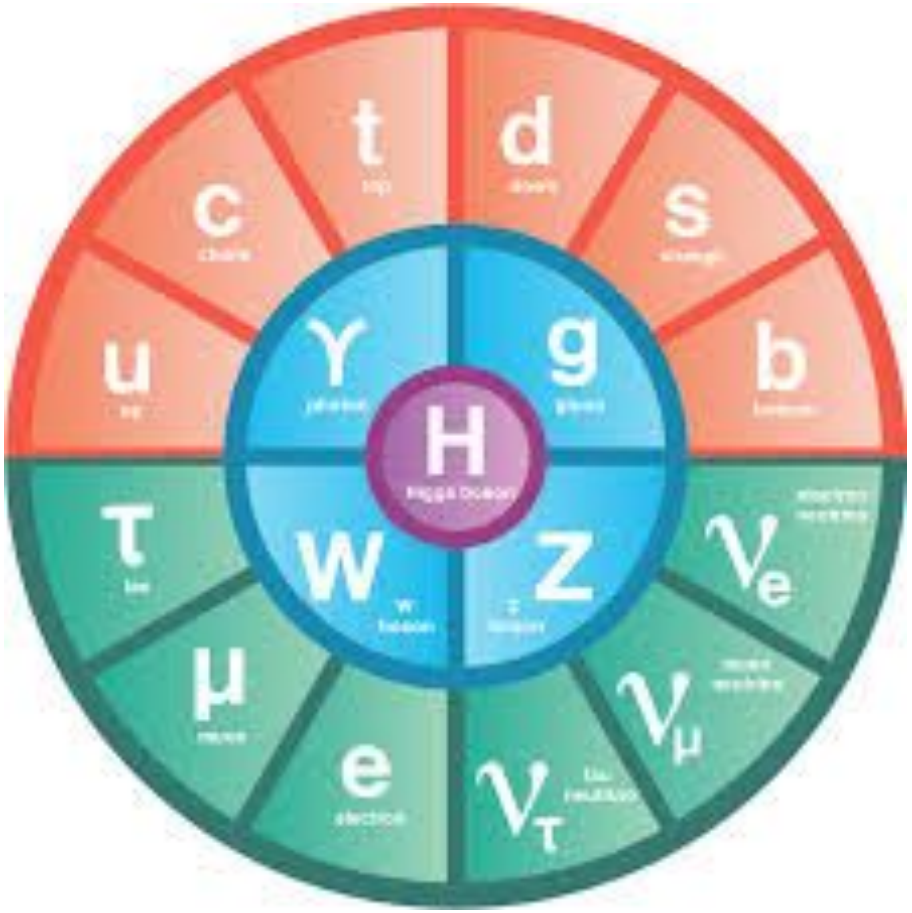
Observation of quark gluon plasma

Sai Neha Santpur

07 October 2020

Introduction

- As of today, we know 61 fundamental particles listed on the right side
- The standard model of particle physics describes the interactions between them using the lagrangian on slide 4
- Quantum chromodynamics (QCD) describes the interactions between quarks and gluons

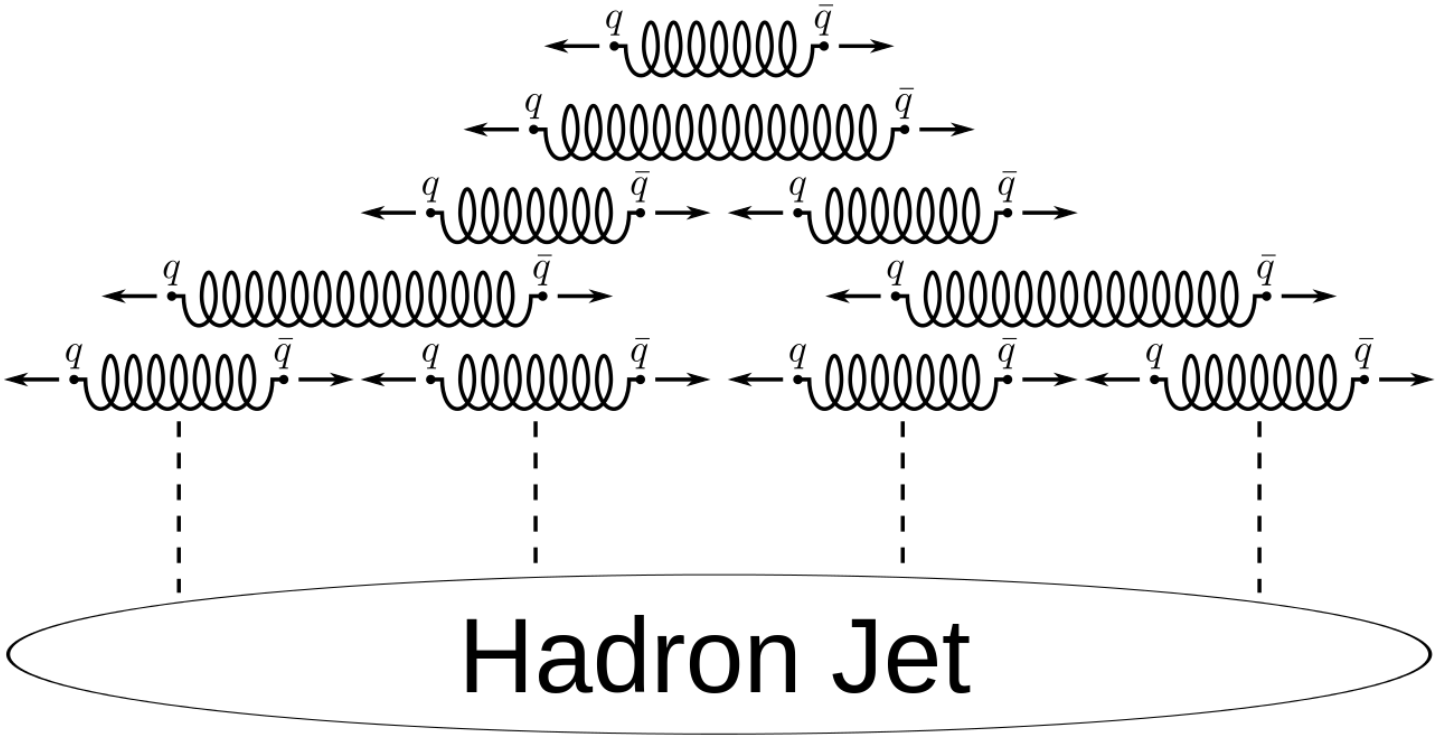


The lagrangian

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

Unique features of QCD

- Gluons are self interacting (unlike photons)
- Two main properties:
  - Color confinement: We cannot observe free quarks and gluons under normal conditions

