Heavy Quark Production and Energy Loss

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With many thanks to Razieh Morad, Miklos Gyulassy, and Yuri Kovchegov
What Are We Interested In?

- Measure the properties of many-body strong force
- Test & understand theory of many-body non-Abelian fields

The Phases of QCD

Early Universe
Future LHC Experiments

Current RHIC Experiments

RHIC Energy Scan

~170 MeV
Crossover

Critical Point

1st order phase transition

Future FAIR Experiments

Quark-Gluon Plasma

Hadron Gas

Vacuum

Nuclear Matter

Neutron Stars

Baryon Chemical Potential

Long Range Plan, 2008
Compare to Easiest QED

- "Simple" Hydrogen Phase Diagram

Calculated, Burkhard Militzer, Diploma Thesis, Berlin, 2000
Why Energy Loss?

Most direct probe of DOF of QGP

pQCD Picture

Production

In-medium Energy Loss

Fragmentation

2012/08/23 Quark Matter 2012
Why Energy Loss?

Most direct probe of DOF of QGP

AdS/CFT Picture

Production

In-medium Energy Loss

Fragmentation
Heavy Quarks in Context

QGP
Heavy Quarks in Context

High $p_T$ Light Hadrons

QGP
Heavy Quarks in Context

High $p_T$ Light Hadrons

QGP

Quarkonia
Heavy Quarks in Context

High $p_T$ Light Hadrons

QGP

Open Heavy Flavor

Quarkonia
Heavy Quarks in Context

- High $p_T$ Light Hadrons
- EM Probes
- Open Heavy Flavor
- Quarkonia

QGP
Heavy Quarks in Context

- High $p_T$ Light Hadrons
- EM Probes
- QGP
- Open Heavy Flavor
- Quarkonia

Your least favorite measurement
Heavy Quarks in Context

- High $p_T$ Light Hadrons
- EM Probes
- Low-$p_T$ particles
- Open Heavy Flavor
- Quarkonia

Your least favorite measurement

QGP
Heavy Quarks in Context

Searching for this coherent, consistent picture
Why Heavy Quarks?

- E-loss picture assumes QGP properties
  \[ \Rightarrow P(\Delta p_T | p_T, L, T, M_Q, R) \]
- Want to test \( P(\Delta p_T) \)
  - A+B, \( \sqrt{s} \), centrality, \( M_h \), …
Qualitative Expectations for HF

• Energy loss decreases with $M_Q$
  
  \[ \Delta E_b < \Delta E_c < \Delta E_{u,d} < \Delta E_g \]

  • For experts: not always true for pQCD (\(\tau_{\text{form}}\) decreases with $M_Q$)

  • DOES NOT IMPLY $R_{AA}$ ORDERING

    – For approx. power law production and energy loss probability $P(\varepsilon)$, $\varepsilon = (E_i - E_f)/E_i$

    \[ \frac{dN}{dp_T} \sim \frac{1}{p_T^{n+1}} \Rightarrow R_{AA} \approx \langle \int d\varepsilon (1 - \varepsilon)^n P(\varepsilon) \rangle \]

    – Larger $n$ => smaller $R_{AA}$ for same energy loss
Importance of Production

- HQ production spectra softer than lights
  => Nontrivial ordering of $R_{AA}(p_T)$

$\sqrt{s} = 2.76$ TeV

See also
Buzzatti, 5C (NB: High-$p_T$ and Jets)
Lesson from RHIC

- Extremely difficult to consistently describe all observables
  - HF suppression places *stringent constraint* on possible E-loss mechanism

Wicks, WAH, Djordjevic, Gyulassy, NPA784 (2007)
Demonstrating E-loss Value

• Compare E-loss observables to data with two very different assumptions of properties of QGP:
  – Strongly coupled medium coupling strongly to a high-$p_T$ particle
  – Weakly coupled medium coupling weakly to a high-$p_T$ particle
Let’s Assume Strong Coupling

- Not crazy
  - $T \sim 250$ MeV, $g(2\pi T) \sim 2$, $\lambda = g^2 N_c \sim 12 \gg 1$
- Always small $T$ scale
  - $T \gtrsim T_c$, lattice deviates from Stefan-Boltzmann
  - $\eta/s \sim 1/4\pi$ readily explained by AdS/CFT

\[
\frac{\epsilon}{\epsilon_{SB}} = \frac{3}{4} + \frac{1.69}{\lambda^{3/2}} + \ldots
\]
Heavy Quark E-Loss in AdS/CFT

