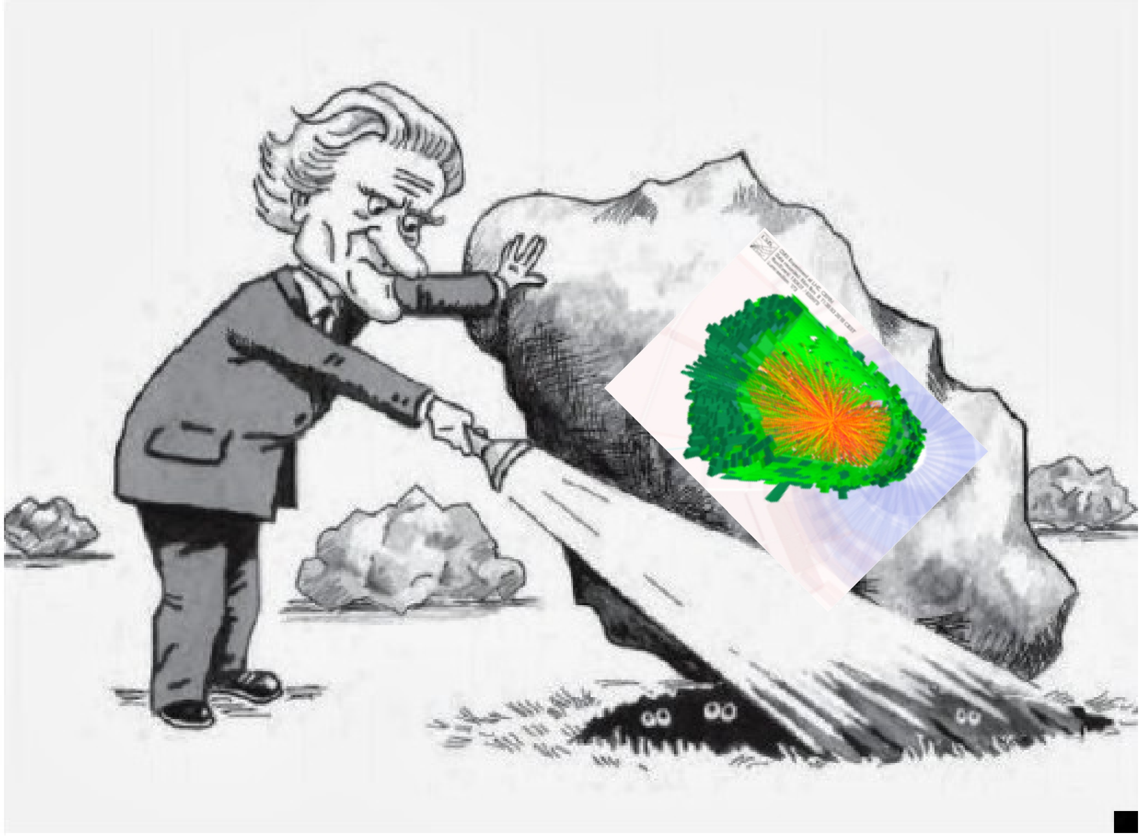
Heavy Ions and Hidden Sectors

5th workshop of the LHC LLP Community



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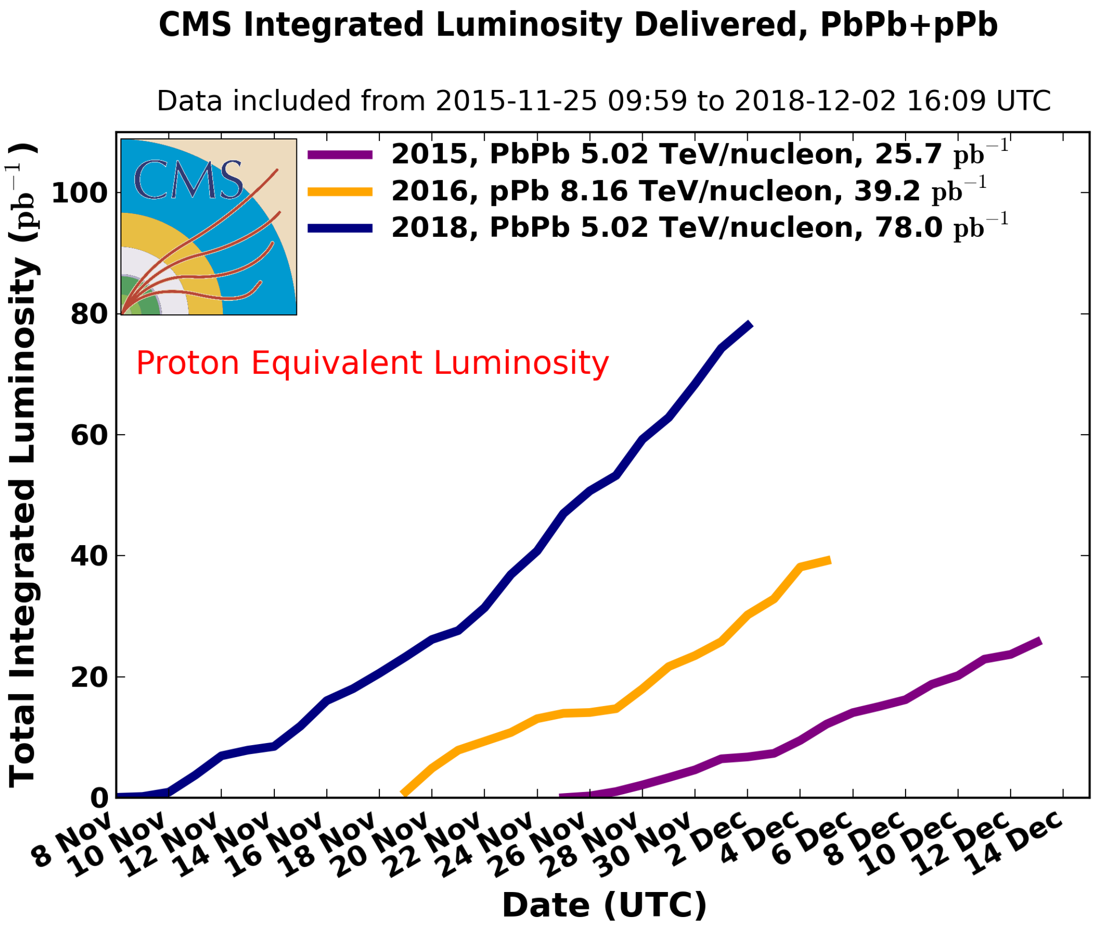
@ UCLouvain, Belgium

Intro: HI @ LHC



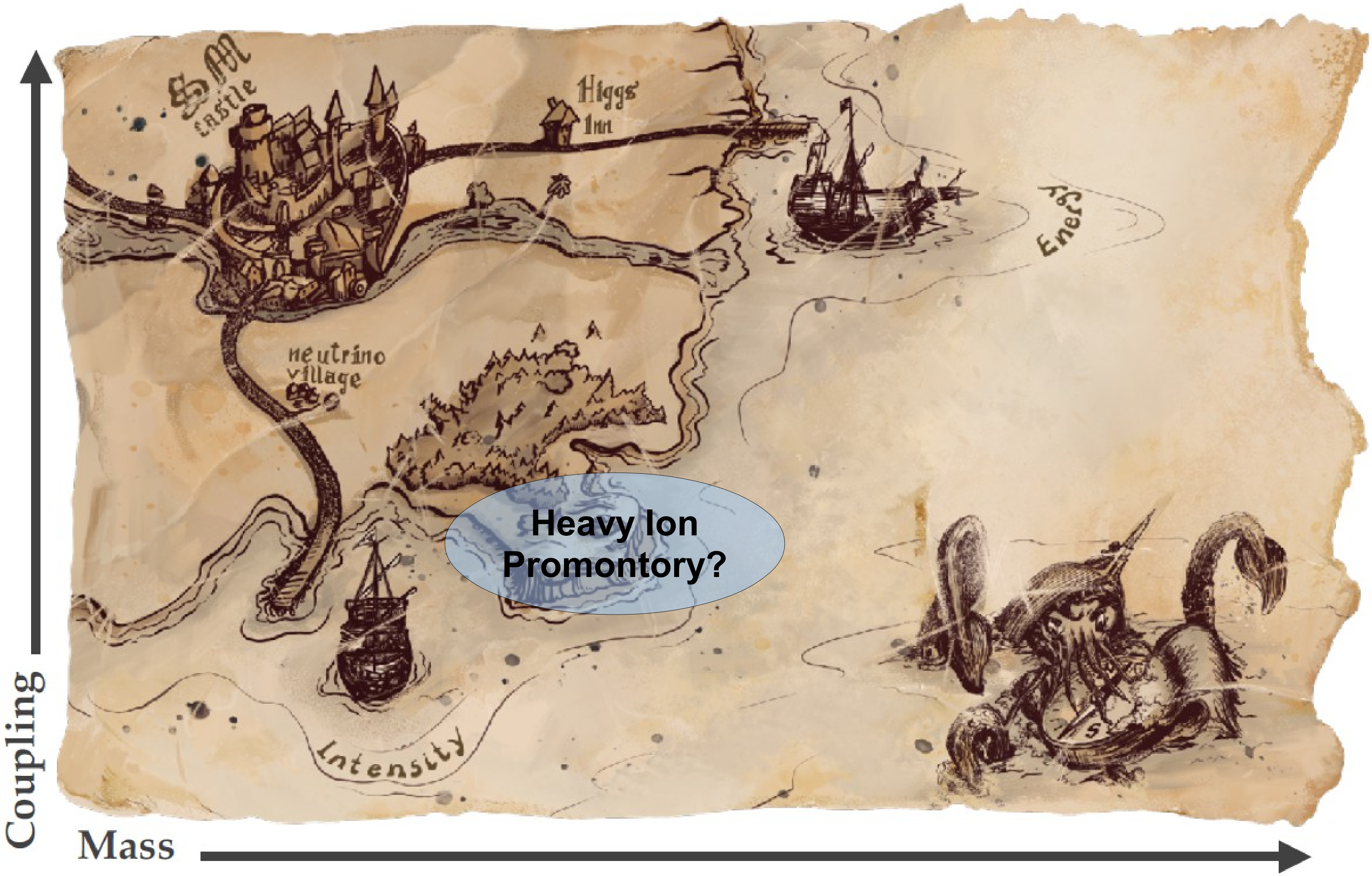
- Typically 1 month per year, mostly **pPb** and **PbPb**
- (2017: also a pilot XeXe run; Run 3: OO, pO, ArAr being discussed in HI community)
- Luminosities are really small (for reasons that I will discuss later): 1.8 *n*b^{-1} in 2018
- √s is smaller (~Z/A)
- But hard scattering is enhanced by O(A^2) wrt pp, modulo nuclear corrections

Outline and references

i. Few examples of existing or potential hidden sector searches in HI runs @ LHC
   - From our workshop "Heavy Ions and Hidden Sectors", 4-5 Dec. 2018 (link), putting together BSM, Heavy Ion and LHC accelerator experts
   - And from its write-up: arXiv:1812.07688 [hep-ph]
   - Also submitted as input to the update of the European Particle Physics Strategy (link)

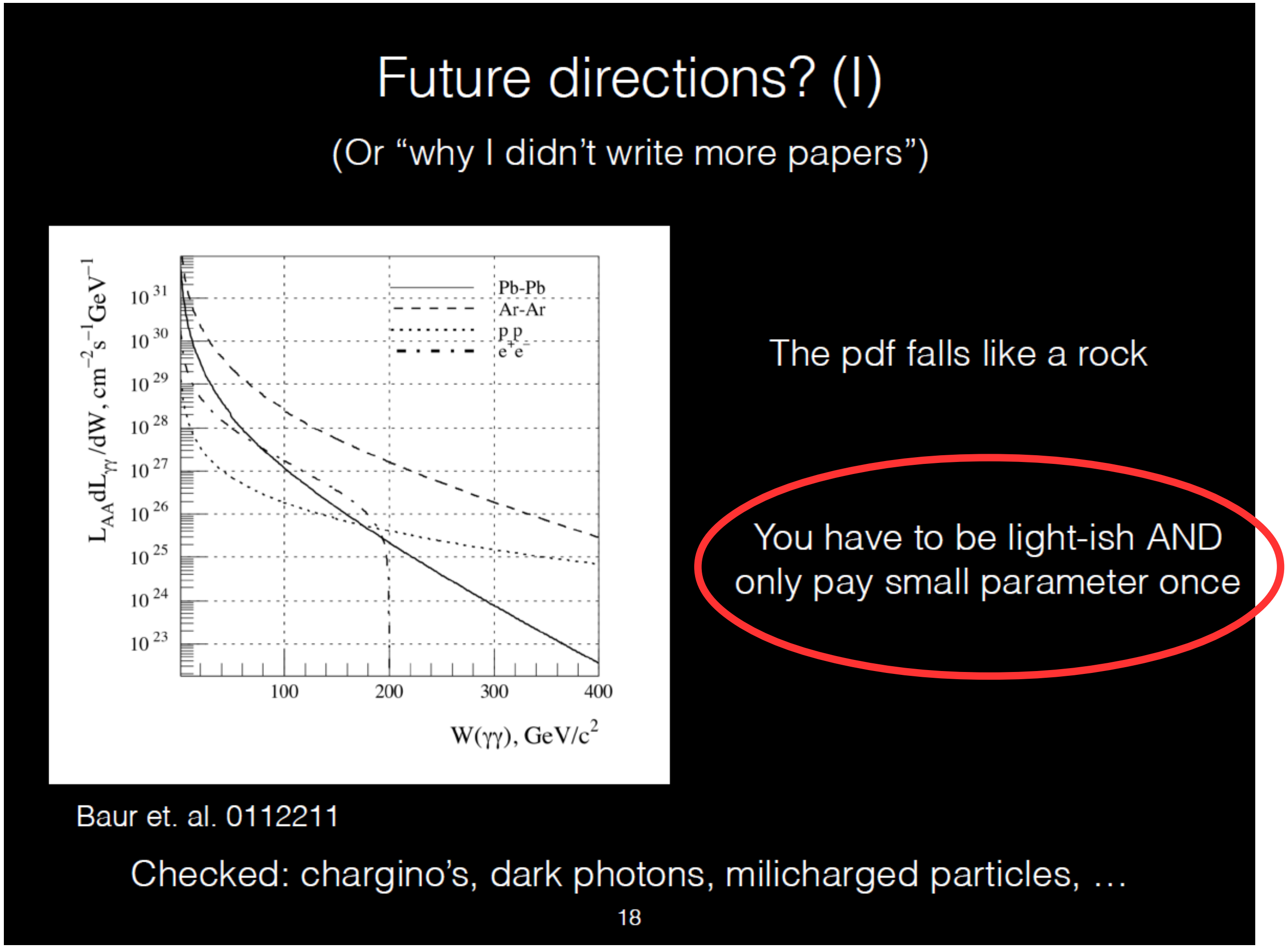
ii. Our study, fleshed out for a specific model (HNL), and what we learned from that
   - From arXiv:1810.09400 [hep-ph] (original proposal)
   - Expanded into: arXiv:1905.09828 [hep-ph]

WHERE IS THE NEW PHYSICS HIDING?



When is it interesting to use Heavy Ions for new physics?

