Quenching of single hadron and photon spectra from RHIC to LHC

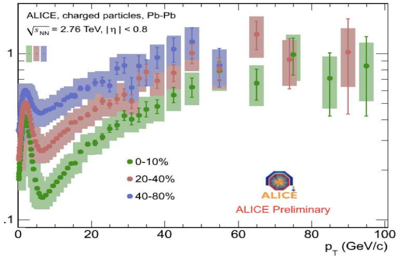
François Arleo

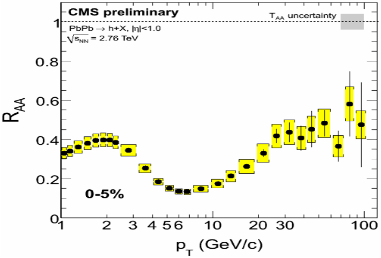
LAPTH, Annecy

GDR PH-QCD Workshop – Orsay, October 2011

Outline

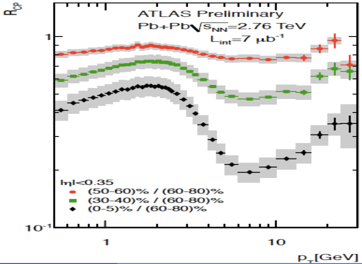
Impressive data at RHIC and LHC exhibit strong quenching of single hadron spectra, suggesting large energy loss effects in dense QCD media





Mind the scales !

- ALICE: lin-log
- CMS: log-lin
- ATLAS: log-log
- What I'd like to see: lin-lin



Outline

Outline

- Reference processes and baseline measurements
- Generic features of energy loss models and quantitative studies
- Photons
- Puzzles and open questions

Reference

FA, arXiv:1109.3121, to appear in J. Phys. G.

Part I

R_{AA} – Definition and baselines

Quenching factor R_{AA}

Definition

Normalized ratio of single inclusive spectra of hadrons and photons

$$R_{AA}(p_\perp, \eta) = \frac{d^2 N^{AA}}{dp_\perp \, d\eta} \Big/ \; T_{AA} \times \frac{d^2 \sigma^{pp}}{dp_\perp \, d\eta}$$

Anatomy of R_{AA}

- pQCD reference processes in the vacuum
- $\langle N_{\rm coll} \rangle = T_{AA} \sigma^{NN}_{\rm inel}$ scaling assumption of hard processes in AA collisions
- pQCD processes modified in dense media

Reference processes in pp collisions

Since $Q \gg \Lambda_{\rm QCD}$, hard processes computable in pQCD in pp collisions

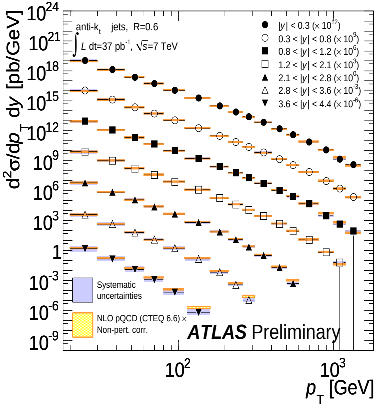
- Constraints on parton densities and fragmentation functions
- Reference process to which heavy-ion data can be compared

Hard processes in heavy-ion collisions

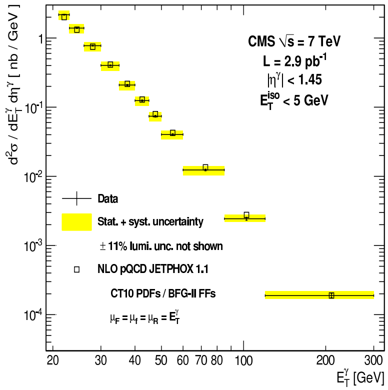
- Large $p_\perp$ hadrons and photons
- Jets
- Heavy quarks, $W^\pm/Z^0$ and Drell-Yan pairs

as well as double inclusive observables e.g. hadron-hadron or γ+jet

Impressive agreement between data and theory for most processes (jets, photons, electroweak bosons) in pp collisions



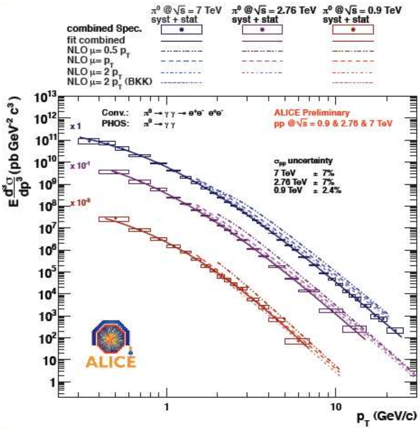
Jets in ATLAS – ATLAS-CONF-2011-047



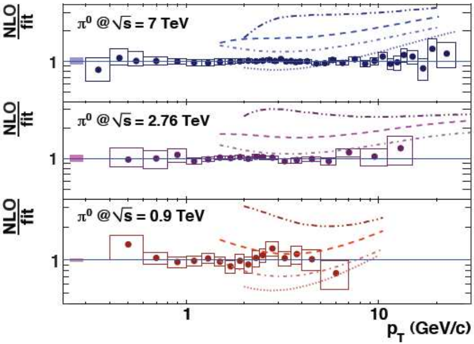
Photons in CMS – 1012.0799

Reference processes: large $p_\perp$ hadrons

Discrepancy reported for single hadron production in pp at LHC



NLO pQCD (W. Vogelsang):
PDF: CTEQ6M5, FF: DSS, scales, μ = 0.5 p_T, p_T, 2 p_T
Also: INCNLO with BKK FF

