Charged particles pair production in pp scattering: survival factor and proton tagging

S. I. Godunov, E. K. Karkaryan, V. A. Novikov, A. N. Rozanov, M. I. Vysotsky, E. V. Zhemchugov

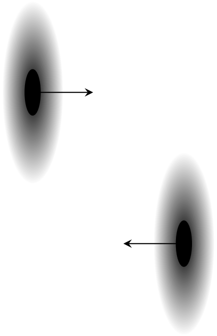
based on

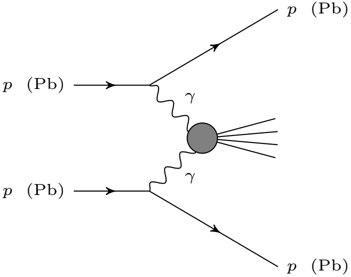
JHEP 2020, 143 (2020)
JHEP 2021, 234 (2021)

supported by the Russian Science Foundation Grant No. 19-12-00123-П

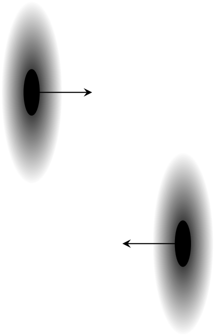
The Physics of the Dimuons at the LHC
June 24, 2022

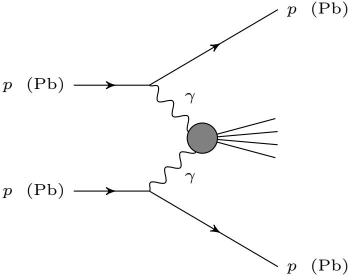
Ultraperipheral collisions (UPC) at the LHC





Ultraperipheral collisions (UPC) at the LHC

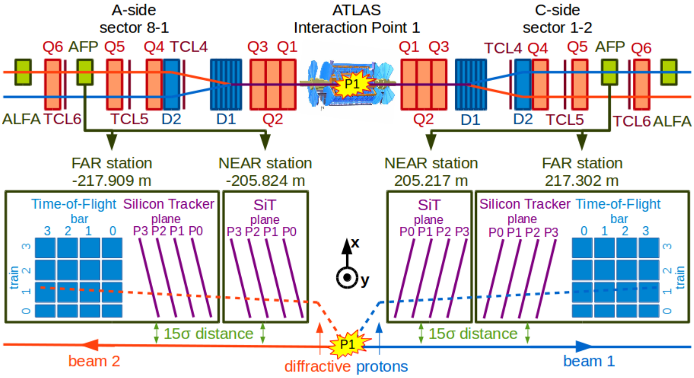




It is possible to detect protons in forward detectors to reconstruct full kinematics!

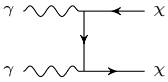
Forward detectors

[1909.10827]



Distance from the IP, m	200	420
ξ range	0.015–0.15	0.002–0.02
6.5 TeV p energy loss, GeV	97.5–975	13–130
in the center-of-mass frame, MeV	14–141	1.9–19
0.5 PeV ^{208}Pb energy loss, TeV	7.8–78	1.0–10
in the center-of-mass frame, GeV	2.9–29	0.37–3.7

Motivation: long-lived charged particles



- Long-lived charged particles
  - Live long enough to escape the detector (like muons).
  - Usual search techniques: $\mathrm{d}E/\mathrm{d}x$, time of flight.
  - Existing bounds [1506.09173, 1609.08382, 1902.01636] are model-dependent.
  - Example: SUSY chargino nearly degenerated with neutralino, $m_\chi \gtrsim 100$ GeV.
- UPC approach [1906.08568]:
  - The particles leave tracks in the central detector allowing for reconstruction of their momenta $\vec{p}_1$, $\vec{p}_2$.
  - Forward detectors provide the proton energies after the collision E_1, E_2.
  - Collision kinematics is reconstructed. The mass of the particle

$$m = \sqrt{\frac{(2E_1E_2 + \vec{p}_1\vec{p}_2)^2 - \vec{p}_1^{\,2}\vec{p}_2^{\,2}}{4E_1E_2 + (\vec{p}_1 + \vec{p}_2)^2}}.$$

- Complementary to $\mathrm{d}E/\mathrm{d}x$ or time of flight measurements.
- Background:
  - $pp \to pp\mu^+\mu^-$ (and other processes producing muons).
  - Pileup and diffractive scattering.

