

Heavy ion collisions: Theoretical aspects (we're interested in)





Preamble

- Many **open questions** emerged over the last few years, due to
 - LHC Run 1 & Run 2 data
 - Phenomenology and more theoretical studies
 - Nicely discussed by Michael Winn – thanks!
- This talk
 - Most important **physics questions** we would like to address at LLR in years to come
 - Emphasis on **phenomenology** and **related measurements**

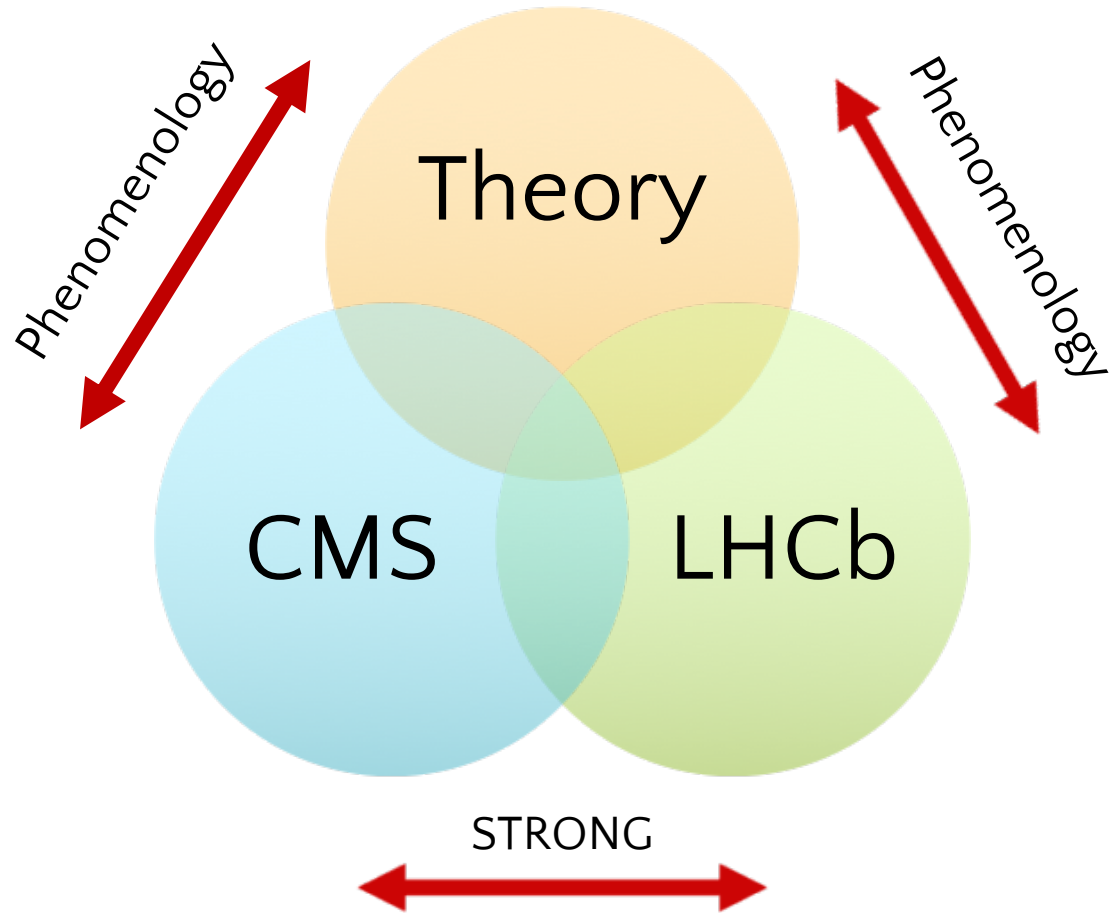




Who are we?

- Theorists
 - F. Arleo (LLR), and two PhD students: G. Falmagne (LLR), C. Naïm (DPhN)
 - Most frequent visitors: E. Ferreiro (Santiago), S. Munier (CPHT), S. Peigné (Subatech)
- ... in close collaboration with experimentalists
 - **CMS**: B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, M. Nguyen (LLR)
 - **LHCb**: F. Fleuret, F. Garcia, É. Maurice (LLR)
 - **COMPASS**: C. Naïm (DPhN), S. Platchkov (DPhN)
- Through **back and forth** exchanges
 - Data to theory: Interpreting present data
 - Theory to data: Suggesting future measurements
- **ANR PRC** grant: COLDLOSS (PI: François), 2019–2023

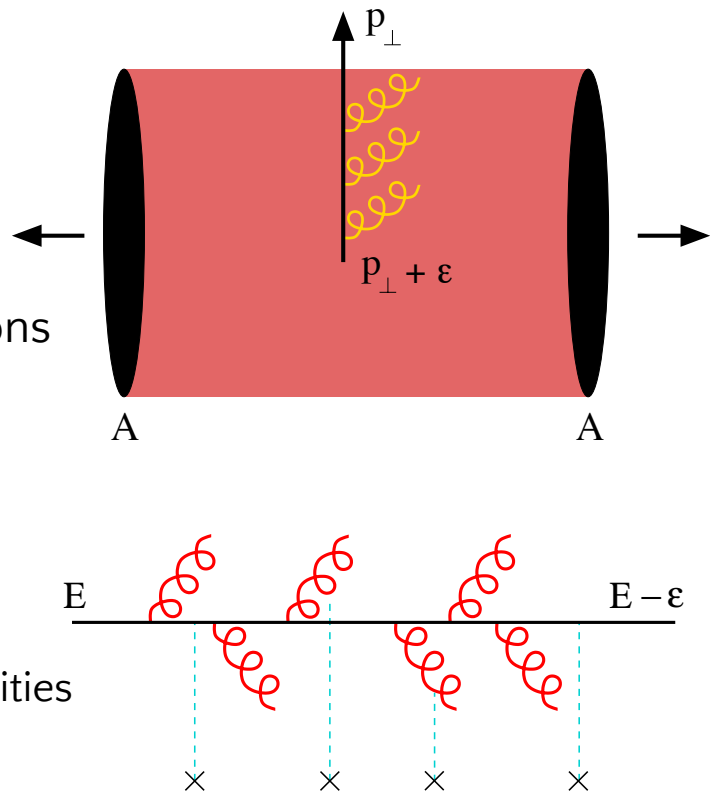


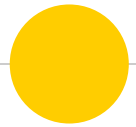




Main topics

- **Jet quenching** in quark-gluon plasma
 - Probing the heavy-quark sector
 - Universality of hadron suppression
- **Quarkonium production**, from pp to AA collisions
 - Fragmentation functions
 - Quarkonia in QGP
- **Coherent energy loss**: a new regime
 - Investigating various hadron species
 - Disentangling energy loss and nuclear parton densities



