SEARCH FOR LONG-LIVED PARTICLES WITH HEAVY ION COLLISIONS AT THE LHC

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Rencontre de Physique des Particules 2019

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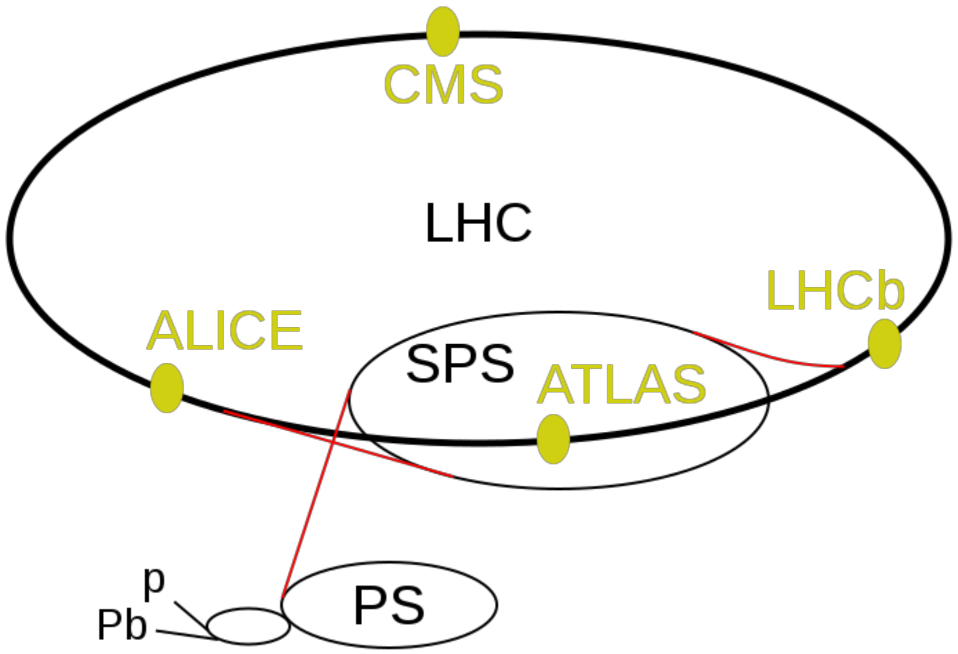
*Based on **arXiv:1810.09400 [hep-ph]** in collaboration with Marco Drewes, Andrea Giammanco, Jan Hajer and Olivier Mattelaer*

The Large Hadron Collider

Main goals:

- Unveil the origin of EWSB
- Search for New Physics
- Study Quark-gluon plasma (QGP)



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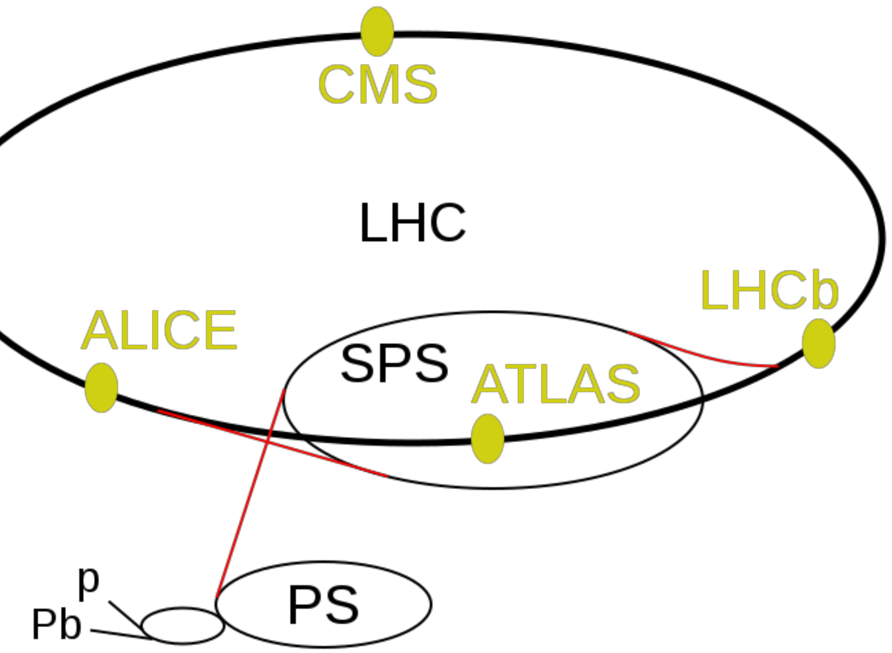
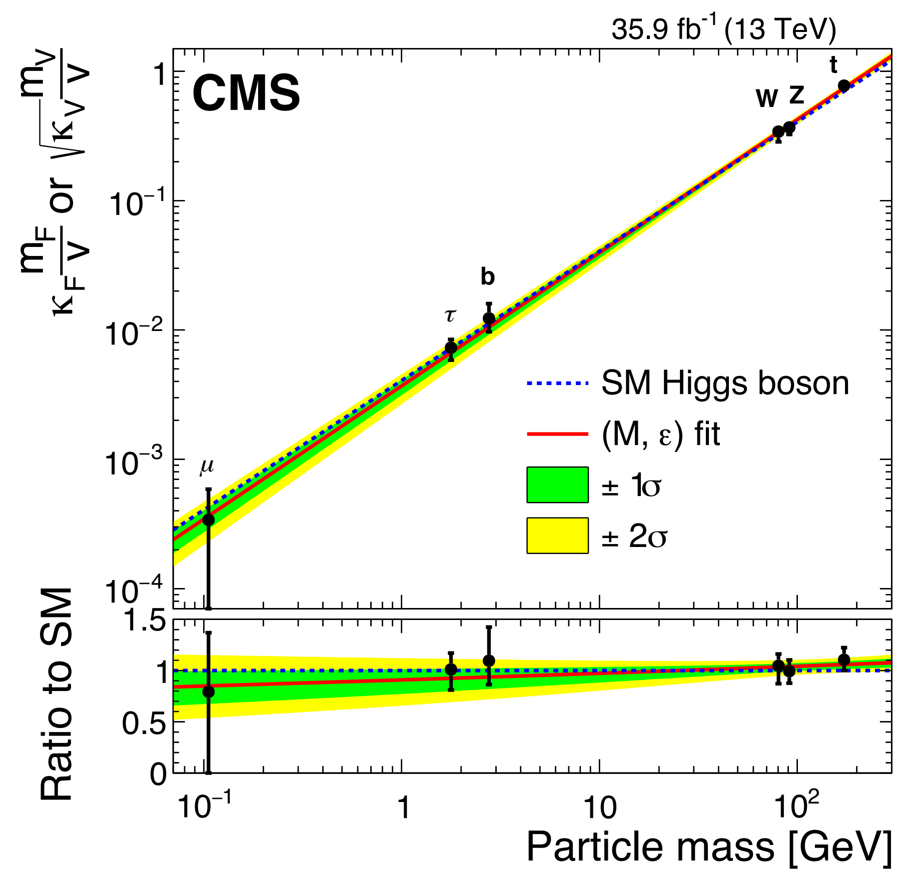


So far…

Discover of a scalar resonance compatible with the **Brout-Englert-Higgs mechanism**



CMS Collaboration, arXiv:1809.10733 [hep-ex]