Slide from
Simon Knapen



Future directions? (I)

(Or "why I didn't write more papers")

The pdf falls like a rock

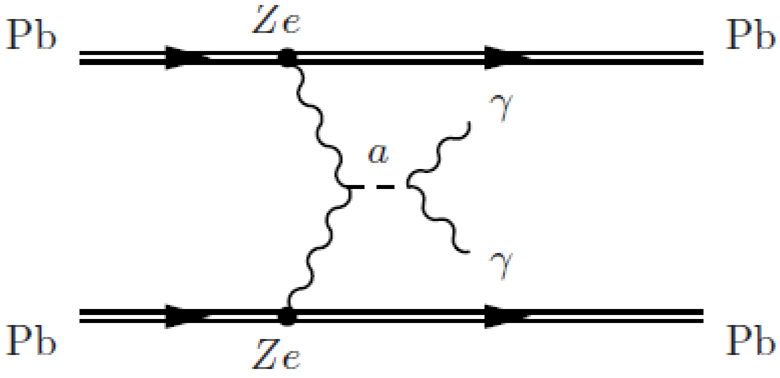
You have to be light-ish AND only pay small parameter once

Baur et. al. 0112211

Checked: chargino's, dark photons, milicharged particles, …

Example #1: ALP

Ultraperipheral collisions: photons are emitted coherently, projectiles stay unbroken (very clean signature, almost empty detector)



Key point: signal scales as Z^4; given Z=82, PbPb runs are competitive with pp

Proposed in:

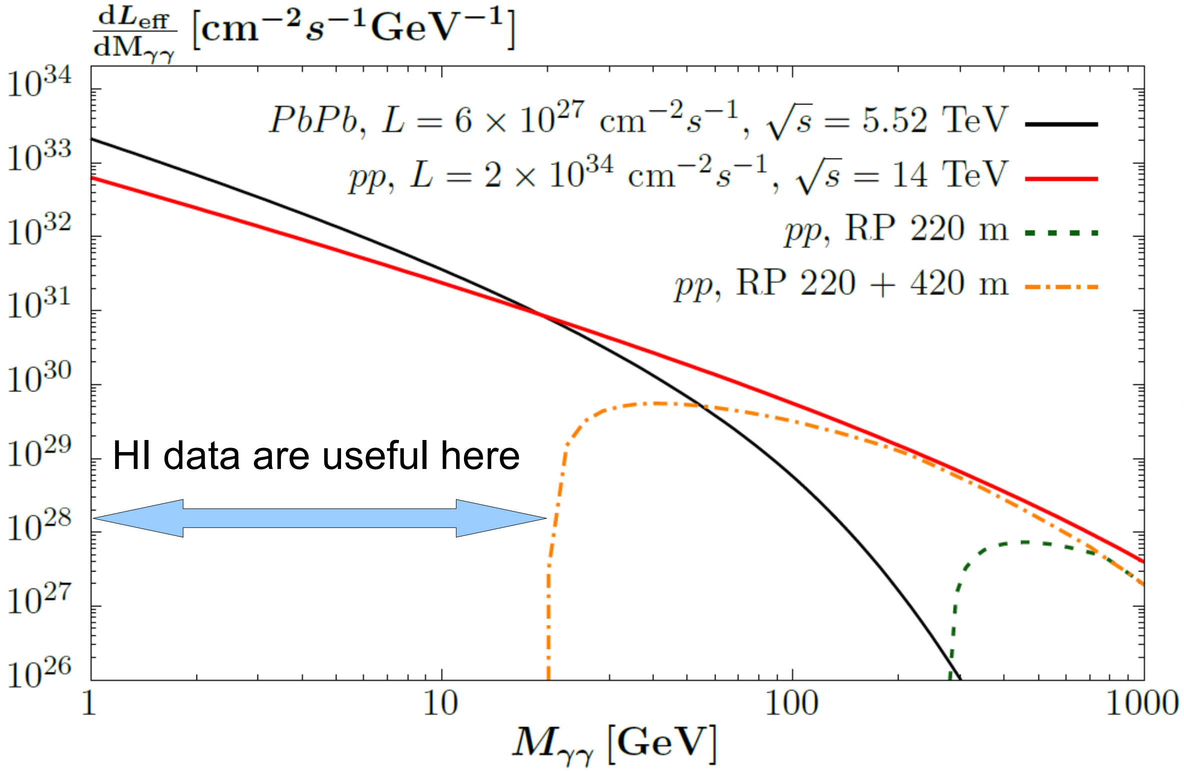
- Knapen, Lin, Lou, Melia, Phys.Rev.Lett. 118 (2017) 171801

Actually made in:

- CMS coll., arXiv:1810.04602 [hep-ex]

No long-lived ALP searches in HI, yet, but same arguments hold

General consideration for $\gamma\gamma$-initiated BSM



HI data are useful here

Plot by David d'Enterria for our community report

Limits on ALP from PbPb 2015 data

CMS coll., arXiv:1810.04602 [hep-ex]

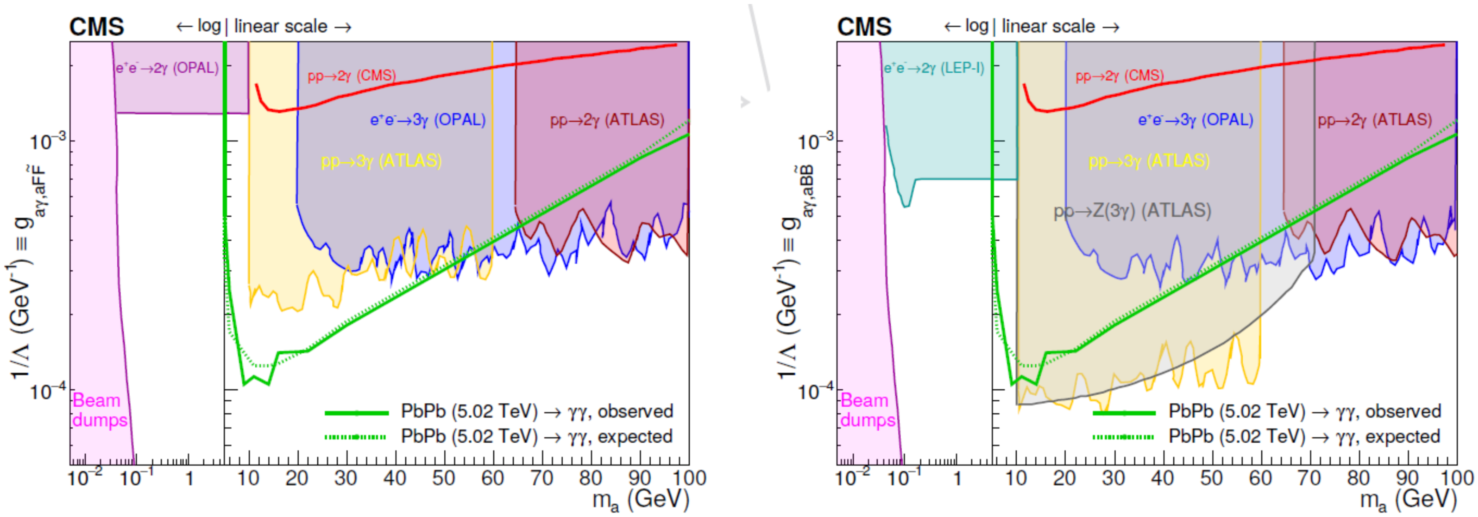


Figure 7: Exclusion limits at 95% CL in the ALP-photon coupling $g_{a\gamma}$ versus ALP mass m_a plane, for the operators $\frac{1}{4\Lambda}aF\tilde{F}$ (left, assuming ALP coupling to photons only) and $\frac{1}{4\Lambda\cos^2\theta_W}aB\tilde{B}$ (right, including also the hypercharge coupling, thus processes involving the Z boson) derived in Refs. [30, 55] from measurements at beam dumps [59], in e^+e^- collisions at LEP-I [55] and LEP-II [56], and in pp collisions at the LHC [13, 57, 58], and compared to the present PbPb limits.

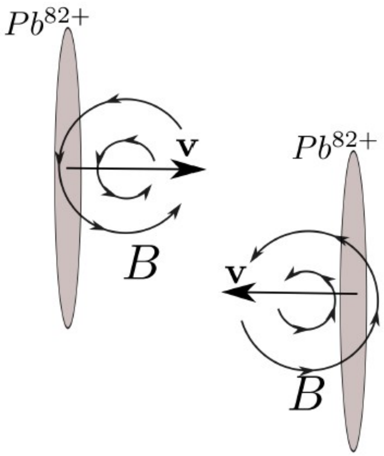
pp data:
CMS: 7 TeV
ATLAS: 8 TeV

Take-home messages:

- PbPb data @ 5.02 TeV (2015) are competitive with pp Run-1 data at 7 and 8 TeV up to large m_a values
- These data cover a blind spot at low m_a values

Example #2: Magnetic Monopoles

Magnetic fields in heavy-ion collisions are the strongest known in the universe, $O(10\text{GeV}^2) = O(10^{16}\text{T})$ at LHC energies.



Slides from
Oliver Gould

1. If **composite** magnetic monopoles exist, how can they be created?

   ~~pp collisions~~, ~~e^+e^- collisions~~ . . .

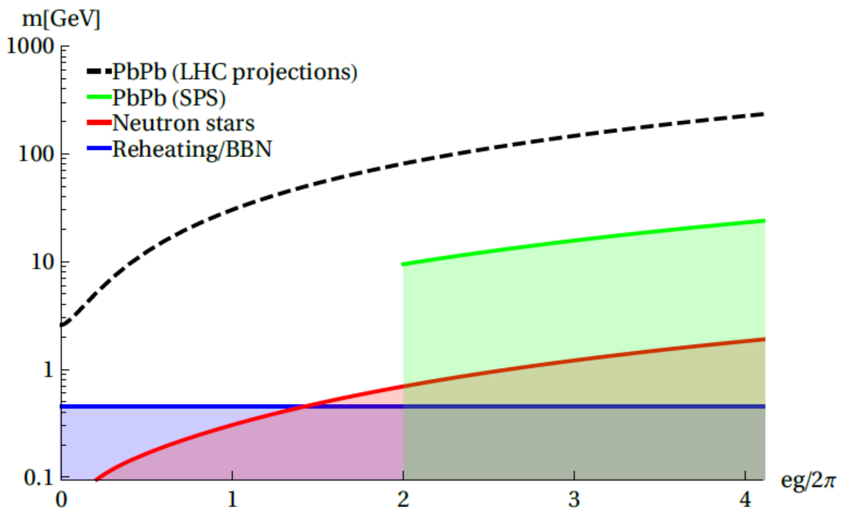
   $PbPb$ collisions ✓, $AuAu$ collisions ✓, . . .

2. If **elementary** magnetic monopoles exist, how can they be created?

   pp collisions? e^+e^- collisions? . . .

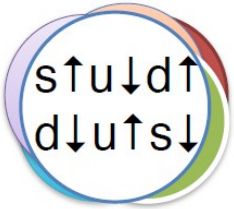
   $PbPb$ collisions ✓, $AuAu$ collisions ✓, . . .

Even more than in previous example, composite MM are a case where very large photon fluxes are a key advantage over pp



Plot by Oliver Gould for our community report

Example #3: Sexaquarks



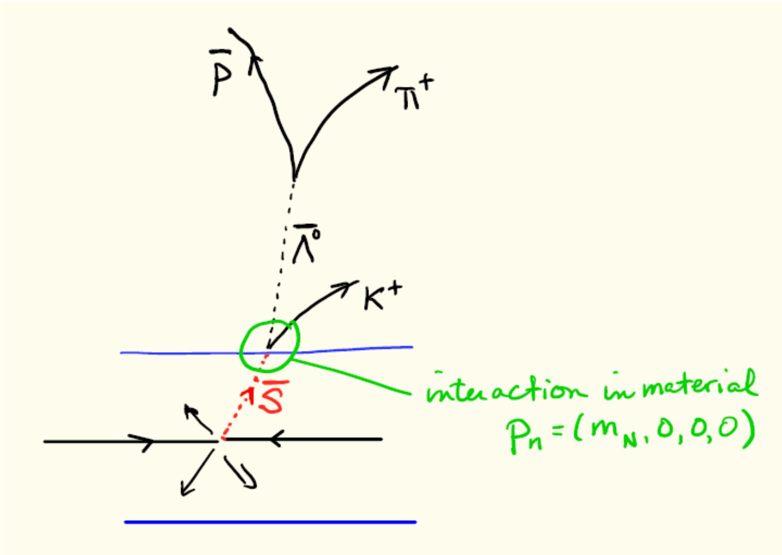
S

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
m ~ 1.7-2 GeV

Crucial fact:
S does not couple to pions => much smaller than usual hadrons => hard to produce with hadrons

Prediction: $\Omega_{DM} / \Omega_b = 4.5 \pm 1$
determined by *stat mech* , *quark masses* & *temp* of *QGP-hadronization transition*
(Ω_{DM} / Ω_b observed = 5.3 ± 0.1)

Slides from
Glennys Farrar



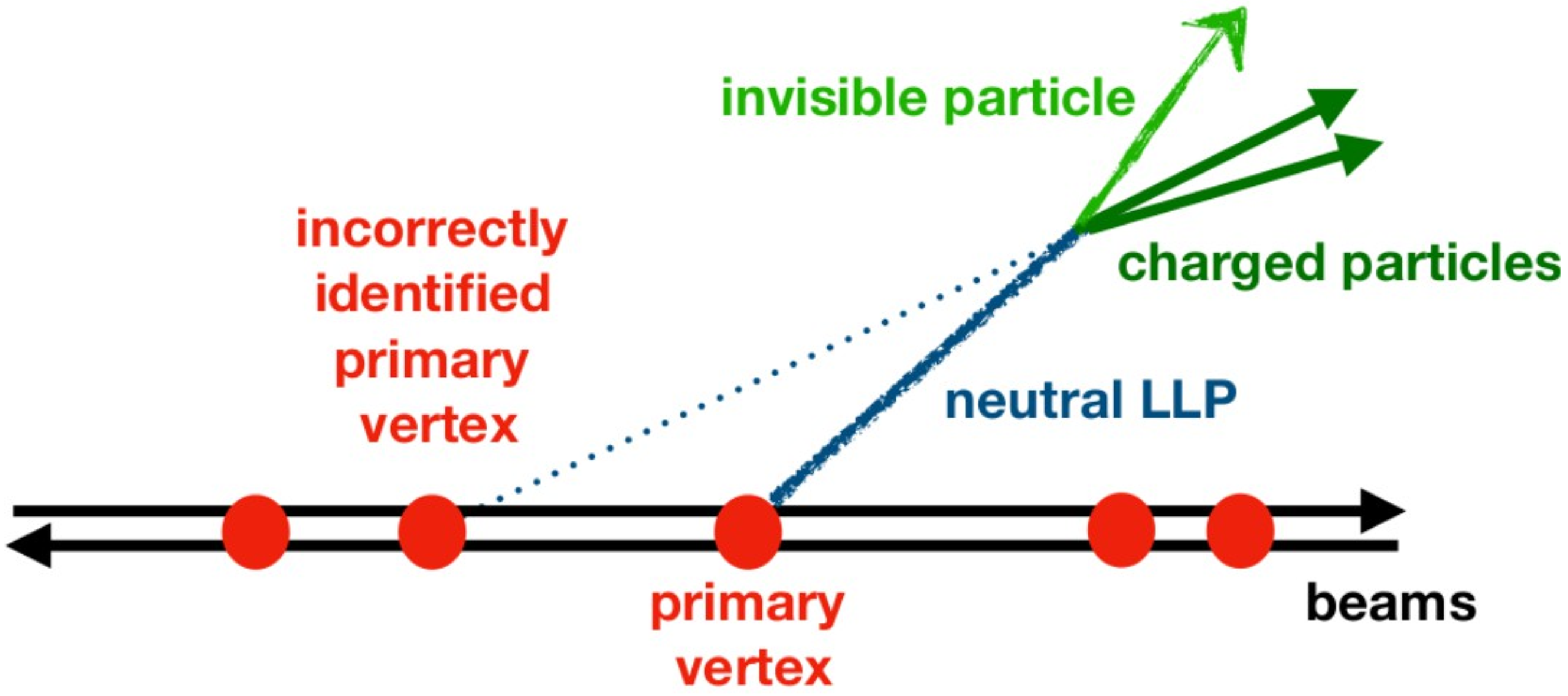
Nothing to do with $\gamma\gamma$ this time; enhancement from the dense hadronic environment (the same mechanism that would make S a viable DM candidate)

