Precision predictions for heavy-ion collisions

From real and virtual photons to heavy quarks

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20 November 2013

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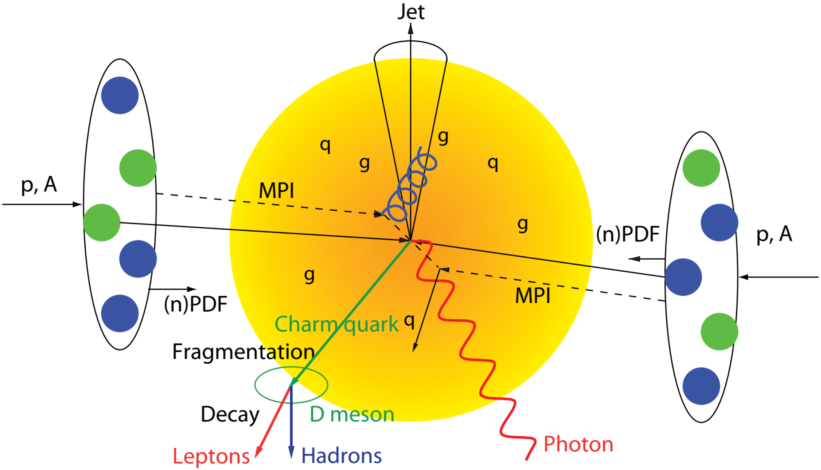
Many facets of QCD in pp, pA and AA collisions



Hard probes (1)

Direct photons:

- Photons not originating from decays (in particular $\pi^0 \to \gamma\gamma$)
- Thermal photons (at low p_T) are an important signal for QGP
- Also prompt photons from hard QCD processes (at larger p_T)

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Massive vector bosons:

- Large nuclear PDF (in particular g) uncertainties at large x
- Transition region: Shadowing $\to$ antishadowing $\to$ EMC effect
- Traditional process (prompt photons) is theoretically uncertain

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- Transition region: Shadowing $\to$ antishadowing $\to$ EMC effect
- Traditional process (prompt photons) is theoretically uncertain
- Massive vector bosons offer a promising alternative

Hard probes (2)

Heavy quarks:

- Mostly produced in early stage / hard collisions
- Energy loss through elastic / inelastic interaction with QGP
- In-medium hadron formation / dissociation

Hard probes (2)

Heavy quarks:

- Mostly produced in early stage / hard collisions
  $\rightarrow$ Massive vs. massless NLO calculations
- Energy loss through elastic / inelastic interaction with QGP
  $\rightarrow$ Monte Carlo simulation required
- In-medium hadron formation / dissociation
  $\rightarrow$ Different fragmentation models

References

- MK, C. Klein-Bösing, F. König, J.P. Wessels
  How robust is a thermal photon interpretation of the ALICE low-p_T data?
  JHEP 1310 (2013) 119 [1307.7034]

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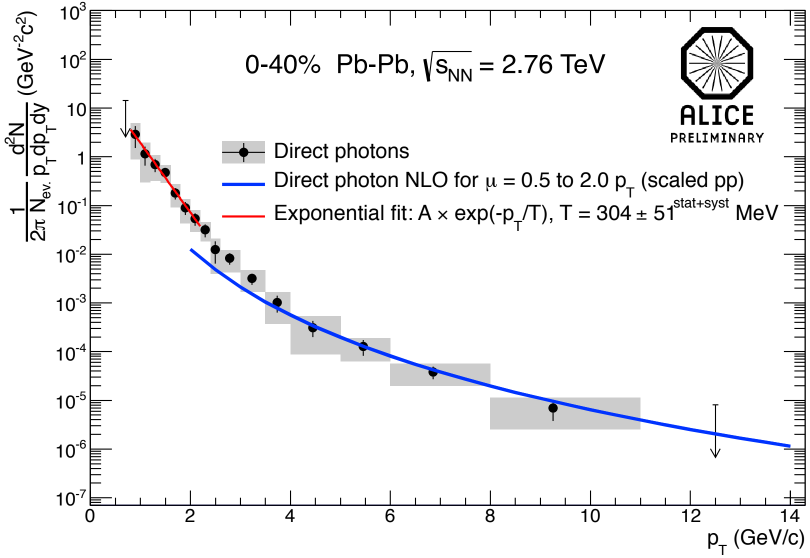
- MK, C. Klein-Bösing, G. Kramer, M. Topp, J.P. Wessels
  NLO Monte Carlo predictions for heavy-quark production at the LHC
  in preparation [1312.nnnn]

Measurement of direct photons in pp and PbPb collisions

M. Wilde et al. [ALICE Coll.], Nucl. Phys. A 904 (2013) 573c



Classification of contributions

Photons:

- Decay / Direct

Classification of contributions

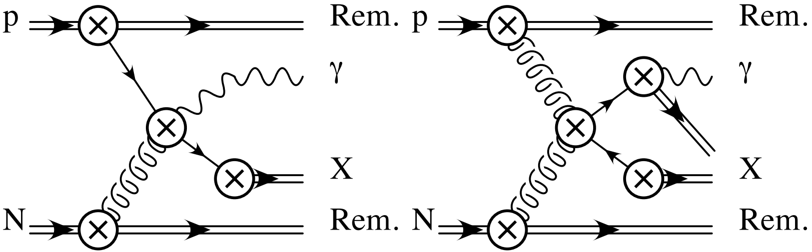
Photons:

