Aspects of photon production in heavy-ion collisions

François Arleo (LLR Palaiseau, France)

Lectures

- Lecture #1 (today)

  Prompt photon production, from pp to AA collisions

- Lecture #2 (Sun. 15, 12:30pm)

  Quark-gluon plasma radiation: thermal photon production

Outline

- Definition
- Perturbative QCD framework
- Prompt photon production in pp collisions
- Prompt photons in nuclear collisions

What prompt photons ?

- A definition

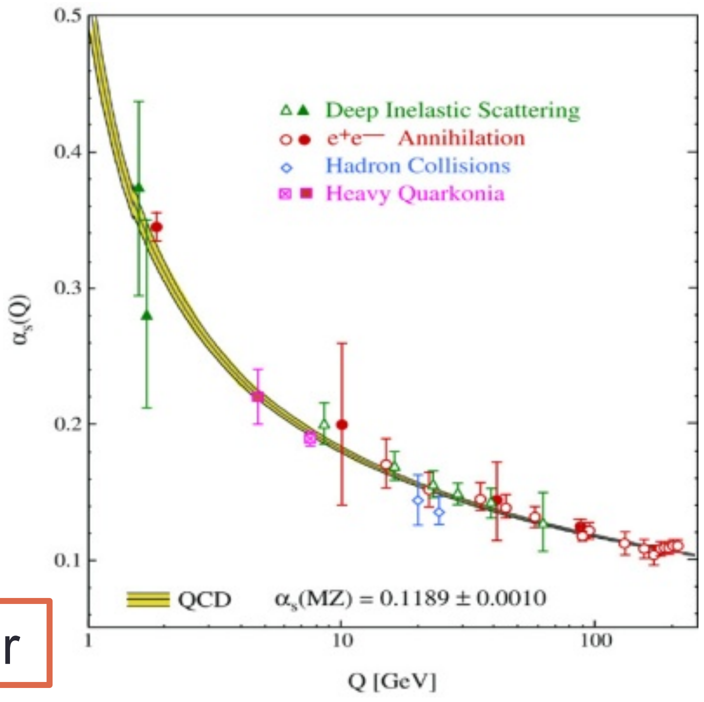
  Prompt photons are produced by the hard scattering of two incoming nucleons [hard = w/ large momentum transfer $Q \gg \Lambda_{QCD}$]

  Prompt photons carry large $p_T \gg \Lambda_{QCD} = O(1\ \text{GeV})$

- Physical consequence

  Asymptotic freedom (Nobel Prize 2004) allows for a perturbative treatment

$$\alpha_s(Q \gg \Lambda_{\text{QCD}}) \ll 1$$



Lecture by A. Kovner

Why bothering about photons ?

- Genuine test of perturbative QCD through a careful comparison between high-precision data and fixed order (NLO) or resummed (NLL) calculations

- Interesting constraints on non-perturbative quantities such as parton distribution functions in a proton (or nucleus)

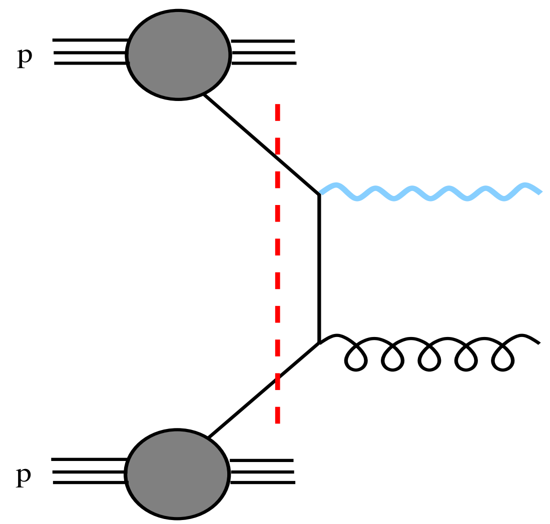
- Allow for a systematic comparison between different systems to probe nuclear effects in p–A and A–A collisions

- Crucial reference process for other hard probes (e.g. jets)

- Important QCD background for (B)SM physics, such as Higgs decay

pQCD calculations in a nutshell

Factorization



Cross section = non-perturbative x perturbative physics

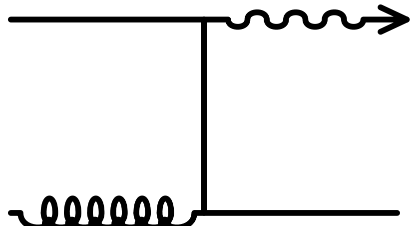
- Factorization theorem used as a (solid) working assumption
- Non-perturbative parton distribution functions
  - Fitted to DIS and pp data
  - Evolution given by perturbative QCD (DGLAP)
- Perturbative QCD amplitudes
  - Computed using Feynman diagram techniques

Diagrammatics

Leading-order contributions O(α α_s)

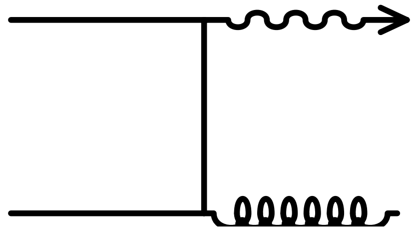
- Compton scattering

$$qg \to q\gamma$$



- Annihilation process

$$q\bar{q} \to g\gamma$$



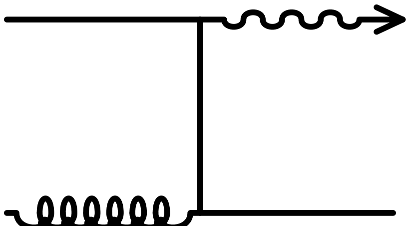
At high energy, only the Compton scattering process is relevant

Diagrammatics

Leading-order contributions $O(\alpha\ \alpha_s)$

- Compton scattering

$$qg \rightarrow q\gamma$$



- Annihilation process

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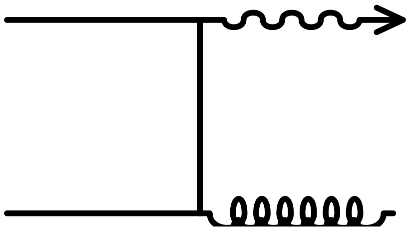
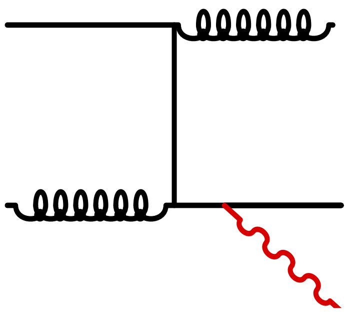


At high energy, only the Compton scattering process is relevant

What about higher-order corrections ?

Diagrammatics

A next-to-leading order contribution O($\alpha\ \alpha_s^2$)

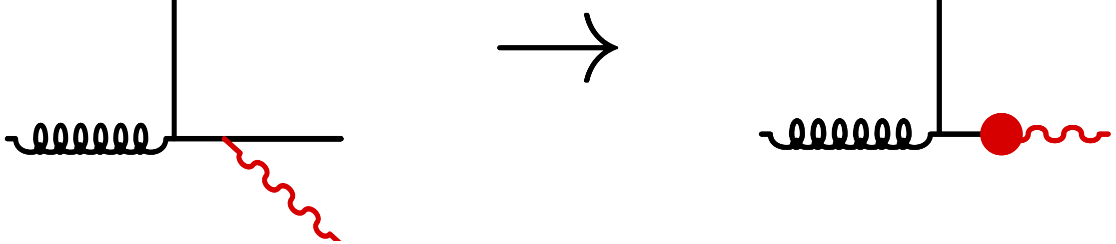


The collinear divergence of this diagram is absorbed into new non-perturbative objects :

quark/gluon fragmentation into a (collinear) photon

Diagrammatics

A next-to-leading order contribution $O(\alpha\ \alpha_s^2)$



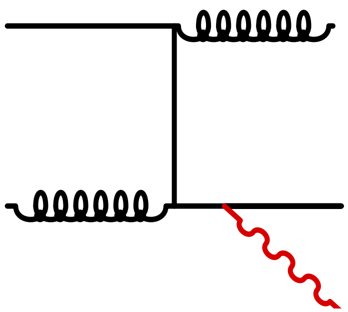
The collinear divergence of this diagram is absorbed into new non-perturbative objects :

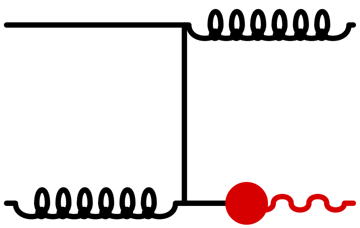
quark/gluon fragmentation into a (collinear) photon

- The $q \to q\ \gamma$ splitting process yields large terms prop. to $\ln(Q/\Lambda_{QCD})$ making fragmentation functions into photons to be $O(\alpha/\alpha_s)$
- The left diagram actually is $O(\alpha_s^2)\ D\gamma/k = O(\alpha\ \alpha_s) = LO$!

Direct vs. fragmentation

Arbitrary distinction between direct and fragmentation at NLO





Direct NLO

Fragmentation LO

Only the sum :

direct + fragmentation

is meaningful and does not depend on the arbitrary fragmentation scale (or ar least hopefully not much)

Ingredients

At LO accuracy

$$\frac{d\sigma^{\mathrm{dir}}}{d\mathbf{p}_{\perp}\,d\eta} = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_{i/p}(x_1, M)\, f_{j/p}(x_2, M)\, \frac{\alpha_s(\mu)}{2\pi}\, \frac{d\hat{\sigma}_{ij}}{d\mathbf{p}_{\perp}\,d\eta}$$

$$\frac{d\sigma^{\mathrm{frag}}}{d\mathbf{p}_{\perp}\,d\eta} = \sum_{i,j,k=q,\bar{q},g} \int dx_1\, dx_2\, f_{i/p}(x_1, M)\, f_{j/p}(x_2, M)\, \frac{dz}{z^2} \times \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 \frac{d\hat{\sigma}^k_{ij}}{d\mathbf{p}_{\perp}\,d\eta}\, D_{\gamma/k}(z, M_F)$$

- $f_{i/p}$: parton distribution functions (e.g. MSTW, CT10, NNPDF)
- $D_{\gamma/k}(z, M_F)$: fragmentation functions into photons (e.g. BFG)
- σ_{ij} and σ_{ij}^k : LO (NLO) partonic cross sections

Scales

Diagrammatic calculation depends on the 3 unphysical scales

- Renormalization scale μ
  - acts on the (running of the) strong coupling constant α_s
  - due to UV divergence
- Factorization scale M
  - acts on the parton distribution functions $f_{i/p}$
  - due to initial-state collinear singularities
- Fragmentation scale M_F
  - acts on the fragmentation functions $D_{\gamma/k}$
  - due to final-state collinear singularities