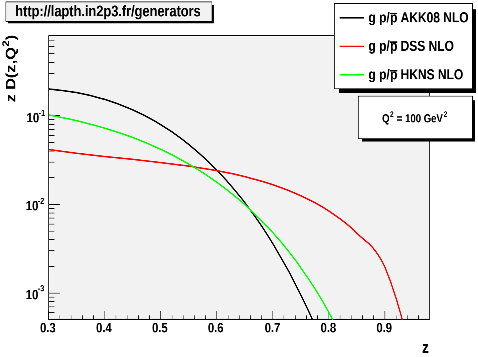


See also FA, Brodsky, Hwang, Sickles 0911.4604

Reference processes: large $p_\perp$ hadrons

Discrepancy reported for single hadron production in pp at LHC

- Still significant uncertainties in the fragmentation, esp. into baryons



Gluon fragmentation function into p+p̄ vs momentum fraction z

Reference processes: large $p_\perp$ hadrons

Discrepancy reported for single hadron production in pp at LHC

- Still significant uncertainties in the fragmentation, esp. into baryons

Wishful thinkings

- Uncertainties in the absolute pp spectra cancel out in the R_{AA} ratio
- Better understanding at larger $p_\perp$

Maybe, maybe not

Need to keep in mind these uncertainties when discussing R_{AA}!

Scaling laws in particle production

Conventional wisdom

- Hard processes $\propto$ number of binary NN collisions $\langle N_{\rm coll} \rangle \sim A^{4/3}$
- Soft processes $\propto$ number of participating nucleons $\langle N_{\rm part} \rangle \sim A$

- This assumption needs to be checked for other hard processes expected to be insensitive to QGP formation
  - Photons, $W^{\pm}/Z^{0}$, Drell-Yan

- $T_{\rm AA}$ not directly accessible but estimated using Glauber model
  - Uncertainties on the normalization ($p_{\perp}$ independent) for all centralities

Nuclear effects on R_{AA}

Apart from energy loss, many cold and hot medium effects can affect R_{AA}

- Nuclear parton distributions (nPDF) and saturation

  nDS 2004, HKN 2007, EPS 2009, nCTEQ 2009

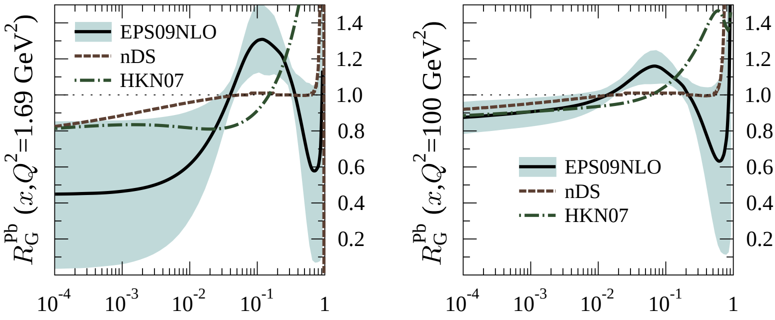
- Flow
- Cronin effect and energy loss in cold matter
- Recombination processes in QGP
- Non-perturbative or higher-twist dynamics at work

Hope

Most of these processes should die out at large $p_{\perp}$ at which energy loss effects remain visible

Nuclear parton densities

$R_i^A(x, Q^2) = f_i^{p/A}(x, Q^2)/f_i^p(x, Q^2)$ poorly constrained experimentally



EPS09 gluon nPDF ratios

Assuming collinear factorization: $R_{AA}(p_\perp) \simeq R_i^A(x_\perp, p_\perp^2) \times R_j^A(x_\perp, p_\perp^2)$

- Dramatic uncertainties at low $p_\perp^2$ and small $x_\perp \simeq 2p_\perp/\sqrt{s}$
- Better under control at larger $p_\perp$, say $p_\perp \gtrsim 10$ GeV

Baselines

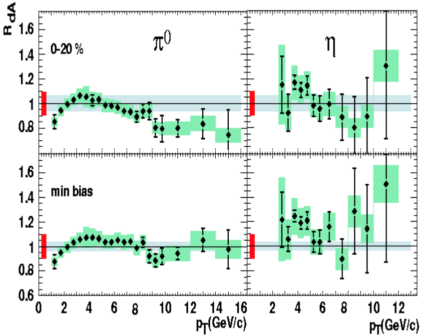
Two strategies to disentangle these effects:

- Need for baseline experiments
  - pA and eA collisions
- Need for baseline observables
  - photons, W/Z^0, Drell-Yan

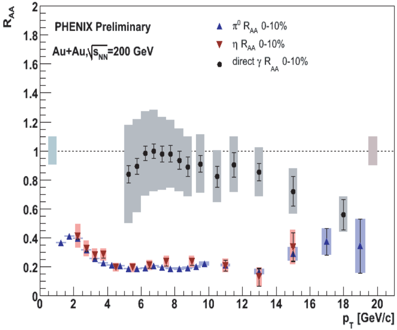
Baselines

Crucial measurements at RHIC

- R^h_{pA} of hadrons in d Au collisions
- R^γ_{AA} of photons in Au Au collisions



PHENIX, from d'Enterria 0902.2011



PHENIX Sakaguchi et al. 0805.4644

Baselines

Crucial measurements at RHIC

- R^h_{pA} of hadrons in d Au collisions
- R^γ_{AA} of photons in Au Au collisions