LHCb and ALICE are able to distinguish π, K, p down to very low momentum

Example #4: our study

- References:
  - M. Drewes, AG, J. Hajer, M. Lucente, O. Mattelaer, *"A Heavy Metal Path to New Physics"*, arXiv:1810.09400
  - M. Drewes, AG, J. Hajer, M. Lucente, *"Long Lived Particle Searches in Heavy Ion Collisions at the LHC"*, arXiv:1905.09828 [hep-ph]
- Can we exploit plain A^2 enhancement? (no Z^4, no QGP)
- Caveat: toy study with many approximations
- We started from some key facts:
  - No pileup in HI runs; this will stay true also in future runs
    - While in pp @ HL-LHC there will be <PU> ~ 200
    - Track multiplicity will be comparable in pp and HI runs
    - Whatever upgrade or algorithm will recover performances for HL-LHC wrt Run-2, will also work for HI wrt pp
  - Much milder trigger thresholds in HI than in pp

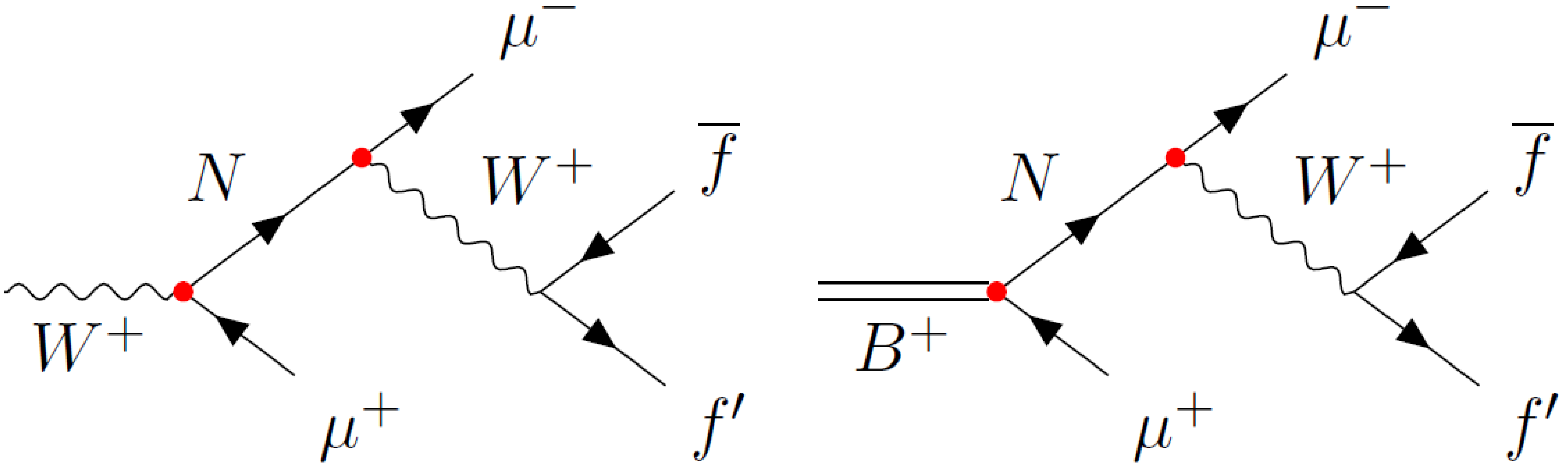
Long Lived Particles and PU



This kind of nuisance does not exist in HI runs, where there is no PU and therefore we always know with extreme precision where all particles are coming from.

(Note: in our simple study we do *not* exploit this advantage)

Representative model

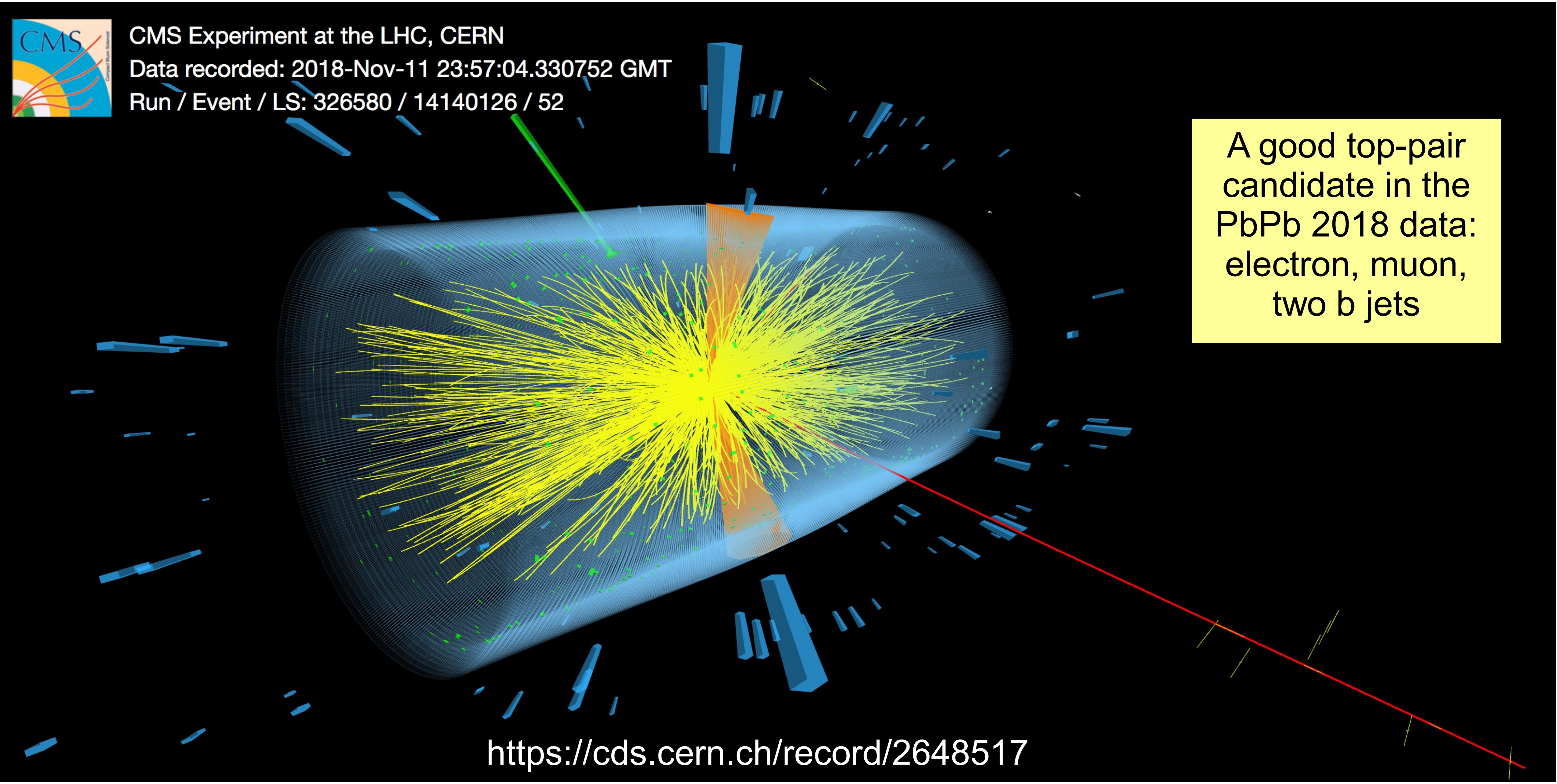


- Heavy neutrino (N), long-lived and lighter than W or B
- Two muons are produced, one displaced → very clean signal
- In particular for the B meson case:
  - Muon spectrum is very soft → very low muon thresholds are a key advantage of HI over pp runs
  - Abundant x-section, even at 5 TeV (depends mildly on √s)

Triggers

- Key point: **μ triggers** are a negligible fraction of the bandwidth during HI runs; expected to be true also in Run-4 and beyond
  - Moreover: the μ triggers used in CMS in the PbPb run of 2018 did not apply any cut to select specifically prompt muons
  - In case of unexpected bandwidth limitations, HLT software allows introduction of displaced muon trigger as backup
- Both our study cases (W and B decays) have two muons, but optimal trigger strategies may depend on context
  - With single-μ trigger you pay cost of inefficiency only once and not twice; but di-μ trigger allows very loose threshold
  - In CMS in 2018, di-μ trigger was "thresholdless", i.e., spectrum only bound by geometric acceptance for enough hits
  - We assume p_T>25 GeV for pp and p_T>3 GeV for any HI

A digression



CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-11 23:57:04.330752 GMT
Run / Event / LS: 326580 / 14140126 / 52

A good top-pair candidate in the PbPb 2018 data: electron, muon, two b jets

https://cds.cern.ch/record/2648517

Note the track multiplicity: factor 2 x HL-LHC, all from a single vertex

Already experiencing both the challenges and the opportunities of the HI environment in this „*high-pt*“ context!

Early blunder

- When we had the idea, obviously we started from PbPb
  - Just because PbPb is what LHC usually collides in HI runs
  - We wondered if A^2 enhancement compensated for low lumi
- But no, we "only" recover 4 orders of magnitude and we need one more to be competitive with pp @ HL-LHC
- This made us curious: what is the limiting factor on the instantaneous PbPb luminosity?
- And when we chatted with the experts, we were informed that the HI community is demanding other beams too

Secondary beams

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

Electromagnetic dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}.$

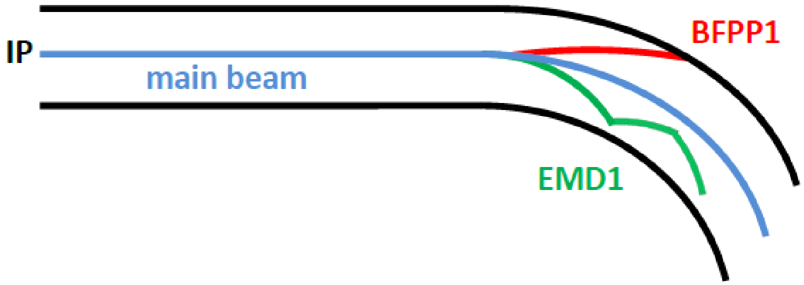
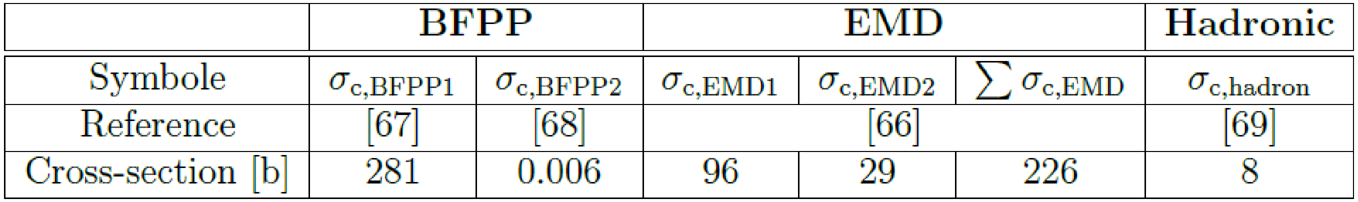


Figure 2.10.: Sketch of the separation of the secondary beams from the main beam in the curved beam pipe inside bending magnets.



	BFPP		EMD			Hadronic
Symbole	$\sigma_{\mathrm{c,BFPP1}}$	$\sigma_{\mathrm{c,BFPP2}}$	$\sigma_{\mathrm{c,EMD1}}$	$\sigma_{\mathrm{c,EMD2}}$	$\sum \sigma_{\mathrm{c,EMD}}$	$\sigma_{\mathrm{c,hadron}}$
Reference	[67]	[68]	[66]			[69]
Cross-section [b]	281	0.006	96	29	226	8

Table 2.3.: Cross-sections for electromagnetic interactions in Pb-Pb collisions at $E_b = 7Z$ TeV.

From Michaela Schaumann (LHC accelerator division)

Which ion is optimal?

$$\frac{dN}{dt} = -(\sigma_{\mathrm{had}} + \sigma_{\mathrm{EMD}} + \sigma_{\mathrm{BFPP}})L - \frac{N}{\tau_{\mathrm{other}}}, \qquad L = \frac{N^2 f_0}{4\pi\beta^* \varepsilon_{xn} k_c}$$

List of species are examples that are of interest.

Some species (e.g., Cu) are difficult to produce in the ECR heavy ion source.

Noble gases are particularly favourable.

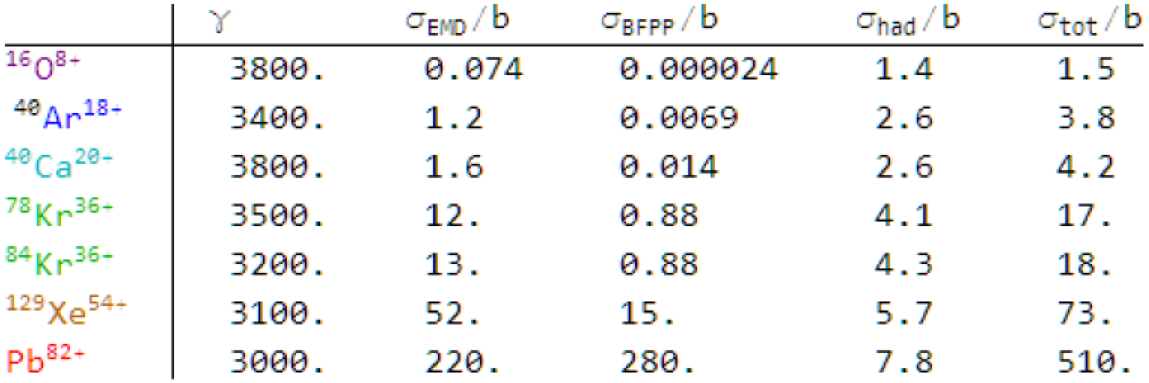
$$\sigma_{\mathrm{EMD1}} \approx (3.42\ \mu b)\frac{(A-Z)Z^3}{A^{2/3}}\log(2\gamma^2 - 1),$$

$$\sigma_{\mathrm{EMD}} \approx 1.95\ \sigma_{\mathrm{EMD1}} \quad \text{(total for all EMD channels)}$$

Cross section scalings from papers by G. Baur et al, S. Klein, I. Pshenichnov, ….

$$\sigma_{\mathrm{BFPP}} \approx Z^7(A\log(2\gamma^2 - 1) + B)$$

Pb is worse in this respect because of high BFPP and EMD cross-sections.
Makes short fills, more time spend refilling, ramping, etc.

