LPCC workshop on *Prospects of p-Pb collisions during the 2012 LHC HI run*
CERN, October 17th 2011

Proton-nucleus theory review

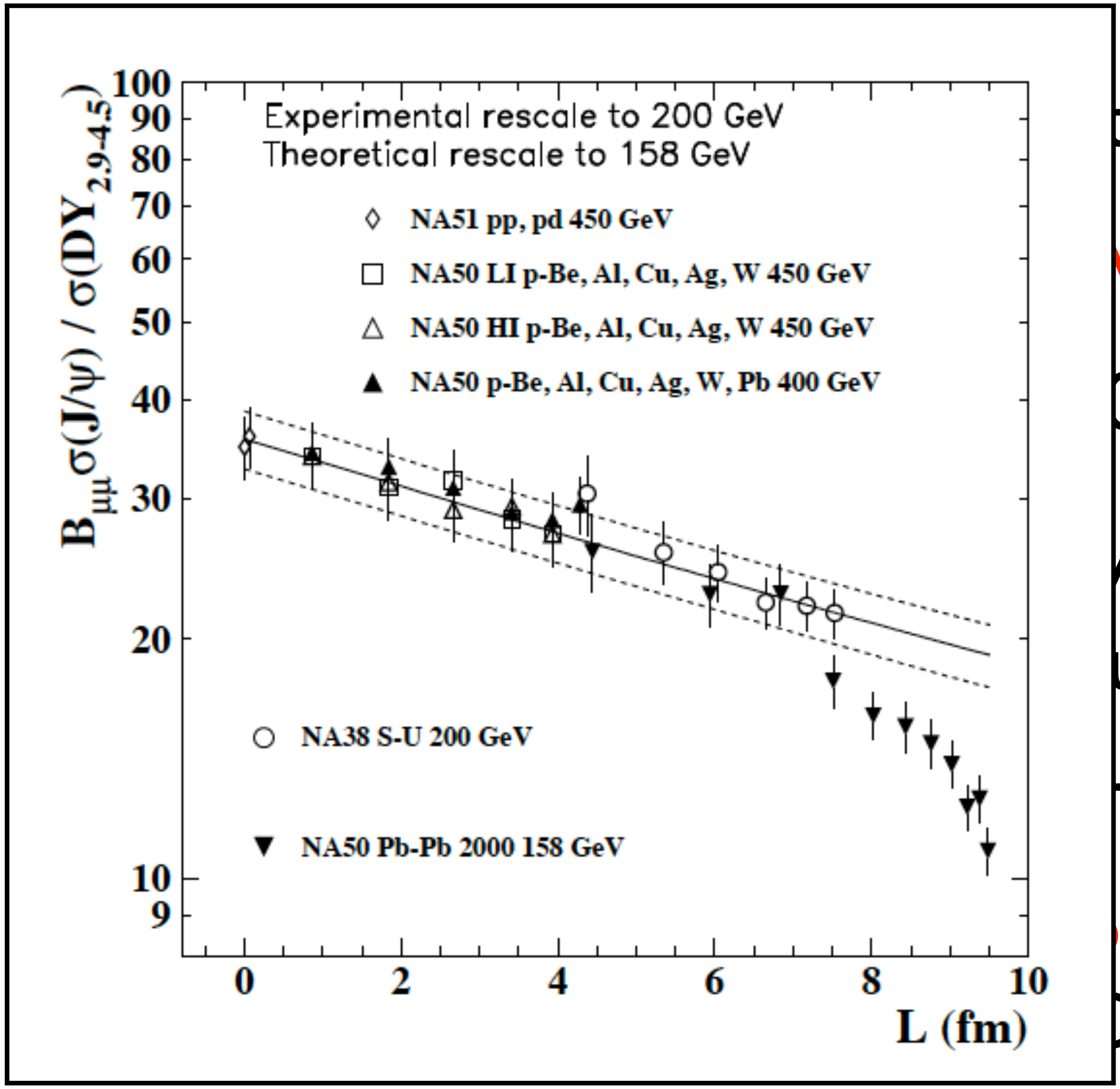
Néstor Armesto
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela
nestor.armesto@usc.es

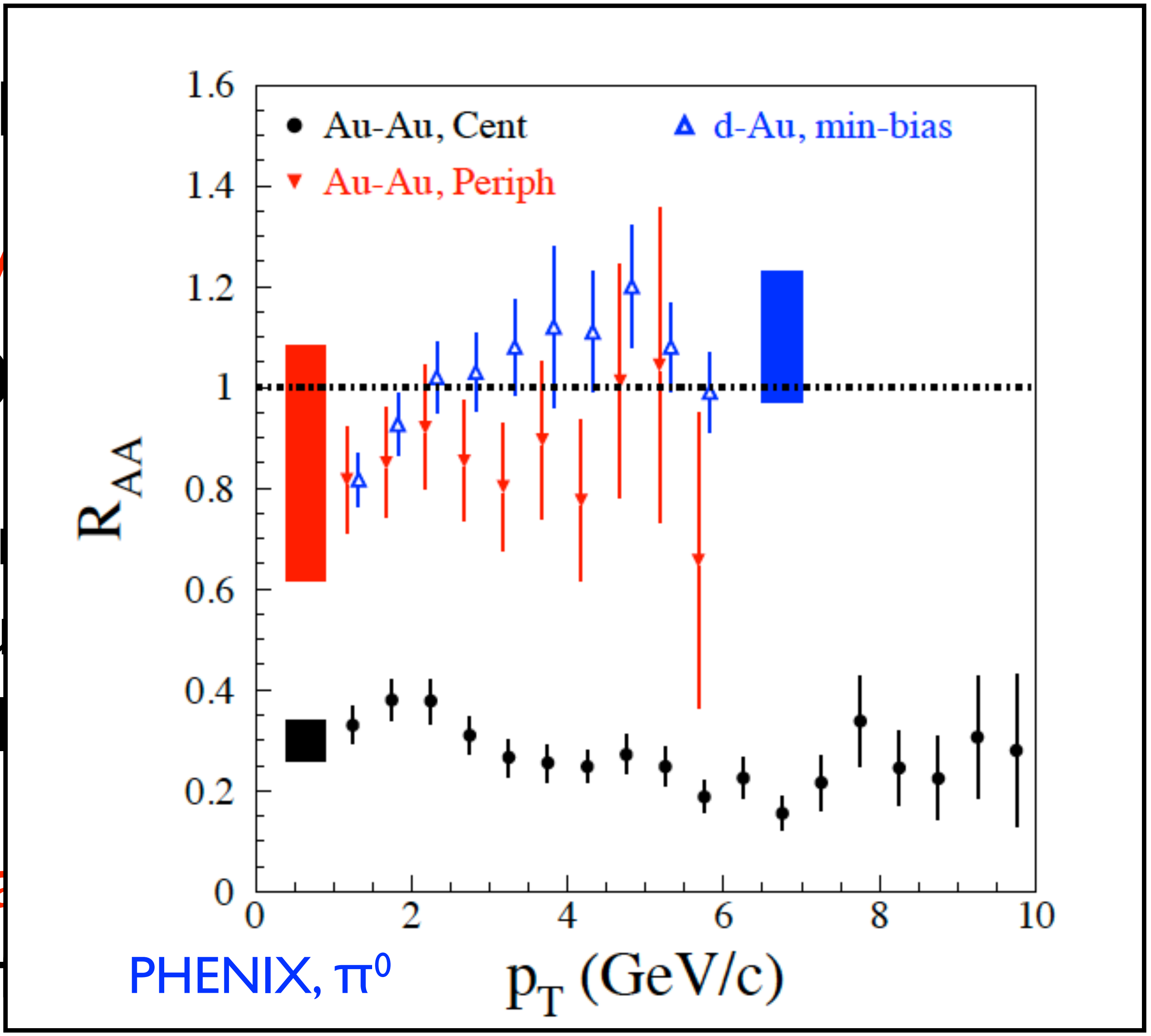
Based on e-Print: arXiv:1105.3919 [hep-ph], submitted to JPG

Contents:

Introduction:

- At the SPS and at RHIC, pA (dAu) runs have been an essential part of the heavy-ion programs. Prominent examples:
  - ➜ SPS: J/ψ absorption in pA → anomalous suppression in PbPb.
  - ➜ RHIC: Cronin in dAu → jet quenching in AuAu as a final state effect.





Proton-nucleus theory review.

Introduction:

- At the SPS and at RHIC, pA (dAu) runs have been an essential part of the heavy-ion programs. Prominent examples:
  - ➜ SPS: J/ψ absorption in pA → anomalous suppression in PbPb.
  - ➜ RHIC: Cronin in dAu → jet quenching in AuAu as a final state effect.

- A pPb run possible @LHC with $<\mathcal{L}>\sim 10^{29}$ cm^{-2}s^{-1} (John Jowett) for **$\int \mathcal{L}$dt~0.1 pb^{-1}** in 2012 (4.4 TeV/n instead of nominal 8.8); $\mathcal{O}(10^6)$ collisions during the feasibility 2011 checks? (Sebastian White).

- Rapidity shift (0.46) due to asymmetric system, smaller for dPb (0.12), but no injector: p+Pb and Pb+p (ALICE μ-arm, LHCb).

$$\boxed{\Delta y \approx \frac{1}{2} \log \frac{Z_1 A_2}{A_1 Z_2}}$$

- All LHC experiments with capabilities for this running mode: ALICE, ATLAS, CMS, LHCb, LHCf,...

Contents:

1. Introduction.

2. pA as benchmark:
    - 2.1 Nuclear PDFs. (Kari Eskola)
    - 2.2 Processes for benchmarking:
        - ➜ Jets. (Guilherme Milhano)
        - ➜ EW bosons. (Carlos Salgado)
        - ➜ Photons. (“)
        - ➜ Open heavy flavor. (“)
        - ➜ Quarkonium. (Andry Rakotozafindrabe)

3. Small-x physics. (Cyrille Marquet and Javier Albacete)

4. Others:
    - 4.1 UPCs: (David d’Enterria)
        - ➜ γp/A.
        - ➜ γγ.
    - 4.2 Implications for Astroparticles.

5. Summary.

Hard probes:

$$R_{AA}(y,p_T) = \frac{\frac{dN_k^{AA}}{dydp_T}}{\langle N_{coll}\rangle \frac{dN_k^{NN}}{dydp_T}}$$ =1 if no nuclear effects

- Assume collinear factorization works for the reference (pp) and for the probe (in AA):

$$d\sigma[A+B\to h+X] \propto \int [dx] \boxed{f_{i/A}(x_i)} \otimes \boxed{f_{j/B}(x_j)} \otimes d\hat{\sigma}[i+j\to k+X](sx_ix_j) \otimes \boxed{D[k\to h+X](z)}$$

cold nuclear matter effects: nPDFs

cold and hot nuclear matter effects

- pA, eA: check factorization and constrain cold nuclear matter effects.

- AB: (check factorization and) characterize the medium.

Hard probes:

$$R_{AA}(y,p_T) = \frac{\frac{dN_k^{AA}}{dydp_T}}{\langle N_{coll}\rangle \frac{dN_k^{NN}}{dydp_T}}$$

=1 if no nuclear effects

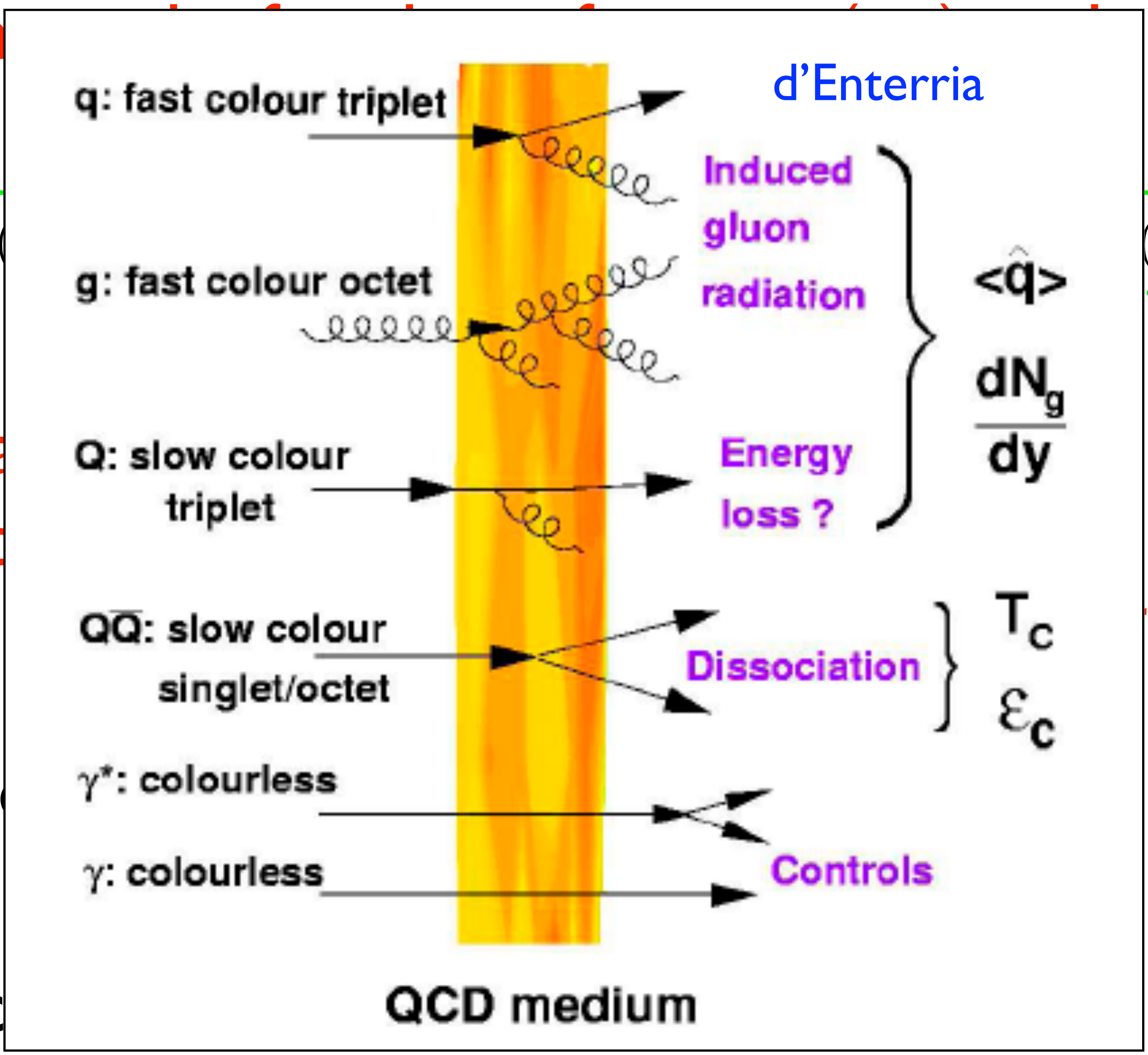
- Assume collinear factorization

for the probe (in AA):

$$d\sigma[A+B\rightarrow h+X] \propto \int [dx] \boxed{f_{i/A}(x_i)} \otimes \boxed{f_{j/B}(} \quad \boxed{(z)}$$

cold nuclea
matter effec
nPDFs

s



- pA, eA: check factorization an

effects.

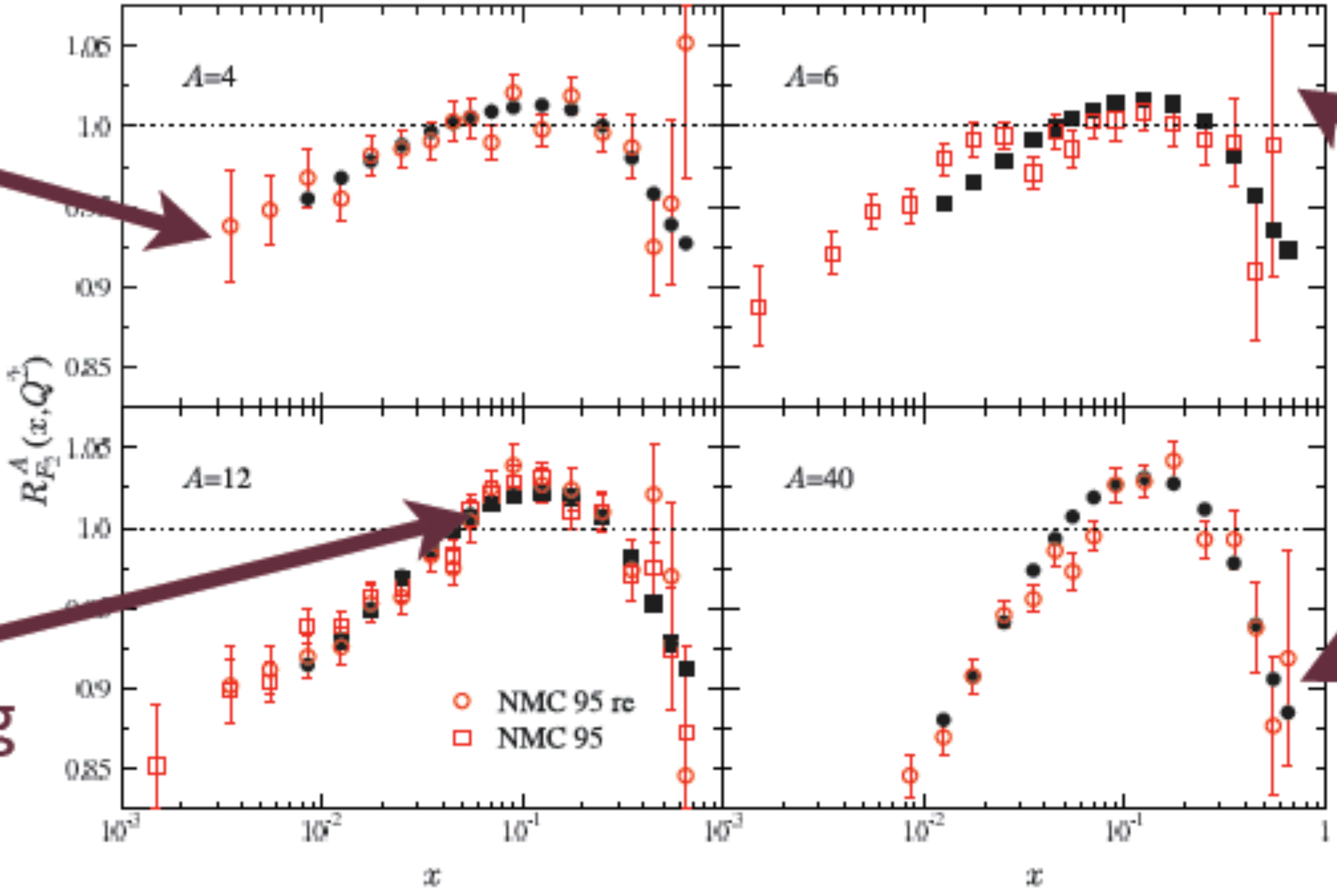
- AB: (check factorization and) c

Proton-nucleus theory review: 2. pA as benchmark.

nPDFs (I):

$$R^A_{F_2}(x,Q^2) = \frac{F^A_2(x,Q^2)}{AF^p_2(x,Q^2)}$$

Eskola



shadowing

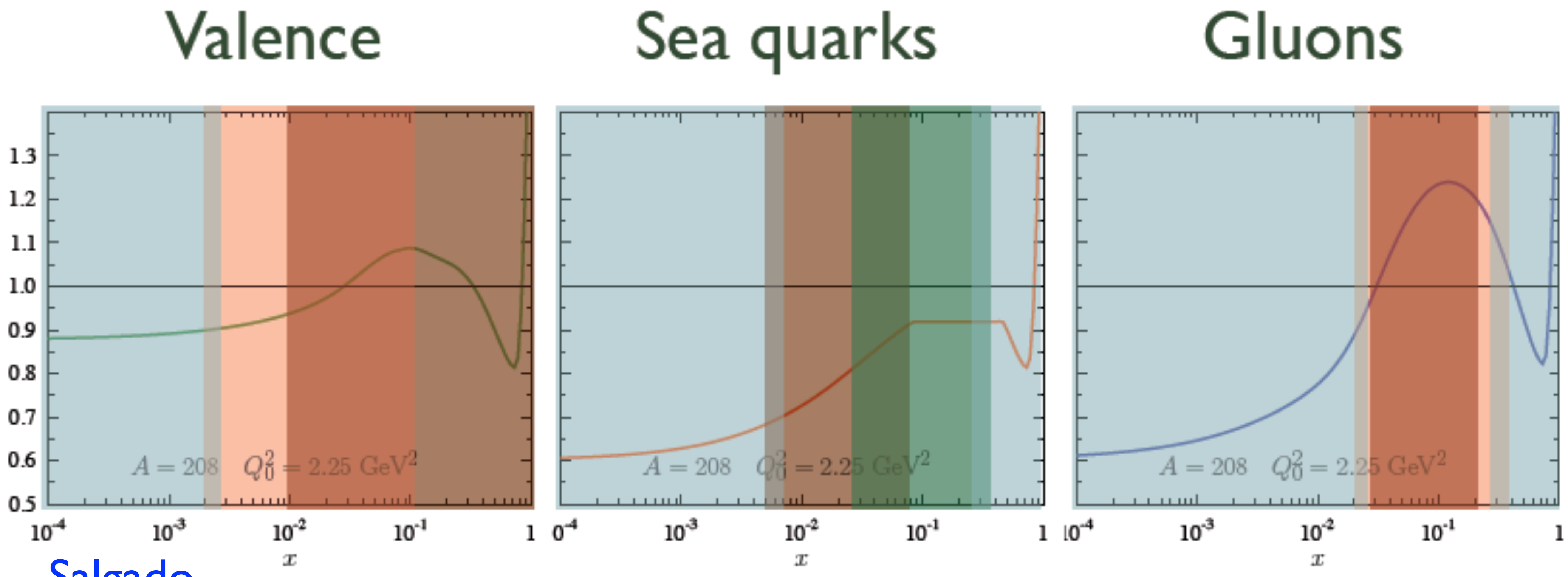
Fermi motion

EMC effect

antishadowing

Proton-nucleus theory review: 2. pA as benchmark.

nPDFs (I):



Salgado

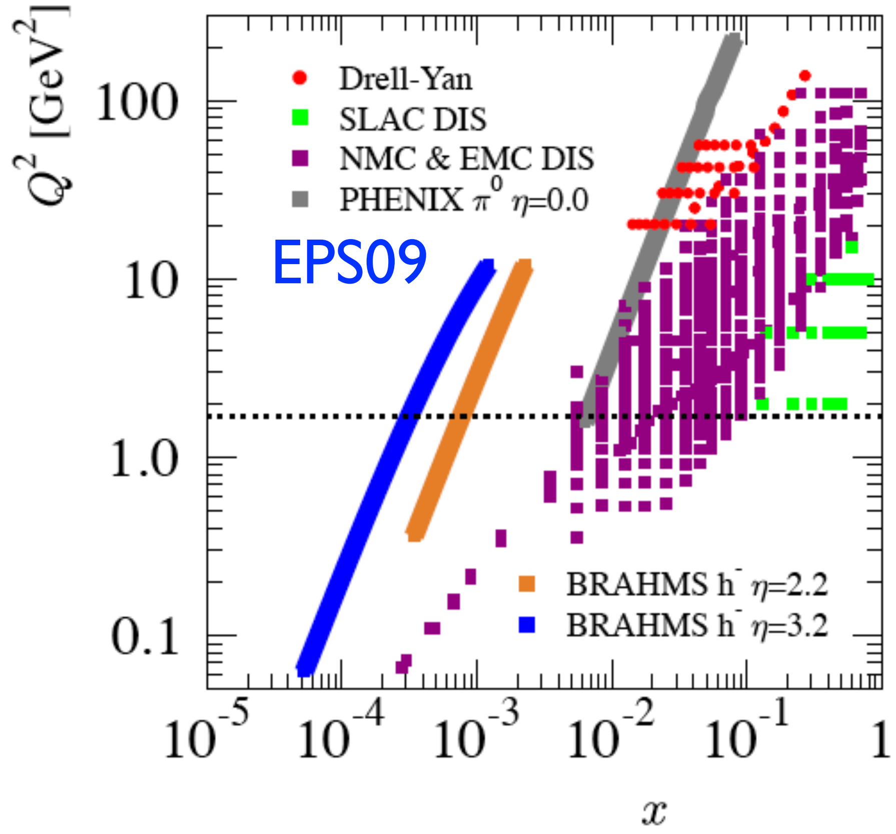
🟫 Constrained by DIS

🟩 Constrained by DY

🟧 Constrained by Sum rules

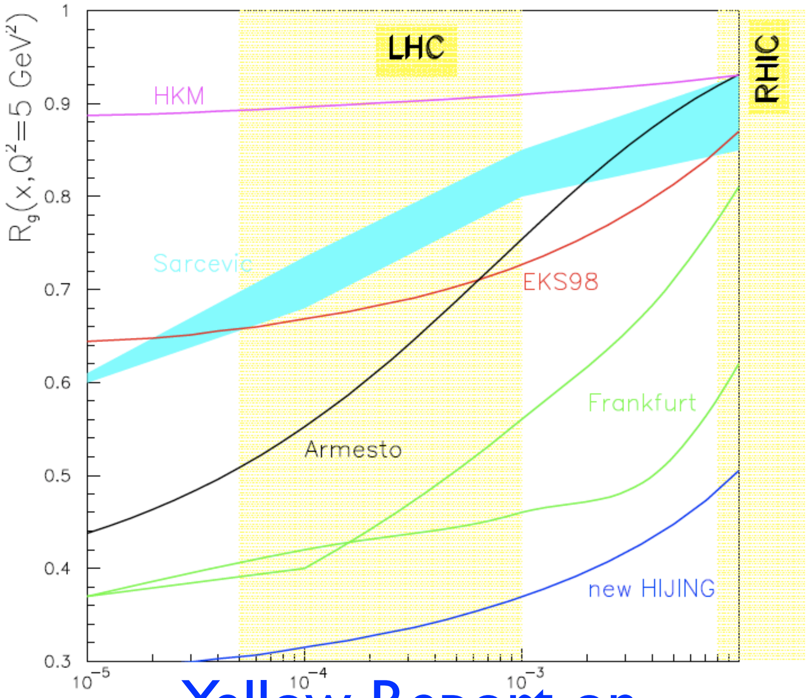
🟦 Assumptions

- Lack of experimental data makes the small-x region unconstrained ⇒ uncertainties on observables.