• Model heavy quark jet energy loss by embedding string in AdS space

\[ \frac{dp_T}{dt} = -\mu p_T \]

\[ \mu = \pi \lambda^{1/2} \frac{T^2}{2M_q} \]

Herzog et al., JHEP 0607 (2006)
Gubser, PRD74 (2006)

– Similar to Bethe-Heitler

\[ \frac{dp_T}{dt} \sim -(T^3/M_q^2) p_T \]

– Very different from usual pQCD and LPM

\[ \frac{dp_T}{dt} \sim -LT^3 \log(p_T/M_q) \]

J Friess, S Gubser, G Michalogiorgakis, S Pufu, Phys Rev D75 (2007)
AdS/CFT and HQ

• String drag: qualitative agreement at RHIC

WAH, PhD Thesis, arXiv:1011.4316

Akamatsu, Hatsuda, and Hirano, PRC79, 2009
AdS/CFT and HQ at LHC

- D Predictions
  - AdS HQ Drag appears to oversuppress $D$
    - Long. fluctuations likely important, not included
- B Predictions
  - Roughly correct description of $B \rightarrow J/\psi$

AlICE 0-20%

![Graph]

$R_{AA}^D$(p_T (GeV/c))

WAH, PANIC11 (arXiv:1108.5876)
ALICE, arXiv:1203.2160
CMS, JHEP 1205 (2012) 063
Light Quark E-Loss in AdS

- Complications:
  - string endpoints fall => painful numerics
  - relation to HI meas.
    - less obvious than HQ
- In principle, compute $T^{\mu \nu}$ from graviton emission
  - Extremely hard

Chesler et al., PRD79 (2009)
AdS/CFT Light $q$ E-Loss

- Static thermal medium $\Rightarrow$ very short therm. time
  - $\tau_{th} \sim 2.7$ fm
    - AdS likely oversuppresses compared to data
- Examine $T \sim 1/\tau^{1/3}$ geom
  - $\tau_{th} \sim 4.1$ fm; Bragg peak disappears

Simple Bragg peak model

R Morad
Strongly Coupled HF @QM

• More information/differing opinions
  – Chesler, “Gravitational collapse and holographic thermalization”, 3D
  – Rajagopal, “Shining a Gluon Beam through Quark-Gluon Plasma”, 5D
  – Ficnar, “Can falling strings in deformed AdS geometries account for the surprising transparency of the sQGP at LHC?”, Poster
Strongly Coupled HF into the Future

- Measure open HF in p+A
  - Midrapidity: test production (Tuchin, 2D)
  - Forward: test CNM HF E-loss

\[ ds^2 = \frac{L^2}{z^2} \left[ -2 dx^+ dx^- + 2 \mu z^4 \theta(x^-) dx^-^2 + dx_+^2 + dz^2 \right] \]

Embedded String in Shock

Before

After

WAH and Kovchegov, PLB680 (2009)

\[ \frac{dp'}{dt'} = -\frac{\sqrt{\lambda}}{2\pi} \frac{\Lambda^2}{M_q} p' \]
Let’s Assume pQCD is the Best Approx

• Also not unreasonable

  – \( \alpha_s(2\pi T) = 0.3 \)

  • Always large \( p_T \) scale

  – \( 2 \rightarrow 2 \) & \( 2 \rightarrow 3 \) pQCD MC suggests \( \eta/s \sim \text{few}/4\pi \)
Let’s Assume pQCD is the Way to Go

• Thermal Field Theory =>
  – Debye mass $\mu \sim gT$
  – Mean free path $\lambda_{mfp} \sim 1/g^2T$

• Entropy/Hydro => $T_{RHIC(LHC)} \sim 350\ (450)\ MeV$
  – $\mu \sim gT \sim 0.7\ (0.8)\ GeV \Rightarrow 1/\mu \sim 0.3\ (0.2)\ fm$
  – $\lambda_{mfp}^{\text{gluon}} \sim 1/g^2T \sim 0.8\ (0.7)\ fm$
  – $R_{Au,Pb} \sim 6\ fm$

• $1/\mu \ll \lambda_{mfp} \ll L$
  – Scattering off separated, well-defined quasiparticles
  – For HQ, order a few collisions, $\sim 4$
pQCD Continued

