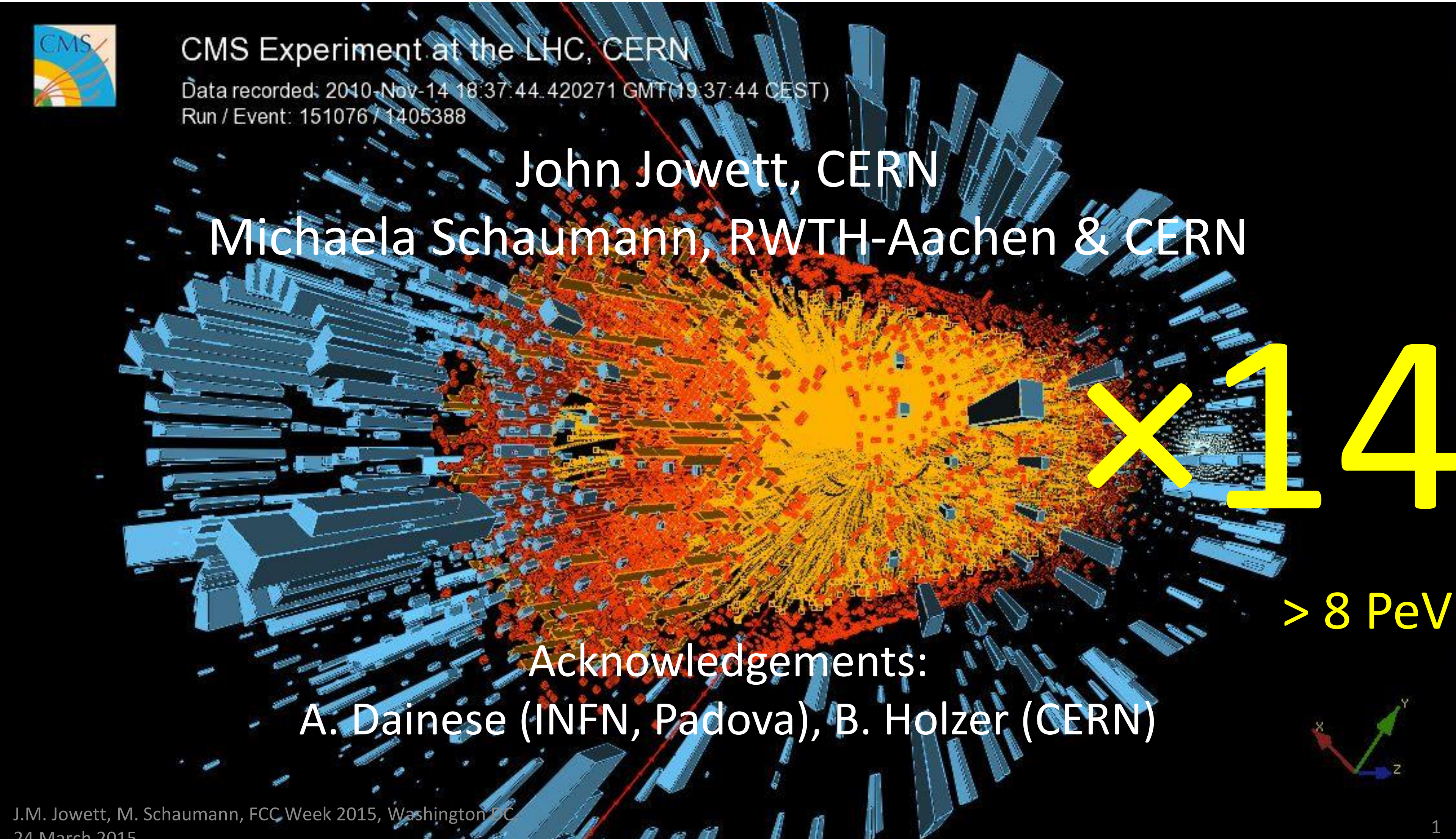
FCC-hh as a Heavy-Ion Collider



John Jowett, CERN
Michaela Schaumann, RWTH-Aachen & CERN

Acknowledgements:
A. Dainese (INFN, Padova), B. Holzer (CERN)

General FCC-hh Parameters

In relation to FCC-hh, assumed working as p-p collider, consider Pb-Pb and p-Pb collisions at maximum energy.

	Units	Injection	Collision
Circumference	[km]	100	100
Main dipole strength	[T]	1.0	16
Bending radius	[m]	10424	10424
Proton equivalent energy	[TeV]	3.3	50
Pb energy	[TeV]	270	4100
Pb energy/nucleon	[TeV]	1.3	19.7
Pb-Pb CM energy $\sqrt{s}$	[TeV]		8200
Pb-Pb CM energy/nucleon pair $\sqrt{s_{NN}}$	[TeV]		39.4
p-Pb C.M. energy $\sqrt{s}$	[TeV]		905
p-Pb C.M. energy/nucleon pair $\sqrt{s_{NN}}$	[TeV]		62.8

Problems that are “in the shadow” of p-p

- Optics design
- Collective effects
  - lower charge per bunch, fewer bunches
  - Including impedance-driven, beam-beam, electron cloud
- Stored beam energy
  - Not as large as in p-p (but still large …)
  - Nevertheless collimation efficiency is likely to be much lower!

What is new with heavy-ion beams w.r.t. protons?

- Synchrotron radiation damping is *twice as fast*

$$\alpha_\varepsilon \propto \frac{Z^5}{m^4} \text{ in the same magnetic field}$$

  - Free natural beam cooling, not limited by beam-beam tune-shift.
- Pb nuclei are accompanied by intense fluxes of high energy quasi-real photons:
  - (Physics interest …)
  - Leads to powerful secondary beams emerging from collision point
  - Extreme luminosity burn-off from electromagnetic cross-sections
  - More complicated interactions with collimators
- Stronger intra-beam scattering ultimately limits emittance

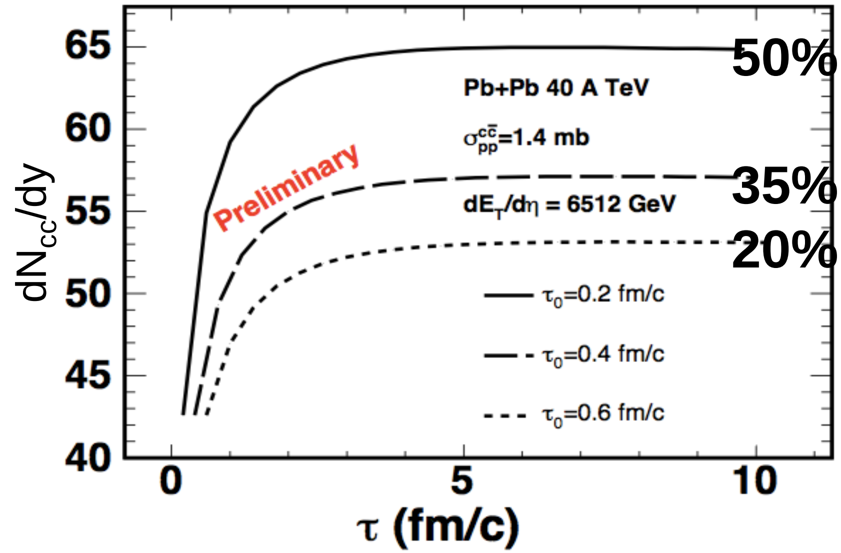
Physics with ions at FCC

- Physics opportunities with heavy ion beams at the FCC (AA, pA) are investigated by a dedicated WG within the FCC-hh group: 4 workshops held (https://indico.cern.ch/event/331669 and links therein)
- Main directions:
  - Quark-Gluon Plasma studies:
    - larger size and stronger expansion → better sensitivity to QGP-fluid properties
    - higher temperature → large thermal charm production? full melting of quarkonia?
    - new hard probes available (e.g. top quarks)
  - Saturation of small-x gluon densities (with pA and eA): reach down $x_{Bjorken} \sim 10^{-6}$ (one order of magnitude smaller than at LHC)
  - Ion beams → photon-induced collisions ($\gamma+\gamma$, γ+A): saturation and EW studies
- More information:
  - Presentation on eA (and AA) physics by M.Ploskon (this workshop)
  - http://arXiv:1407.7649 (Nuclear Physics A 931, 2014, 1163–1168)
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons

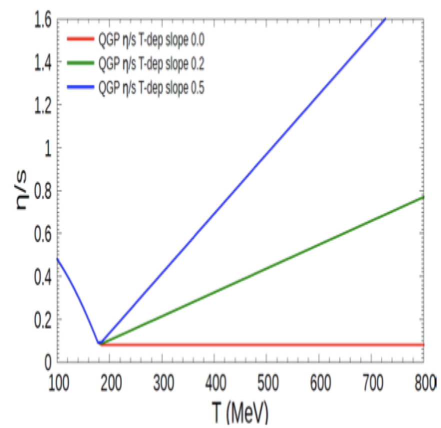
Slide from A. Dainese

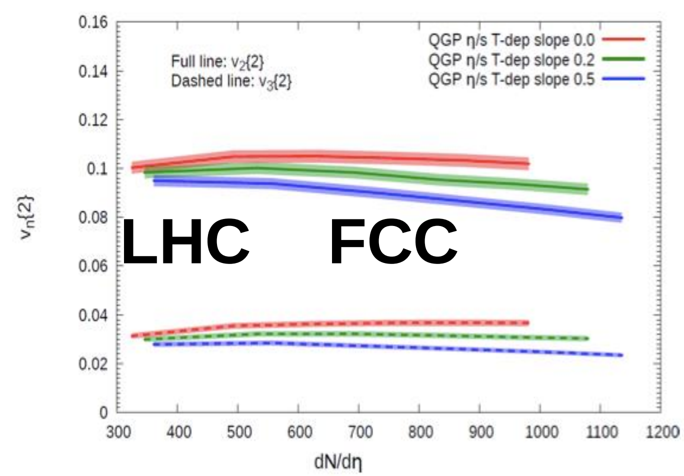
Just two examples

- Significantly larger initial temperature? Could reach close to 1 GeV?
  - Abundant “thermal” production of c-cbar pairs in the medium?
  - Full suppression of quarkonia (Y(1S) may not be suppressed at LHC)
- Anisotropic flow measurements become sensitive to currently-inaccessible properties of the QGP: e.g. temperature dependence of viscosity



Based on B.-W. Zhang et al. PRC77 (2008)





Slide from A. Dainese

G. Denicol in https://indico.cern.ch/event/331669

Previous references on AA & pA in FCC-hh

- M. Schaumann, Ions at the Future Hadron Collider, 16-17 Dec. 2013, CERN https://indico.cern.ch/event/288576/
- M. Schaumann, FCC Study Kick-off Meeting, 12-15 Feb. 2014, Geneva https://indico.cern.ch/event/282344/
- M. Schaumann, Ions at the Future Hadron Collider https://indico.cern.ch/event/331669/ (update to 100 km)

- M. Schaumann, Chapter 9 of thesis submitted to RWTH, Aachen
- M. Schaumann, "Potential performance for Pb-Pb, p-Pb and p-p collisions in a future circular collider", paper submitted to Phys. Rev. ST-AB

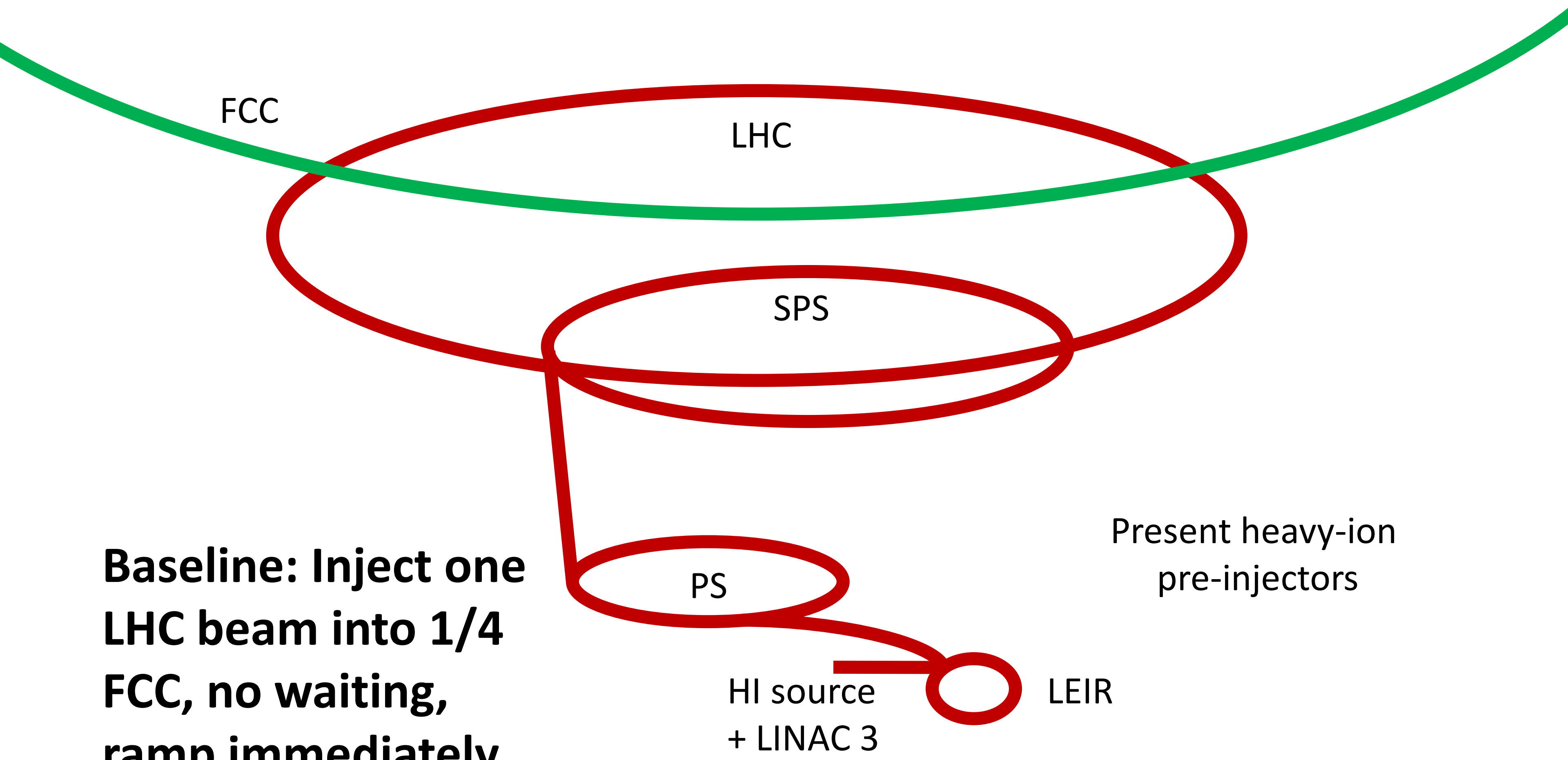
Studies focussed on emittance and luminosity evolution with strong radiation damping, IBS and luminosity burn-off, etc.

CERN Heavy-Ion Injector Complex

- Present study *very conservatively* assumes the Pb injector performance achieved for LHC p-Pb run in 2013
- Potential upgrades needing study
  - Better ion source?
  - Upgrade/replacement of LEIR, faster cooling, higher injection into PS ?
  - Degradation of bunches along trains at SPS injection (alternatives to fixed harmonic acceleration with present 200 MHz RF system?)
- LHC as HEB injector into FCC-hh

Heavy Ion Pre-Accelerator Chain

Straw-man assumption to estimate (conservative) beam parameters and luminosity:
LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.



Baseline: Inject one LHC beam into 1/4 FCC, no waiting, ramp immediately.

Pb Beam Parameters in LHC and FCC-hh

Best injector performance achieved in 2013 p-Pb run.

Average beam parameters from 2013 are assumed as
VERY conservative baseline for FCC-hh!
Improvements are already under study for HL-LHC!

