

PhD Defense

Clayton Bennett

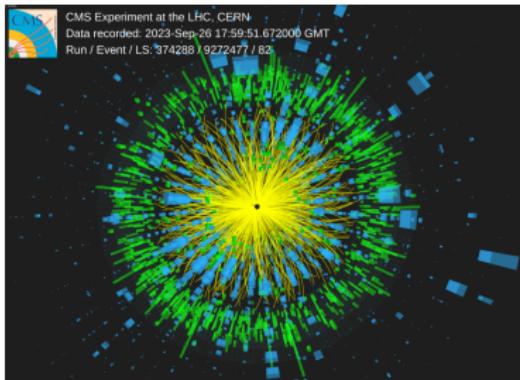
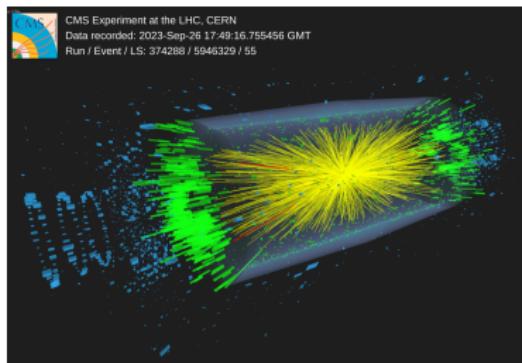
University of Illinois at Chicago
The CMS Collaboration

December 4, 2023



Outline

- ① The Quark Gluon Plasma
- ② Jets as probes of the Quark Gluon Plasma
- ③ b -jet measurements with CMS



First 2023 PbPb collision at 5.36 TeV

The Quark Gluon Plasma

The Standard Model of Particle Physics

QUARKS	mass → ≈2.3 MeV/c ² charge → 2/3 spin → 1/2	≈1.275 GeV/c ² 2/3 1/2	≈173.07 GeV/c ² 2/3 1/2	0 0 1	≈126 GeV/c ² 0 0
	u up	c charm	t top	g gluon	Higgs boson
	d down	s strange	b bottom	γ photon	
LEPTONS	0.511 MeV/c ² -1 1/2	105.7 MeV/c ² -1 1/2	1.777 GeV/c ² -1 1/2	91.2 GeV/c ² 0 1	Z boson
	e electron	μ muon	τ tau	Z	
	ν _e electron neutrino	ν _μ muon neutrino	ν _τ tau neutrino	W W boson	Gauge Bosons

https://en.wikipedia.org/wiki/Standard_Model

- Quantum field theory that describes
 - Quantum electrodynamics
 - Electroweak interactions
 - Quantum chromodynamics
 - Gravity
- Quarks and leptons interact via the exchange of gauge bosons
 - QED → γ
 - EW → W^\pm, Z
 - QCD → g
- H is a mass-giving scalar boson
- **Experimentally verified**
- Still open questions...
 - muon g – 2 anomaly
 - non-zero neutrino mass
 - baryon asymmetry

Quantum Chromodynamics

- **Quantum chromodynamics (QCD)** is a quantum field theory describing the **strong interaction** between quarks and gluons
- **Confinement:** fundamental feature of QCD

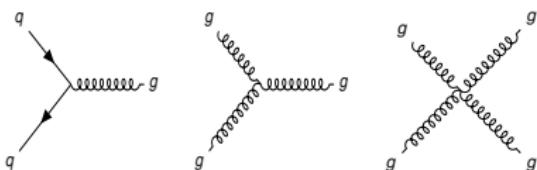
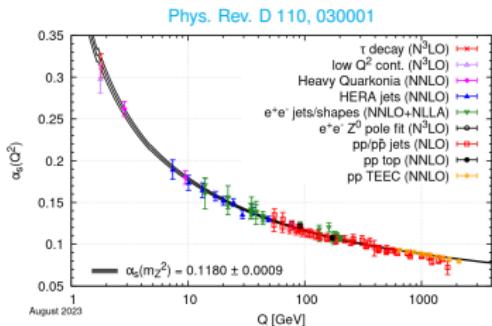
$$V_{\text{QCD}}(Q^2) = \underbrace{-\frac{4\alpha_s(Q^2)}{3r}}_{\text{QED-like short-range}} + \underbrace{\lambda r}_{\text{QCD long-range}}$$

- QCD is a quantum field theory with **asymptotic freedom**

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \left[\alpha_s(\mu^2) \frac{(11n_c - 2n_f)}{12\pi} \right] \ln \left(\frac{Q^2}{\mu^2} \right)}$$

$$\boxed{\lim_{Q \rightarrow \infty} \alpha_s(Q^2) \rightarrow 0}$$

- Large $Q^2 \rightarrow$ strong-force coupling gets **weaker**

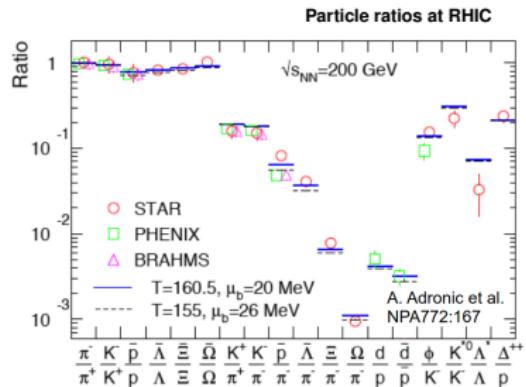
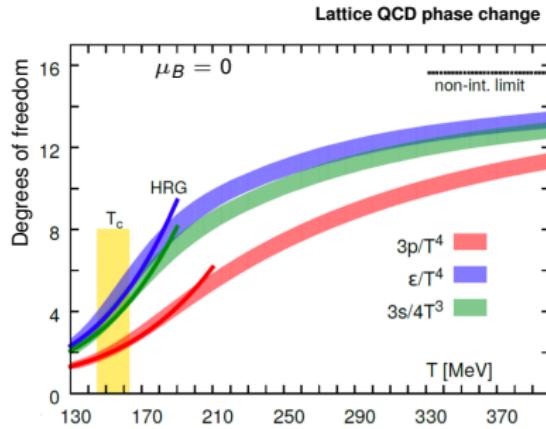


Deconfinement in heavy-ion collisions

- Lattice QCD predicts that partons break away from strong-force bonds at sufficient energy density → **deconfinement**
- Critical temperature (T_c)