At LHC

- Urgent need for p A runs at LHC

Salgado et al. 1105.3919

- First measurements on photons and W/Z bosons in Pb Pb collisions

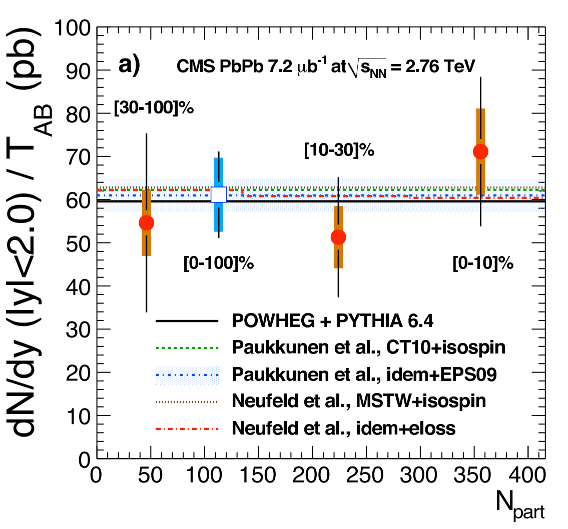
Baselines

Crucial measu

- R^h_{pA} of ha
- R^γ_{AA} of ph

At LHC

- Urgent ne
- First mea



o et al. 1105.3919

Pb collisions

CMS 1102.5435

Part II

R_{AA} – Hadrons

Energy loss effects on R_{AA}: generic features

Toy model

$$\frac{1}{\langle N_{\rm coll} \rangle} N^h_{\rm AA}(p_\perp) = \int d\epsilon\, \mathcal{P}(\epsilon)\, N^h_{pp}(p_\perp + \epsilon)$$

$$\simeq N^h_{pp}(p_\perp) \times \left[1 + (1 - p_0)\, \langle \epsilon \rangle \frac{dN^h_{pp}(p_\perp)}{dp_\perp}\right]$$

- $\mathcal{P}(\epsilon)$ quenching weight — Baier Dokshitzer Mueller Schiff 2001
- $p_0 = \exp(-N_g)$: probability for no energy loss, N_g number of gluons radiated — Salgado Wiedemann 2003

Energy loss effects on R_{AA}: generic features

Toy model

$$R_{AA}^{h}(p_{\perp}) \simeq 1 - (1-p_0)\,\frac{\langle\epsilon\rangle(p_{\perp})}{p_{\perp}}\; n^{h}(x_{\perp}) \qquad n^{h}(x_{\perp}) \equiv \left|\frac{d\ln N_{pp}^{h}(p_{\perp})}{d\ln p_{\perp}}\right|$$

$n(x_{\perp})$ depends on the logarithmic slope of the PDF and FF

- Almost independent of $x_{\perp}$ at small $x_{\perp}$
- Larger for baryons than for mesons, e.g. $n^{p} \gtrsim n^{\pi}$
- Largest at high $x_{\perp}$: $n^{\mathrm{RHIC}} > n^{\mathrm{LHC}}$ at fixed $p_{\perp}$

Energy loss effects on R_{AA}: generic features

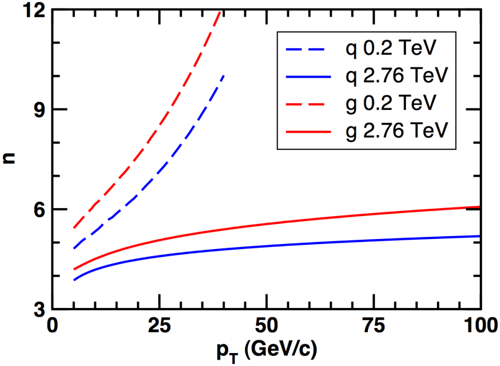
Toy model

$R^h_{AA}(p_\perp) \simeq$

$\left.\frac{\ln N^h_{pp}(p_\perp)}{d \ln p_\perp}\right|$

$n(x_\perp)$ depends

- Almost in
- Larger for
- Largest at



Horowitz Gyulassy 1104.4958

Energy loss effects on R_{AA}: generic features

Toy model

$$R^h_{AA}(p_\perp) \simeq 1 - (1 - p_0)\, \frac{\langle\epsilon\rangle(p_\perp)}{p_\perp}\, n^h(x_\perp) \qquad n^h(x_\perp) \equiv \left| \frac{d \ln N^h_{pp}(p_\perp)}{d \ln p_\perp} \right|$$

Qualitative features

- $R_{AA}(p_\perp) > p_0$
  - Upper limit from RHIC and LHC: $p_0 < 0.1$ (i.e. $N_g > 2$)
- R_{AA} depends on the power law index of the vacuum spectrum
  - Stronger suppression for baryons than for mesons
  - Large uncertainty from the FF poorly known at large z
- R_{AA} depends on the fractional energy loss $\langle\epsilon\rangle(p_\perp)/p_\perp$
  - Large $p_\perp$ lever arm should probe the energy dependence of $\langle\epsilon\rangle(p_\perp)$

$p_\perp$ lever arm at the LHC

Assuming $\langle\epsilon\rangle(p_\perp) \propto p_\perp^\alpha$ and fixing $R_{AA}(p_\perp = 20\ \text{GeV}) = 0.4$ at LHC

Which R_{AA} at $p_\perp = 100$ GeV ?

$$\begin{aligned} \alpha = 0 &\qquad R_{AA}(p_\perp = 100\ \text{GeV}) = 0.88 \\ \alpha = 0.3 &\qquad R_{AA}(p_\perp = 100\ \text{GeV}) = 0.79 \\ \alpha = 0.5 &\qquad R_{AA}(p_\perp = 100\ \text{GeV}) = 0.73 \\ \alpha = 1 &\qquad R_{AA}(p_\perp = 100\ \text{GeV}) = 0.40 \end{aligned}$$

The $p_\perp^{\text{max}}$ value at which $R_{AA}(p_\perp^{\text{max}}) \simeq 1$ – for various centralities – should definitely help to determine the amount of energy loss in the medium

Warning: don't take these numbers too seriously, this is a qualitative illustration of the powerful $p_\perp$ lever arm at the LHC