- Decay / Direct
    - Thermal / Prompt

Classification of contributions

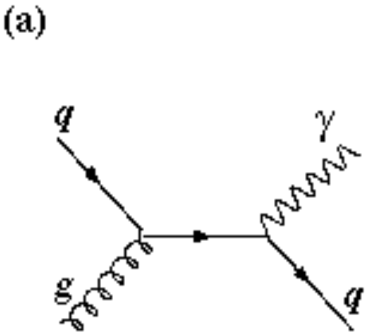
Photons:

- Decay / Direct
  - Thermal / Prompt
    - Direct / Fragmentation

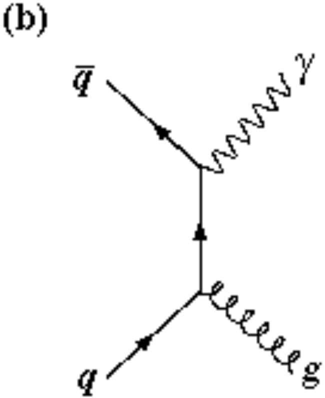


Partonic production of direct photons at LO

QCD Compton process:

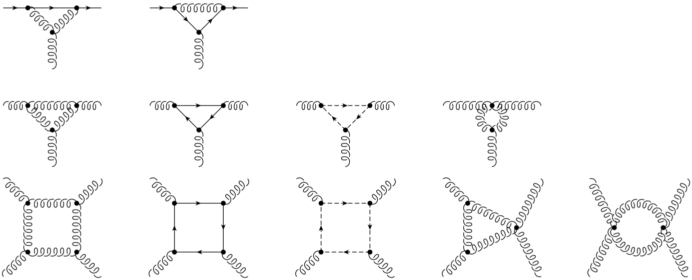


Quark-antiquark fusion:



NLO corrections to partonic processes

Virtual loop corrections:



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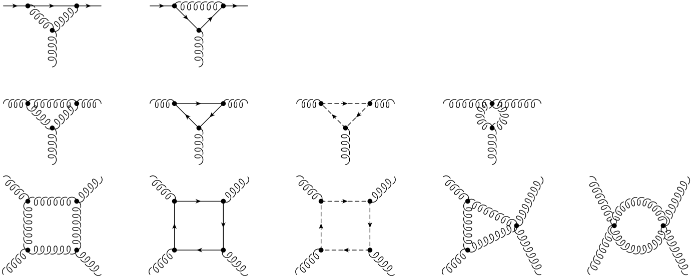
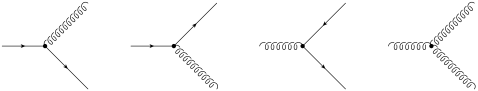


Real emission corrections:



Renormalization and factorization

NLO corrections to partonic processes:

$$|\mathcal{M}^V|^2_{ab\to 12} = \ln\left(\frac{\mu^2}{p_T^2}\right)|\mathcal{M}^B|^2_{ab\to 12}\,\beta_0 + \ldots$$

$$|\mathcal{M}^R|^2_{ab\to 123} = \ln\left(\frac{\mu_f^2}{p_T^2}\right)|\mathcal{M}^B|^2_{cb\to 12}\,P_{c\leftarrow a}(x) + \ldots$$

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Evolution equations (e.g. for quark fragmentation):

$$\frac{\mathrm{d}D_{\gamma/q}}{\mathrm{d}\ln\mu^2} = \frac{\alpha}{2\pi}P_{\gamma\leftarrow q}\otimes D_{\gamma/\gamma} + \frac{\alpha_s}{2\pi}\left[P_{q\leftarrow q}\otimes D_{\gamma/q} + P_{g\leftarrow q}\otimes D_{\gamma/g}\right]$$

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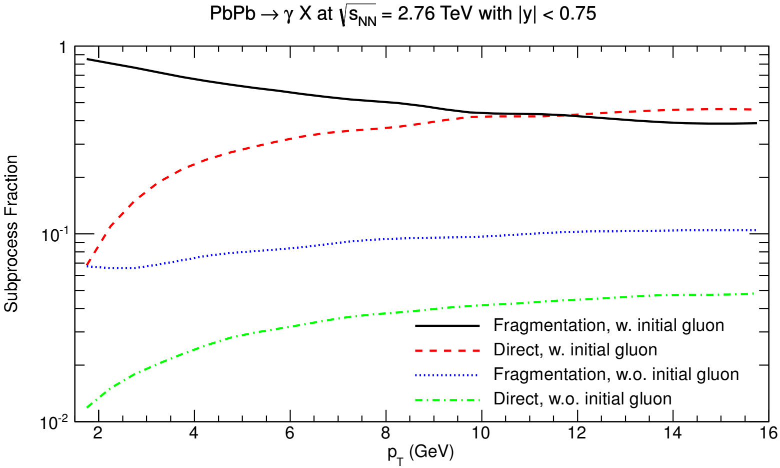
Hadronic cross section:

$$\frac{d\sigma^\gamma_{AB}}{dp_T} = \int f_{a/A}(x_a,\mu_f^2)\,f_{b/B}(x_2,\mu_f^2)\,D_{\gamma/c}(z,\mu_D^2)\,\frac{d\hat\sigma^c_{ab}}{dt}(\mu^2,\mu_f^2,\mu_D^2)$$