Scales

Diagrammatic calculation depends on the 3 unphysical scales

- Renormalization scale μ
- Factorization scale M
- Fragmentation scale M_F

Scale variation at a given order allows

unknown higher-order corrections to be estimated

Usually one takes

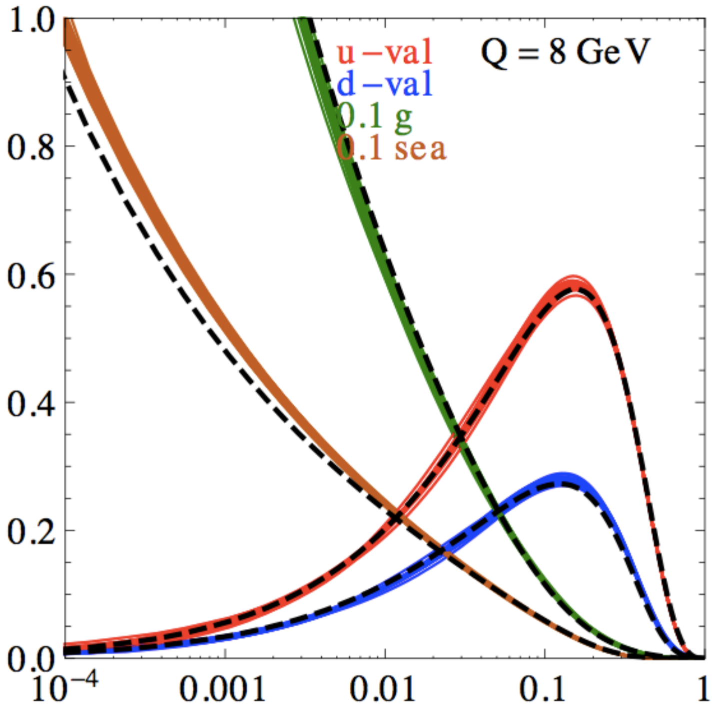
$$1/4 - 1/2\,Q \;\lesssim\; \mu \sim M \sim M_F \;\lesssim\; 2 - 4\,Q \qquad Q = \mathcal{O}\left(p_\perp\right)$$

(Note: no scale variation in an all-order calculation !)

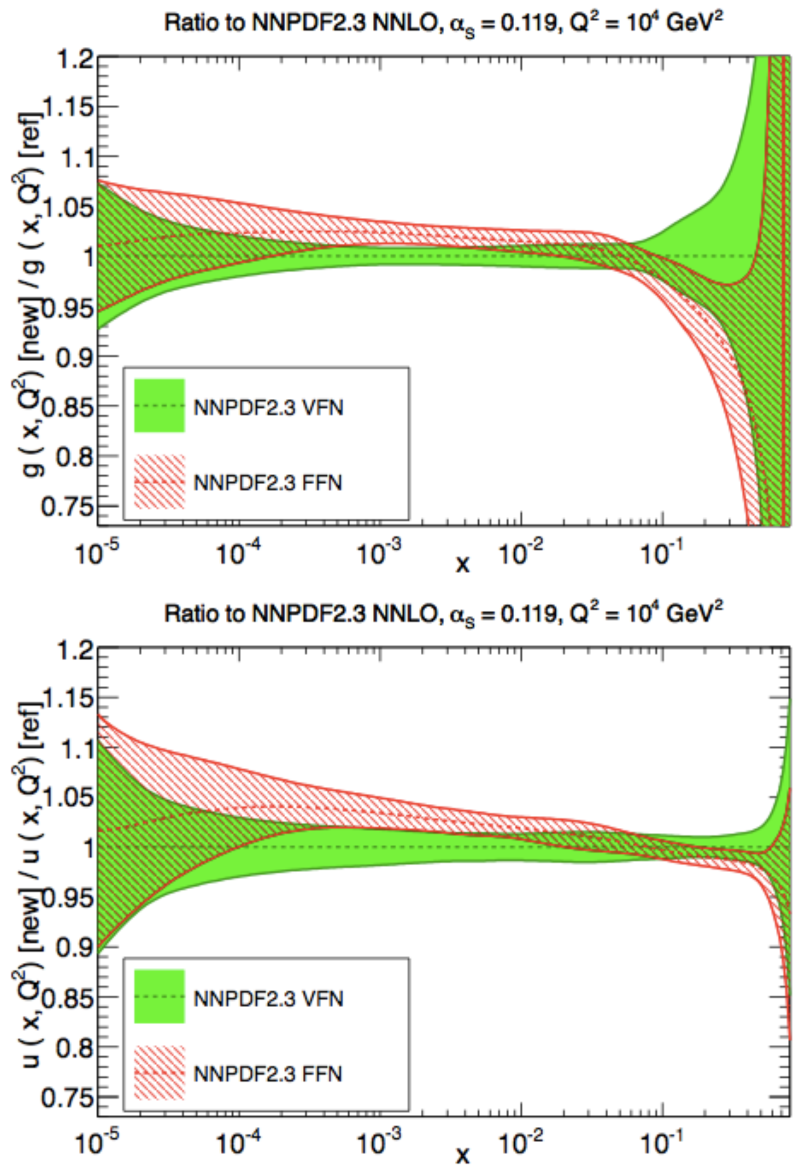
Prompt photons in pp collisions

Uncertainties (1/3)

- Parton distribution functions
  very well constrained (~ 5-10%)
  except at very small or large x



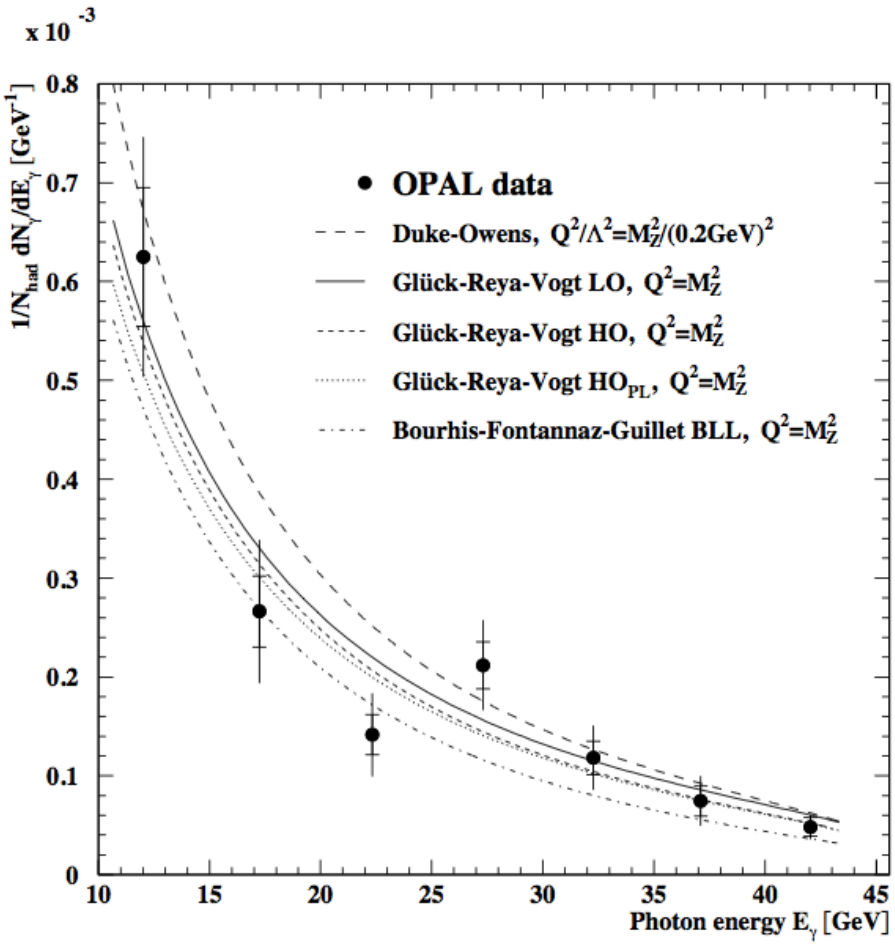
[CT10 coll, 1302.6246]



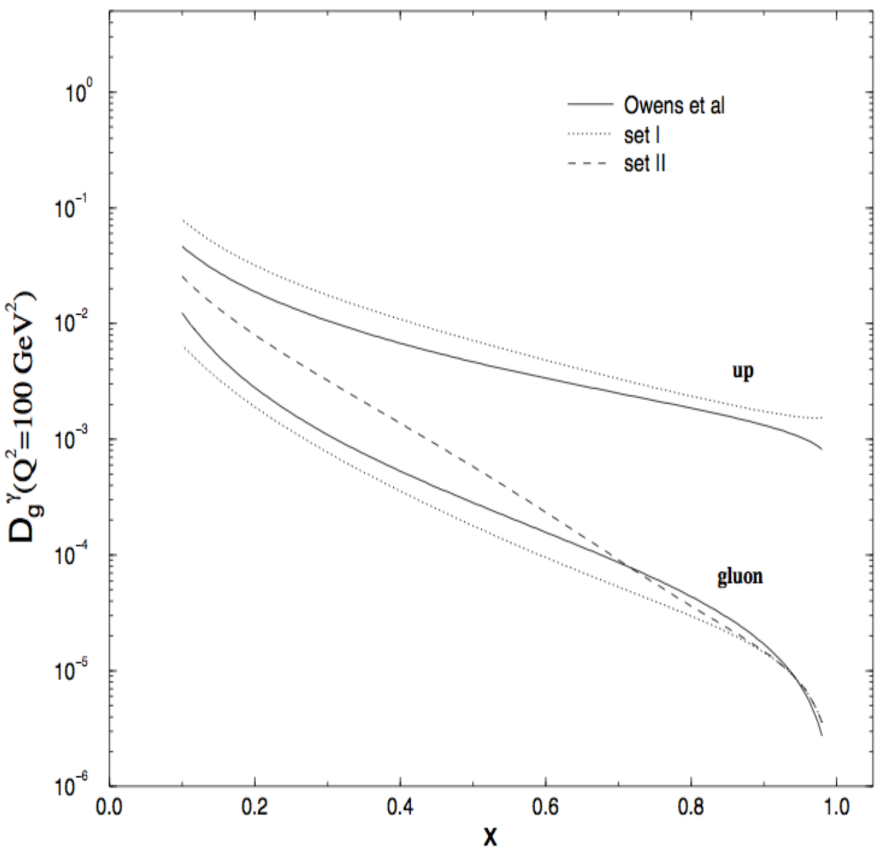
[NNPDF coll, 1303.1189]

Uncertainties (2/3)

