Nuclear PDFs from LHC data

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Outline

- Proton PDFs - Recent progress
- Nuclear PDFs
- nPDFs constraints from the pPb run
- Towards collider-only nuclear PDFs

Proton PDFs
Recent Progress

Parton Distribution Functions

- Hadronic cross sections factorize into **perturbatively calculable partonic cross sections** and **non perturbative Parton Distribution Functions** (PDFs)

$$\sigma_X(s, M_X^2) \;=\; \sum_{a,b} \int_{x_{\min}}^{1} dx_1\, dx_2\, f_{a/h_1}(x_1, M_X^2) f_{b/h_2}(x_2, M_X^2) \hat{\sigma}_{ab\to X}\, (x_1 x_2 s, M_X^2)$$

- The dependence of PDFs with the **resolution scale Q^2** is dictated by the **DGLAP evolution equations**, with kernels computed in pQCD up to **$O(\alpha_s^3)$**

$$\frac{d}{dt}\begin{pmatrix}\Sigma(N,Q^2)\\ g(N,Q^2)\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix}\gamma^S_{qq}(N,\alpha_s(t)) & 2n_f\gamma^S_{qg}(N,\alpha_s(t))\\ \gamma^S_{gq}(N,\alpha_s(t)) & \gamma^S_{gg}(N,\alpha_s(t))\end{pmatrix} \otimes \begin{pmatrix}\Sigma(N,Q^2)\\ g(N,Q^2)\end{pmatrix}$$

$$f_i(N,Q^2) \equiv \int_0^1 dx\, x^{N-1} f_i(x,Q^2)$$

(DGLAP factorizes in Mellin space)

- The dependence of PDFs on **Bjorken-x** (*parton momentum fraction* at LO) is purely **non-perturbative**, and needs to be determined from a **global analysis of hard scattering data:** this makes possible **predictions** for hadron collider processes

PDF parametrization

- PDF parametrization should be flexible and robust enough to avoid any theoretical bias in the PDF global analysis

- The standard approach consist on choosing a **relatively simple functional form** and fit some of its parameters from data (no guidance from QCD possible)

$$f_i(x, Q_0^2) = x^{\alpha_i}(1-x)^{\beta_i} g_i(x),$$

- However the requirements of precision physics made an unbiased parametrization preferable, i.e. **NNPDF** uses a particular type of **artificial neural networks: Multi layer feed-forward Perceptrons**

$$\xi_i = g\left(\sum_j \omega_{ij}\xi_j - \theta_i\right), \qquad g(x) = \frac{1}{1+e^{-\beta x}}$$

Ex.: 1-2-1 NN:

$$\xi_1^{(3)}(\xi_1^{(1)}) = \frac{1}{1 + e^{\theta_1^{(3)} - \frac{\omega_{11}^{(2)}}{1+e^{\theta_1^{(2)} - \xi_1^{(1)}\omega_{11}^{(1)}}} - \frac{\omega_{12}^{(2)}}{1+e^{\theta_2^{(2)} - \xi_1^{(1)}\omega_{21}^{(1)}}}}}$$

- Other possibilities like Chebyshev polynomials have been investigated by other groups (CT, MSTW, HERAPDF). Unbiased parametrizations are crucial to achieve **faithful PDF error estimation**

PDF Uncertainties: The Hessian Method

- Determine best-fit PDF parameters by χ^2 minimization
- **Expand quadratically** around minimum and define 68% CL by a **suitable tolerance**

$$\Delta\chi^2_{\rm global} \equiv \chi^2_{\rm global} - \chi^2_{\rm min} = \sum_{i,j=1}^{n} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \qquad H_{ij} = \frac{1}{2}\frac{\partial^2\,\chi^2_{\rm global}}{\partial a_i \partial a_j}\bigg|_{\rm min}$$

Textbook statistics: $\Delta\chi^2=1$

- PDF errors on physical observables can be computed by **linear error propagation**

$$\Delta F = \frac{1}{2}\sqrt{\sum_{k=1}^{n}\left[F(S_k^+) - F(S_k^-)\right]^2},$$

Eigenvectors from Hessian matrix diagonalization

- Used by CT, MSTW, HERAPDF, ABKM, JR (with different variants). Same technique adopted in **nuclear PDF analysis**: EPS, DSSZ, ... Some important drawbacks:
  - Relies on the **Gaussian approximation** and **linear error propagation**
  - The **determination of tolerance** non-trivial when combining many datasets. For example, CT assumes **$\Delta\chi^2$=100**, and DSSZ (nPDFs) vaires **$\Delta\chi^2$ from 1 to 30. Statistical meaning of PDF errors lost?**

PDF Uncertainties: The Monte Carlo Method

- Generate a large number of Monte Carlo replicas of the experimental data with the same underlying probability distribution

sys errors　　stat error

$$F_{I,p}^{(\mathrm{art})(k)} = \underbrace{S_{p,N}^{(k)}}_{\text{lumi error}} F_{I,p}^{(\mathrm{exp})}\left(1+\sum_{l=1}^{N_c} r_{p,l}^{(k)}\sigma_{p,l} + r_p^{(k)}\sigma_{p,s}\right) \quad , \; k=1,\ldots,N_{\mathrm{rep}} \gg 1$$

random numbers

- Perform a **PDF determination** on each of these MC replicas

- The set of PDF replicas form a **representation of the probability density in the space of parton distribution functions**

- PDF uncertainties can be propagated to physical cross sections using textbook statistics, no need of linear/gaussian assumptions

Central PDF prediction = Expectation Value of MC sample

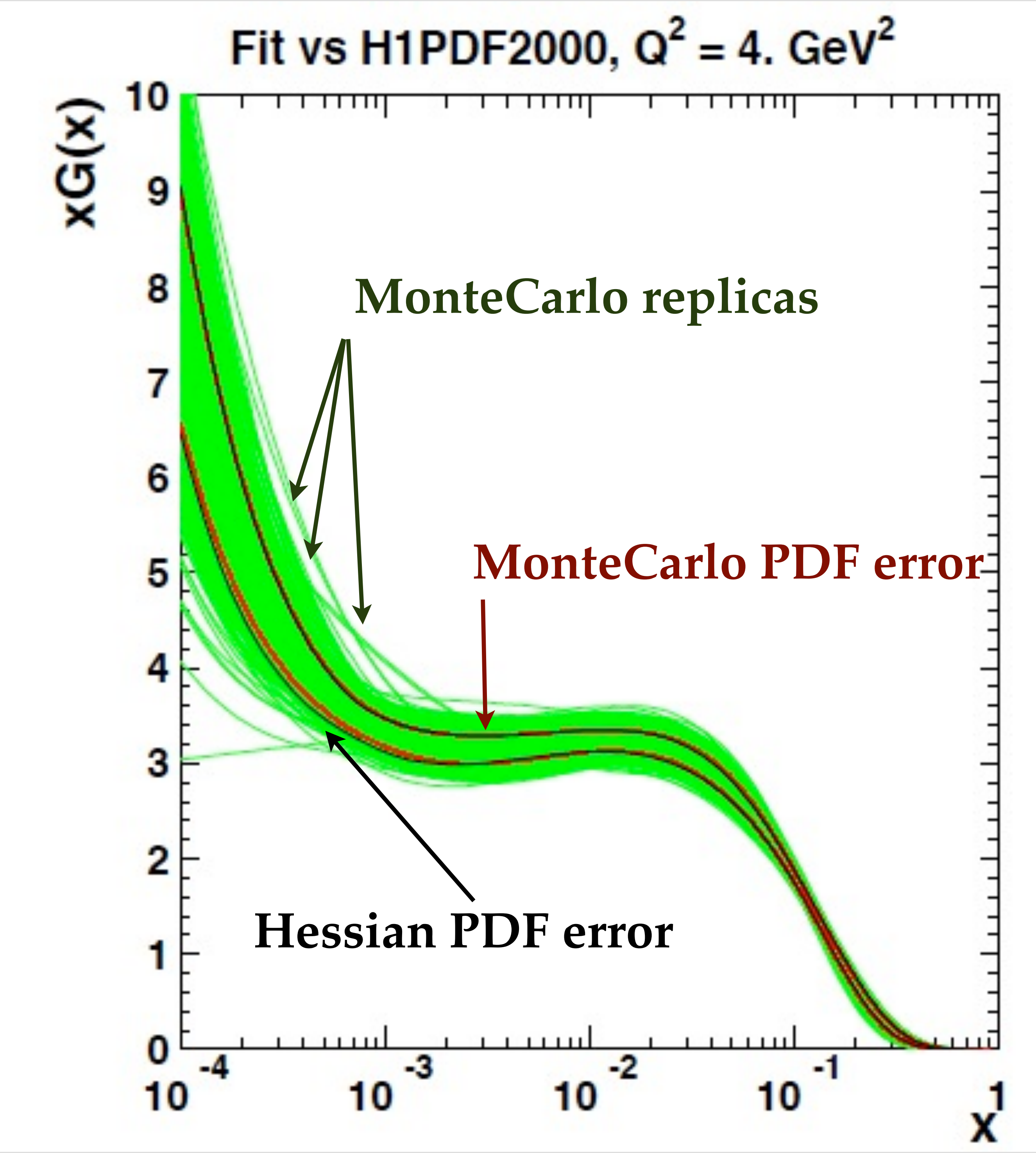
$$\langle \mathcal{O} \rangle = \int \mathcal{O}[f]\,\mathcal{P}(f)\,Df = \frac{1}{N}\sum_{k=1}^{N}\mathcal{O}[f_k]$$

PDF Uncertainty = Standard Deviation of MC sample

$$\Delta f = \sqrt{\frac{1}{N}\sum_{k=1}^{N} f_k^2 - \left(\frac{1}{N}\sum_{k=1}^{N} f_k\right)^2}$$

PDF Uncertainties: Hessian vs Monte Carlo

- Hessian and Monte Carlo methods **statistically equivalent** if gaussian quadratic approximation is realistic and no tolerances are introduced
- HERA-LHC workshop proceedings: with the **HERAPDF** framework, Hessian and Monte Carlo methods shown to be **numerically equivalent** in a QCD analysis of H1 data
- **Monte Carlo method more flexible** with deviations from the quadratic approximation and combinations of many experiments
- MC method used by the **NNPDF** analysis, but also studies by **MSTW** and **HERAPDF**



Experimental dataset

MSTW2008

Process	Subprocess	Partons	x range
$\ell^\pm \{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+ \{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$	$\gamma^* c \to c$, $\gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm \nu) X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-) X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

- Global QCD analysis extract information from a very large number of experiments: **deep-inelastic scattering, Drell-Yan, W and Z production, jet and photon production**
- This is mandatory to constrain **all PDF combinations** for **all relevant Bjorken-*x***

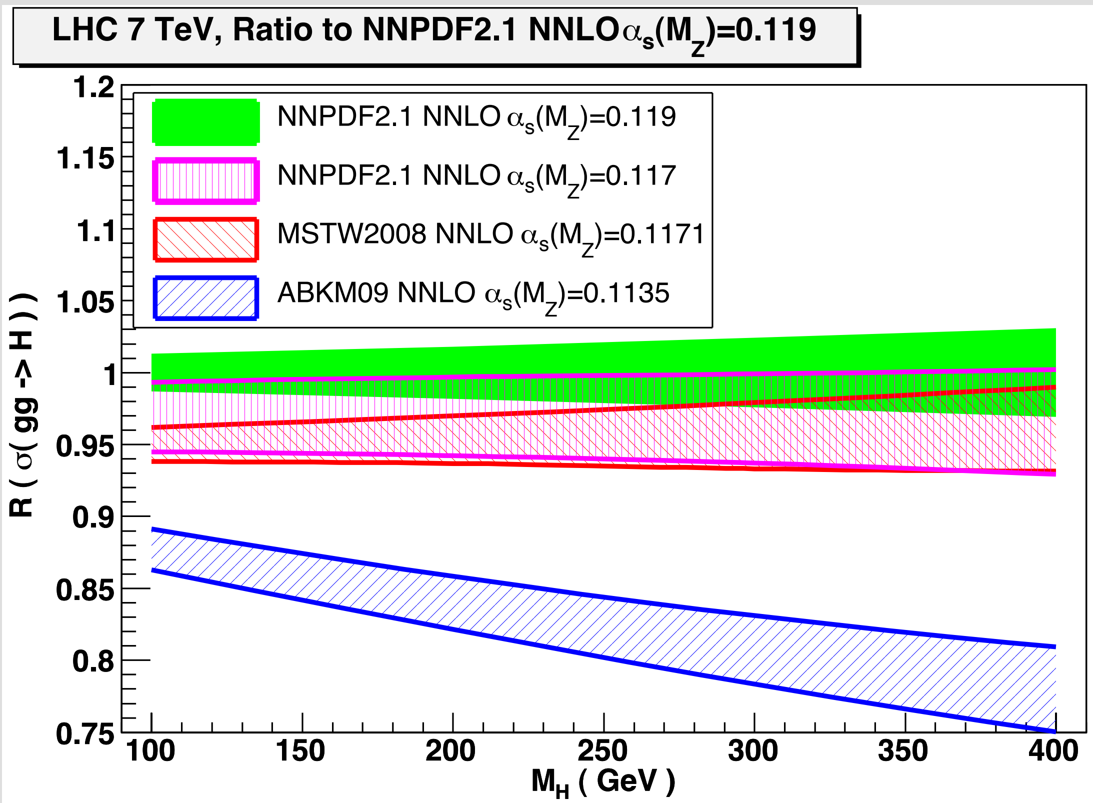
PDF landscape

	DATASET	PERT. ORDER	HQ TREATMENT	α_s	PARAM.	UNCERT.
ABM11	DIS Drell-Yan	NLO NNLO	FFN (BMSN)	Fit (multiple values available)	6 indep. PDFs Polynomial (25 param.)	Hessian ($\Delta\chi^2$=1)
CT10	**Global**	LO NLO NNLO	GM-VFNS (S-ACOT)	External (multiple values available)	6 indep. PDFs Polynomial (26 param.)	Hessian ($\Delta\chi^2$=100)
JR09	DIS Drell-Yan Jets	NLO NNLO	FFN VFN	Fit	5 indep. PDFs Polynomial (15 param.)	Hessian ($\Delta\chi^2$=1)
HERAPDF1.5	DIS (HERA)	NLO NNLO	GM-VFNS (TR)	External (multiple values available)	5 indep. PDFs Polynomial (14 param.)	Hessian ($\Delta\chi^2$=1)
MSTW08	**Global**	LO NLO NNLO	GM-VFNS (TR)	Fit (multiple values available)	7 indep. PDFs Polynomial (20 param.)	Hessian ($\Delta\chi^2$~25)
NNPDF2.1/2.3	**Global**	LO NLO NNLO	GM-VFNS (FONLL)	External (multiple values available)	7 indep. PDFs Neural Nets (259 param.)	Monte Carlo

