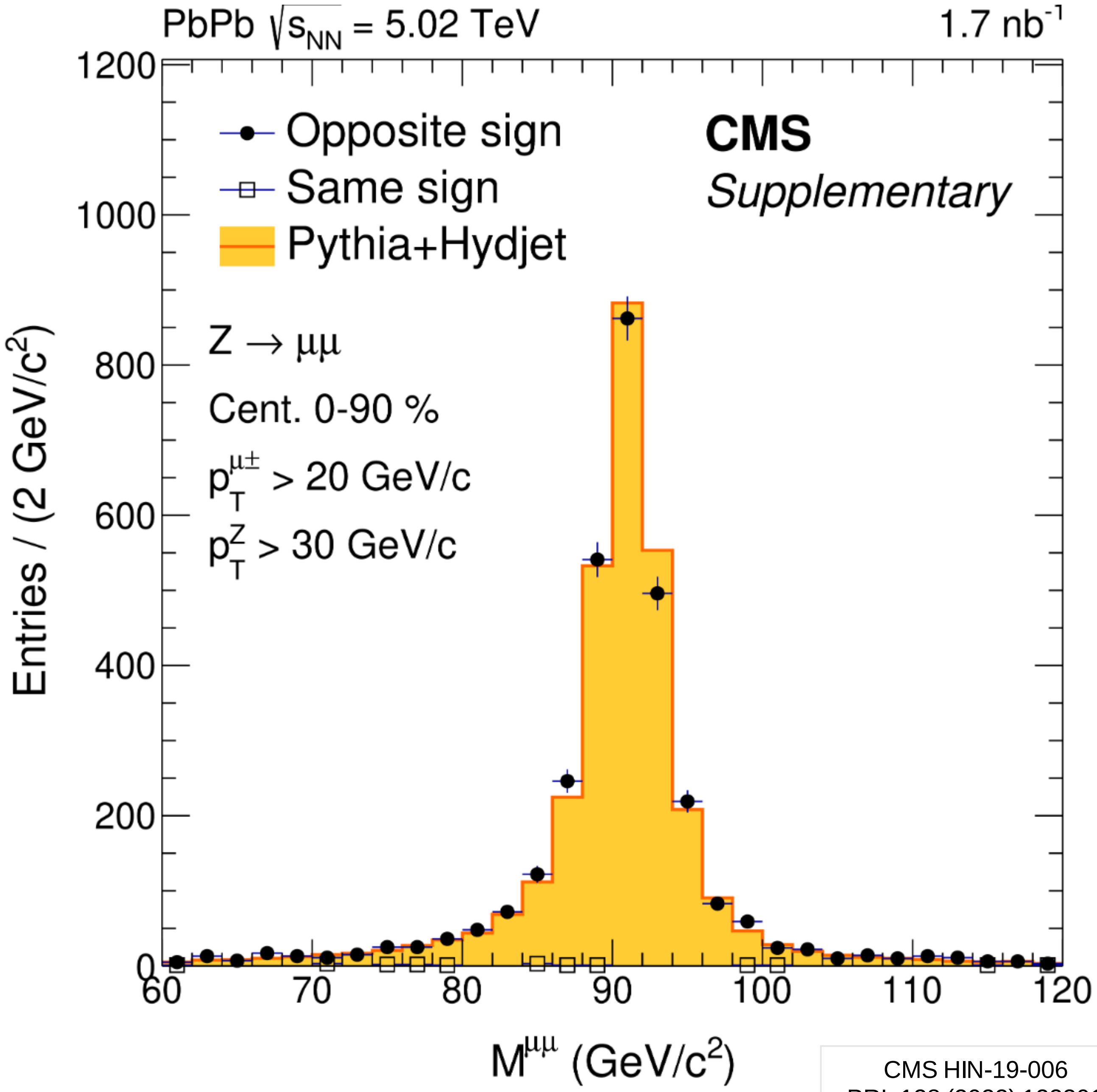
Backup Slides

Z^0 Boson and Charged Hadron Track Selection

- $Z^0 \rightarrow \mu^+\mu^-$ selections:
  - Muons: $|\eta_\mu| < 2.4$, $|p_{T,\mu}| > 20$ GeV/c,
  - Z^0 Bosons:
    - 60 GeV/c^2 < $M_{\mu\mu}$ < 120 GeV/c^2
    - **40 GeV/c < $|p_T^Z|$ < 350 GeV/c**
    - $|y_Z| < 2.4$

- Charged hadron selections:
  - $|\eta_{ch}| < 2.4$, $1 < p_T^{ch} < 10$ GeV/c.
  - Muon rejection: $\Delta R_{ch,\mu} > 0.0025$ between Muon candidates and charged hadron tracks



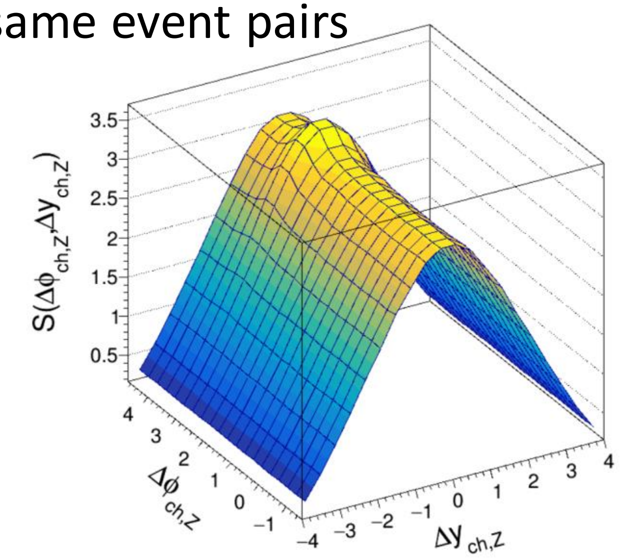


CMS HIN-19-006
PRL 128 (2022) 122301

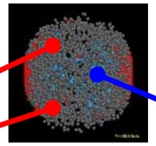
Z^0-Hadron Correlation Function: Event Mixing

Average Signal pair distribution:

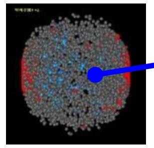
same event pairs



Z^0 Event 1

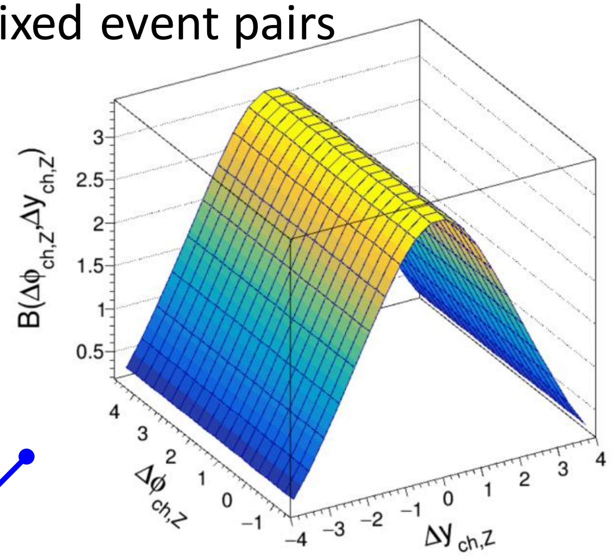


Z^0 Event 2



Average Background pair distribution:

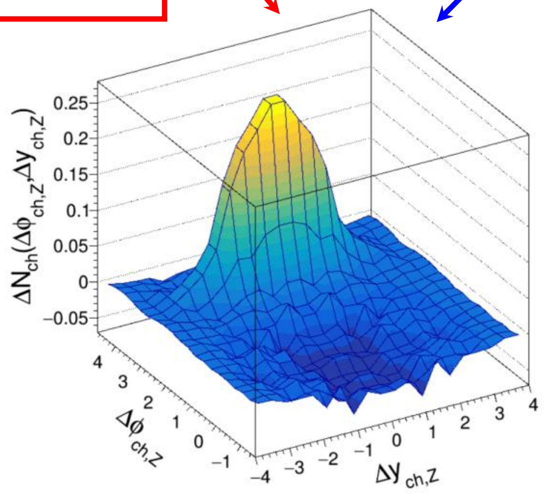
mixed event pairs



$$S(\Delta\phi_{ch,Z}, \Delta y_{ch,Z}) = \frac{1}{N_z} \frac{d^2 N^{same}}{d\Delta\phi_{ch,Z} d\Delta y_{ch,Z}}$$

$$B(\Delta\phi_{ch,Z}, \Delta y_{ch,Z}) = \frac{1}{N_z} \frac{d^2 N^{mix}}{d\Delta\varphi_{ch,Z} d\Delta y_{ch,Z}}$$

$$\Delta N_{ch} = S - B$$



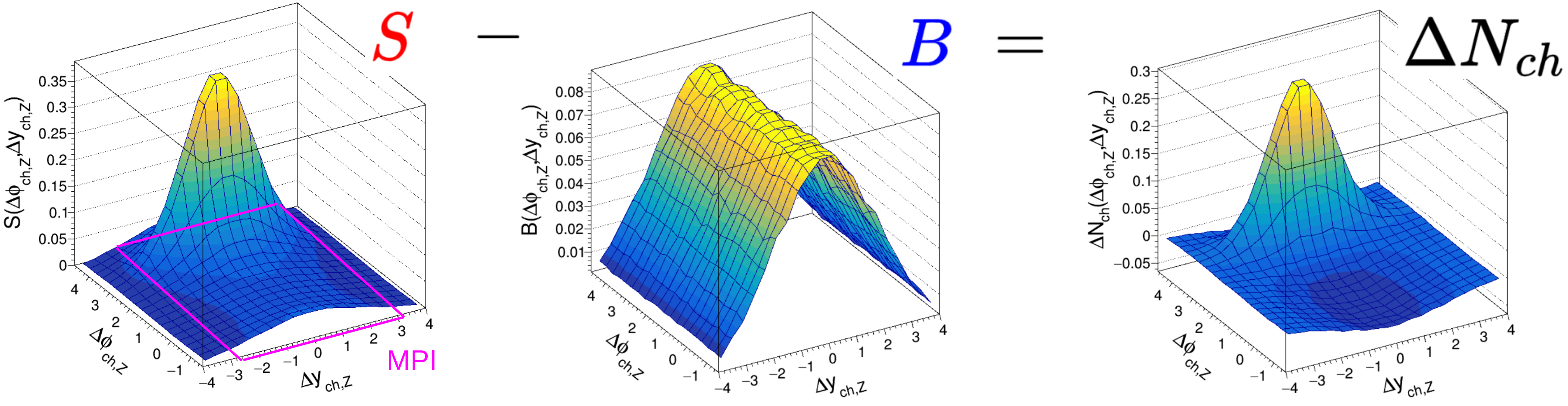
$\Delta y_{ch,Z} = y_z - \eta_{ch}$

$\Delta\varphi_{ch,Z} = \varphi_z - \varphi_{ch}$

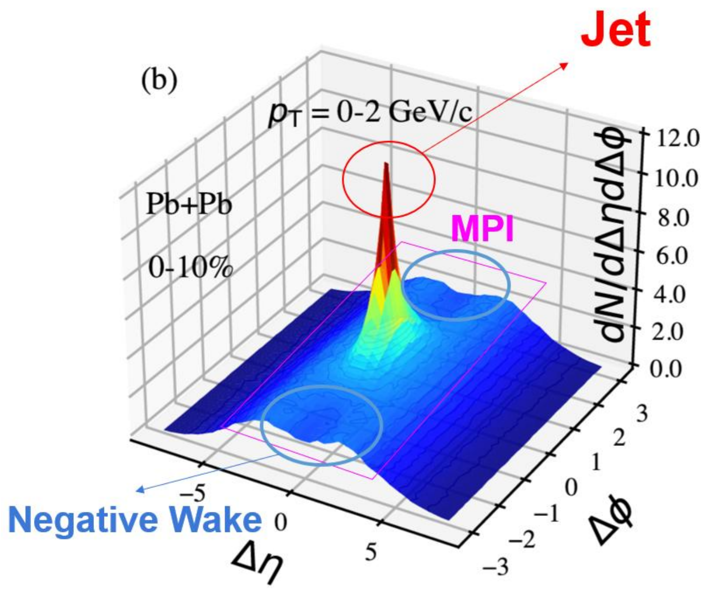
Demonstration with PYTHIA+HYDJET (Generator level events)

Integral of the ΔN_{ch} correlation function will be ~0

Mixed Event Subtraction in **PYTHIA8 pp** Events

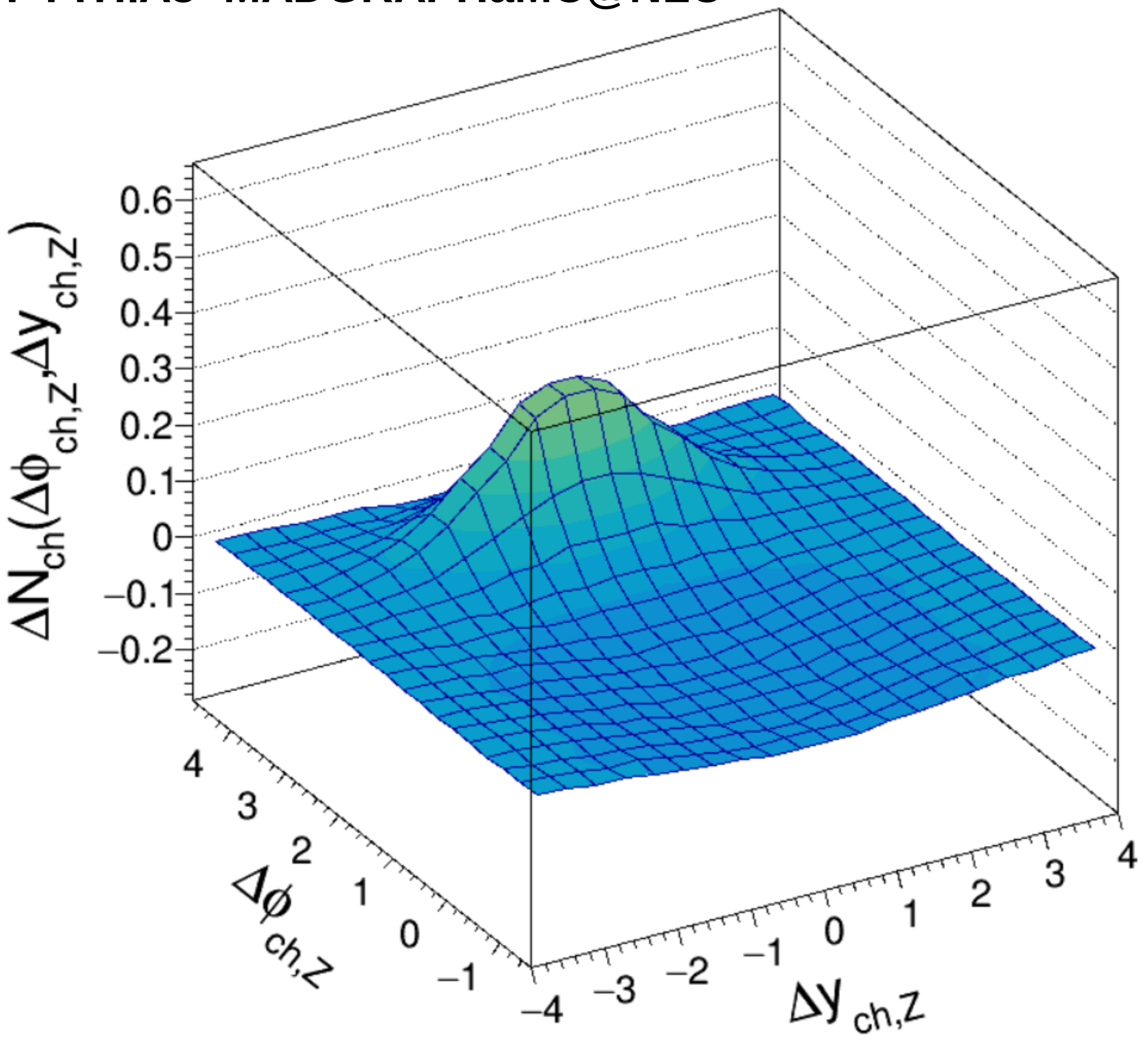


- Mixed event subtraction is also performed in **pp** analysis
- Tight correlation between charged hadron in jet and Z^0 not only in $\Delta\phi$ **but also Δy** due to Z^0 p_T and rapidity selection
- The procedure suppresses the uncorrelated "Multi-Parton Interaction (MPI) ridge" at fixed $\Delta\eta$ (Δy)

