Thesis Preliminary Exam

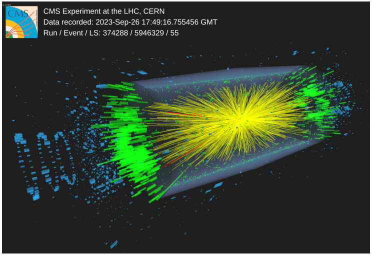
Clayton Bennett

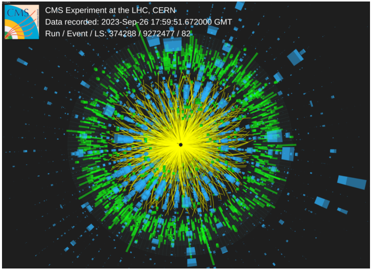
University of Illinois at Chicago
The CMS Collaboration

December 4, 2023

Outline

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

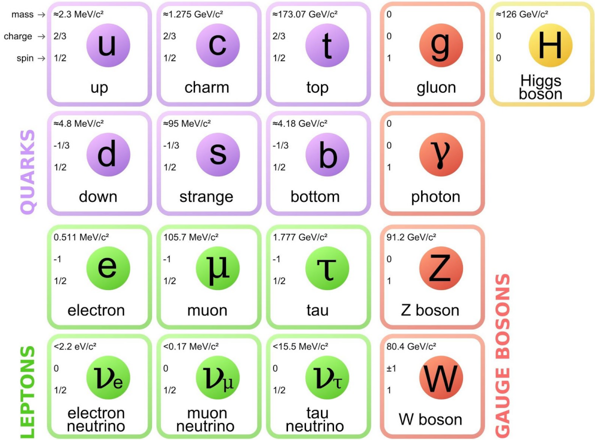




First 2023 PbPb collision at 5.36 TeV

The Quark Gluon Plasma

The Standard Model of Particle Physics



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 $\rightarrow \gamma$
  - EW $\rightarrow W^{\pm}, Z$
  - QCD $\rightarrow g$
- 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

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

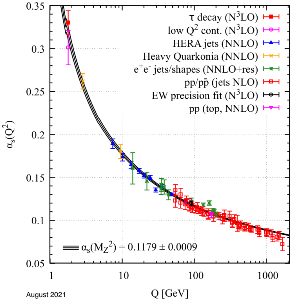
- QCD is a quantum field theory with **asymptotic freedom**

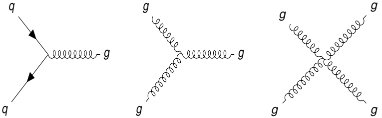
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \left[\alpha_s(\mu^2)\frac{(11n_c - 2n_f)}{12\pi}\right]\ln\left(\frac{Q^2}{\mu^2}\right)}$$

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

- Large Q^2 → strong-force coupling gets **weaker**

Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

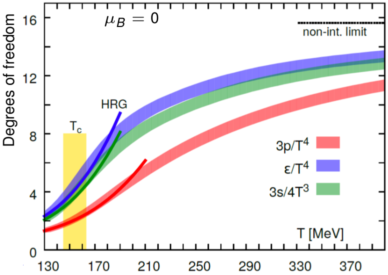




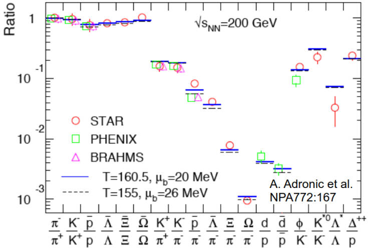
Deconfinement in heavy-ion collisions

- Lattice QCD predicts that partons break away from strong-force bonds at sufficent energy density $\rightarrow$ **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: $\boldsymbol{T_c \approx 158.0 \pm 0.6}$ **MeV**
- Evidence of $T_{\mathrm{exp}} > T_c$
  - Estimations of particle ratios
    - $dn_i \sim \exp\{(E_i - \mu_B)/T\}\, d^3p_i$
    - $\frac{\bar{p}}{p} = \exp\{-2\mu_B/T\}$
    - $\frac{K}{\pi} = \exp\{-(E_K - E_\pi)/T\}$
- System at extreme T and P $\rightarrow$ deconfined phase of quarks and gluons $\rightarrow$ **Quark Gluon Plasma** (QGP)

