# Quenching of single hadron and photon spectra from RHIC to LHC

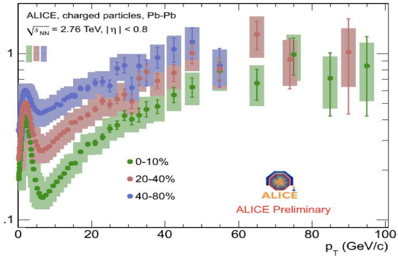
François Arleo

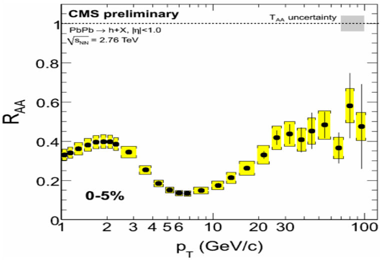
LAPTH, Annecy

Quark Matter 2011

# This talk

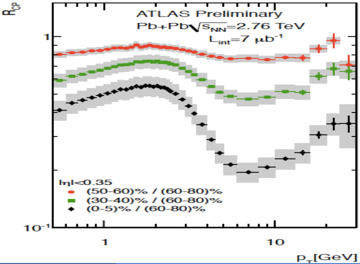
Impressive data at RHIC and LHC exhibit strong quenching of single hadron spectra, suggesting large energy loss effects in dense QCD media




Mind the scales !

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



# This talk

## Outline

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

I will not address jet production and more exclusive observables

Talk by K. Zapp at 10.50am today

# 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
- $\langle N_{\mathrm{coll}} \rangle = T_{AA}\, \sigma_{\mathrm{inel}}^{NN}$ scaling assumption of hard processes in AA collisions
- pQCD processes modified in dense media

# Reference processes in pp collisions

Since $Q \gg \Lambda_{\mathrm{QCD}}$, 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

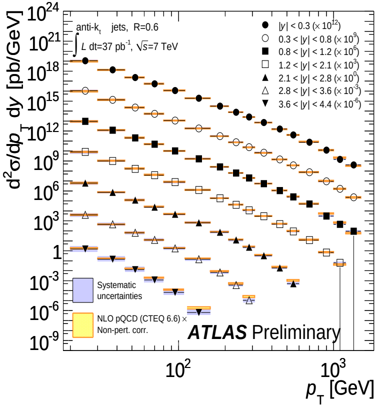
## Hard processes in heavy-ion collisions

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

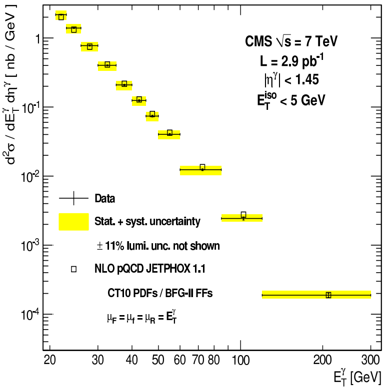
as well as double inclusive observables e.g. hadron-hadron or $\gamma$+jet

# Reference processes: jets and photons

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

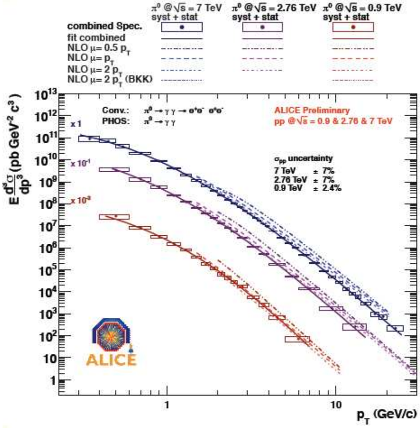



Jets in ATLAS – ATLAS-CONF-2011-047




Photons in CMS – 1012.0799

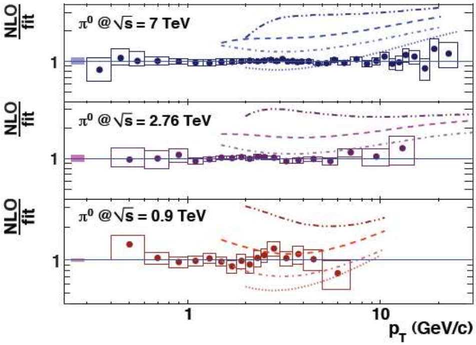
Discrepancy reported for single hadron production in pp at LHC




