Perspectives of photon physics at future colliders

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DFG

Graduiertenkolleg 2149
Research Training Group

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Photon 2003 (Frascati): "... workshop on $\gamma\gamma$ collisions"

Executive Summary, Research Promotion Bureau, MEXT, March 7, 2019

Following the opinion of the Scientific Council of Japan, MEXT has not yet reached declaration for hosting the ILC in Japan at this moment. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from the domestic academic community.

MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

The ILC project has certain scientific significance in particle physics particularly in the precision measurements of the Higgs boson, and also has possibility in the technological advancement and in its effect on the local community, although the SCJ pointed out some concerns with the ILC project. Therefore, considering the above points, MEXT will continue to discuss the ILC project with other governments while having an interest in the ILC project.

CERN press release, May 13, 2019

The European particle physics community is meeting this week in Granada, Spain, to discuss the roadmap for the future of the discipline. The aim of the symposium is to define scientific priorities and technological approaches for the coming years and to consider plans for the medium- and long-term future.

Opinion of E. Elsen (CERN RD), May 29, 2019

To fully understand the absolute width of the Higgs, for example, a lepton machine will be needed, and no fewer than four implementations were discussed. So, one key conclusion is that if we are to cover all the bases, no single facility will suffice. One way forward was presented by the ACFA Chair, Geoff Taylor, representing the Asian view, who advocated a lepton machine for Asia, while Europe would focus on advancing the hadron frontier.

Outline

SM @ LHC: [N.Saoulidou (CMS), E.Masson (ALICE), M.Höfer (NNLO), L.Cieri (NNLO), F.Siegert (MC); F. Kapusta ($4l$), V. Goncalvez, A. Luszczak, I. Babiarz ($c\bar{c}$), M. Broz (ALICE), V. Khoze, A. Szczurek (WW, $t\bar{t}$), D. d'Enterria (h)]

- T. Jezo, MK, F. König
  Prompt photon production and photon-hadron jet correlations with POWHEG
  JHEP 1611 (2016) 033
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  Inclusive dijet photoproduction in UPCs at the LHC in NLO QCD
  Phys. Rev. C (in press), 1811.10236
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  Constraints on nuclear PDFs from dijet photoproduction at the LHC
  Eur. Phys. J. C 79 (2019) 396
- Z. Citron, V. Guzey, MK et al.
  Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams
  Physics HL-LHC and perspectives HE-LHC (WG 5), 1812.06772

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SM @ EIC: [cf. A. Luszczak ($c\bar{c}$), E. Aschenauer (EIC)]

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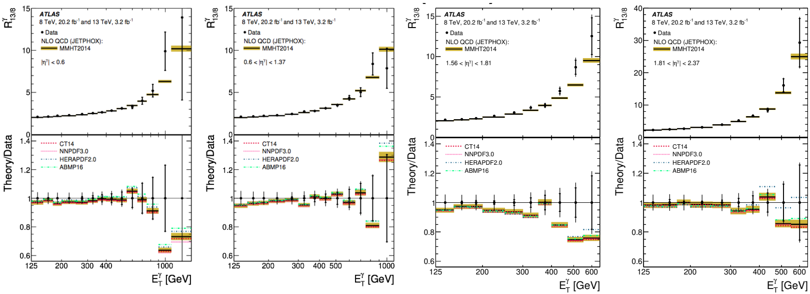
BSM @ LHC:
[F. Giacchino (ALPs), L. Harland-Lang (SUSY DM); X. Chu, G. Kozlov, C. Taruggi, L. Peruzzo (γ_D); O. Gould (Monopoles)]

- X. Cid Vidal, J. Fiaschi, MK, M. Sunder et al.
  Beyond the Standard Model physics at the HL-LHC and HE-LHC
  Physics HL-LHC and perspectives HE-LHC (WG 3), 1812.07831

Prompt photon production at the LHC

ATLAS Coll., JHEP 1904 (2019) 093, ALICE Coll., 1906.01371;
N. Saoulidou, E. Masson, M. Höfer, F. Siegert, talks at Photon 2019



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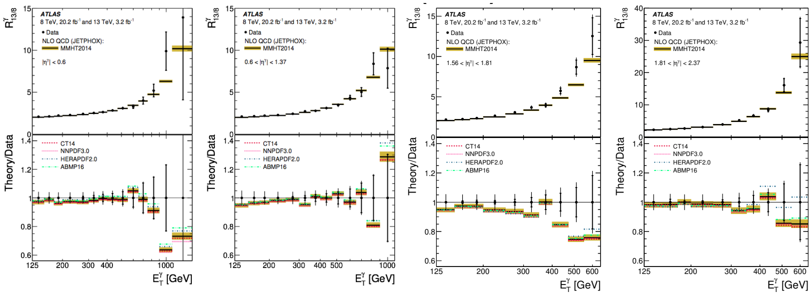

E_T distribution of inclusive photons well described at NLO.
Not only Z+jets, but also γ+jets requires resummation/PS.
Important constraints on gluon PDF at low x in protons and nuclei.