	LHC Design	LHC 2011	LHC 2013	FCC-hh
Beam Energy [Z TeV]	7	3.5	4	50
β-function at the IP [m]	0.5	1.0	0.8	1.1
No. Ions per bunch $[10^8]$	0.7	1.20 ± 0.25	1.40 ± 0.27	1.4
Transv. normalised emittance $[\mu m. \mathrm{rad}]$	1.5	1.7 ± 0.2	~ 1.5	1.5
RMS Beam Size at IP $[\mu m]$	15.9	33.9	26.6	8.8
RMS bunch length $[\mathrm{cm}]$	7.94	9.8 ± 0.7	9.8 ± 0.1	8
Number of bunches	592	358	358	432
Peak Luminosity $[10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-1}]$	1	0.5 (Pb-Pb)	110 (p-Pb)	?

Geometric emittance at injection > protons – possible issue for aperture choice?

Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

with

$$A = f_{\rm rev} k_b/(4\pi\beta^*)$$

$f_{\rm rev}$: revolution freq.
k_b : no. bunches/beam
β^* : β-function at IP
N_b : no. particles/bunch
ϵ : geom. emittances
σ_s : bunch length

$\sigma_{c,\rm tot}$: total cross-section
$\alpha_{\rm IBS}$: IBS growth rate
$\alpha_{\rm rad}$: rad. damping rate

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only shown here, more included in simulations):

Intensity:
$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\sigma_{c,\rm tot} A \frac{N_b^2}{\sqrt{\epsilon_x\epsilon_y}}$$

Hor. Emittance:
$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} = \epsilon_x(\alpha_{{\rm IBS},x} - \alpha_{{\rm rad},x})$$

Ver. Emittance:
$$\frac{\mathrm{d}\epsilon_y}{\mathrm{d}t} = \epsilon_y(\alpha_{{\rm IBS},y} - \alpha_{{\rm rad},y})$$

Bunch Length:
$$\frac{\mathrm{d}\sigma_s}{\mathrm{d}t} = \frac{1}{2}\sigma_s(\alpha_{{\rm IBS},s} - \alpha_{{\rm rad},s})$$

Analytical solution difficult, due to dependence of $\alpha_{\rm IBS}$ on $N_b, \epsilon_x, \epsilon_y, \sigma_s$.

Effects on the Emittance – a new regime

Intra-Beam Scattering (IBS)

Multiple small-angle Coulomb scattering within a charged particle beam.

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

Growth Times	Unit	FCC @ 50Z TeV
$1/\alpha_{\mathrm{IBS,s}}$	[h]	29.1
$1/\alpha_{\mathrm{IBS,x}}$	[h]	30.0

(Synchrotron) Radiation Damping

A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.

Emittance Shrinkage

Damping rate is **constant** for a given energy:

$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

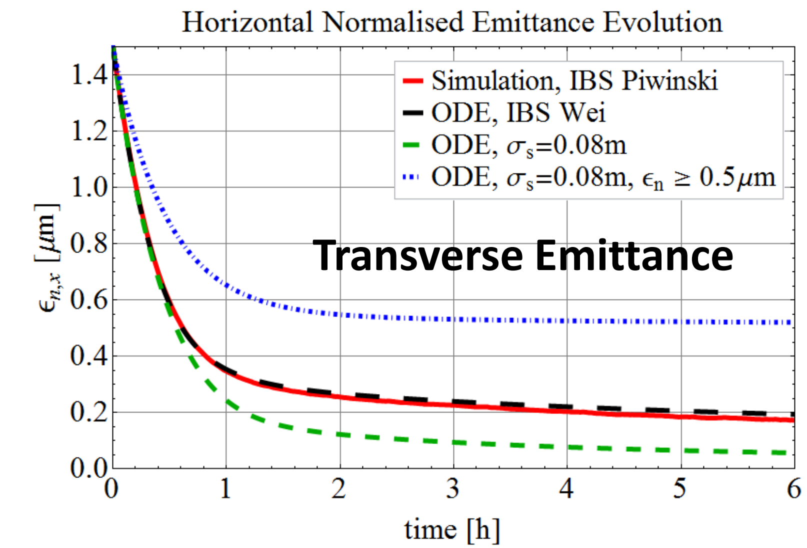
Damping Times	Unit	FCC @ 50Z TeV
$1/\alpha_{\mathrm{rad,s}}$	[h]	0.24
$1/\alpha_{\mathrm{rad,x}}$	[h]	0.49

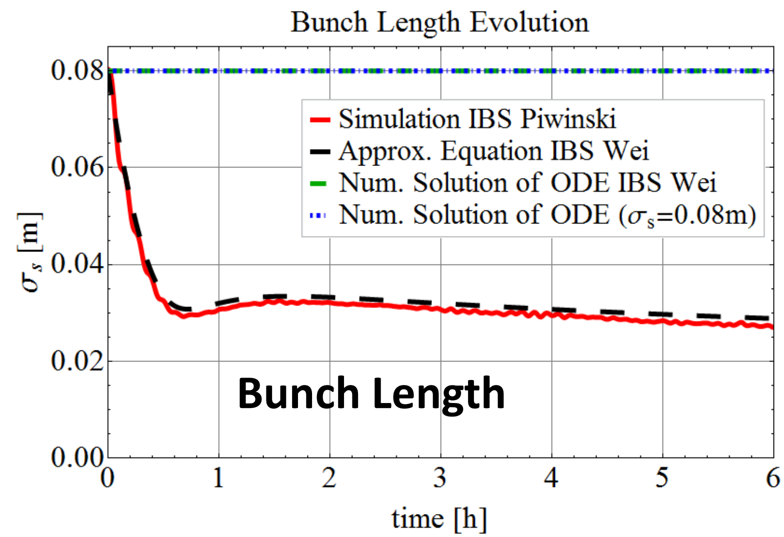
Fast emittance decrease at the beginning of the fill, until IBS becomes strong enough to counteract the radiation damping.