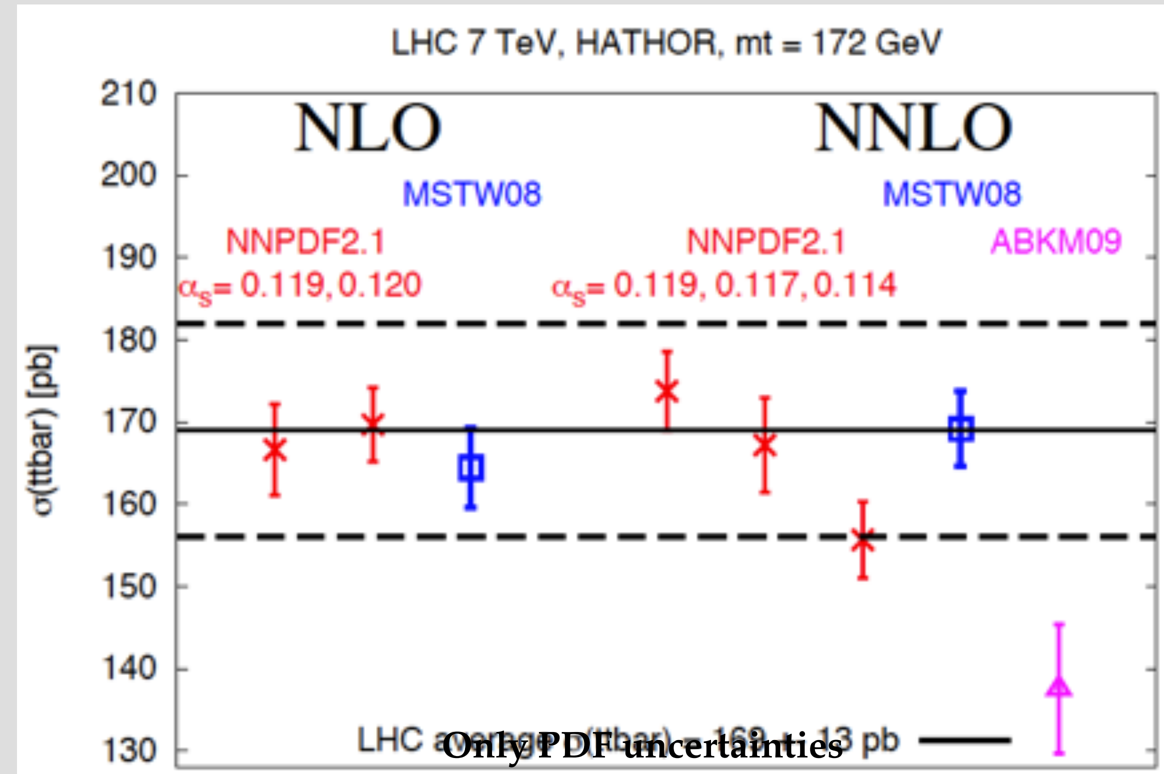
Main difference between PDF sets: choice of dataset, but also statistical methodology, treatment of NLO/NNLO corrections and heavy quarks, the strong coupling, ...

Relevance for LHC Phenomenology

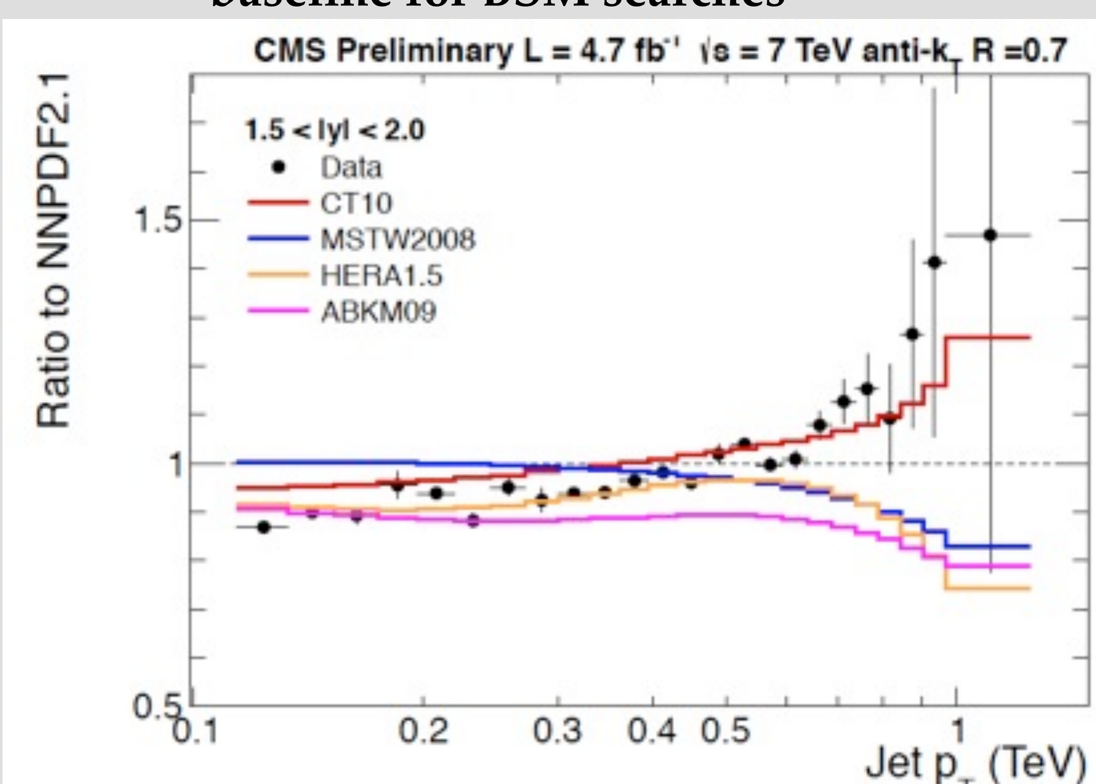
Higgs ggF xsec: basis of SM Higgs searches



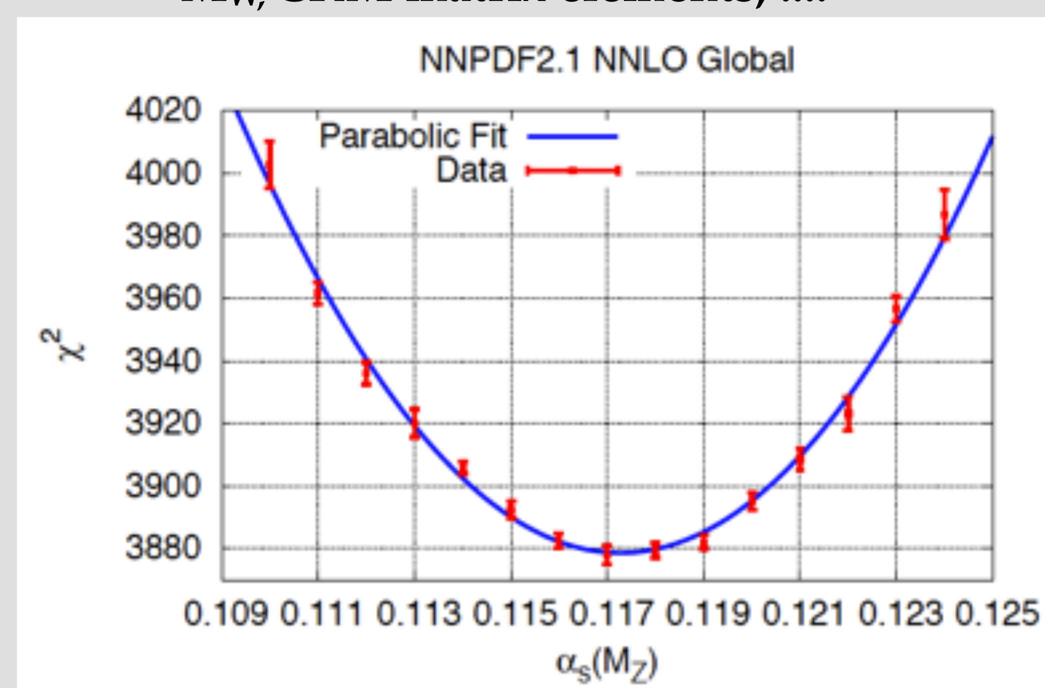
ttbar xsec: towards PDF discrimination with LHC data



Predict SM cross sections up to very large pT: baseline for BSM searches



Precision determination of SM parameters: α_S, M_W, CKM matrix elements, ….



$$\alpha_s^{\rm NNLO}\left(M_Z\right) = 0.1173 \pm 0.0007^{\rm stat} \pm 0.0001^{\rm proc}$$

Nuclear PDFs

Nuclear Parton Distributions

- In principle, one could extract PDFs for heavier nuclei as in the proton case. Need to assume that **QCD factorization holds in nuclei** as in protons

- The scarceness of nuclear data requires to simultaneously fit the dependence with **Bjorken-x** and with the **nuclear number *A*** as **deviations from a proton PDF set:**

$$f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^{\mathrm{CTEQ6.1M}}(x, Q^2)$$

EPS09

- Also **isospin symmetry** has to be taken into account - important difference as compared to proton PDFs

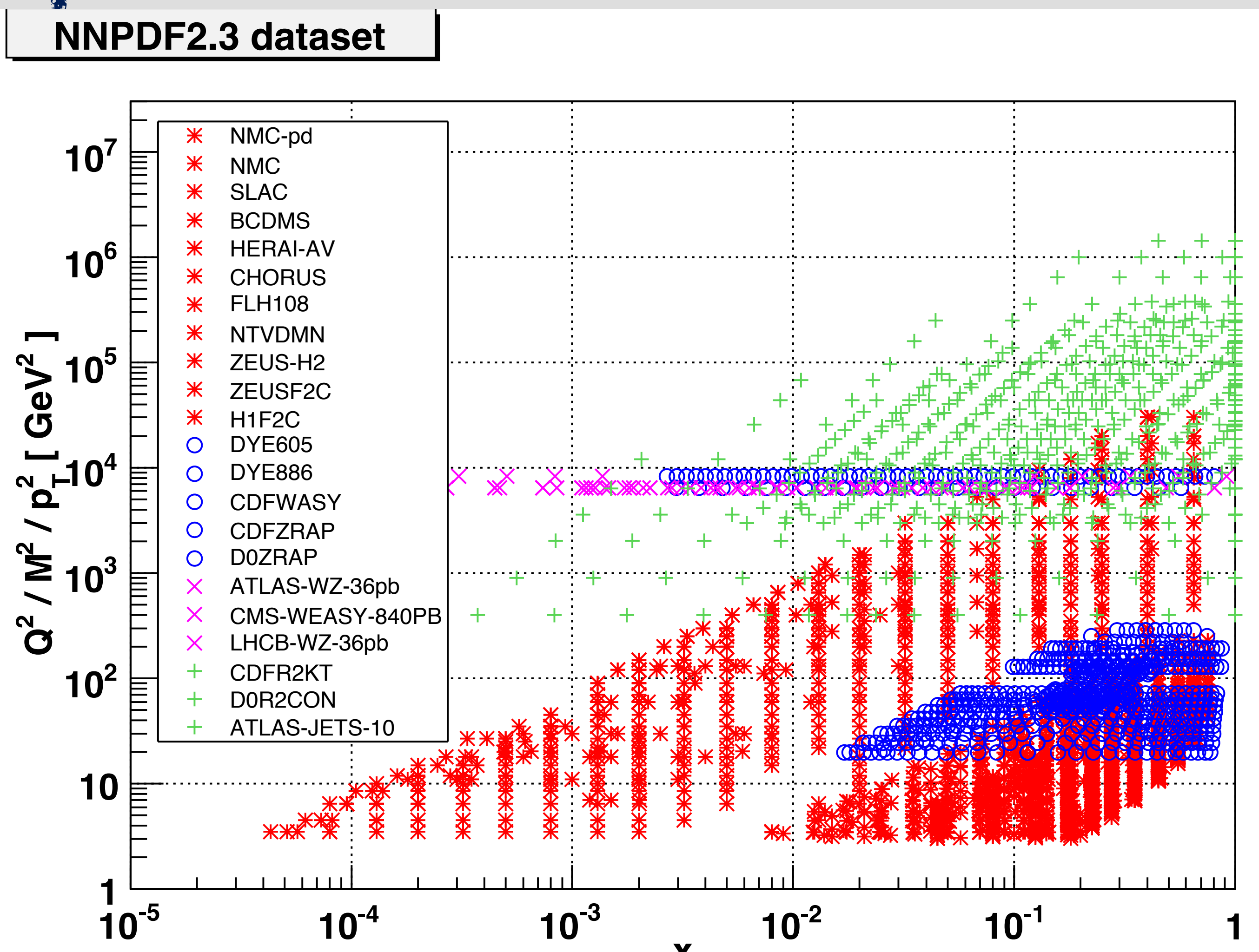
$$\begin{aligned} u_A(x, Q^2) &= \frac{Z}{A} f_u^A(x, Q^2) + \frac{A-Z}{A} f_d^A(x, Q^2) \\ d_A(x, Q^2) &= \frac{Z}{A} f_d^A(x, Q^2) + \frac{A-Z}{A} f_u^A(x, Q^2) \end{aligned}$$