- Fragmentation functions poorly constrained by data



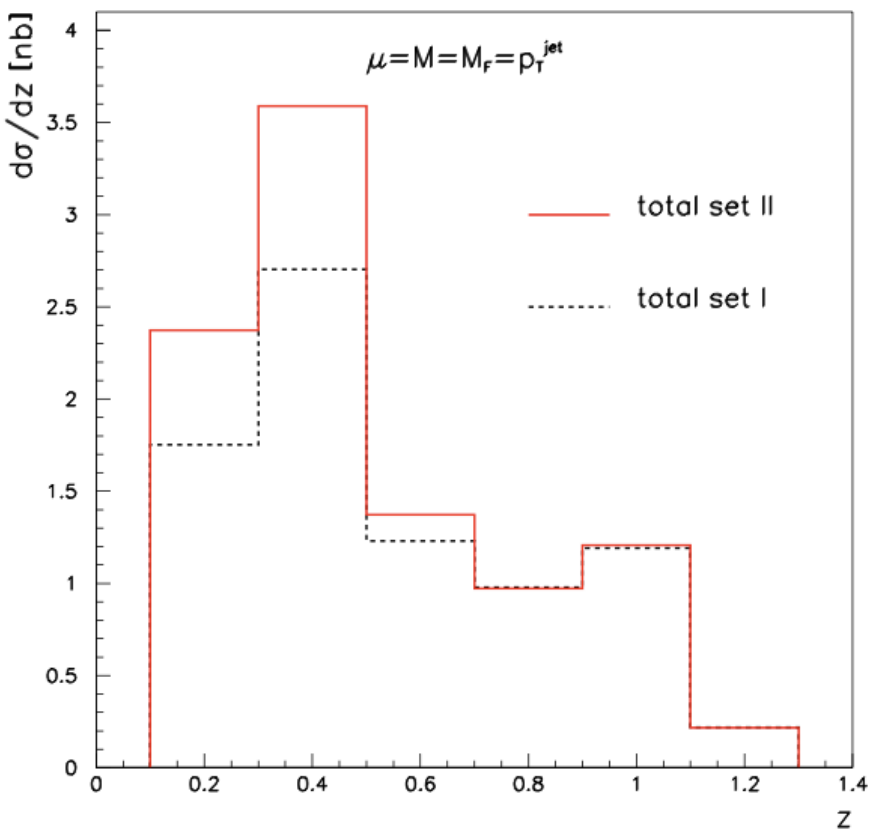
[OPAL coll, hep-ex/9708020]



[Bourhis Fontannaz Guillet, hep-ph/9704447]

Uncertainties (2/3)

- Fragmentation functions poorly constrained by data
- Could be accessible through photon–jet measurements

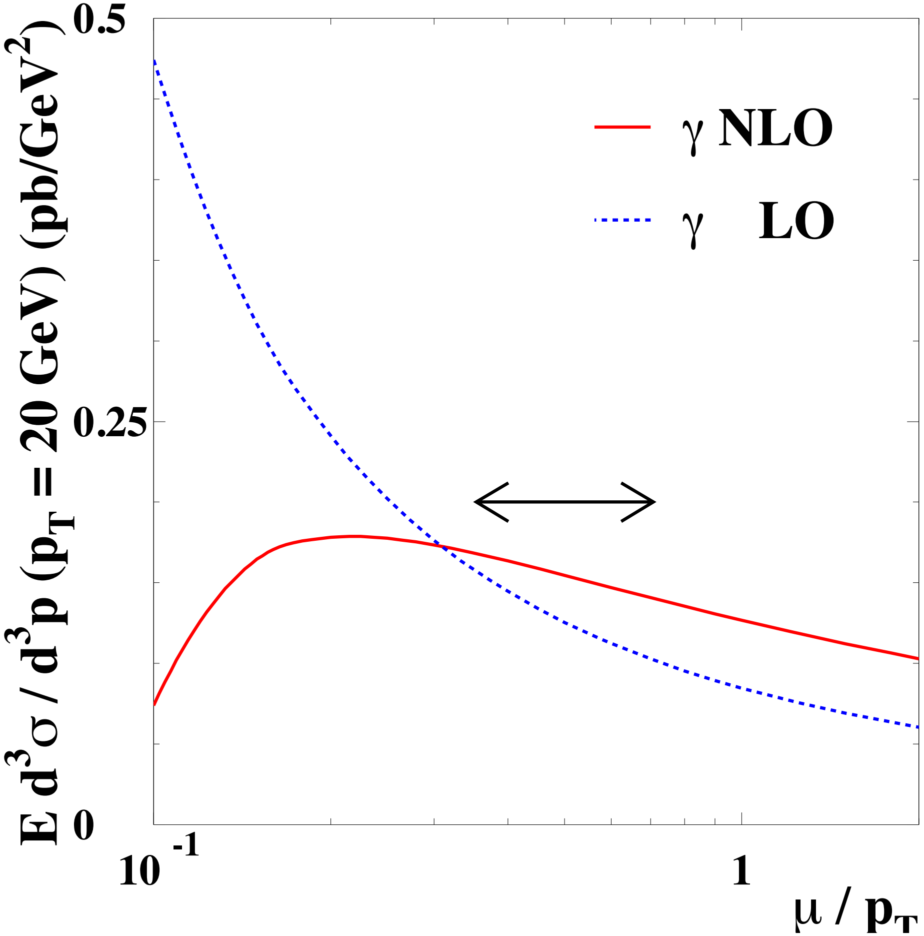


$$z_\gamma = -\frac{\vec{p}_T^{\,\gamma} \cdot \vec{p}_T^{\,\text{jet}}}{\|\vec{p}_T^{\,\text{jet}}\|^2}$$

[Belghobsi, Fontannaz, Guillet, Heinrich, Pilon, Werlen 0903.4834]

Scale dependence (3/3)

- Important at leading order
- Rather moderate (few tens of percent) at NLO



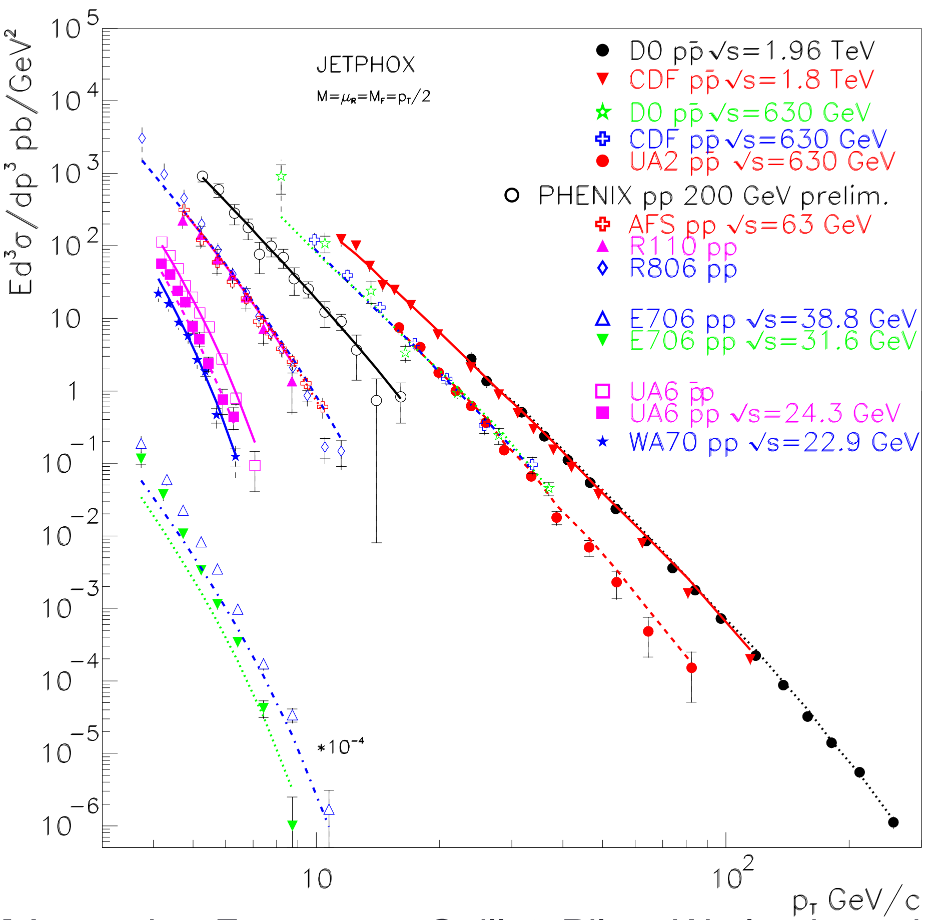
p–p collisions at RHIC

$\sqrt{s}$ = 200 GeV

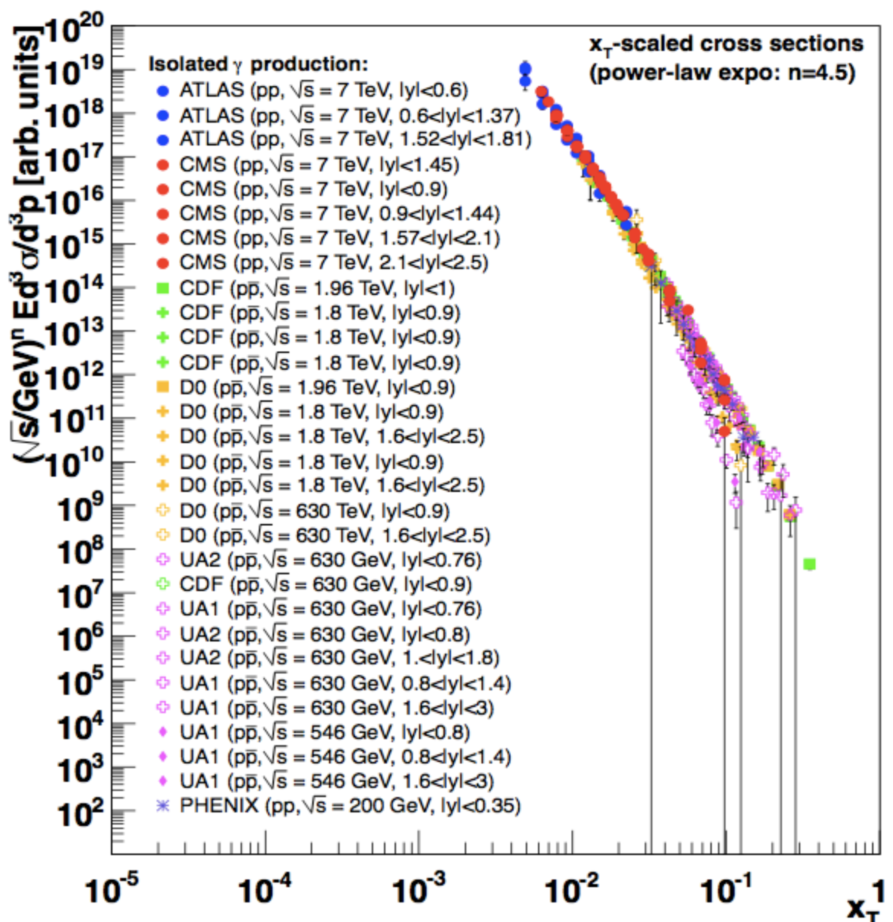
[FA, hep-ph/0601075]