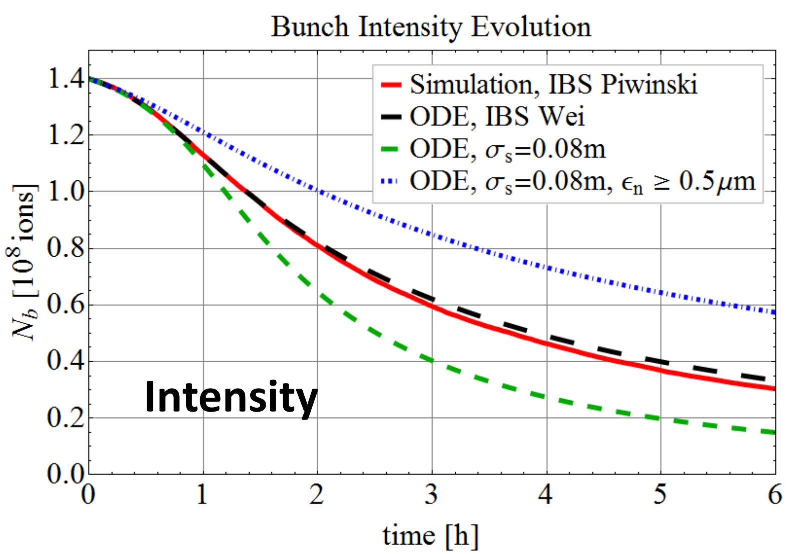
Pb-Pb

BEAM AND LUMINOSITY EVOLUTION

Pb-Pb Beam Evolution



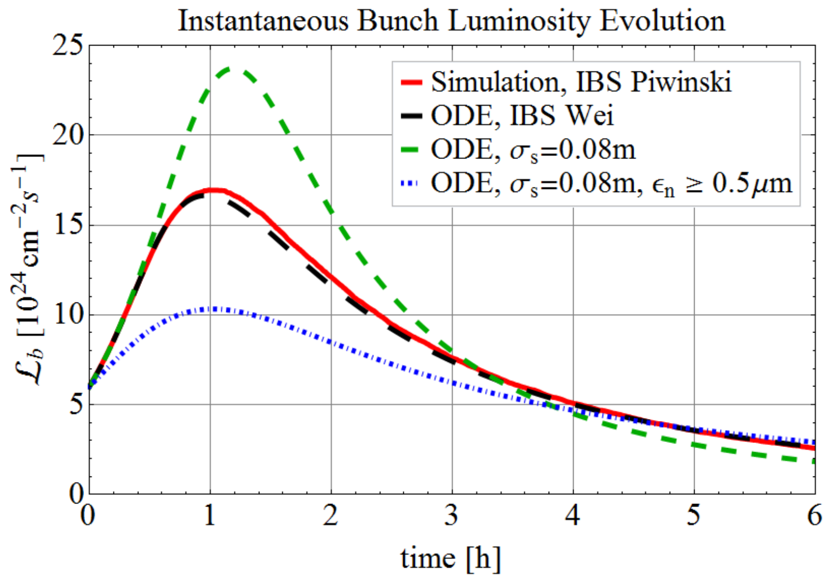


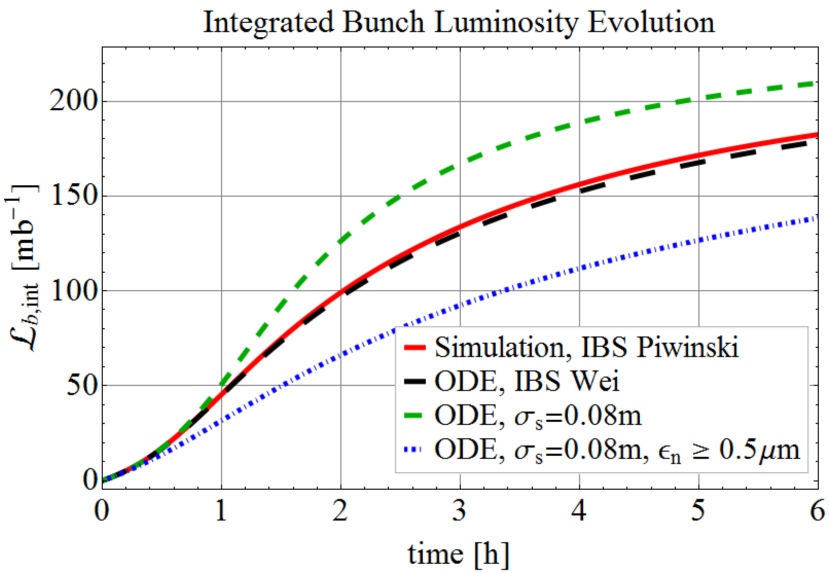


- **Red: tracking simulation** taking into account IBS, rad. damping, burn-off, …
- **Black:** numerical solution of the ODE system on slide 7, using J. Wei's analytical IBS formalism*.
  → emittances and bunch length become very small!
- **Green:** $d\sigma_s/dt = 0$: artificial longitudinal blow-up to σ_s = 8cm.
- **Blue:** artificial longitudinal and transverse blow-up to σ_s = 8cm and $\epsilon_n \geq 0.5\mu m$.

*J. Wei: *Evolution of Hadron Beams under Intrabeam Scattering*, Conf.Proc. C930517 (1993) 3651-3653, PAC 1993.

Pb-Pb Luminosity Evolution





If the beam dimensions become too small and artificial blow-up has to be used, the luminosity will be affected:

- **Peak Enhancement for long. blow-up**, since long. and horizontal IBS are reduced, due to larger $\sigma_s \rightarrow$ smaller ϵ_n.
- **Reduced luminosity**, due to blown-up ϵ_n.

Summary for free beam evolution

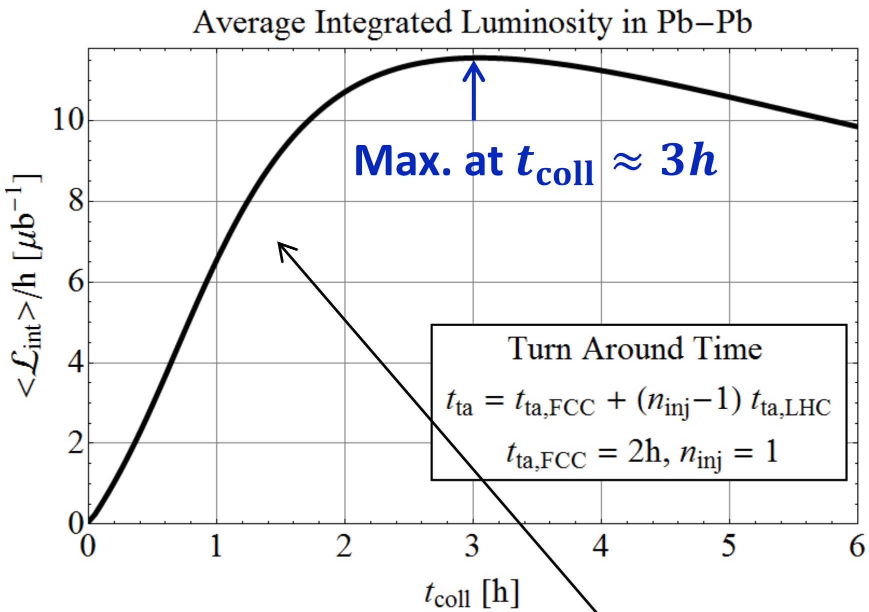
(no artificial blow-up)

	Unit	per Bunch	whole Beam
L_{initial}	[Hz/mb]	0.006	2.6
L_{peak}	[Hz/mb]	0.017	7.3
$L_{\mathrm{int,fill}}$	[μb^{-1}]	0.13	57.8

Pb-Pb Average Luminosity

Average Luminosity per hour:

$$\langle \mathcal{L}_{\mathrm{int}} \rangle = \frac{1}{t_{\mathrm{coll}} + t_{\mathrm{ta}}} \int_0^{t_{\mathrm{coll}}} \mathcal{L}_{\mathrm{inst}}(t)\mathrm{d}t$$



t_{coll} = time in collisions → *to be optimised*

For free beam parameter evolution, red case from previous slide.

$$t_{\mathrm{ta}} = t_{\mathrm{ta,FCC}} + (n_{\mathrm{inj}} - 1)t_{\mathrm{ta,LHC}}$$

= turn-around time

= time dump → next collisions

Assumption $\boldsymbol{t_{\mathrm{ta,FCC}} = 2h}$ (cycle time FCC, without injections)

$\boldsymbol{n_{inj} = 1}$ (no. injections from LHC)