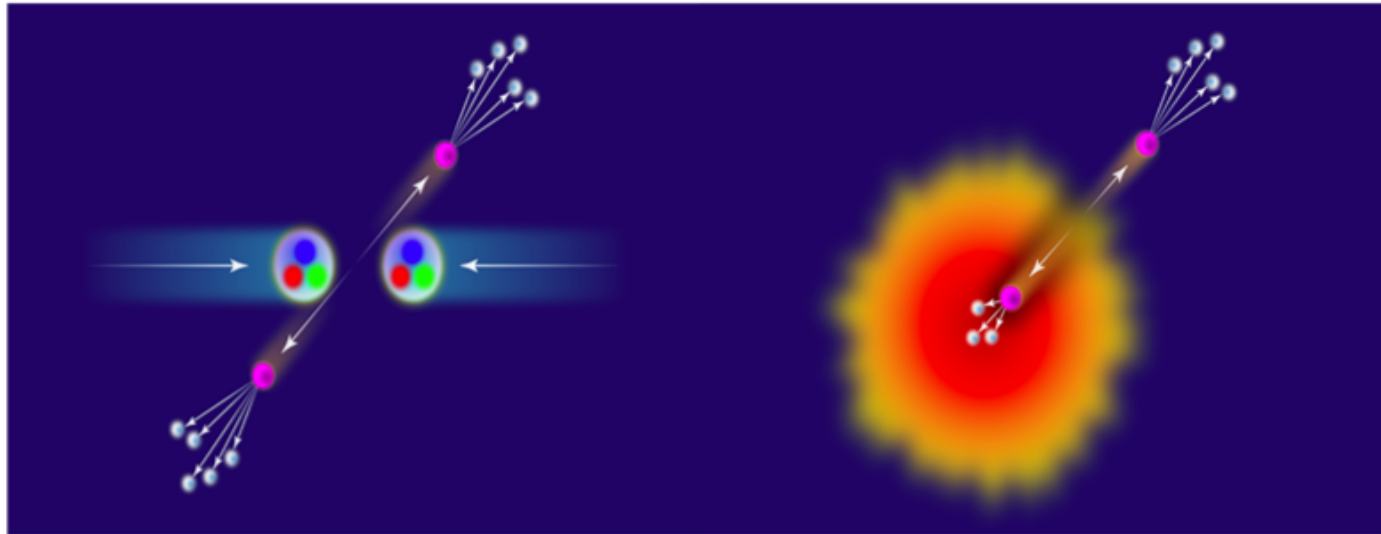


Jet quenching



Jet quenching

- Relative suppression of high p_{\perp} jets in AA collisions, with respect to pp collisions, due to parton energy loss in QGP
- Tools: **sophisticated pQCD frameworks** embedded in hydrodynamical models



proton-proton

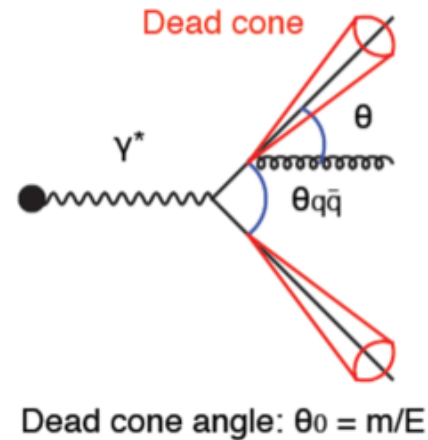
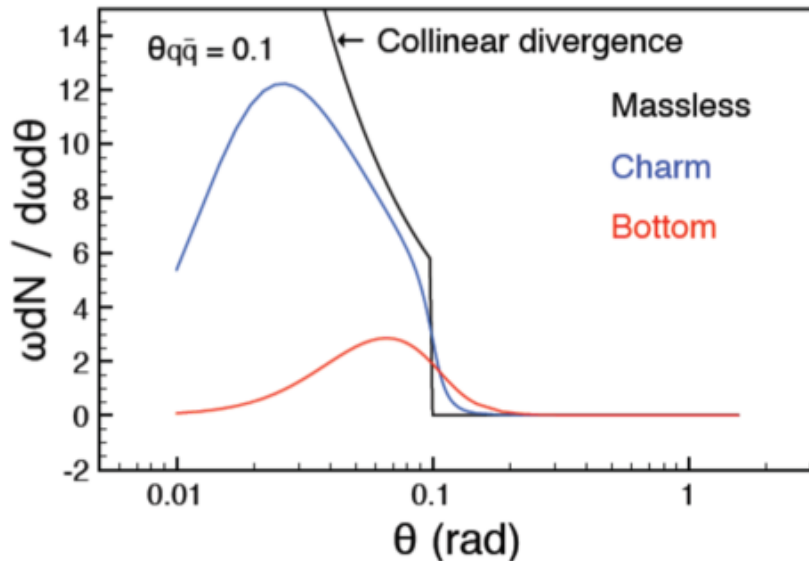
nucleus-nucleus



Dead cone for massive quarks?