World data

Impressive measurements from fixed-target (WA70, WA98,. . .) to collider (ISR, RHIC, Tevatron, LHC) experiments



[Aurenche, Fontannaz, Guillet, Pilon, Werlen hep-ph/0602133]



[d'Enterria, Ichou, PoS (2011) 291]

Isolation

Recall that direct and fragmentation components are arbitrary

What is observable and NOT arbitrary are

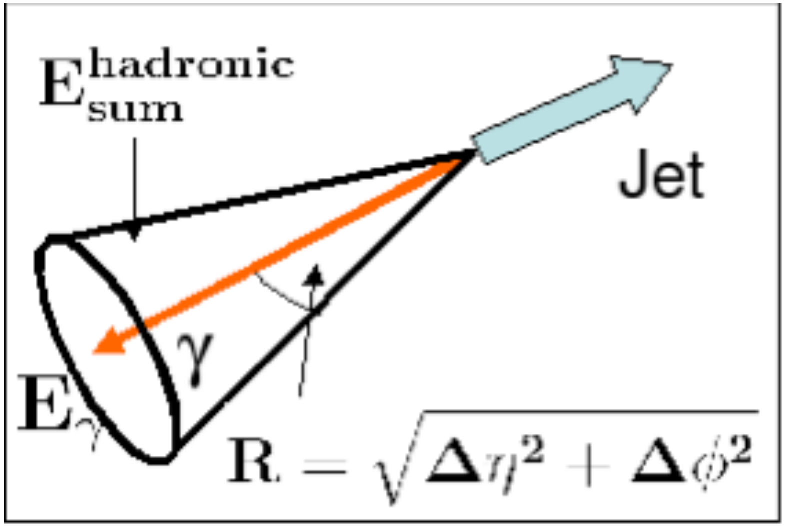
inclusive and isolated photons

- Inclusive: no selection on the final-state
- Isolated: only select γ with low hadronic activity around it
  - depends on isolation criteria, e.g.

$$E_T^{had} \leq E_T^{max}$$

for particles in a cone

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



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Recall that direct and fragmentation components are arbitrary

What is observable and NOT arbitrary are

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Experimentally

- Inclusive production measured essentially at fixed-target experiments and RHIC
- Isolated measurements at RHIC, Tevatron, and LHC

Pros and cons

Pros

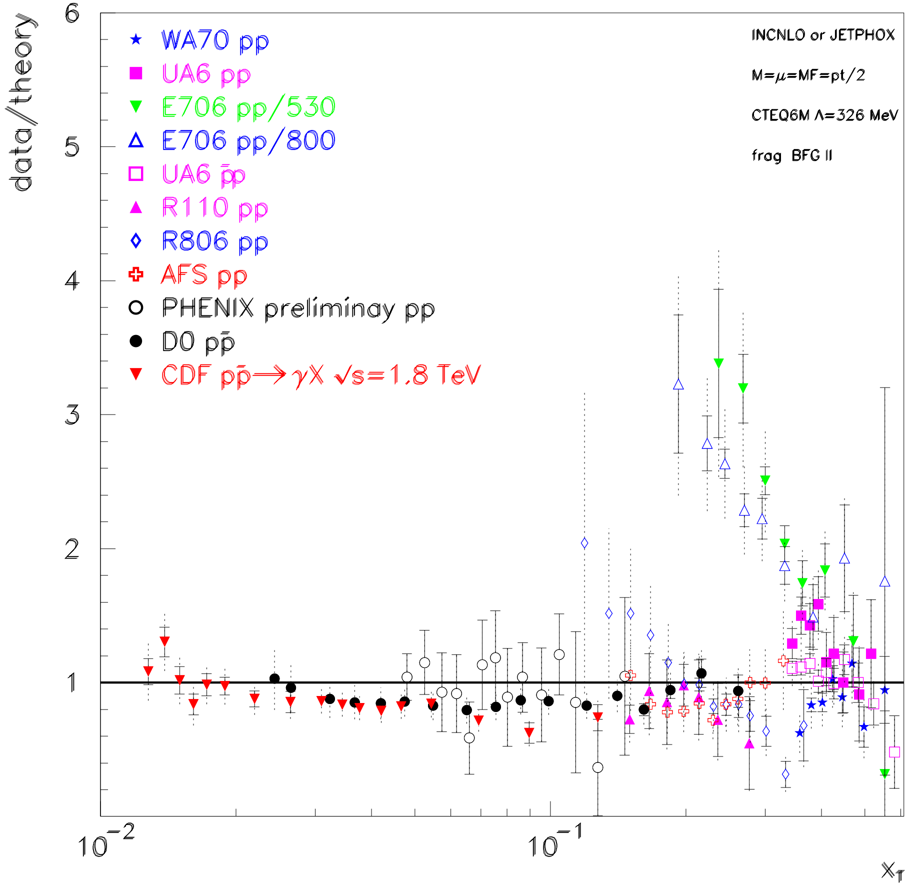
- Strongly suppress the contribution from hadron (π^0, η) decays
- Reduce the sensitivity on the fragmentation functions

Cons

- Needs a reliable theoretical description of multiple emission processes
  - Sensitive to underlying events
  - Beyond the fixed-order calculations
  - Interesting developments of Monte Carlo showers matched with NLO calculations (POWHEG)

Isolated data vs. theory

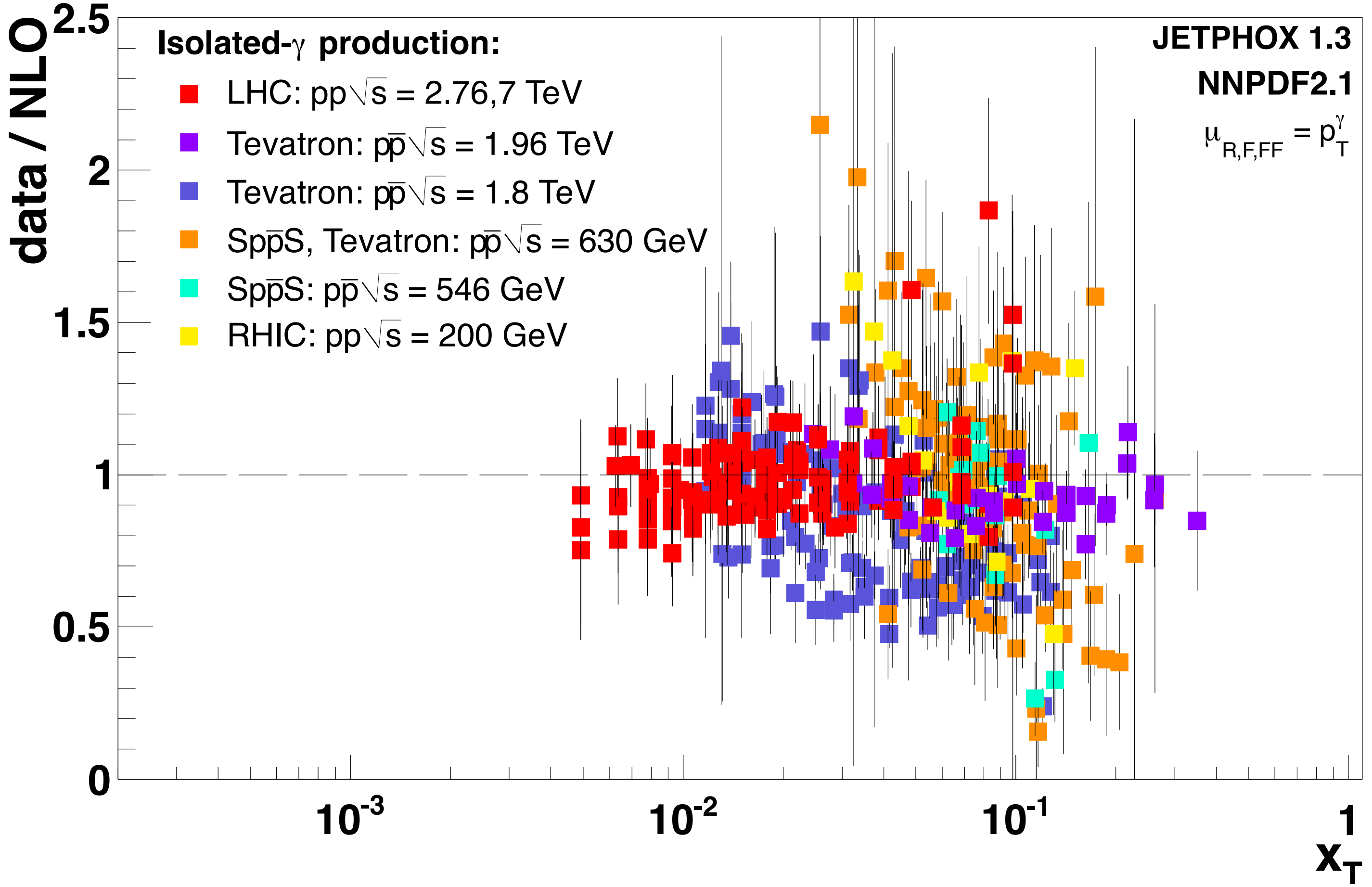
Very good description of isolated photon world-data, from fixed target experiments to Tevatron…



[Aurenche, Fontannaz, Guillet, Pilon, Werlen hep-ph/0602133]

Isolated data vs. theory

Very good description of isolated photon world-data, from fixed target experiments to Tevatron… up to the LHC



[d'Enterria, Rojo, 1202.1762]

Prompt photons in nuclear collisions

Prompt photon in heavy ion collisions

First of all

no real predictivity of pQCD in heavy ion collisions !

☹ Do not allow one to quantify properly theoretical uncertainties

- can't be as quantitative as pp phenomenology

☺ Rather exploratory

- lots of activity and new ideas… fun !

Prompt photon in heavy ion collisions

First of all

no real predictivity of pQCD in heavy ion collisions !

… but potentially very useful !

