DAFNE-TF to benchmark models and probe Future Circular Colliders (HE-LHC and FCC-hh) challenges in optics and collective effects

T. Pieloni for many colleagues of FCC-hh and HE-LHC teams

C. Tambasco, X. Buffat, S. Antipov, S. Arsenyev, F. Giordano, J. Keintzel, B. Salvant, L. Mether, M. Migliorati, G. Rumolo, G. Iadarola, M. Giovannozzi, E. Metral, M. Schenk, S. Furuseth, N. Biancacci, M. Migliorati, N. Mounet, R. Tomas, B. Salvachua, L. Coyle , F. Zimmermann, D. Schulte, J. Wenninger….and many more.

Thanks to M. Zobov for useful discussions

Outline

- FCC-hh and HE-LHC colliders: layout and parameter tables
- Challenges and possible studies: synchrotron radiation and benchmark
- Collective effects and optics
  - Beam-beam effects and limits
  - Two beam impedance
  - Coherent effects: impedance, beam-beam and electron cloud
  - BTFs and Landau damping
  - Low beta insertions and strong beam-beam head-on effect
- Machine learning techniques applied to accelerator optimization
- Summary

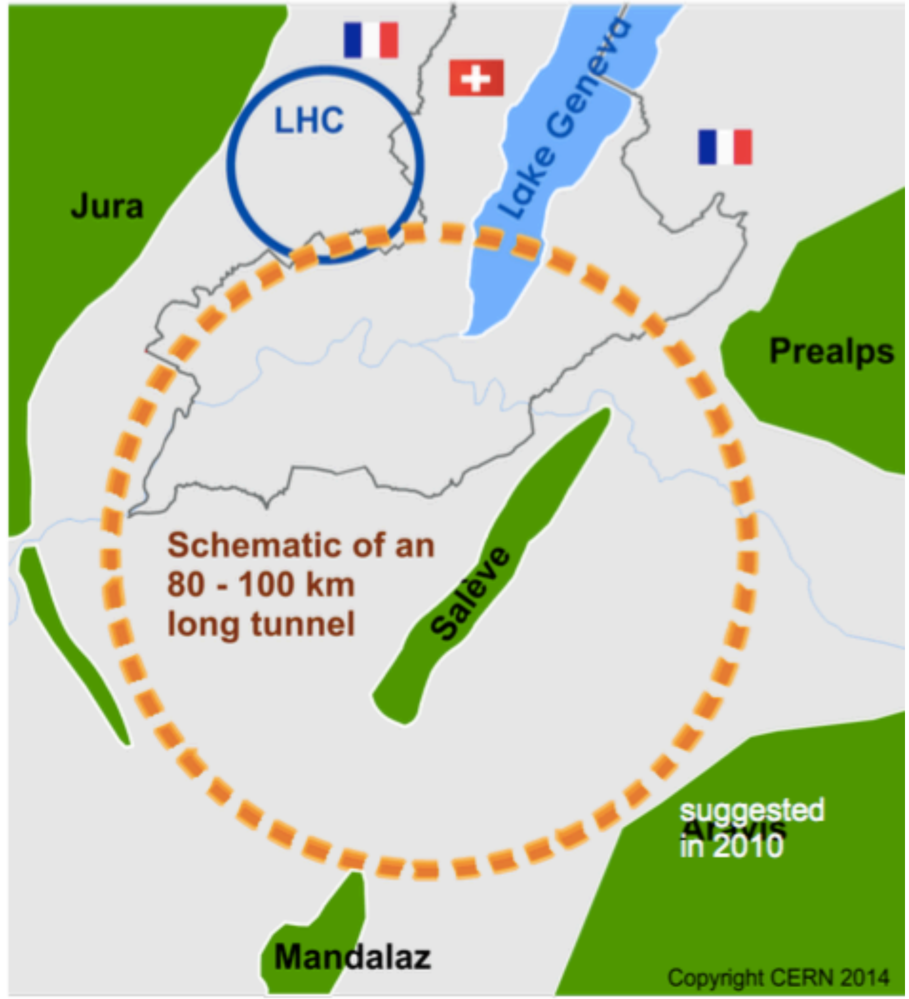
Future Circular Collider Study
CDR for European Strategy Update 2019/20

international FCC collaboration (CERN as host lab) to design:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

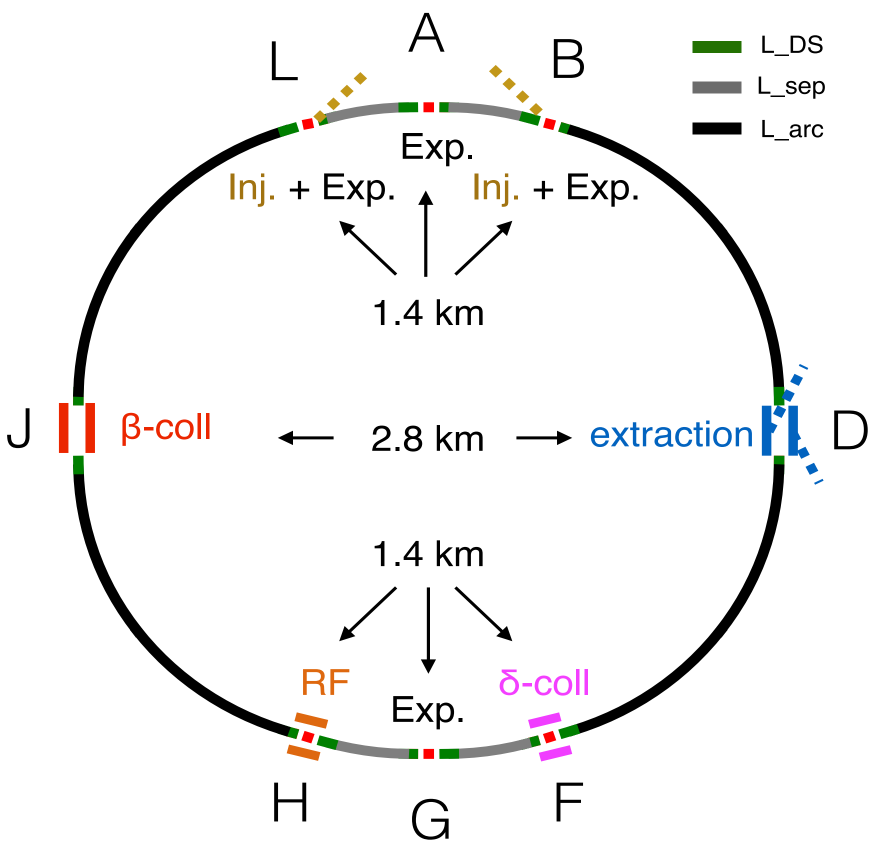
~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),**
  as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



F. Zimmermann HE-LHC review Dec 2017

Future Circular Collider-hh (FCC-hh)



Physics Goals:

7x LHC collision energy with FCC-hh magnet technology (16 Tesla SC magnets)

c.m. energy = 100 TeV

target luminosity ≥ ab^{-1} over 20 years

key technologies:

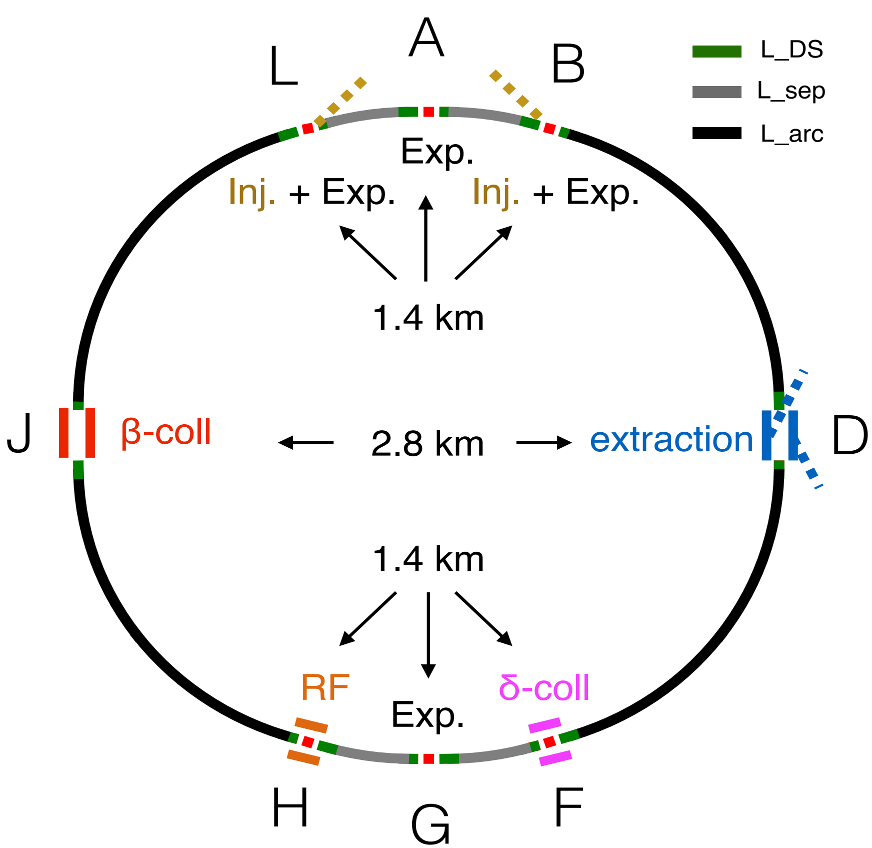
Superconducting magnets 16 Tesla & vacuum system

Crab cavities for geometric overlap (20%)

beam:

HL-LHC/LIU parameters (25 ns baseline)

