Incorporating quarkonium data into nuclear PDF fits

Stéphane Delorme

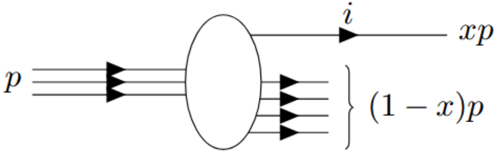
(under grant no. 2019/34/E/ST2/00186)

Quarkonia as Tools 2023

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

PDFs

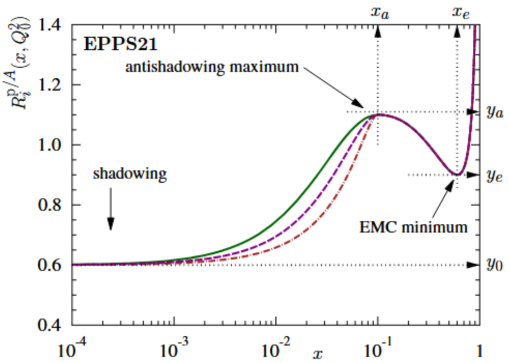
- Probability densities to find a parton with a momentum fraction x inside of a hadron of momentum p



- Enter calculations involving hadrons in the initial state
- Non-perturbative, Universal objects
- Fitted on experimental data
- Only focus on collinear PDFs

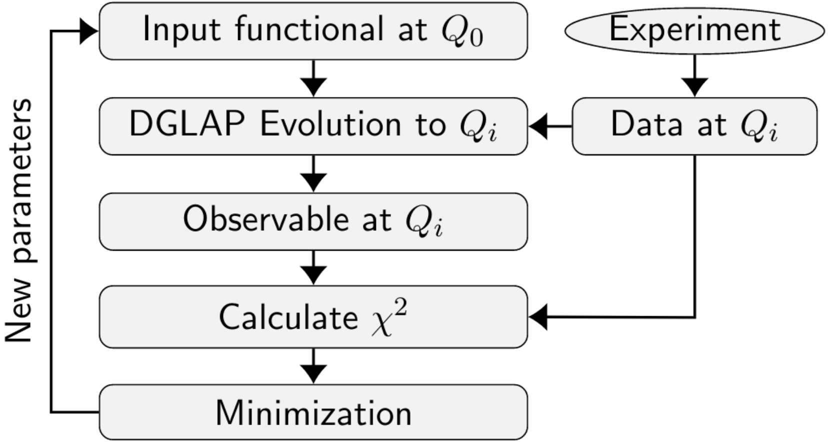
Nuclear PDFs

- PDFs are modified when nuclei are involved
- The nuclear PDF is not just Z times the proton PDF + N times the neutron PDF



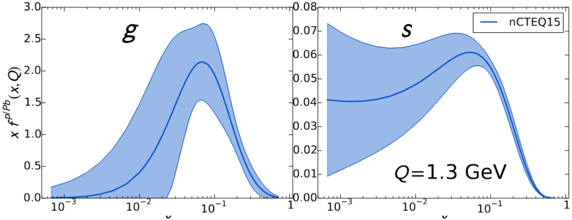
- $f_i^A(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$
- $f_i^{p/A}(x, Q^2) = R_i^{p/A}(x, Q^2) f_i^p(x, Q^2)$
- Isospin symmetry to obtain $f_i^{n/A}(x, Q^2)$

"Standard" fitting procedure



Current status of nPDFs

- More precise (n)PDFs → more precise predictions for observables measured at colliders (notably the future EIC)

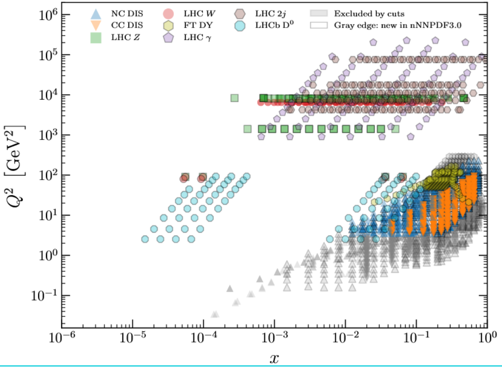


- Very large gluon uncertainties, especially at low x
  → large uncertainties on other flavors via DGLAP evolution