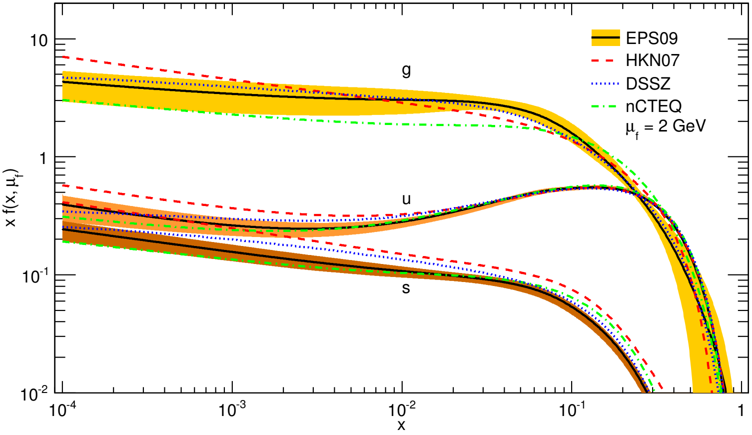
Transverse-momentum dependence of partonic processes

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



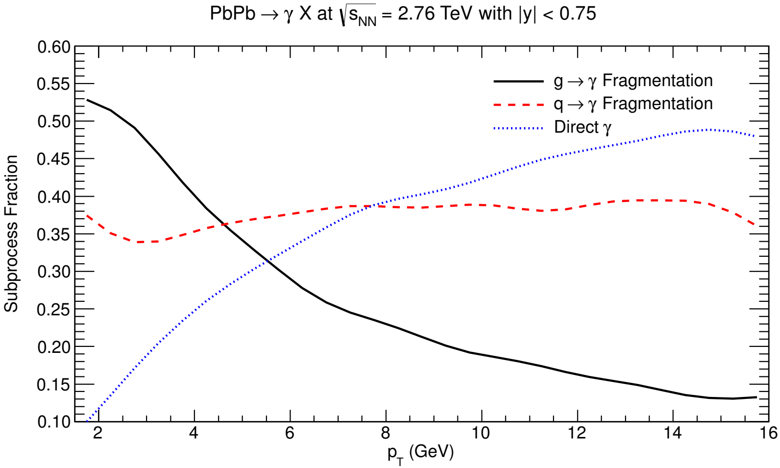
Nuclear PDF uncertainties

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



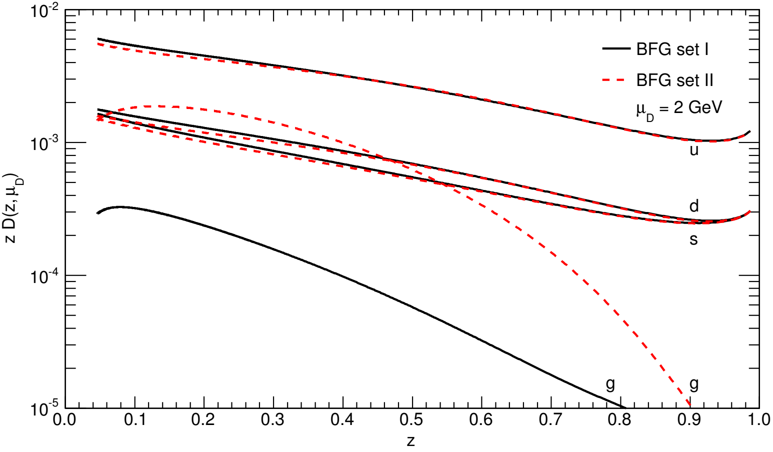
Transverse-momentum dependence of fragmentation

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



Fragmentation function uncertainties

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



Measurement of direct photons in pp and PbPb collisions

M. Wilde et al. [ALICE Coll.], Nucl. Phys. A 904 (2013) 573c

- Invariant yield:

$$\frac{1}{2\pi\, N_{\mathrm{ev}}}\frac{\mathrm{d}N}{\Delta y\, p_T \mathrm{d}p_T} \quad = \quad \langle T_{\mathrm{PbPb}}\rangle_{0-40\%}\frac{\mathrm{d}\sigma}{2\pi\,\Delta y\, p_T \mathrm{d}p_T}$$

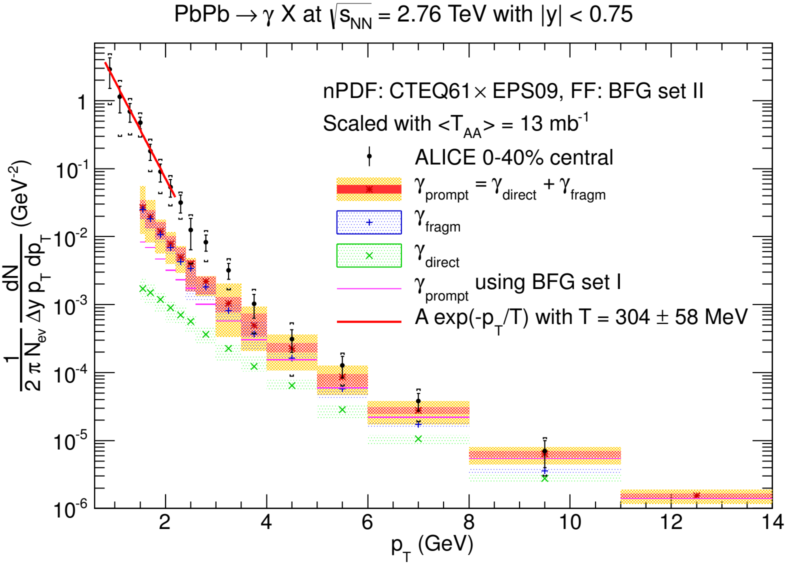
- Nuclear overlap function:

$$\langle T_{\mathrm{PbPb}}\rangle_{0-40\%} \quad = \quad 12.8 \,\pm\, 1.3\,(\mathrm{stat.}) \,\pm\, 0.2\,(\mathrm{syst.})\ \mathrm{mb}^{-1}$$

- Rapidity range: $|y| < 0.75$

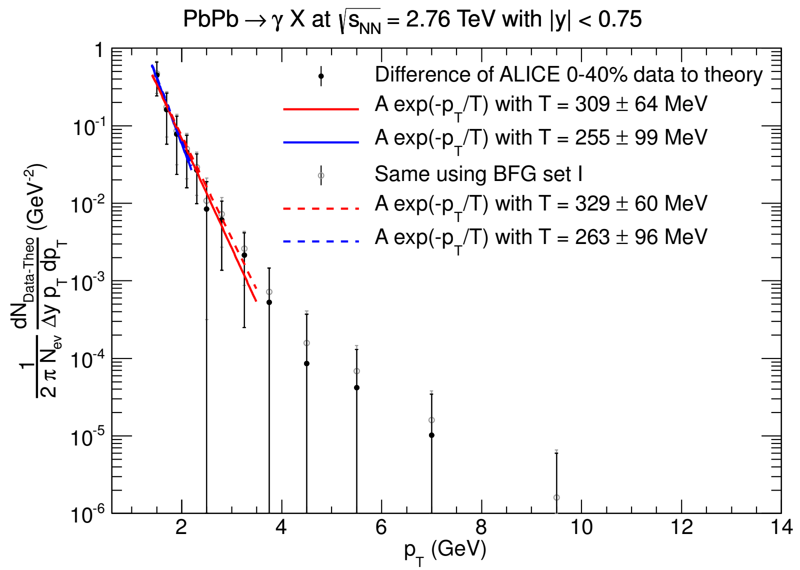
Transverse-momentum distribution of direct photons

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



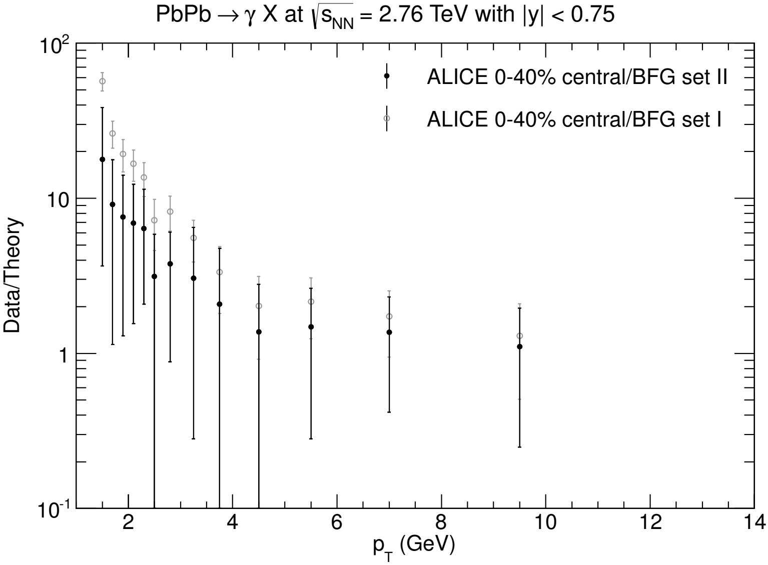
Exponential fit to pQCD subtracted ALICE data

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



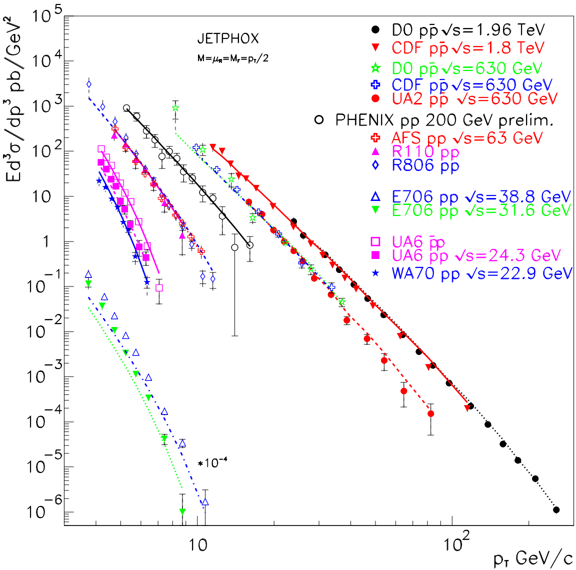
Reliability of pQCD prediction at large p_T