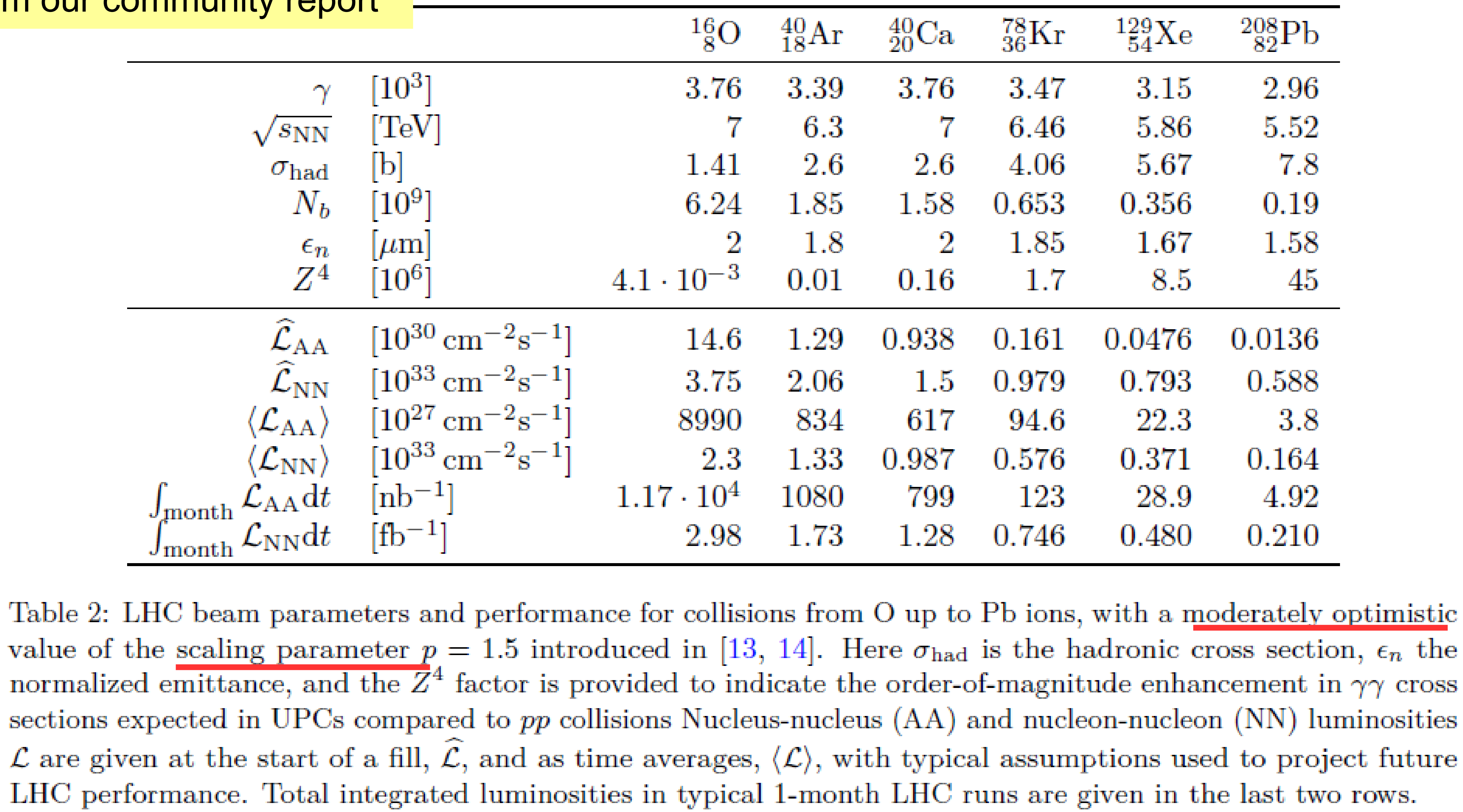


	γ	σ_{EMD} / b	σ_{BFPP} / b	σ_{had} / b	σ_{tot} / b
$^{16}\mathrm{O}^{8+}$	3800.	0.074	0.000024	1.4	1.5
$^{40}\mathrm{Ar}^{18+}$	3400.	1.2	0.0069	2.6	3.8
$^{40}\mathrm{Ca}^{20+}$	3800.	1.6	0.014	2.6	4.2
$^{78}\mathrm{Kr}^{36+}$	3500.	12.	0.88	4.1	17.
$^{84}\mathrm{Kr}^{36+}$	3200.	13.	0.88	4.3	18.
$^{129}\mathrm{Xe}^{54+}$	3100.	52.	15.	5.7	73.
Pb^{82+}	3000.	220.	280.	7.8	510.

From Jo Jowett at the HL/HE-LHC workshop, June 2018 (updated), link

Which ion is optimal?

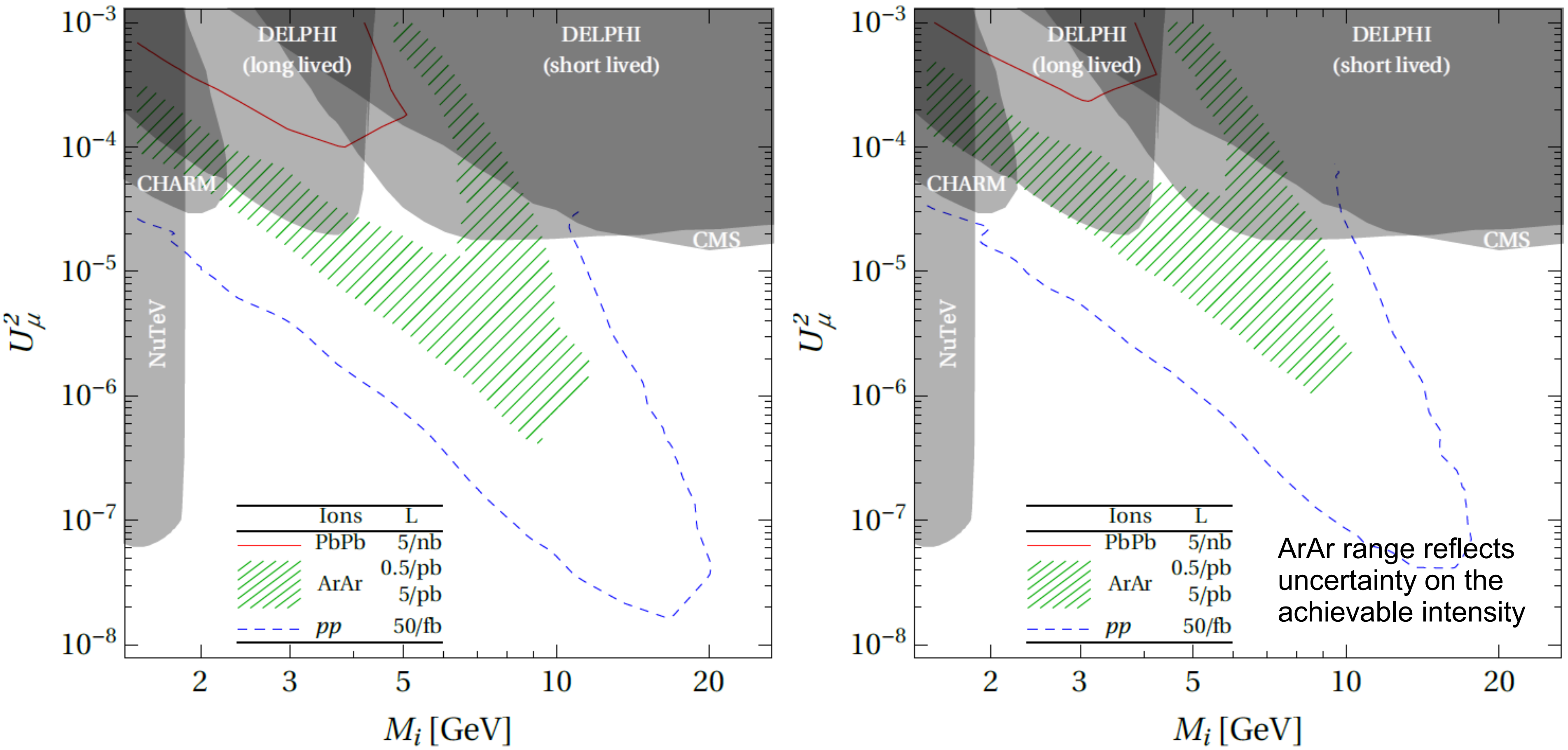
From our community report



		$^{16}_{8}$O	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{78}_{36}$Kr	$^{129}_{54}$Xe	$^{208}_{82}$Pb
γ	$[10^3]$	3.76	3.39	3.76	3.47	3.15	2.96
$\sqrt{s_{\mathrm{NN}}}$	[TeV]	7	6.3	7	6.46	5.86	5.52
σ_{had}	[b]	1.41	2.6	2.6	4.06	5.67	7.8
N_b	$[10^9]$	6.24	1.85	1.58	0.653	0.356	0.19
ϵ_n	$[\mu\mathrm{m}]$	2	1.8	2	1.85	1.67	1.58
Z^4	$[10^6]$	$4.1 \cdot 10^{-3}$	0.01	0.16	1.7	8.5	45
$\widehat{\mathcal{L}}_{\mathrm{AA}}$	$[10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	14.6	1.29	0.938	0.161	0.0476	0.0136
$\widehat{\mathcal{L}}_{\mathrm{NN}}$	$[10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	3.75	2.06	1.5	0.979	0.793	0.588
$\langle\mathcal{L}_{\mathrm{AA}}\rangle$	$[10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	8990	834	617	94.6	22.3	3.8
$\langle\mathcal{L}_{\mathrm{NN}}\rangle$	$[10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	1.33	0.987	0.576	0.371	0.164
$\int_{\mathrm{month}} \mathcal{L}_{\mathrm{AA}}\mathrm{d}t$	$[\mathrm{nb}^{-1}]$	$1.17 \cdot 10^4$	1080	799	123	28.9	4.92
$\int_{\mathrm{month}} \mathcal{L}_{\mathrm{NN}}\mathrm{d}t$	$[\mathrm{fb}^{-1}]$	2.98	1.73	1.28	0.746	0.480	0.210

Table 2: LHC beam parameters and performance for collisions from O up to Pb ions, with a moderately optimistic value of the scaling parameter $p = 1.5$ introduced in [13, 14]. Here σ_{had} is the hadronic cross section, ϵ_n the normalized emittance, and the Z^4 factor is provided to indicate the order-of-magnitude enhancement in $\gamma\gamma$ cross sections expected in UPCs compared to pp collisions Nucleus-nucleus (AA) and nucleon-nucleon (NN) luminosities $\mathcal{L}$ are given at the start of a fill, $\widehat{\mathcal{L}}$, and as time averages, $\langle\mathcal{L}\rangle$, with typical assumptions used to project future LHC performance. Total integrated luminosities in typical 1-month LHC runs are given in the last two rows.

Perspectives for the W case



(a) Exclusion with $2\,\sigma$.

(b) Discovery with $5\,\sigma$.

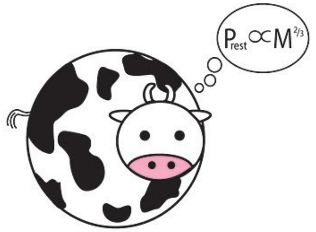
ArAr range reflects uncertainty on the achievable intensity

- Signal generation from MadGraph, with ad hoc extension for HI; detector simulation à la DELPHES (using efficiencies from HL-LHC cards)
- Results for 1-month running time in Run 4
- Bottom line: for heavy mothers, insufficient enhancement to overcome stat

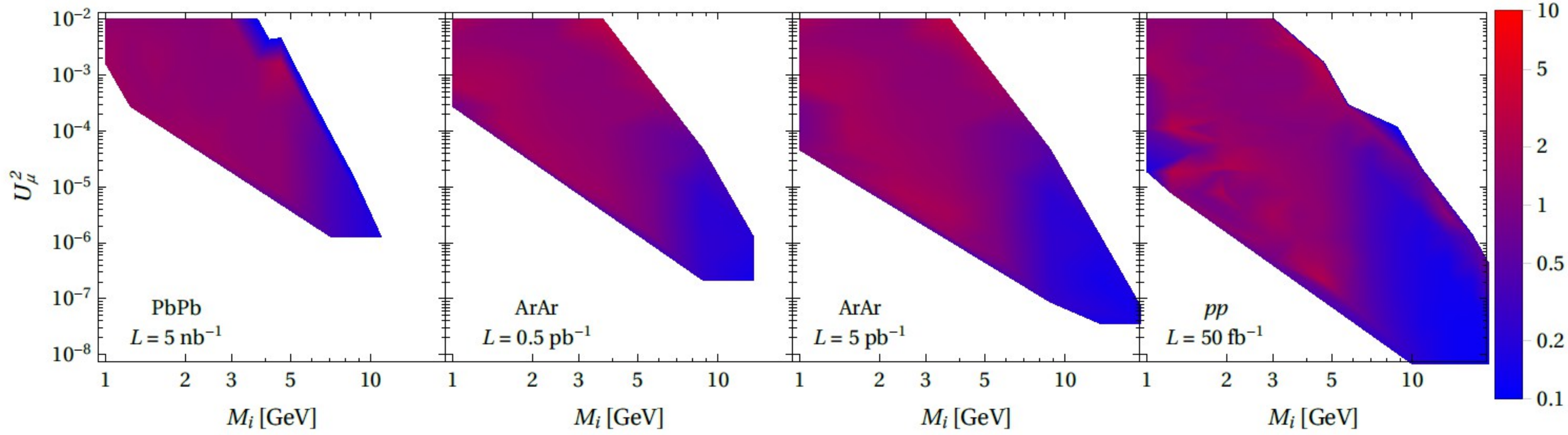
Simulation vs analytic formula

- In the B-decay case we could not simulate the signal the same way, so we resort to analytical formula fitted to W simulation
- Quite a spherical cow, but any mismodeling affects pp and HI the same way

$$N_d = \frac{L\sigma_B}{9}\left(1-\frac{M^2}{m_B^2}\right)^2 U_\mu^2 \left(e^{-l_0/\lambda_0}-e^{-l_1/\lambda_0}\right) f_{\text{cut}}$$

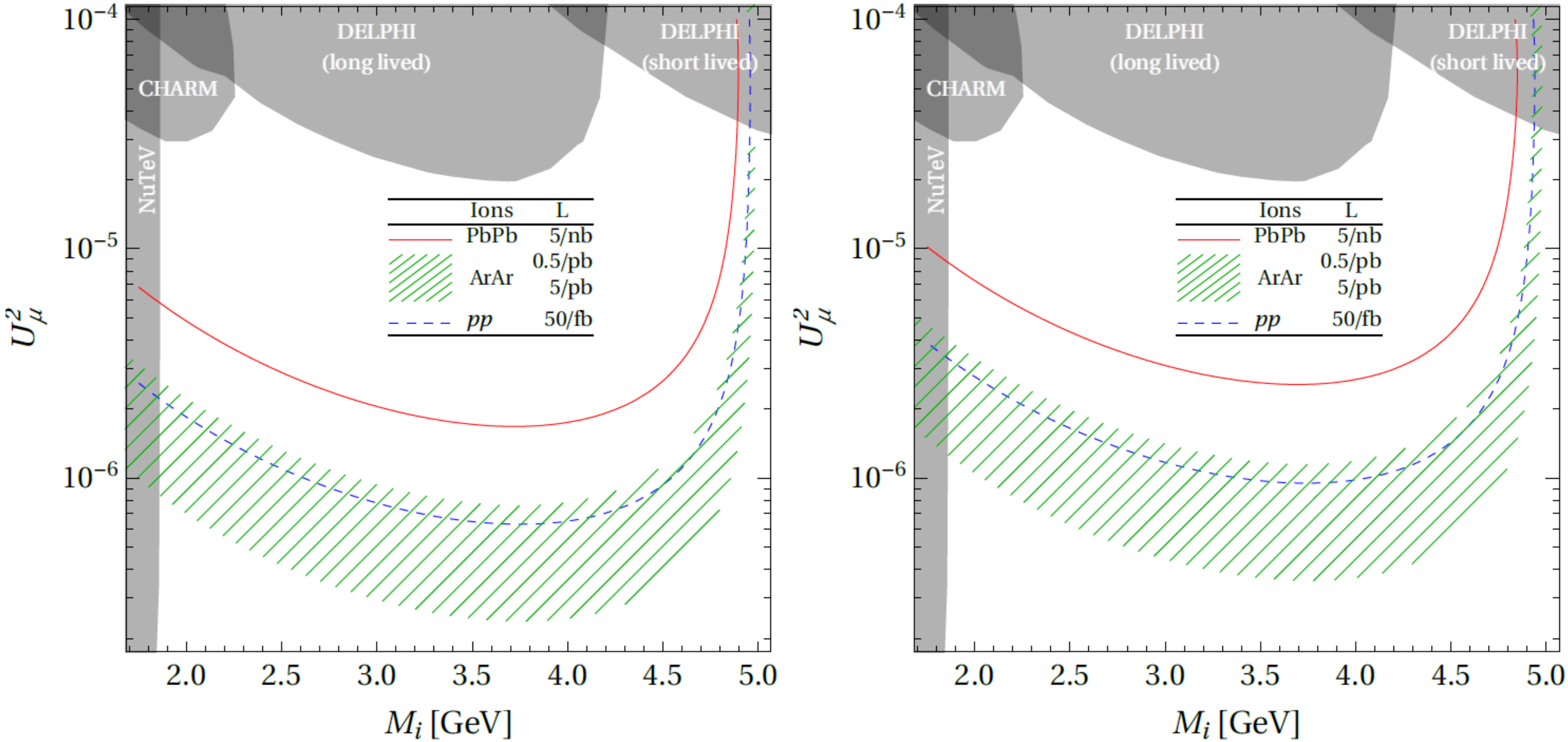


Gif stolen from here



Analytic approximation used in the B meson case is **accurate within factor of 2** apart from fringe regions

Perspectives for the B case

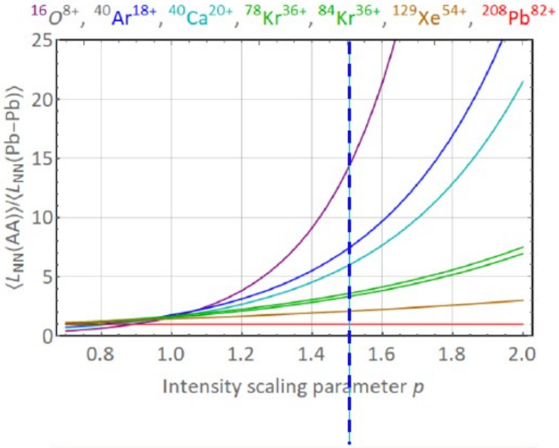


(a) Exclusion with $2\,\sigma$.