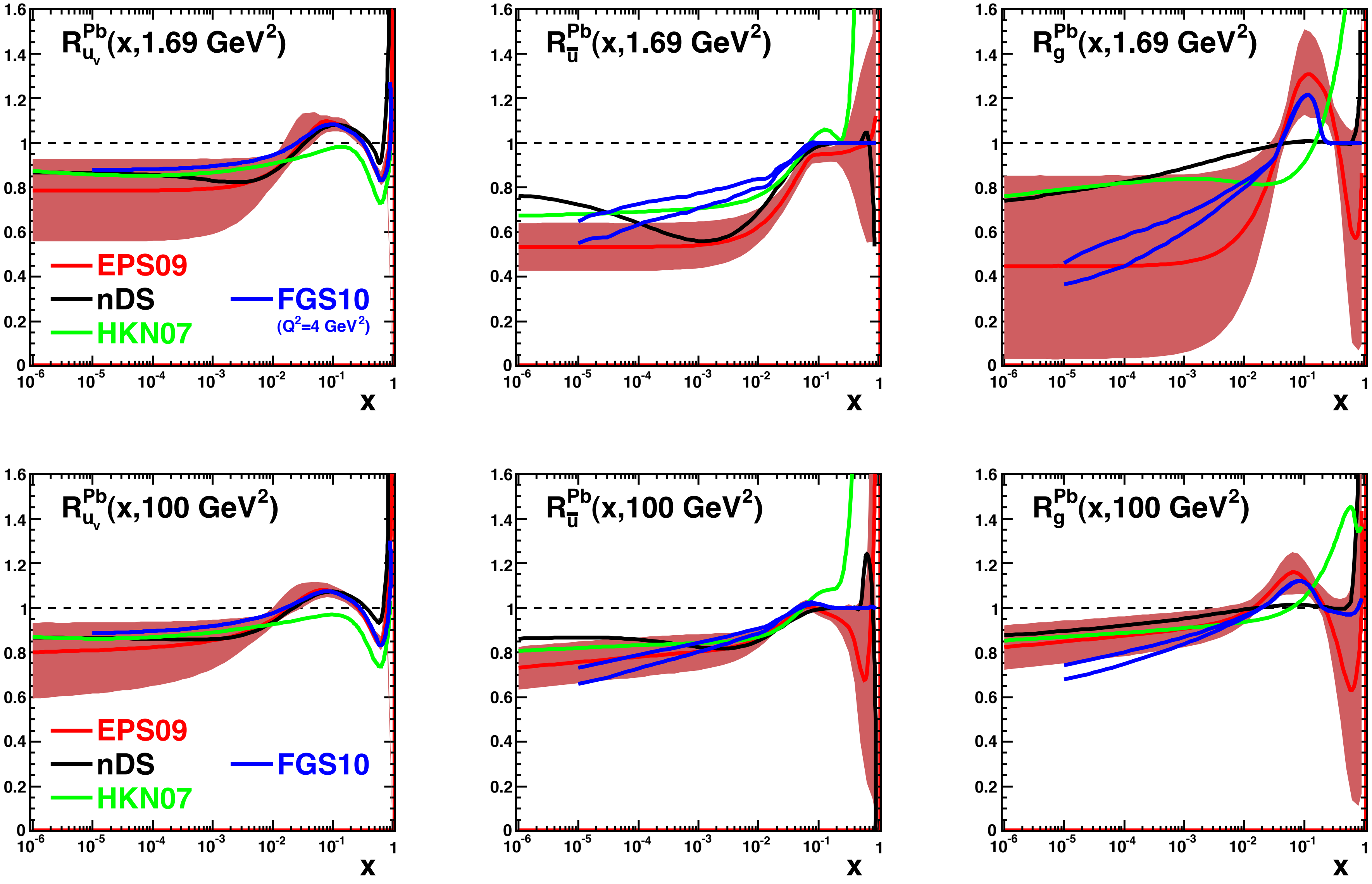
'LHC without HERA'

nPDFs (II):



Yellow Report on
Hard Probes, 2004

- Models give vastly different results for the nuclear glues at small scales and x.



- Available DGLAP analysis at NLO show large uncertainties at small scales and x.
- eA colliders not available before ~ 2020: EIC,LHeC?

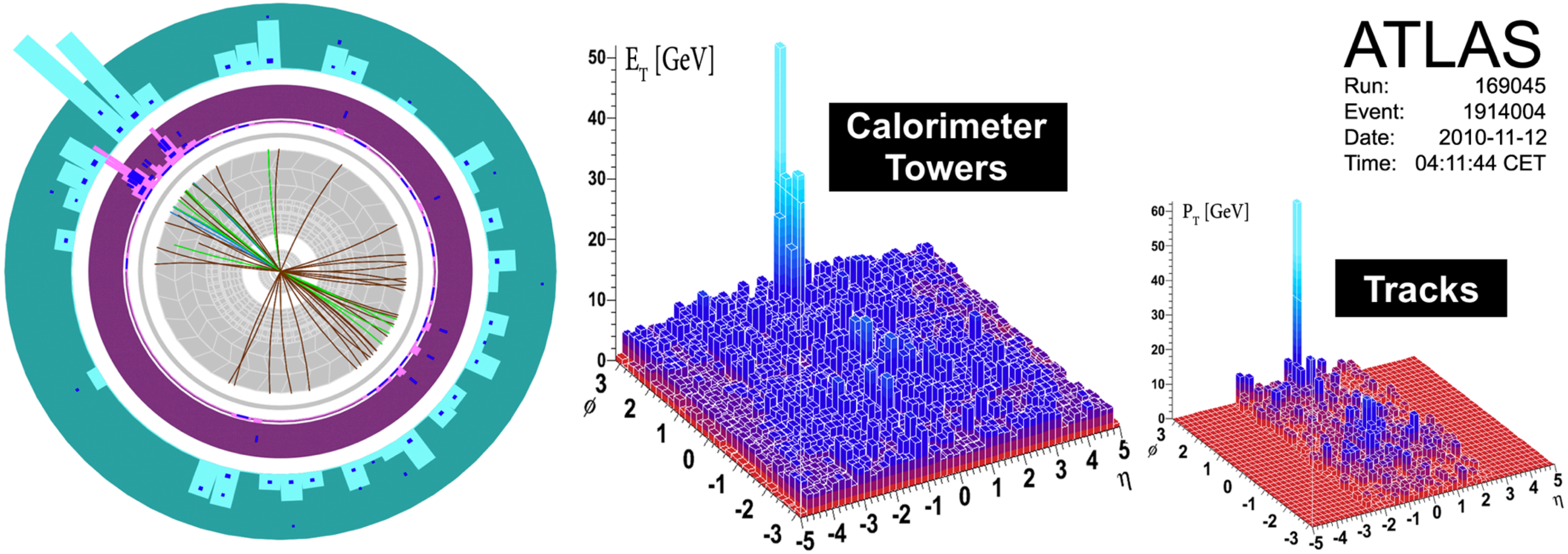
Jets: motivation

- Jets offer a less biased observable for jet quenching than single hadrons (or even dihadrons).

- Many interesting features in PbPb@LHC, not yet understood in theoretical models:
  - ➜ Dijet momentum imbalance: eloss without broadening?
  - ➜ Momentum balance by soft large-angle particles.
  - ➜ Similar R_{AA} as charged.
  - ➜ Influence of background substraction on medium characterization.

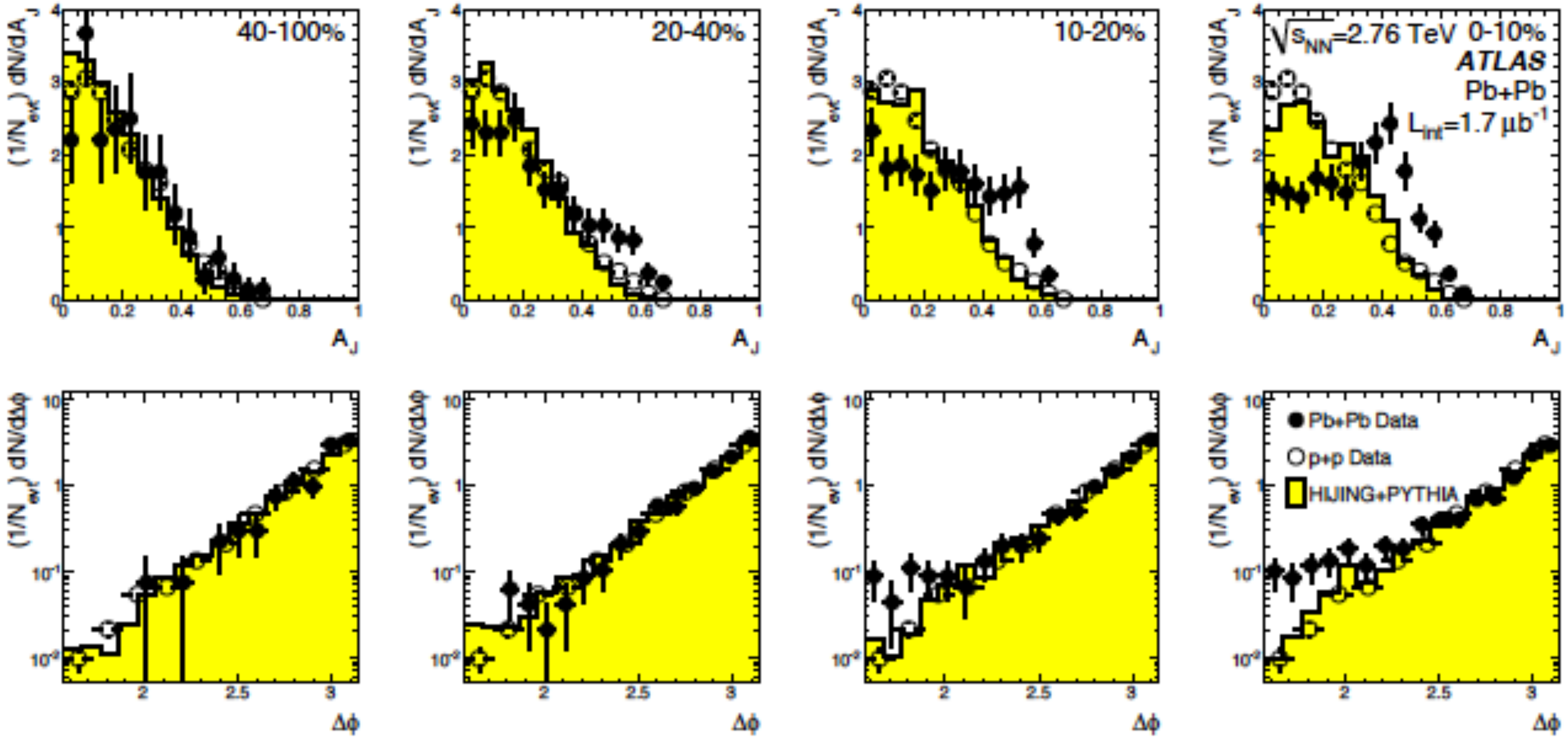
- Very few studies in pA (dAu@RHIC).

Jets: motivation

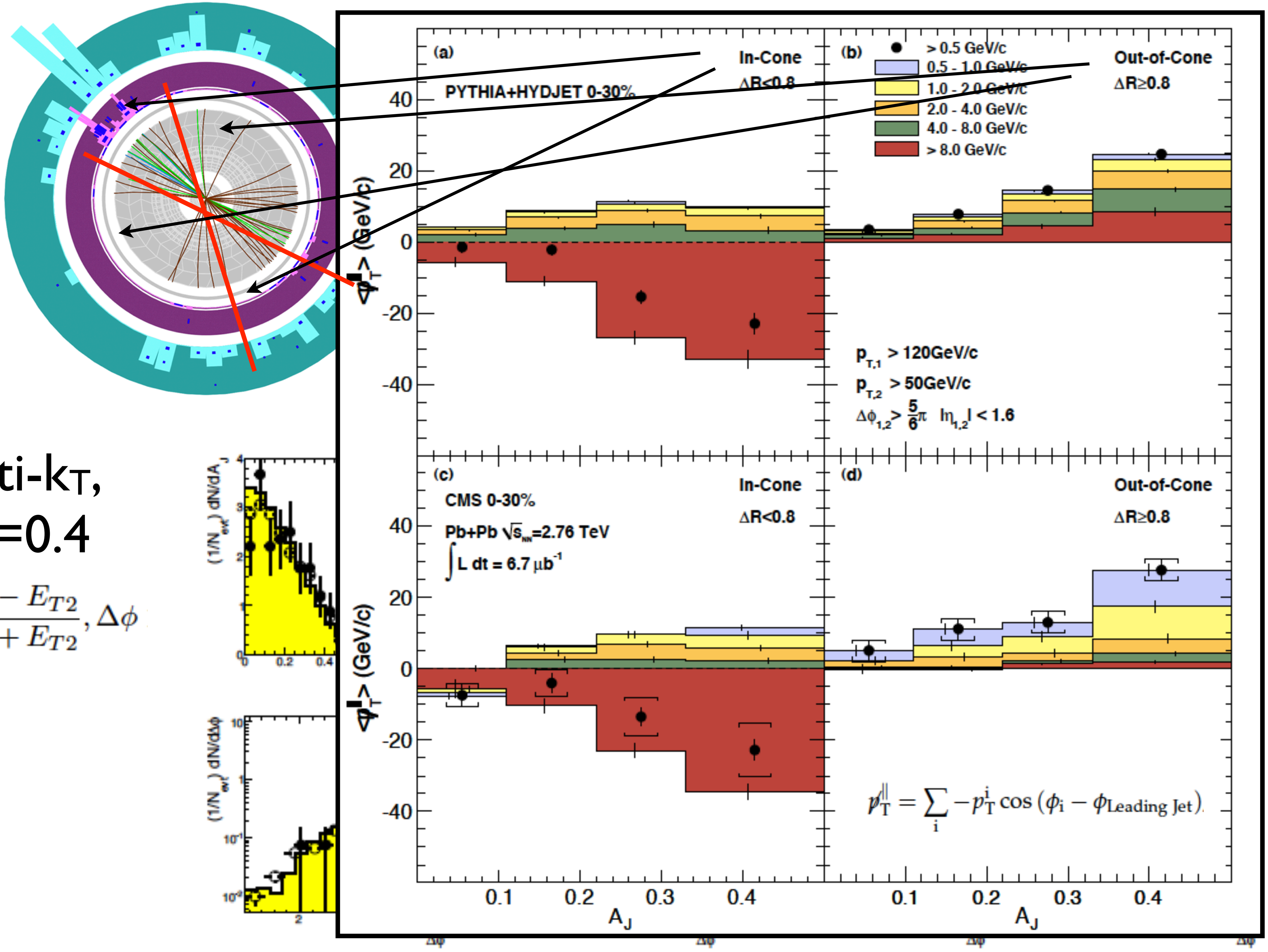


anti-k_T,
D=0.4

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi$$



Jets: motivation

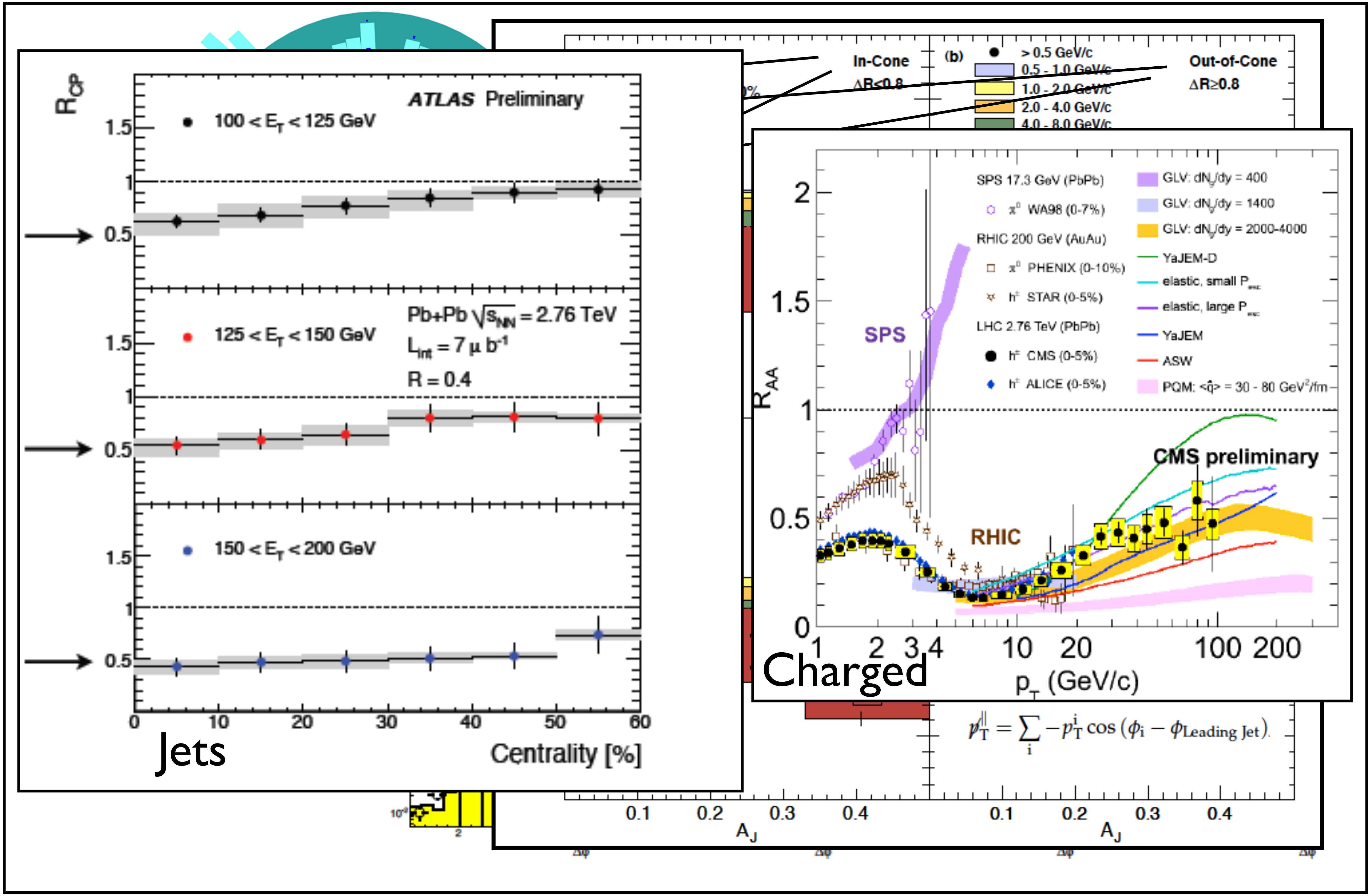


$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}).$$

anti-k$_T$,
D=0.4

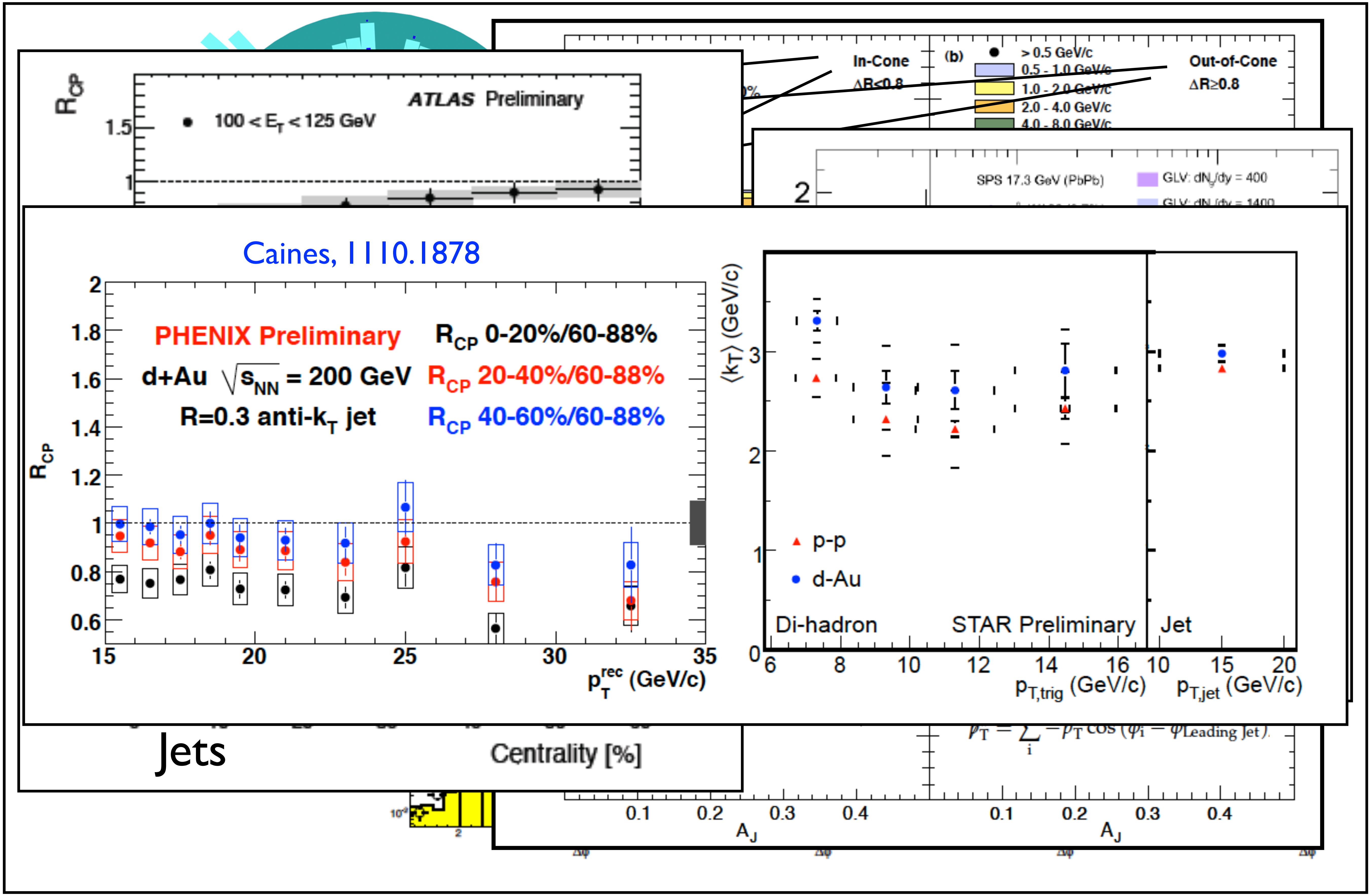
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi$$

Jets: motivation



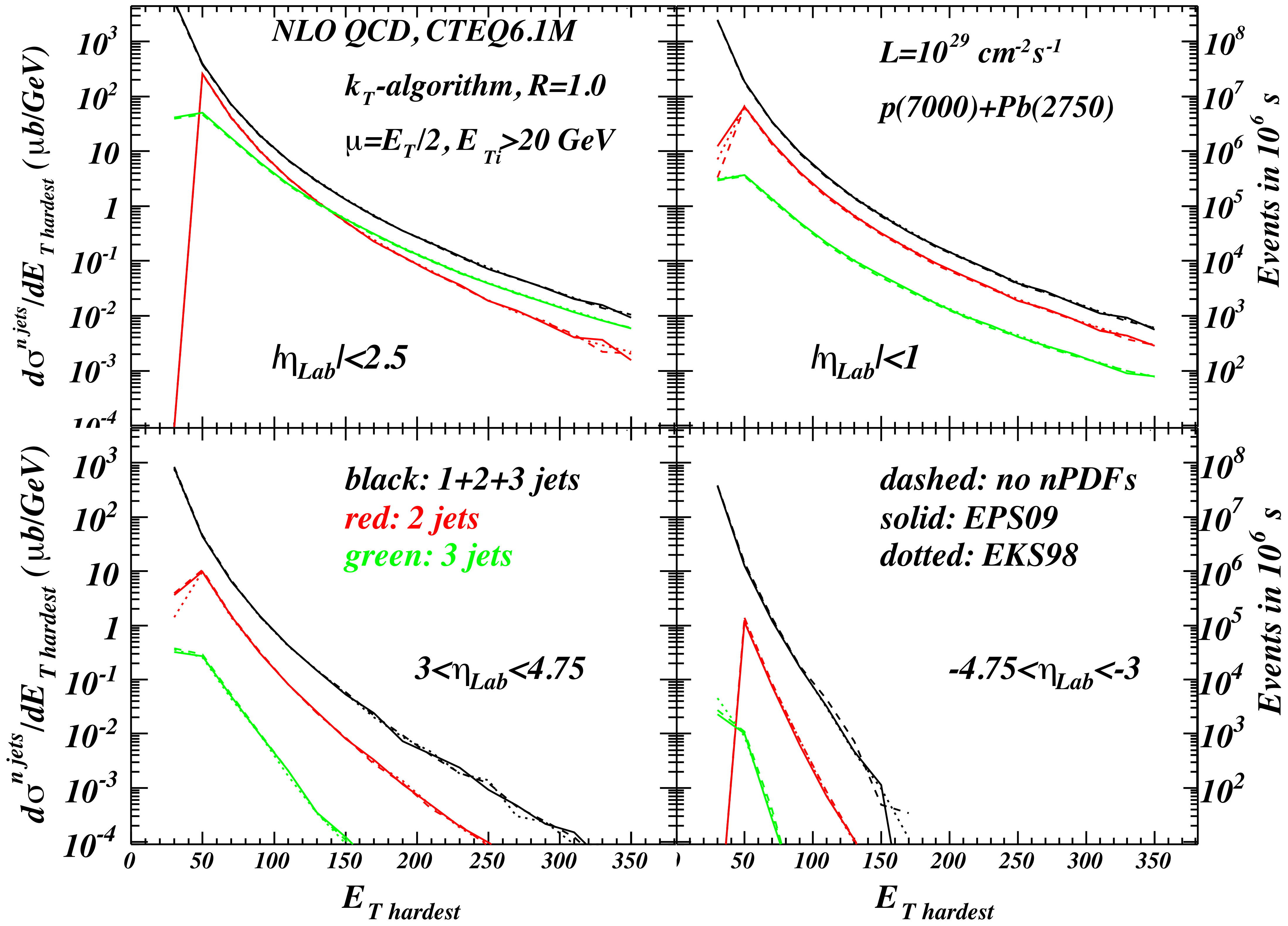
$$p\!\!\!/_{T}^{\parallel} = \sum_{i} -p_{T}^{i} \cos\left(\phi_{i} - \phi_{\text{Leading Jet}}\right)$$

Jets: motivation


Caines, 1110.1878

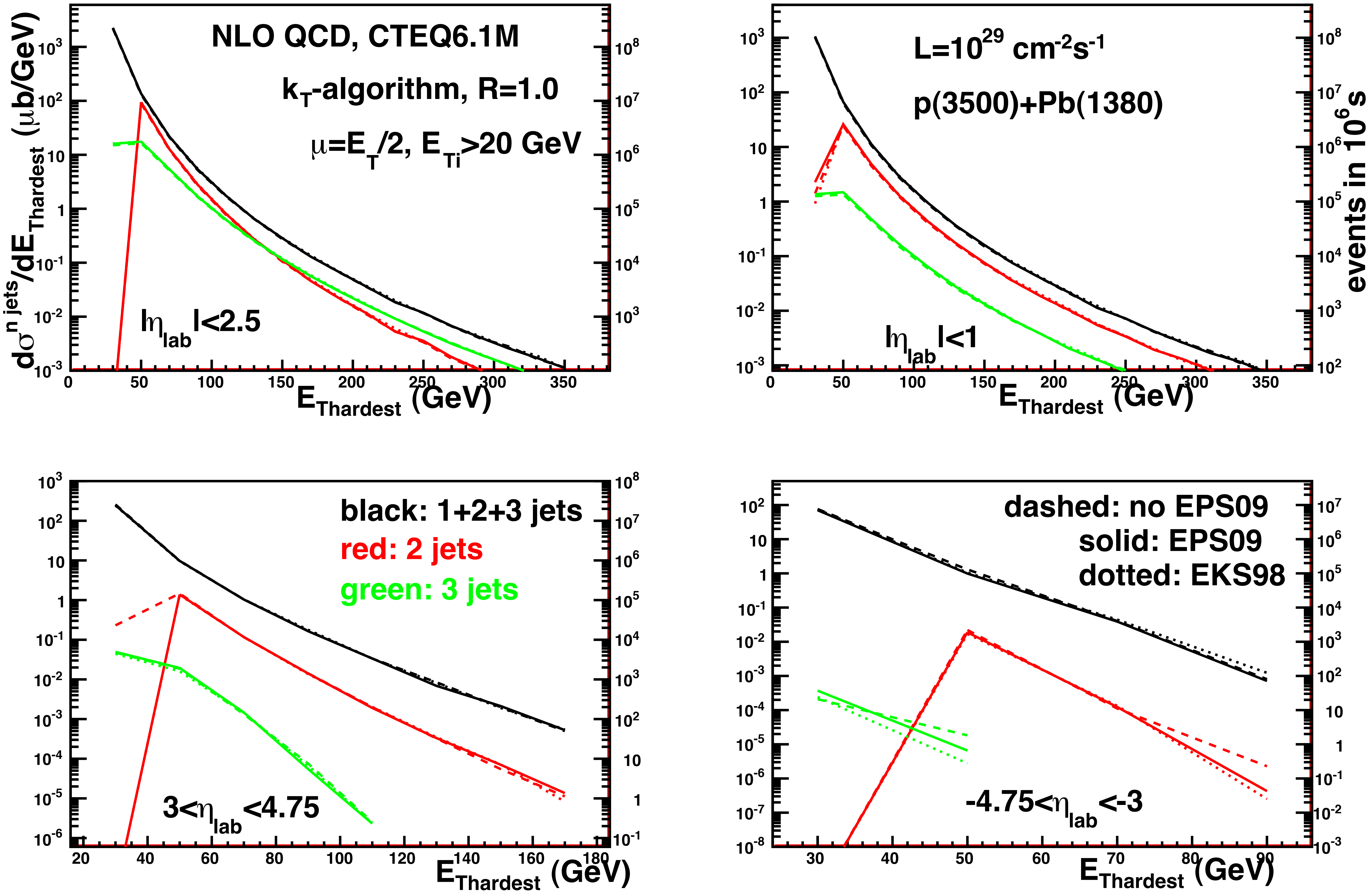
Jets

Jets in pPb at 8.8 TeV/n:

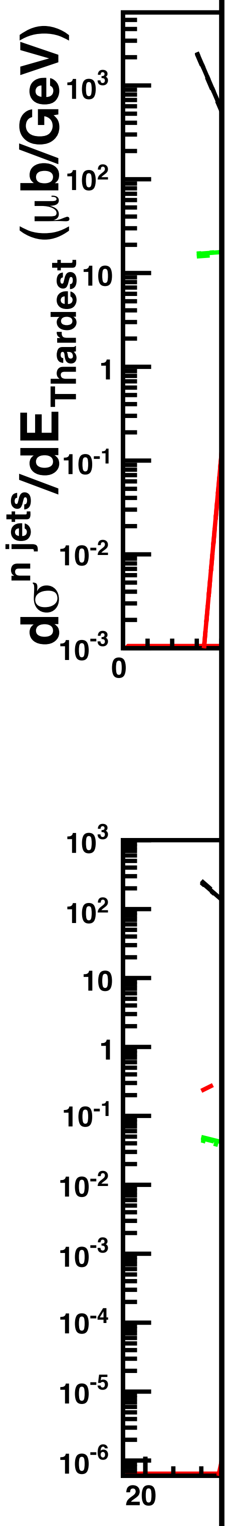


Proton-nucleus theory review: 2. pA as benchmark.