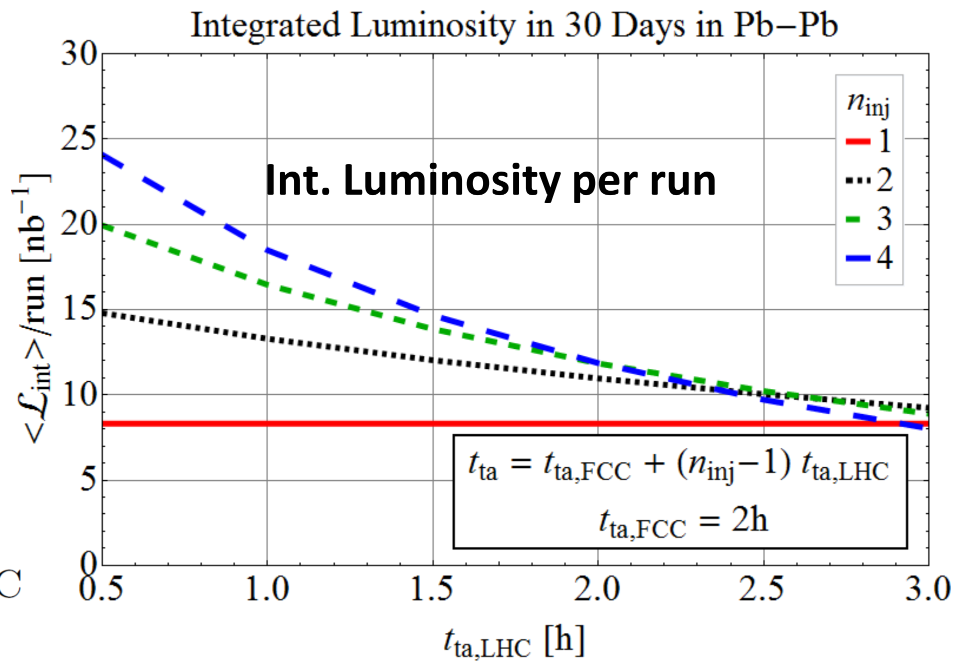
Pb-Pb Integrated Luminosity per Run

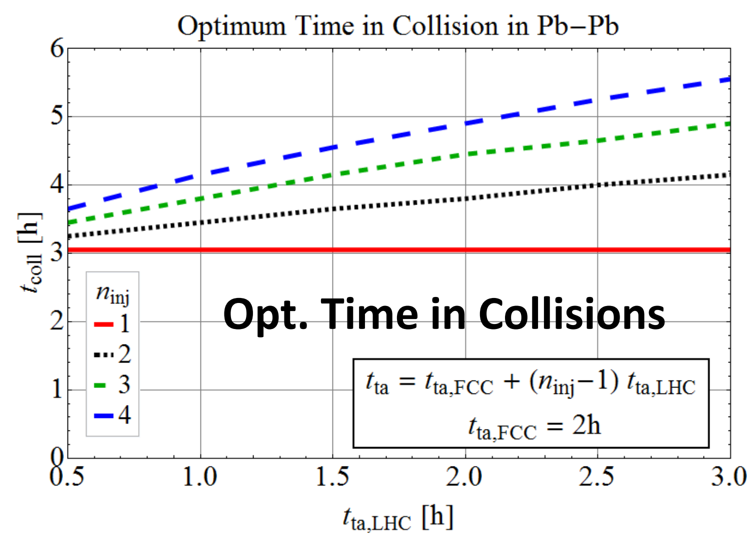
- Assumption $t_{ta,FCC} = 2h$.

- **Consider more LHC injections**:
  → max. $n_{inj} = 4$ (= FCC Length)
  → Dwell time at FCC inj. plateau
    → lengthen
    $$t_{\rm ta} = t_{\rm ta,FCC} + (n_{\rm inj} - 1)t_{\rm ta,LHC}$$
  → Particle losses (& emittance growth)
    → Loss rate of Pb at injection: $R_{\rm loss} = 5\%$
    → Total beam intensity:

$$N_{\rm beam} = k_b N_b \sum_{i=1}^{n_{\rm inj}} (1 - R_{\rm loss} t_{\rm ta}(i-1))$$

→ <□$_{int}$> □ $(N_{beam}/k_b N_b)^2 \times$ <□$_{int}$>



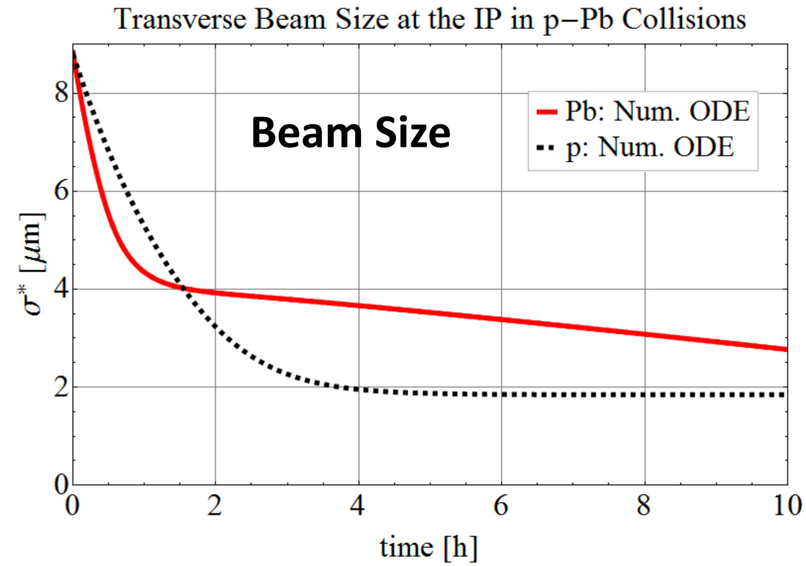


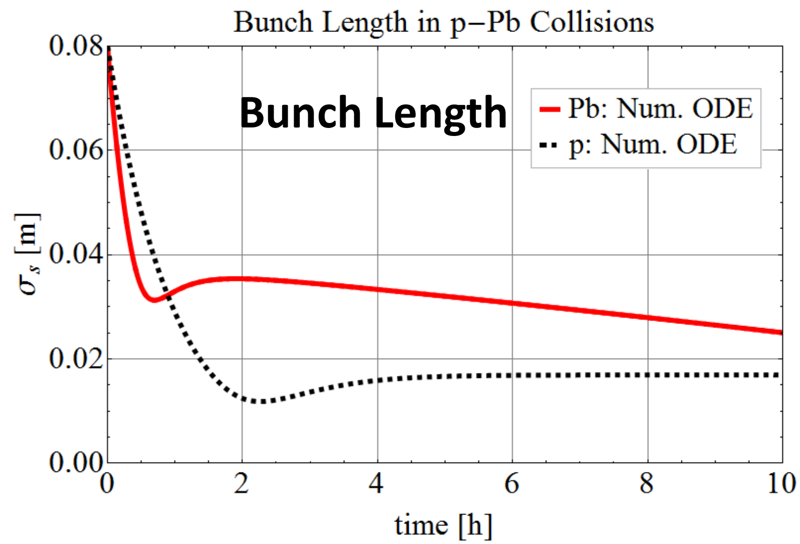
p-Pb

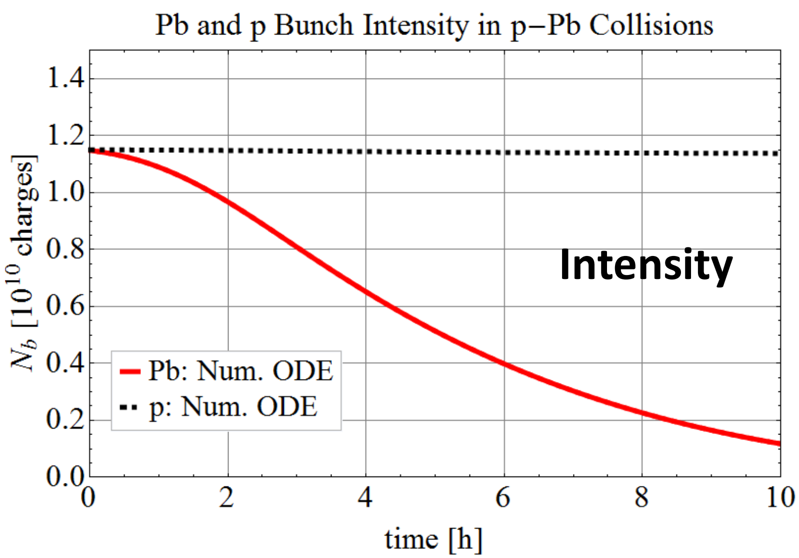
BEAM AND LUMINOSITY EVOLUTION

LHC has shown that p-Pb, injecting and ramping with unequal revolution frequencies is feasible. This will work for injection (provided we keep independent RF systems) and may not even be necessary in FCC ring.

p-Pb Beam Evolution (1 Experiment)



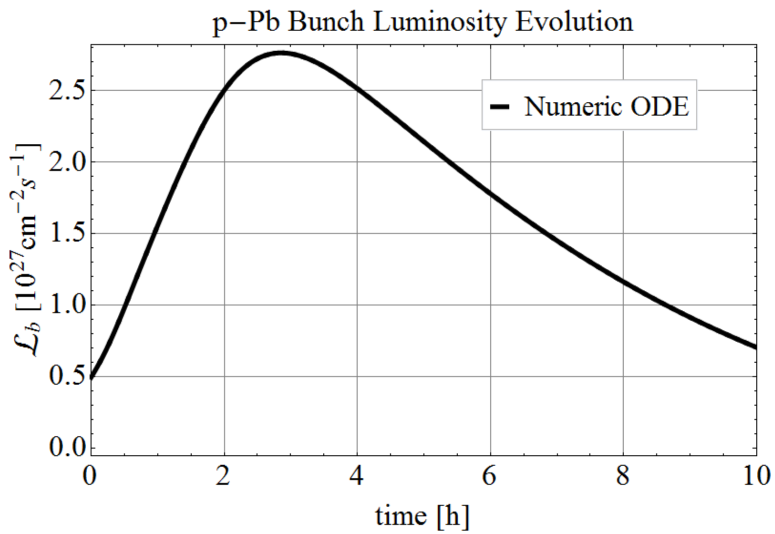




Initial conditions:

- Pb-beam as for Pb-Pb operation.
- Equal beam sizes, σ*, for p and Pb.
- Rad. damping $\propto Z^5/A^4 \approx 2$
  $\rightarrow 2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$
- IBS scales with $\propto (Z^2/A)^2 N_b$
- $N_b(\mathrm{p}) \approx 100\, N_b(Pb)$
  $\rightarrow$ Fast Pb burn-off, while $N_b(\mathrm{p}) \approx$ const.