Ideal playground for energy loss

$$\Lambda_{\rm QCD} \ll \langle\epsilon\rangle \ll p_\perp \ll \frac{\sqrt{s}}{2}$$

1. In all frameworks, gluon emission is perturbative
   - $\langle\epsilon\rangle \sim \hat{q}L^2$: medium should be dense/thick enough
2. Soft gluon emission and eikonal approximation
   - Badly broken at low $p_\perp$, severe limitation at RHIC
   - Strong surface bias effect — Eskola et al. hep-ph/0406319
3. Strong bias effect as phase-space gets restricted (also large y)
   - Does not allow one to observe the increase of $R_{\rm AA}(p_\perp)$ at RHIC

Ideal playground for energy loss

$$\Lambda_{\rm QCD} \ll \langle\epsilon\rangle \ll p_\perp \ll \frac{\sqrt{s}}{2}$$

Dramatic differences between RHIC and LHC !

RHIC $0.2 \text{ GeV} \ll \langle\epsilon\rangle_{\text{RHIC}} \ll 5 - 20 \text{ GeV} \ll 100 \text{ GeV}$

LHC $0.2 \text{ GeV} \ll \langle\epsilon\rangle_{\text{LHC}} \simeq 2.4 \ \langle\epsilon\rangle_{\text{RHIC}} \ll 10 - 100 \text{ GeV} \ll 1.4 - 2.8 \text{ TeV}$

RHIC

- $R_{\text{AA}} \simeq 0.2$: dense medium produced, energy loss at work
- $p_\perp$ & $\sqrt{s}$ not too large complicates the interpretation

LHC

- Slightly denser medium : $(dN/dy)_{\text{LHC}} \simeq 2.4 \ (dN/dy)_{\text{RHIC}}$
- Much larger phase space available: less bias and hopefully less affected by other phenomena at large $p_\perp$

Ideal playground for energy loss

$$\Lambda_{\rm QCD} \ll \langle\epsilon\rangle \ll p_\perp \ll \frac{\sqrt{s}}{2}$$

Dramatic differences between RHIC and LHC !

RHIC	$0.2\ \text{GeV} \ll \langle\epsilon\rangle_{\text{RHIC}} \ll 5-20\ \text{GeV} \ll 100\ \text{GeV}$
LHC	$0.2\ \text{GeV} \ll \langle\epsilon\rangle_{\text{LHC}} \simeq 2.4\ \langle\epsilon\rangle_{\text{RHIC}} \ll 10-100\ \text{GeV} \ll 1.4-2.8\ \text{TeV}$

How to compare RHIC and LHC ?

- At fixed $p_\perp$ and same centrality: same $p_\perp$ and L, different $\hat{q}$
- At fixed $p_\perp$ and particle density: same $p_\perp$ and $\hat{q}$, different L
- At fixed $x_\perp$: same slopes and nPDF/saturation effects, different $p_\perp$

Computing R_{AA}

General strategy

1. Pick an energy loss framework
2. Choose the main ingredients
   - radiative and/or collisional energy loss
3. Cold (matter) dishes
   - nPDF, Cronin effect, etc.
4. Model the medium produced
   - Fix the amount of energy loss
   - Hydrodynamical evolution: 1D Bjorken expansion, 2D/3D ideal hydro, 2D viscous hydro, etc.
5. Compare to data

Radiative energy loss: computing single gluon spectrum

Multiple soft scattering

- BDMPS-Z & ASW-MS — Baier Dokshitzer Mueller Peigné Schiff 1995-1998, Zakharov 1996-2000 Armesto Salgado Wiedemann 2000-2003
  - Static (Debye-screened) scatterers finite L, expanding medium
- AMY — Arnod Moore Yaffe 2001-2002
  - Hot QGP, infinite, static, uniform, assuming $g^2 T \ll gT \ll T$
  - Extension to finite L and expanding media — Arnold 0808.2767

Few (hard) scattering

- DGLV — Djordjevic Gyulassy Lévai Vitev 2000-2003
  - Opacity expansion $n = L/\lambda = \mathcal{O}(1)$
  - Static (Debye-screened) scatterers, finite L, expanding medium
- Higher-twist framework — Guo Wang 2000-2001
  - Rescattering of highly virtual partons, power expansion in $\hat{q}L/Q^2$
  - Extension towards multiple scattering — Majumder 2009

Radiative energy loss: multi-gluon emission

BDMPS-Z / ASW / DGLV

- Poisson approximation of independent gluon emission

$$\mathcal{P}(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \, \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right) \exp\left(- \int d\omega \, \frac{dI}{d\omega}\right)$$

Higher Twist

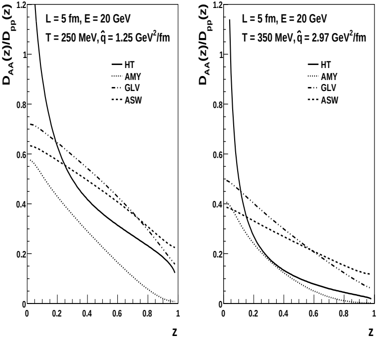
- Follows virtuality ordering given by DGLAP evolution

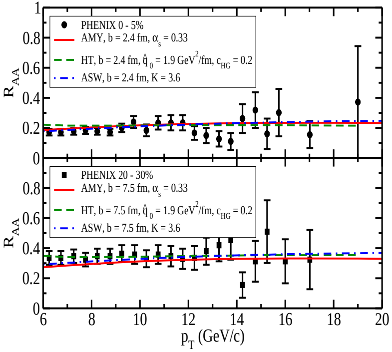
AMY

- Solving rate equation

$$\begin{aligned}\frac{dP_{q\bar{q}}(p)}{dt} &= \int_{-\infty}^{\infty} d\ell \; P_{q\bar{q}}(p+\ell) \, \frac{d\Gamma^{q}_{qg}(p+\ell,\ell)}{d\ell dt} \\ &\quad - P_{q\bar{q}}(p) \, \frac{d\Gamma^{q}_{qg}(p,\ell)}{d\ell dt} + \; 2P_{g}(p+\ell) \, \frac{d\Gamma^{g}_{q\bar{q}}(p+\ell,\ell)}{d\ell dt}\end{aligned}$$