• **Two types of E-loss**
  
  – **Collisional (elastic) 2→2**
    
    • Bjorken, FERMILAB-PUB-82-059-THY
    • Braaten and Thoma, PRD44:2625–2630, 1991
    • Djordjevic, Phys.Rev. C74 (2006) 064907
    • Adil et al., Phys.Rev. C75 (2007) 044906

  – **Radiative (inelastic) 2→3**
    
    • Scales => ~few scatterings, mult. coh. em. => LPM
    • Must include interference with production radiation

• Majumder and van Leeuwen, PPNPA66 (2011), and refs therein
Asymptotic Analytic pQCD

• Naively, $\Delta E_{el} \ll \Delta E_{rad}$ as $E \to \infty$

• Elastic E-loss:
  
  \[ \frac{d p_T}{dt} \sim -T^2 \log\left(\frac{p_T}{M_Q}\right) \]

• Radiative E-loss, in expected deep LPM regime:
  
  \[ \frac{d p_T}{dt} \sim -L T^3 \log\left(\frac{p_T}{M_Q}\right) \]
  
  – Compare to Bethe-Heitler $\frac{d p_T}{dt} \sim -(T^3/M^2)p_T$
Results

• Naively, \( \Delta E_{el} \ll \Delta E_{rad} \) as \( E \to \infty \)

Finite RHIC/LHC kinematics: both radiative and collisional energy loss processes are important for \( p_T \sim 5 \text{ GeV/c} \) and higher
Compare to RHIC & LHC

- RHIC $R_{AA}$: not unreasonable $\rho_{med}$
  - $dN_g/dy = 1400^{+200}_{-375}$
  - $\alpha_s = 0.3$, fixed

- For LHC predictions: change only $\rho_{med} \propto dN_{ch}/d\eta$
Set Scale for our Expectations

- NLO pQCD in pp System ~ factor of 2
Global Qualitative Agreement

• LO pQCD E-loss correct to factor $\sim 2$
Potential Improvements at QM

• MC, parton cascade: Uphoff, poster
• NLO ansatz, better modeling: Buzzatti, 5C
• Additional Channels
  – In-medium fragmentation: Sharma, 2D
  – Non-perturbative 2→2 x-scns: He, Poster
• Be careful with:
  – Uncontrolled (& esp. uncontrollable) physics
  – Radiative only or Elastic only
  – Lack of finite time effects: wrong L dependence
  – Approximating pQCD with Langevin: far from central limit theorem, wrong $p_T$ dependence
Does pQCD or AdS Yield Correct Mass & Momentum Dependencies at LHC?

Qualitatively, corrections to AdS/CFT result will drive double ratio to unity

WAH, PANIC11 (arXiv:1108.5876)

See also:
WAH, M. Gyulassy, PLB666 (2008)
Take-away Messages

1. E-loss depends on $p_T, L, T, M_Q$
   1. $M_Q$ dependence provides unique insight into E-loss, QGP properties
   2. Want to vary others, too: consistent, coherent picture

2. Multiple observables demand simultaneous description: **hard**
   1. Difficult to describe data with AdS/CFT?
   2. LO pQCD gives reasonable qualitative description
      1. How do we understand sQGP(hydro) => wQGP(E-loss)

3. $p+$A is more than control experiment
4. HF E-loss physics exciting with much fascinating research ahead!
Rich and Vigorous HF E-loss Theory

• **Talks:**
  – Cao, “Heavy quark evolution and flow in hot and dense medium,” 6A
  – Buzzatti, “A Running Coupling Explanation of the Surprisingly Transparency of the QGP at LHC,” 5C
  – Gossiaux, “Heavy quark quenching from RHIC to LHC and the consequences of gluon damping,” 7E
  – Rapp, “Comprehensive Analysis of In-Medium Quarkonia from SPS to LHC,” 1D
  – Sharma, “High transverse momentum quarkonium production and dissociation in heavy ion collisions,” 2D

