

Marco Drewes, Université catholique de Louvain

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# A Heavy Metal Path to New Physics

08. 07. 2021

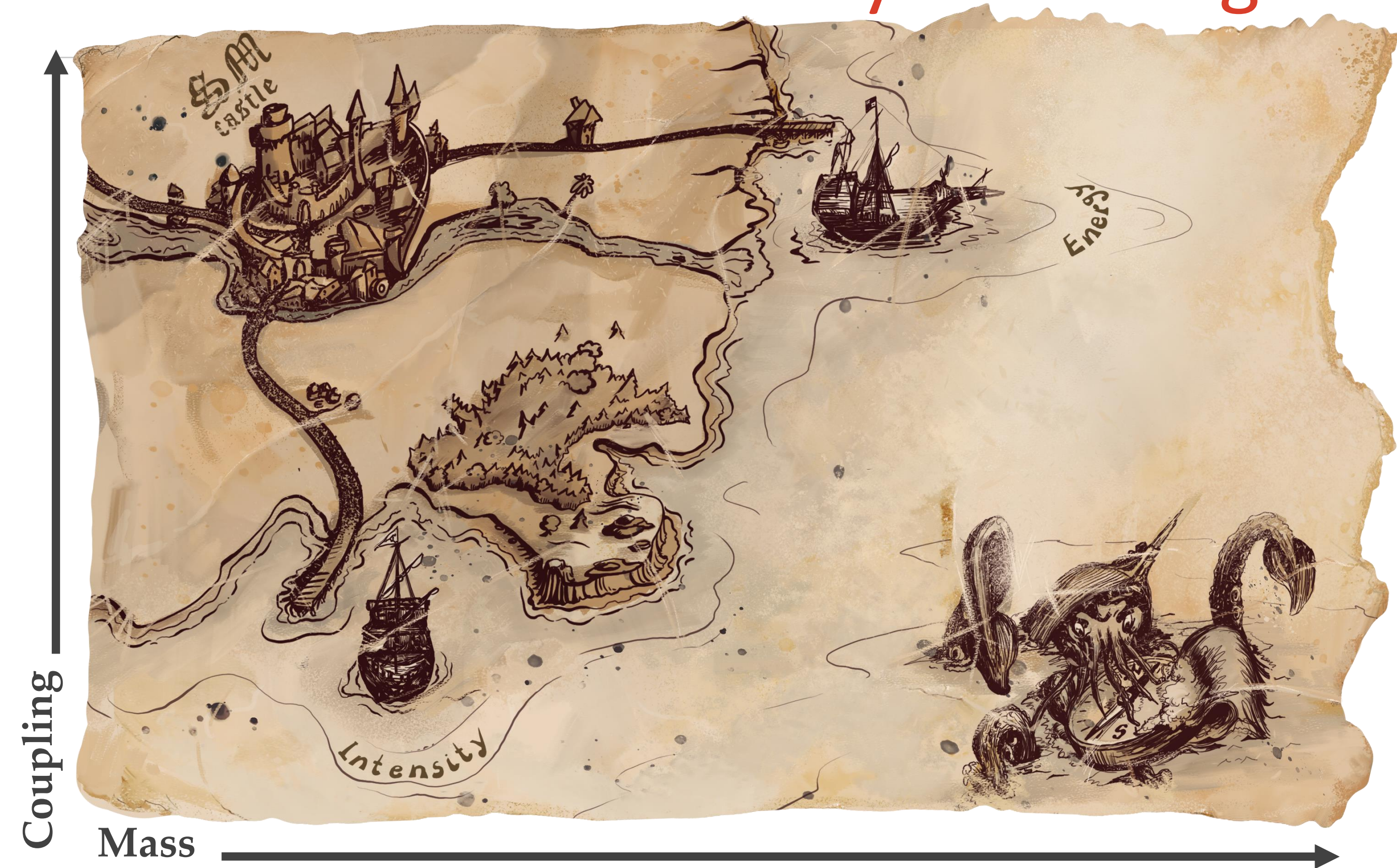
QUARKS 2020

2021 Online Workshops

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# Where is the New Physics hiding?





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CP3 – UCLouvain  
December 4-5 2018

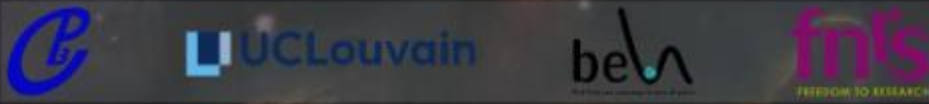
*Organising Committee*  
Marco Drewes  
Andrea Giammanco  
Jan Hajer  
Fabio Maltoni

*Speakers include*  
Roderik Bruce  
Pieter David  
David d'Enterria  
Glennys Farrar (tbc)  
Oliver Gould  
Lucian Harland-Lang  
Sonia Kabana  
Simon Knapen  
Georgios Krintiras  
Guilherme Milhano  
Swagata Mukherjee  
Jeremi Niedziela  
Jessica Prisciandaro  
Valerii Pugach  
Federico Redi  
Michaela Schaumann

# HEAVY IONS AND HIDDEN SECTORS

In the recent past, several proposals have been made to search for new phenomena in heavy ion collisions at the Large Hadron Collider, e.g. axion-like particles, long-lived particles or magnetic monopoles. The objective of this workshop is to connect members of the involved communities to explore these ideas. It provides a unique opportunity for theorists, experimentalists and accelerator physicists who previously had little interaction with each other to discuss new approaches as well as practical and fundamental limitations, and to form collaborations for future research.

Registration: [agenda.irmp.ucl.ac.be/event/3186](https://agenda.irmp.ucl.ac.be/event/3186)



ECT\*  
EUROPEAN COMMISSION  
EUROPEAN RESEARCH INFRASTRUCTURE PROGRAMME

ONLINE Workshop  
**STRONG<sup>\*</sup>**  
2020

## Heavy Ions and New Physics

May 20-21, 2021 on ZOOM Platform

**Abstract | Main Topics**

In the recent past, several proposals have been made to exploit heavy ion collisions at the Large Hadron Collider (LHC) to search for new phenomena in particle physics, including axion-like particles, long-lived particles beyond the Standard Model and magnetic monopoles.

The objective of this workshop is to bring together members of the involved communities to exploit the potential of these ideas, either during scheduled LHC runs or in dedicated efforts at the LHC or future colliders. We want to create a unique opportunity for exchange between scientists working in different fields of experimental physics, theoretical physics, accelerator physics and detector physics that otherwise have little connection.

**Keynote speakers**

Elena BRATKOVSKAYA (GSI) – Roderik BRUCE (CERN) – Émilien CHAPON (CERN) – Mateusz DYNDAL (CERN)  
Hesham EL FAHAW (UCLouvain) – Glennys FARRAR (NYU) – Oliver FISCHER (Liverpool University)  
Taku GURU (Tokyo University) – Lucian HARLAND-LANG (Oxford University)  
Yen-Jie LEE (Massachusetts Inst. of Technology) – Tanguy PÉROG (KIT, IAP)  
James PHILLIPS (Alberta University) – Arttu RAJANTIE (Imperial College)  
Suvrat RAO (Hamburg University) – Kristof SCHMIEDER (CERN) – Ralf ULRICH (KIT)  
Aditya UNETHI (Alabama University) – Susanne WESTHOFF (Heidelberg University)

**Program**

**Organizers**

Marco DREWES (UCLouvain); David D'ENTERRIA (CERN);  
Andrea GIAMMANCO (UCLouvain); Jan HAJER (Basel University)

\* This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824069

Director of the ECT\*: Professor Gert Aarts | The ECT\* is part of the Fondazione Bruno Kessler. The Centre is funded by the Autonomous Province of Trento, funding agencies of EU Member and Associated states, and by INFN-TIFPA and has the support of the Department of Physics of the University of Trento.

First dedicated Workshop at UCLouvain in 2018:

<https://agenda.irmp.ucl.ac.be/event/3186/>

Second workshop online with support of ECT\* in 2021 (**140+ registered participants!**):

<https://indico.cern.ch/e/Heavy-Ions-and-New-Physics>



# New physics searches with heavy-ion collisions at the CERN Large Hadron Collider

Roderik Bruce<sup>1</sup>, David d'Enterria<sup>\*2</sup>, Albert de Roeck<sup>2</sup>, Marco Drewes<sup>3</sup>,  
Glennys R. Farrar<sup>4</sup>, Andrea Giammanco<sup>3</sup>, Oliver Gould<sup>5</sup>, Jan Hajer<sup>3</sup>,  
Lucian Harland-Lang<sup>6</sup>, Jan Heisig<sup>3</sup>, John M. Jowett<sup>1</sup>, Sonia Kabana<sup>†7</sup>,  
Georgios K. Krintiras<sup>‡3</sup>, Michael Korsmeier<sup>8,9,10</sup>, Michele Lucente<sup>3</sup>,  
Guilherme Milhano<sup>11,12</sup>, Swagata Mukherjee<sup>13</sup>, Jeremi Niedziela<sup>2</sup>, Vitalii A. Okorokov<sup>14</sup>,  
Arttu Rajantie<sup>15</sup>, and Michaela Schaumann<sup>1</sup>

This document summarises proposed searches for new physics accessible in the heavy-ion mode at the CERN Large Hadron Collider (LHC), both through hadronic and ultraperipheral  $\gamma\gamma$  interactions, and that have a competitive or, even, unique discovery potential compared to standard proton-proton collision studies. Illustrative examples include searches for new particles — such as axion-like pseudoscalars, radions, magnetic monopoles, new long-lived particles, dark photons, and sexaquarks as dark matter candidates — as well as new interactions, such as non-linear or non-commutative QED extensions. We argue that such interesting possibilities constitute a well-justified scientific motivation, complementing standard quark-gluon-plasma physics studies, to continue running with ions at the LHC after the Run-4, i.e., beyond 2030, including light and intermediate-mass ion species, accumulating nucleon-nucleon integrated luminosities in the accessible  $\text{fb}^{-1}$  range per month.

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# New Particles in HI Collisions?

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- **New production mechanisms**
  - in the strong electromagnetic fields generated in ultra-peripheral collisions (fly-by)
  - in the quark-gluon plasma itself
- **Different backgrounds compared to proton collisions**
  - absence of pile-up
  - modified triggers



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# New Particles in HI Collisions?

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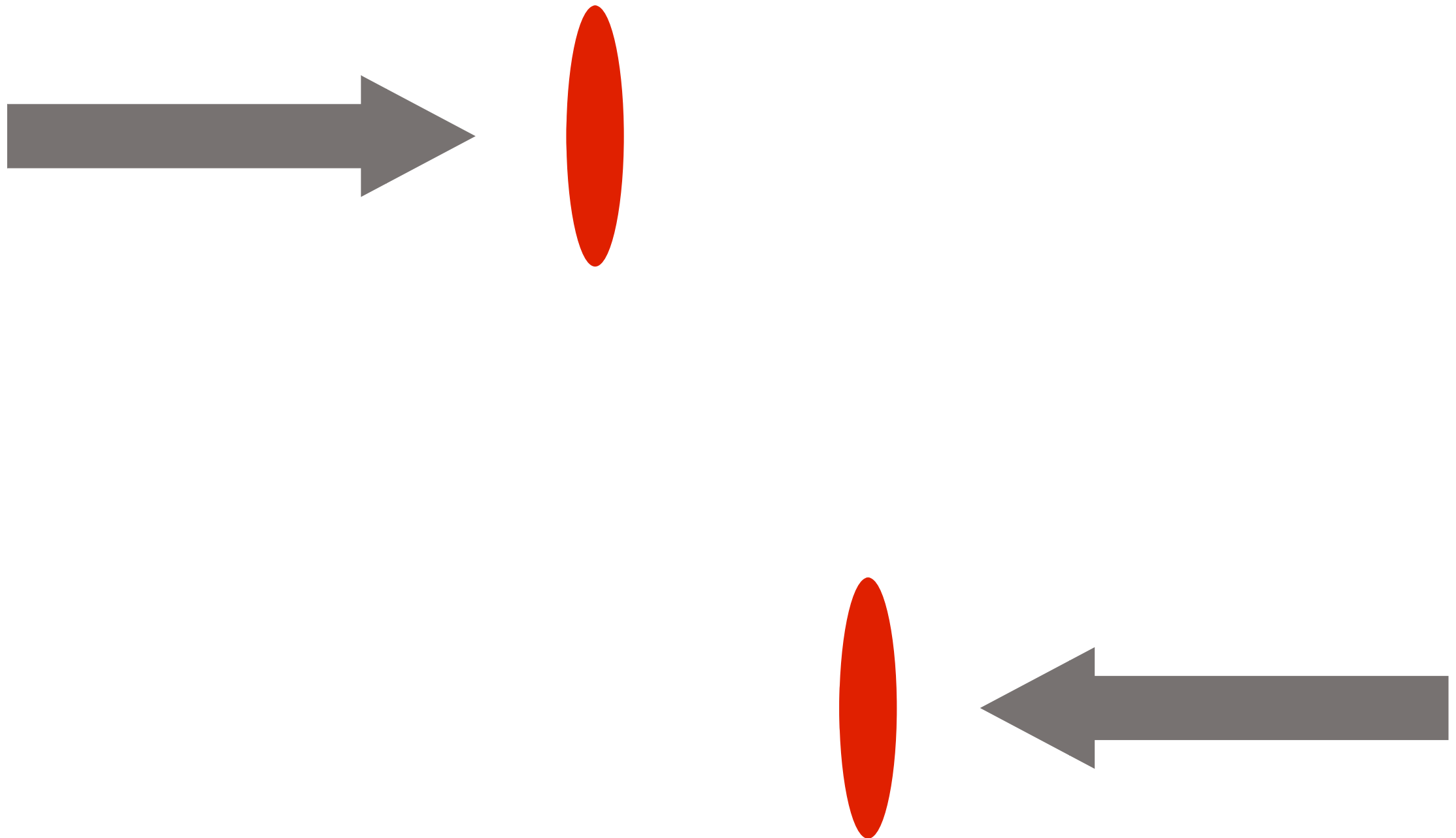
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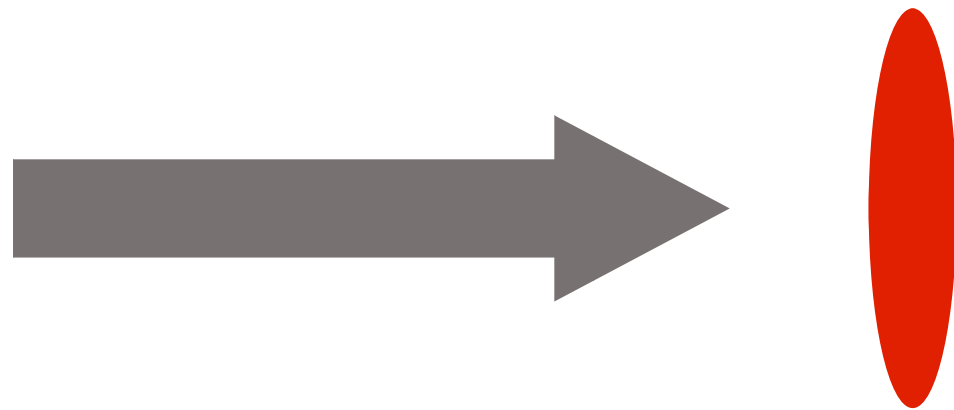
# Ultra-peripheral Collision (fly-by)