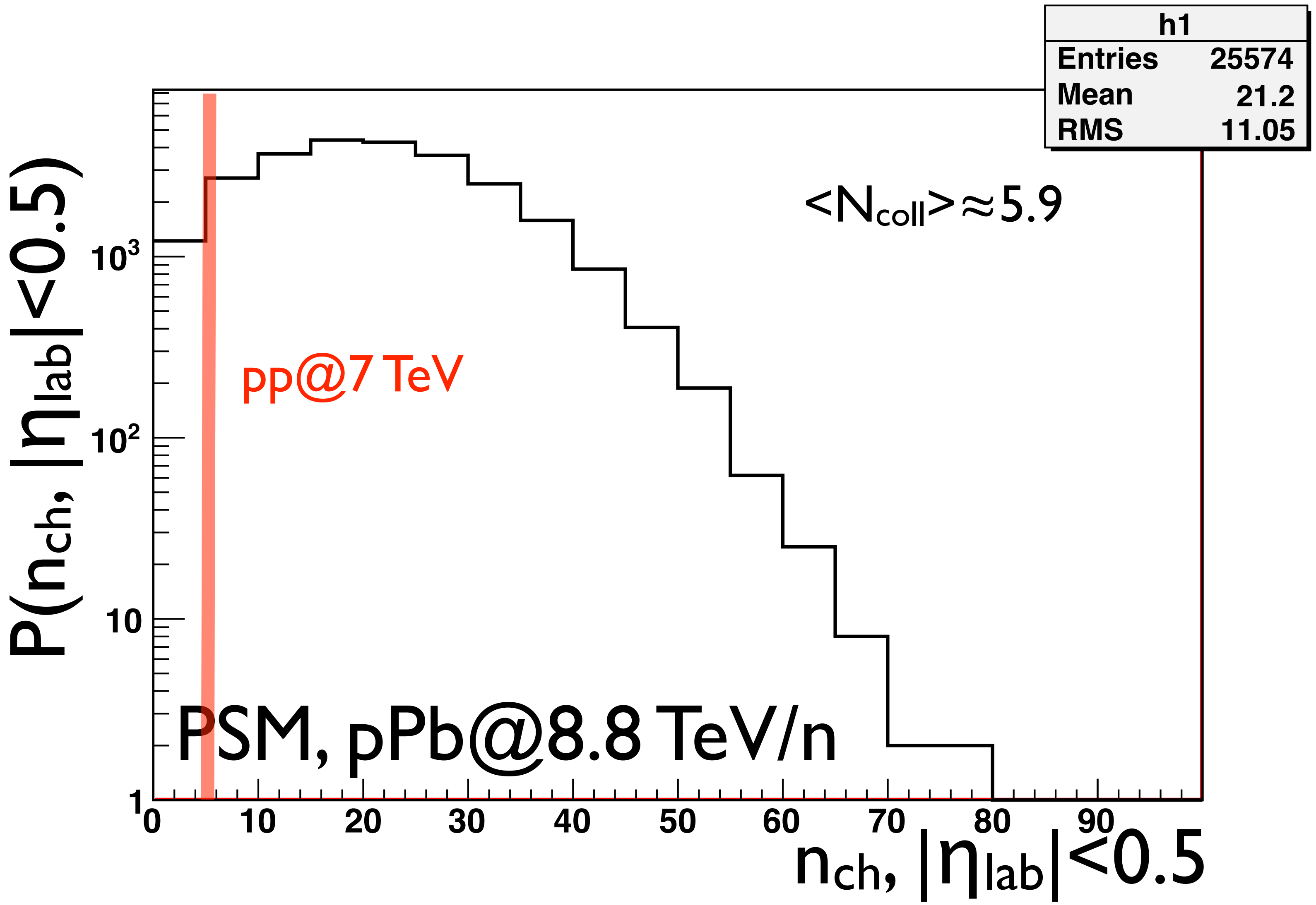
Jets in pPb at 4.4 TeV/n:

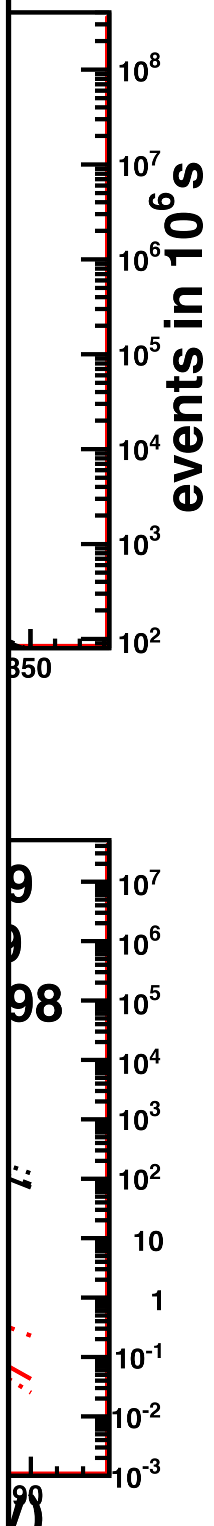


Jets in pPb at 4.4 TeV/n:

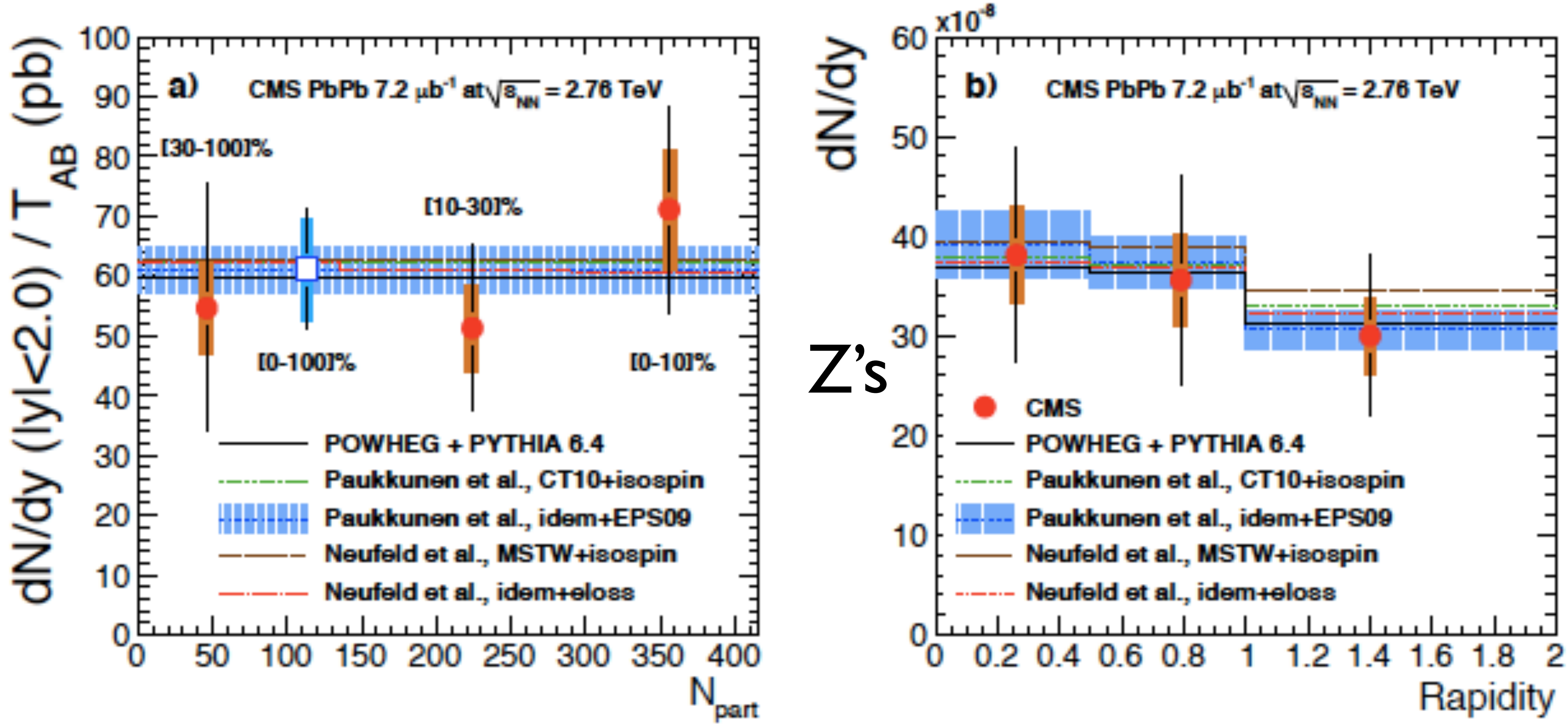


- Abundant yields expected upto large E_T.
- Small ($\mathcal{O}(10\,\%)$) nuclear effects expected.
- More realistic jet-finding algorithms, more recent PDFs, studies of background substraction,... pending.

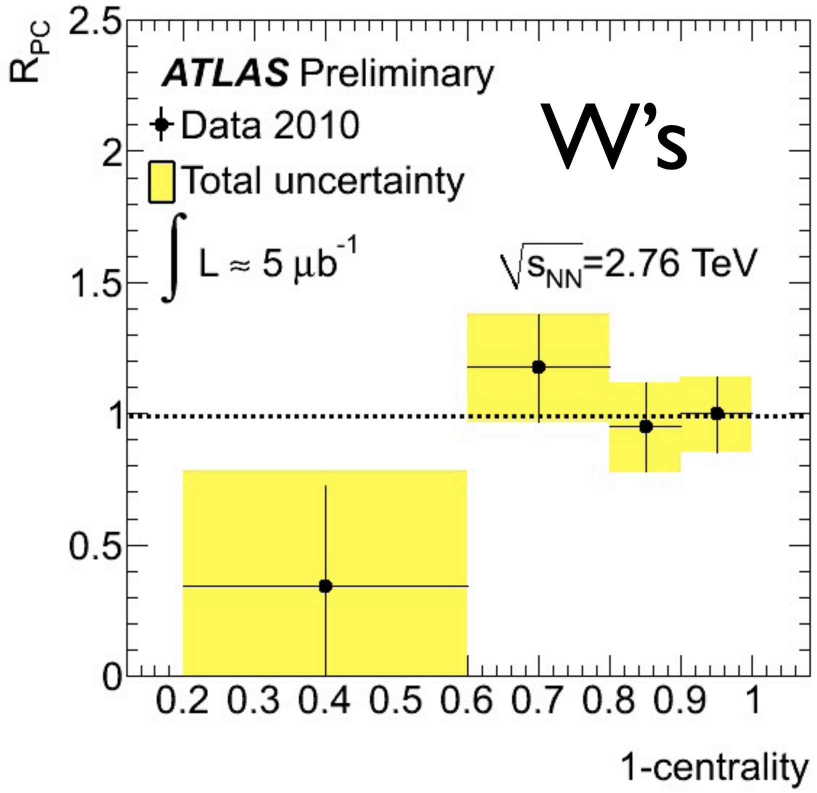




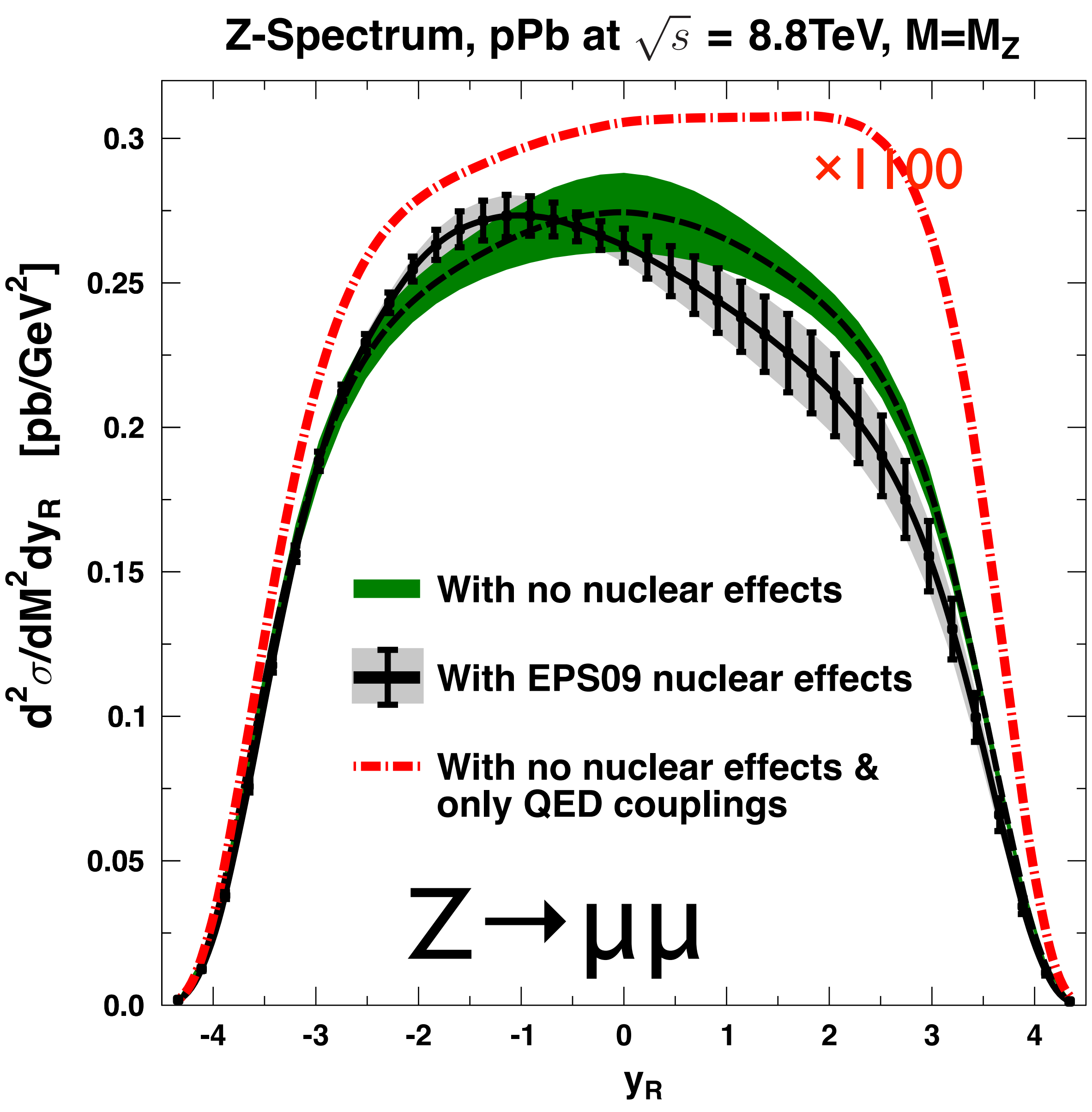
EW bosons: motivation

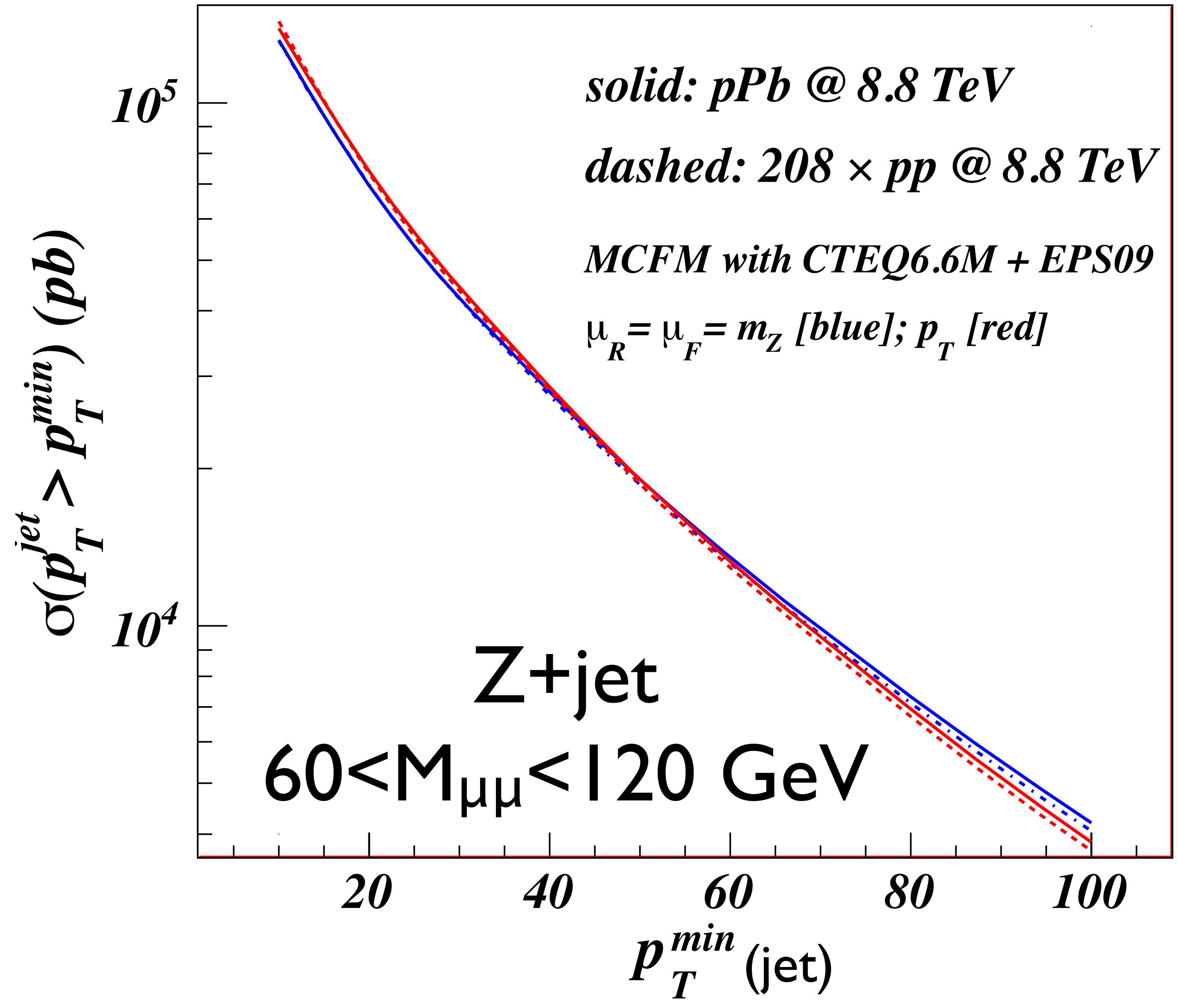


- EW bosons are, with photons, the canonical medium-blind observable: check of collinear factorization (N_{coll}-scaling) and of the Glauber model, constrains on nPDFs, callibrate jet energy via γ,Z+jet.
- Already available in PbPb at the LHC.



EW bosons in pPb at 8.8 TeV/n:



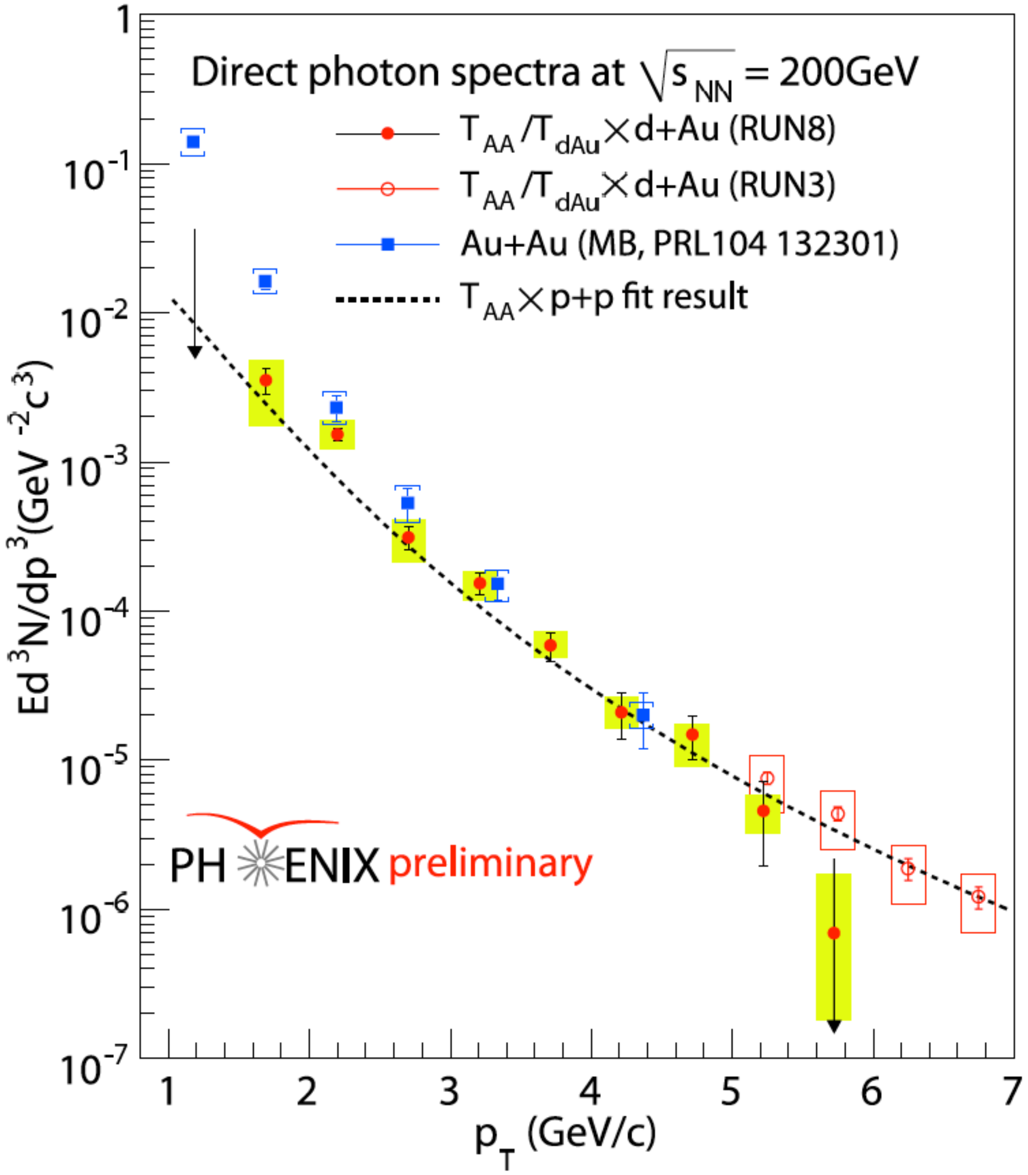


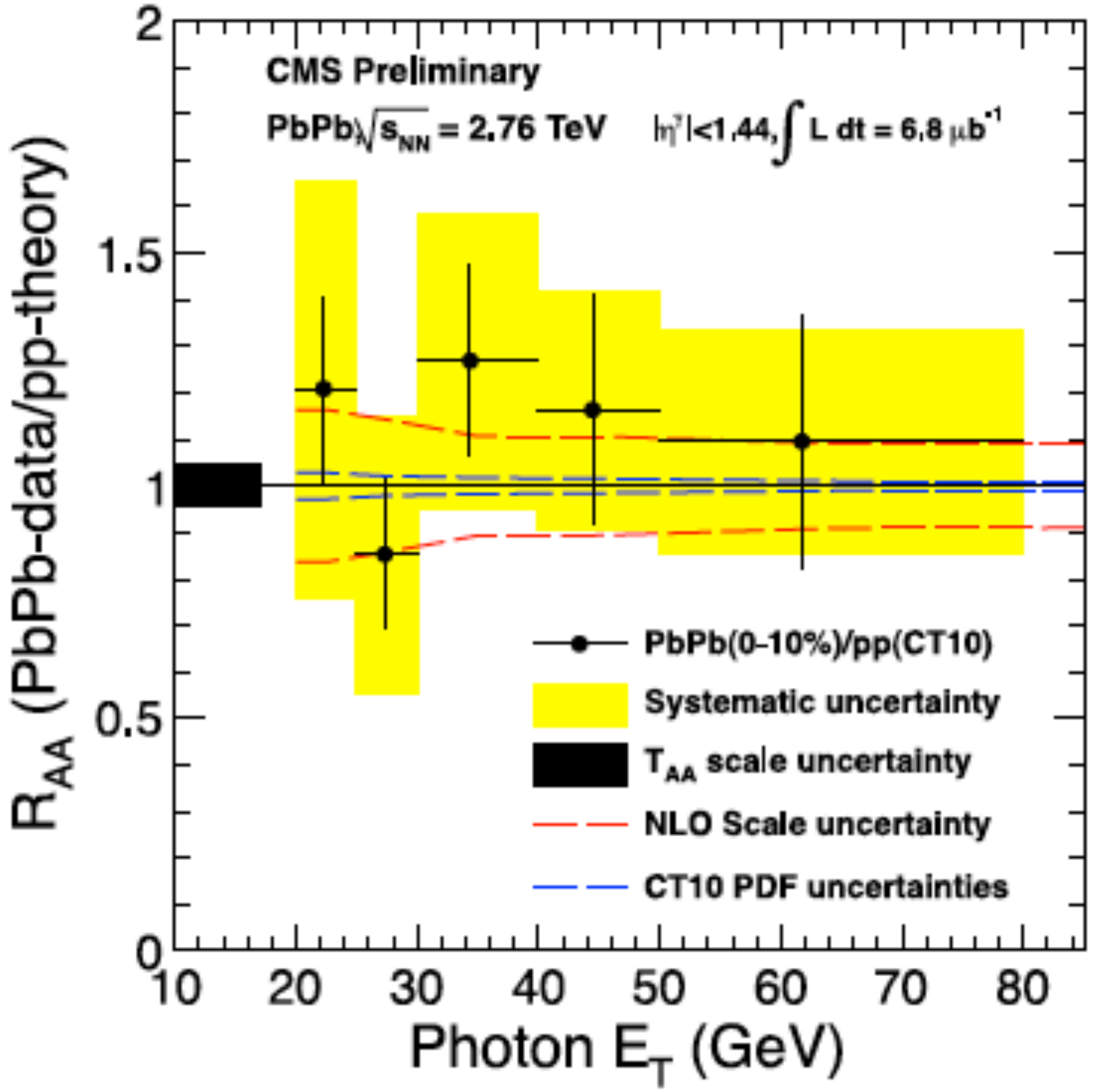
- Isospin effects 'corrected' in pPb: possibility to constrain nPDFs.
- 4000 (1000) Z's expected at $|y_R|=0$ (3).
- Luminosity important for Z+jet (reconstruction, cuts, etc.).

