Marco Drewes, Université catholique de Louvain

# A Heavy Metal Path to New Physics

08. 07. 2021

QUARKS 2020

2021 Online Workshops

# Where is the New Physics hiding?

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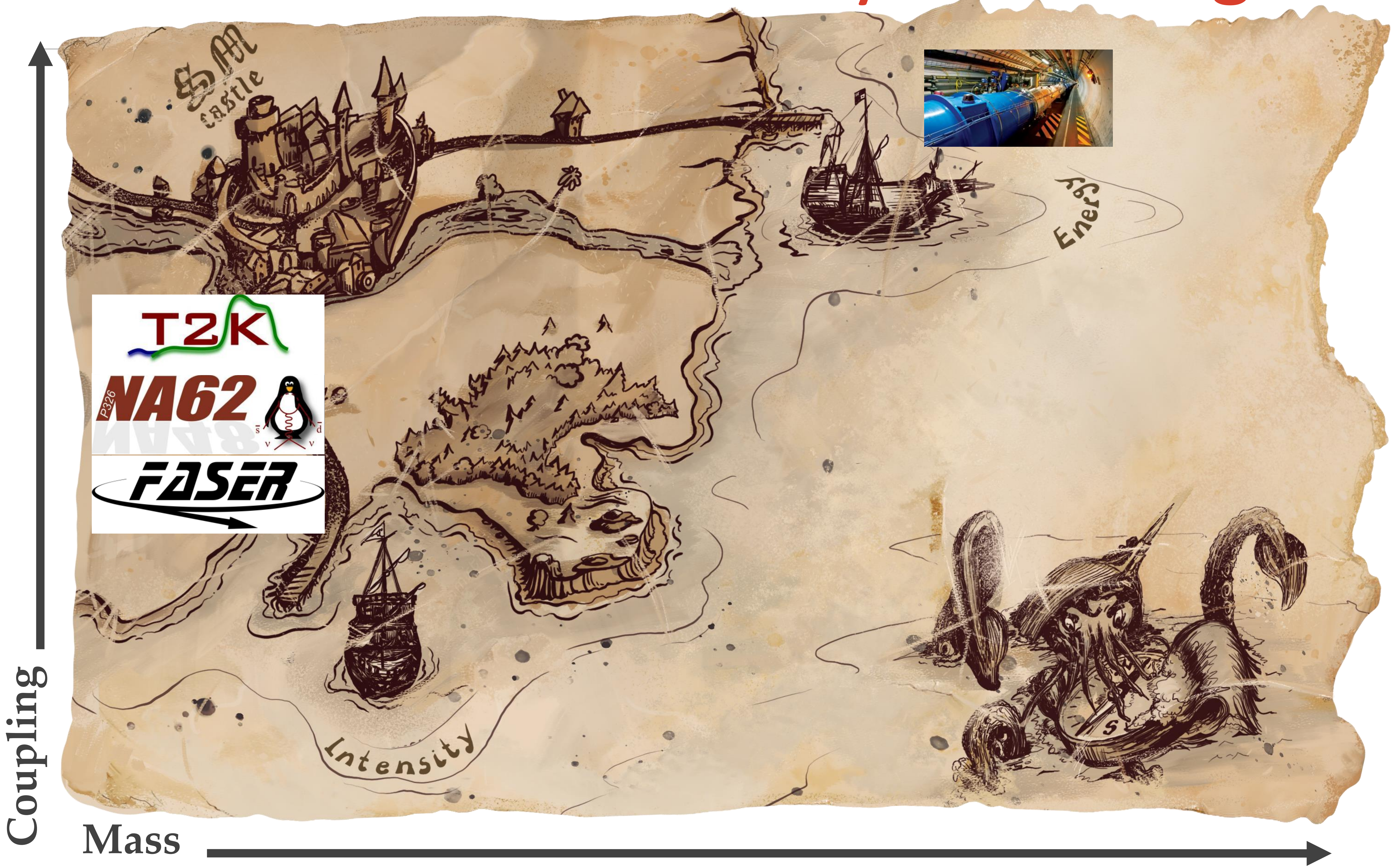

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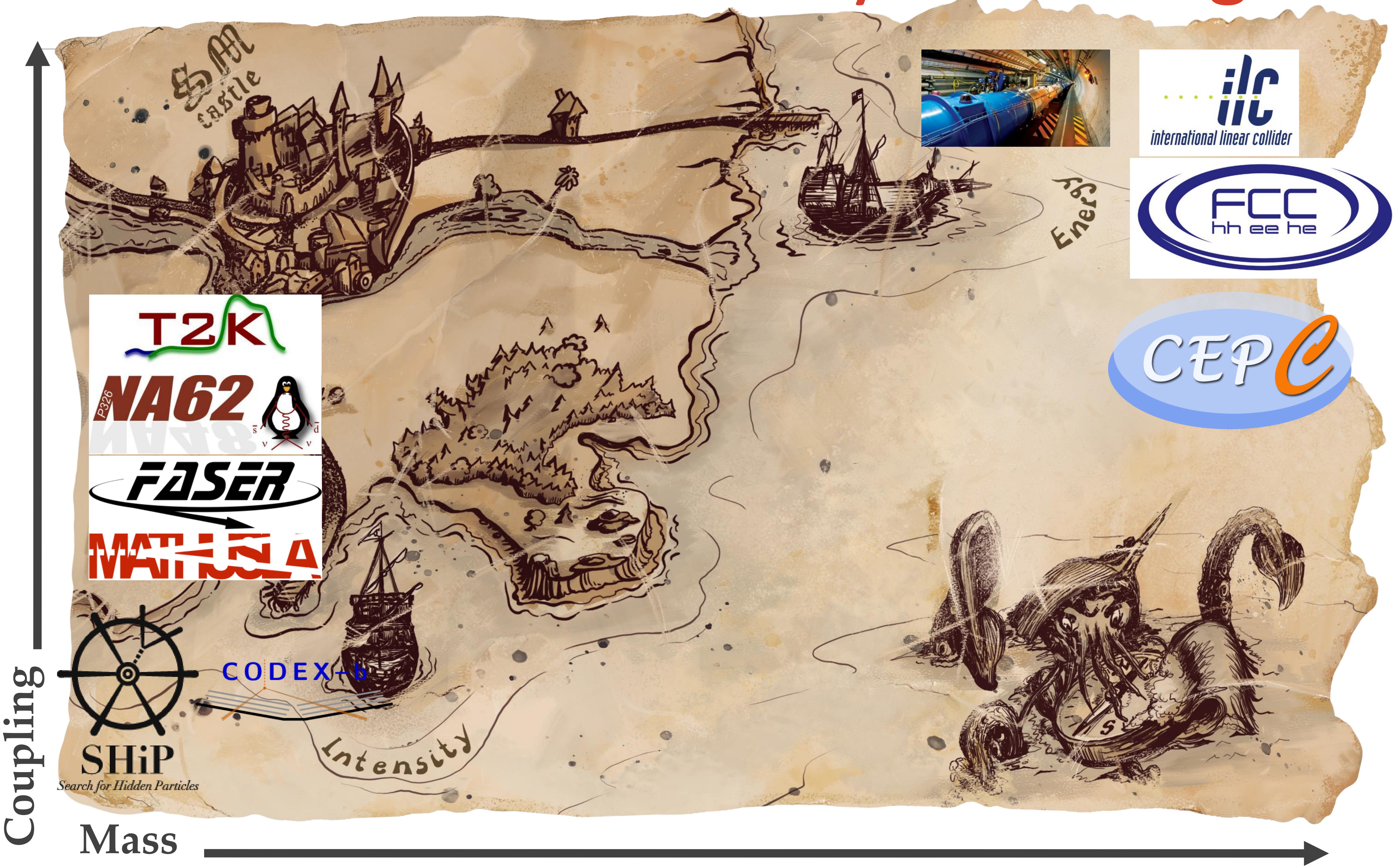

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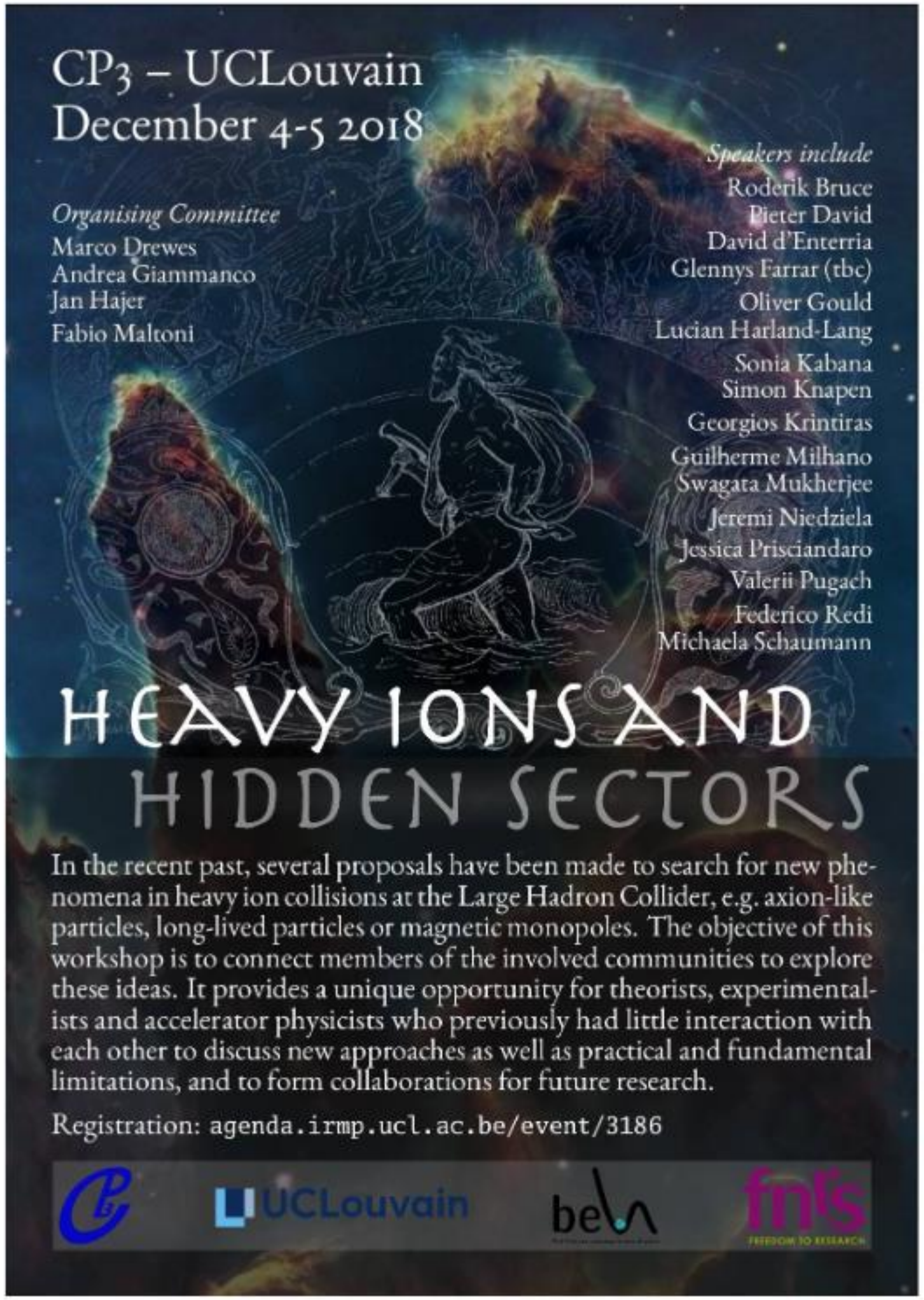


**First dedicated Workshop at UCLouvain in 2018:**

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

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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 fb$^{-1}$ range per month.

**J.Phys. G47 (2020) no.6, 060501**, e-Print: **arXiv:1812.07688 [hep-ph]**

# New Particles in HI Collisions?

- **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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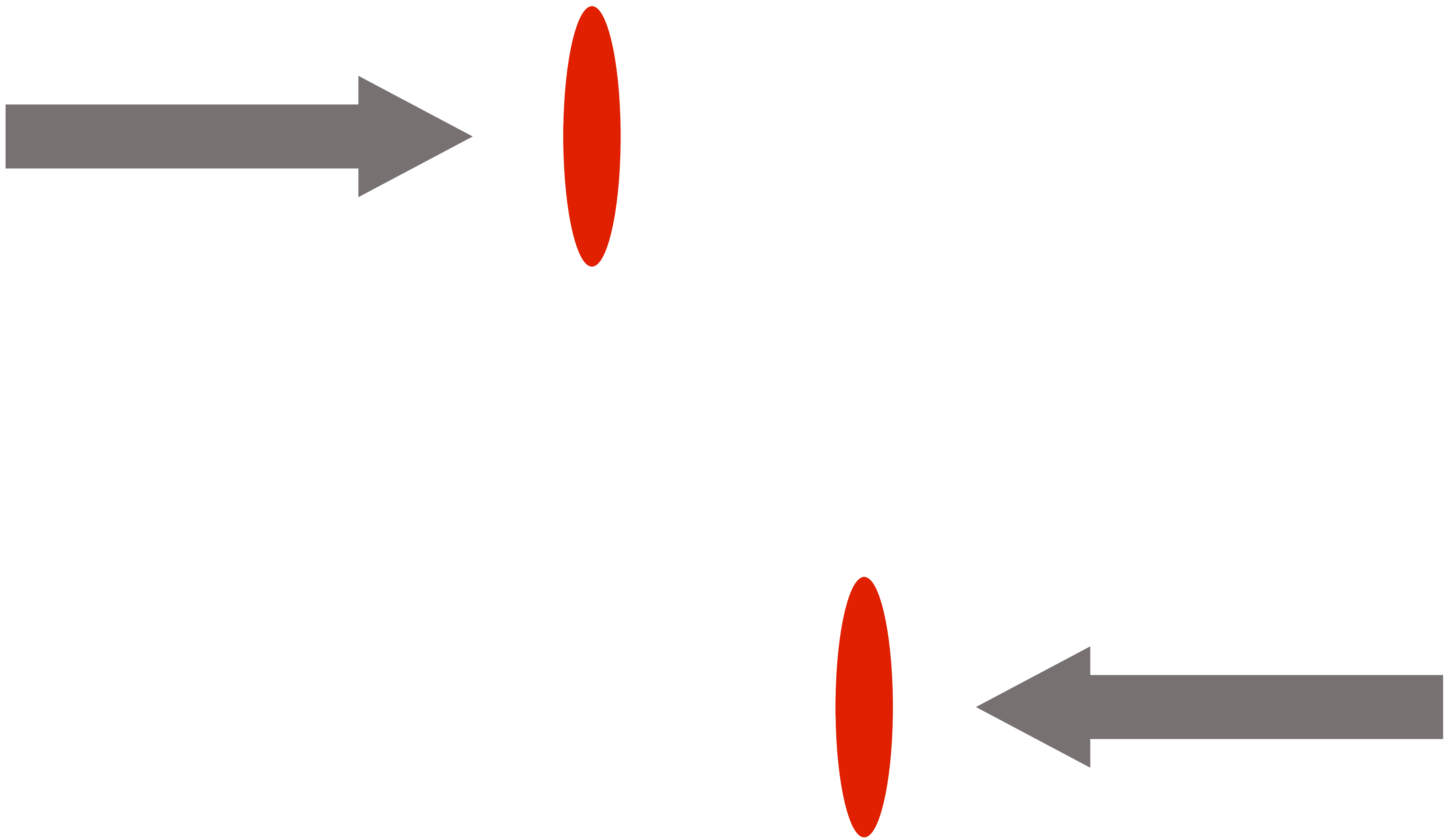
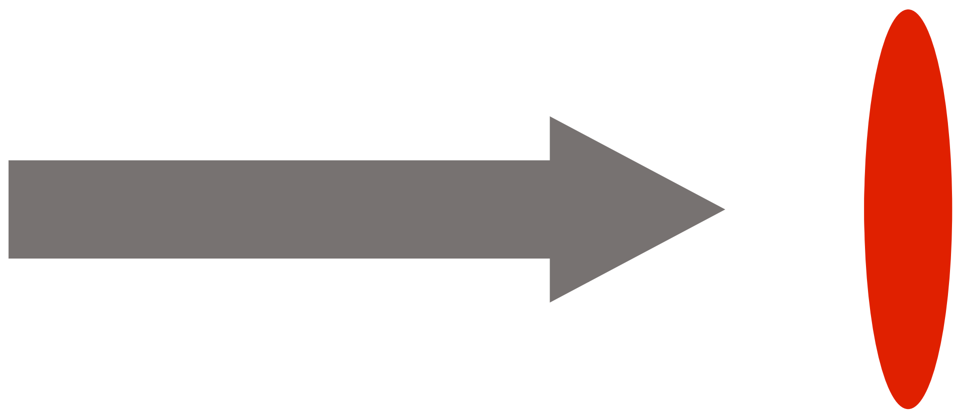
# Ultra-peripheral Collision (fly-by)