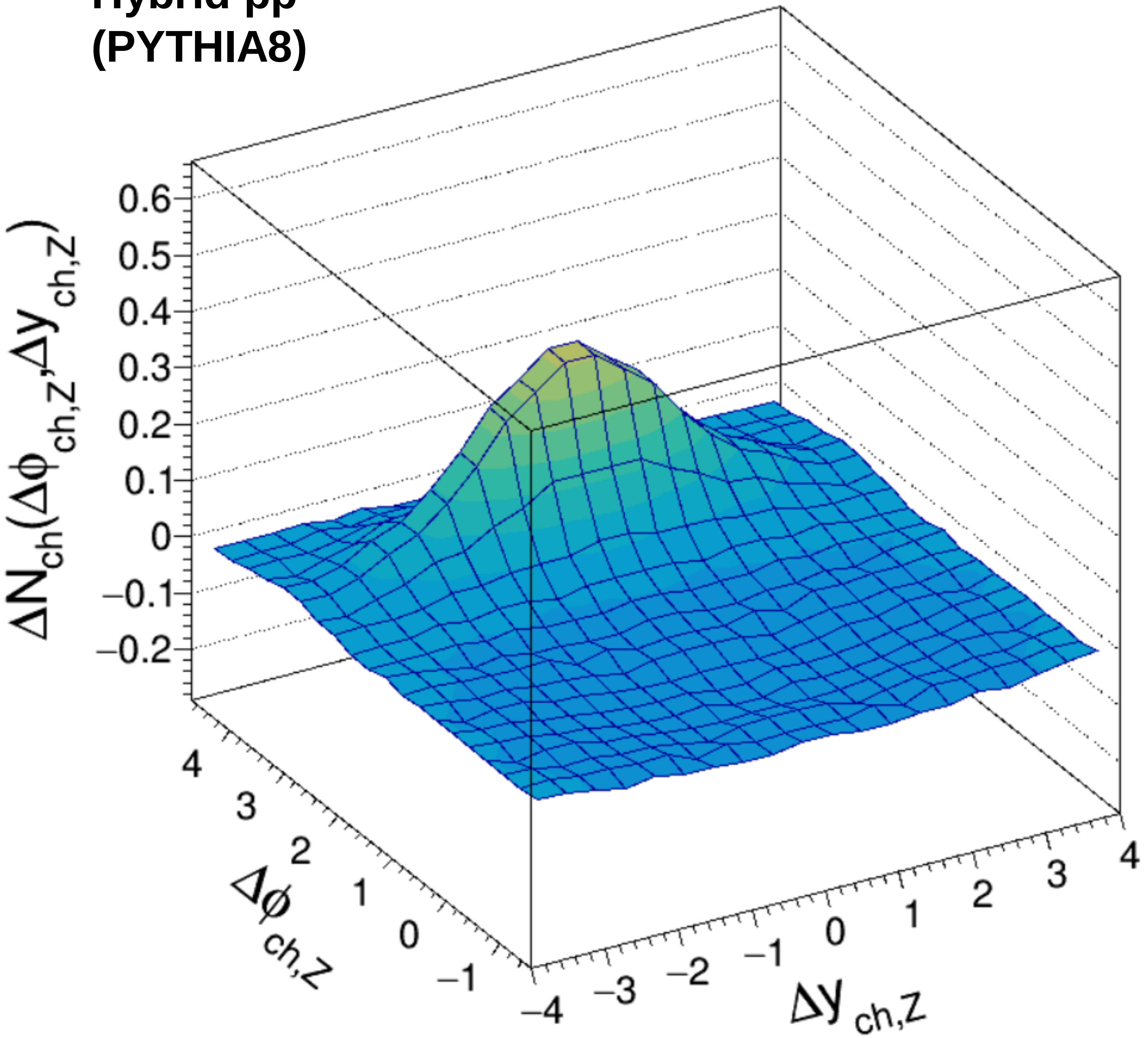


Predictions from Models in pp for Charged Hadron p_T 1-2 GeV

PYTHIA8+MADGRAPHaMC@NLO

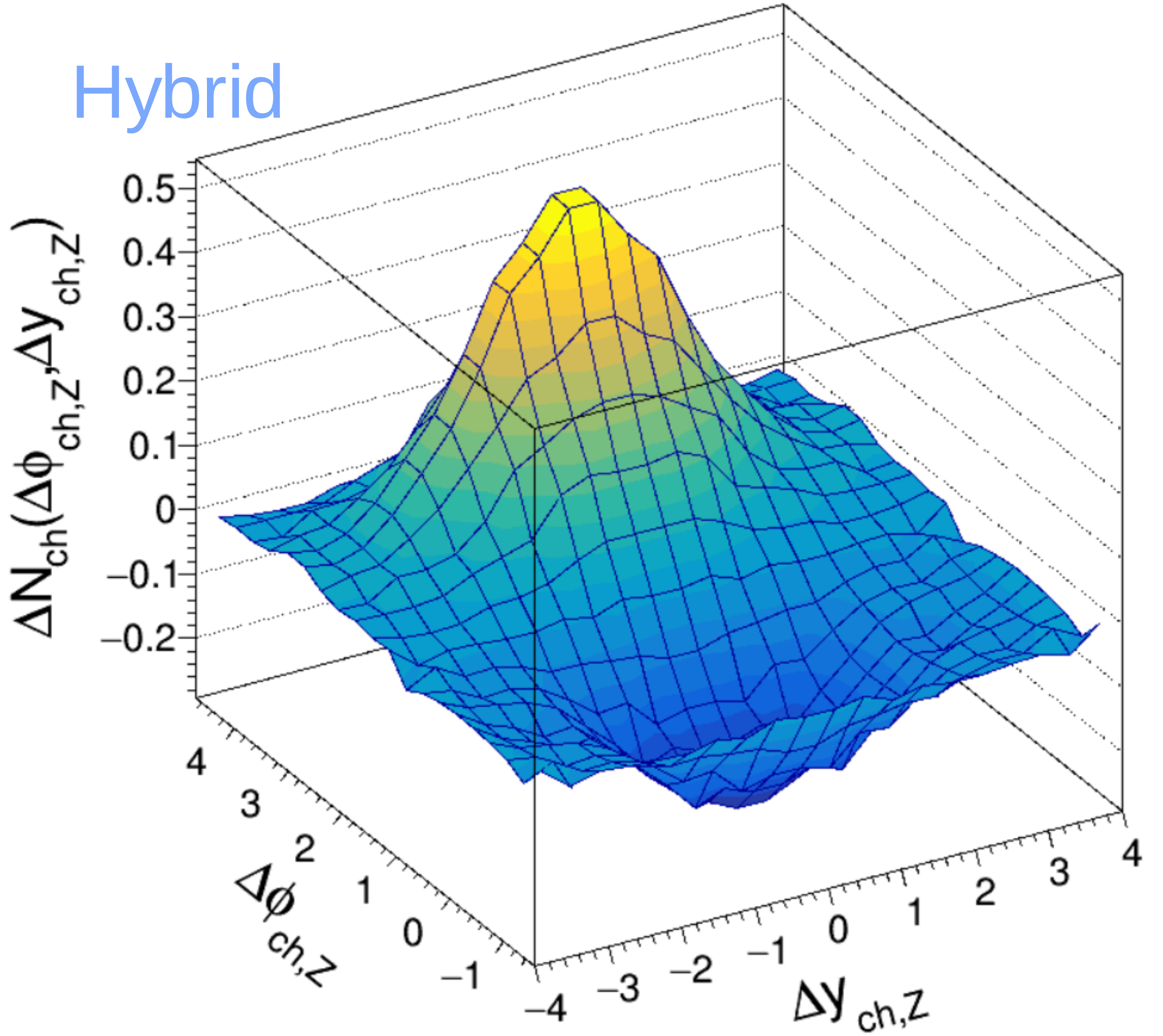


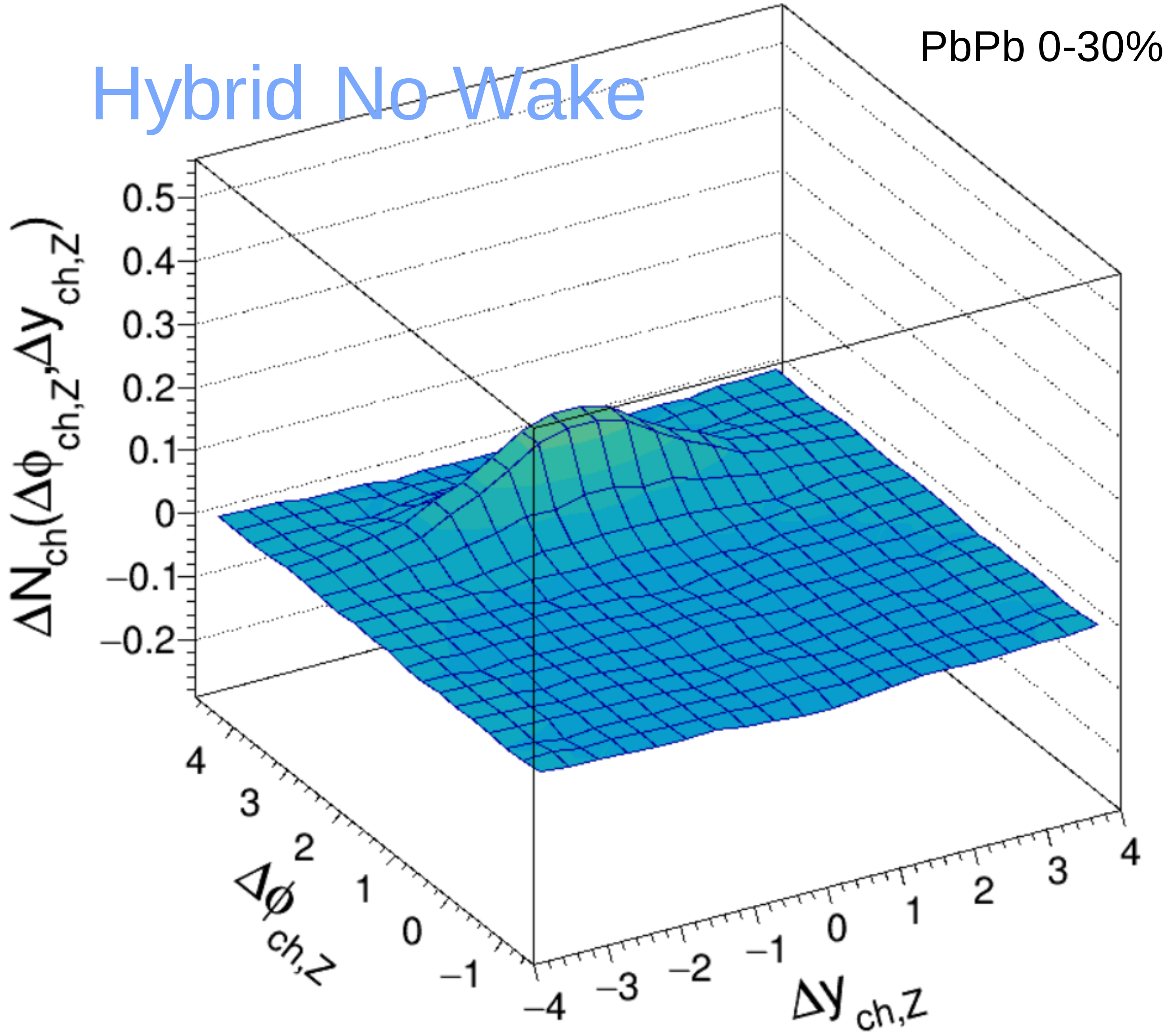
Hybrid pp (PYTHIA8)



- NLO event generator gives a slightly **broader jet peak** than PYTHIA8
- Identical subtraction procedure applied to both MC model results and the data analysis

Predictions from Models for Charged Hadron p_T 1-2 GeV

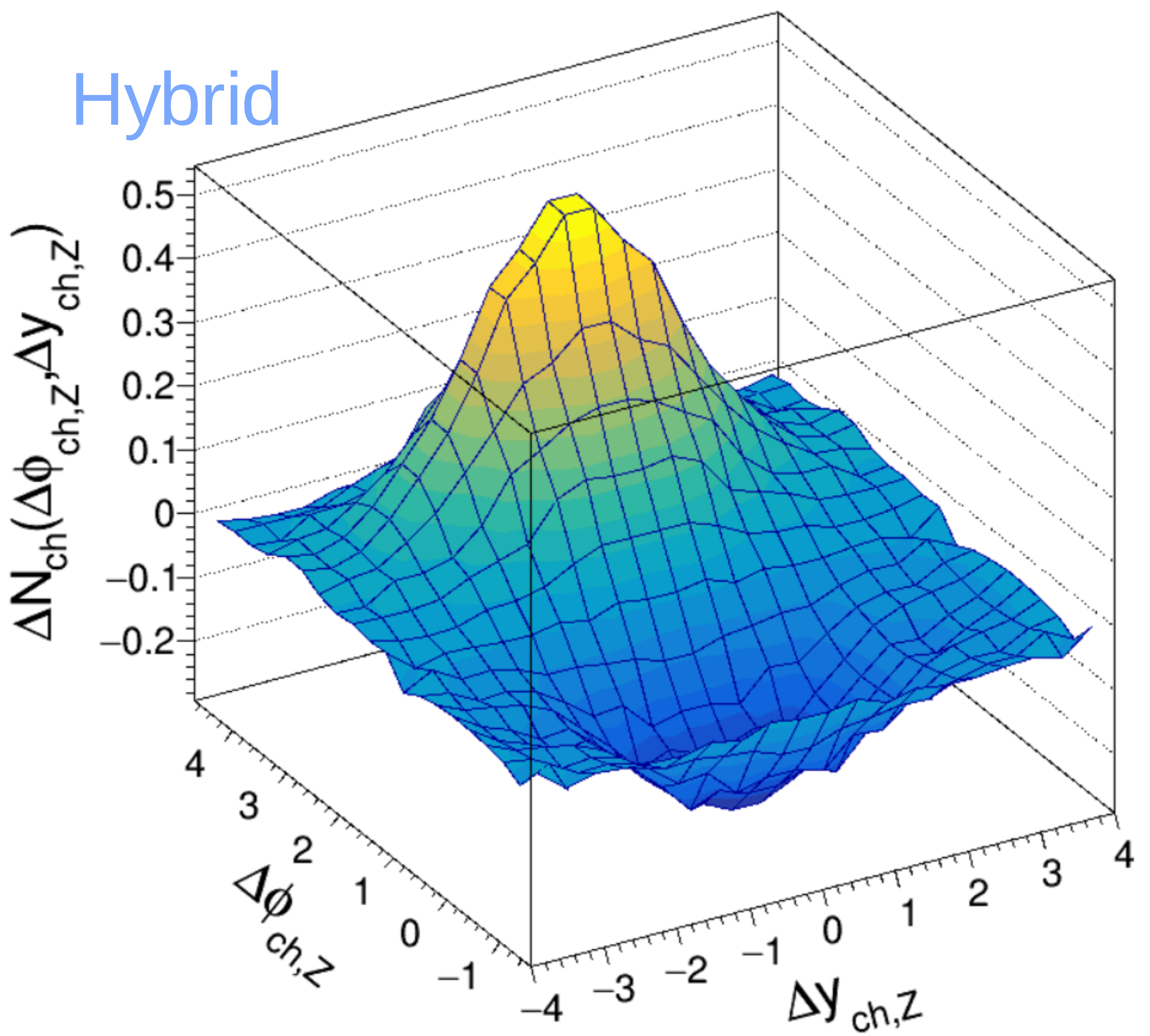




- **Hybrid**: **QGP** wake creates a **Z-side dip structure** and significantly enhance the jet peak (pQCD parton shower + AdS/CFT drag + hydro medium response)

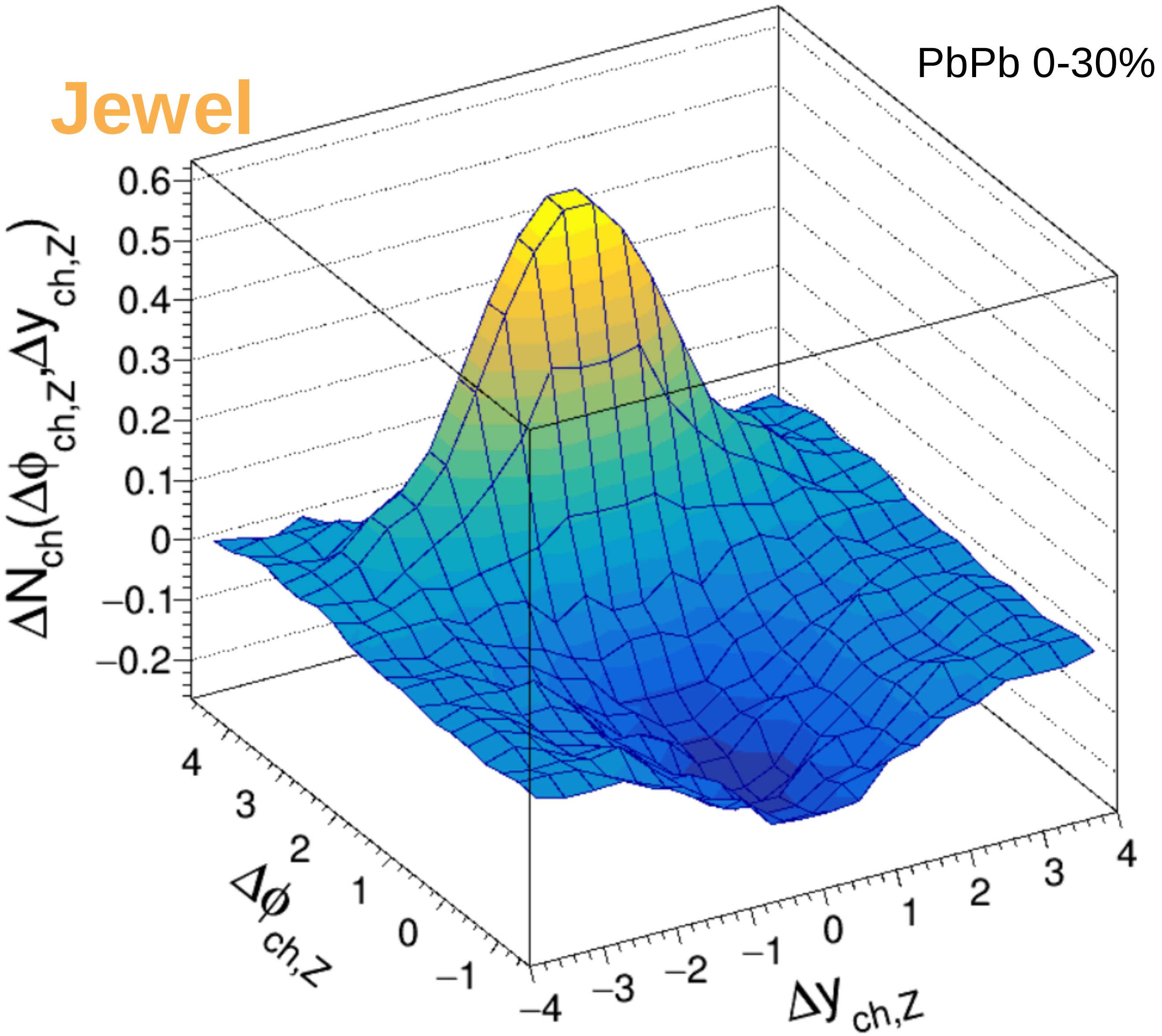
Predictions from Models for Charged Hadron p_T 1-2 GeV

Hybrid



PbPb 0-30%

Jewel

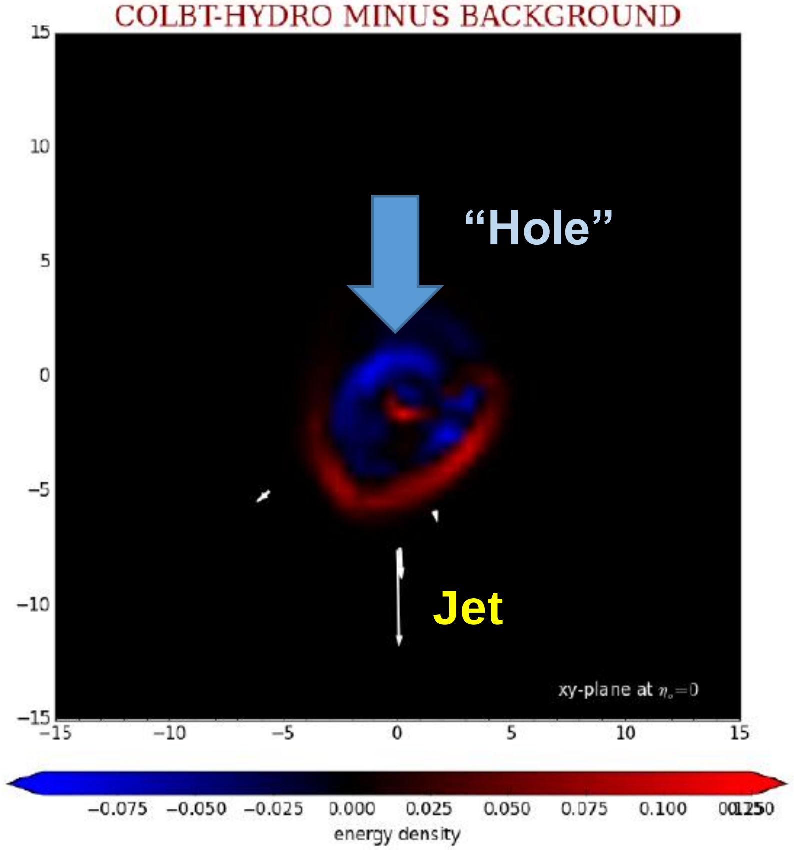


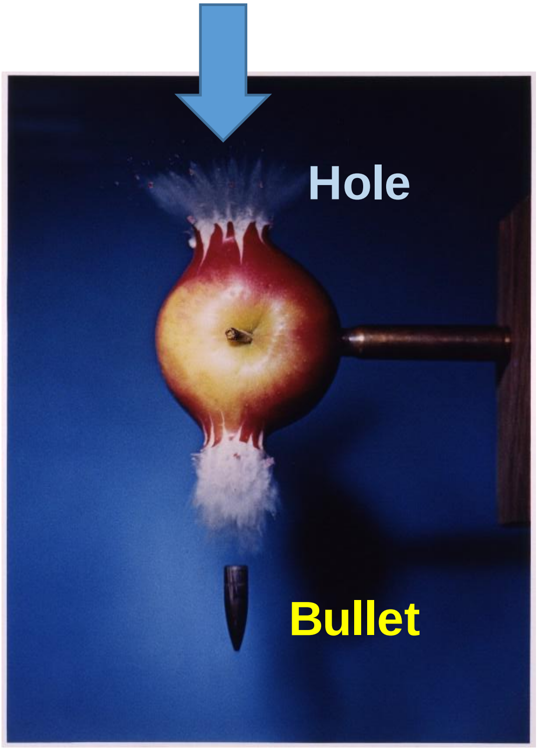
- **Hybrid**: **QGP** wake creates a Z-side dip structure and significantly enhance the jet peak
- **Jewel**: recoil partons are responsible for the effects (pQCD with **no re-scattering**)

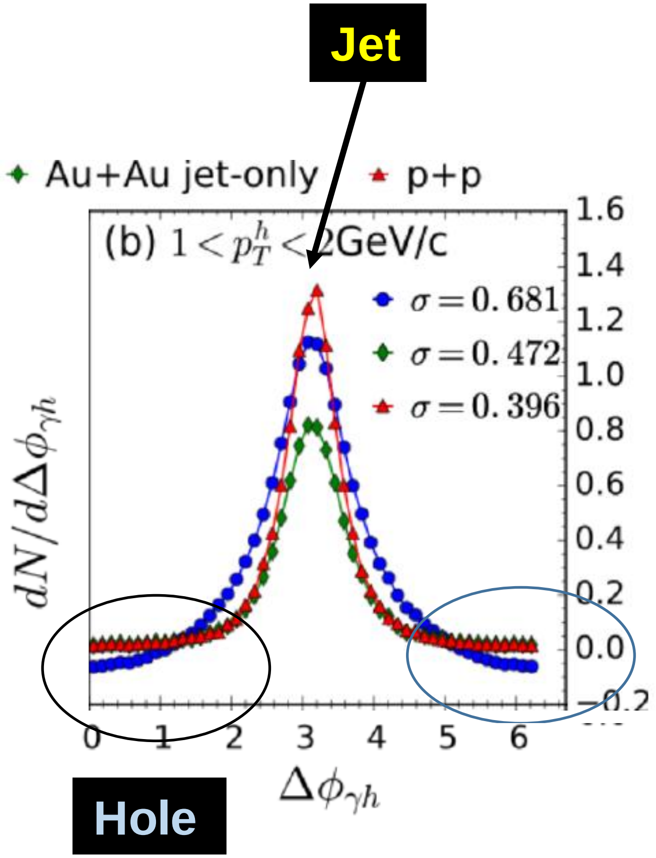
Measure the “Depletion” due to Medium Recoil

CoLBT

Tan Luo, Xin-Nian Wang



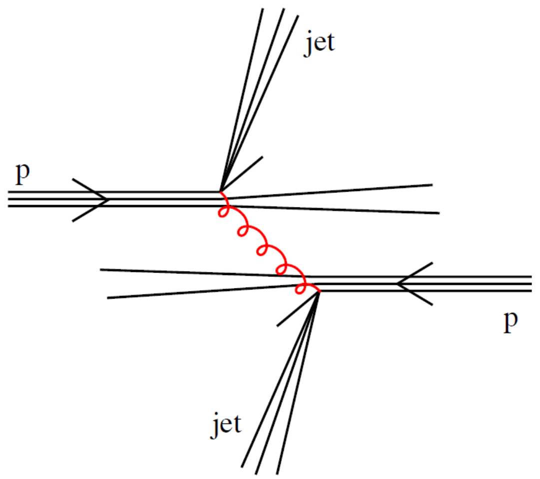




Measure the **boson-side associated yield** with photon-jet and **Z-jet**

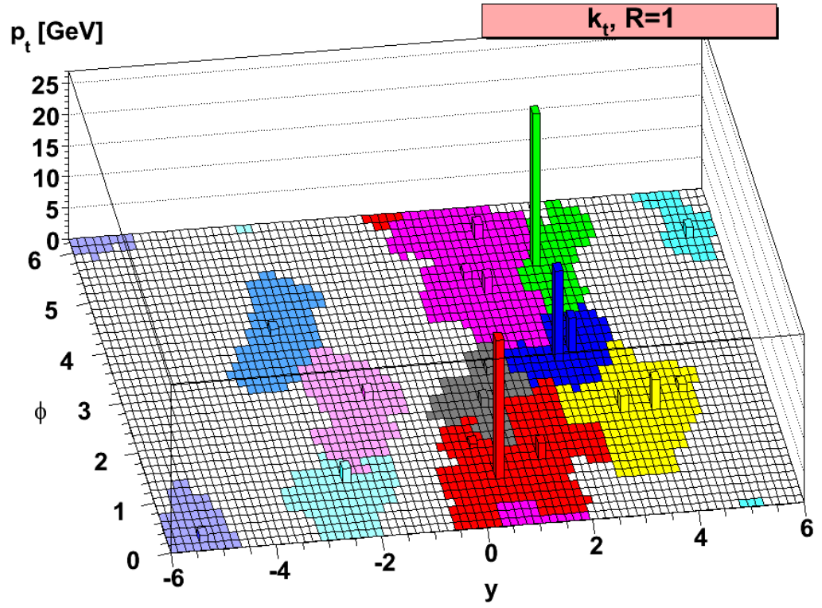
k_T algorithm

From Gavin Salam



$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = p_{ti}^2$$

PP event



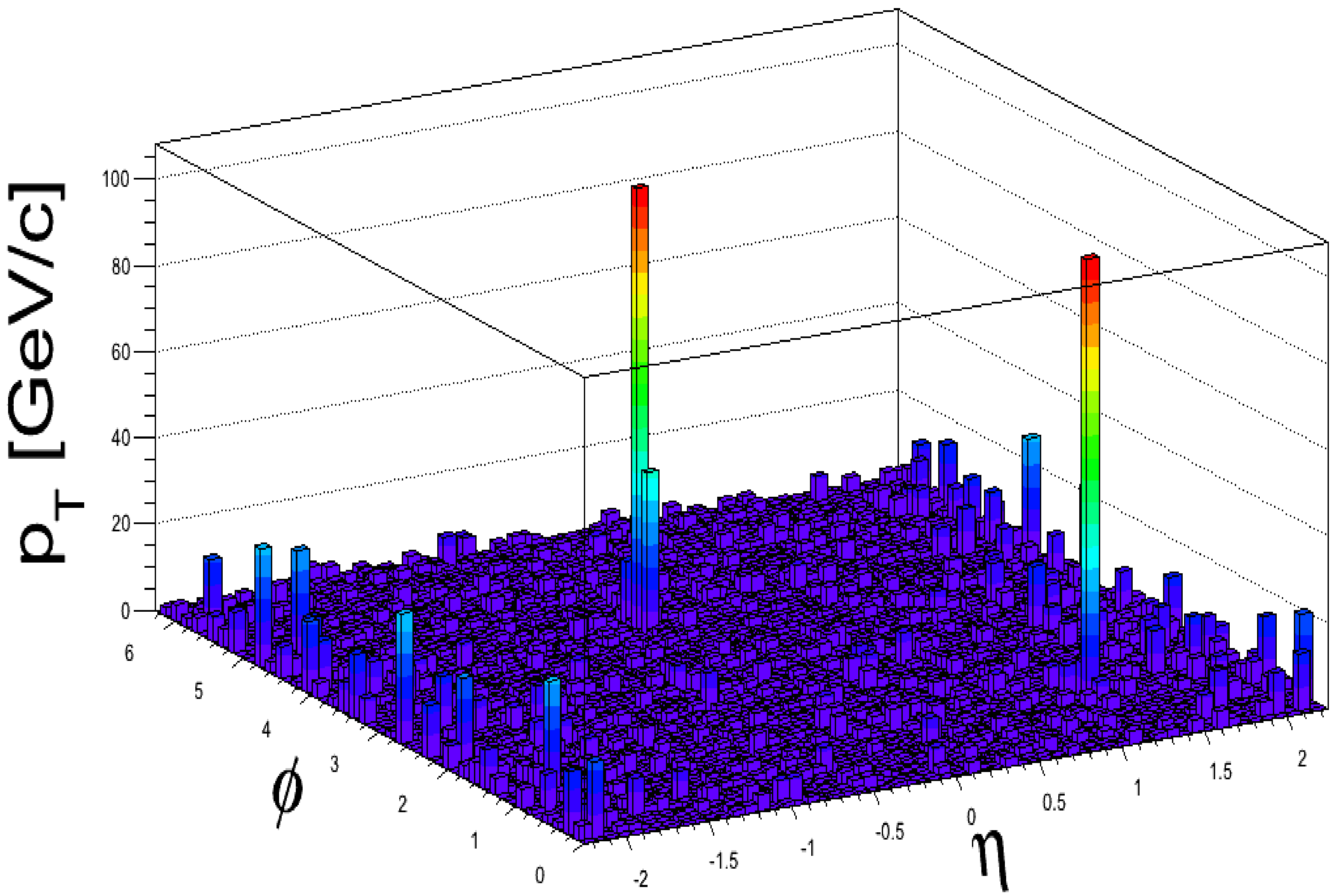
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- 1. Find smallest of d_{ij}, d_{iB}
  2. if ij, recombine them
  3. if iB, call i a jet and remove from list of particles
  4. repeat from step 1 until no particles left.

