

Thesis Preliminary Exam

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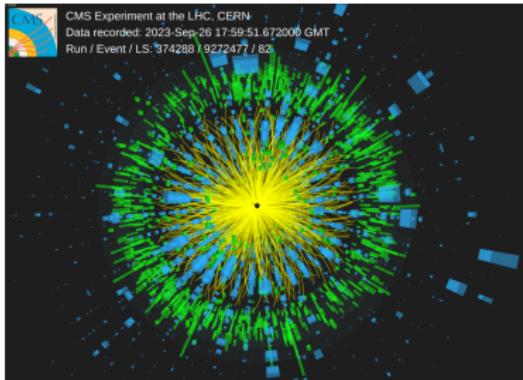
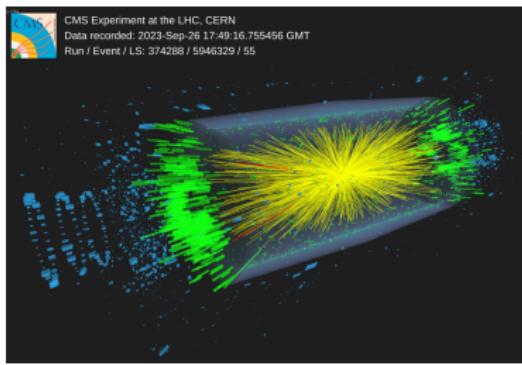
University of Illinois at Chicago
The CMS Collaboration

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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

QUARKS	mass → ≈2.3 MeV/c ²	charge → 2/3	spin → 1/2	u	c	t	g	Higgs boson
	≈4.8 MeV/c ²	-1/3	1/2	d	s	b	γ	
	0.511 MeV/c ²	-1	1/2	e	μ	τ	Z	
LEPTONS	<2.2 eV/c ²	0	1/2	electron neutrino	μ _ν	τ _ν	W	
	<0.17 MeV/c ²	0	1/2	muon neutrino	τ _ν			
	<15.5 MeV/c ²	0	1/2	tau neutrino				
GAUGE BOSONS								
	≈1.275 GeV/c ²	2/3	1/2	charm	≈173.07 GeV/c ²	2/3	0	
	≈4.18 GeV/c ²	-1/3	1/2	bottom	≈126 GeV/c ²	0	0	
	105.7 MeV/c ²	-1	1/2	muon	0	0	1	
	1.777 GeV/c ²	-1	1/2	tau	0	1	0	
	91.2 GeV/c ²	0	1	Z boson	0	1	1	
	80.4 GeV/c ²	±1	1	W boson	0	1	0	

- 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

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
 - $q\bar{q} \rightarrow q\bar{q} + q\bar{q}$ (particles from vacuum)

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

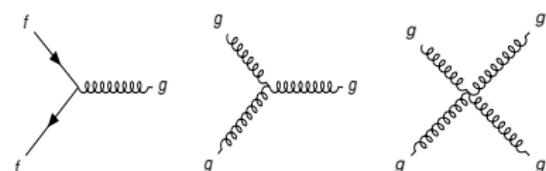
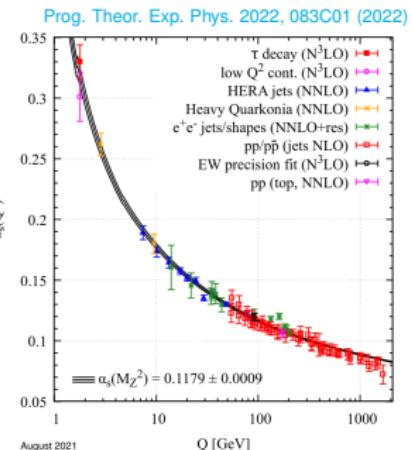
QED-like short-range

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

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

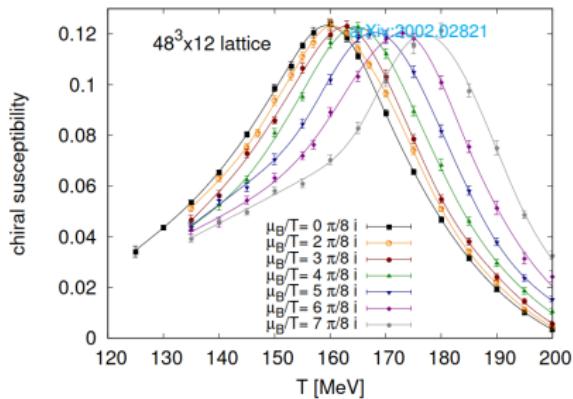
$$\boxed{\lim_{Q \rightarrow \infty} \alpha_s(Q^2) \rightarrow 0}$$