Production of charged particles in photon fusion

Accessible analytically!

$$\sigma(pp \to pp\tilde{\chi}_1^+\tilde{\chi}_1^-) = \int_0^\infty \int_0^\infty \sigma(\gamma\gamma \to \tilde{\chi}_1^+\tilde{\chi}_1^-)\, n(\omega_1)\, n(\omega_2)\, \mathrm{d}\omega_1\, \mathrm{d}\omega_2.$$

Production of charginos in photon fusion is given by the Breit-Wheeler cross section,

$$\sigma(\gamma\gamma \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = \frac{4\pi\alpha^2}{s}\left[\left(1 + \frac{4m_\chi^2}{s} - \frac{8m_\chi^4}{s^2}\right)\ln\frac{1+\sqrt{1-4m_\chi^2/s}}{1-\sqrt{1-4m_\chi^2/s}} - \left(1+\frac{4m_\chi^2}{s}\right)\sqrt{1-\frac{4m_\chi^2}{s}}\right],$$

where $\sqrt{s} \equiv \sqrt{4\omega_1\omega_2}$.
The equivalent photon approximation provides the momentum distribution of photons:

$$n(\omega) = \frac{\alpha}{\pi^2\omega}\int \frac{\vec{q}_\perp^{\,2}\, F^2(\vec{q}_\perp^{\,2} + \omega^2/\gamma^2)}{(\vec{q}_\perp^{\,2} + \omega^2/\gamma^2)^2}\, \mathrm{d}^2 q_\perp,$$

where q is the photon 4-momentum, $-q^2 = \vec{q}_\perp^{\,2} + (\omega/\gamma)^2 = Q^2$, F is the form factor.

In our calculations we took into account only leading contribution described by the Dirac form factor. To further improve the accuracy the form factor should be more precise.

Fiducial cross section

Cuts: $\xi_{\min} < \xi < \xi_{\max}$, $p_T > \hat{p}_T$, $|\eta| < \hat{\eta}$.

$$\sigma_{\text{fid.}}(pp \to pp\,\tilde{\chi}_1^+\tilde{\chi}_1^-) = \int\limits_{(4\xi_{\min}E)^2}^{(4\xi_{\max}E)^2} \mathrm{d}s \int\limits_{\max\left(\hat{p}_T,\,\frac{\sqrt{s/4-m_\chi^2}}{\cosh\hat{\eta}}\right)}^{\sqrt{s/4-m_\chi^2}} \mathrm{d}p_T\,\frac{\mathrm{d}\sigma(\gamma\gamma\to\tilde{\chi}_1^+\tilde{\chi}_1^-)}{\mathrm{d}p_T}\int\limits_{\frac{1}{\hat{x}}}^{\hat{x}}\frac{\mathrm{d}x}{8x}\,n\left(\sqrt{\frac{sx}{4}}\right)\,n\left(\sqrt{\frac{s}{4x}}\right),$$

where $x = \omega_1/\omega_2$, and

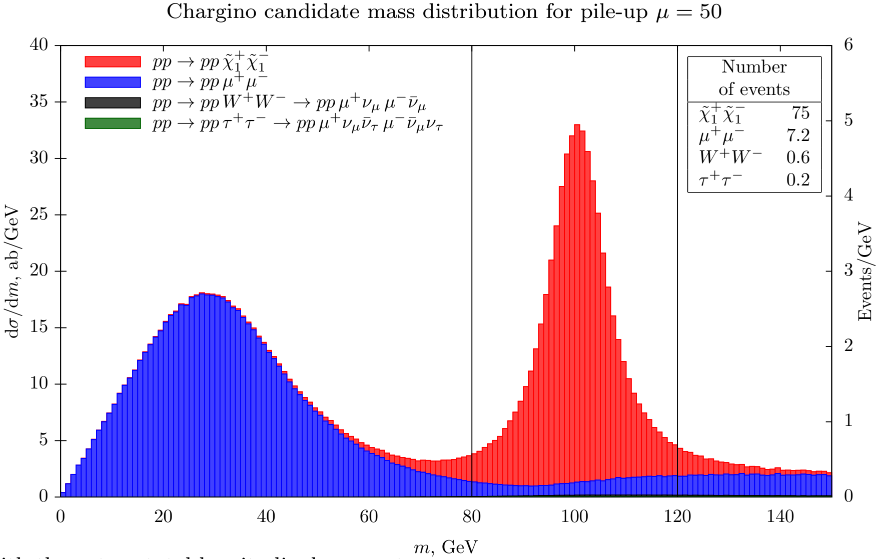
$$\hat{x} = \left(\hat{X} + \sqrt{\hat{X}^2+1}\right)^2,$$

$$\hat{X} = \frac{\sqrt{s}\,p_T}{2(p_T^2+m_\chi^2)}\left(\sinh\hat{\eta} - \sqrt{\cosh^2\hat{\eta} + \frac{m_\chi^2}{p_T^2}}\cdot\sqrt{1-\frac{4(p_T^2+m_\chi^2)}{s}}\right).$$

The differential with respect to p_T cross section is

$$\frac{\mathrm{d}\sigma(\gamma\gamma\to\tilde{\chi}_1^+\tilde{\chi}_1^-)}{\mathrm{d}p_T} = \frac{8\pi\alpha^2 p_T}{s(p_T^2+m_\chi^2)}\cdot\frac{1-\dfrac{2(p_T^4+m_\chi^4)}{s(p_T^2+m_\chi^2)}}{\sqrt{1-\dfrac{4(p_T^2+m_\chi^2)}{s}}}.$$

Results for 100 GeV particles pair production



with the cut on total longitudinal momentum:

$$|p_{\parallel,1} + p_{\parallel,2} - (\xi_1 - \xi_2)E| < 20 \text{ GeV}$$

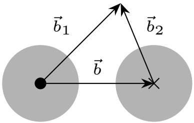
Integrated luminosity: 150 fb^{-1}

What is next?