S.D. Ellis & Soper, '93

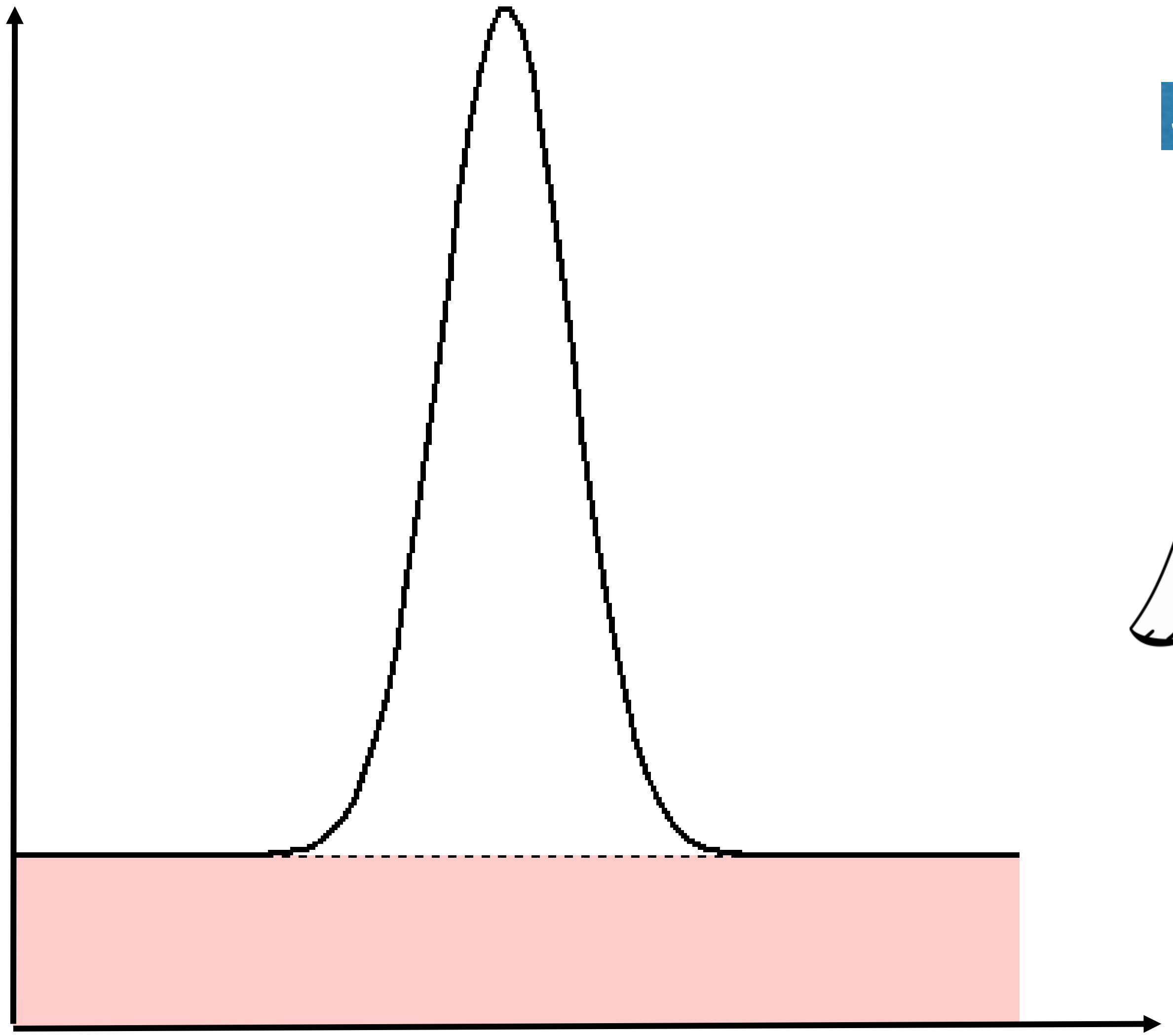
Clustering start from low p_T particles. Clustered shape has irregular shape.
In heavy ion collisions, the large background fluctuation could affect the clustering more

A jet event in CMS



Background changes with η due to particle density and detector geometry

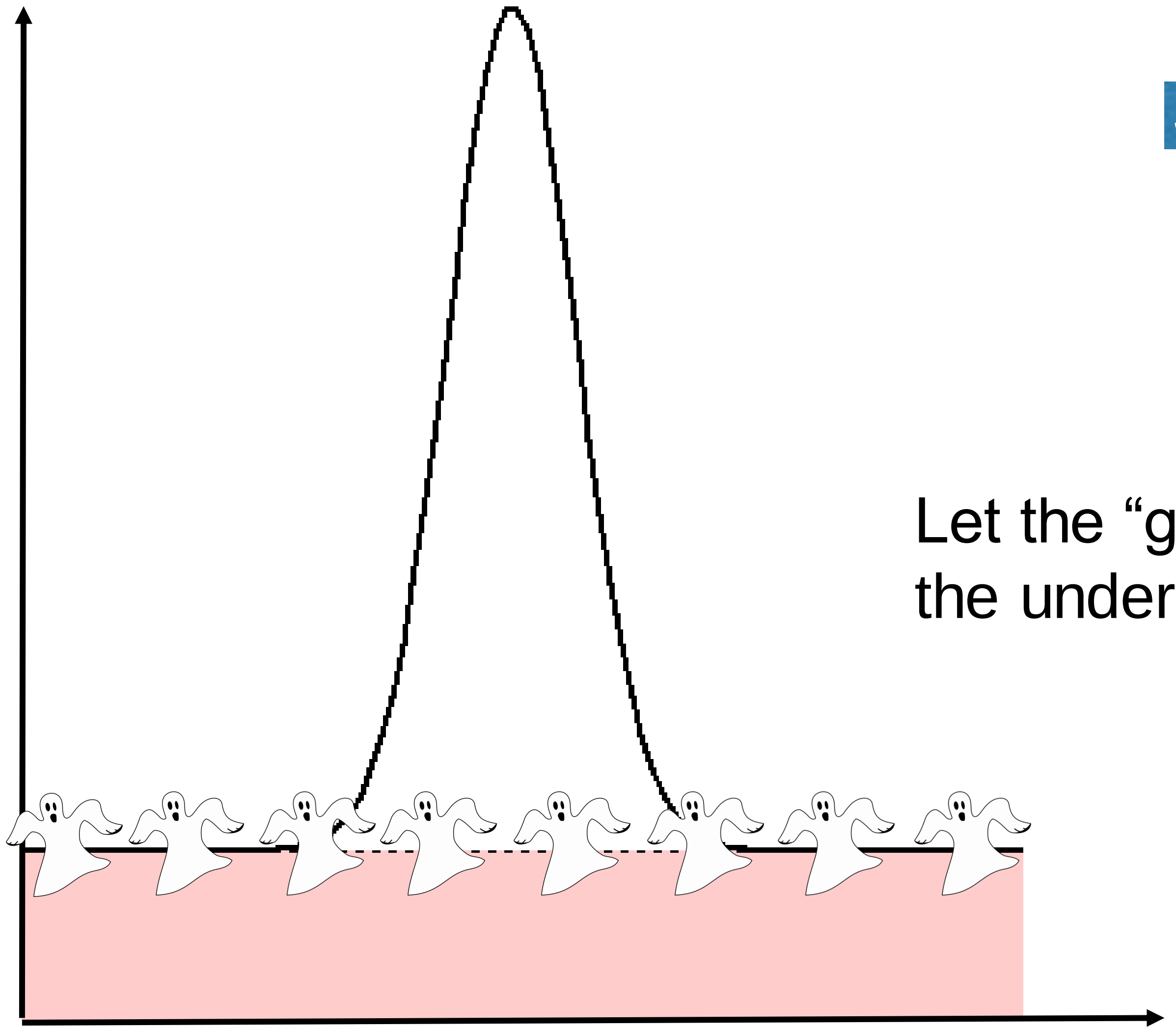
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction

Constituent Subtraction

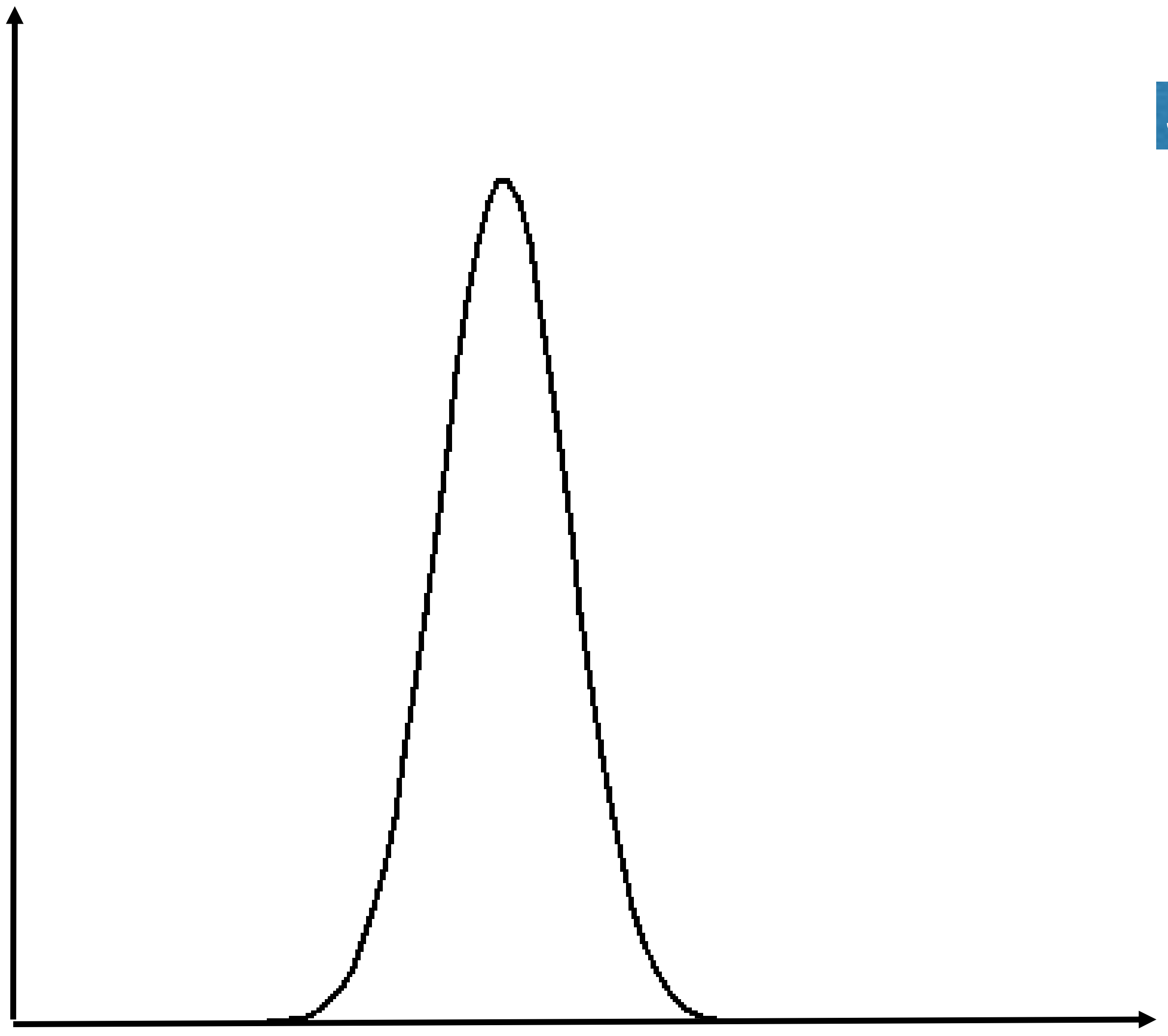


JHEP06 (2014) 092

Let the “ghost” remove the underlying event

Constituent subtraction

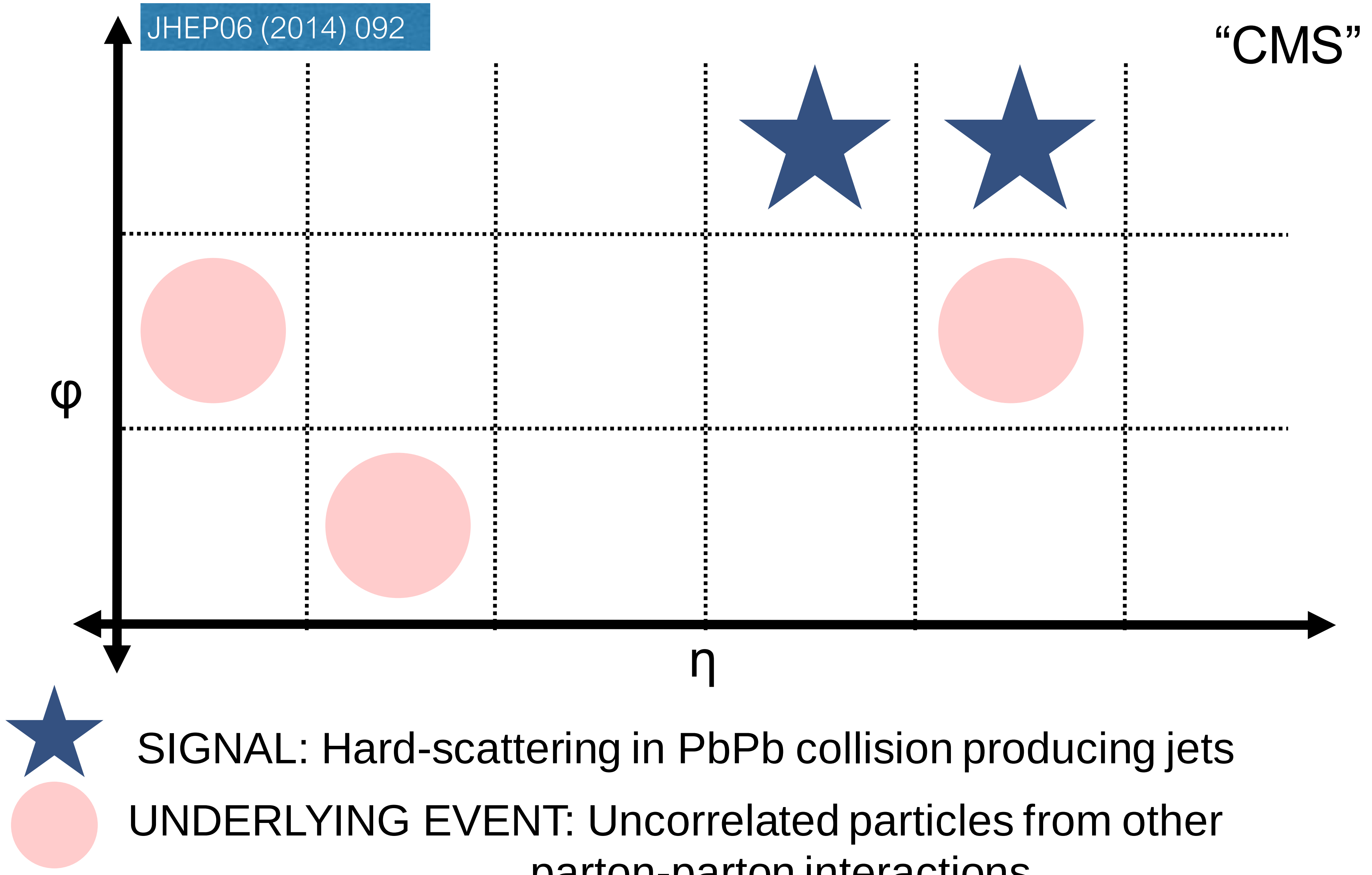
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction

Constituent Subtraction

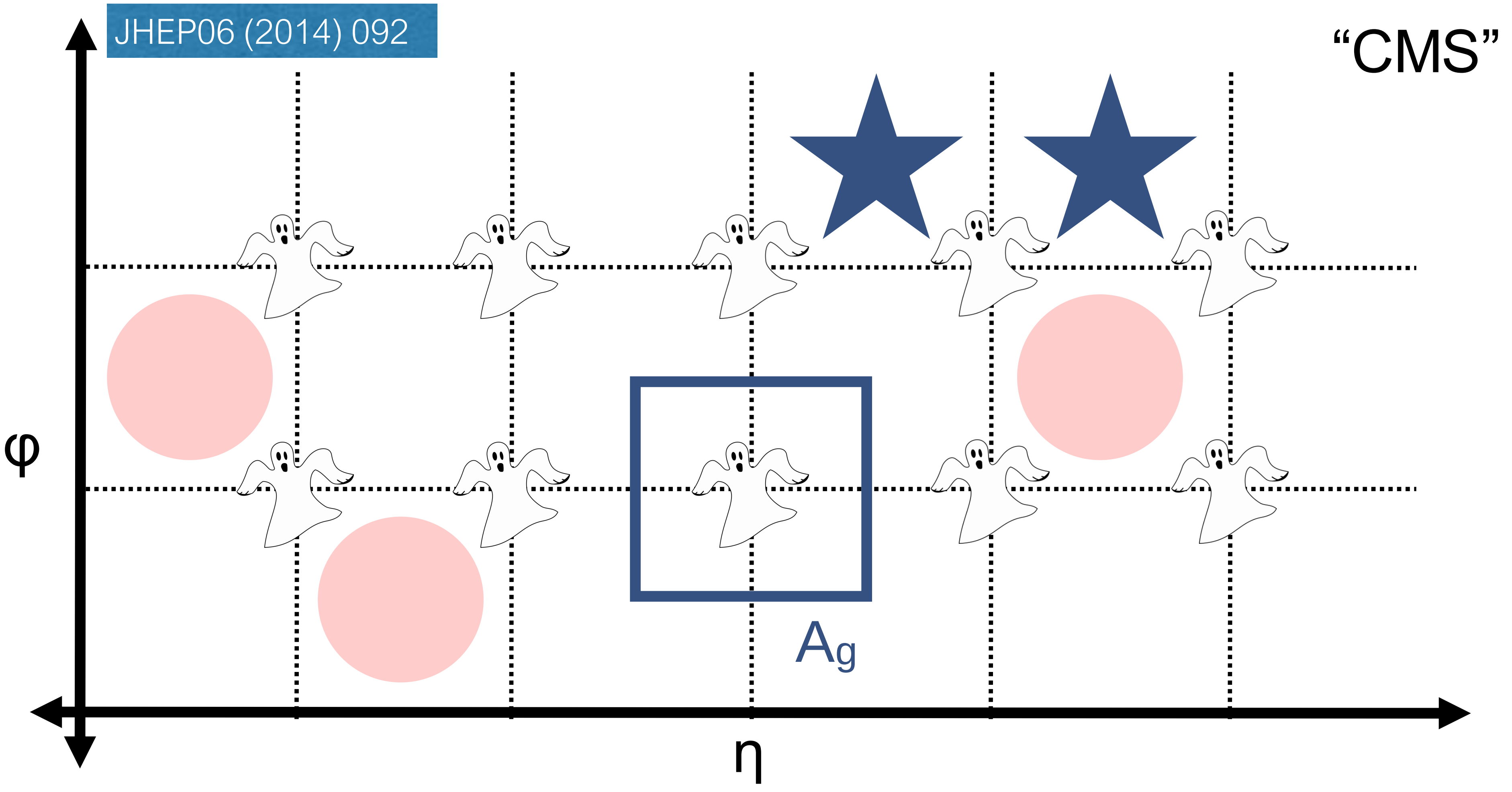


SIGNAL: Hard-scattering in PbPb collision producing jets

UNDERLYING EVENT: Uncorrelated particles from other parton-parton interactions

From Chris McGinn (MIT)

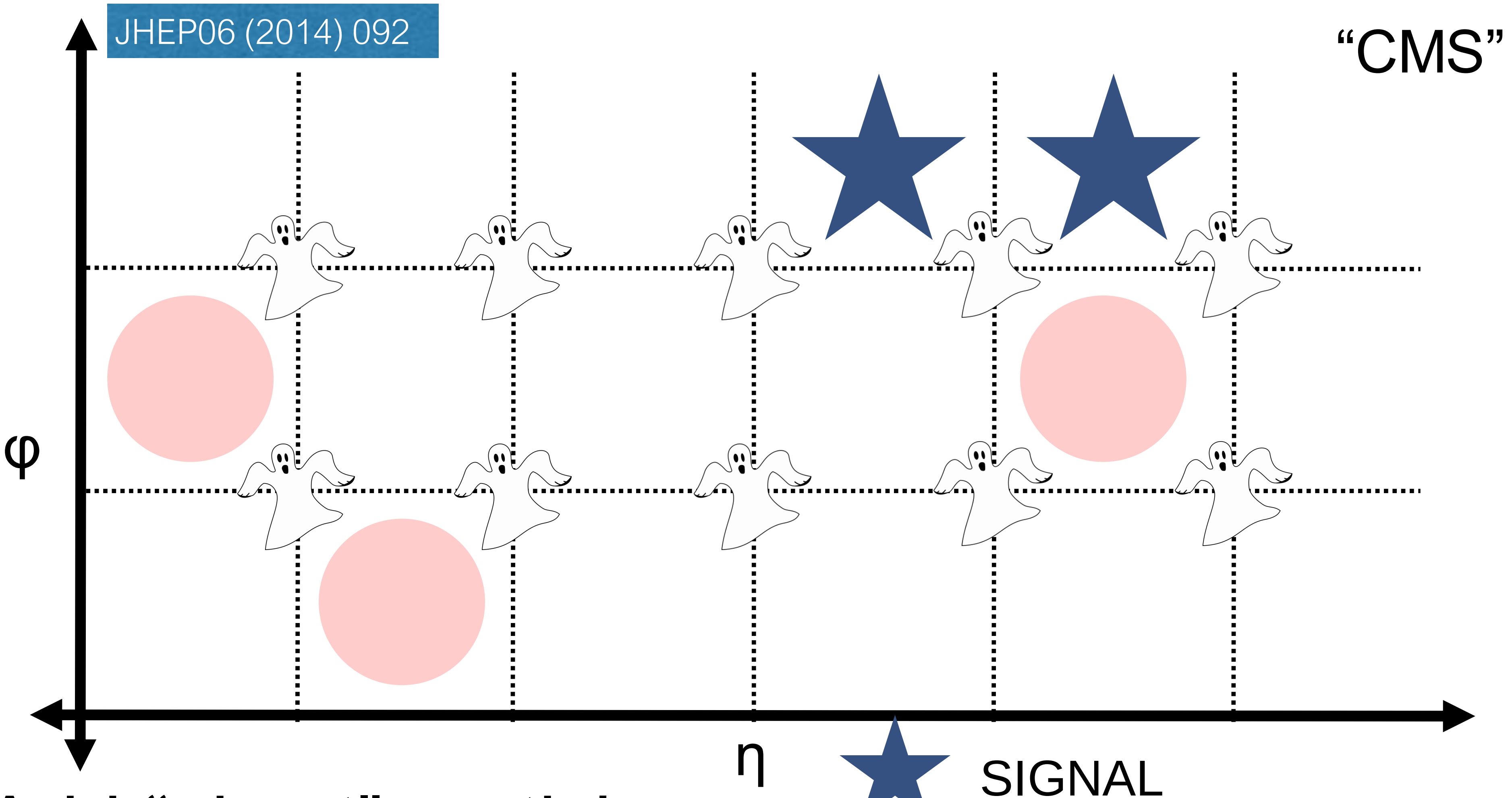
Constituent Subtraction

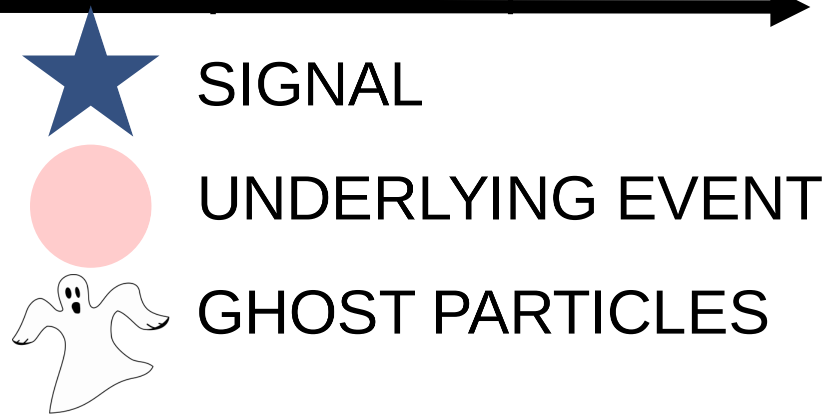


GHOST PARTICLES: Artificial particles added to the event on an η-φ grid. Ghosts are given a p_T according to ρ times the area the inhabit, A_g