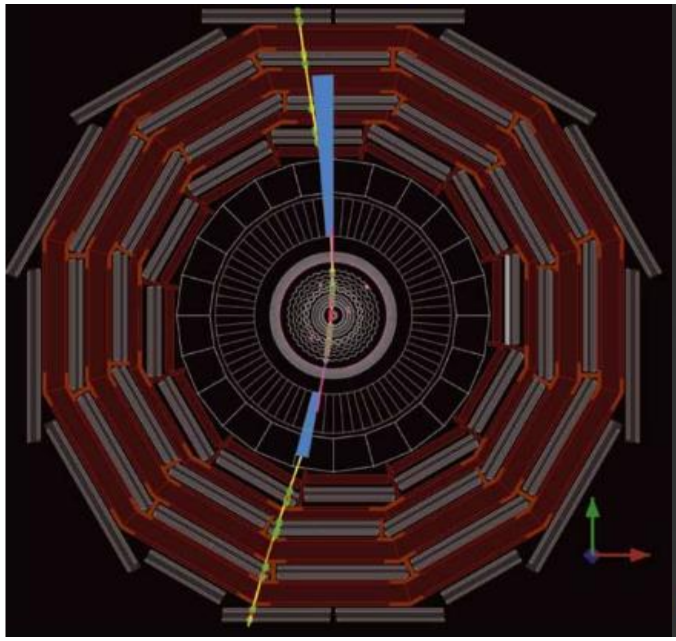


# Ultra-peripheral Collision (fly-by)

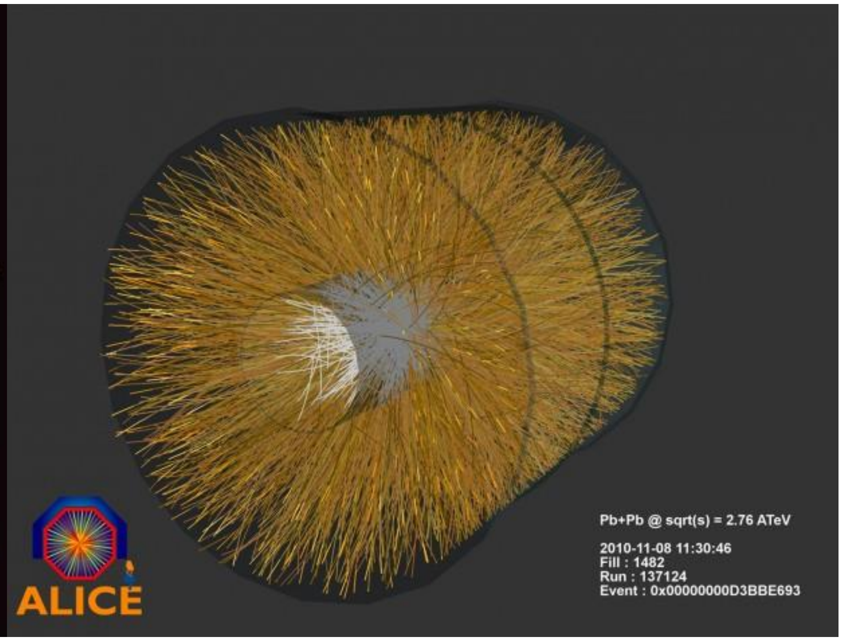


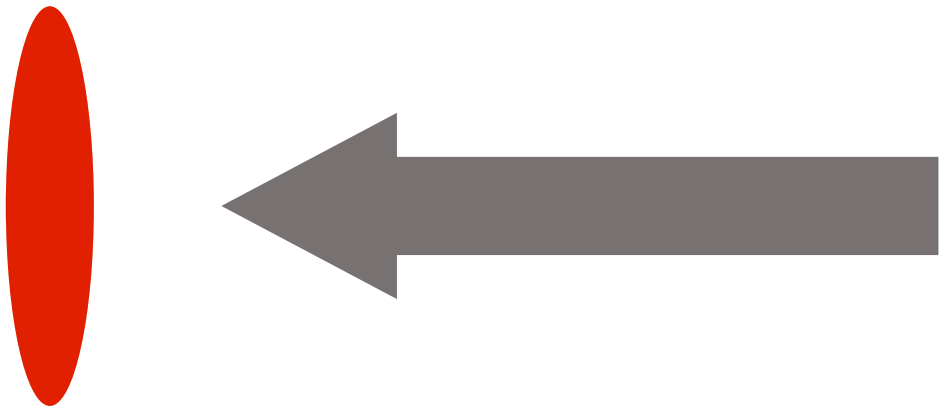
- impact parameter $b$ is much larger than ion radius $R$
- almost no hadronic backgrounds

ultra-peripheral collision



head-on collision



# The LHC as a Photon Collider

- electromagnetic fields in HI collisions are strongest ever created (> $10^{14}$ Tesla)

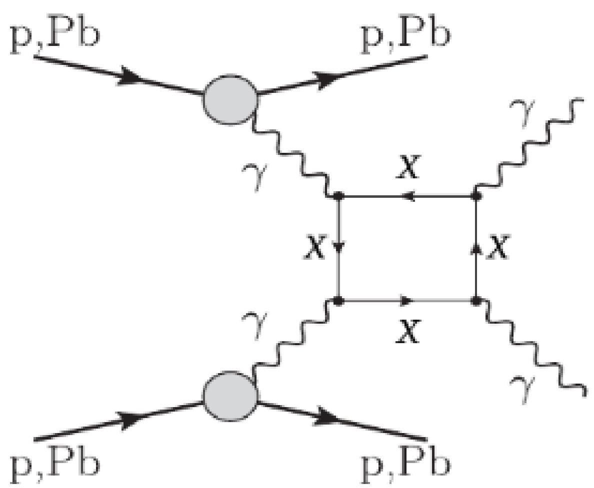
- In a HI fly-by, one can study light-by-light scattering
  CMS: 1810.04602
  ATLAS: 1702.01625, 1904.03536

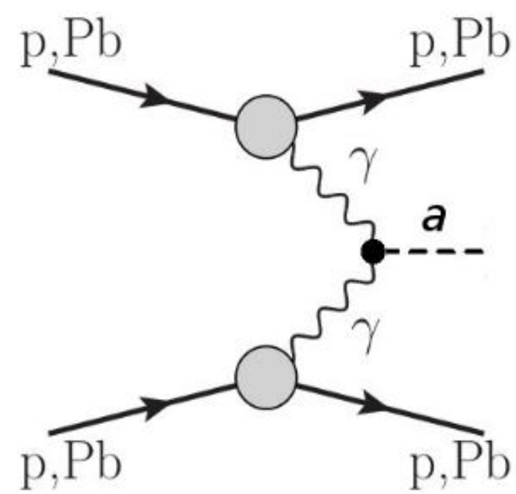
- In the "equivalent photon approximation" the fields can be modelled by plane waves of nearly on-shell photons (Weizsäcker 34, Williams '34)

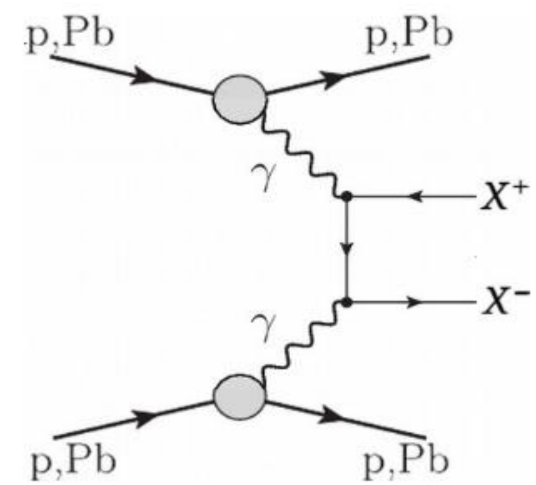
$$N(E,\vec{b}) = \frac{Z^2\alpha}{\pi^2}\left(\frac{E}{\gamma}\right)^2 K_1^2\left(\frac{E|\vec{b}|}{\gamma}\right)$$

# The LHC as a Photon Collider

- Opens several channels to produce new particles



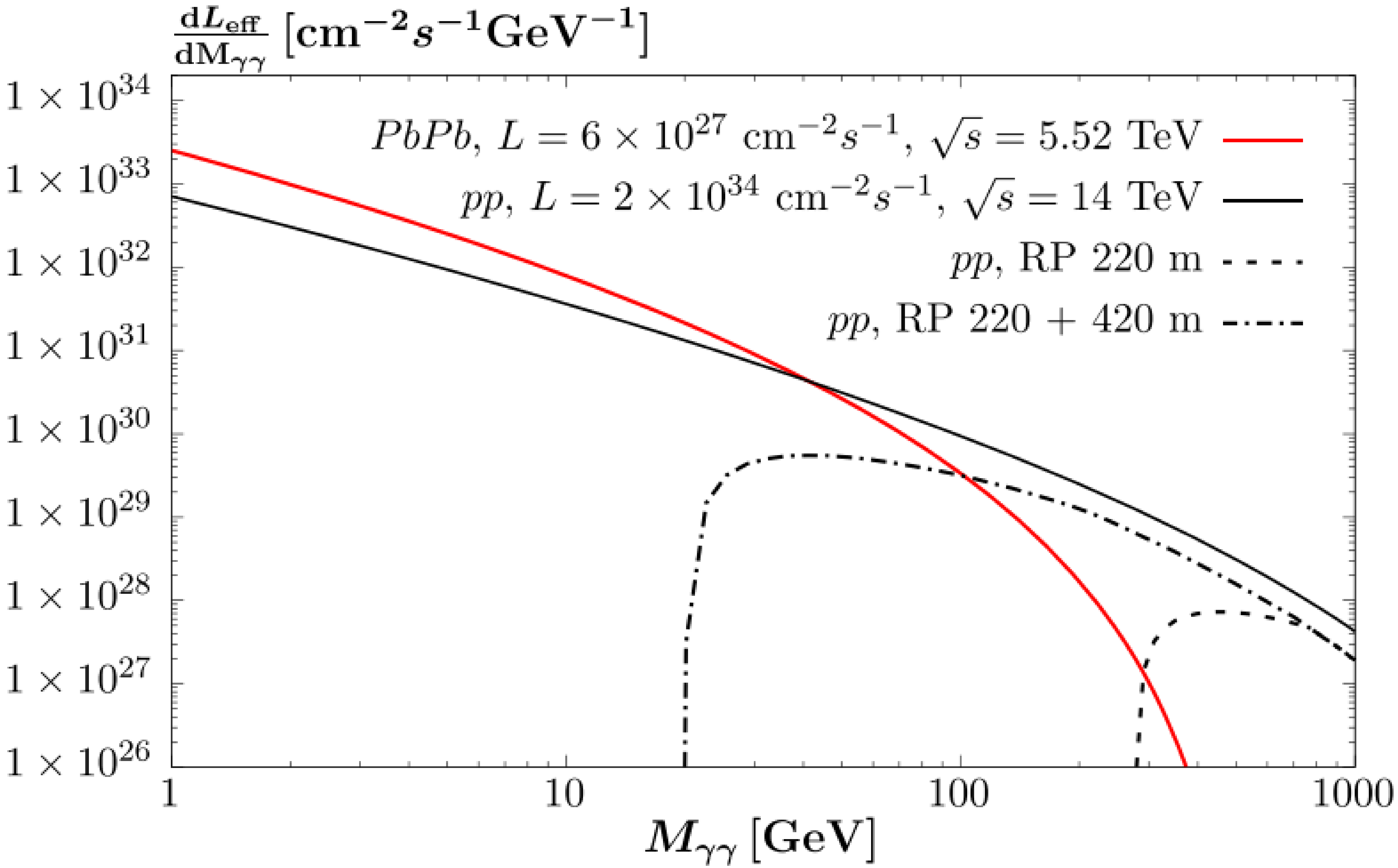




- In equivalent photon approximation

$$\sigma_{A_1A_2\to A_1XA_2} = \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1) n(x_2)\, \hat{\sigma}_{\gamma\gamma\to X} = \int \mathrm{d}m_{\gamma\gamma} \frac{\mathrm{d}\mathcal{L}_{\mathrm{eff}}}{\mathrm{d}m_{\gamma\gamma}} \hat{\sigma}_{\gamma\gamma\to X}$$

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

# Effective γγ-Luminosity



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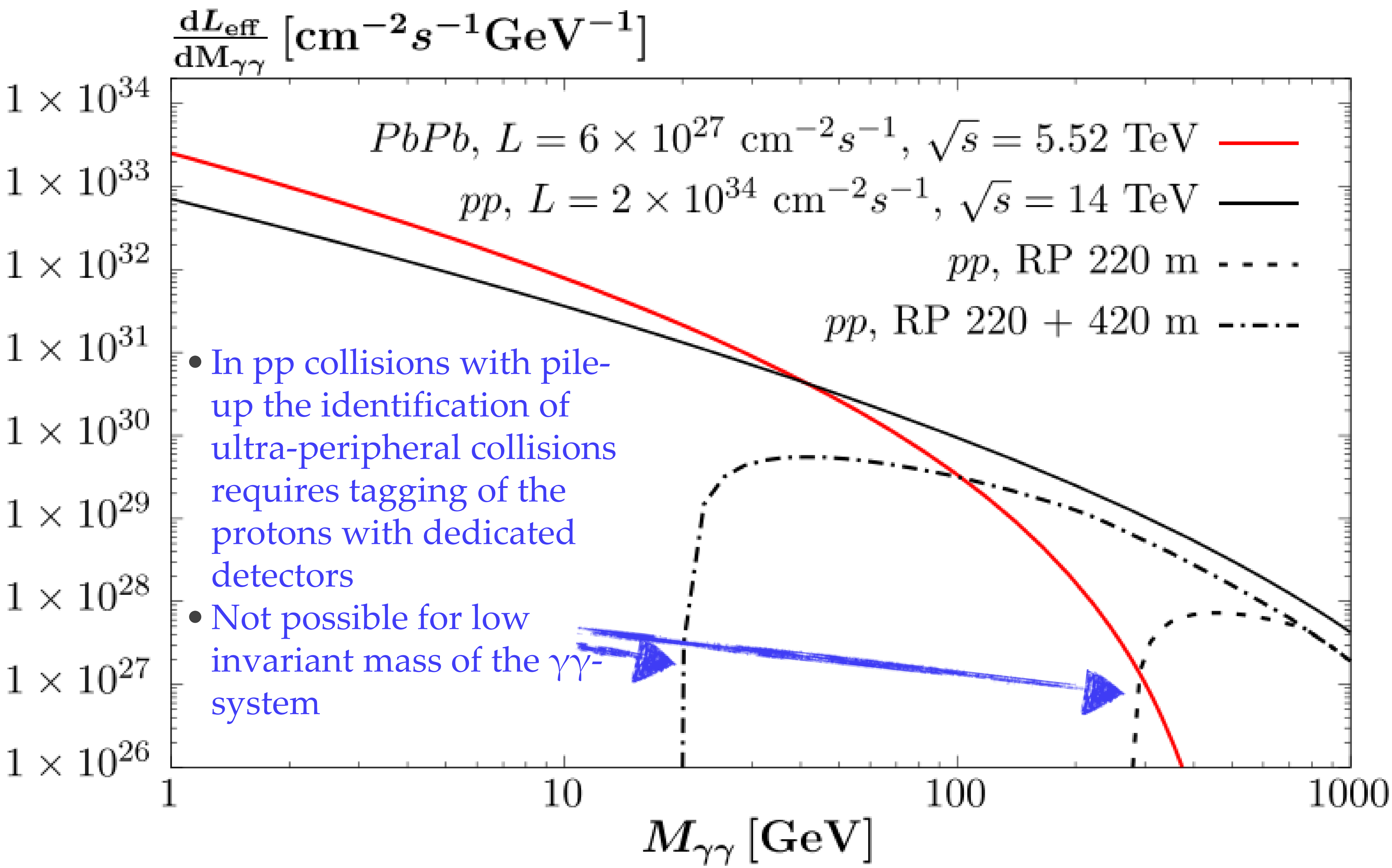
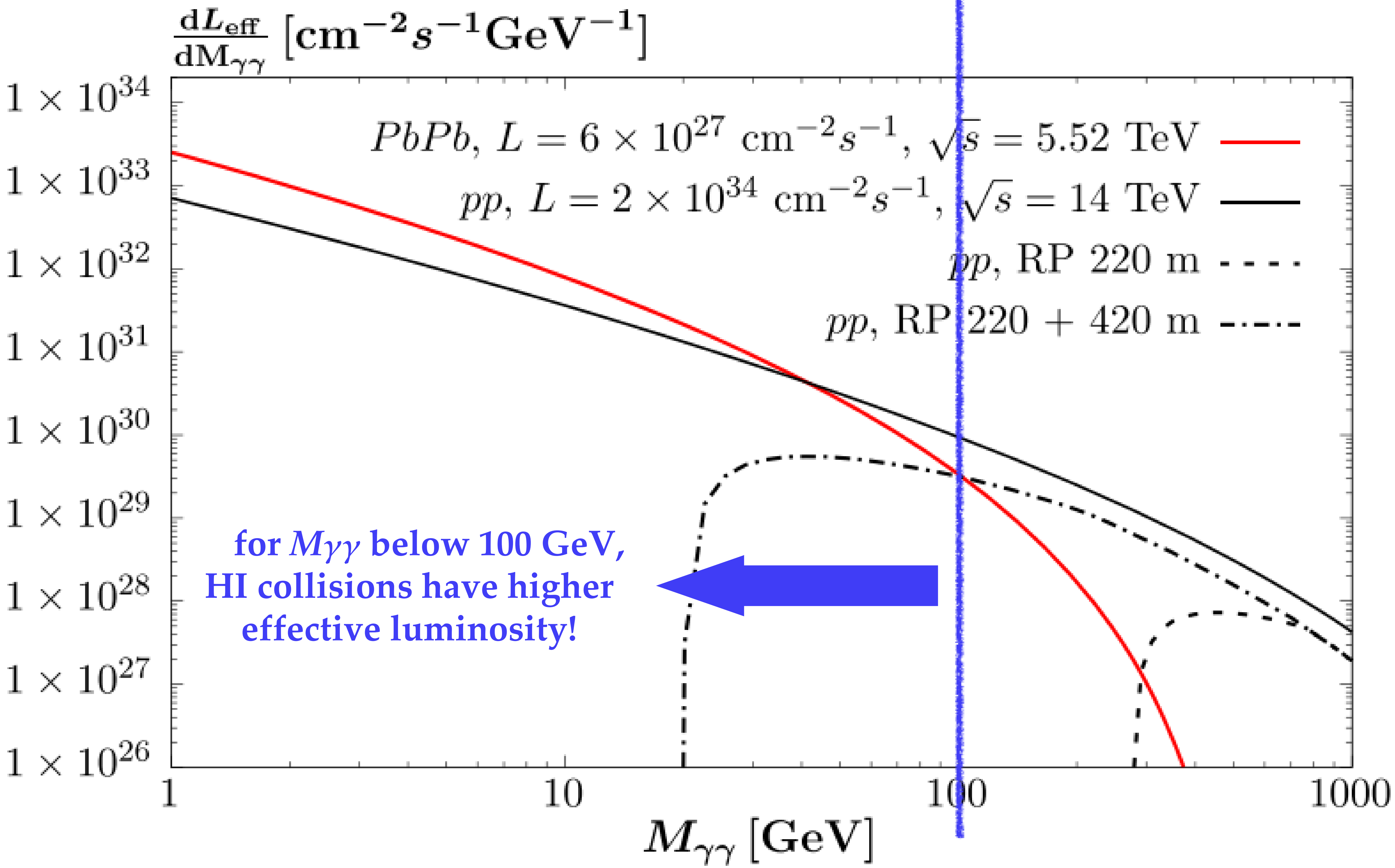
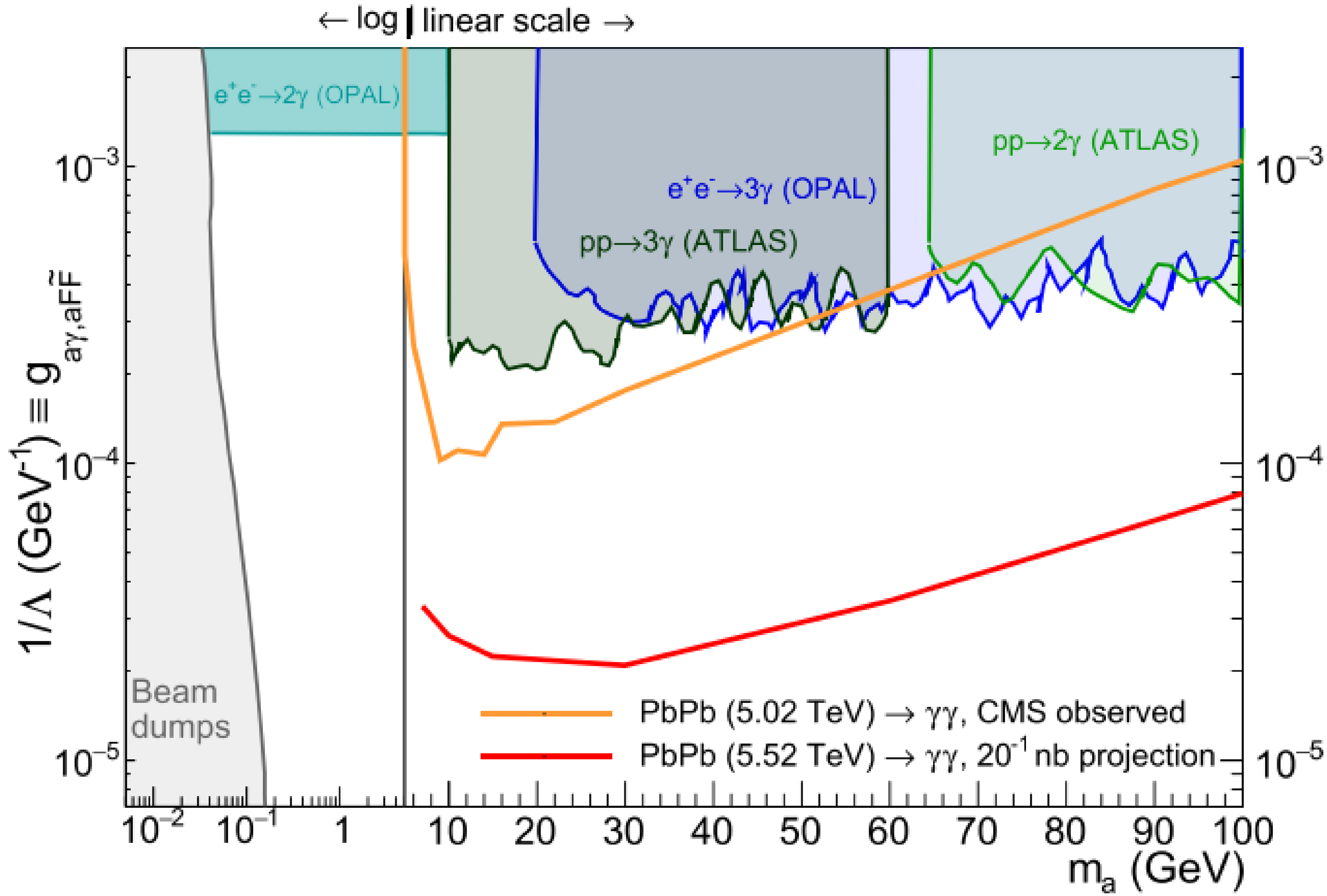