• **Posters:**
  – Abir, “Soft gluon emission and energy loss of heavy flavors in relativistic heavy ion collisions”
  – Akamatsu, “Quantum Description of Impurities - Heavy Quarks and Quarkonia”
  – Begum, “Suppression of D-mesons production at relativistic heavy ion collisions”
  – Durham, “A detailed study of open heavy flavor production, enhancement, and suppression at RHIC”
  – Ficnar, “Can falling strings in deformed AdS geometries account for the surprising transparency of the sQGP at LHC?”
  – Levai, “Charm production in the early phase and the charm baryon-to-meson ratios at LHC energies”
  – Nahrgang, “Influence of a realistic medium description including fluctuations on heavy quark observables”
  – Petran, “Charm contribution to final hadron yield at LHC”
  – Uphoff, “Open heavy flavor and J/psi at RHIC and LHC within a transport model”
  – van Hees, “Heavy-quark diffusion at the LHC within a UrQMD-hydrodynamical hybrid model”
  – Vogel, “Influence of the medium evolution on heavy quark observables”
  – Vogel, “Heavy quark energy loss in p+p collisions at the LHC”
PHENIX Preliminary

- Charm: 200 GeV Au+Au MB
- $\pi^0$ PRL 101, 232301 (2008)
- Bottom: 200 GeV Au+Au MB

$R_{AA}$ vs Electron $p_T$ (GeV/c)
$R_{D/h}$ vs $p_T$ for Au-Au collisions with $\sqrt{s_{NN}} = 200$ GeV and $\hat{q} = 14$ GeV$^2$/fm.

- Solid line: $q/g$
- Dashed line: $q/g + c_{p_T}$ slope
- Dotted line: $q/g + c_{p_T}$ slope + c fragm.
- Red line: $q/g + c_{p_T}$ slope + c fragm. + c mass

Large uncertainties are indicated.

Armesto et al., NPA774 (2006)
• Bremsstrahlung Radiation
  – Weakly-coupled plasma
    • Medium organizes into Debye-screened centers
  – $T \sim 350 \ (450) \ \text{MeV}$, $g \sim 1.9 \ (1.8)$
    • $\mu \sim gT \sim 0.7 \ (0.8) \ \text{GeV}$
    • $\lambda_{\text{mfp}} \sim 1/g^2T \sim 0.8 \ (0.7) \ \text{fm}$
    • $R_{\text{Au,Pb}} \sim 6 \ \text{fm}$
    – $1/\mu << \lambda_{\text{mfp}} << L$
      • multiple coherent emission

– LPM
  \[ \frac{dp_T}{dt} \sim -LT^3 \log(p_T/M_q) \]

– Bethe-Heitler
  \[ \frac{dp_T}{dt} \sim -(T^3/M_q^2) \ p_T \]
What About Elastic Loss?

- Appreciable!
- Finite time effects small

$T_0 = 0.225 \text{ GeV}$
$L = 4 \text{ fm}$
$\alpha_s = 0.3$
$M_c = 1.5 \text{ GeV}$

- For pQCD comparisons with data, use WHDG Rad+El+Geom model; formalism valid for $g/lq$ & $hq$
pQCD Not Quantitative at RHIC

- Lack of simultaneous description of multiple observables
  - even with inclusion of elastic loss

See also J Jia from QM09, J Nagle QM09
Quant. (Qual?) Conclusions Require...

• Further experimental results
• Theoretically, investigation of the effects of
  – higher orders in
    • $\alpha_s$ (large)
    • $k_T/xE$ (large)
    • $M_Q/E$ (large?)
    • opacity (large?)
  – geometry
    • uncertainty in IC (small)
    • coupling to flow (large?)
    • $E_{\text{loss geom. approx.}}$ (?)
    • $\tau < \tau_0$ (large: see Buzzatti and Gyulassy)
    • dyn. vs. static centers
    • hydro background (see Djordjevic)
  – better treatment of
    • Coh. vs. decoh. multigluons (see Mehtar-Tani)
    • elastic $E$-loss
    • $E$-loss in confined matter
(Data – pQCD)/Data

LO
Calculation
Strong Coupling Calculation

• The supergravity double conjecture:
  \[ \text{QCD} \Leftrightarrow \text{SYM} \Leftrightarrow \text{IIB} \]

  – \textcolor{red}{IF} super Yang-Mills (SYM) is not too different from QCD, &
  – \textcolor{red}{IF} we believe Maldacena conjecture
  – Then a tool exists to calculate strongly-coupled QCD in SUGRA
And D, B (?) $R_{AA}$ at LHC

– NB: $R_{AA}$ requires production, E-loss, FF
  • Does not immediately follow that $R_{AA}^{\pi} \ll R_{AA}^{D} \ll R_{AA}^{B}$
Comparing to RHIC, LHC

- In principle, can compute $T_{mn}$ from graviton emission

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Extremely hard

Gubser, Pufu, Yarom, JHEP 0709 (2007)
See also Friess et al., PRD75 (2007)
AdS/CFT Light q E-Loss & Dist.