- **Momentum and baryon** sum rules must apply for all **nuclear numbers *A***

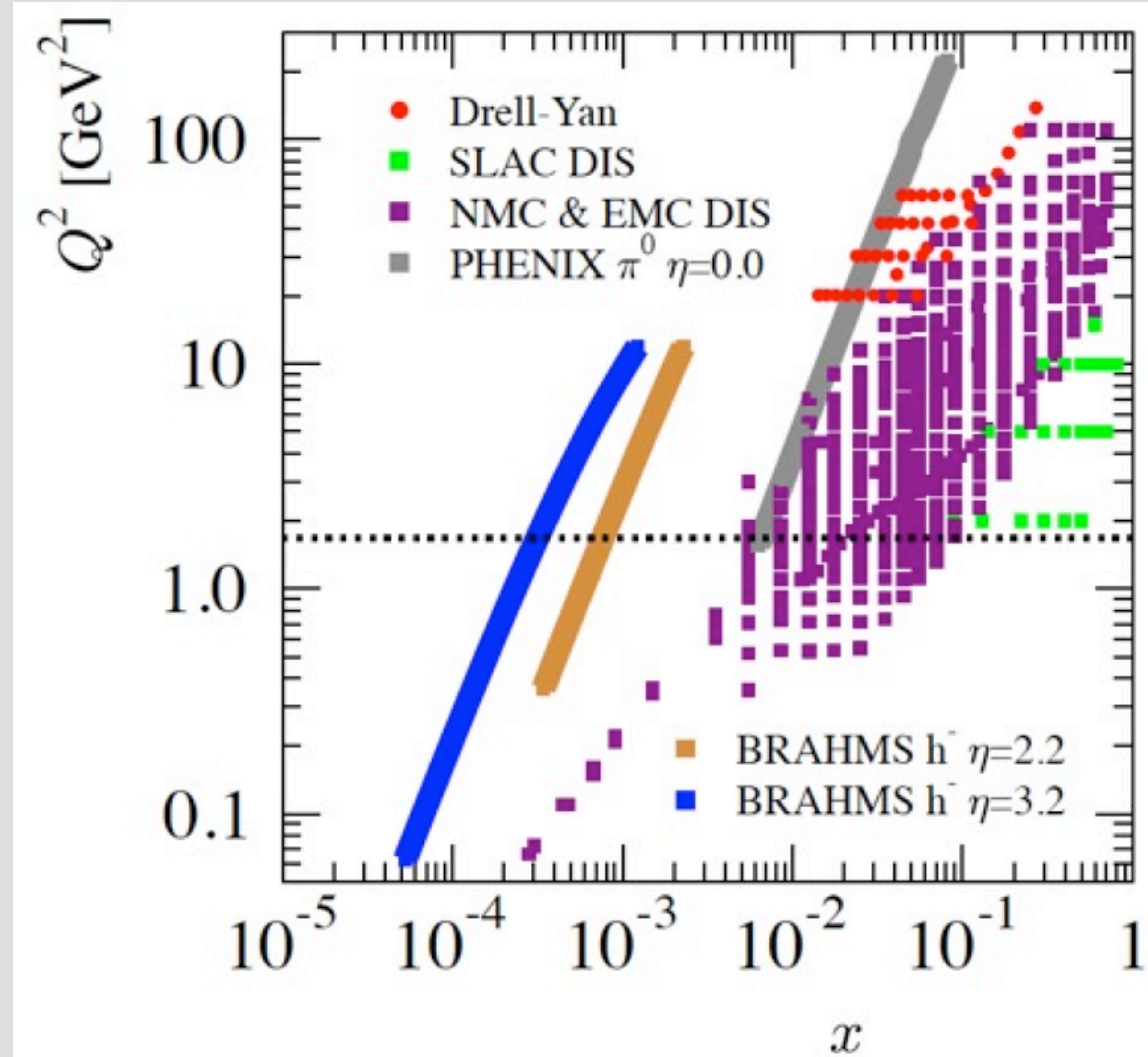
$$\sum_{i=q,\overline{q},g} \int_0^1 dx\, x f_i^A(x, Q_0^2) = 1, \quad \int_0^1 dx \left[f_{u_V}^A(x, Q_0^2) + f_{d_V}^A(x, Q_0^2) \right] = 3$$

Nuclear Parton Distributions - The dataset

Proton PDFs: NNPDF2.3



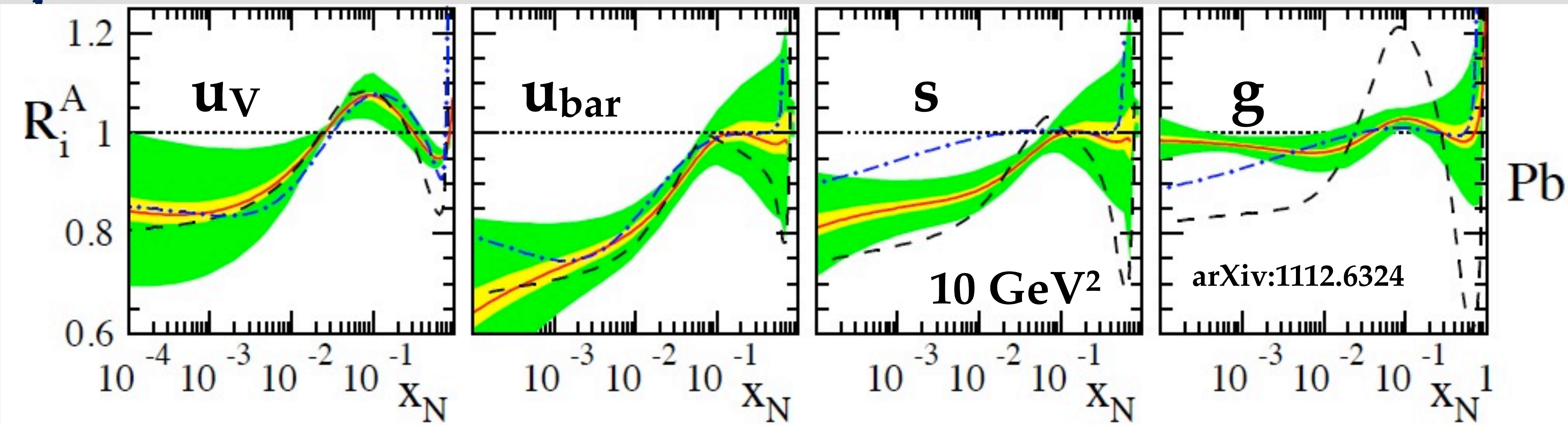
Nuclear PDFs: EPS09



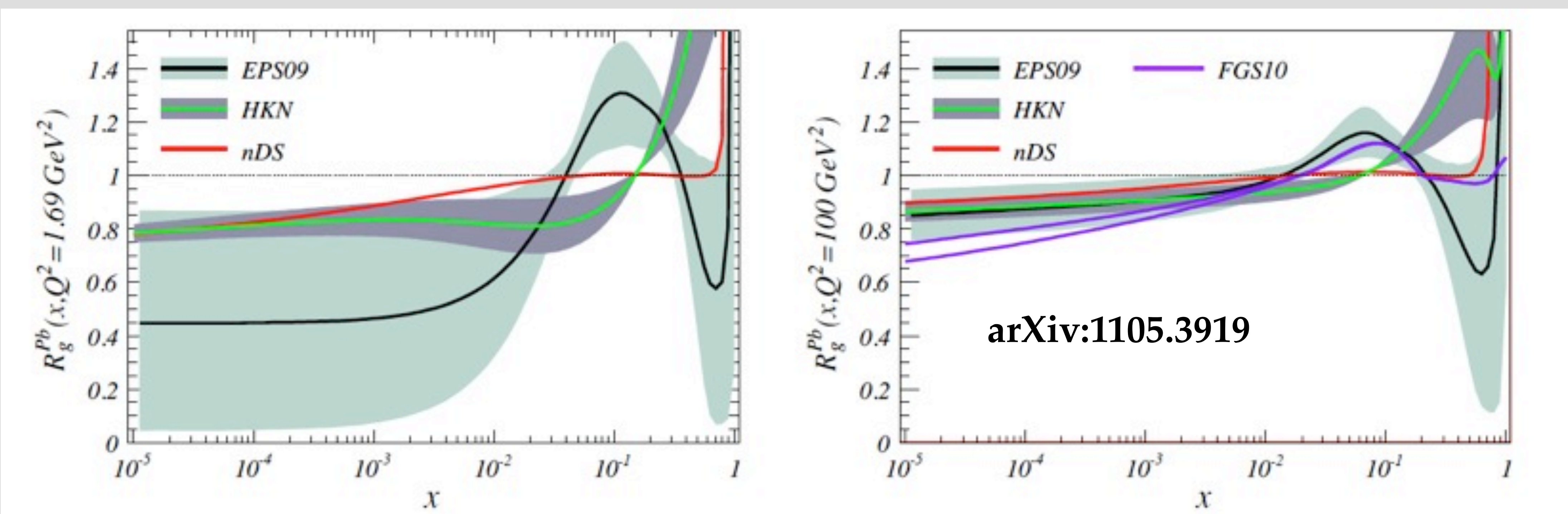
- Main differences is the **lack of HERA nuclear data**: **reduced sensitivity to small-x quark sea and gluon** in nPDF analysis. Need for an EIC, but also **opportunities in pPb at the LHC**
- **Reduced range in Q^2**, but less important since **DGLAP washes out** nuclear modifications
- Also, **less data for wider parameter space** in nPDFs, since also *A* **dependence** needs to be determined

Nuclear Parton Distributions

Nuclear modifications in Pb estimated to be in the range **20% - 50% with large uncertainties**



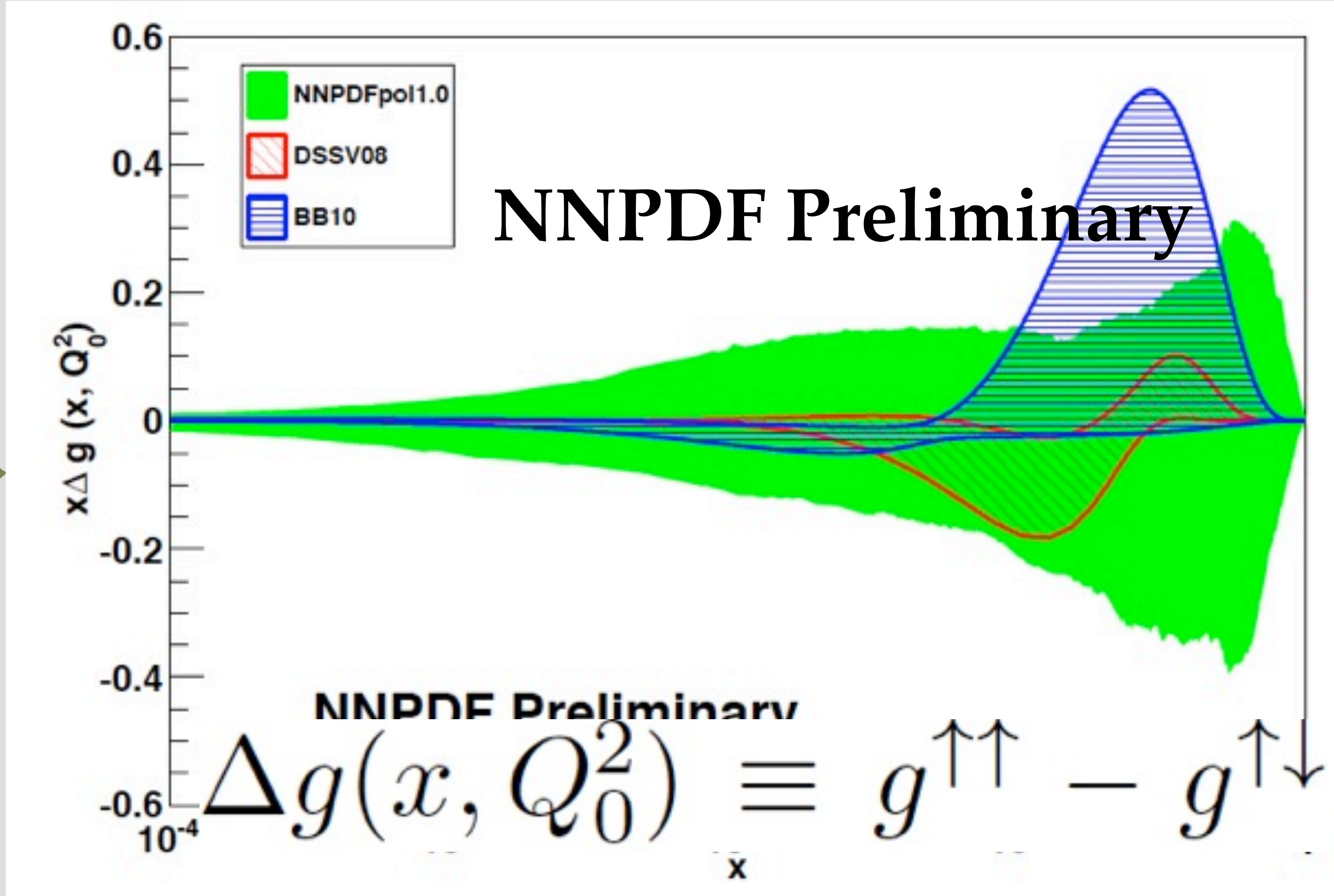
DGLAP evolution reduces **nuclear effects at small-*x***, but not at **large-*x***



Nuclear Parton Distributions - some caveats

- Nuclear PDFs are extracted assuming a given functional form both f**or the dependence on Bjorken-*x* and in nuclear *A***
- As such, they are potentially affected by **sizable parametrization bias**, specially in regions like **small-*x* with almost no data**, which are of **direct relevant at the LHC**
- Also the **Hessian (gaussian) approximation** used for PDF uncertainties might break down
- Therefore, **nuclear effects at the LHC** could in principle be **rather larger than estimated**

Illustration: Recent NNPDF determination of Polarized PDFs suggests much larger PDF uncertainties, specially for the polarized gluon



$$\Delta g(x, Q_0^2) \equiv g^{\uparrow\uparrow} - g^{\uparrow\downarrow}$$

Nuclear PDFs: Constraints from the pPb run

The LHC pPb program

- Late this year the LHC will collide **protons with Lead nuclei at 5 TeV** center of mass energy, with luminosity about 25 nb (?)