- How much energy a heavy quark loses in QGP
 - Is there a 'dead cone' leading to reduced energy loss ? [Dokshitzer Kharzeev 2001]

$$(\Delta E_g >) \Delta E_q > \Delta E_c > \Delta E_b$$



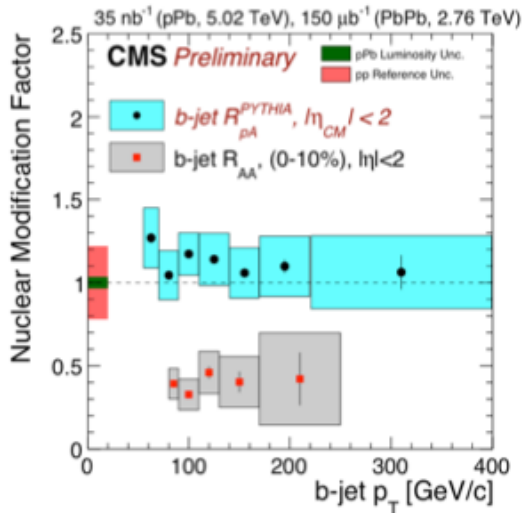
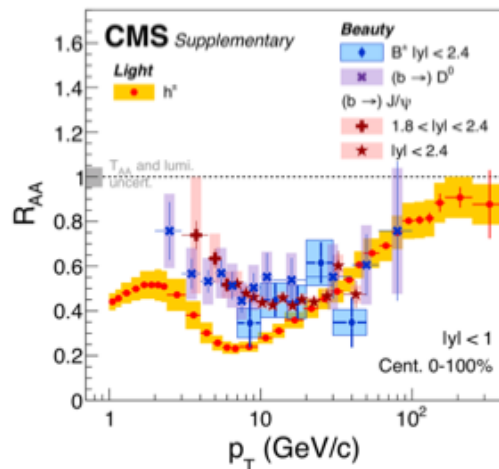


Dead cone for massive quarks?

- How much energy a heavy quark loses in QGP
 - Is there a 'dead cone' leading to reduced energy loss ?
- Still an open question despite many attempts
 - Compare D mesons with B mesons (or, non-prompt J/psi)
 - Compare inclusive jets with b-quark jets
- Some hints, but no evidence so far
 - No dead cone or data dominated by **gluon** fragmentation ?
 - Double b-quark jets** to favor heavy quark production

[PhD S. Lisniak (dir M. Nguyen) 2013-2016]

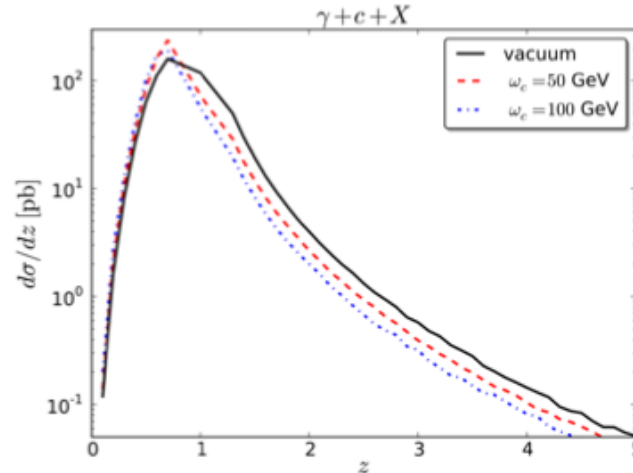
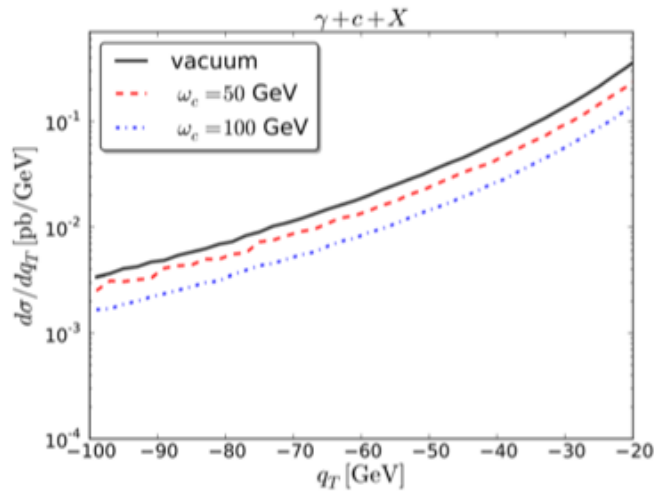
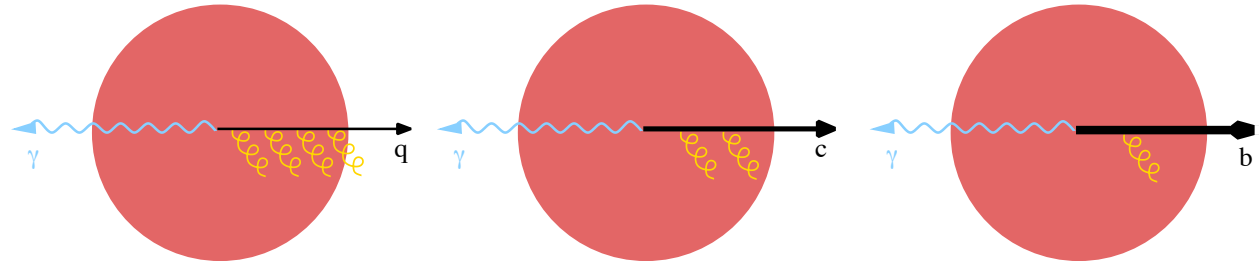
$$(\Delta E_g >) \Delta E_q > \Delta E_c > \Delta E_b$$





Photon plus heavy-quark jet ($\gamma+Q$)

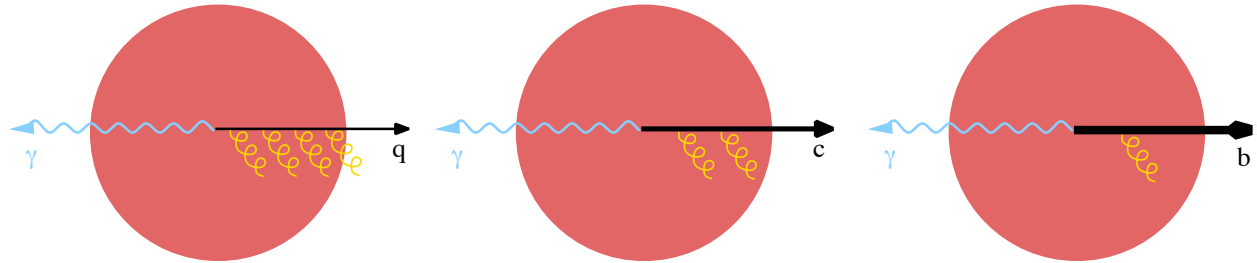
- Proposed to probe heavy quark energy loss in QGP [T. Stavreva, F. Arleo, I. Schienbein 2013]