Prompt photon production with POWHEG

T. Jezo, MK, F. König, JHEP 1611 (2016) 033

"Fragmentation" contribution: [S. Höche et al., Phys. Rev. D 81 (2010) 034026]

- QED parton shower ($q \to q\gamma$), matched to NLO direct cont.
- Suppressed wrt. to QCD by α/α_s, color factors, multiplicities
- Globally only 2% photons in total QCD+QED event samples
- Reweight QED radiation by $C = 50\,(100)$, check independence

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Renormalization and factorization scales:

- $\mu = \mu_p = p_T^{\gamma,q,g}$ (from underlying Born process)

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Born-level event generation cut:

- $pp \to \gamma + X$ has coll. divergence at LO $\to$ impose $p_T > p_T^{\rm min}$
- Influences events at low p_T $\to$ region of interest for thermal γ

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Similar spike issue as for dijets:

- Symmetrization of FS parton splitting (`doublefsr = 1`)
- Removal of events with very large weights (`scalup`)

Isolated photon + jet production with CMS

CMS Coll., CMS PAS HIN-13-006

Proton-proton and proton-lead collisions:

- $\sqrt{s}_{\mathrm{pp}} = 2.76$ TeV, $\mathcal{L}$ (Run 2013) = 5.3 pb^{-1}
- $\sqrt{s}_{\mathrm{pPb}} = 5.02$ TeV, $\mathcal{L}$ (Run 2013) = 30.4 nb^{-1}

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Isolated photons:

- In $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, $E_T^{\rm iso} \leq 5$ GeV
- No photons with $|\eta^\gamma - \eta^{\rm track}| < 0.02$, $|\phi^\gamma - \phi^{\rm track}| < 0.15$
- $p_T^\gamma > 40$ GeV and $|\eta^\gamma| < 1.44$

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Jets:

- Anti-k_T cluster algorithm with $R = 0.3$
- $p_T^{\rm jet} > 30$ GeV and $|\eta^{\rm jet}| < 1.6$

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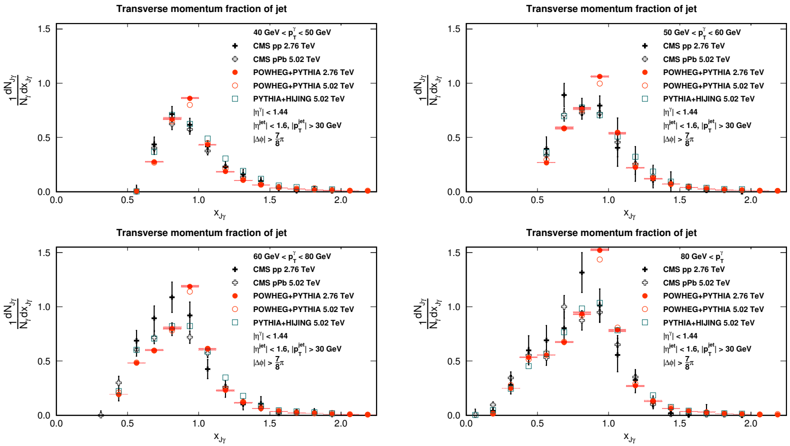
Choice of PDFs:

- CTEQ 6.1 $\overline{\mathrm{MS}}$ (p) and nCTEQ15-np (Pb, no pion data)

Transverse momentum ratio of jets over photons with CMS

MK, C. Klein-Bösing, H. Poppenborg, JHEP 1803 (2018) 081

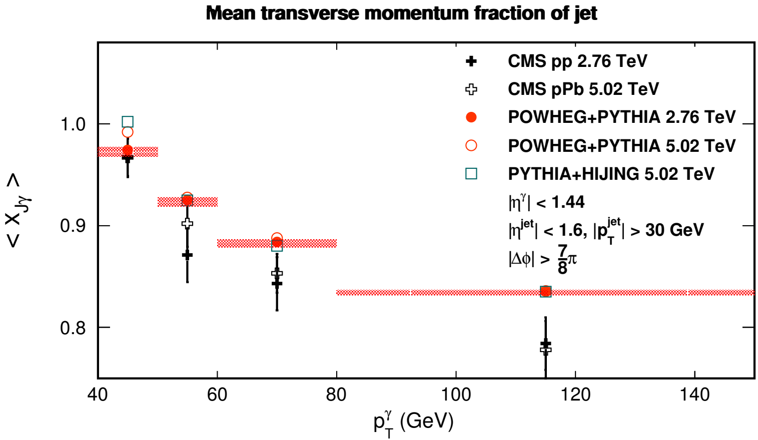


No significant cold nuclear effects, softer (and more) jets at large p_T^γ

POWHEG peak sharper/at higher $x_{J\gamma}$ than PYTHIA → CMS resolution?