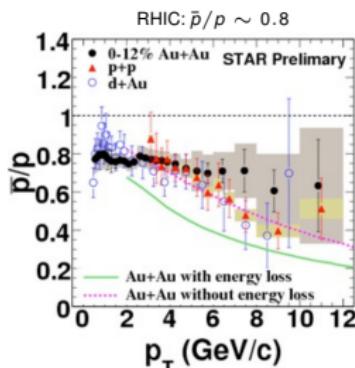
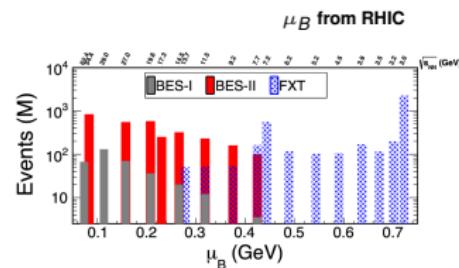
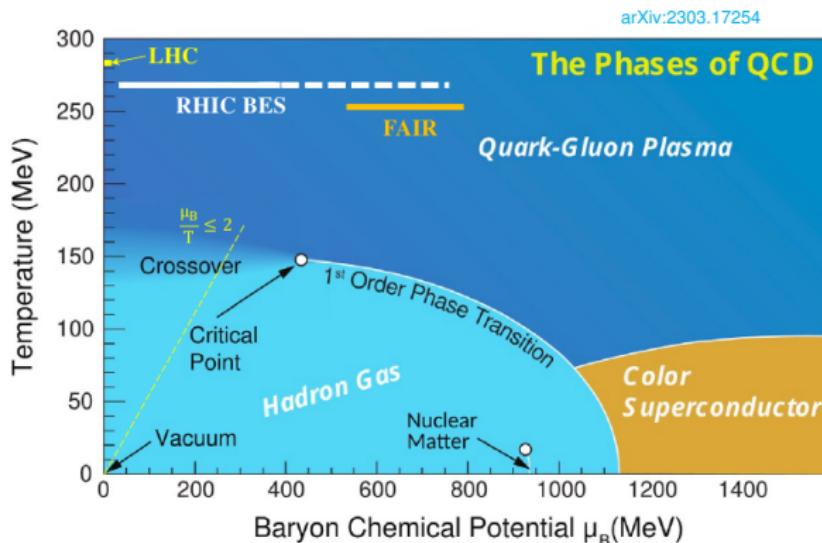
- T_c via lattice QCD / simple confinement models ($\mu_B = 0$)
- T_c for non-zero μ_B is challenging
- state-of-the-art:
 $T_c \approx 158.0 \pm 0.6 \text{ MeV}$

- Evidence of $T_{\text{exp}} > T_c$
 - Estimations of particle ratios
 - $d n_i \sim \exp \{(E_i - \mu_B)/T\} d^3 p_i$
 - $\frac{\bar{p}}{p} = \exp \{-2\mu_B/T\}$
 - $\frac{K}{\pi} = \exp \{-(E_K - E_\pi)/T\}$
- System at extreme T and P → deconfined phase of quarks and gluons
→ **Quark Gluon Plasma (QGP)**



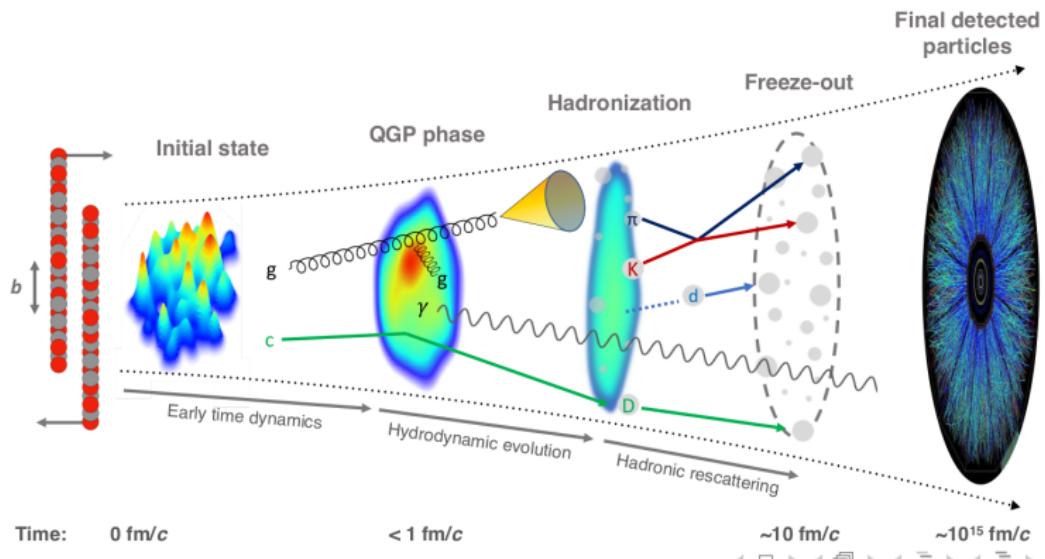
Phases of QCD

- For $\frac{\mu_B}{T} \leq 2$, QGP-to-hadron phase transition is a **smooth crossover**
- Above some critical point, the QGP-to-hadron transition is expected to become a **first-order phase transition**
- Beam Energy Scan at RHIC → map the phase-diagram by varying μ_B

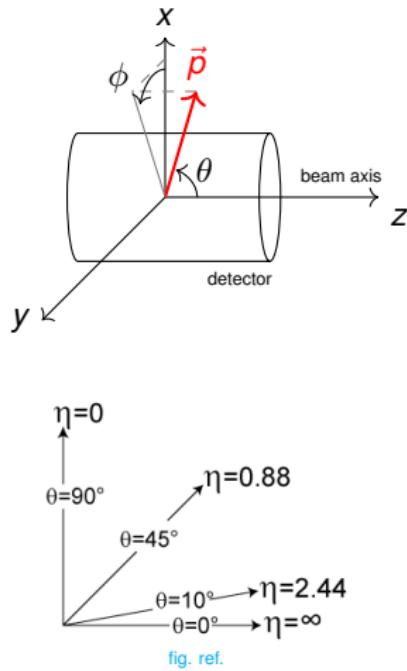


QGP at Particle Colliders

- We can create QGP in the lab by colliding heavy nuclei ($v \approx c$) in particle accelerators (such as RHIC and LHC)
- QCD predicts rich phase dynamics prior to particle detection
 - Non-equilibrated initial state
 - **Strongly-interacting QGP phase** that flows as a relativistic hydrodynamic fluid
 - Medium expansion, cooling, and **hadronization**
 - Hadronic rescattering and **freeze-out**



Kinematics in Particle Detectors



- Detector geometry warrants the use of cylindrical coordinate system

transverse momentum : $p_T = |\vec{p}| \sin \theta$

$$\text{rapidity} : y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

$$\text{pseudo-rapidity} : \eta = \frac{1}{2} \ln \left(\frac{p + p_z}{p - p_z} \right)$$

$$\rightarrow -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$$

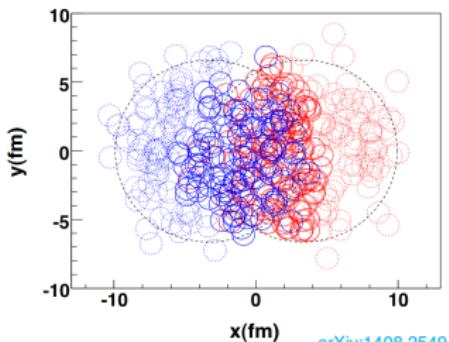
- Why are these variables common in particle physics experiments?