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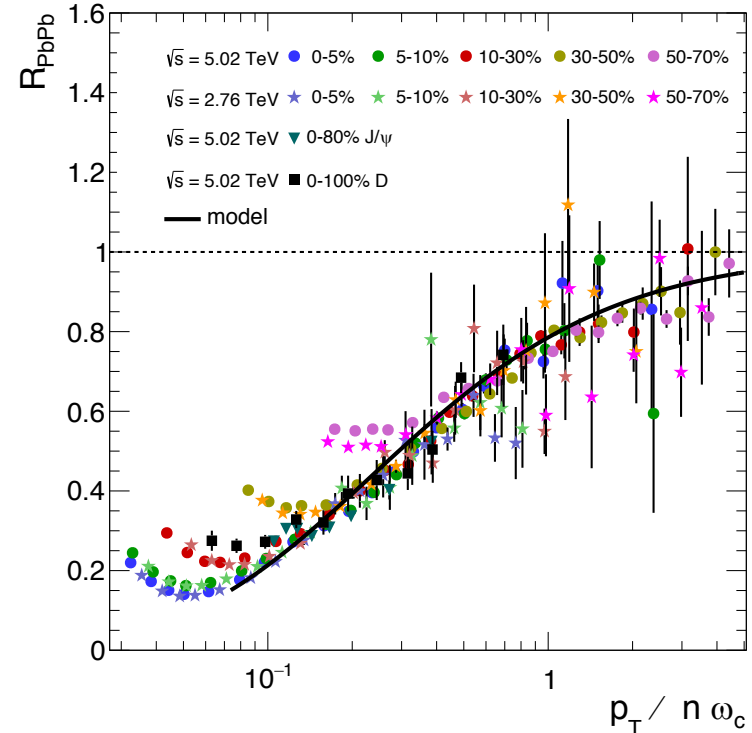
- Accessible in CMS at Run 3 & 4 !
 - Obvious LLR expertise with Inna and Matt
 - Reasonable counting rates

	$\sigma_{\gamma+Q}^{pp}$ [pb]	$\sigma_{\gamma+Q}^{PbPb}$ [nb]	$N_{\gamma+Q}^{PbPb}$
$\gamma + c$ (noEL)	112.5	4820	2410
$\gamma + c$ ($\omega_c = 50$ GeV)	98	4200	2100
$\gamma + c$ ($\omega_c = 100$ GeV)	83	3556	1778
$\gamma + b$ (noEL)	15.5	664	332
$\gamma + b$ ($\omega_c = 50$ GeV)	14.7	630	315
$\gamma + b$ ($\omega_c = 100$ GeV)	14.4	617	308



Quenching universality

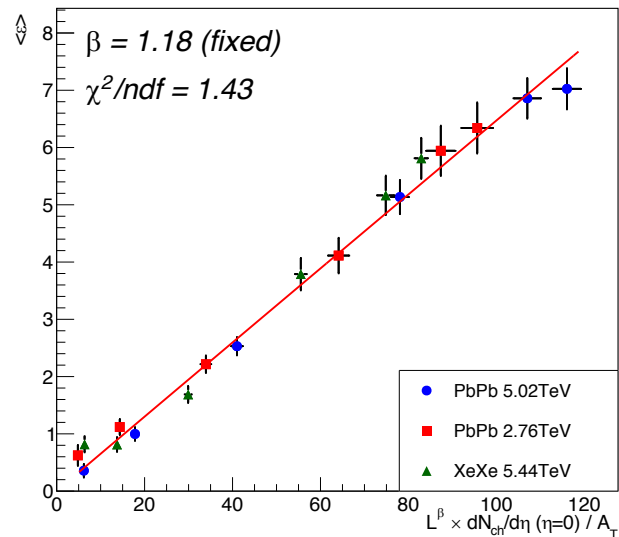
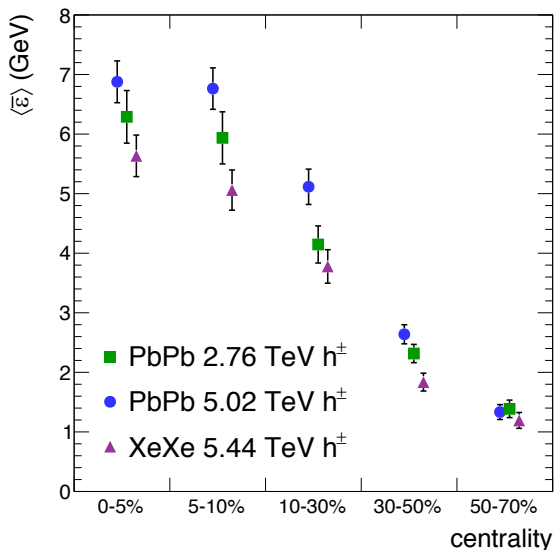
- ◉ Evidence for a **universal behavior** of hadron quenching at LHC [F. Arleo 2017]
 - All collision centralities and two energies
 - In agreement with simple analytic model
- ◉ **Many questions** raised
 - How to relate **energy loss to physical quantities** ?
 - Investigate new observables, e.g. **yield asymmetries**
 - How to understand that J/ψ follow the same trend?
- ◉ **Need more data** for further check of universality
 - What about Y and quarkonia excited states?
 - **Other collision systems** and collision energies

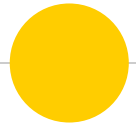




A new scaling

- Extracted parton energy loss **related to path length dependence**
- **New scaling** of energy loss vs. soft multiplicity
 - Expected... and observed in PbPb and XeXe ! [F. Arleo, G. Falmagne, in preparation]
 - Probes pathlength dependence of energy loss $\Delta E \propto L^\alpha$