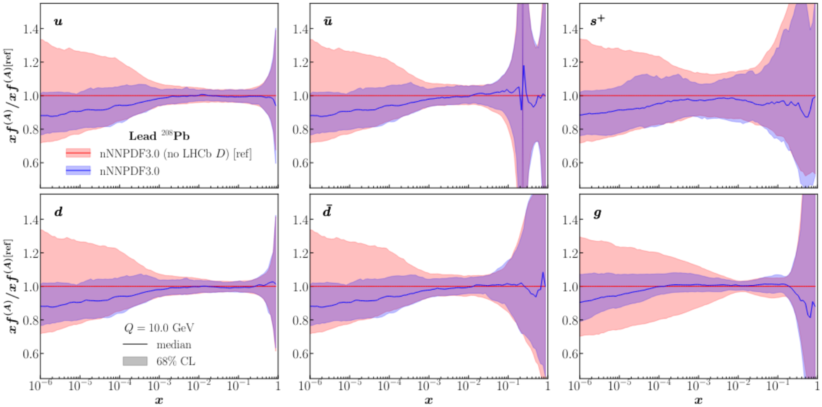
Won't be an exhaustive overview, for a more detailled one see I. Schienbein talk at QCD@LHC 2022

nNNPDF3.0 (2201.12363)

- Parametrization of the bound proton PDFs $f_i^{p/A}$ using neural networks at scale $Q_0 = 1$ GeV
  (see Valerio's lecture on collinear PDFs)
- 256 parameters
- 2188 data points (1467 old, 721 new)
- Processes:
  - (ν)DIS (411 new points)
  - DY (146 new points)
  - WZ
  - γ prompt production from ATLAS 8 TeV
  - Dijet (New data from CMS 5 TeV)
  - D meson data from LHCb 5 TeV
    Included via Bayesian reweighting
    (not fitted)



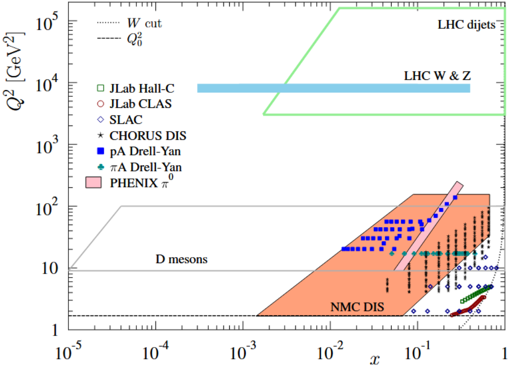
nNNPDF3.0 (2201.12363)



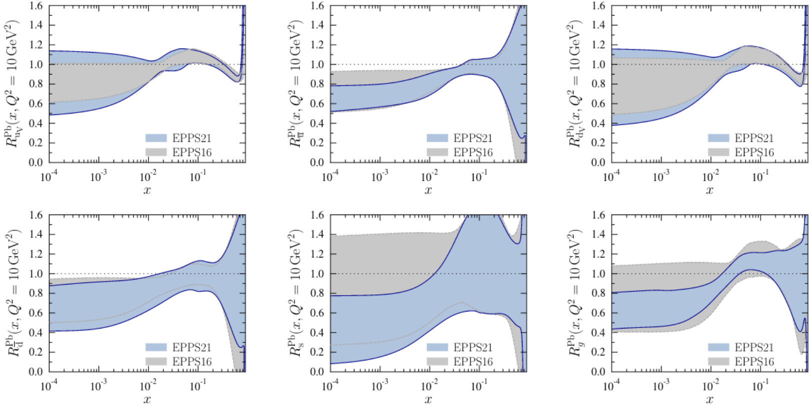
- Large reduction of gluon uncertainties thanks to LHCb D meson data.