Proton-nucleus theory review: 2. pA as benchmark.

Photons: motivation

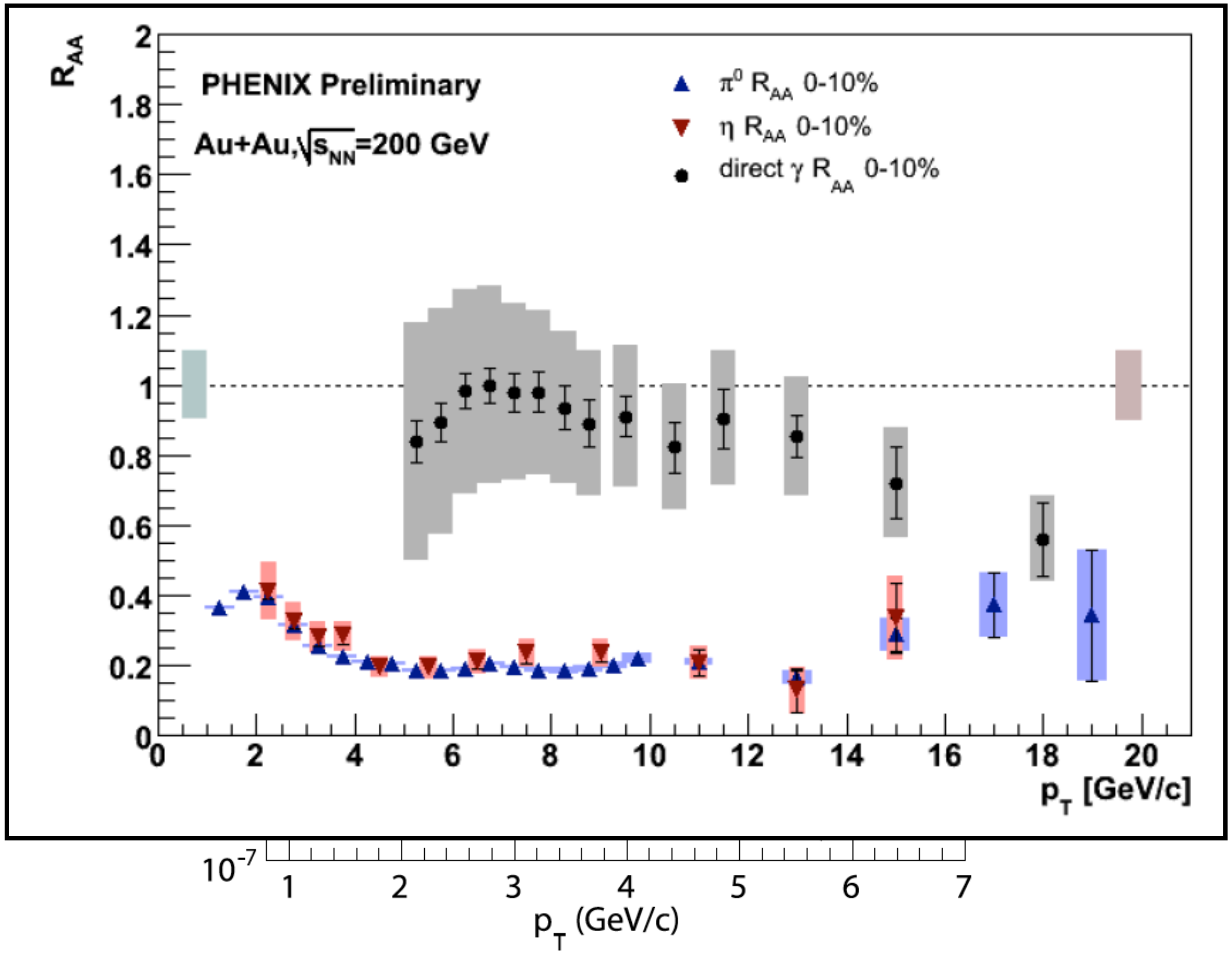
- Photons at low p_T are the smoking gun of a hot medium.
- At large p_T, they are the baseline for hot nuclear matter effects.
- They are affected from nuclear effects: nPDFs, and uncertainties from the fragmentation contribution $q \rightarrow \gamma \Rightarrow pA$ may clarify this.

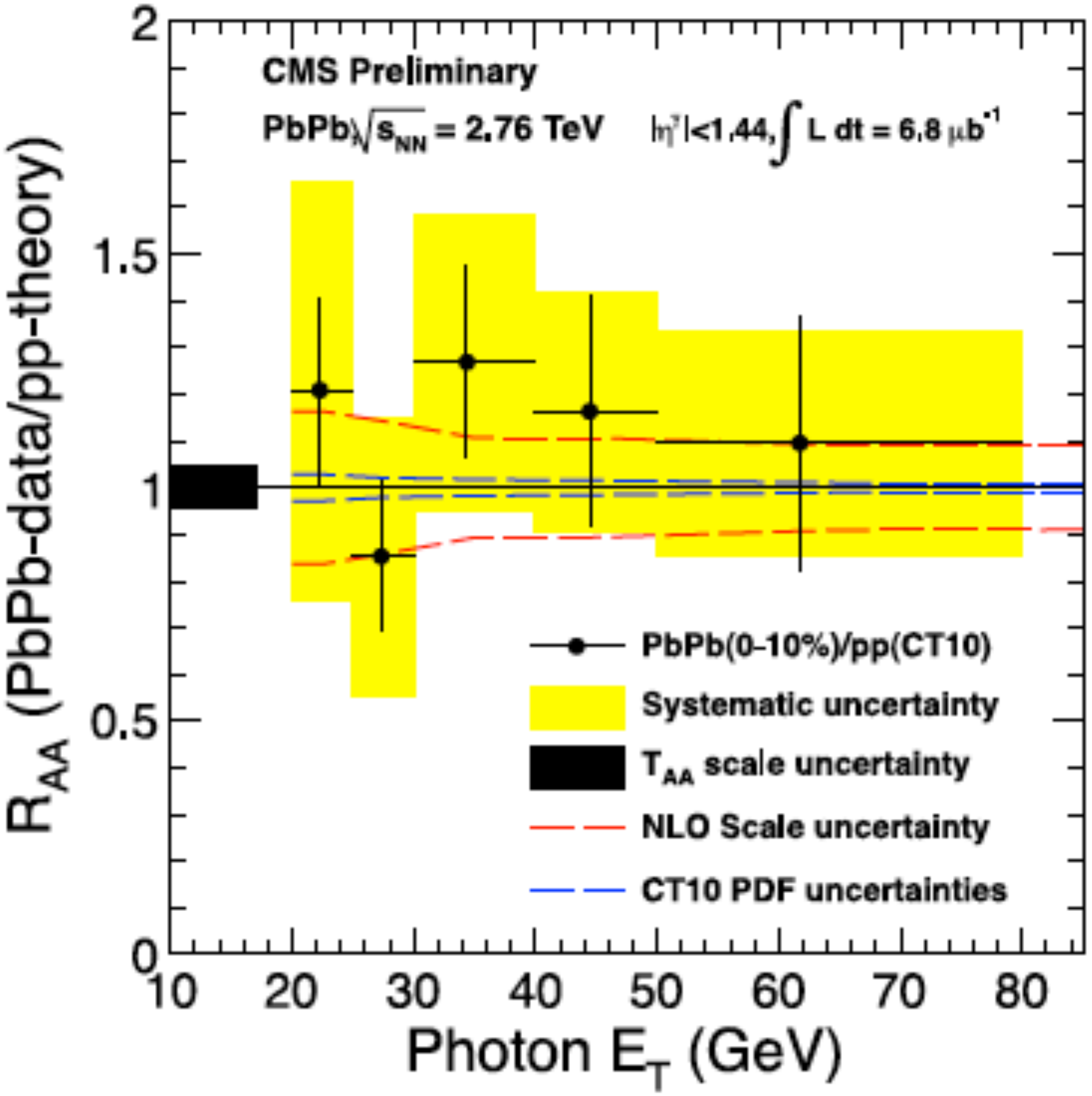




Photons: motivation

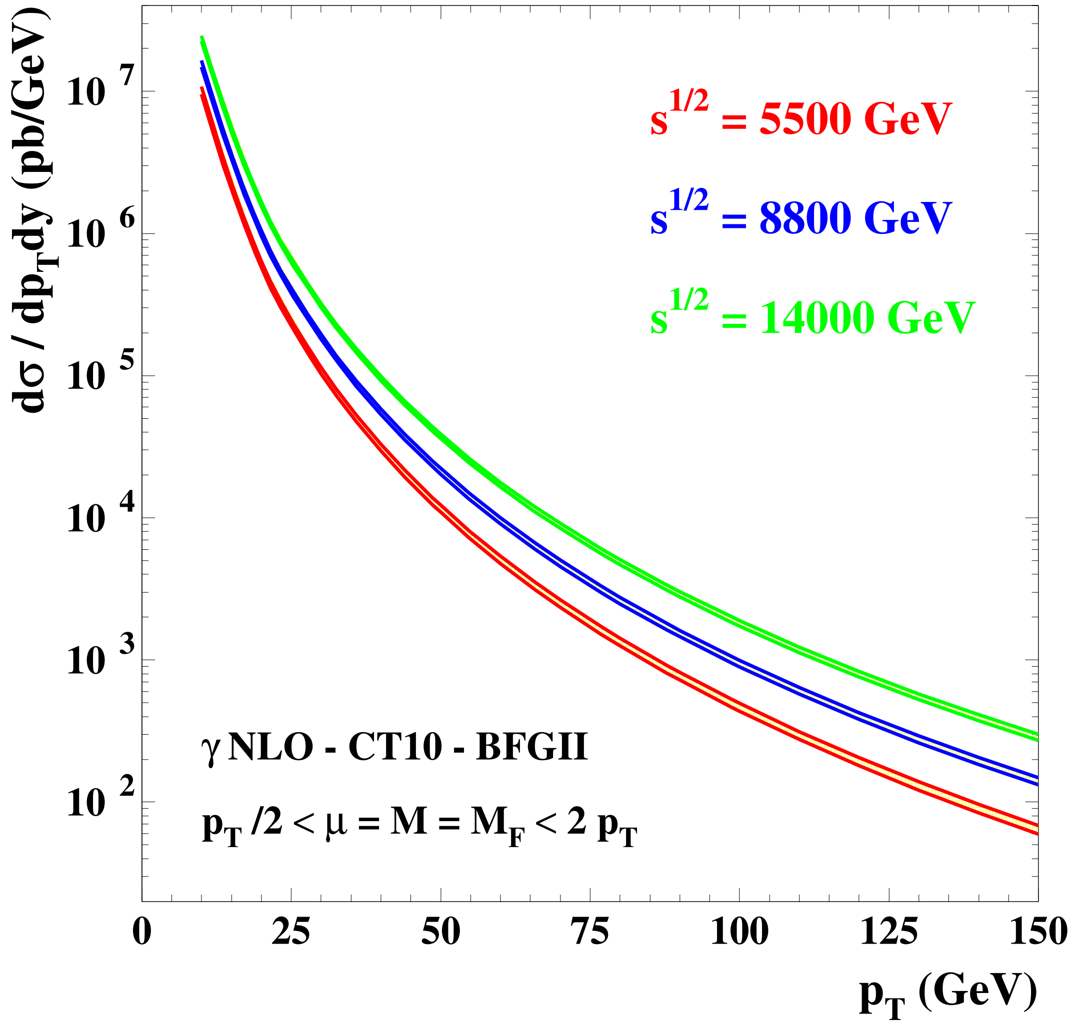
- Photons at low p_T are the smoking gun of a hot medium.
- At large p_T, they are the baseline for hot nuclear matter effects.
- They are affected from nuclear effects: nPDFs, and uncertainties from the fragmentation contribution q→γ ⇒ pA may clarify this.

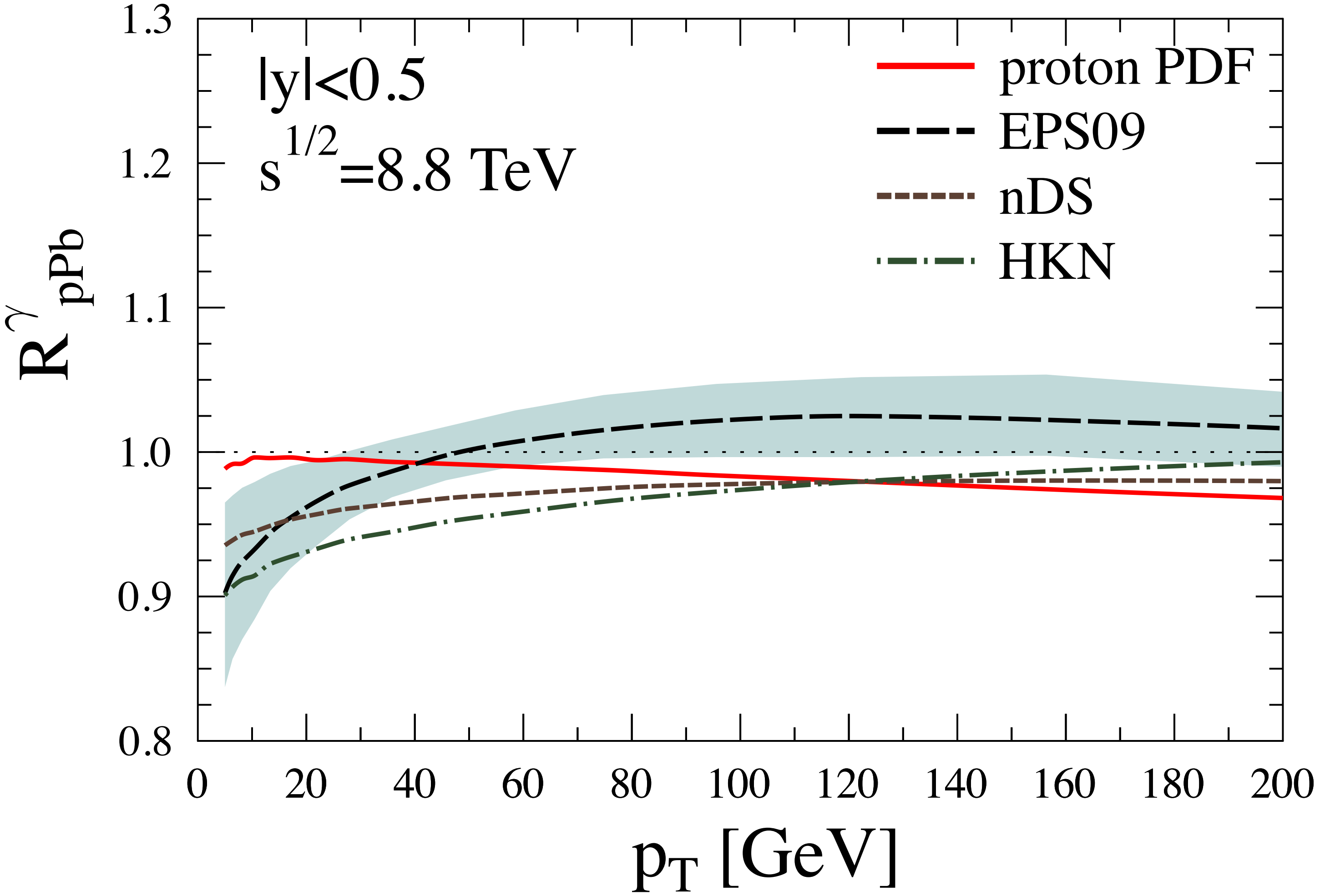




Proton-nucleus theory review: 2. pA as benchmark.

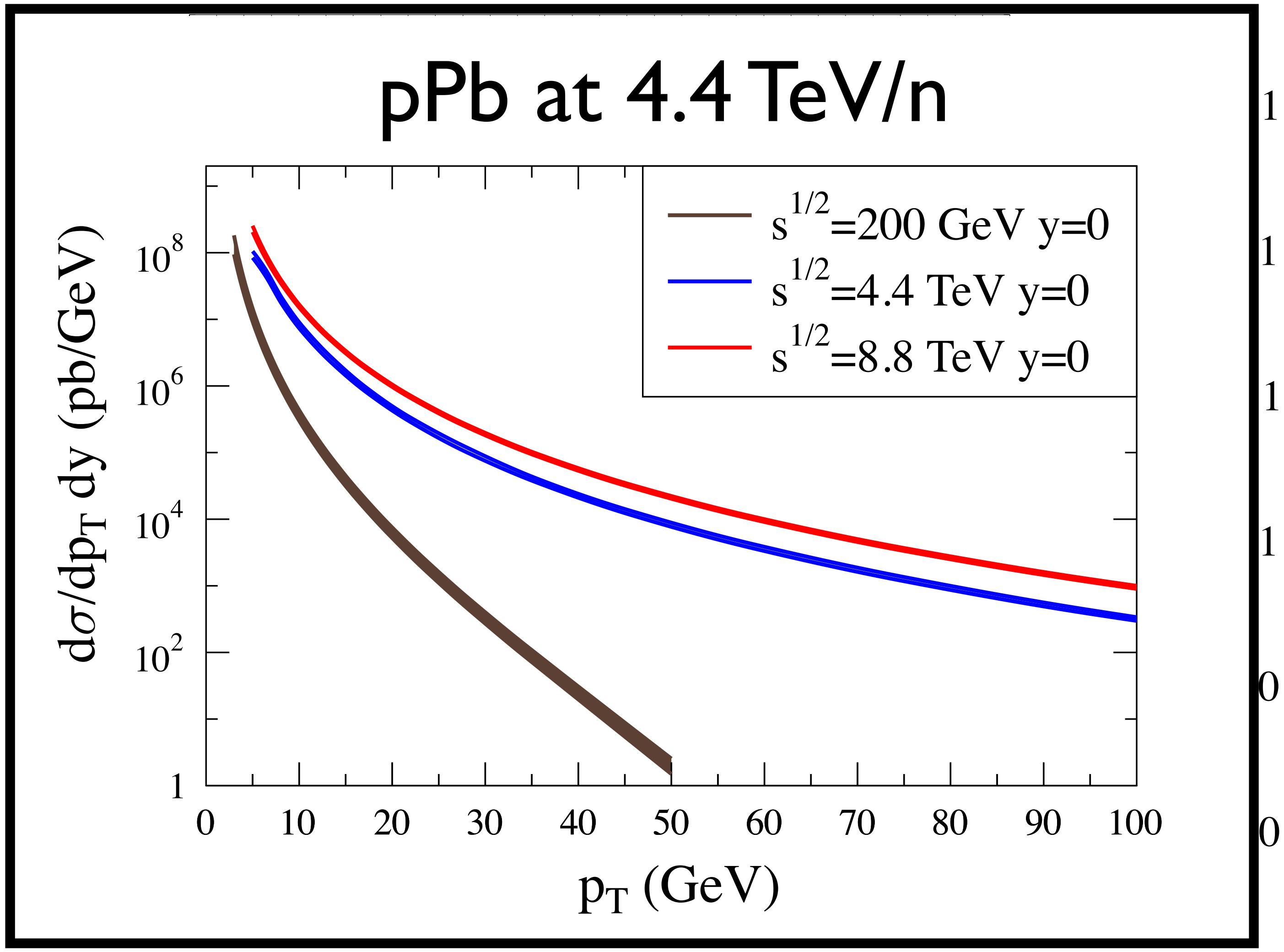
Photons in pPb at 8.8 TeV/n:

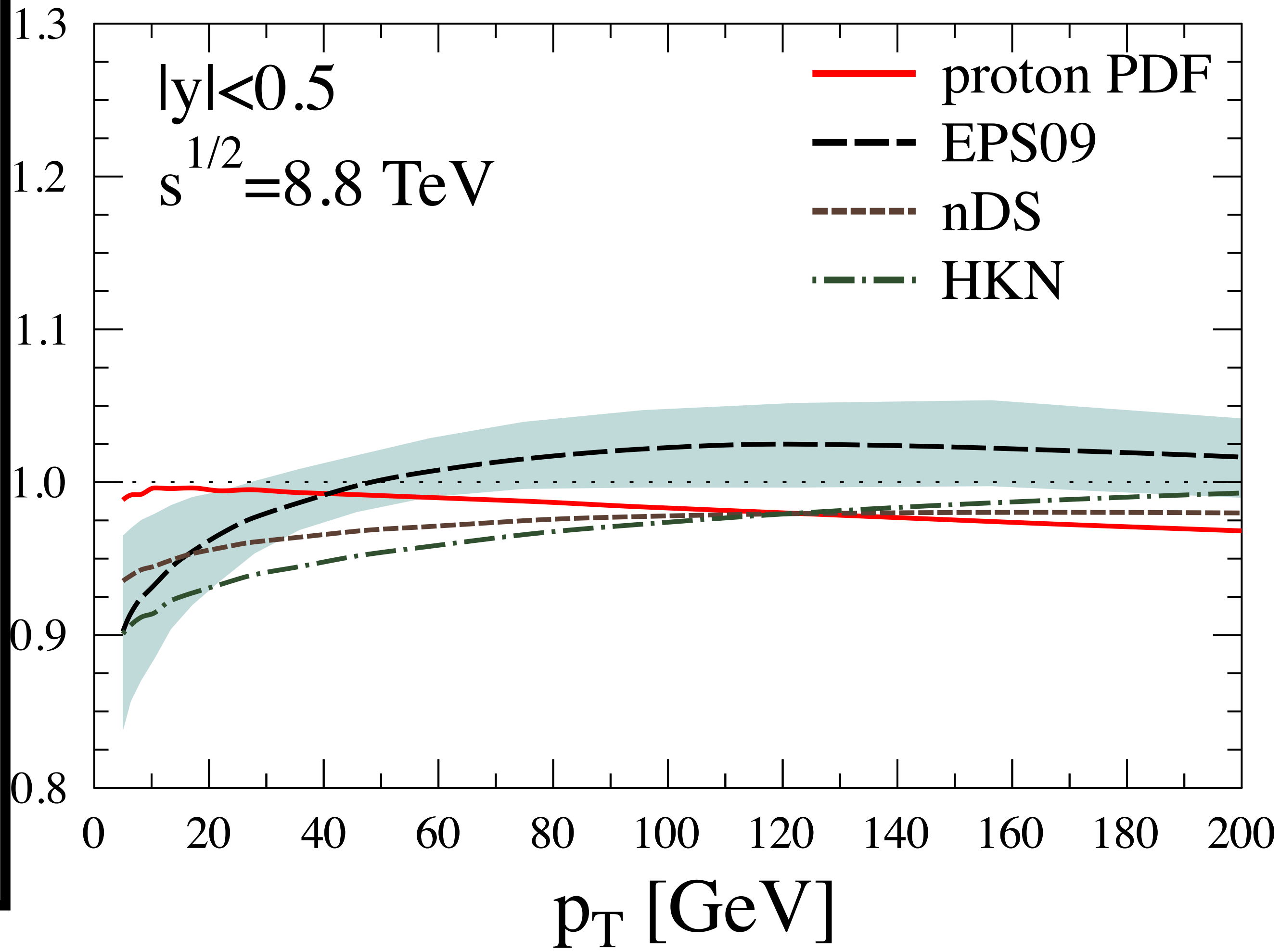




- Abundant yields up to 50 GeV/c for $\int \mathcal{L}dt \sim 0.1$ pb^{-1}.
- Modest ($\mathcal{O}(10\,\%)$) nuclear effects.
- Role of isolation cuts for fragmentation to be determined.