NLO pQCD (W. Vogelsang):

PDF: CTEQ6M5, FF: DSS, scales, $\mu = 0.5\, p_T, p_T, 2\, p_T$

Also: INCNLO with BKK FF

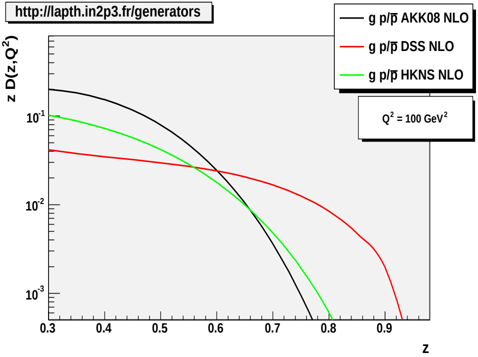



ALICE $\pi^0$ – Reygers, Mon 23, 4.20pm

# 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

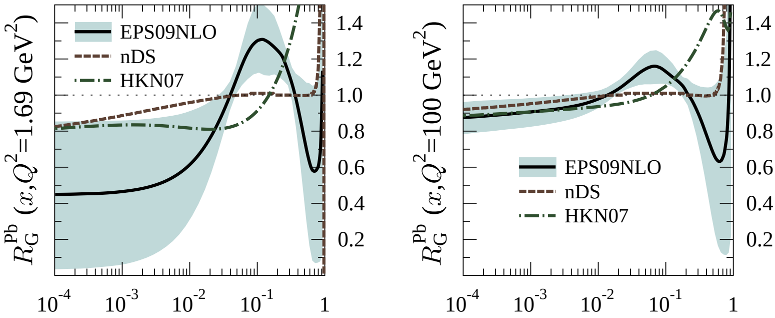
  nDS 2004, HKN 2007, EPS 2009, nCTEQ 2009

  Albacete, Tue. 24, 8.30am
- 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

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

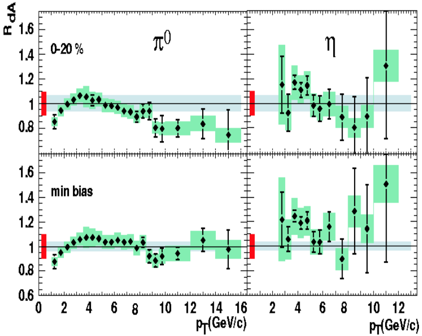
    Armesto, Thu. 26, 3.20pm; Salgado, Sat. 28, 10am; Staśto, Sat. 28, 10.30am

- Need for baseline observables
  - photons, $W/Z^0$, Drell-Yan

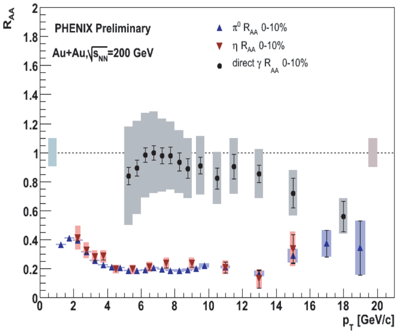
# Baselines

## Crucial measurements at RHIC

- $R^h_{pA}$ of hadrons in d Au collisions
- $R^\gamma_{AA}$ 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
- $R^\gamma_{AA}$ 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