EPPS21 (Eur. Phys. J. C 82, 413 (2022))

- Parametrization of the nuclear modification factor $R_i^{p/A}$ at $Q_0 = 1.3$ GeV
- 24 free parameters (from 20 in EPPS16)
- 2077 data points (1742 old, 335 new)
- Processes:
  - (ν)DIS (New data from JLAB)
  - DY
  - SIH
  - WZ (New $W^{\pm}$ data from CMS 8 TeV)
  - Dijet (New data from CMS 5 TeV)
  - D meson data from LHCb 5 TeV



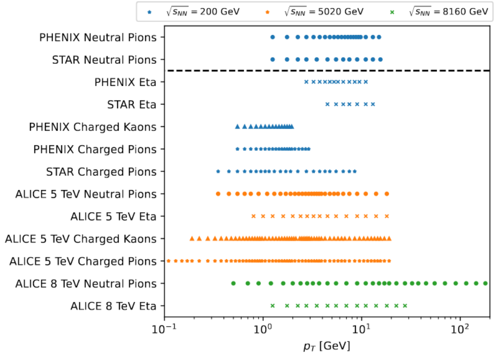
EPPS21 (Eur. Phys. J. C 82, 413 (2022))



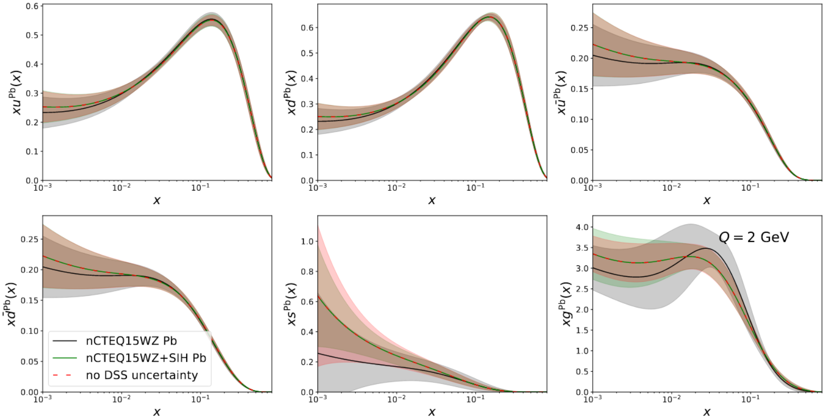
- Important reduction of gluon and strange quark uncertainties. Due to D meson data for the gluon and due to W data and gluon uncertainty reduction for the strange quark

nCTEQ15WZSIH (Phys. Rev. D 104, 094005)

- Parametrization of the bound proton PDFs $f_i^{p/A}$ at $Q_0 = 1.3$ GeV
- 19 parameters
- 936 data points (860 old, 76 new)
- Processes:
  - DIS
  - DY
  - WZ
  - SIH ($\pi^0, \pi^\pm, K^\pm$) from RHIC/LHC



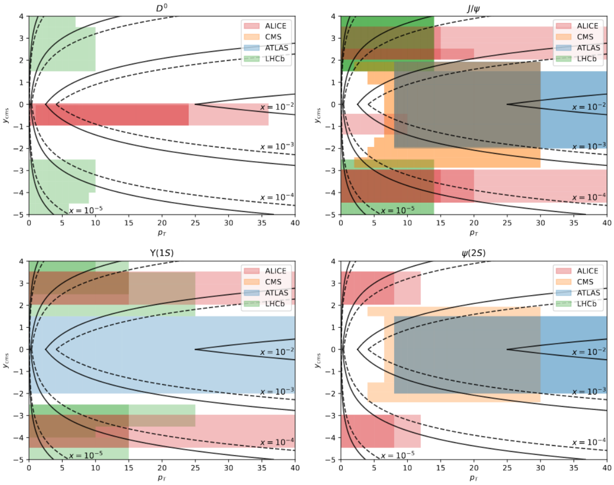
nCTEQ15WZSIH (Phys. Rev. D 104, 094005)



- Flattening of the gluon nPDF around x = 0.05 and reduction of uncertainties thanks to SIH meson data

Why quarkonia? (And open heavy flavors)

- Large data sets from LHC experiments
- Sensitivity to gluon nPDFs down to very low x ($\approx 10^{-4.5}$)



nCTEQ15HQ (Phys. Rev. D 105, 114043)