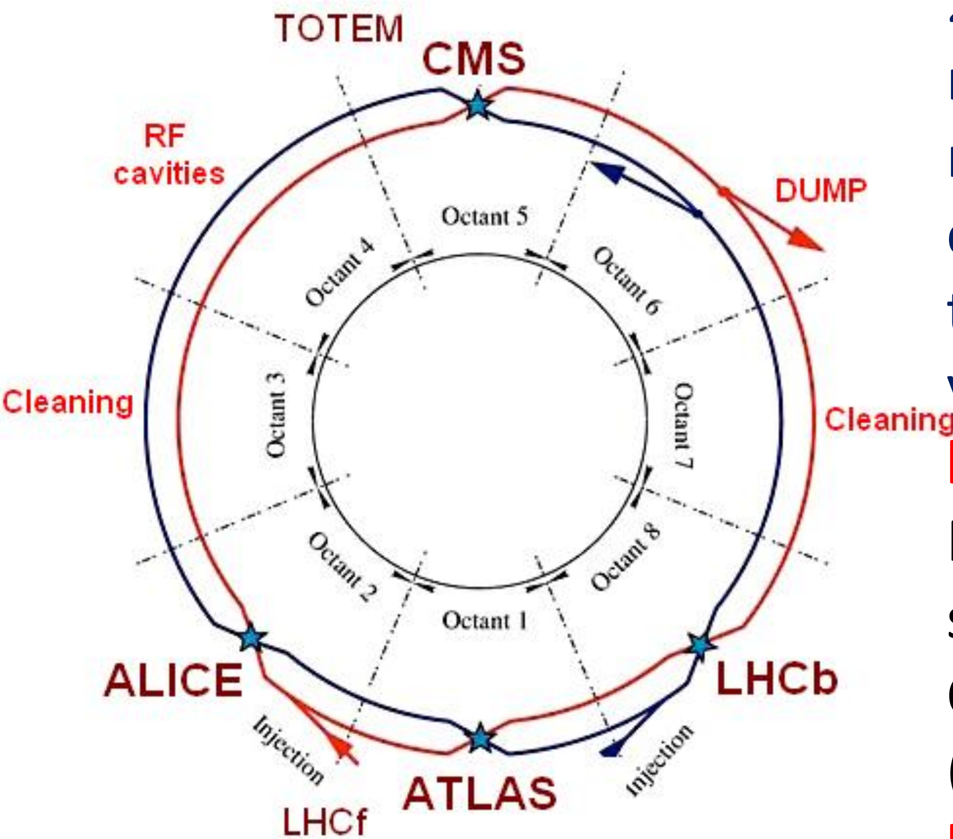
Future Circular Collider-hh (FCC-hh)



Two high-luminosity experiments
(A and G)
Two **low luminosity experiments**
combined with injection (L and B)
Two collimation insertions
Betatron cleaning (J)
Momentum cleaning (F)
Extraction insertion (D)
Clean insertion with **RF** (H)

Circumference 97.75 km
Can use LHC or SPS as injector

High Energy LHC (HE-LHC)



physics goals:

2x LHC collision energy with FCC-hh magnet technology (16 Tesla SC magnets)

c.m. energy = 27 TeV 14TeV x 16T/8T

target luminosity ≥ 10 ab^{-1} over 20 years

key technologies:

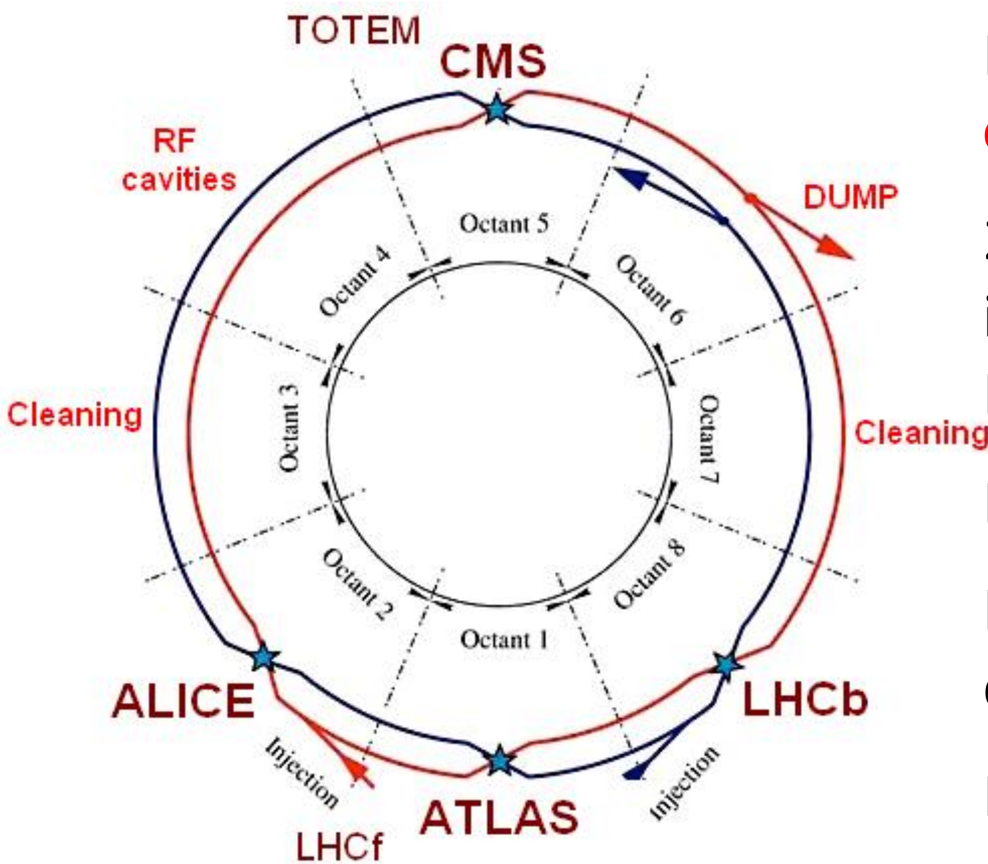
FCC-hh magnets 16 Tesla & vacuum system

Crab cavities for geometric overlap (50%)

beam:

HL-LHC/LIU parameters (25 ns baseline)

Hadron colliders at Higher energies



IR 1& 5 Two **high-luminosity experiments**

2 **secondary experiments** (perhaps including one e-p collision point) in IRs 2 & 8, shared with injection

IR3: **momentum collimation**

IR4: **radiofrequency (RF)** and diagnostics

IR6: **beam extraction**

IR7: **betatron collimation**

Hadron Colliders Parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		**27**	14	14
dipole field [T]	16		**16**	8.33	8.33
circumference [km]	97.75		**26.7**	26.7	26.7
beam current [A]	0.5		**1.1**	1.1	0.58
bunch intensity [10^{11}]	1	1	**2.2**	2.2	1.15
bunch spacing [ns]	25	25	**25**	25	25
synchr. rad. power / ring [kW]	2400		**101**	7.3	3.6
SR power / length [W/m/ap.]	28.4		**4.6**	0.33	0.17
long. emit. damping time [h]	0.54		**1.8**	12.9	12.9
beta* [m]	1.1	0.3	**0.25 (min)**	0.15 (min.)	0.55 (0.25)
normalized emittance [μm]	2.2		**2.5**	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	**28**	5 (lev.)	1
events/bunch crossing	170	1000	**800**	132	27
stored energy/beam [GJ]	8.4		**1.3**	0.7	0.36

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Max Beam-Beam tune shift (2-4 Exp)	**0.03-0.06**		**0.02-0.04**	**0.02**	**0.018**

Pushed beam-beam effects, collimation (impedance), electron cloud effects, interaction region optics…

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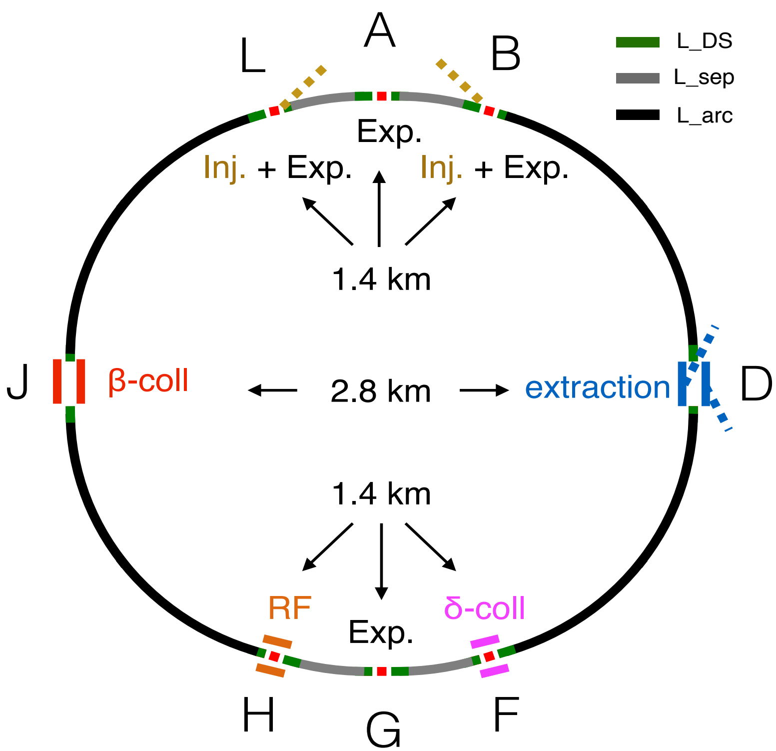
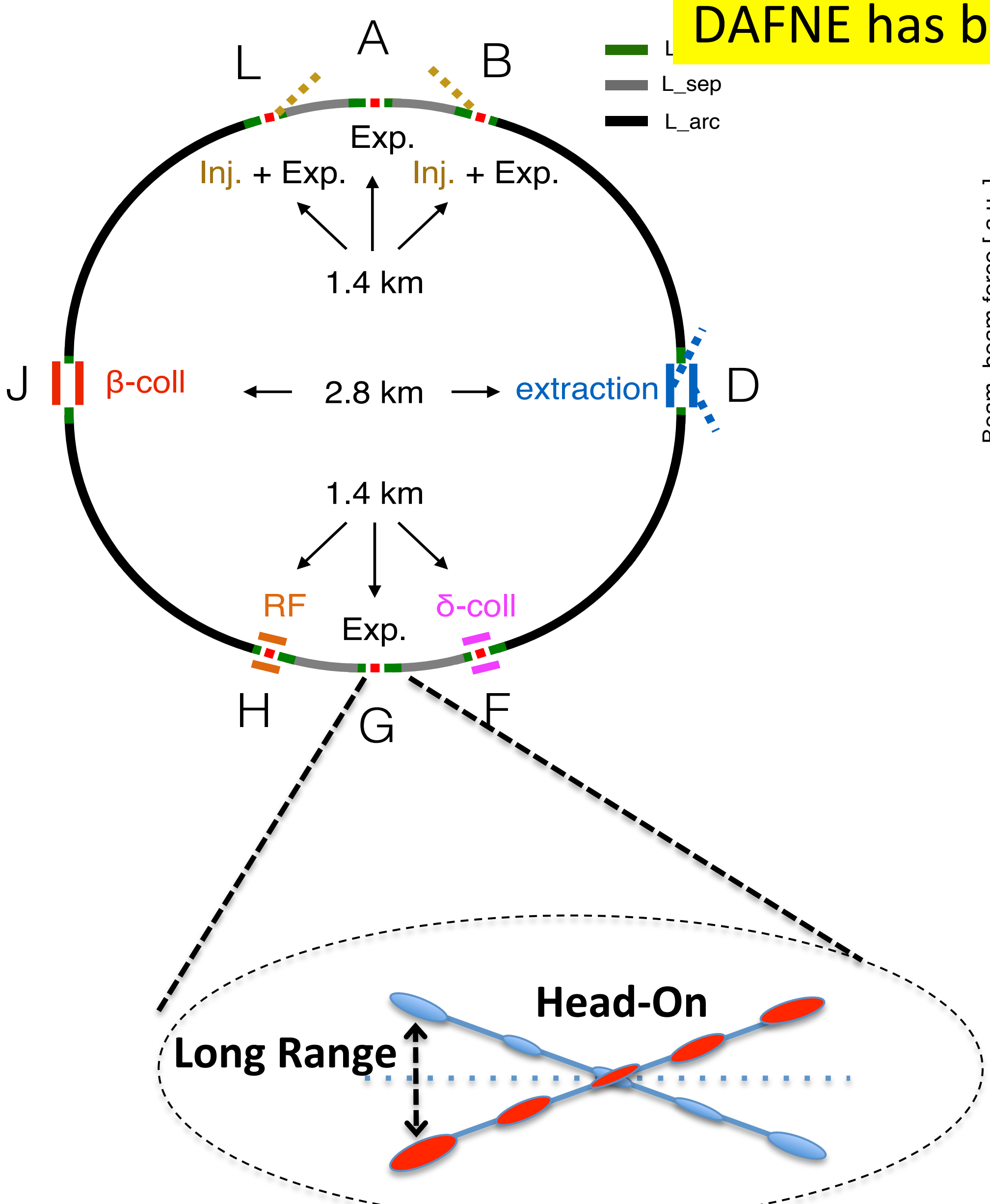
Radiation damping becomes a non negligible effect in Proton dynamics