- In pp collisions with pile-up the identification of ultra-peripheral collisions requires tagging of the protons with dedicated detectors
- Not possible for low invariant mass of the $\gamma\gamma$-system

# Effective γγ-Luminosity



# Axion-like Particles

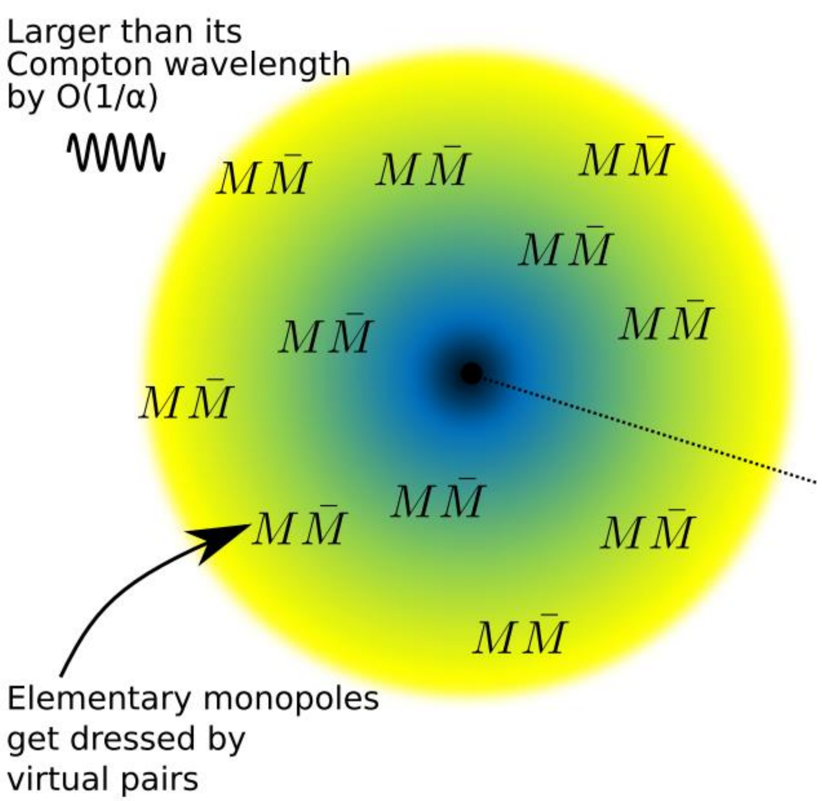


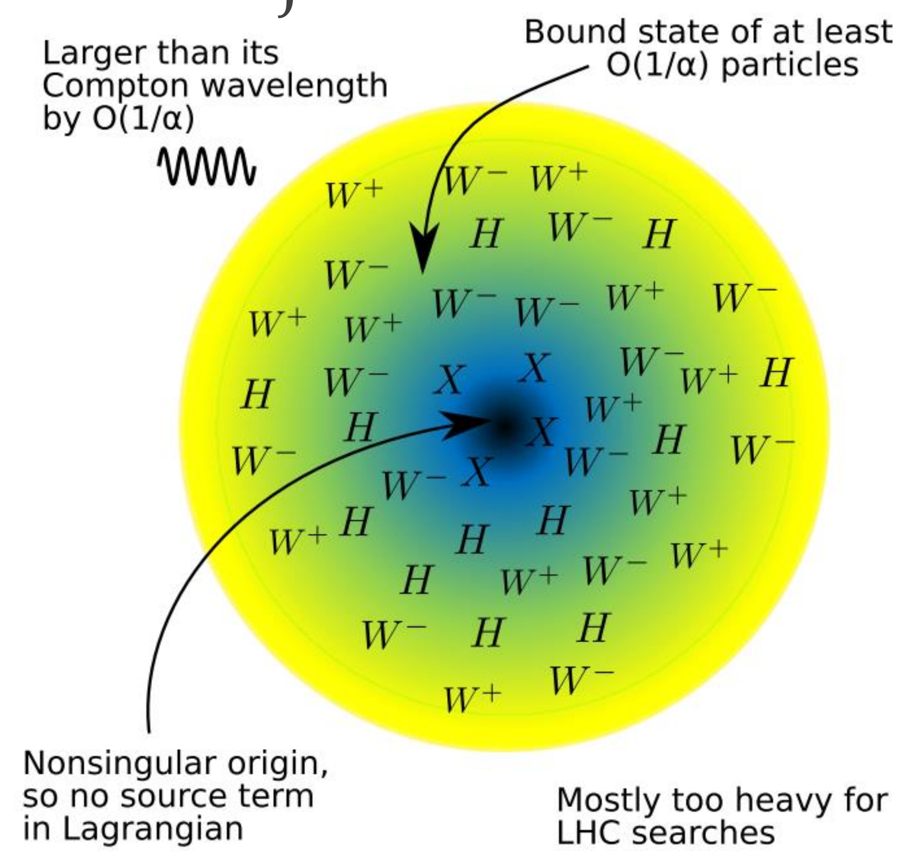

from arXiv:1812.07688

see also al 1607.06083 and LHCb 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




figures: Oliver Goud

**➜ 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
  Afflek/Manton 82

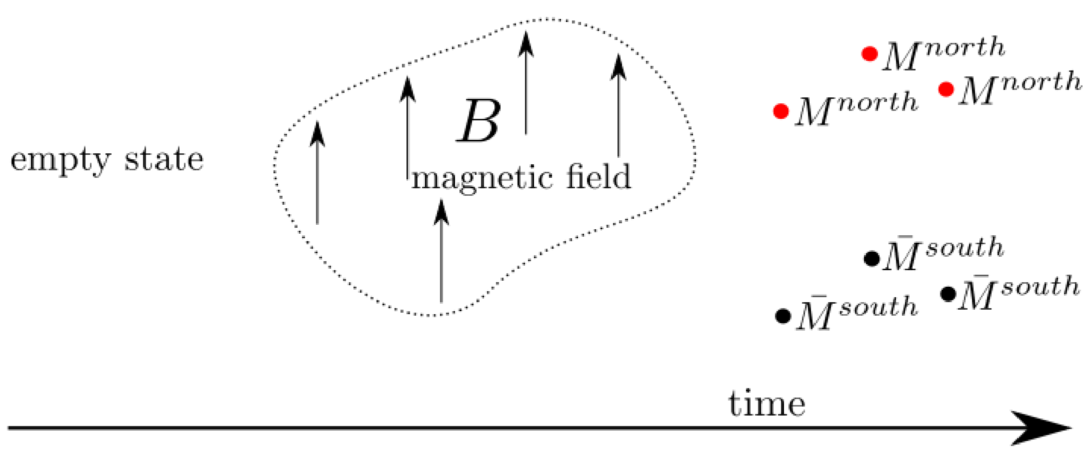
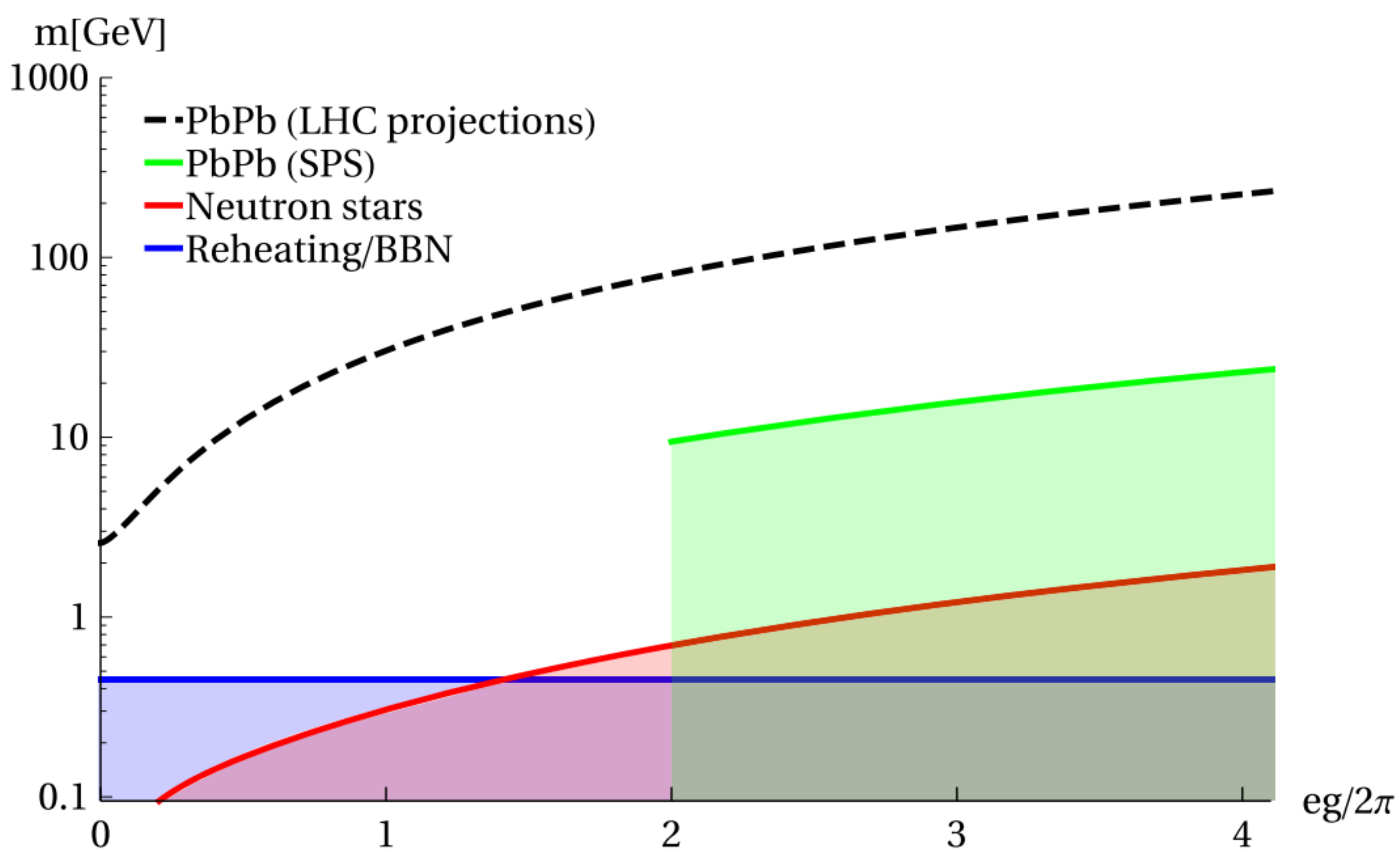
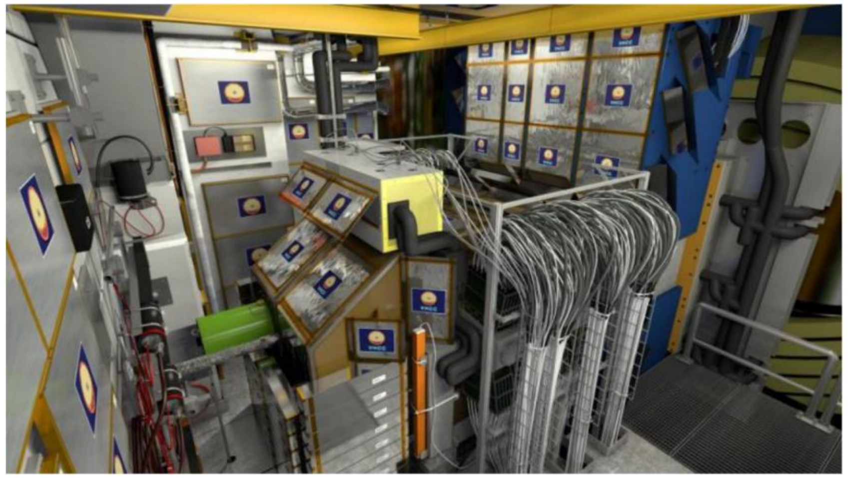



figure: Oliver Goud

**➜ production in HI collisions possible!**




- dedicated experiment: MoEDAL



Gould/Rajantie 1705.07052, see also 2103.14454, 1902.04388,

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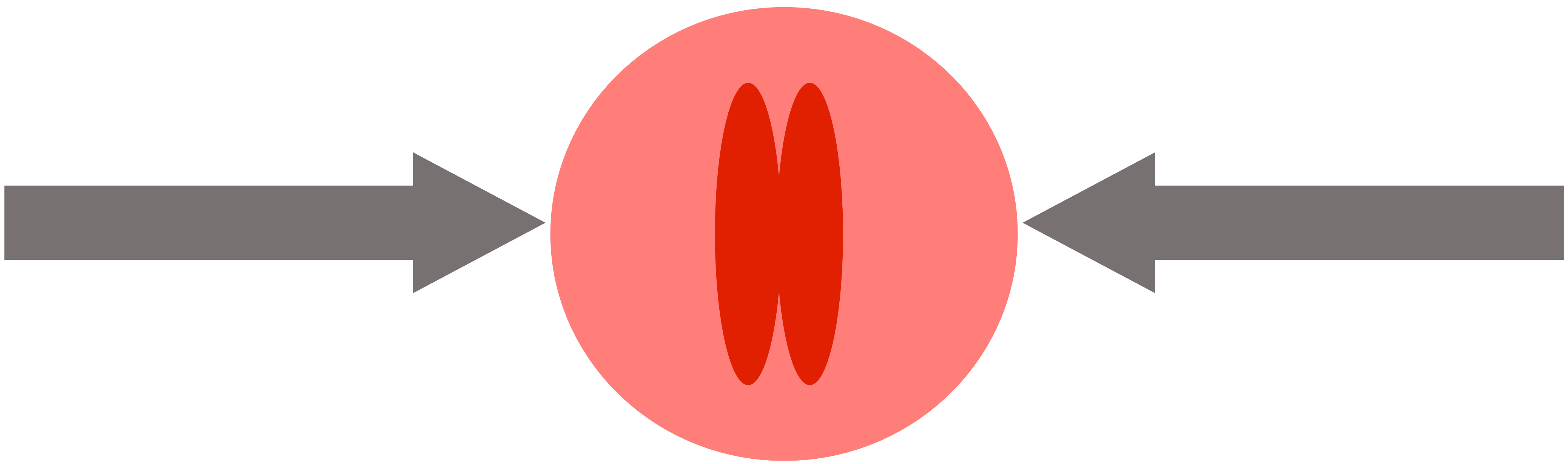
# Production from QGP