- Data-driven approach to include D/quarkonium data (implemented from Phys. Rev. Lett. 121, 052004, Phys. Rev. D 104, 014010)
- Parametrization of the nPDFs at $Q_0 = 1.3$ GeV
- 19 parameters (same as nCTEQ15WZSIH)
- 1484 data points (936 old, 548 new)
- Processes:
  - DIS
  - DY
  - WZ
  - SIH
  - D meson data from LHCb
  - Quarkonium data from LHC

$$xf_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

$$c_k \Rightarrow c_k(A) \equiv p_k + a_k(1 - A^{-b_k})$$

Heavy flavor fitting procedure

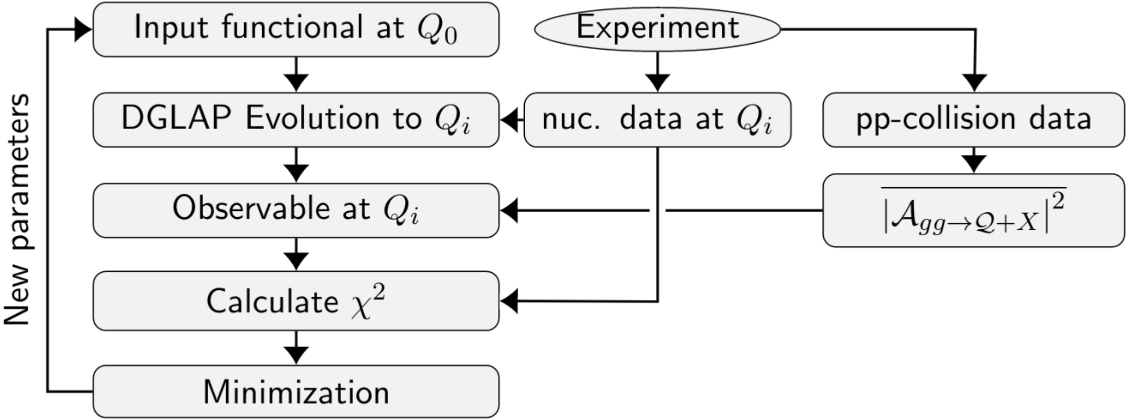
- Cross-section parametrized as:

$$\sigma(AB \to \Phi + X) = \int dx_1 dx_2 f_{1,g}(x_1, \mu) f_{2,g}(x_2, \mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}(gg \to \Phi + X)|^2} dPS$$

$$\overline{|\mathcal{A}(gg \to \Phi + X)|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} e^{a|y|} \times \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2}} & p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{p_T^2}{M_Q^2}} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_q^2}\right)^{-n} & p_T > \langle p_T \rangle \end{cases}$$

- 2 assumptions:
  - gg-channel dominant
  - Only consider 2→2 kinematics
- 5 additionnal parameters
- a parameter added to include rapidity dependence