Models need up-grade and benchmark → study impacts on dynamics

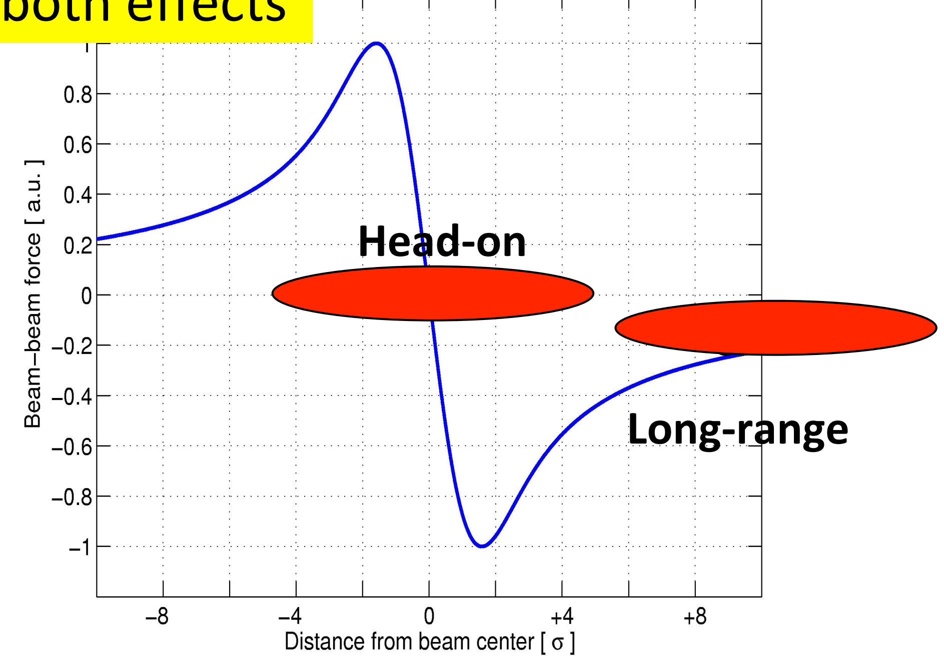
Beam-Beam Effects



Beam-Beam Effects



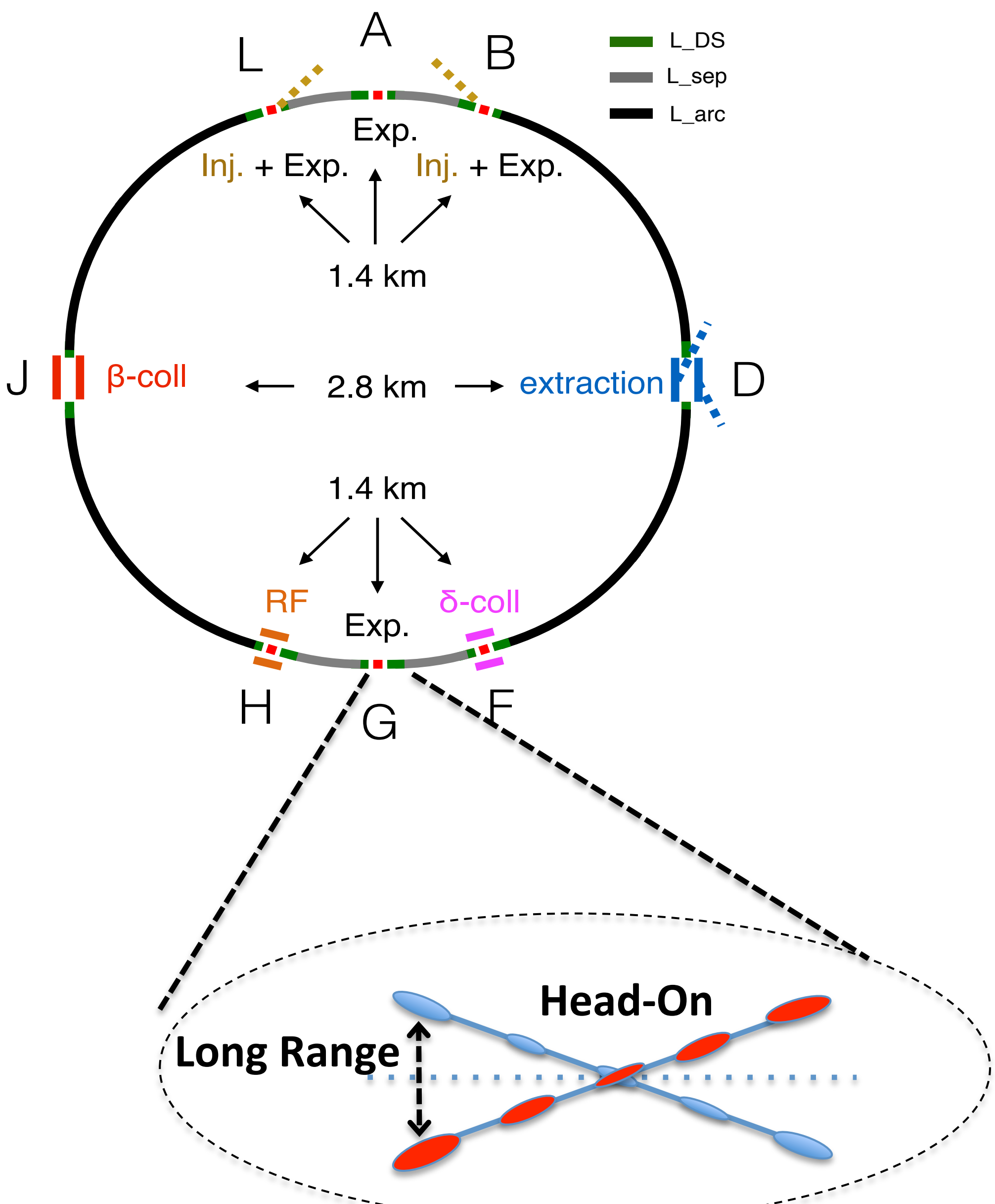
DAFNE has both effects

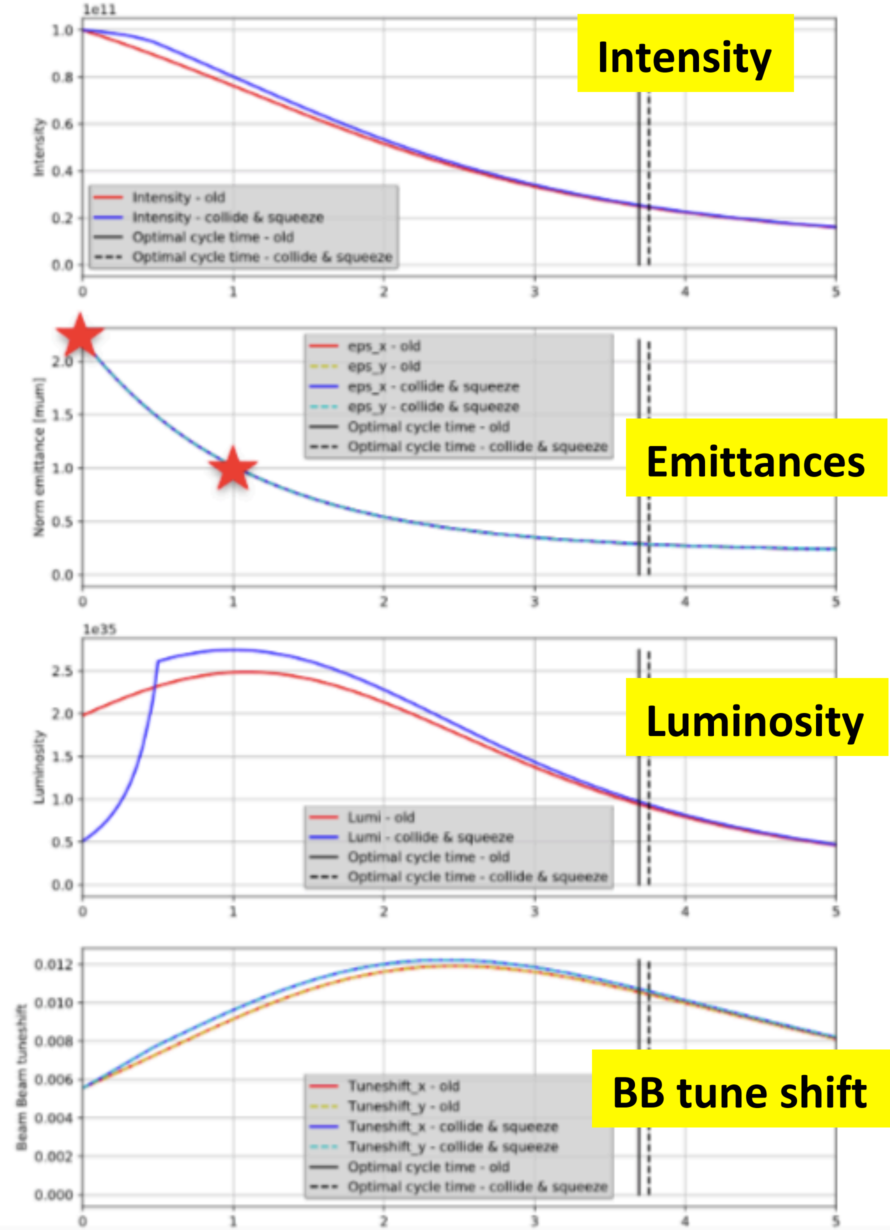


For 25 ns bunch spacing :

- 2 (4) Head-on collisions → **total maximum BB tune shift of 0.03** (0.06 with two lower luminosity experiments)
- **360 Long-range** interactions

FCC-hh parameters evolution





X. Buffat and S. Arseniev

FCC-hh parameters evolution

Emittance shrinking :

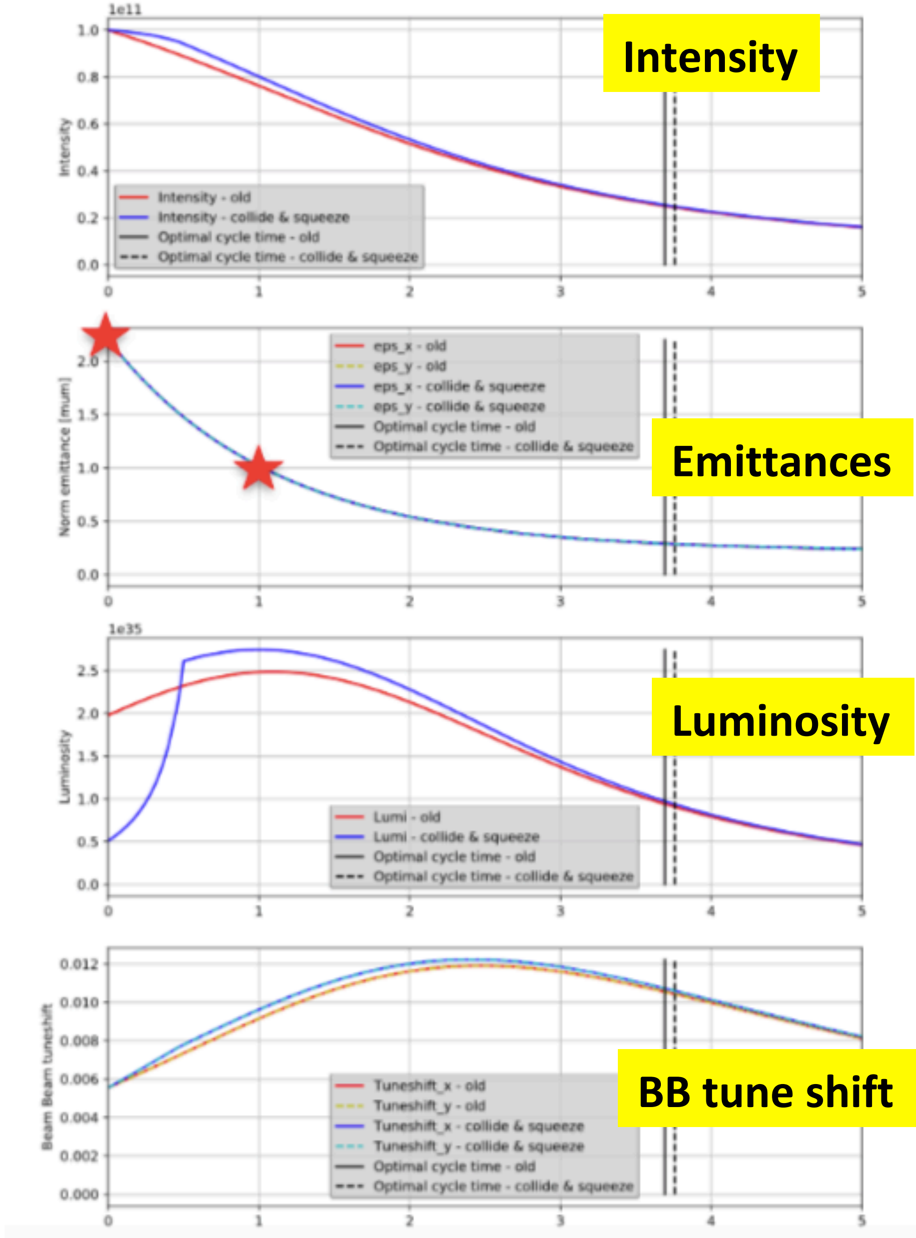
- larger head-on BB
- Weaker long-ranges

Where are the limits?

Beam-beam models and collective effects should account for radiation damping on protons!

What will change in the beam dynamics? Specially in interplays with other collective effects and pushed optics?

Explore mitigation techniques.



X. Buffat and S. Arseniev

Radiation damping
Models upgrade and benchmark

Collective effects **codes** need to be **upgrade** to take into account radiation damping which so far was not relevant in the LHC and HL-LHC

Up-date models (COMBI code for beam-beam effects) with relevant physics effects, model the DAFNE lattice and interaction region layout