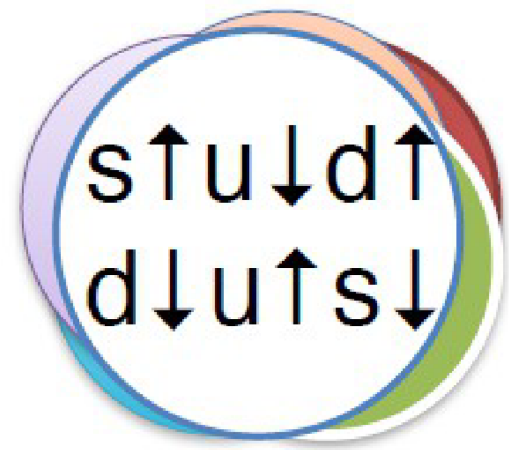


# Sexaquarks

- hypothetical colour-singlet state of 6 quarks

Farrar [1708.08951](1708.08951)

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




S

- potential DM candidate   Farrar [1805.03723](1805.03723)

prediction: $\Omega_{DM}/\Omega_b = 4.5 \pm 1$   Planck: $\Omega_{DM}/\Omega_b = 5.4 \pm 0.05$

- 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](CERN-THESIS-2019-278)

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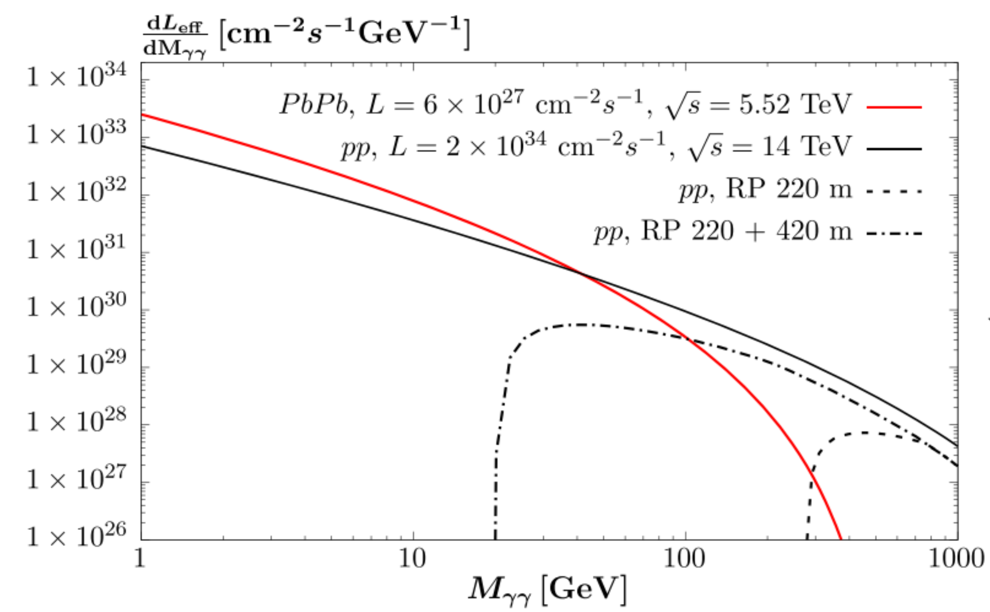
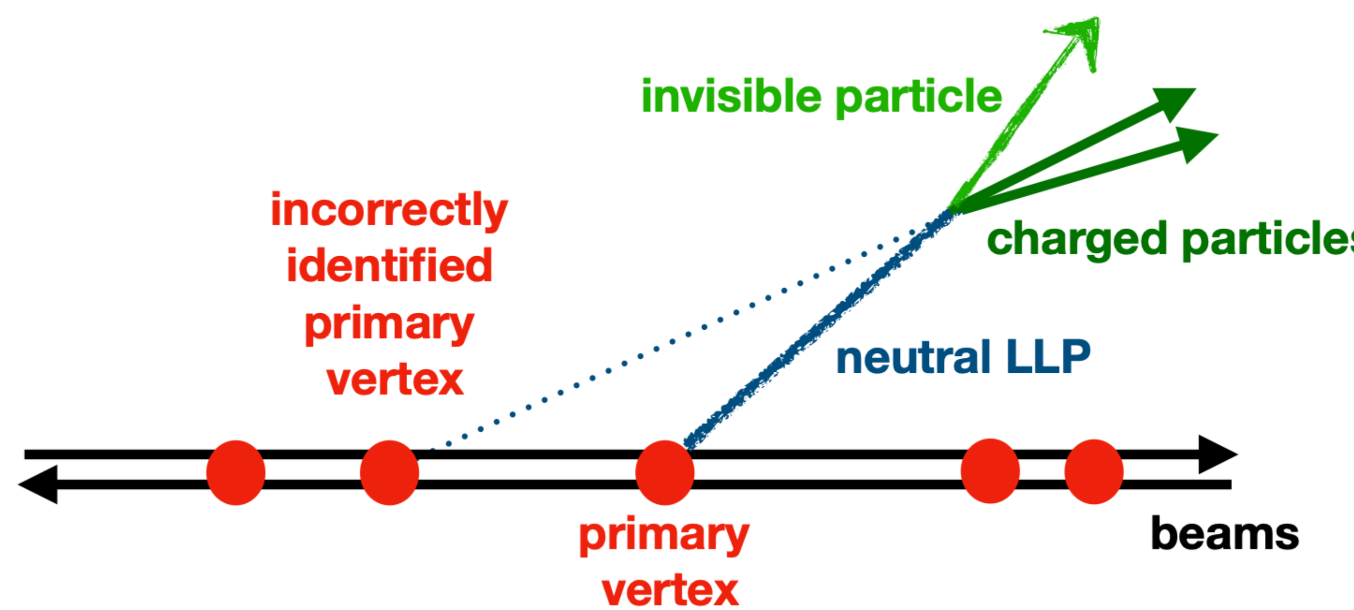
# Pile-up Issues

- 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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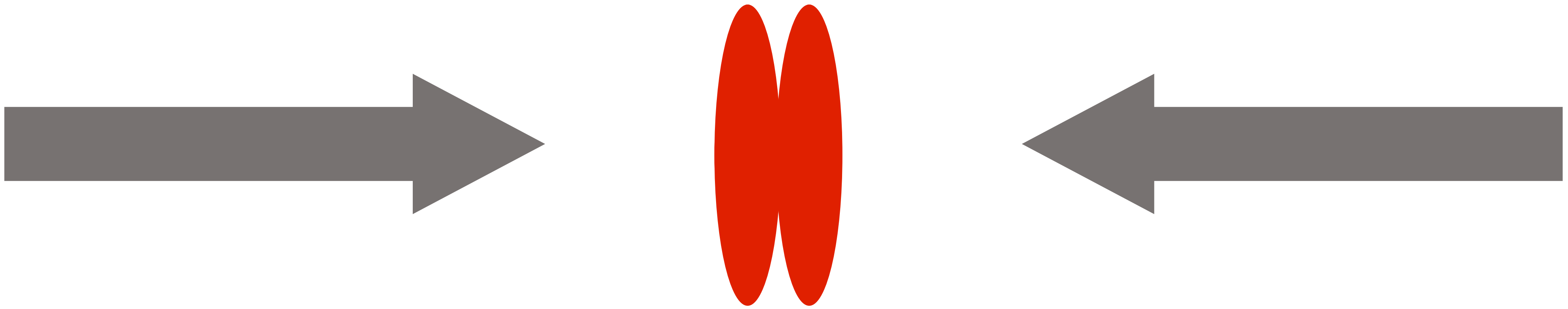
# A clean environment?



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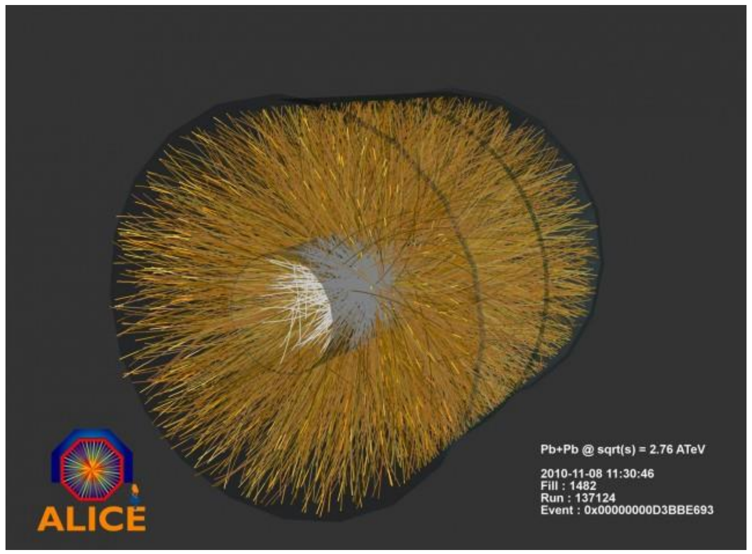


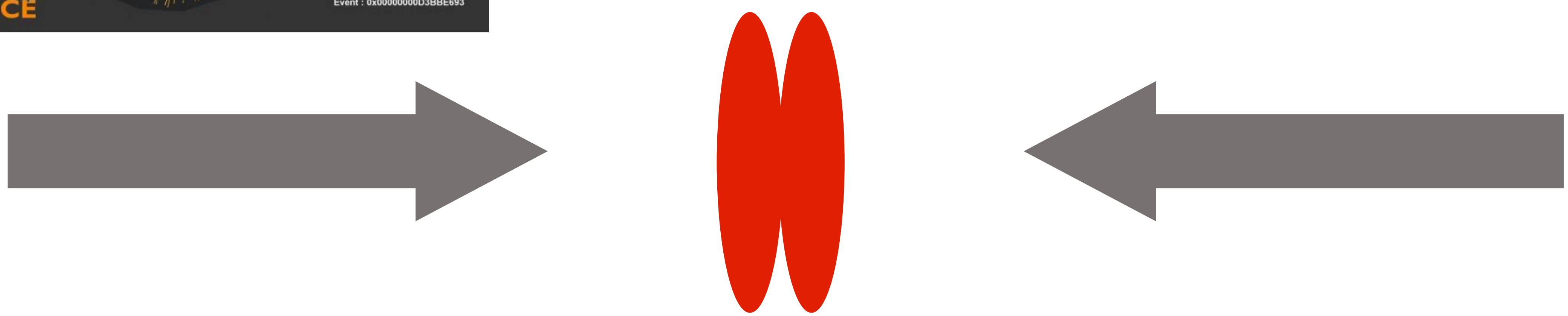

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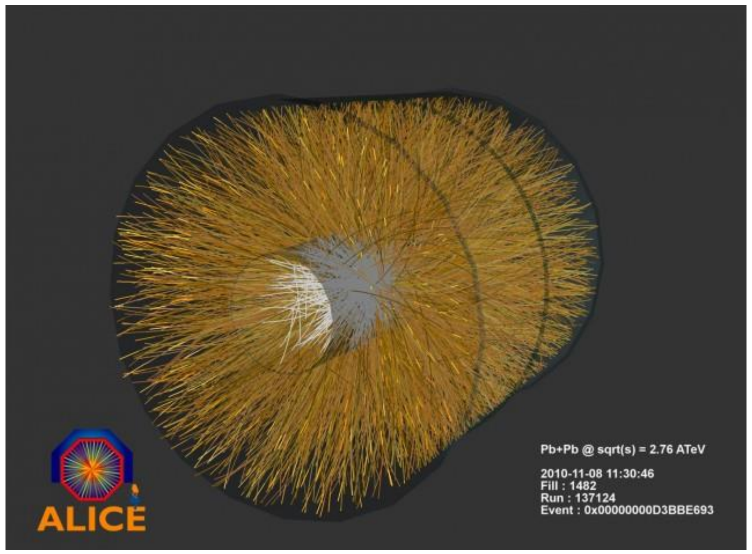
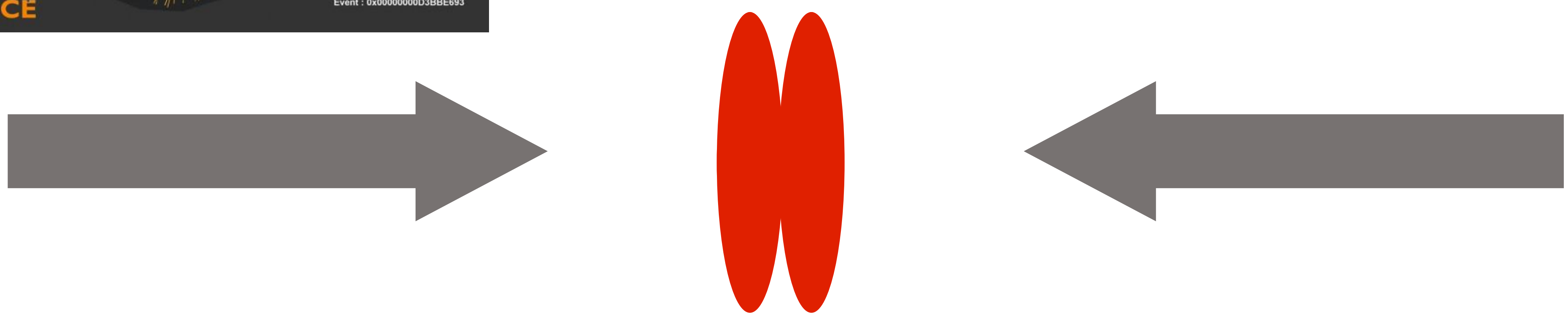


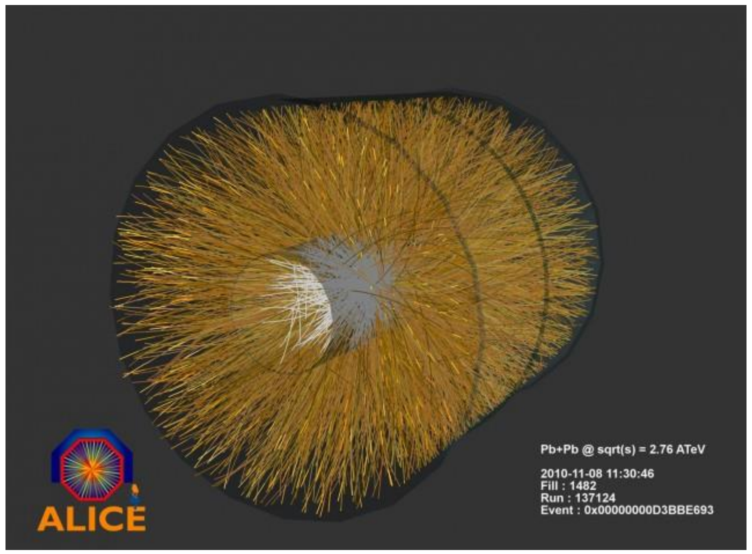



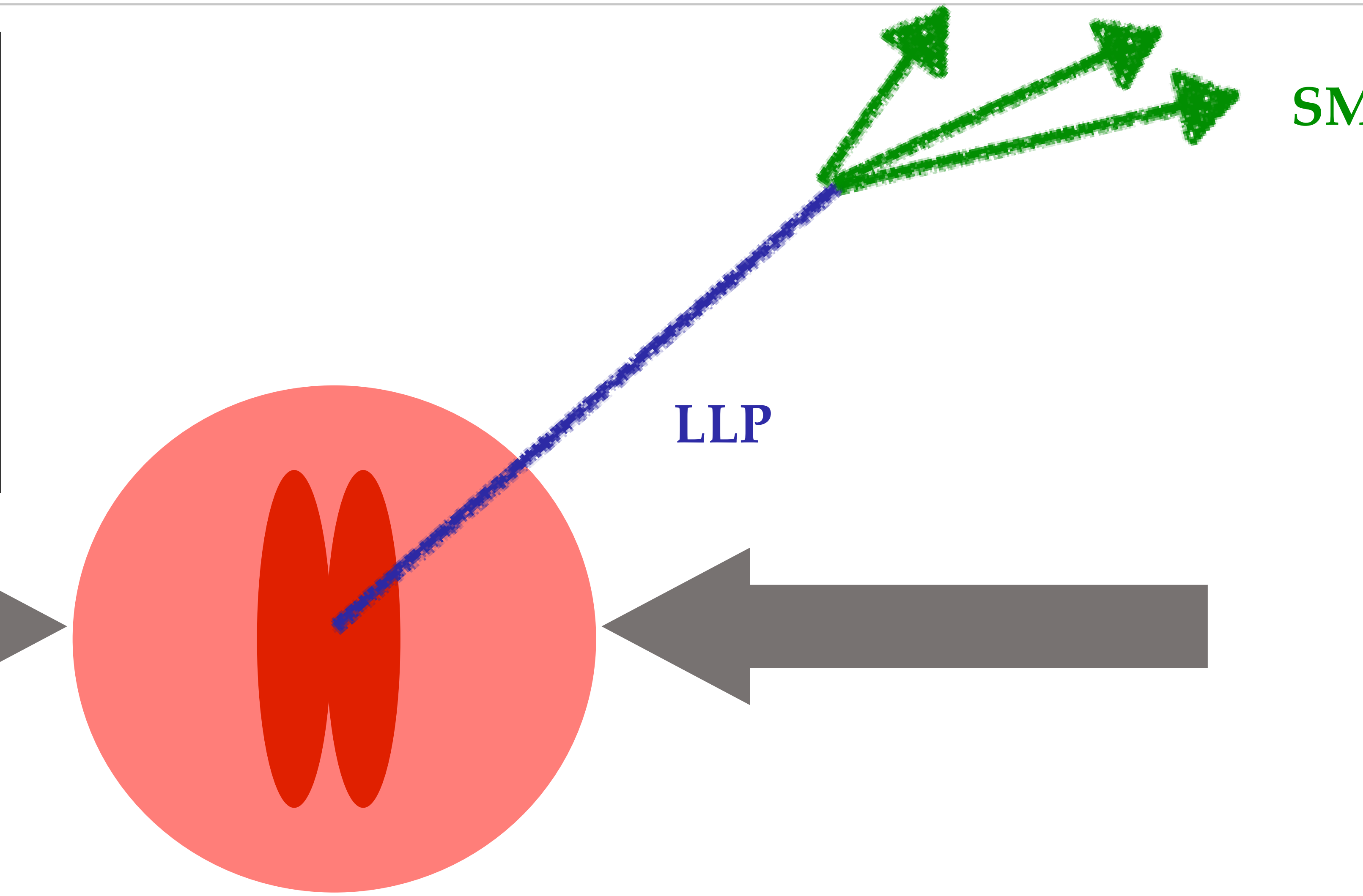
- but: HL-LHC will have ~ 200 pile-up events per bunch crossing, ~5000 charged particles per hard scattering!