- $\sum_i p_{T,i} = 0 + \epsilon$
- Δy is invariant for boosts along z -axis

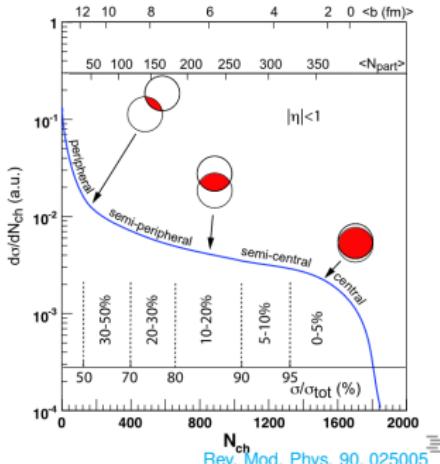
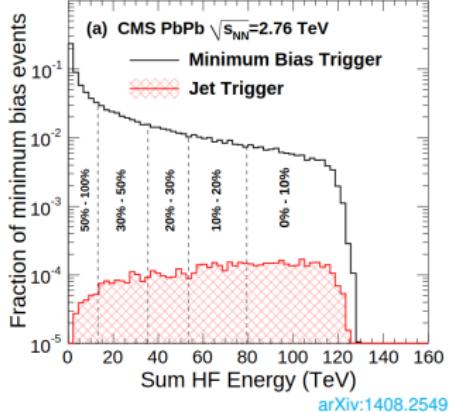
Centrality

- **Centrality** is a measure of the nuclear overlap in a collision event
- Derived from multiplicity distributions, forward-energy distribution
- Essential for categorizing events based on QGP-formation status
- Relate observables back to impact parameter via Glauber model

PbPb collision simulation



arXiv:1408.2549

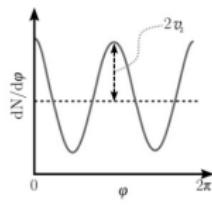
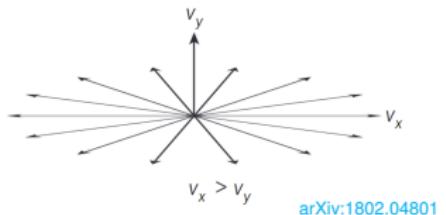
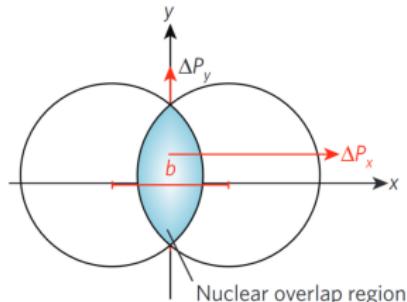


Flow in HI Collisions

- QGP is often modeled as a **hydrodynamic fluid** → initial spacial anisotropies result in momentum-space anisotropies
- Flow harmonics v_n → quantify the ϕ -space anisotropy

$$\frac{dN}{d\phi} = A \cdot \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \bar{\Psi}_n)] \right)$$

- v_2 is most closely correlated with the initial-state geometry
- v_2 scales with parton number → flow is contributed on the parton level → **evidence of deconfinement**
- Hydrodynamic models → QGP is a near *perfect fluid*



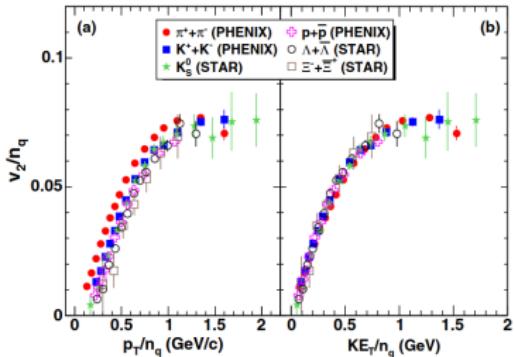
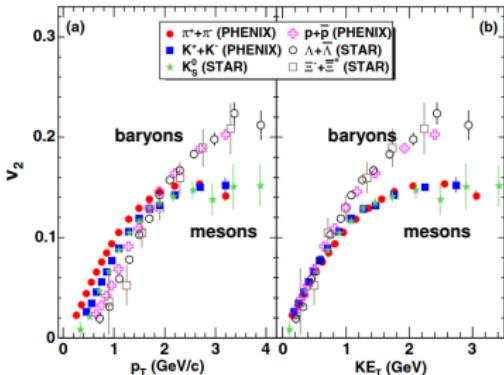
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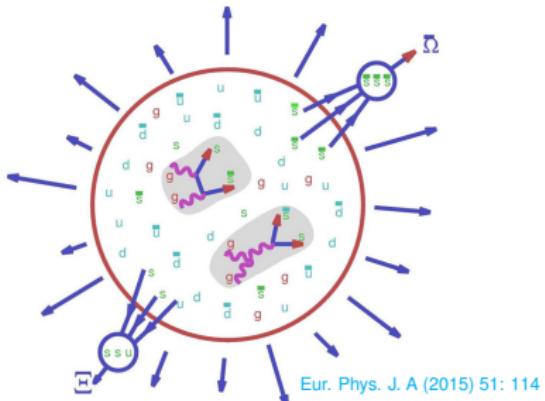
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Phys. Rev. Lett. 98, 162301



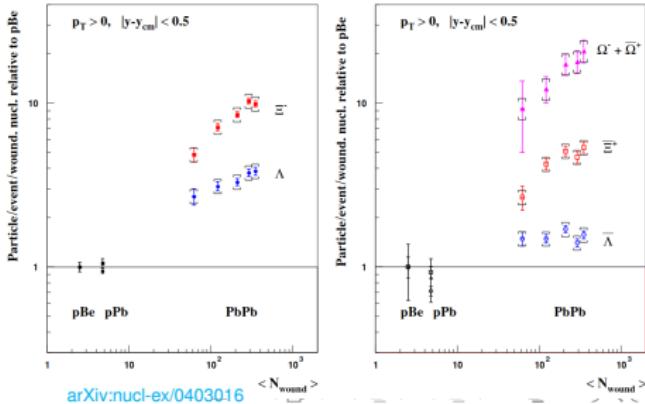
Strangeness Enhancement in HI Collisions

- QGP state → increased production of s and \bar{s} quarks
- Expect an yield-increase in strange particles
 - $\Lambda(uds)$, $\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$
 - $\Xi(dss)$, $\bar{\Xi}(\bar{d}\bar{s}\bar{s})$
 - $\Omega(sss)$, $\bar{\Omega}(\bar{s}\bar{s}\bar{s})$
- Enhancement increases with strangeness and multiplicity → **consistent with QGP formation**



Eur. Phys. J. A (2015) 51: 114

Strangeness enhancement observed by NA57 at SPS (CERN)