→ **benchmark for different damping scales** (wigglers) the beam-beam effects (luminosity evolution, particle losses/background, emittance and tune spreads)

→ This should be repeated **for different beam-beam strengths and type of interactions**:
- → For different head-on parameters
- → For different long-range effects
- → With two experiments → study the impact of phase advance on beam-beam effects (orbit effects, beating compensation or enhancements, stronger head-on effect to test limits)

…many more combinations possible following the DAFNE experience and particularity

Radiation damping
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Work: up-grade codes and model DAFNE beam-beam effects
Might require changes in IR optics (separation bumps, crossing angle reduction), turn back on the second experiment, arcs lattice to have tunable phase advance between two collision points
Will need DAFNE collective effects and optics experts

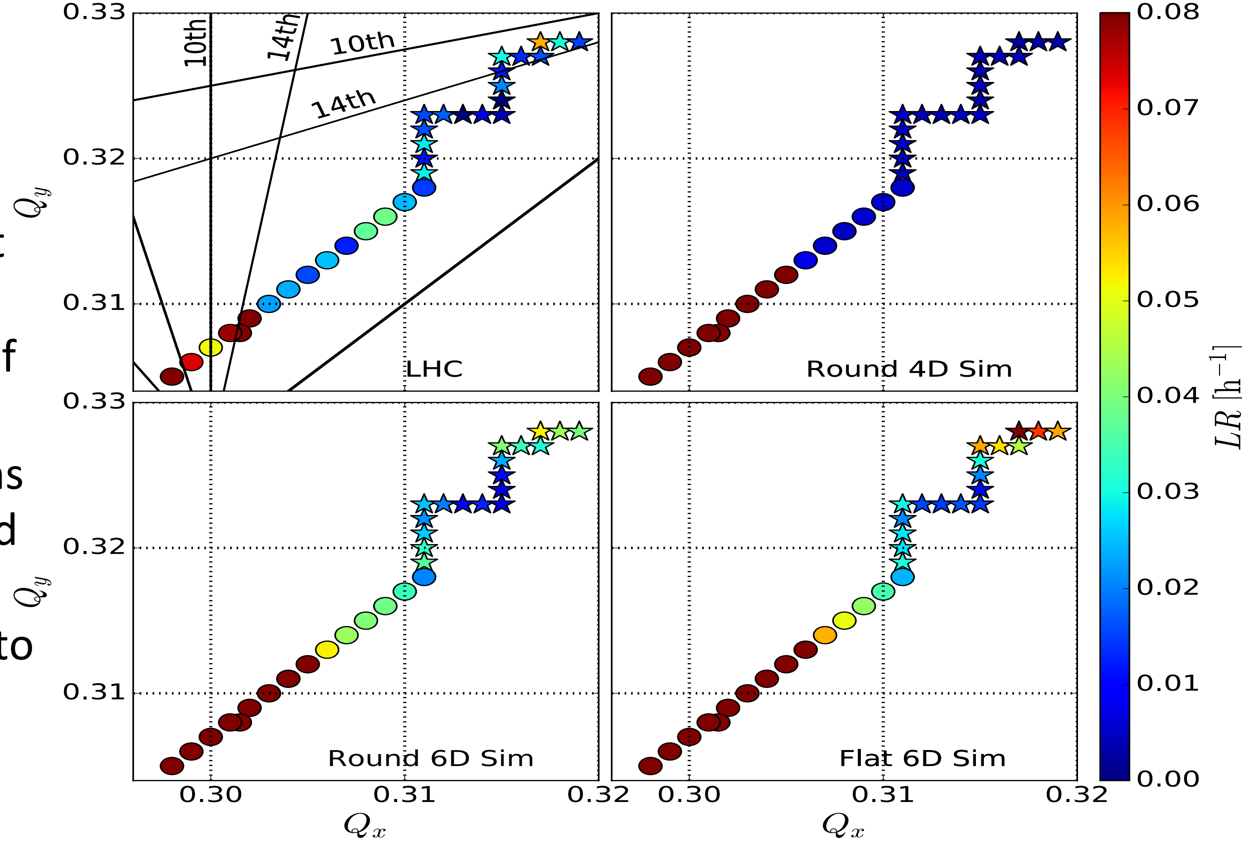
Head-on limitations
Emittance growth and losses

Model developed for FCC-hh of loss rates with 6D beam-beam and simplified lattice!