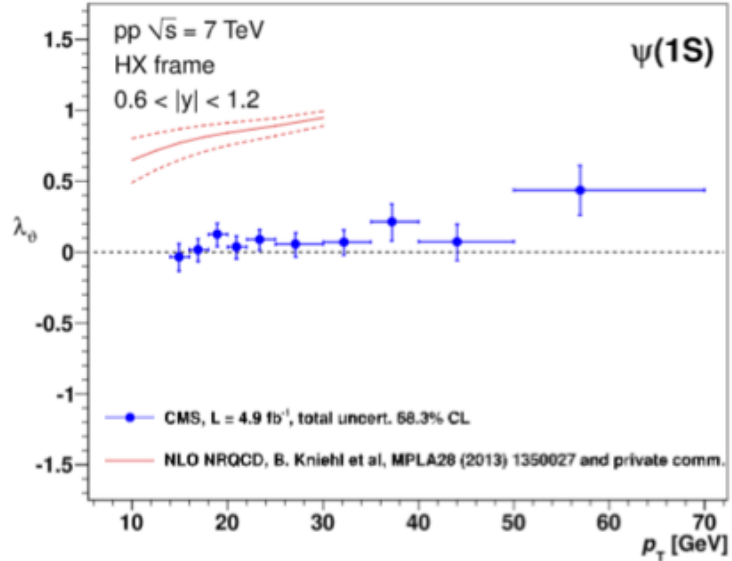
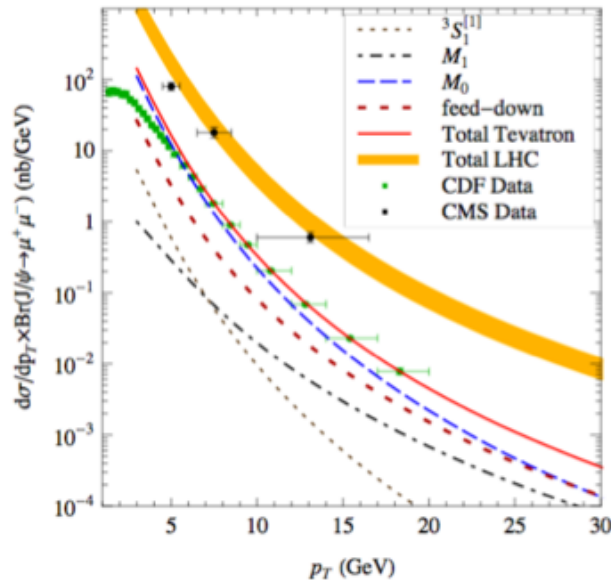


Quarkonium production



Understanding quarkonium production

- 45 years after its discovery, quarkonium production remains elusive
- Several frameworks although none of them (yet) fully satisfactory
 - Non-Relativistic QCD and Color singlet model: many successes but also some failures

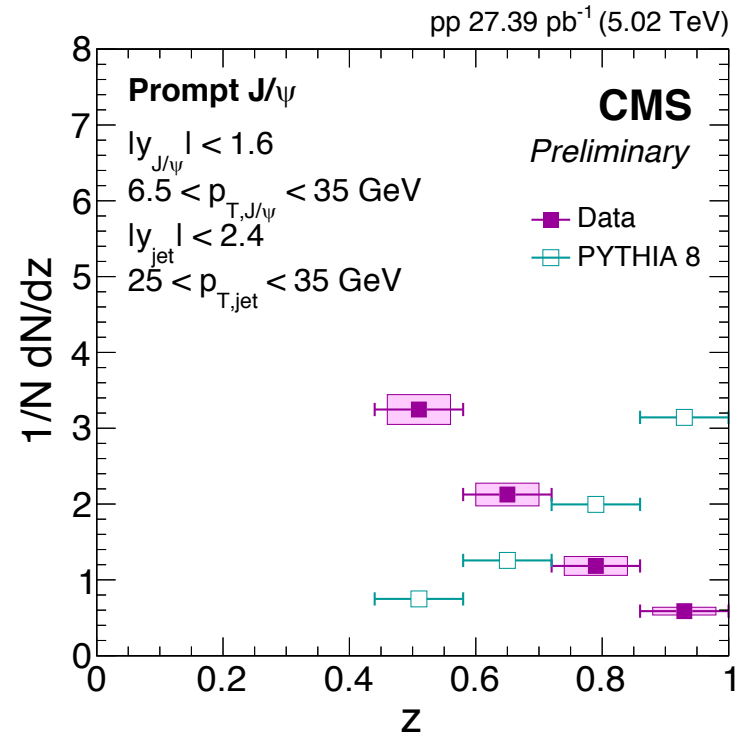
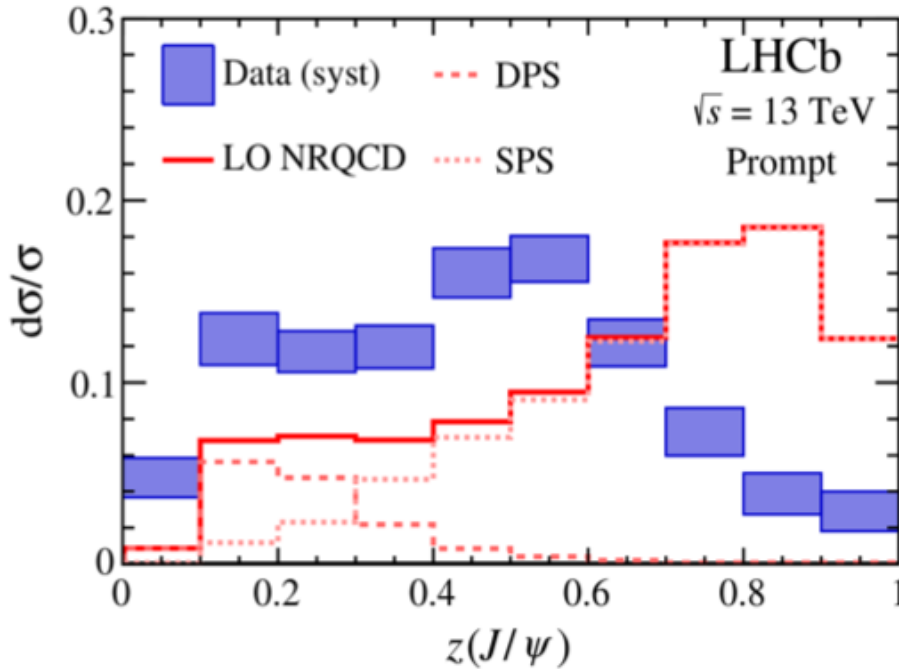




Understanding quarkonium production

- New data from LHCb and CMS on J/ψ fragmentation functions !