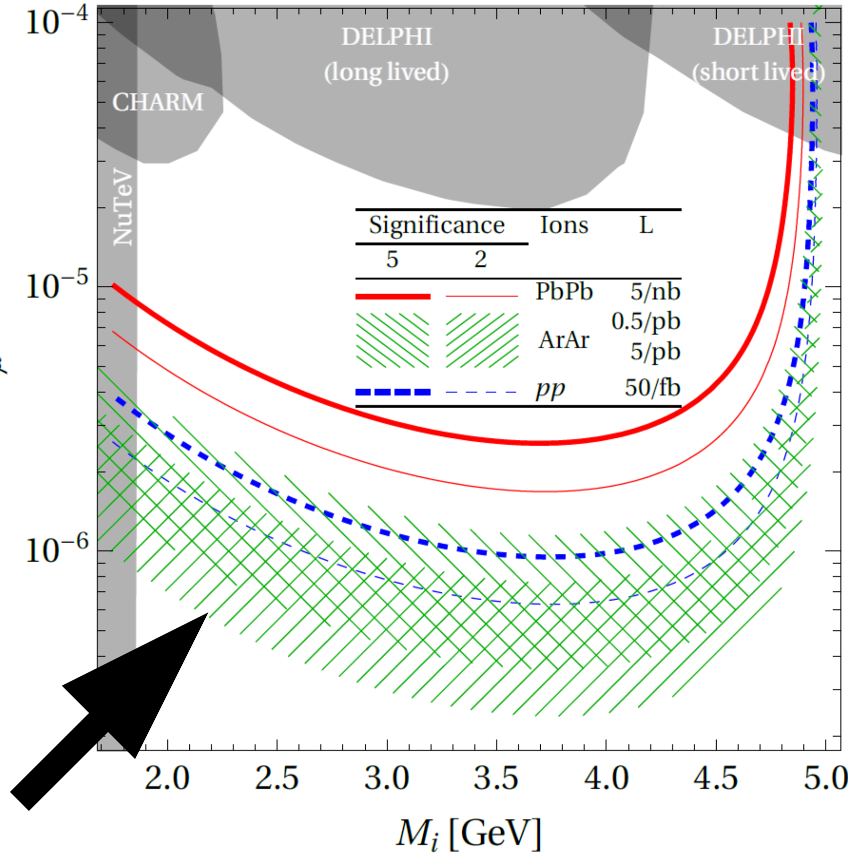
(b) Discovery with $5\,\sigma$.

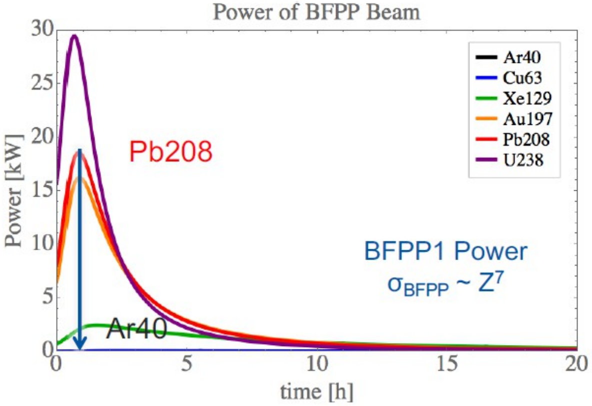
- Several approximations have been made, but would mostly affect pp and HI curves in the same direction
- By far the main uncertainty of this study is the achievable Ar luminosity
- Bottom line: for light mothers, intermediate ion mass is interesting!

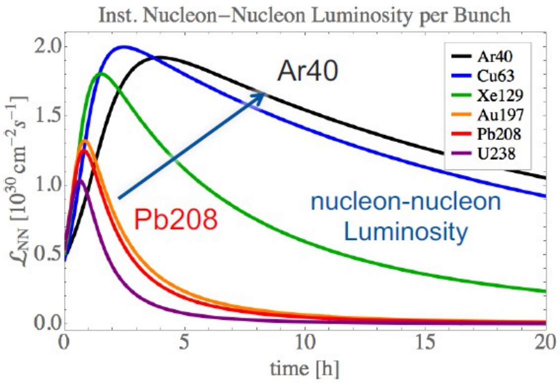
Trade-off between A^2 factor and maximum luminosity



Nucleon-nucleon luminosity in 1-month run: **gains** ranging up to a **factor ~13 for lightest considered ion (O) at p=1.5**





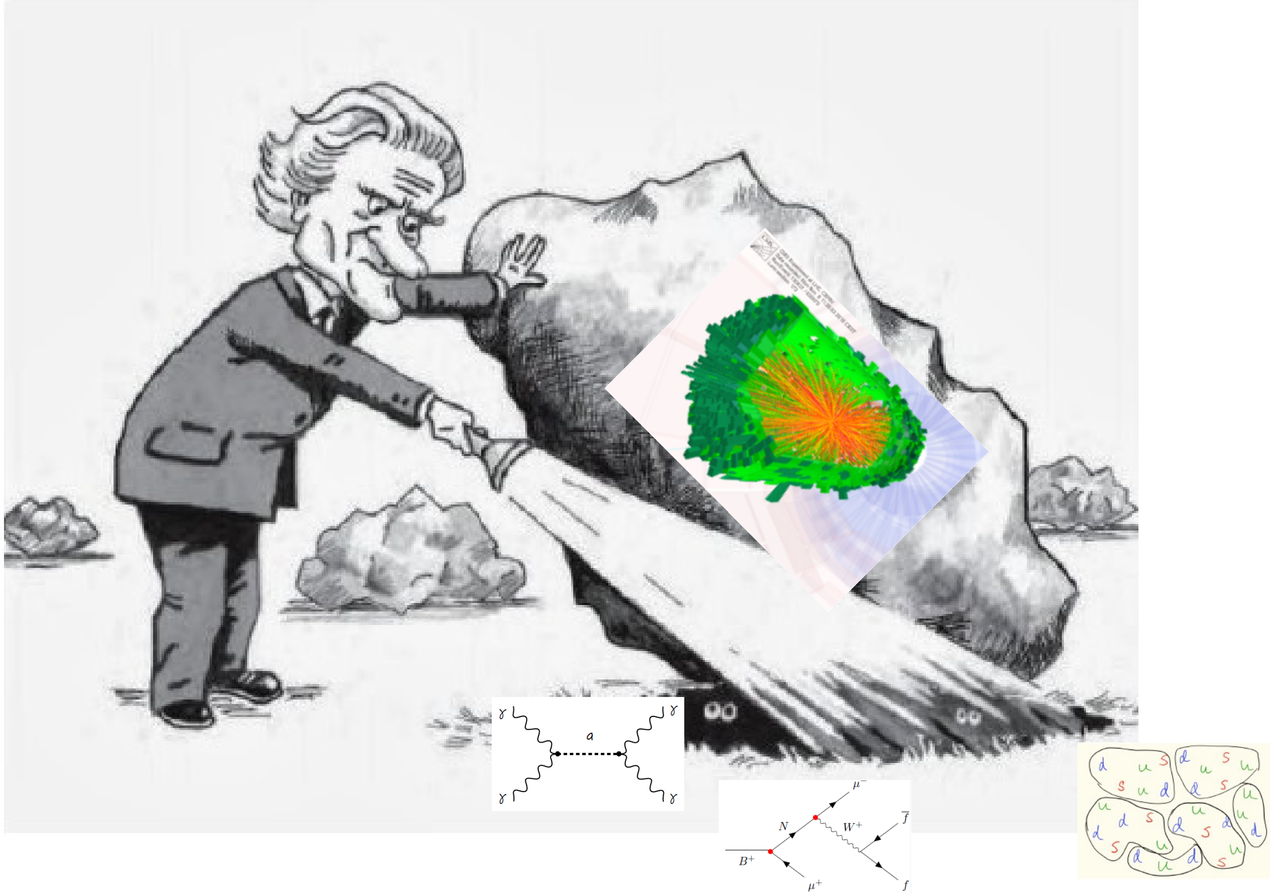


Independently, but for the same reason, ArAr runs are being advocated in the HI community: trade-off between size of the QGP and integrated luminosity potentially achievable

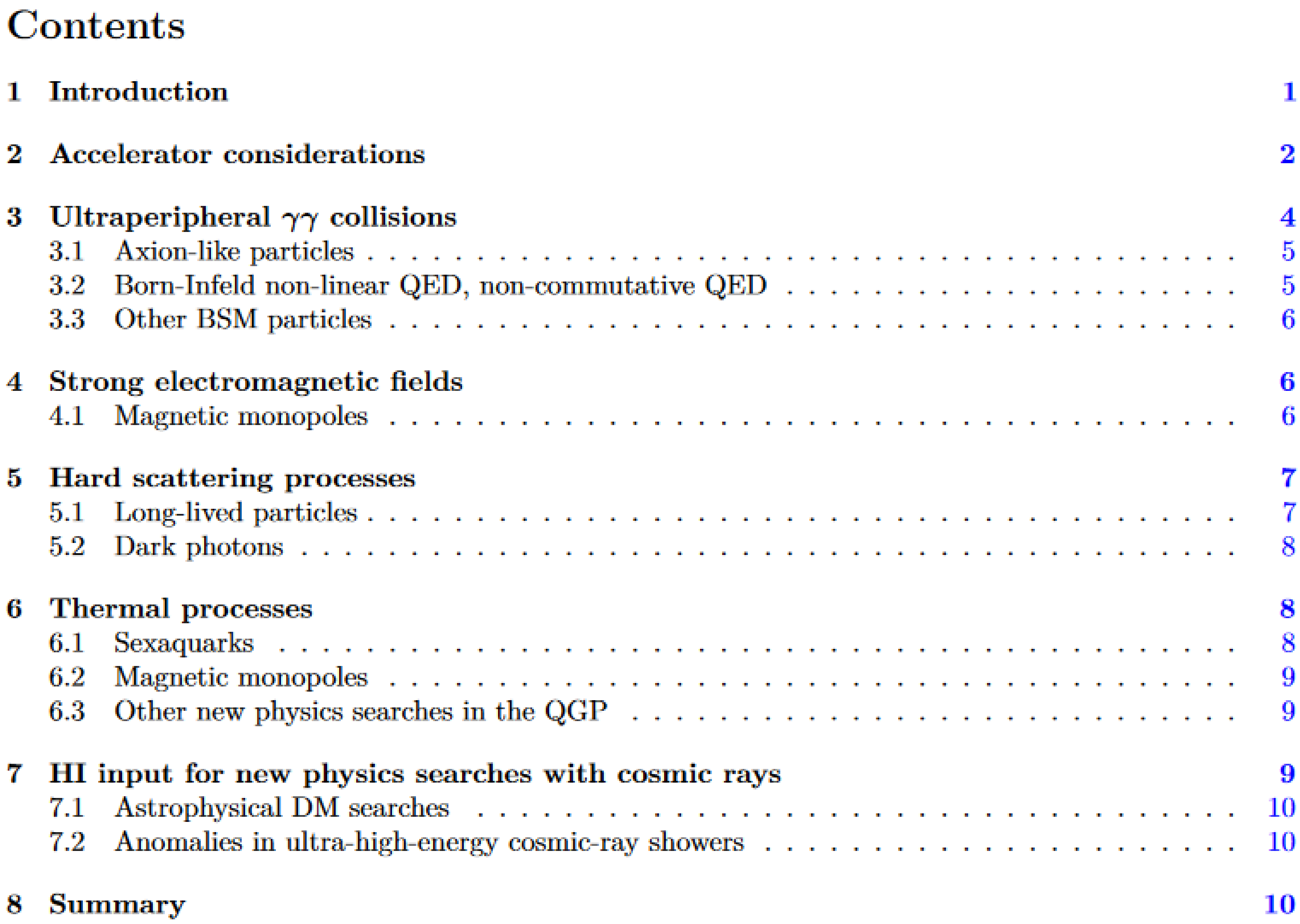
Summary

- HI data may help to cover a few **blind spots** in the **low-mass / low-coupling regime**, in the same vein of other ideas to maximize the utility of LHC data (e.g., parking, scouting, the exotic program of LHCb, dedicated low-cost detectors, etc.)
- HI data severely limited in statistics:
  - Technical limitations on instantaneous luminosity
  - Planning limitation: not more than 1 month per year (unless we find excess of a signal that can better be studied in HI!)
- Searches where HI data have an edge:
  - BSM coupled to photons: $\gamma\gamma \rightarrow X$ rate enhanced by Z^4
  - Non-linear QED or QCD enhancements
- We also learned in which cases it may be worth considering LLP scenarios with just A^2 enhancement
  - And we learned the need for intermediate-mass ions
  - Probably generalizable to a variety of soft and clean signatures

Thanks for your attention!