Mean jet transverse momentum fraction with CMS

MK, C. Klein-Bösing, H. Poppenborg, JHEP 1803 (2018) 081

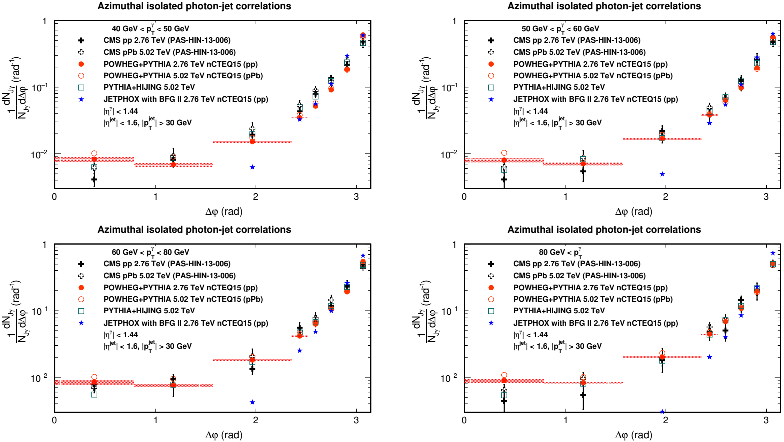


Higher $p_T^\gamma \rightarrow$ possible to produce ≥ 1 jets (e.g. "Mercedes star")

No Quark-Gluon-Plasma $\rightarrow$ not a sign of rescattering in the medium!

Azimuthal correlation of photons and jets with CMS

MK, C. Klein-Bösing, H. Poppenborg, JHEP 1803 (2018) 081

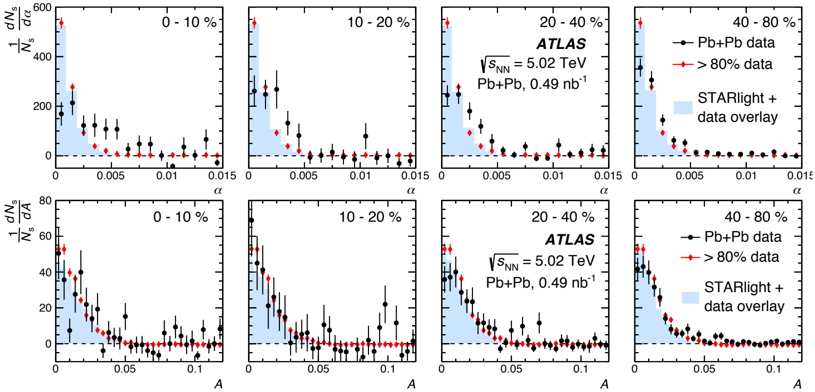


No significant cold nuclear effects, flatter distributions at large p_T^γ

POWHEG NLO + PYTHIA 8 PS describes data within errors

Acoplanarity and lepton imbalance in $\gamma\gamma \to \mu\mu$

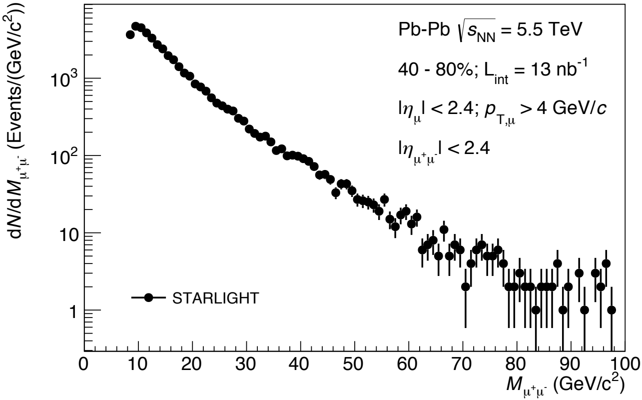
ATLAS Collaboration, M. Aaboud et al., 1806.08708



Mostly back-to-back in UPCs ($> 80\%$), data agree with STARlight.
α no longer peaked in central collisions $\to$ EM rescattering in QGP.
A unchanged $\to$ no significant energy loss, little bremsstrahlung.