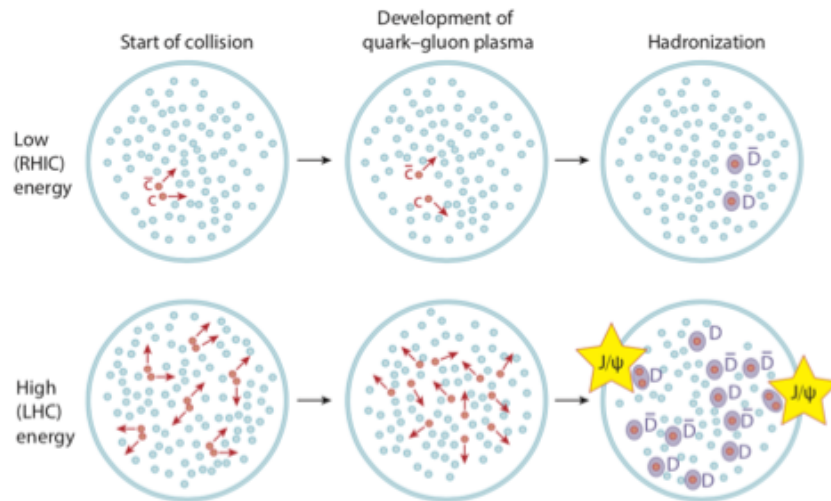
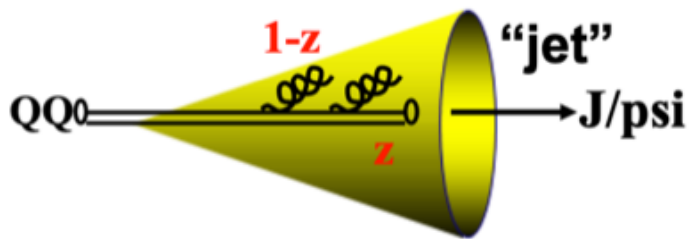
[PhD B. Diab (dir M. Nguyen) 2017-2020]





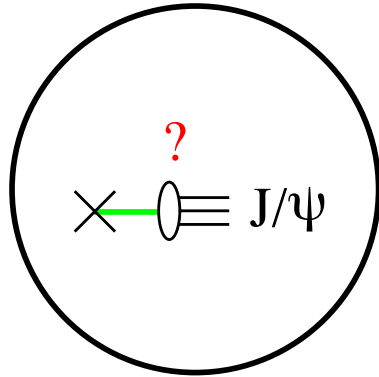
Understanding quarkonium production

- New data from LHCb and CMS on J/ψ fragmentation functions !
- **Dramatic impact** on our understanding of QGP effects
 - Possibly **stronger contributions** of fragmentation processes hence **energy loss effects**
- **Revisit the usual picture** Debye screening vs. Recombination
 - Future data from **LHCb SMOG** on χ_c in **AA collisions** for the first time

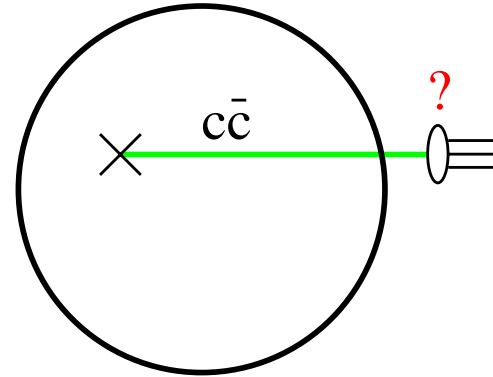


Quarkonium formation dynamics

- Use the nucleus as a **femtometer detector** for quarkonium formation



Small boost $\gamma \sim 1$

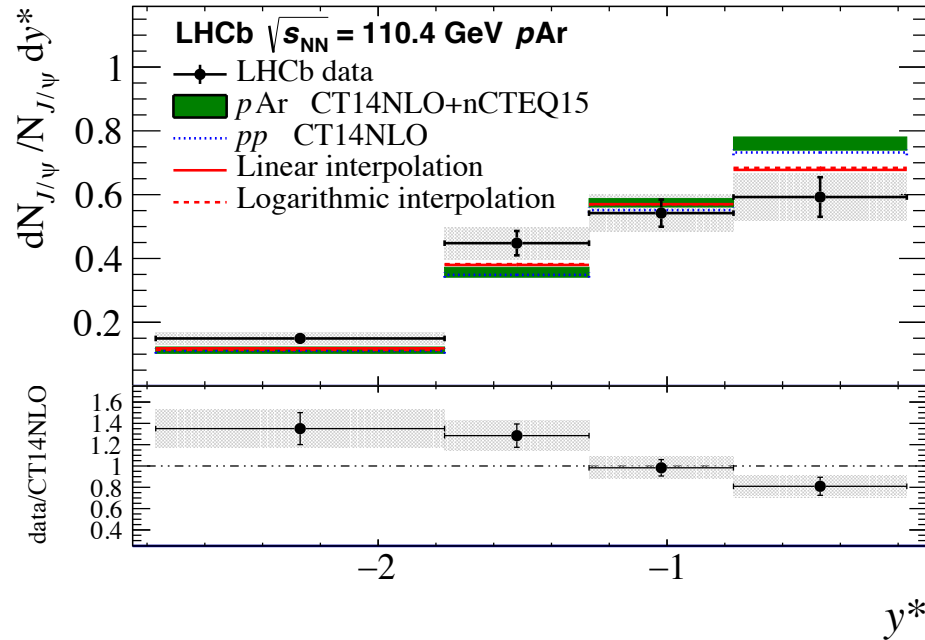


Large boost $\gamma \gg 1$

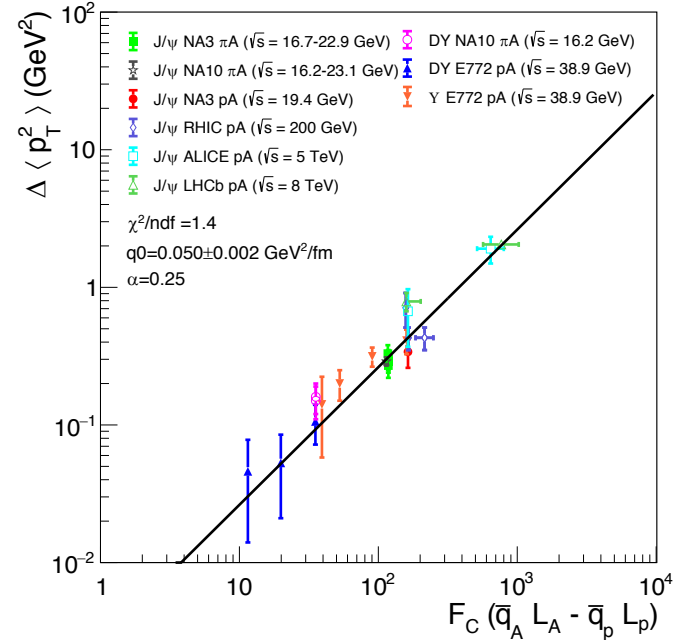


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[LHCb SMOG, PRL 2019]