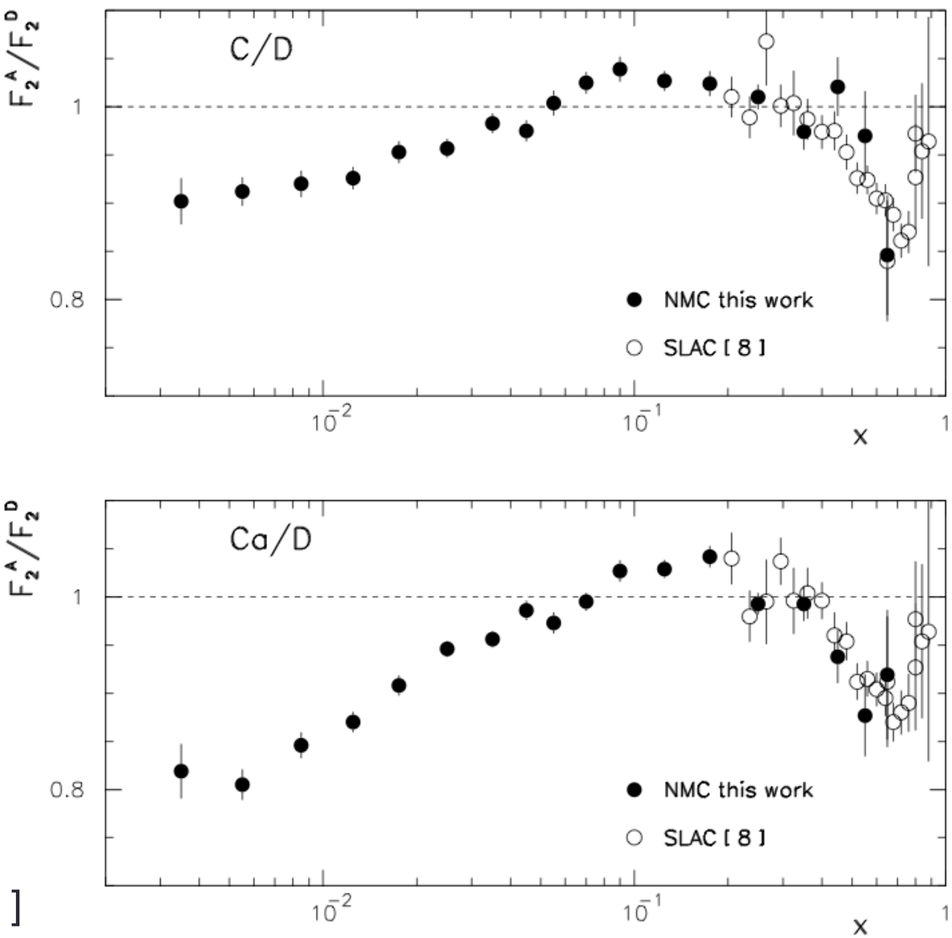
- Probe of nuclear parton distribution functions
- A good (?) reference for hard processes sensitive to hot medium effects
- Photon – jet correlations help to constrain parton energy loss in the medium

Lecture II by S. Peigné

Nuclear PDF

- Structure functions F_2 are modified in nuclei
  - First observed by the EMC experiment (DIS on nuclei)
  - Depends on x and Q^2

$$R_{F_2} \equiv \frac{F_2^A(x,Q^2)}{A \times F_2^p(x,Q^2)}$$

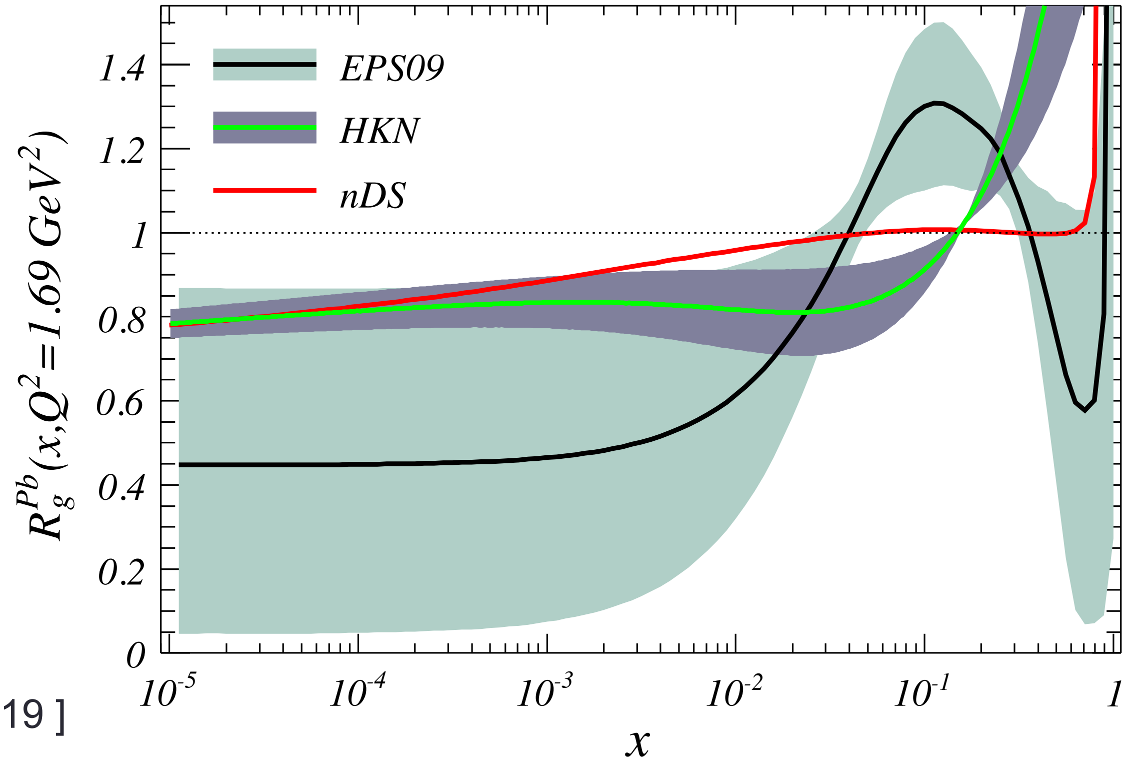


[NMC, hep-ph/9503291]

Extracting nuclear PDF (nPDF)

- Global fit analyses carried out to extract nuclear parton densities
  - EKS98, HKN04, nDS, EPS09, DSSZ…
  - Use mostly DIS & Drell-Yan data (but not photons)
  - Large uncertainties at small x where (almost) no data is available yet

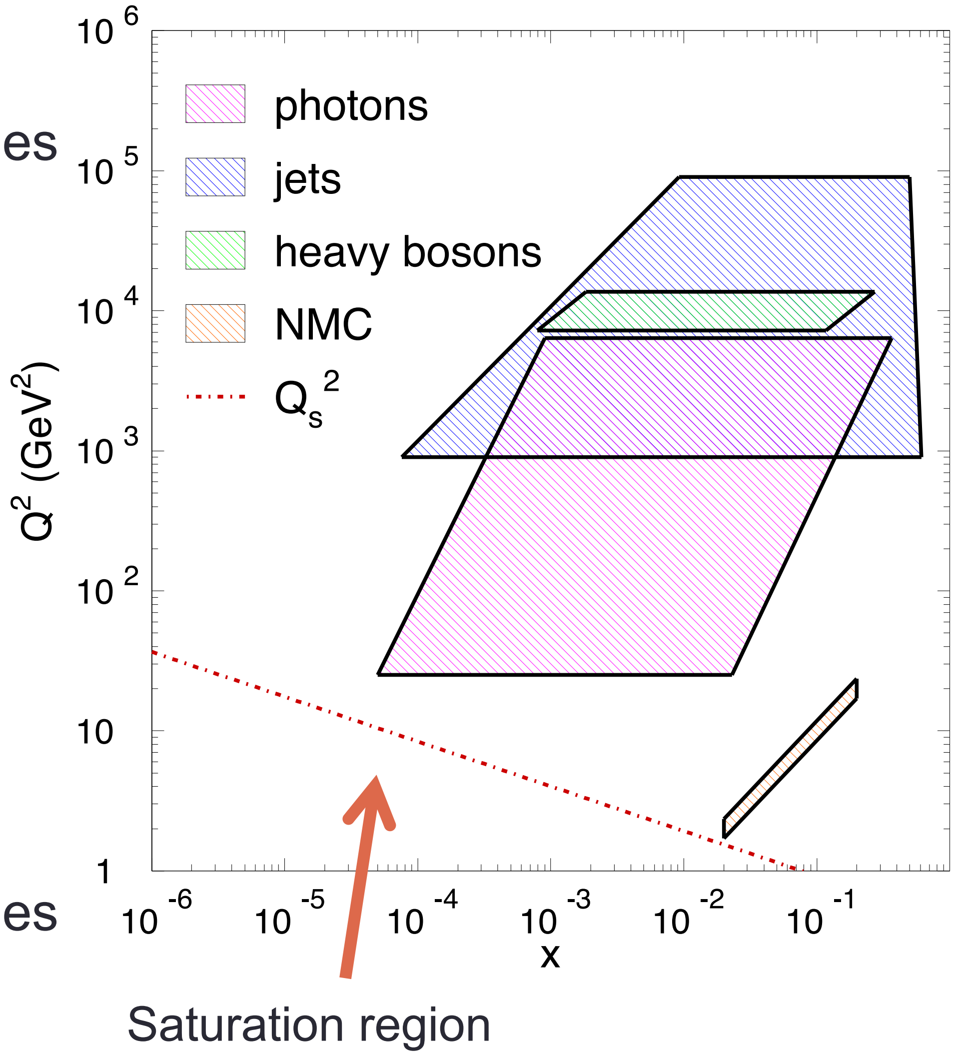
$$R_g \equiv \frac{G^{p/A}(x,Q^2)}{G^p(x,Q^2)}$$



[C. Salgado et al, 1105.3919]

Probing nuclear PDF at LHC

- Jets
  - Probes quark and gluon densities
  - High rates
  - Rich phenomenology
  - Large scales $Q^2 > 10^3$ GeV^2
- Weak bosons and Drell-Yan
  - Probe quark densities
  - Large scales $Q^2 > 10^4$ GeV^2
- Prompt photons
  - Probes quark and gluon densities
  - Rich phenomenology
  - Low $Q^2 > 10$–10^3 GeV^2



Lectures by E. Iancu

Probing nuclear PDF in pA collisions

Simple relationship between R_{pA} and nuclear PDF

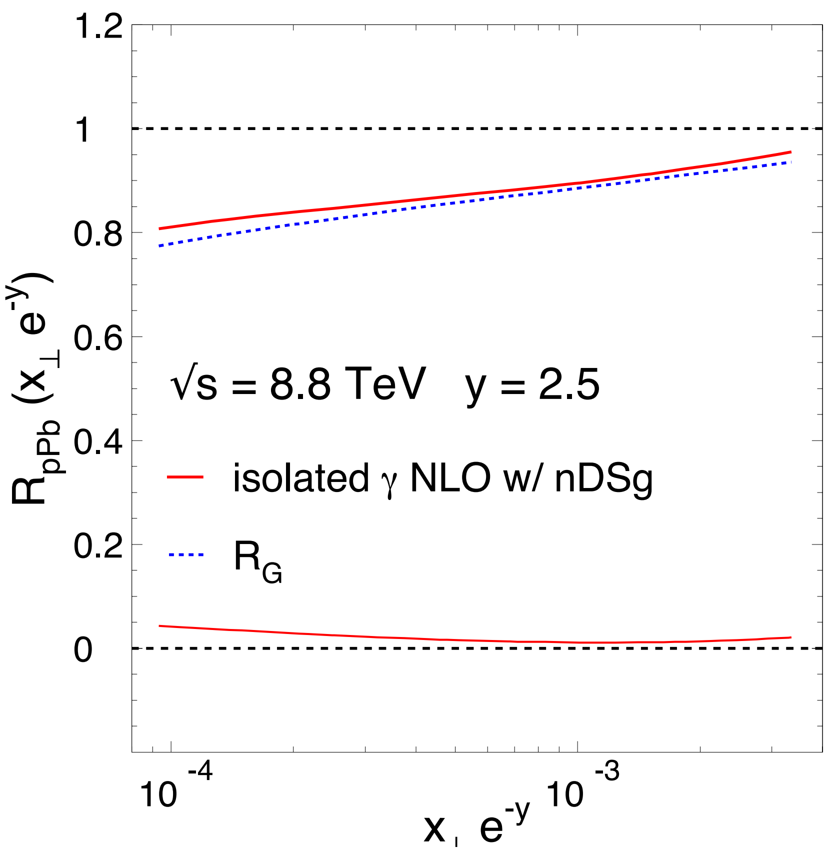
$$R_{pA}(p_\perp, y) = \frac{d^3\sigma}{dy\ d^2p_\perp}(p + A \to \gamma + X) \Big/ \frac{A\ d^3\sigma}{dy\ d^2p_\perp}(p + p \to \gamma + X)$$

