Perturbative QCD

Konnevesi Retreat 2022

Ilkka Helenius

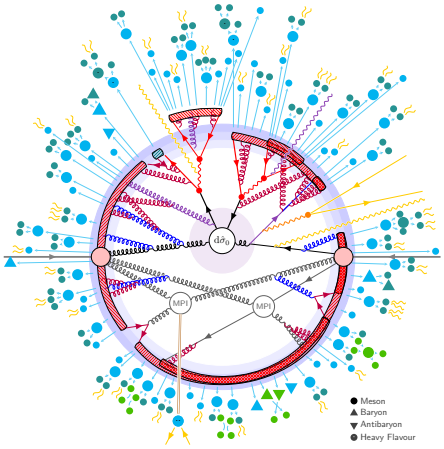
November 17th, 2022

Perturbative QCD

- Hannu Paukkunen
- Ilkka Helenius

Ongoing research

- Nuclear Parton Distribution Functions and evolution equations
- Heavy-flavour production
- Fragmentation Functions
- Ultra-peripheral collisions
- Pythia Monte-Carlo event generator



[figure by P. Skands]

Collinear factorization

Factorize long- and short-distance physics

$$\frac{\mathrm{d}\sigma^{AB\to h+X}}{\mathrm{d}p_\mathrm{T}\eta} = \int \frac{\mathrm{d}z}{z}\mathrm{d}x_1\mathrm{d}x_2\, f_i^A(x_1,\mu_\mathrm{fact})\, f_j^B(x_2,\mu_\mathrm{fact})\frac{\mathrm{d}\sigma^{ij\to k+X}}{\mathrm{d}p_\mathrm{T}\eta}\, D_k^h(z,\mu_\mathrm{frag}) + \mathcal{O}(1/Q^2)$$

- $f_i^A(x,\mu_\mathrm{fact})$: Describe the partonic content of colliding hadron, determined in global analysis applying DGLAP equations
- $\frac{\mathrm{d}\sigma^{ij\to k+X}}{\mathrm{d}p_\mathrm{T}\eta}$: Partonic coefficent functions, calculated in perturbative QCD
- $D_k^h(z,\mu_\mathrm{frag})$: Parton-to-hadron fragmentation functions, determined in global analysis applying DGLAP equations

DGLAP evolution equations for PDFs

$$\frac{\partial f_i(x,Q^2)}{\partial\log(Q^2)} = \frac{\alpha_\mathrm{s}(Q^2)}{2\pi}\sum_j\int_x^1\frac{\mathrm{d}z}{z}\,P_{ij}(z)\,f_j(x/z,Q^2)$$

Nuclear parton distribution functions (nPDFs)

Factorize initial-state nuclear effects

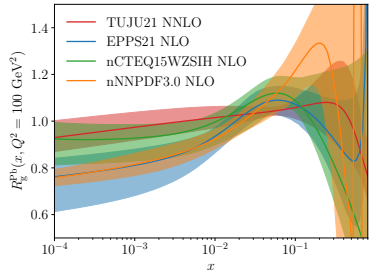
- Parametrize nuclear modification at the initial scale $Q_0^2 = \mathcal{O}(m_c)$

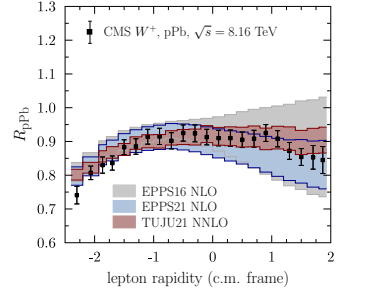
$$f_i^{p/A}(x, Q_0^2) = R_i^A(x, Q_0^2) f_i(x, Q_0^2)$$

- Fit parameters in $R_i^A(x, Q_0^2)$ using experimental data

Contributions to several analyses

- EPPS21 [Eskola, Paakkinen, Paukkunen, Salgado; EPJC 82 (2022) 5, 413]
- TUJU21 [Helenius, Walt, Vogelsang; PRD 105 (2022) 9, 9]
- nCTEQ15 [Duwentäster et. al.; PRD 105 (2022) 11, 114043]