- Wide range of possible physics studies, from **baseline to PbPb measurements**, **nuclear PDFs**, **tests of factorization, small-x and CGC phenomenology**

- The scientific opportunities were summarized in a **detailed report**:

arXiv:1105.3919

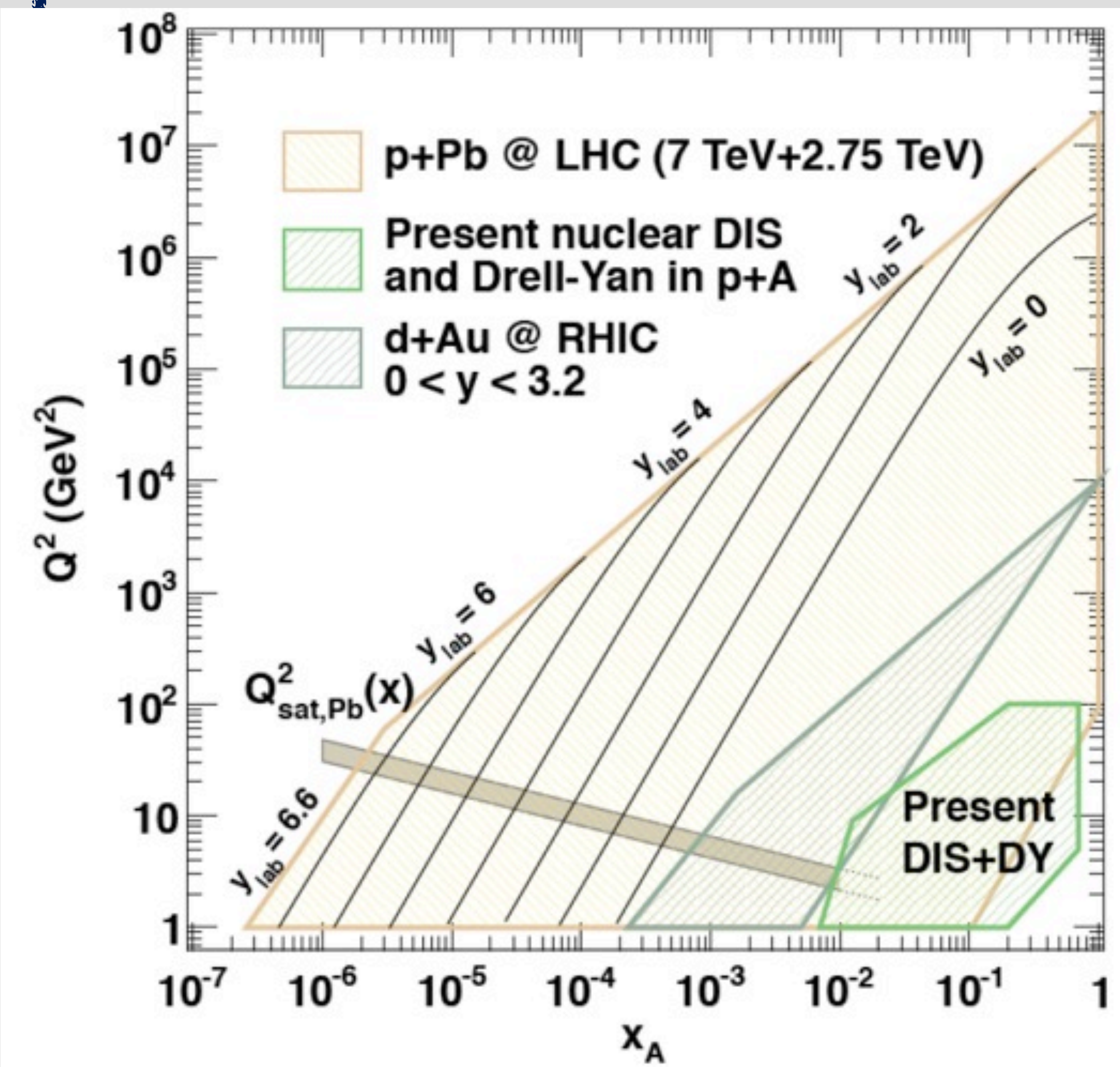
CERN-PH-TH/2011-119
LHC-Project-Report-1181

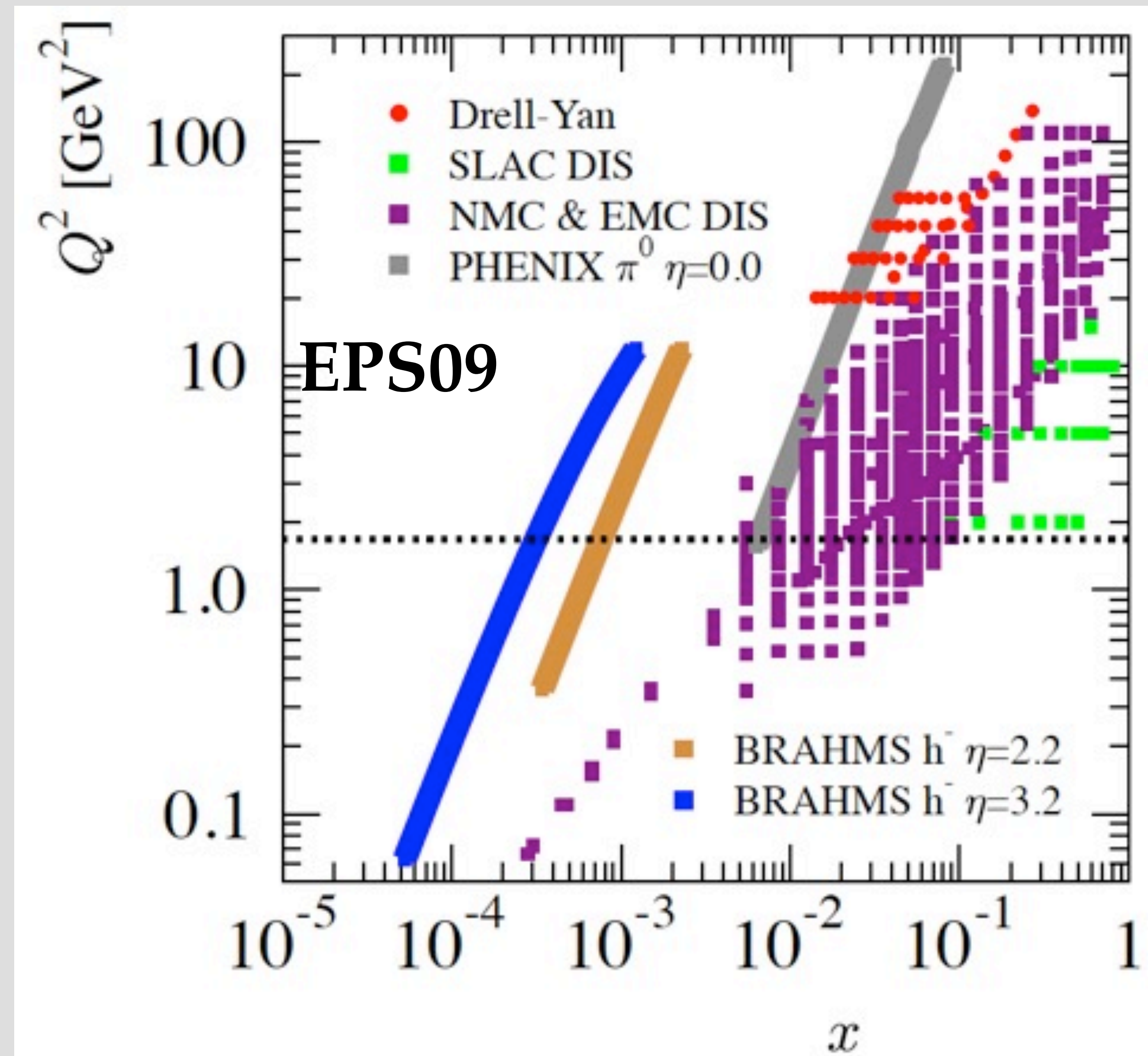
Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

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]

The LHC pPb program

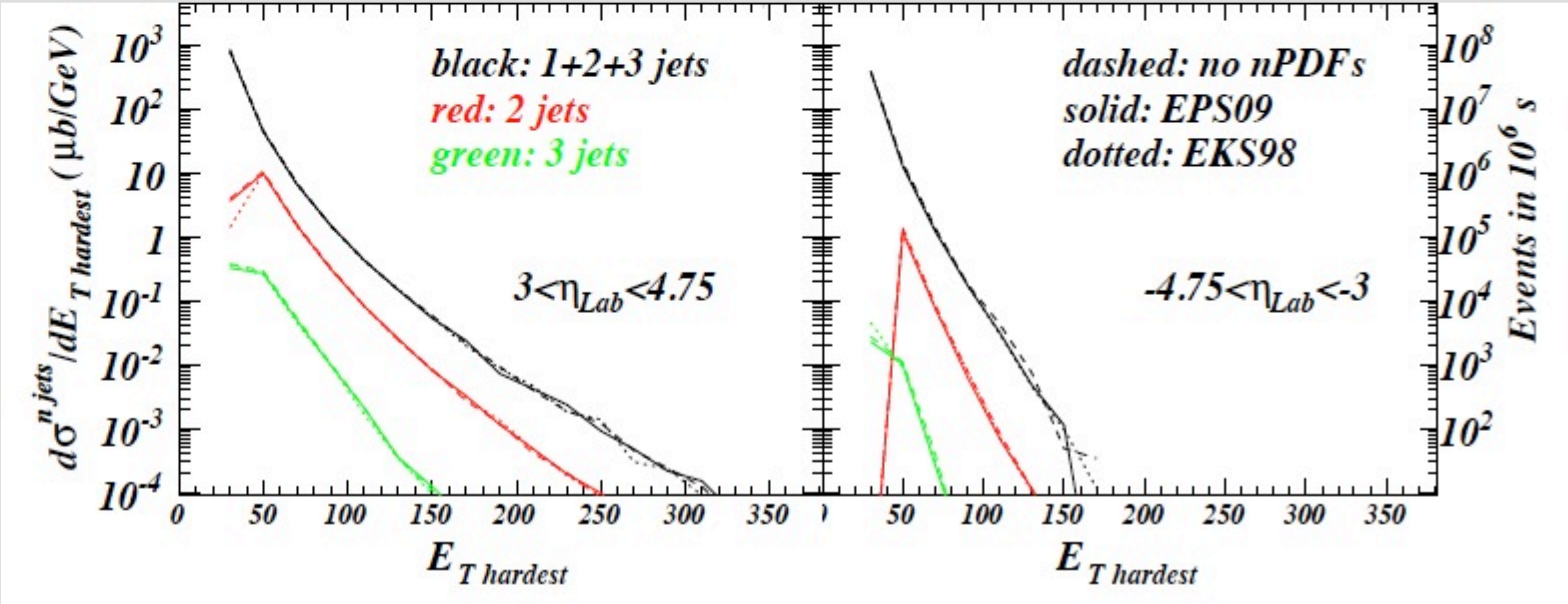
- **Greatly extended kinematical range in pPb collisions**, specially if forward region available for pPb data taking



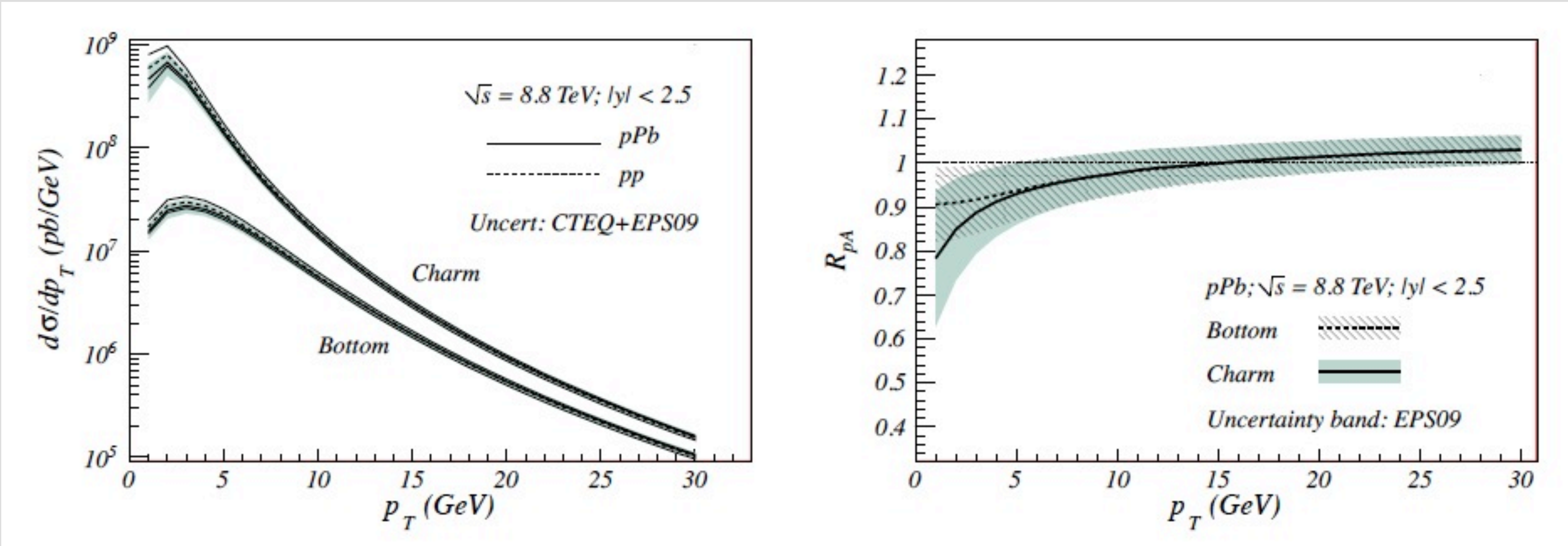


Inclusive jet production

- Inclusive jets in pPb are a crucial baseline to **understand jet quenching in PbPb**
- They are also important to **constrain nuclear modifications** of the Lead PDF
- **nPDF effects are moderate, O(20%) at most**, but yields are large, so it should be possible to access them



Open heavy flavor production



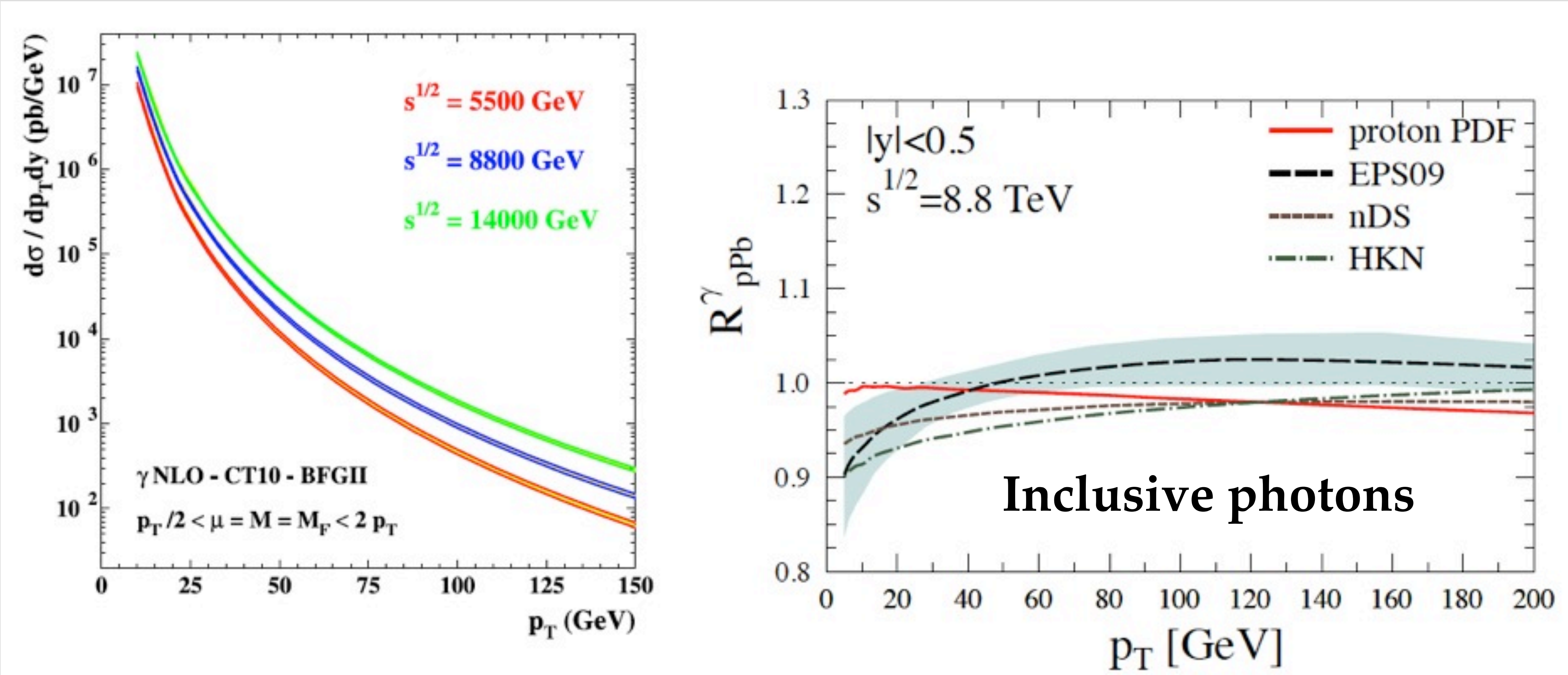
- Open heavy flavor is another essential measurement to **understand heavy flavor jet quenching in PbPb**

- They are also important to **constrain nuclear modifications** of the Lead PDF

- **nPDF effects can be as large O(30%),** but require to reconstruct the transverse momentum of the heavy meson down to vert small scales

Photon production

- Complementary information from the **gluon nPDF**s as compared to inclusive jets. Also **important benchmark** for photon production in PbPb
- Large rates, but **requires to isolate the direct photon signa**l from the fragmentation component and the copious background from shower decays
- Nuclear effects can be almost **20%** at **small p_T**, enhanced in **isolated** as compared to **inclusive** photon data



Towards Collider-Only Nuclear PDFs?