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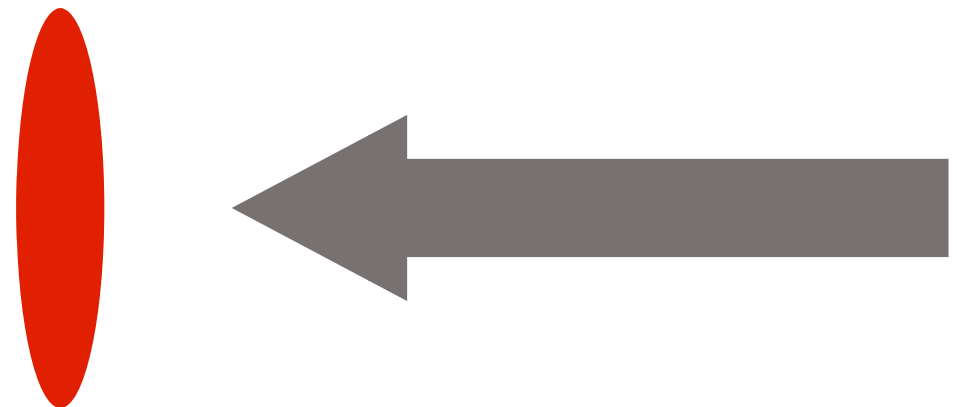
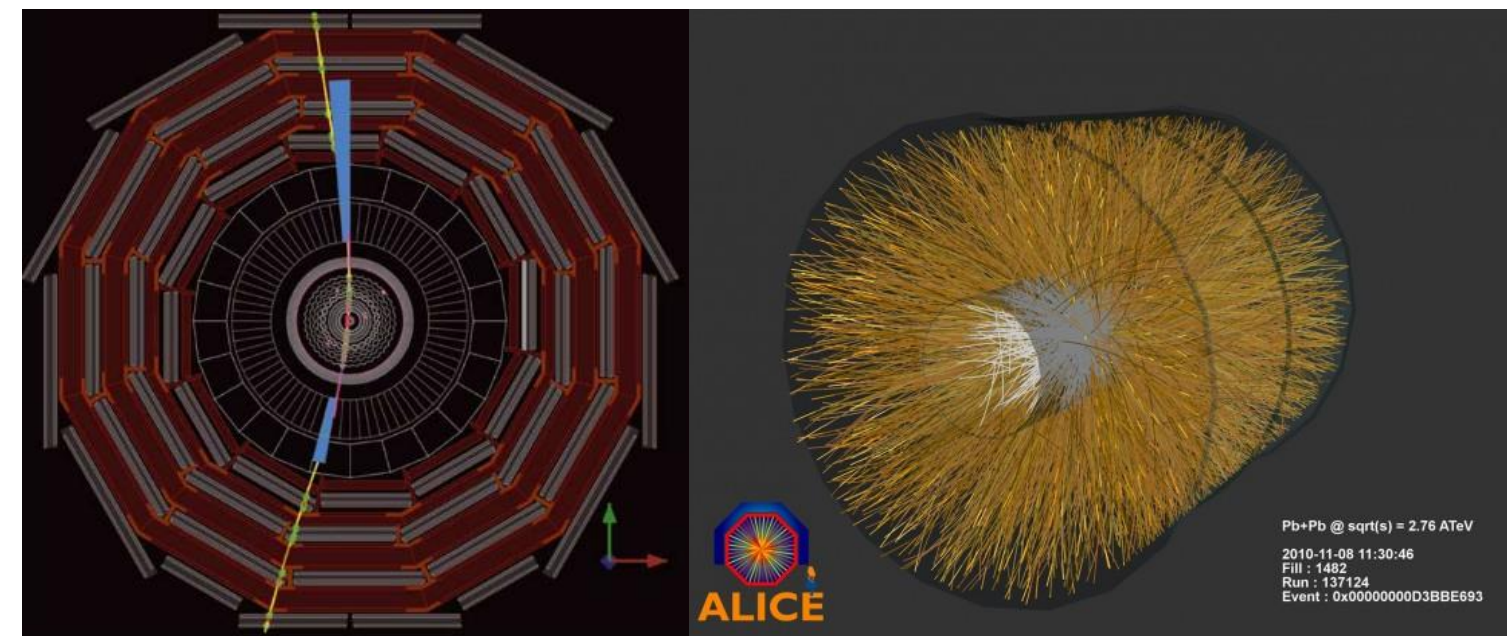
# Ultra-peripheral Collision (fly-by)



- impact parameter  $b$  is much larger than ion radius  $R$
- almost no hadronic backgrounds

ultra-peripheral collision

head-on collision





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# The LHC as a Photon Collider

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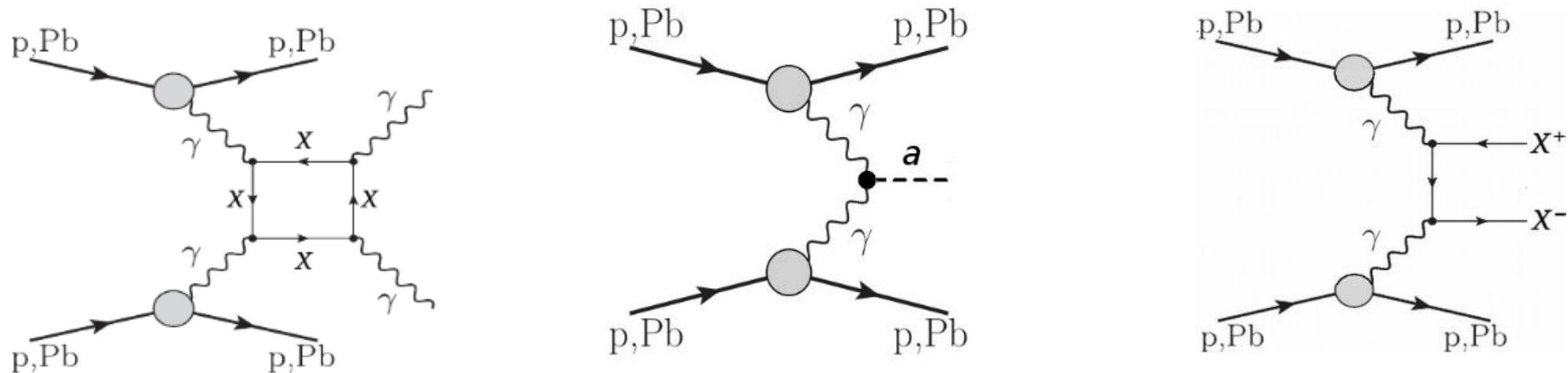
- electromagnetic fields in HI collisions are strongest ever created ( $> 10^{14}$  Tesla)
- In a HI fly-by, one can study light-by-light scattering  
CMS: [1810.04602](#)  
ATLAS: [1702.01625](#), [1904.03536](#)
- In the “equivalent photon approximation” the fields can be modelled by plane waves of nearly on-shell photons (Weizsäcker 34, Williams ‘34)

$$N(E, \vec{b}) = \frac{Z^2 \alpha}{\pi^2} \left( \frac{E}{\gamma} \right)^2 K_1^2 \left( \frac{E |\vec{b}|}{\gamma} \right)$$



# The LHC as a Photon Collider

- Opens several channels to produce new particles



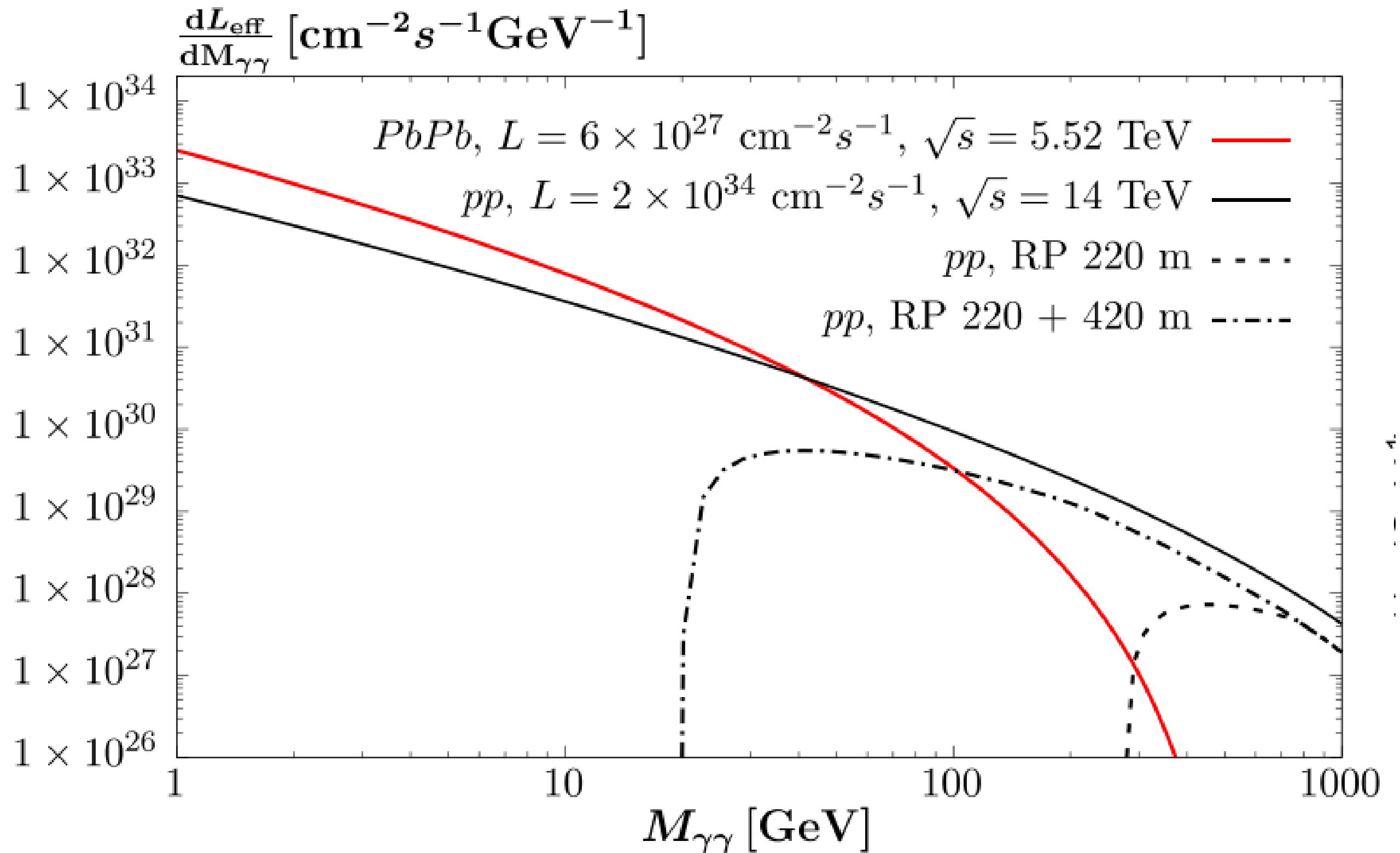
- In equivalent photon approximation

$$\sigma_{A_1 A_2 \rightarrow A_1 X A_2} = \int dx_1 dx_2 n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \rightarrow X} = \int dm_{\gamma\gamma} \frac{d\mathcal{L}_{\text{eff}}}{dm_{\gamma\gamma}} \hat{\sigma}_{\gamma\gamma \rightarrow X}$$

- enhancement  $\sim Z^4$ , i.e., more than  $10^7$  for Pb-Pb!
- can compensate for the lower integrated luminosity!