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



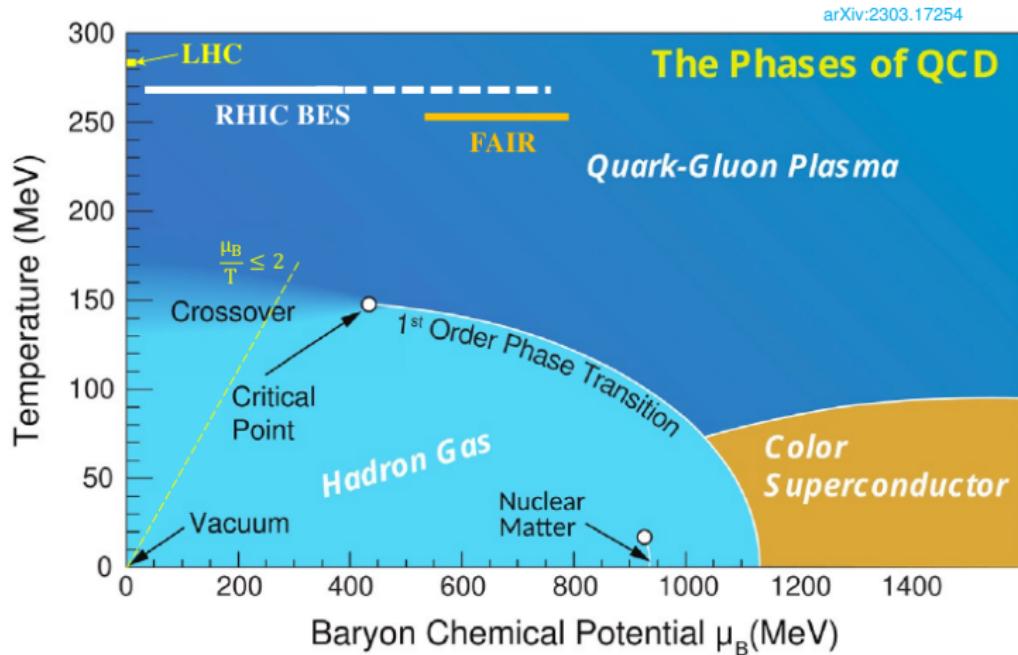
Deconfinement

- 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
 $T_c \approx 158.0 \pm 0.6 \text{ MeV} \approx 1.8 \cdot 10^{12} \text{ K}$



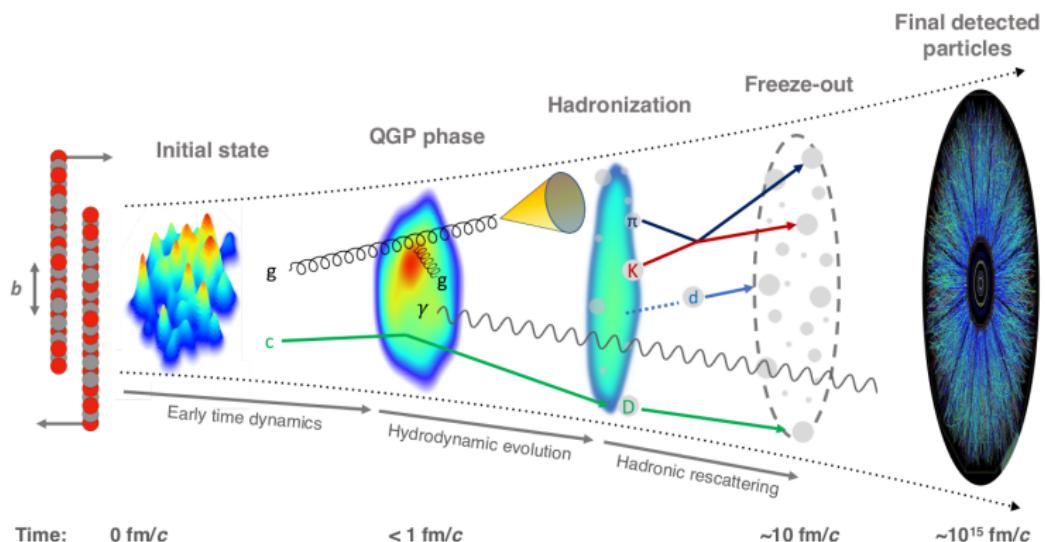
Phases of QCD

- 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**



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

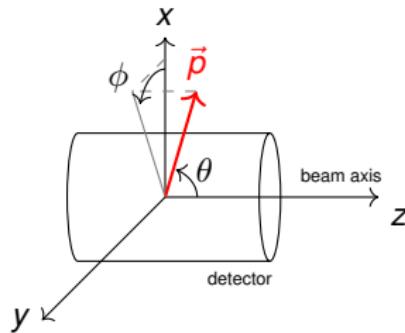
- Detector geometry warrants the use of cylindrical coordinate system

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?