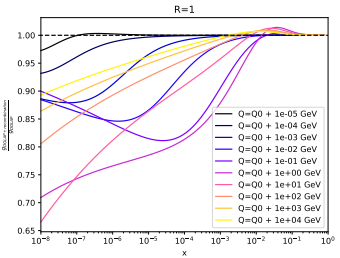
Non-linear evolution in proton PDFs

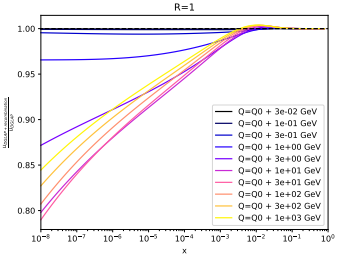
Include recombination effects to DGLAP

[Pit Duwentäster, Vadim Guzey]

- Old GLR does not conserve momentum
- Energy-conserving gluon recombination terms $P_i^{gg\to g}$ and $P_i^{gg\to q\bar{q}}$ available

  [Zhu and Ruan NPB 559 (1999) 378–392]
- Combine with linear DGLAP terms
- Compare evolution with the linear one for CJ15 proton PDFs
- R parameter related to proton size
- Aim: Global fit including HERA data





DGLAP and BK evolution

Compare two evolution equations

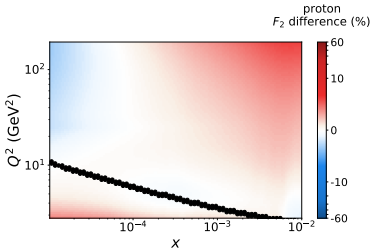
[Armesto, Lappi, Mäntysaari, Paukkunen, Mirja Tevio; Phys.Rev.D 105 (2022) 11, 114017]

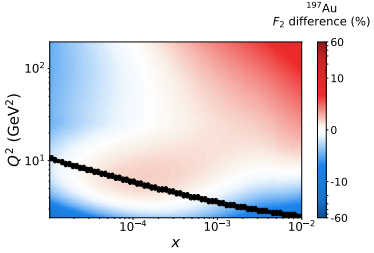
- Match the structure functions F_2 and F_L at x, Q^2 region where both applicable
- Evolve with DGLAP and BK and see where they differ

$$\text{Relative difference} = \frac{F_2^{\text{BK}} - F_2^{\text{DGLAP}_{\text{Rew}}}}{F_2^{\text{BK}}}$$

- Differences pronounced in nuclear case

Ongoing work to study evolution in a physical basis





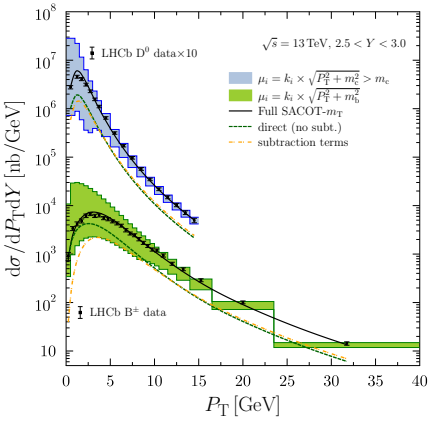
Heavy-flavour production

Two well-defined limits

- Fixed-flavour number scheme valid at low p_T
- Massless scheme at high p_T

Generalized-mass-variable-flavour-number scheme (GMVFNS)

- Combines the regions, applicable at any p_T
- SACOT-m_T scheme with kinematic constraints
  [Helenius, Paukkunen; JHEP 05 (2018) 196]
- Applied also to p+Pb collisions to constrain nPDFs [Eskola, Helenius, Paakkinen, Paukkunen; JHEP 05 (2020) 037]
- And to double-heavy flavour production
  [Helenius, Paukkunen; PLB 800 (2020) 135084]