Photons in pPb at 8.8 TeV/n:

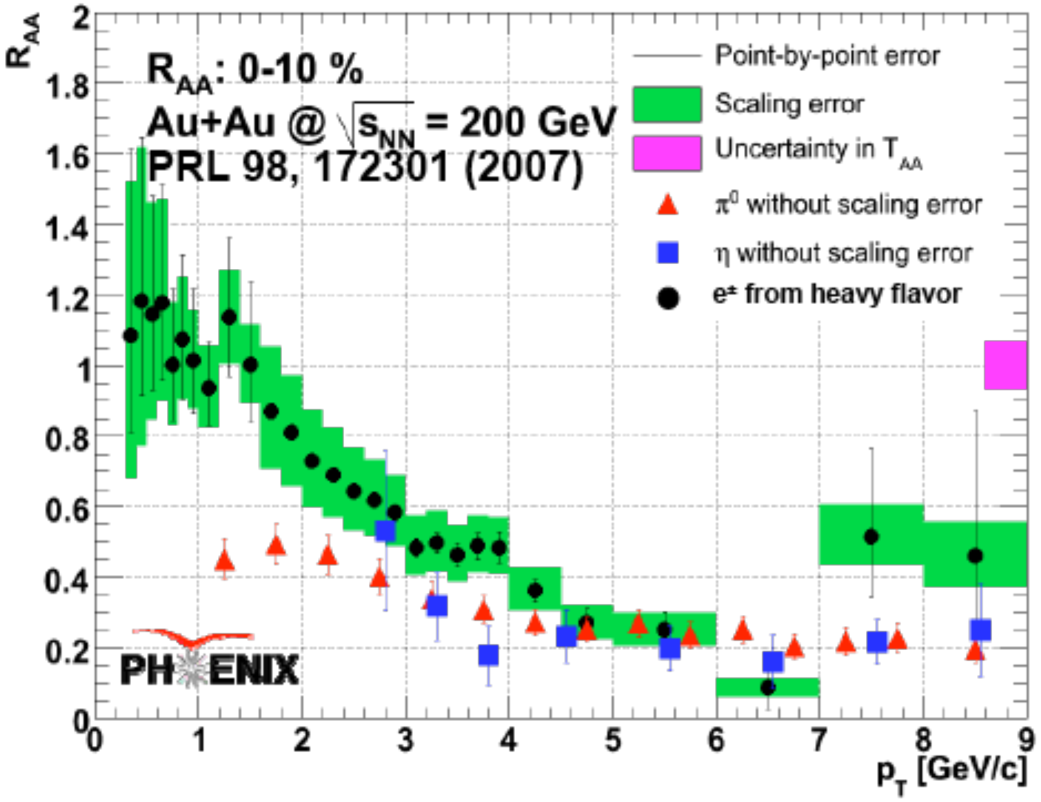

pPb at 4.4 TeV/n

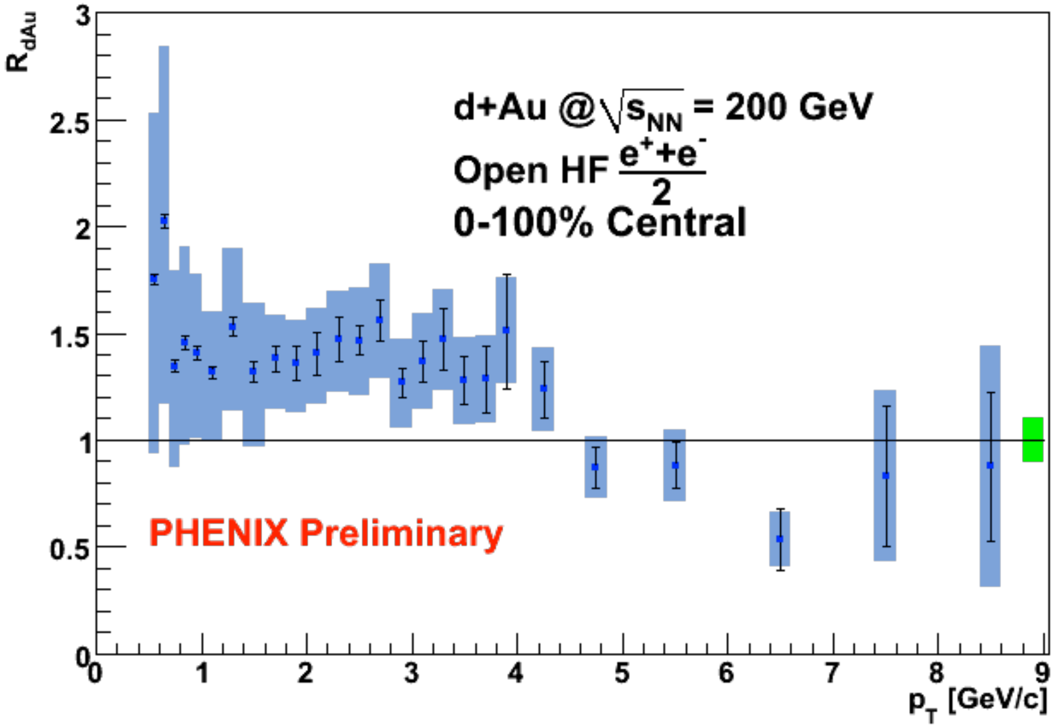


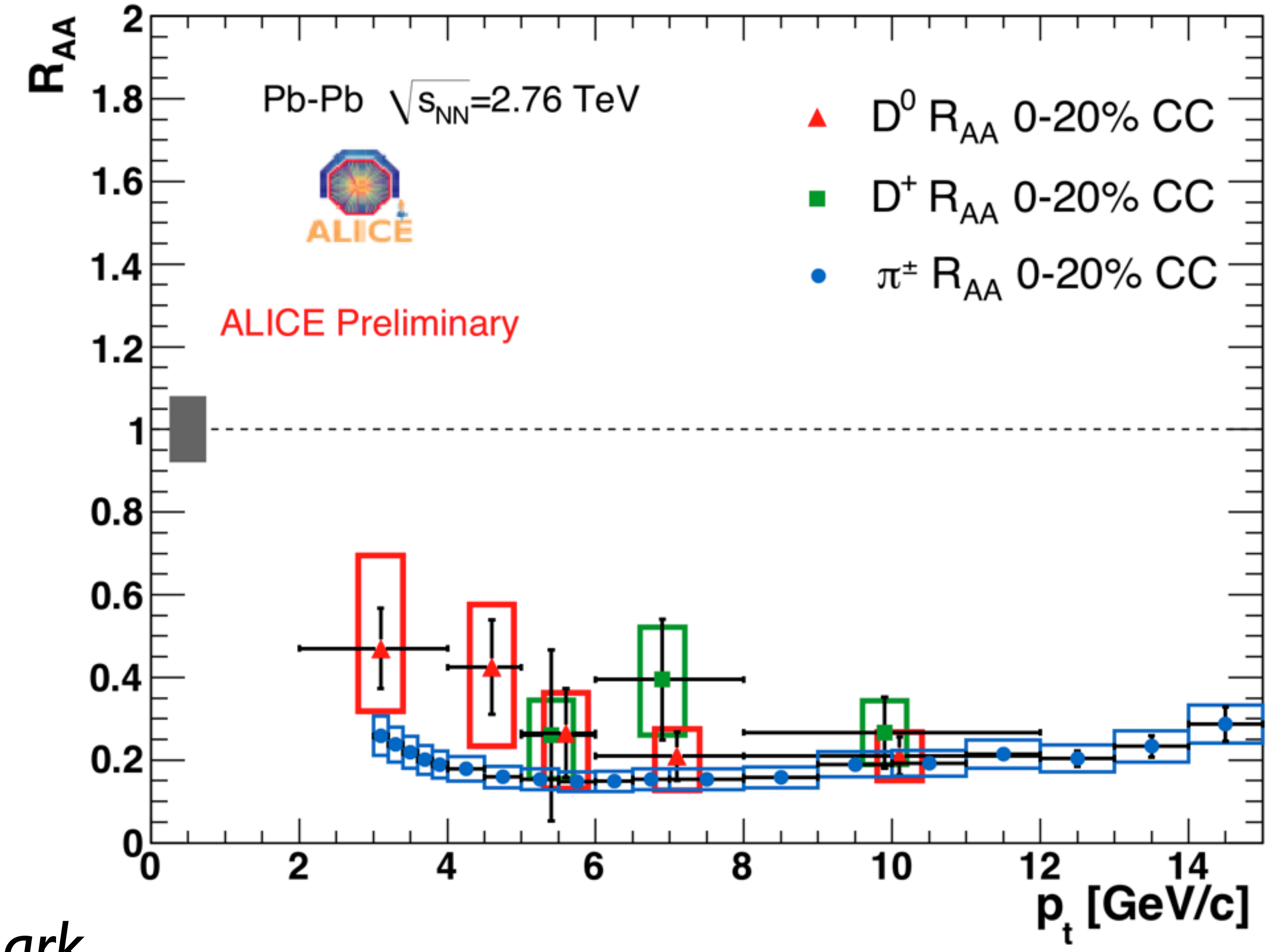
- Abundant yields up to 50 GeV/c for $\int \mathcal{L}dt \sim 0.1$ pb^{-1}.
- Modest ($\mathcal{O}$(10 %)) nuclear effects.
- Role of isolation cuts for fragmentation to be determined.

Open heavy flavor: motivation

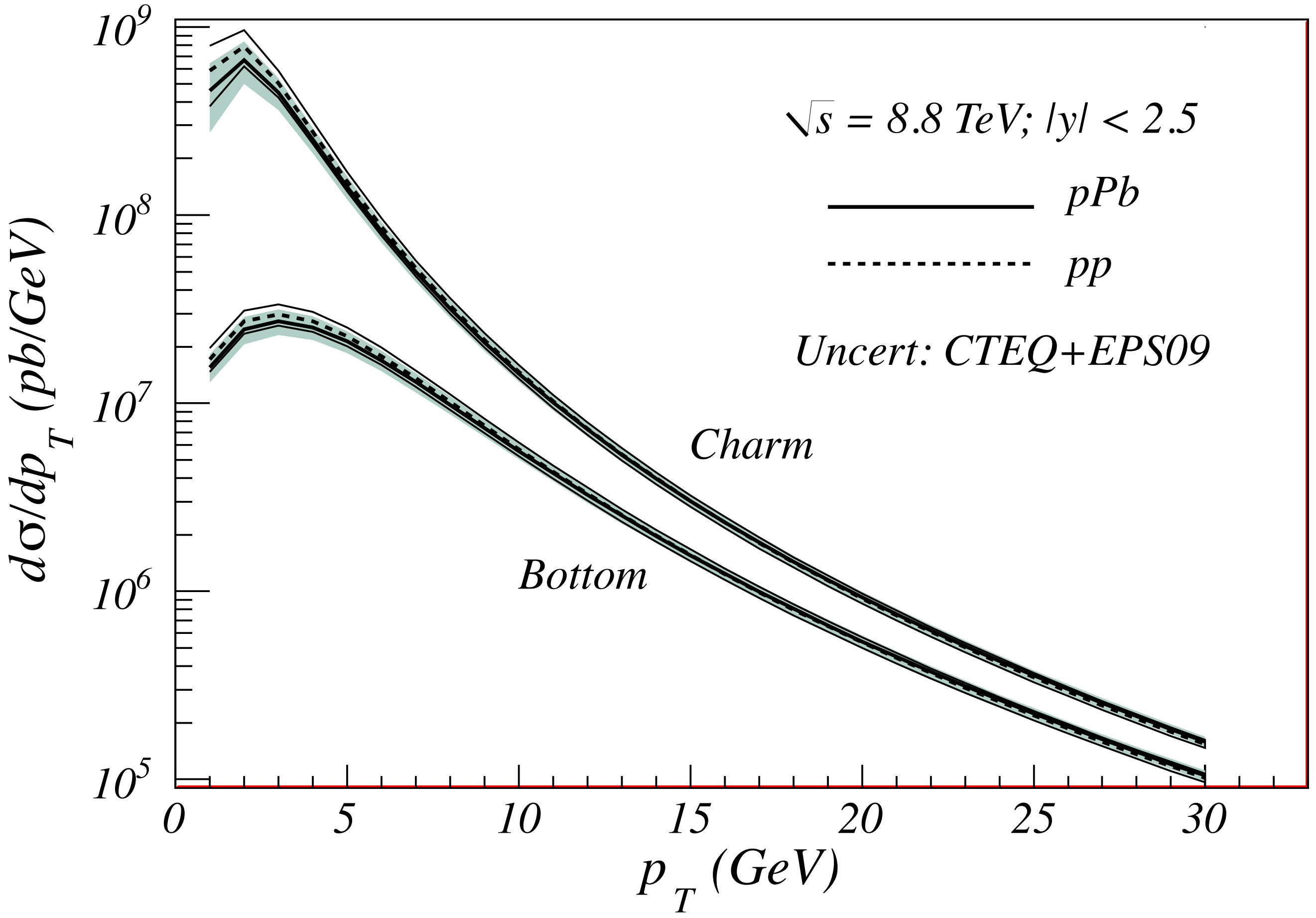
- Nuclear modification of HQ in HIC expected to offer strong constrains on the mechanism of eloss: mass effect.
- RHIC: non-photonic electrons demand theory to determine c/b contributions.
- LHC: direct measurement of HQs.

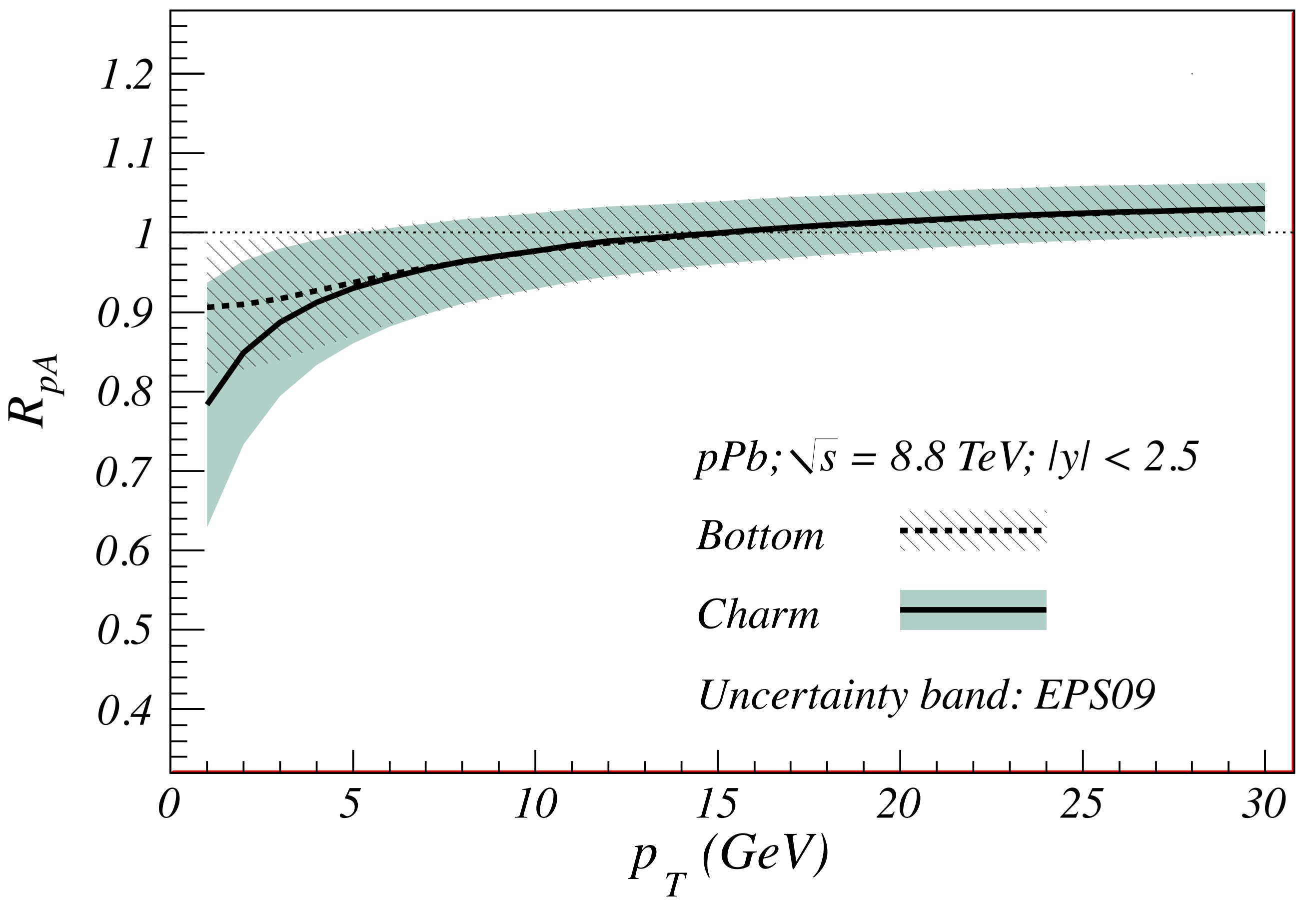






Open HF in pPb at 8.8 TeV/n:



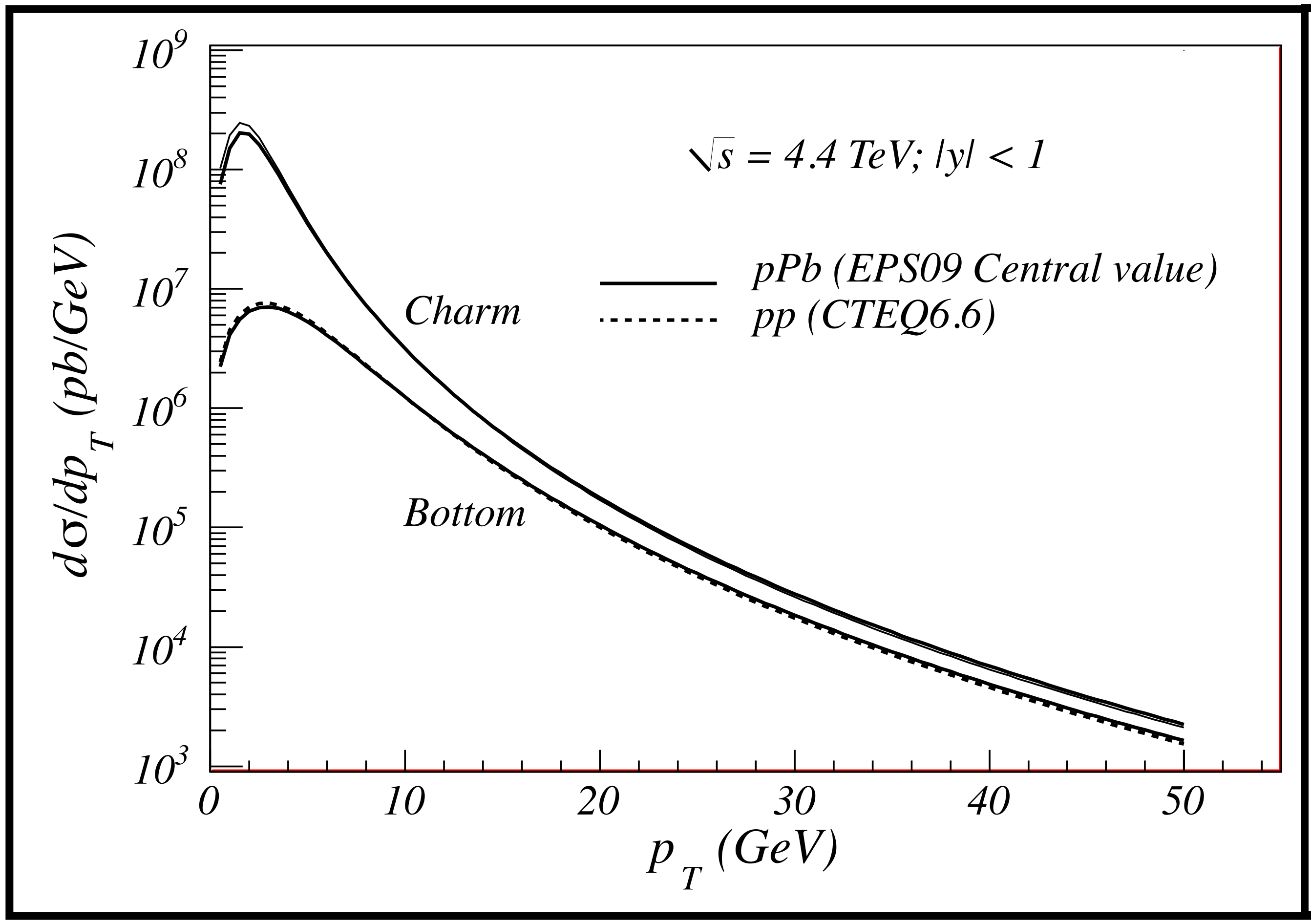


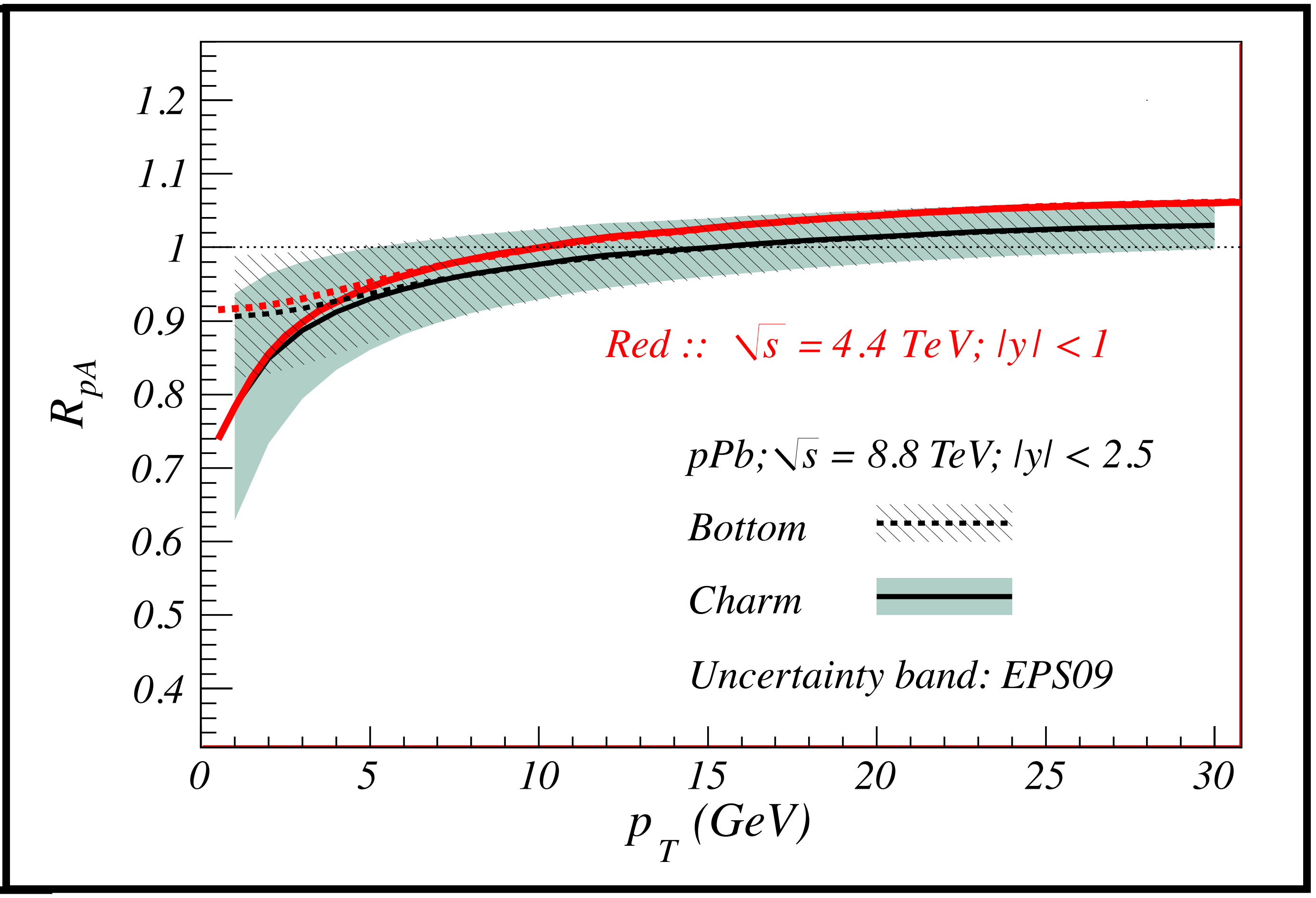
- FONLL (NLO): large yields of mesons up to 30 GeV/c for $\int \mathcal{L}dt \sim 0.1$ pb^{-1}.

- Large nuclear effects for small p_T: pPb required for PbPb.
- Meson reconstruction efficiency to be studied; b-tagged jets.

Open HF in pPb at 8.8 TeV/n:

pPb at 4.4 TeV/n



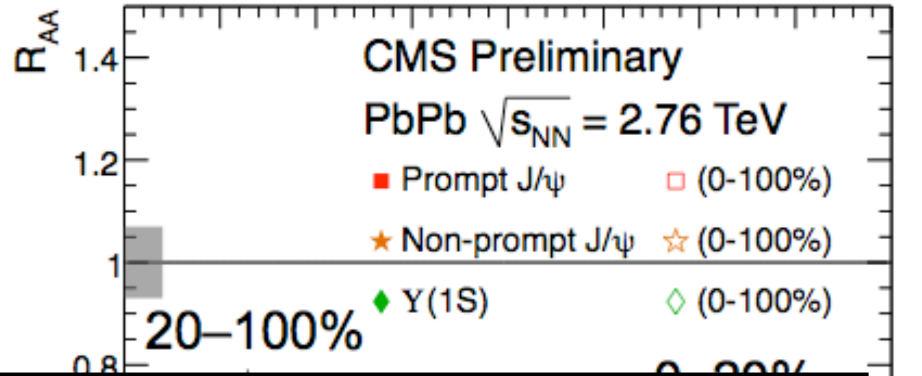


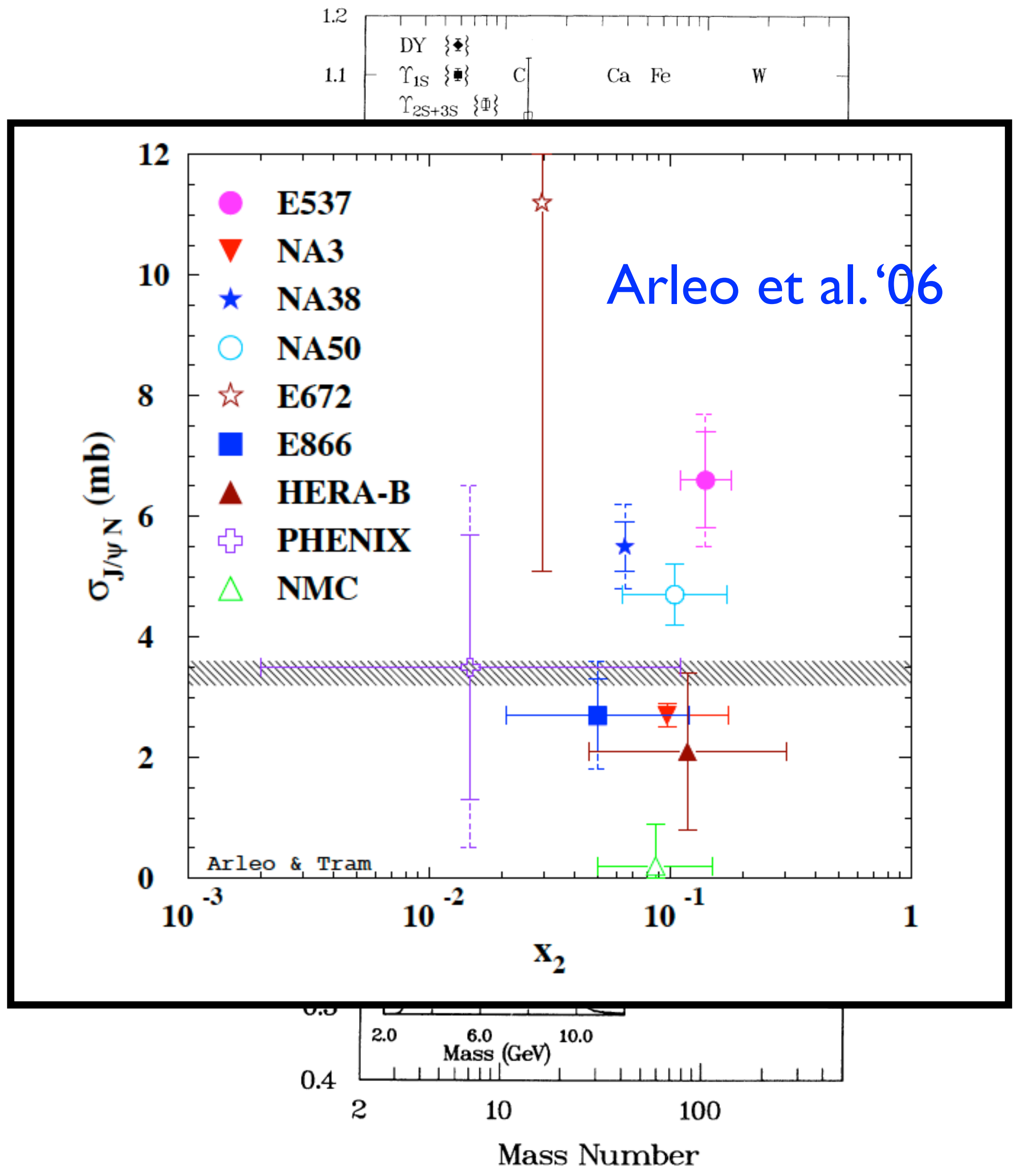
- FONLL (NLO): large yields of mesons up to 30 GeV/c for $\int \mathcal{L}dt \sim 0.1$ pb^{-1}.

- Large nuclear effects for small p_T: pPb required for PbPb.
- Meson reconstruction efficiency to be studied; b-tagged jets.