- Suggests wide angle energy loss

Simple Bragg peak model

JO Noronha, M Gyulassy, and G Torrieri, PRL102 (2009)

WAH, JPhysG38 (2011)

Δε/ε_{SYM} > 0.3

“Neck”
Energy Loss in QGP

• Claim: LHC predictions from rigorously RHIC constrained pQCD E-loss in qualitative/quantitative agreement with current data
  – Want to stress test the theory with as many experimental levers as possible

• Counter-claim: LHC predictions from AdS/CFT not falsified by current data
  – Want an obvious distinguishing measurement
Qualitative Expectations for LHC

- For approx. power law production and energy loss probability $P(\varepsilon)$, $\varepsilon = (E_i - E_f)/E_i$

$$\frac{dN}{dp_T} \sim \frac{1}{p_T^{n+1}} \Rightarrow R_{AA} \approx \langle \int d\varepsilon (1 - \varepsilon)^n P(\varepsilon) \rangle$$

- Asymptotically, pQCD $\Rightarrow$ 
  $\Delta E/E \sim \log(E/\mu)/E$
  - $\sim$ flat $R_{AA}(p_T)$ at RHIC
  - Rising $R_{AA}(p_T)$ at LHC

- NB: LHC is a glue machine
• $p_T$ rise in data readily understood from generic perturbative physics!
Rise in $R_{AA}$ a Final State Effect?

- Is rise really due to pQCD?
- Or other quench (flat?)
+ initial state CNM effects a la CGC?

Y-J Lee, QM11

Require $p + A$ and/or direct $\gamma$
pQCD and Jet Measurements

- CMS sees redistribution of lost energy at large angles
  - Naive pQCD expectation: collinear radiation

\[ p_T^\parallel = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}) \]

0-30% Central PbPb

Wyslouch, CMS, QM11
pQCD and Wide Angle Radiation

- Naively, pQCD =>
  \[ x_{\text{typical}}, \theta_{\text{typical}} \sim \mu/E; \mu \sim 0.5 \text{ GeV} \]
- All current Eloss calculations assume small angle emission
  \[ (k_T \ll xE) \]
- Collinear approximation is (maximally) violated; \( x_{\text{typ}} \sim \mu/E \)
- pQCD is not inconsistent with data

arXiv:1102.1957 [nucl-ex]

\[ x = 0.025 \]
\[ E = 10 \text{ GeV} \]
\[ L = 5 \text{ fm} \]
\[ \mu \sim 0.46 \text{ GeV} \]
\[ \lambda \sim 1.25 \text{ fm} \]
WHDG Compared to $R_{CP}$

- Examine $R_{CP}$, ratio of central to peripheral $R_{AA}$
  - $p + p$ uncertainty cancels
  - 0-5% $R_{AA}$ to 70-80% $R_{AA}$
  - Validity of $E$-loss in very peripheral collisions?

WAH and M Gyulassy, NPA872 (2011)
Comparing AdS and pQCD

• But what about the interplay between mass and momentum?
  – Take ratio of $c$ to $b$ $R_{AA}(p_T)$
    • pQCD: Mass effects die out with increasing $p_T$
      \[
      R_{pQCD}^{cb}(p_T) \sim 1 - \alpha_s n(p_T) L^2 \log(M_b/M_c) \left( \hat{q}/p_T \right)
      \]
      – Ratio starts below 1, asymptotically approaches 1. Approach is slower for higher quenching
    • ST: drag independent of $p_T$, inversely proportional to mass. Simple analytic approx. of uniform medium gives
      \[
      R_{pQCD}^{cb}(p_T) \sim n_b M_c/n_c M_b \sim M_c/M_b \sim 0.27
      \]
      – Ratio starts below 1; independent of $p_T$
Top Energy Predictions

- For posterity:

WAH and M Gyulassy, *in preparation*
RHIC $R^{cb}$ Ratio

- Wider distribution of AdS/CFT curves due to large $n$: increased sensitivity to input parameters
- Advantage of RHIC: lower $T$ => higher AdS speed limits

WAH, M. Gyulassy, JPhysG35 (2008)
Chesler et al., PRD79 (2009)
Motivating High Momentum Probes

What does jet quenching teach us?