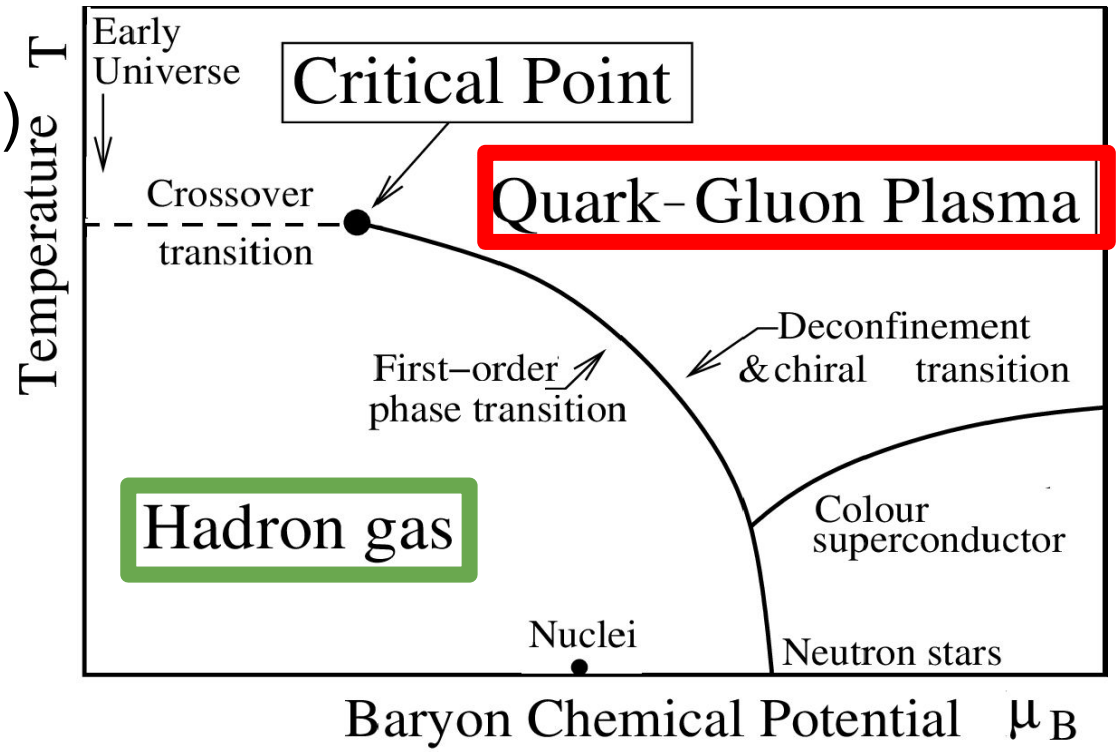


Unique features of QCD

- Gluons are self interacting (unlike photons)
- Two main properties:
  - Color confinement: We cannot observe free quarks and gluons under normal conditions
  - Asymptotic freedom: As energy increases (or length scale decreases), the strong coupling strength decreases (unlike QED)
    - If we walk back the evolution of our universe to very high temperatures or energies, QCD predicts that free quarks and gluons in principle should exist

Quark Gluon Plasma

- Definition: Quark gluon plasma (QGP) is a high density interacting system of quarks and gluons in a near thermal equilibrium
- It is a near ideal gas
- Early universe (10^{-12} to 10^{-6}s) was filled with QGP
- As universe cooled down, the phase transition eventually led to the formation of the hadrons we see today
- Lattice QCD calculations predict the T_c~175 MeV
- QGP theory was proposed in late 1970s

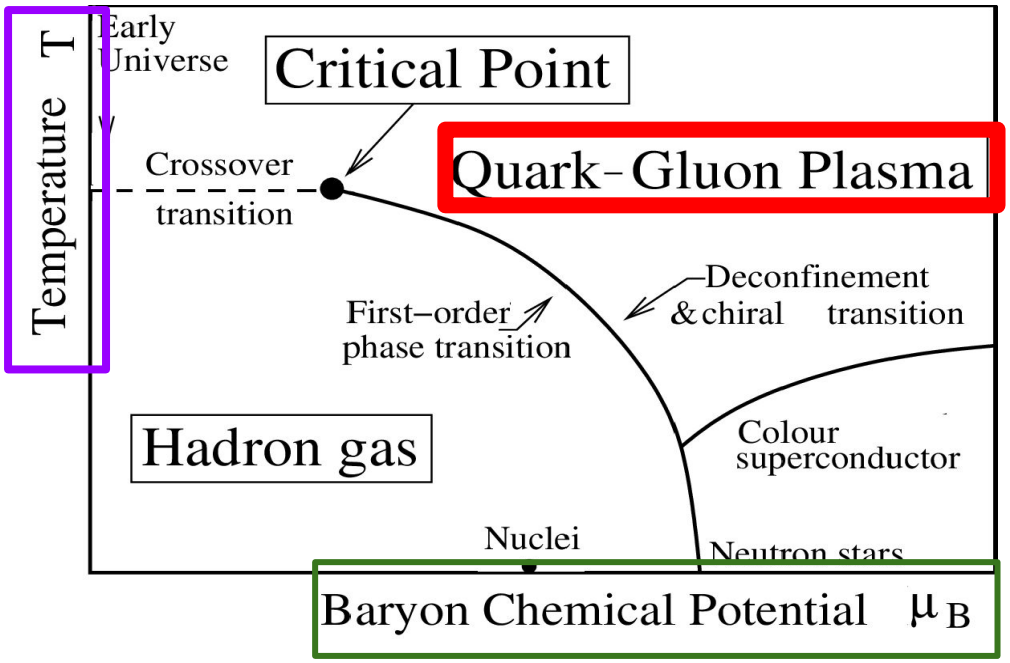


Why are QGP interesting to study?

- QGP provides a very important probe to study early universe
- It is another handle to validate the Standard Model of particle physics and learn more about QCD
  - Electroweak sector has been probed in great detail
  - QCD is complex to study as there are two regimes perturbative QCD (high energies) and non-perturbative QCD (low-energies)
    - We still do not understand how free quarks and gluons hadronize (though there are some nice models that try to fill the gap)

How do we recreate QGP in our lab?

- This diagram shows we need to have high energy and high density of strongly interacting particles to begin with
- High energy ⟶ Use colliders
- High density ⟶ Use heavy nuclei for example S,W, Au, Cu or Pb
- We essentially collide heavy ions at high energies to create QGP



Discovery of QGP

- WA85 at CERN (1991):
  - First claims of QGP discovery come from WA85 experiment
  - Here, Sulphur collisions on fixed target Tungsten were studied at $\sqrt{s}$ = 200 GeV/nucleon
  - Discovery paper here (Last sentence points to QGP)

Discovery of QGP

- WA85 at CERN (1991):
  - First claims of QGP discovery come from WA85 experiment
  - Here, Sulphur collisions on fixed target Tungsten were studied at $\sqrt{s}$ = 200 GeV/nucleon
  - Discovery paper here (Last sentence points to QGP)
- WA97 at CERN (1999):
  - Officially announced by CERN in 1999 based on results from WA97 experiment
  - Here, Pb-Pb collisions were studied at $\sqrt{s}$ = 158 GeV/nucleon with larger statistics
  - Discovery paper here
- By 1999, it was firmly established that we create a new state of matter or QGP at high baryon density and energies in the laboratory

Beginning the heavy ion program at CERN

- How did the heavy ion program start? Link

1. The beginnings

In October 1980, a Letter of Intent [1] to study Ne–Pb reactions at the CERN Proton-Synchrotron, was submitted by a GSI–LBL Collaboration:

Study of particle production and target fragmentation in central ^{20}Ne on Pb reactions, at 12 GeV per nucleon energy of the CERN-PS external beam
Spokesman of the collaboration: R. Stock, GSI Darmstadt
27 October, 1980
Letter of Intent GSI Darmstadt – LBL Berkeley Collaboration

Abstract: We propose to study in two simultaneous experiments the target fragmentation modes, and π^- , K^0 and Λ production in central collisions of ^{20}Ne with a heavy target nucleus. The acceleration of ^{20}Ne at the PS will be facilitated by a high-charge state ^{20}Ne source, provided by us. Experimental equipment will be *the Plastic Ball and Wall spectrometer, currently employed by us at the Bevalac, LBL Berkeley* and *a streamer chamber now used at CERN by the Munich group*. The experiments require acceleration of about 10^7 Ne ions per PS cycle, and a split in the external beam delivering about 10^4 ions/s to *the streamer chamber* and the main part of the intensity to the *Plastic Ball* and *Wall*. The anticipated time of experiment is about the spring of 1983, with the long lead-time caused mostly by source construction and injector linac acceleration tests.

