Some notes about comovers

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Ingredients for the cross section

$$\tau \frac{d\rho^{\mathcal{Q}}}{d\tau}(b,s,y) = -\sigma^{co-\mathcal{Q}}\, \rho^{co}(b,s,y)\, \rho^{\mathcal{Q}}(b,s,y)$$

$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\text{geom}}\left(1 - \frac{E_{\text{Binding}}}{\langle E_{co}\rangle}\right)^n$$

$\sigma_{\text{geom}} \equiv \pi r^2_{\mathcal{Q}_{b\bar{b}}}$

$E_{\text{Binding}} \equiv 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, *i.e.* the threshold energy to break the bound state

$E^{co} = \sqrt{p^2 + m^2_{co}}$ the average energy of the comovers in the quarkonium rest frame

- Geometrical cross section: $\sigma^{Q}_{\text{geo}} \simeq \pi r^2_Q$, where r_Q is the quarkonium Bohr radius
- It can be evaluated by solving the Schrodinger equation with a well-choosen potential reproducing the quarkonium spectroscopy
- Cornell potential: **Satz arXiv:0512217**

$$V(r) = \sigma\, r - \frac{\alpha}{r}$$

$$m_c = 1.25 \text{ GeV},\ m_b = 4.65 \text{ GeV},\ \sqrt{\sigma} = 0.445 \text{ GeV},\ \alpha = \pi/12$$

- Equivalent

arXiv:1903.08063

$$a_0 = \frac{2}{MC_F\alpha_s(1/a_0)}$$

$$M = M_b = 4.78 \text{ GeV and } M = M_c = 1.67 \text{ GeV}$$

Ingredients for the cross section

	E_{thr}^{Q}	r_Q	σ_{geo}^{Q}
Υ(1S)	1100 MeV	0.14 fm	0.62 mb
χ_b(1P)	670 MeV	0.22 fm	1.52 mb
Υ(2S)	540 MeV	0.28 fm	2.46 mb
χ_b(2P)	300 MeV	0.34 fm	3.63 mb
Υ(3S)	200 MeV	0.40 fm	5.03 mb
χ_b(3P)	50 MeV	0.55 fm	10.21 mb

	E_{thr}^{Q}	r_Q	σ_{geo}^{Q}
J/ψ	630 MeV	0.25 fm	1.96 mb
χ_c(1P)	200 MeV	0.36 fm	4.07 mb
ψ(2S)	50 MeV	0.45 fm	6.36 mb

Ingredients for the cross section

- The temperature dependence comes through the comover distributions

$$\mathcal{P}(E^{\rm co};T_{\rm eff}) \propto \frac{1}{e^{E^{\rm co}/T_{\rm eff}}-1}$$

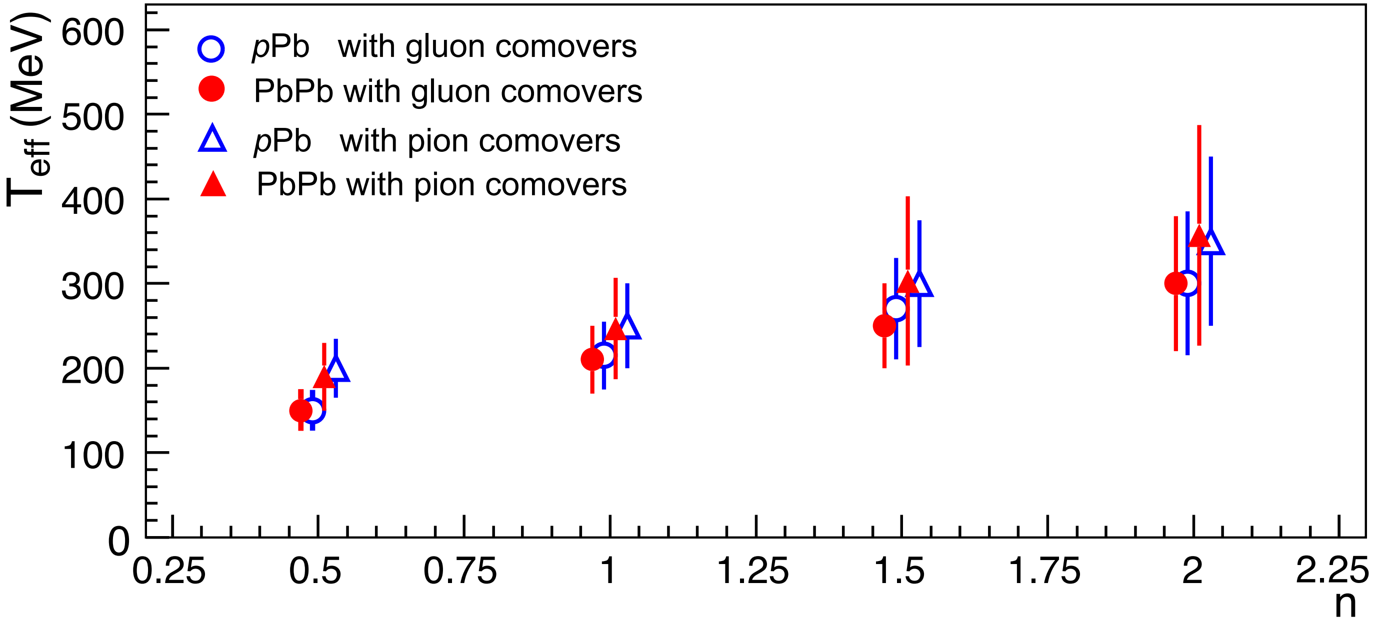
- Average over BE distribution of the comovers