Lattice QCD phase change

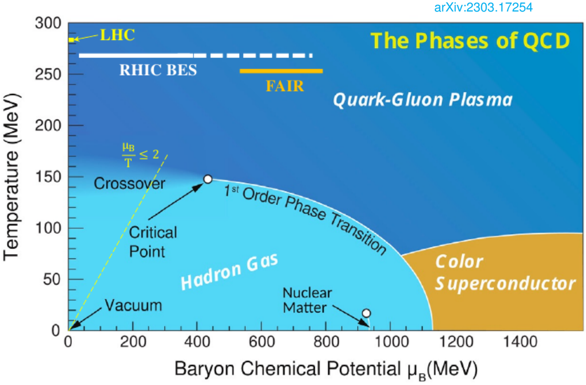


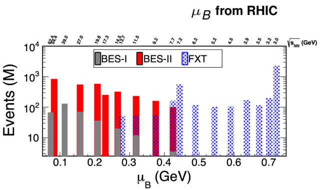
Particle ratios at RHIC

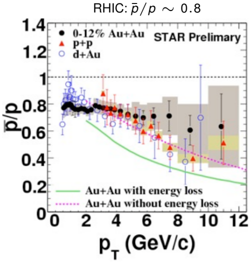


Phases of QCD

- For $\frac{\mu_B}{T} \leq \mathbf{2}$, 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 $\rightarrow$ map the phase-diagram by varying μ_B

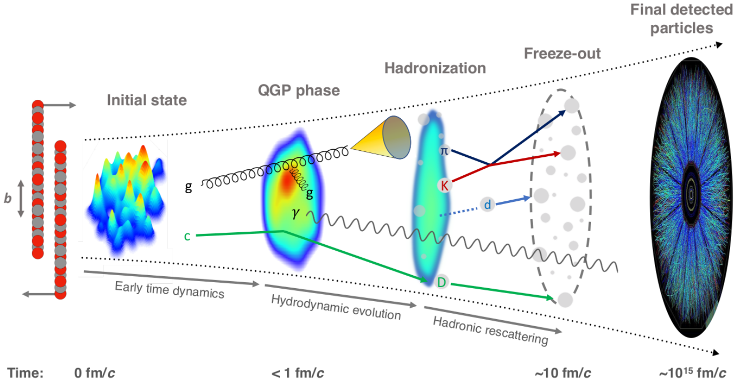




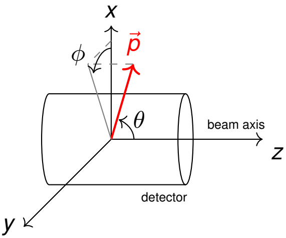


QGP at Particle Colliders

- 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



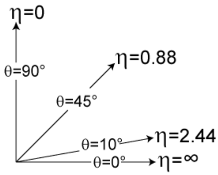


fig. ref.

- Detector geometry warrants the use of cylindrical coordinate system

$$\text{transverse momentum}: p_{\mathrm{T}} = |\vec{p}| \sin\theta$$

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

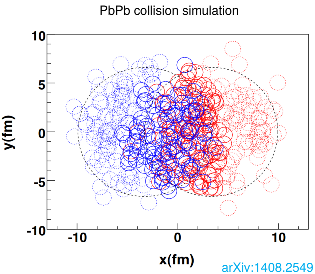
$$\text{psuedo-rapidity}: \eta = \frac{1}{2}\ln\left(\frac{p+p_z}{p-p_z}\right)$$