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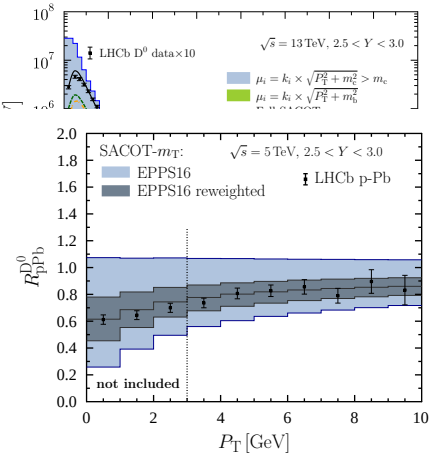

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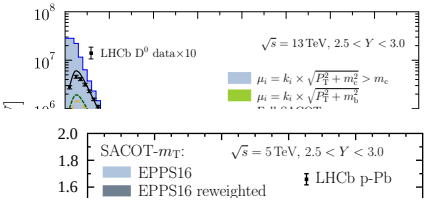
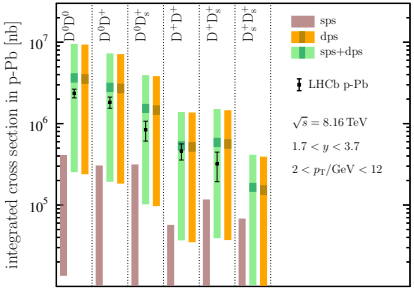




Heavy-flavour decays

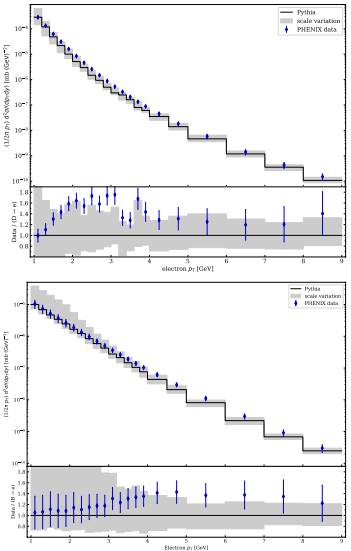
Leptons from heavy-flavour decays

- Experimentally decay leptons can be identfied from displaced vertex
- Theoretically involves convolution of heavy-flavour spectra with “decay function”

Decays with PYTHIA

[Alex Tolvanen, MSc thesis]

- Sample heavy-meson kinematics from SACOT-m_{T} cross section
- Feed particle to PYTHIA to select decay channel and sample kinematics
- Pick decay leptons and form differential cross section



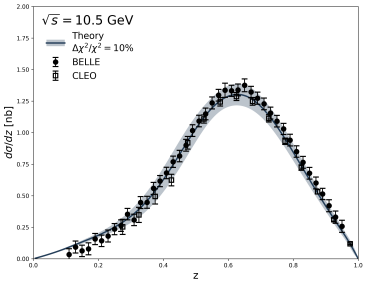
Heavy-meson fragmentation functions (FFs)

- Similarly as PDFs, also FFs require non-perturbative input to be fitted to data
- Only few works for heavy-flavour FFs, we have applied KKKS08

New heavy-flavour FF analysis

[Manuel Epele]

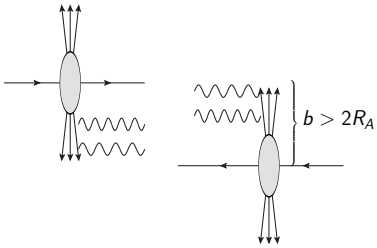
- Apply LEP, BELLE and other e^+e^- data
- Carefully address radiative corrections
- Hessian error analysis to quantify the uncertainty propagation



- Good description of the applied $D^{\pm *}$ data

Ultra-peripheral collisions (UPCs)

- Collisions with large impact parameter
  $\Rightarrow$ No hadronic interactions
- Photons emitted by the charged beam particle may interact



Equivalent photon approximation (EPA)

[Sami Yrjänheikki, MSc thesis]

- Allows to factorize photon flux from the hard-process cross section
- Applied to exclusive dilepton production in p+p
- Comparison with (different) EPA and full calculation