From Chris McGinn (MIT)

Constituent Subtraction





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

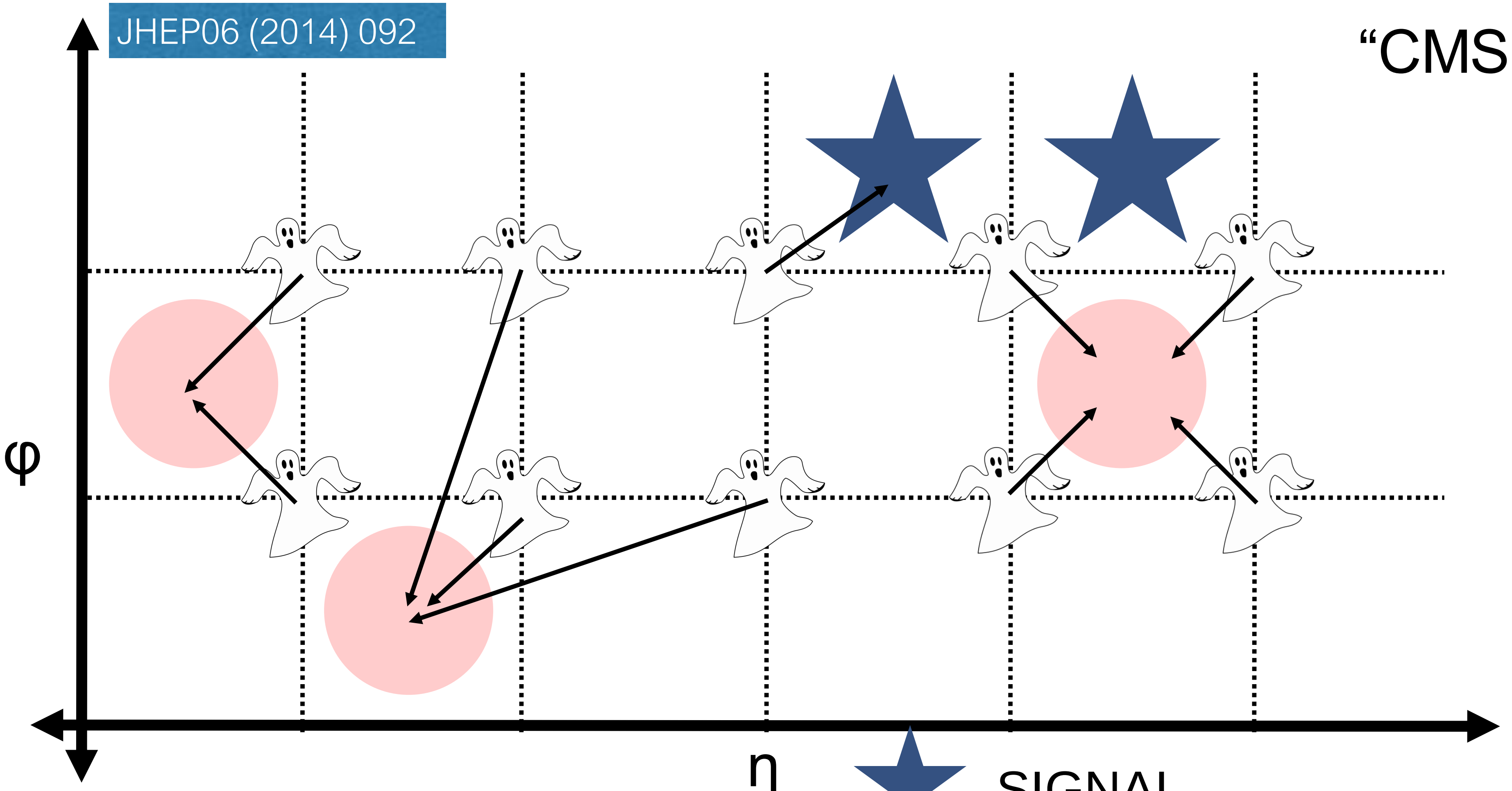
$$p_{\mathrm{T}}^{g} = A_g \cdot \rho,$$

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

Constituent Subtraction

JHEP06 (2014) 092

"CMS"



- Combine iteratively with real particles by minimizing metric:

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

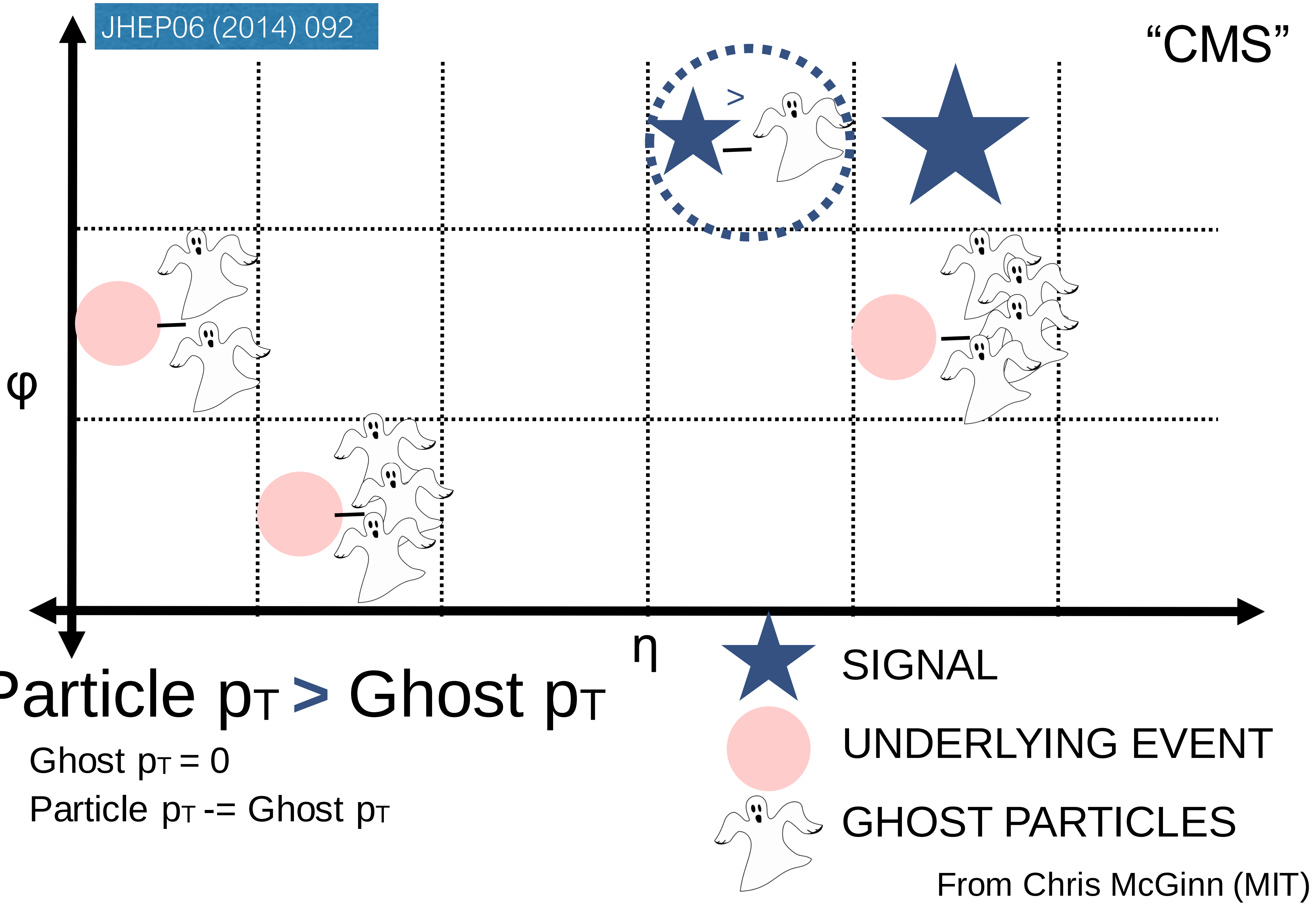
SIGNAL

UNDERLYING EVENT

GHOST PARTICLES

From Chris McGinn (MIT)

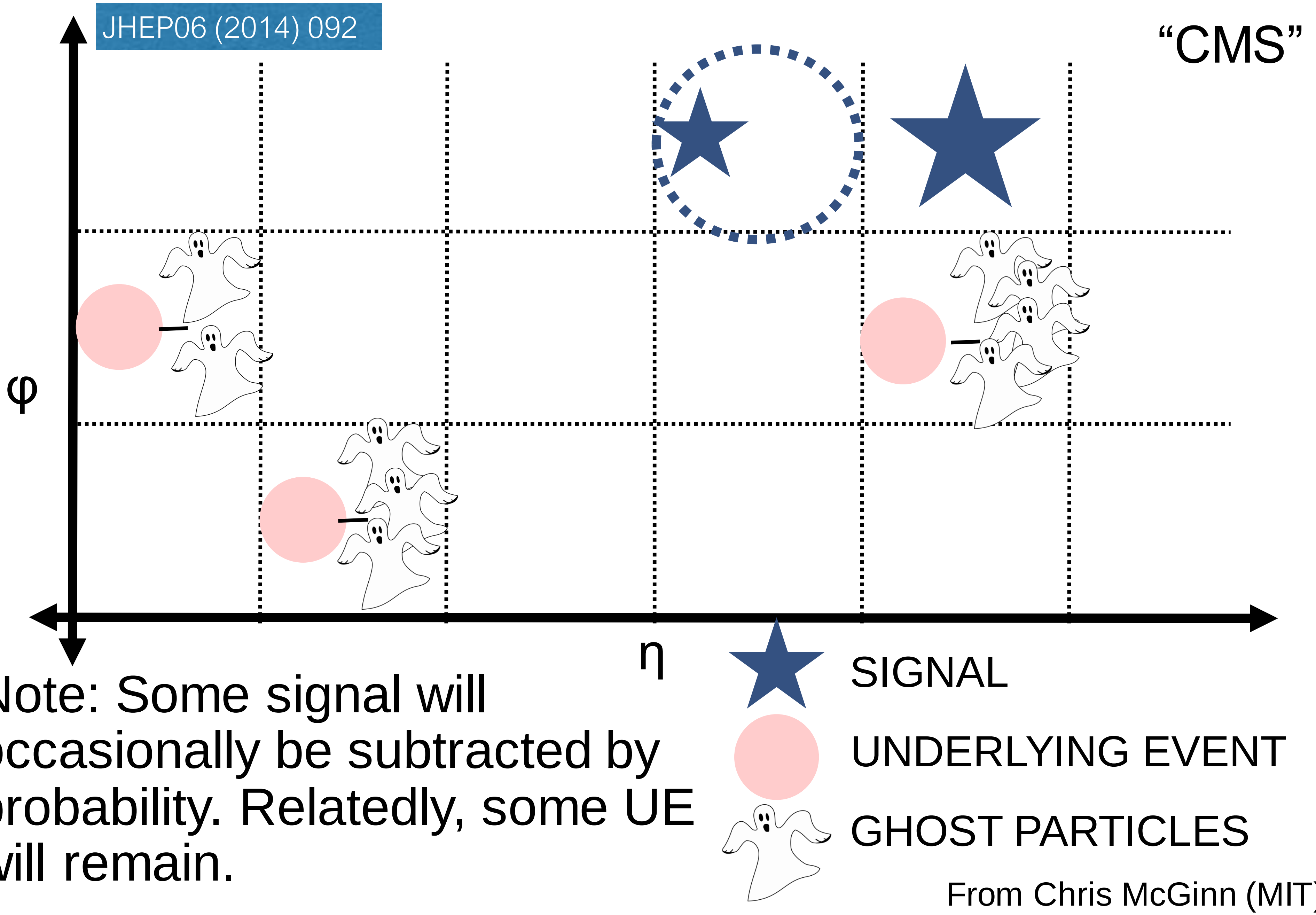
Constituent Subtraction



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

From Chris McGinn (MIT)

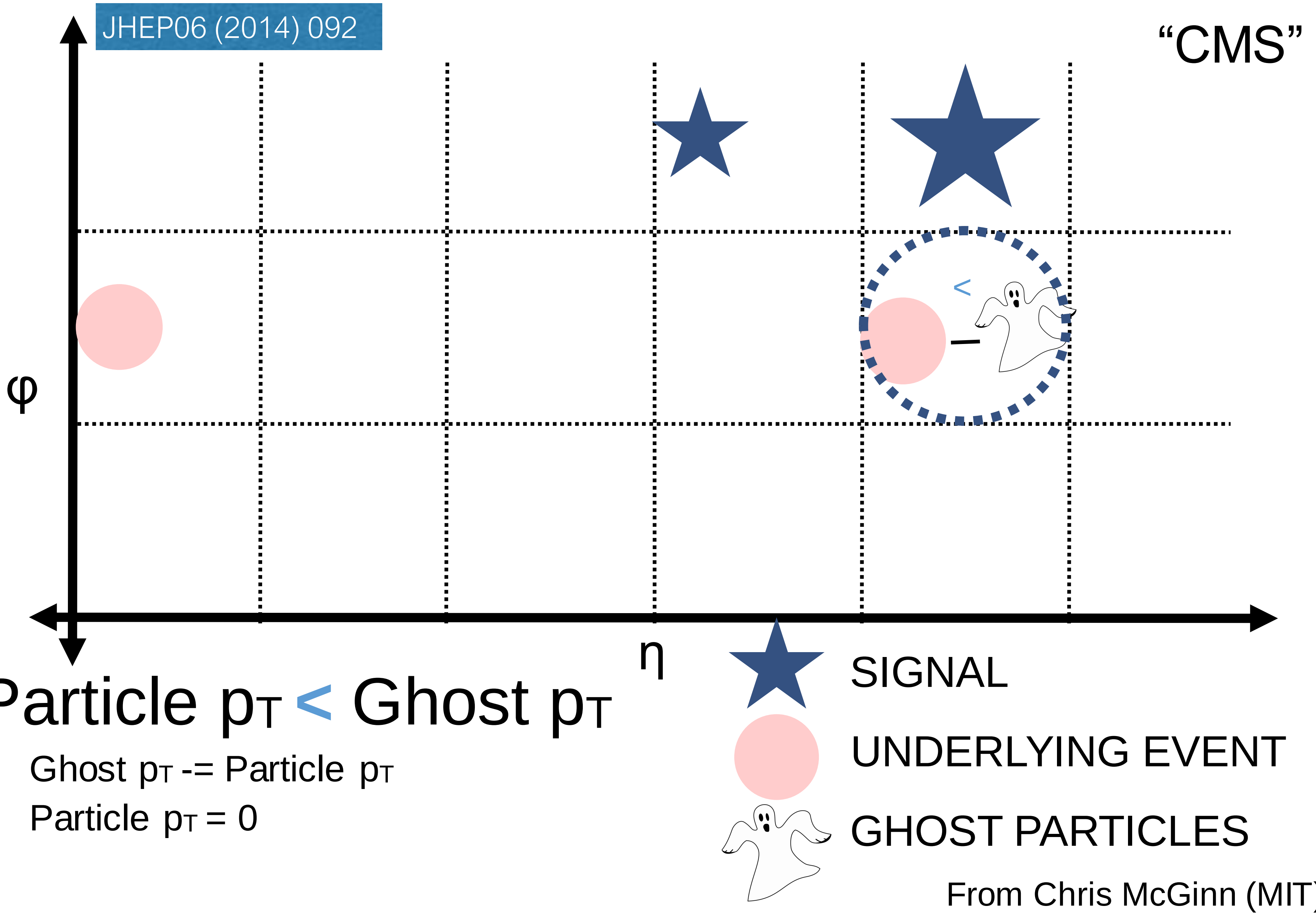
Constituent Subtraction



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

From Chris McGinn (MIT)

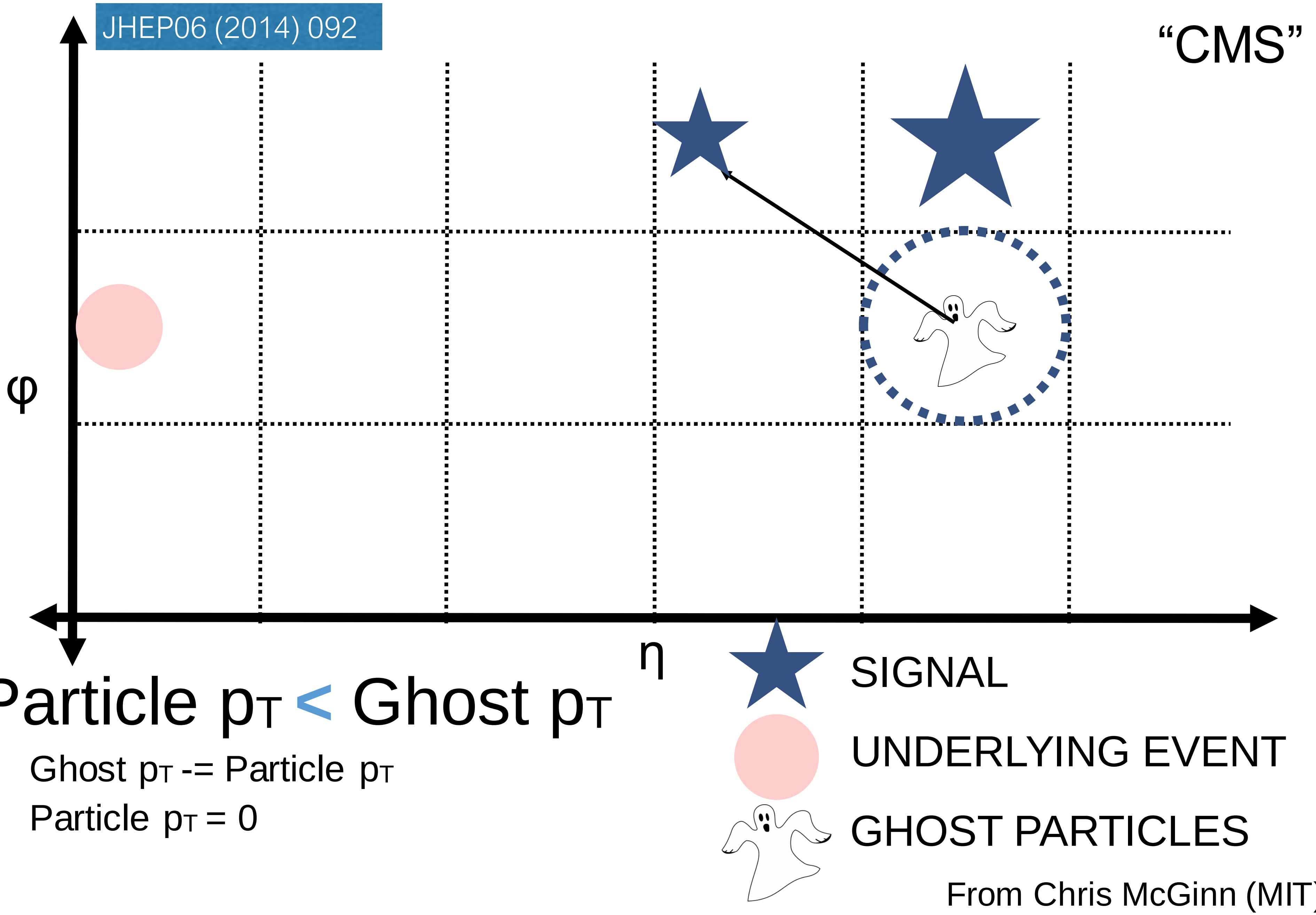
Constituent Subtraction



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

From Chris McGinn (MIT)

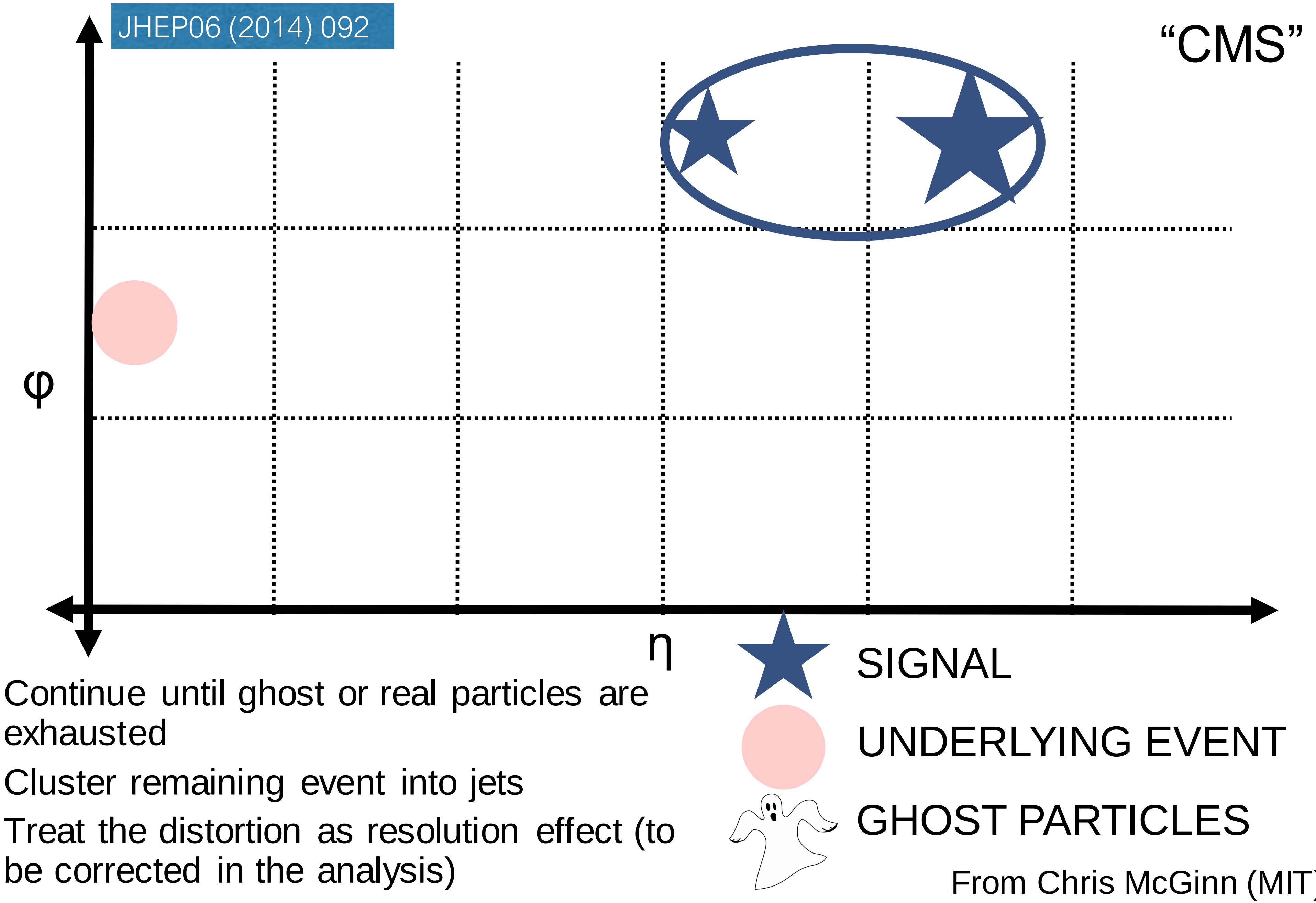
Constituent Subtraction



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

From Chris McGinn (MIT)