MK, C. Klein-Bösing, F. König, J.P. Wessels, JHEP 1310 (2013) 119



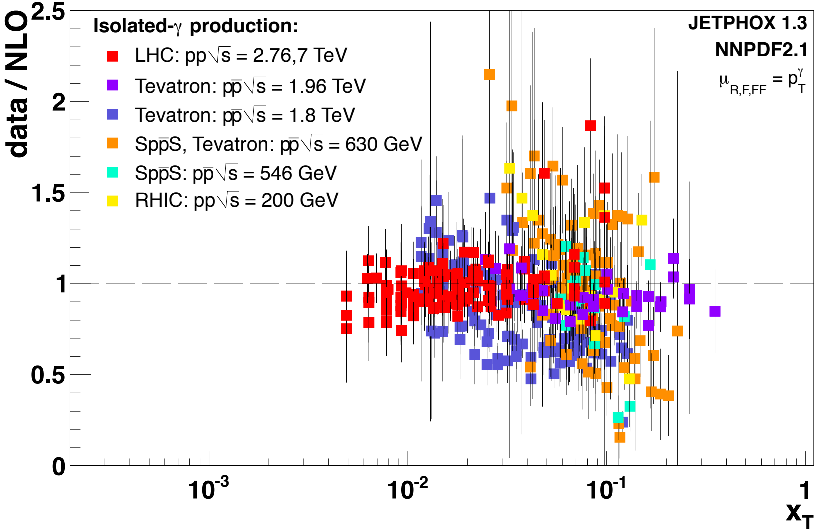
Pre-LHC prompt photon data

P. Aurenche, M. Fontannaz, J.P. Guillet, M. Werlen, Phys. Rev. D 73 (2006) 094007



Post-LHC prompt photon data

D. d'Enterria, J. Rojo, Nucl. Phys. B 860 (2012) 311



Comparison of theory with experiment

Observations:

- Large discrepancies at small p_T and $\sqrt{s}$
- Better agreement at large p_T and $\sqrt{s}$

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Remedies:

- Resummation (k_T, threshold, joint) $\rightarrow$ small enhancement
- Large fragmentation contributions $\rightarrow$ apply isolation criteria
- PDFs with intrinsic k_T $\rightarrow$ little experimental information
- Virtual photons / weak bosons $\rightarrow$ mass as regulator

NLL predictions for weak boson production

M. Brandt, MK, Phys. Rev. D 88 (2013) 054002

Hadronic cross section:

$$\frac{d^2\sigma^{\gamma^*}_{h_1 h_2}}{dp_T^2 dy} = \sum_{ij} \int dx_1 dx_2 f^i_{h_1}(x_1, \mu_f^2) f^j_{h_2}(x_2, \mu_f^2) \frac{s d^2\hat{\sigma}^{\gamma^*}_{ij}}{dt du}(Q, p_T, y; \mu^2, \mu_f^2)$$

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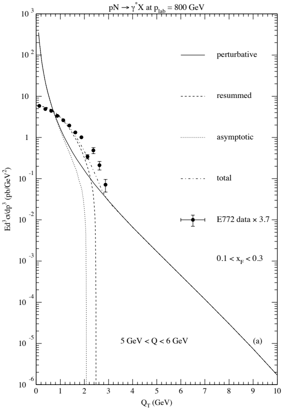
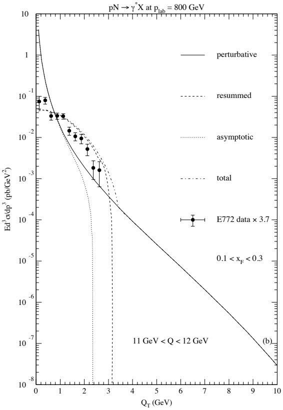
Partonic cross section: [Arnold, Kauffman, Nucl. Phys. B 349 (1991) 381]

- p_T-resummation at NLL
- $\sigma^{\rm tot} = \sigma^{\rm res} + \sigma^{\rm per} - \sigma^{\rm asy}$
- Scale uncertainty: $\mu, \mu_f = [0.5; 2] \times \sqrt{Q^2 + p_T^2}$

Fixed-target virtual photon data

E.L. Berger, L.E. Gordon, MK, Phys. Rev. D 58 (1998) 074012





LHC weak boson data

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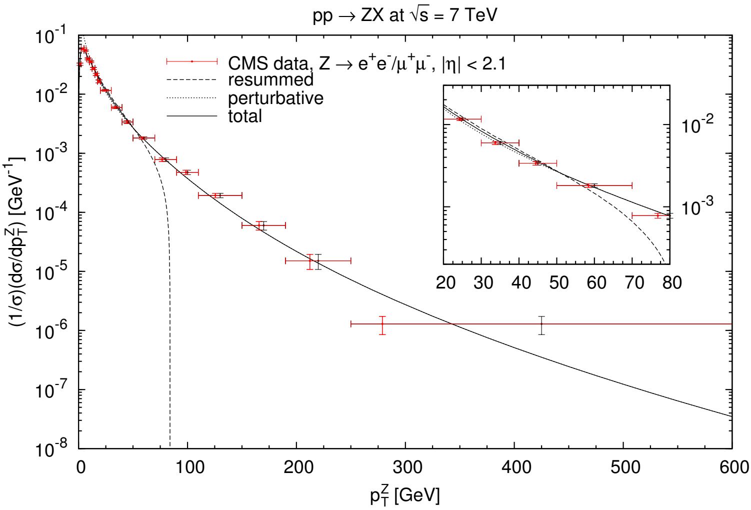