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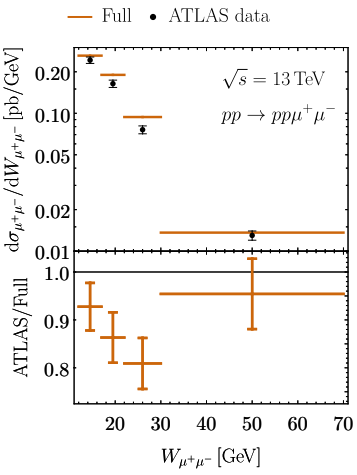

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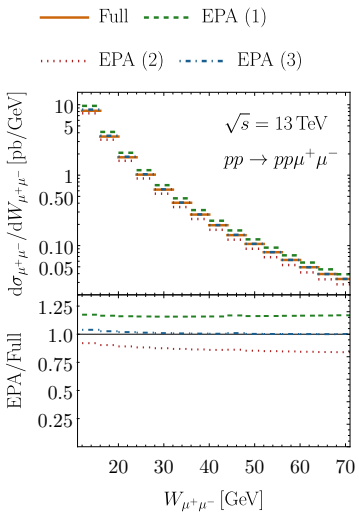


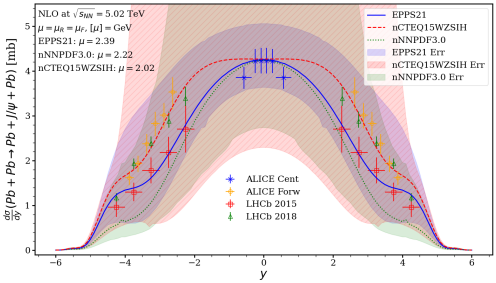
Exclusive heavy-meson production

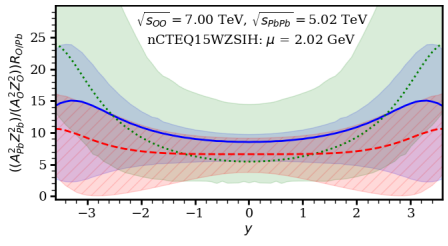
NLO calculation for J/Ψ production in ultra-perihperal Pb+Pb collisions

[Eskola, Flett, Guzey, Löytäinen, Paukkunen; PRC 106 (2022) 3, 035202]

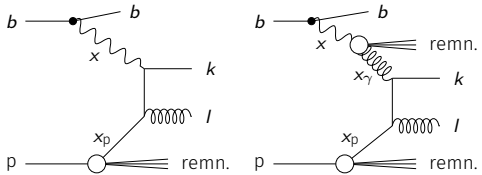
- First pQCD-based calculation at NLO for exclusive J/Ψ in UPCs
- Sensitive to nPDFs at small-x
- Large scale uncertainty
- Applied also to O+O, ratio to reduce the scale uncertainty

  [Eskola, Flett, Guzey, Löytäinen, Paukkunen; arXiv:2210.16048 [hep-ph]]

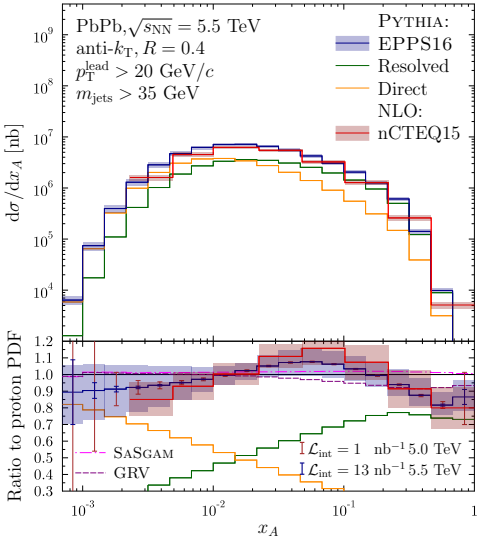




Inclusive dijet production in UPCs

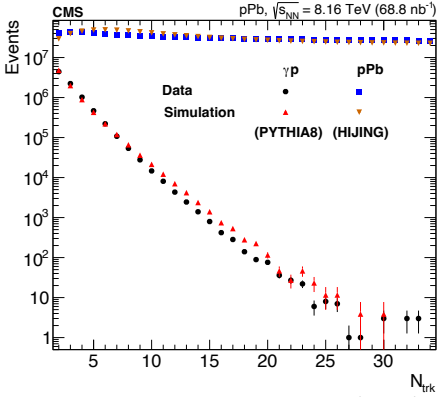


- Another novel process potentially sensitive to nuclear PDFs
- Small-x reach more limited than with J/Ψ but theoretically cleaner
- Exact potential to be quantified
  [Paakkinen, Guzey]
- NLO and LO Pythia in agreement



