Thesis Preliminary Exam

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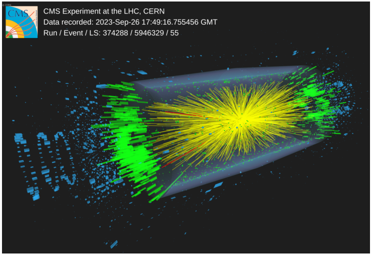
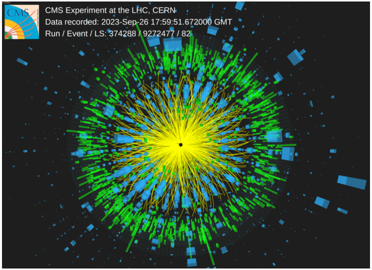
Outline

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

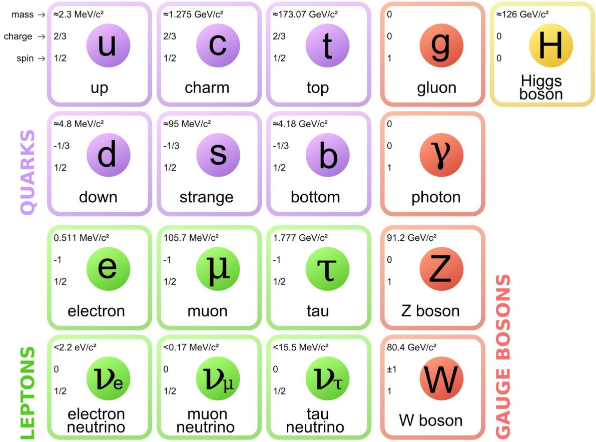




First 2023 PbPb collision at 5.36 TeV

The Quark Gluon Plasma

The Standard Model of Particle Physics



- 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**

Quantum Chromodynamics

- **Quantum chromodynamics** (QCD) is a quantum field theory describing the **strong interaction** between **quarks** and **gluons**
- **Confinement**: fundamental feature of QCD
  - Strong force grows with separationS
  - $q\bar{q} \to q\bar{q} + q\bar{q}$ (particles from vacuum)

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

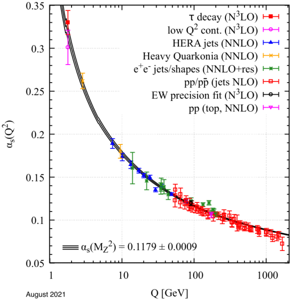
- QCD is a quantum field theory with **asymptotic freedom**

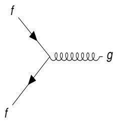
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \left[\alpha_s(\mu^2)\frac{(11n_c - 2n_f)}{12\pi}\right] \ln\left(\frac{Q^2}{\mu^2}\right)}$$

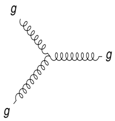
$$\boxed{\lim_{Q\to\infty} \alpha_s(Q^2) \to 0}$$

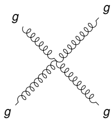
- Large Q^2 $\to$ strong-force coupling gets **weaker**, potential $V_{\rm QCD}$ gets **less attractive**

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



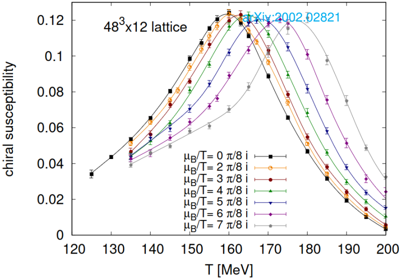






Deconfinement

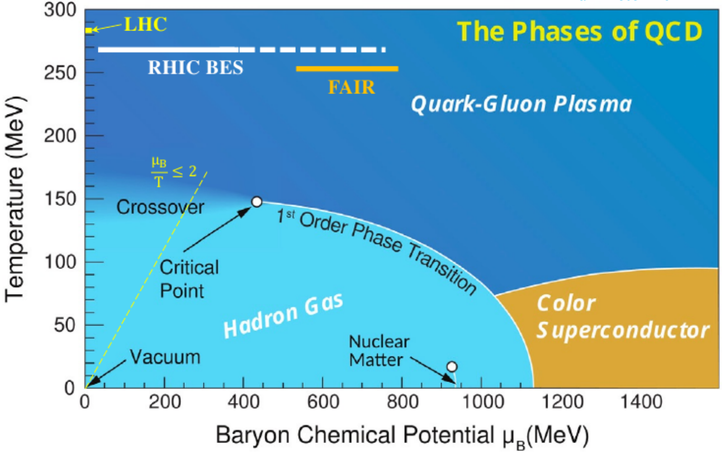
- Lattice QCD predicts a deconfined phase of quarks and gluons known as the **Quark Gluon Plasma** at extreme temperatures and pressures
- At $\mu_B \sim 0$, the critical temperature for this phase-change is $\boldsymbol{T_c \approx 158.0 \pm 0.6}$ **MeV** $\boldsymbol{\approx 1.8 \cdot 10^{12}}$ **K**