At forward rapidity

$$R_{pA} \simeq R_G\left(2p_\perp/\sqrt{s} \times \exp(-y)\right)$$

At backward rapidity

$$R_{pA} \simeq R_{F_2}\left(2p_\perp/\sqrt{s} \times \exp(-y)\right)$$



[FA, Gousset, 0707.2944]

Prompt photons as « standard candle »

Prompt photons allow for checking the nucleon–nucleon binary scaling in heavy-ion collisions

In A–A collisions, one assumes that in absence of nuclear effects

$$\mathrm{d}N_{\mathrm{AB}}(b) = N^{\mathrm{coll}}_{\mathrm{AB}}(b) \times \mathrm{d}N_{\mathrm{pp}}$$

However

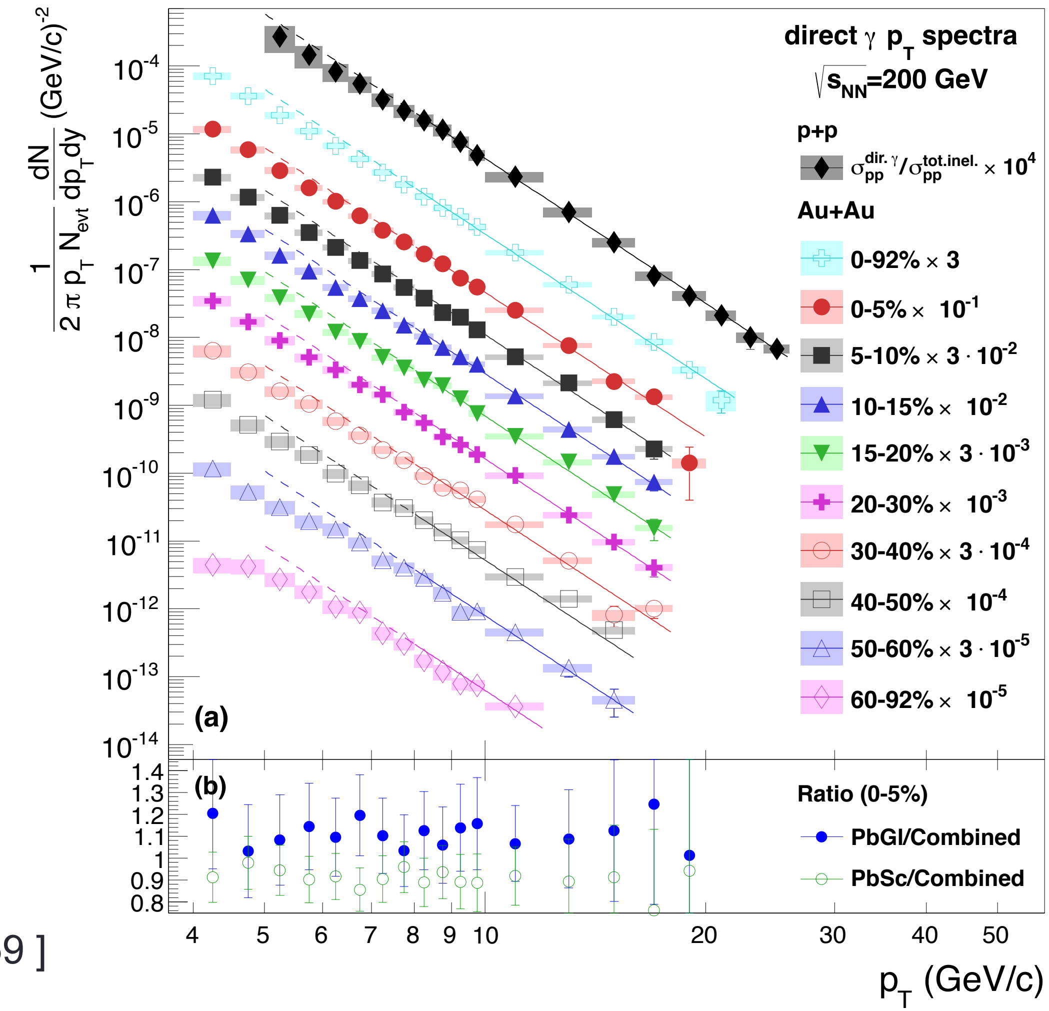
- Assumption which needs to be checked using processes insensitive to medium effects
- The number of collisions not well determined (Glauber model)

Prompt photons as « standard candle »

Prompt photons allow for checking the nucleon–nucleon binary scaling in heavy-ion collisions

PHENIX

$\sqrt{s_{NN}} = 200$ GeV



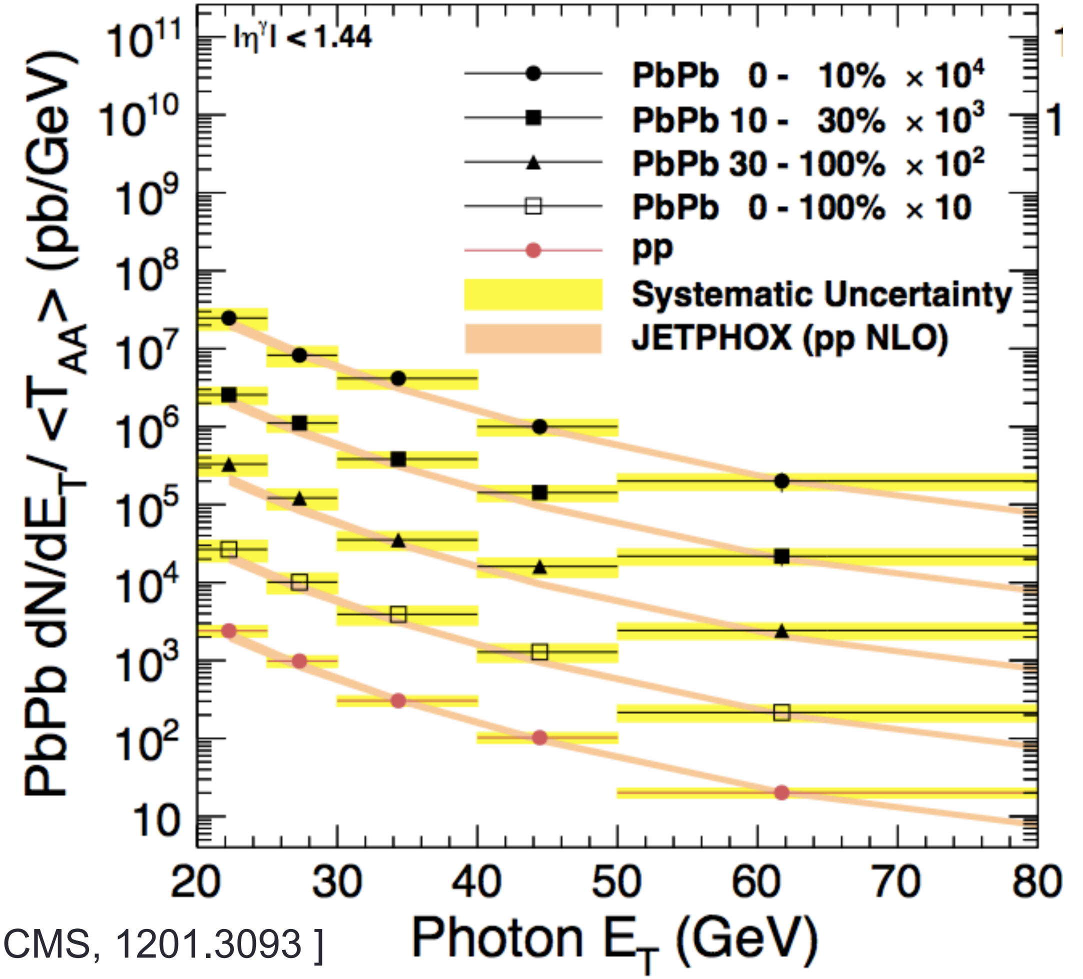
[PHENIX, 1205.5759]

Prompt photons as « standard candle »

Prompt photons allow for checking the nucleon–nucleon binary scaling in heavy-ion collisions

CMS

$\sqrt{s_{NN}} = 2.76$ TeV



[CMS, 1201.3093]

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Does this mean that prompt photons

are insensitive to medium effects ?

Prompt photons as « standard candle »

Prompt photons allow for checking the nucleon–nucleon binary scaling in heavy-ion collisions

Does this mean that prompt photons

are insensitive to medium effects ?