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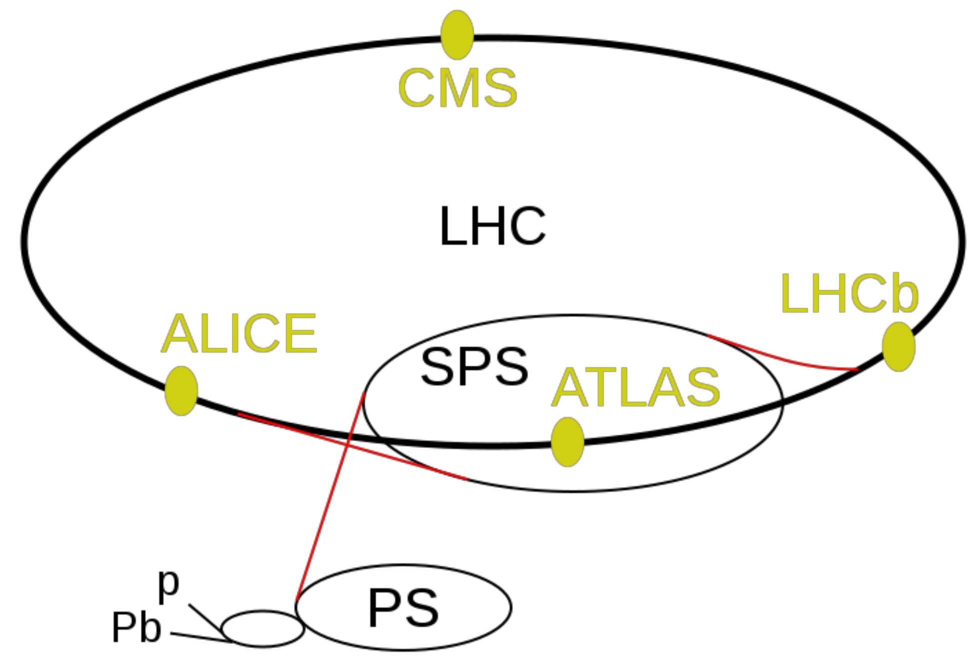
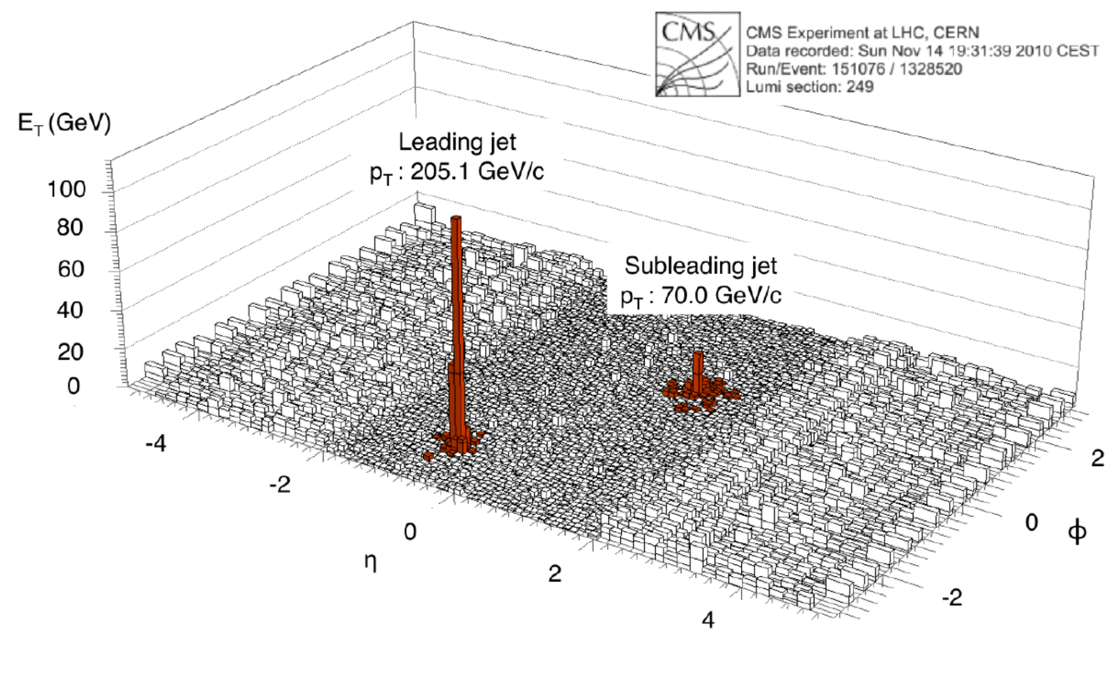
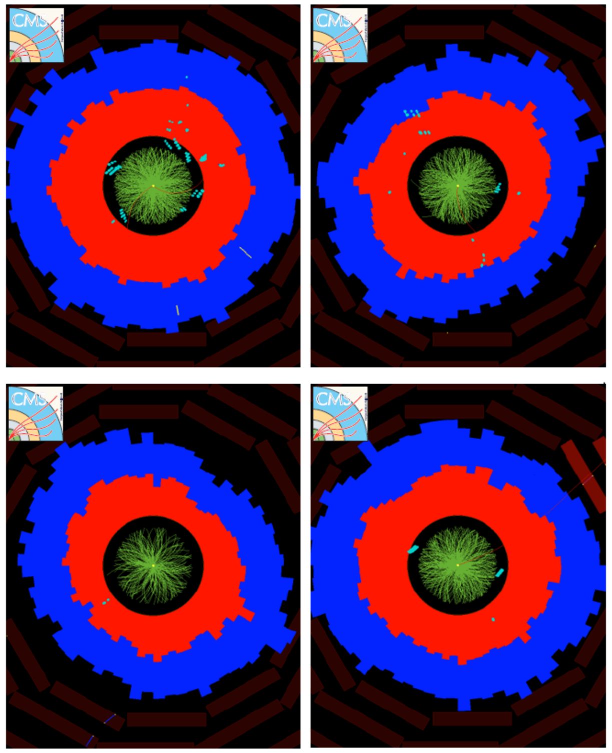


So far…

QGP dynamics observed in Heavy Ion collisions





W. Busza, K. Rajagopal and W. van der Schee, arXiv:1802.04801 [hep-ph]

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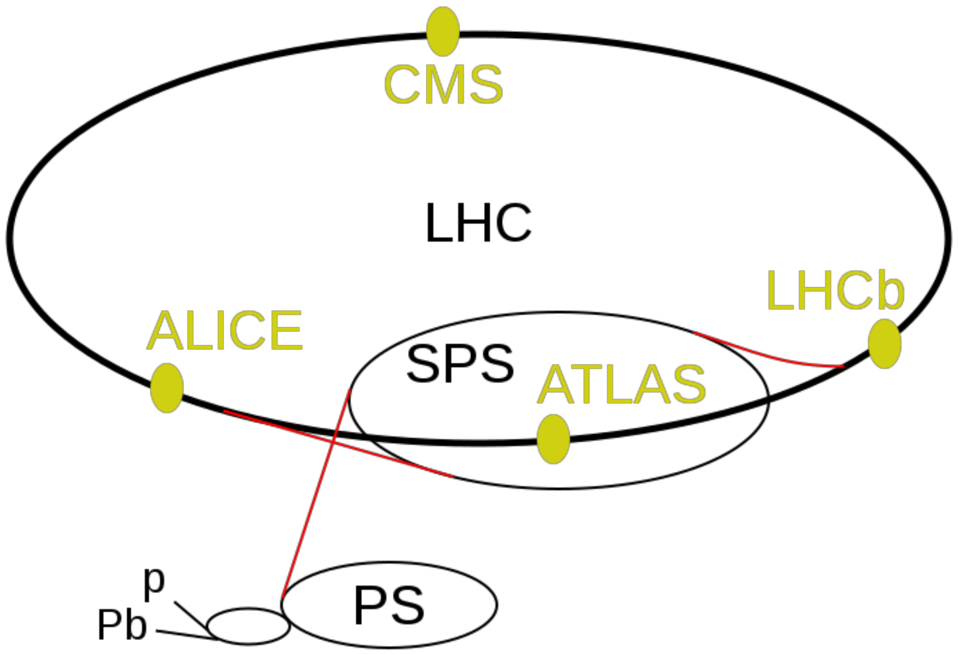


So far…

No New Physics observed!

But we expect it to exist

The quest for new physics

Several observations call for new physics beyond the Standard Model: neutrino masses and mixing, dark matter, baryogenesis…

Why new physics has not been observed at the LHC?

The reason could be a linear combination of:

The NP energy scale is too large → Need for more powerful colliders (*energy frontier*)

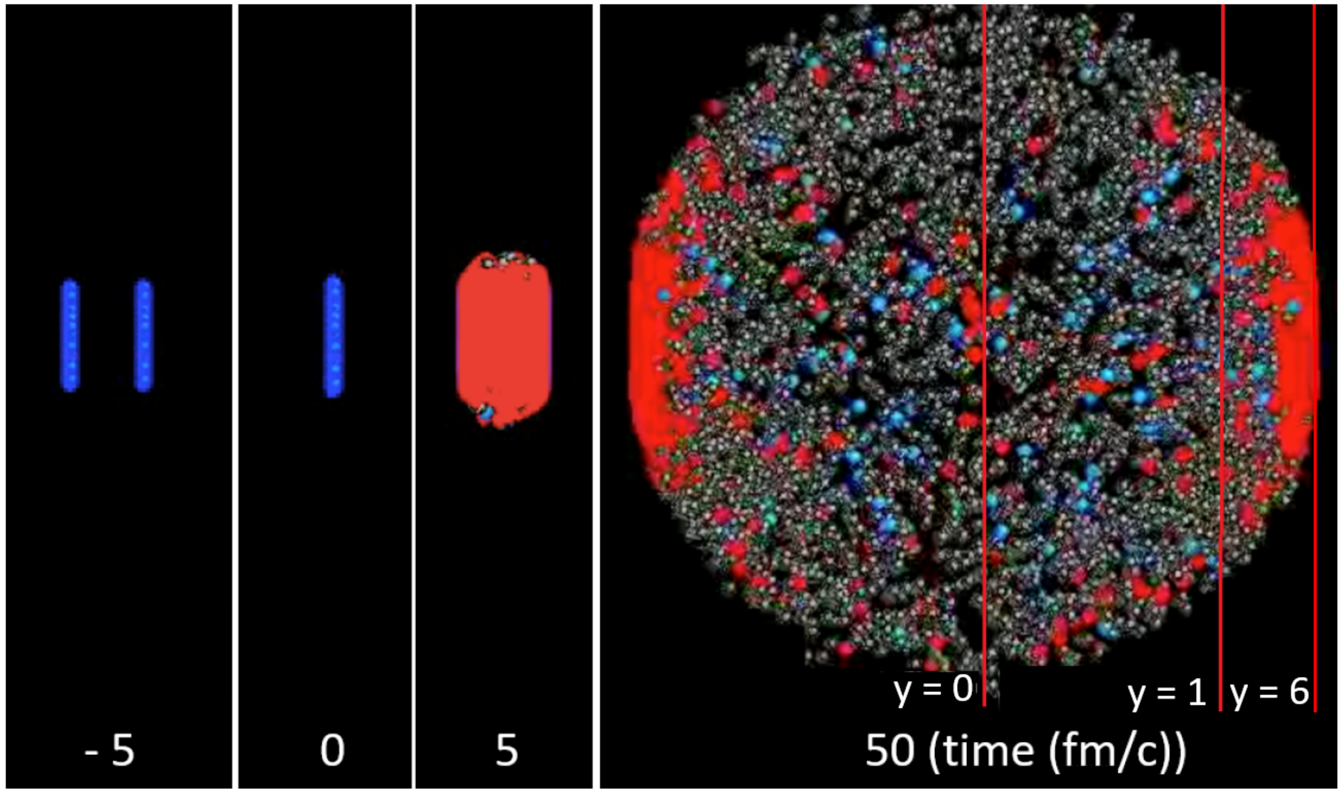
The NP is feebly coupled → Need for more collisions (*intensity frontier*)

e.g. low-scale seesaw, freeze-in DM, freeze-in leptogenesis…

Can we do more with existing machines?