Phases of QCD

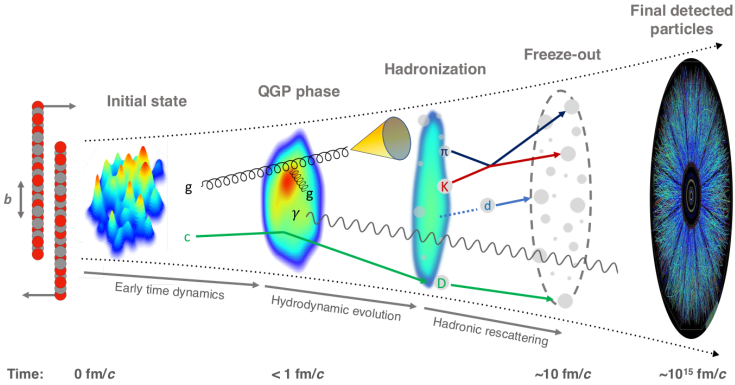
- For $\frac{\mu_B}{T} \leq 2$, QGP-to-hadron phase transition is a **smooth crossover**
- Above some critical point, the QGP-to-hadron transition is expected to become a **first-order phase transition**

arXiv:2303.17254

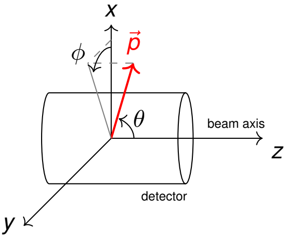


QGP at Particle Colliders

- 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
  - **Strongly-interacting QGP phase** that flows as a relativistic hydrodynamic fluid
  - Medium expansion, cooling, and **hadronization**
  - Hadronic rescattering and **freeze-out**



Kinematics



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

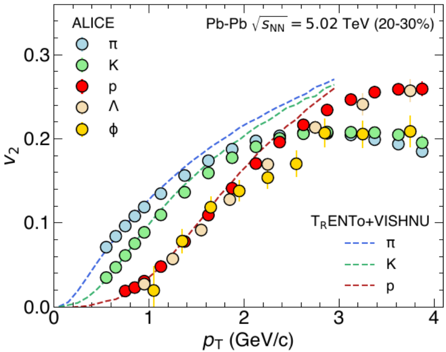
Centrality

Flow in the QGP

- QGP is a hydrodynamic fluid $\rightarrow$ initial spacial anisotropies result in momentum-space anisotropies
- v_n measurements quantify the ϕ-space anisotropy

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

- Flow harmonics v_n are observed to scale with parton number $\rightarrow$ further evidence of deconfinement



Jets as Probes of the QGP

Factorization Theorems in QCD

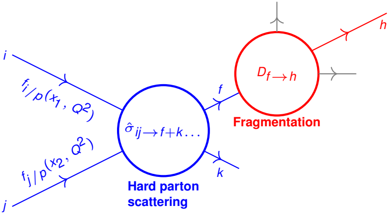
- **Hard processes in pp** $\rightarrow$ short-distance physics of partons $\otimes$ long-distance phyiscs of hadrons

Cross-section factorization in pp collisions

$$d\sigma^{p+p\rightarrow h+X} = \sum_f d\sigma^{p+p\rightarrow f+X} \bigotimes D_{f\rightarrow h}(z, \mu_F^2)$$

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

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



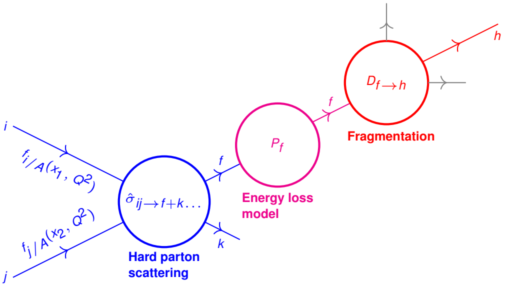
- Cross-section in vacuum is perturbatively calculable!
- Fragmentation is non-perturbative $\rightarrow$ must rely on QCD-inspired models