Robles, Thu. 26, 3pm; Sandström, Thu. 26, 3.20pm; Kim, Fri. 27, 5.30pm

Benhabib, poster

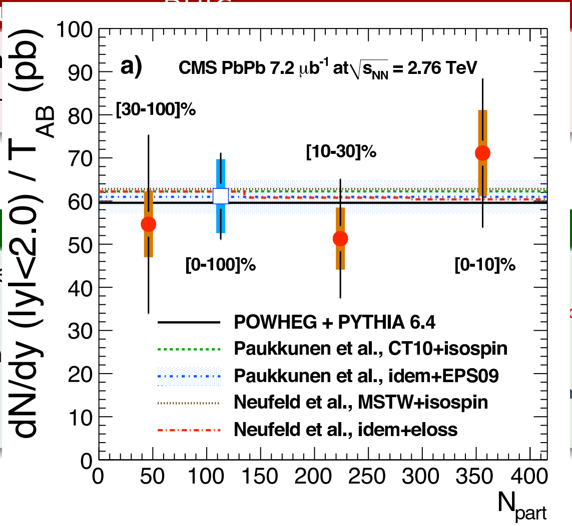
# Baselines

## Crucial meas

- $R^h_{pA}$ of ha
- $R^\gamma_{AA}$ of ph

## At LHC

- Urgent ne
  o et al. 1105.3919
- First mea
  Pb collisions
  n, Fri. 27, 5.30pm
  Benhabib, poster




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

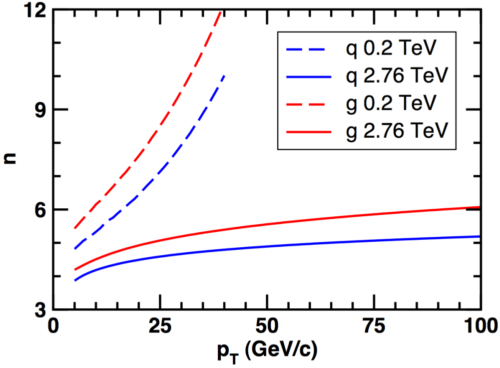
$$R^h_{AA}(p_\perp) \simeq 1 - (1 - p_0)\, \frac{\langle\epsilon\rangle(p_\perp)}{p_\perp}\, n^h(x_\perp) \qquad n^h(x_\perp) \equiv \left| \frac{d \ln N^h_{pp}(p_\perp)}{d \ln p_\perp} \right|$$

$n(x_\perp)$ 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 $p_\perp$

## Toy model

$$R^h_{AA}(p_\perp) \simeq \qquad \frac{\ln N^h_{pp}(p_\perp)}{d \ln p_\perp}\Bigg|$$




Horowitz Gyulassy 1104.4958

$n(x_\perp)$ depends

- Almost in
- Larger for
- Largest at

# 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 ?

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

The $p_\perp^{\max}$ value at which $R_{AA}(p_\perp^{\max}) \simeq 1$ – 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

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

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 $R_{\mathrm{AA}}(p_\perp)$ 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 $\quad 0.2\ \text{GeV} \ll \langle\epsilon\rangle_{\text{RHIC}} \ll 5-20\ \text{GeV} \ll 100\ \text{GeV}$

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

**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

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

Dramatic differences between RHIC and LHC !

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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

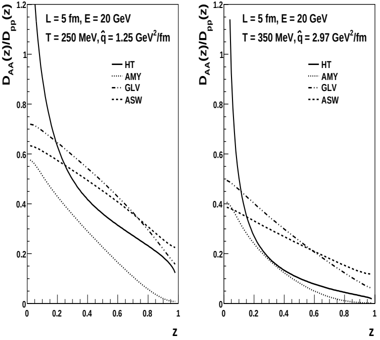
- Follows virtuality ordering given by DGLAP evolution