Heavy ion collisions

Each nucleus ${}^{A}_{Z}N$ contains A nucleons



In *NN* collisions, number of parton level interactions enhanced by a factor A^2

For instance with ${}^{208}_{82}\mathrm{Pb}$ ▶ $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{\mathrm{pp}}} \propto A^2 \simeq 4.3 \times 10^4$

Features of Heavy Ions runs

Features of Heavy Ions runs

Smaller collision energy

The charge to mass ratio is smaller for heavy ions → **Smaller energy collision per nucleon**

$$\sqrt{s_{\mathrm{PbPb}}} = 5.52\ \mathrm{TeV}$$

$$\sqrt{s_{\mathrm{pp}}} = 14\ \mathrm{TeV}$$

Scaling factor

$$\frac{\sigma_{\mathrm{pp}}\,(14\ \mathrm{TeV})}{\sigma_{\mathrm{PbPb}}\,(5.52\ \mathrm{TeV})}$$

- Typically larger for gluon-initiated processes than for quark-antiquark ones
- Grows with the particle masses in the final state

Lower instantaneous luminosity

LHC can only collect a sizeably lower luminosity with heavy ions due to machine limitations

Int. luminosity	expected *pp*	expected PbPb
Run 2	100 fb^{-1}	1 nb^{-1}
HL LHC	3000 fb^{-1}	10 nb^{-1}

This is due to ultraperipheral electromagnetic interactions:

Bound-Free Pair-Production (BFPP): $\sigma_{\mathrm{BFPP}} \propto Z^7$

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^+$$

Electromagnetic Dissociation (EMD): $\sigma_{\mathrm{EMD}} \propto \frac{(A-Z)\,Z^3}{A^{2/3}}$

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}$$

For *PbPb* with E_b=7ZTeV

	BFPP		EMD			Hadronic
Symbole	$\sigma_{\mathrm{c,BFPP1}}$	$\sigma_{\mathrm{c,BFPP2}}$	$\sigma_{\mathrm{c,EMD1}}$	$\sigma_{\mathrm{c,EMD2}}$	$\sum \sigma_{\mathrm{c,EMD}}$	$\sigma_{\mathrm{c,hadron}}$
Cross-section [b]	281	0.006	96	29	226	8

M. Schaumann, CERN-THESIS-2015-195

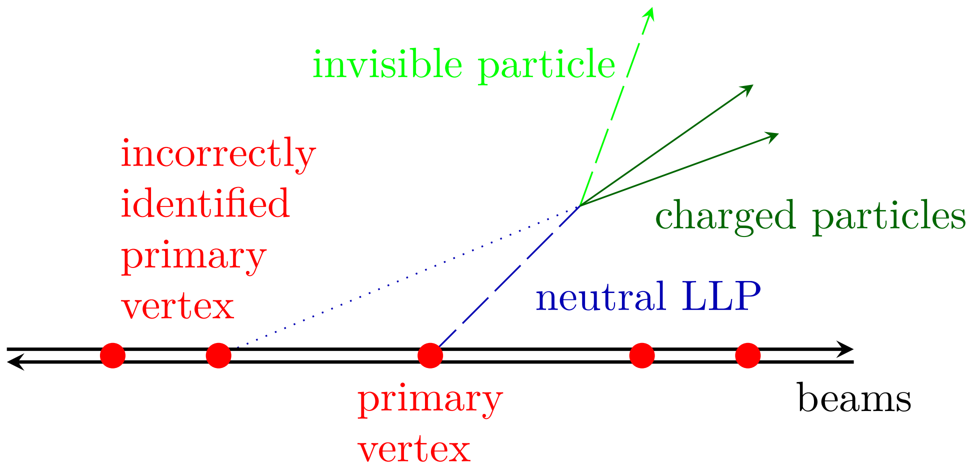
Cross section enhancement

In *NN* collisions, number of parton level interactions enhanced by a factor A^2

This partially compensates the loss in statistics due to a lower luminosity

Lower primary vertex mis-identification

There is no pile-up in heavy ion collisions!

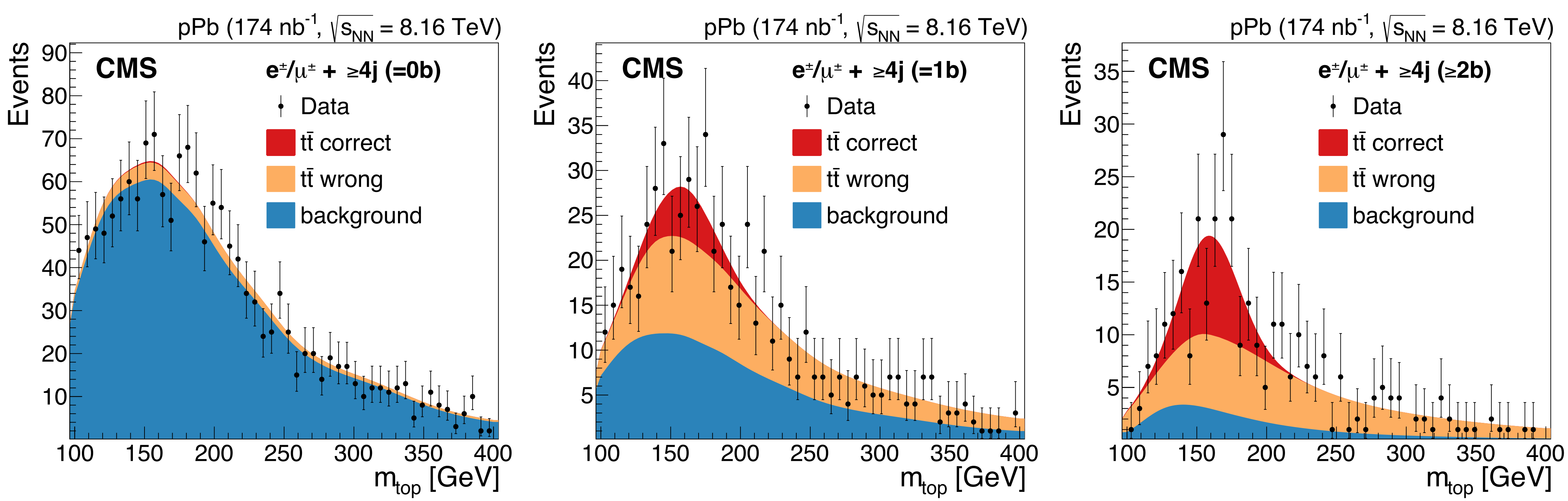


This allows to better identify primary vertices

Background reduction

For instance, misidentification rate of light-jets is **smaller in pPb than in pp** events (0.1 % vs 0.8%)

No *b*-tagged jets | 1 *b*-tagged jets | 2 *b*-tagged jets



CMS Collaboration, arXiv:1709.07411 [nucl-ex]

Lower instantaneous luminosity (!)