Invariant mass reach at the HL-LHC (Runs 3 and 4)

S. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, CPC 212 (2017) 258

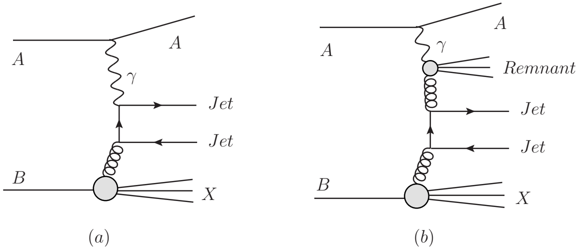


High masses correspond to $\gamma\gamma$ interactions in/near nuclei, i.e. increased interactions with QGP medium/magnetic field!

At low mass, e^+e^- should interact more than $\mu^+\mu^-$ and $\tau^+\tau^-$.

Inclusive dijet photoproduction at the LHC (1)

V. Guzey, MK, Phys. Rev. C (in press), 1811.10236



Hadronic/partonic cross sections related by photon flux/PDFs:

$$d\sigma(AB \to AB + 2\,\text{jets} + X) = \sum_{a,b} \int dy \int dx_\gamma \int dx_A\, f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/B}(x_A, \mu^2) d\hat{\sigma}(ab \to \text{jets})$$

Photon flux for relativistic point-like charge Z:

$$f_{\gamma/A}(y) = \frac{2\alpha Z^2}{\pi} \frac{1}{y} \left[\zeta K_0(\zeta) K_1(\zeta) - \frac{\zeta^2}{2} (K_1^2(\zeta) - K_0^2(\zeta)) \right]$$

with $\zeta = y m_p b_{\min}$ (no strong int. for $b > b_{\min} = 2.1\, R_{\mathrm{Pb}} = 14.2\,\mathrm{fm}$).

Inclusive dijet photoproduction at the LHC (2)

V. Guzey, MK, Phys. Rev. C (in press), 1811.10236

Theoretical approach:

- Partonic cross section calculated in NLO QCD
- Scale choice: $\mu_r = \mu_f = 2E_{T,1}$ (NLO = LO, NLO' = 0)
- Photon PDFs: GRV HO
- Nuclear PDFs: nCTEQ15, $\Delta\sigma = \frac{1}{2}\sqrt{\sum_{k=1}^{31} (\sigma(f_k) - \sigma(f_{k+1}))^2}$

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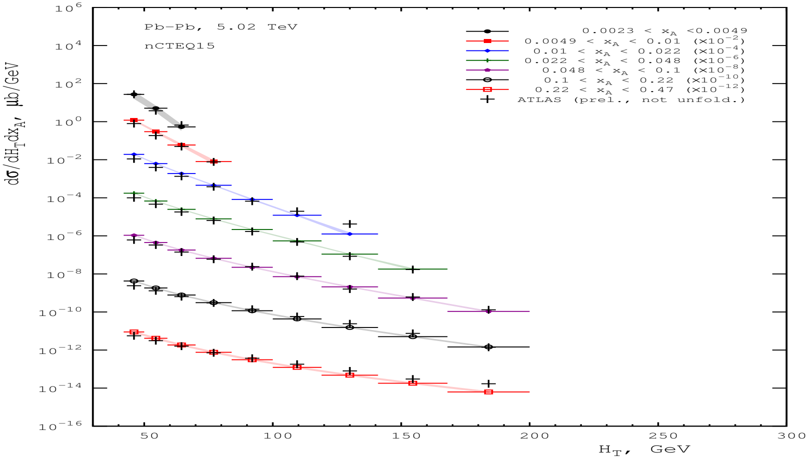
Experimental conditions:

- Anti-k_T algorithm, $R = 0.4$
- $E_{T,1} > 20$ GeV, $E_{T,2} > 15$ GeV, $H_T = \sum_i E_{T,i} > 35$ GeV
- Rapidities: $|\eta_{1,2}| < 4.4$
- Combined jet mass: $m_{\rm jets} > 35$ GeV