Topics covered in our "community report"

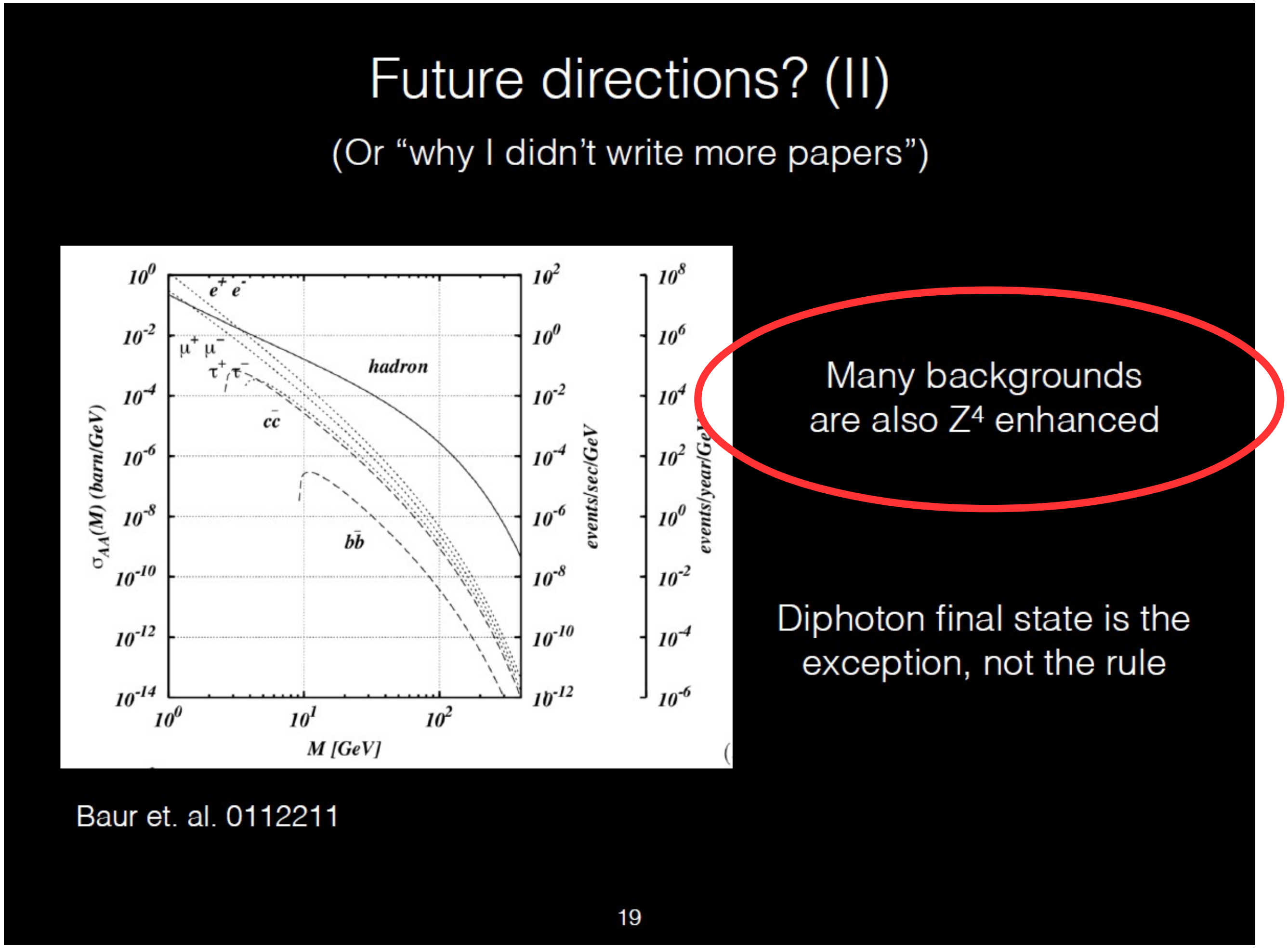


Contents

https://arxiv.org/abs/1812.07688

The problem with UPCs

Simon Knapen



Future directions? (II)

(Or “why I didn’t write more papers”)

Many backgrounds are also Z^4 enhanced

Diphoton final state is the exception, not the rule

Baur et. al. 0112211

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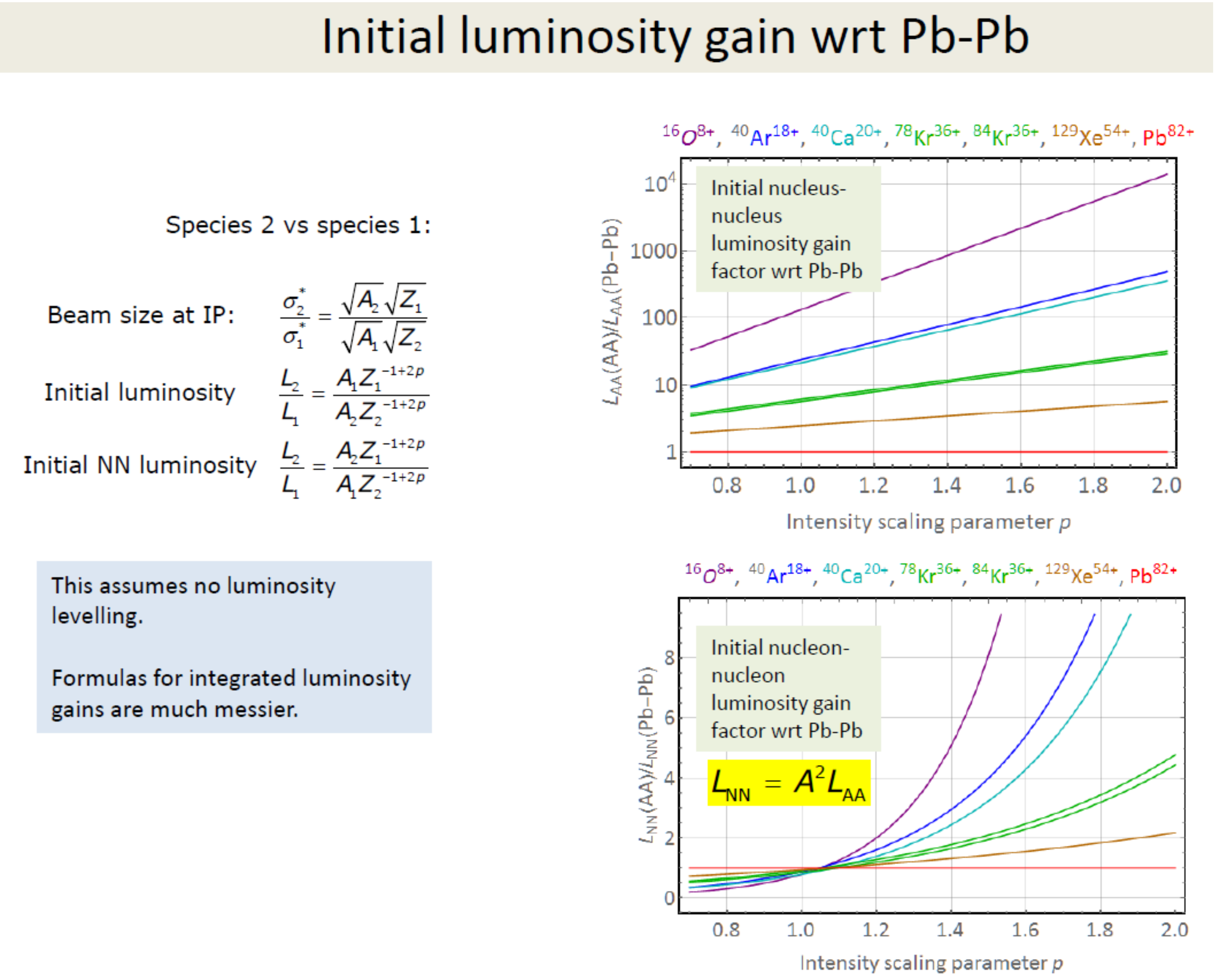
Which ion is optimal?



Initial luminosity gain wrt Pb-Pb

Species 2 vs species 1:

Beam size at IP: $\frac{\sigma_2^*}{\sigma_1^*} = \frac{\sqrt{A_2}\sqrt{Z_1}}{\sqrt{A_1}\sqrt{Z_2}}$

Initial luminosity $\frac{L_2}{L_1} = \frac{A_1 Z_1^{-1+2p}}{A_2 Z_2^{-1+2p}}$

Initial NN luminosity $\frac{L_2}{L_1} = \frac{A_2 Z_1^{-1+2p}}{A_1 Z_2^{-1+2p}}$

This assumes no luminosity levelling.

Formulas for integrated luminosity gains are much messier.

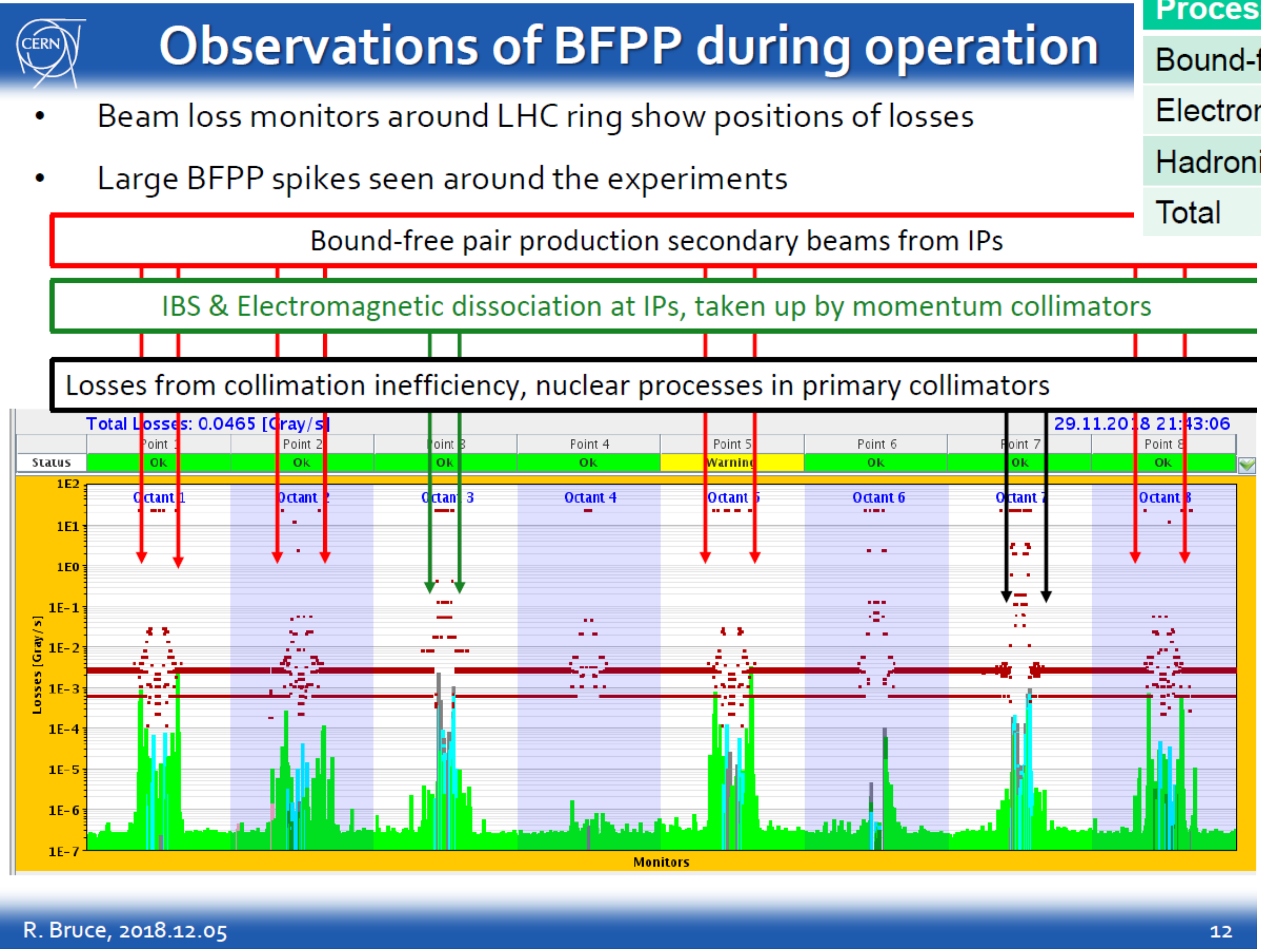
Initial nucleus-nucleus luminosity gain factor wrt Pb-Pb

Initial nucleon-nucleon luminosity gain factor wrt Pb-Pb

$L_{NN} = A^2 L_{AA}$

Source: Jo Jowett, HL/HE-LHC workshop, June 2018 (updated), link

Limiting effects



Observations of BFPP during operation

- Beam loss monitors around LHC ring show positions of losses
- Large BFPP spikes seen around the experiments

Bound-free pair production secondary beams from IPs

IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators

R. Bruce, 2018.12.05

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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

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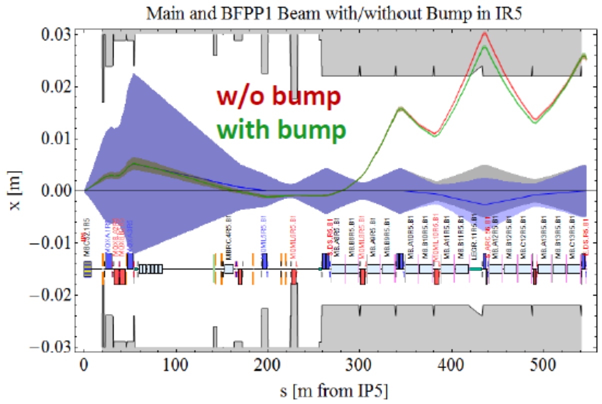
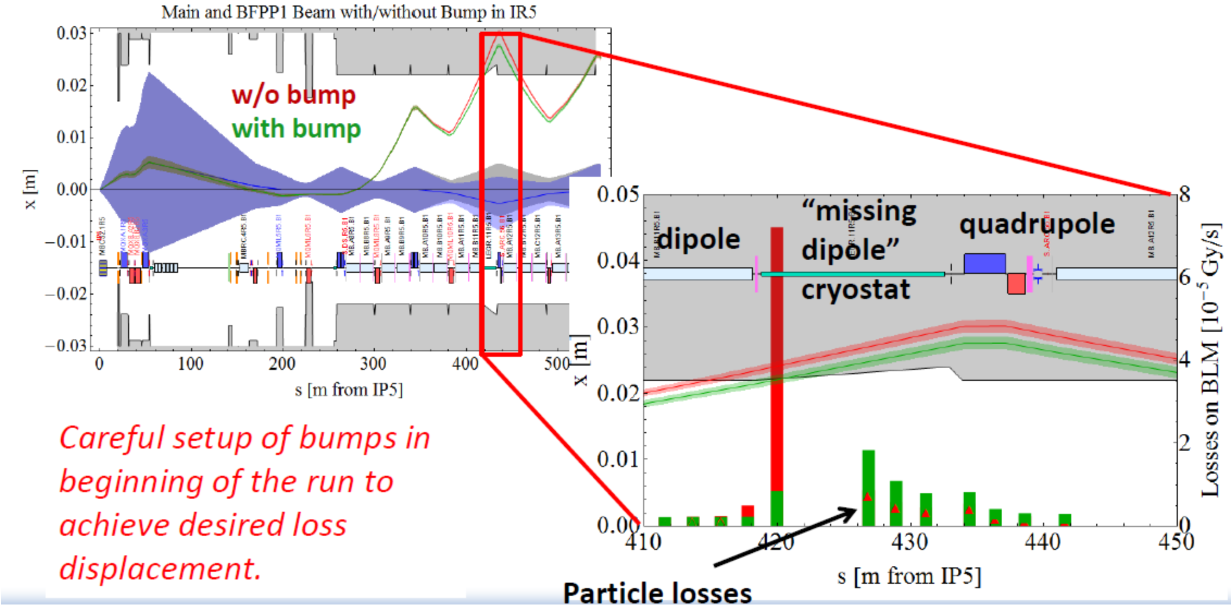


Careful setup of bumps in beginning of the run to achieve desired loss displacement.