The lower instantaneous luminosity can enable to lower the trigger thresholds

Can test regions of parameter space that are difficult to be tested with protons

E.g. scenarios involving light mediators result in signatures with low transverse momentum p_T

Larger track multiplicity

Huge number of tracks from PbPb events, but same vertex

In ATLAS/CMS tracking acceptance

For central events at $\sqrt{s_{\mathrm{PbPb}}} = 5.52\ \mathrm{TeV}$

ALICE Collaboration, arXiv:1512.06104 [nucl-ex]

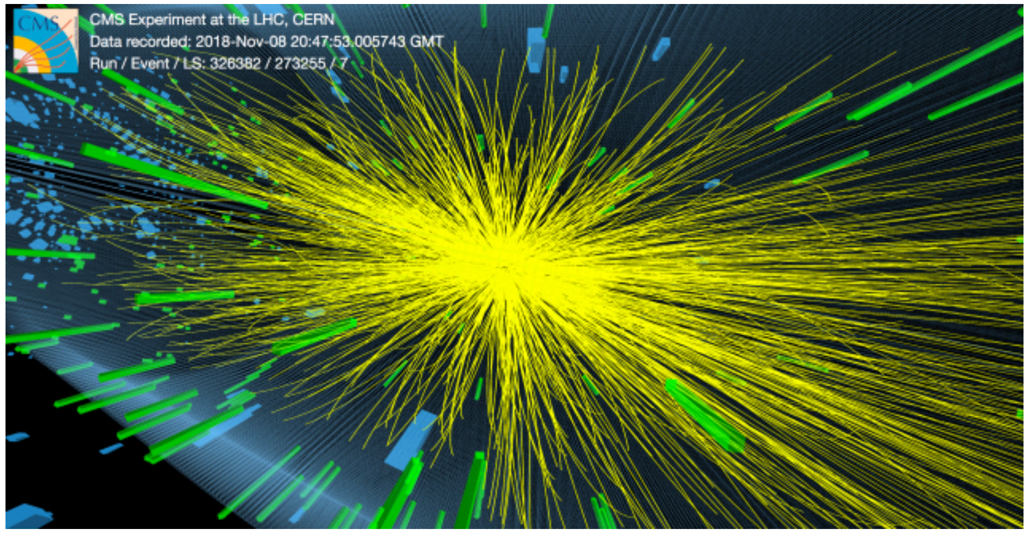
~ 10 000 charged tracks

In *pp* multiplicity mainly due to pile-up

CMS Collaboration, arXiv:1507.05915 [hep-ex]
ATLAS Collaboration, arXiv:1606.01133 [hep-ex]
ALICE Collaboration, arXiv:1509.08734 [nucl-ex]

~ 750 charged tracks for Run 3
~ 5 000 charged tracks at HL-LHC

G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, and L. Rossi, 10.5170/CERN-2015-005
G. Apollinari, O. Brüning, T. Nakamoto and L. Rossi, arXiv:1705.08830 [physics.acc-ph]



Not big difference at HL-LHC, and we expect vertex reconstruction to be affected more from pile-up than from track multiplicity
(cf. b-tagging performance in top searches with *pp* and *p*Pb)

Initial bunch intensity

The initial number of ions per bunch
***N_b* is a key parameter for luminosity**

Luminosity at one interaction point is proportional to N_b^2

We use the empirical expression

$$N_b\left({}^{A}_{Z}N\right) = N_b\left({}^{208}_{82}\mathrm{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$$

where
p = 1 **conservative** assumption
p = 1.9 **optimistic** assumption

J. Jowett, Workshop on the physics of HL-LHC, and perspectives at HE-LHC, (2018)

The XeXe run achieved *p* = 0.75 after only few hours of tuning ▶ This allows to be optimistic

Result for different ions

pp and PbPb are two extreme cases
Intermediate ions could be interesting

p = 1.9
t_a = 2.5 h

			Cross section						Luminosity			
	M [GeV]	$\sqrt{s_{NN}}$ [TeV]	σ_{EMD} [b]	σ_{BFPP} [b]	σ_{had} [b]	σ_{tot} [b]	σ_W [nb]	$A^2\sigma_W$ [μb]	L_0 [$1/\mu\text{b s}$]	τ_b [h]	L_{ave} [$1/\mu\text{b s}$]	N_{N}/N_p [1]
${}^{1}_{1}$H	0.931	14.0	0	0	0.0710	0.07	56.0	0.0560	21.0×10^3	75.0	15.0×10^3	1
${}^{16}_{8}$O	14.9	7.00	0.074	24×10^{-6}	1.41	1.48	28.0	7.17	94.3	6.16	35.2	0.30
${}^{40}_{18}$Ar	37.3	6.30	1.2	0.0069	2.6	3.81	25.2	40.3	4.33	11.2	2.00	0.0957
${}^{40}_{20}$Ca	37.3	7.00	1.6	0.014	2.6	4.21	28.0	44.8	2.90	12.4	1.38	0.0735
${}^{78}_{36}$Kr	72.7	6.46	12	0.88	4.06	16.9	25.8	157	0.311	9.40	0.135	0.0253
${}^{84}_{36}$Kr	78.2	6.00	13	0.88	4.26	18.1	24.0	169	0.311	8.77	0.132	0.0266
${}^{129}_{54}$Xe	120	5.86	52	15	5.67	72.67	23.4	390	0.0665	4.73	0.0223	0.0103
${}^{208}_{82}$Pb	194	5.52	220	280	7.8	508	22.1	955	0.0136	1.50	2.59×10^{-3}	0.0029

↑ W boson production cross section

↑ # events w.r.t. proton runs

BSM search with central heavy ions collisions

In central collisions a QGP is created

Very busy environment, but extending to few fm only

→ Difficult to probe prompt decays, but ideal for displaced vertices

Benchmark model: SM + *n* right-handed neutrinos (a.k.a. HNL)

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \left(\frac{\mathrm{i}}{2} \overline{\nu_{Ri}} \partial\!\!\!/ \nu_{Ri} - F_{ai} \overline{\ell_{La}} \varepsilon \phi^* \nu_{Ri} - \frac{1}{2} \overline{\nu^c_{Ri}} (M_M)_{ij} \nu_{Rj} + \mathrm{h.c.} \right)$$

After EWSB with <ϕ> = *v*, $m_\nu = -v^2 F M_M^{-1} F^T$

n = 2 can already account for ν data and BAU, n = 3 for DM as well

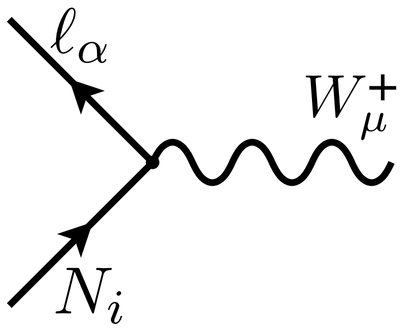
Particle spectrum

3 light neutrinos (sub-eV): mass differences and mixing fixed by oscillation data

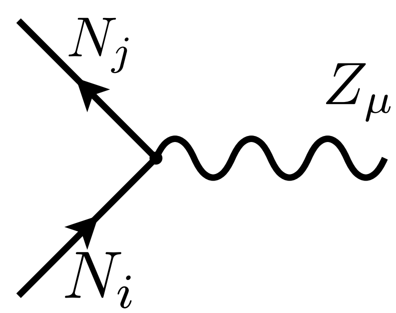
n HNLs: masses ~ M_M and coupling with SM ~ v F/M_M

HNL phenomenology

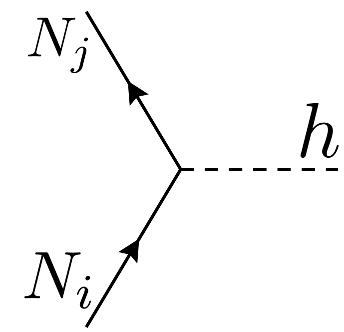
$$C_{ij} \equiv \sum_{\alpha=e,\mu,\tau} \mathcal{U}^*_{\alpha i}\,\mathcal{U}_{\alpha j}$$