Comparison to preliminary ATLAS data

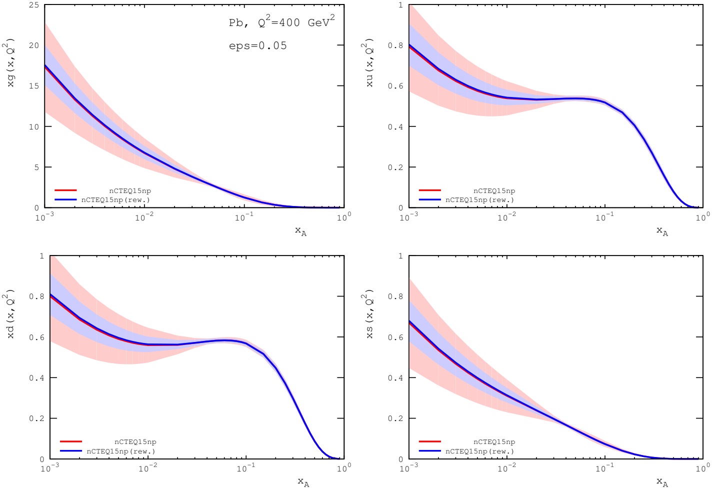
A. Angerami et al. [ATLAS Coll.], ATLAS-CONF-2017-011



Excellent agreement, also for other kinematic distributions (x_A, z_γ).
NB: ATLAS data not yet unfolded for detector response.

Bayesian reweighting study of future ATLAS data

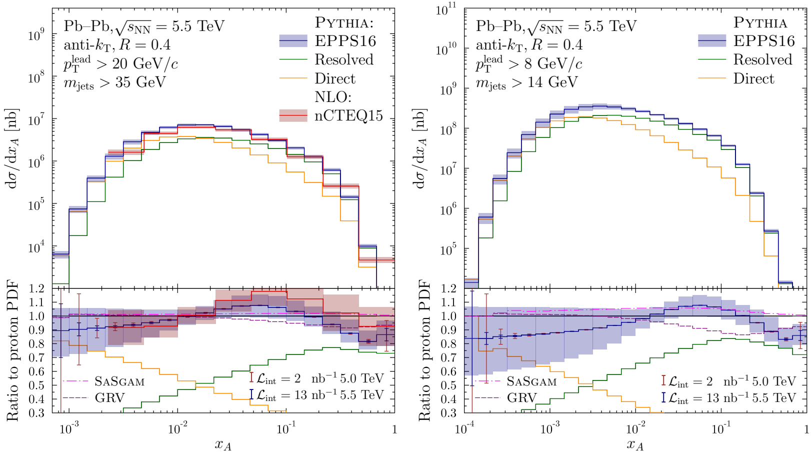
V. Guzey, MK, Eur. Phys. J. C 79 (2019) 396



nCTEQ15(np) uncertainties reduced by (more than) factor of two.

Inclusive dijet photoproduction at the HL-LHC

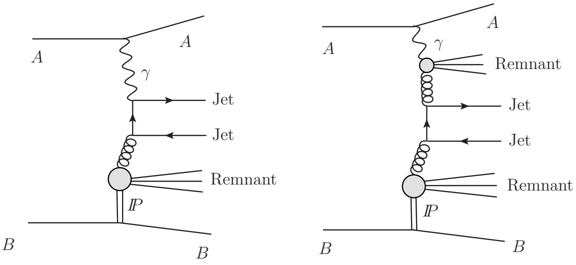
Z. Citron, V. Guzey, I. Helenius, MK, H. Paukkunen et al., 1812.06772



Large potential for improvement in nuclear shadowing region.
Resolved photon PDF uncertainty at low p_T and in EMC region.

Diffractive dijet photoproduction at the LHC

V. Guzey, MK, JHEP 1604 (2016) 158



(a) (b)

Cross sections related by Pomeron flux/diffractive PDFs:

$$d\sigma = \sum_{a,b} \int dt \int dx_{\mathbb{P}} \int dz_{\mathbb{P}} \int dy \int dx_\gamma S^2(y) f_{\gamma/p}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/p}^{D(4)}(x_{\mathbb{P}}, z_{\mathbb{P}}, t, \mu^2) d\hat{\sigma}^{(n)}_{ab\to \mathrm{jets}}$$

Rapidity gap survival probability: $S^2(x) = \frac{\int d^2b \, |\mathcal{M}(x,b)|^2 P(s,b)}{\int d^2b \, |\mathcal{M}(x,b)|^2}$

Two-channel eikonal model: [V. Khoze, A. Martin, M. Ryskin, EPJC 18 (2000) 167]