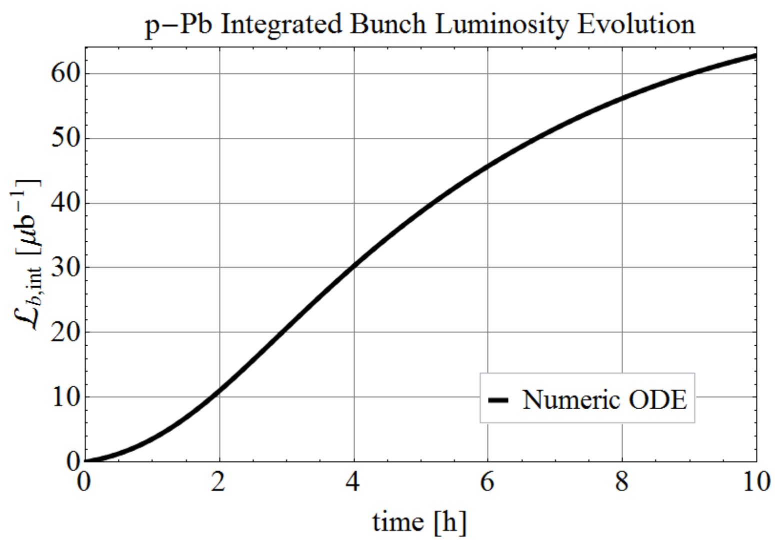
p-Pb Luminosity Evolution (1 Experiment)



Peak shifted to later times
→ p shrinks slower than Pb

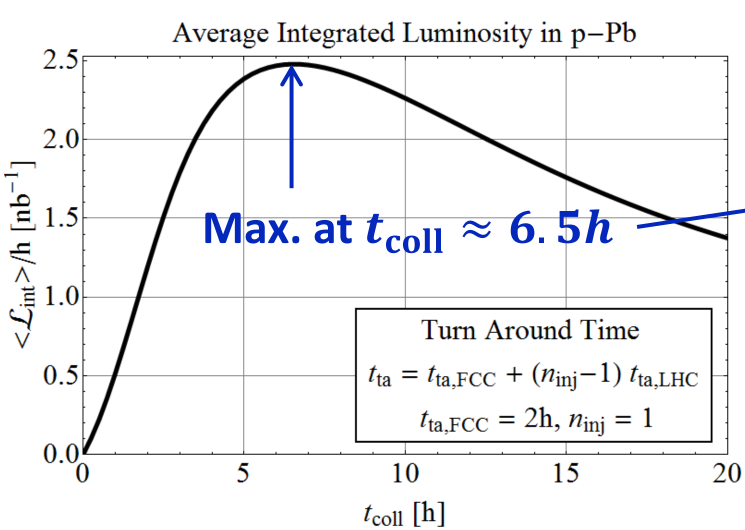
$$2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$$

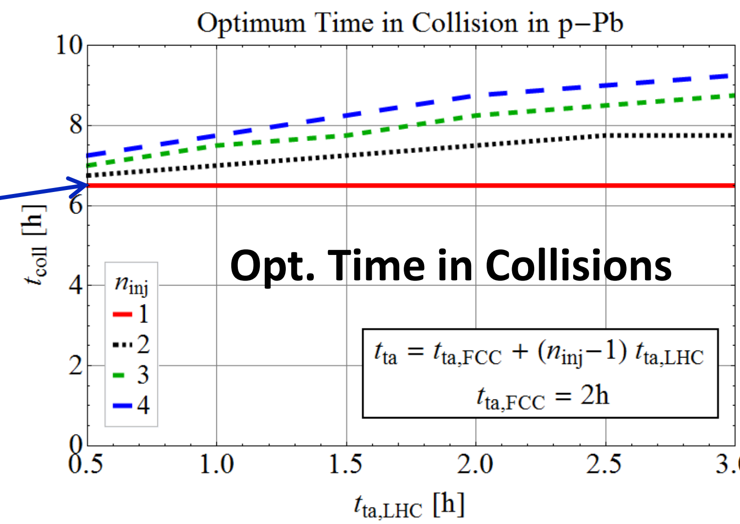
Luminosity decay slower
→ N_b(p) ≈ const.
→ 1/e-Luminosity lifetime ≈ 14h.

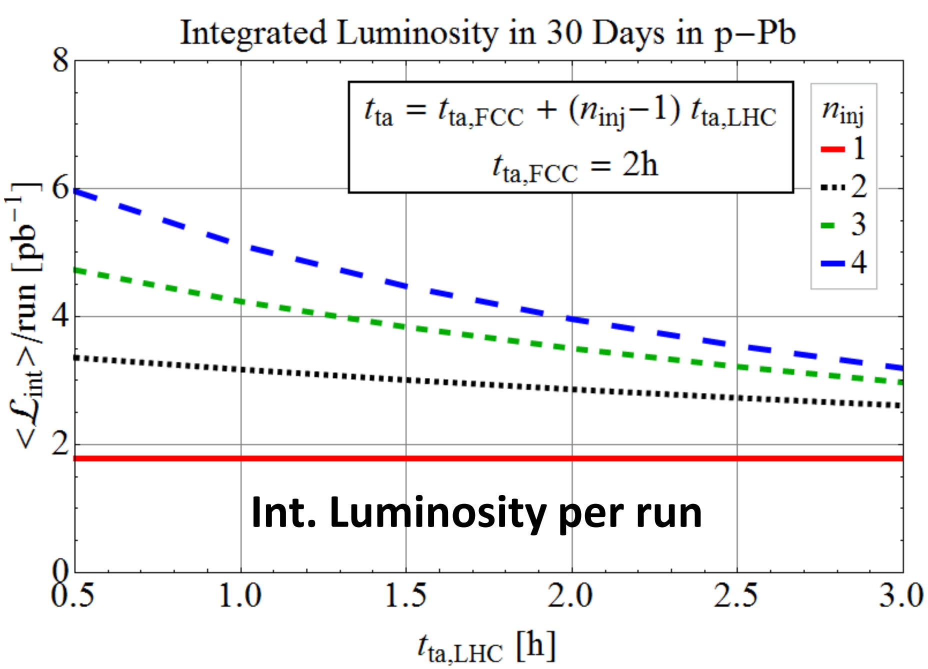


	Unit	per Bunch	whole Beam
L_{initial}	[Hz/mb]	0.5	213
L_{peak}	[Hz/mb]	2.8	1192
$L_{\mathrm{int,fill}}$	[μb^{-1}]	48.7	21068

p-Pb Luminosity vs. Turn-Around Time







For $n_{inj} = 1$

→ Optimised fill length = 6.5h

→ $<\square_{int}>$/run ≈ 1.7pb^{-1}

$n_{inj} > 1$ could give higher $<\square_{int}>$/run

→ But **uncertainty** on prediction significantly enhanced.

→ Early beam aborts and longer inj. times, due to lost beams in the LHC, reduce $<\square_{int}>$/run.

→ injection and fill times are both in the order of **10h**!