Beginning the heavy ion program at CERN

- How did the heavy ion program start? Link

1. The beginnings

In October 1980, a Letter of Intent [1] to study Ne–Pb reactions at the CERN Proton-Synchrotron, was submitted by a GSI–LBL Collaboration:

Study of … **n Pb**
reactio … **am**

L

This triggered a long approval process resulting in the start of the heavy ion program at CERN with much larger energies than anticipated

Abstract: We propose to study in two simultaneous experiments the target fragmentation modes, and π^- , K^0 and Λ production in central collisions of ^{20}Ne with a heavy target nucleus. The acceleration of ^{20}Ne at the PS will be facilitated by a high-charge state ^{20}Ne source, provided by us. Experimental equipment will be *the Plastic Ball and Wall spectrometer, currently employed by us at the Bevalac, LBL Berkeley* and *a streamer chamber now used at CERN by the Munich group*. The experiments require acceleration of about 10^7 Ne ions per PS cycle, and a split in the external beam delivering about 10^4 ions/s to *the streamer chamber* and the main part of the intensity to the *Plastic Ball* and *Wall*. The anticipated time of experiment is about the spring of 1983, with the long lead-time caused mostly by source construction and injector linac acceleration tests.

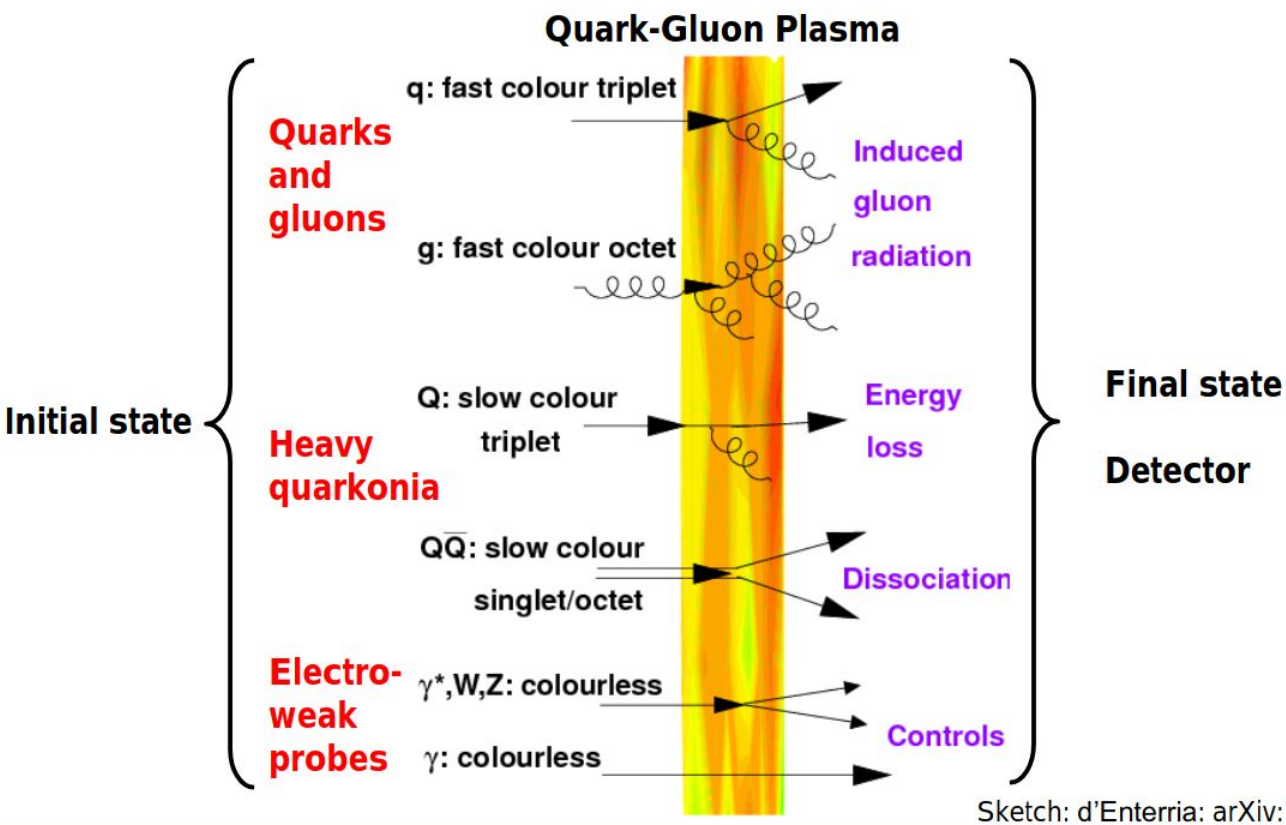
Signatures of QGP

- Strangeness enhancement:
  - Lattice QCD calculations predicted that the strange quarks and anti-quarks are produced in abundance in a QGP
  - Note m_s~93 MeV
  - When QGP eventually hadronizes, this results in large number of strange baryons which are produced in thermal equilibrium
  - We can collide heavy ions and count the rate of strange baryon production and compare it to pp collisions.

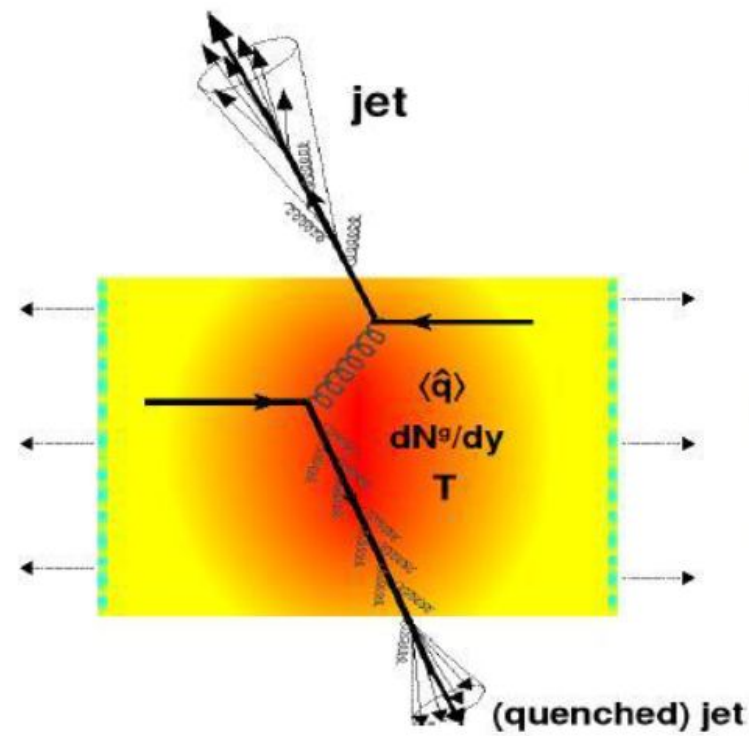
Excess in strange baryon rate ⇒ creation of QGP