- Improve the precision of the obtained results
  - Survival factor (both protons should remain intact after interaction; number of clean UPC events should be smaller)
  - Polarization effects (equivalent photons are polarized and it was not taken into account)

- Check our methods with Standard Model processes
  - Muon pair production in UPC is a great check!
  - Semi-inclusive processes with one proton in forward detectors are also measured experimentally

Assuming only electromagnetic interactions:



$$n(\omega) = \frac{2\alpha}{\pi\omega} \int_0^\infty \left[\frac{F(q_\perp^2 + (\omega/\gamma)^2)}{q_\perp^2 + (\omega/\gamma)^2} \right]^2 q_\perp^3 \mathrm{d}q_\perp,$$

$$\sigma(pp \to ppX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \, \sigma(\gamma\gamma \to X) \, n(\omega_1) \, n(\omega_2).$$

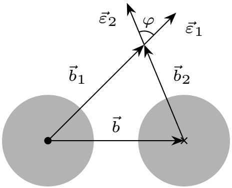
Including strong interactions:

$$n(\omega) = \int n(b,\omega) \, \mathrm{d}^2 b, \quad n(b,\omega) = \frac{\alpha}{\pi^2\omega} \left[\int_0^\infty \frac{F(q_\perp^2 + (\omega/\gamma)^2)}{q_\perp^2 + (\omega/\gamma)^2} J_1(bq_\perp) \, q_\perp^2 \mathrm{d}q_\perp \right]^2,$$

$$\sigma(pp \to ppX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, \sigma(\gamma\gamma \to X) \, n(b_1,\omega_1) \, n(b_2,\omega_2) \, P(|\vec{b}_1 - \vec{b}_2|).$$

$P(b)$ is the probability for the protons to survive after the collision with the impact parameter b. It is extracted from experimental data by fitting with the following function:

$$P(b) = \left(1 - \mathrm{e}^{-\frac{b^2}{2B}} \right)^2$$



$$\sigma(pp \to ppX) = \int\limits_0^\infty \mathrm{d}s \left[\sigma_\parallel(\gamma\gamma \to X) \frac{\mathrm{d}L_\parallel}{\mathrm{d}s} + \sigma_\perp(\gamma\gamma \to X) \frac{\mathrm{d}L_\perp}{\mathrm{d}s} \right],$$

where

$$\frac{\mathrm{d}L_\parallel}{\mathrm{d}s} = \frac{1}{4} \int\limits_{-\infty}^{\infty} \mathrm{d}y \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, n\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right) P(b) \cos^2\varphi,$$

$$\frac{\mathrm{d}L_\perp}{\mathrm{d}s} = \frac{1}{4} \int\limits_{-\infty}^{\infty} \mathrm{d}y \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, n\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right) P(b) \sin^2\varphi$$

are photon-photon luminosities.

Survival factor

$$\sigma(pp \to ppX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, \sigma(\gamma\gamma \to X) \, n(b_1, \omega_1) \, n(b_2, \omega_2) \, P(|\vec{b}_1 - \vec{b}_2|)$$

vs

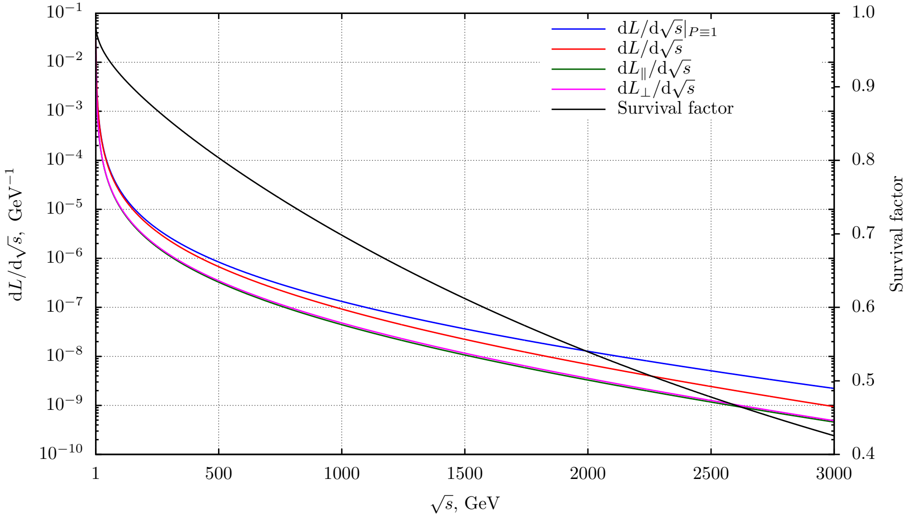
$$\sigma(pp \to ppX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \, \sigma(\gamma\gamma \to X) \, n(\omega_1) \, n(\omega_2)$$