Major effort to compare systematically the various frameworks





Majumder Van Leeuwen 1002.2206

Bass et al. 0808.0908

https://wiki.bnl.gov/TECHQM

Collisional energy loss

- First considered by Bjorken

  Bjorken 1982, Braaten Thoma 1991 Thoma Gyulassy 1991 Mustafa Thoma 2005

- Full calculation including the running of α_s Peigné Peshier 0802.4364

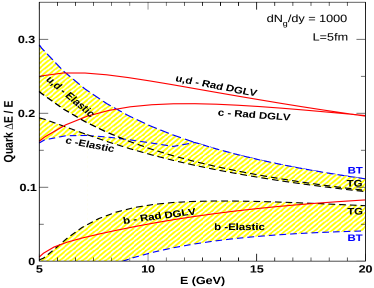
$$-\frac{d\langle\epsilon\rangle_{\text{coll}}}{dx} = \frac{4\pi T^2}{3}\,\alpha_s(m_D^2)\,\alpha_s(ET)\left(1+\frac{n_f}{6}\right)\ln\frac{ET}{m_D^2}\left[1+\mathcal{O}\left(\alpha_s(m_D^2)\right)\right]$$

leading to 30% uncertainty in the amount of energy loss

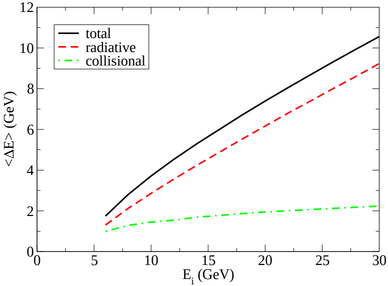
Phenomenology

- For long time assumed to be negligible : $\langle\epsilon\rangle_{\text{coll}} \ll \langle\epsilon\rangle_{\text{rad}}$
- Might explain HQ energy loss at RHIC (single electron puzzle) due to the smaller radiative energy loss Wicks et al. nucl-th/0512076
- Also taken into account for light quark quenching

Collisional energy loss



Wicks et al. (WHDG) nucl-th/0512076



Qin et al. (AMY) 0710.0605

- $\langle\epsilon\rangle_b^{\text{coll}} \simeq \langle\epsilon\rangle_b^{\text{rad}}$ while $\langle\epsilon\rangle_{q,c}^{\text{coll}} \lesssim 0.5\langle\epsilon\rangle_{q,c}^{\text{rad}}$
- $\langle\epsilon\rangle^{\text{coll}}/\langle\epsilon\rangle^{\text{rad}}$ gets smaller at large E

LHC phenomenology – BDMPS-ASW

Renk Holopainen Paatelainen Eskola 1103.5308

Hadron production at LO & EPS09 nPDF

- BDMPS radiative energy loss w/ medium-averaged quenching weights
- Embedded in $2+1$D ideal hydro with EKRT initial conditions

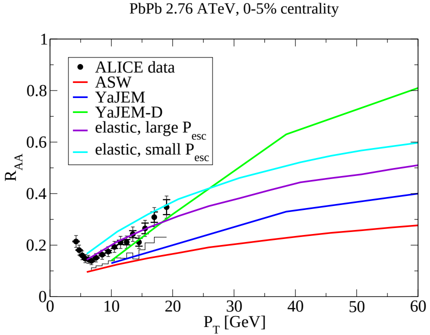
Strategy

- Fix the amount of energy loss in Au Au at RHIC: $\hat{q} \propto K\ \epsilon^{3/4}$
- Constrain hydro model using ALICE low $p_\perp$ spectra

LHC phenomenology – BDMPS-ASW

Renk Holopainen Paatelainen Eskola 1103.5308

Results



- Different $p_\perp$ dependence of R_{AA} expected
- Too strong suppression requiring large rescaling
- Crucially depends on the pp reference spectrum

LHC phenomenology – WHDG

Horowitz Gyulassy 1104.4958

Hadron production at LO & no nPDF

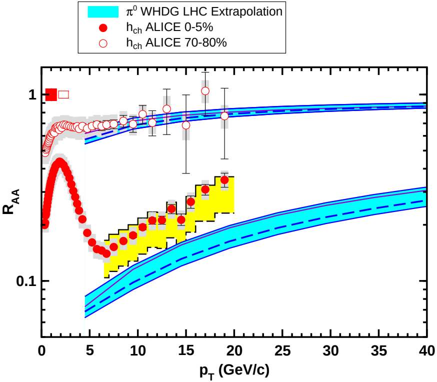
- DGLV radiative energy loss with Poisson probability distributions
- Braaten-Thoma collisional energy loss with Gaussian prob. dist.
- Geometrical fluctuations in 1D Bjorken model

Constrained predictions

- Fix the energy loss in Au Au at RHIC
- Scaled with $(dN/dy)_{\rm LHC}$ / $(dN/dy)_{\rm RHIC}$
- Predictions of $R_{\rm AA}$ (and $R_{\rm CP}$) at 2.76 and 5.5 TeV

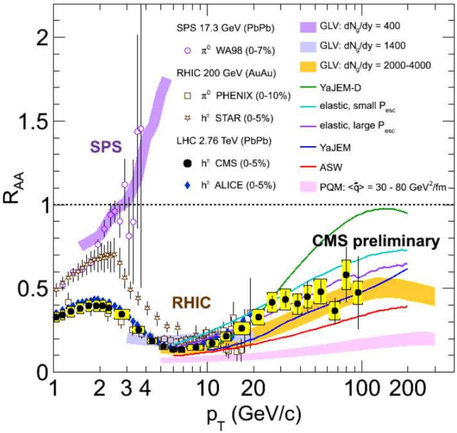
LHC phenomenology – WHDG

Results



- Too strong suppression in central collisions
- Conjectures about the reduced opacity: running α_s? Saturation? etc.