Other signatures of QGP

- Jet quenching: Jet traversing QGP loses energy due to collision and gluon bremsstrahlung
- Direct probes like dilepton and diphoton

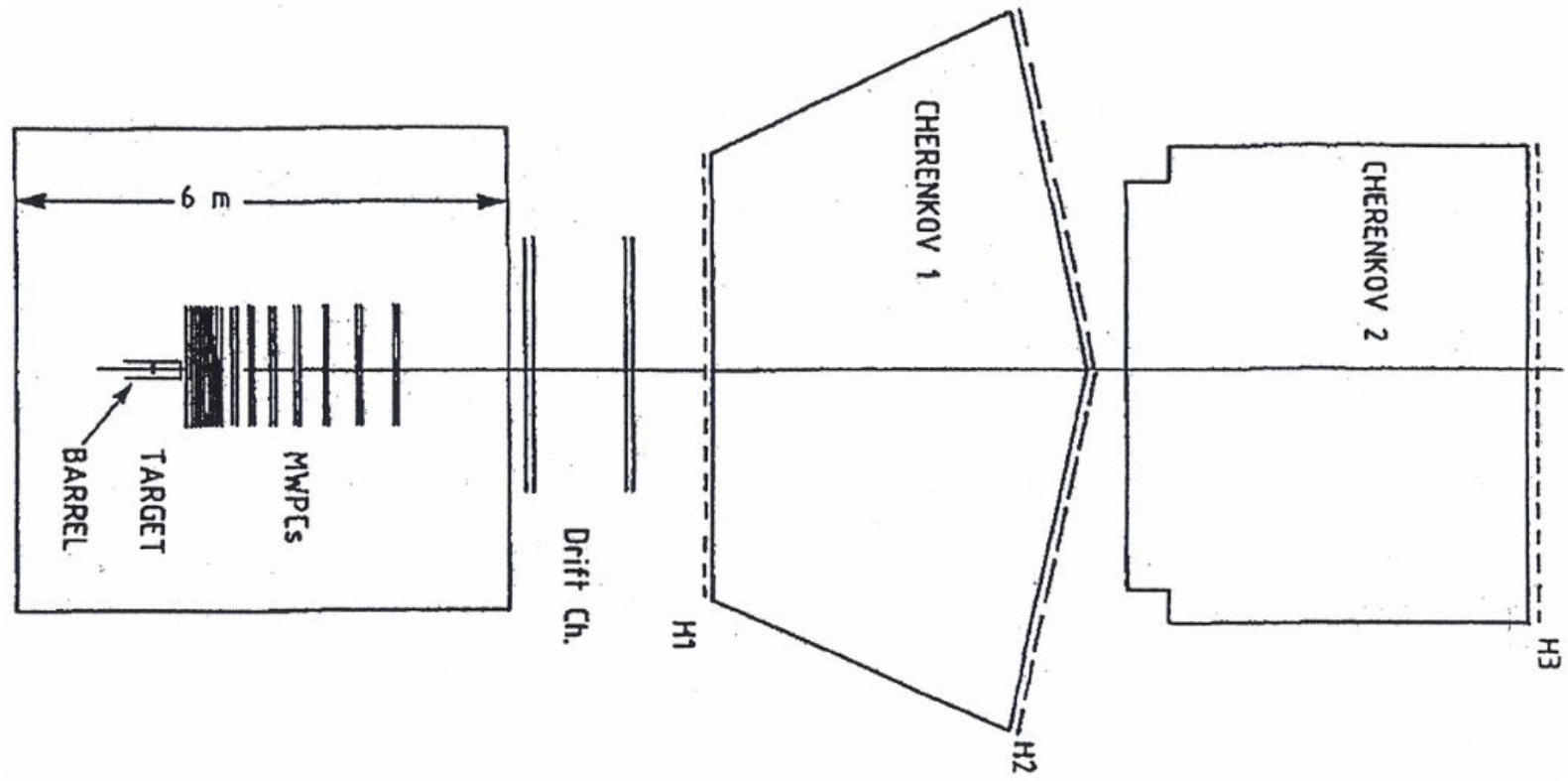


Sketch: d'Enterria: arXiv:1207.4362



WA85

- Sulphur beam is incident on fixed Tungsten target at $\sqrt{s}$ = 200 GeV/nucleon
- CERN Omega spectrometer was used as the detector