→ multiplicity in Pb-Pb collisions only factor ~2 higher, for lighter nuclei even lower! CMS [1902.03603]

- and: vertexing in HI extremely good

# Long Lived Particles




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

# LLP searches in Heavy Ion Runs?

**Con**

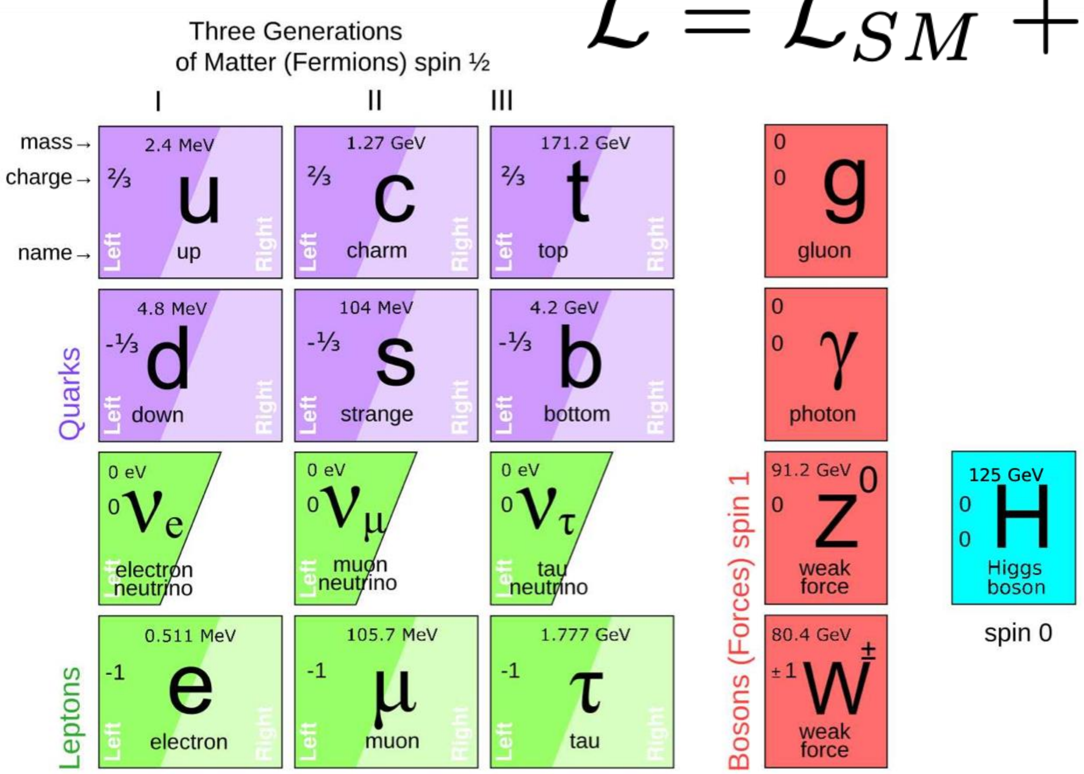
1. high track multiplicity
2. low instantaneous luminosity
3. lower collision energy per nucleon
4. runs are shorter

**Pro**

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

MaD/Giammanco/Hajer/Lucente/Mattelaer 1810.09400

# The Seesaw Mechanism (type I)




$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$

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

**Can explain** Asaka/Shaposhnikov 05

- **Neutrino masses**
- **Leptogenesis**
- **Dark Matter**

three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

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

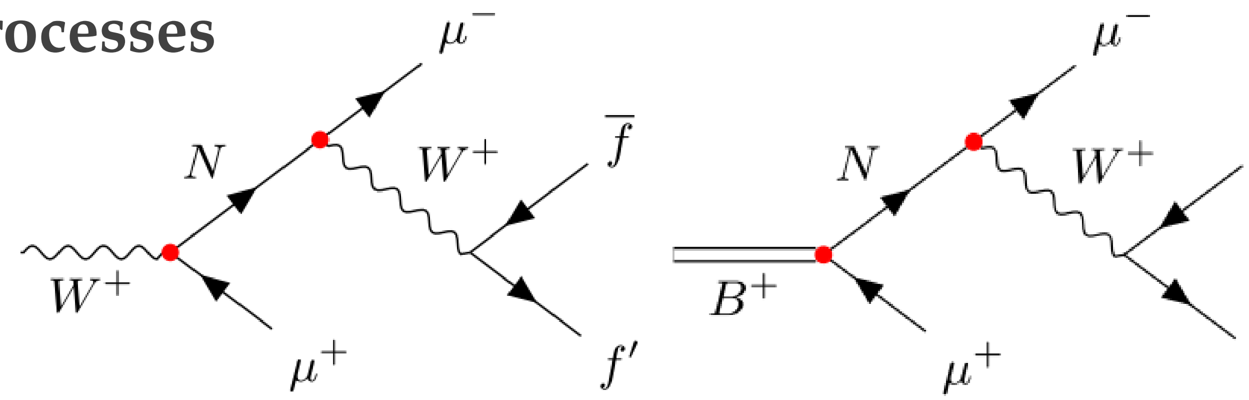
# Displaced Vertex Search

**Model**

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

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

**Processes**



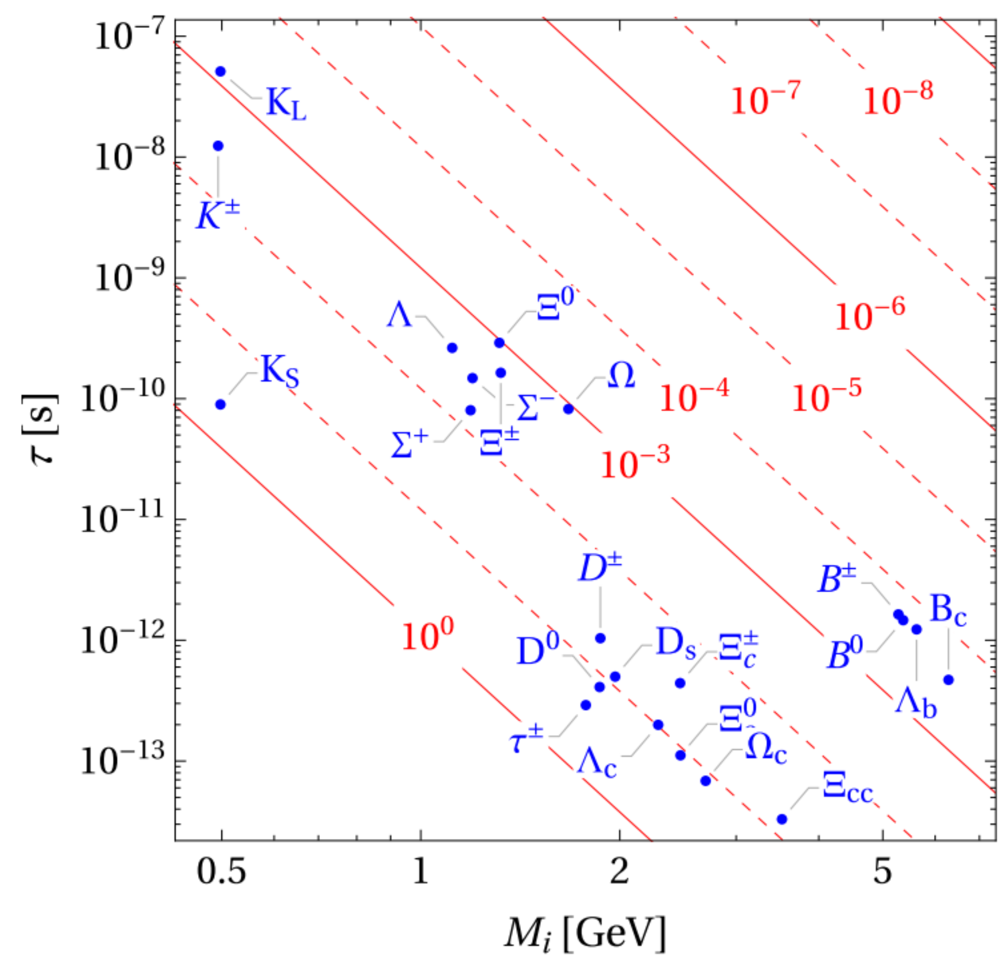

heavy neutrinos can be produced in $W$ or $B$ decays

**Analysis**

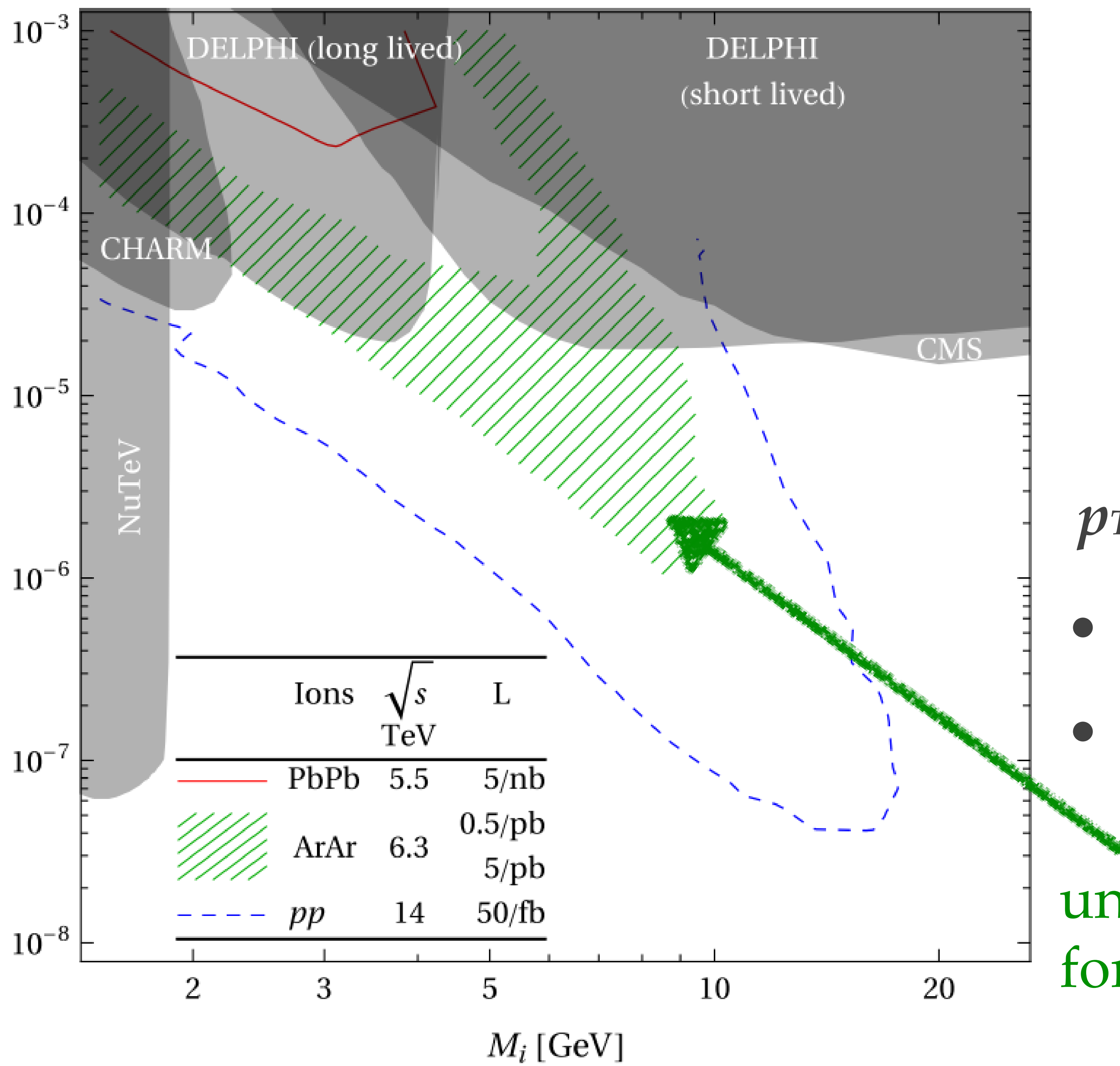
- we perform a displaced vertex (DV) search

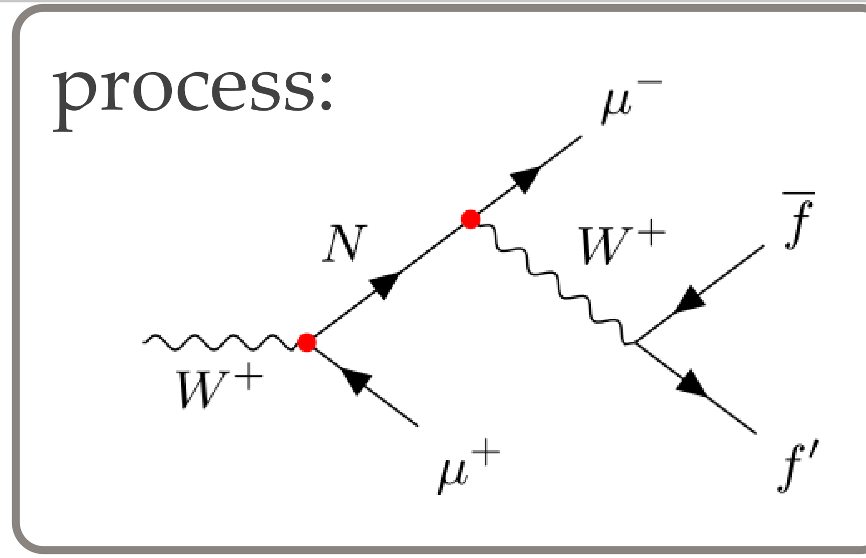
  $\Gamma \propto U^2 M^5$ with $U^2 = |\theta|^2$

- 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




**$p_T$ cuts used:**

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

uncertainty in the *p* factor for argon collisions

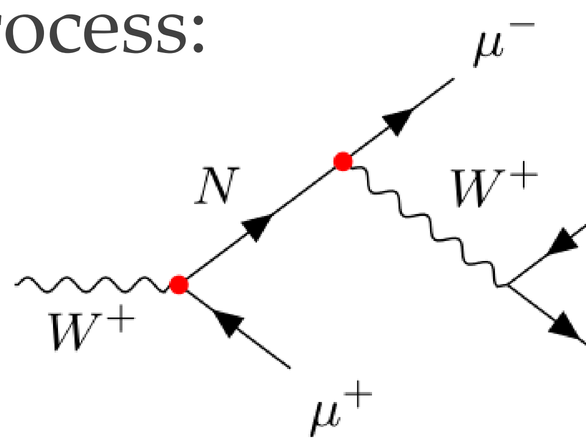
MaD/Giammanco/Hajer/Lucente/Mattelaer 1810.09400, 1905.09828

# A Spherical Detector Model

simple analytic formula for # events:

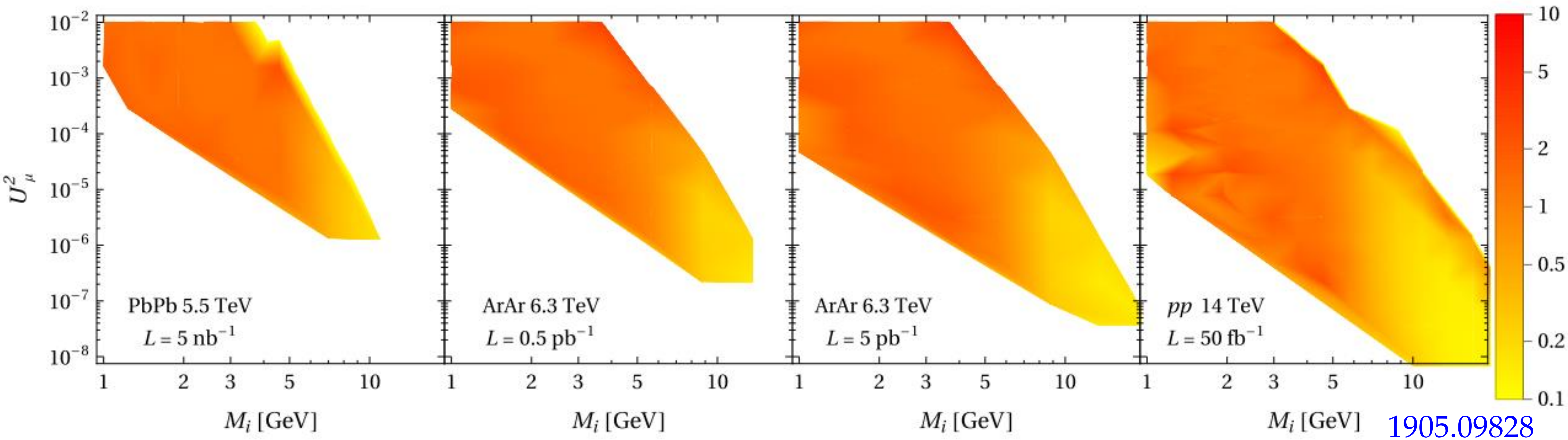
$$N_{\rm obs} \simeq L\sigma_\nu U_\mu^2 \left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right)\right] f_{\rm cut}$$

process:




use $l_0 = 5mm$, determine $\lambda(p)$ from simulation and fit $l_1 = 20cm$

ratio of # events predicted by averaged analytic formula and simulation:



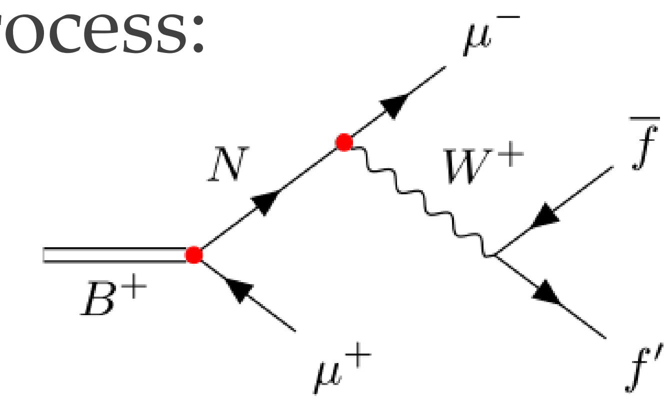

1905.09828

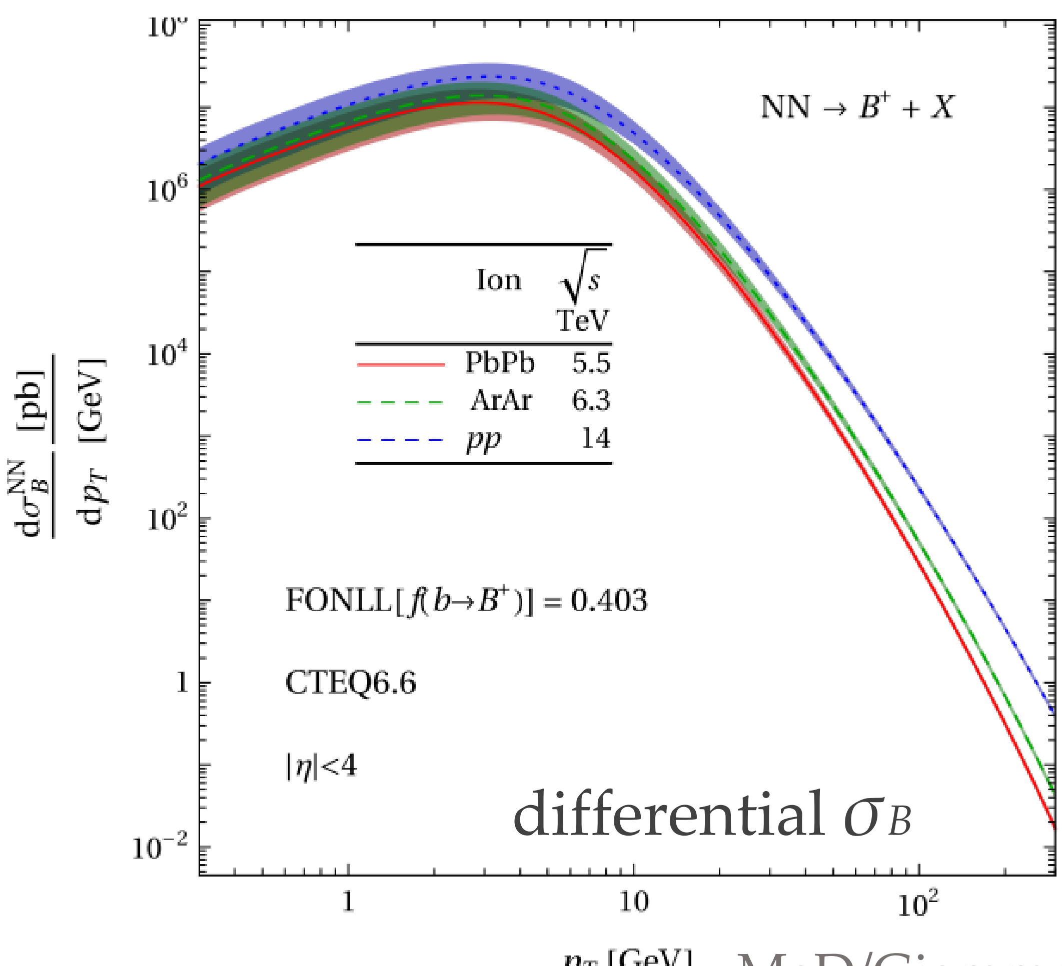
# Heavy Neutrinos in B Decays

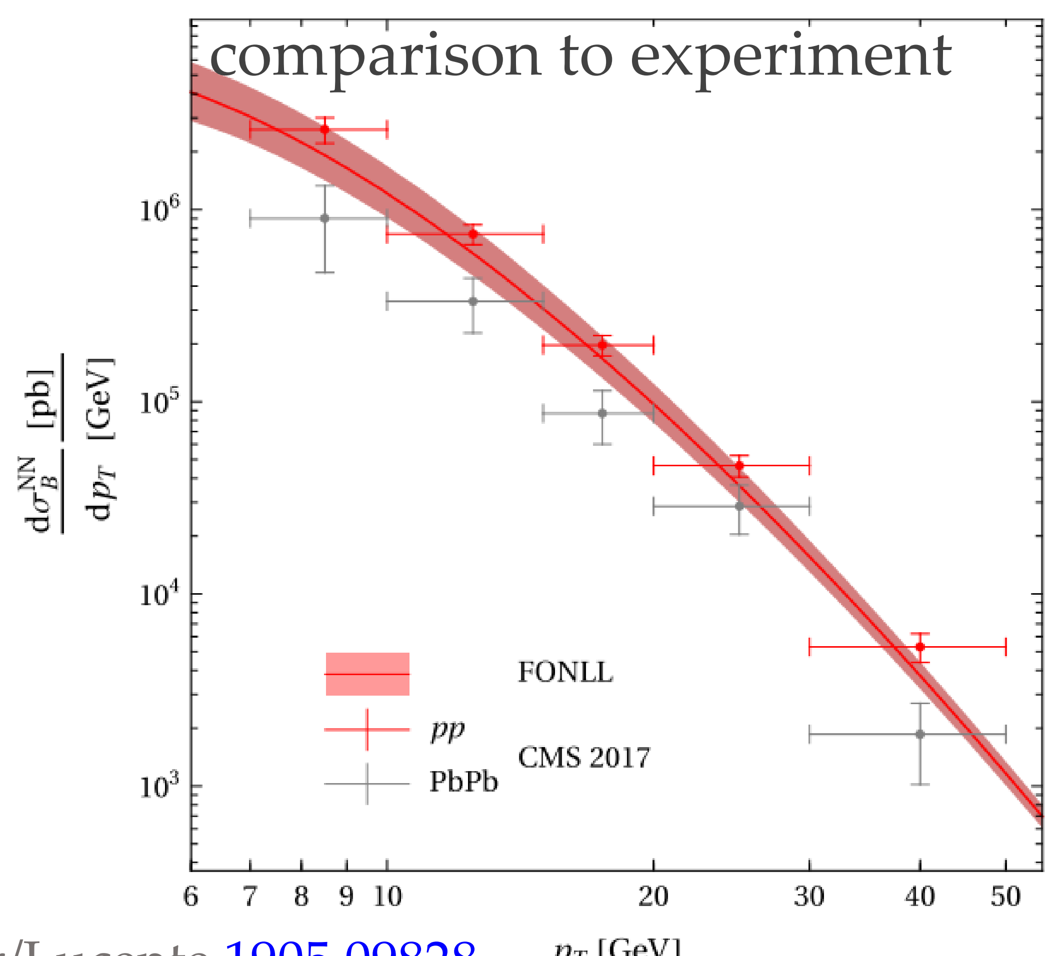
number of observable events:

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

process:

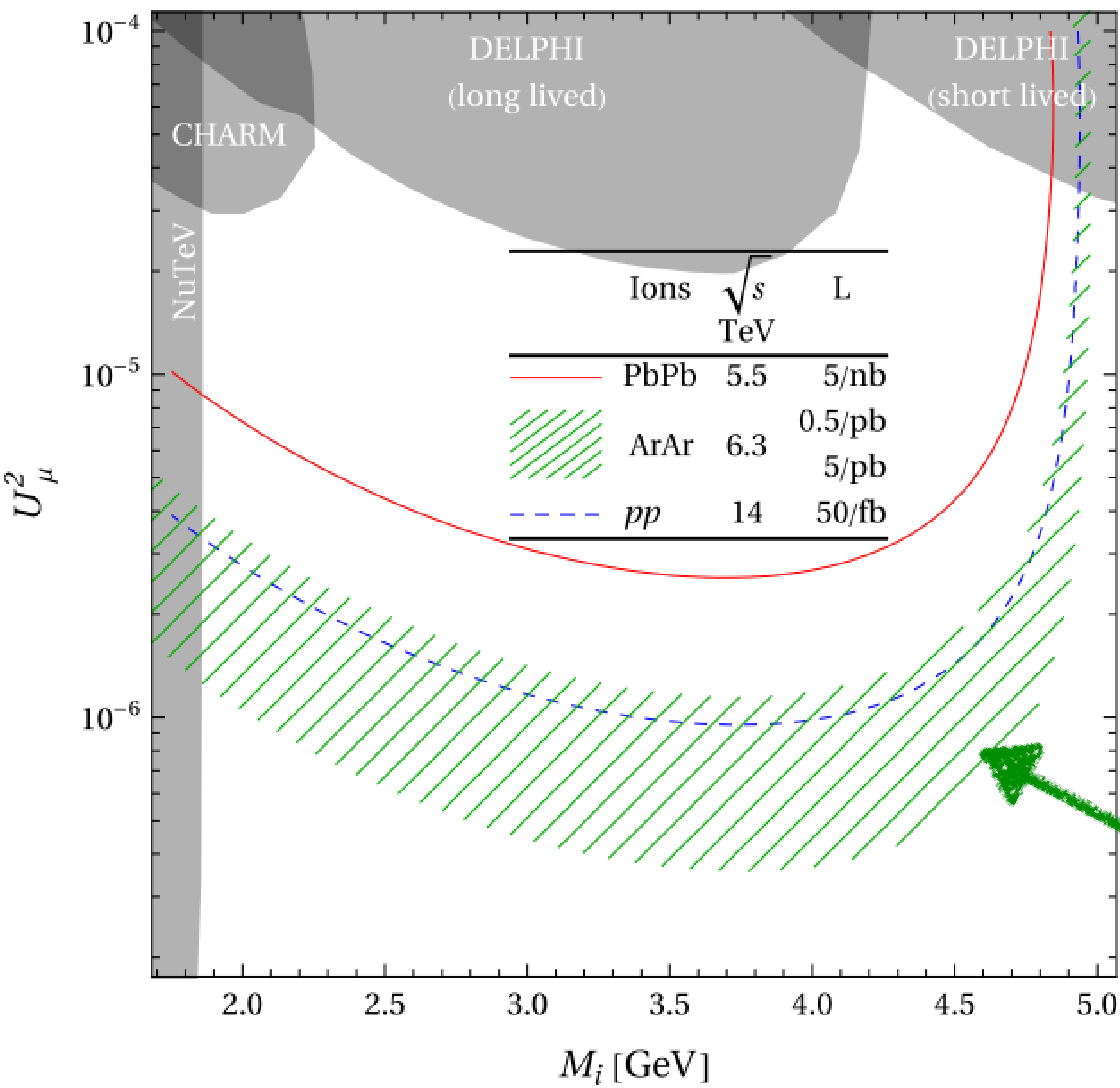


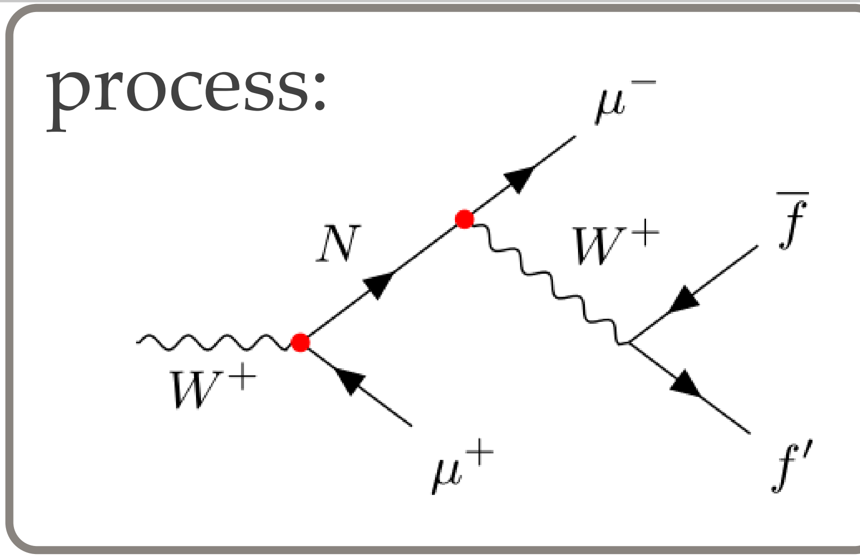




MaD/Giammanco/Hajer/Lucente [1905.09828]

# Heavy Neutrinos in B Decays

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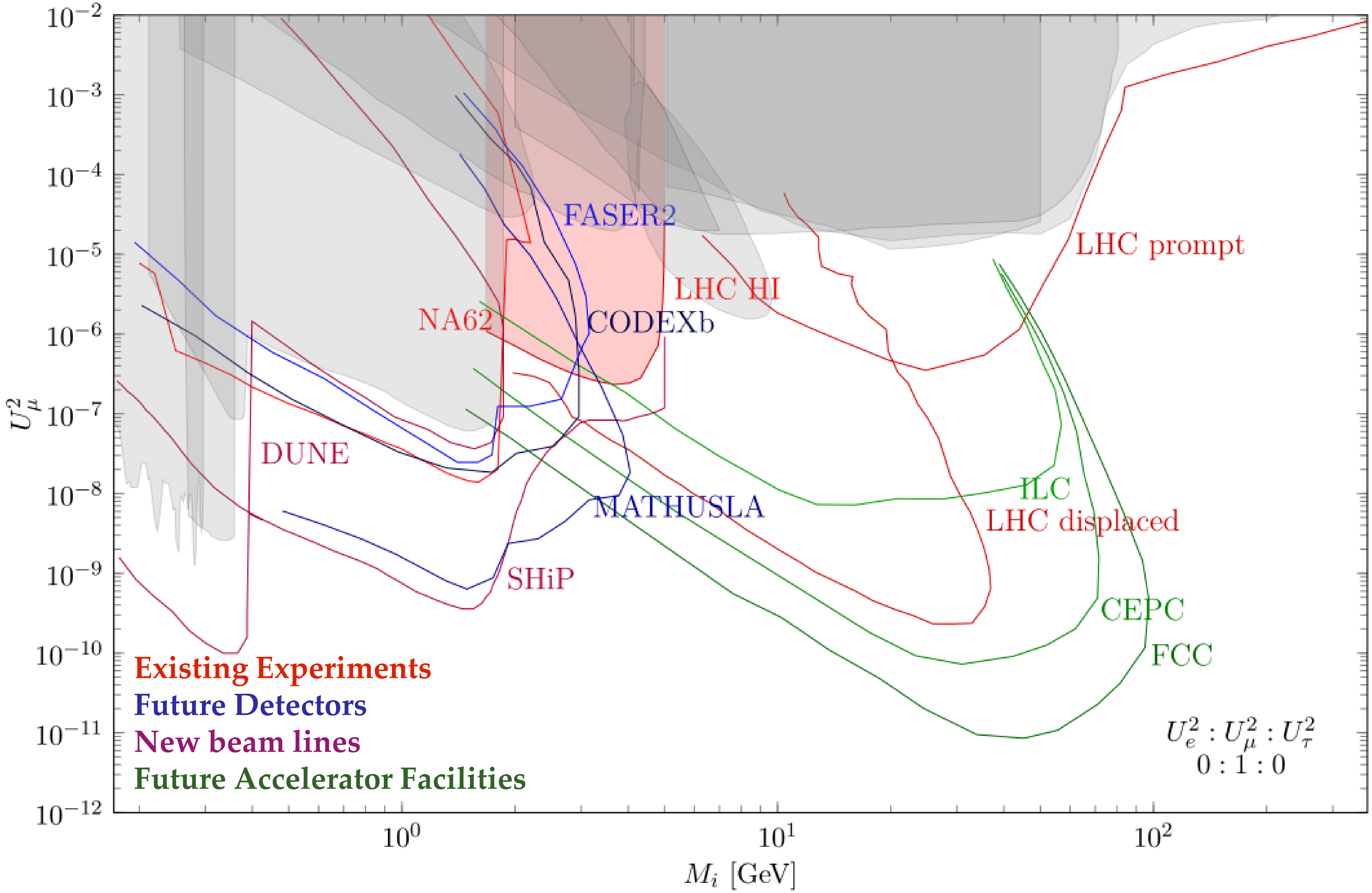
MaD/Giammanco/Hajer/Lucente/Mattelaer 1810.09400, 1905.09828