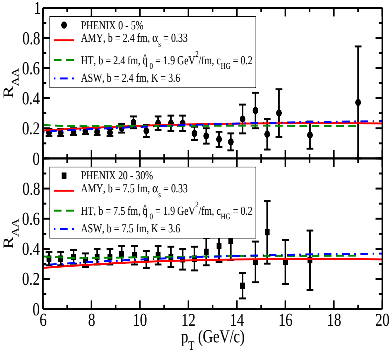
## AMY

- 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

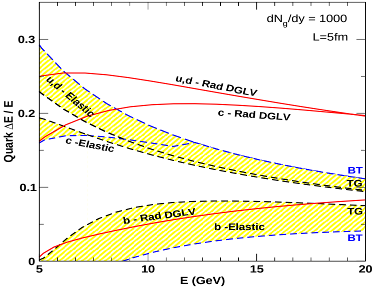
- Full calculation including the running of $\alpha_s$ Peigné Peshier 0802.4364

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

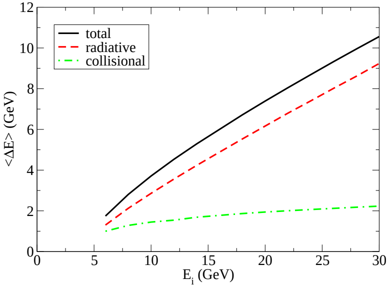
leading to 30% uncertainty in the amount of energy loss

## Phenomenology

- For long time assumed to be negligible : $\langle\epsilon\rangle_{\mathrm{coll}} \ll \langle\epsilon\rangle_{\mathrm{rad}}$
- 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




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 & Renk, Tue 24, 4.40pm

Hadron production at LO & EPS09 nPDF within three energy loss models

- BDMPS radiative energy loss w/ medium-averaged quenching weights
- YaJEM: Virtuality gain during medium evolution $\Delta Q^2_{\rm tot} = \int d\zeta \hat{q}(\zeta)$
- Toy-model elastic energy loss: $\mathcal{P}^{\rm coll}(\epsilon) = p_{\rm esc}\ \delta(\epsilon) + \text{Gaussian}(\langle\epsilon\rangle, \sigma)$

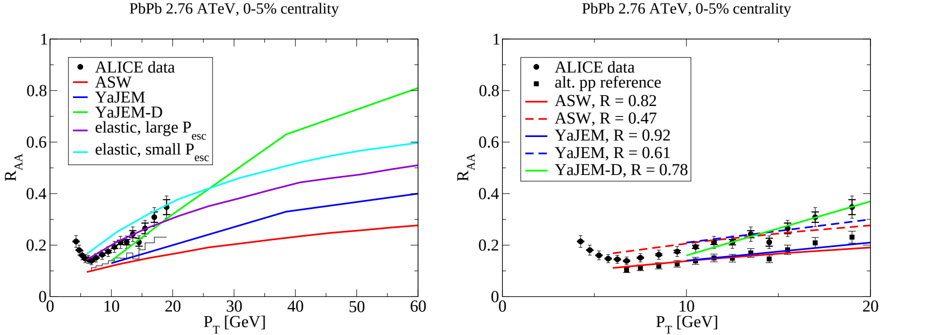
- Embedded in $2+1$D ideal hydro with EKRT initial conditions