Alleviating actions

ATLAS/CMS:

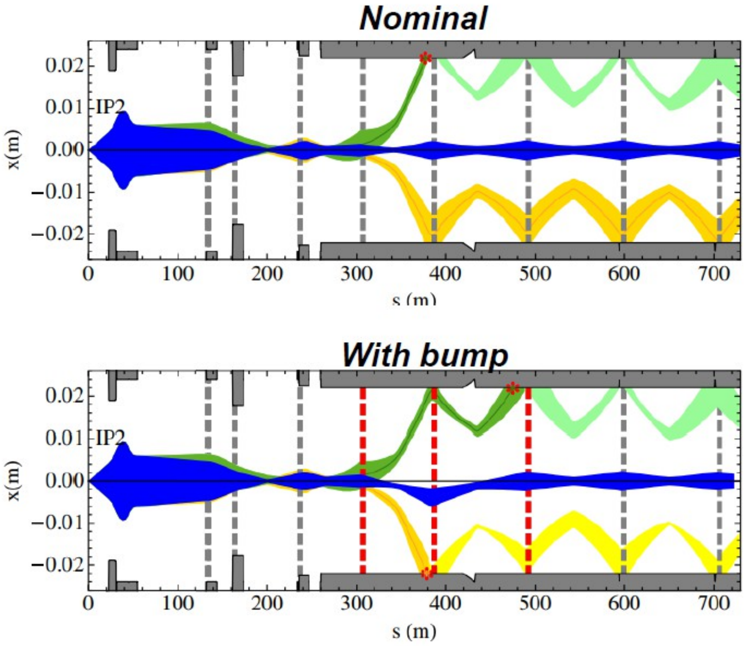
- With bumps, achieved ~6E27 cm^{-2}s^{-1} in ATLAS / CMS



Careful setup of bumps in beginning of the run to achieve desired loss displacement.

Particle losses

Partial solution in ALICE:



ALICE anyway leveled at 1E27 cm^{-2}s^{-1}

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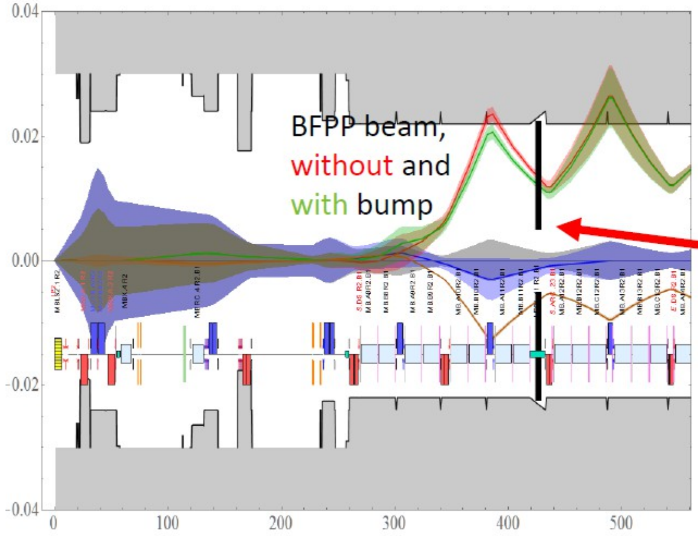
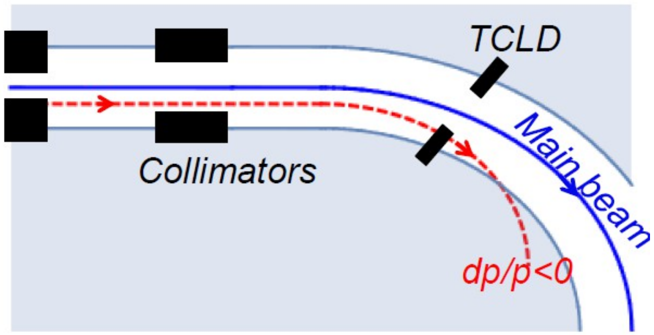
Future alleviation: collimators



TCLD collimator
(post LS2)



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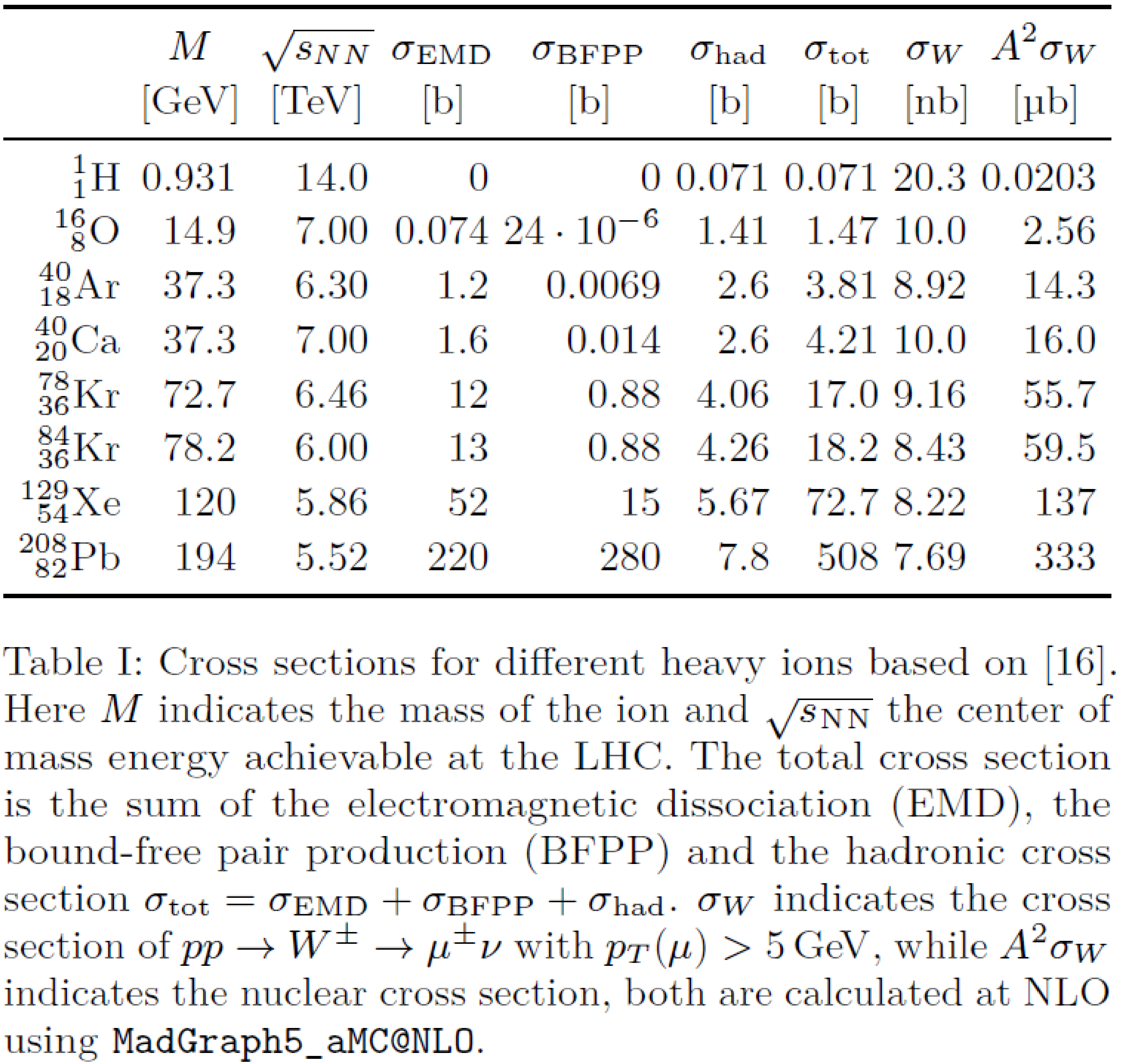
- LHC collimation much less efficient with nuclear beams than with protons
  - Very high probability of nuclear breakup in primary collimator
  - Fragments very often miss downstream collimation stages
  - Different charge-to-mass ratio => fragments bent wrongly and lost in the first few dipoles

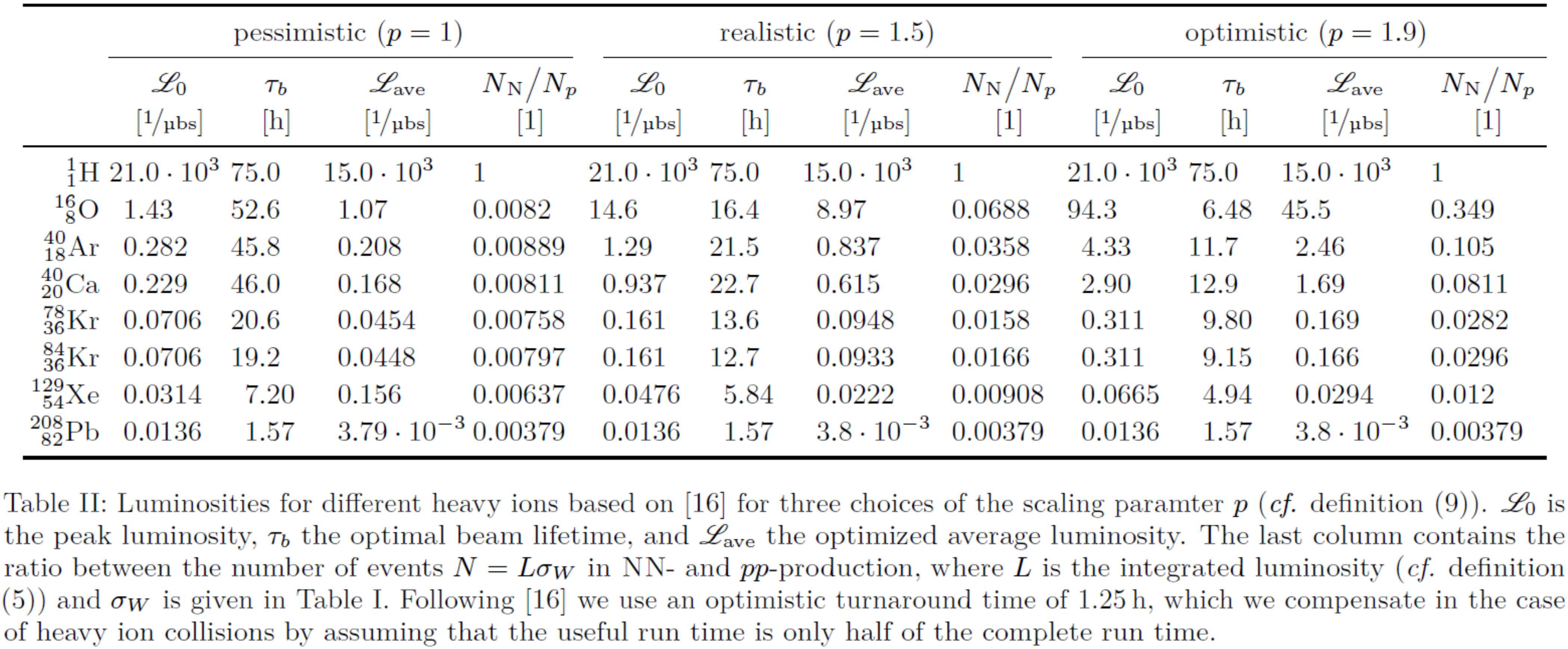
- Measured leakage to cold magnets factor ~100 worse of Pb ions than protons



	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]
$^{1}_{1}\mathrm{H}$	0.931	14.0	0	0	0.071	0.071	20.3	0.0203
$^{16}_{8}\mathrm{O}$	14.9	7.00	0.074	$24 \cdot 10^{-6}$	1.41	1.47	10.0	2.56
$^{40}_{18}\mathrm{Ar}$	37.3	6.30	1.2	0.0069	2.6	3.81	8.92	14.3
$^{40}_{20}\mathrm{Ca}$	37.3	7.00	1.6	0.014	2.6	4.21	10.0	16.0
$^{78}_{36}\mathrm{Kr}$	72.7	6.46	12	0.88	4.06	17.0	9.16	55.7
$^{84}_{36}\mathrm{Kr}$	78.2	6.00	13	0.88	4.26	18.2	8.43	59.5
$^{129}_{54}\mathrm{Xe}$	120	5.86	52	15	5.67	72.7	8.22	137
$^{208}_{82}\mathrm{Pb}$	194	5.52	220	280	7.8	508	7.69	333

Table I: Cross sections for different heavy ions based on [16]. Here M indicates the mass of the ion and $\sqrt{s_{\mathrm{NN}}}$ the center of mass energy achievable at the LHC. The total cross section is the sum of the electromagnetic dissociation (EMD), the bound-free pair production (BFPP) and the hadronic cross section $\sigma_{\mathrm{tot}} = \sigma_{\mathrm{EMD}} + \sigma_{\mathrm{BFPP}} + \sigma_{\mathrm{had}}$. σ_W indicates the cross section of $pp \to W^{\pm} \to \mu^{\pm}\nu$ with $p_T(\mu) > 5\,\mathrm{GeV}$, while $A^2\sigma_W$ indicates the nuclear cross section, both are calculated at NLO using `MadGraph5_aMC@NLO`.

3 scenarios



	pessimistic ($p = 1$)				realistic ($p = 1.5$)				optimistic ($p = 1.9$)			
	$\mathscr{L}_0$ $[1/\mu\text{bs}]$	τ_b [h]	$\mathscr{L}_\text{ave}$ $[1/\mu\text{bs}]$	N_N/N_p [1]	$\mathscr{L}_0$ $[1/\mu\text{bs}]$	τ_b [h]	$\mathscr{L}_\text{ave}$ $[1/\mu\text{bs}]$	N_N/N_p [1]	$\mathscr{L}_0$ $[1/\mu\text{bs}]$	τ_b [h]	$\mathscr{L}_\text{ave}$ $[1/\mu\text{bs}]$	N_N/N_p [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	$21.0 \cdot 10^3$	75.0	$15.0 \cdot 10^3$	1
$^{16}_{8}\text{O}$	1.43	52.6	1.07	0.0082	14.6	16.4	8.97	0.0688	94.3	6.48	45.5	0.349
$^{40}_{18}\text{Ar}$	0.282	45.8	0.208	0.00889	1.29	21.5	0.837	0.0358	4.33	11.7	2.46	0.105
$^{40}_{20}\text{Ca}$	0.229	46.0	0.168	0.00811	0.937	22.7	0.615	0.0296	2.90	12.9	1.69	0.0811
$^{78}_{36}\text{Kr}$	0.0706	20.6	0.0454	0.00758	0.161	13.6	0.0948	0.0158	0.311	9.80	0.169	0.0282
$^{84}_{36}\text{Kr}$	0.0706	19.2	0.0448	0.00797	0.161	12.7	0.0933	0.0166	0.311	9.15	0.166	0.0296
$^{129}_{54}\text{Xe}$	0.0314	7.20	0.156	0.00637	0.0476	5.84	0.0222	0.00908	0.0665	4.94	0.0294	0.012
$^{208}_{82}\text{Pb}$	0.0136	1.57	$3.79 \cdot 10^{-3}$	0.00379	0.0136	1.57	$3.8 \cdot 10^{-3}$	0.00379	0.0136	1.57	$3.8 \cdot 10^{-3}$	0.00379

Table II: Luminosities for different heavy ions based on [16] for three choices of the scaling paramter p (*cf.* definition (9)). $\mathscr{L}_0$ is the peak luminosity, τ_b the optimal beam lifetime, and $\mathscr{L}_\text{ave}$ the optimized average luminosity. The last column contains the ratio between the number of events $N = L\sigma_W$ in NN- and pp-production, where L is the integrated luminosity (*cf.* definition (5)) and σ_W is given in Table I. Following [16] we use an optimistic turnaround time of 1.25 h, which we compensate in the case of heavy ion collisions by assuming that the useful run time is only half of the complete run time.