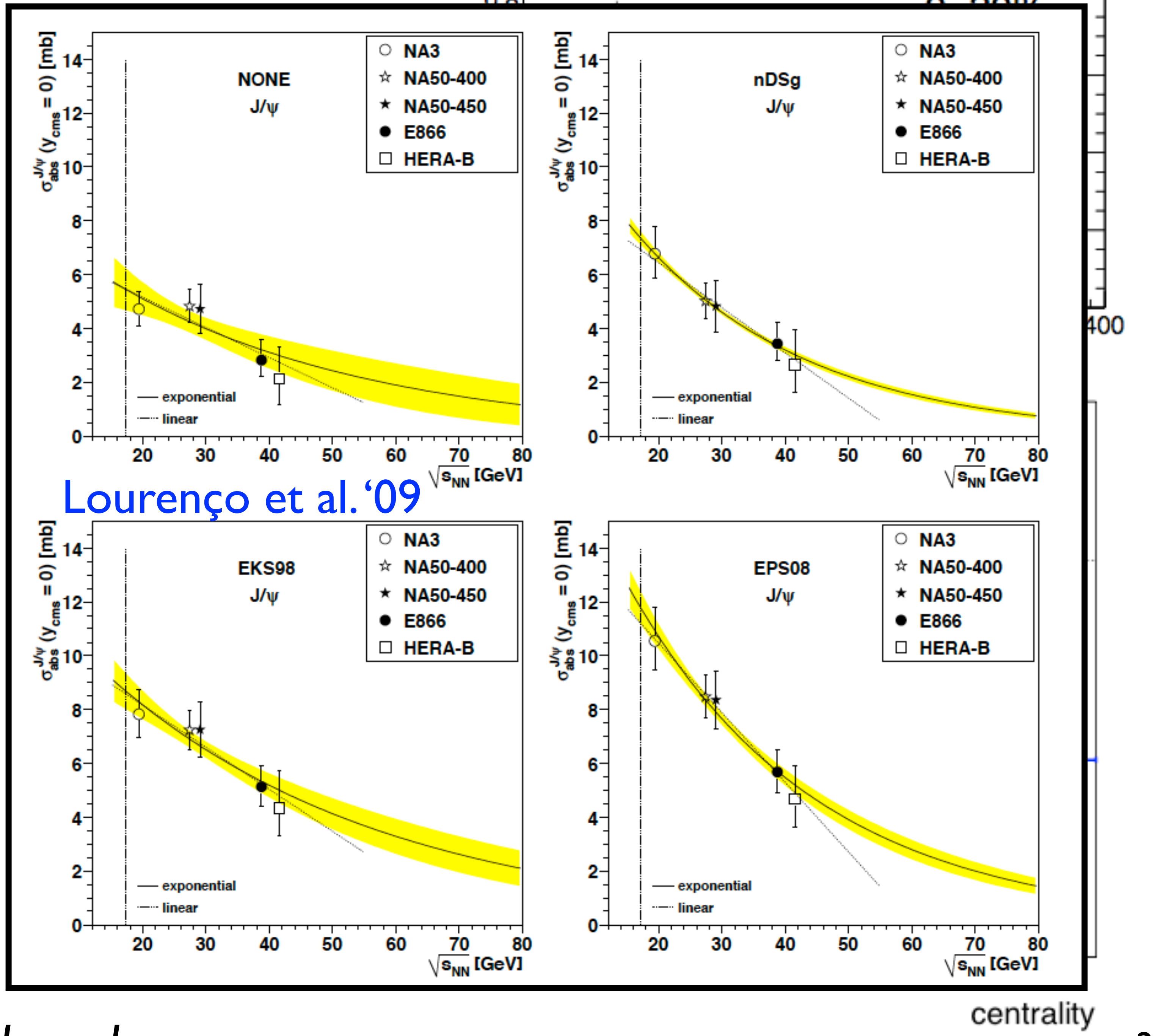
Quarkonium: motivation

- Cold nuclear matter effects on QQbar crucial: little theoretical control on energy dependence and (mass, p_T, x_F) behavior of absorption, large effect of nPDFs.





Arleo et al.'06



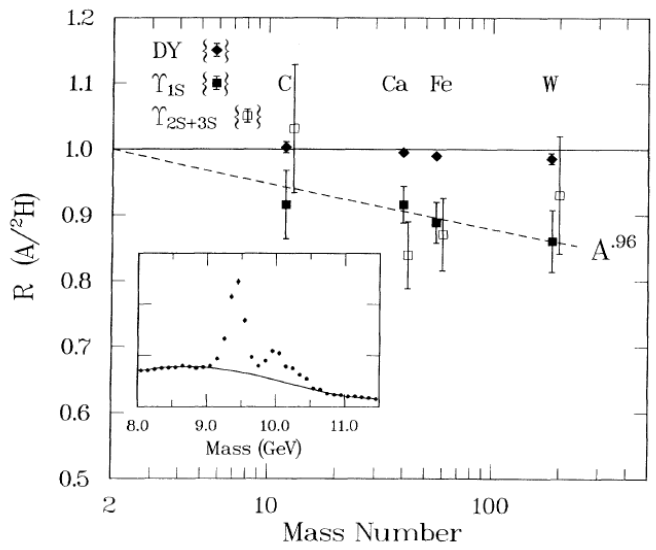
Lourenço et al.'09

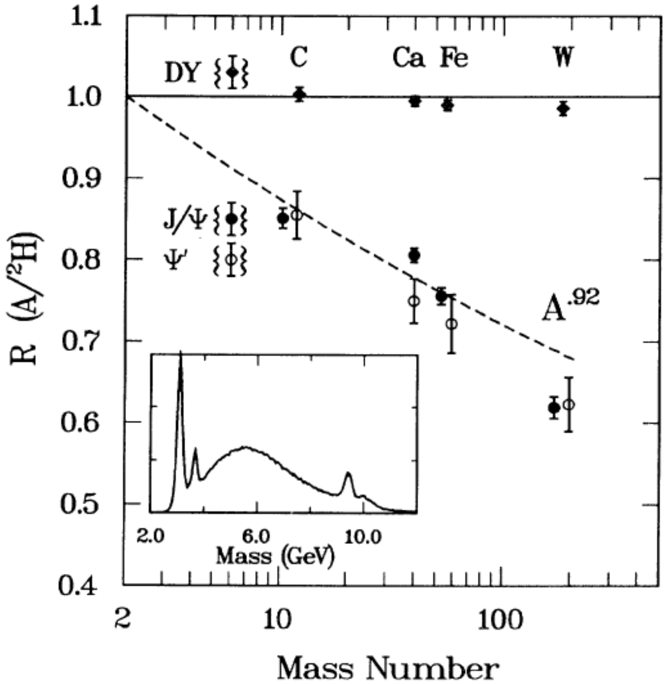
Proton-nucleus theory review: 2. pA as benchmark.

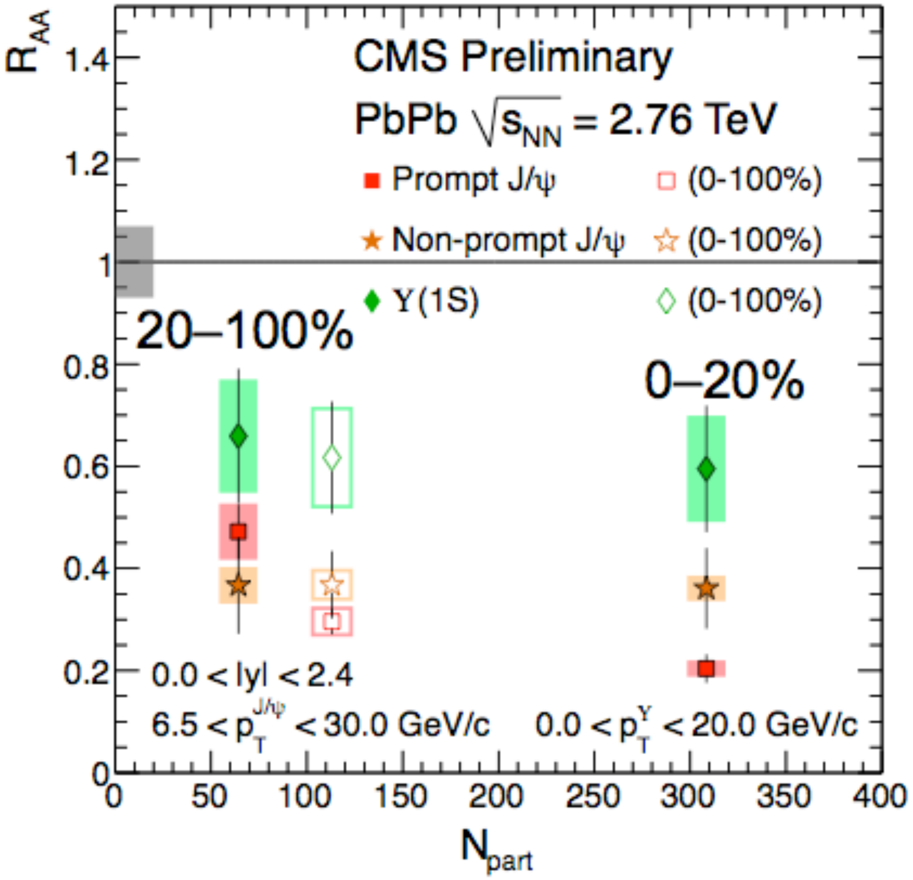
Quarkonium: motivation

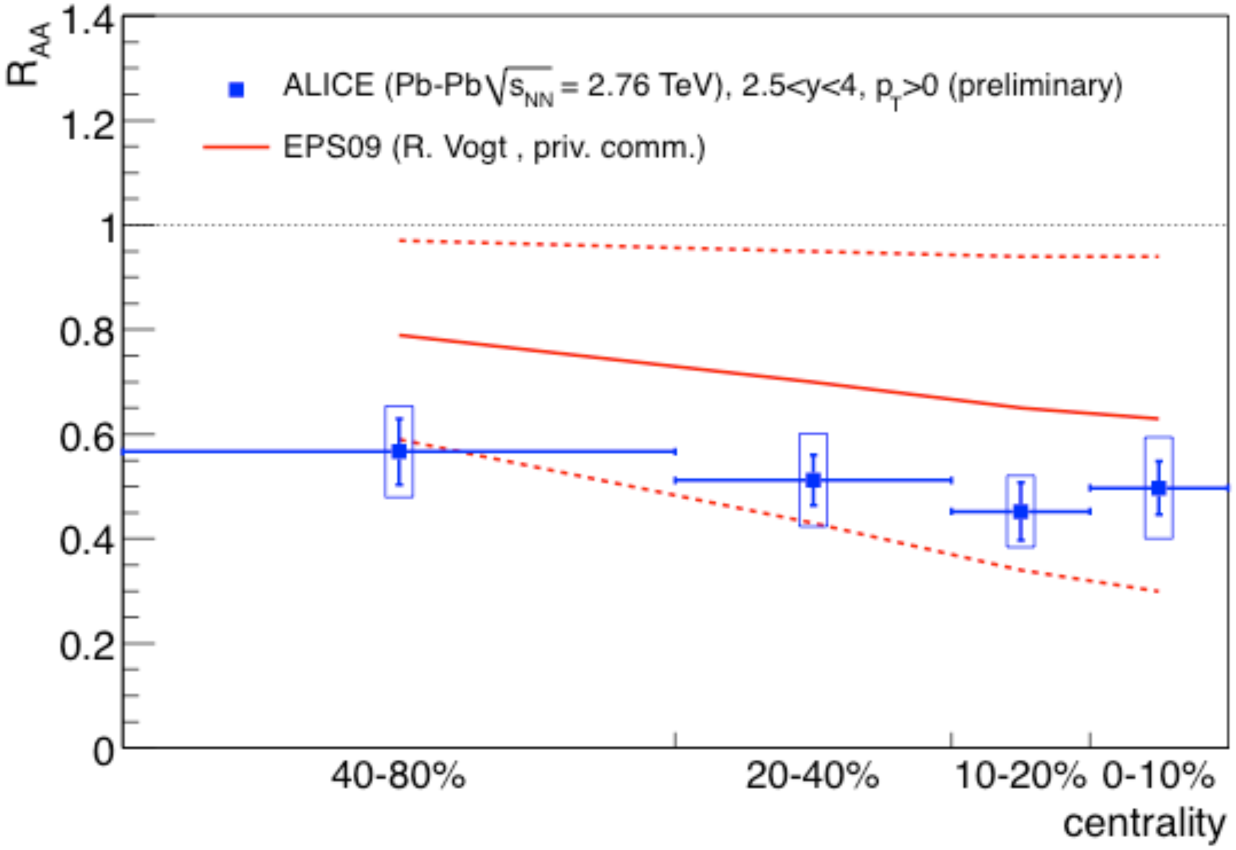
- Cold nuclear matter effects on QQbar crucial: little theoretical control on energy dependence and (mass, p_T, x_F) behavior of absorption, large effect of nPDFs.

E772, 1991

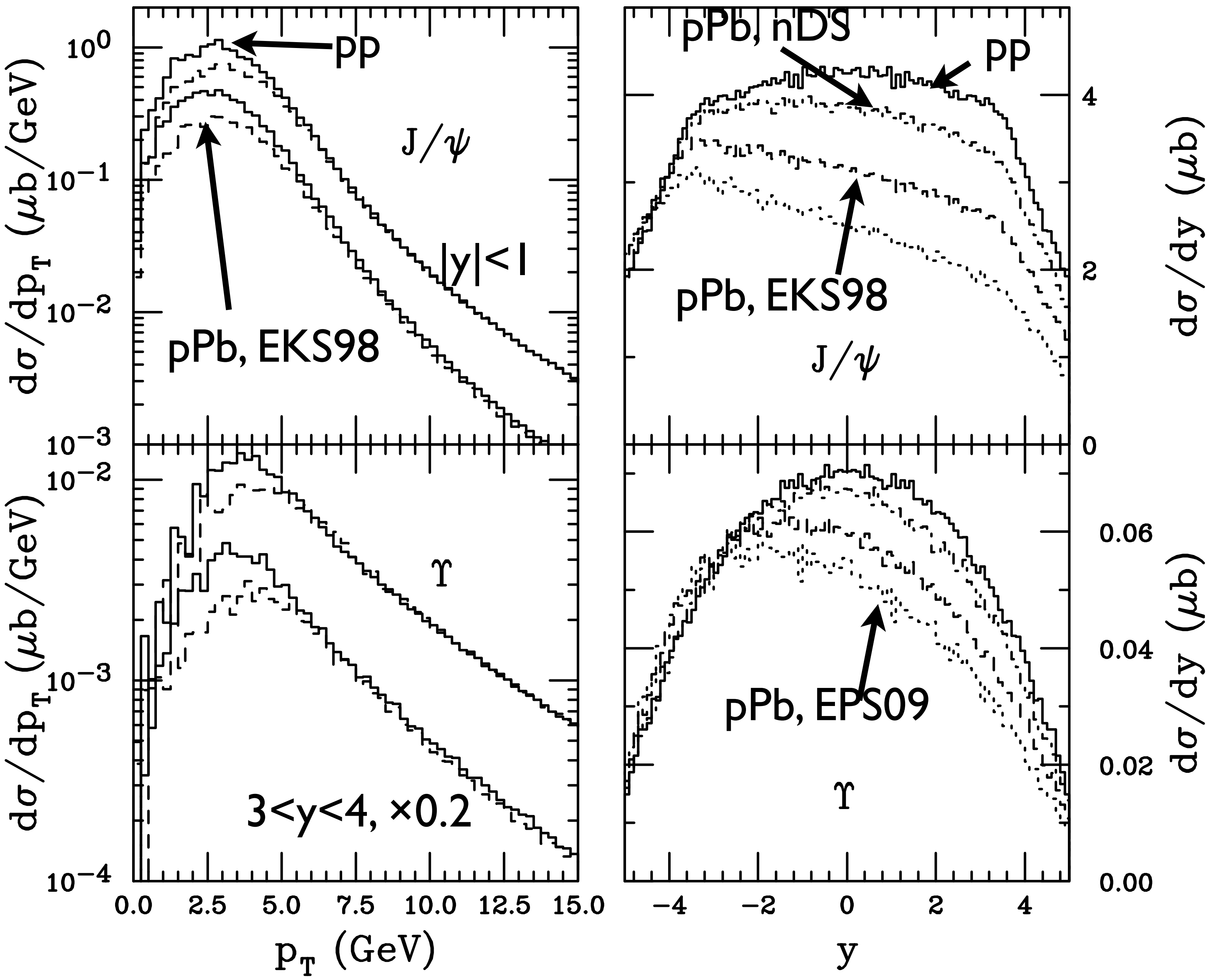








Quarkonium in pPb at 8.8 TeV/n:



- CEM: large yields of QQbar for $\int \mathcal{L}dt \sim 0.1$ pb^{-1}.
- Large nuclear effects for small p_T: pPb required for PbPb.
- Larger luminosity would extend the reach in p_T for ϒ.

Contents:

1. Introduction.

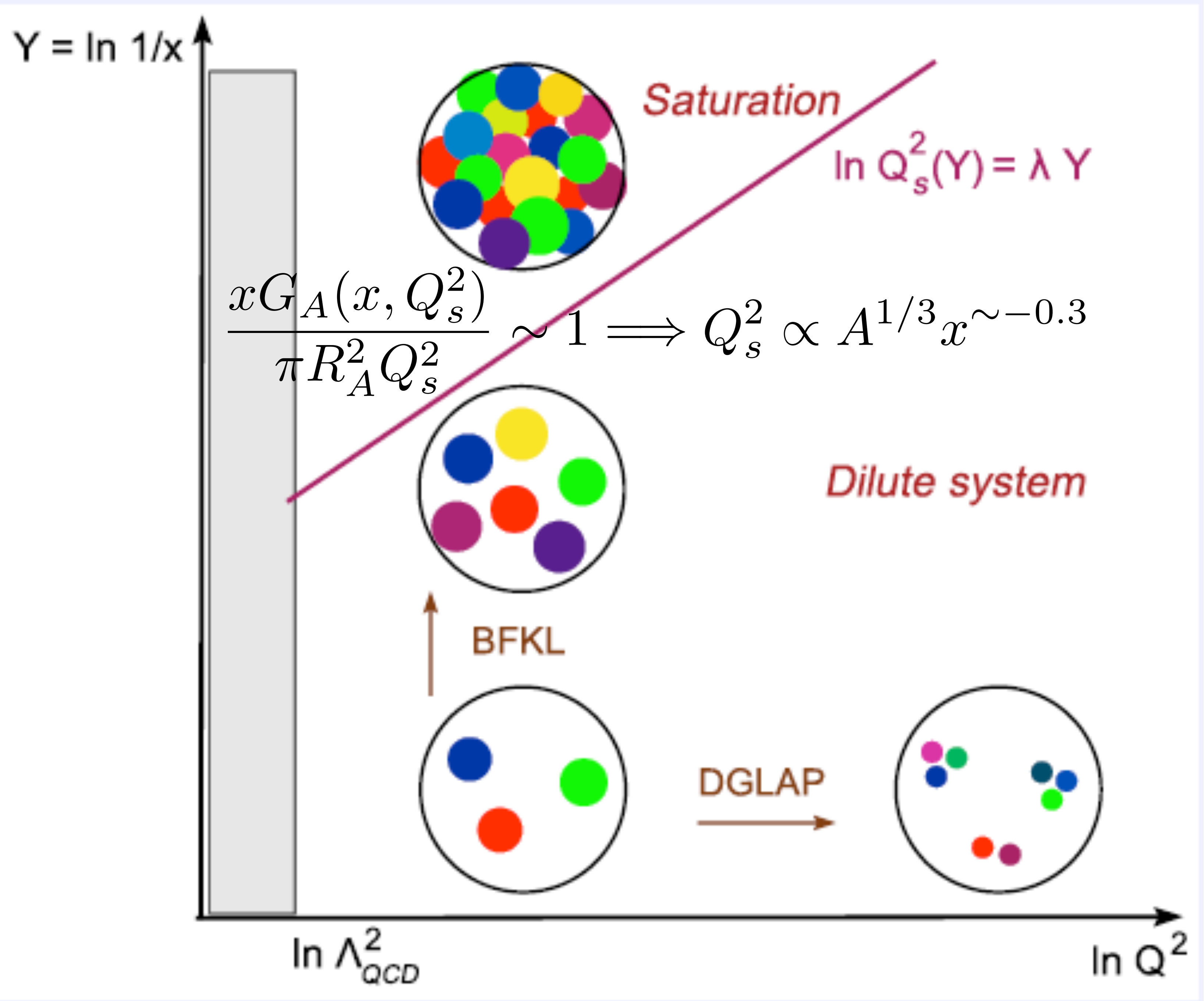
2. pA as benchmark:
    - 2.1 Nuclear PDFs. (Kari Eskola)
    - 2.2 Processes for benchmarking:
        - ➜ Jets. (Guilherme Milhano)
        - ➜ EW bosons. (Carlos Salgado)
        - ➜ Photons. (“)
        - ➜ Open heavy flavor. (“)
        - ➜ Quarkonium. (Andry Rakotozafindrabe)

3. Small-x physics. (Cyrille Marquet and Javier Albacete)

4. Others:
    - 4.1 UPCs: (David d’Enterria)
        - ➜ γp/A.
        - ➜ γγ.
    - 4.2 Implications for Astroparticles.

5. Summary.

The ‘QCD phase’ diagram:



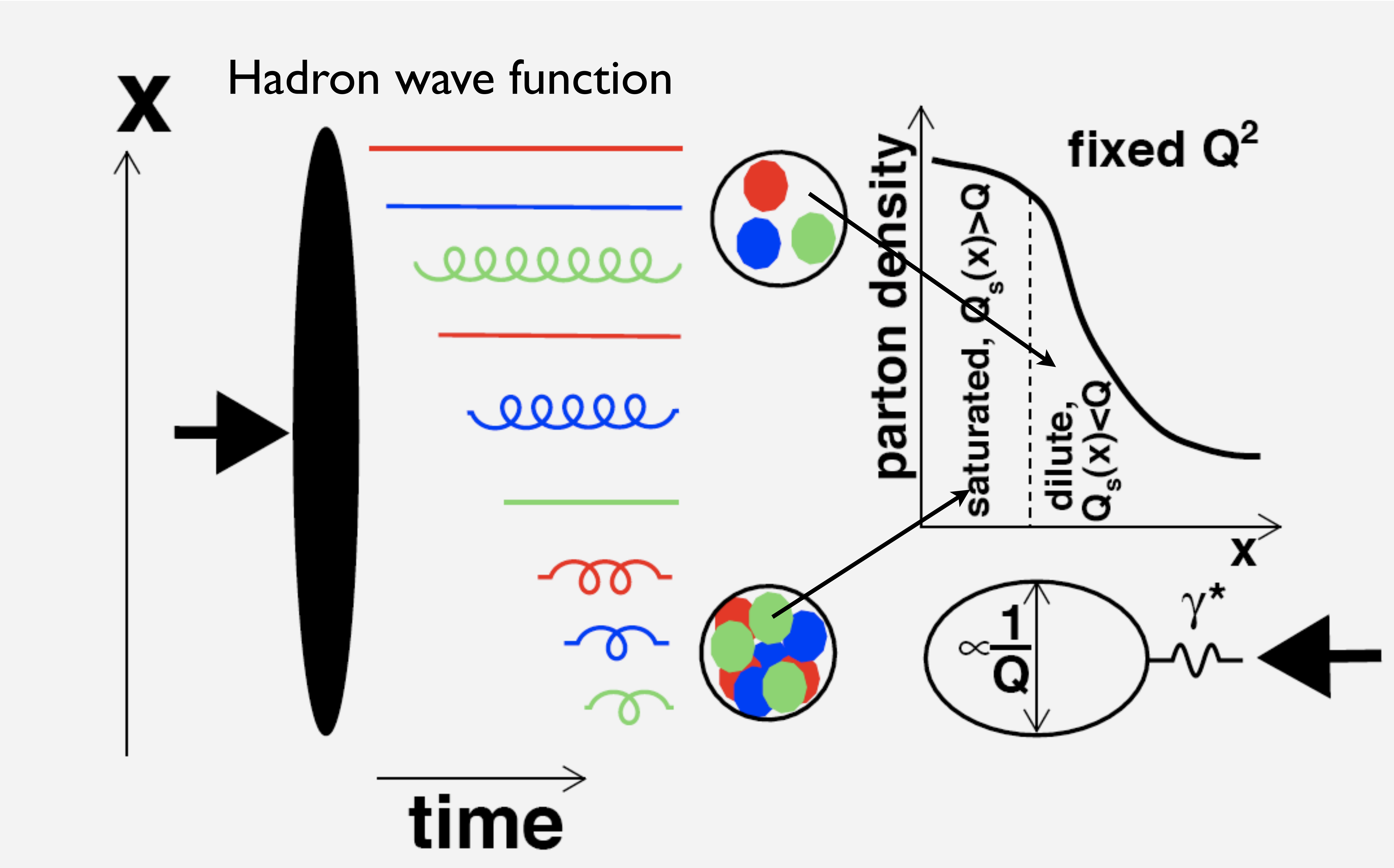
$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

Origin in the early 80’s: GLR, Mueller et al, McLerran-Venugopalan.