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

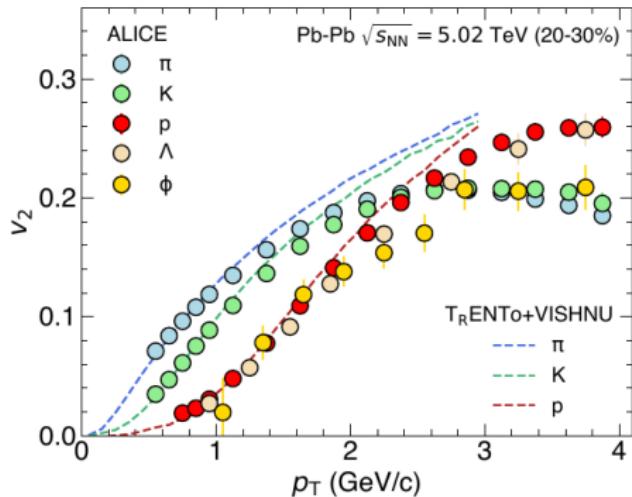
Centrality

Flow in the QGP

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

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

- Flow harmonics v_n are observed to scale with parton number → further evidence of deconfinement



Jets as Probes of the QGP

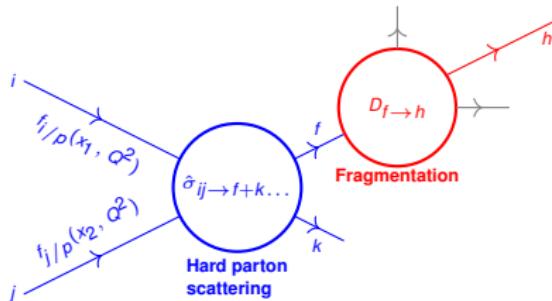
Factorization Theorems in QCD

- Hard processes in $p\bar{p}$ → short-distance physics of partons \otimes long-distance physics of hadrons

Cross-section factorization in $p\bar{p}$ collisions

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

- We use hard processes in $p\bar{p}$ collisions as a reference when we study QGP medium effects



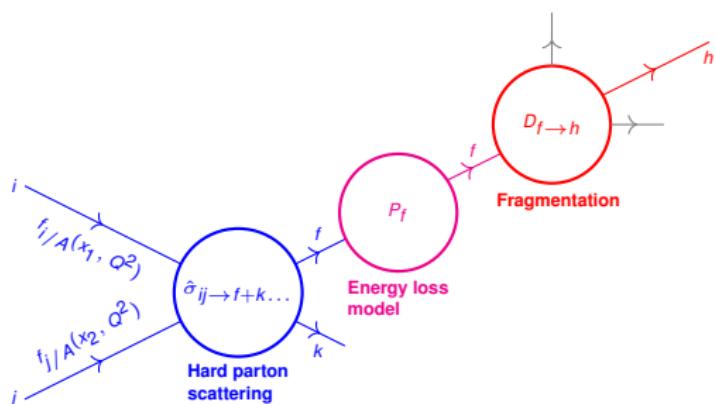
- Cross-section in vacuum is perturbatively calculable!
- Fragmentation is non-perturbative → must rely on QCD-inspired models

Factorization Theorems in QCD

- Hard processes in AA → short-distance physics of partons \otimes Model-dependent energy loss of partons in the QGP \otimes long-distance physics of hadrons

Cross-section factorization in AA collisions

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



- Factorization theorems unknown 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