First comparisons to LHC losses data during dedicated experiment

- Total Beam-Beam parameter of 0.02
- GPU accelerated 6D simulations (CABIN) compared to measured losses in the LHC.
- Clear impact of Piwinski angle to loss mechanism
- Tune dependency
- Good qualitative agreements
- Work on going on quantitative estimates (**magnets errors**)

LHC DATA



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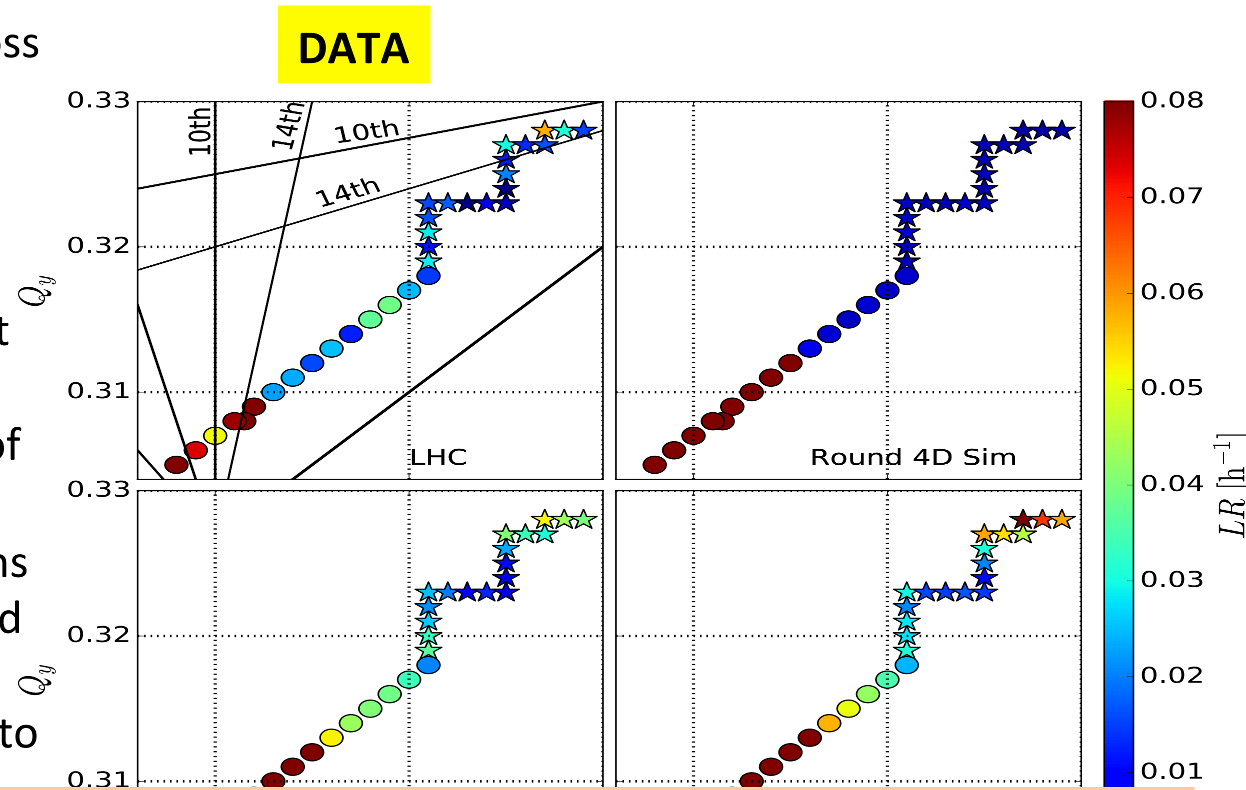
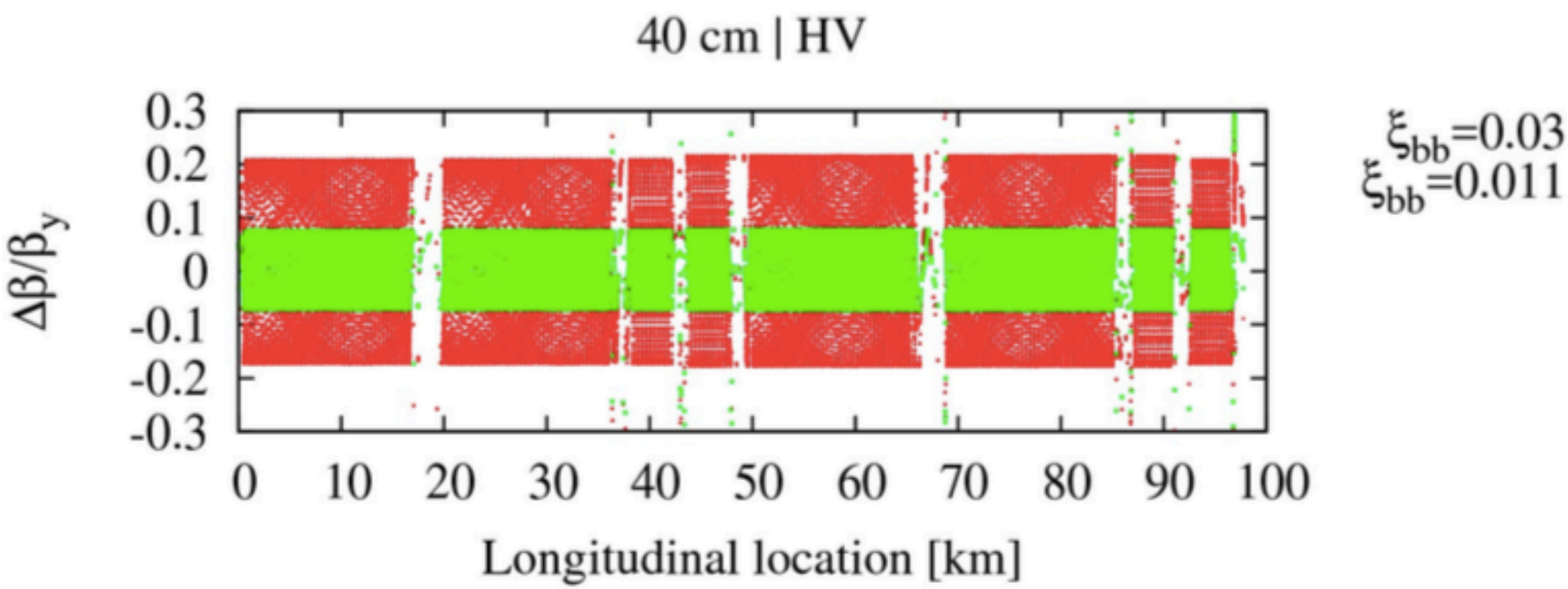


- **Need to explore possible limitations of large beam-beam parameter (0.03-0.06)**
- **in the presence of external noise, for different damping times, different working**
- **points, with and without long-ranges BB** …

→ LHC cannot reach these configurations !

Head-on Beam-beam β-beating is important

Head-on interaction at two IPs will result in a very important beating of roughly 30%



FCC-hh: ξ_{bb}= up to 0.03 + 2 low lumi experiments → 0.05

R. Tomas, T. Pieloni, X. BUffat

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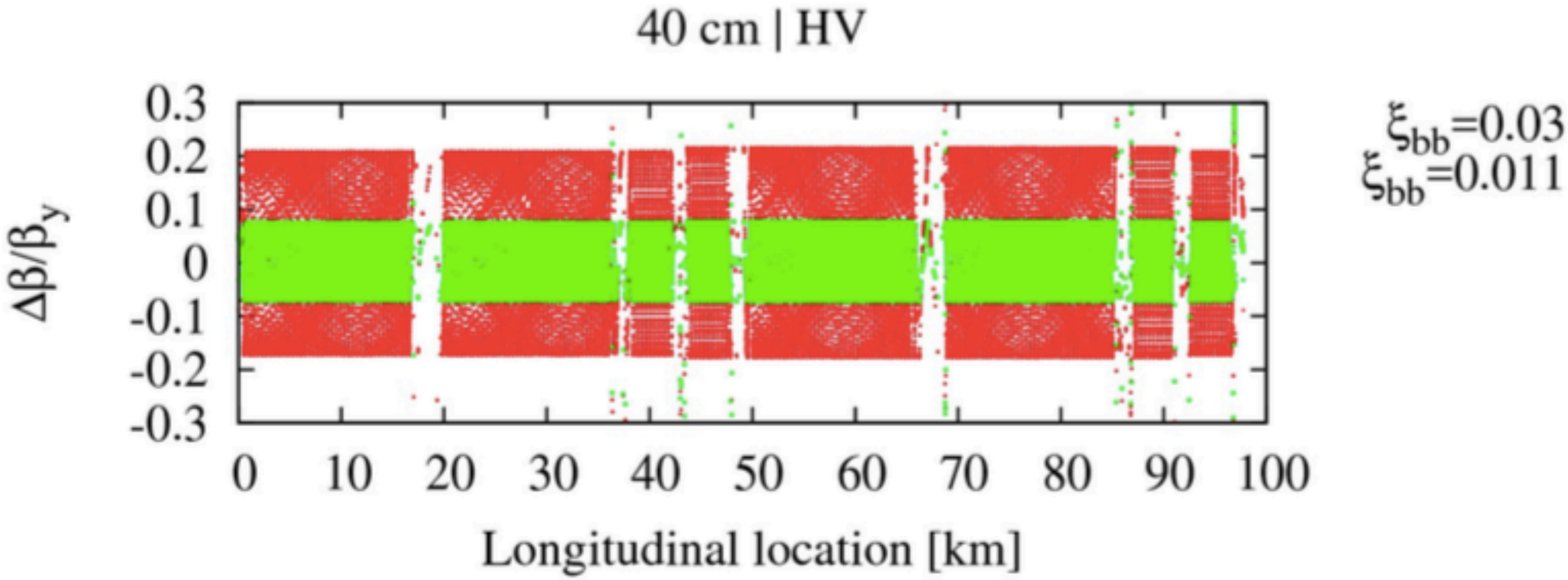


FCC-hh: ξ_{bb}= up to 0.03 + 2 low lumi experiments → 0.05

- Study Impact on collimation system, is it important? Tolerances 10% on coll.
- Study Impact performances → luminosity enhancement (like in lepton colliders)
- **Propose a correction scheme and explore compensation techniques.**

R. Tomas, T. Pieloni, X. BUffat

Coherent Instabilities

Coherent Instabilities not yet understood have been identified in LHC and impact the performances of the LHC from 2012 till today… still very important!