Constituent Subtraction

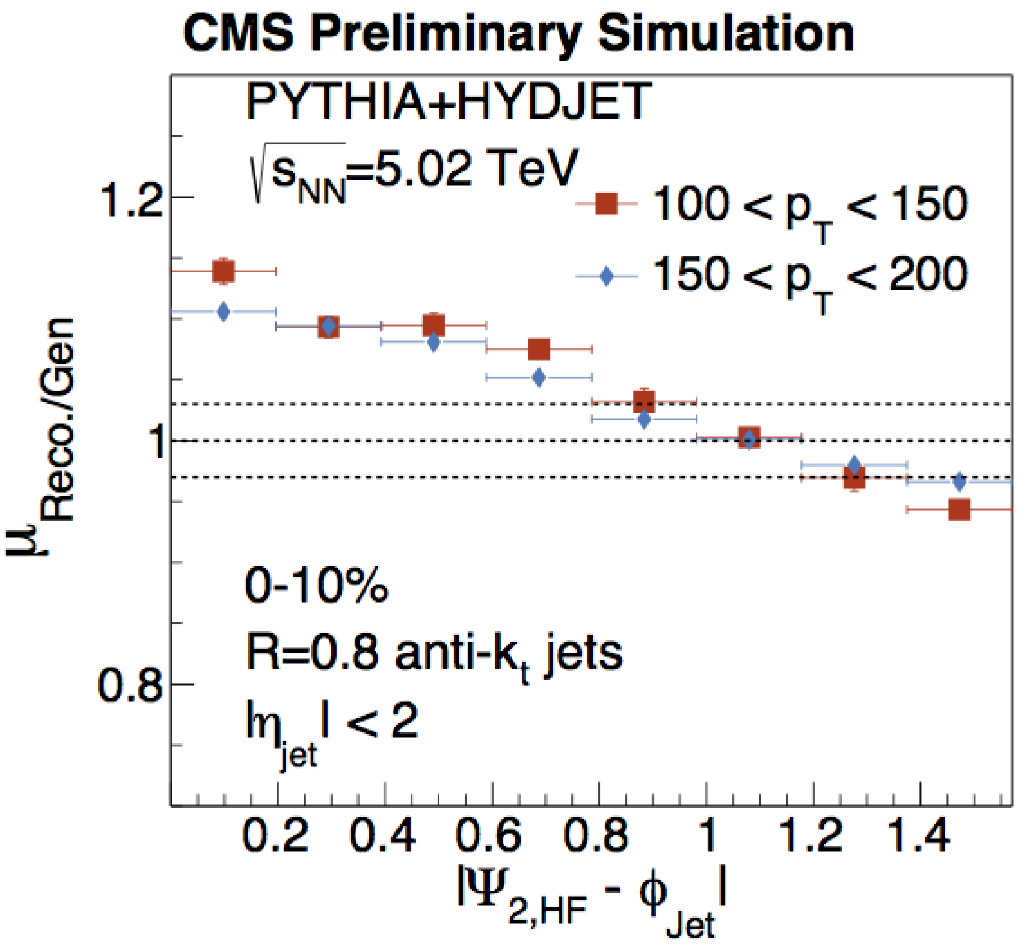


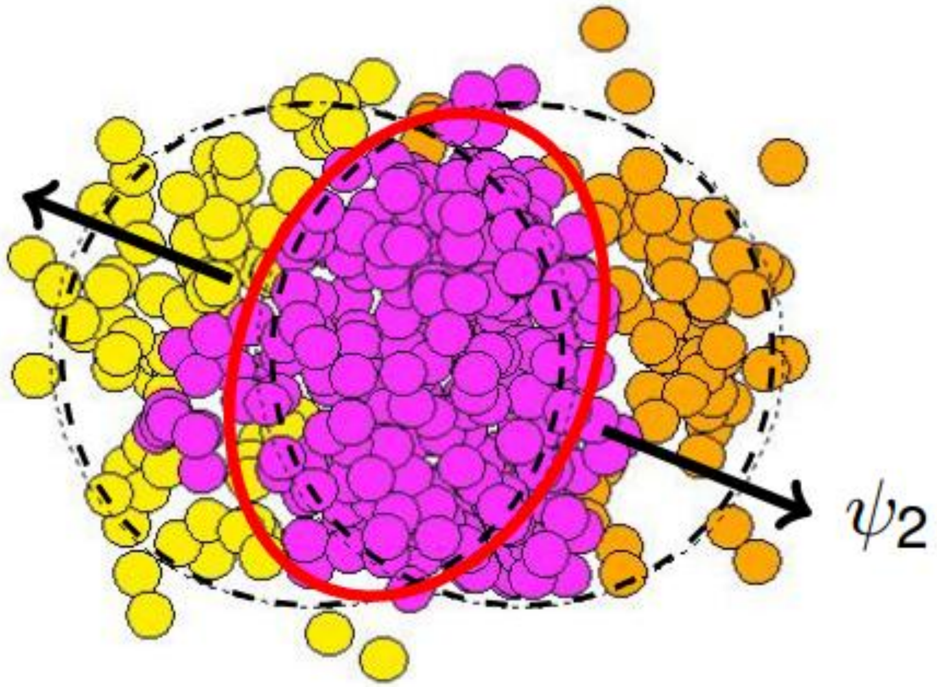
- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets
- Treat the distortion as resolution effect (to be corrected in the analysis)

From Chris McGinn (MIT)

Dependence on the Azimuthal Angle

“Jet response” vs. azimuthal angle
μ=1: perfectly subtracted

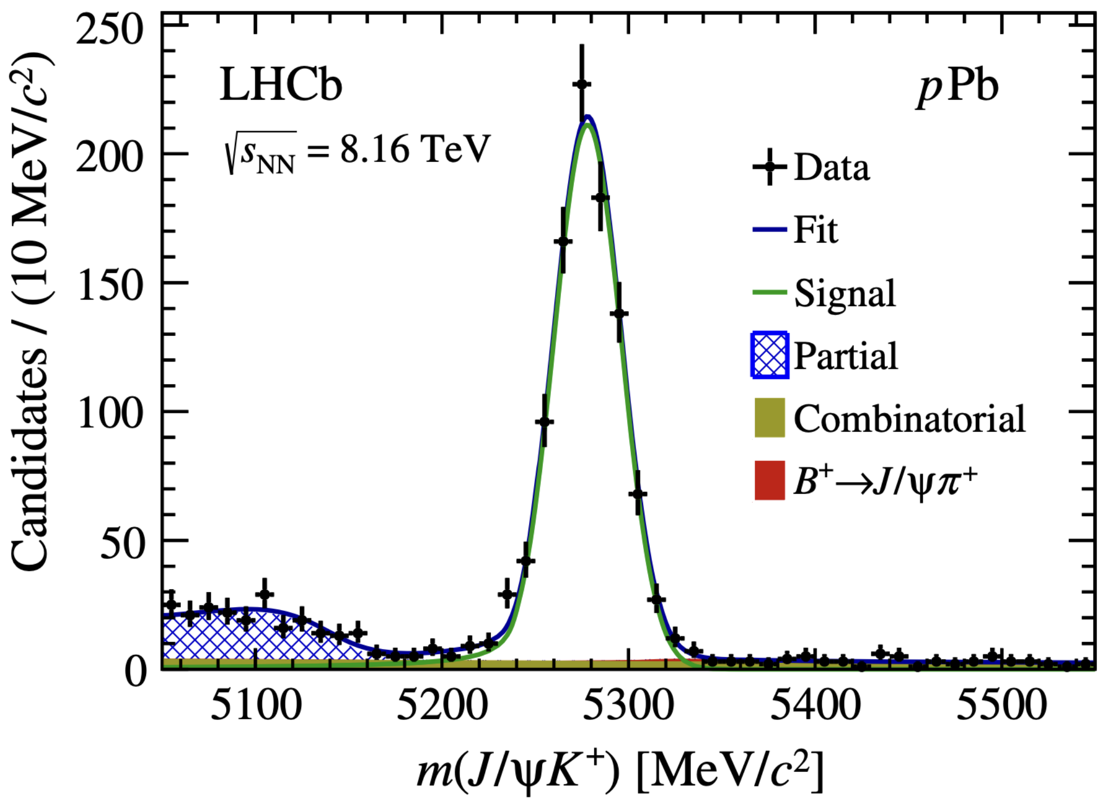




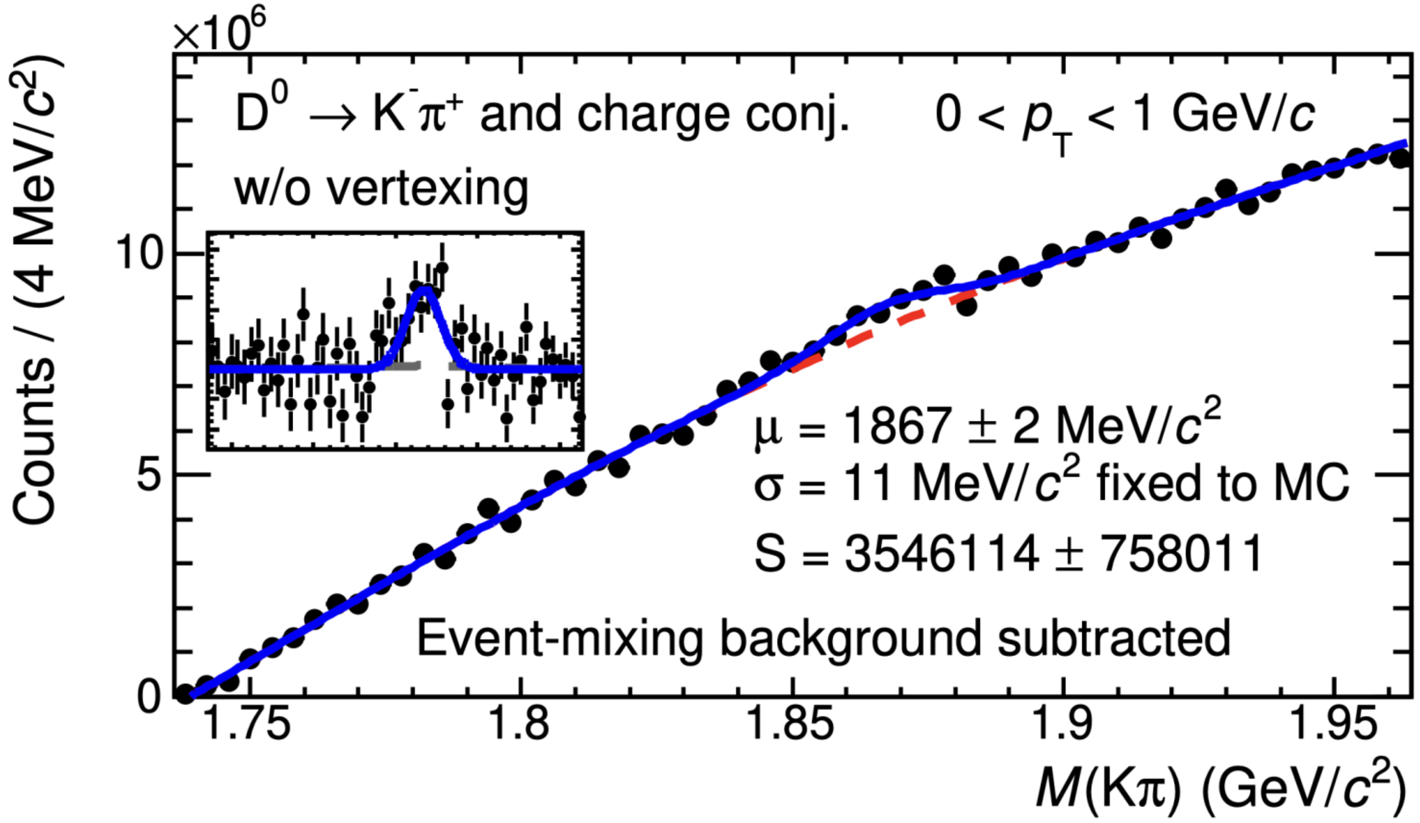
Large dependence on the azimuthal angle with respect to the event plane

Invariant Mass Fit Extension

[PRD 99 (2019) 052011]



[JHEP 01 (2022) 174]

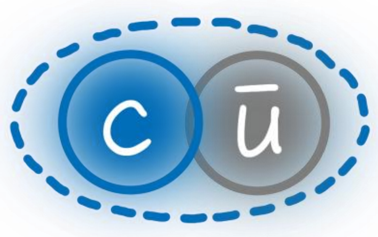


- What peaking backgrounds for $B^+ \to J/\psi K^+$?
- What functions are used to model each component?

- What is the event-mixing technique used to achieve measurements down to 0 p_T by ALICE

Heavy Flavor Hadron Detection

Charm

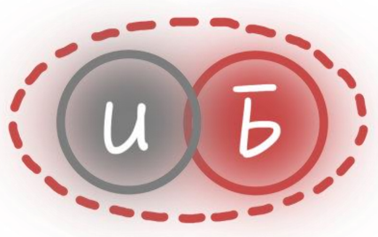


D^0 ($c \to D^0 \sim O(50\%)$)

Mass 1.865 GeV

$c\tau \sim$ 120 μm

Beauty

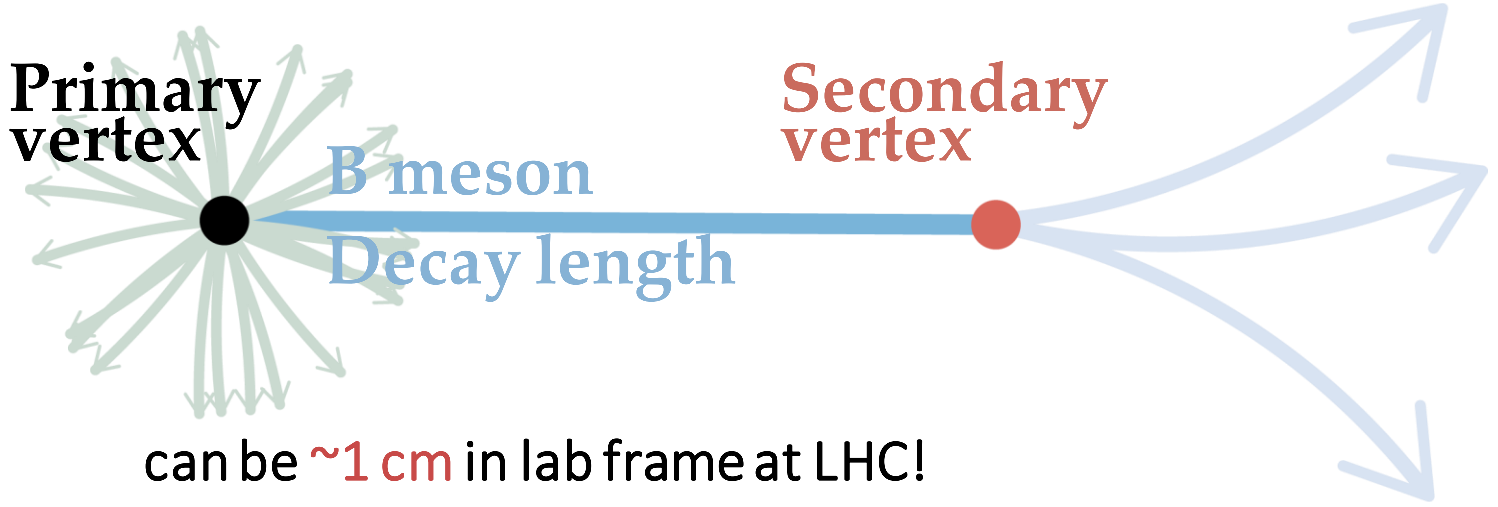


B^+ ($b \to B^+ \sim O(40\%)$)

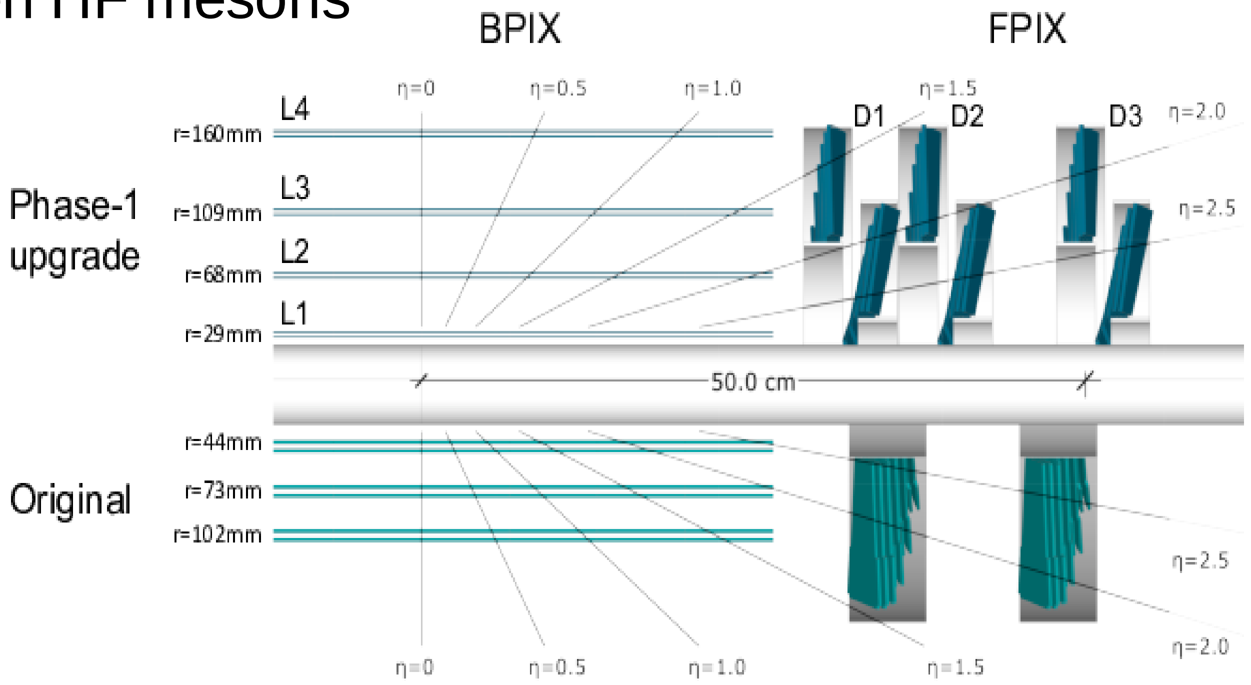
Mass 5.279 GeV

$c\tau \sim$ 490 μm

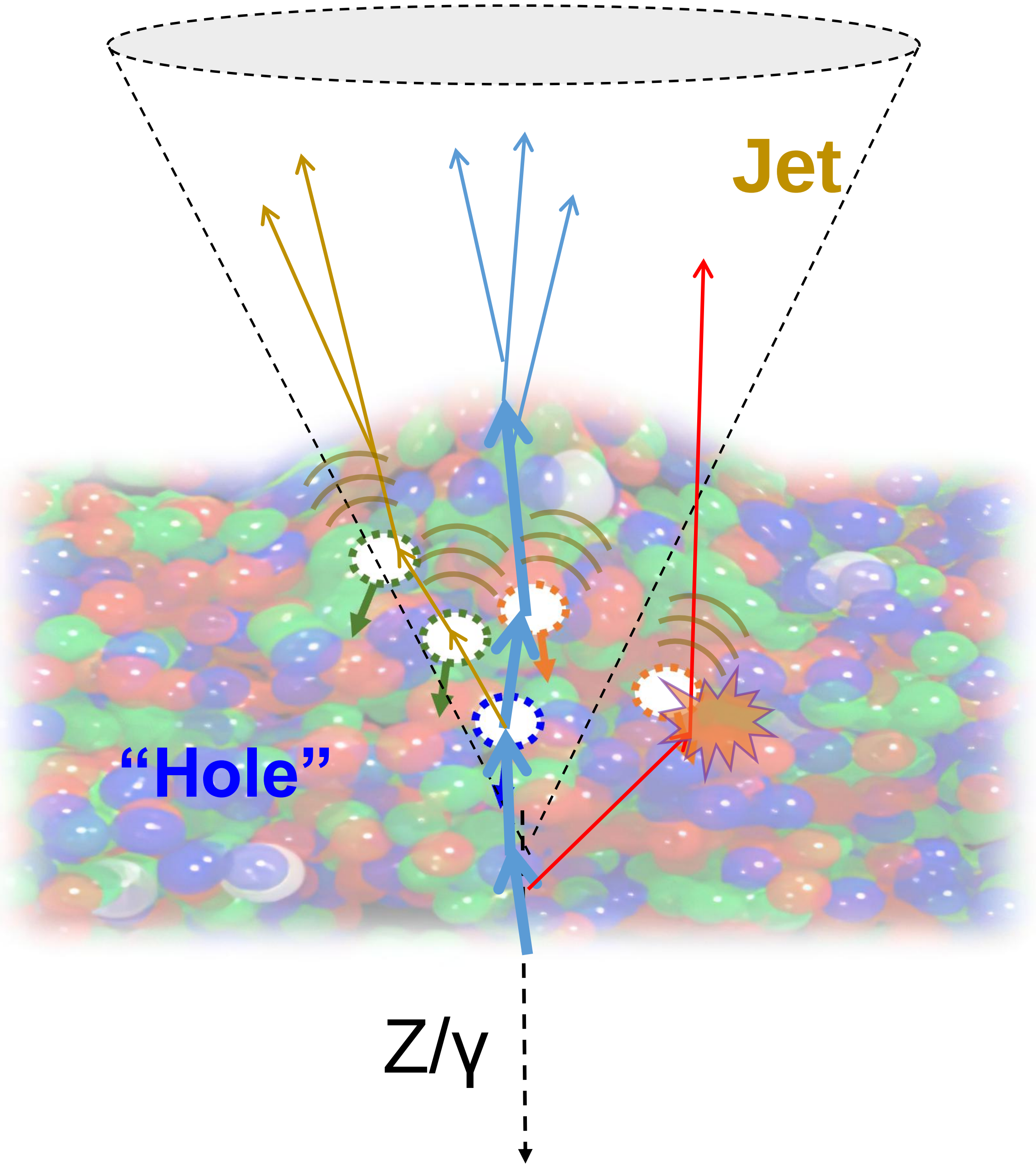
Displaced secondary vertex is an experiment signature of open HF mesons



can be ~1 cm in lab frame at LHC!