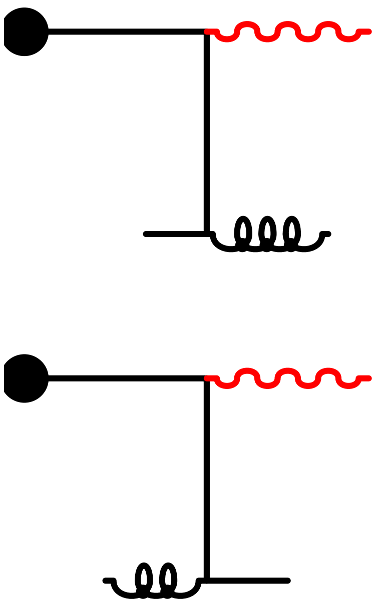
Bueno, no es muy claro…

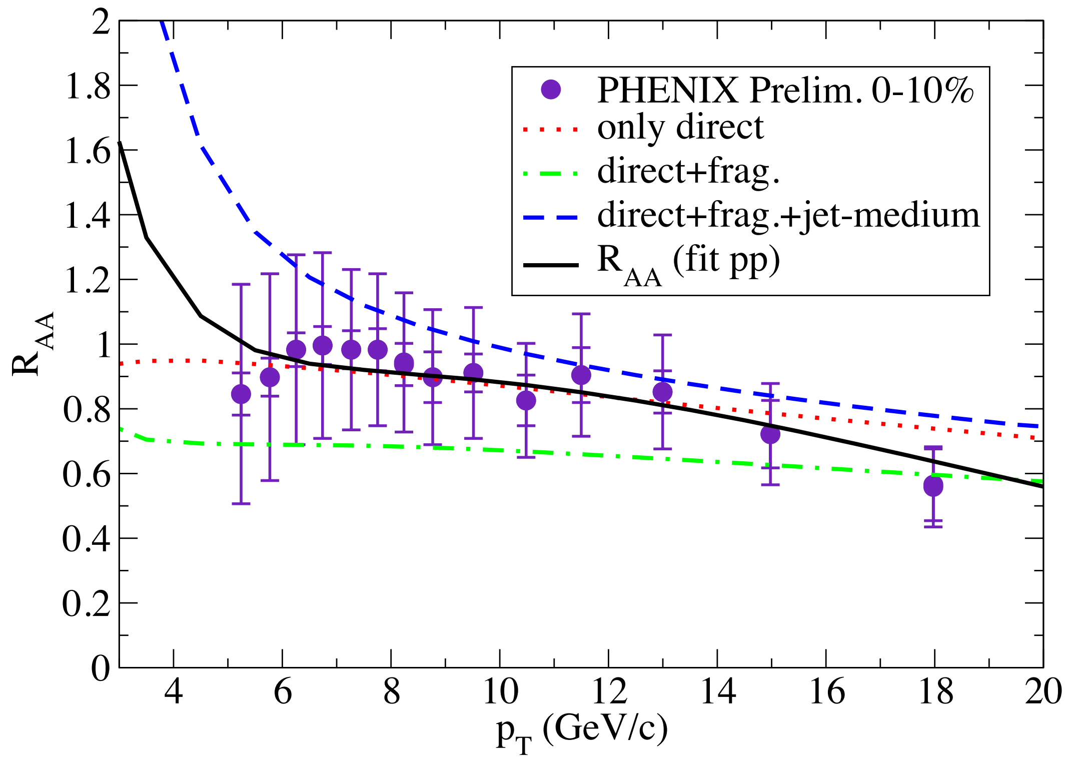
A variety of (sometimes contradictory) processes have been discussed…

Hot medium effects

- Enhancement of isolated photons in A A collisions from jet – photon conversion

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



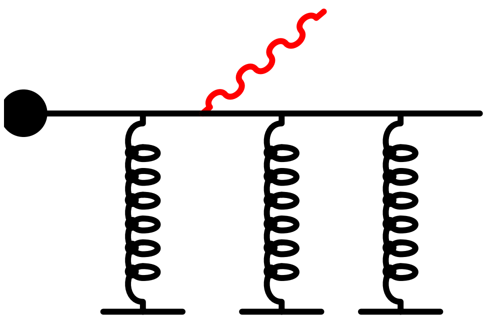


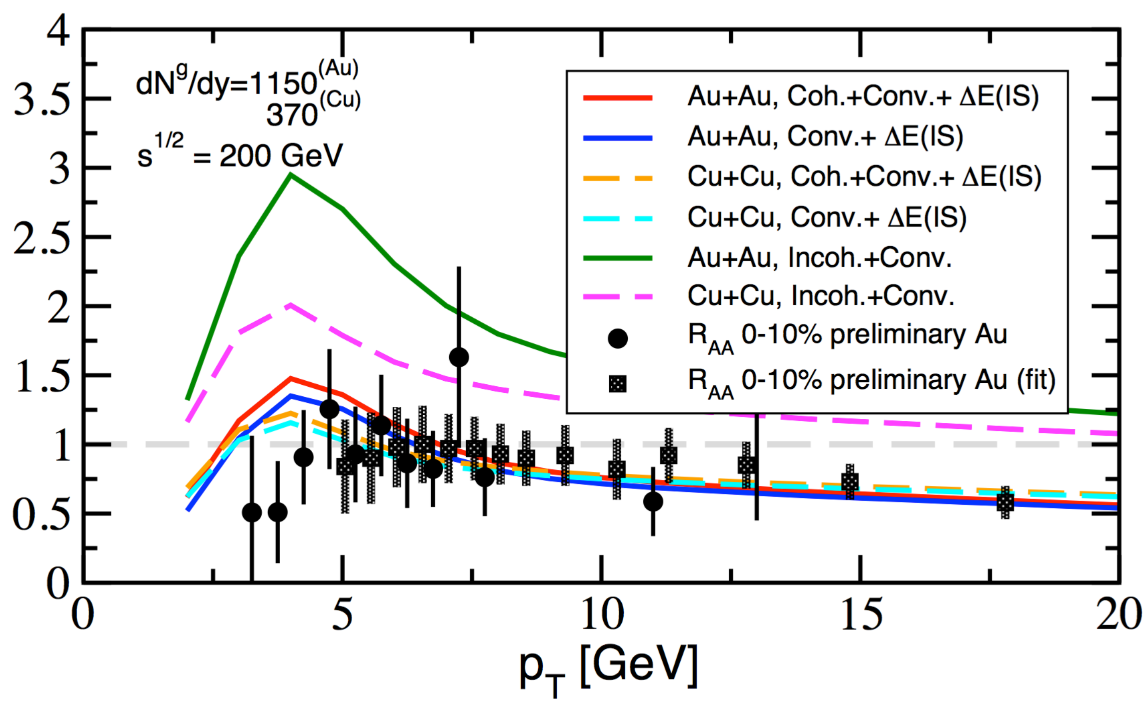
[Qin Ruppert Gale Jeon Moore 0906.3280]

Hot medium effects

Quarks and gluons propagating through quark-gluon plasma lose energy by radiating gluons… and possibly photons too

[Zakharov hep-ph/0405101]



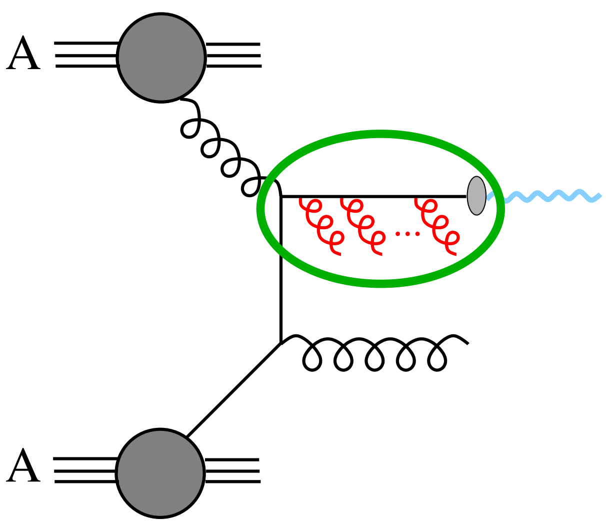


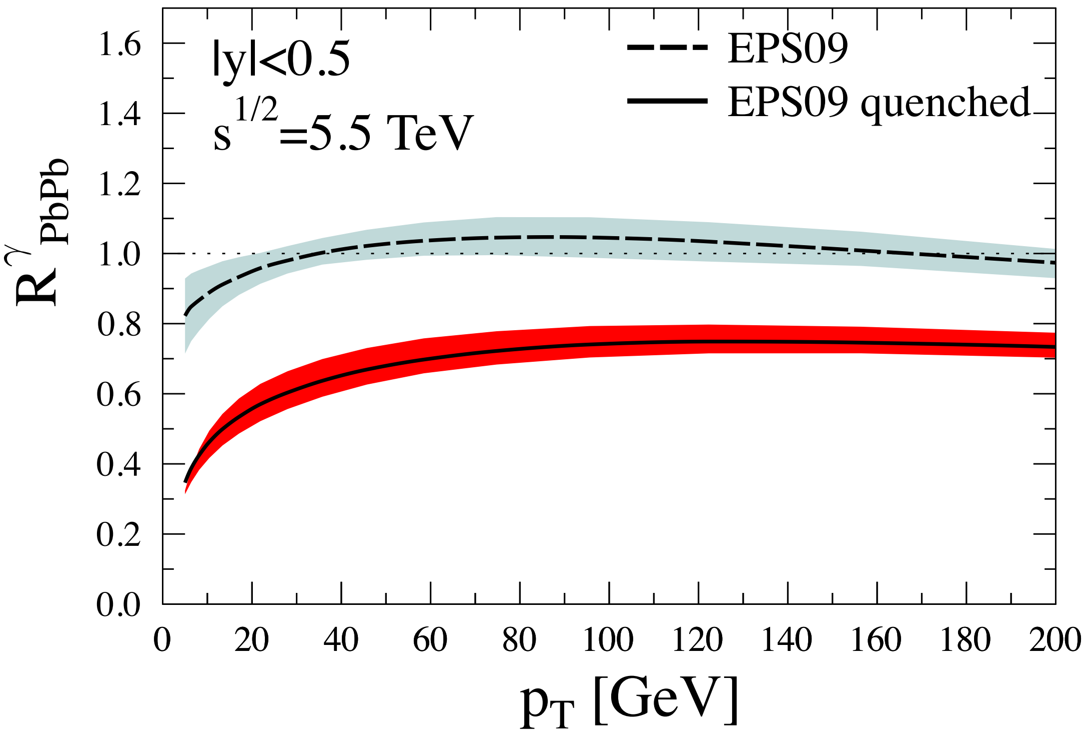
[Vitev Zhang 0804.3805]

Hot medium effects

Quarks and gluons propagating through quark-gluon plasma lose energy by radiating gluons… or does it quench fragmentation photons ?