N.B. *Collider-Only* for Proton PDF means
HERA + Tevatron + LHC data only

Collider-Only for Nuclear PDFs means
RHIC + LHC data only

No Fixed Target data in Collider-Only PDF sets

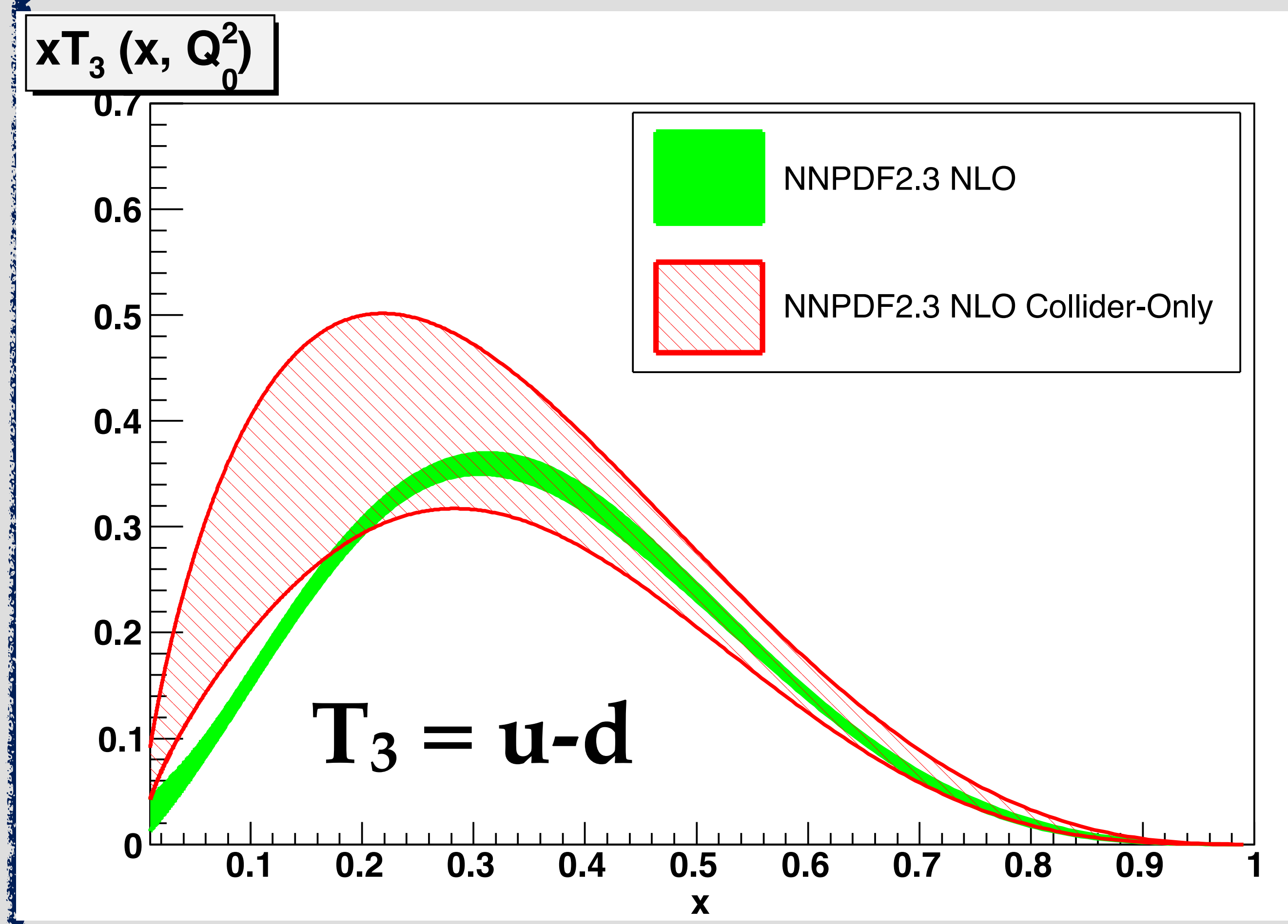
Collider-only Nuclear PDFs?

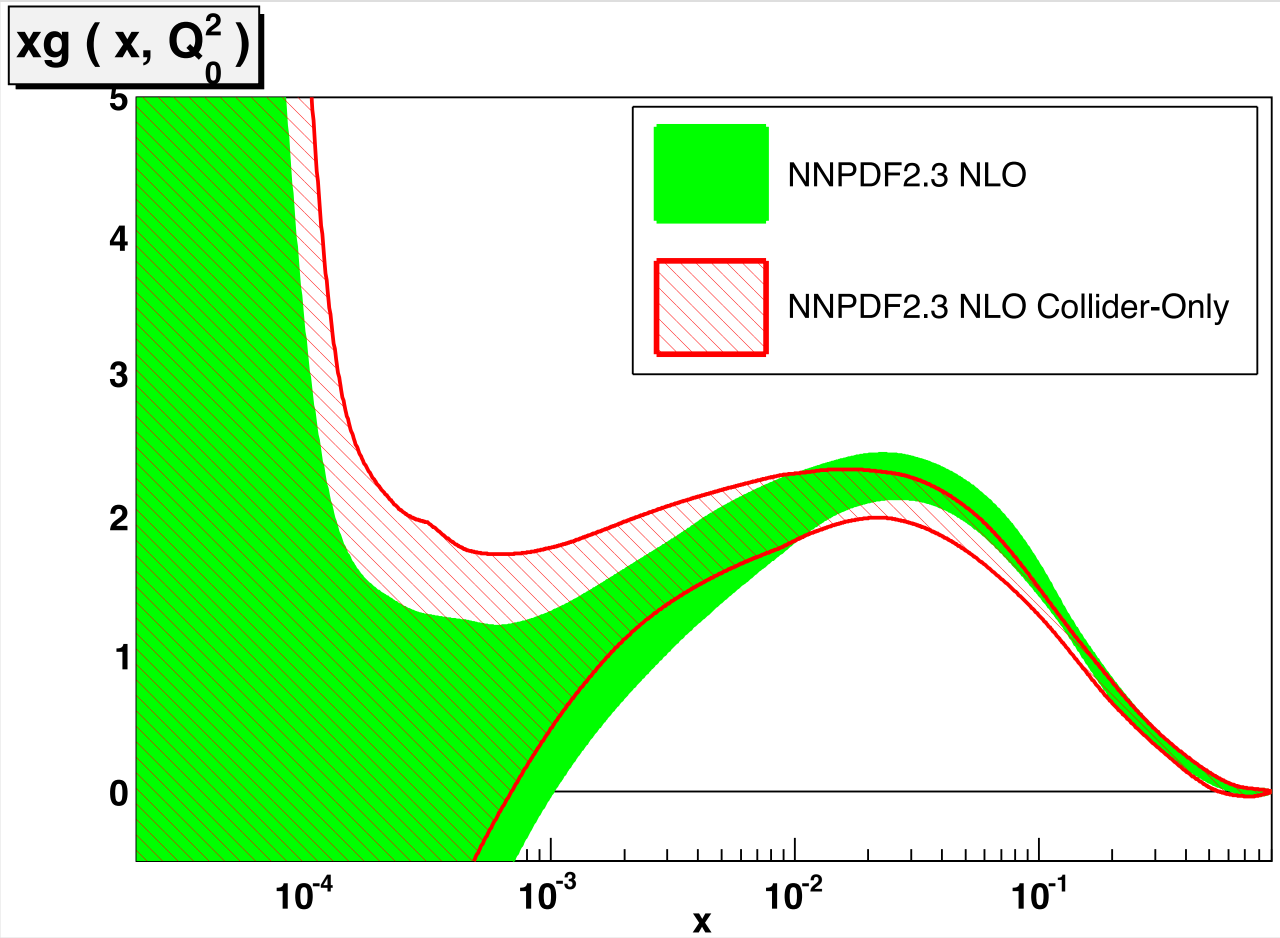
- The **determination of Lead PDFs** (independently from all other nuclear data) from the **LHC pPb** run is appealing for several reasons:
  - **Stringent test of the factorization hypothesis** that underlies any nPDF analysis
  - No need to parametrize **dependence with nuclear number** A
  - **Independent validation of nuclear PDF modifications** determined from lower energy data and DGLAP evolved in **Q^2**

- The feasibility of this program requires:
  - The **highest possible luminosity** to reduce statistical and systematic errors in all relevant hard processes
  - A **careful assessment of the more constraining hard processe**s are, and of the **optimal way of presenting the results** (i.e. with the full experimental correlation matrix)
  - A **robust statistical methodology** in Pb PDFs determination to avoid **theoretical bias** and allow a **reliable interpretation of the results**

Collider-only proton PDFs

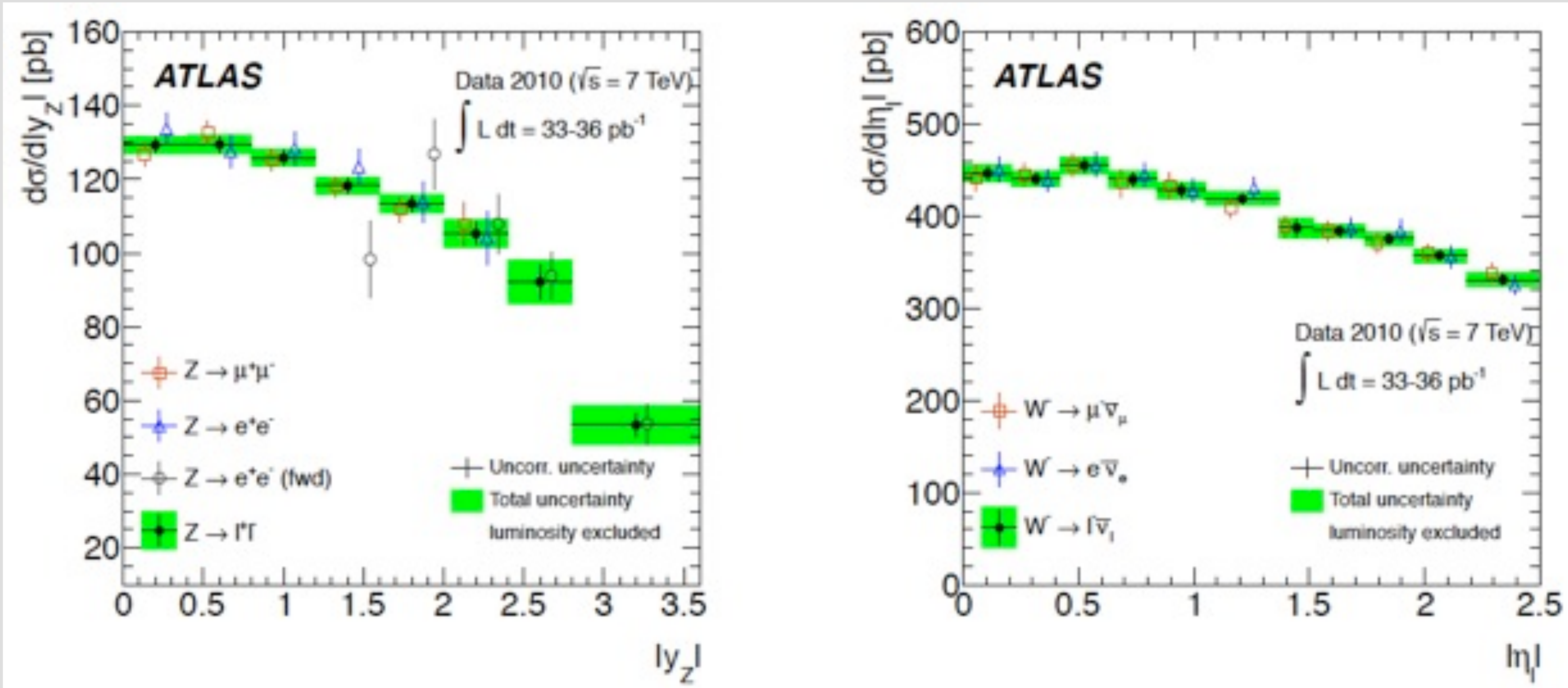
- With available LHC data, PDF sets based on **collider only data** have reduced uncertainties are compared to pre-LHC collider-only sets - but still not competitive with global fits
- NNPDF2.3 **collider-only:** HERA-I inclusive, HERA F2c, ZEUS HERA-II, TeVatron Z and W, LHC W/Z, ATLAS and Tevatron Run-II inclusive jets
- **Collider-only fits** still large uncertainties for **flavour separation** and **strangeness**, will be improved soon with **more LHC data available**
- **Collider data** more robust theoretically and experimentally than **fixed target data**





W and Z production

- ATLAS has measured the ***W* and *Z* lepton rapidity distributions** from **36 pb $^{-1}$**
- The correlation between **W$^+$**, **W$^-$** and **Z** imposes **tight constraints on light quark PDFs** in a **large range of Bjorken-x**, including strangeness. Crucial for nPDFs where a *HERA-like* experiment is not available