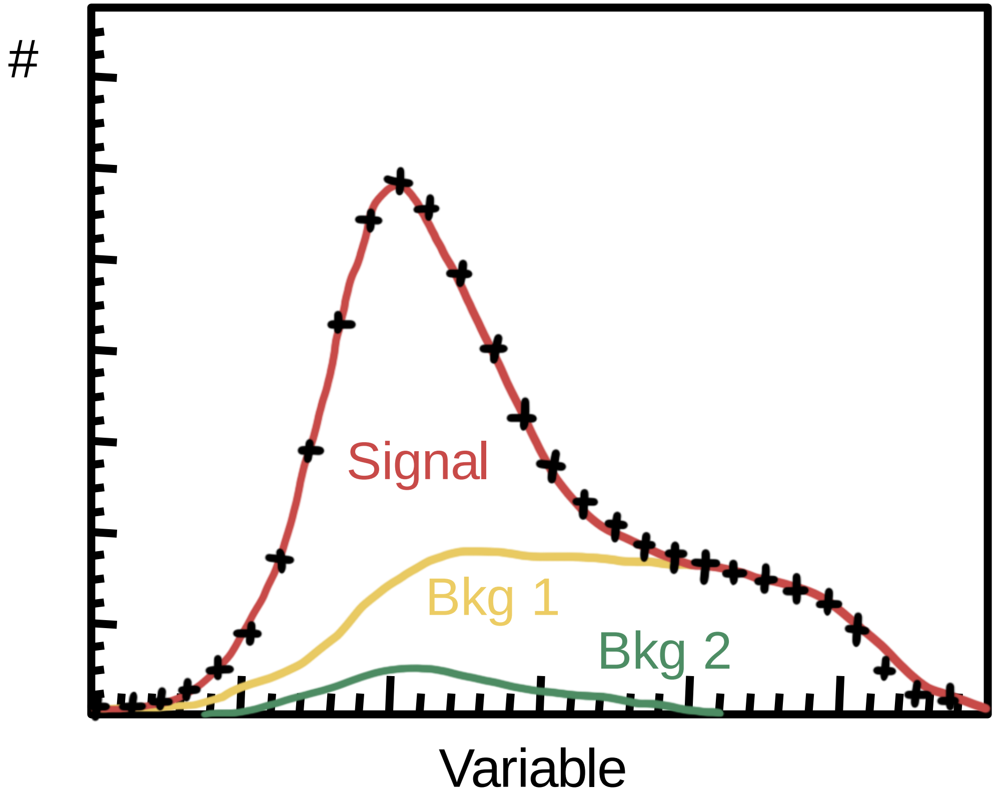


QGP Transport Properties and Structure with Jets



- 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

Signal Extraction: Heavy Flavor Decay Leptons



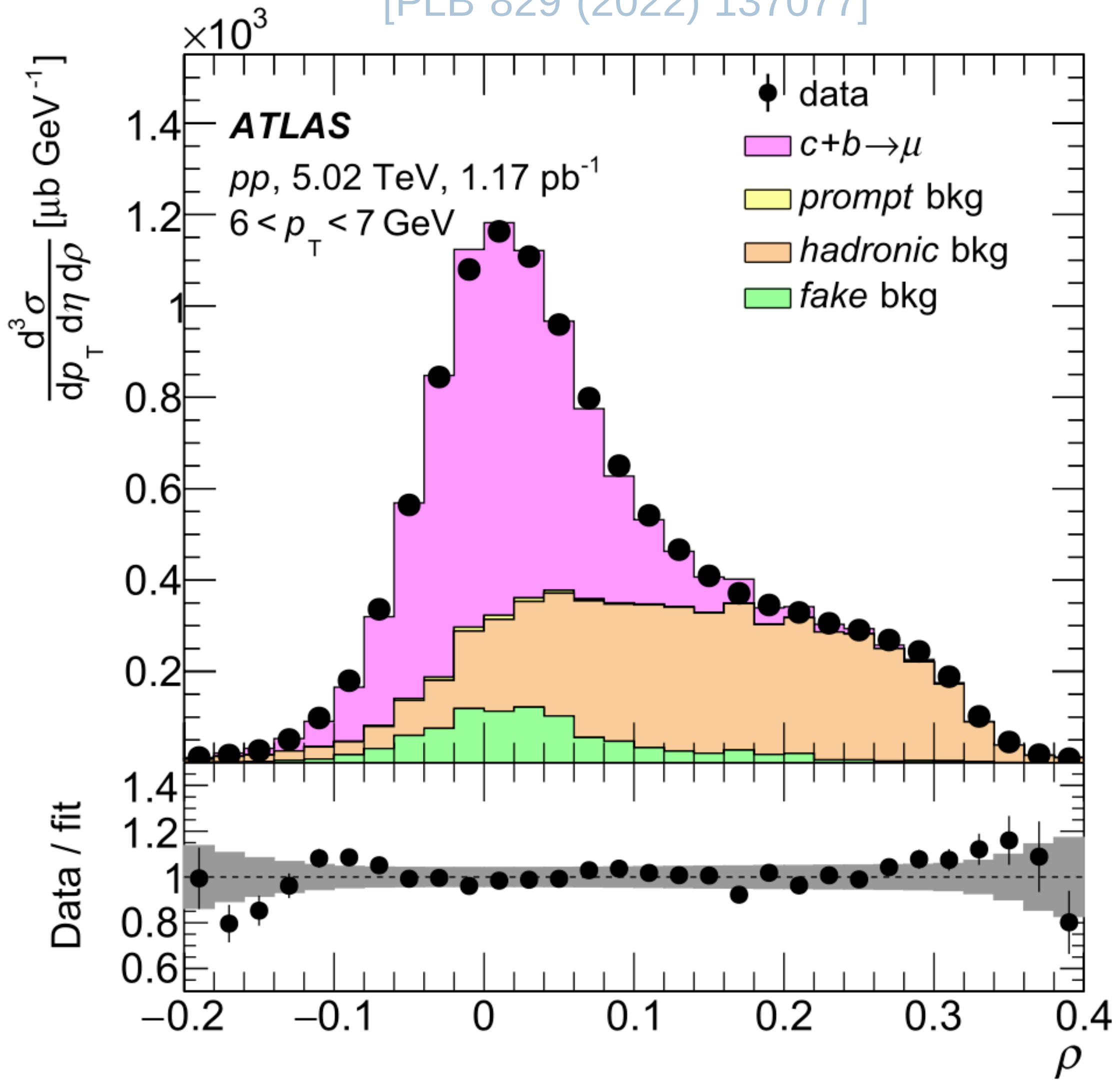
Template fit on a variable to extract the yields of signals

- Identify sources of backgrounds
- Determine variables, which should have *either*
  - distinct shapes between components, *or*
  - well-known yields
- Determine templates
  - Data-driven is the best
  - Simulation is commonly used
    - Need to correct or evaluate data-MC difference

This idea will be used again and again…

Signal Extraction: HF Decay Muons - Example

[PLB 829 (2022) 137077]



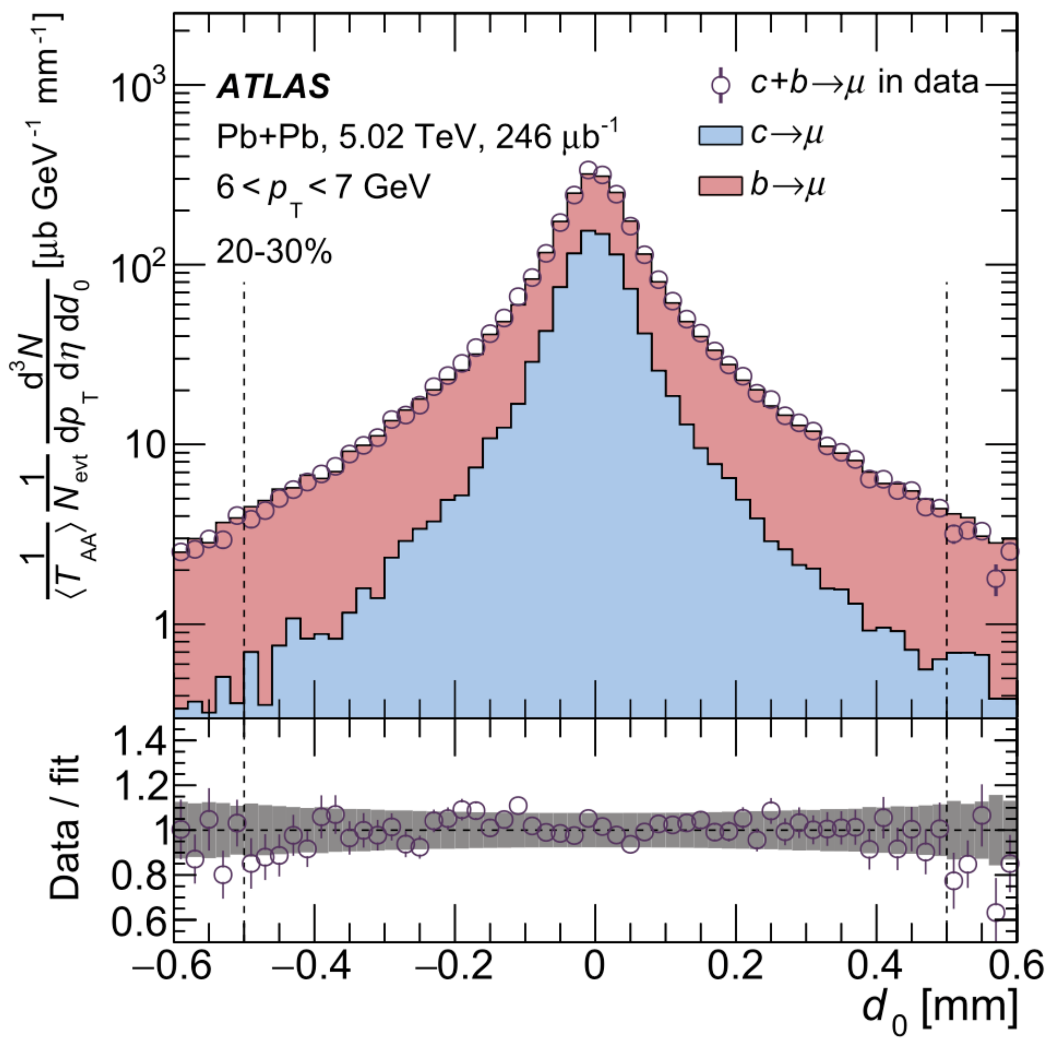
- Sources of backgrounds
  - *prompt* bkg muon from decay of J/ψ, ψ(2S), Y, W/Z
  - *hadronic* bkg muon from π / K decay in inner tracker or punching through the calorimeter
  - *fake* bkg wrongly reconstructed/identified track

- Variables
  - ρ Difference of muon momentum determined in the inner tracker and in the muon chamber
  - *hadronic* and *fake* bkg shapes different from signals
  - *prompt* bkg yields scaled from previous measurements

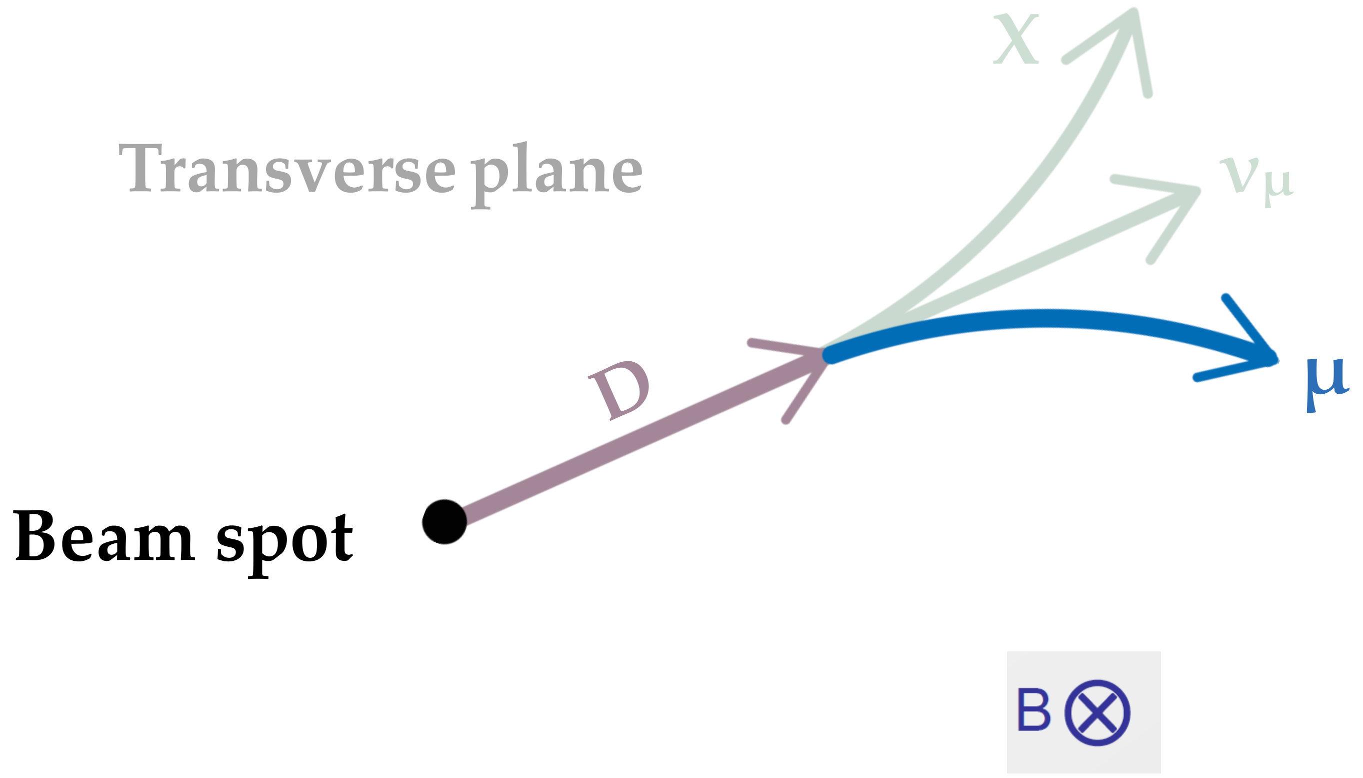
- Templates
  - From simulations

Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

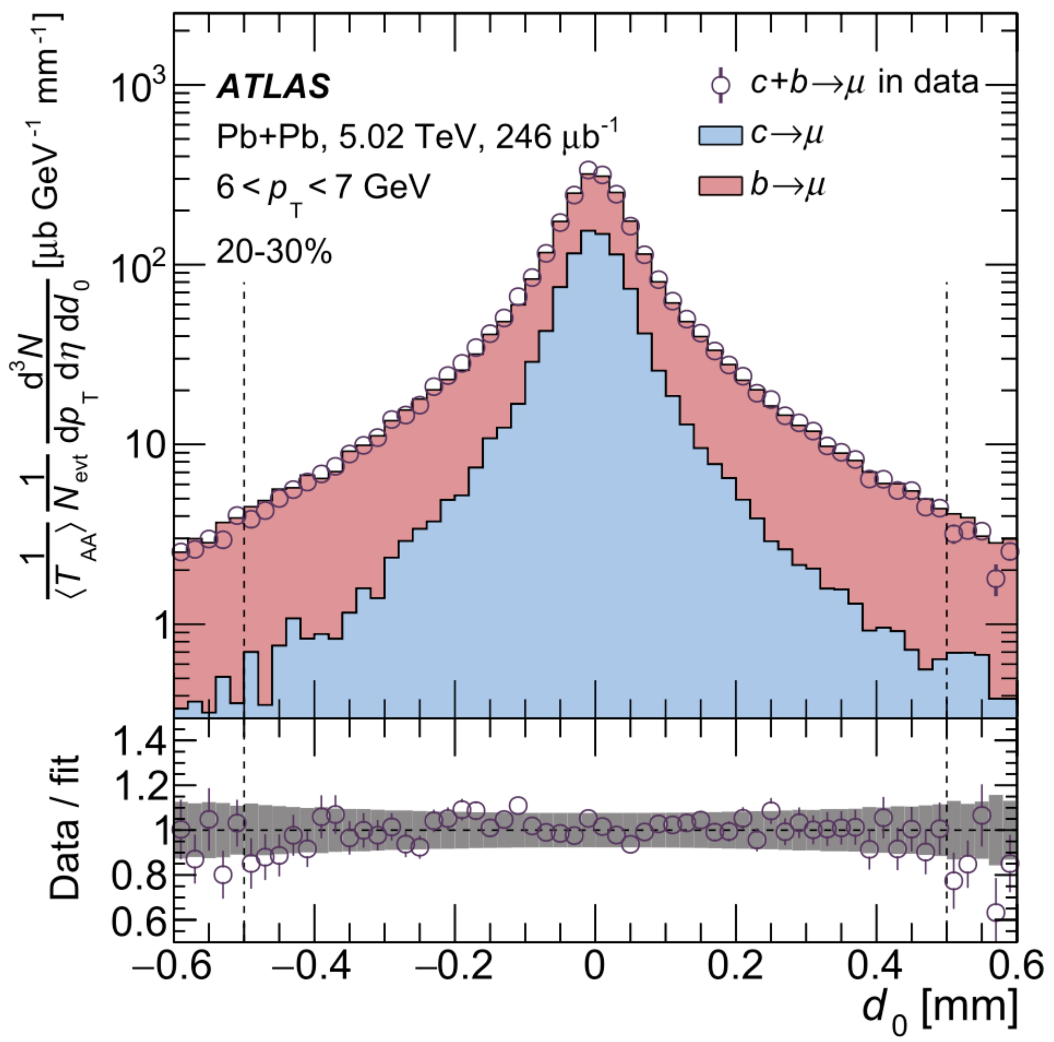


Template fit on Variables d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)

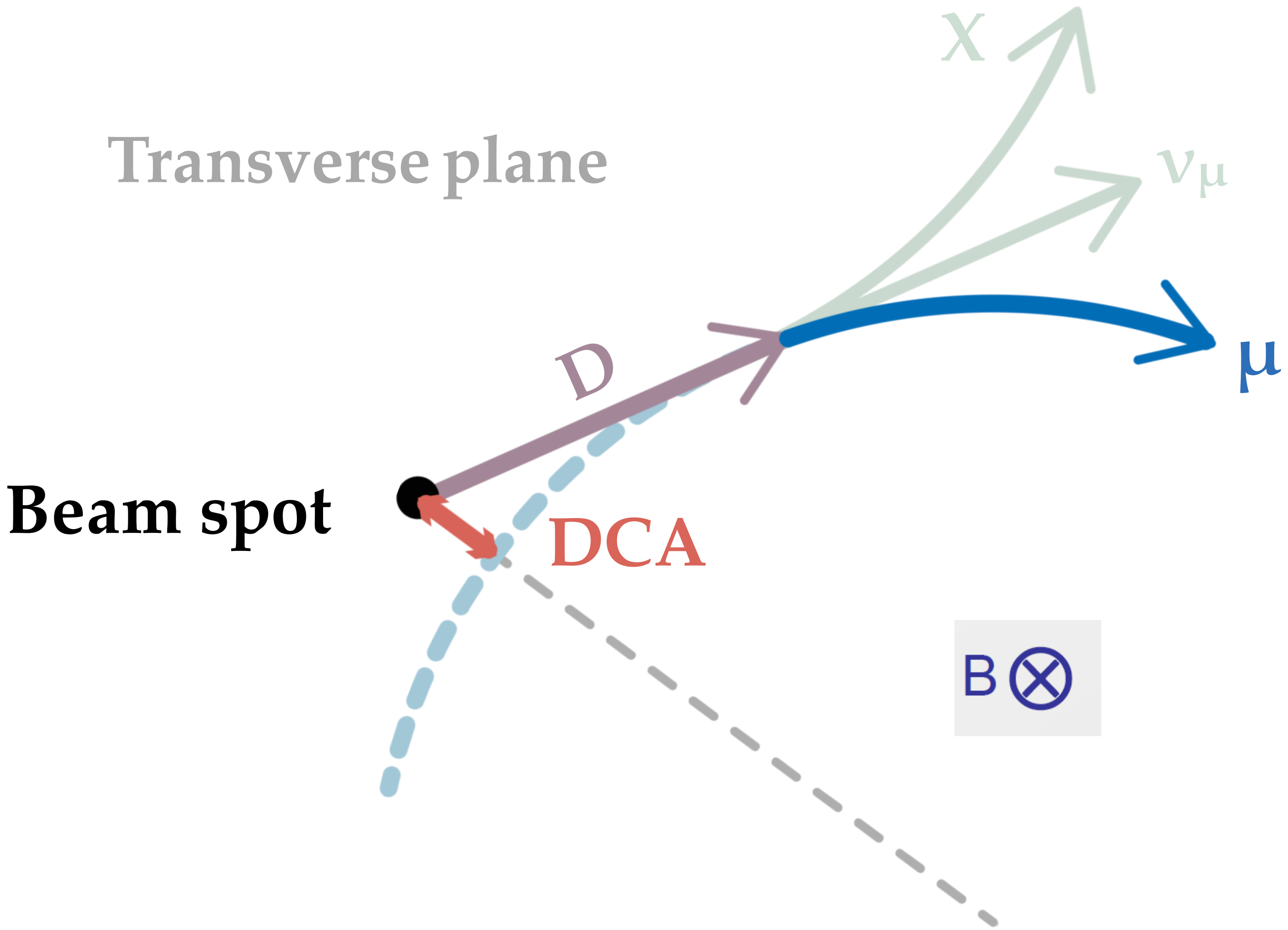


Signal Extraction: Separate c→ and b→μ

[PLB 829 (2022) 137077]