$$\propto i\,\frac{g}{\sqrt{2}}\mathcal{U}_{\alpha i}$$

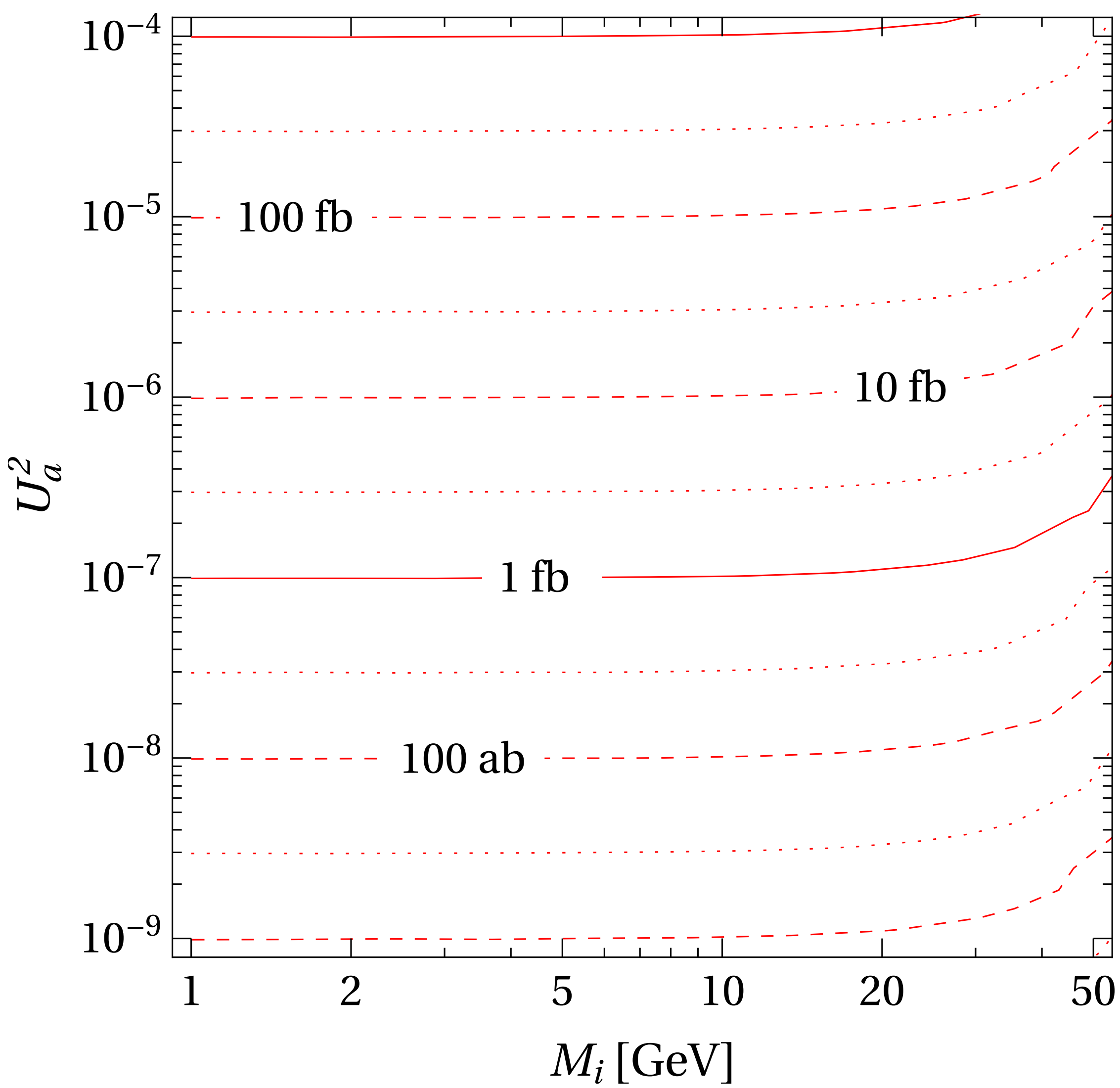


$$\propto i\,\frac{g}{4c_w}C_{ji}$$

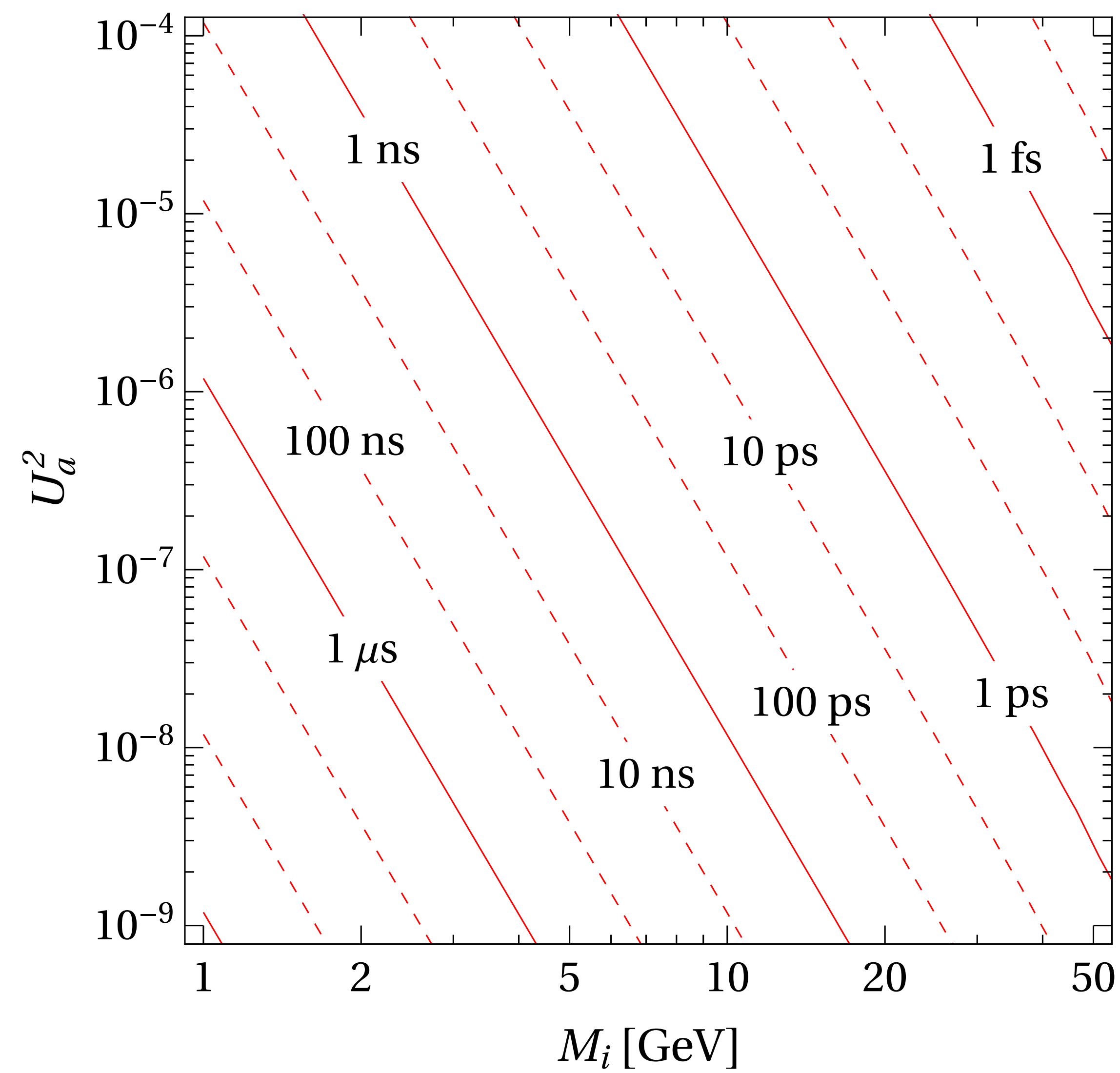


$$\propto i\,\frac{g}{4}\frac{m_j}{M_W}C_{ji}$$

Production cross section



Lifetime



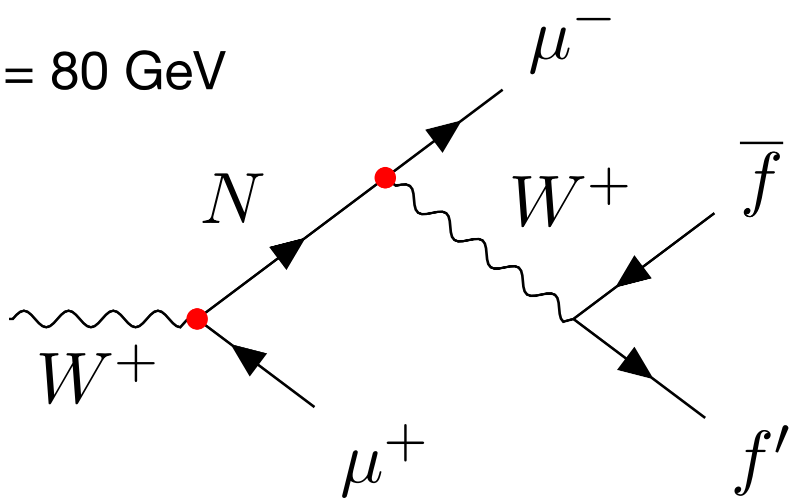
σ ∝ U_a^2 for M ≲ 50 GeV

GeV masses result in observable **macroscopic displacement**

HNL production/decay

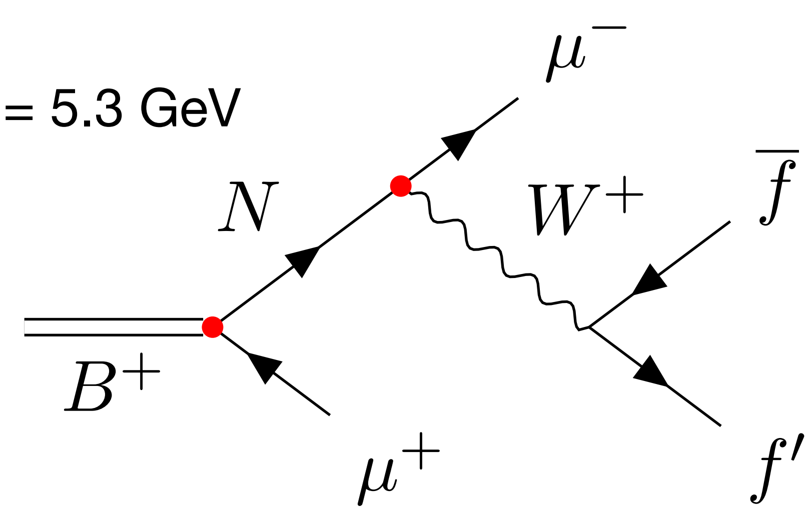
We consider two channels: W and B mediated HNL production

M_W = 80 GeV



- Fully simulated using `MadGraph5_aMC@NLO`
- trigger on first μ with **p_T > 25 GeV**
- search for displaced μ with d > 5 mm

M_B = 5.3 GeV



- Cannot be fully simulated in `MadGraph5_aMC@NLO`
- Use analytic estimate validated against W simulation

$$N_d = \frac{L_{\text{int}}\sigma_B^{[A,Z]}}{9}\left[1-\left(\frac{M_i}{m_B}\right)^2\right]^2 U_\mu^2\left(e^{-l_0\lambda}-e^{-l_1\lambda}\right) f_{\text{cut}}$$