Neglecting the polarization,

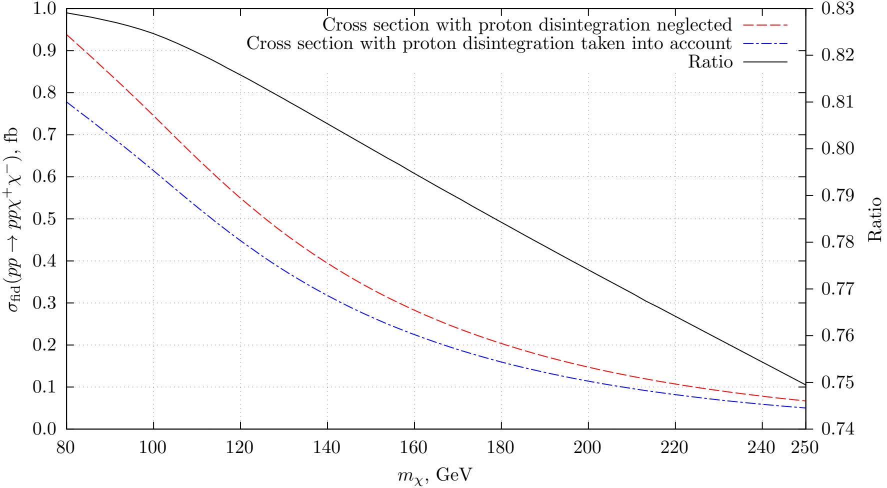
$$S(s) = \frac{\mathrm{d}L/\mathrm{d}s}{\mathrm{d}L/\mathrm{d}s|_{P=1}},$$

where $L = L_{\parallel} + L_{\perp}$.

Survival factor in pp collisions

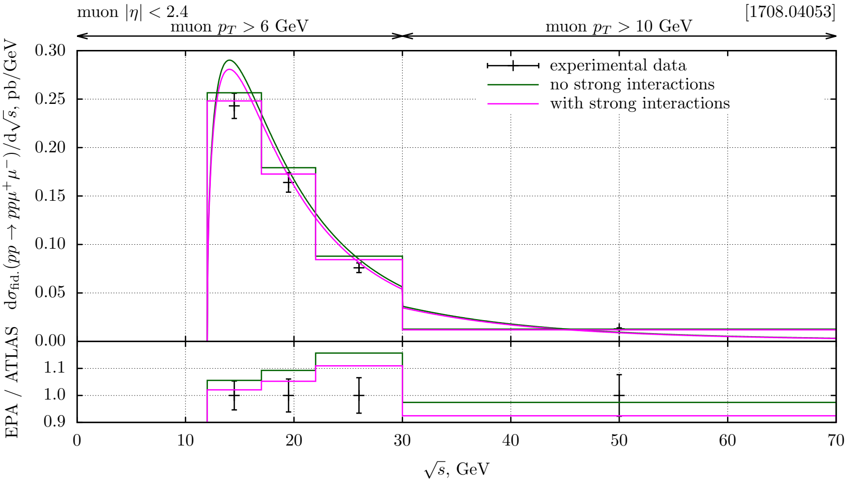


Fiducial cross section with both protons in forward detectors



$$p_T > 20 \text{ GeV}, \ |\eta| < 4.5$$

ATLAS experiment: $pp \to pp\mu^+\mu^-$ (without forward detectors)

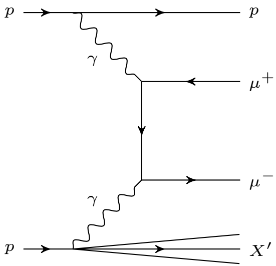


Integrated cross section:

- Experiment: 3.12 ± 0.07 (stat.) ± 0.10 (syst.) pb.
- No strong interactions: 3.39 pb, `SuperChic`: 3.58 pb.
- With strong interactions: 3.26 pb, `SuperChic`: 3.43 pb.