$$\langle\sigma^{{\rm co}-Q}\rangle(T_{\rm eff},n) = \frac{\int_{E^Q_{\rm thr}}^{\infty} dE^{\rm co}\,\mathcal{P}(E^{\rm co};T_{\rm eff})\,\sigma^{{\rm co}-Q}(E^{\rm co})}{\int_{E^Q_{\rm thr}}^{\infty} dE^{\rm co}\,\mathcal{P}(E^{\rm co};T_{\rm eff})}$$

Ingredients for the cross section

- Average over BE distribution of the comovers $\mathcal{P}(E^{\rm co};T_{\rm eff}) \propto 1/(e^{E^{co}/T_{eff}}-1)$

$$\langle \sigma^{\rm co-Q}\rangle(T_{\rm eff},n) = \frac{\int_{E^Q_{\rm thr}}^{\infty} dE^{\rm co}\,\mathcal{P}(E^{\rm co};T_{\rm eff})\,\sigma^{\rm co-Q}(E^{\rm co})}{\int_{E^Q_{\rm thr}}^{\infty} dE^{\rm co}\,\mathcal{P}(E^{\rm co};T_{\rm eff})}$$



- Using pPb CMS and ATLAS data at 5.02 TeV we fit T_{eff} and n. Also with PbPb CMS data

- By varying n between 0.5 and 2, we obtain T_{eff} in the range from 200 to 300 MeV both for **partons** or **hadrons**

Ingredients for the cross section

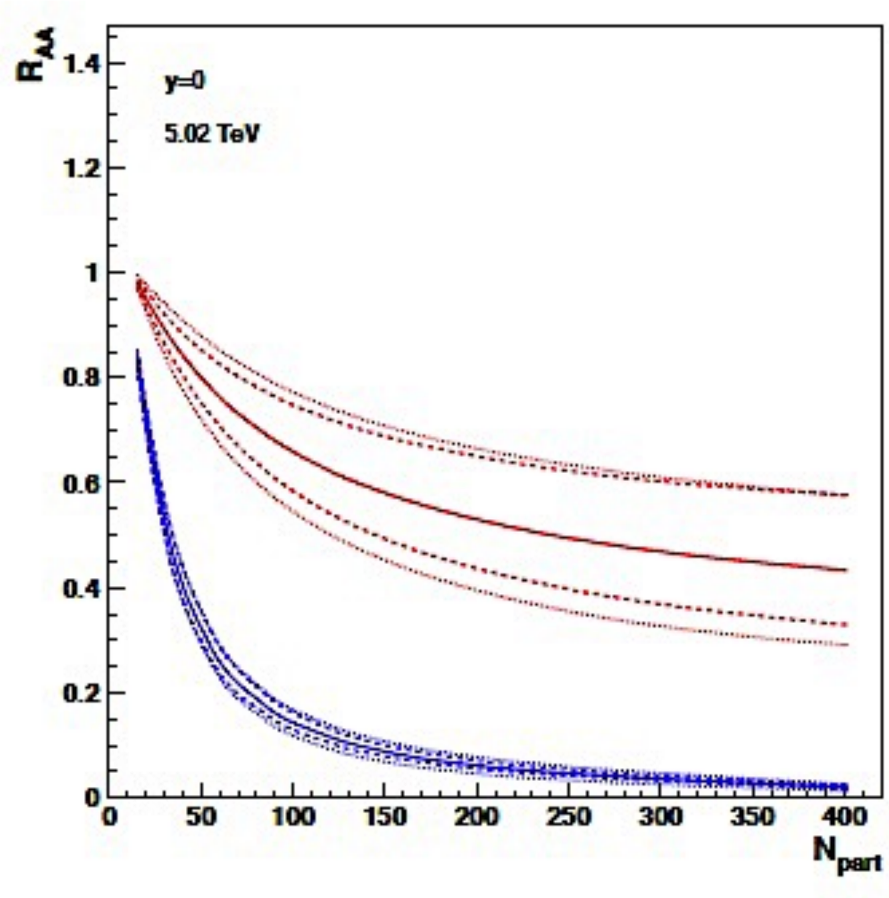
- For T=250±50 MeV and n=1:

	$E_{\rm thr}^{Q}$	r_Q	$\sigma_{\rm geo}^{Q}$	$\sigma_{\rm gluon}^{Q}$	$\sigma_{\rm hadron}^{Q}$
$\Upsilon(1S)$	1100 MeV	0.14 fm	0.62 mb	$0.13^{+0.02}_{-0.02}$ mb	$0.12^{+0.02}_{-0.02}$ mb
$\chi_b(1P)$	670 MeV	0.22 fm	1.52 mb	$0.48^{+0.07}_{-0.07}$ mb	$0.43^{+0.06}_{-0.07}$ mb
$\Upsilon(2S)$	540 MeV	0.28 fm	2.46 mb	$0.92^{+0.12}_{-0.14}$ mb	$0.80^{+0.11}_{-0.12}$ mb
$\chi_b(2P)$	300 MeV	0.34 fm	3.63 mb	$1.92^{+0.17}_{-0.22}$ mb	$1.61^{+0.16}_{-0.18}$ mb
$\Upsilon(3S)$	200 MeV	0.40 fm	5.03 mb	$3.18^{+0.22}_{-0.28}$ mb	$2.60^{+0.23}_{-0.28}$ mb
$\chi_b(3P)$	50 MeV	0.55 fm	10.21 mb	$6.90^{+0.14}_{-0.35}$ mb	$5.33^{+0.28}_{-0.37}$ mb