- For **L_{pPb}=25 nb^{-1}**, corresponding for hard probes to **L_{pp}=5 pb^{-1}**, we can reescale the statistical errors of the ATLAS measurement

Data Set	$N_{\rm dat}$	$[\eta_{\rm min}, \eta_{\rm max}]$	$\langle \Delta_{\rm stat} \rangle$ pp 36 pb^{-1}	$\langle \Delta_{\rm stat} \rangle$ pPb 25 nb^{-1}
W^+	11	$[0, 2.4]$	1.4 %	3.8 %
W^-	11	$[0, 2.4]$	1.6 %	4.3 %
Z	8	$[0, 3.2]$	2.8 %	7.6 %

- Feasible for pPb with enough accuracy for **Pb PDFs constraints**. Better than measuring the **W lepton asymmetry only**. Improved baseline for **W and Z production in PbPb**

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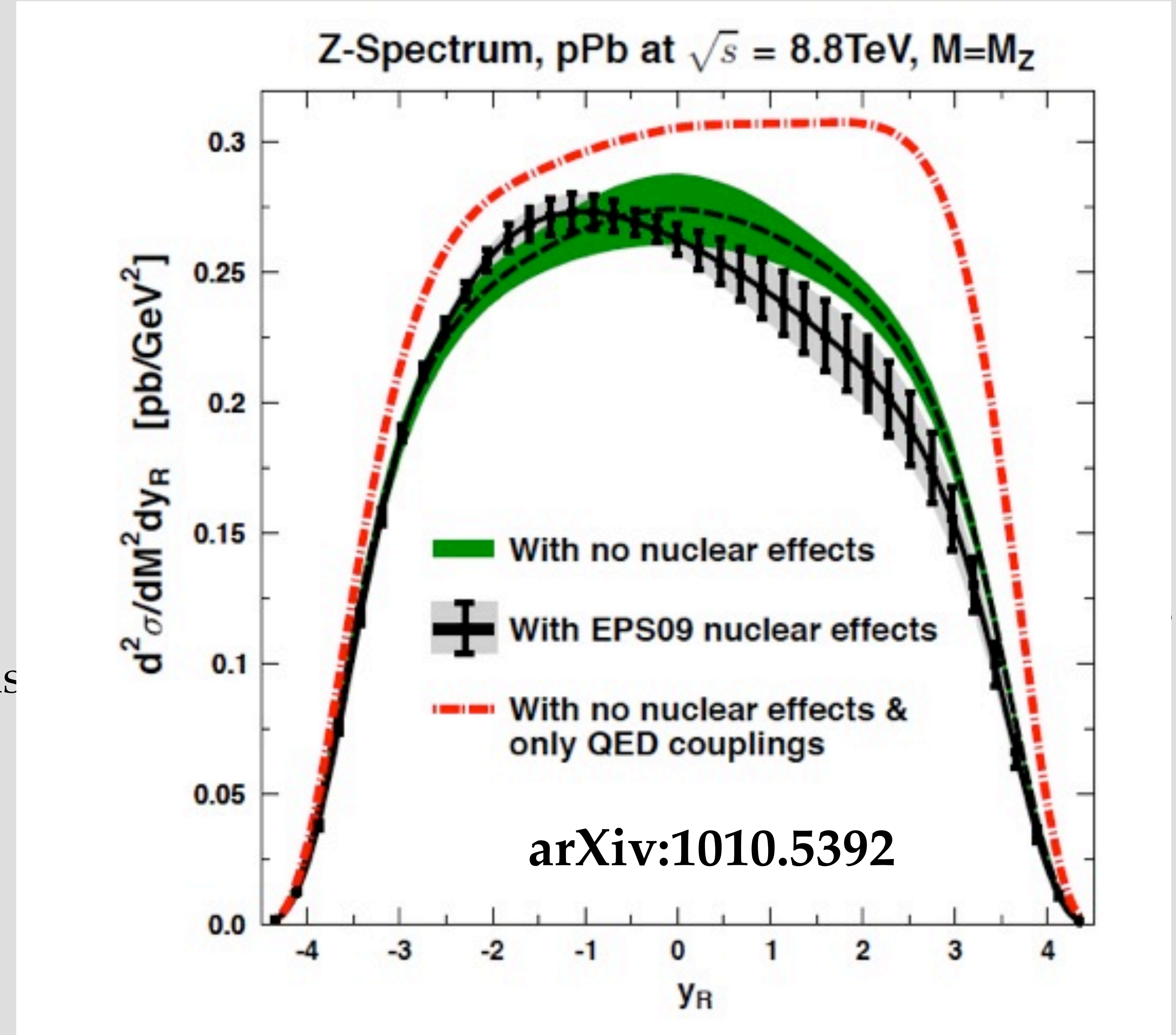

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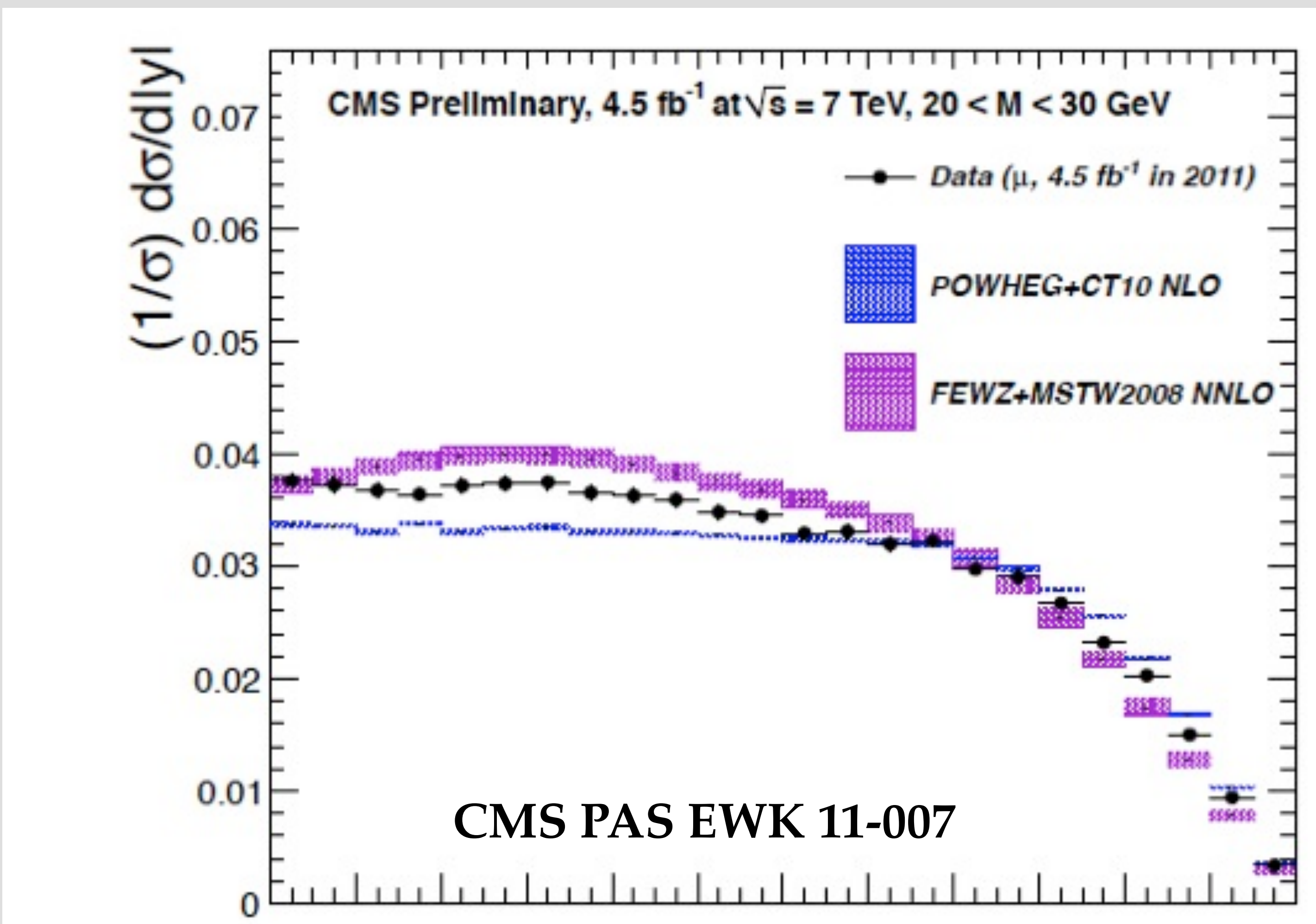
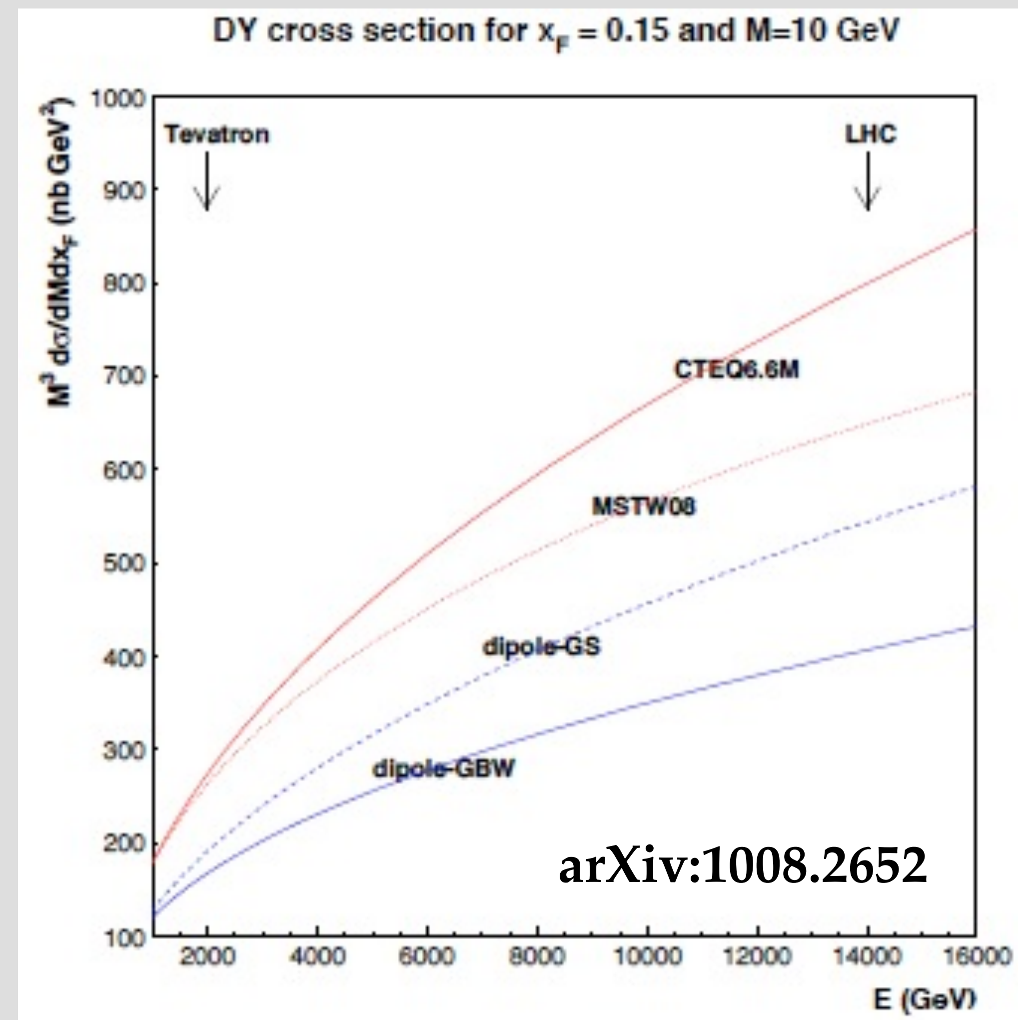
Low mass Drell-Yan production

- **Low mass Drell-Yan** is **very sensitive to nuclear modifications of PDFs of quarks and antiquarks** down to **very small-*x*** thanks to **low scales probed**
- **Clean measurement with small background**, already performed by CMS in pp
- Measurements in **forward rapidities** also interesting for **small-x / CGC studies**





- Need to **optimize binning in M and y** and **estimate rates for pPb**. Potentially very important measurement of the pPb run.