LHC new data vs. theory



- Radiative energy loss (slightly) undershoot data
- Don't draw premature conclusions because of a (dis)agreement !

Quantifying the slope of R_{AA}

Remarks

- Magnitude of R_{AA} depends on $\langle N_{\rm coll} \rangle$ scaling (Glauber) and the value of $\hat{q}$
- Slope of R_{AA} depends on the dynamics of energy loss models

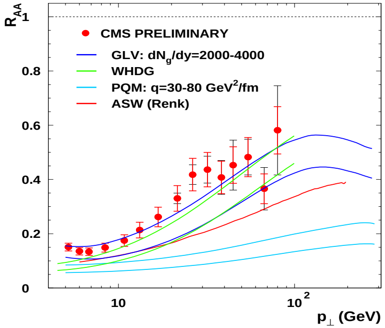
R_{AA} logarithmic slope

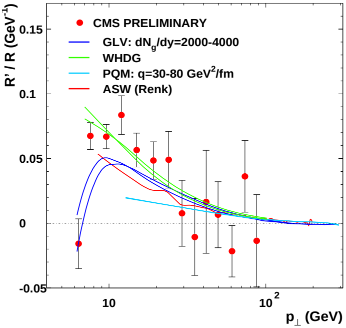
$$R'_{\log} = \frac{d \ln R_{AA}}{dp_\perp}$$

- Free of normalization uncertainties
- Should be mostly sensitive to statistical uncertainties

FA, 1109.3121

Quantifying the slope of R_{AA}





FA, 1109.3121

- Errror bands (from varying $\hat{q}$) shrink
- Change of slope at low $p_\perp$ predicted in only one model

Part III

R_{AA} – Photons

Prompt photons

An ideal probe in nuclear collisions

- p p : constraints on gluon PDFs and possible saturation effects

  Ichou d'Enterria 1005.4529 Kopeliovich et al. 0902.4287

- p A : constraints on nuclear PDFs or energy loss in cold matter

  FA Gousset 0707.2944 Brenner-Mariotto Gonçalves 0807.1680

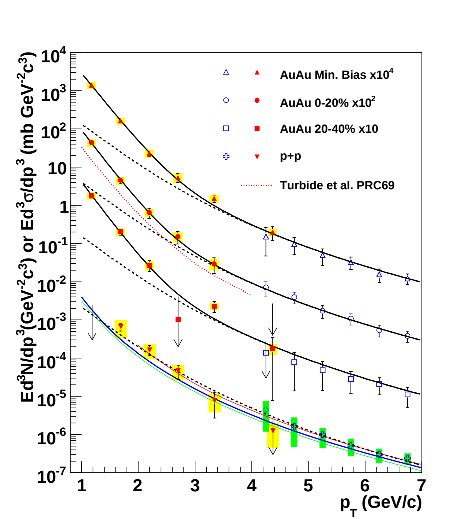
  FA Eskola Paukkunen Salgado 1103.1471 Vitev Zhang 0804.3805

- A A collisions
  - QGP thermal emission at low $p_{\perp} = \mathcal{O}(T)$
  - Good reference process: photons escape the medium without re-interaction

Prompt photons

An ideal probe in nuclear collisions

- p p : constrai... tion effects
  liovich et al. 0902.4287
- p A : constrai... cold matter
  ...o Gonçalves 0807.1680
  Vitev Zhang 0804.3805
- A A collisions
  - QGP ther...
  - Good refe... n without re-interac...



PHENIX 0804.4168

Prompt photons

An ideal probe in nuclear collisions

- p p : constraints on gluon PDFs and possible saturation effects

  Ichou d'Enterria 1005.4529 Kopeliovich et al. 0902.4287

- p A : constraints on nuclear PDFs or energy loss in cold matter

  FA Gousset 0707.2944 Brenner-Mariotto Gonçalves 0807.1680

  FA Eskola Paukkunen Salgado 1103.1471 Vitev Zhang 0804.3805

- A A collisions
  - QGP thermal emission at low $p_\perp = \mathcal{O}(T)$
  - Good reference process: photons escape the medium without re-interaction

Not as simple, though. . .

Prompt photons

- Delicate measurement because of the large $\pi^0 \rightarrow \gamma\gamma$ background
- Due to a simple isospin effect, R_{AA}^{γ} not normalized to unity

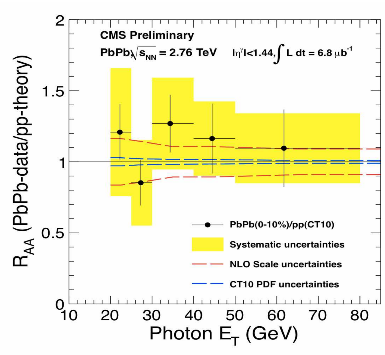
$$\text{QED coupling} : \sigma(ug \rightarrow u\gamma)/\sigma(dg \rightarrow d\gamma) = e_u^2/e_d^2 = 4$$