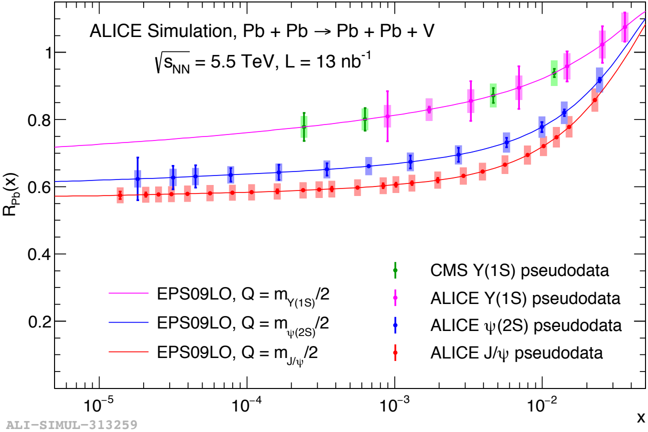
$$P(s,b) = \frac{1}{4(1-\gamma^2)} \left[(1+\gamma)^3 e^{-(1+\gamma)^2 \Omega(s,b)} + (1-\gamma)^3 e^{-(1-\gamma)^2 \Omega(s,b)} + 2(1-\gamma^2) e^{-(1-\gamma^2)\Omega(s,b)} \right]$$

with $\gamma = 0.4$ and optical density $\Omega(s,b)$.

Exclusive quarkonium photoproduction at HL-LHC

ALICE Coll., ALICE-PUBLIC-2019-001; V. Guzey, E. Kryshen, M. Strikman, M. Zhalov, PLB 726 (2013) 290

$$R_{\mathrm{Pb}} = \sqrt{\sigma_{\gamma\mathrm{Pb}}(m/2)/\sigma^{\mathrm{IA}}_{\gamma\mathrm{Pb}}(m/2)} \text{ with } \sigma^{\mathrm{IA}}_{\gamma\mathrm{Pb}} = \sigma_{\gamma p} \cdot \int |F_{\mathrm{Pb}}(t)|^2 dt$$



Sensitivity to scale dependence of nucl. shadowing (also in dijets)!

Jets in DIS and photoproduction at aNNLO

MK, G. Kramer, B. Pötter, Eur. Phys. J. C 1 (1998) 261; N. Kidonakis, Int. J. Mod. Phys. A 19 (2004) 1793

QCD factorization theorem:

$$\mathrm{d}\sigma = \sum_{a,b} \int \mathrm{d}y\, f_{\gamma/e}(y) \int \mathrm{d}x_\gamma\, f_{a/\gamma}(x_\gamma, \mu_\gamma) \int \mathrm{d}x_A\, f_{b/A}(x_A, \mu_A) \mathrm{d}\sigma_{ab}(\alpha_s, \mu_R, \mu_\gamma, \mu_A)$$

Partonic cross section:

$$\mathrm{d}\sigma_{ab} = \mathrm{d}\sigma^B_{ab} \frac{\alpha_s(\mu_R)}{\pi} \left[c_3 D_1(z) + c_2 D_0(z) + c_1 \delta(1-z)\right] + \frac{\alpha_s^{d_{\alpha_s}+1}(\mu_R)}{\pi} \left[A^c D_0(z) + T_1^c \delta(1-z)\right]$$

Logarithmic enhancement near partonic threshold:

$$D_l(z) = \left[\frac{\ln^l(1-z)}{1-z}\right]_+ \quad \text{with} \quad z = \frac{(p_1+p_2)^2}{(p_a+p_b)^2} \;\to\; 1$$

Coefficients for $\gamma q \to qg$:

$$c_3 = C_F - N_C$$

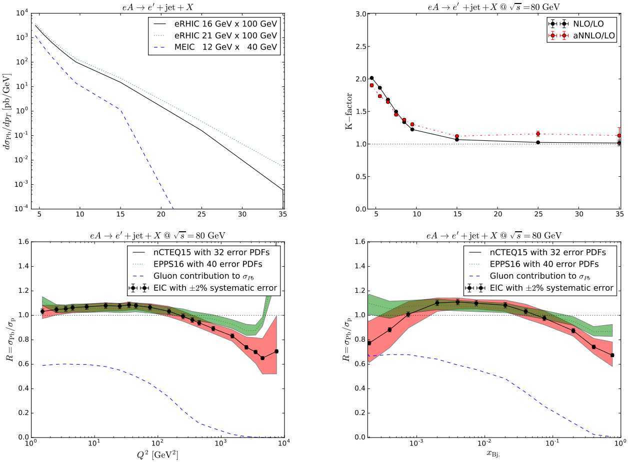
$$c_2 = C_F \left[-\ln\left(\frac{\mu_A^2}{s}\right) - \frac{3}{4} + 2\ln\left(\frac{-u}{s}\right)\right] + N_C \ln\left(\frac{t}{u}\right) - \frac{\beta_0}{4}$$

$$c_1^\mu = -\frac{3C_F}{4} \ln\left(\frac{\mu_A^2}{s}\right) + \frac{\beta_0}{4} \ln\left(\frac{\mu_R^2}{s}\right)$$

Similarly for other processes.