Transverse momentum dependence of contributions

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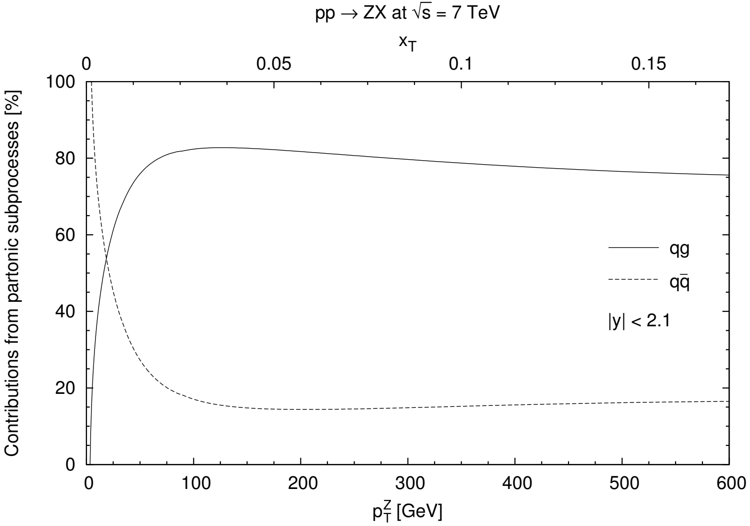
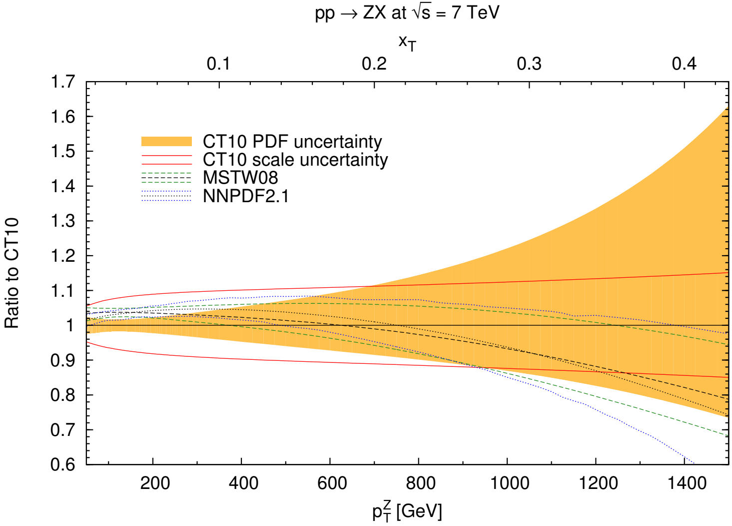


PDFs from LHC vector boson production

M. Brandt, MK, Phys. Rev. D 88 (2013) 054002



Nuclear collisions

M. Brandt, MK, F. König, in preparation

Thermal effects in AA collisions:

- Real photons: Excess at $p_T \leq 4$ GeV, $T = 304 \pm 58$ MeV

  [MK, C. Klein-Bösing, F. König, J.P. Wessels, 1307.7034]
- Weak bosons: $R_{AA} \sim 1$ [ATLAS PRL 110, 022301; CMS PAS HIN-13-004]
- Virtual photons: Interesting transition region!

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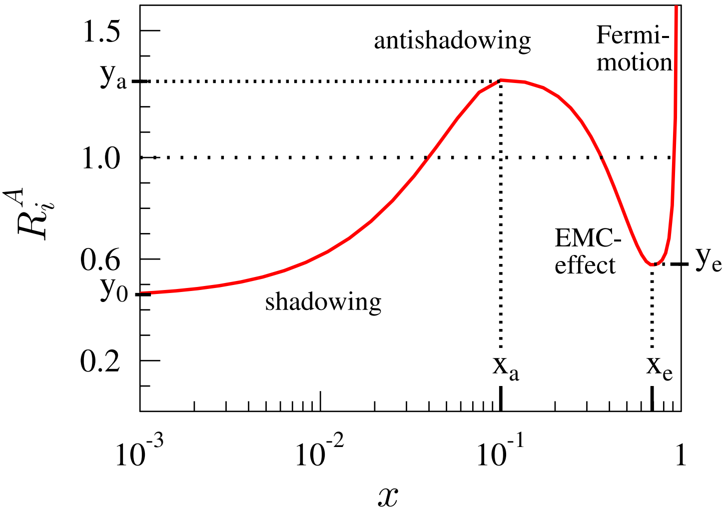
- Virtual photons: Interesting transition region!