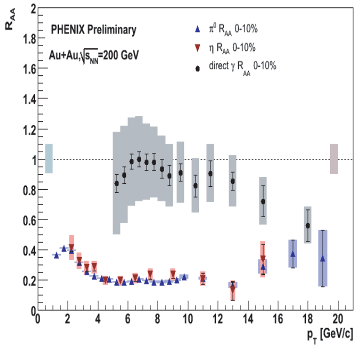
$R_{pA}(p_\perp, y) < 1$ when valence quarks dominate

- large $p_\perp$
- backward rapidity in p A and also forward rapidity in d A and A A

- Despite common belief, prompt photons may actually be sensitive to hot medium effects through a variety of processes

Inclusive (PHENIX) and isolated (CMS) measurements

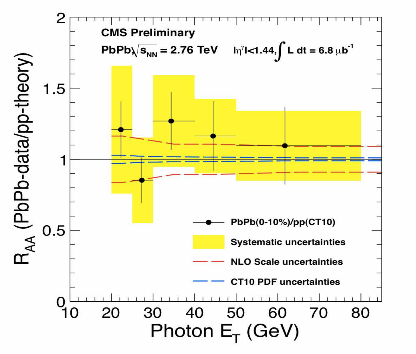


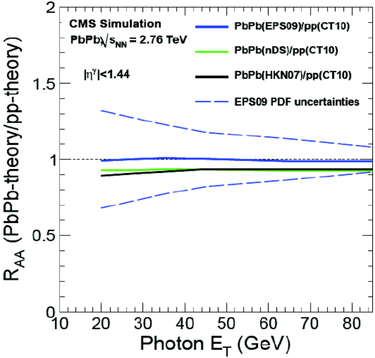


PHENIX Sakaguchi et al. 0805.4644

- No strong medium effects observed
- Uncertainties at RHIC prevent from drawing quantitative conclusions

Inclusive (PHENIX) and isolated (CMS) measurements

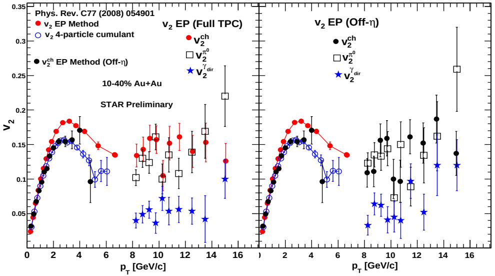


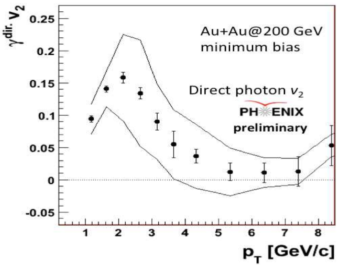


- No strong medium effects observed
- Uncertainties at RHIC prevent from drawing quantitative conclusions

Prompt photons at RHIC/LHC: v_2

Large $p_\perp$ azimuthal anisotropy (v_2) measured by STAR & PHENIX





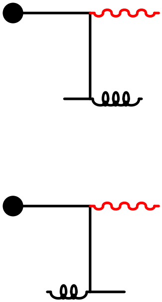
STAR Hamed 1008.4894 PHENIX 1105.4126

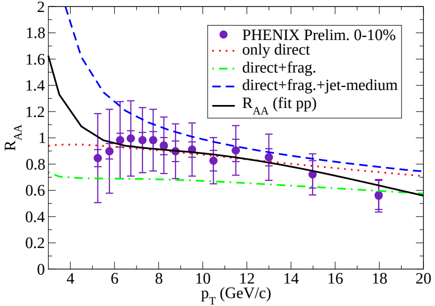
- Positive v_2 reported by STAR
  - π^0 contamination, non-flow contributions, genuine medium effects ?
- PHENIX compatible with vanishing v_2 yet compatible with STAR

Jet – photon conversion in QGP

Fries Müller Srivastava nucl-th/0208001 Turbide Gale Jeon Moore hep-ph/0502248

- Enhancement of isolated photons in A A collisions





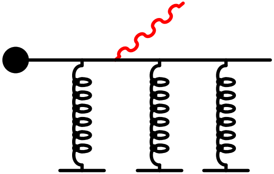
Qin Ruppert Gale Jeon Moore 0906.3280

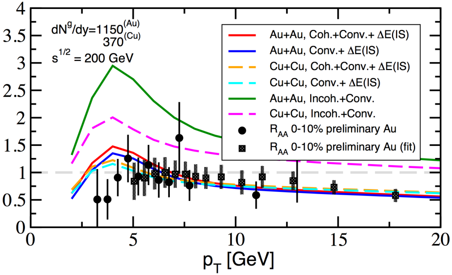
Medium-induced photon emission

Zakharov hep-ph/0405101

- Similar to medium-induced gluon emission leading to enhancement of non-isolated photons in A A collisions
- Also studied in DIS on nuclei

Majumder Fries Müller 0711.2475



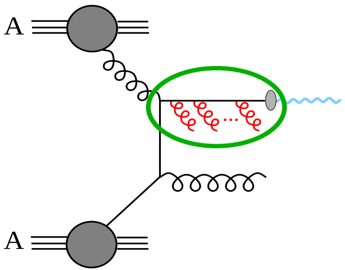


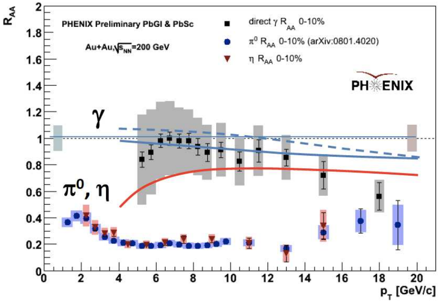
Vitev Zhang 0804.3805

Quenching of fragmentation photons

Jalilian-Marian Orginos Sarcevic hep-ph/0101041 FA hep-ph/0601075

- Similar to the quenching of single hadrons leading to the suppression of non isolated photons
- Warning: distinction between direct and fragmentation is not physical