Heavy flavor fitting procedure

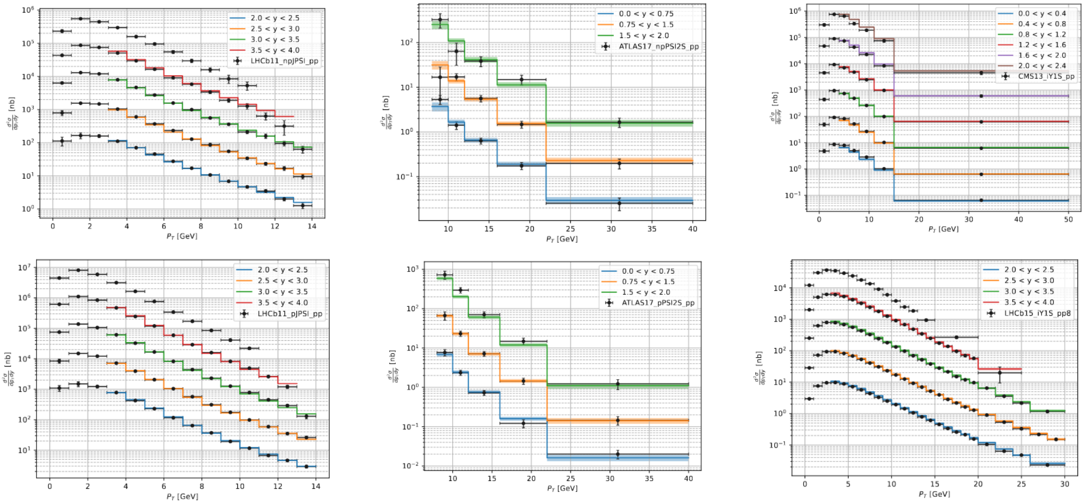


Proton-proton baseline

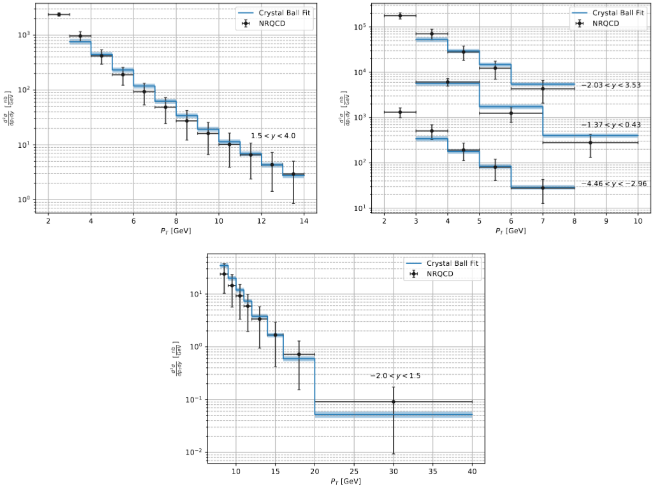
- Cuts imposed on data
  - $p_T < 3$ GeV
  - Data outside $-4 \leq y_{cms} \leq 4$

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
κ	0.33457	0.47892	0.15488	0.94524	0.21589	0.45273
λ	1.82596	0.30379	0.12137	0.06562	0.07528	0.13852
$\langle p_T \rangle$	2.40097	5.29310	-7.65026	8.63780	8.98819	7.80526
n	2.00076	2.17366	1.55538	1.93239	1.07203	1.64797
a	-0.03295	0.02816	-0.08083	0.22389	-0.10614	0.06179
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

Proton-proton baseline



Comparison with NRQCD calculations (J/Ψ)

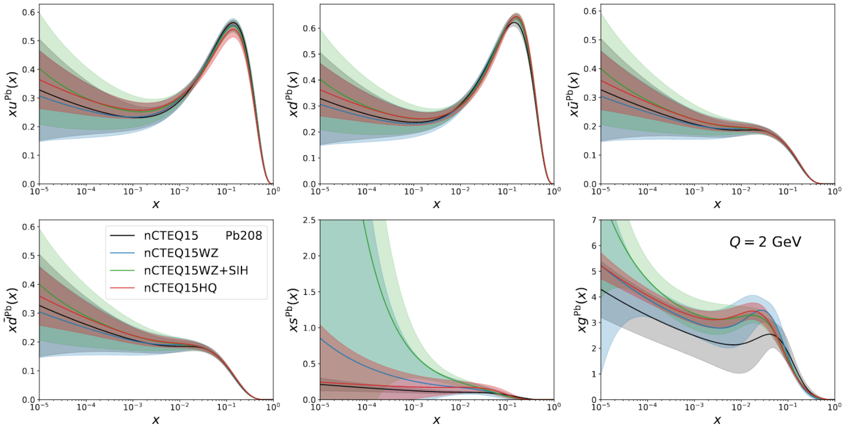


- NRQCD from M. Butenschön and B. Kniehl
  Phys. Rev. Lett. 106 (2011) 022003
- NRQCD uncertainties due to scale variation from $\frac{\mu_{\text{NRQCD},0}}{2}$ to 2 $\mu_{\text{NRQCD},0}$.
- $\mu_{NRQCD,0} = \sqrt{p_{\text{T}}^2 + 4m_c^2}$
- Very good agreement, smaller uncertainties for the Crystal ball fit