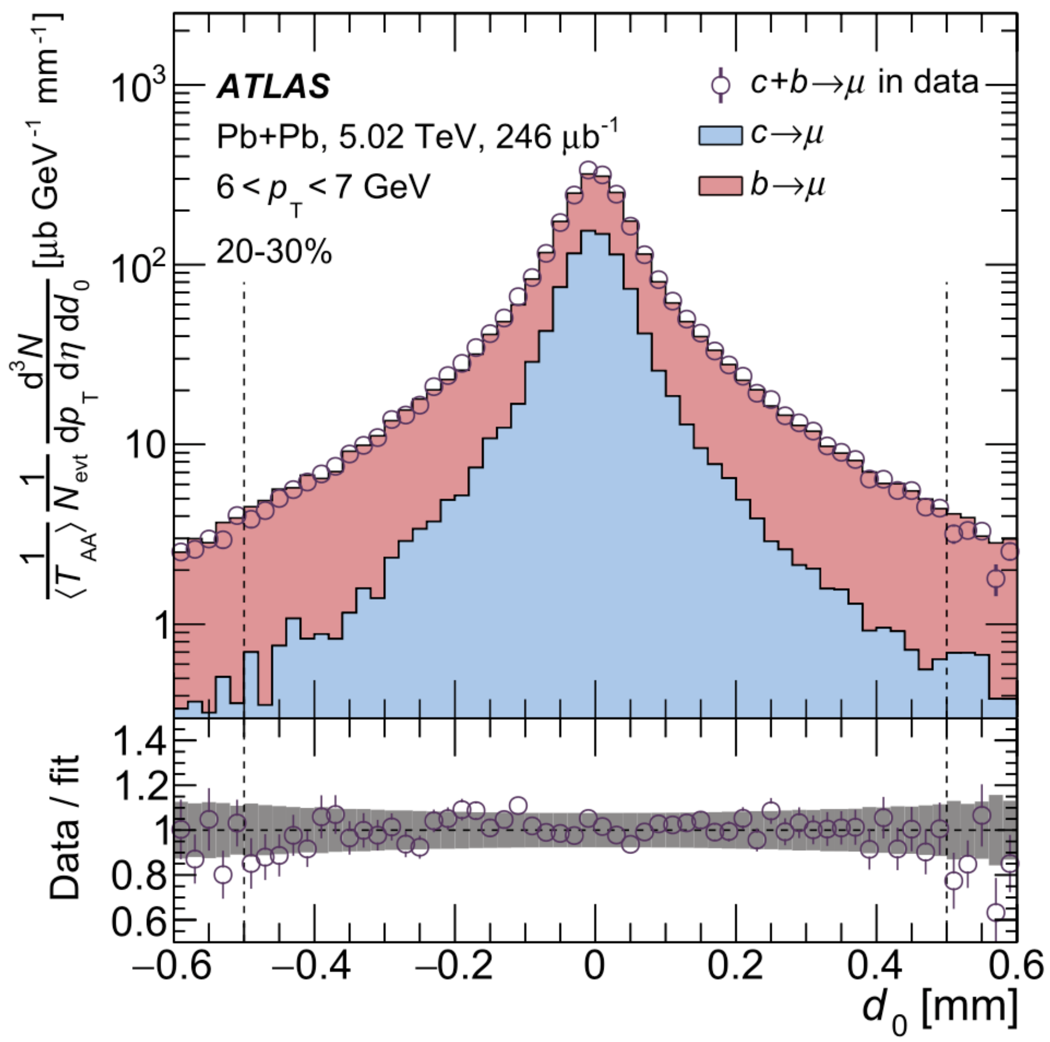


Template fit on Variables d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)

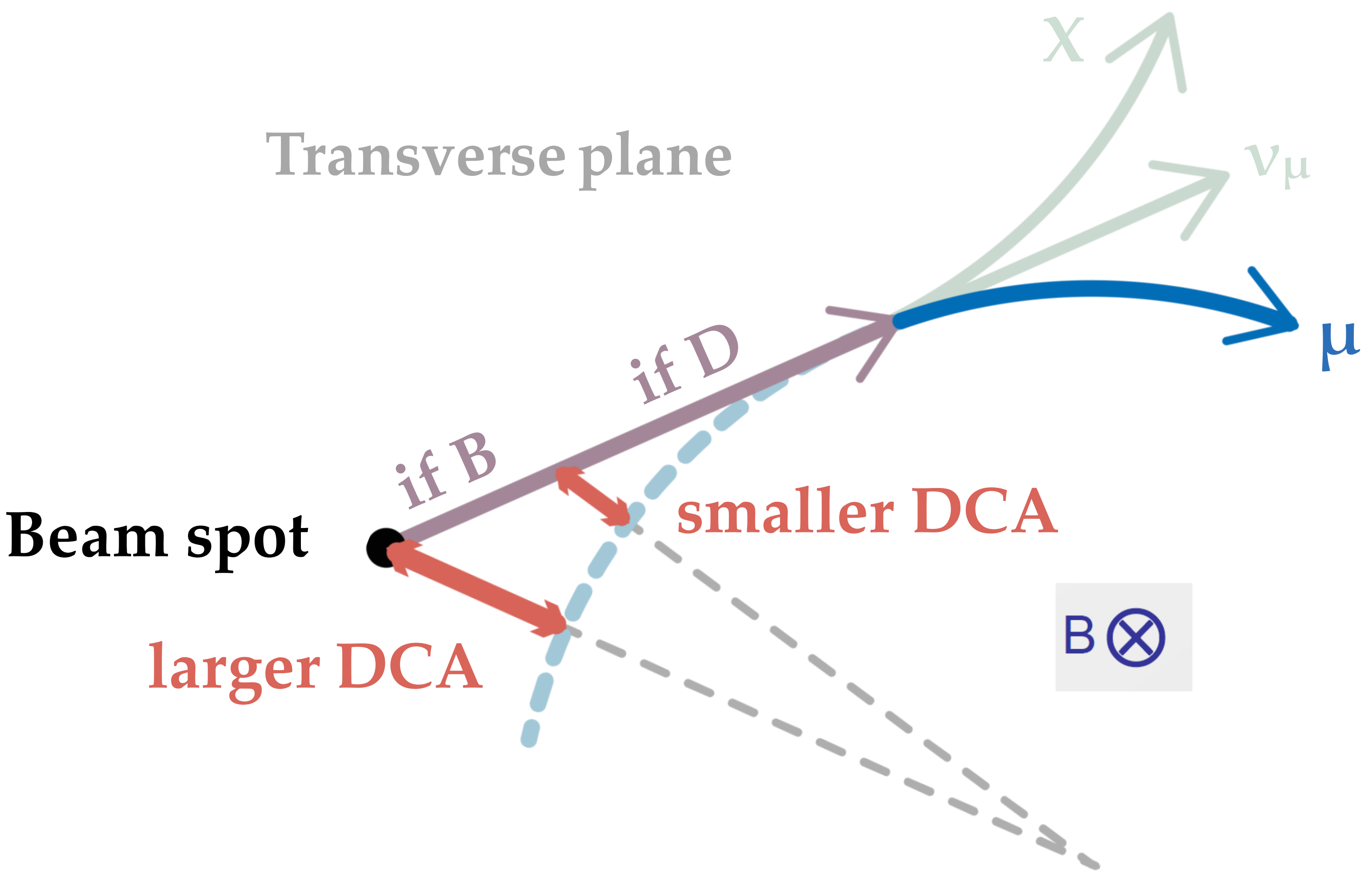


Signal Extraction: Separate c→ and b→μ

[PLB 829 (2022) 137077]



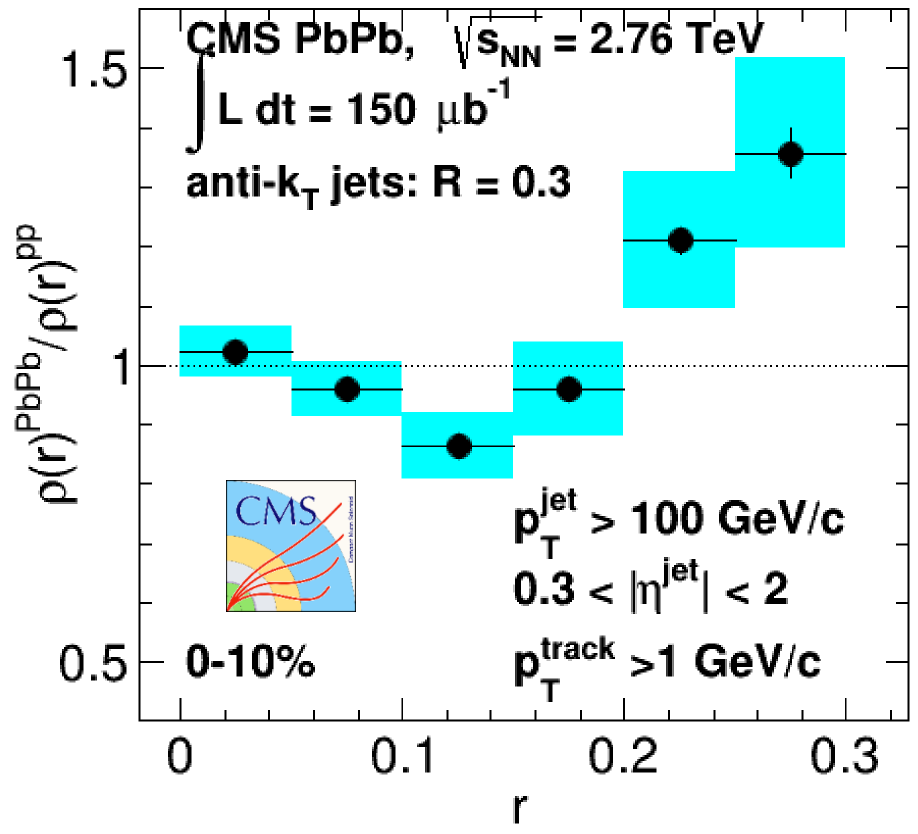
Template fit on Variables d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)



Inclusive Jet Transverse and Longitudinal Structure

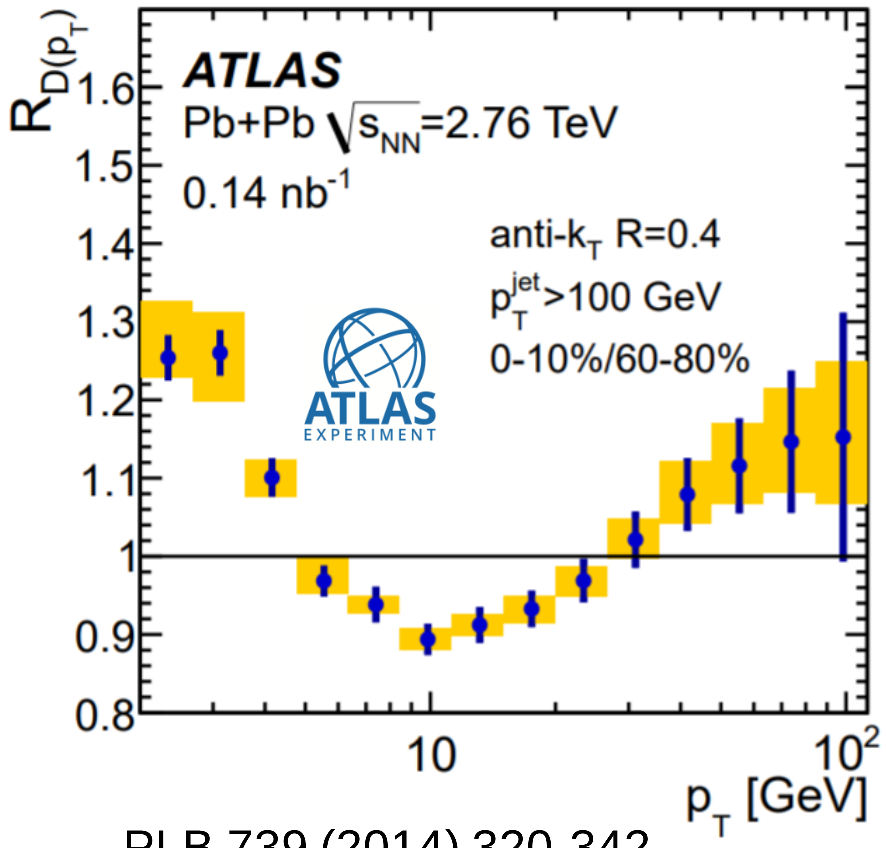
$$\frac{PbPb}{pp}$$

Jet Transverse Structure



PLB 730 (2014) 243-263

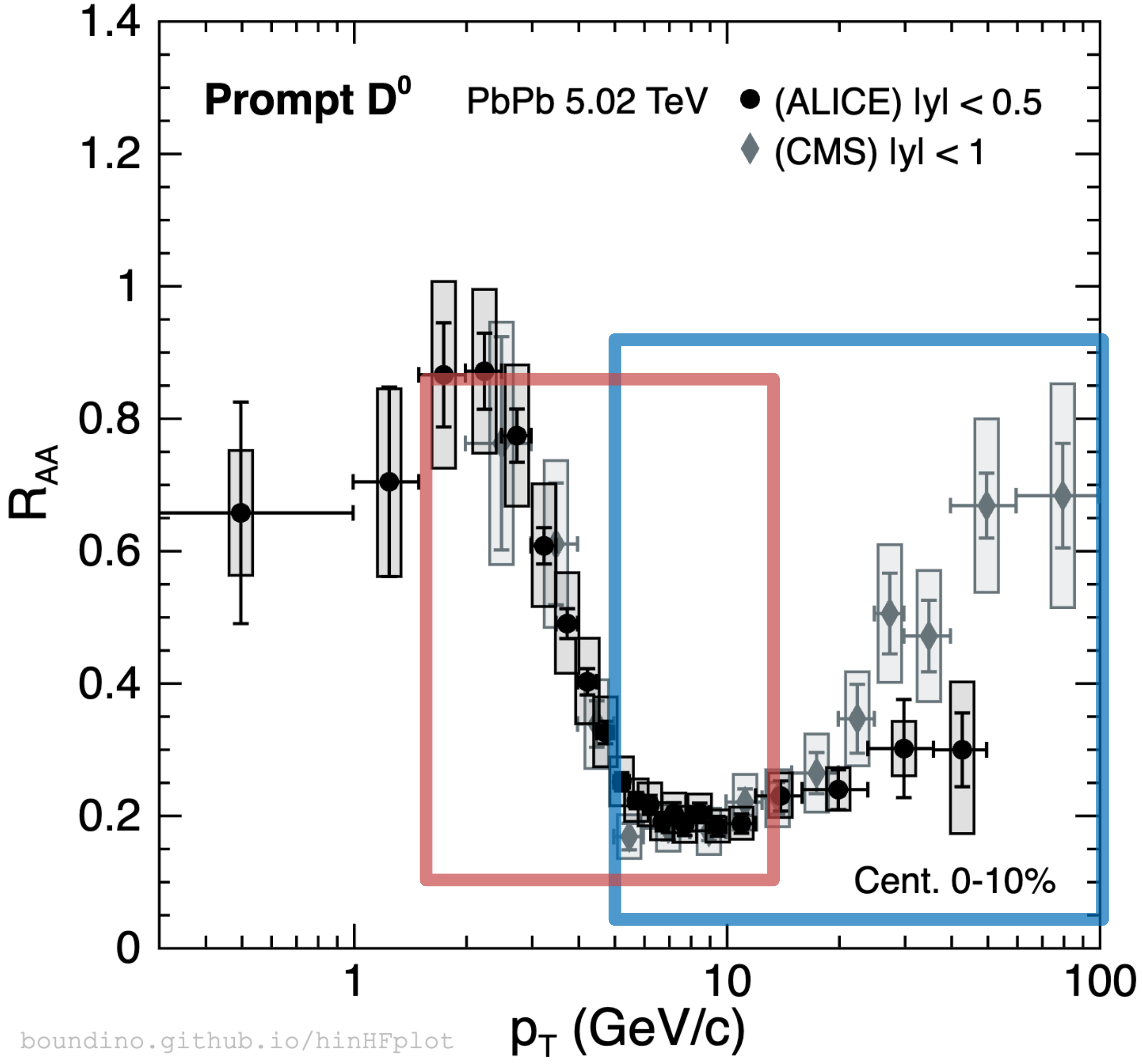
Jet Longitudinal Structure



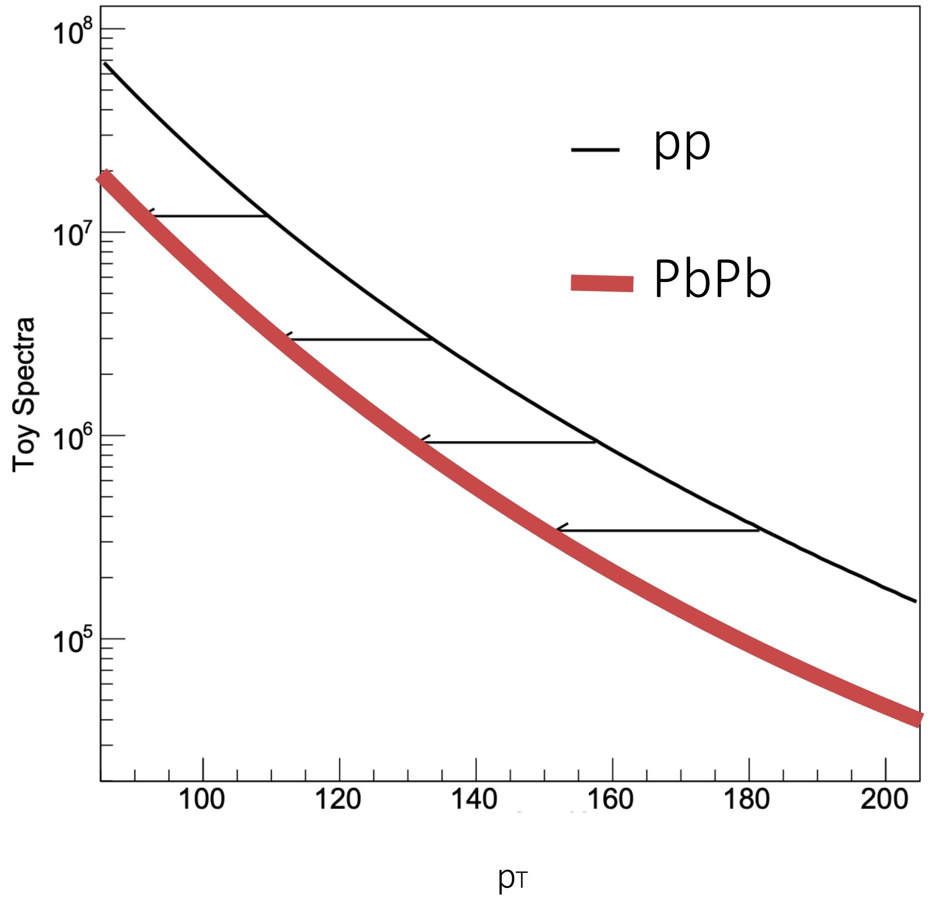
PLB 739 (2014) 320-342

- 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

D^0 R_{AA} Understanding the Shape

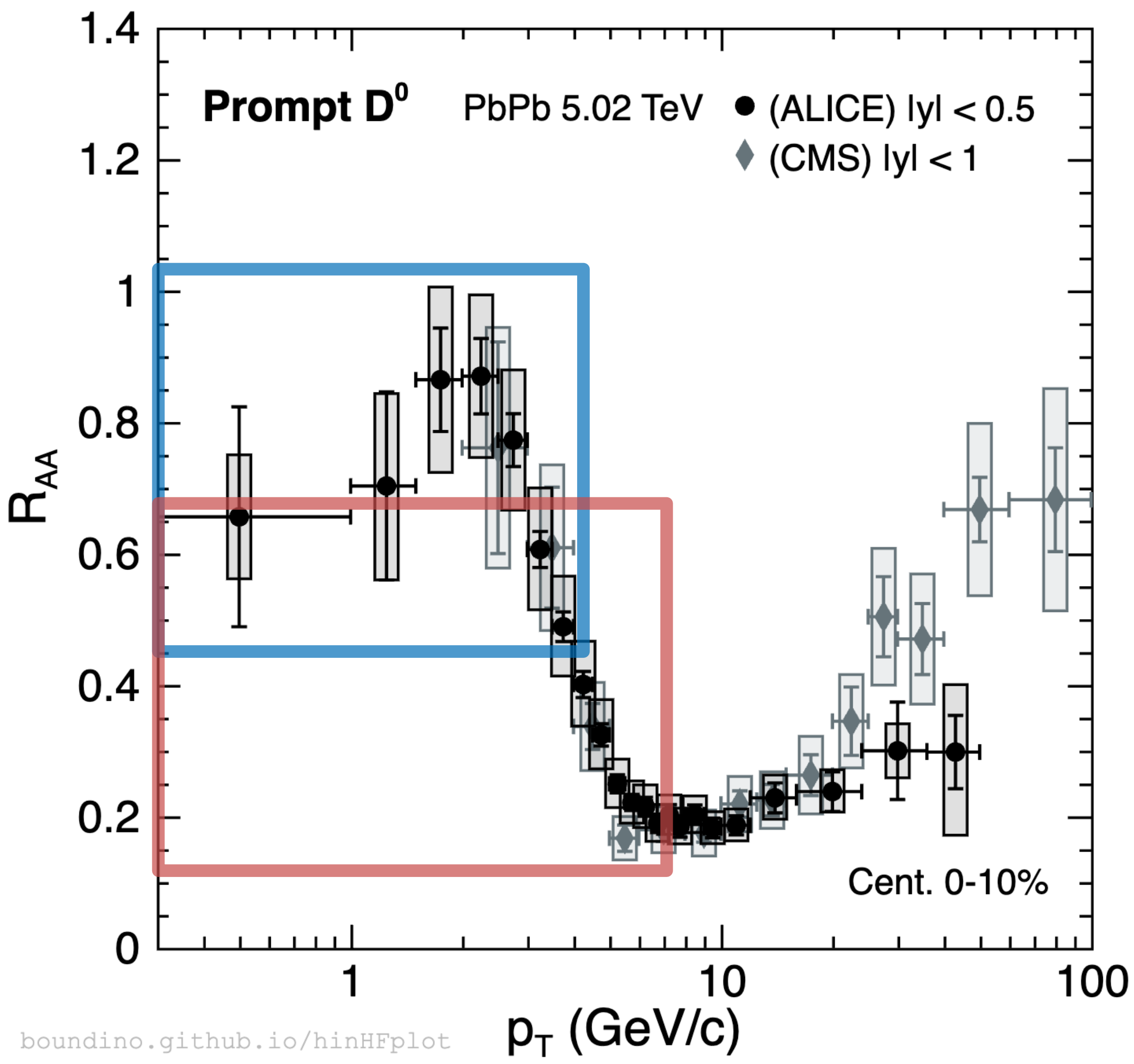


- Multiple effects interplay
  - Collisional and radiative energy loss
  - p_T shape before modification



JHEP 01 (2022) 174 PLB 782 (2018) 474

D^0 R_{AA} Understanding the Shape



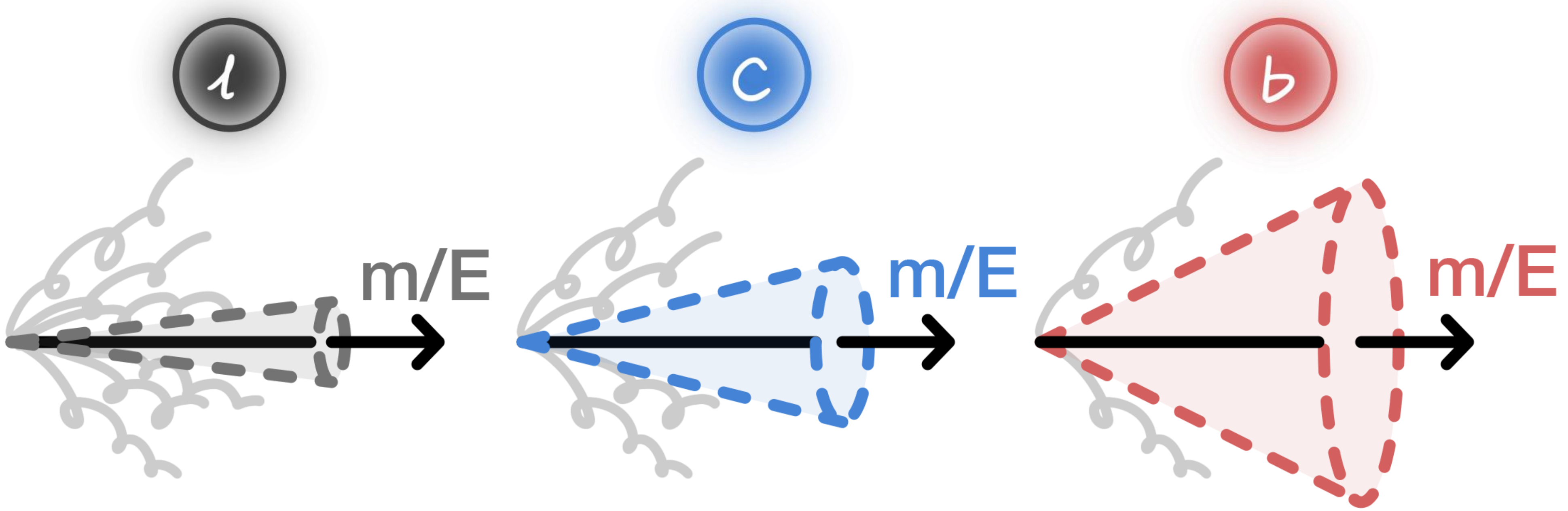
JHEP 01 (2022) 174   PLB 782 (2018) 474

- Multiple effects interplay
  - Collisional and radiative energy loss
  - p_T shape before modification
    - lower slope at high p_T
  - Collective flow + hadronization
    - medium pushes very low-p_T partons to higher p_T
    - get kinematics from light quark
  - nPDF shadowing
    - suppress low p_T