Semi-inclusive processes with proton(s) in forward detector

[2009.14537]



Experimental selections:

- $p_T > 15$ GeV.
- $|\eta| < 2.4$.
- $p_T^{\mu\mu} < 5$ GeV.
- 20 GeV $< m_{\mu\mu} < 70$ GeV or $m_{\mu\mu} > 105$ GeV.
- At least one proton hits a forward detector.

$$\sigma_{\text{inelastic}}(pp \to pX\mu^+\mu^-) = \sum_q \sigma(pq \to pq\mu^+\mu^-)$$

For $\left(\frac{p_T^{\mu\mu}}{m_{\mu\mu}}\right)^2 \ll 1$,

$$\sigma(pq \to pq\mu^+\mu^-) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2\, \sigma(\gamma\gamma \to \mu^+\mu^-)\, n_p(\omega_1)\, n_q(\omega_2),$$

$$n_q(\omega) = \frac{Q_q^2\alpha}{\pi\omega} \int_{\omega/E}^{1} \mathrm{d}x \int_{(\omega/x\gamma)^2}^{(p_T^{\mu\mu})^2} \mathrm{d}Q^2\, \frac{q_\perp^2}{Q^2} f_q(x, Q^2)$$

Preliminary results

- Experiment: 7.2 ± 1.6 (stat.) ± 0.9 (syst.) ± 0.2 (lumi.) fb.

- Exclusive process ($pp \to pp\mu^+\mu^-$): 8.0 fb.
- Inclusive process ($pp \to pX\mu^+\mu^-$): 8.7 fb.

Survival factor should reduce the cross section by up to $\sim 30\%$.
Errors are to be estimated yet.

Conclusions

- Ultraperipheral collisions provide us with the model-independent method for New Physics searches in photon-photon fusion.
- Detection of both protons in forward detectors allows for full kinematics reconstruction. (From ATLAS paper we know that detection of one proton is also very efficient for background elimination.)
- Equivalent Photons Approximation (EPA) provides us with results in relatively compact integral form suitable for standard integration routines without MC simulations ("semi-analytical results").
- EPA yields accurate numerical results.
- Survival factor is calculated for a broad range of invariant masses and gives noticeable corrections.
- Preliminary results for semi-inclusive muon pair production cross section are not very close to the experiment but these results are not final yet (effects like survival factor should be taken into account).
- **`libepa`** (https://github.com/jini-zh/libepa) — a library for calculations of cross sections of ultraperipheral collisions under the equivalent photons approximation.

A lot to do:

- Introduce more accurate proton form factor in our calculations.
- Understand uncertainties in semi-inclusive processes calculation.
- ...

Backup slides

In this case $F(Q^2) \approx G_D(Q^2)$, and the equivalent photon spectrum is given by

$$n_p(\omega)\,\mathrm{d}\omega = \frac{\alpha}{\pi}\left[(4a+1)\ln\left(1+\frac{1}{a}\right) - \frac{24a^2+42a+17}{6(a+1)^2}\right]\frac{\mathrm{d}\omega}{\omega},$$

where $a = (\omega/\Lambda\gamma)^2$.

The most accurate description of nucleus charge distribution appears to be in the form of Bessel decomposition:

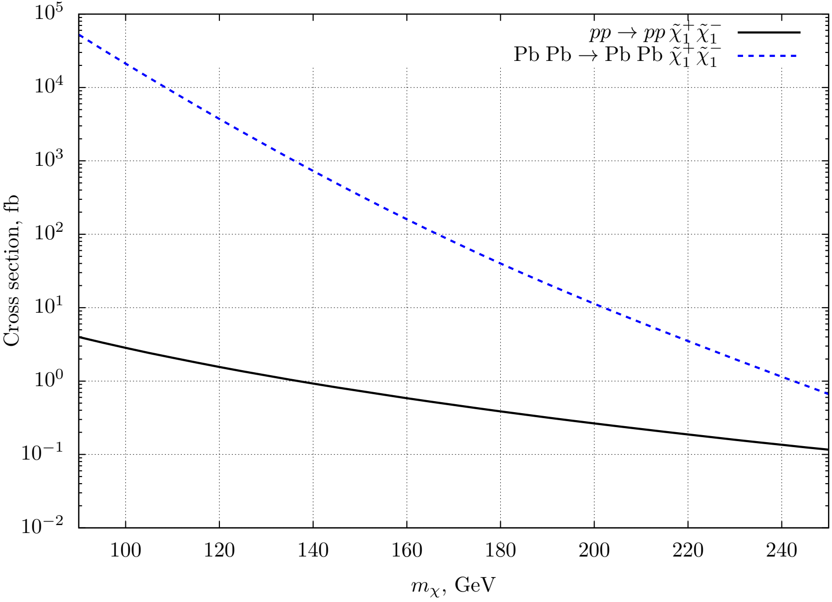
$$\rho(r) = \sum_{n=1}^{N} a_n \, j_0(n\pi r/R) \, \theta(R - r),$$

where $j_0(x) = \sin x/x$ is the spherical Bessel function of order zero, $\theta(x)$ is the Heaviside step function, a_n and R are parameters of the decomposition. The form factor is the Fourier transform of the charge distribution:

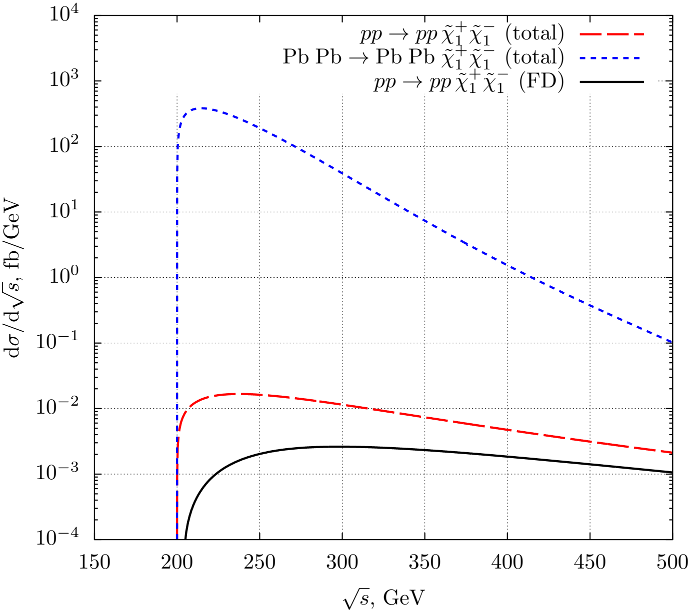
$$F(\vec{q}^{\,2}) = \frac{\int \rho(r) \mathrm{e}^{i\vec{q}\vec{r}} \mathrm{d}^3 r}{\int \rho(r) \mathrm{d}^3 r} = \frac{\sin|\vec{q}|R}{|\vec{q}|R} \cdot \frac{\sum\limits_{n=1}^{N} \frac{(-1)^n a_n}{n^2\pi^2 - \vec{q}^{\,2} R^2}}{\sum\limits_{n=1}^{N} \frac{(-1)^n a_n}{n^2 \pi^2}}.$$

Numerical values of a_n and R are provided.

Total cross section



Differential cross sections ($m_\chi = 100$ GeV)



Charginos in ultraperipheral collisions

For $m_\chi = 100$ GeV, pp collision energy 13 TeV, PbPb collision energy 5.02 TeV/(nucleon pair),

- $\sigma(pp \to pp\, \tilde{\chi}_1^+ \tilde{\chi}_1^-) = 2.84$ fb,
- $\sigma(\text{Pb Pb} \to \text{Pb Pb}\, \tilde{\chi}_1^+ \tilde{\chi}_1^-) = 21.2$ pb $\Rightarrow$ for 2.4 nb^{-1} there are 0.053 events

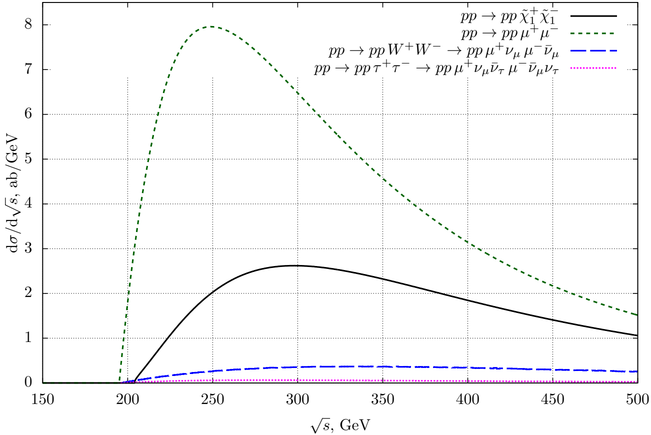
Experimental cuts:

- Both protons hit the forward detectors.
- Transverse momentum of each chargino > 20 GeV.
- Pseudorapidity of each chargino < 2.5.

Fiducial cross section: $\sigma_{\text{fid}}(pp \to pp\tilde{\chi}_1^+ \tilde{\chi}_1^-) = 0.72$ fb.

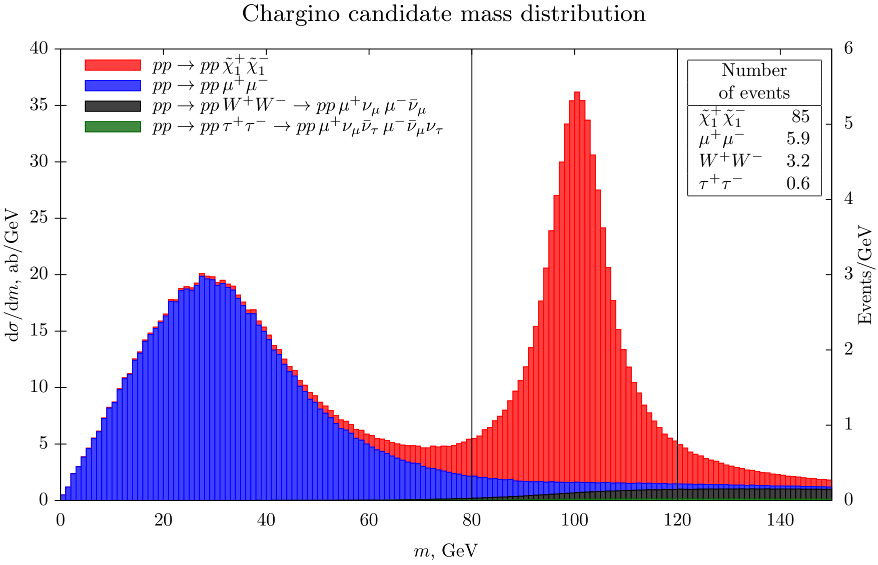
For heavy ion to hit forward detector, its energy loss should be at least 7.8 TeV. Therefore fiducial cross section is suppressed by both the Breit–Wheeler cross section and nucleus form factor. But it is still possible to look for chargino in UPC with the help of Eloss and TOF methods if there will be enough statistics.