Factorization Theorems in QCD

- **Hard processes in AA** $\rightarrow$ short-distance physics of partons $\bigotimes$ Model-dependent energey loss of partons in the QGP $\bigotimes$ long-distance phyiscs of hadrons

Cross-section factorization in AA collisions

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



- Factorization theorems unkown for processes embedded in a QGP medium
- Energy loss mechanisms
  - Collisional energy loss
    - Elastic scattering with medium
    - Dominant for heavy quarks
  - Radiative energy loss
    - Inelastic scattering with medium (gluon Bremsstrahlung)
    - Dominant for light quarks

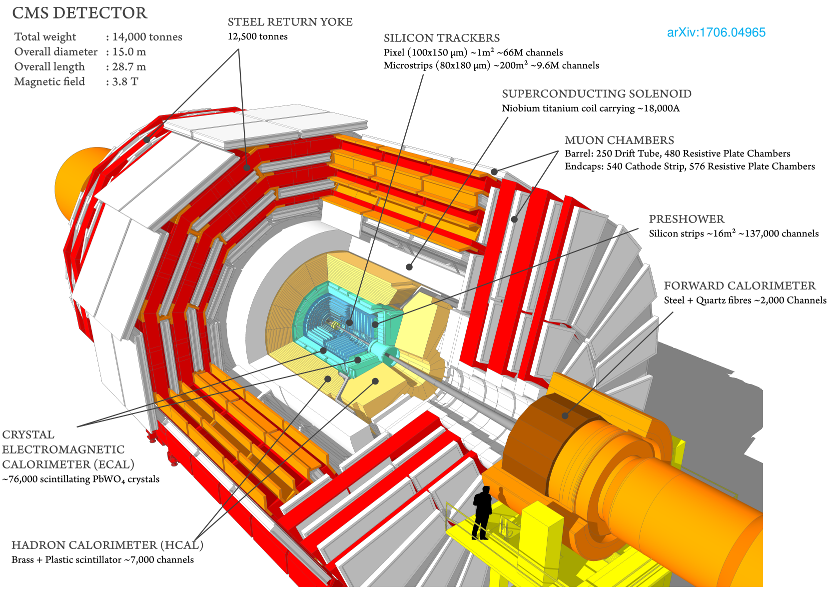
Jets

b-jet measurements with CMS

- Jets resulting from a framgenting *b*-quark are interesting objects because they are good tests many theories
  - Heavy flavor QCD
  - B-meson physics
- Many methods have been deployed to identify *b*-jets
  - Impact Parameter (IP) Significance
    - IP is the distance between the primary vertex and the point of closest approach of a track
    - *b*-jets tend to have wider IP distributions
  - Secondary Vertex Reconstruction
  - *b*-jets tend to have secondary vertices due to in-flight decays
  - Jet Probability
  - Soft Lepton Tagging
  - Deep Learning Techniques

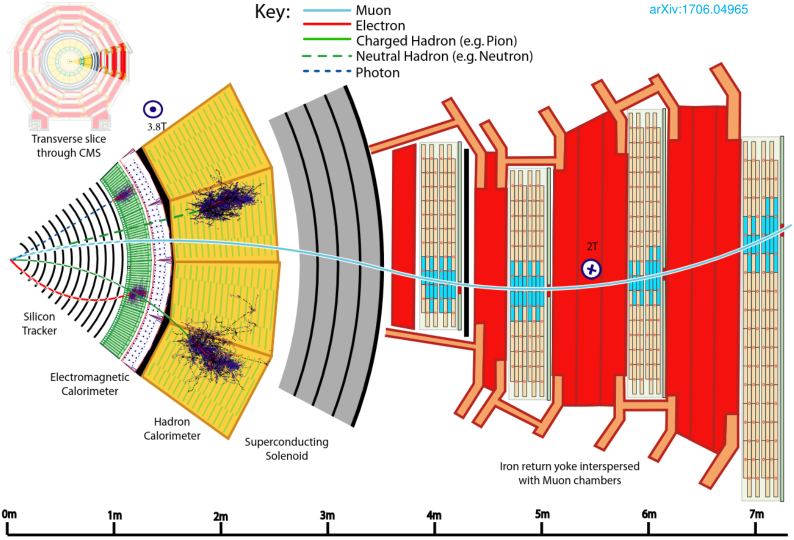
Muon rel-p_T

CMS Detector



arXiv:1706.04965

CMS Detector



Jet Reconstruction in Heavy Ion Collisions