**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

Renk Holopainen Paatelainen Eskola 1103.5308 & Renk, Tue 24, 4.40pm

## Results




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

# LHC phenomenology – WHDG

Horowitz Gyulassy 1104.4958 & Horowitz, Thu. 26, 3.40pm

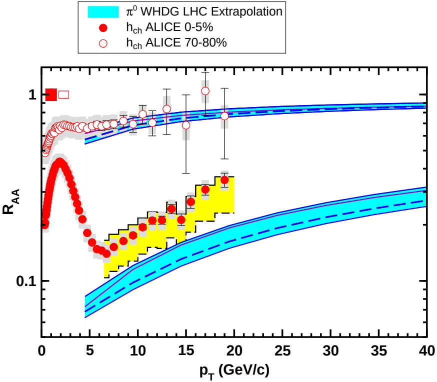
## Hadron production at LO & no nPDF

- 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

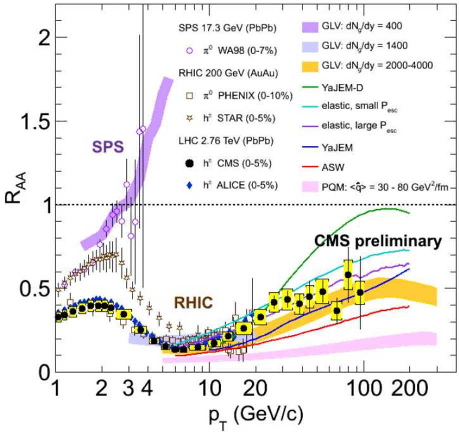
- Fix the energy loss in Au Au at RHIC
- Scaled with $(dN/dy)_{\mathrm{LHC}}$ / $(dN/dy)_{\mathrm{RHIC}}$
- Predictions of $R_{\mathrm{AA}}$ (and $R_{\mathrm{CP}}$) at 2.76 and 5.5 TeV

## Results




- Too strong suppression in central collisions
  - Is energy loss $\langle\epsilon\rangle \propto n_g$ (and $n_g \propto dN/dy$) ?
- Conjectures about the reduced opacity: running $\alpha_s$? Saturation? etc.

# LHC new data vs. theory




CMS – Lee

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

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
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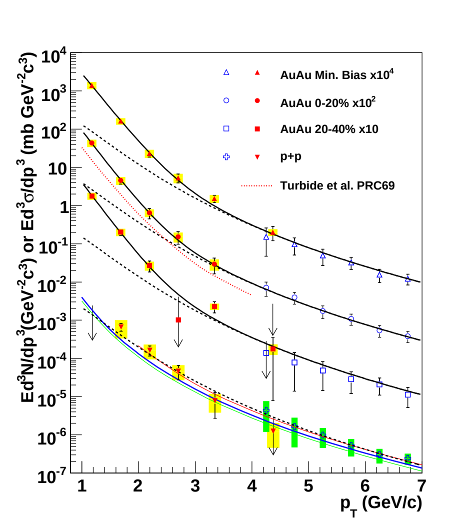


PHENIX 0804.4168

# Prompt photons

## An ideal probe in nuclear collisions

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- 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 $\pi^0 \to \gamma\gamma$ background
- Due to a simple isospin effect, $R^{\gamma}_{\text{AA}}$ not normalized to unity

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

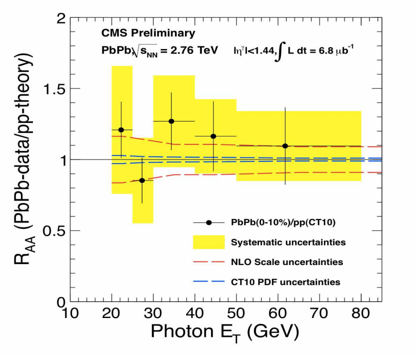
**$R_{pA}(p_\perp, y) < 1$ when valence quarks dominate**

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

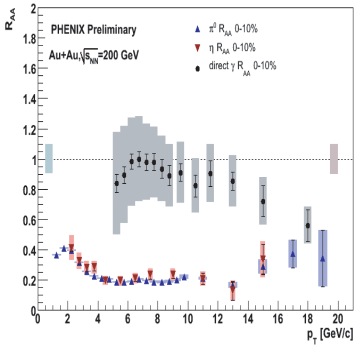
- Despite common belief, prompt photons may actually be sensitive to hot medium effects through a variety of processes

# Prompt photons at RHIC/LHC: $R_{AA}$

## Inclusive (PHENIX) and isolated (CMS) measurements




CMS – Lee




PHENIX Sakaguchi et al. 0805.4644

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

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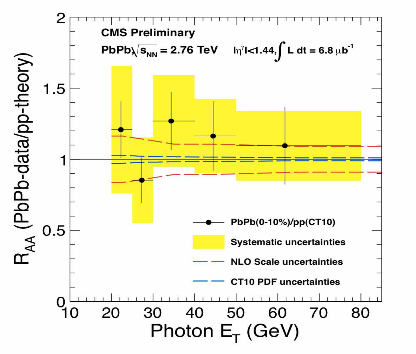