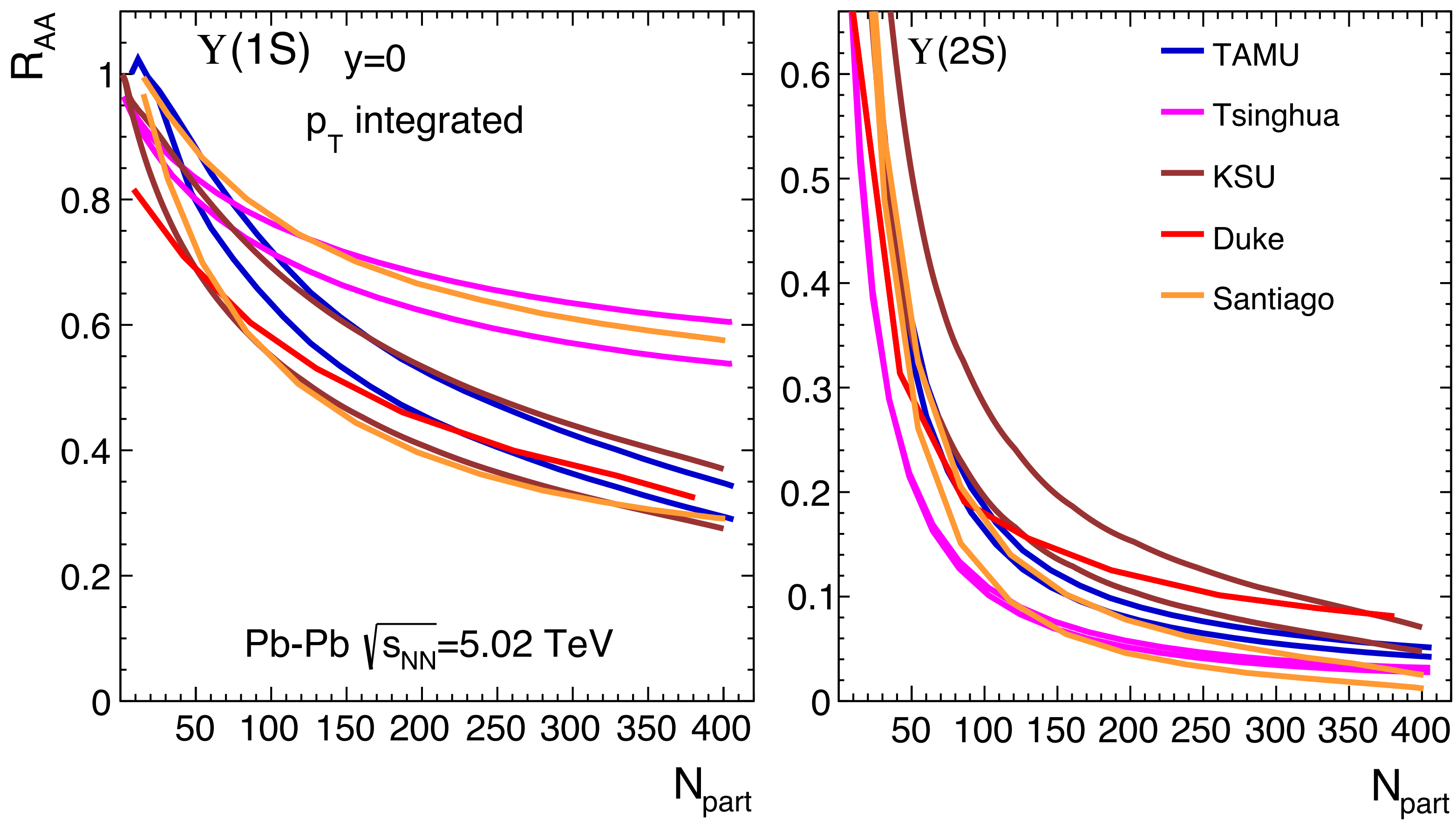
	$E_{\rm thr}^{Q}$	r_Q	$\sigma_{\rm geo}^{Q}$	$\sigma_{\rm gluon}^{Q}$	$\sigma_{\rm hadron}^{Q}$
J/ψ	630 MeV	0.25 fm	1.96 mb	$0.65^{+0.09}_{0.10}$ mb	$0.58^{+0.08}_{0.10}$ mb
$\chi_c(1P)$	200 MeV	0.36 fm	4.07 mb	$2.75^{+0.17}_{-0.40}$ mb	$2.11^{+0.18}_{-0.23}$ mb
$\psi(2S)$	50 MeV	0.45 fm	6.36 mb	$5.59^{+0.11}_{-0.17}$ mb	$4.31^{+0.23}_{-0.29}$ mb