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

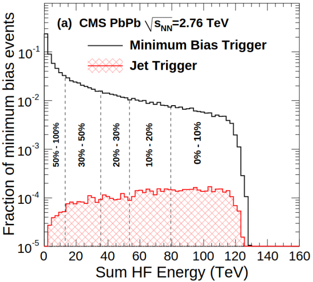
- Why are these variables common in particle physics experiments?
  - $\sum_i p_{\mathrm{T},i} = 0 + \epsilon$
  - Δy is invariant for boosts along z-axis

Centrality

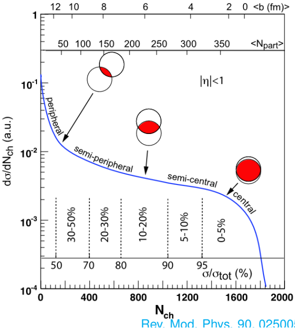
- **Centrality** is a measure of the nuclear overlap in a collision event
- Derived from multiplicity distibutions, forward-energy distribution
- Essential for categorizing events based on QGP-formation status
- Relate observables back to impact parameter via Glauber model



arXiv:1408.2549



arXiv:1408.2549



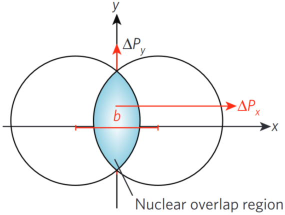
Rev. Mod. Phys. 90, 025005

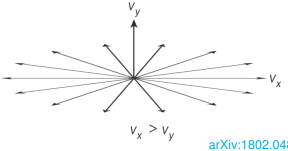
Flow in HI Collisions

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

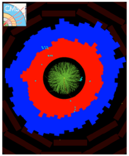
$$\frac{dN}{d\phi} = A \cdot \left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \bar{\Psi}_n)\right]\right)$$

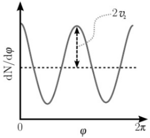
- v_2 is most closely correlated with the initial-state geometry
- v_2 scales with parton number $\rightarrow$ flow is contributed on the parton level $\rightarrow$ **evidence of deconfinement**
- Hydrodynamic models $\rightarrow$ QGP is a near *perfect fluid*





arXiv:1802.04801





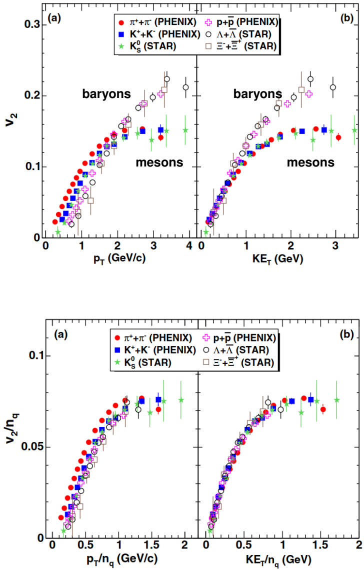
Flow in HI Collisions

Phys. Rev. Lett. 98, 162301

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

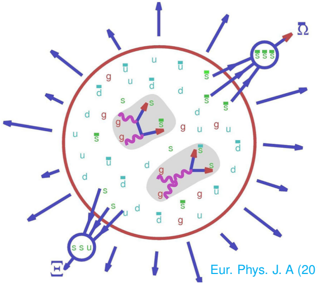
$$\frac{dN}{d\phi} = A \cdot \left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \bar{\Psi}_n)\right]\right)$$

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



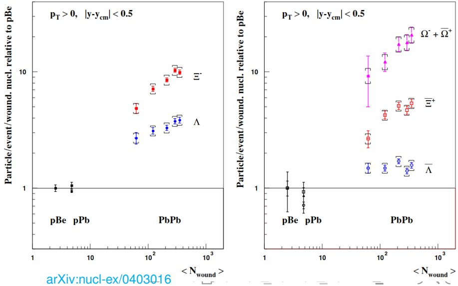
Strangeness Enhancement in HI Collisions

- QGP state $\rightarrow$ 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 $\rightarrow$ **consistent with QGP formation**