nPDFs data sets and cuts

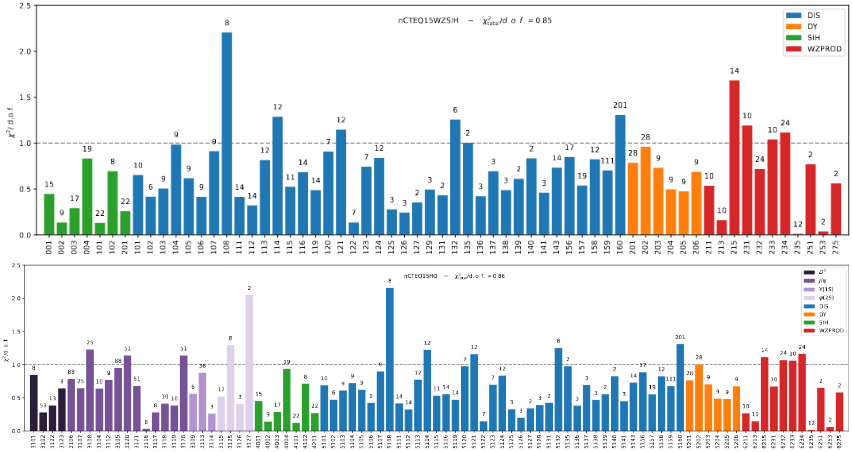
- Includes data sets from nCTEQ15WZSIH
- Same 19 parameters as nCTEQ15WZSIH
- 499 additionnal data points for $pPb \to D^0 + X$, $pPb \to J/\Psi + X$, $pPb \to \Psi(2S) + X$ and $pPb \to \Upsilon(1S) + X$
- Same cuts as the proton-proton baseline with additionnal cuts:
  - D^0 data with $p_T > 15$ GeV is excluded (no baseline data)
  - 2 points from the 2018 LHCb $\Upsilon(1S)$ dataset are excluded (high χ^2, may be explained by their presence at the high-p_T edge of the experiment)

nPDFs fit

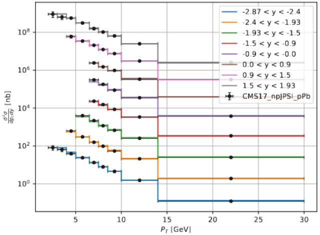


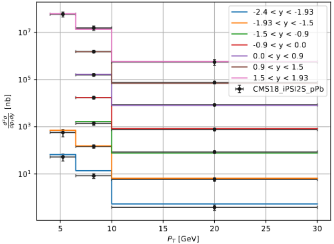
- Gluon uncertainties greatly reduced, especially at very low x

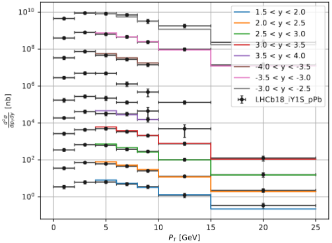
nPDFS fit χ^2

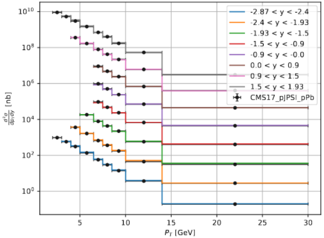


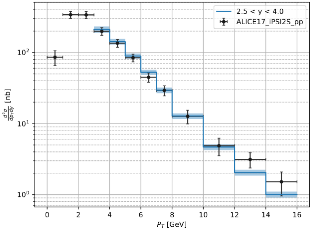
Data comparison

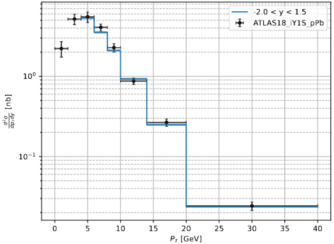












Conclusions

- Global effort towards the determination of more precise (n)PDFs

- Data-driven approach reducing the uncertainties on the low x gluon nPDF
- Compatible with other data sets
- Fast calculation,compared against rigorous pQCD calculations

- However, does the collinear factorization still holds? (effect of saturation at low x and moderately hard scales)
- What about effects like fully coherent energy loss?