Several studies on-going to understand such effects.

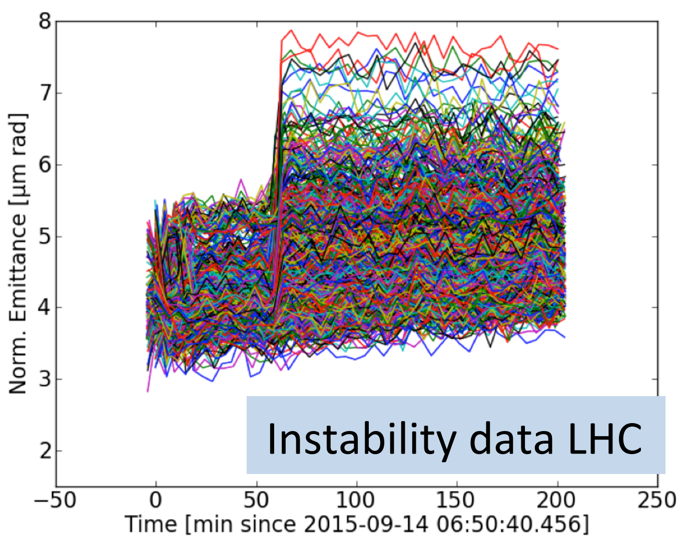
Main topics of study at LHC:

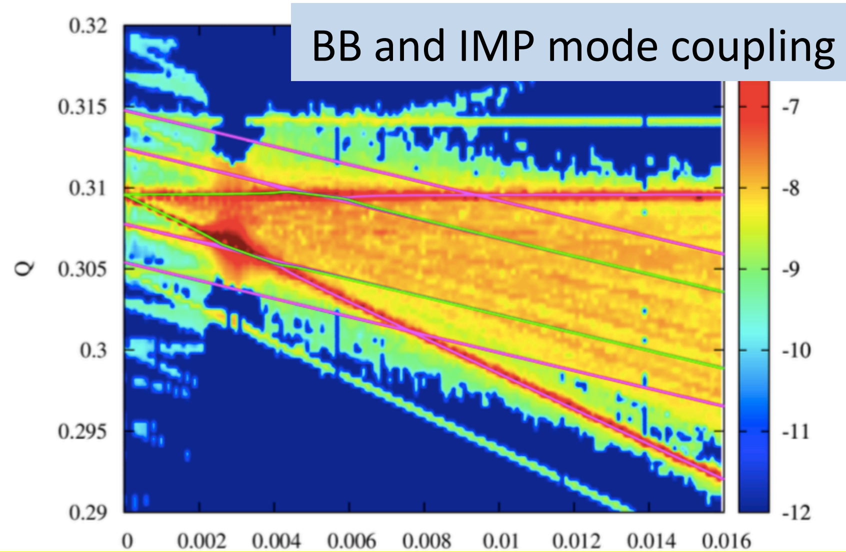
Loss of Landau damping due to "interplay" of optics non-linearities, beam-beam, electron cloud...and impedance

Mode coupling effects: coupling between coherent beam-beam, impedance and electron cloud…?

Impact of noise on stability main source

DAFNE-TF can be a perfect testing machine since all effects exist together!





S. White et al., *Phys. Rev. Spec. Top. Accel. Beams 17, 041002 (2014)*.

E. Metral et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016

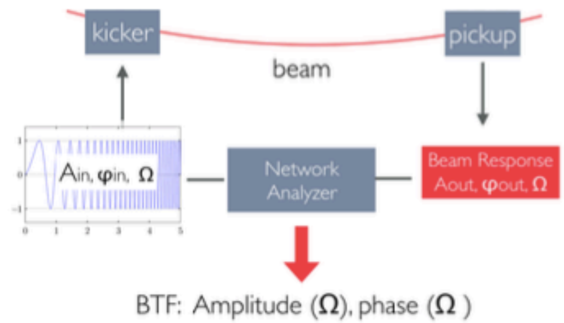
Landau damping and BTFs

BENCHMARK WITH EXPERIMENTAL DATA :

Installation of Beam Transfer Function system in the LHC to quantify and measure beam stability

Beam **T**ransfer **F**unction measurements are direct measurements of the dispersion integral:

$$\mathrm{BTF} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x,J_y) - i\epsilon} dJ_x dJ_y$$

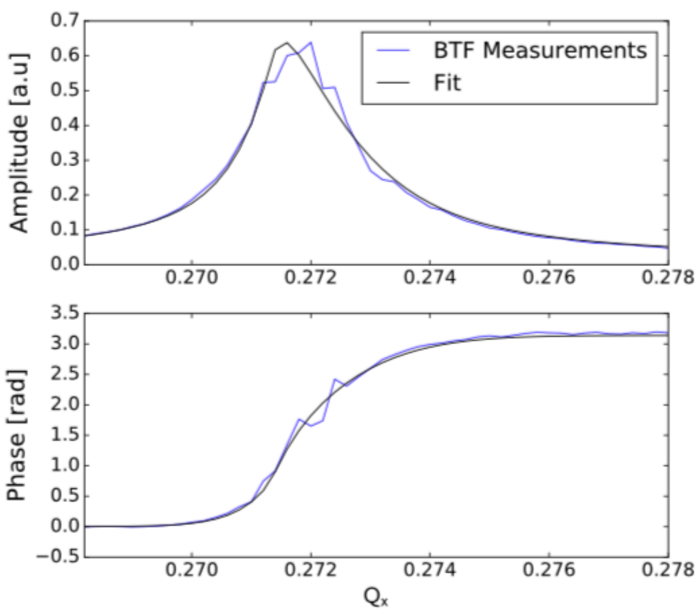


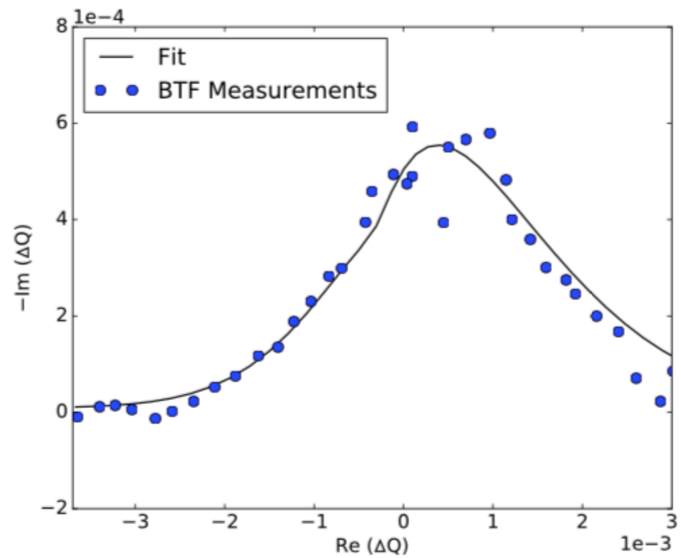
$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$

$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

Stability Diagram (SD)

$$BTF \propto SD^{-1}$$





Stability diagrams have been measured for the first time in the LHC by using BTFs

C Tambasco

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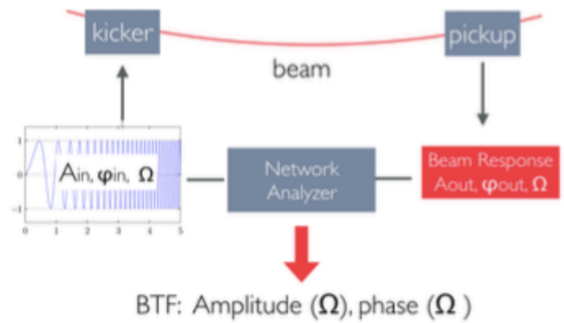

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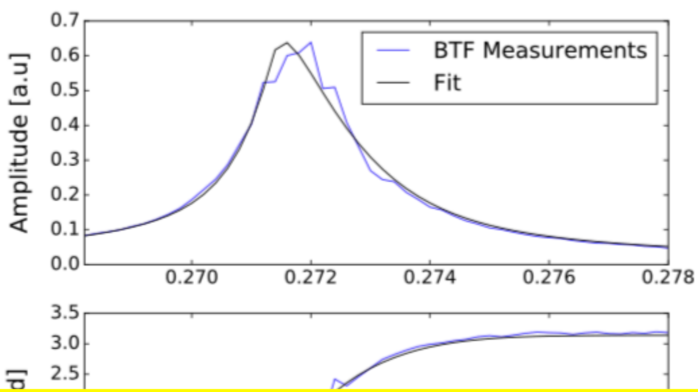
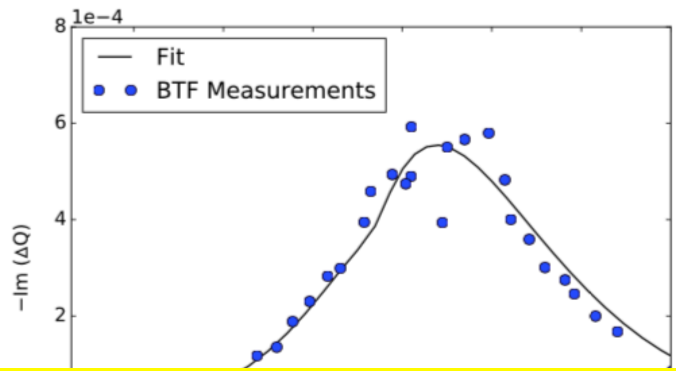




Stability diagrams have been measured for the first time in the LHC by

Explore Landau damping in presence of beam-beam, electron cloud and impedance.