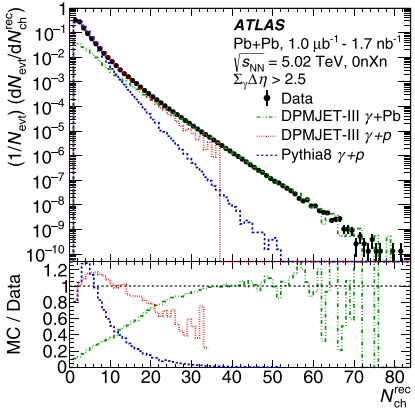
Ultra-peripheral heavy-ion collisions with PYTHIA

(Pb $\rightarrow \gamma$)+p: [CMS: Murillo Quijada, QM2022]



- Multiplicities well reproduced with γp

(Pb $\rightarrow \gamma$)+Pb:[ATLAS: PRC 104, 014903 (2021)]

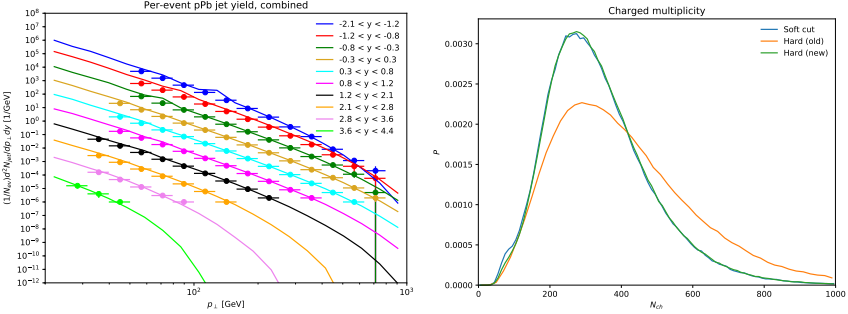


- High multiplicities missed with γp
  $\Rightarrow$ Multi-nucleon interactions

[Marius Utheim]

Hard-processes in p+Pb with Angantyr in Pythia

[Marius Utheim]



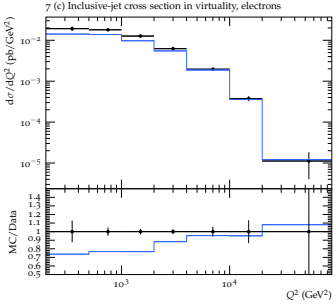
- Soft QCD: Use MC Glauber to derive impact parameters for n-n collisions
- Hard QCD: Replace smallest impact parameter n-n with a Pythia event

  $\Rightarrow$ Underlying event structures do not match
- Fixed by reweighting with impact-parameter dependent weight

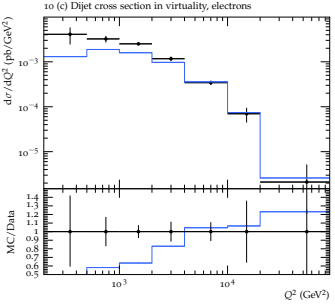
Multi-jet merging in DIS with PYTHIA

[Joni Laulainen]

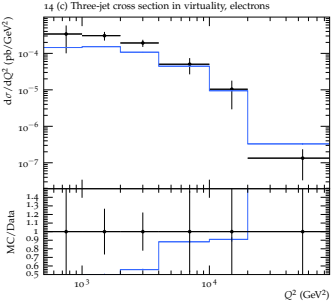
Inclusive



Dijet



Trijet



- DIS events with one scattered parton in the final state + parton shower
- Okay for inclusive jets but falls below for di- and trijet

  $\Rightarrow$ Need to merge hard-process events with higher parton multiplicities