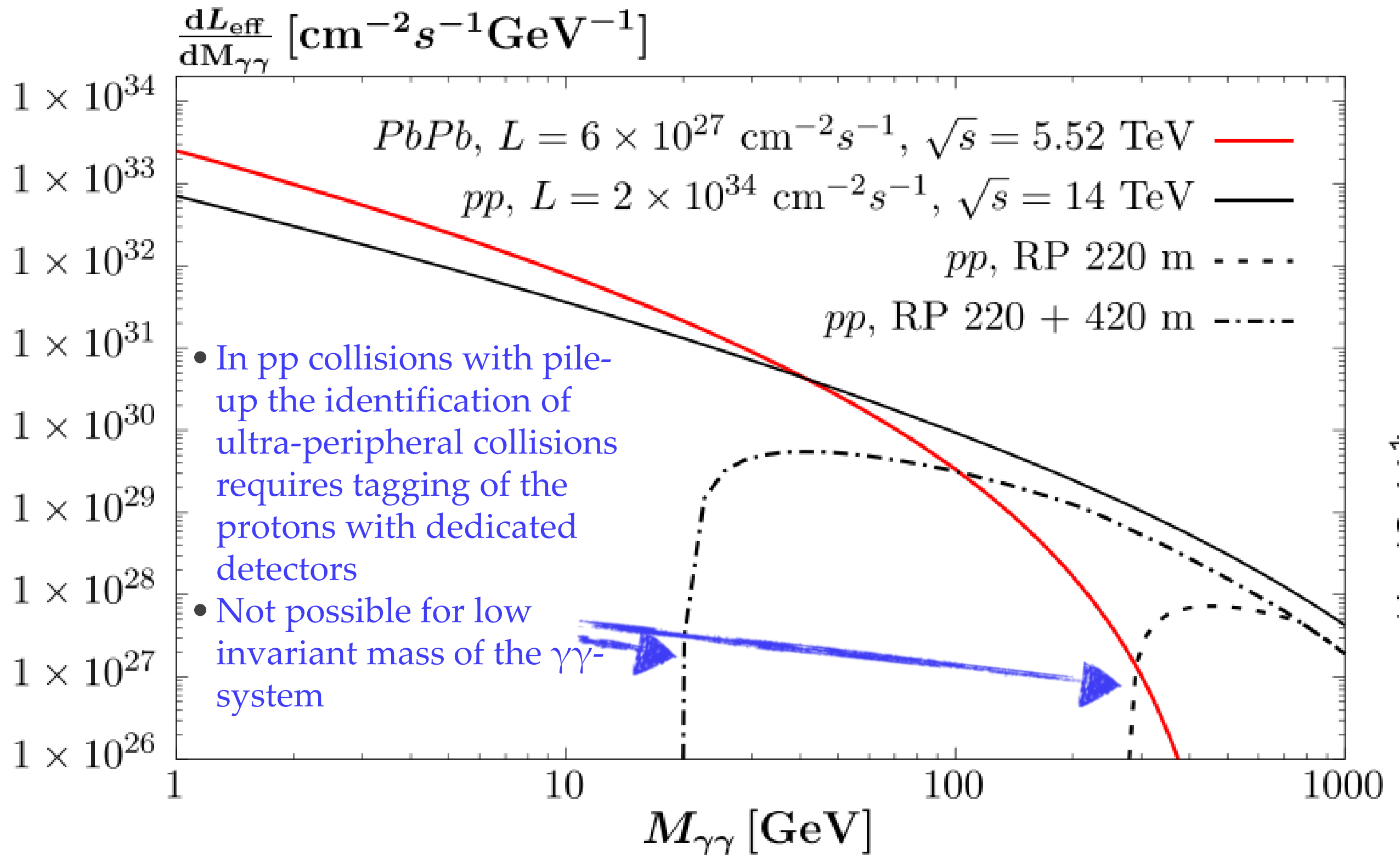


# Effective $\gamma\gamma$ -Luminosity



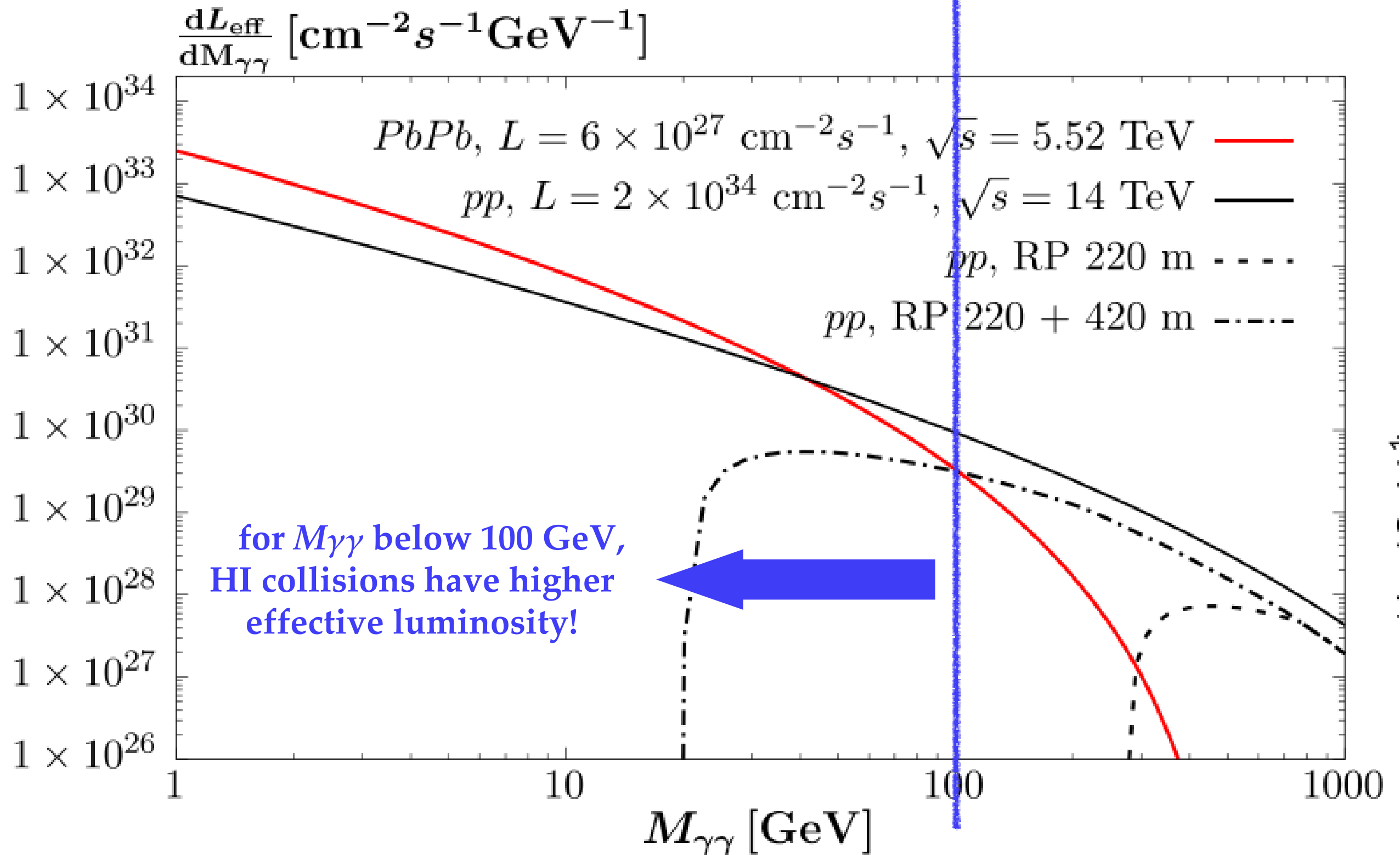


# Effective $\gamma\gamma$ -Luminosity

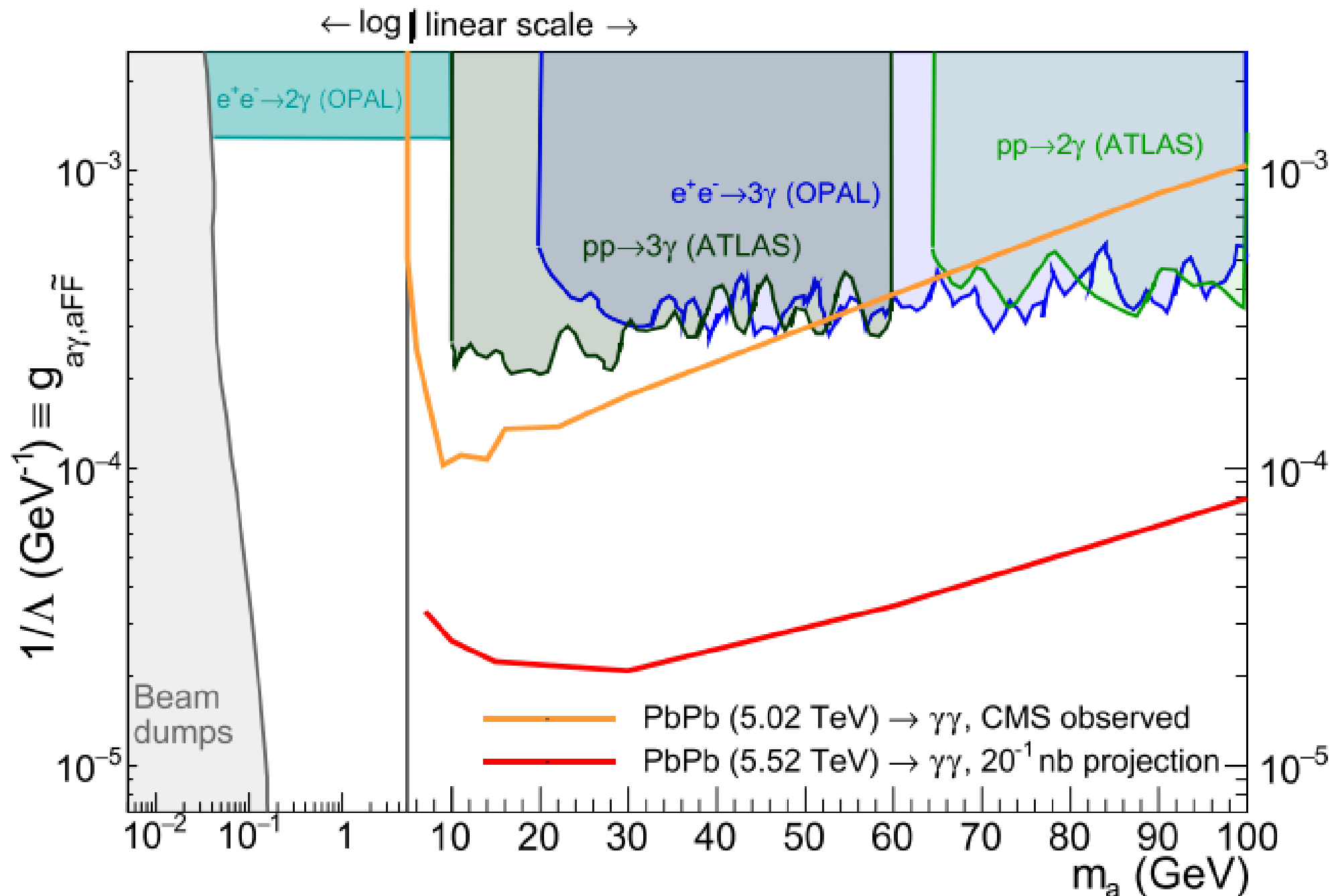




# Effective $\gamma\gamma$ -Luminosity



# Axion-like Particles

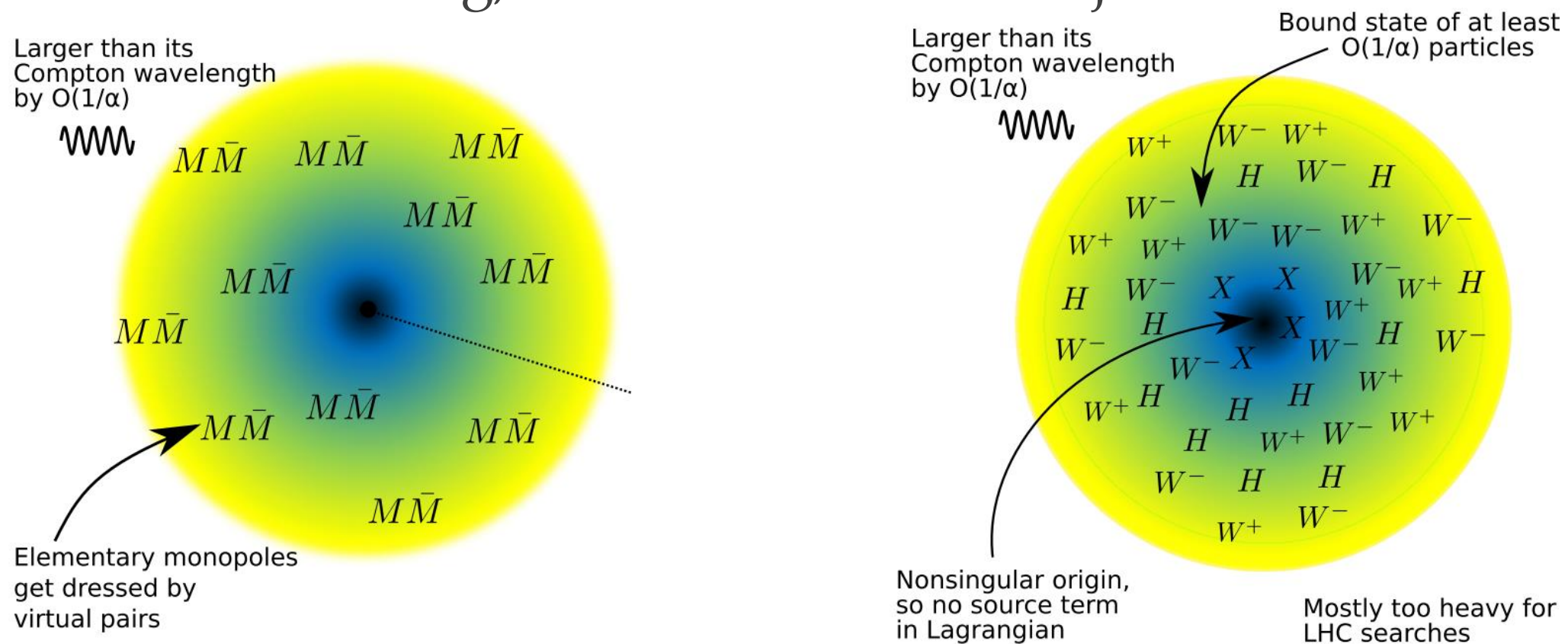


from [arXiv:1812.07688](https://arxiv.org/abs/1812.07688)  
see also al [1607.06083](https://arxiv.org/abs/1607.06083) and LHCb [2103.01862](https://arxiv.org/abs/2103.01862),



# Magnetic Monopoles

- Magnetic monopoles can exist as singular “elementary” objects (e.g. *Dirac monopole*) or topological field configurations (e.g. *'t Hooft–Polyakov monopole*)
- Due to screening, both are extended objects

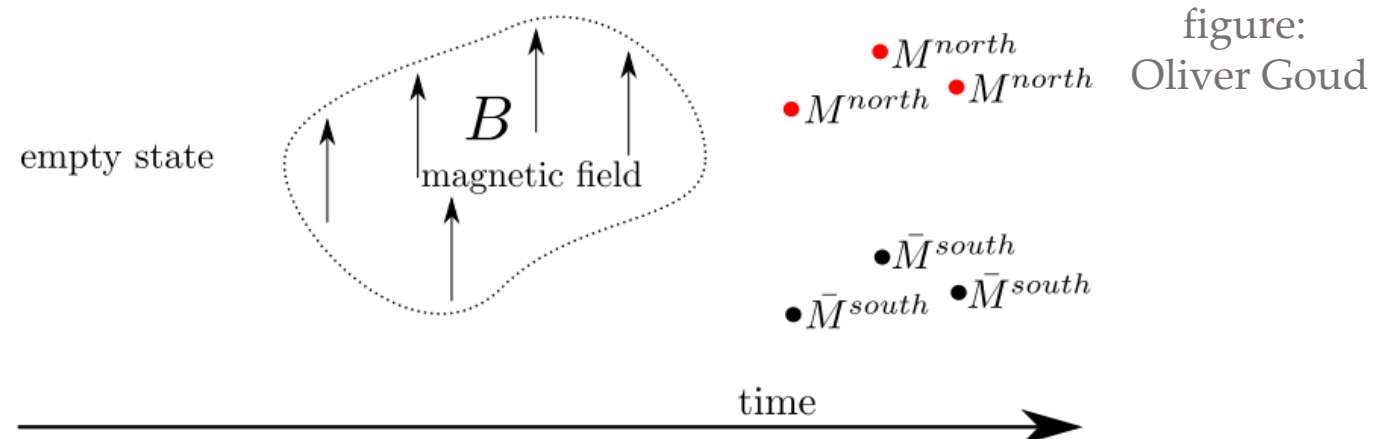


→ exponential suppression of production in  $pp$  collisions due to small overlap with point-like scattering

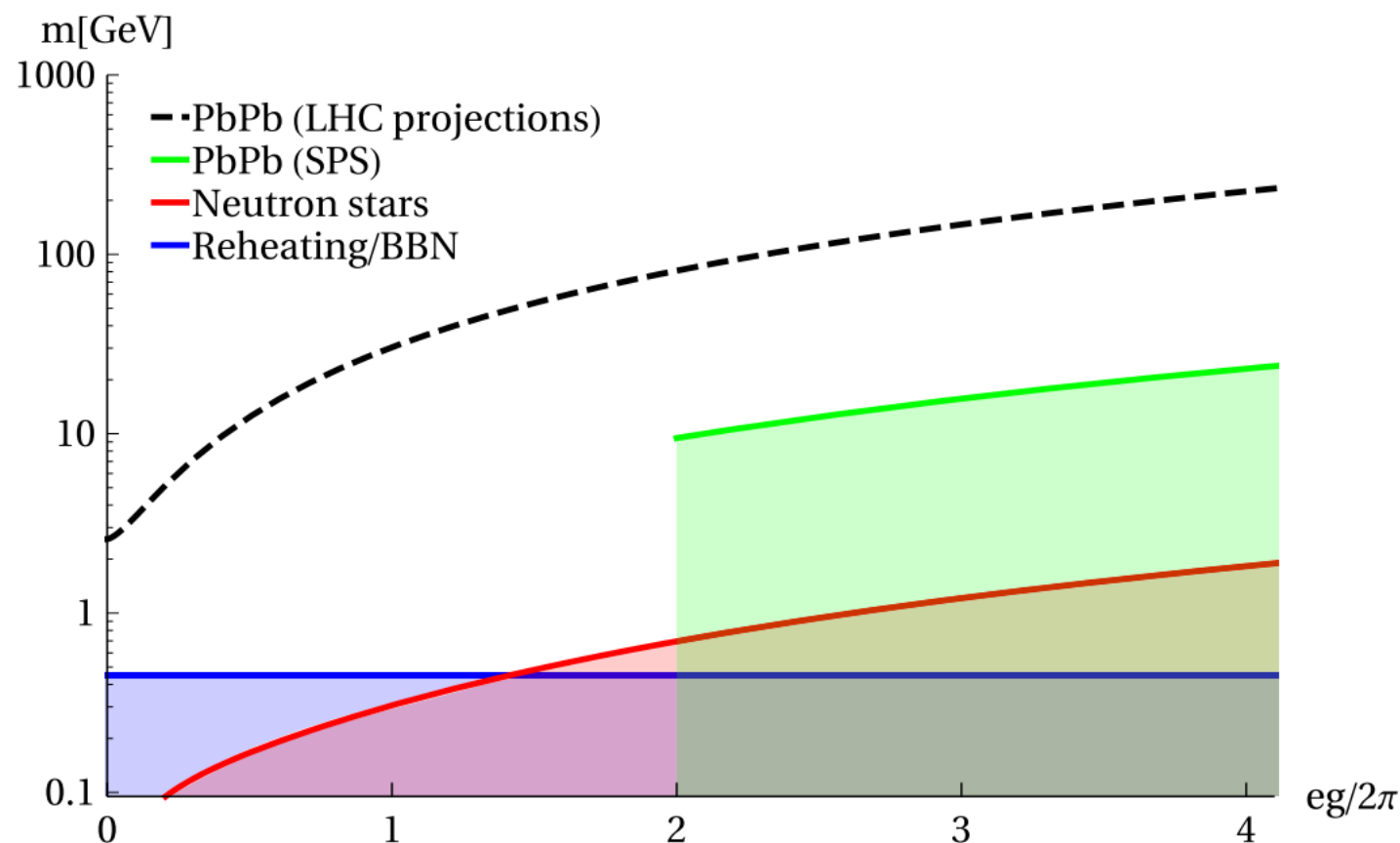
# Magnetic Monopoles

- Schwinger-effect allows for non-perturbative production in strong magnetic fields

Affleck/Manton 82



→ production in HI collisions possible!



- dedicated experiment: MoEDAL



Gould/Rajantie [1705.07052](#), see also [2103.14454](#), [1902.04388](#),



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# New Particles in HI Collisions?

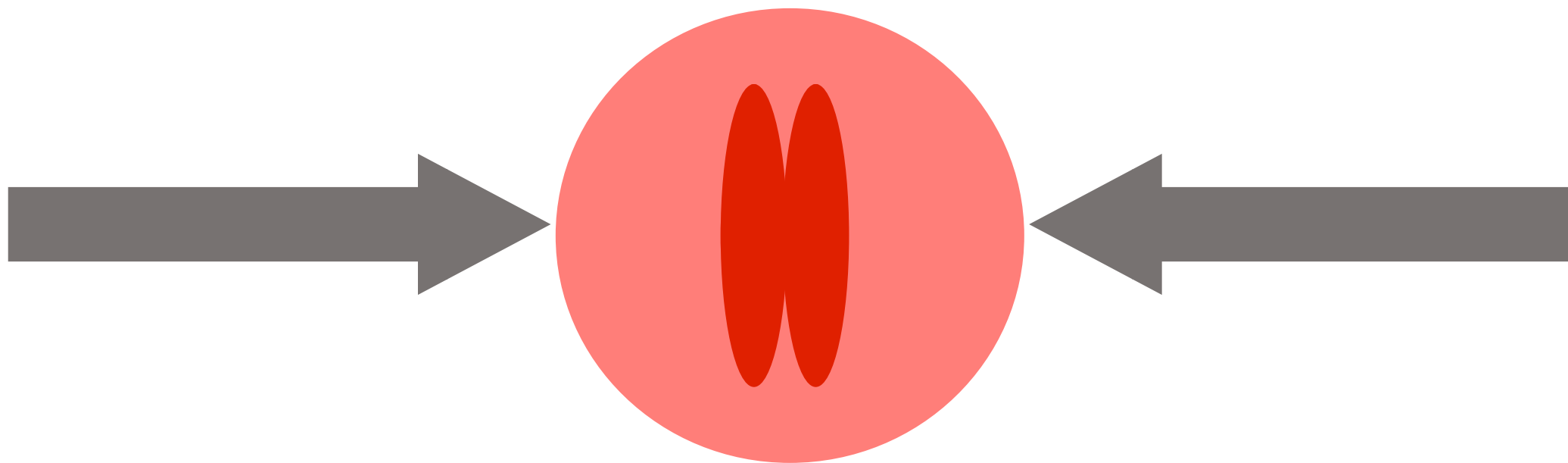
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# Production from QGP

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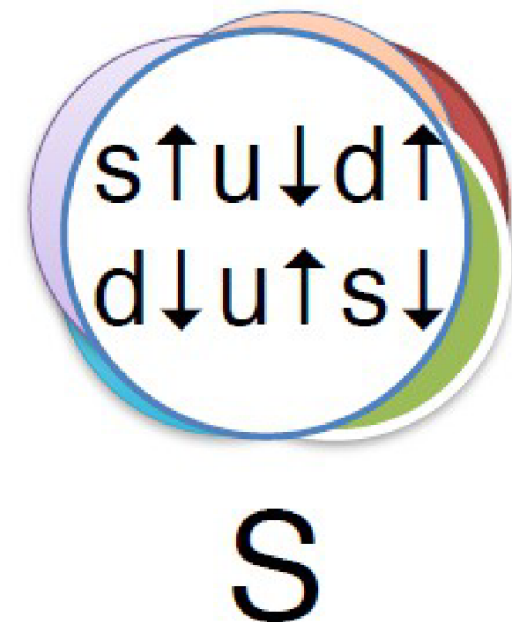
# Sexaquarks

- hypothetical colour-singlet state of 6 quarks

Farrar [1708.08951](#)

- proposed properties

- extremely stable
- spin 0
- no net flavour
- small coupling to pions, hardons
- mass 1.7 - 2 GeV



- potential DM candidate Farrar [1805.03723](#)

prediction:  $\Omega_{\text{DM}}/\Omega_{\text{b}} = 4.5 \pm 1$

Planck:  $\Omega_{\text{DM}}/\Omega_{\text{b}} = 5.4 \pm 0.05$

- thermal production in QGP... but how to detect???

proposed channel:  $\bar{S} + n \rightarrow \bar{\Lambda}^0 + K_S^0 \rightarrow \bar{p} + \pi^+ + \pi^- + \pi^+$

de Clercq [CERN-THESIS-2019-278](#)

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# New Particles in HI Collisions?