Will need development of Beam-Transfer Function System in DAFNE

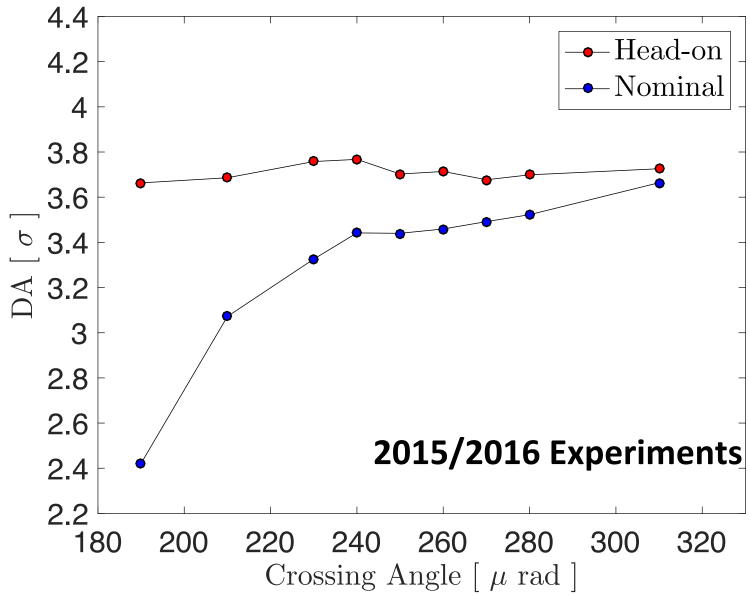
Head-on Limit: Losses

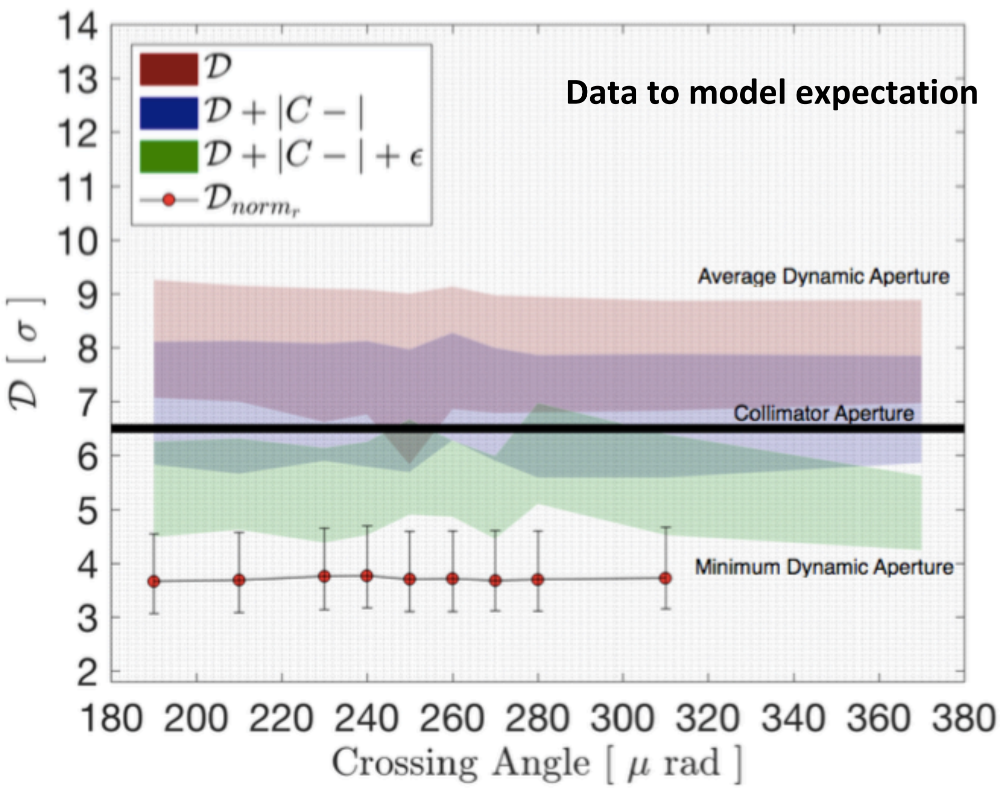
Head-on beam-beam can result in losses and emittance growth.

FCC pushes to a total beam-beam tune shift to 0.03 and beyond

From LHC experience head-on colliding bunches losses cannot be fully explained by only single particle effects (Dynamic aperture simulations)

Phys Rev Spec Top-AB, 15(2):024001, 2012)





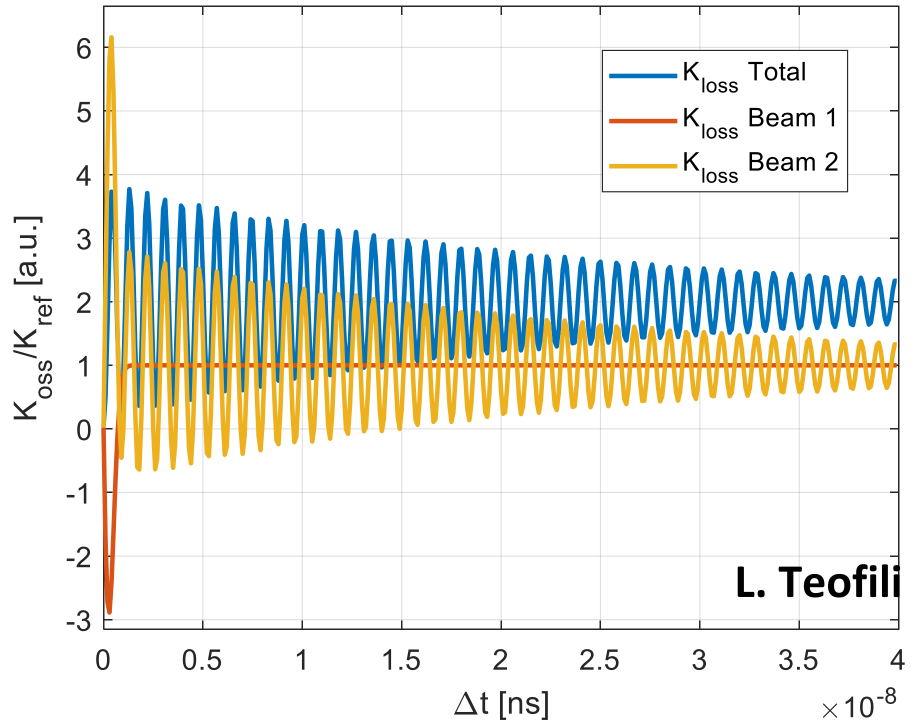
What is the impact of large crossing angles?
Long-range beam-beam effects?
How will losses change with radiation damping?

@IPAC2017 TUPVA026, TUPVA029

2 beam impedance effects

- Motivations:
- LHC observations at the TDI, triplet magnets in the IP and LHCB VELO detector triggered the study of two beam effects on heating and stability.
- Analytical formulae [1] and simulation tools are available to quantify the power loss of two beams with any kind of filling pattern and bunch distribution.

The energy lost from the two beam can be up to 4 times the energy loss by the single beam. The two beams can also cancel out their effects on the total energy loss



Use existing devices in common beam pipes (i.e. Y-chamber and bellow in the DAFNE IR SIDDARTA) to predict and measure the power loss with one and two beams

Wakefield and Energy Dissipation Of Two Counter Rotating Beams. Impedance meeting of the 2nd November. L. Teofili, M. Migliorati, G. Rumolo, G. Iadarola…

Chromaticity Dependence on Beam Size

Colliders → very pushed low beta insertions β^* → smaller and smaller (25 cm)

The FFS has challenge to have highest beta functions at strongest gradient location

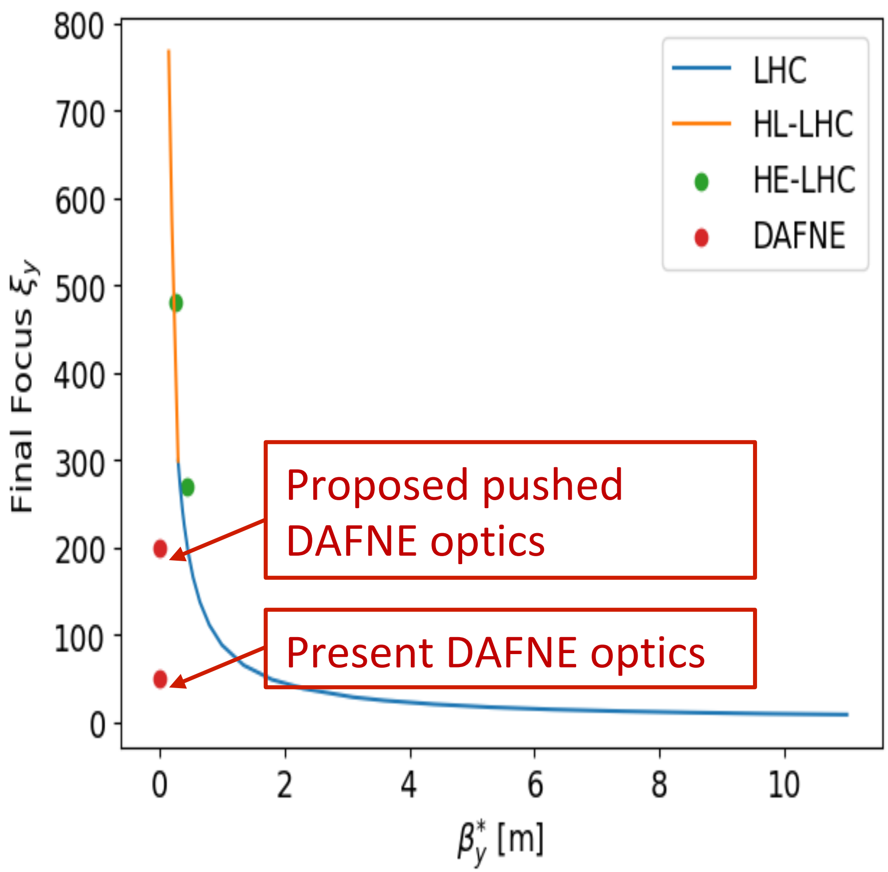
→Very large $k_{FFS} * \beta_{FFS} = \xi$

Any non-linearity is enhanced due to these conditions of pushed β^*

- Beta-beating
- Chromaticity
- ...