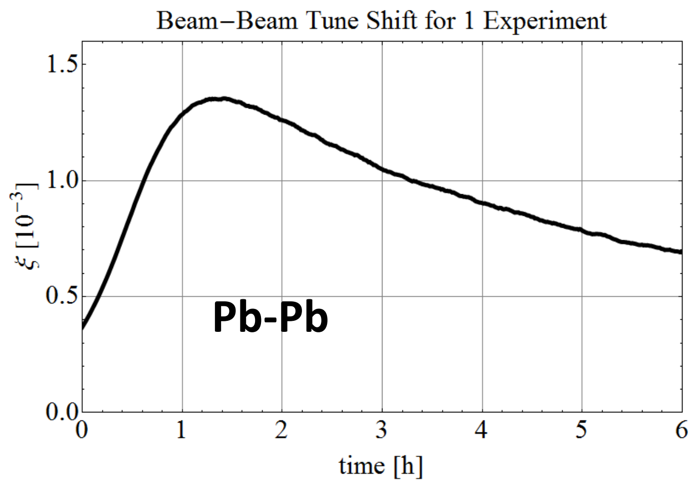
POTENTIAL LIMITATIONS

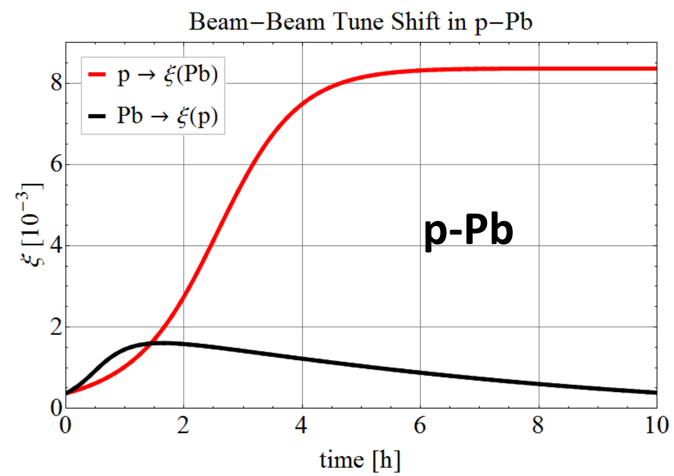
Beam-Beam Tune Shift

Beam-beam tune shift per experiment:

- Beam *m* receives kick from Beam *n*
- *u,v =x, y*

$$\xi_{m,u} = \frac{N_{b,n} r_{p0} Z_m Z_n \beta^*}{2\pi A_m \gamma_m \sigma_{n,u}(\sigma_{n,u} + \sigma_{n,v})}$$





Beam-Beam Parameter per Experiment	Unit	LHC Design p-p	LHC Design Pb-Pb	FCC Pb-Pb	FCC p-Pb
Initial	$[10^{-3}]$	3.7	0.18	0.37	0.37
Peak	$[10^{-3}]$	3.7	0.18	1.4	8.3

The tune shift due to beam-beam interactions remains well below assumed limit for Pb-Pb, but comes close to the limit for Pb in p-Pb collisions.

γ-γ and γ-A processes in Pb-Pb collisions at FCC-hh

$$\text{BFPP1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$

$$\sigma = 354\ \text{b}, \quad \delta = 0.01235$$

$$\text{BFPP2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{80+} + 2e^{+},$$

$$\sigma \approx 10\ \text{mb}, \quad \delta = 0.02500$$

$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n\ ,$$

$$\sigma = 200\ \text{b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{P b}^{82+} + {}^{206}\text{Pb}^{82+} + 2n\ ,$$

$$\sigma = 35\ \text{b}, \quad \delta = -0.00970$$

Each of these makes a secondary beam emerging from the IP with rigidity change

$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Hadronic cross section is 8 b (so much less power in debris).

Extensively discussed for LHC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 071002 (2009)

Beam losses from ultraperipheral nuclear collisions between $^{208}\text{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

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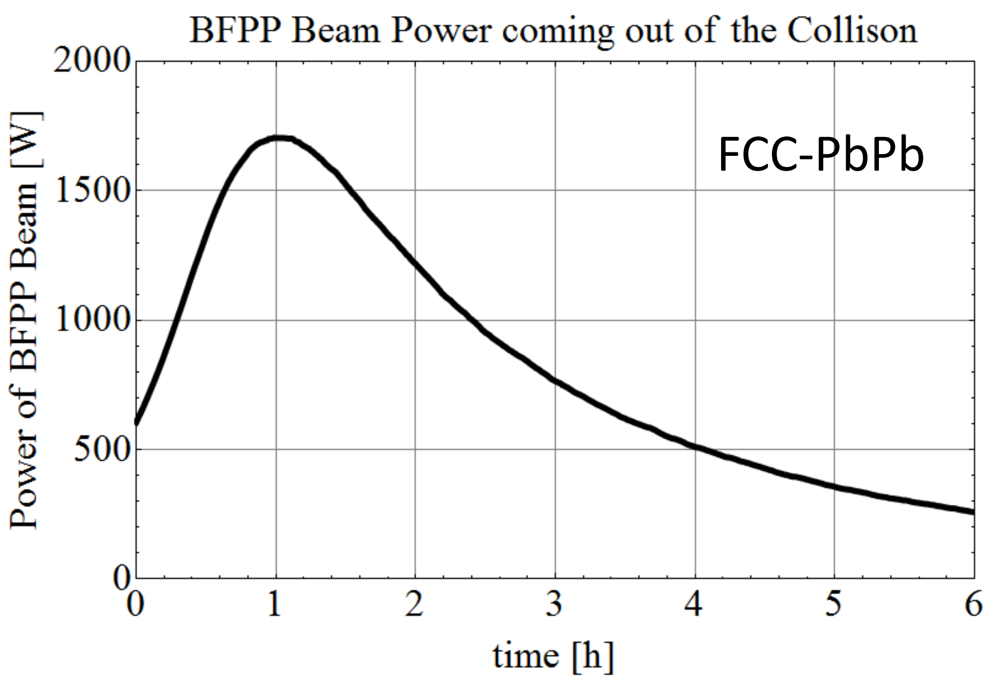
(Received 13 May 2009; published 29 July 2009)

BFPP1 Beam Power in Pb-Pb for FCC-hh

BFPP1 Beam power: $P = \sigma_c \, L \underbrace{E}_{4.1\ \text{PeV}} \approx 1.7\ \text{kW (peak)}$