# Other Heavy Neutrino Searches



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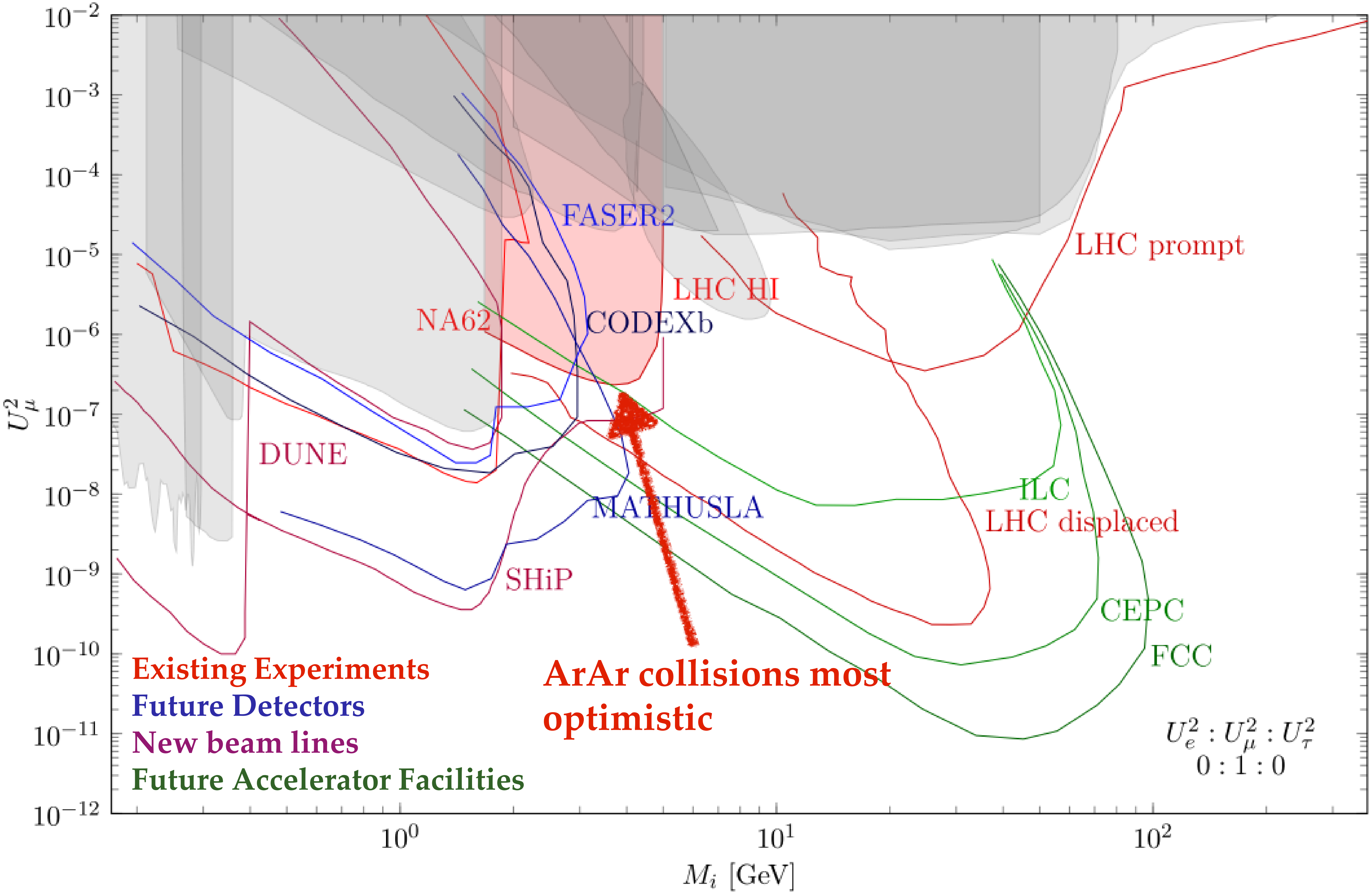
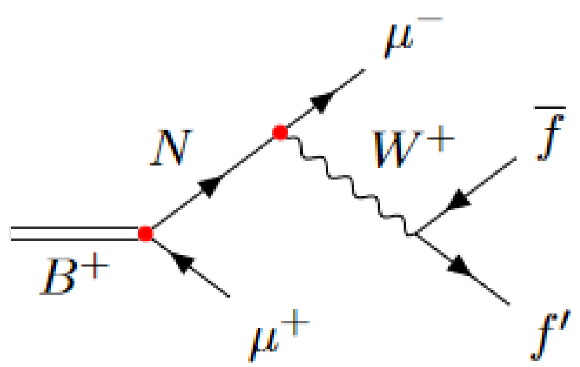
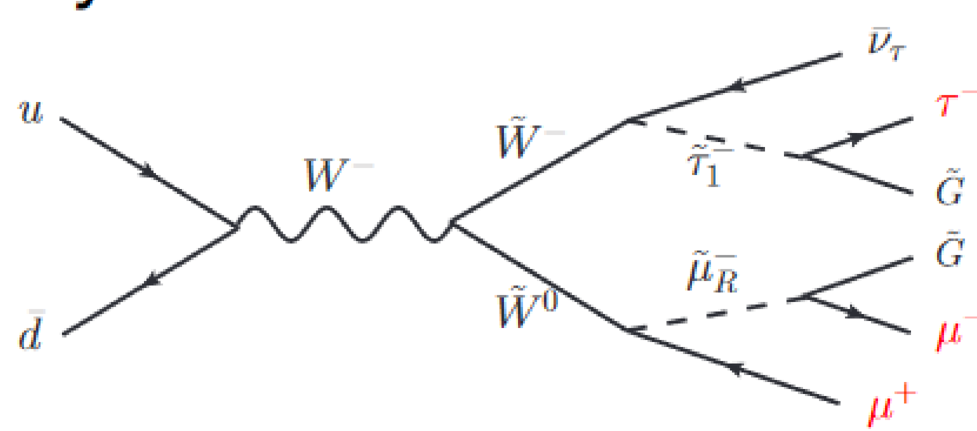


# Soft Lepton Scenarios

- **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

[slide by Susanne Westhoff]

# Conclusions

## Summary

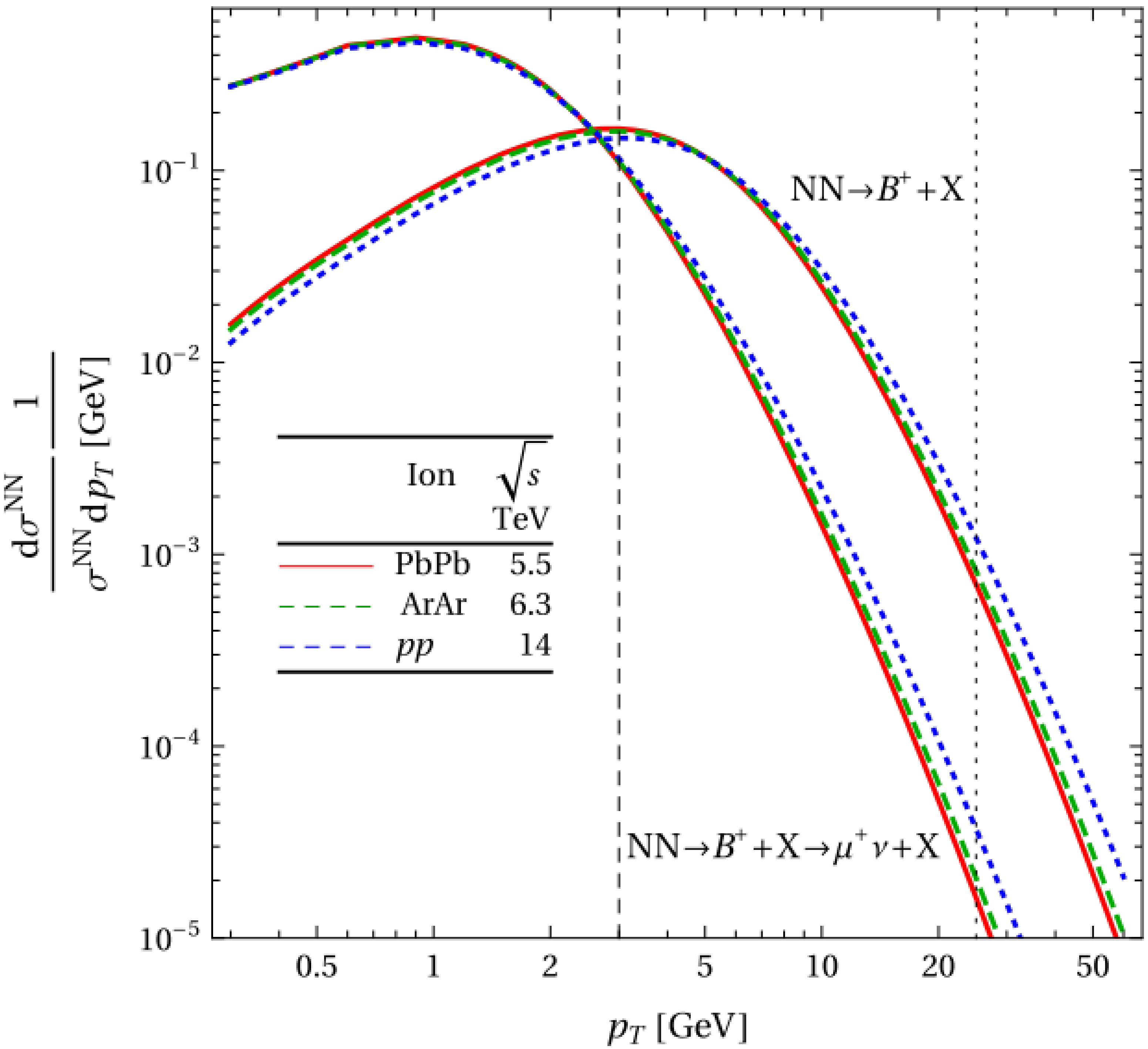
- HI collisions can be used to probe New Physics
- In some scenarios and/or parameter regions searches in HI collisions can be more sensitive than in proton collisions
- This can help to fully exploit the existing facilities and "turn every stone"

## Next steps

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

# Backup Slides

# Heavy Neutrinos in B Decays




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

MaD/Giammanco/Hajer/Lucente [1905.09828](1905.09828)

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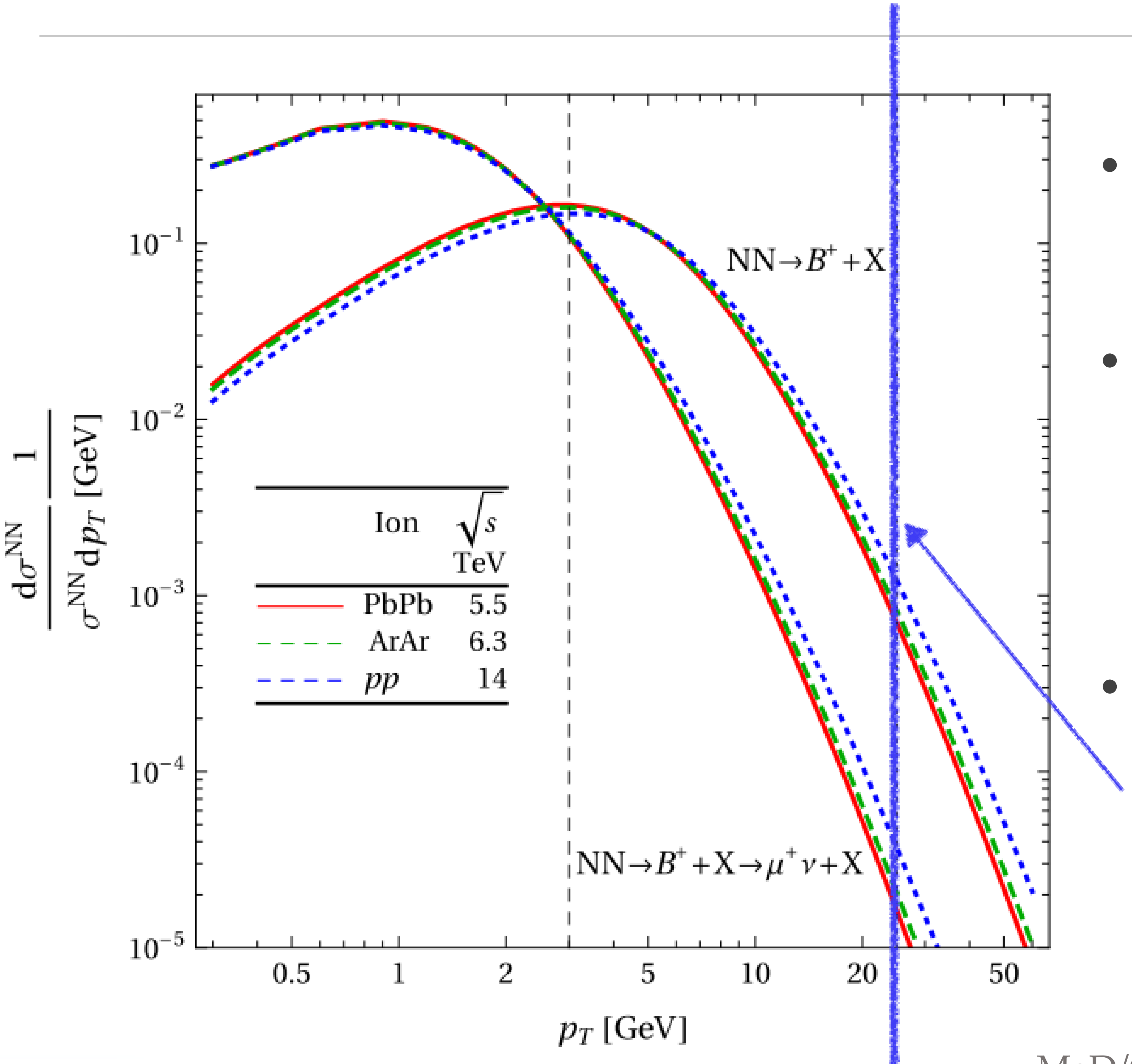


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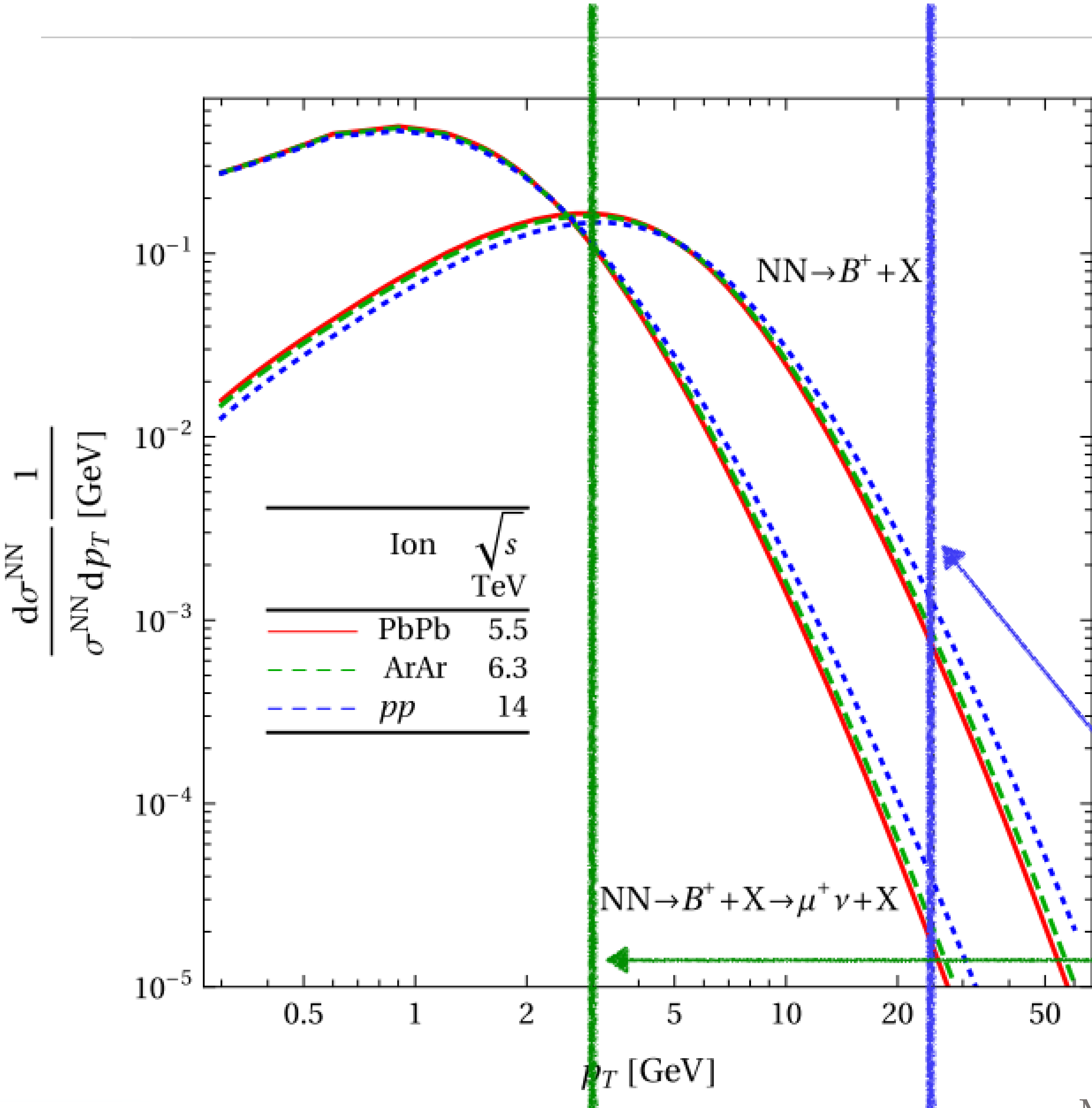


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cut at 25 GeV in pp collisions misses most events!