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

Strangeness enhancement observed by NA57 at SPS (CERN)



arXiv:nucl-ex/0403016

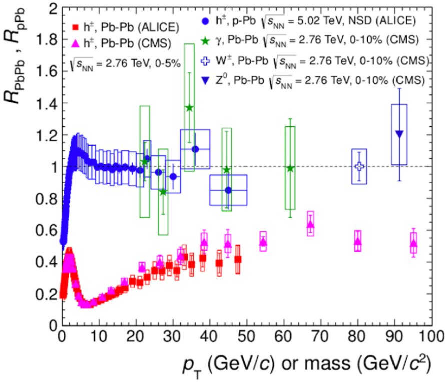
Charged Particle Suppression

- 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

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

- 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

arXiv:1012.1004



Jets as Probes of the QGP

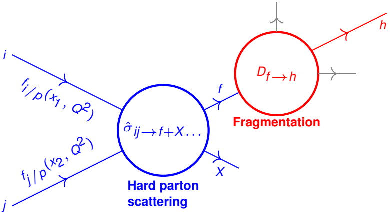
Hard processes in pp

- **Hard processes**: high-energy interaction between quarks and gluons
- Hard-process $\rightarrow$ short-distance physics of partons $\bigotimes$ long-distance phyiscs of hadrons

Cross-section factorization in pp collisions

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

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



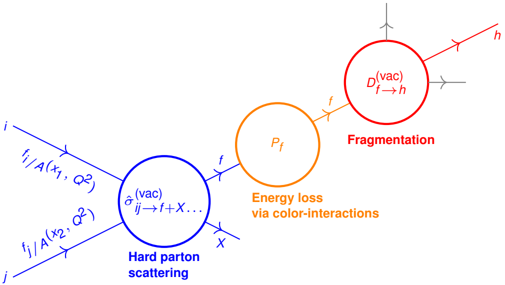
- Cross-section in vacuum is perturbatively calculable!
- Fragmentation is non-perturbative $\rightarrow$ must rely on QCD-inspired models
- Leading hadron $\rightarrow$ **hard probe**

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 $\rightarrow$ short-distance physics of partons $\bigotimes$ energy loss of partons in the QGP $\bigotimes$ long-distance phyiscs of hadrons

Cross-section factorization in AA collisions

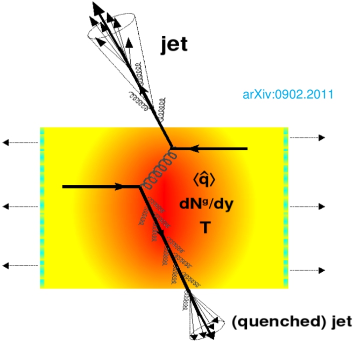
$$d\sigma^{A+A\rightarrow h+X} = \sum_f d\sigma^{A+A\rightarrow f+X}_{(\text{vac})} \bigotimes P_f(\Delta E, L, \hat{q}) \bigotimes D^{(\text{vac})}_{f\rightarrow h}(z, \mu^2)$$



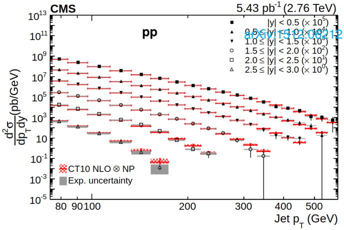
- Factorization theorems unkown for processes embedded in a QGP medium
- Vacuum-like hard-scattering and fragmentation
- How is energy transfered to the medium?
  - Collisional energy loss
    - Elastic scattering with medium, high p
  - Radiative energy loss
    - Inelastic scattering with medium (gluon 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
- $\tau^{\text{hard-scatter}} \ll \tau^{\text{QGP-formation}} \rightarrow$ initial state unaffected by medium
- Use **relative jet yields** in pp and PbPb to measure medium properties



Jet production cross-section: data vs. theory



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"