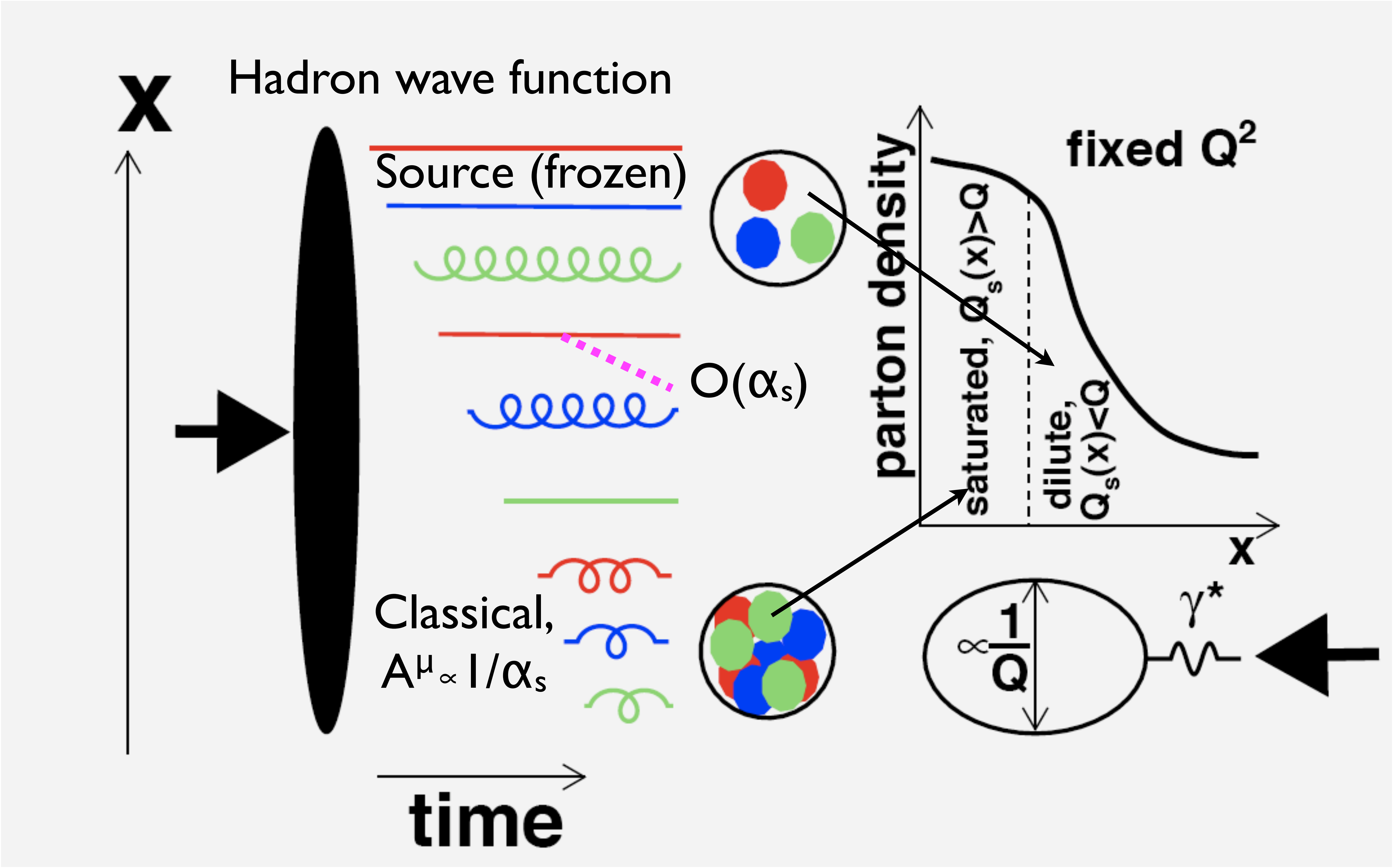
Our aims: understanding

- The implications of unitarity in a QFT.
- The behavior of QCD at large energies.
- The hadron wave function at small x.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

Saturation ideas: CGC



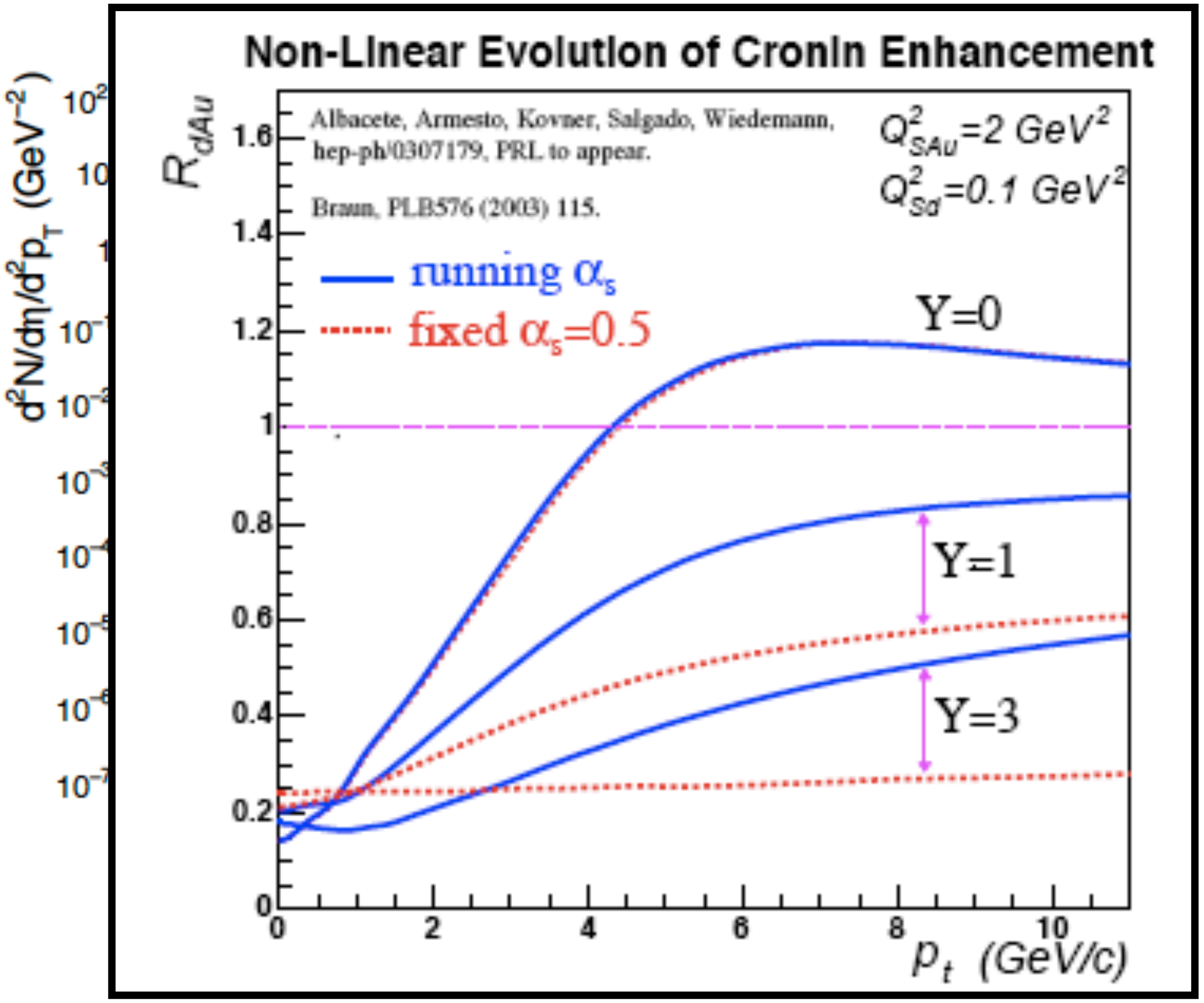
Saturation ideas: CGC

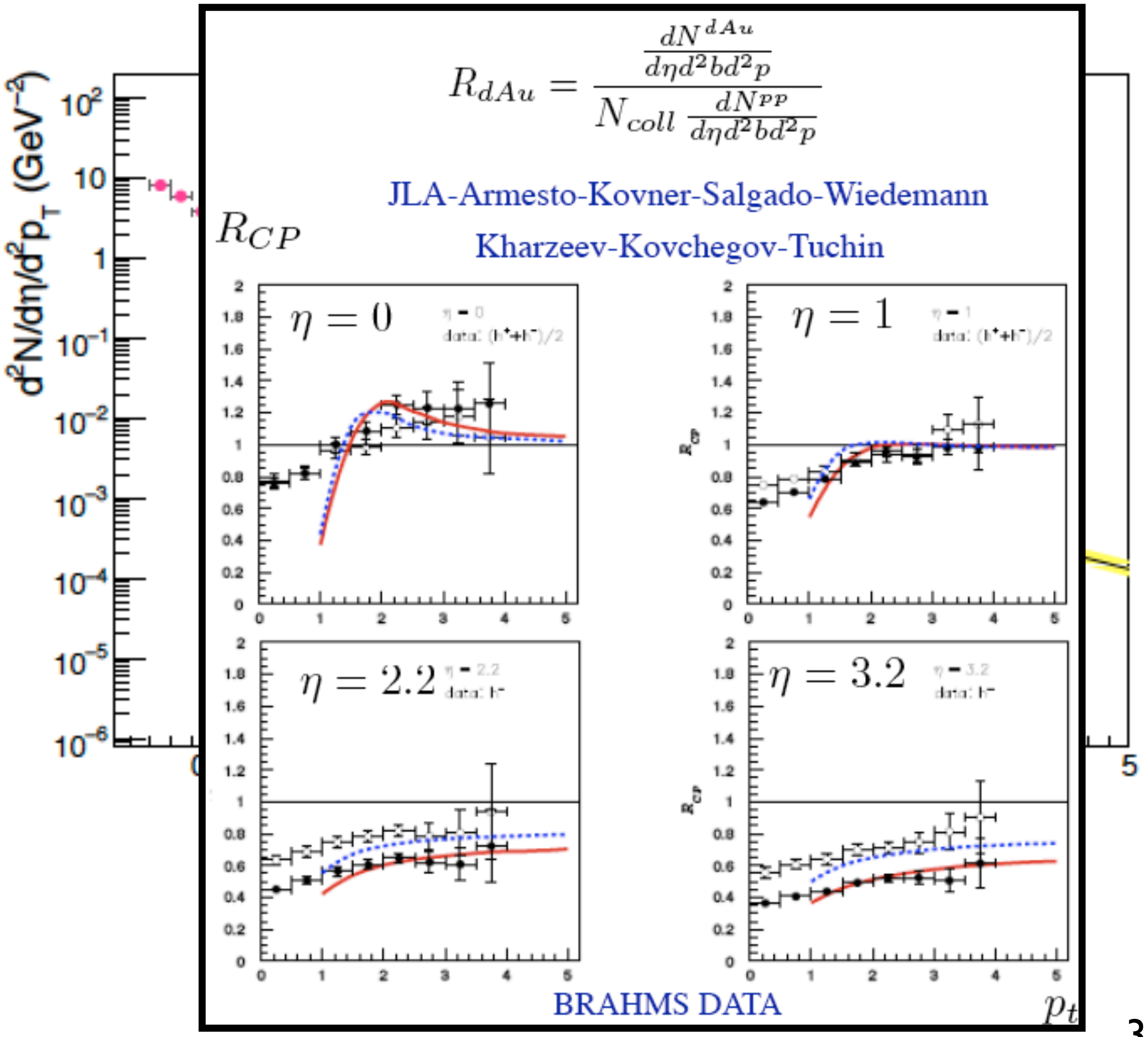


Proton-nucleus theory review: 3. Small-x physics.

Features in dAu@RHIC:

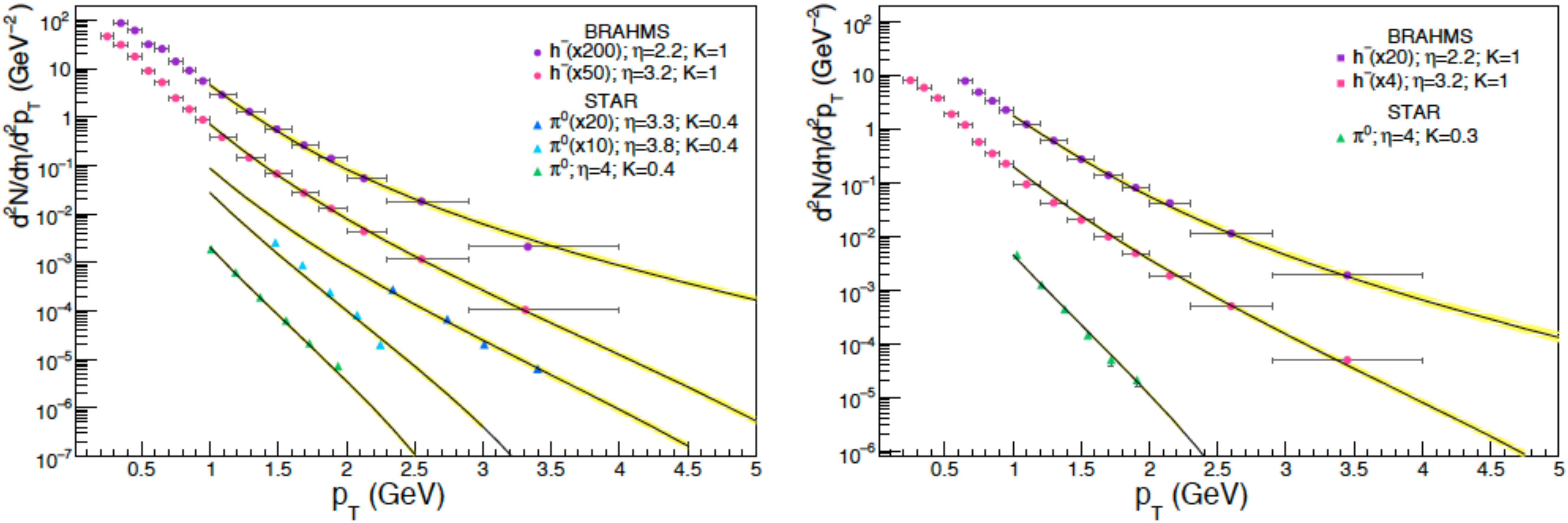
- Control experiment for initial state effects in AA: Cronin in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities predicted by small-x evolution.
- Azymuthal decorrelation in the forward region also seen.





Features in dAu@RHIC:

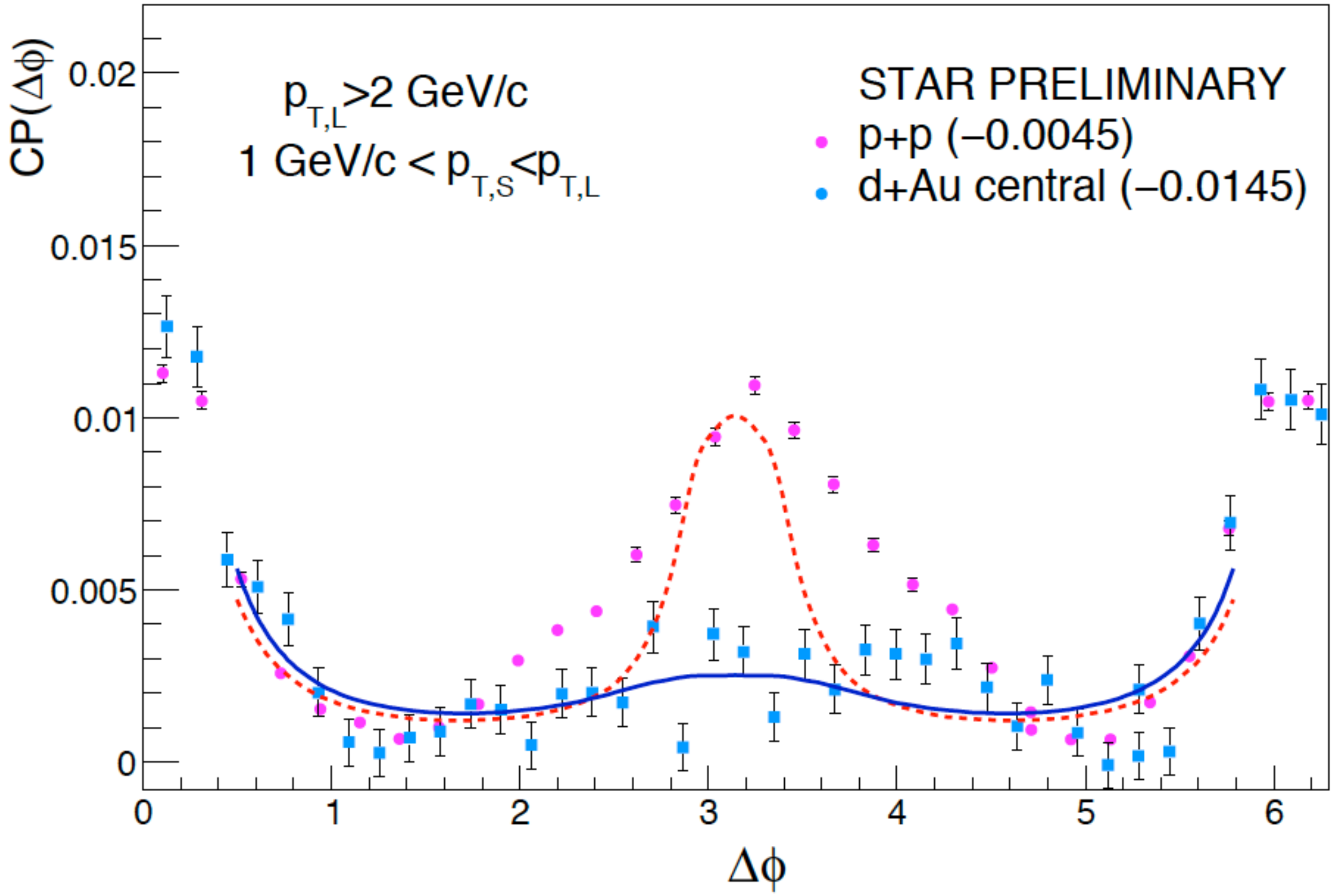
- Control experiment for initial state effects in AA: Cronin in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities predicted by small-x evolution.
- Azymuthal decorrelation in the forward region also seen.



Albacete-Marquet '10

Features in dAu@RHIC:

- Control experiment for initial state effects in AA: Cronin in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities predicted by small-x evolution.
- Azymuthal decorrelation in the forward region also seen.



Albacete-Marquet '10

$$N_{pair}(\Delta\phi) = \int_{y_i,|p_{i\perp}|} \frac{dN^{dAu\to h_1h_2X}}{d^3p_1 d^3p_2} \Big/ N_{trig} = \int_{y,\ p_\perp} \frac{dN^{dAu\to hX}}{d^3p}$$

Features in dAu@RHIC:

- Control experiment for initial state effects in AA: Cronin in dAu

at m

the

- Su n.
- A

- Saturation physics describes these data, but:

  ➜ The normalization is not determined by the calculation ↔ problems to compute the b-dependence.

  ➜ A full NLO analysis is still missing.

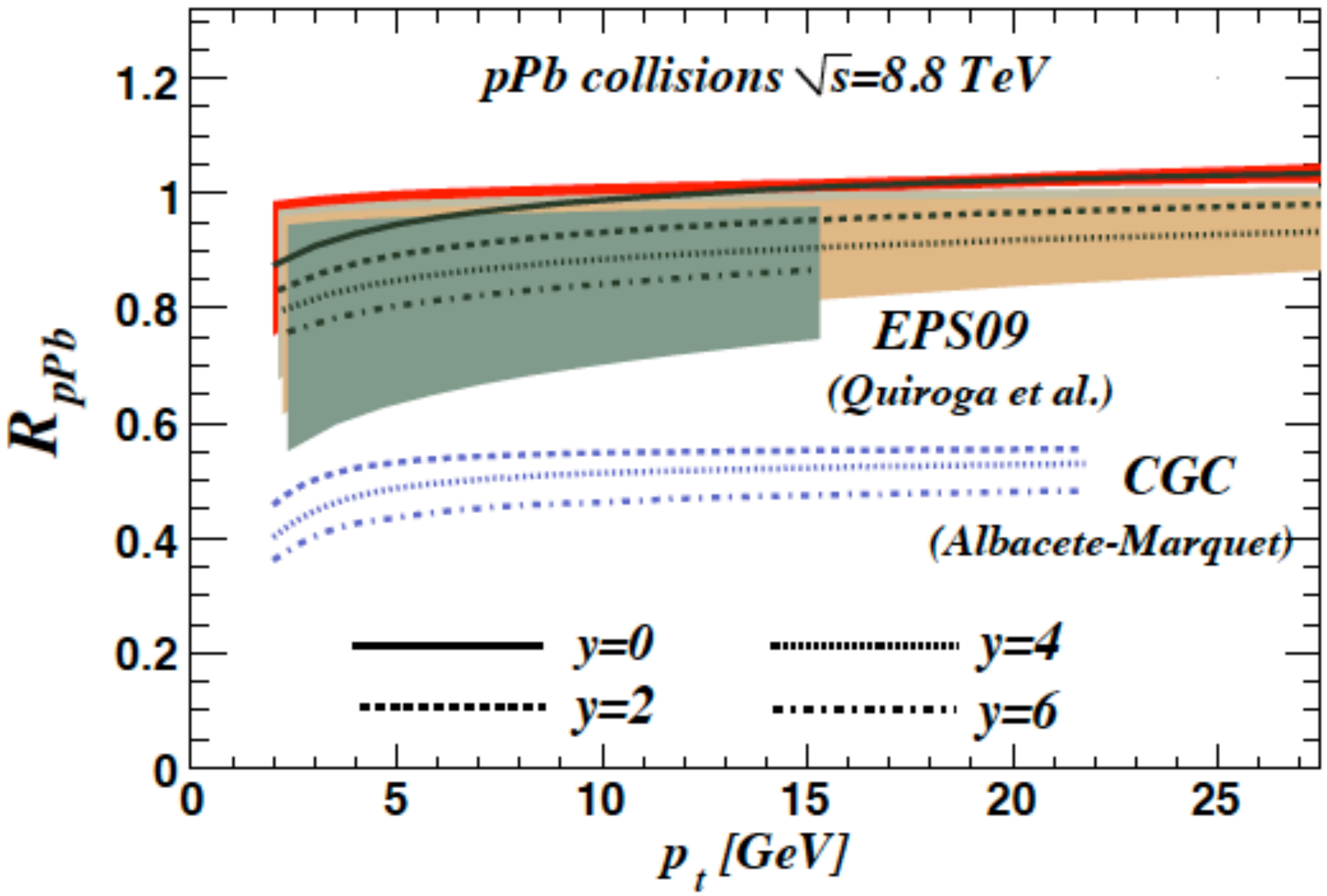
  ➜ RHIC data lie at the edge of phase space.

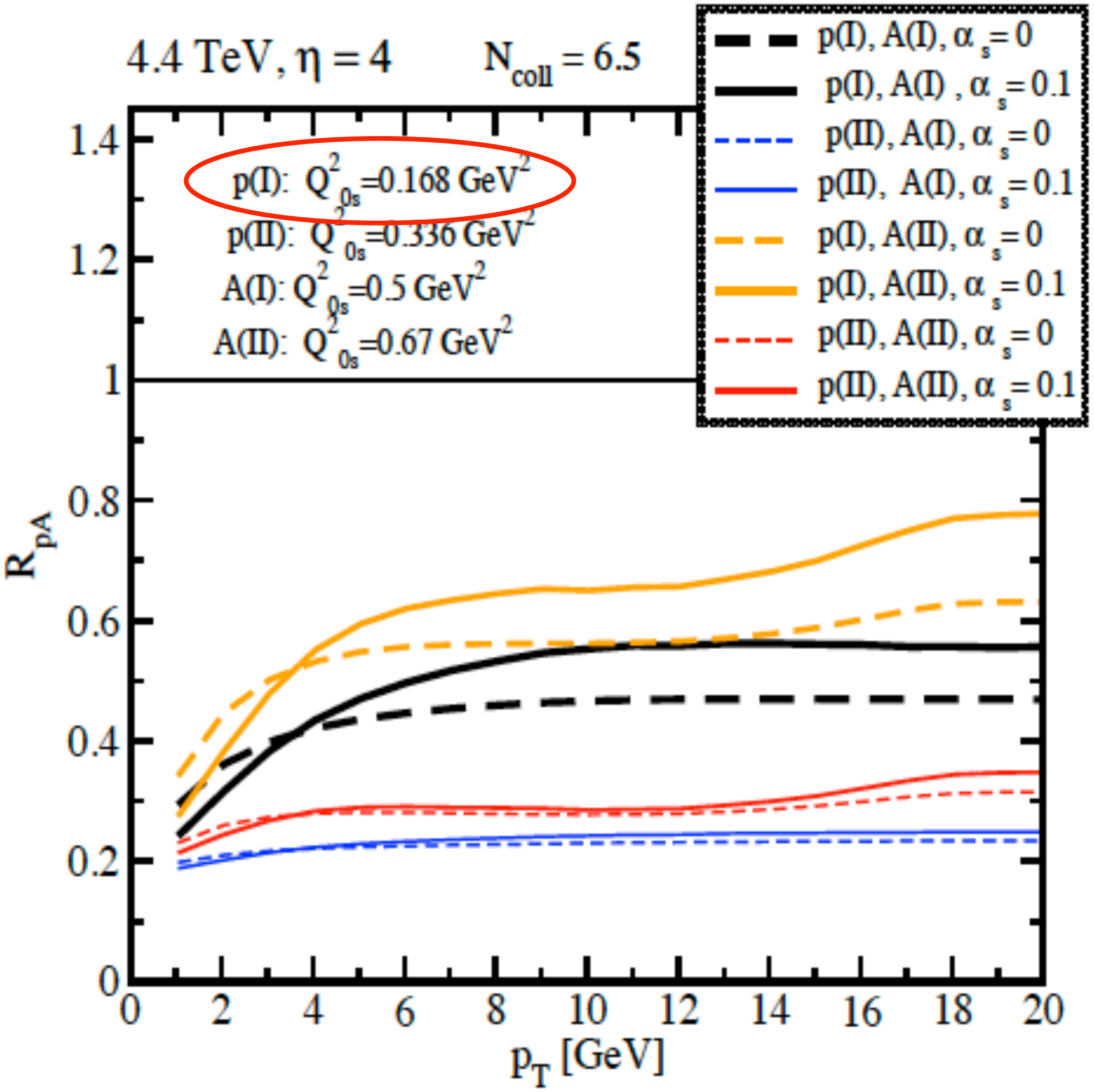
- Other descriptions exist: NLO pQCD (problems with pp reference), eloss models,...

- **Note**: these studies are very important to understand the mechanism of soft/semihard particle production: ridge, initial conditions for HIC, isotropization,...⇒ ‘benchmarking’ the bulk.

pPb at the LHC:

- Offers the best possibility (before lepton-ion colliders) to test:
  ➜ The small-x glue far from the kinematical limits.
  ➜ The production mechanism: clear differences between collinear factorization and saturation?





Jalilian-Marian & Rezaeian, 1110.2810

Contents:

1. Introduction.

2. pA as benchmark:
    - 2.1 Nuclear PDFs. (Kari Eskola)
    - 2.2 Processes for benchmarking:
        - ➜ Jets. (Guilherme Milhano)
        - ➜ EW bosons. (Carlos Salgado)
        - ➜ Photons. (“)
        - ➜ Open heavy flavor. (“)
        - ➜ Quarkonium. (Andry Rakotozafindrabe)

3. Small-x physics. (Cyrille Marquet and Javier Albacete)

4. Others:
    - 4.1 UPCs: (David d’Enterria)
        - ➜ $\gamma p/A$.
        - ➜ $\gamma\gamma$.
    - 4.2 Implications for Astroparticles.

5. Summary.

UPCs: motivation

- pA compared to pp:
  - ➜ Enhancement factor Z^2 in photon flux.
  - ➜ No event pileup.
  - ➜ Nuclear dissociation makes Pomeron background easy to detect.

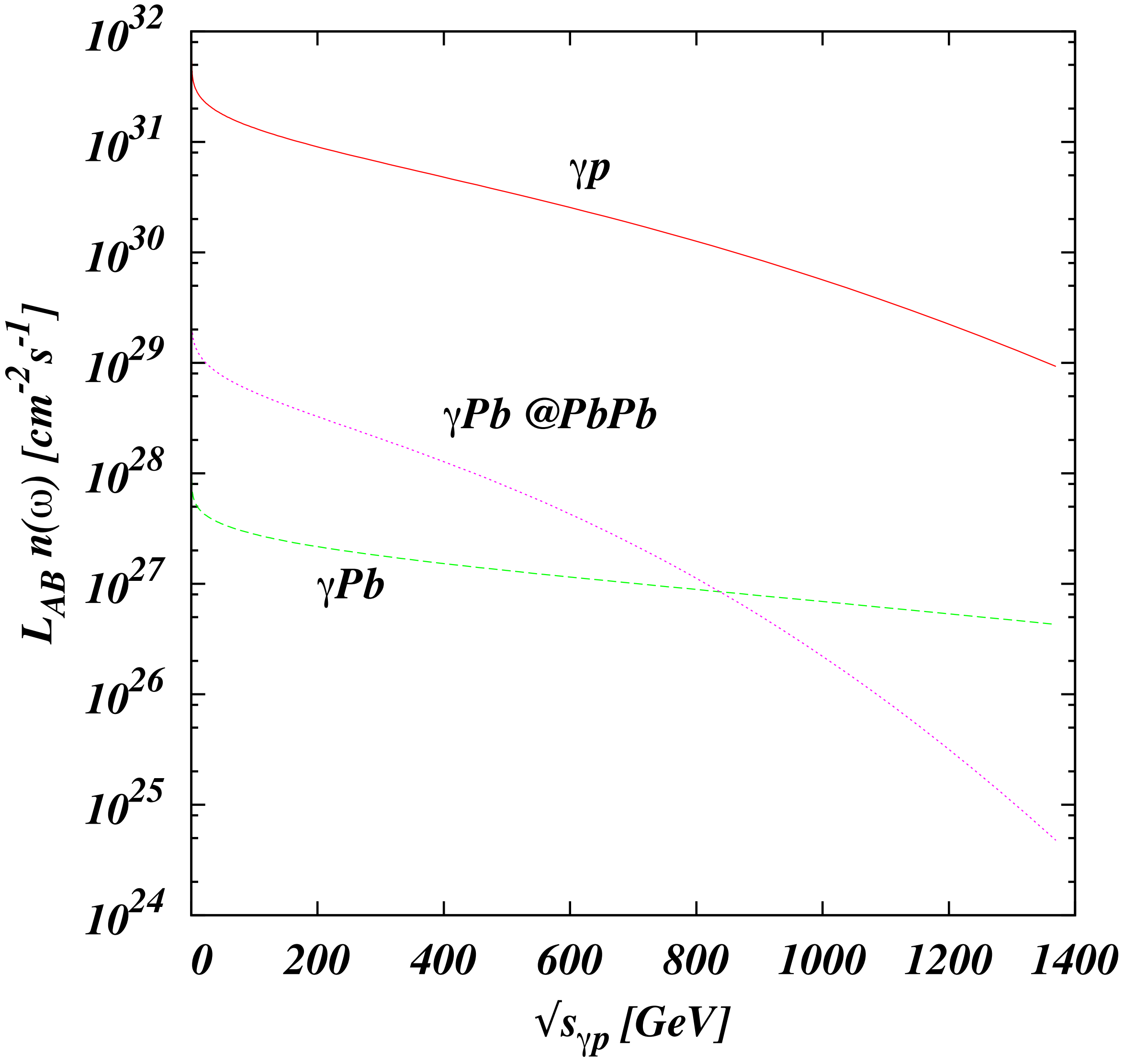
- pA compared to AA:
  - ➜ ~1000 larger luminosity.
  - ➜ Higher cms energies.
  - ➜ Backgrounds easier to be removed (e.g. those leading to forward neutron production).