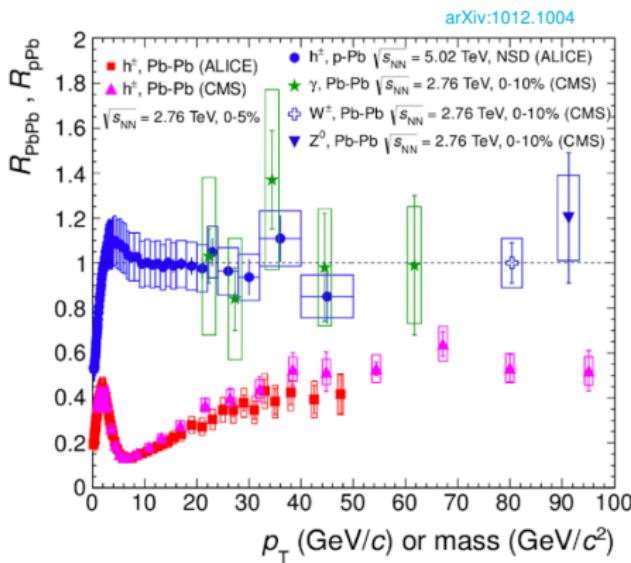


Charged Particle Suppression

- Charged hadrons **heavily suppressed** in central collisions, but not in peripheral collisions
- Charged-hadron R_{AA} : measure of the suppression of charged hadrons in AA collisions as compared to pp collisions

$$R_{AA}^{\text{ch}}(p_T) = \frac{dN_{\text{ch}}^{\text{AA}} / dp_T}{\langle N_{\text{coll}} \rangle dN_{\text{ch}}^{\text{pp}} / dp_T}$$

- No suppression in small systems (pp, pPb)
- Colorless objects (γ , W^\pm , Z) are not suppressed
- Partons **lose energy via color interactions** as they traverse the QGP



Jets as Probes of the QGP

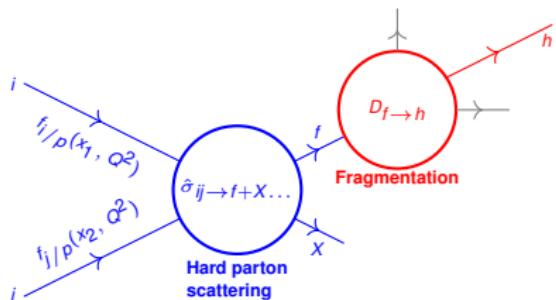
Hard processes in pp

- **Hard processes:** high-energy interaction between quarks and gluons
- Hard-process → short-distance physics of partons \otimes long-distance physics of hadrons

Cross-section factorization in pp collisions

$$\begin{aligned} d\sigma^{p+p \rightarrow h+X} &= \sum_f d\sigma^{p+p \rightarrow f+X} \otimes D_{f \rightarrow h}(z, \mu^2) \\ &= \sum_{i,j,X,f,\dots} f_{i/p}(x_1, Q^2) \otimes f_{j/p}(x_2, Q^2) \otimes \hat{\sigma}_{ij \rightarrow f+X\dots} \otimes D_{f \rightarrow h}(z, \mu^2) \end{aligned}$$

- We use hard processes in pp collisions as a reference when we study QGP medium effects



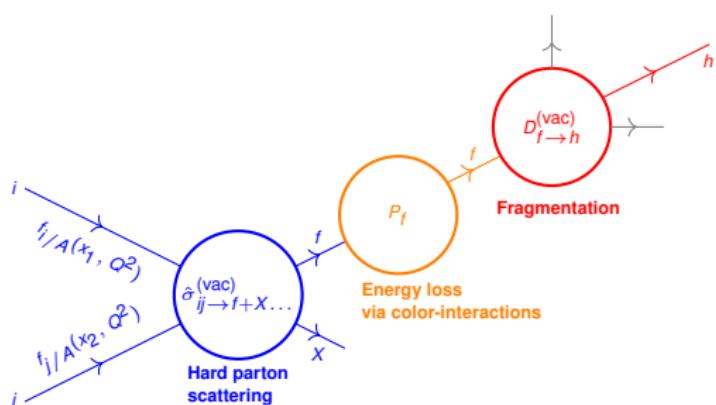
- Cross-section in vacuum is perturbatively calculable!
- Fragmentation is non-perturbative → must rely on QCD-inspired models
- Leading hadron → **hard probe**

Hard Processes in AA

- Hard processes in AA: high-energy interaction between quarks and gluons, followed by the production of QGP if system reaches sufficient energy density
- Hard-process time-scales → short-distance physics of partons \otimes energy loss of partons in the QGP \otimes long-distance physics of hadrons

Cross-section factorization in AA collisions

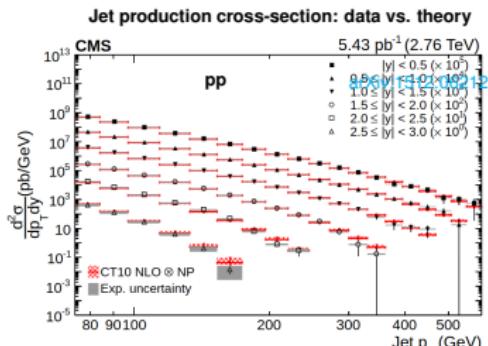
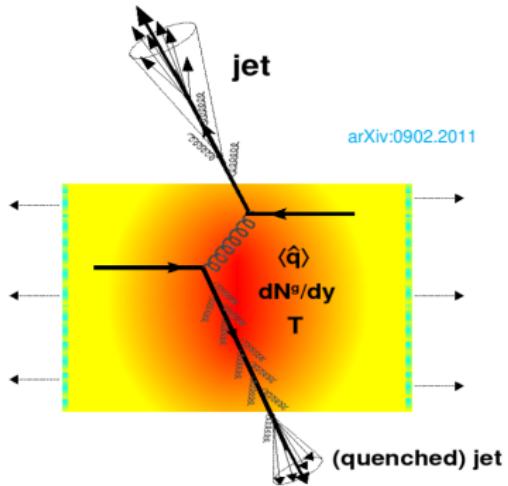
$$d\sigma^{A+A \rightarrow h+X} = \sum_f d\sigma_{(\text{vac})}^{A+A \rightarrow f+X} \otimes P_f(\Delta E, L, \hat{q}) \otimes D_{f \rightarrow h}^{(\text{vac})}(z, \mu^2)$$



- Factorization theorems unknown for processes embedded in a QGP medium
- Vacuum-like hard-scattering and fragmentation
- How is energy transferred to the medium?
 - Collisional energy loss
 - ▶ Elastic scattering with medium, high p
 - Radiative energy loss
 - ▶ Inelastic scattering with medium (gluon Bremsstrahlung), low p

Jets

- A jet is
 - the result of a **high- Q^2** parton-parton interaction
 - a **collimated spray of hadrons** resulting from parton fragmentation
 - a **self-generating hard-probe** of the QGP
- Jets are **well calibrated** in small systems (pp , e^+e^-)
- Jets are often produced in back-to-back pairs
- $\tau_{\text{hard-scatter}} \ll \tau_{\text{QGP-formation}} \rightarrow \text{initial state unaffected by medium}$
- Use **relative jet yields** in pp and $PbPb$ to measure medium properties