Mass Dependence of Energy Loss

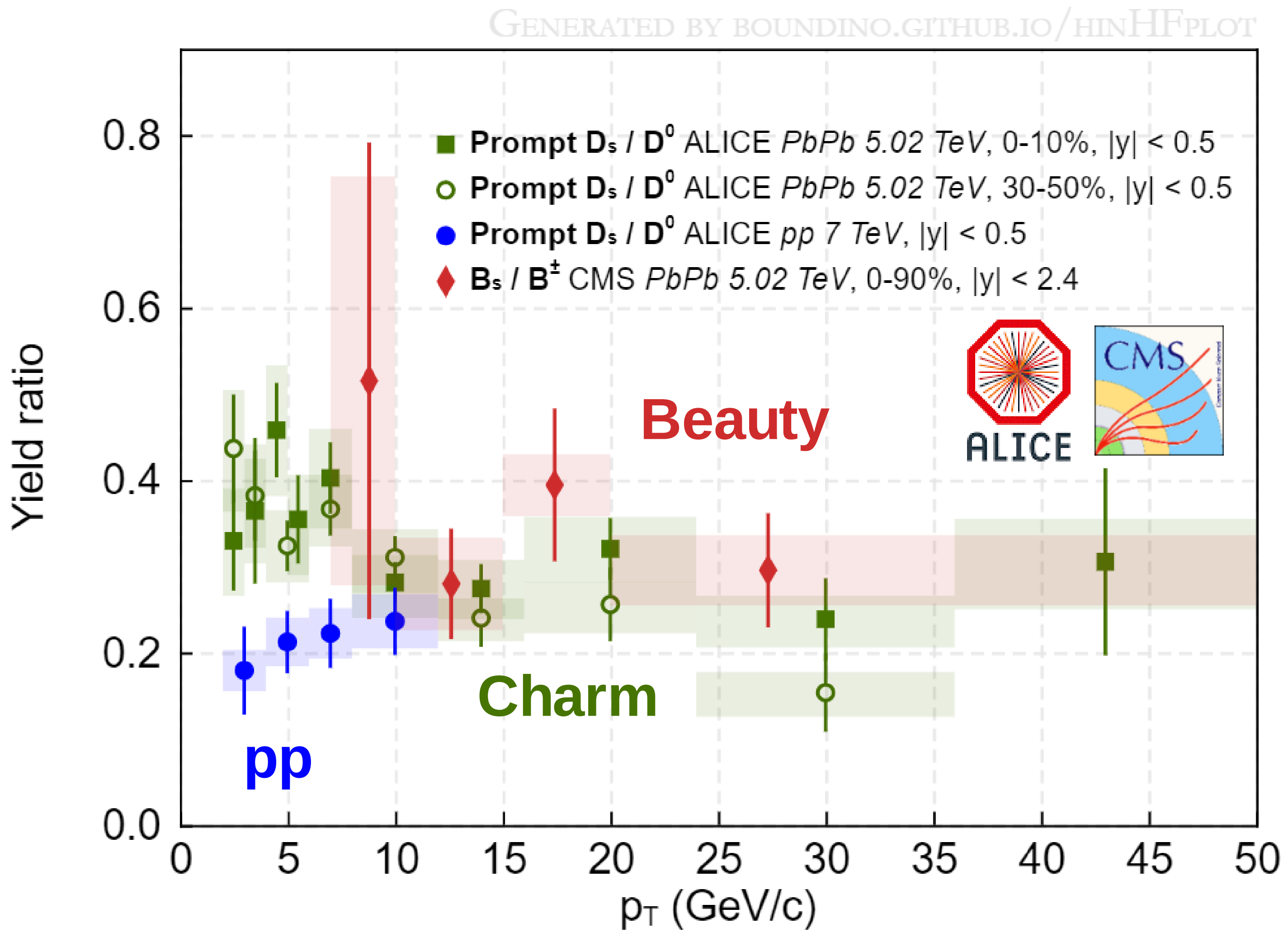
- Flavor dependent energy loss:
  Dead cone effect

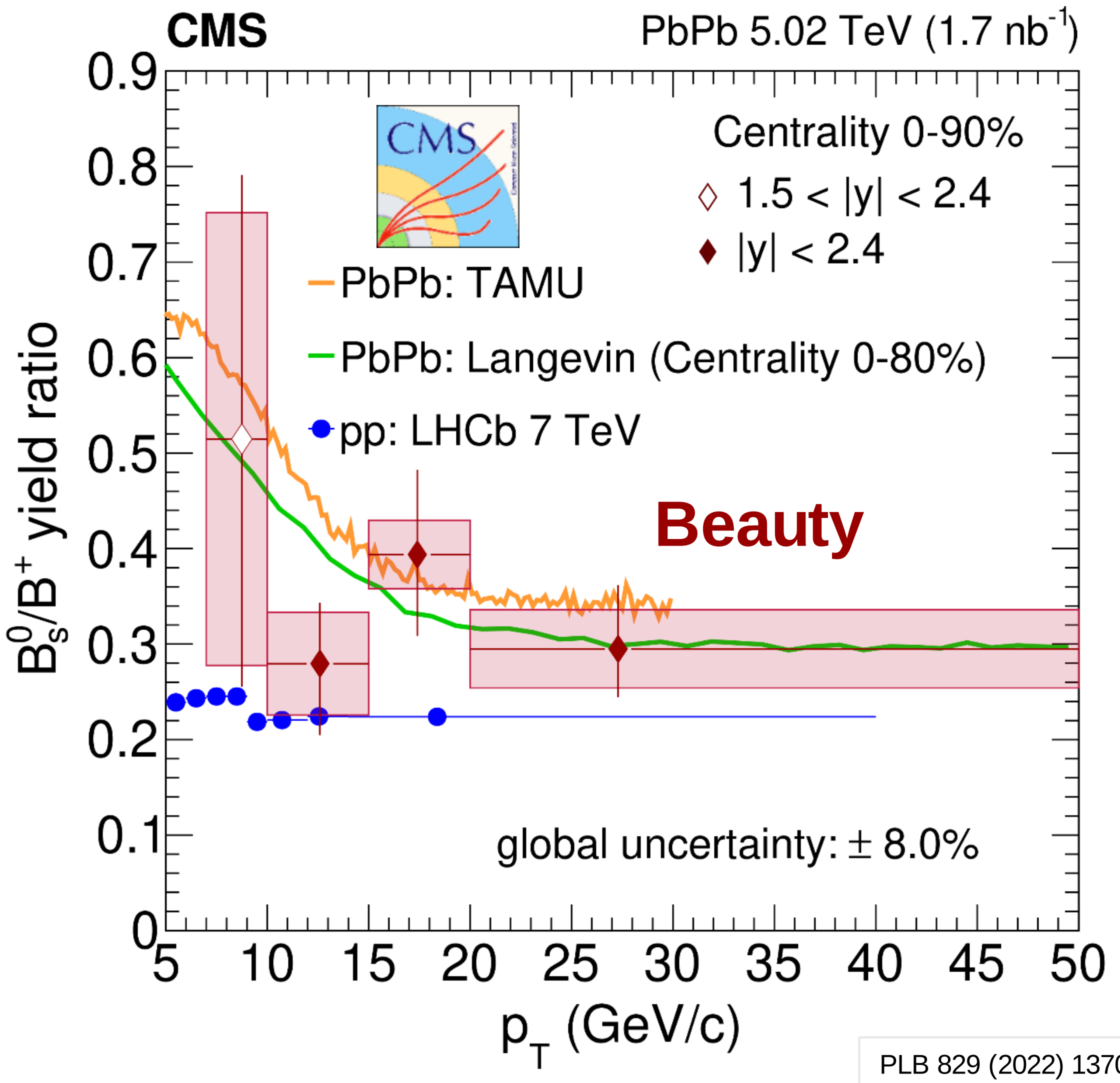
  - Radiation is suppressed inside θ < m/E
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$



Larger energy loss → Smaller energy loss

Charm and Beauty Hadronization

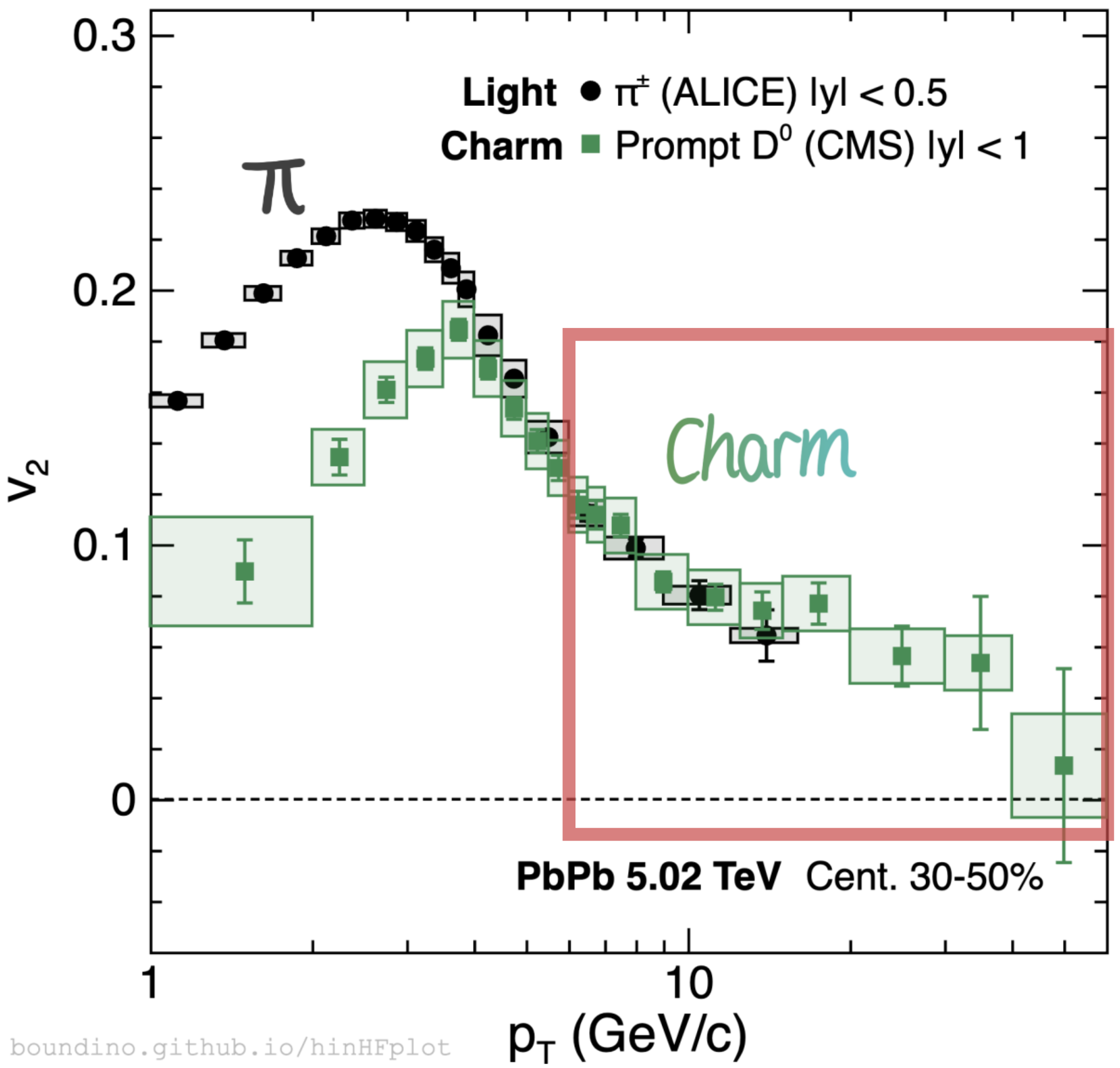




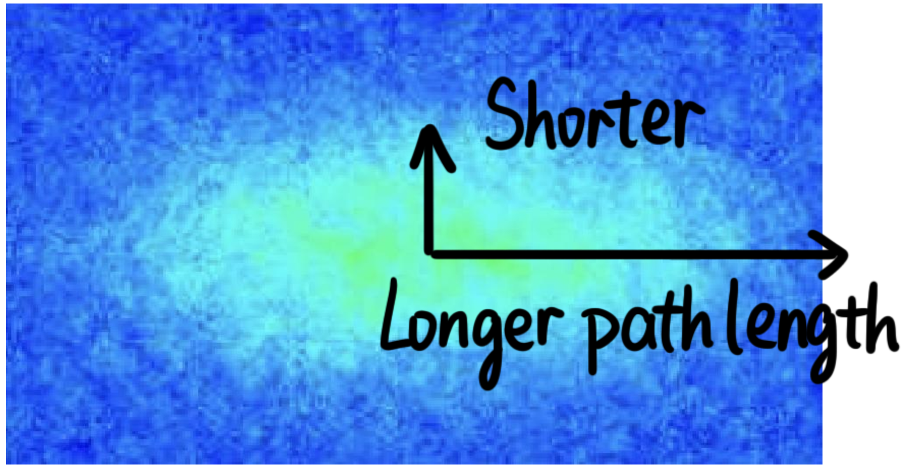
PLB 829 (2022) 137062

- The magnitude of D_s/D^0 and B_s/B^+ are similar in **pp** and PbPb collisions
- Difference between PbPb data and **pp reference** decreases at high p_T

Collective Flow Open Charm



- Non-zero D meson v_2 up to high p_T
  - Same magnitude with light hadrons
  - Path-length dependence of energy loss



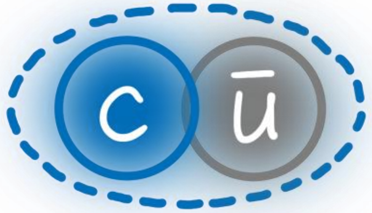
PLB 816 (2021) 136253 PLB 813 (2021) 136054 PLB 807 (2020) 135595

Example Heavy Flavor Hadrons

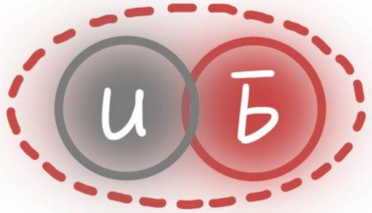
Charm

Beauty

Open heavy flavor

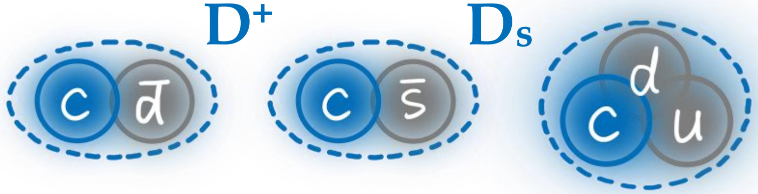


D^0 ($c \to D^0$ ~ O(50%))
Mass 1.865 GeV
cτ ~ 120 μm

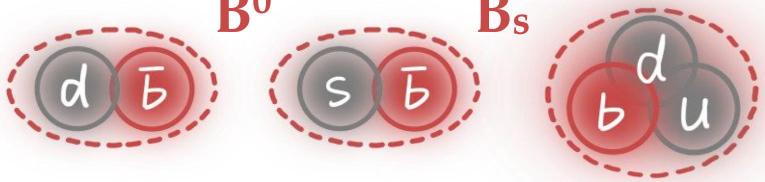


B^+ ($b \to B^+$ ~ O(40%))
Mass 5.279 GeV
cτ ~ 490 μm

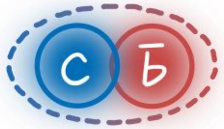
D^+ D_s Λ_c



B^0 B_s Λ_b

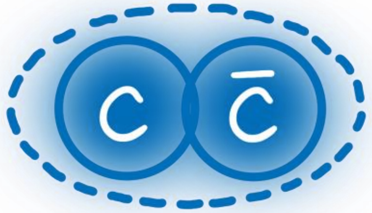


B_c^+

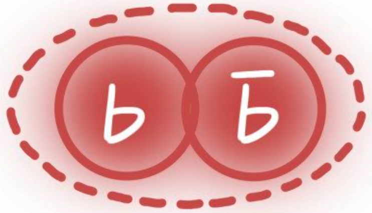


Quarkonia

J/ψ
ψ(2S), χ_c



ϒ(1S)
ϒ(2S), ϒ(3S)



Signal Extraction Fully Reconstruction

Commonly used decay modes

$D^0 \rightarrow$	$K^- \pi^+$
$D^+ \rightarrow$	$K^- \pi^+ \pi^+$
$D_S^+ \rightarrow$	$\varphi (K^+ K^-) \pi^+$
$D^{*+} \rightarrow$	$D^0 (K^- \pi^+) \pi^+$
$\Lambda_c^+ \rightarrow$	$p K^- \pi^+$ larger BR
$\Lambda_c^+ \rightarrow$	$p K_s^0 (\pi^+ \pi^-)$ K_s improves purity
$B^+ \rightarrow$	$J/\psi (\mu^+\mu^-) K^+$
$B^+ \rightarrow$	$D^0 (K^+ \pi^-) \pi^+$
$B^0 \rightarrow$	$J/\psi (\mu^+\mu^-) K_s^0 (\pi^+ \pi^-)$
$B^0 \rightarrow$	$D^- (K^+ \pi^- \pi^-) \pi^+$
$B_S^0 \rightarrow$	$J/\psi (\mu^+\mu^-) \varphi (K^+ K^-)$
$\Lambda_b^0 \rightarrow$	$\Lambda_c^+ (p K^- \pi^+) \pi^-$

Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
  - Acceptance
  - Resolution

Signal Extraction: Fully Reconstruction

Commonly used decay modes

D^0	$\rightarrow$	$K^- \pi^+$
D^+	$\rightarrow$	$K^- \pi^+ \pi^+$
D_S^+	$\rightarrow$	$\varphi (K^+ K^-) \pi^+$
D^{*+}	$\rightarrow$	$D^0 (K^- \pi^+) \pi^+$
Λ_c^+	$\rightarrow$	$p K^- \pi^+$
Λ_c^+	$\rightarrow$	$p K_s^0 (\pi^+ \pi^-)$
B^+	$\rightarrow$	$J/\psi (\mu^+ \mu^-) K^+$
B^+	$\rightarrow$	$D^0 (K^+ \pi^-) \pi^+$
B^0	$\rightarrow$	$J/\psi (\mu^+ \mu^-) K_s^0 (\pi^+ \pi^-)$
B^0	$\rightarrow$	$D^- (K^+ \pi^- \pi^-) \pi^+$
B_S^0	$\rightarrow$	$J/\psi (\mu^+ \mu^-) \varphi (K^+ K^-)$
Λ_b^0	$\rightarrow$	$\Lambda_c^+ (p K^- \pi^+) \pi^-$

lower background

better acceptance

Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
    - more daughters have worse purity
    - lepton channels lower combinatorial background
  - Acceptance *e.g.*
    - muons difficult to access low p_T at mid rapidity
  - Resolution

Signal Extraction: Fully Reconstruction

Commonly used decay modes

D^0	$\rightarrow$	$K^- \pi^+$
D^+	$\rightarrow$	$K^- \pi^+ \pi^+$
D_S^+	$\rightarrow$	$\varphi\,(K^+ K^-)\,\pi^+$
D^{*+}	$\rightarrow$	$D^0\,(K^- \pi^+)\,\pi^+$
Λ_c^+	$\rightarrow$	$p\,K^- \pi^+$
Λ_c^+	$\rightarrow$	$p\,K_s^0\,(\pi^+ \pi^-)$
B^+	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,K^+$
B^+	$\rightarrow$	$D^0\,(K^+ \pi^-)\,\pi^+$
B^0	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,K_s^0\,(\pi^+ \pi^-)$
B^0	$\rightarrow$	$D^-\,(K^+ \pi^- \pi^-)\,\pi^+$
B_S^0	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,\varphi\,(K^+ K^-)$
Λ_b^0	$\rightarrow$	$\Lambda_c^+\,(p\,K^- \pi^+)\,\pi^-$

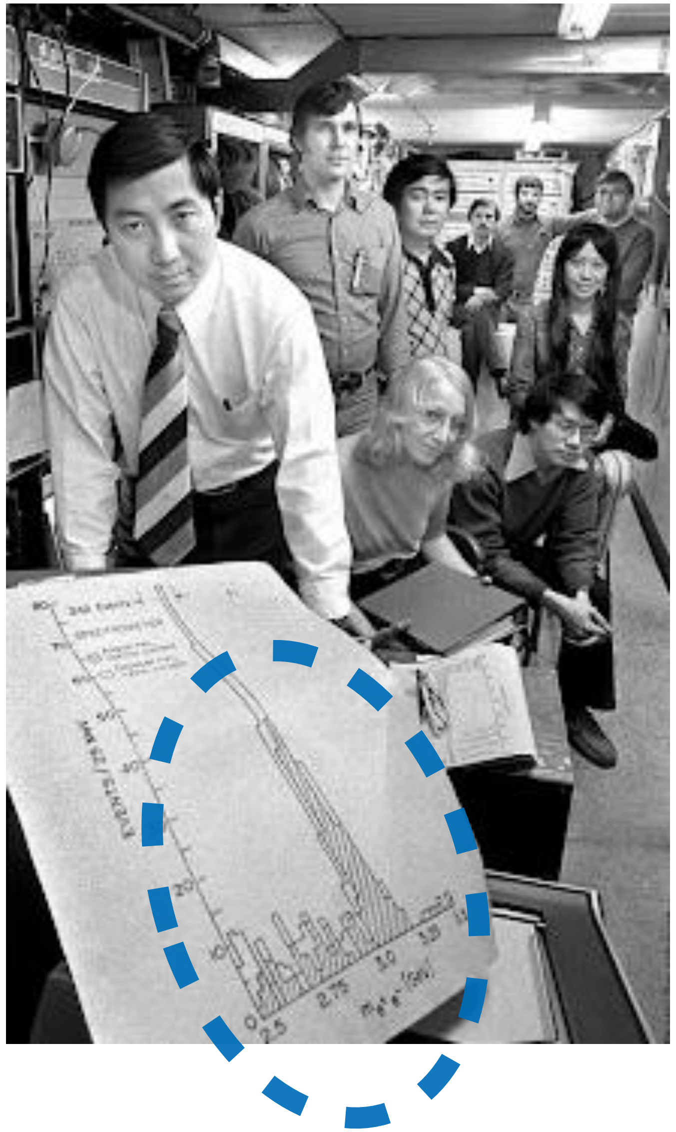
Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
    - more daughters have worse purity
    - lepton channels lower combinatorial background
  - Acceptance *e.g.*
    - muons difficult to access low p_T at mid rapidity
  - Resolution

- Determine templates
  - Identify potential peaking background

Signal Extraction: Fully Reconstruction

Discovery of J/ψ



Fit on invariant mass

- Pair all the potential decay daughter particles in an event

[PRL 33 (1974) 1404]