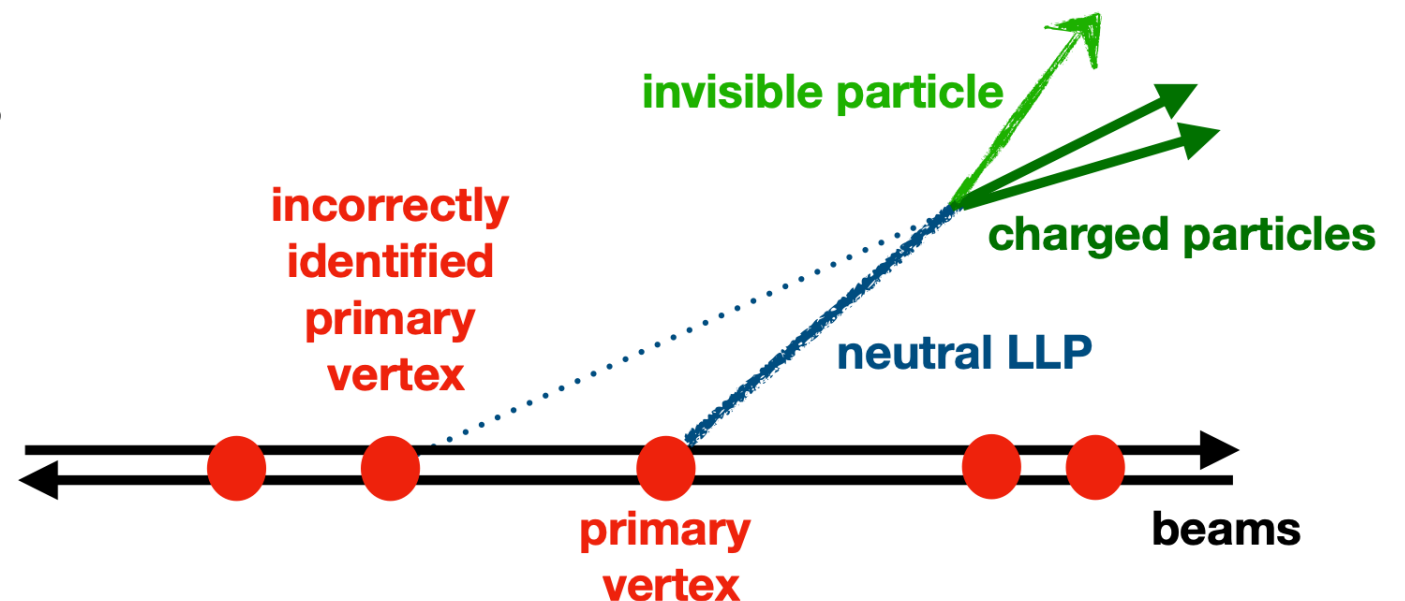
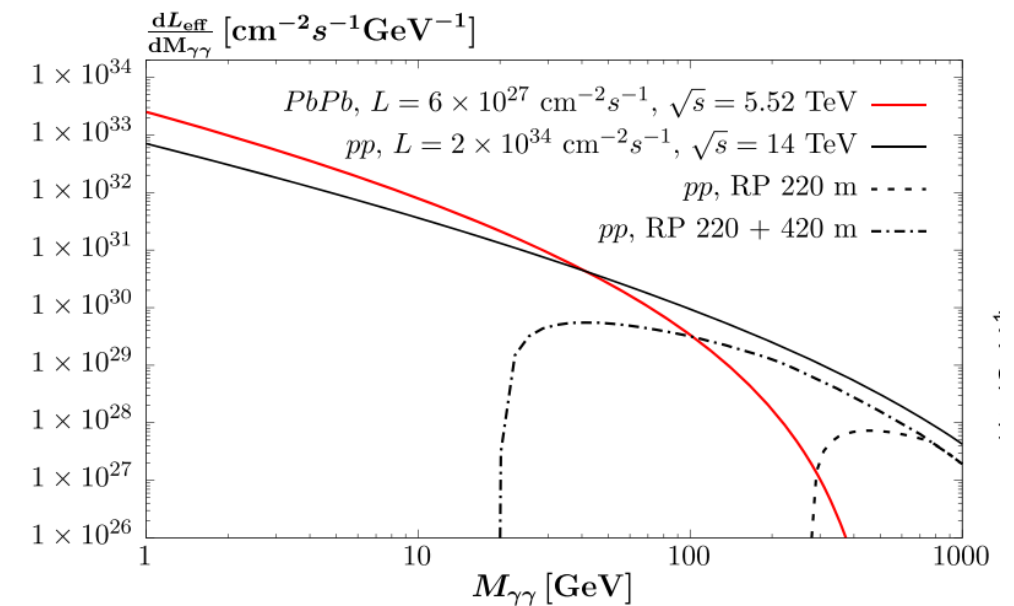
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# Pile-up Issues

- for ALP searches: pile-up requires tagging, leading to a decreased effective  $\gamma\gamma$  luminosity
- In long lived particle searches pile-up can lead to primary vertex mis-identification



**HI collisions are free of pile-up!**

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# New Particles in HI Collisions?

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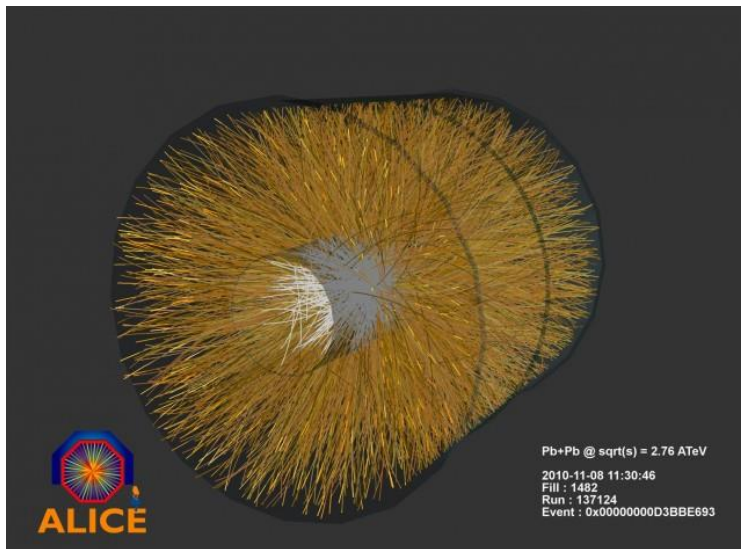
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# A clean environment?

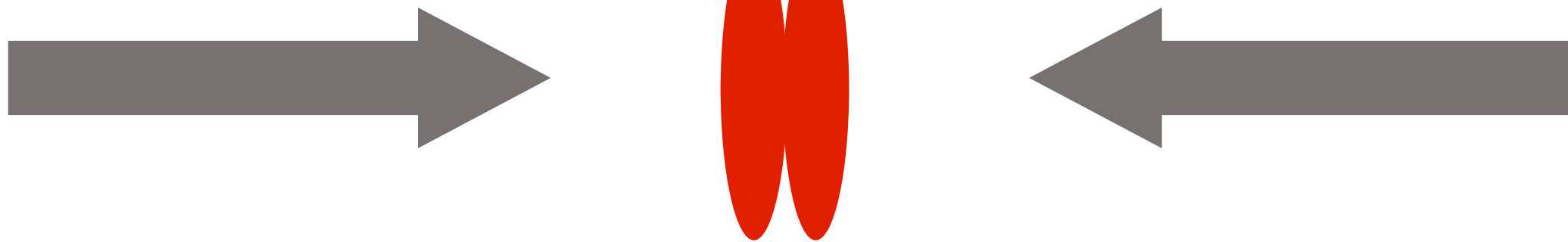
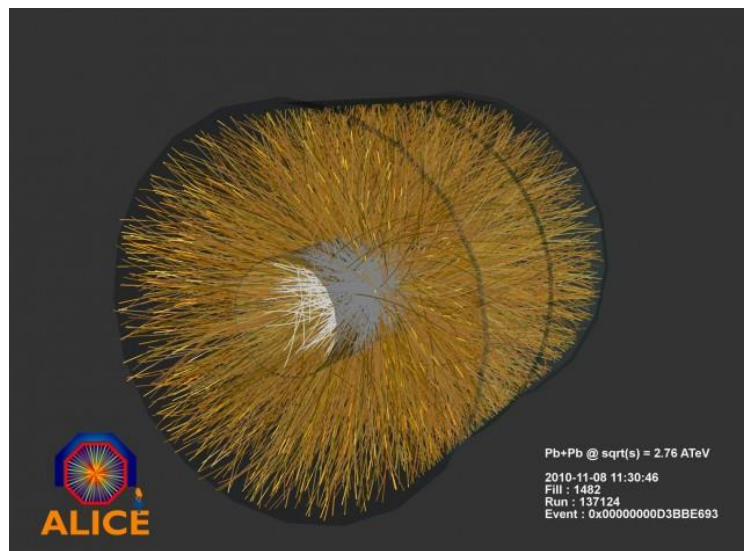
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# A clean environment?



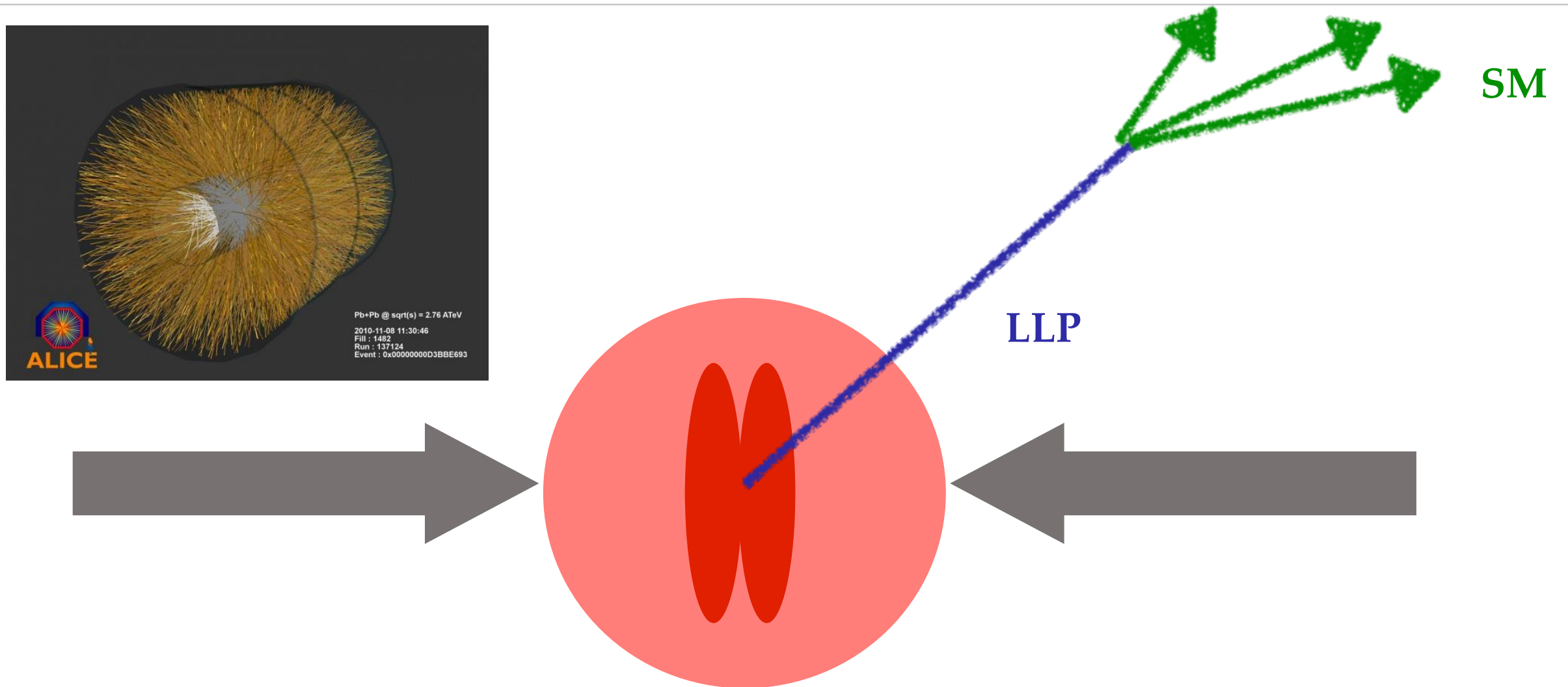
# A clean environment?



- but: HL-LHC will have  $\sim 200$  pile-up events per bunch crossing,  $\sim 5000$  charged particles per hard scattering!
- ⇒ multiplicity in Pb-Pb collisions only factor  $\sim 2$  higher, for lighter nuclei even lower! CMS [1902.03603](#)
- and: vertexing in HL extremely good



# Long Lived Particles



- displacement clearly distinguishes secondary vertex from the mess in the luminous region

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# LLP searches in Heavy Ion Runs?