Jets in Experiment

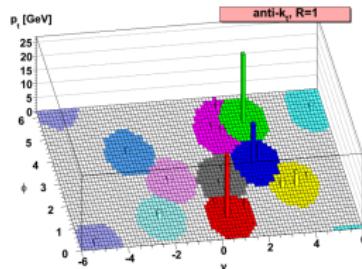
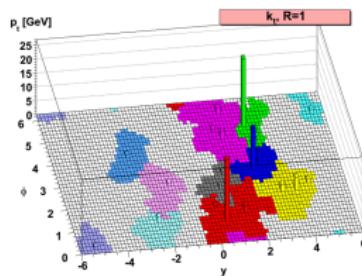
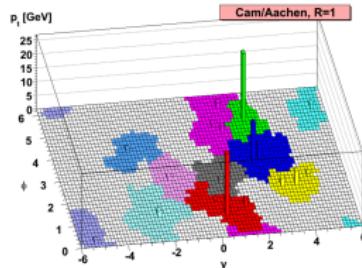
- A jet is the result of a **jet algorithm**, which is a computational process to cluster groups of collimated particles
- There are many types of jet algorithms, often differentiated by their choice of “distance parameter”

$$d_{ij} = \min(p_{T,i}^{2k}, p_{T,j}^{2k}) \frac{\Delta R_{ij}^2}{R^2}$$

$k = 0 \rightarrow$ Cambridge-Aachen algorithm

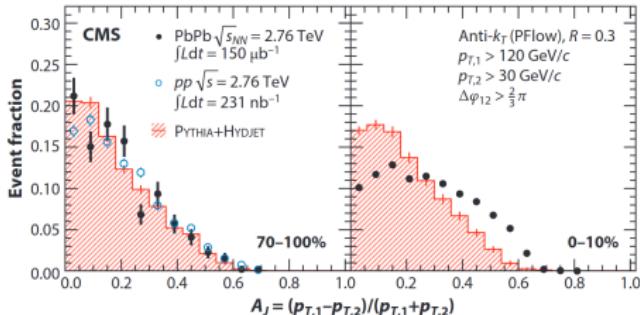
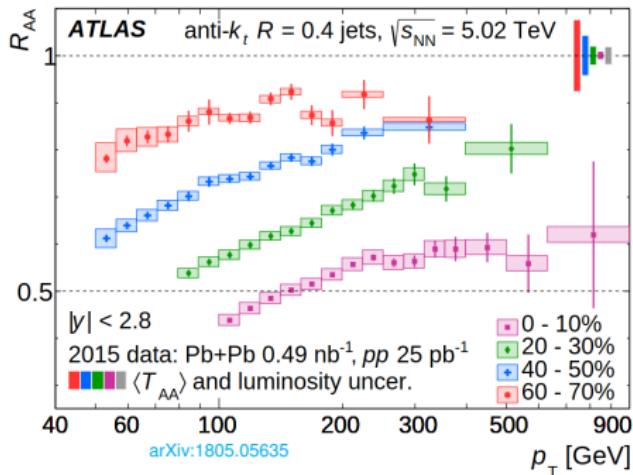
$k = 1 \rightarrow k_T$ algorithm

$k = -1 \rightarrow$ anti- k_T algorithm



- Iteratively cluster pairs of tracks with smallest d_{ij} and “build” jets

Jet Suppression and Asymmetry



- Jet R_{AA} : measure of the suppression of jet production in AA collisions as compared to pp collisions

$$R_{AA}^{\text{jet}}(p_T) = \frac{dN_{\text{jet}}^{\text{AA}}/dp_T}{\langle N_{\text{coll}} \rangle dN_{\text{jet}}^{\text{pp}}/dp_T}$$

- We expect asymmetric suppression in dijet events, since one jet will interact with more QGP than the other
- Quantify via dijet-asymmetry A_J

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

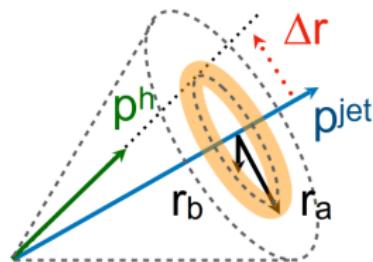
- Jet suppression & asymmetry → **consistent with presence of QGP**
- Not seen in small systems (pp, pPb)

Jet Shapes in HI Collisions

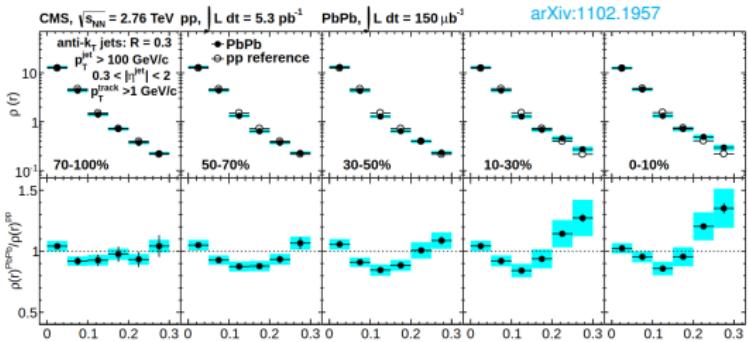
HIN-18-020

- The **jet shape** is the transverse momentum weighted distribution of particles around the jet axis

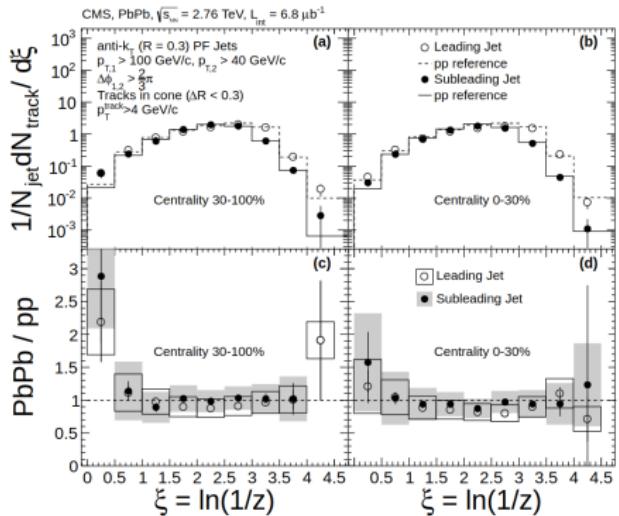
$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in [r_a, r_b]} p_T^{\text{ch}}}{p_T^{\text{jet}}}$$



- Jets are **broader** in central collisions
- Consistent with picture of a medium-modified parton cascade
- Energy is “pushed out” of the sides of the jet cone via broadening