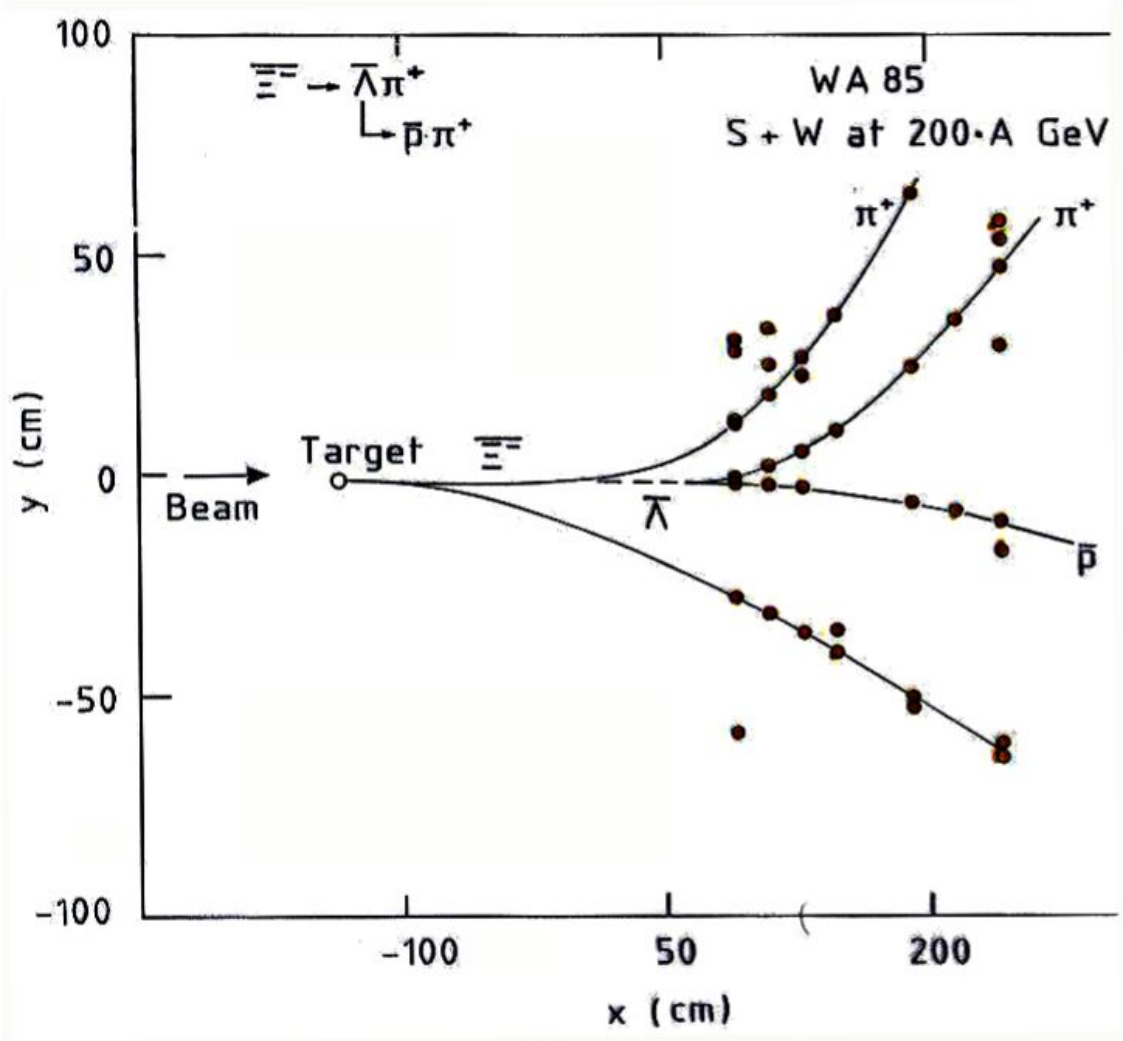


WA85

- Sulphur beam is incident on fixed Tungsten target at $\sqrt{s}$ = 200 GeV/nucleon
- CERN Omega spectrometer was used as the detector
  - 1.8T superconducting magnet
  - Each collaboration can decide what subdetectors they want to use
  - WA85 setup:
    - Multiwire proportional chambers (MWPC) to detect the charged particles and photons along with the position
    - The voltage bias on these MWPC was tuned such that only tracks with pT>1 GeV were recorded in the central rapidity region (to reduce the occupancy)

Detecting strange particles at WA85

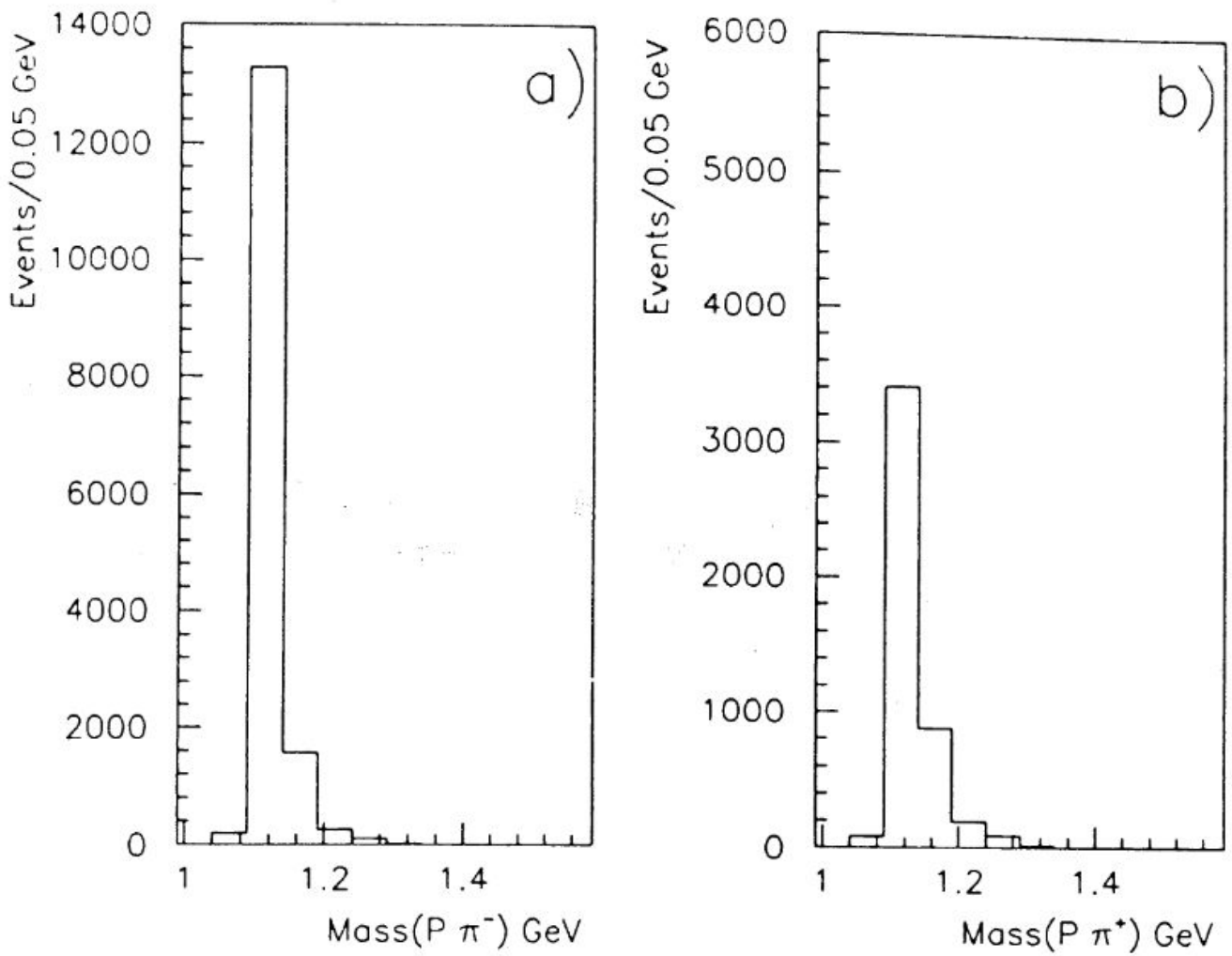
- Ξ^- (dss)
  - m~1321 MeV
  - Decays into Λπ-
- Λ (uds)
  - m~1115 MeV
  - Decays into p+π0 and nπ+



(a)