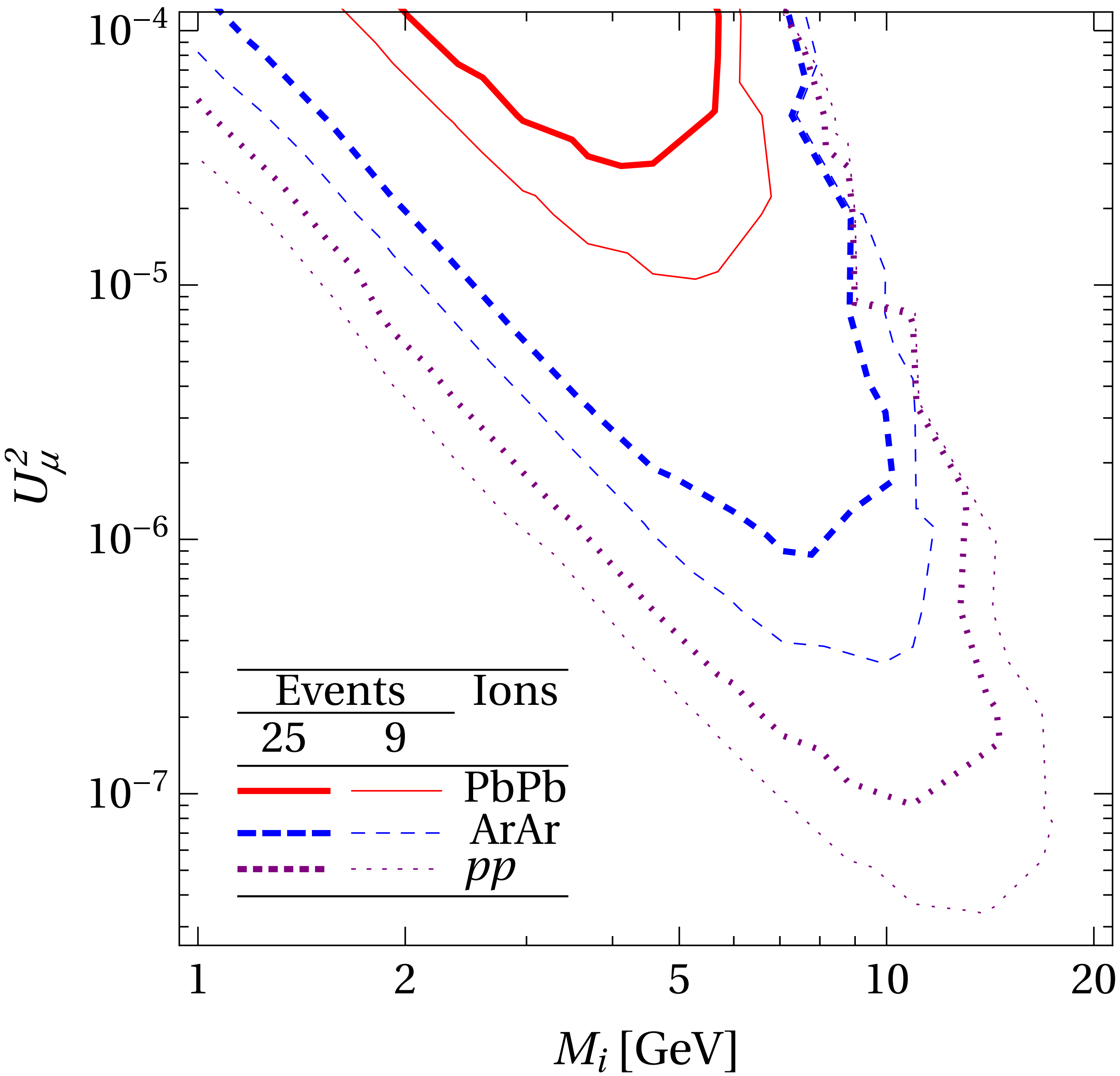
- trigger on first μ with **p_T > 3 GeV for HI collisions**, realistic online trigger for pp collisions
- search for displaced μ with d > 5 mm

Results

Same running time

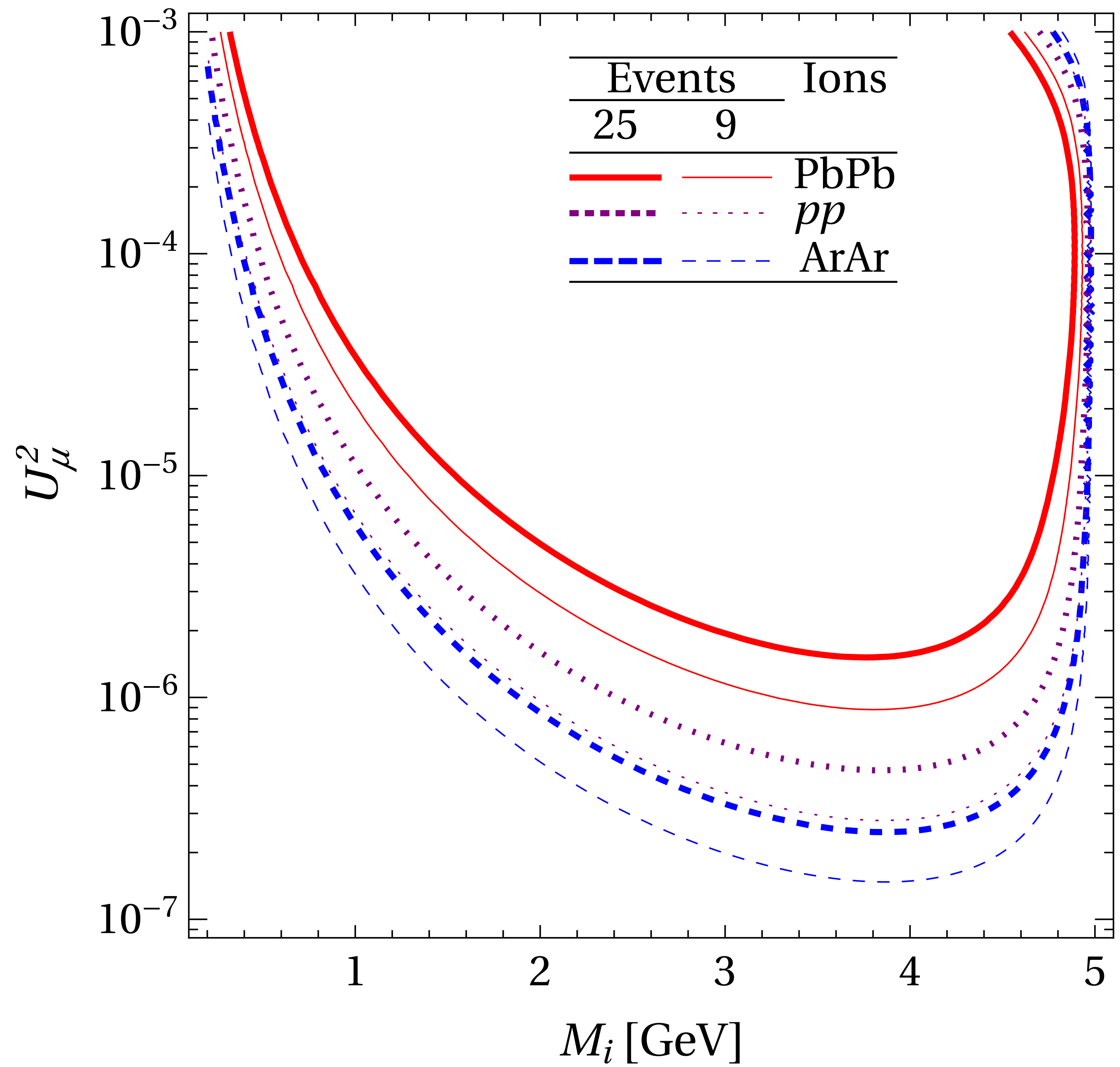
$$L_{\text{int}}(pp) = 5.79 \times 10^4 \text{ pb}^{-1}$$
$$L_{\text{int}}(\text{ArAr}) = 7.72 \text{ pb}^{-1}$$
$$L_{\text{int}}(\text{PbPb}) = 10^{-2} \text{ pb}^{-1}$$

W-production (simulation)



- Event rate **not competitive**
- **Complementary** test of BSM

B-production (estimate)



- Gain from low p_T **overcompensates** smaller luminosity
- **Intermediate** mass **ions** more competitive than *pp* and PbPb

Conclusion

Heavy ion collisions allow to search for **hidden new physics**

Intermediate ions can be very interesting for searches of new physics

Lower trigger requirements could be the key advantage of heavy ion collisions over proton collisions

Better primary vertex identification is also an advantage (not exploited here)