Jet Fragmentation in HI Collisions



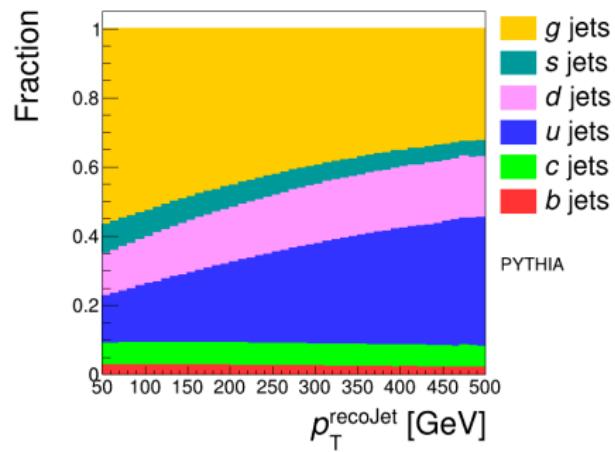
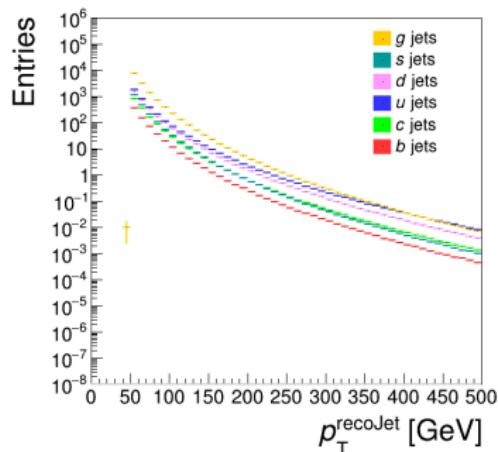
- Parametrize in-jet energy distribution via variables ξ and z

$$\xi = \ln \frac{1}{z}, \quad z = \frac{p_{||}^{\text{track}}}{p_{\perp}^{\text{jet}}}$$

- Fragmentation functions in PbPb consistent with $pp \rightarrow \text{fragmentation}$ is vacuum-like
- Partons lose energy prior **prior to fragmentation**, then redistribute their remaining energy as they would in vacuum

Jet Flavor

- In MC, we know the jet's initial fragmenting parton → **jet flavor**
- *Quark jets*: jets resulting from fragmenting u,d,s,c,b quarks
- *Gluon jets*: jets resulting from g fragmentation
 - Higher multiplicity due to gluon self-splitting
- In data, we cannot know the jet-flavor directly → must infer from other observables



***b*-jet measurements with CMS**

CMS Detector

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2$ $\sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2$ $\sim 9.6\text{M}$ channels

arXiv:1706.04965

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

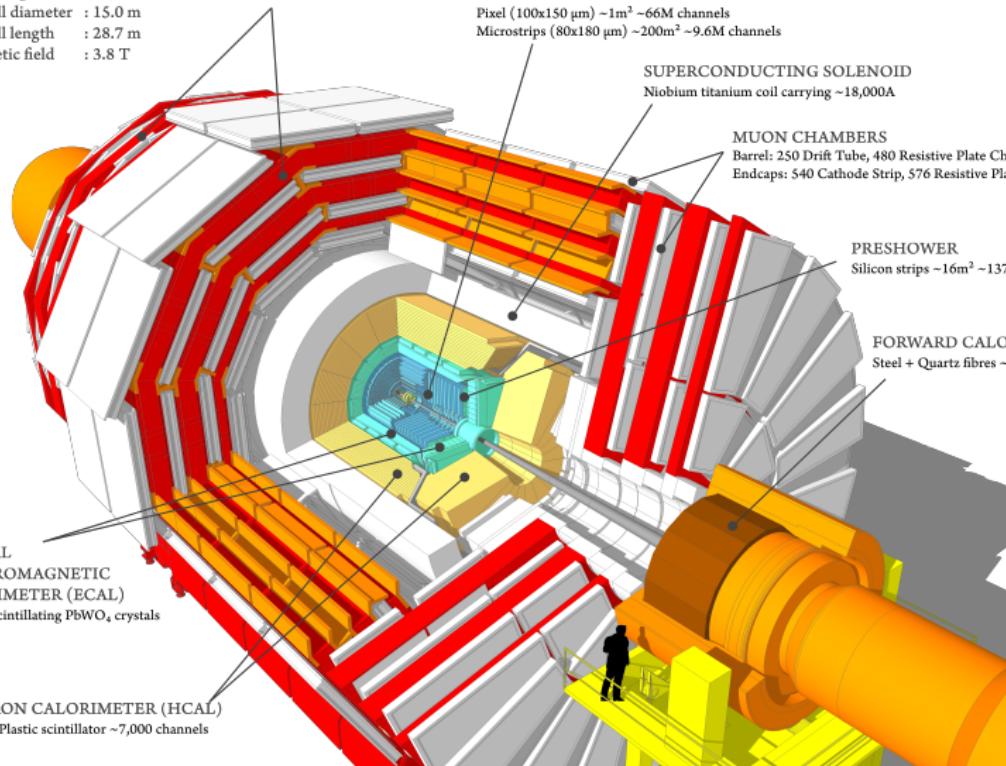
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2$ $\sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

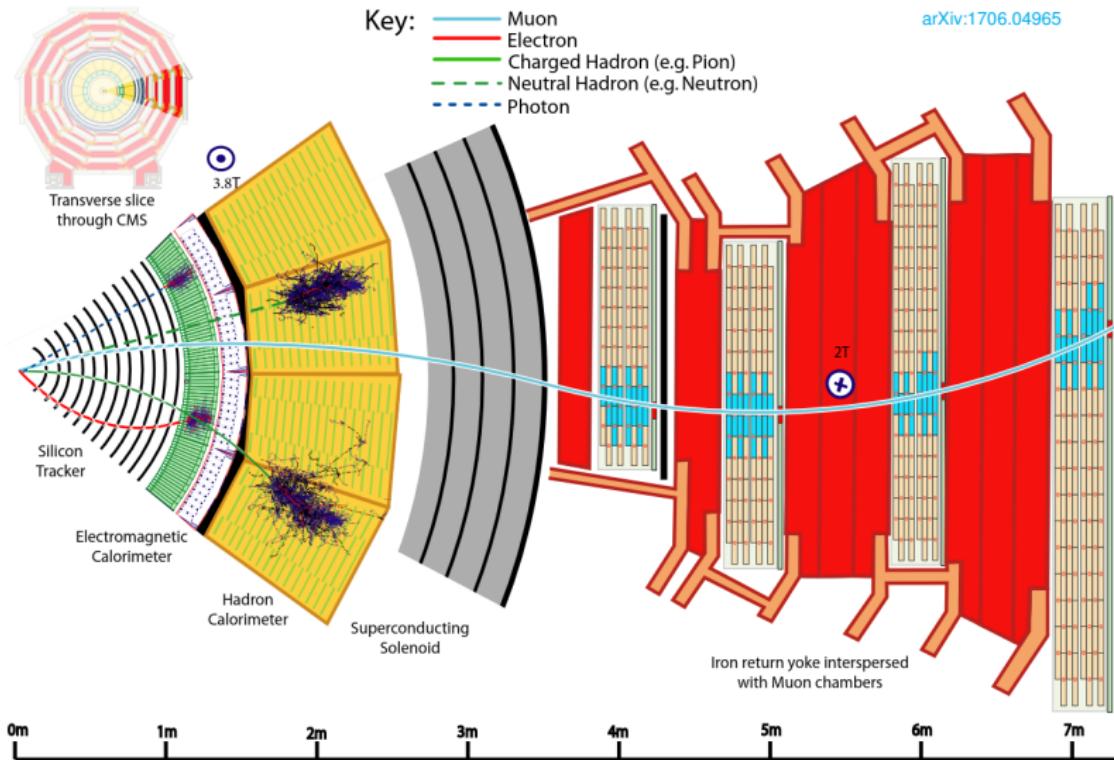
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