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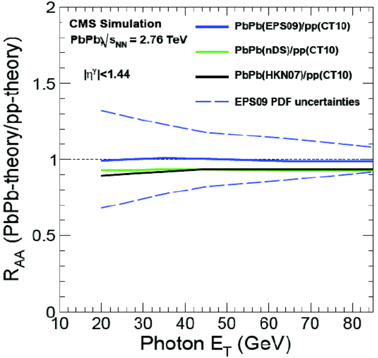


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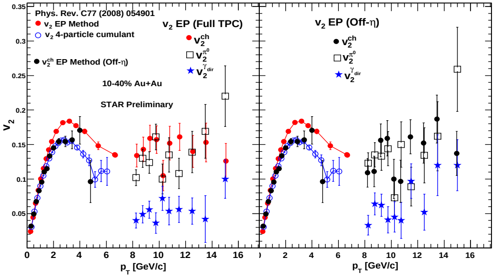
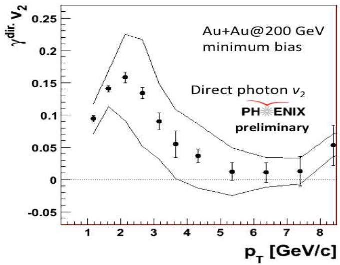
Large $p_\perp$ azimuthal anisotropy ($v_2$) measured by STAR & PHENIX




STAR Hamed 1008.4894



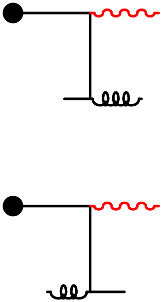

PHENIX 1105.4126

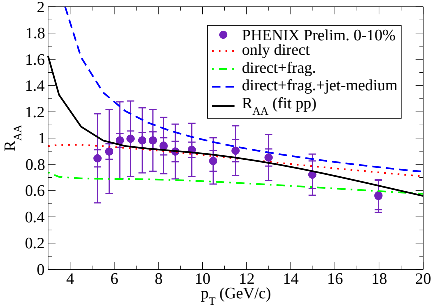
- Positive $v_2$ reported by STAR
  - $\pi^0$ contamination, non-flow contributions, genuine medium effects ?
- PHENIX compatible with vanishing $v_2$ yet compatible with STAR

# 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





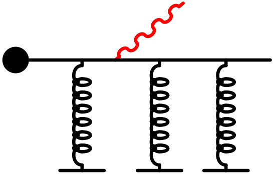

Qin Ruppert Gale Jeon Moore 0906.3280

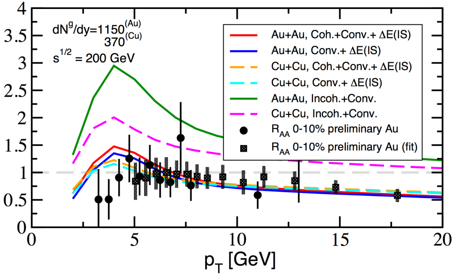
# Medium-induced photon emission

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



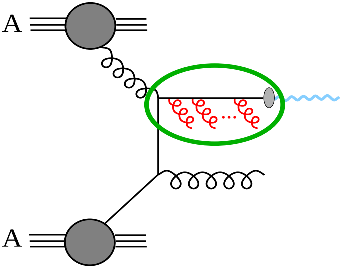


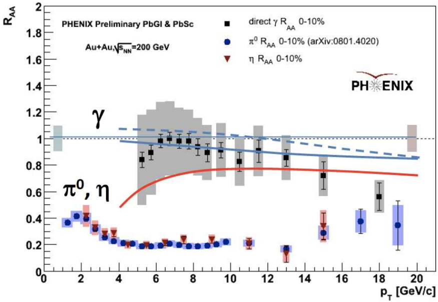

Vitev Zhang 0804.3805

# 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

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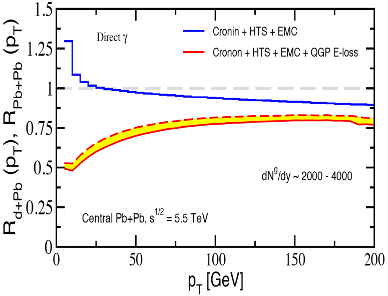