Nuclear PDFs from inclusive jets in DIS

MK, K. Kovarik, J. Potthoff, Phys. Rev. D 95 (2017) 094013



p_T reach to $\sim$ 25 GeV, aNNLO effects small compared to NLO.
Kinematic reach: $Q^2 \leq 10^3$ GeV^2, $x \geq 10^{-4}$, $\sim$ inclusive DIS.
Reduction of gluon uncertainty at low x by factor of 5 to 10.

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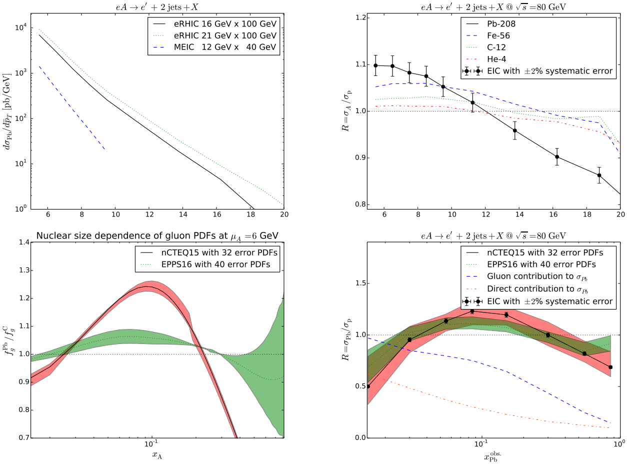
MK, K. Kovarik, Phys. Rev. D 97 (2018) 114013



Kinematic reach: $\bar{p}_T^2 \leq 400$ GeV^2, $x \geq 10^{-2}$, less than in DIS.
Still, reduction of nPDF uncertainties by factor of 5 to 10.
Nuclear dependence differs significantly in nCTEQ15 and EPPS16.

Dark matter searches with mono-photons

X. Cid Vidal et al., 1812.07831

Competitive, when DM is part of electroweak triplet $(\chi^0, \chi^\pm)$.
Different dependence on model parameters (EW repr., mass split.).
Motivated by AMSB (Wino) or minimal models with SM mediator.
$m_{\chi^\pm} = m_{\chi^0} + 165$ MeV (EW loops), $\chi^\pm \to \chi^0 +$ soft $\pi^\pm$.
DM stabilized by R parity or $B - L$, $m_{\chi^0} \leq 3$ TeV for thermal Ω_{χ^0}.

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Dominant background: $Z(\to \nu\nu)\gamma$.
Also W/Z+jet, tt, ZZ/WW with electrons/jets faking photons.
Main cuts: $\not{E}_T > 150$ GeV, $p_T^\gamma > 150$ GeV, $|\eta^\gamma| < 2.37$.
Photon isolation from MET: $\Delta\phi > 0.4$.

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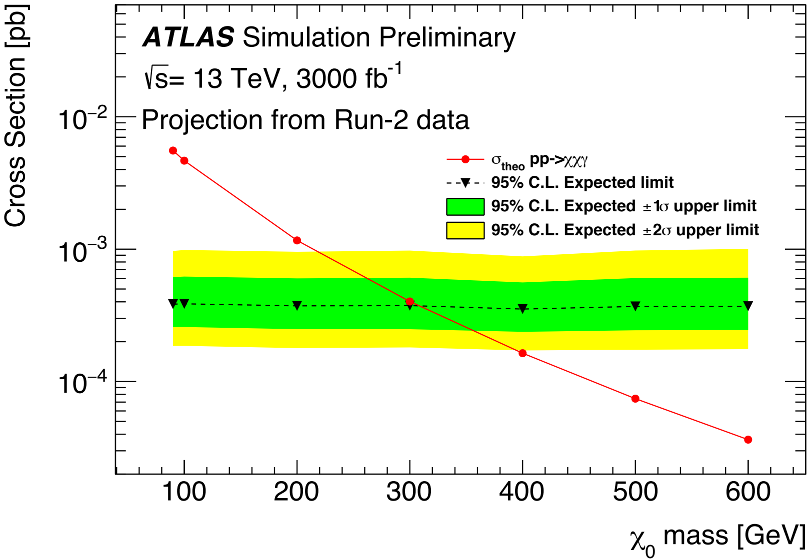
LEP limit: $m_{\chi^0} > 90$ GeV.