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## Con

1. high track multiplicity
2. low instantaneous luminosity
3. lower collision energy per nucleon
4. runs are shorter

## Pro

1.  $A^2$  enhancement of # of nucleon collisions
2. no pile up
3. can operate main detectors with very low triggers

# The Seesaw Mechanism (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \not{\partial} \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$

$$- \frac{1}{2} (\bar{\nu}_R^c M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Can explain

Asaka/Shaposhnikov 05

- Neutrino masses
- Leptogenesis
- Dark Matter

| Three Generations of Matter (Fermions) spin 1/2 |                              |                            |                            |
|-------------------------------------------------|------------------------------|----------------------------|----------------------------|
|                                                 | I                            | II                         | III                        |
| mass →                                          | 2.4 MeV                      | 1.27 GeV                   | 171.2 GeV                  |
| charge →                                        | 2/3                          | 2/3                        | 2/3                        |
| name →                                          | u<br>up                      | c<br>charm                 | t<br>top                   |
| Quarks                                          | Left Right                   | Left Right                 | Left Right                 |
|                                                 | 4.8 MeV                      | 104 MeV                    | 4.2 GeV                    |
|                                                 | -1/3                         | -1/3                       | -1/3                       |
|                                                 | d<br>down                    | s<br>strange               | b<br>bottom                |
| Leptons                                         | Left Right                   | Left Right                 | Left Right                 |
|                                                 | 0 eV                         | 0 eV                       | 0 eV                       |
|                                                 | 0                            | 0                          | 0                          |
|                                                 | $\nu_e$<br>electron neutrino | $\nu_\mu$<br>muon neutrino | $\nu_\tau$<br>tau neutrino |
|                                                 | 0.511 MeV                    | 105.7 MeV                  | 1.777 GeV                  |
|                                                 | -1                           | -1                         | -1                         |
|                                                 | e<br>electron                | $\mu$<br>muon              | $\tau$<br>tau              |
|                                                 | Left Right                   | Left Right                 | Left Right                 |

Bosons (Forces) spin 1

0  
0  
g  
gluon

0  
0  
 $\gamma$   
photon

91.2 GeV  
0  
Z  
weak force

80.4 GeV  
 $\pm 1$   
W<sup>±</sup>  
weak force

125 GeV  
0  
H  
Higgs boson

spin 0

three light neutrinos mostly "active" SU(2) doublet

$$\nu \simeq U_\nu (\nu_L + \theta \nu_R^c)$$

$$\text{with masses } m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T$$

three heavy mostly singlet neutrinos

$$N \simeq \nu_R + \theta^T \nu_L^c$$

$$\text{with masses } M_N \simeq M_M$$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80





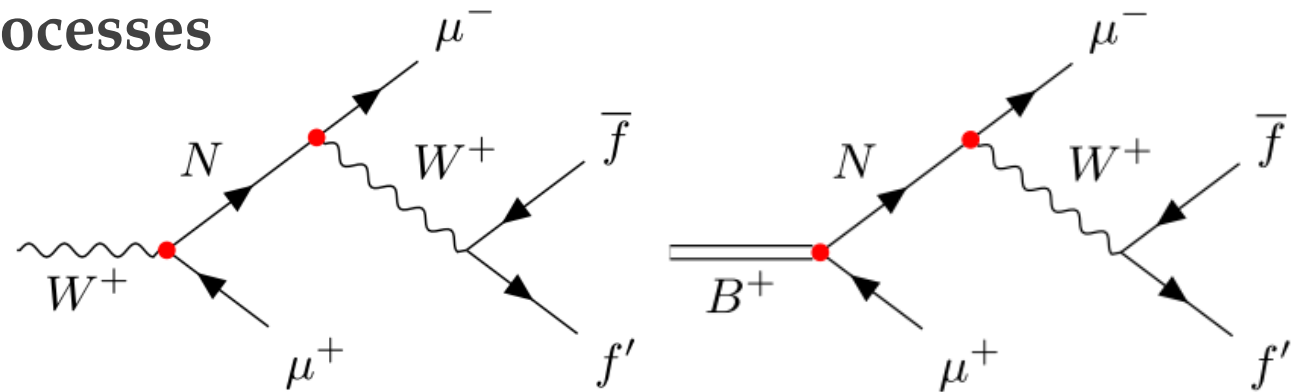
# Displaced Vertex Search

# Model

$$\mathcal{L} \supset -\frac{m_W}{v} \bar{N} \theta_a^* \gamma^\mu e_{La} W_\mu^+ - \frac{m_Z}{\sqrt{2}v} \bar{N} \theta_a^* \gamma^\mu \nu_{La} Z_\mu - \frac{M}{v} \theta_a h \bar{\nu}_{L\alpha} N + \text{h.c.}$$

we assume that  $N$  mixes only with  $\nu_\mu$

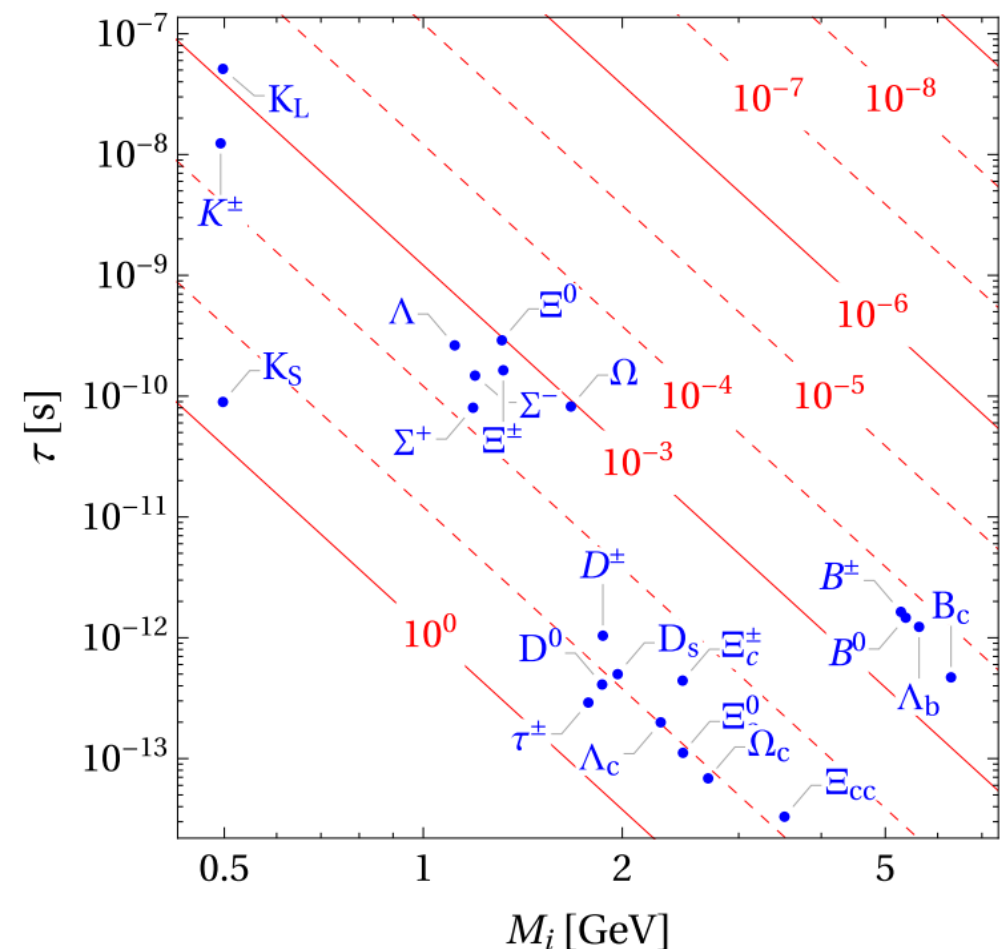
# Processes



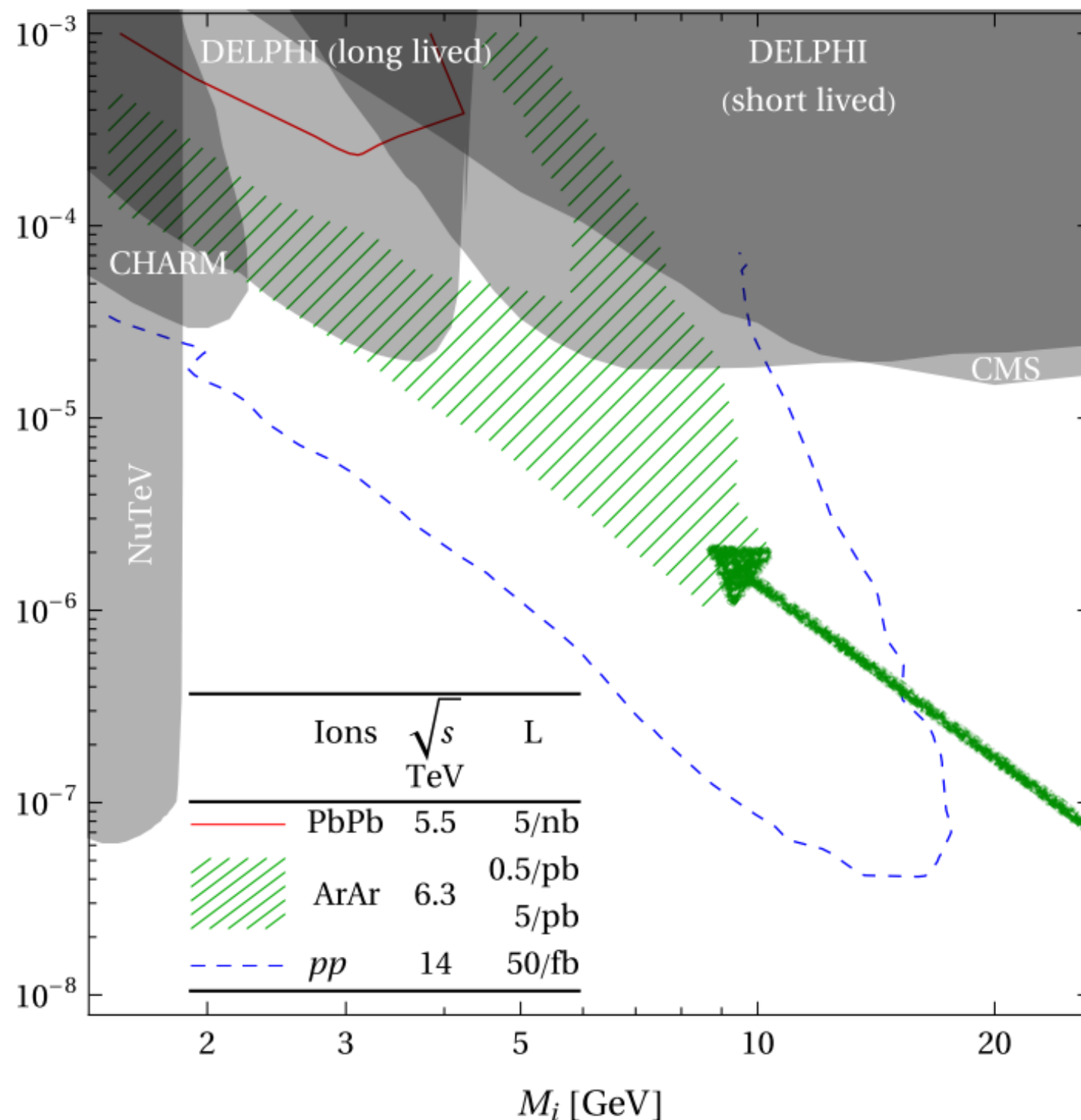
heavy neutrinos can be produced in  $W$  or  $B$  decays

## Analysis

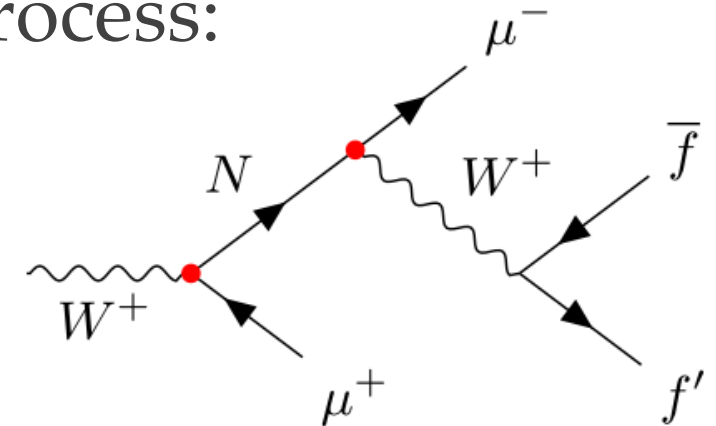
- we perform a displaced vertex (DV) search  
 $\Gamma \propto U^2 M^5$  with  $U^2 = |\theta|^2$
- to remove SM backgrounds we require a minimum displacement of 5mm
- to remove backgrounds from interactions with the detector material we impose a DV invariant mass cut of 5 GeV
- DV reconstruction efficiency drops linearly with displacement [1710.04901](#)



# Heavy Neutrino Production in W Decays



process:



$p_T$  cuts used:

- 25 GeV for pp collisions
- 3 GeV for HI collisions

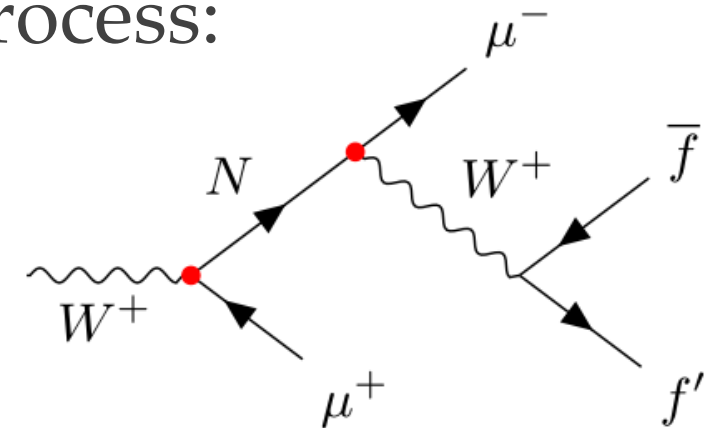
uncertainty in the  $p$  factor  
for argon collisions

# A Spherical Detector Model

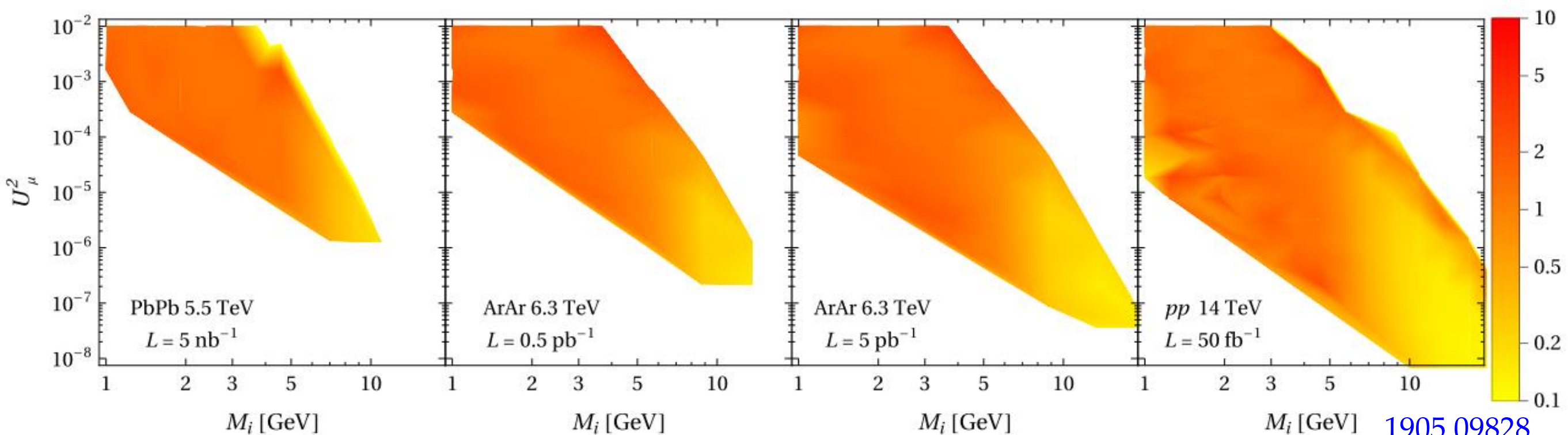
simple analytic formula for # events:

$$N_{\text{obs}} \simeq L \sigma_{\nu} U_{\mu}^2 \left[ \exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right) \right] f_{\text{cut}}$$

process:



use  $l_0 = 5\text{mm}$ , determine  $\lambda(p)$  from simulation and fit  $l_1 = 20\text{cm}$   
 ratio of # events predicted by averaged analytic formula and simulation:



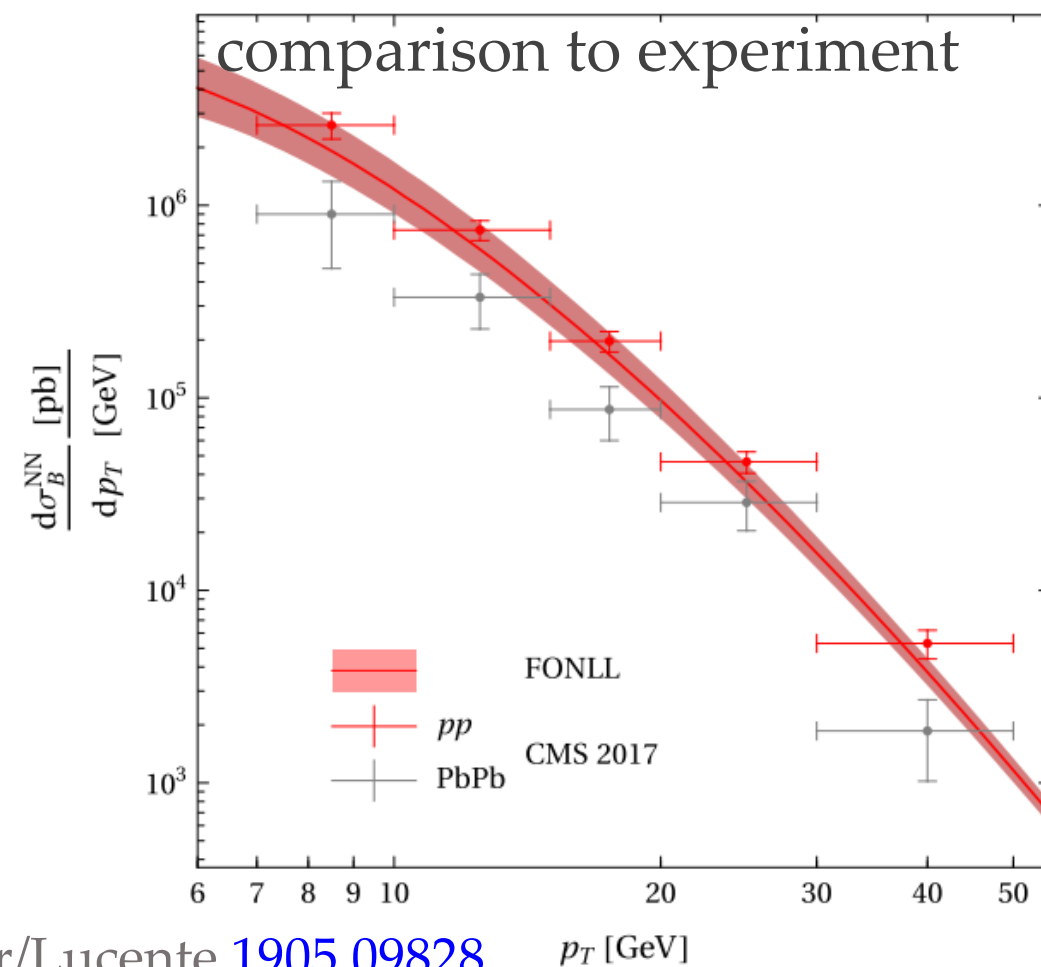
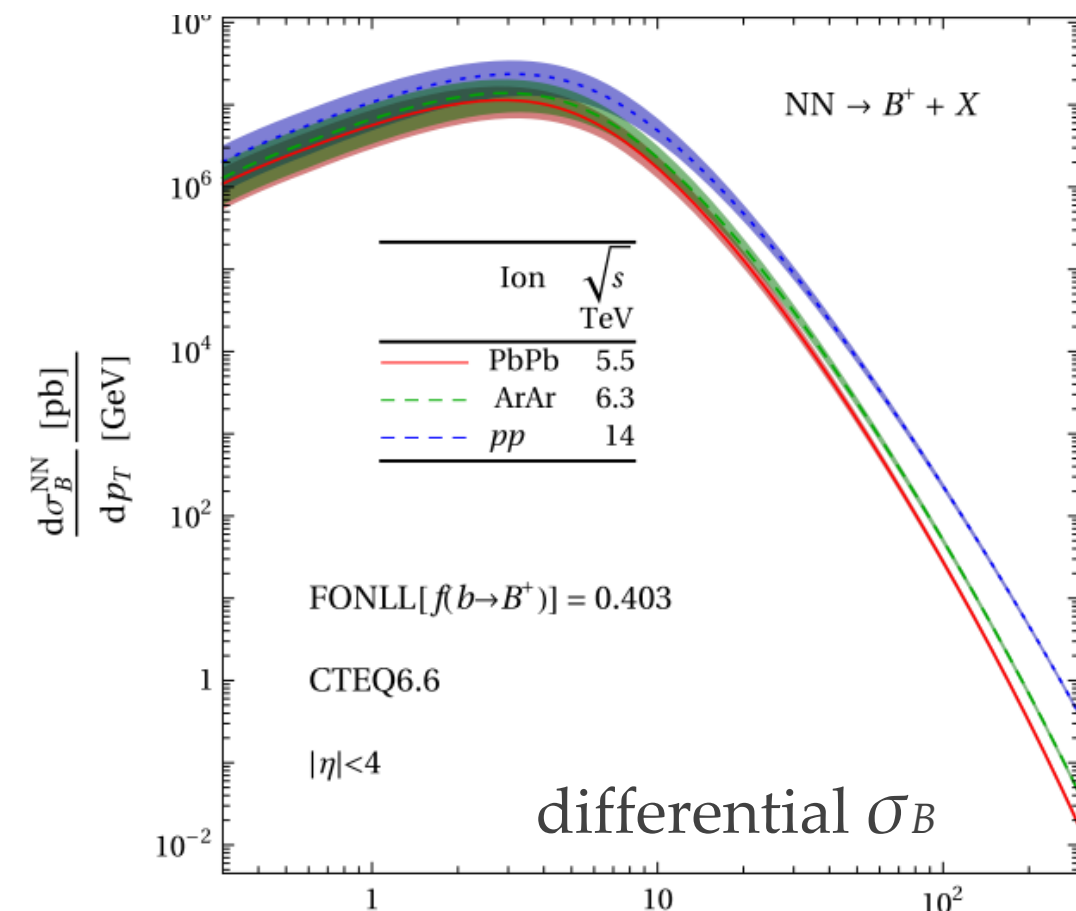
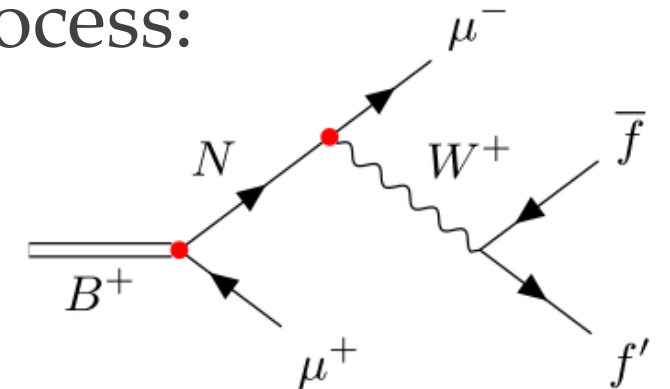


# Heavy Neutrinos in B Decays

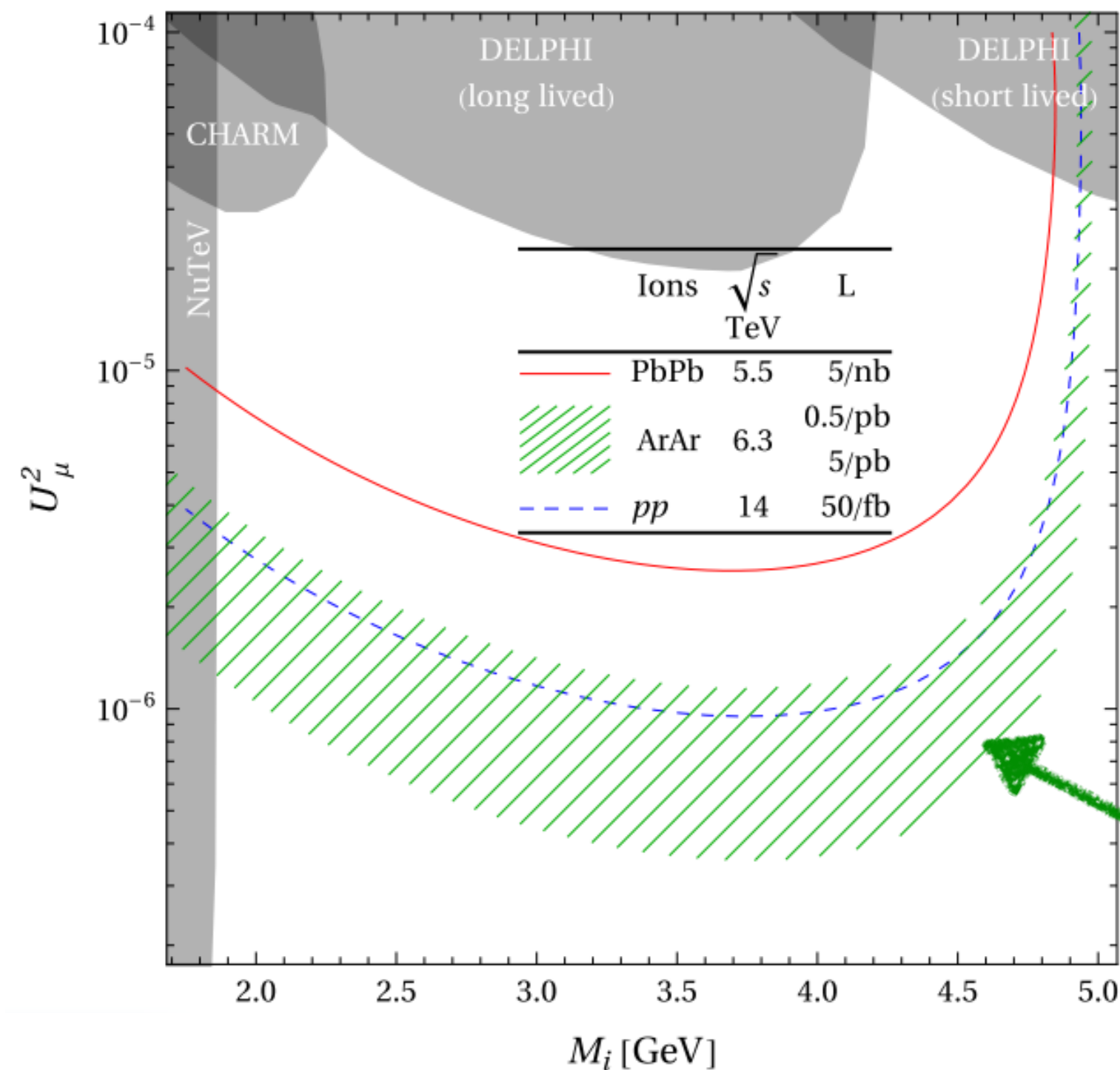
number of observable events:

$$N_{\text{obs}} = \frac{L\sigma_B}{9} \left(1 - \frac{M^2}{m_B^2}\right)^2 U_\mu^2 \left(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N}\right) f_{\text{cut}}$$

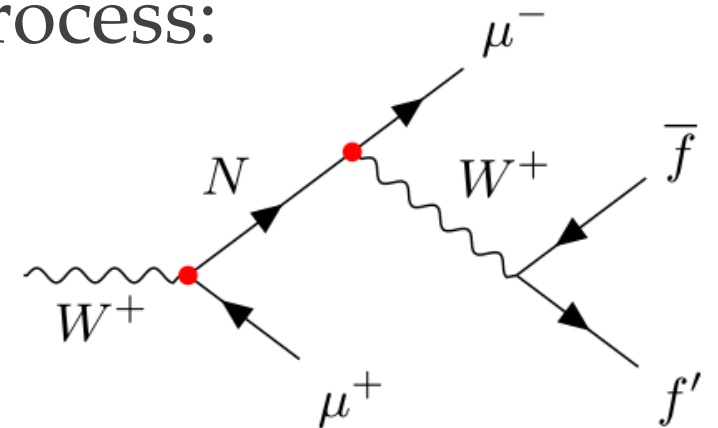
process:



# Heavy Neutrinos in B Decays



process:

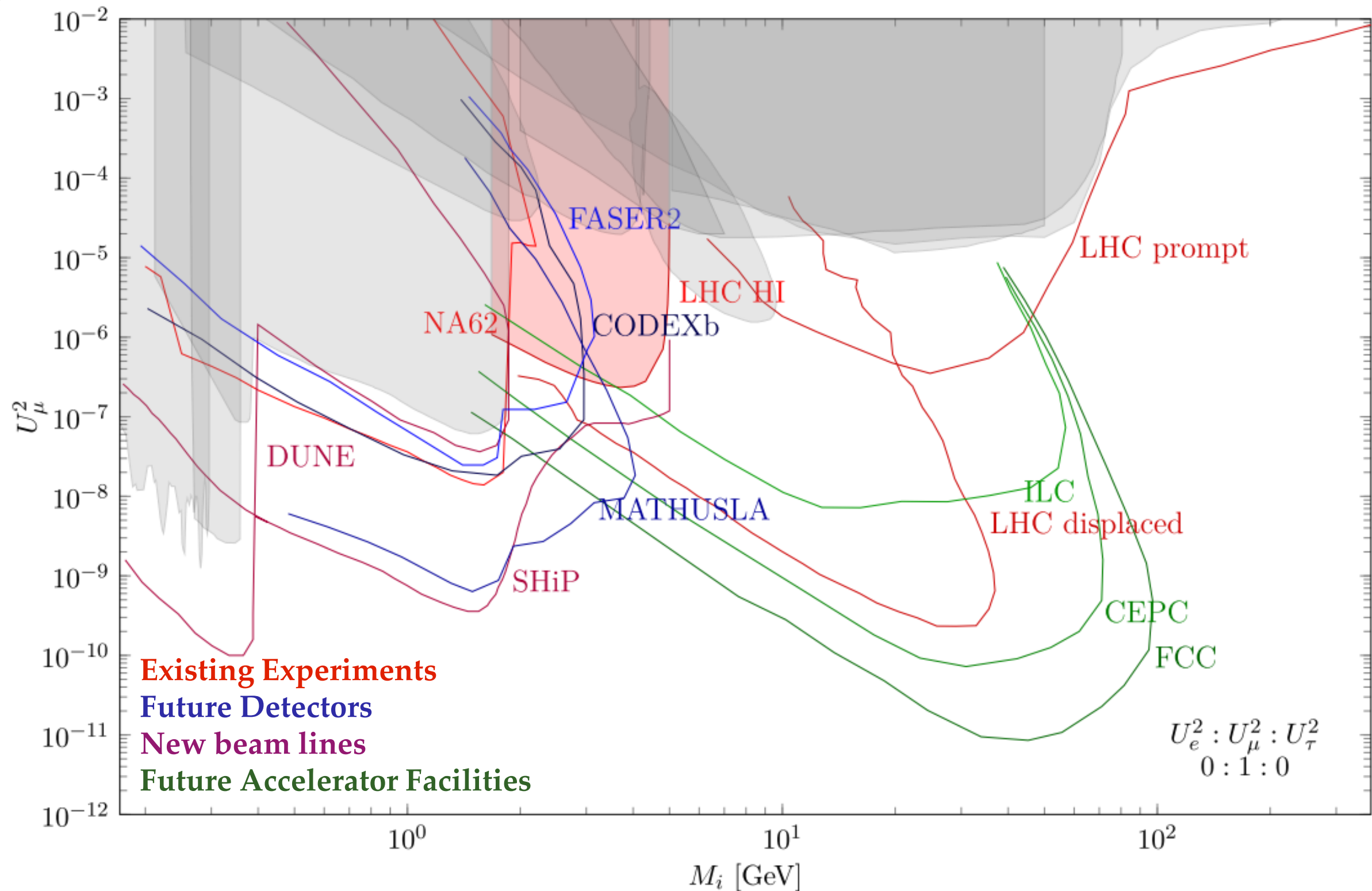


**cuts used:**

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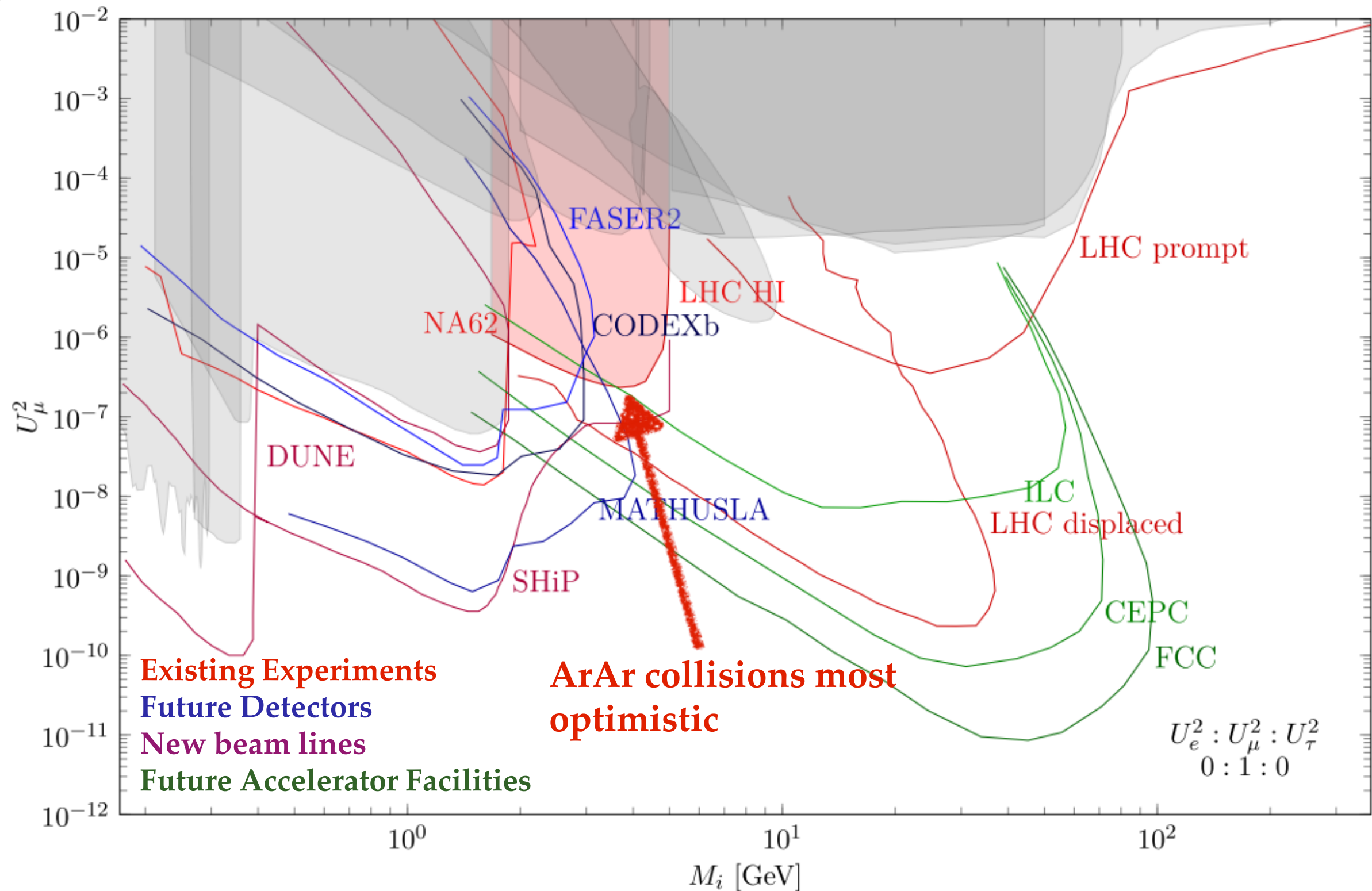
uncertainty in the  $p$  factor  
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# Other Heavy Neutrino Searches