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

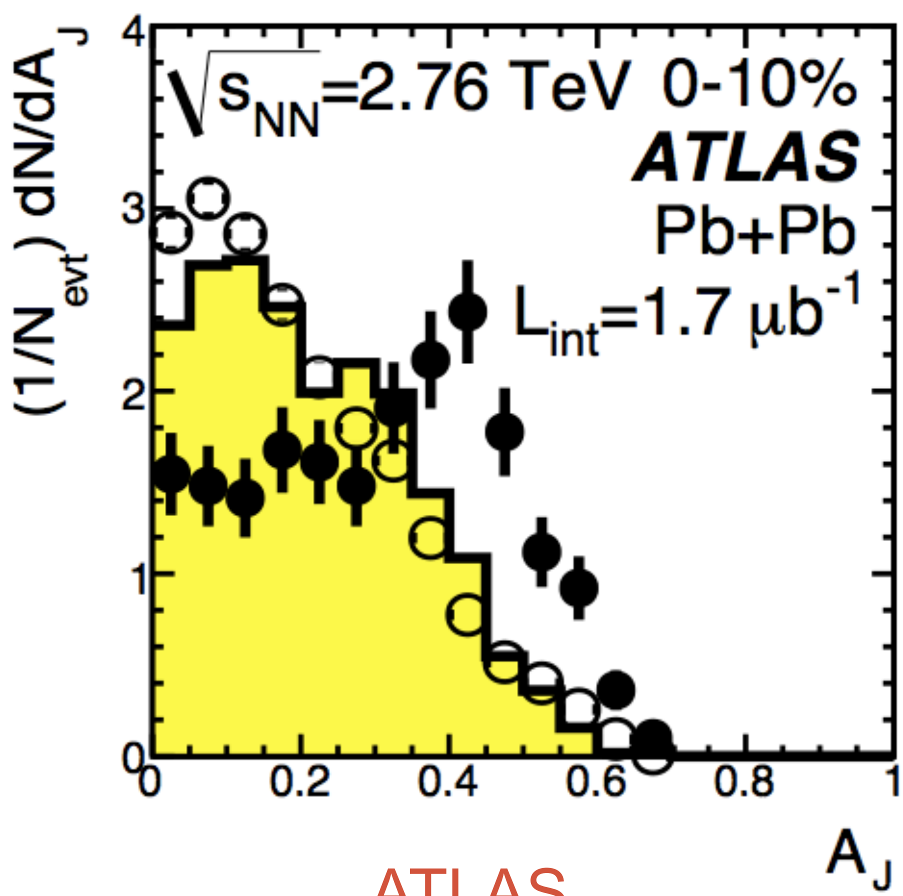




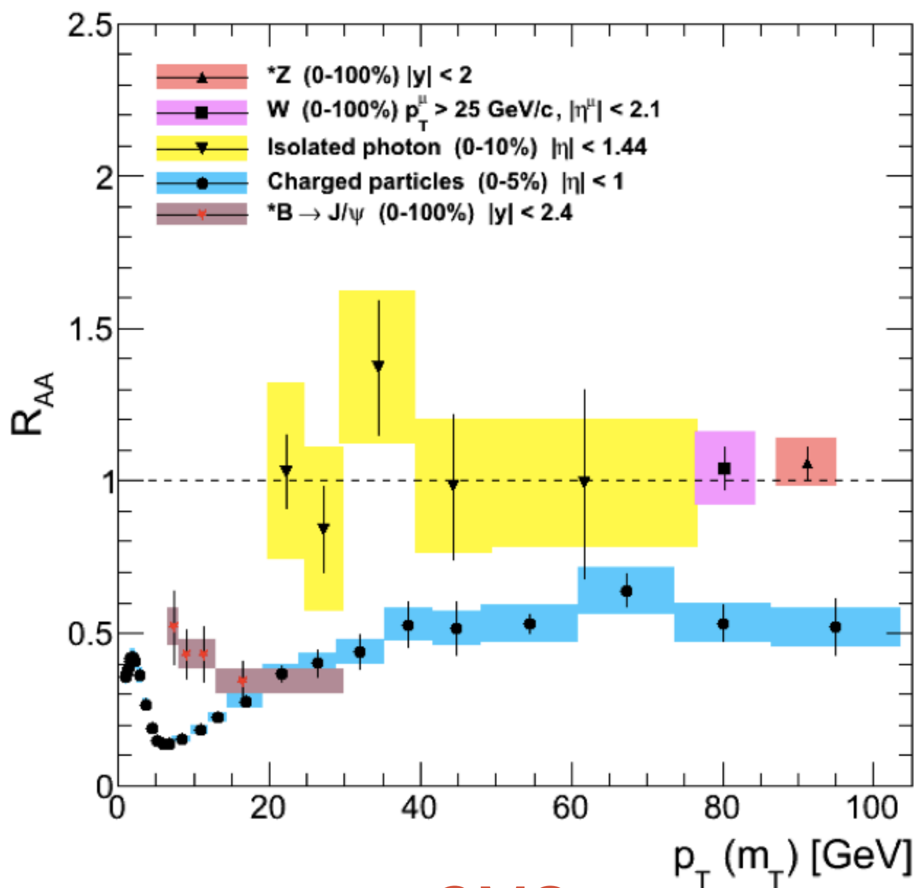
[FA Eskola Paukkunen Salgado 1103.1471]

Correlation studies

Jet quenching is one of the most spectacular result from heavy-ion collisions at RHIC and LHC



ATLAS



CMS

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Need to go beyond single hadron production to better understand medium modifications of fragmentation processes

Photon – jet and photon – hadron momentum correlations

Correlation studies

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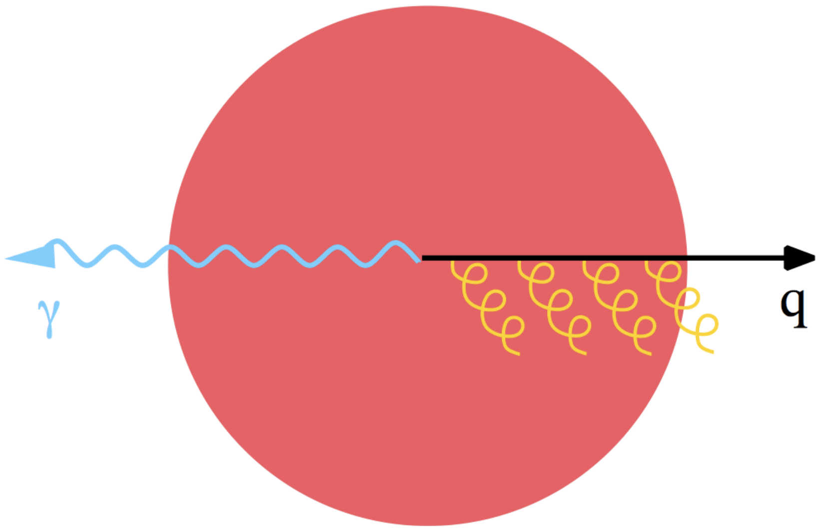
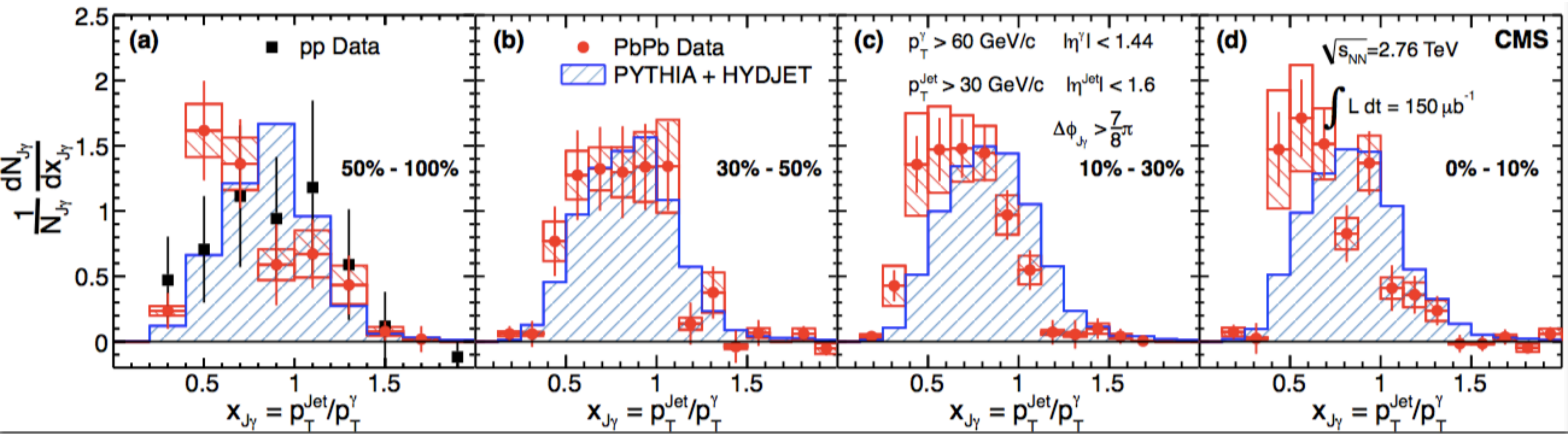
Idea

Use the photon momentum
as a proxy for that of the parton (jet)



Photon – jet in heavy-ion collisions

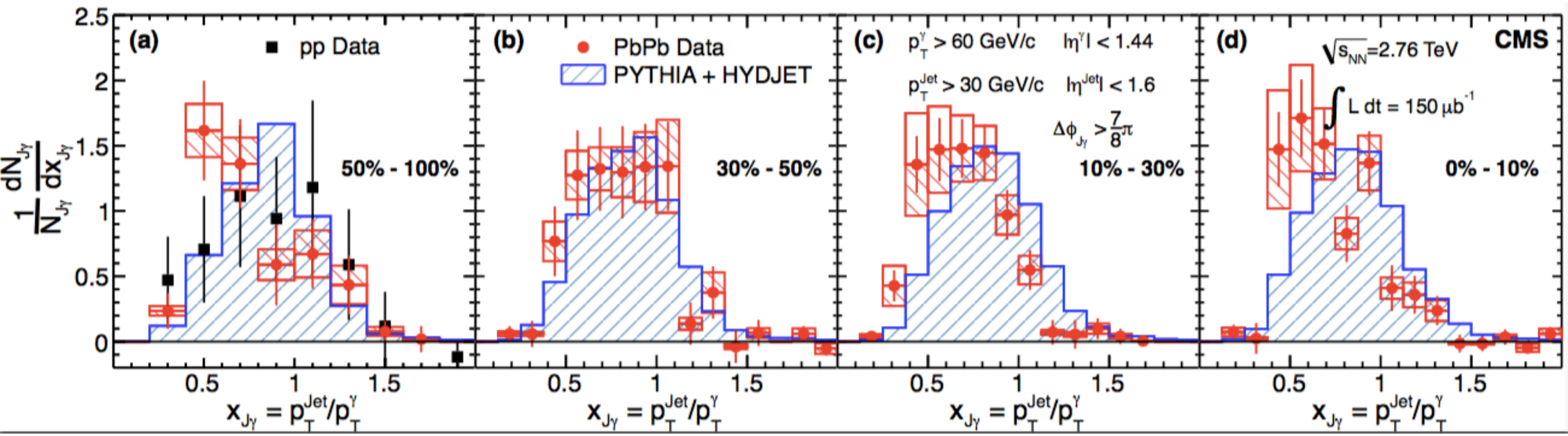
- Significant asymmetry reported !



[CMS, 1205.0206]

Photon – jet in heavy-ion collisions

- Significant asymmetry reported !
- … but still a lot to be performed before extracting parton energy loss in the medium



[CMS, 1205.0206]

Summary

- Prompt photons in proton–proton collisions
  - Beautiful test of perturbative QCD in hadronic collisions
- Prompt photons in proton–nucleus collisions
  - A promising probe of nuclear parton densities
- Prompt photons in heavy–ion collisions
  - Seems quite insensitive of medium effects (despite many opposite suggestions)
  - Might be used as a counter of binary nucleon–nucleon collisions
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Muchas gracias !