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

MaD/Giammanco/Hajer/Lucente 1905.09828

# 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 |

[Meier et al. 2001]

Bound-Free Pair Production (BFPP): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$

[Pshenichnov et al. 2001]

Electromagnetic Dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$

# Beam Losses

**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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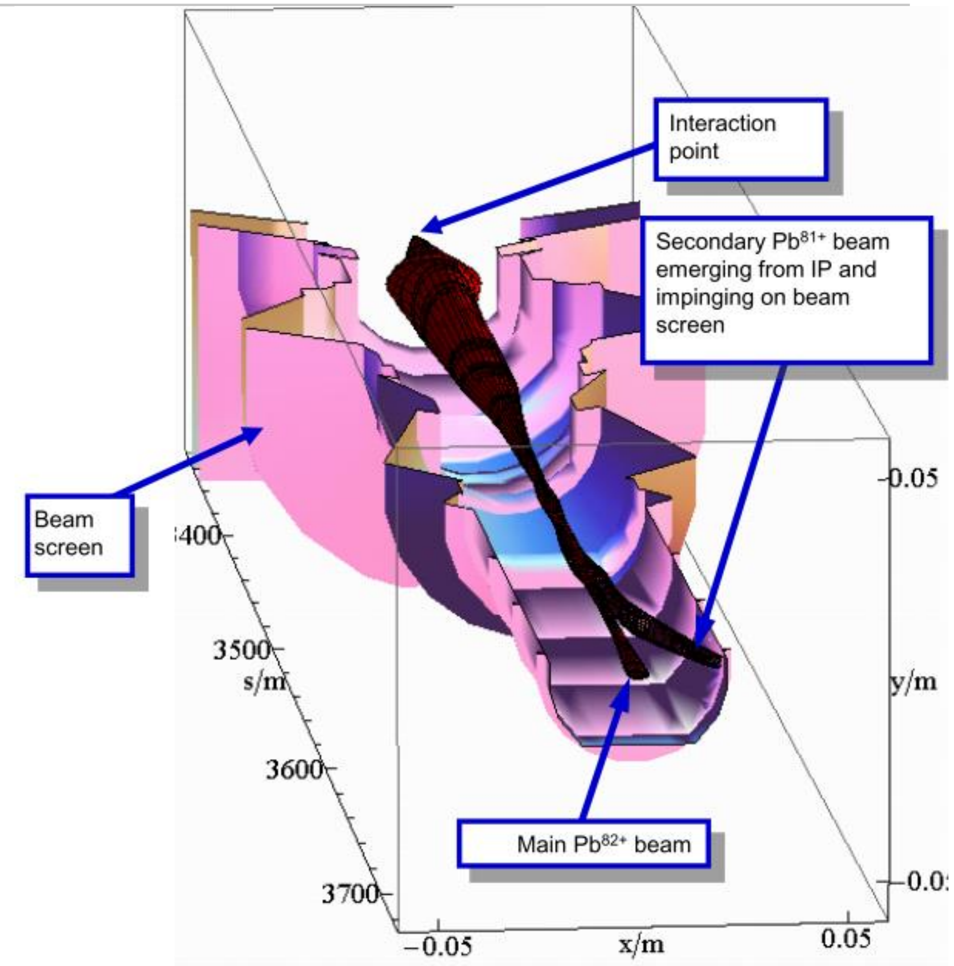


figures:
Roderik Bruce

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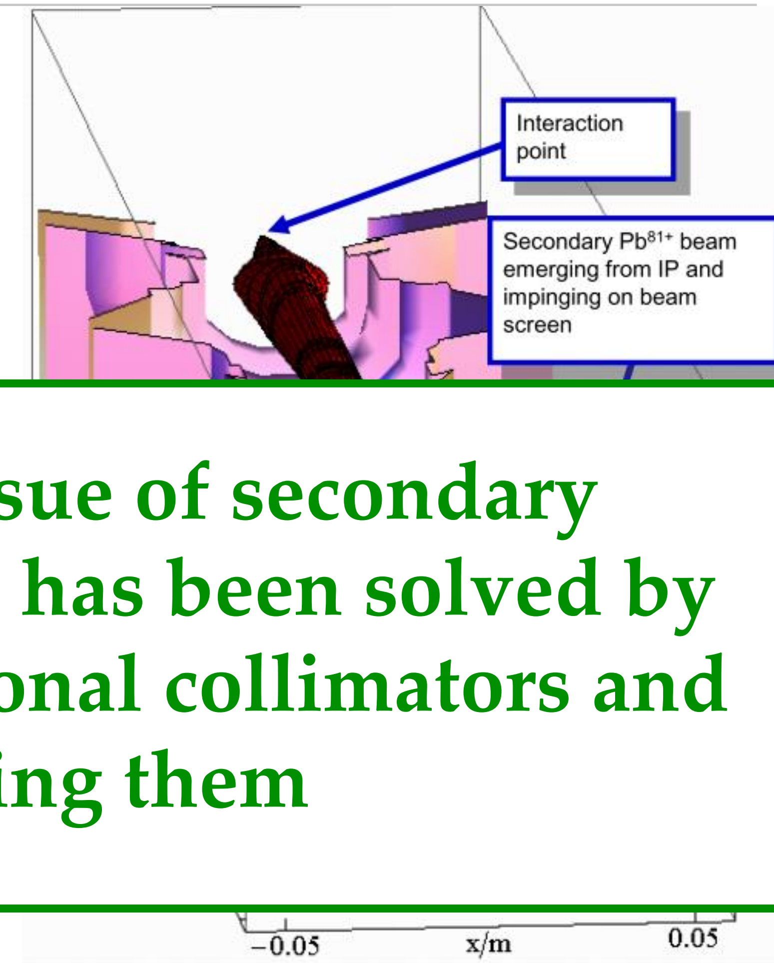


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figures: Roderik Bruce

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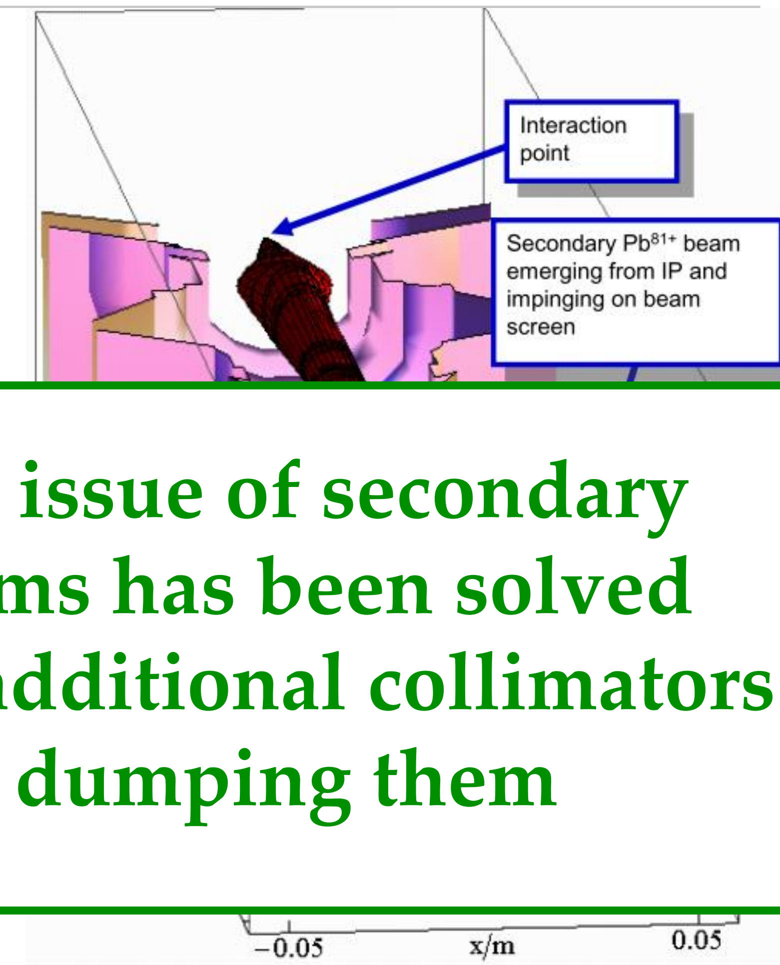


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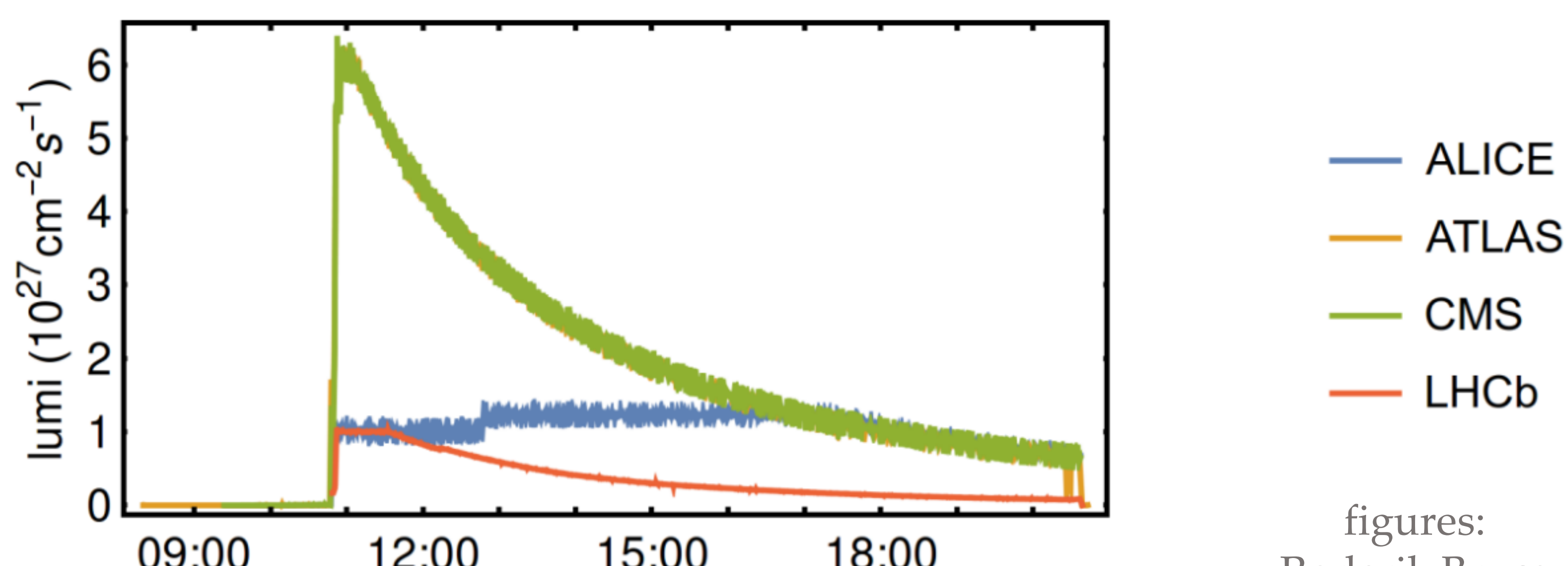


figures:
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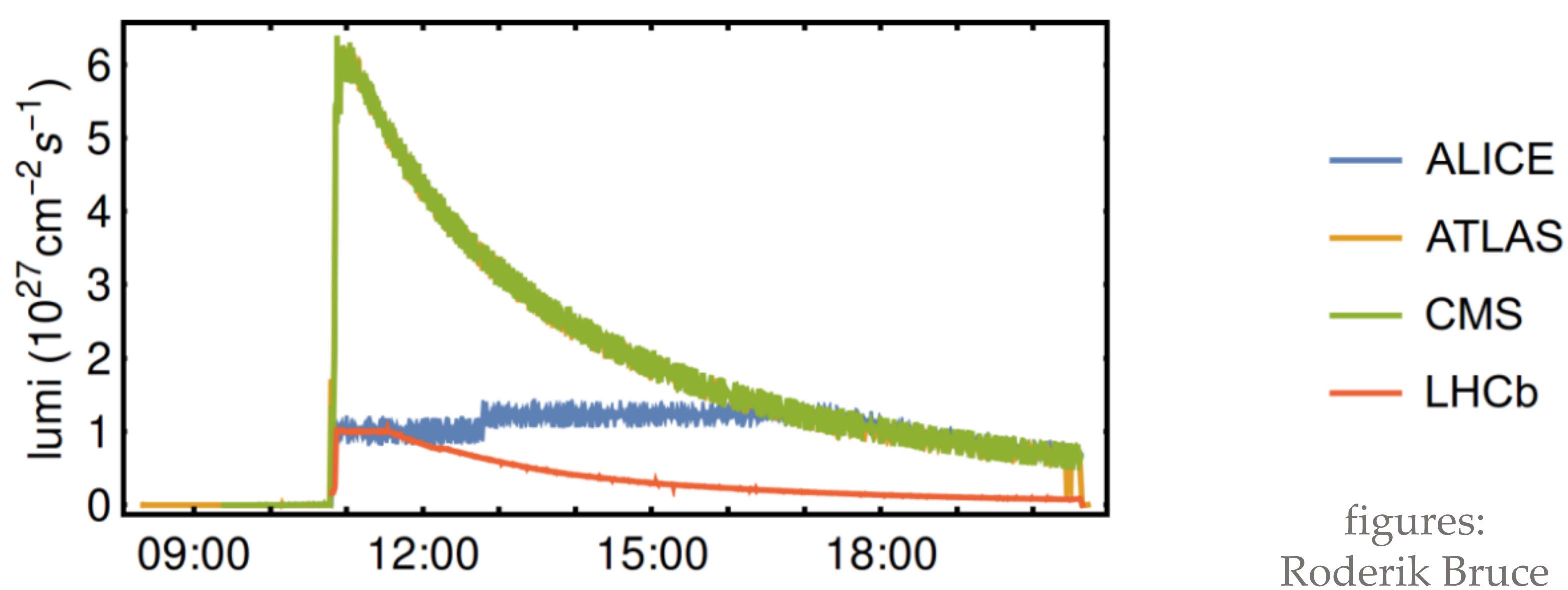
# Limited Beam Lifetime

- initial number of ions per bunch $N_b\left({}^A_Z\mathrm{N}\right) = N_b\left({}^{208}_{82}\mathrm{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$
- time evolution $\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0\tau_b}$ with beam lifetime $\tau_b \propto \frac{1}{\sigma_{\mathrm{tot}} n_{\mathrm{IP}} N_0}$
- integrated luminosity is maximised for refill at $t_{\mathrm{opt}} = \tau_b\sqrt{\theta_{\mathrm{ta}}}$

with $\theta_{\mathrm{ta}} = \frac{t_{\mathrm{ta}}}{\tau_b}$ for a given turnover time $t_{\mathrm{ta}}$

- maximal average luminosity $\mathscr{L}_{\mathrm{ave}}(t_{\mathrm{opt}}) = \frac{L_0}{\left(1+\sqrt{\theta_{\mathrm{ta}}}\right)^2}$

- **integrated luminosity depends on ion species**
- **parameter $p$ that characterises # ions/bunch and is not known for most ions!**




figures: Roderik Bruce

# Limited Beam Lifetime

| | pessimistic ($p = 1$) | | | | optimistic ($p = 1.9$) | | | |
|---|---|---|---|---|---|---|---|---|
| | $\mathscr{L}_0$ [$\mu bs^{-1}$] | $\tau_b$ [h] | $\mathscr{L}_{ave}$ [$\mu bs^{-1}$] | $N_{XX}/N_{pp}$ [1] | $\mathscr{L}_0$ [$\mu bs^{-1}$] | $\tau_b$ [h] | $\mathscr{L}_{ave}$ [$\mu bs^{-1}$] | $N_{XX}/N_{pp}$ [1] |
| $^{1}_{1}H$ | $21.0 \cdot 10^3$ | 75.0 | $15.0 \cdot 10^3$ | 1 | $21.0 \cdot 10^3$ | 75.0 | $15.0 \cdot 10^3$ | 1 |
| $^{16}_{8}O$ | 1.43 | 52.6 | 1.07 | 0.0082 | 94.3 | 6.48 | 45.5 | 0.349 |
| $^{40}_{18}Ar$ | 0.282 | 45.8 | 0.208 | 0.00889 | 4.33 | 11.7 | 2.46 | 0.105 |
| $^{40}_{20}Ca$ | 0.229 | 46.0 | 0.168 | 0.00811 | 2.90 | 12.9 | 1.69 | 0.0811 |
| $^{78}_{36}Kr$ | 0.0706 | 20.6 | 0.0454 | 0.00758 | 0.311 | 9.80 | 0.169 | 0.0282 |
| $^{84}_{36}Kr$ | 0.0706 | 19.2 | 0.0448 | 0.00797 | 0.311 | 9.15 | 0.166 | 0.0296 |
| $^{129}_{54}Xe$ | 0.0314 | 7.20 | 0.156 | 0.00637 | 0.0665 | 4.94 | 0.0294 | 0.0120 |
| $^{208}_{82}Pb$ | 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.

And use a model where HI collisions offer no other advantage.

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