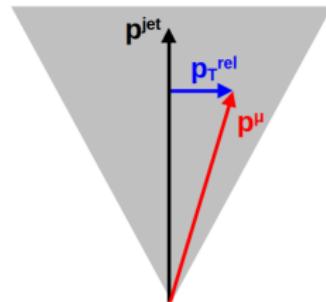
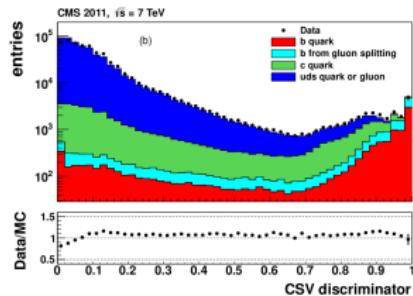
CMS Detector

arXiv:1706.04965



b-jet Identification

- Many reconstructed objects can be used to discriminate between *b* and light-jets
 - Tracks
 - Vertices
 - Leptons
- Combined-secondary-vertex (CSV) discriminator
 - Combines vertex (and secondary vertex) information with track-based lifetime info in a complicated algorithm
 - *b*-jets tend to contain secondary vertices
 - Succeeded by *DeepCSV*, a neural-network-based discriminator
- Muon rel- p_T
 - Measures muon's transverse momentum relative to jet-axis
 - *b*-quarks tend to impart more transverse momentum into daughter muons



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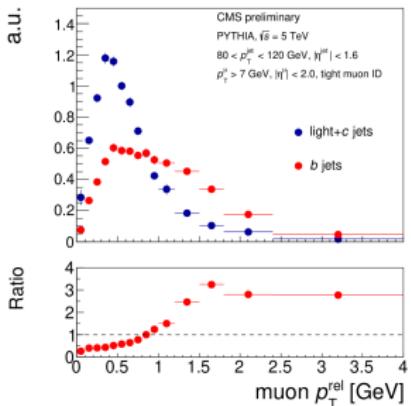
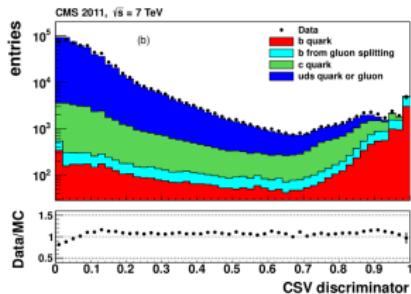
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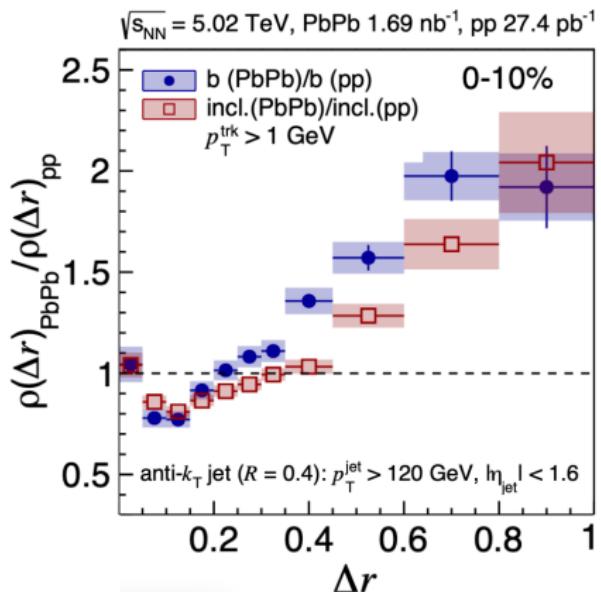
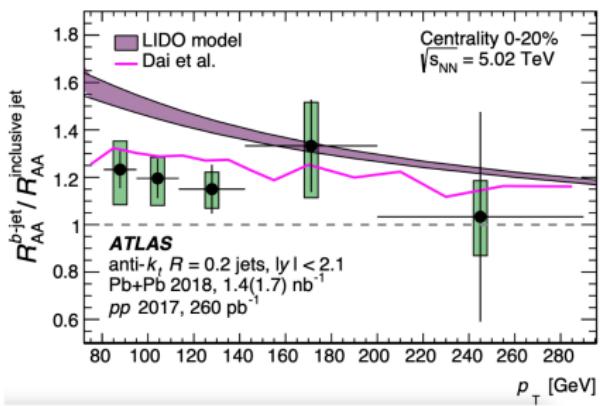
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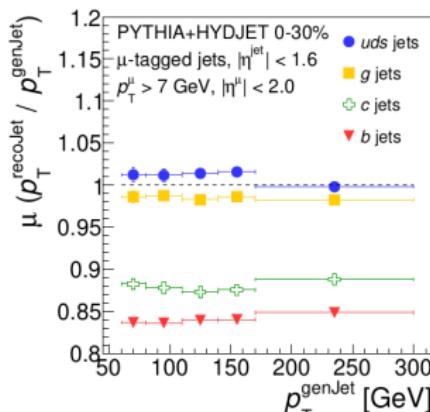
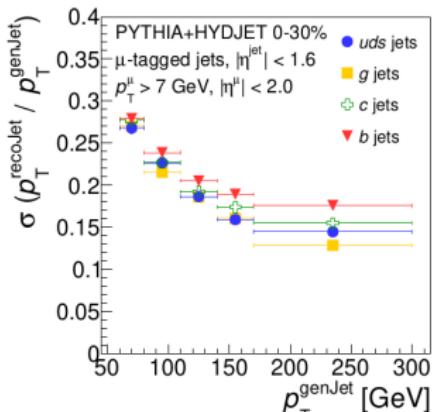
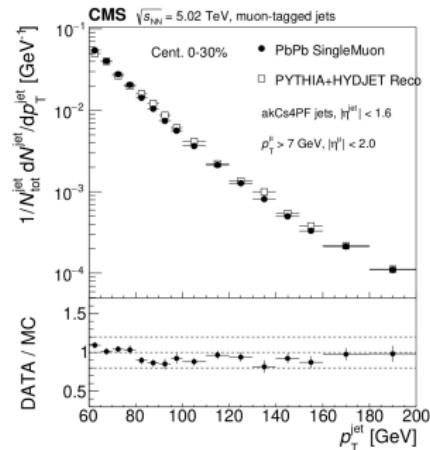
b-jet Results

- *b*-jet R_{AA} and jet-shape have been measured
- *b*-jets are **less suppressed** and **broader**