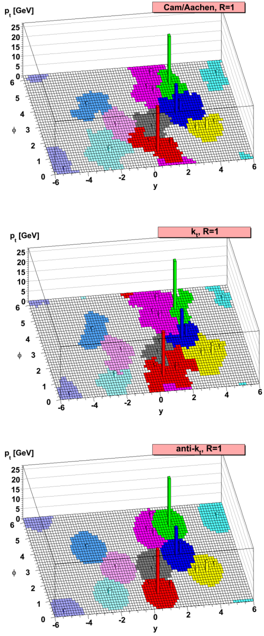
$$d_{ij} = \min(p_{\mathrm{T},i}^{2k}, p_{\mathrm{T},j}^{2k}) \frac{\Delta R_{ij}^2}{R^2}$$

$k = 0 \rightarrow$ Cambridge-Aachen algorithm

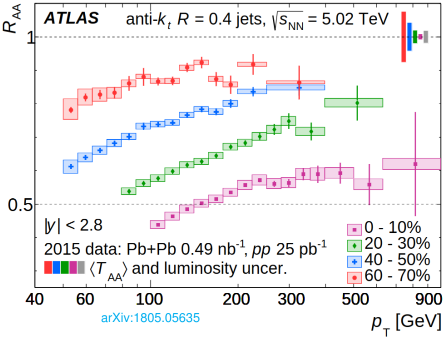
$k = 1 \rightarrow k_\mathrm{T}$ algorithm

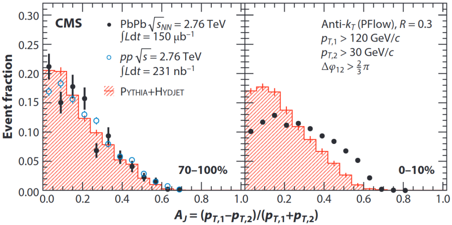
$k = -1 \rightarrow$ anti-k_T algorithm

- 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

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

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

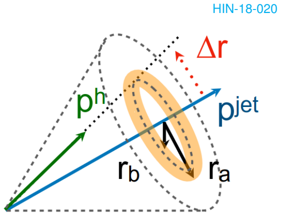
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

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

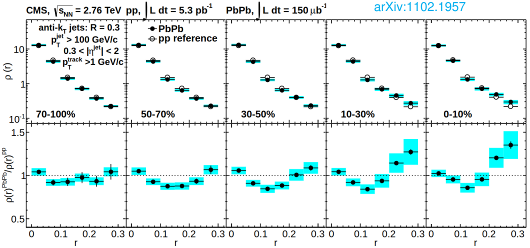
Jet Shapes in HI Collisions

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

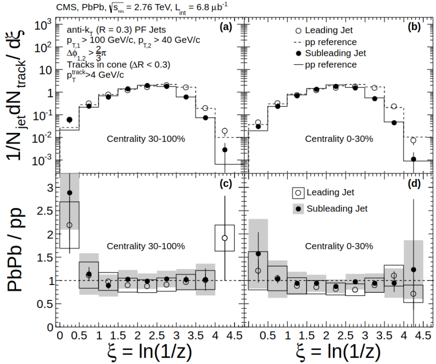
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\sum_{\text{jets}} \frac{\sum_{\text{tracks}\in[r_a,r_b)} p_T^{ch}}{p_T^{jet}}$$



- 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



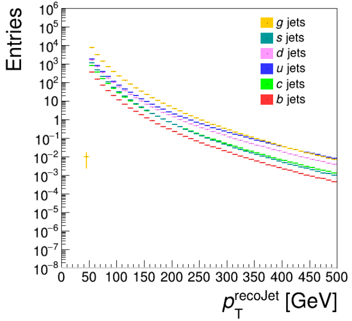
- Parametrize in-jet energy distribution via variables ξ and z

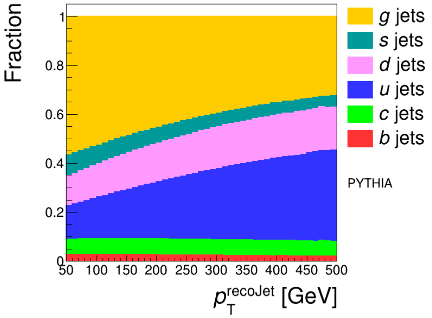
$$\xi = \ln\frac{1}{z}, \quad z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}$$