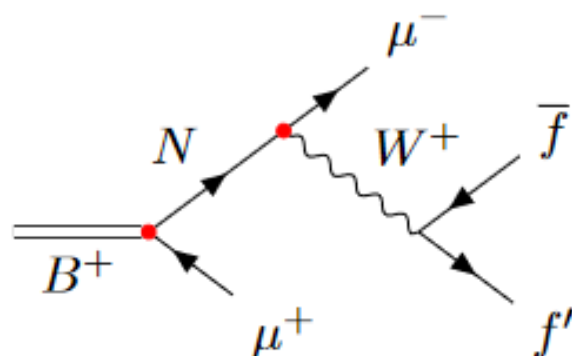
# Other Heavy Neutrino Searches



# Soft Lepton Scenarios

- GeV-scale particles: heavy neutral leptons

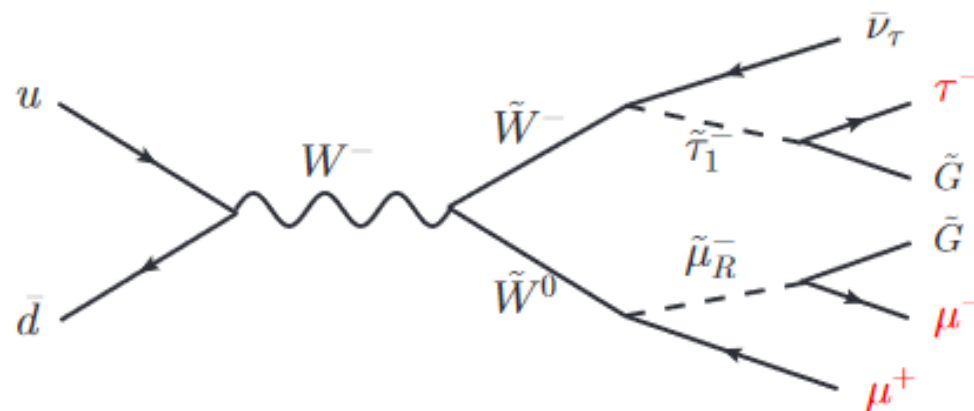
Drewes et al. 1810.09400



- cascade decays: SUSY

Evans, Shelton 1601.01326

Ruderman, Shih 1009.1665



- compressed dark sectors

Filimonova, Westhoff 1812.04628

Bharucha et al. 1804.02357

leptophilic dark matter

Junius et al. 1904.07513

D'Agnolo et al. 1906.09269

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# Conclusions

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## Summary

- HI collisions can be used to probe New Physics
- In some scenarios and/or parameter regions searches in HI collisions can be more sensitive than in proton collisions
- This can help to fully exploit the existing facilities and “turn every stone”

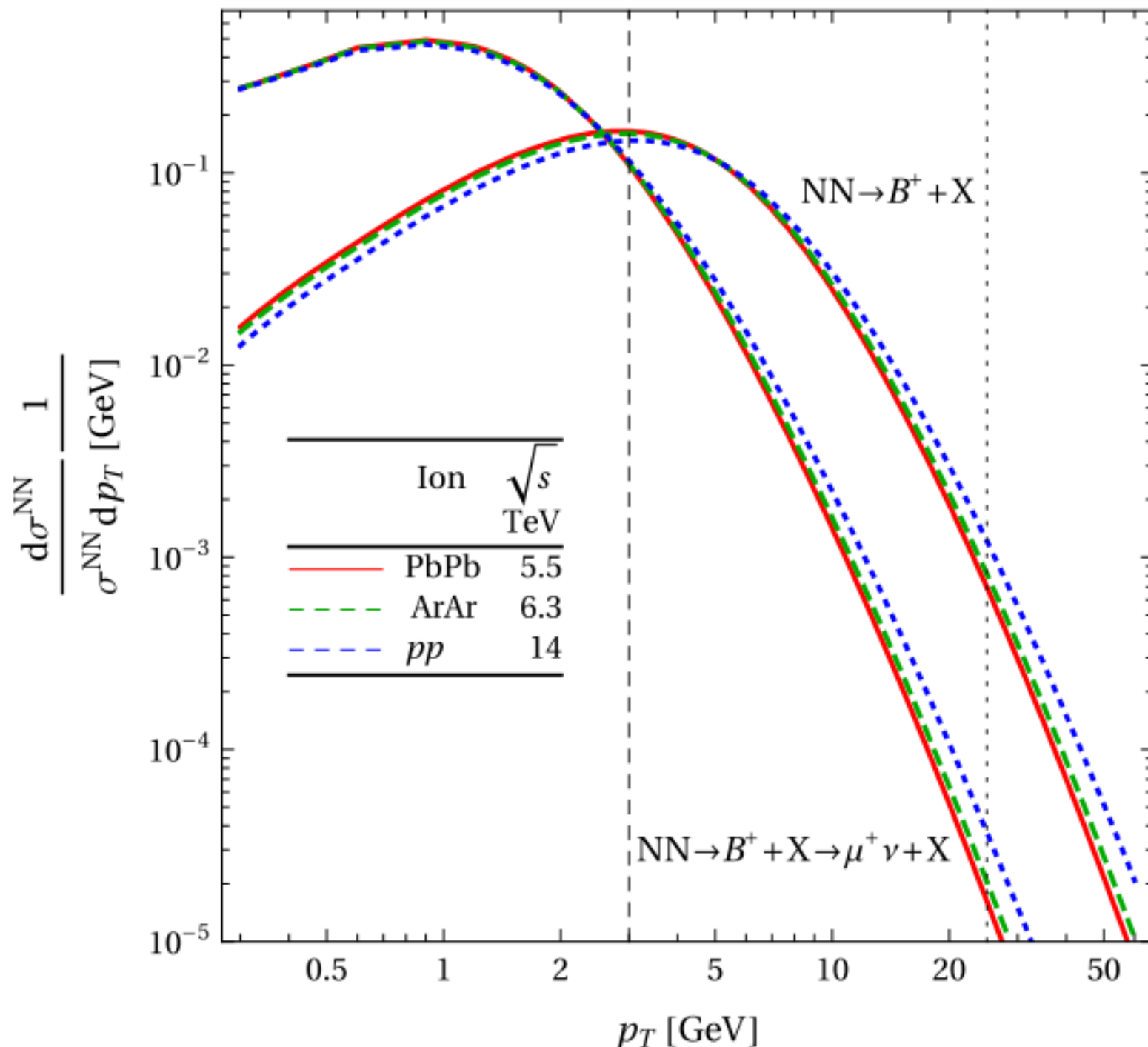
## Next steps

- contribution to Snowmass in progress  
[https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7\\_EF8-207.pdf](https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7_EF8-207.pdf)
- **A short Snowmass WP is planned - your input is welcome!**



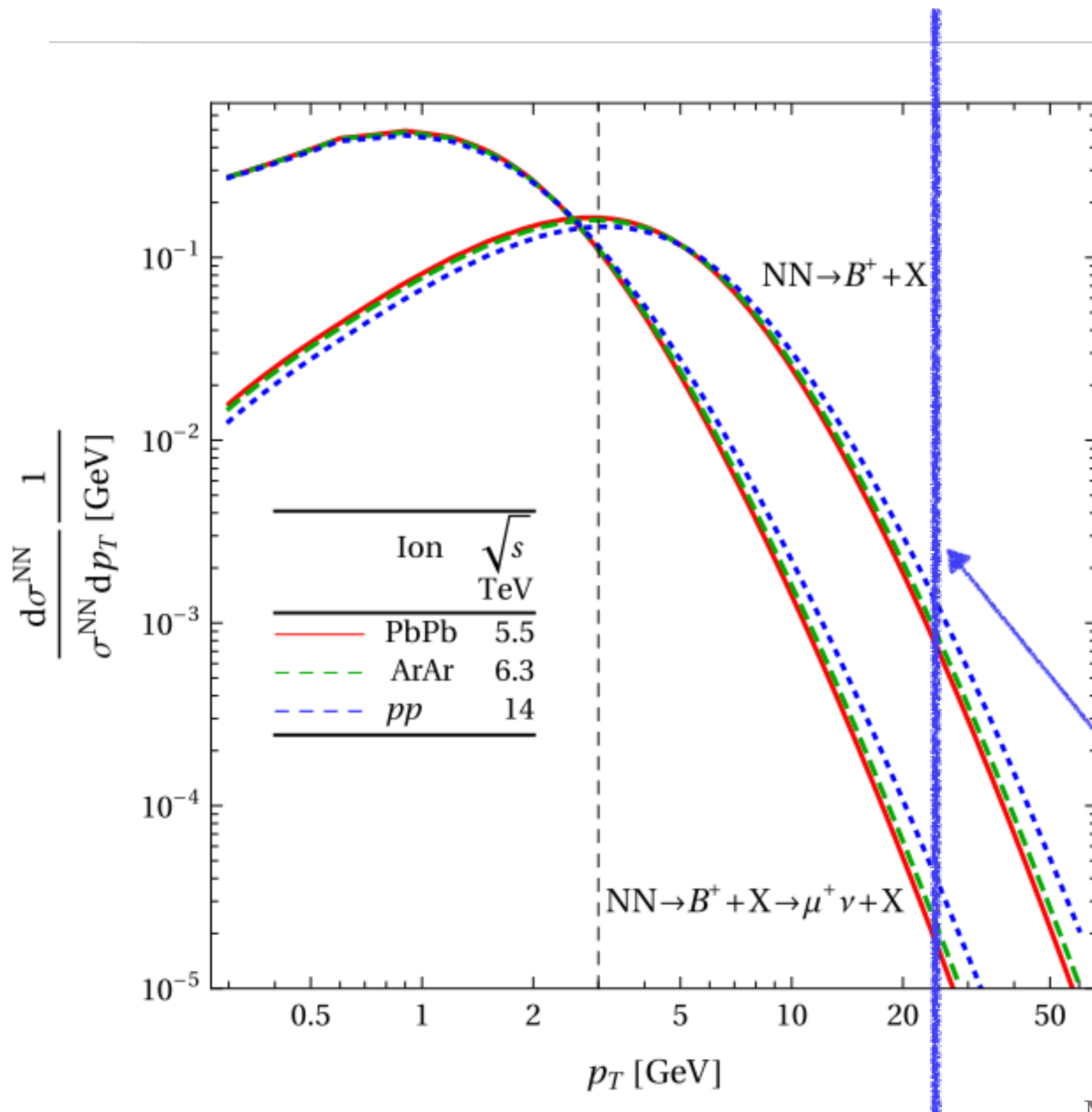
Backup Slides

# Heavy Neutrinos in B Decays



- momentum distribution of leading  $\mu$  is hard to determine
- consider two extremes:
  - the decaying B meson itself
  - $\mu$  produced along with a massless light neutrino
- impose  $p_T$  cuts on those

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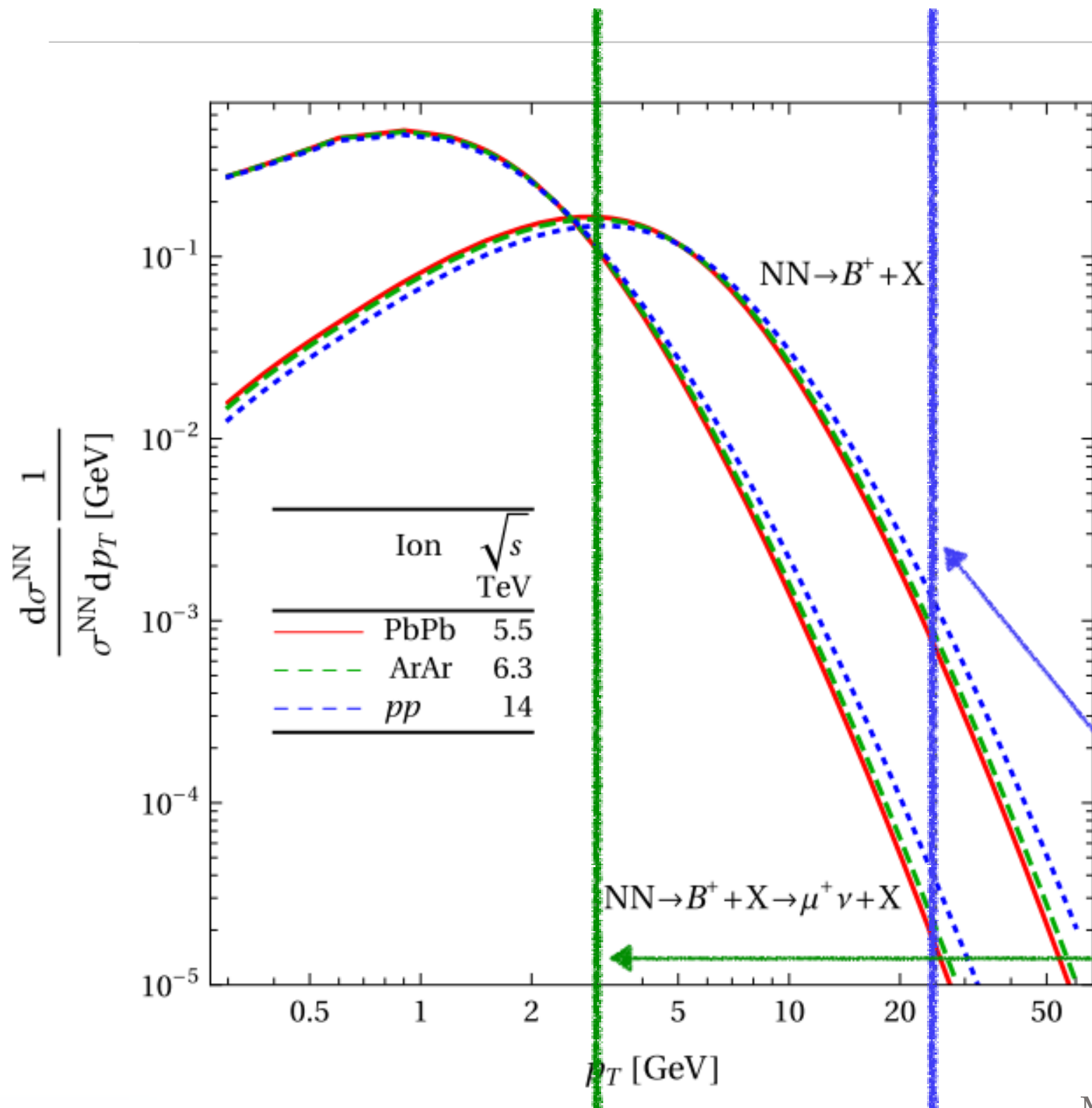


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cut at 25 GeV in pp collisions  
misses most events!

cut at 3 GeV in HI collisions  
includes a much larger fraction!