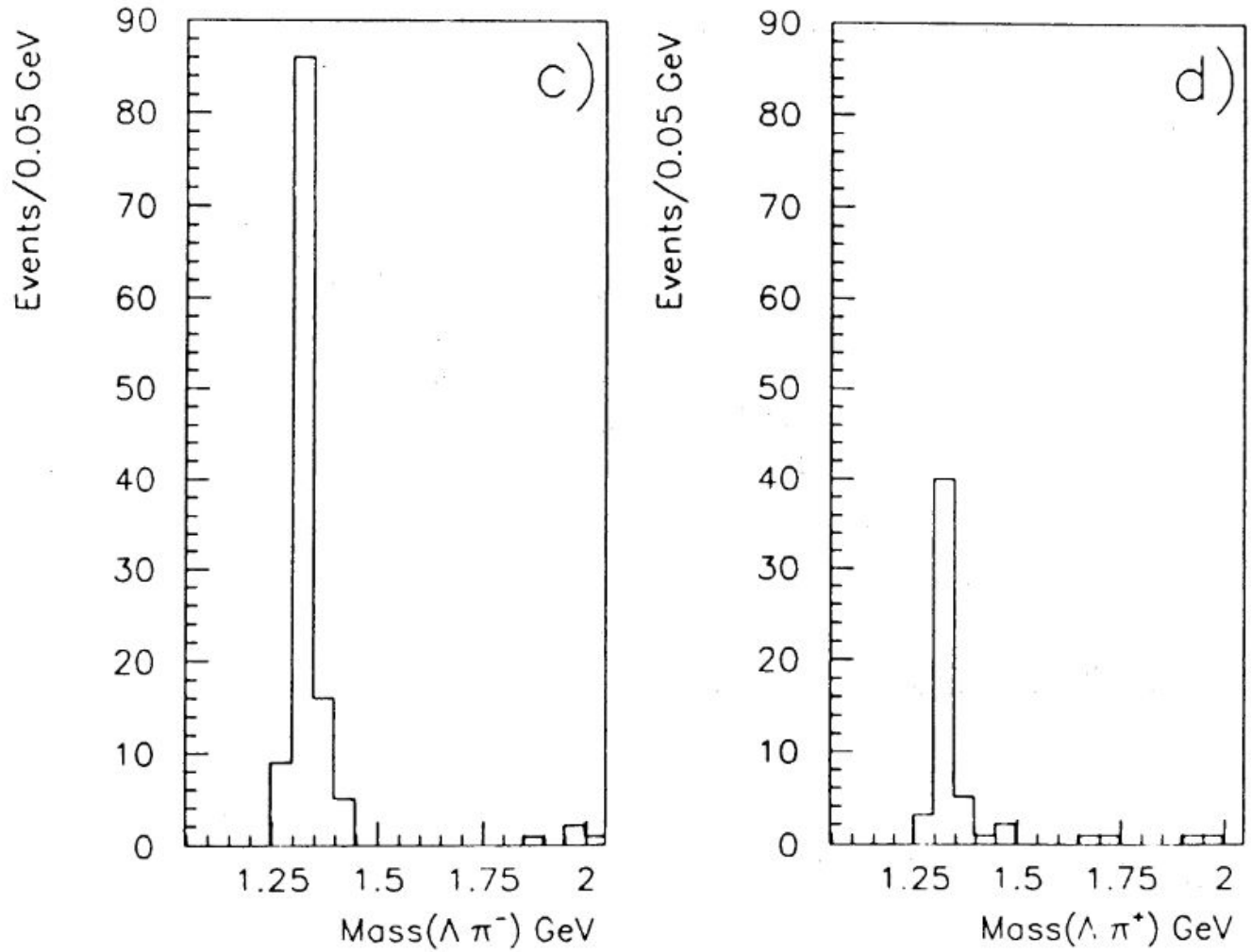
Λ selection

- m~1115 MeV
- Very clear peaks with little background
- 10 million triggers were used for this study
- Λ candidates are selected around 50 MeV of its mass
- This resulted in 13307Λ and 3407 Λbar
- Further cut on rapidity was introduced to reduce Kaon contamination and finally obtained 5856Λ and 1138Λbar



Ξ selection

- m~1321 MeV
- Ξ candidates are chosen within 100MeV of the mass
- They ended up with 108Ξ and 44Ξbar candidates



$$\overline{\Xi^-}/\Xi^- = 0.39 \pm 0.07 \text{ and } \overline{\Lambda}/\Lambda = 0.19 \pm 0.01.$$

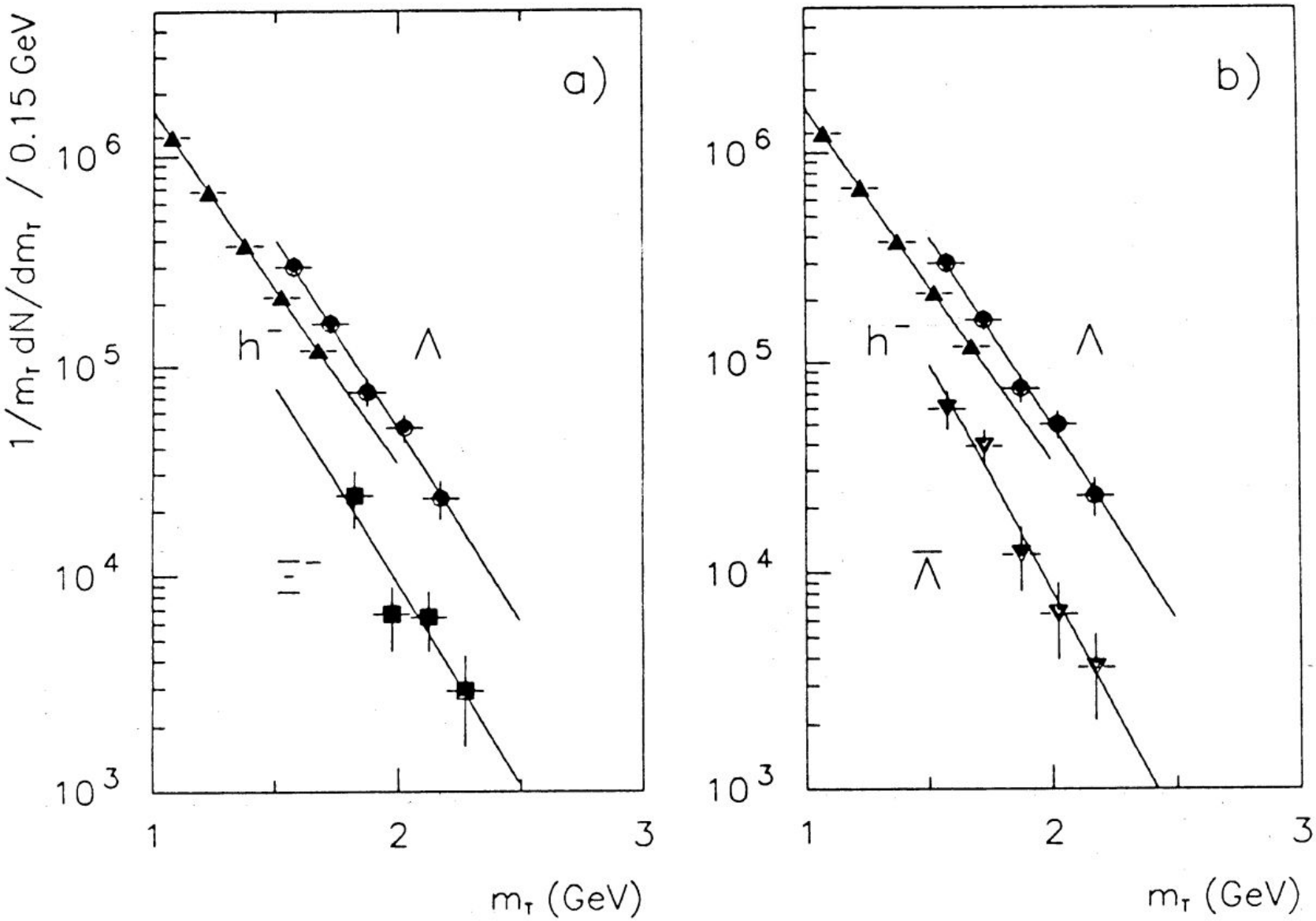
Transverse mass distribution

- Transverse mass ($\sqrt{(p_T^2 + m^2)}$) of particles from a thermal source are expected to have following distribution:

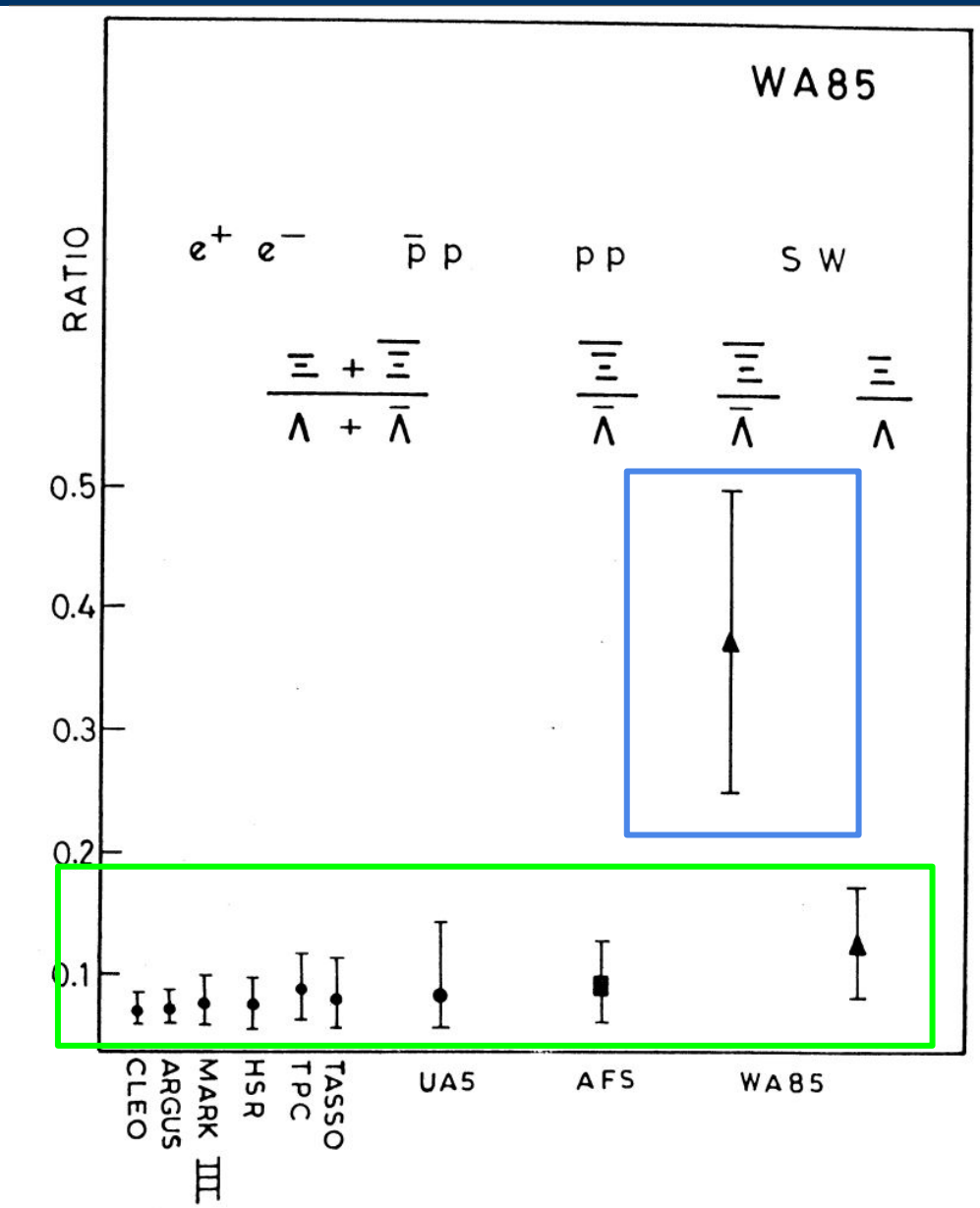
$$\frac{1}{m_T}\frac{dN}{dm_T} \sim e^{-\beta m_T}$$

  where β is the inverse temperature of the source
- For Λ candidates there is significant contamination from Ξ decays as the decay region is far from the target
  - Knowing the number of Ξ produced and simulating the Λ production from this, the contamination is subtracted
- The slopes from the m_T plot shown in next slide result in 1/β around 250 MeV

m_T plot

- 
a)
b)
$1/m_T\, dN/dm_T$ / 0.15 GeV
10^6
10^5
10^4
10^3
h^-
Λ
Ξ^-
$\bar{\Lambda}$
1
2
3
m_T (GeV)

Comparison of rates to other experiments



Result from WA85 in 1991

- Production rate of Ξ-bar/Λbar is enhanced with respect to pp interactions

in previous publications [5]. The results indicate that our $\overline{\Xi^-}$ production rate, relative to $\overline{\Lambda}$, is enhanced with respect to p p interactions; this result is difficult to explain in terms of non-QGP models [11] or QGP models with complete hadronisation dynamics [12]. We note, however, that sudden hadronisation from QGP near equilibrium could reproduce this enhancement [2].

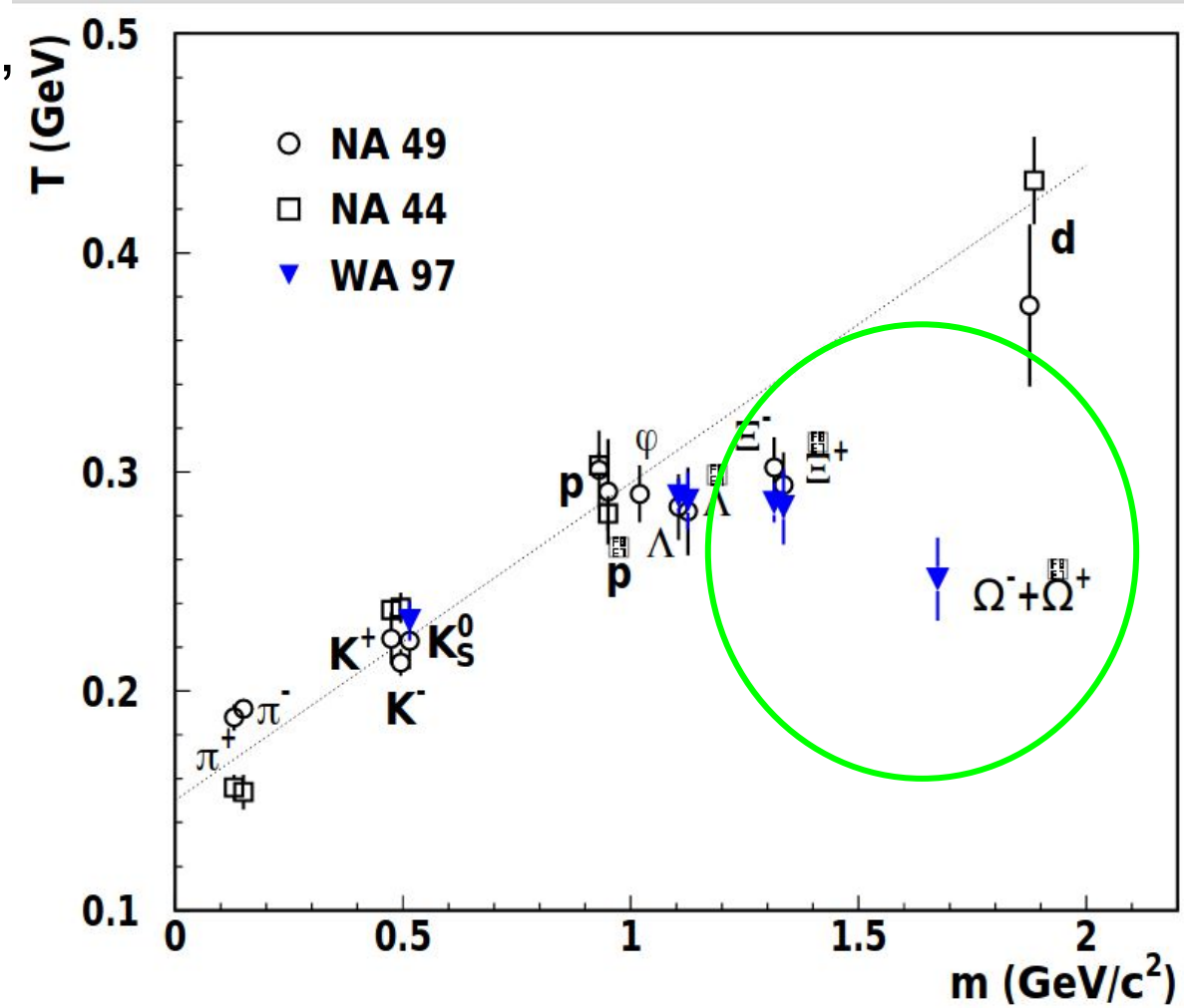
- This result was very encouraging but people were still skeptical of the 50% uncertainties
- Verification of this result by WA97 with large statistics and lower uncertainties was paramount in firmly establishing the discovery of QGP!