Nuclear PDFs from pA collisions:

- Real photons [F. Arleo, K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 1104 (2011) 055]
- Photons + heavy quarks [F. Arleo, I. Schienbein, T. Stavreva, JHEP 1302 (2013) 072]
- Virtual photons [M. Brandt, MK, F. König, in preparation]
- Weak bosons (isospin effects!) [M. Brandt, MK, F. König, in preparation]

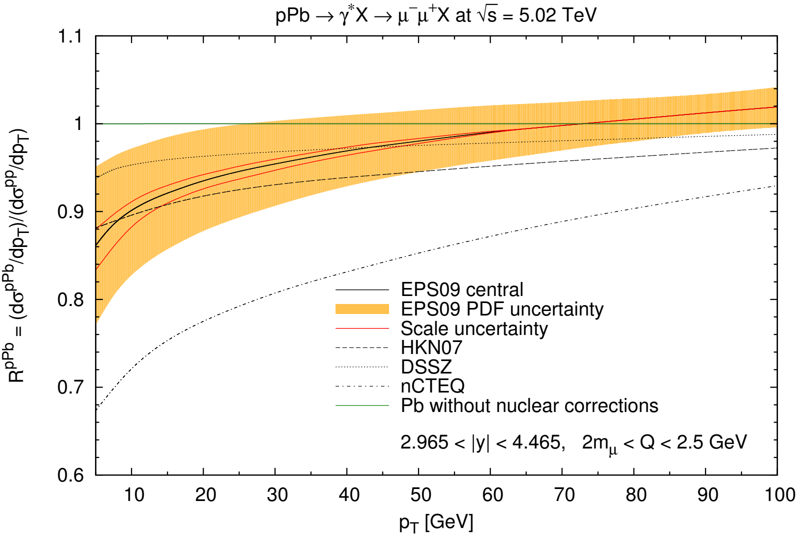
Nuclear modification of PDFs

K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904 (2009) 065



nPDFs from low-mass lepton pair production (1)

M. Brandt, MK, F. König, in preparation



nPDFs from low-mass lepton pair production (2)

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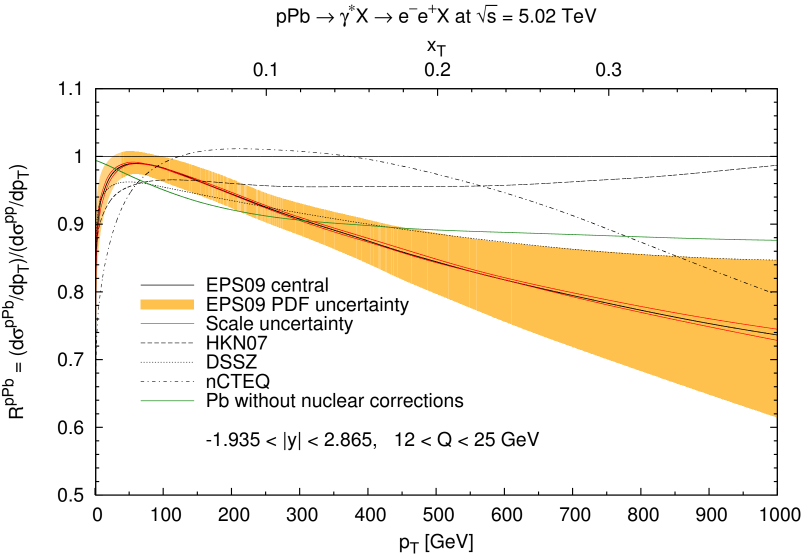
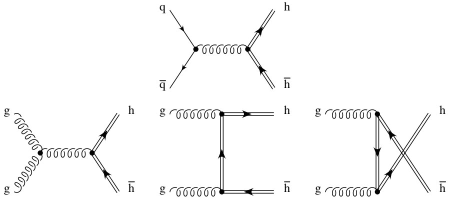


Heavy-quark production in hadron collisions (1)

MK, C. Klein-Bösing, G. Kramer, M. Topp, J. Wessels, in preparation

Partonic processes at LO:



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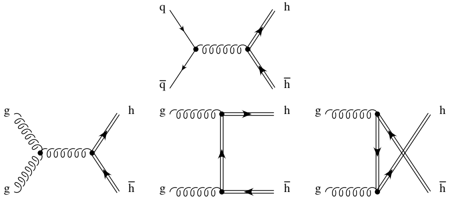

FONLL: [M. Cacciari, M. Greco, P. Nason, JHEP 05 (1998) 007]

- NLO calculation with massive quarks
  $\rightarrow$ Correct for $p_T \leq m$
- Massless limit $\otimes$ perturbative massive FFs evolved via DGLAP
  $\rightarrow$ Correct for $p_T \gg m$ (but no qg, qq contributions at LO)
- Logarithmic matching conditions for α_s, PDFs and FFs
  $\rightarrow$ FONLL = FO + (NLL - FOM0)$\times G(m, p_T)$

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MK, C. Klein-Bösing, G. Kramer, M. Topp, J. Wessels, in preparation

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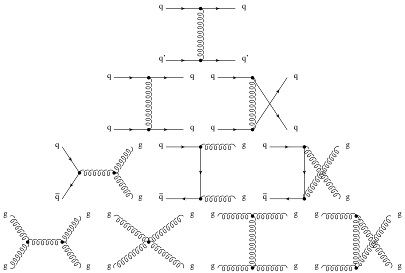

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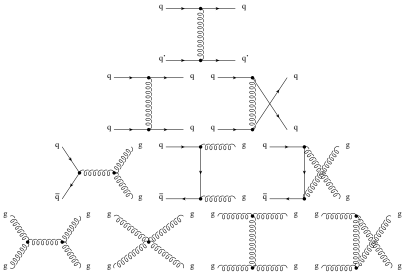


GM-VFNS: [B. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, EPJC 72 (2012) 2082]