# What limits the luminosity?

- injector chain limitations
- beam losses

*Cross sections for Pb-Pb collisions at 2.76 TeV / nucleon*

| Process                      | Cross section (b) |
|------------------------------|-------------------|
| Bound-free pair production   | 281               |
| Electromagnetic dissociation | 226               |
| Hadronic nuclear inelastic   | 8                 |
| Total                        | 515               |

Bound-Free Pair Production (BFPP):  $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+$  [Meier et al. 2001]

Electromagnetic Dissociation (EMD):  $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n$  [Pshenichnov et al. 2001]

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# Beam Losses

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Beam losses lead to two kinds of problems

- **formation of secondary beams**

ions with the “wrong” mass to charge ratio form a new beam that can quench a magnet

- **limited beam lifetime**

frequent re-fills reduce the integrated luminosity

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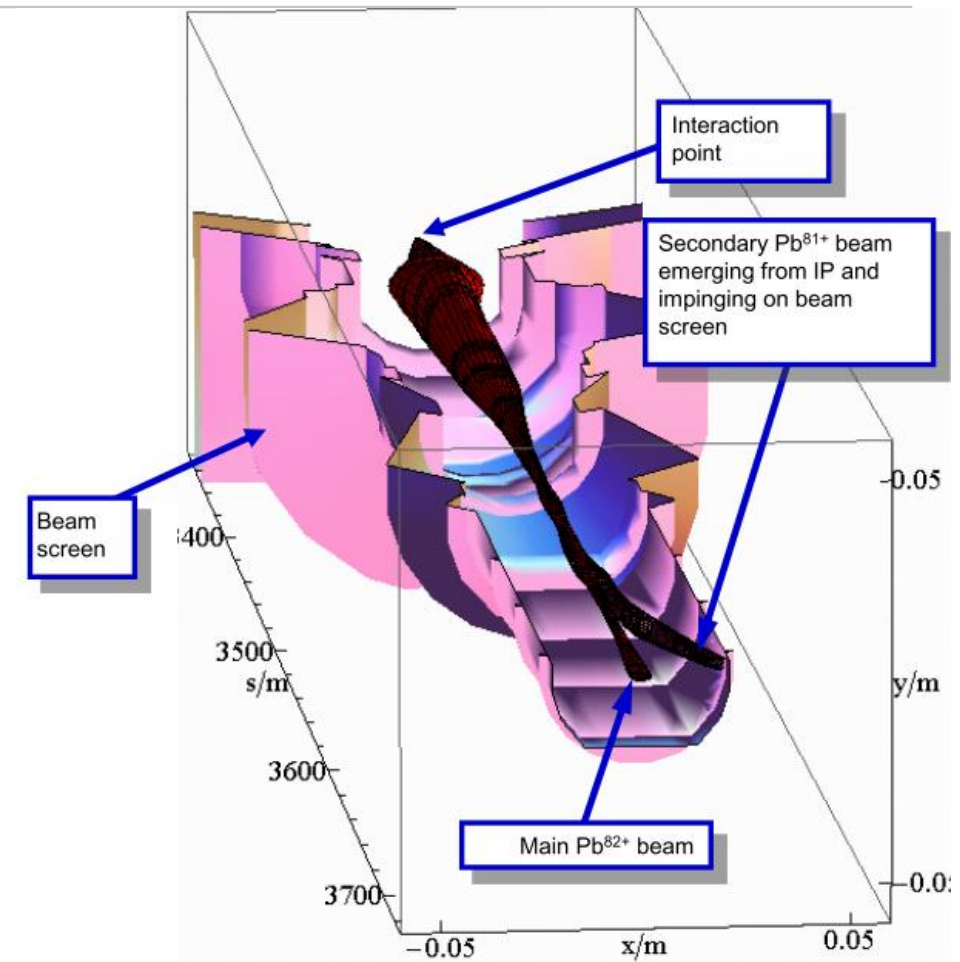
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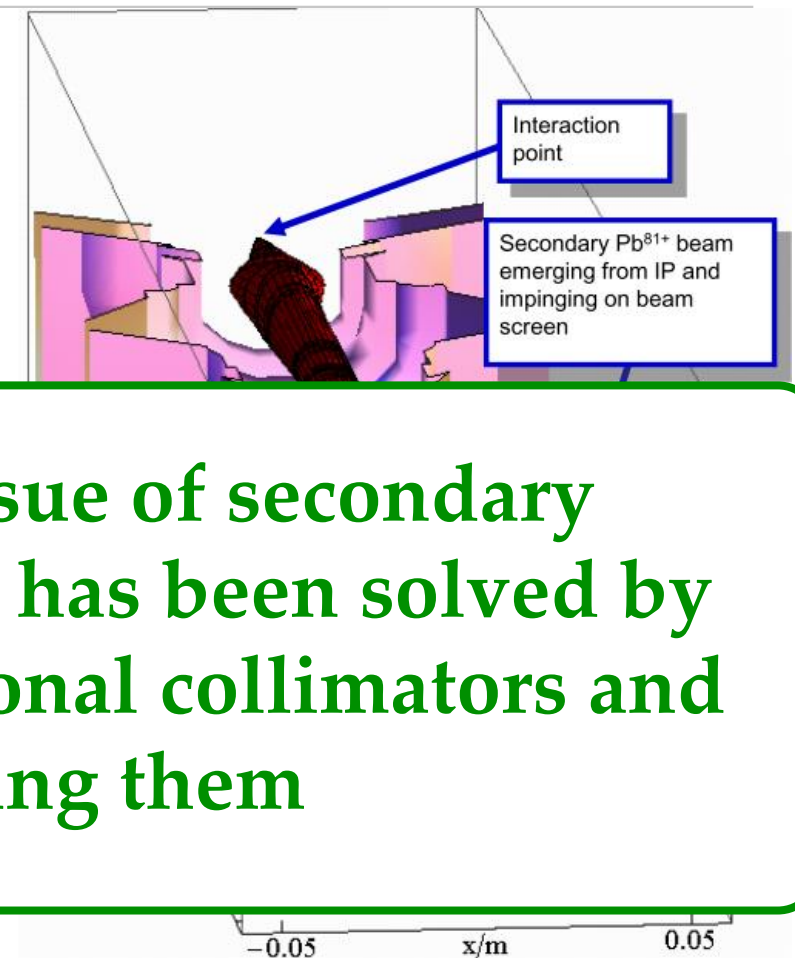
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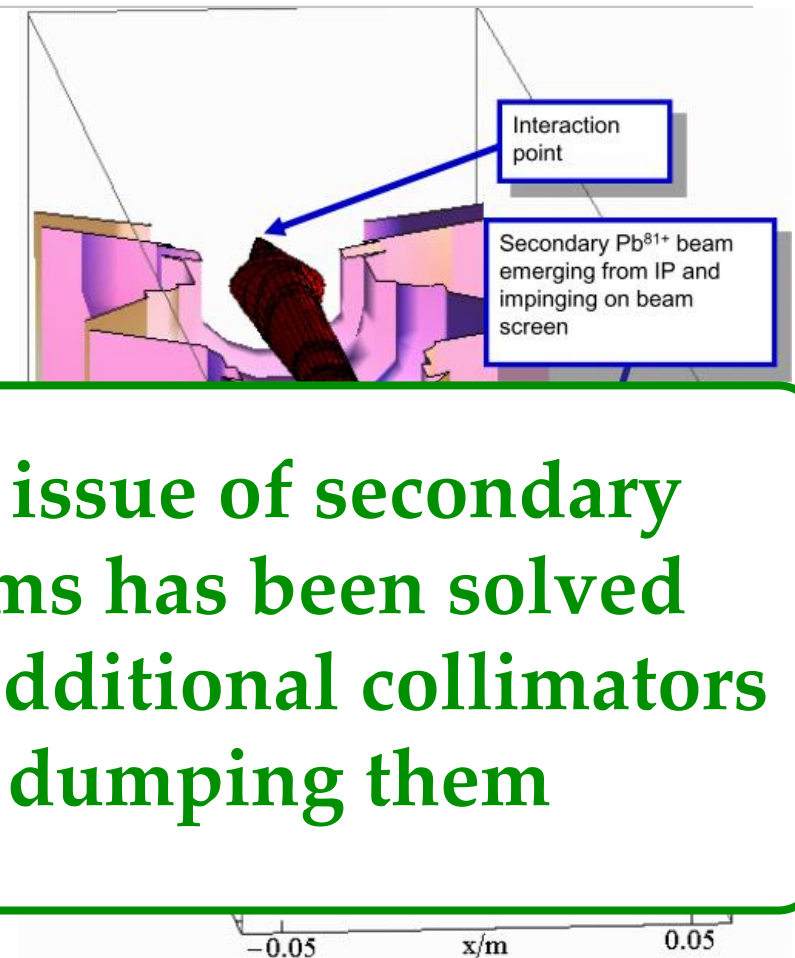
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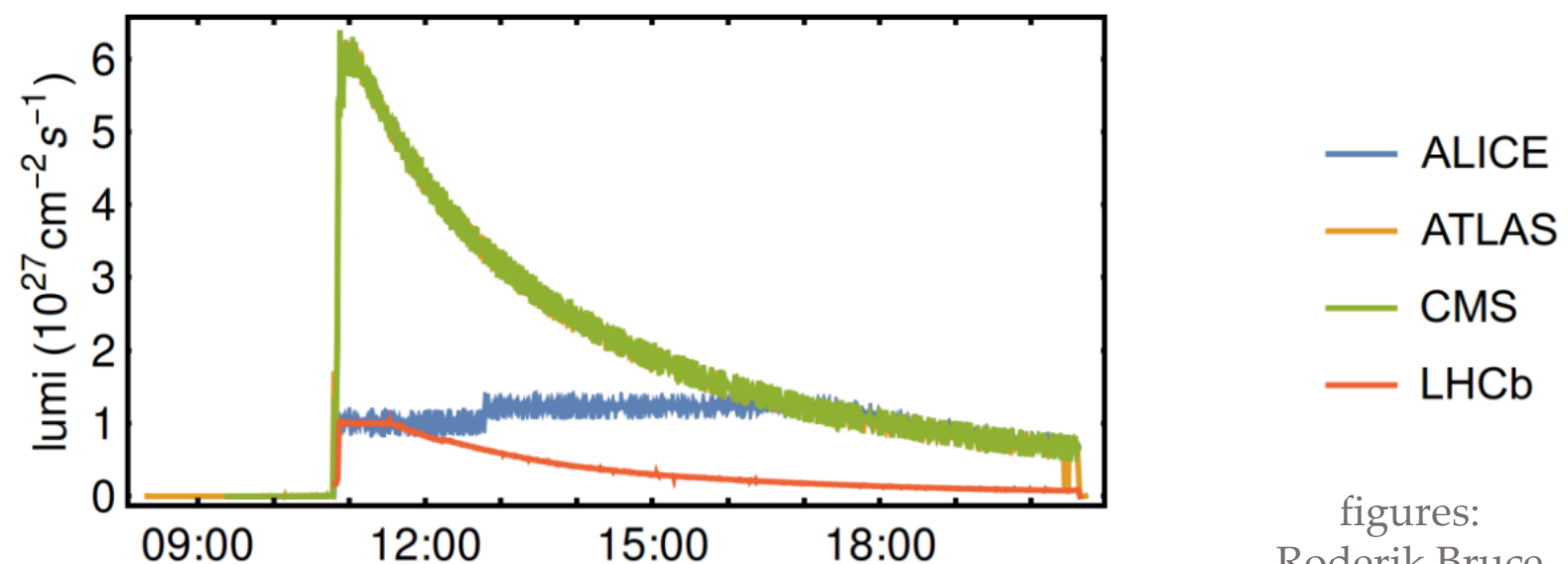
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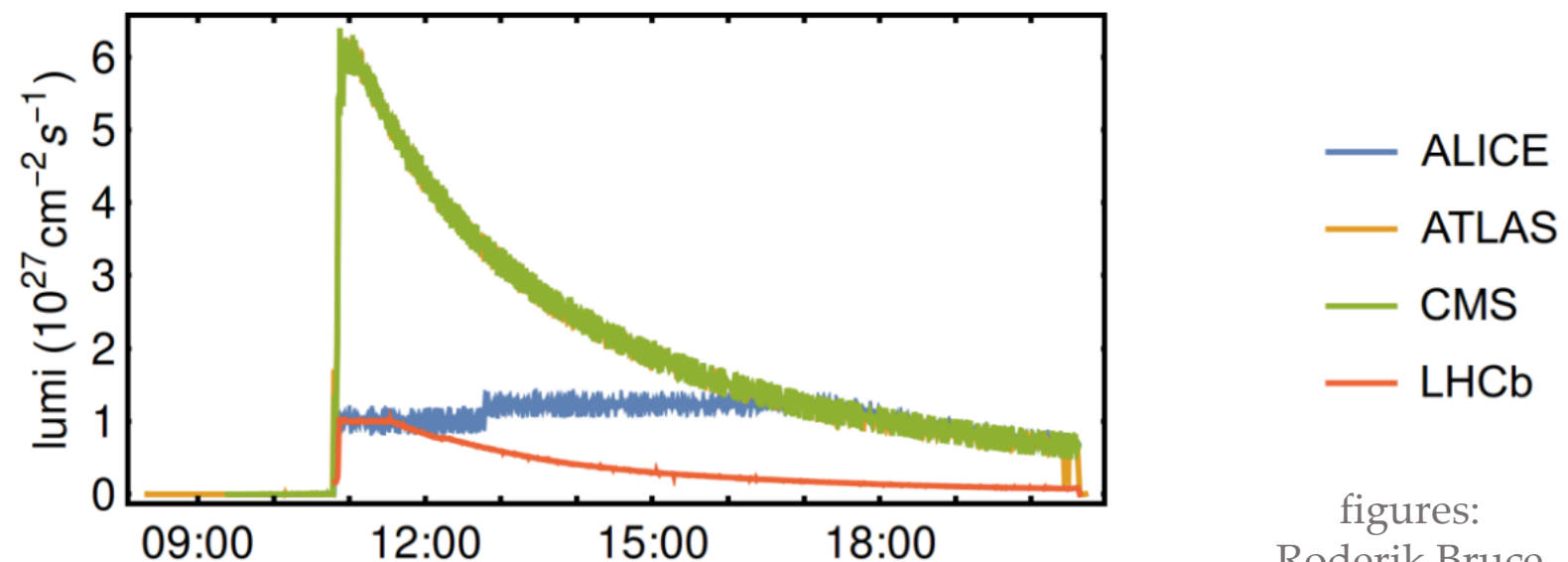
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figures:  
Roderik Bruce

# Limited Beam Lifetime

- initial number of ions per bunch  $N_b\left(\frac{A}{Z}\text{N}\right) = N_b\left({}^{208}_{82}\text{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$
- time evolution  $\frac{dN_b}{dt} = -\frac{N_b^2}{N_0\tau_b}$  with beam lifetime  $\tau_b \propto \frac{1}{\sigma_{\text{tot}}n_{\text{IP}}N_0}$
- integrated luminosity is maximised for refill at  $t_{\text{opt}} = \tau_b\sqrt{\theta_{\text{ta}}}$   
with  $\theta_{\text{ta}} = \frac{t_{\text{ta}}}{\tau_b}$  for a given turnover time  $t_{\text{ta}}$
- maximal average luminosity  $\mathcal{L}_{\text{ave}}(t_{\text{opt}}) = \frac{L_0}{(1 + \sqrt{\theta_{\text{ta}}})^2}$
- **integrated luminosity depends on ion species**
- **parameter  $p$  that characterises # ions/bunch and is not known for most ions!**



# Limited Beam Lifetime

|                        | pessimistic ( $p = 1$ )                    |                 |                                                       |                               | optimistic ( $p = 1.9$ )                   |                 |                                                       |                               |
|------------------------|--------------------------------------------|-----------------|-------------------------------------------------------|-------------------------------|--------------------------------------------|-----------------|-------------------------------------------------------|-------------------------------|
|                        | $\mathcal{L}_0$<br>[ $\mu\text{bs}^{-1}$ ] | $\tau_b$<br>[h] | $\mathcal{L}_{\text{ave}}$<br>[ $\mu\text{bs}^{-1}$ ] | $N_{\text{XX}}/N_{pp}$<br>[1] | $\mathcal{L}_0$<br>[ $\mu\text{bs}^{-1}$ ] | $\tau_b$<br>[h] | $\mathcal{L}_{\text{ave}}$<br>[ $\mu\text{bs}^{-1}$ ] | $N_{\text{XX}}/N_{pp}$<br>[1] |
| $^1_1\text{H}$         | $21.0 \cdot 10^3$                          | 75.0            | $15.0 \cdot 10^3$                                     | 1                             | $21.0 \cdot 10^3$                          | 75.0            | $15.0 \cdot 10^3$                                     | 1                             |
| $^{16}_8\text{O}$      | 1.43                                       | 52.6            | 1.07                                                  | 0.0082                        | 94.3                                       | 6.48            | 45.5                                                  | 0.349                         |
| $^{40}_{18}\text{Ar}$  | 0.282                                      | 45.8            | 0.208                                                 | 0.00889                       | 4.33                                       | 11.7            | 2.46                                                  | 0.105                         |
| $^{40}_{20}\text{Ca}$  | 0.229                                      | 46.0            | 0.168                                                 | 0.00811                       | 2.90                                       | 12.9            | 1.69                                                  | 0.0811                        |
| $^{78}_{36}\text{Kr}$  | 0.0706                                     | 20.6            | 0.0454                                                | 0.00758                       | 0.311                                      | 9.80            | 0.169                                                 | 0.0282                        |
| $^{84}_{36}\text{Kr}$  | 0.0706                                     | 19.2            | 0.0448                                                | 0.00797                       | 0.311                                      | 9.15            | 0.166                                                 | 0.0296                        |
| $^{129}_{54}\text{Xe}$ | 0.0314                                     | 7.20            | 0.156                                                 | 0.00637                       | 0.0665                                     | 4.94            | 0.0294                                                | 0.0120                        |
| $^{208}_{82}\text{Pb}$ | 0.0136                                     | 1.57            | $3.79 \cdot 10^{-3}$                                  | 0.00379                       | 0.0136                                     | 1.57            | $3.8 \cdot 10^{-3}$                                   | 0.00379                       |

**taken at face value, HI collisions are never competitive!**

However, not every event can be seen... what about cuts?

Let's be conservative and only play with the  $p_T$  trigger cut.

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(actually we used the model that comes now simply because we know it well)