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

Jet Flavor

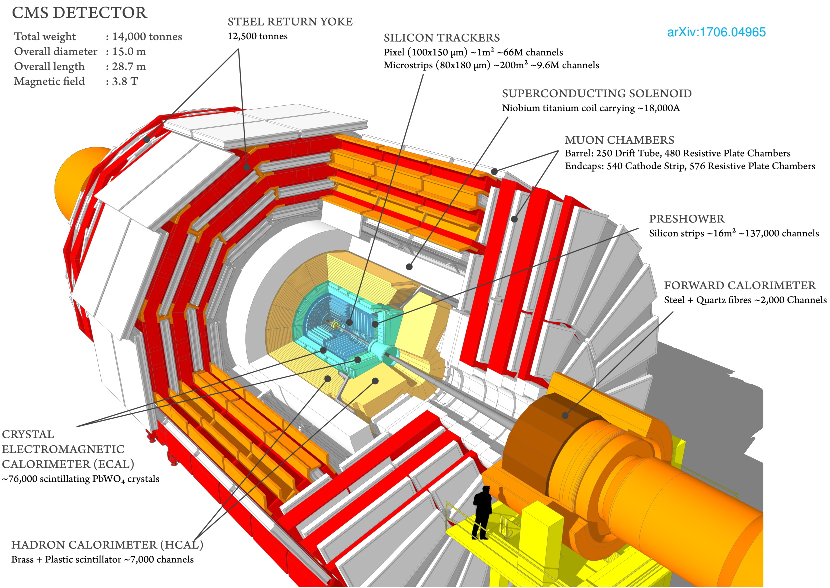
- In MC, we know the jet's initial fragmenting parton $\rightarrow$ **jet flavor**
- *Quark jets*: jets resulting from fragmenting u,d,s,c,b quarks
- *Gluon jets*: jets resulting from g fragmentation
  - Higher mulitplicity due to gluon self-splitting
- In data, we cannot know the jet-flavor directly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