WA97 discovering QGP in 1999

- Obtained transverse mass spectra of the strange particles in Pb-Pb collisions at 158 GeV/nucleon

Link

- Singly strange particles (K, Λ) are consistent with linear increase while Ω and Ξ are not
- Suggests multi-strange baryons decouple early from the hot and dense expanding system as predicted in QGP!

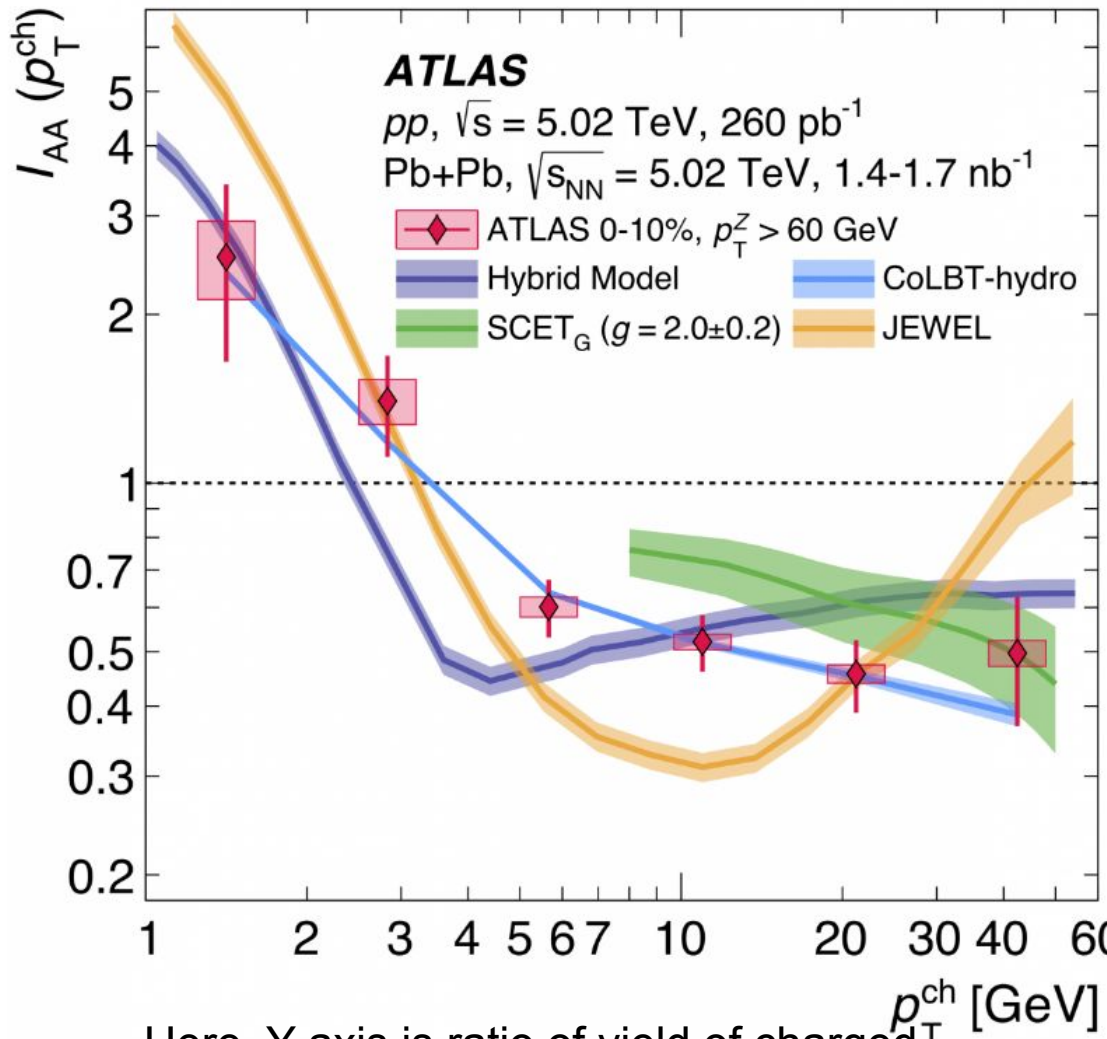


What is QGP used for today?

- Since its discovery in 1990s, we have STAR,PHENIX,etc at RHIC to study the QGP and its properties in great detail using Au-Au collisions
- ALICE, ATLAS, CMS at LHC can explore QGP produced in Pb-Pb collisions
- Questions to address:
  - How do “free” quarks and gluons behave?
  - How does matter interact with this plasma?
  - Understand the QCD phase transition

Recent highlight from ATLAS

- Jet quenching result from August 2020
- How do we know a jet has traversed QGP? Use a high energy photon or Z boson produced in the opposite direction of the jet as a “tag”
- The result demonstrates that the quarks and gluons lose energy in the QGP leading to a few high momentum particles while the remaining energy is redistributed into low energy fragments around the resulting jet
- [Paper here]



Here, Y axis is ratio of yield of charged particles produced opposite to Z boson in Pb-Pb to pp collisions

Summary

- QCD predicts the existence of quark gluon plasma in the early universe at high temperatures and baryon densities (right around 10μs after the big bang)
- Exploring QGP helps us look into the past and understand the evolution of the universe
- Quark gluon plasma was discovered in 1999 (and 1991) at CERN
- Today, we have dedicated experiments to study the QGP and use it as a tool to understand QCD at RHIC and LHC