[F. Arleo, C. Naïm, in preparation]



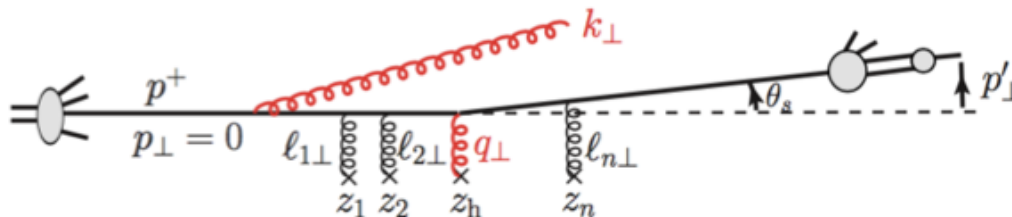
New perspectives on energy loss in pA collisions



New regime for energy loss in pA collisions

- Interference between initial and final state due to long-lived gluons leads to **new parametric dependence for energy loss in pA collisions** [F. Arleo, S. Peigné 2010's]

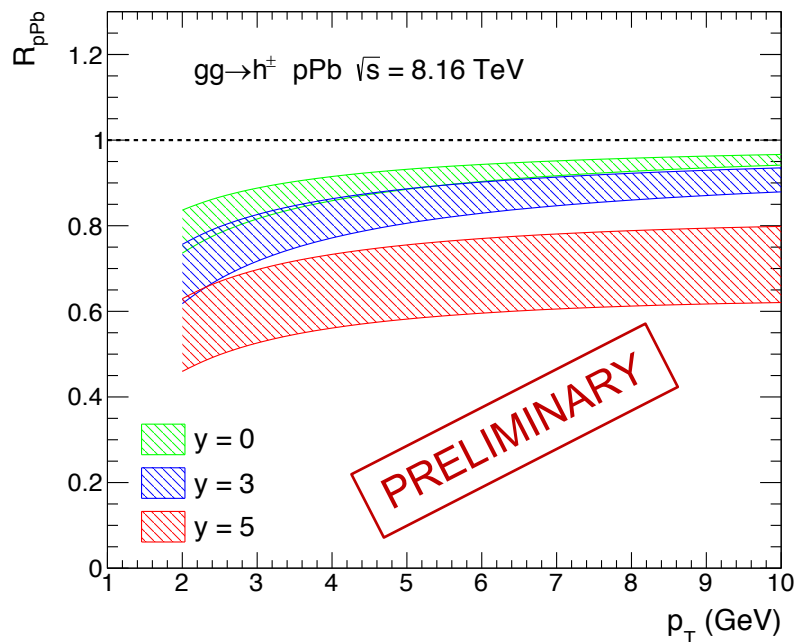
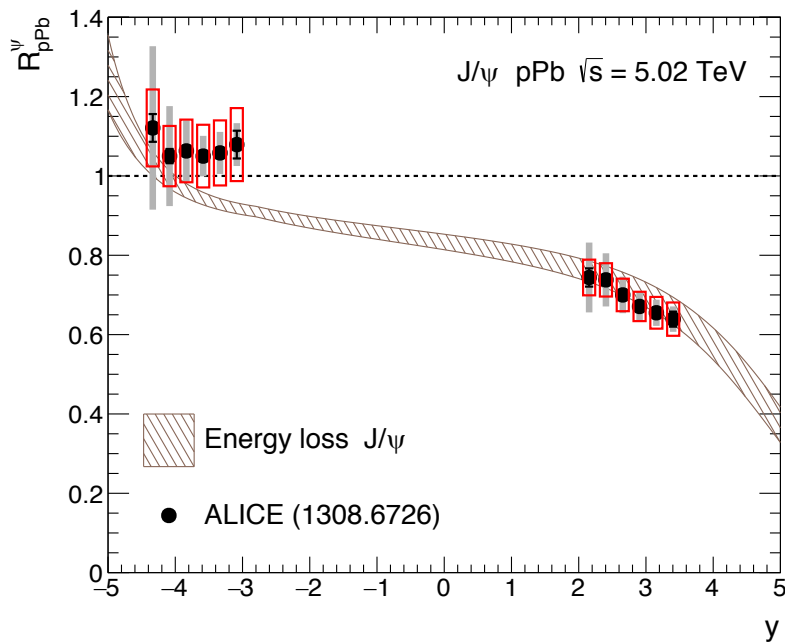
$$\Delta E_{\text{coh}} \propto \alpha_s \frac{\sqrt{\hat{q}L}}{M_{\perp}} E \quad (\gg \Delta E_{\text{LPM}})$$





A new regime for parton energy loss

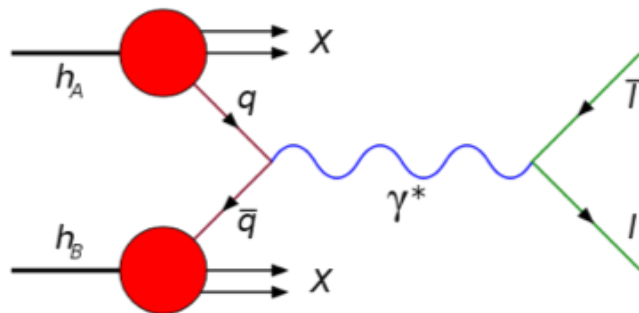
- Important at all energies, especially at large rapidity
- **Dramatic effects on quarkonium production...** in perfect agreement with data, incl. LHC(b)
- **Light hadron production in pA collisions** currently investigated [F. Arleo, S. Peigné, in preparation]