Background: reactions producing a pair of muons.



Reaction	Cross section, fb
$pp \to pp\, \tilde{\chi}_1^+ \tilde{\chi}_1^-$	0.72
$pp \to pp\, \mu^+ \mu^-$	1.60
$pp \to pp\, W^+W^- \to pp\, \mu^+\mu^-\, \nu_\mu \bar{\nu}_\mu$	0.15
$pp \to pp\, \tau^+\tau^- \to pp\, \mu^+ \nu_\mu \bar{\nu}_\tau\, \mu^- \bar{\nu}_\mu \nu_\tau$	0.02

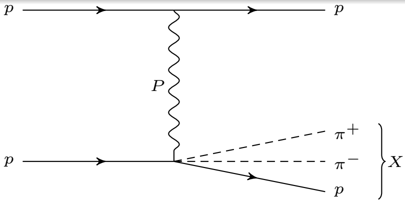
Signal



Integrated luminosity: 150 fb^{-1}

Pile-up

The combination of low energy muons with protons from low mass diffractive dissociation is mimicking the chargino production in UPC.



L. A. Harland-Lang *et al.*, JHEP 1904 (2019) 010, arXiv:1812.04886, Appendix B

Probability for a proton to hit the forward detector after dissociation $P_{\mathrm{SD}} \approx 0.01$.

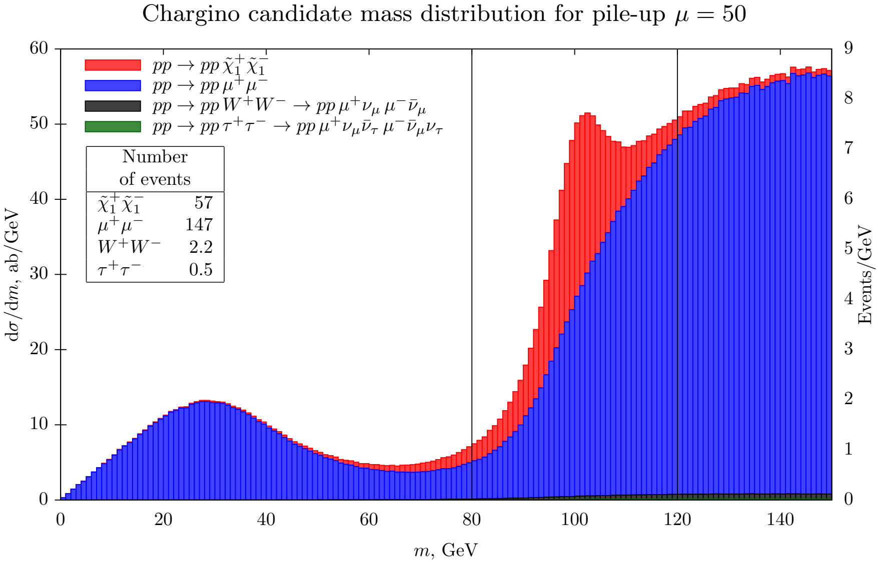
About 40% of bunch crossings with 50 collisions at once will produce at least one proton hitting one of the forward detectors!

A.B.Kaidalov *et al.*, Phys.Lett.B45 (1973) 493

V.A. Khoze, A.D. Martin, M.G. Ryskin, J.Phys. G44 (2017) no.5, 055002, arXiv:1702.05023

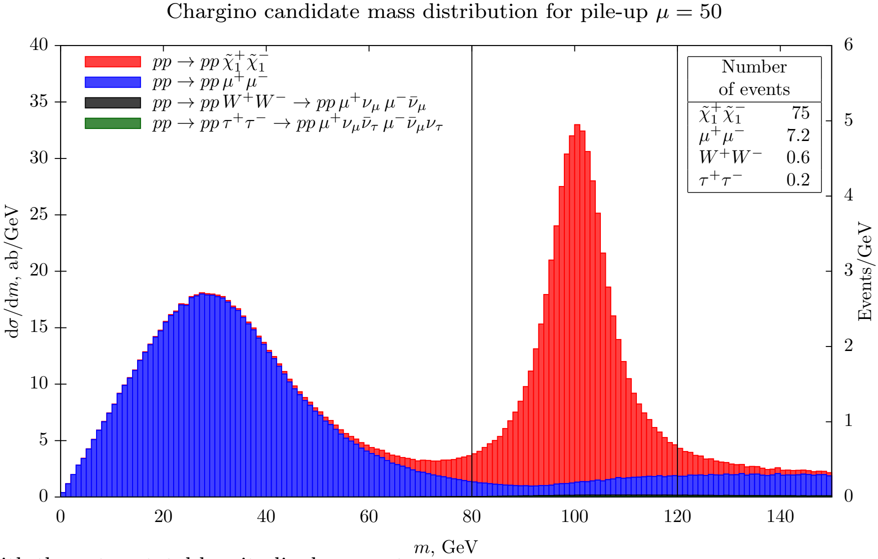
Low mass approximation:

$$M_X^2 \frac{\mathrm{d}\sigma}{\mathrm{d}M_X^2} \propto 1 + \frac{2\ \mathrm{GeV}}{M_X}.$$



Integrated luminosity: 150 fb^{-1}

Results for 100 GeV particles pair production

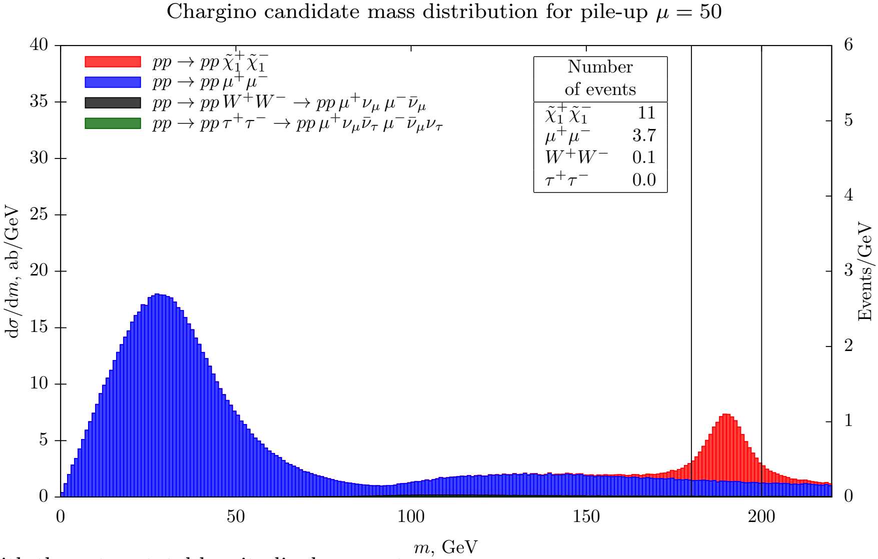


with the cut on total longitudinal momentum:

$$|p_{\parallel,1} + p_{\parallel,2} - (\xi_1 - \xi_2)E| < 20 \text{ GeV}$$

Integrated luminosity: 150 fb^{-1}

Results with $m_\chi = 190$ GeV

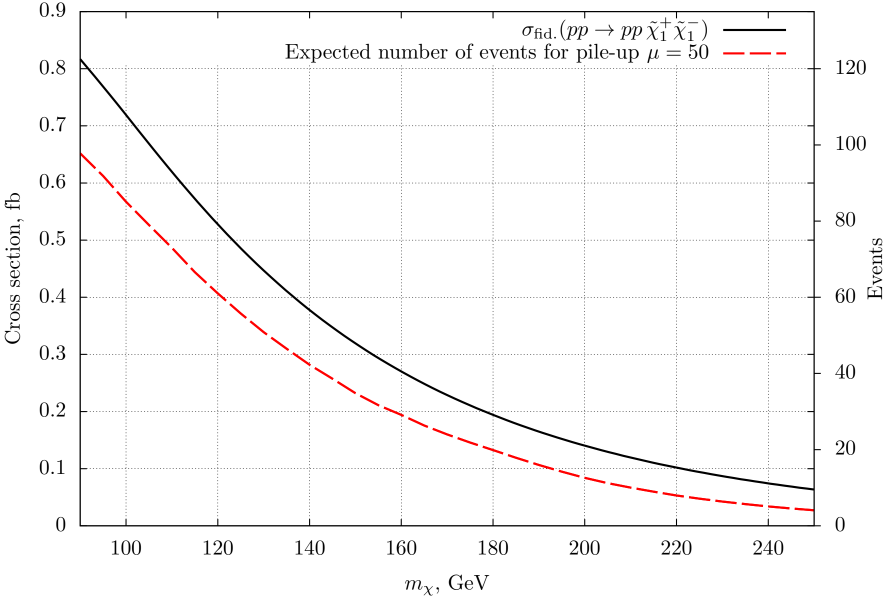


with the cut on total longitudinal momentum:

$$|p_{\parallel,1} + p_{\parallel,2} - (\xi_1 - \xi_2)E| < 20 \text{ GeV}$$

Integrated luminosity: 150 fb^{-1}

Fiducial cross sections



Accessible masses and lifetimes