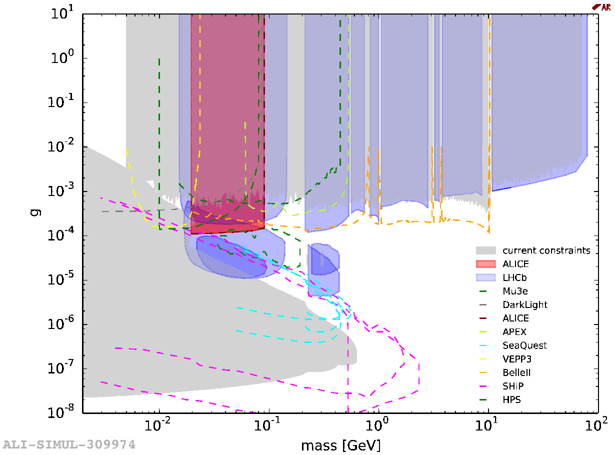
HL-LHC constraints on WIMPs from mono-photons

X. Cid Vidal et al., 1812.07831



HL-LHC constraints on dark photons

ALICE Coll., ALICE-PUBLIC-2019-001; LHCb Coll., Phys. Rev. Lett. 120 (2018) 061801

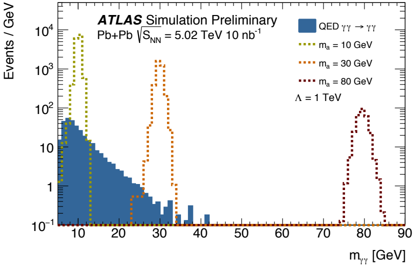


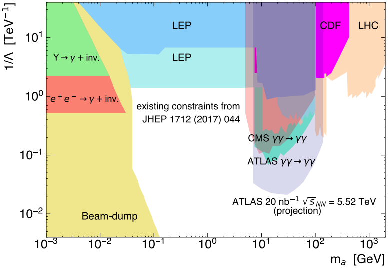
ALICE: $\pi^0 \to \gamma A' \to \gamma e^+e^-$ with $M_{ee} \in [20; 90]$ MeV.

LHCb: $A' \to \mu^+\mu^-$ with $M_{\mu\mu} \in [0.214; 70]$ GeV.

HL-LHC constraints on ALPs from light-by-light

ATLAS Coll., Nature 13 (2017) 852; CMS Coll., 1810.04602





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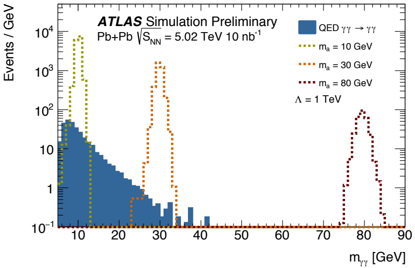

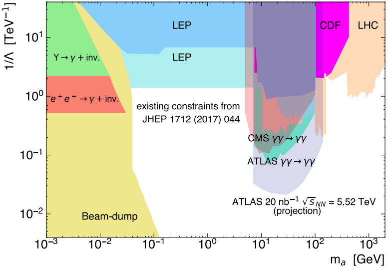

$Z^4 = 4.5 \cdot 10^7$ enhancement $\rightarrow$ exclusive $\gamma\gamma$ production in UPCs.
Light-by-light scattering now also observed by CMS.
Invariant mass peaks clearly visible above falling QED background.
Provides best sensitivity for $m_a \in [7; 140]$ GeV.

HL-LHC constraints on other BSM from light-by-light

Z. Citron et al., 1812.06772

Graveyard of BSM theories:

- Monopoles at $\sqrt{s_{pp}} = 7$ TeV: [I. Ginzburg, A. Schiller, PRD 57 (1998) 6599]

$$M < n \cdot 7.4,\ 10.5,\ 19\ \mathrm{TeV\ for}\ J_M = 0,\ 1/2,\ 1$$

- SUSY: ILC studies [G. Gounaris, P. Porfyriadis, F. Renard, EPJC9 (1999) 673]
- Low-scale gravity: $M_{\mathrm{Pl.}} \geq 5...8\,\sqrt{s_{\gamma\gamma}}$ for $D = 4 + (2, 4, 6)$ [K. Cheung, PRD 61 (2000) 015005]
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Resurrection:

- SUSY: Promising for $m_{\tilde{l}} \sim m_{\tilde{\chi}^0}$ [L. Harland-Lang, talk at Photon 2019]
- Monopoles: $m < 2$ TeV (ATLAS 13 TeV) [O. Gould, talk at Photon 2019]

Summary

SM @ LHC:

- Prompt photons + jets
- Inclusive photon-photon scattering
- Exclusive photon-photon scattering

SM @ EIC:

- Inclusive jet production in DIS
- Dijet photoproduction

BSM @ LHC:

- Mono-photons
- Dark photons
- Light-by-light scattering