How to extract reliably nPDF

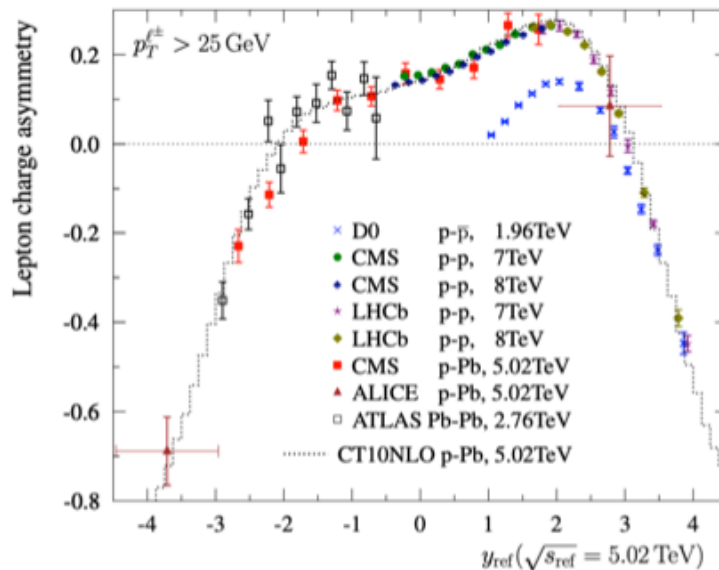
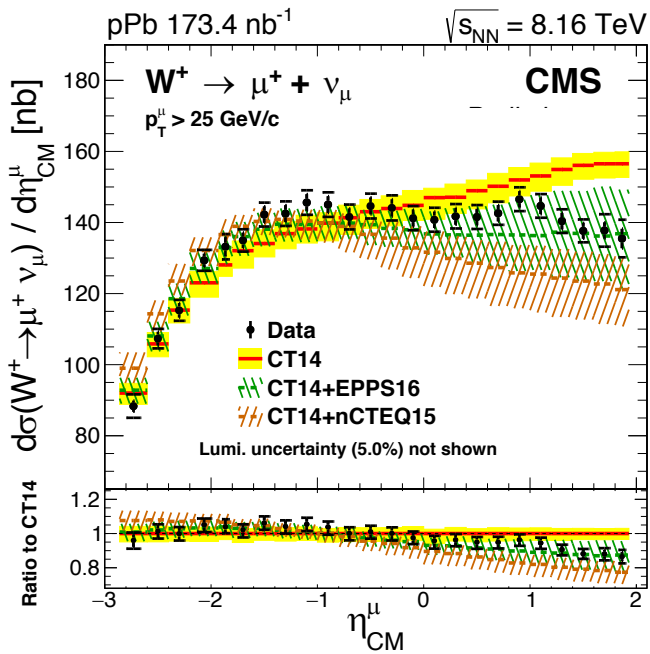
- Energy loss questions the **reliable extraction of nuclear parton densities** in pA collisions
- Need to use either **W/Z boson** or **Drell-Yan lepton pair production** [F. Arleo, S. Peigné 2016]





How to extract reliably nPDF

- Energy loss questions the reliable extraction of nuclear parton densities in pA collisions
- Need to use either **W/Z boson** or **Drell-Yan** lepton pair production [F. Arleo, S. Peigné 2016]
 - Crucial data from CMS (now) and LHCb (future) [PhD A. Florent 2014, A. Ståhl 2018 (dir R. G. de Cassagnac)]

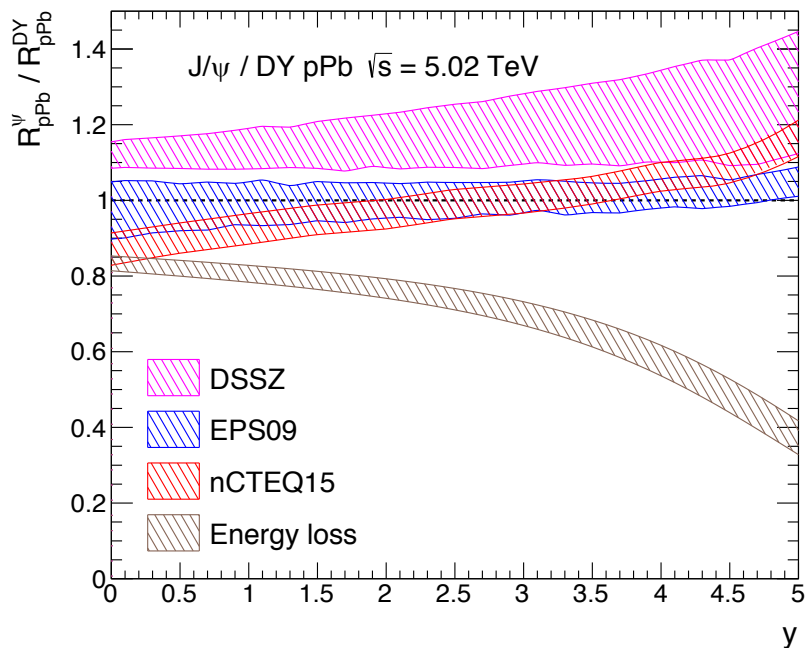


[F. Arleo, É. Chapon, H. Paukkunen, 2016]



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New strategy to extract nPDF !

- ◉ **Include energy loss in nPDF global fit analyses** [F. Arleo, S. Peigné, I. Schienbein 2019 –]
- ◉ Projet Théorie-IN2P3 to be submitted



Summary

- ◉ **Important theoretical activity** on several topics
 - ◉ Jet quenching, theory of parton energy loss, quarkonium production in pA collisions
- ◉ **In close contact with experiments** (and experimentalists!)
 - ◉ CMS, LHCb, COMPASS
- ◉ **Many new projects** and developments
 - ◉ Quarkonium asymmetries in AA collisions (LHC)
 - ◉ Quarkonium formation dynamics in pA collisions (SMOG)
 - ◉ Hadron production (and exotica) in pA collisions at LHC
 - ◉ Extracting nuclear PDF including energy loss