Results direct upsilon

- nCTEQ15 shadowing included
- No recombination



Results direct upsilon



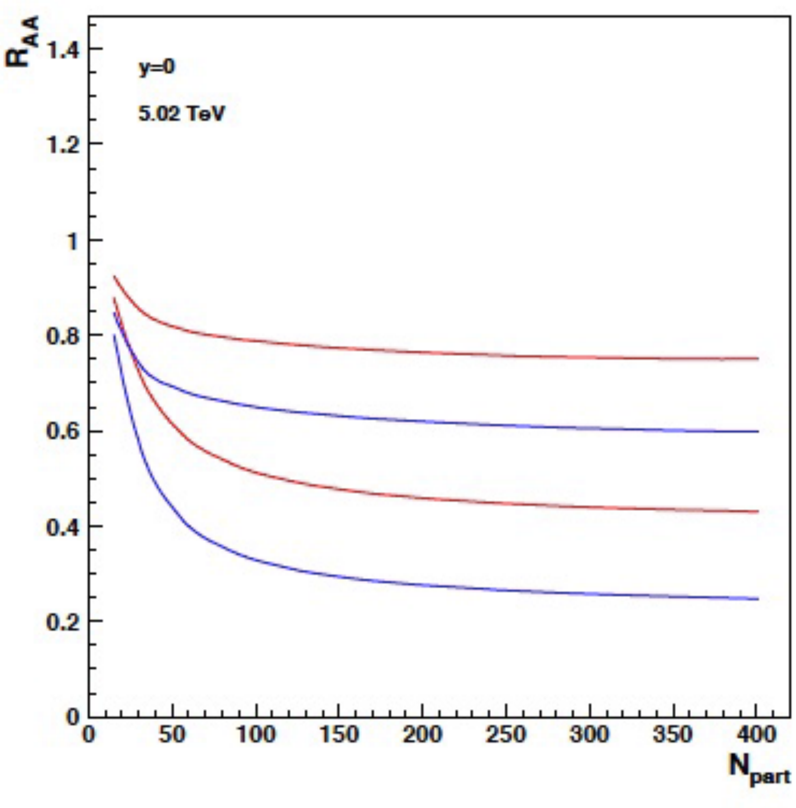
Results direct charmonium

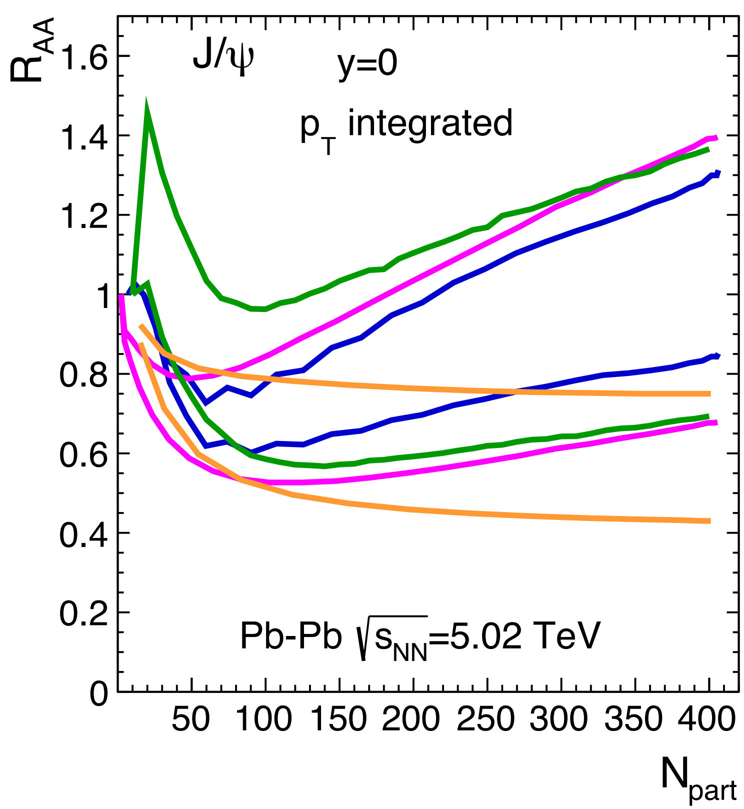
$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}\,(b,s,y) \;=\; -\sigma_{co}\left[N^{co}(b,s,y)N_{J/\psi}(b,s,y)\;-\;N_c(b,s,y)N_{\bar{c}}(b,s,y)\right]$$

- Recombination proportional to $\frac{\left(\mathrm{d}\sigma_{pp}^{c\bar{c}}/\mathrm{d}y\right)^2}{\sigma_{pp}\,\mathrm{d}\sigma_{pp}^{J/\psi}/\mathrm{d}y}$ $\qquad \mathrm{d}\sigma_{pp}^{c\bar{c}}/\mathrm{d}y$ = 0.45 to 0.7 mb

+

- nCTEQ15 shadowing included





nCTEQ15 vs EPPS16

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16
Order in α_s	NLO	NLO	NNLO	NLO	NLO
DIS in ℓ^-+A	✓	✓	✓	✓	✓
Drell-Yan in p+A	✓	✓	✓	✓	✓
RHIC pions d+Au	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan in π+A					✓
LHC p+Pb dijets					✓
LHC p+Pb W, Z					✓
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$	$1.3\,\mathrm{GeV}$
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	16	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35	52
proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavour separation				partial	full
Reference	JHEP 0904 065	PR D85 074028	PR D93, 014026	PR D93 085037	EPJ C77 163