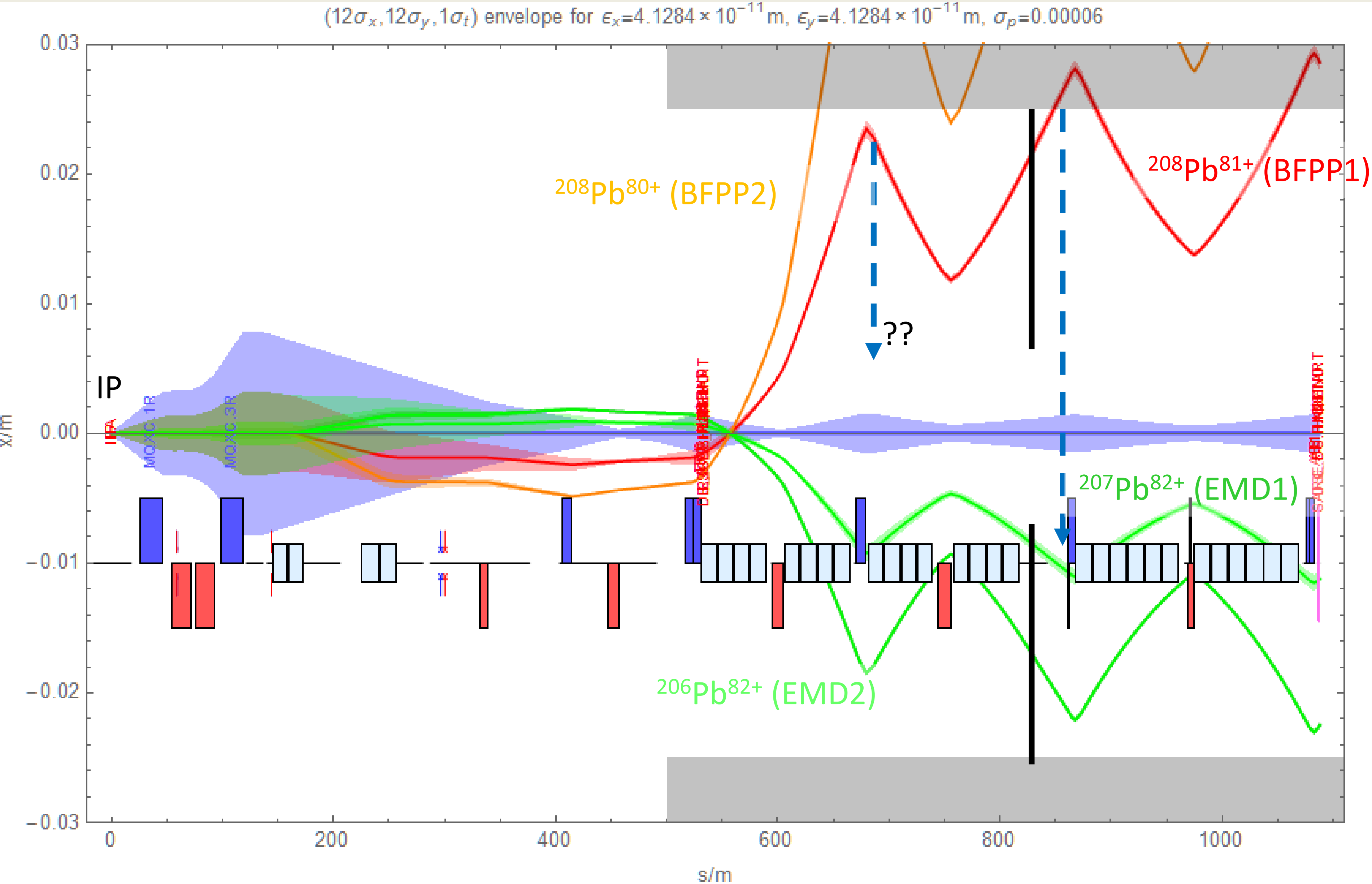
nominal LHC: $P \approx$ 26W

→ already expected to cause operational problems and poaaible long-term damage



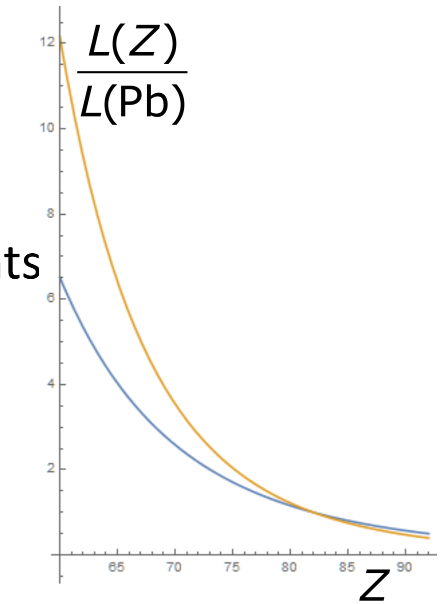
Countermeasures (e.g., DS collimators) have to be considered in initial lattice & hardware design.

Secondary beams from Pb-Pb collisions (Lattice V4 baseline)



Smaller Z Ions – Impact on hadronic event count

- Lower Z possibly higher N_b available from injectors
- Contribution of ultra-peripheral electromagnetic processes to the total cross-section would be reduced:
  - $\sigma_{\mathrm{BFPP}} \propto Z^7$
  - $\sigma_{\mathrm{EMD}} \propto Z^4$
  - ➢ Increased luminosity lifetime, more particles available for hadronic interactions.
  - ➢ Reduced secondary beam power emerging from collision point.
- Radiation damping rate does not change much for Z>60:
  - $\alpha_{\mathrm{rad}} \propto Z^5/A^4$



- Lower Z beams would put more burn-off into hadronic events

$$N_{\mathrm{hadronic}} = \sigma_h \int L\,dt \propto \frac{\sigma_h}{\sigma_h + \sigma_{\mathrm{BFPP}} + \sigma_{\mathrm{EMD}}} N_{tot} \propto Z^{-(6\text{--}8)}$$

- Worth considering small Z reduction from Pb to, e.g.,

Heavy-Ion Beam Parameter Summary

	Unit	LHC Design	FCC Injection	FCC Collision	FCC Collision
General Beam Parameters					
Operation mode	-	Pb-Pb	Pb	Pb-Pb	p-Pb
Beam energy	[TeV]	574	270	4100	50
Relativistic γ-factor		2963.5	1397	21168	53290
No. of bunches	-	592	432		
No. of particles per bunch	[10^8]	0.7	1.4		115
Transv. norm. emittance	[μm.rad]	1.5	1.5		3.75
RMS bunch length	[cm]	7.94	10.0	8.0	
RMS energy spread	[10^{-4}]	1.1	1.9	0.6	
Long. emittance (4σ)	[eVs/charge]	2.5	2.6	10.1	
Circulating beam current	[mA]	6.12	2.38		
Stored beam energy	[MJ]	3.8	2.6	39.8	
Intra Beam Scattering					
Long. IBS emit. growth time	[h]	7.7	6.2	29.2	4×10^3
Hor. IBS emit. growth time	[h]	13	10.0	30.0	4×10^3
Synchrotron Radiation					
Long. emit. rad. damping time	[h]	6.3	852	0.24	0.5
Hor. emit. rad. damping time	[h]	12.6	1704	0.49	1.0
Power loss per ion	[W]	2.0×10^{-9}	1.1×10^{-11}	5.7×10^{-7}	3.4×10^{-9}
Power loss per meter in main bends	[W/m]	0.005	1.0×10^{-5}	0.53	0.26
Energy loss per ion per turn	[MeV]	1.12	0.01	775.3	4.7
Synchrotron radiation power per ring	[W]	83.9	0.7	34389	17016
Critical photon energy	[eV]	2.77	0.08	269.3	4300.8

Heavy-Ion Luminosity Summary

	Unit	LHC Design	FCC Collision	FCC Collision
Luminosity				
Operation mode	-	Pb-Pb	Pb-Pb	p-Pb
β-function at the IP	[m]	0.5	1.1	
Initial RMS beam size at IP	[μm]	15.9	8.8	
Initial luminosity	[Hz/mb]	1	2.6	213
Peak luminosity	[Hz/mb]	1	7.3	1192
Integrated luminosity per fill	[μb^{-1}]	<15	57.8	21068
Integrated luminosity per run	[nb^{-1}]	-	8.3	1784
Initial bb tune shift per IP	[10^{-4}]	1.8	3.7	3.7
Total cross-section	[b]	515	597	2
Peak BFPP beam power	[W]	26	1705	0
Initial beam current lifetime	[h]	<11.2 (2 exp.)	10.9	39.3
Luminosity lifetime ($\mathcal{L}_0/e$)	[h]	<5.6 (2 exp.)	6.2	14.0

Future work needed

- Number of active experiments to be considered very carefully! 1 or 2 ?
- Counter measures for (few kW) secondary beams from IPs
  - Robust collimators/absorbers in dispersion suppressors
  - Shower calculations, magnet quench risks, etc.
- Include heavy ion beams in future evolution of injector chain
  - Maximise no. of ions injected in collider!!
  - Do we have to live with present limits in SPS?
- Extend LHC heavy-ion collimation studies to FCC
  - Does synchrotron radiation damping solve this for us ?
- Vacuum effects?

Collaboration welcome!

Conclusions and Outlook

- With very conservative assumptions (past LHC Pb beams), FCC-hh has clear potential for high luminosity nucleus-nucleus and proton-nucleus collisions
- New, highly efficient collider regime of strong radiation damping can be fully exploited with heavy-ion beams
- Photon-photon and photonuclear processes create powerful secondary beams emerging from IP
  - Foresee counter-measures *from the start* (cf LHC experience)
- Extreme luminosity burn-off is a fact of nature – physics community might want to consider somewhat lower-Z species ?

BACKUP SLIDES