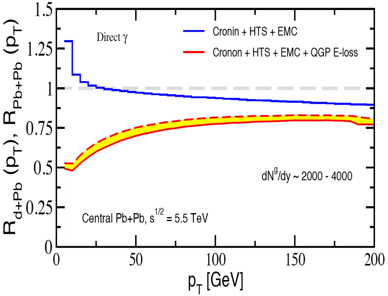


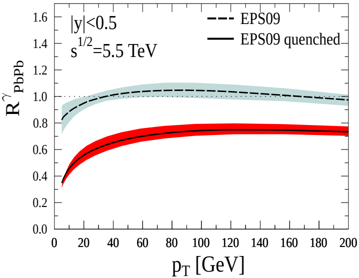
FA hep-ph/0601075

Quenching of fragmentation photons

Jalilian-Marian Orginos Sarcevic hep-ph/0101041 FA hep-ph/0601075

- Similar to the quenching of single hadrons leading to the suppression of non isolated photons
- Warning: distinction between direct and fragmentation is not physical





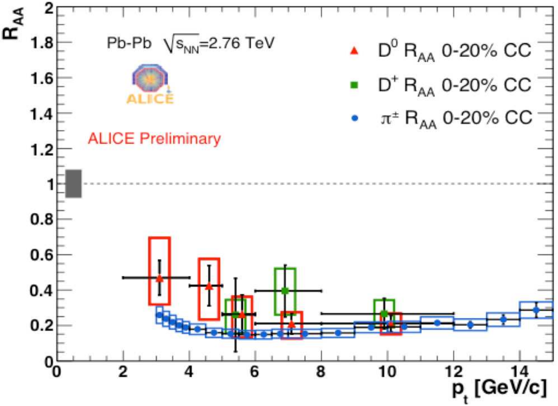
Vitev in 0711.0974 FA Eskola Paukkunen Salgado 1103.1471

Open questions & Puzzles

- Does factorization work in (pp and) nuclear collisions   Collins 0708.4410
- Is energy loss perturbative? Is AdS/CFT phenomenology satisfying?
- Extending energy loss frameworks
  - Beyond leading order, soft/collinear limit, running coupling, etc.
- Meson vs. baryon R_{AA}
  - Hierarchy according to the FF slopes ? Test q vs. g: $\epsilon_g/\epsilon_q = 9/4$?
- Heavy-quark energy loss
  - Is the hierarchy $\epsilon_q > \epsilon_c > \epsilon_b$ correct ?   Aurenche Zakharov 0907.1918
  - Light vs. heavy quark quenching puzzle at LHC, again ?
- Forward R_{pA}/R_{AA}: saturation or energy loss ?
- If energy loss models reproduce R_{AA}, what to conclude for saturation ?

Open questions & Puzzles

- Does factorization work in (pp and) nuclear collisions Collins 0708.4410
- Is energy loss perturbative? Is AdS/CFT phenomenology satisfying?
- Extending
  - Beyo ling, etc.
- Meson vs.
  - Hiera $/\epsilon_q = 9/4$?
- Heavy-qu
  - Is the akharov 0907.1918
  - Light ?
- Forward
- If energy or saturation ?



Open questions & Puzzles

- Does factorization work in (pp and) nuclear collisions Collins 0708.4410
- Is energy loss perturbative? Is AdS/CFT phenomenology satisfying?
- Extending energy loss frameworks
  - Beyond leading order, soft/collinear limit, running coupling, etc.
- Meson vs. baryon R_{AA}
  - Hierarchy according to the FF slopes ? Test q vs. g: $\epsilon_g/\epsilon_q = 9/4$?
- Heavy-quark energy loss
  - Is the hierarchy $\epsilon_q > \epsilon_c > \epsilon_b$ correct ? Aurenche Zakharov 0907.1918
  - Light vs. heavy quark quenching puzzle at LHC, again ?
- Forward R_{pA}/R_{AA}: saturation or energy loss ?
- If energy loss models reproduce R_{AA}, what to conclude for saturation ?

Open questions & Puzzles

- Does factorization work in (pp and) nuclear collisions Collins 0708.4410
- Is energy loss perturbative? Is AdS/CFT phenomenology satisfying?
- Extending energy loss frameworks
  - Beyond leading order, soft/collinear limit, running coupling, etc.
- Meson vs. baryon R_{AA}
  - Hierarchy according to the FF slopes ? Test q vs. g: $\epsilon_g/\epsilon_q = 9/4$?
- Heavy-quark energy loss
  - Is the hierarchy $\epsilon_q > \epsilon_c > \epsilon_b$ correct ? Aurenche Zakharov 0907.1918
  - Light vs. heavy quark quenching puzzle at LHC, again ?
- Forward R_{pA}/R_{AA}: saturation or energy loss ?
- If energy loss models reproduce R_{AA}, what to conclude for saturation ?

How to properly quantify theoretical uncertainties?

Summary

Single hadron quenching at RHIC

- First evidence for parton energy loss in QCD media although R_{AA} affected by many other processes

Single hadron quenching at LHC

- New era for parton energy loss studies w/ larger phase-space available
- Too strong quenching from simple RHIC extrapolation (?)
- Crucial need for p Pb collisions
- Systematic RHIC/LHC comparison at fixed $p_{\perp}$, $x_{\perp}$, dN/dy needed

Prompt photons

- Final PHENIX data needed on R_{AA}, interesting v_2
- First isolated photons in AA collisions (CMS)
- Probe nPDF/saturation (low $p_{\perp}$) and test $\langle N_{\mathrm{coll}} \rangle$ scaling (large $p_{\perp}$)
- As yet, no evidence for hot medium effects on photons