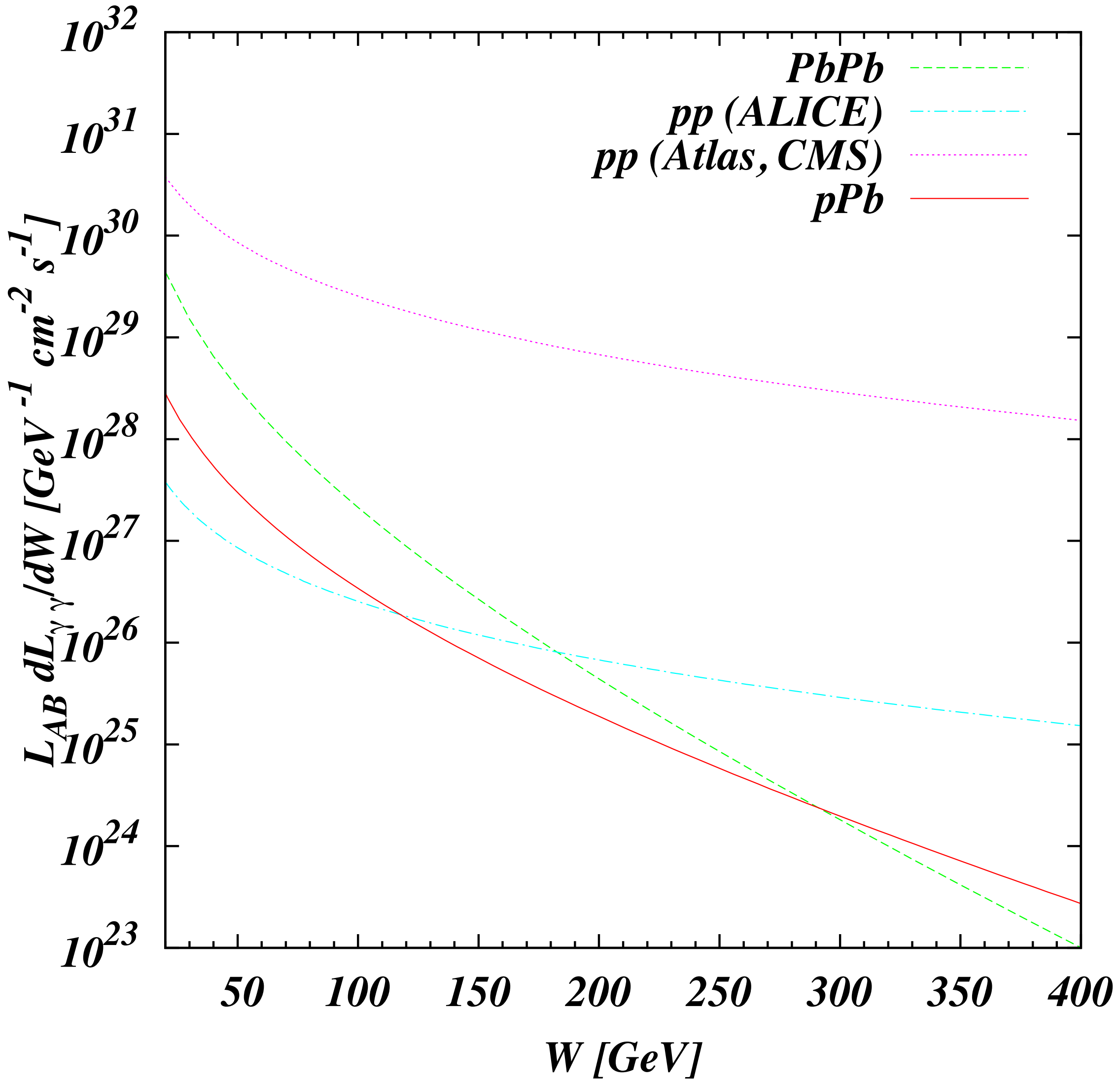
- γp/A: proton/nucleus DIS, test the small-x glue and saturation. E.g. b-rate measurable at $x\sim10^{-4}$ for $p_T\sim5$ GeV, exclusive vector meson production,... Also nuclear EM dissociation as a luminometer.

- γγ: luminometer, QCD studies (spectroscopy, cross section,...) and EW couplings (even Higgs).

UPCs in pPb:

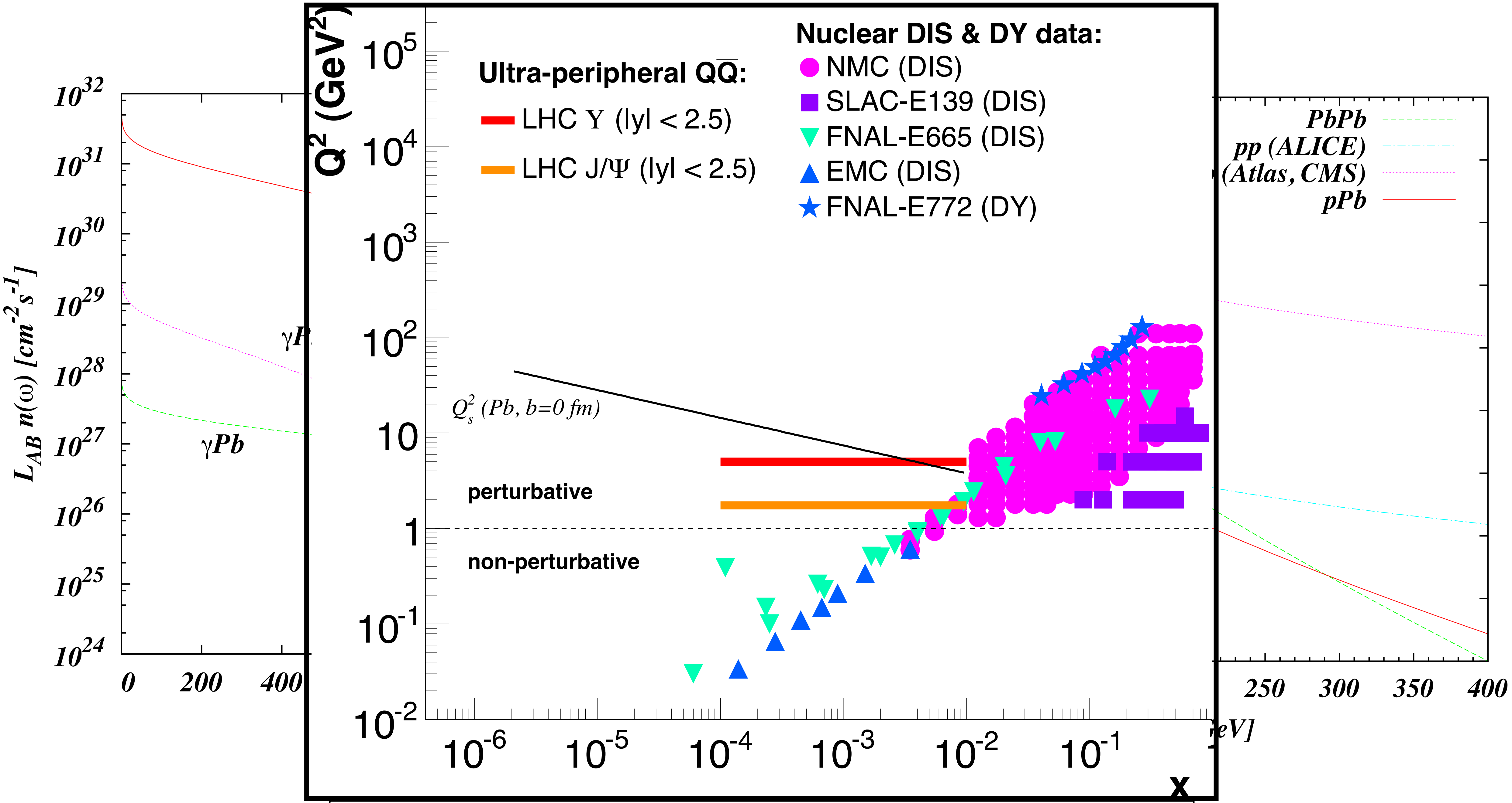
- Large luminosities in γp.
- Interesting kinematical coverage.





UPCs in pPb:

- Large luminosities in γp.
- Interesting kinematical coverage.



Preliminary; LHeC Design Study Report, CERN 2011

Cosmic rays:

- Hadronic models required for the extraction of chemical composition of the primary (γ, ν, p, He, Fe,...) in cosmic ray showers.

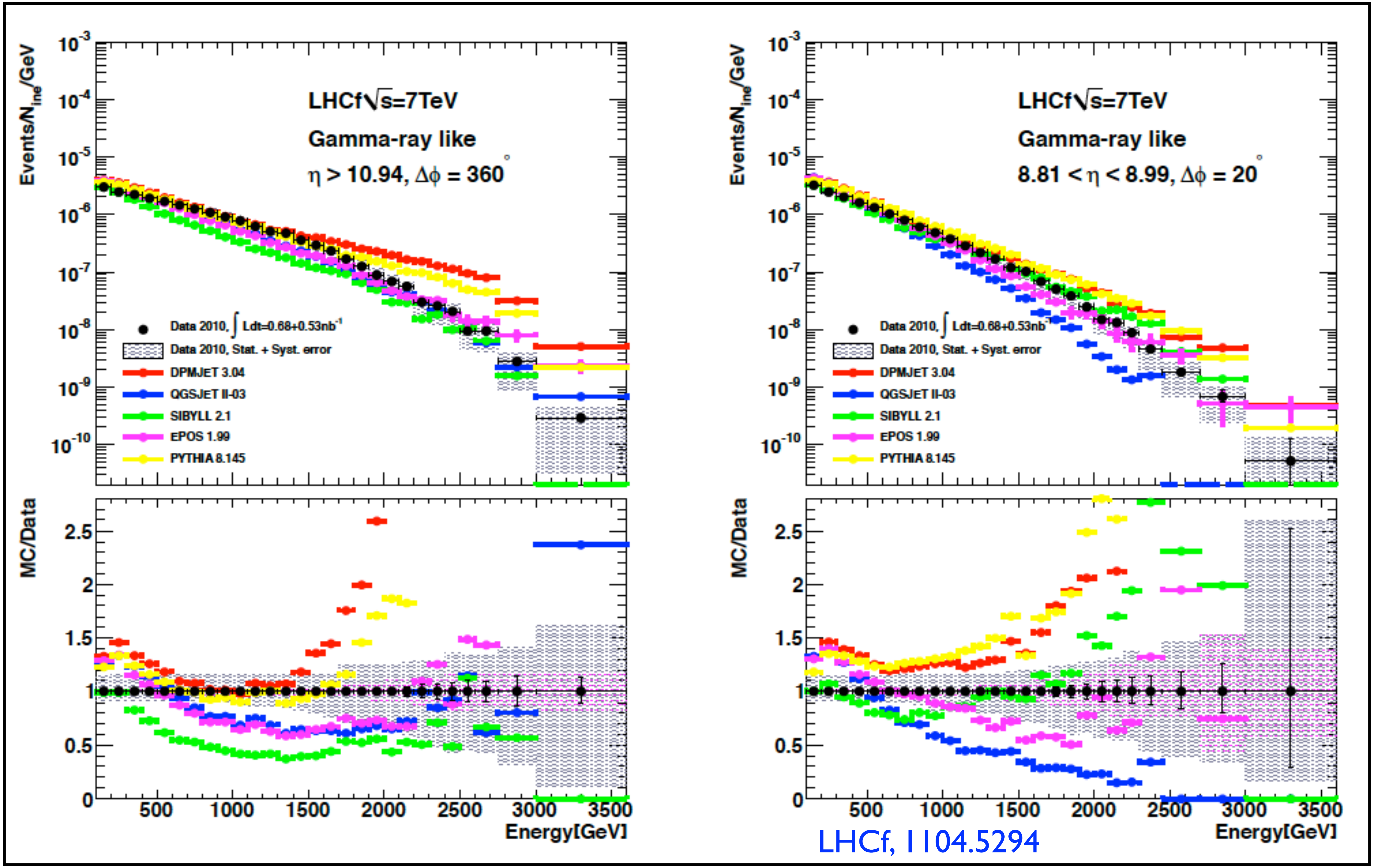
- Large uncertainties in models (e.g. μ-production not understood, composition depending on the model, etc.) for $E>10^{15}$ eV.

- pA of uttermost important (as air in basically N and O) for model verification, $E\sim10^{17}$ eV.

- Shower development determined by particle production in the forward region: ZDC, LHCf.

- Note: comparison with hadronic models already undergoing in pp.

Cosmic rays:



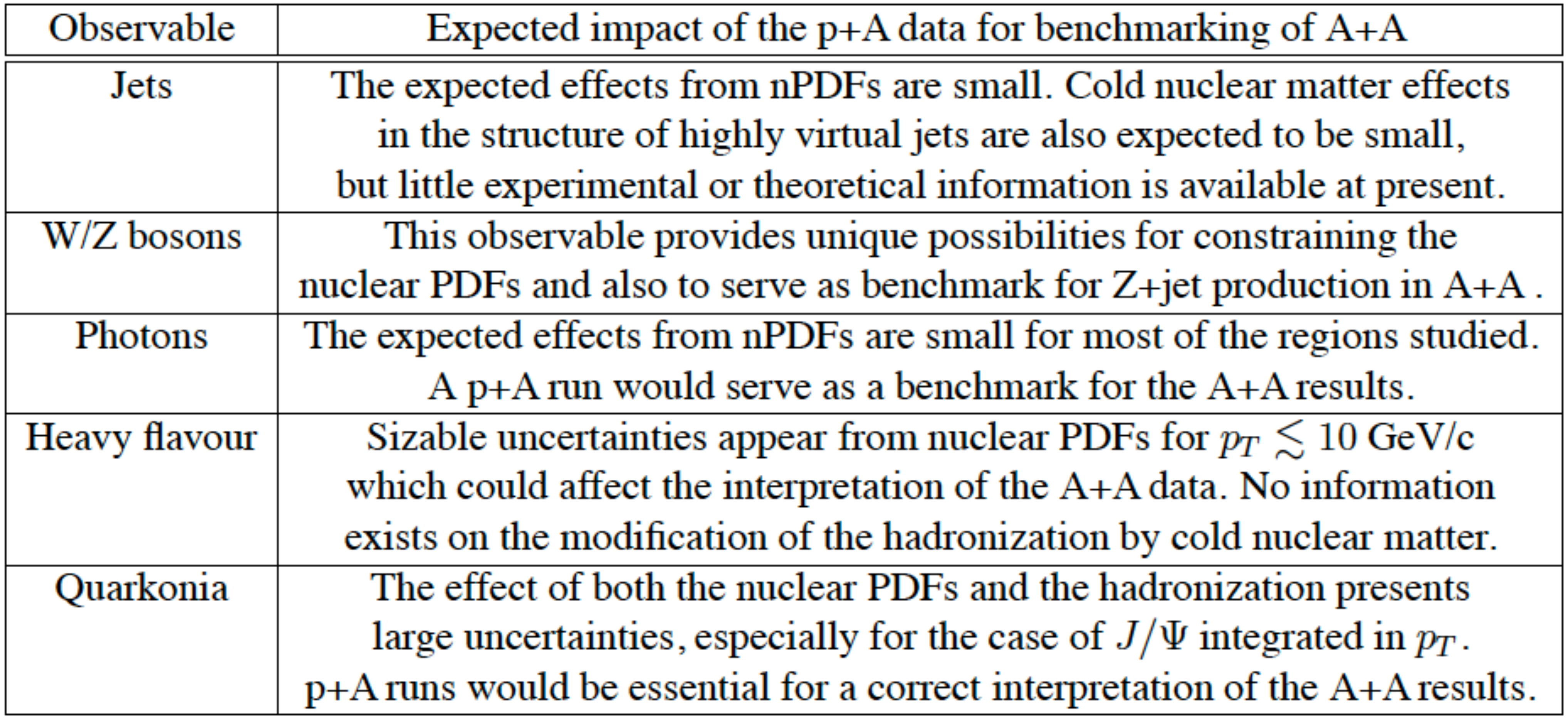
LHCf, 1104.5294

Proton-nucleus theory review: 4. Others.

Summary:

- A pPb run at the LHC offers huge possibilities (unique before IA colliders) for:

A) Benchmarking for the HIC program, particularly for reducing uncertainties coming from nPDFs:



Observable	Expected impact of the p+A data for benchmarking of A+A
Jets	The expected effects from nPDFs are small. Cold nuclear matter effects in the structure of highly virtual jets are also expected to be small, but little experimental or theoretical information is available at present.
W/Z bosons	This observable provides unique possibilities for constraining the nuclear PDFs and also to serve as benchmark for Z+jet production in A+A .
Photons	The expected effects from nPDFs are small for most of the regions studied. A p+A run would serve as a benchmark for the A+A results.
Heavy flavour	Sizable uncertainties appear from nuclear PDFs for $p_T \lesssim 10$ GeV/c which could affect the interpretation of the A+A data. No information exists on the modification of the hadronization by cold nuclear matter.
Quarkonia	The effect of both the nuclear PDFs and the hadronization presents large uncertainties, especially for the case of J/Ψ integrated in p_T . p+A runs would be essential for a correct interpretation of the A+A results.

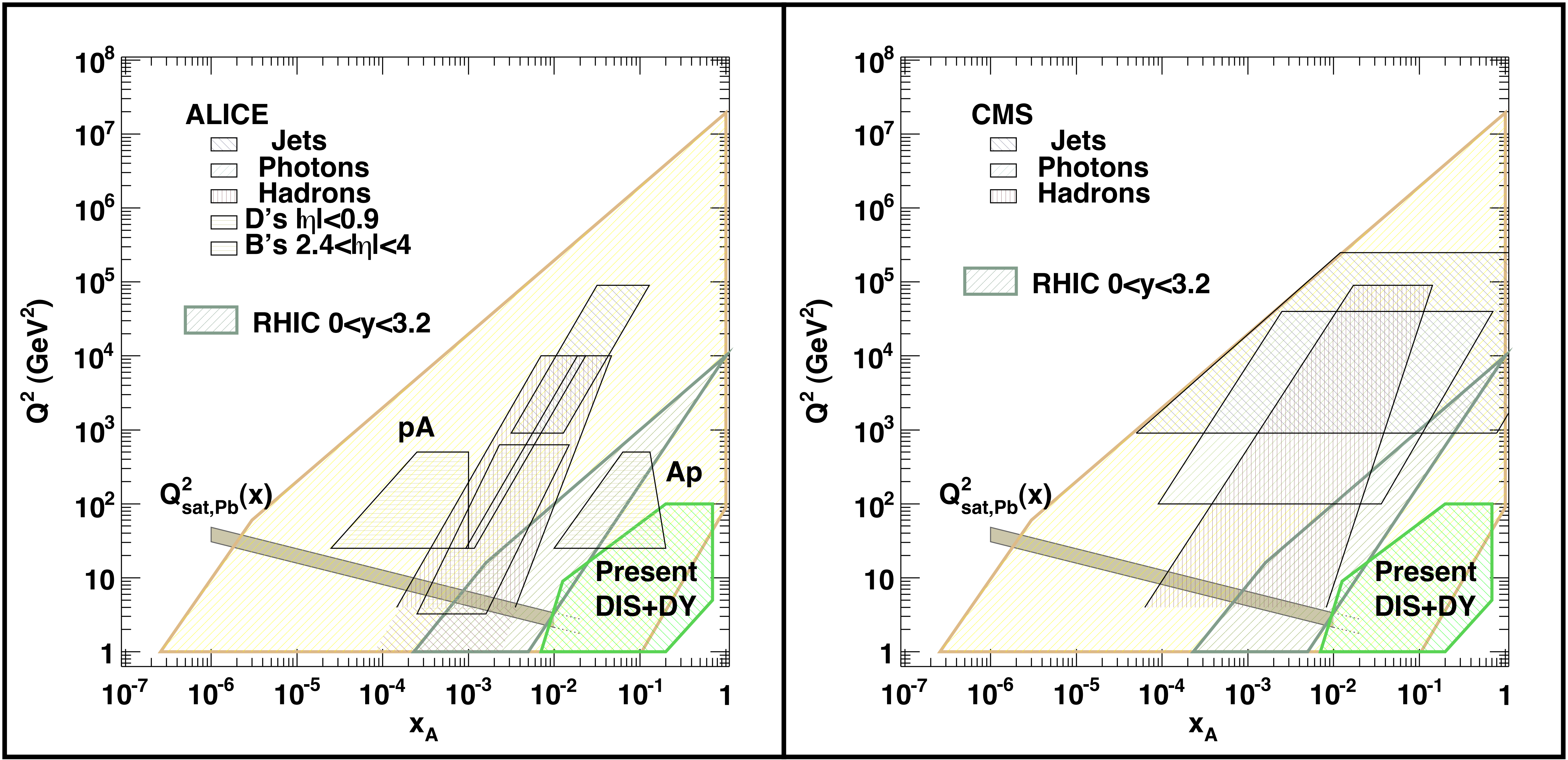
B) Discovery: clarifying the relevance of saturation physics.

C) Others: UPCs, measurements of interest for UHECR.

Summary:

- A pPb run at the LHC offers huge possibilities (unique before IA colliders) for:

A) Benchmarking for the HIC program, particularly for reducing



C) Others: UPCs, measurements of interest for UHECR.

Summary:

- A pPb run at the LHC offers huge possibilities (unique before IA colliders) for:

A) Benchmarking for the HIC program, particularly for reducing

- Note: <$\mathcal{L}$>~10^{29} cm^{-2}s^{-1} (i.e. ~10^{11} events for σ_{in}=1 b in 10^6 s)

should suffice for most for most studies but Z+jets, Υ at large p_T, γPb and γγ.

- Rescaling in energy could be done as for HI (or specific pp run):

$$\sigma(pp \to X; \sqrt{s_{\mathrm{PbPb/pPb}}}) = \frac{\sigma^{\mathrm{TH}}(pp \to X; \sqrt{s_{\mathrm{PbPb/pPb}}})}{\sigma^{\mathrm{TH}}(pp \to X\sqrt{s_{pp}})}\sigma^{\mathrm{EXP}}(pp \to X; \sqrt{s_{pp}})$$

x_A x_A

C) Others: UPCs, measurements of interest for UHECR.

Proton-nucleus theory review.

arXiv:1105.3919 [hep-ph] authors:

Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

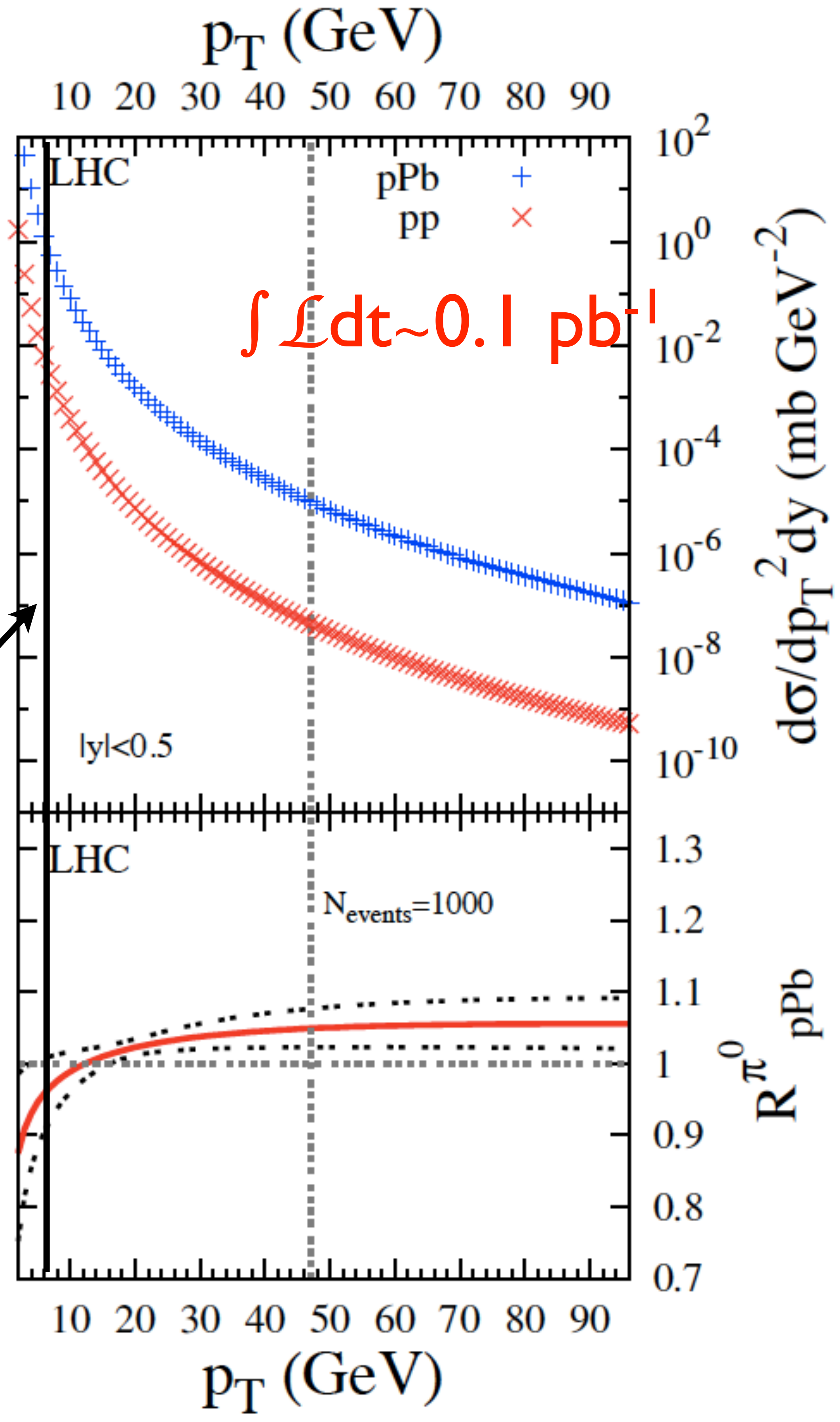
Editor: *C. A. Salgado*[1]
Authors: *J. Alvarez-Muñiz*[1], *F. Arleo*[2], *N. Armesto*[1], *M. Botje*[3], *M. Cacciari*[4], *J. Campbell*[5], *C. Carli*[6], *B. Cole*[7], *D. D'Enterria*[8,9], *F. Gelis*[10], *V. Guzey*[11], *K. Hencken*[12]*, *P. Jacobs*[13], *J. M. Jowett*[6], *S. R. Klein*[13], *F. Maltoni*[14], *A. Morsch*[8], *K. Piotrzkowski*[14], *J. W. Qiu*[15], *T. Satogata*[15], *F. Sikler*[16], *M. Strikman*[17], *H. Takai*[15], *R. Vogt*[13,18], *J. P. Wessels*[8,19], *S. N. White*[15], *U. A. Wiedemann*[20], *B. Wyslouch*[21]†, *M. Zhalov*[22]

Thanks a lot to Jaime Álvarez and Carlos Salgado for comments!

Many thanks to you all for your attention!

Backup: pion distribution

Quiroga, Milhano, Wiedemann, 1002.2537



$\int \mathcal{L}dt \sim 0.1\ \mathrm{pb}^{-1}$

$\int \mathcal{L}dt \sim 10^3\ \mathrm{mb}^{-1}$

Proton-nucleus theory review.