Searches for **displaced new physics** circumvent the noisy inner tracker

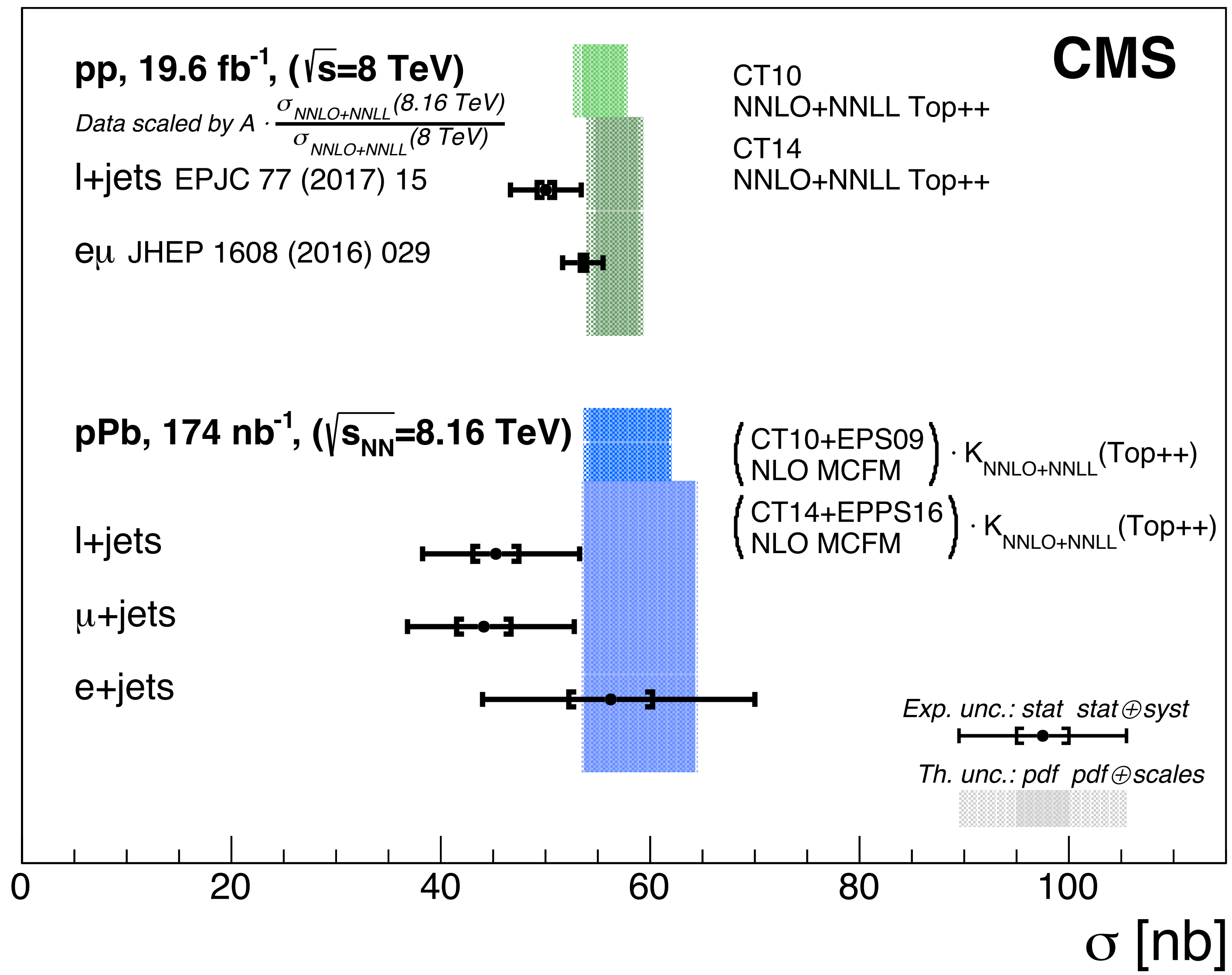
HNL are a **simple example** of this idea, but other models are just as well testable

Backup

Example: SM tests with Heavy Ions

$t\bar{t}$ cross section measurement in *pp* and *p*Pb collisions

CMS Collaboration, arXiv:1709.07411 [nucl-ex]



$^{208}_{82}\mathrm{Pb}$

174 nb^{-1} collected in *p*Pb collisions

corresponds to 174 x A_{Pb} nb^{-1} ≃ 36 pb^{-1}

Example: BSM tests with Heavy Ions

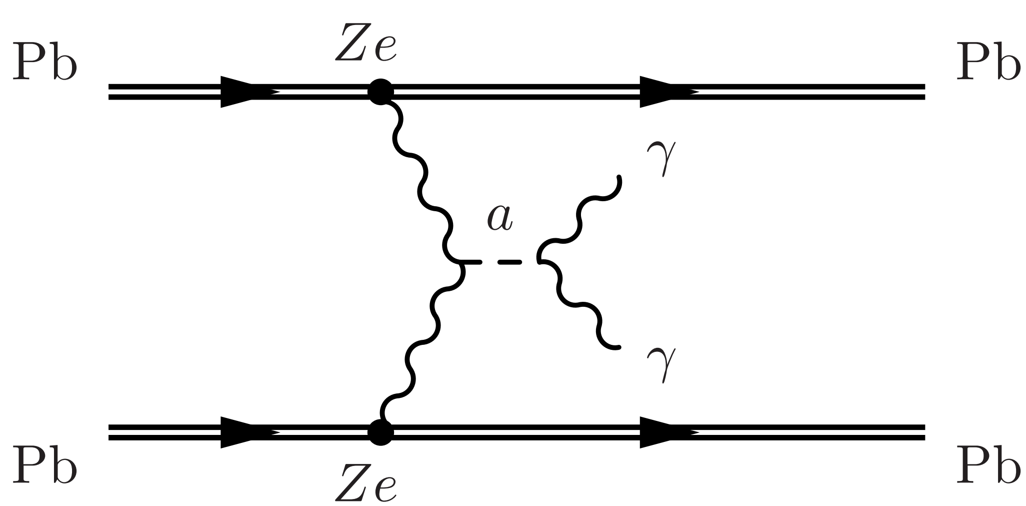
Testing axion-like particles with ultra-peripheral heavy-ion collisions

S. Knapen, T. Lin, H. K. Lou and T. Melia, arXiv:1607.06083 [hep-ph]

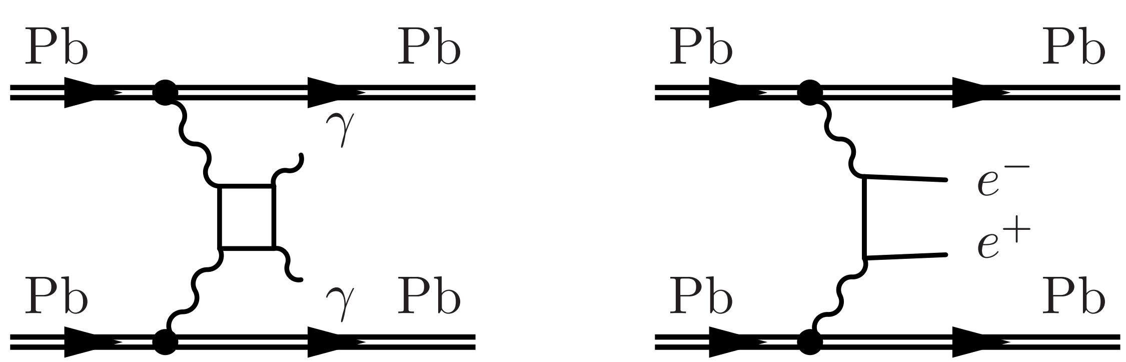
$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$