- NLO massless calculation $\otimes$ massless FFs evolved via DGLAP
  $\rightarrow$ Correct for $p_T \gg m$
- Non-logarithmic terms from massive calculation
  $\rightarrow$ Correct for $p_T \leq m$ (but no logarithmic matching)

Heavy-quark production in hadron collisions (3)

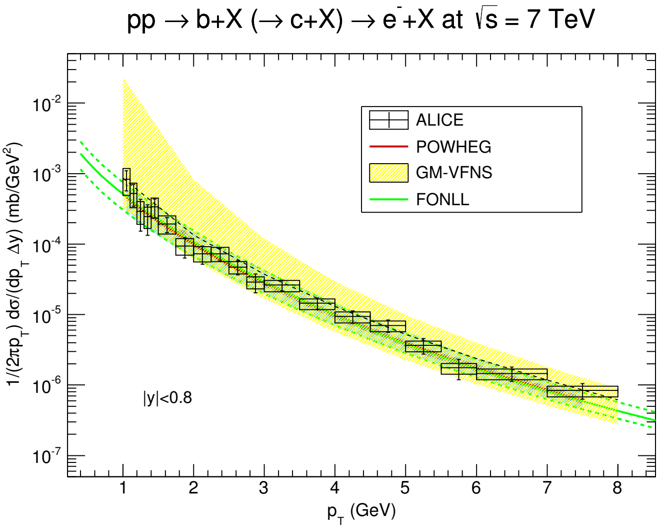
MK, C. Klein-Bösing, G. Kramer, M. Topp, J. Wessels, in preparation

NEW: POWHEG [S. Frxione, G. Ridolfi, P. Nason, JHEP 09 (2007) 126]

- NLO calculation with massive quarks
  $\rightarrow$ Correct for $p_T \leq m$ (but no logarithmic matching)
- Full parton showering and fragmentation with PYTHIA
- Exact implementation of experimental cuts
- Systematic study of PDF uncertainty with CTEQ6.6
- Predictions for $\sqrt{s} = 5.02$ TeV

Electrons from B decays in pp collisions at 7 TeV

MK, C. Klein-Bösing, G. Kramer, M. Topp, J. Wessels, in preparation



Electrons from *B* decays in pp collisions at 5.02 TeV

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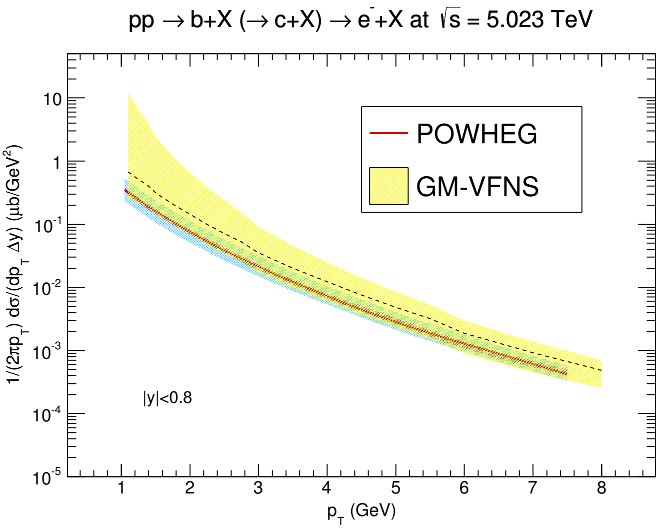
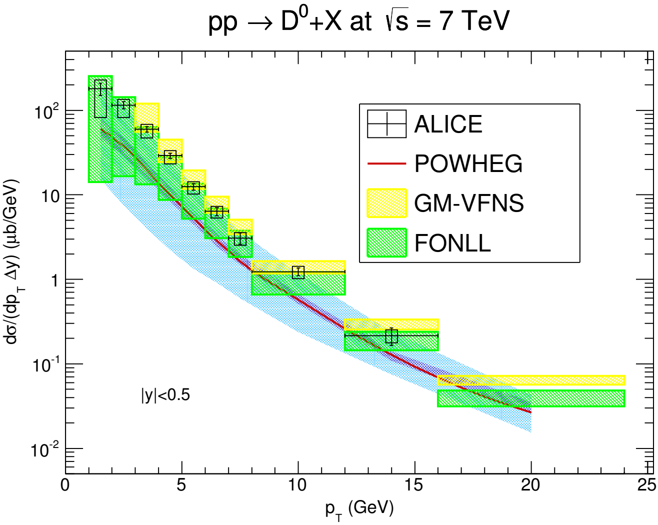


D^0 mesons in pp collisions at 7 TeV

MK, C. Klein-Bösing, G. Kramer, M. Topp, J. Wessels, in preparation



Conclusion

Prompt photons:

- Thermal photons extracted after subtracting NLO QCD
- Uncertainties from scales, PDFs and FFs taken into account
- ALICE data well described by exp./power law at low/high p_T

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- ALICE data well described by exp./power law at low/high p_T

Weak bosons:

- Mass serves as an infrared regulator $\rightarrow$ no need for isolation
- Production dominated by QCD Compton process at high p_T
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Conclusion

Prompt photons:

- Thermal photons extracted after subtracting NLO QCD
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Heavy quarks:

- Three theoretical approaches: FONLL, GM-VFNS, POWHEG
- Only NLO Monte Carlo will allow for quenching studies
- First results in pp test of reliability and PDF sensitivity