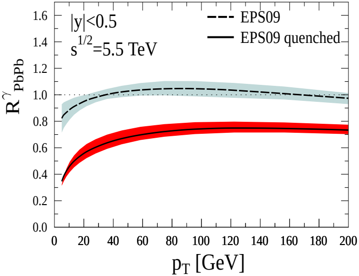


Vitev in 0711.0974 FA Eskola Paukkunen Salgado 1103.1471

# Medium effects on photon production

## Qualitative predictions

| | |
|---|---|
| Conversion | $R_{AA} > 1$ ($v_2 < 0$) of isolated photons at low $p_\perp$ |
| Ind. emission | $R_{AA} > 1$ ($v_2 < 0$) of inclusive photons at low $p_\perp$ |
| $\gamma$ quenching | $R_{AA} < 1$ ($v_2 > 0$) of inclusive photons at intermediate $p_\perp$ |

For more. . .

Photons: Thu. 26 3pm - 5.20pm (Ravel AB)

Jet quenching: Thu. 26 3pm - 5.20pm (Europe)
& Fri. 27 5.30pm - 7.30pm (Verdi)

# 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 ?

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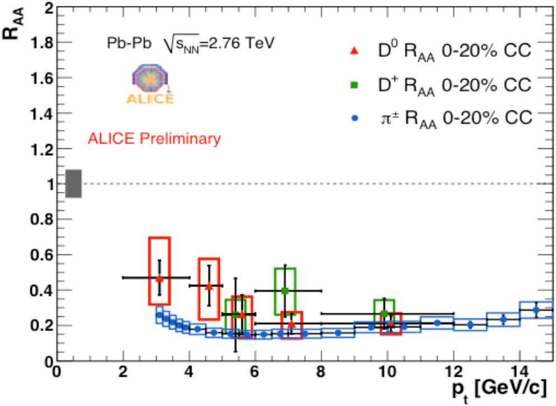

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How to properly quantify theoretical uncertainties?

# 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 $\langle N_{\rm coll} \rangle$ scaling (large $p_\perp$)
- As yet, no evidence for hot medium effects on photons

# The End

That's all, thanks for your attention !


Thanks to many colleagues and in particular N. Armesto, D. d'Enterria and S. Peigné

Part IV

# Back-up

Chen Hirano Wang Wang Zhang 1102.5614 & Zhang, Thu. 26, 4pm

## Hadron production at NLO & no nPDF

- Fragmentation function in cold matter given by modified DGLAP eq.

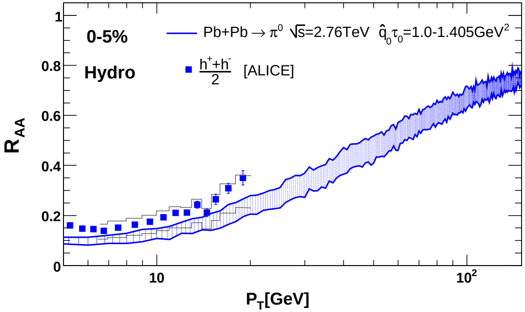
$$\tilde{D}_q^h = D_q^h + \frac{\alpha_s}{2\pi} \int_{\Lambda^2}^{Q^2} \left[ \Delta\gamma_{q\to qg} \otimes D_q^h + \Delta\gamma_{q\to gq} \otimes D_g^h \right]$$

  with medium splitting functions depending on quark-gluon correlations inside nuclei

- Extension for QGP & hadronic gas, assuming radiative energy loss
- Embedded in $3+1$D ideal hydro with HIJING2.0 initial conditions

See also Majumder Shen 1103.0809

## Results




- Too strong suppression expected
- Recombination processes at work ?