The photon-photon luminosity is enhanced by Z^4 w.r.t. proton collisions

Signal



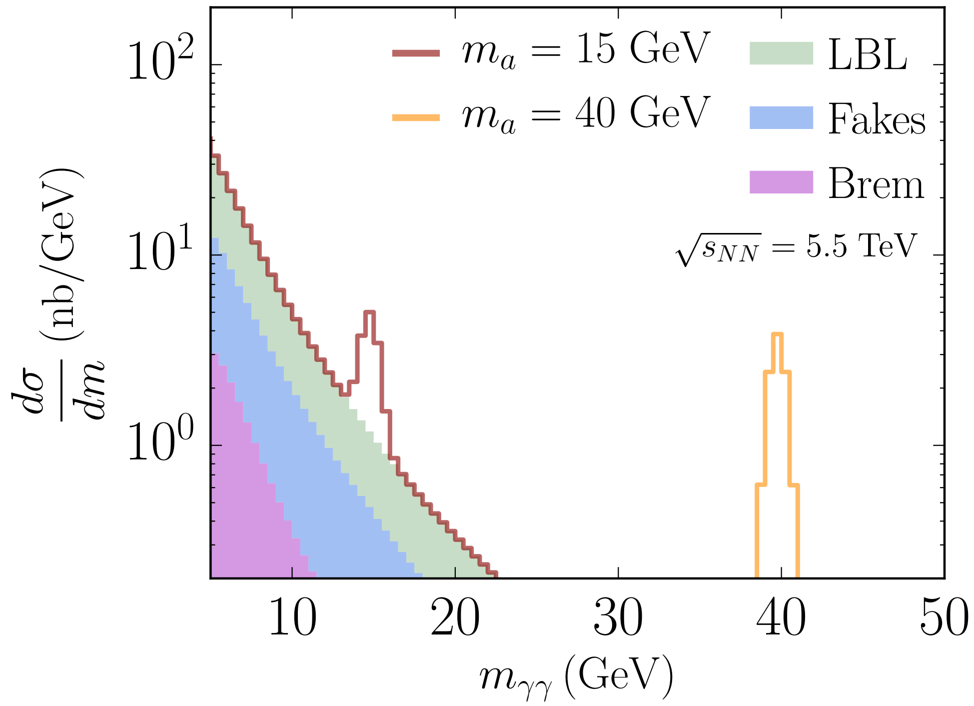
Background



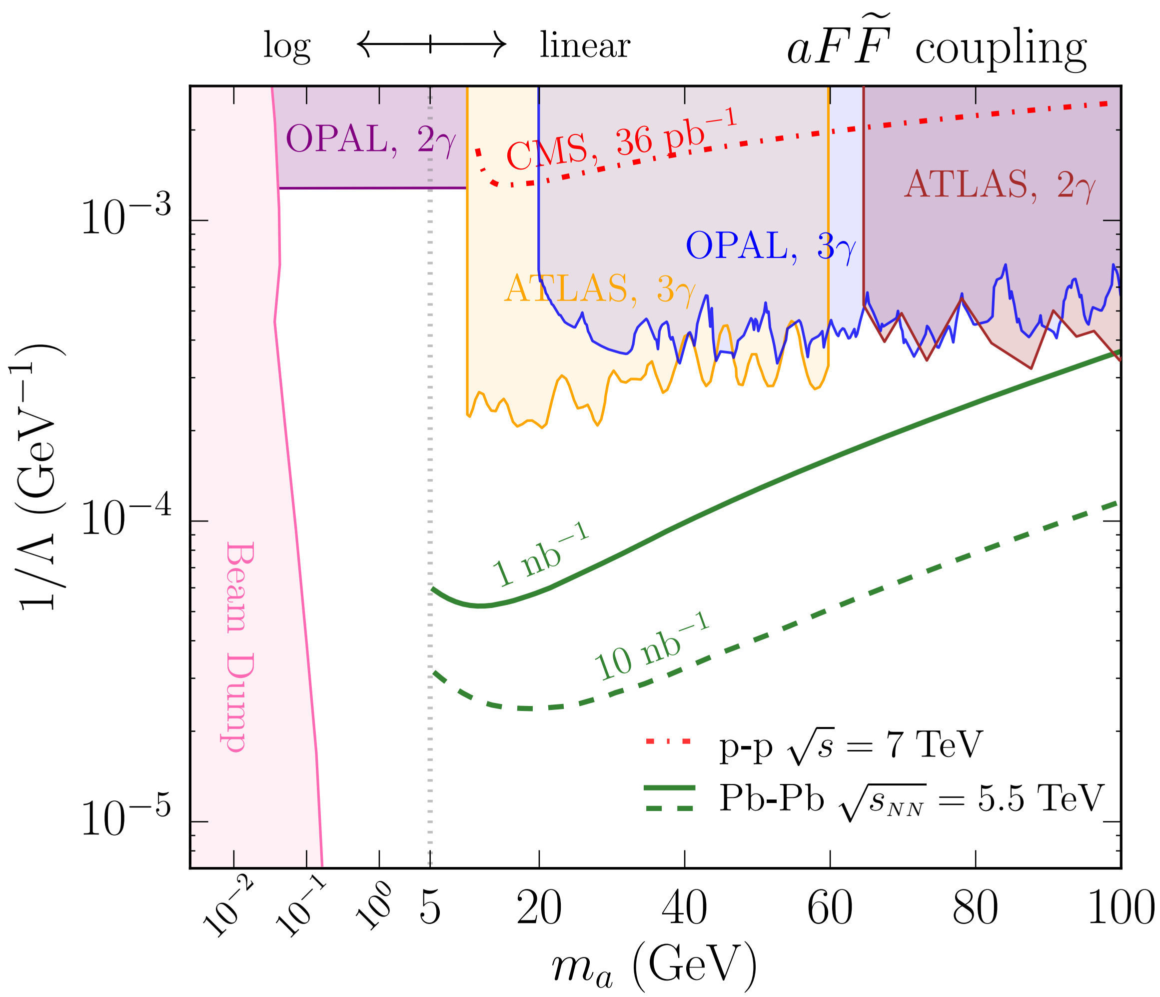
Nuclei do not fragment in the process

Axion-like particles with Heavy Ion collisions

S. Knapen, T. Lin, H. K. Lou and T. Melia, arXiv:1607.06083 [hep-ph]



Signal and background simulation



Expected sensitivity

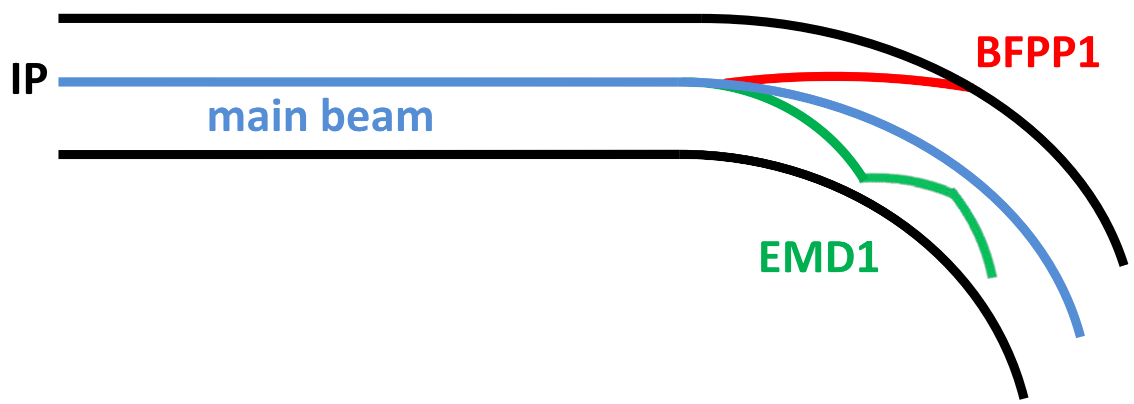
1 nb^{-1}: current PbPb run

10 nb^{-1}: HL PbPb run

PbPb searches can provide stronger limits w.r.t. *pp* ones

Impact of electromagnetic processes

Two problems arise



Creation of secondary beams with wrong charge to mass ratio

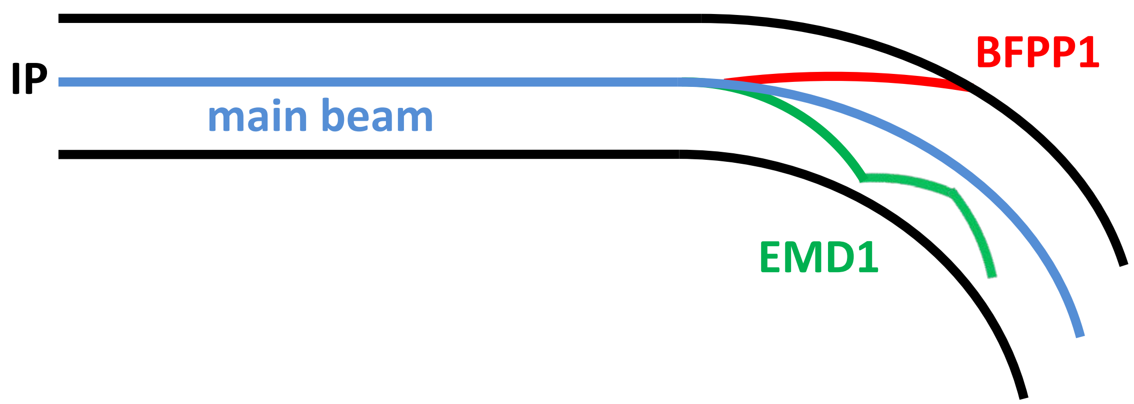
▼

Risk of quenching magnets!

M a c h i n e

Impact of electromagnetic processes

Two problems arise



Creation of secondary beams with wrong charge to mass ratio

▼

Risk of quenching magnets!

Machine

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0 \tau_b}$$

$$\tau_b = \frac{n_b}{\sigma_{\mathrm{tot}} n_{\mathrm{IP}}} \frac{N_0}{L_0}$$

- N_b: number of ions per bunch
- N_0: initial value for N_b
- n_b: number of bunches per beam
- n_{IP}: number of interaction points
- L_0: initial value for luminosity

Larger value of σ_{tot}

▼

Faster beam decay

Physics

M. Benedikt, D. Schulte and F. Zimmermann, Phys. Rev. ST Accel. Beams 18 (2015) 101002

Luminosity estimation

From $\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0 \tau_b}$ ▶ $N_b(t) = \frac{N_0}{1+\theta_t}$ with $\theta_t = \frac{t}{\tau_b}$

The luminosity at one interaction point is $L = k\ N_b^2$

where k is a parameter depending on the other beam properties (revolution frequency, number of bunches, emittance, width)

The integrated luminosity is thus $\Sigma(t) = L_0 \tau_b \frac{\theta_t}{1+\theta_t}$

Turnaround time t_a: *average time between two physics runs*

Average luminosity $L_{\mathrm{ave}}(t) = \frac{\Sigma(t)}{t + t_{\mathrm{ta}}}$ maximised for $t_{\mathrm{opt}} = \tau_b \sqrt{\theta_{\mathrm{ta}}}$

$$L_{\mathrm{ave}}(t_{\mathrm{opt}}) = \frac{L_0}{\left(1+\sqrt{\theta_{\mathrm{ta}}}\right)^2}$$