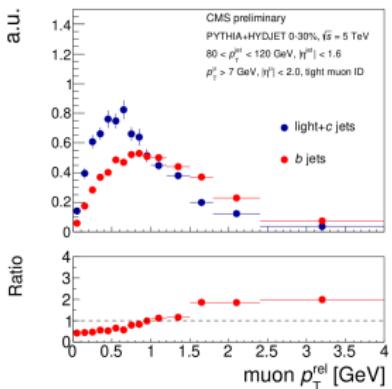
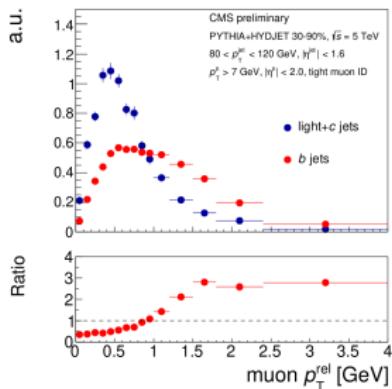
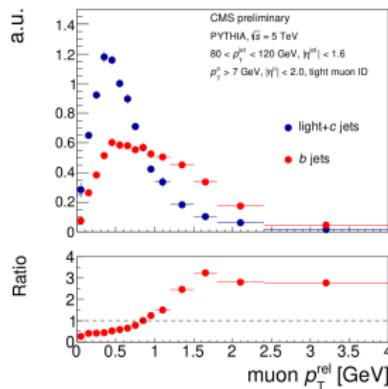
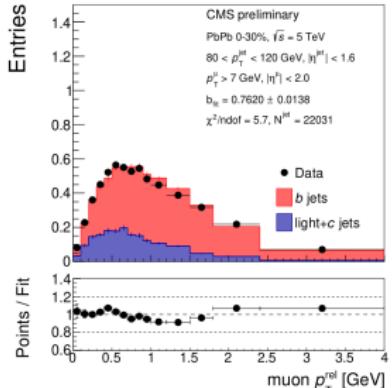
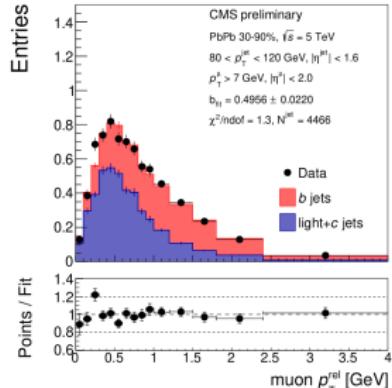
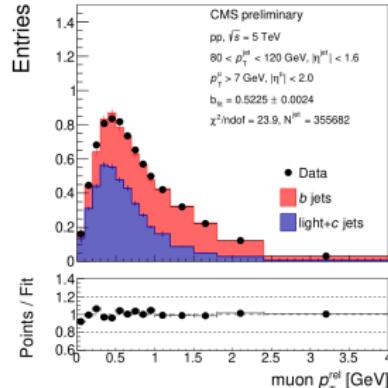


Muon-tagged Jets

- Muon-tagged jets are well described by data
- μ -tagged b and c -jets are under-reconstructed \rightarrow neutrino production
- b jets have worse reconstruction resolution than lights

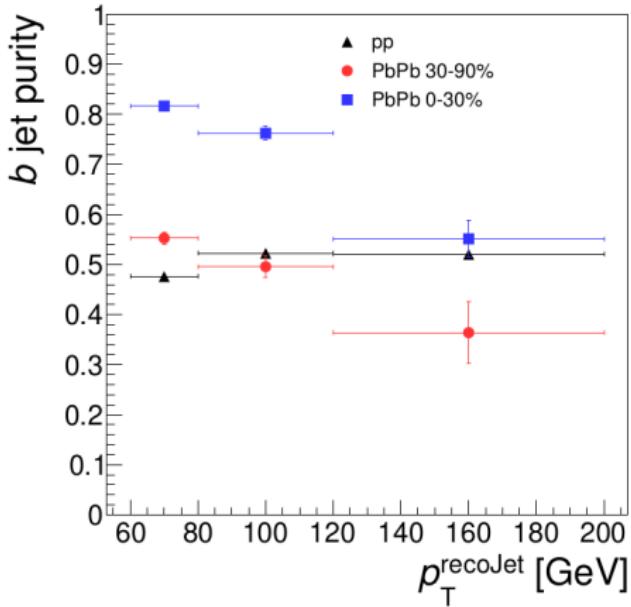


Muon rel- p_T Template Fitting



b-jet Purity and Fraction

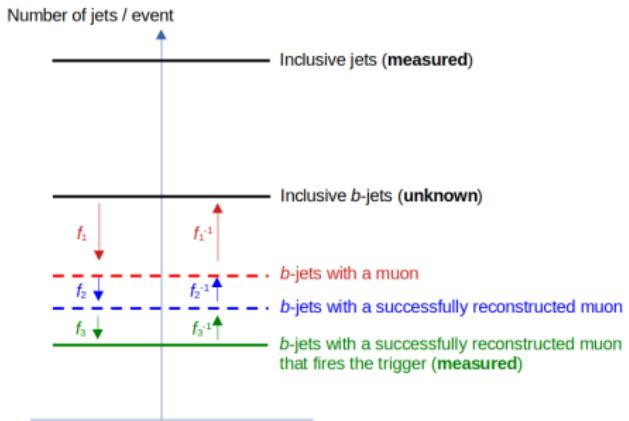
- *b*-purity measurements from template fits give us an estimated ***b*-jet spectra**
- Correct for trigger, muon-reconstruction, and muon-tagging
- Obtain an inclusive *b*-jet fraction
- pp/PbPb differences in *b*-jet fraction could indicate mass dependence on jet-quenching
- Work ongoing!



b-jet Purity and Fraction

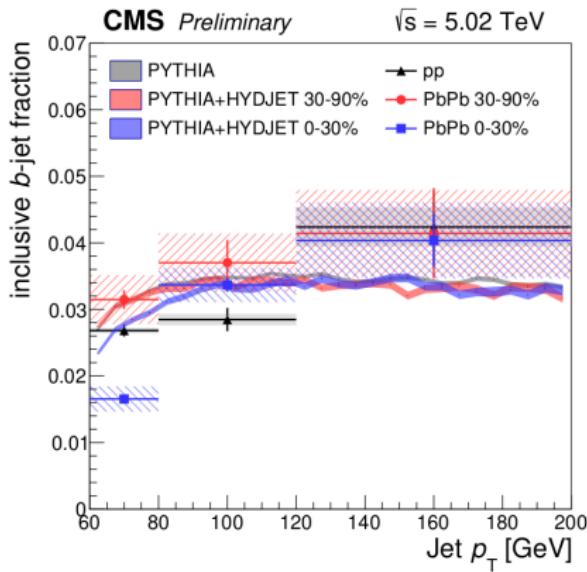
- *b*-purity measurements from template fits give us an estimated ***b*-jet spectra**
- Correct for trigger, muon-reconstruction, and muon-tagging
- Obtain an inclusive *b*-jet fraction
- pp/PbPb differences in *b*-jet fraction could indicate mass dependence on jet-quenching
- Work ongoing!

Correction Factors



b-jet Purity and Fraction

- *b*-purity measurements from template fits give us an estimated ***b*-jet spectra**
- Correct for trigger, muon-reconstruction, and muon-tagging
- Obtain an inclusive *b*-jet fraction
- pp/PbPb differences in *b*-jet fraction could indicate mass dependence on jet-quenching
- Work ongoing!



Summary

- QCD → partons can break free of strong-force bonds at sufficient energy density
- Create deconfined state via relativistic heavy-ion collisions
- Use jets as in-situ probes of the QGP medium
- We can use lepton tagging to identify b -jets → study mass-dependence of medium interactions
- Input into QGP loss-energy models

THANK YOU!