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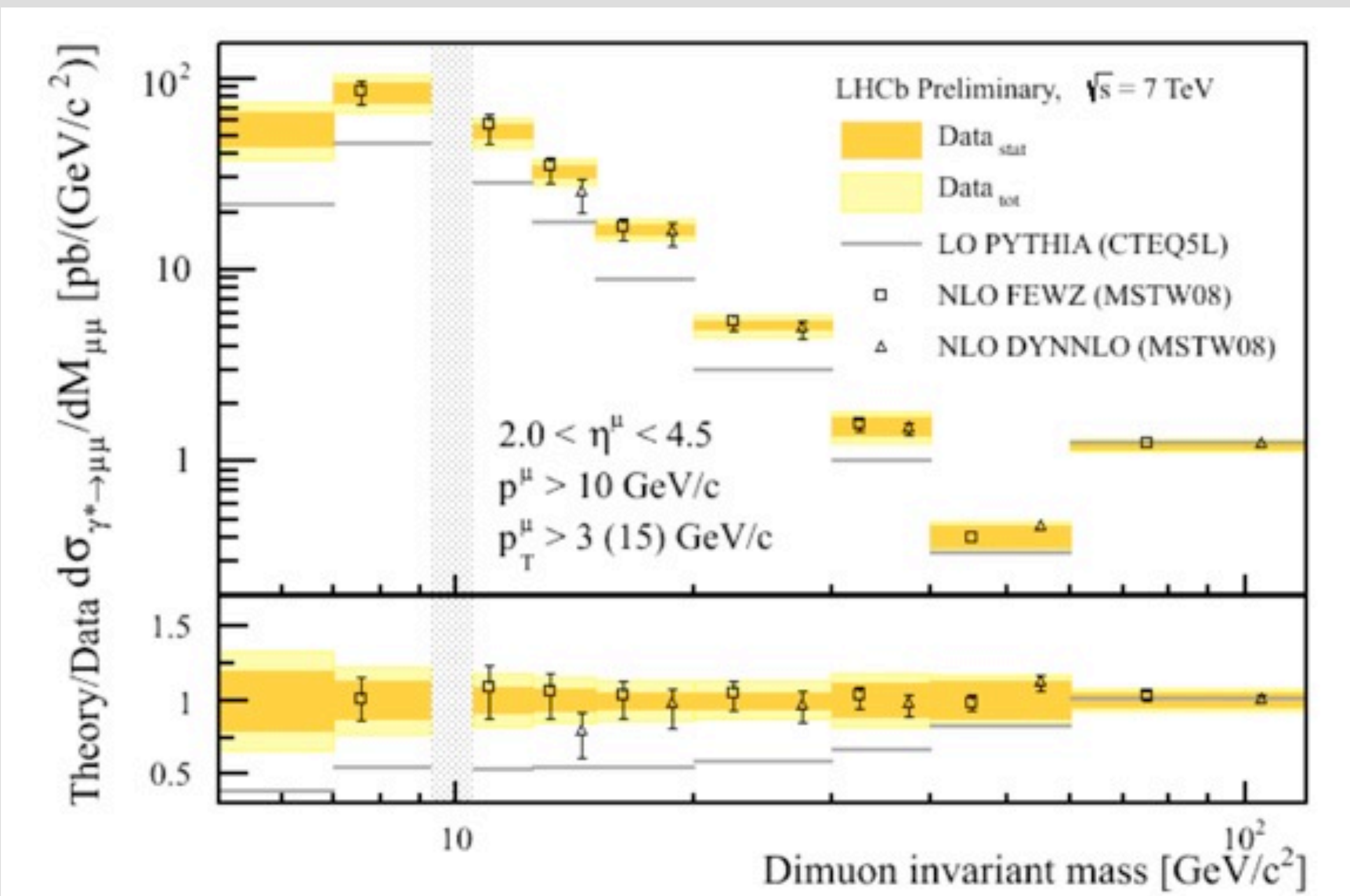
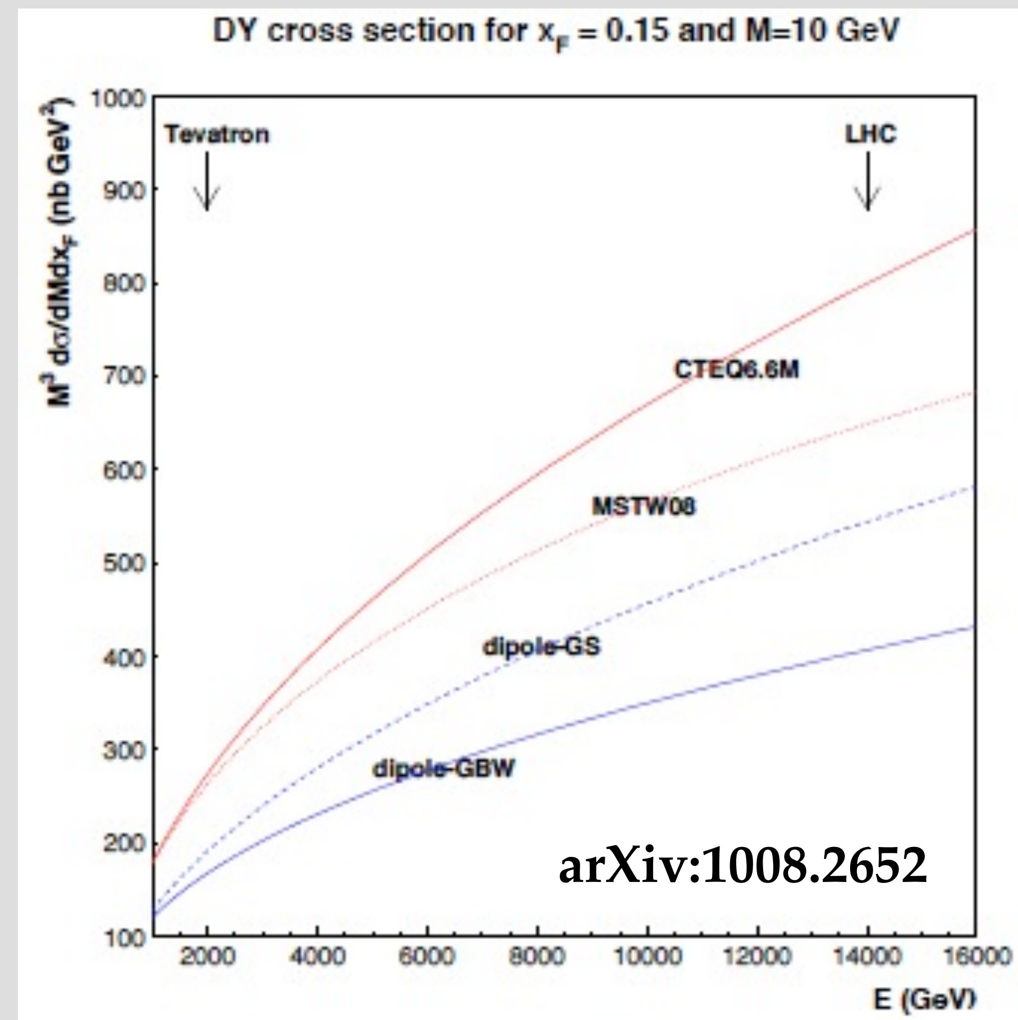
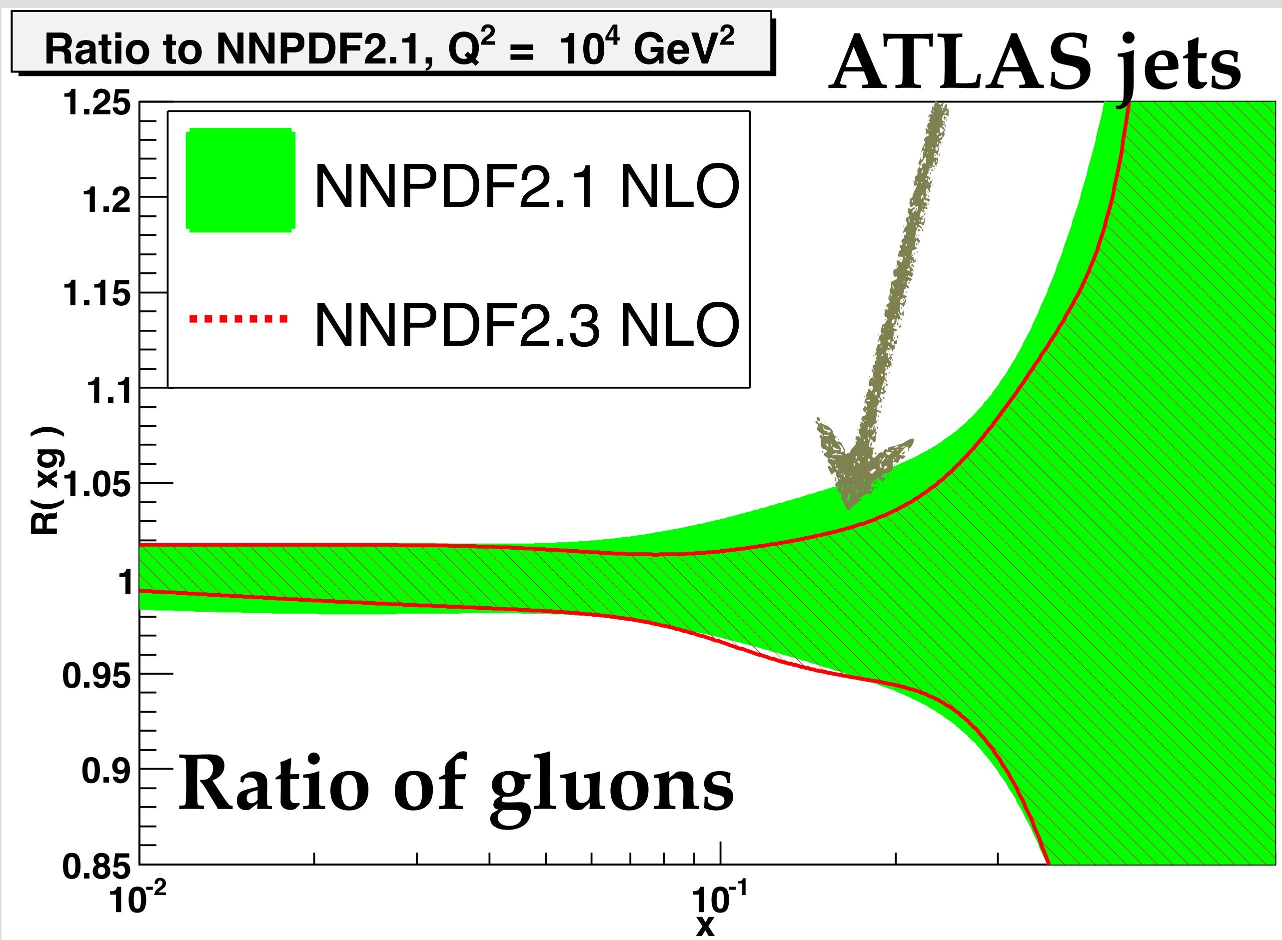


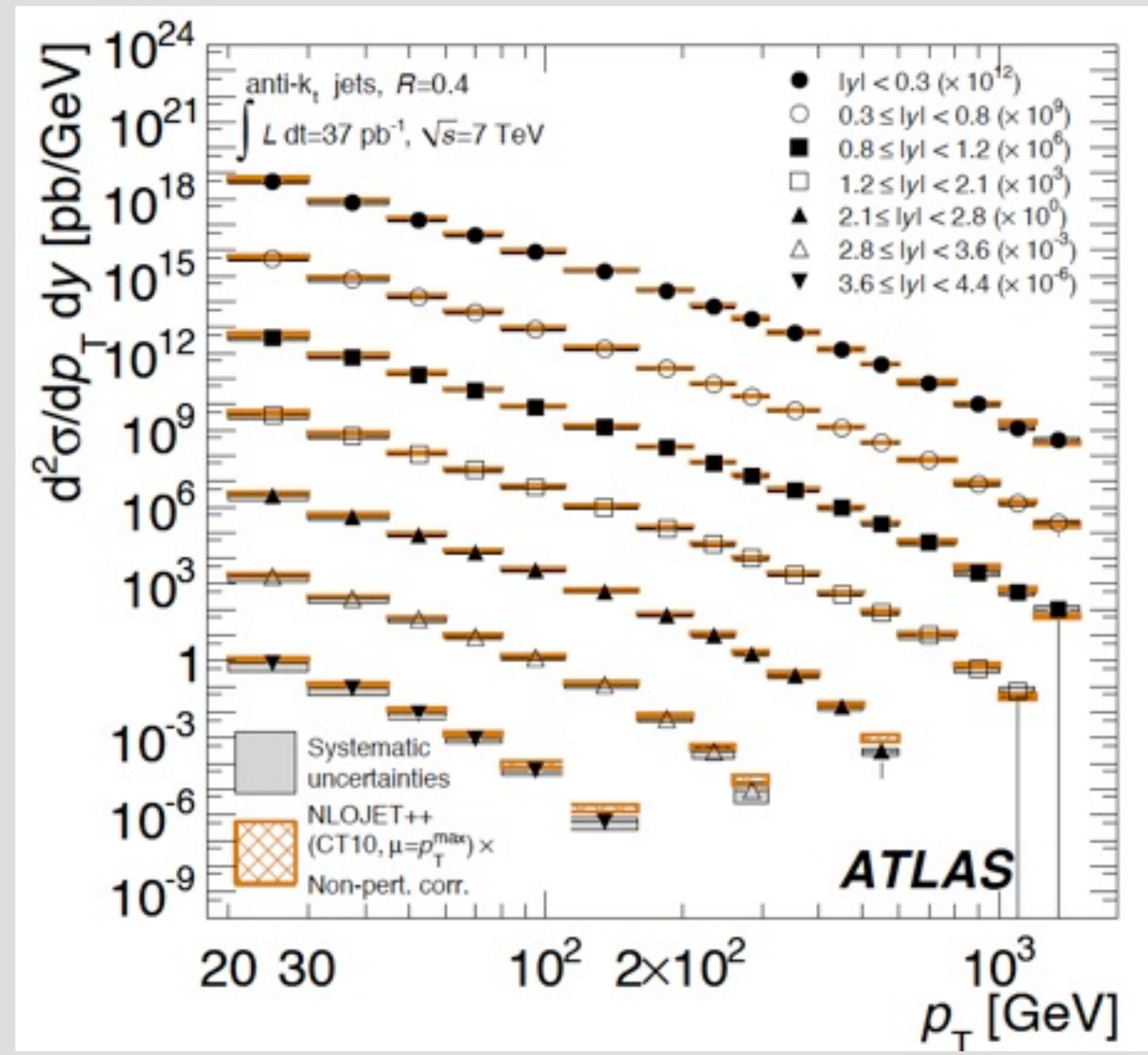


- Need to **optimize binning in M and y** and **estimate rates for pPb**. Potentially very important measurement of the pPb run.

Inclusive jet production

- ATLAS and CMS have provided **inclusive jet cross sections**, ATLAS already included in NNPDF2.3, **constraints on large-*x* gluon**
- Constraints on the gluon PDF from **medium and large p_T** data, and moderate **non-perturbative** corrections at **small p_T**