What is the parton probe scattering from?

Probe integrates over a range of $Q^2$

Medium

What scale sets this transition? ↓↑

Medium

pQCD Scattering from Quasiparticles with size $\sim \mu_{\text{Debye}}$

Strong Coupling
No Quasiparticles

$\mu_{\text{Debye}} \rightarrow 0$

AdS/CFT

What is the makeup of the medium?
Light Quark and Gluon E-Loss

\[ \Delta L_{q_{\text{therm}}}^q \sim E^{1/3} \]
\[ \Delta L_{q_{\text{therm}}}^q \sim (2E)^{1/3} \]

Gubser et al., JHEP0810 (2008)
Chesler et al., PRD79 (2009)
Arnold and Vaman, JHEP 1104 (2011)

See also Marquet and Renk, PLB685 (2010), and Jia, WAH, and Liao, arXiv:1101.0290, for \( v_2 \)

- Light quarks and gluons: generic Bragg peak
  - Leads to lack of \( T \) dependence?
Varying $\alpha_s$ has huge effect

- $\langle \varepsilon \rangle_{\text{rad}, \text{pQCD}} \sim \alpha_s^3$; $\langle \varepsilon \rangle_{\text{el}, \text{pQCD}} \sim \alpha_s^2$

- Role of running coupling, irreducible uncertainty from non-pert. physics?
- Nontrivial changes from better elastic treatment
Quantification of Collinear Uncertainty

- Factor ~ 3 uncertainty in extracted medium density!
- "qhat" values from different formalisms consistent w/i unc.

PHENIX 0-5% π⁰

Rad Only

WAH and B Cole, PRC81, 2010
Coll. Approx. and Constrained $v_2$

- Fix $dN_g/dy$ from $R_{AA}$, calculate $v_2$
  - Expect: larger $v_2$ for smaller opening angle
    - $\tau_{coh} = xE/kT^2$ larger for smaller $\theta_{max}$
      - more paths in deep LPM ($\Delta E \sim L^2$) region

- Rad Only

- Rad + El

- Not large sensitivity
Geometry, Early Time Investigation

- **Significant** progress made
  - Full geometry integration, dynamical scattering centers
  - RHIC suppression with $dN_g/dy = 1000$
  - Large uncertainty due to unconstrained, non-equilibrium $\tau < \tau_0$ physics
  - Future work: higher orders in opacity

\[
\frac{dN_g}{d\chi_+}(x, \phi) = \frac{c_R \alpha_s}{\pi} \int d\tau \frac{d^2 k}{\pi} \frac{d^2 q}{\pi} \frac{1}{x_+ q^2 (q^2 + \mu^2(\tau))} \frac{9}{2} \pi \alpha_s^2
\]

\[
\times \frac{2(k + q)}{(k + q)^2 + \chi(\tau)} \left( \frac{(k + q)}{(k + q)^2 + \chi(\tau)} - \frac{k}{k^2 + \chi(\tau)} \right)
\]

\[
\times \left( 1 - \cos \left( \frac{(k + q)^2 \chi(\tau)}{2x_+ E} \tau \right) \right) \rho_{QG}(x + \nu \tau, \tau)
\]

Buzzatti and Gyulassy, 1106.3061

Pion Tomography

A. Buzzatti et al: BWHDG

2012/08/23 Quark Matter 2012
– Speed limit estimate for applicability of AdS drag
  • $\gamma < \gamma_{\text{crit}} = (1 + 2M_q/\lambda^{1/2} T)^2$
    $\sim 4M_q^2/(\lambda T^2)$
    – Limited by $M_{\text{charm}} \sim 1.2$ GeV
  • Similar to BH → LPM
    – $\gamma_{\text{crit}} \sim M_q/(\lambda T)$
– No Single $T$ for QGP
  • smallest $\gamma_{\text{crit}}$ for largest $T$
    $T = T(\tau_0, x=y=0): "("
  • largest $\gamma_{\text{crit}}$ for smallest $T$
    $T = T_c: "["$
pQCD pp Predictions vs. Data

CMS, arXiv:1202.2554

ALICE, arXiv:1205.5423