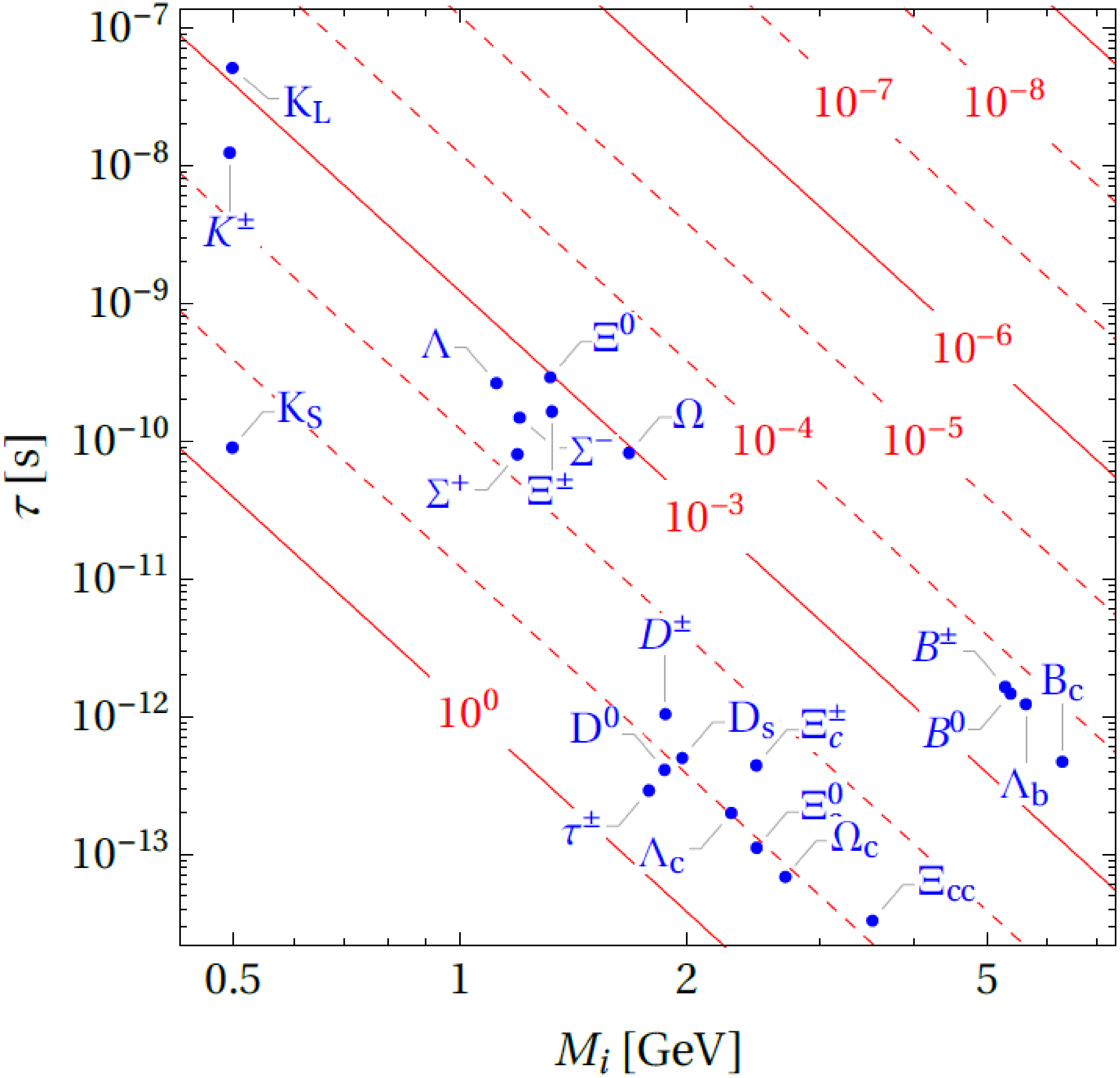
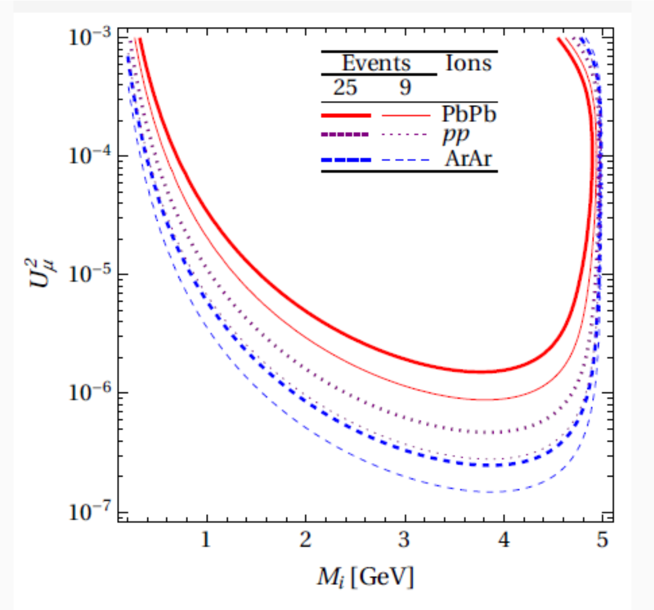
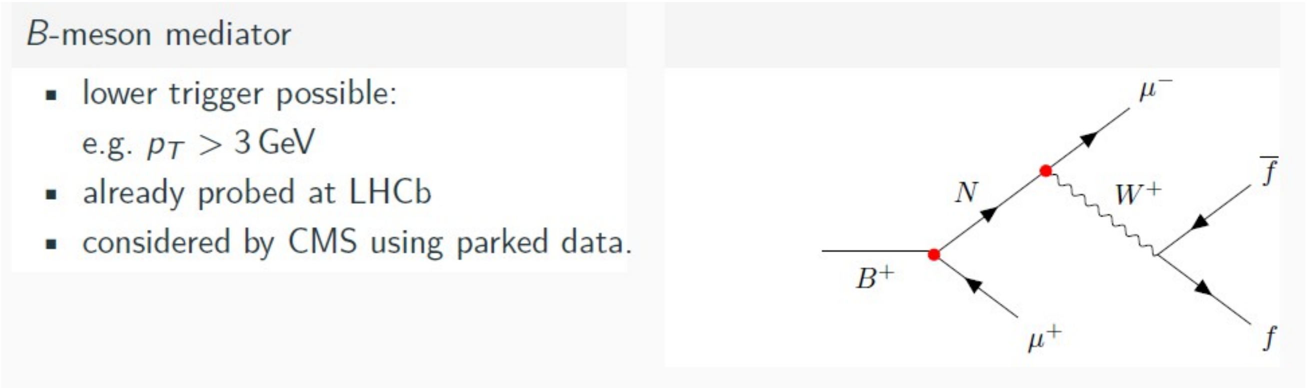


Figure 3: Heavy neutrino mixing U^2 as a function of its mass and life time (red lines) compared to potentially relevant SM backgrounds (blue dots). Figure taken from reference [82].

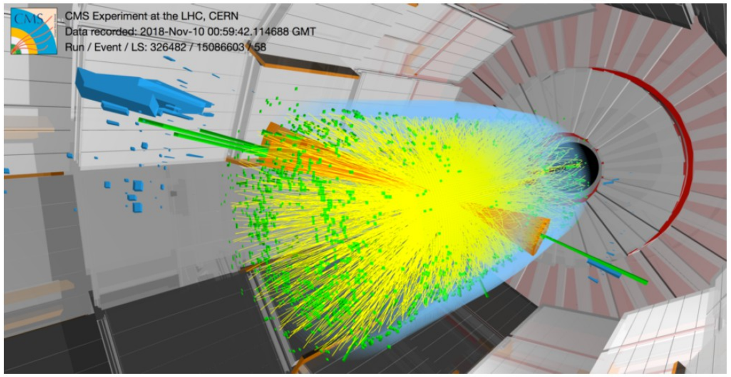
LLPs from b hadrons





B-meson mediator

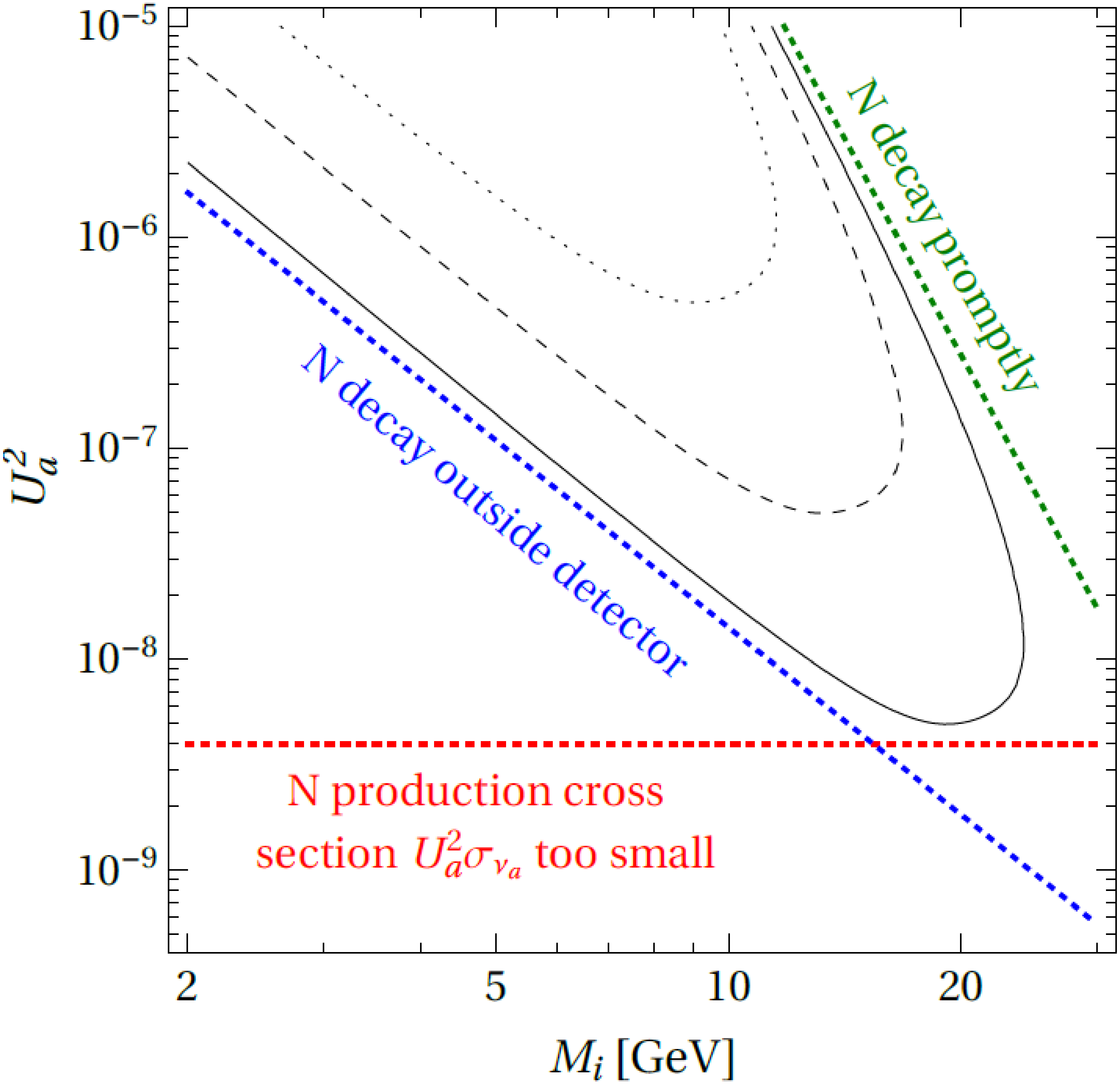
- lower trigger possible:
  e.g. $p_T > 3\,\text{GeV}$
- already probed at LHCb
- considered by CMS using parked data.

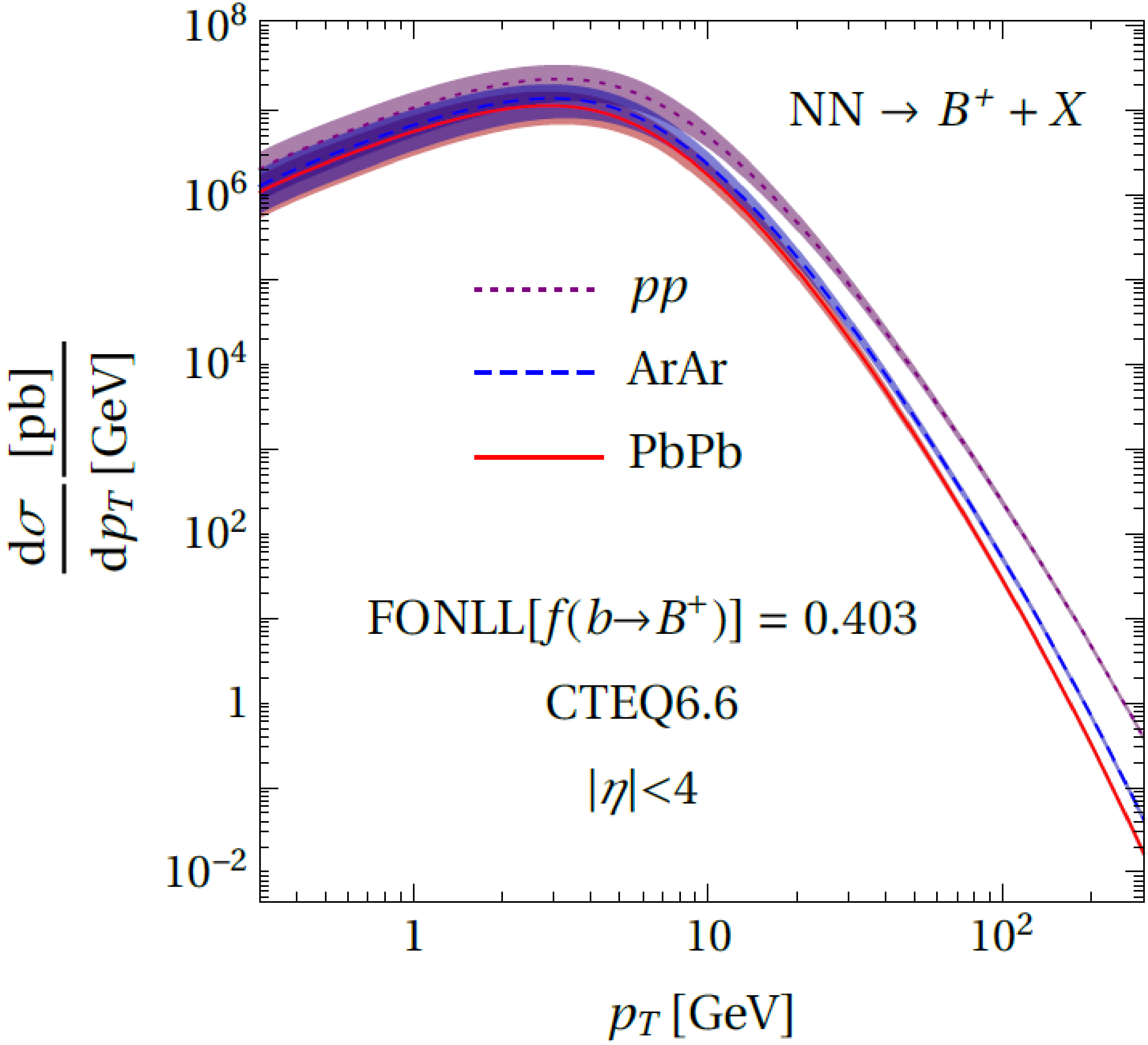


Jets from b's in HI

Discussion at the workshop:

- Considering generic b quarks: gain statistics
- Or stick to specific hadron(s) but apply mass cuts to reduce backgrounds (if any)
- Consider same-sign muons: much much cleaner, but theorically controversial?
- In pp, also LHCb and CMS-parking can go to low trigger thresholds
- Ideal benchmark is a low-mass search that is limited by PV multiplicity, but in that case also LHCb is expected to do well


U_a^2
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
5
10
20
M_i [GeV]
N decay promptly
N decay outside detector
N production cross section $U_a^2\sigma_{\nu_a}$ too small



$\frac{d\sigma}{dp_T}$ [pb] / [GeV]
10^8
10^6
10^4
10^2
1
10^{-2}
1
10
10^2
p_T [GeV]
NN → $B^+ + X$
pp
ArAr
PbPb
FONLL[$f(b \to B^+)$] = 0.403
CTEQ6.6
$|\eta|<4$