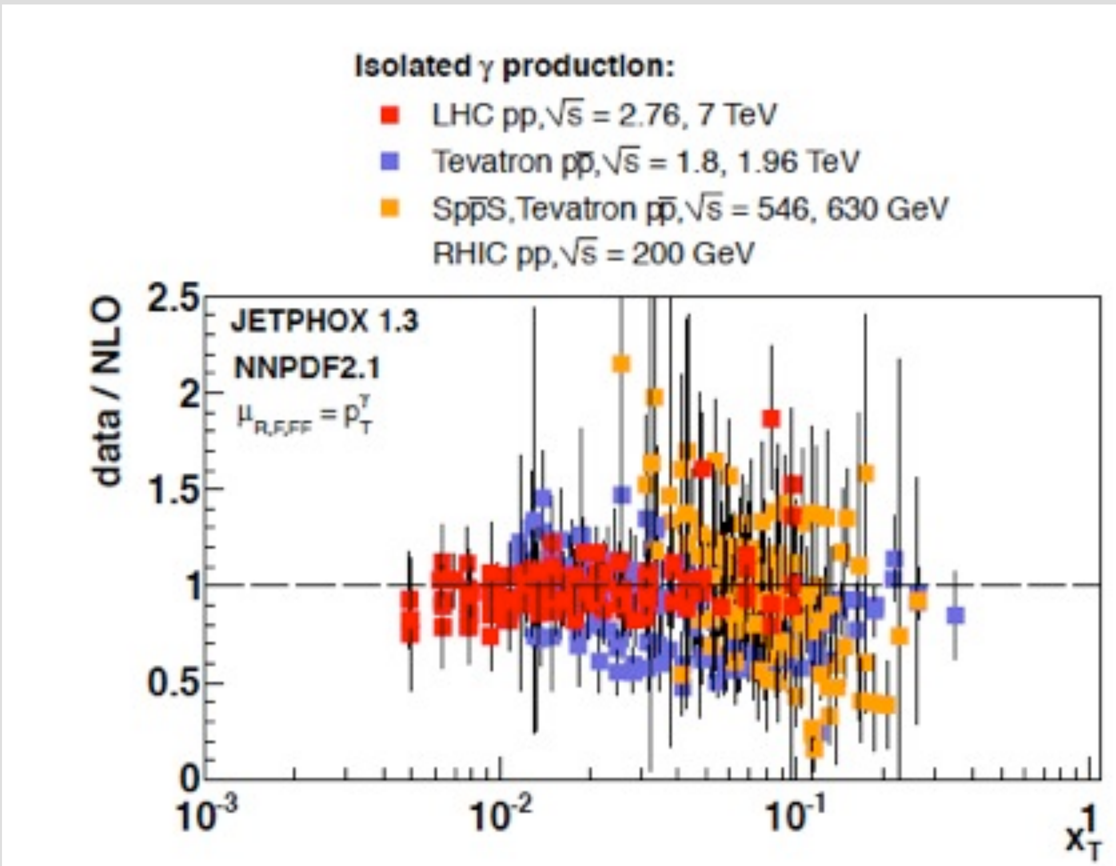


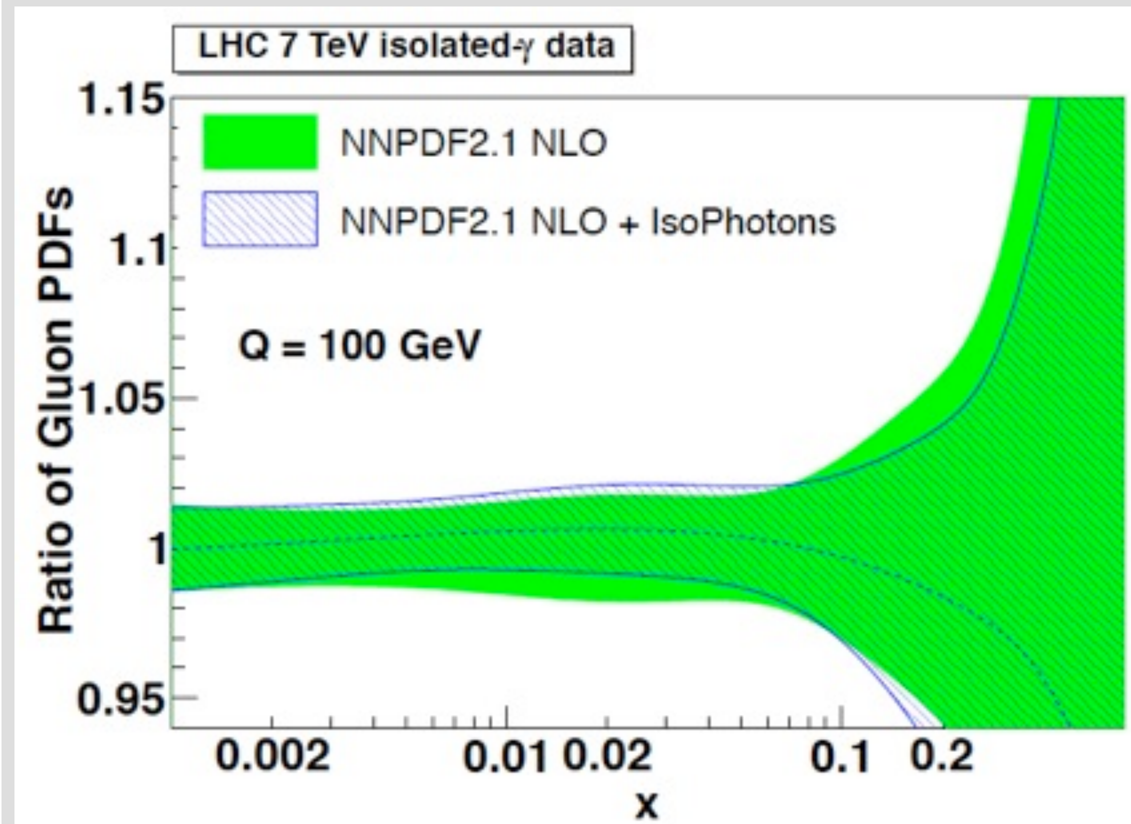


- To **disentangle nuclear corrections** in the **jet data from pPb** important to minimize non-perturbative corrections at **small p_T**

Isolated photon production

- ATLAS and CMS have measured with **36 pb $^{-1}$** isolated photon cross section differentially in the **photon p_T** and **rapidity**
- Recent reanalysis of all available isolated photon data **from PHENIX to LHC energies** concludes that **isolated photon data provides a direct handle on the gluon proton PDF**





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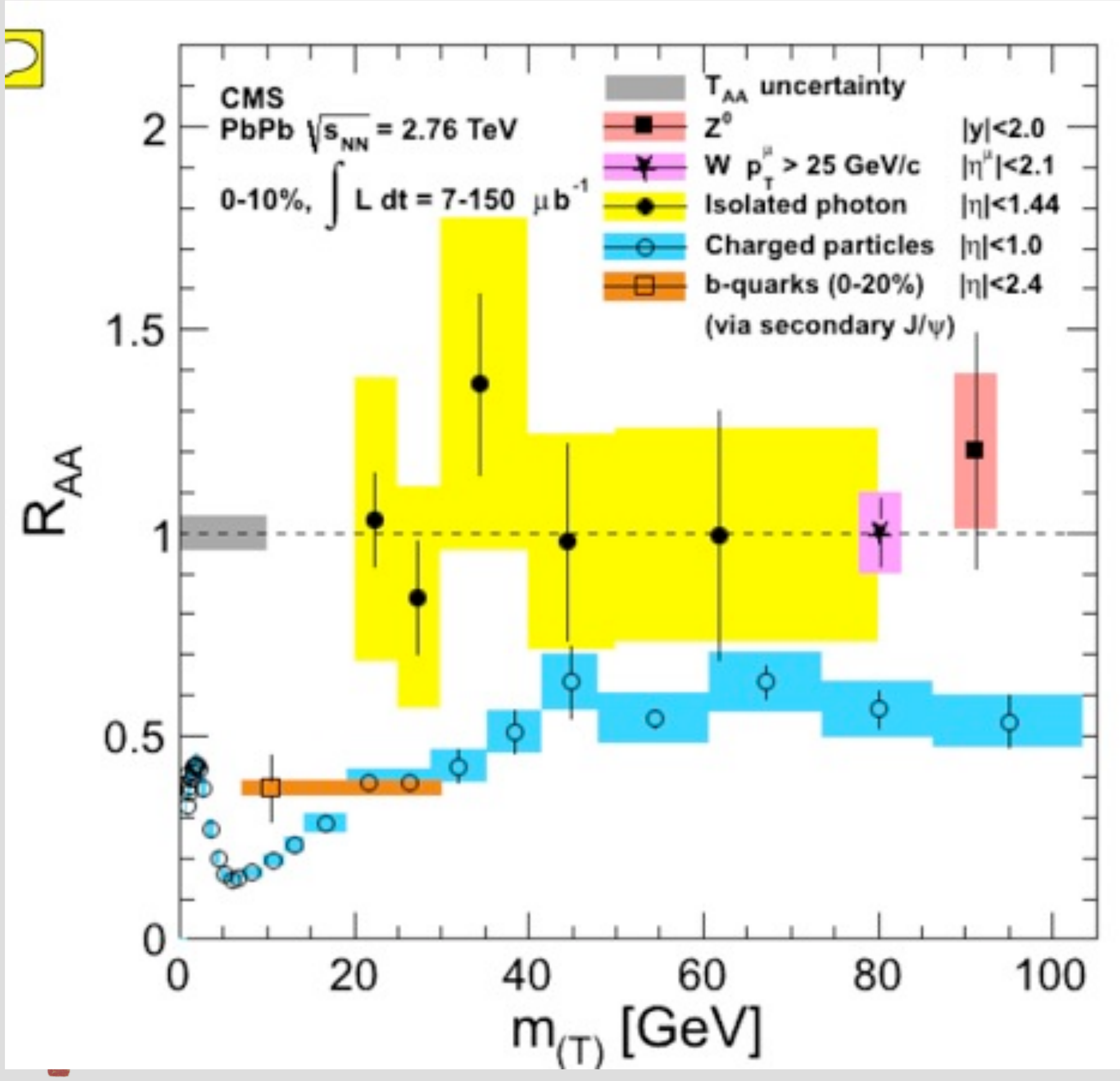
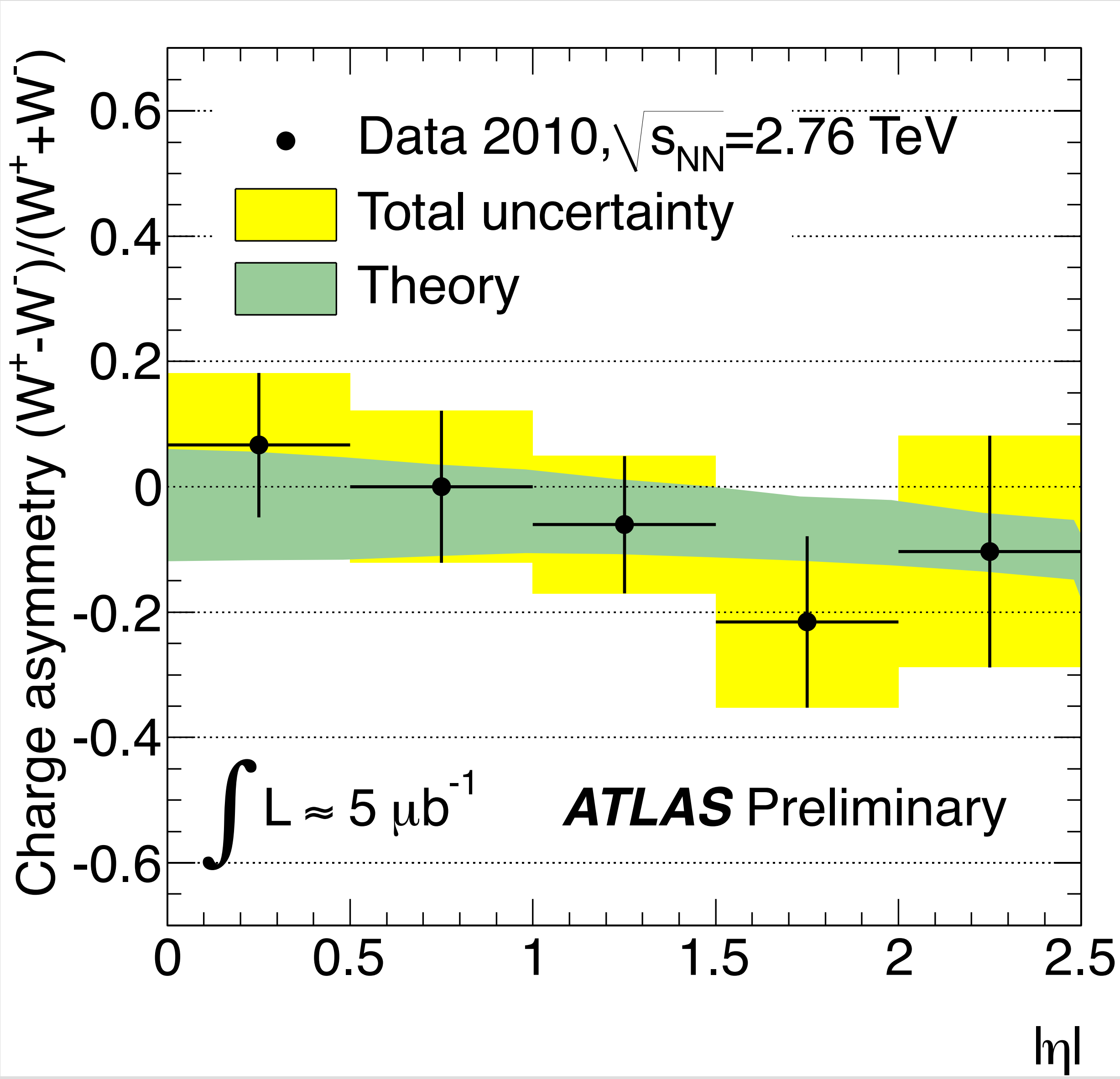
- The constraints to the gluon PDFs dominated by **the central region at low transverse momentum**, where yields are largest, and also when nuclear effects more important

$\eta_\gamma, p_{T,\gamma}$	$\langle\Delta_{\rm stat}\rangle$ pp 36 pb^{-1}	$\langle\Delta_{\rm stat}\rangle$ pPb 25 nb^{-1}
0, 25 GeV	2 %	5 %
1.8 ,25 GeV	8 %	20 %
0, 250 GeV	15 %	40 %

Gauge Boson production in Heavy Ion Collisions

- The feasibility of **isolated photon** and ***W,Z* production** has already been demonstrated in the much more complex environment of **PbPb collisions**
- **Color neutral hard probes** at the LHC are **not suppressed by hot nuclear matter effects**, as already verified in RHIC (for photons only)
- The corresponding measurements in **pPb** should have smaller experimental errors thanks to the **cleaner environment**





Absolute Luminosity in pPb collisions

- In heavy ion collisions, it is typical to provide results in terms of **yields,** normalized to a **proton-proton** reference
- It would be desirable to provide instead **absolute cross sections** for the **pPb data: maximizes sensitivity to cold nuclear matter** effects with reduced theory input
- This requires a **luminosity determination in pPb**, for example with a Van der Meer scan. **Is this feasible?**

CMS pp Luminosity Winter 2012: 2.2% uncertainty

Source	Uncertainty (%)
Stability across pixel detector regions	0.3
Pixel gains and pedestals	0.5
Dynamic inefficiencies	0.4
Length-scale correction	0.5
Beam width evolution	0.6
Beam intensity - DCCT	0.3
Beam intensity - FBCT	0.5
Beam intensity - Ghosts	0.2
Scan-to-scan variations	1.5
Afterglow	1.0
Total	**2.2**

Summary and outlook

- The pPb run offers interesting possibilities for **nuclear PDF constraints** and detailed **validation of factorization in pPb collisions**

- The most important measurements in terms of Lead PDF constraints are the ***W,Z* lepton rapidity distribution** and **low mass Drell-Yan for quarks**, and **jets and isolated photons for the gluon**, all with full experimental correlation matrix. Forward measurements (LHCb) greatly extend kinematic reach.

- The ultimate potential of the pPb program will be dictated by the **final integrated luminosity.** If luminosity is increased, additional nPDFs probes can be envisaged: **W+charm, photon+jets, top quarks**, ...

- It is possible (and desirable) to perform a **Pb PDF analysis based on LHC pPb data** alone. A **toy analysis based on pseudo data** could be performed prior to data taking to **optimize the measurements and the experimental analysis**.