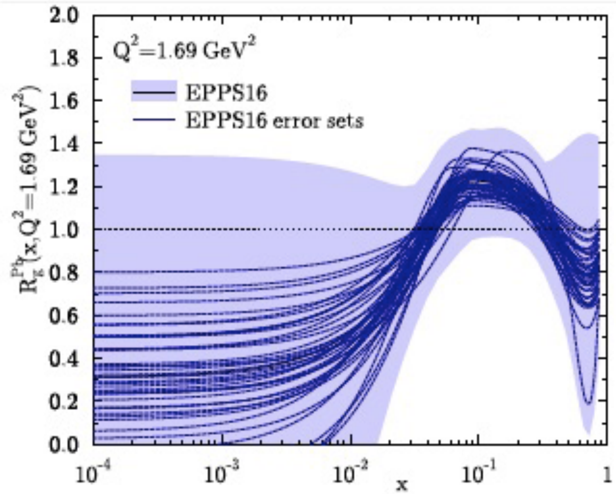
[Table: H. Paukkunen]

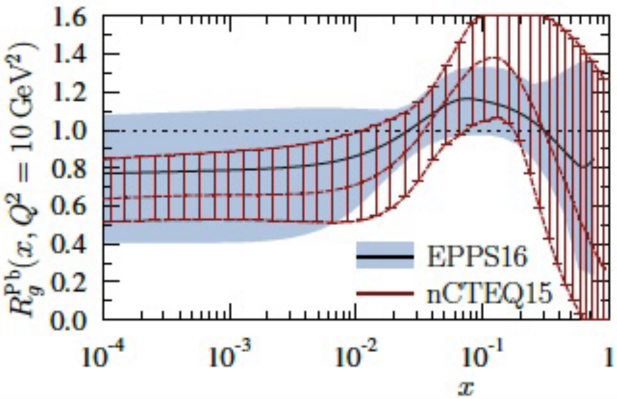
nCTEQ15 vs EPPS16

Gluons

Nuclear modification

- Data constrain gluons only around $x \sim 0.1$
  $\Rightarrow$ Large uncertainties at small-x
- However, scale evolution rapidly shrinks the uncertainties at small-x as these originate from well-constrained quarks at higher x
- Reasonable agreement between the analyses
  - Intermediate x: Smaller uncertainty in EPPS16 due to dijet data
  - Small x: Smaller uncertainty in nCTEQ15 probably due to more restrictive parametrization





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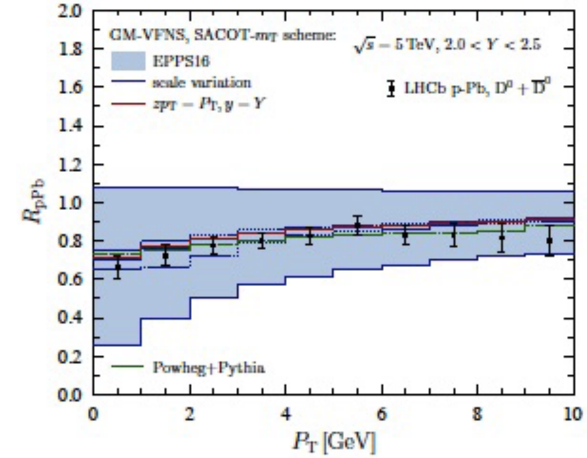
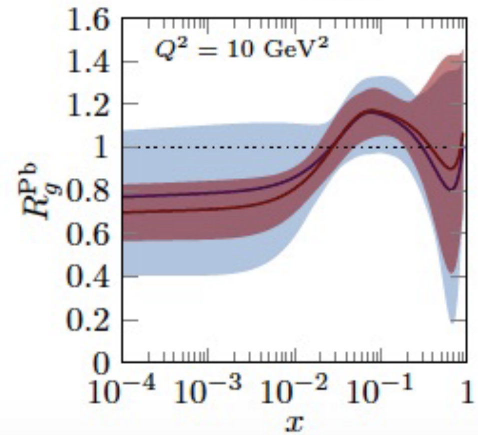
nCTEQ15 vs EPPS16

Heavy-flavour R_{pPb} impact on nPDFs

Strong constraints for gluons

- LHCb data up to $Y = 4$ [JHEP 1710 (2017) 090]
- Sensitivity down to $x \sim 10^{-5}$
- Impact studied with reweighting method
  - Assuming simplified kinematics [Kusina et al., PRL 121, 052004]
  - With full GM-VFNS NLO calculation [Paukkunen et al., *to appear*]
- Good agreement with collinear factorization
- Provides significant reduction of the small-x gluon uncertainty
- Shadowing consistent with the dijet R_{pPb}





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