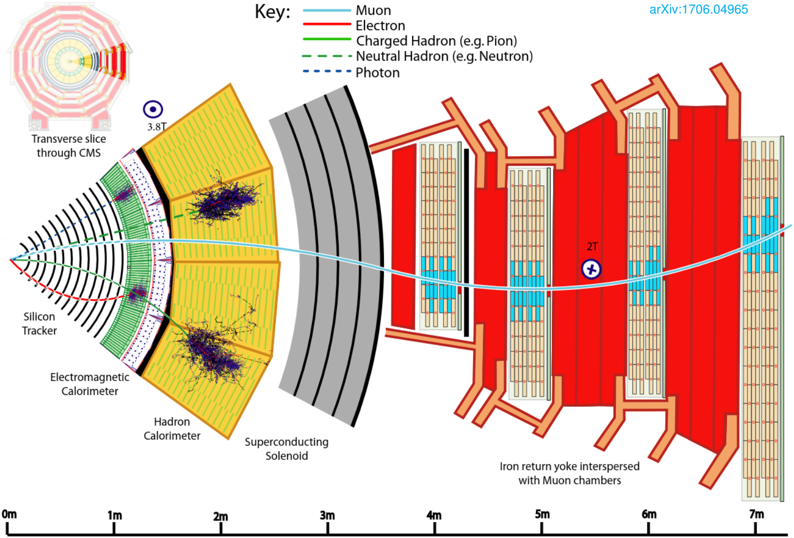
b-jet measurements with CMS

CMS Detector



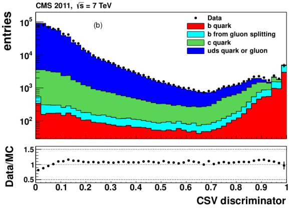
arXiv:1706.04965

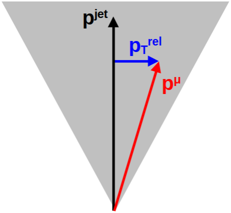
CMS Detector



b-jet Indetification

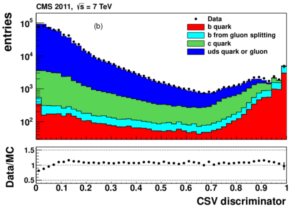
- Many reconstructed objects can be used to discriminate between *b* and light-jets
  - Tracks
  - Vertices
  - Leptons
- Combined-secondary-vertex (CSV) discriminator
  - Combines vertex (and secondary vertex) information with track-based lifetime info in a complicated algorithm
  - *b*-jets tend to 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

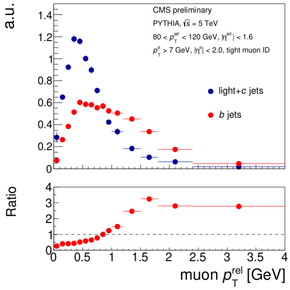




b-jet Indetification

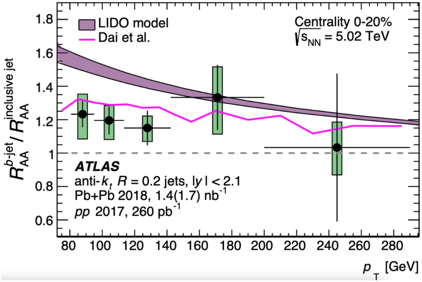
- Many reconstructed objects can be used to discriminate between *b* and light-jets
  - Tracks
  - Vertices
  - Leptons
- Combined-secondary-vertex (CSV) discriminator
  - Combines vertex (and secondary vertex) information with track-based lifetime info in a complicated algorithm
  - *b*-jets tend to 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

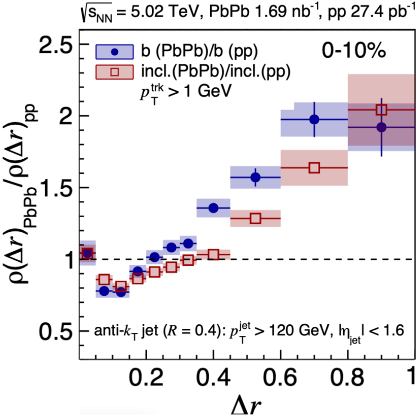




b-jet Results

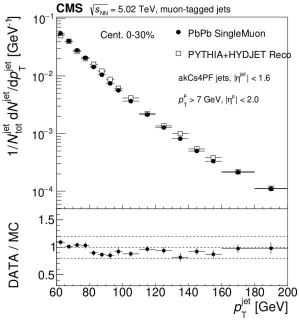
- *b*-jet R_{AA} and jet-shape have been measured
- *b*-jets are **less suppressed** and **broader**