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 $\sim 18,000\text{A}$

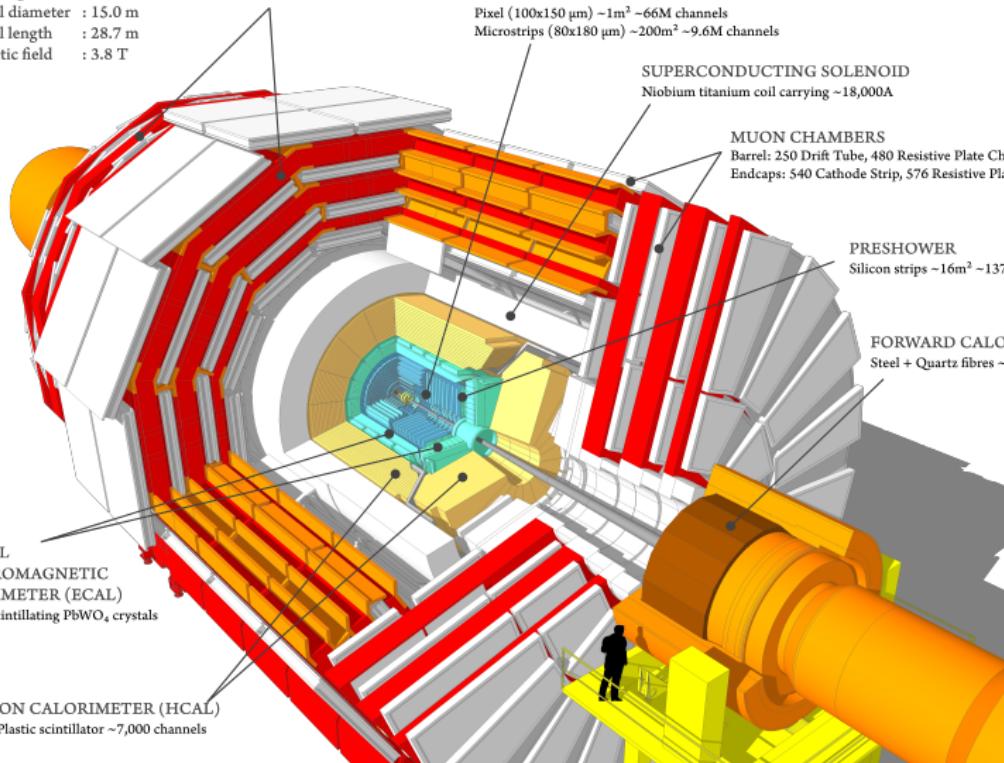
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

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

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

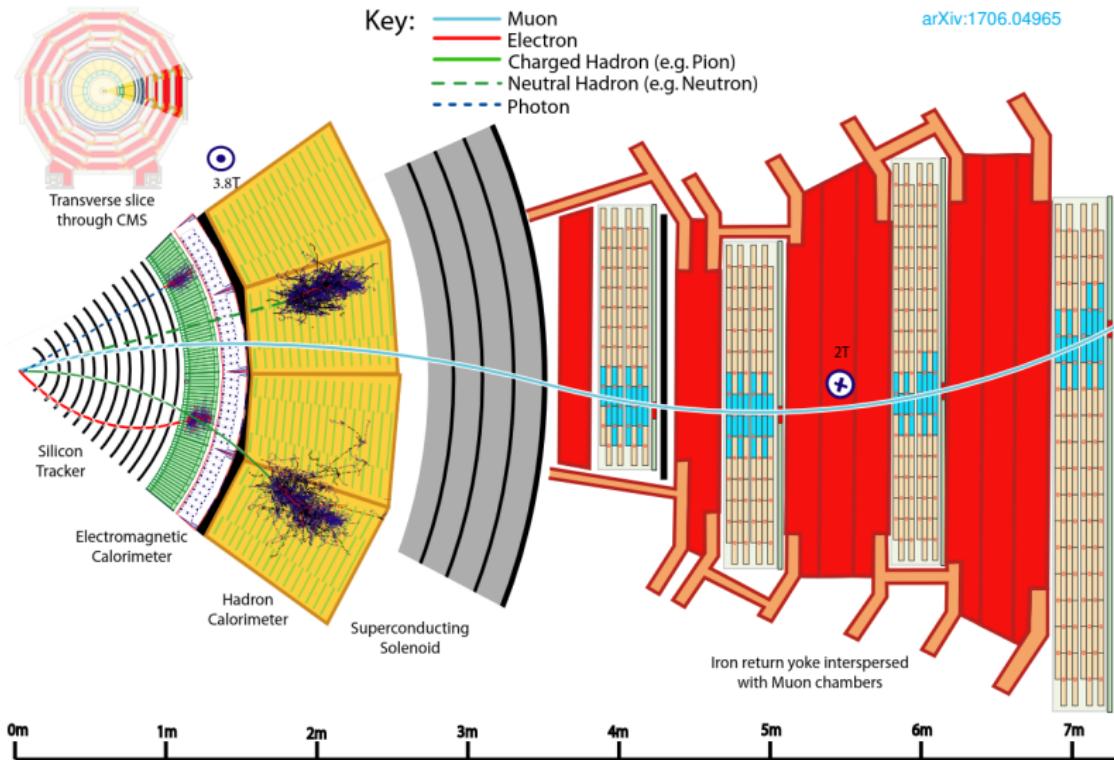
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

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



CMS Detector

arXiv:1706.04965



Jet Reconstruction in Heavy Ion Collisions