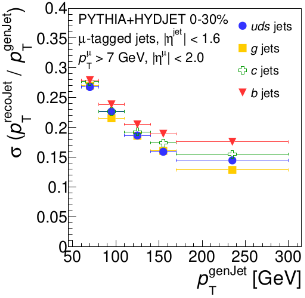


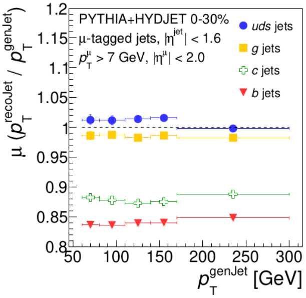


Muon-tagged Jets

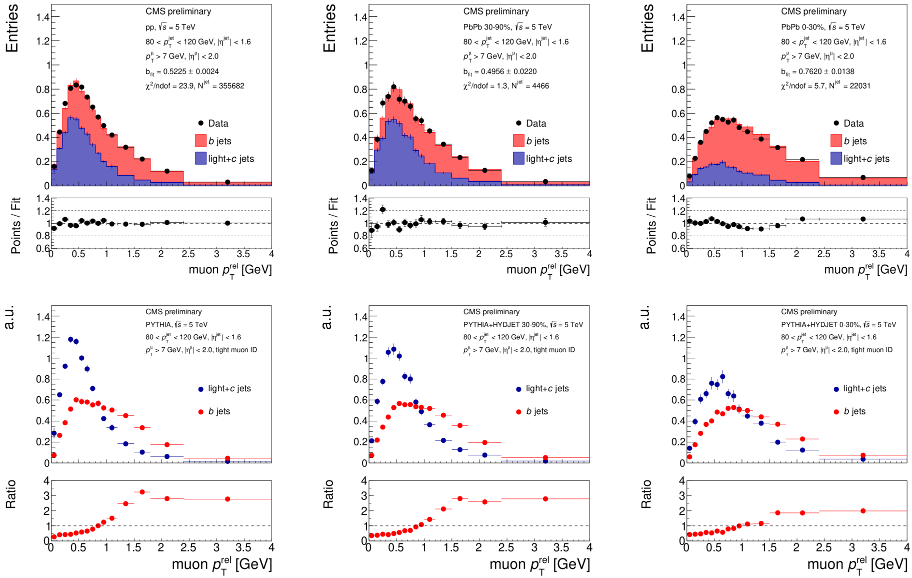
- Muon-tagged jets are well described by data
- μ-tagged *b* and *c*-jets are under-reconstructed $\rightarrow$ neutrino production
- *b* jets have worse reconstruction resolution than lights





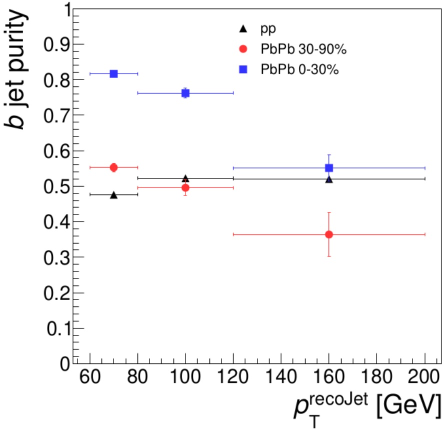


Muon rel-p_T Template Fitting



b-jet Purity and Fraction

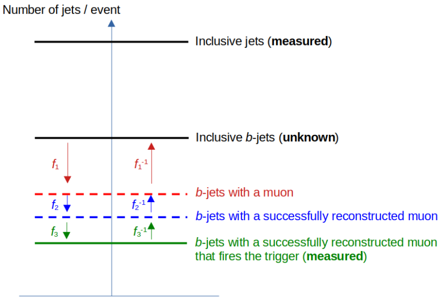
- *b*-purity measurements from template fits give us an estimated ***b*-jet spectra**
- Correct for trigger, muon-reconstruction, and muon-tagging
- Obtain an inclusive *b*-jet fraction
- pp/PbPb differences in *b*-jet fraction could indicate mass dependence on jet-quenching
- Work ongoing!



b-jet Purity and Fraction

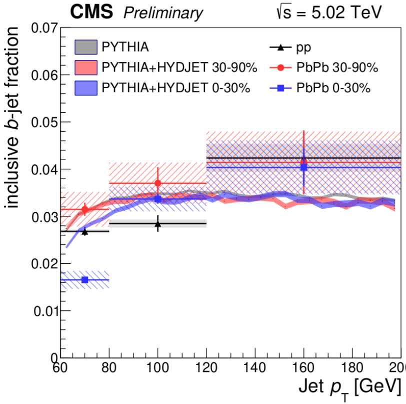
- *b*-purity measurements from template fits give us an estimated ***b*-jet spectra**
- Correct for trigger, muon-reconstruction, and muon-tagging
- Obtain an inclusive *b*-jet fraction
- pp/PbPb differences in *b*-jet fraction could indicate mass dependence on jet-quenching
- Work ongoing!

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 $\rightarrow$ 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 $\rightarrow$ study mass-dependence of medium interactions
- Input into QGP loss-energy models

THANK YOU!