HE-LHC, HL-LHC and LHC Parameters

- L* of about 23 m
- FFS: Triplet
- Round beams



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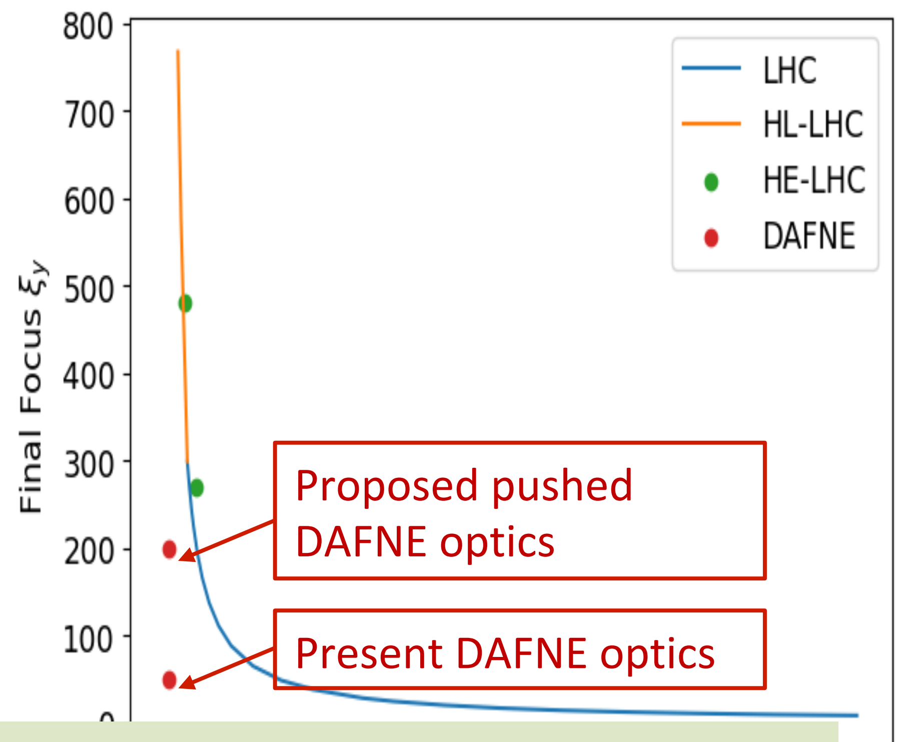


Measure contribution and compare to expectation → possibly implement and test correction schemes

- Round beams

J. Keintzel, R. Tomas.

Reproduce Chromaticity at DAFNE

- Proposed pushed DAFNE optics with β* = (from 9 mm → 2mm)
- Operate effects of pushed low β* optics
- Test correct schemes for the observed effects (i.e. high chromaticity, beating…)
- Requires strong FF doublet with larger aperture

	LHC	HL-LHC	HE-LHC		DAFNE	
β^*y [m]	0.3	0.15	0.45	0.25	0.009	0.002
L* [m]	23	23	23	23	0.294	0.294
ξy=K1L . βy	300	770	270	480	50	200*

* Estimates for pushed optics

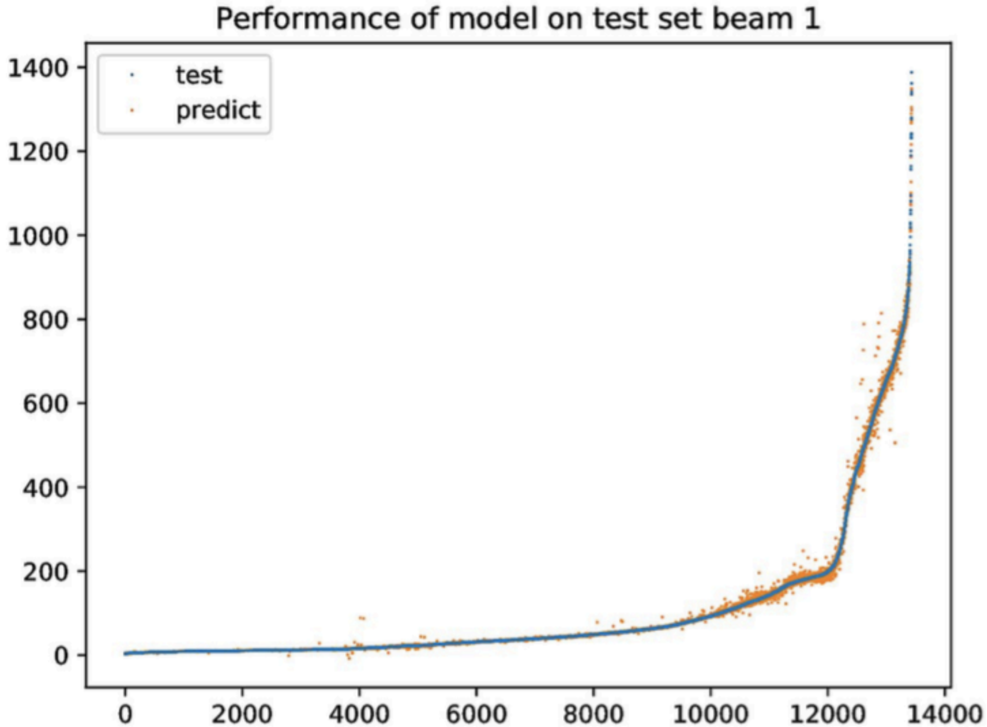
J. Keintzel, R. Tomas.

Machine learning with DAFNE dataset

- PACMAN project between EPFL-PSI supported by the Swiss Data Science Center In collaboration with Operation team at CERN

We have in this frame 1 PhD, 1 Post-doctoral researcher

- Apply ML techniques to accelerator optimization
- Train a model on DAFNE OP data that predict performances (losses, luminosity) as a function of beam and machine parameters
- Explore larger parameter space during experiments to probe the model predictions
- Explore if there is any knowledge transfer applicable between DAFNE and LHC/FCC-hh



Model versus Data
LHC First testing 2017 data

L. Coyle, B. Salvachua, T. Pieloni, J. Wenninger

Summary

- **DAFNE is a unique machine that experiences all in once**:
  - Beam-beam effects
  - Electron cloud
  - Impedance

Plus Synchrotron Radiation

- The **dynamics of collective effects**, in particularly the interplay of them is still a very large domain of research and represents still a limiting factor in present and future colliders
  - LHC shows already it's limits and models are not fully describing the observations
  - FCC will add to the picture important radiation damping → models and hands on benchmark on DAFNE can be a fundamental component.
- **Study the interplay of all these effects** for different pushed optics configurations in the presence of important radiation damping is an area of study where DAFNE-TF can represent a unique tool for the beam dynamics teams in the FCC collaboration and LHC teams working on these subjects
- Machine time in LHC is always very limited
- **Several ideas start flowing in the community but will need detailed** simulation studies with DAFNE experts to be ready for 2020 experiments. For hardware devices to be installed will need discussions with DAFNE teams

Summary

- **DAFNE is a unique machine that experiences all in once**:
  - Beam-beam effects

Future hadron facilities will start facing effects typical of lepton colliders due to the energy scale of interest.
All models will need up-grades an benchmark to real data is always fundamental!
In this frame we will have the opportunity to train young physicist with hands on a unique collider DAFNE very reach in collective effects → train the next generation of accelerator physicists for the design of the next Future collider project!

on these subjects

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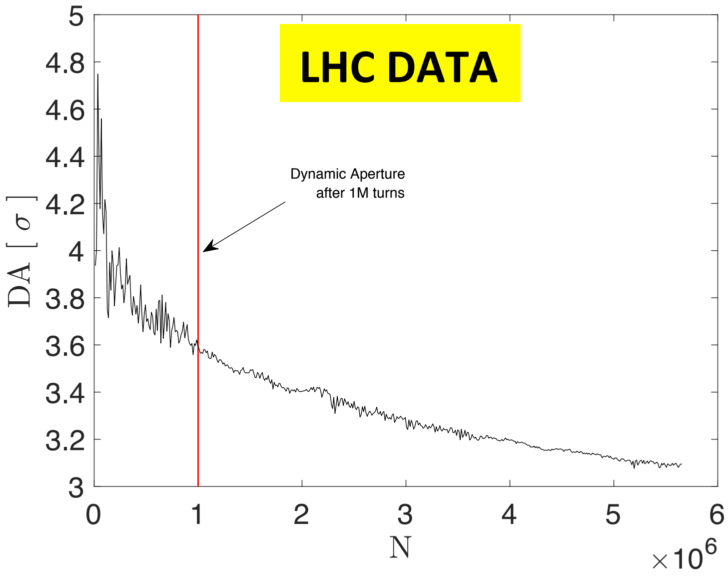
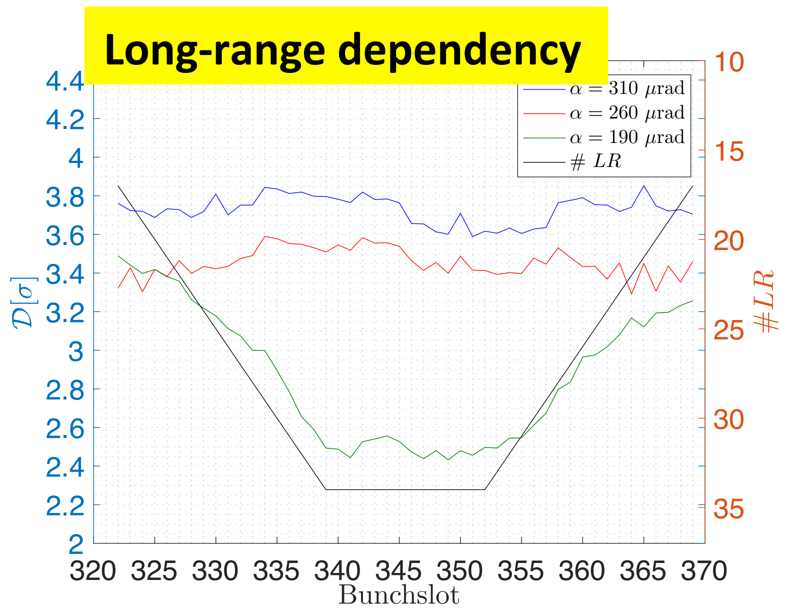
Thank you !

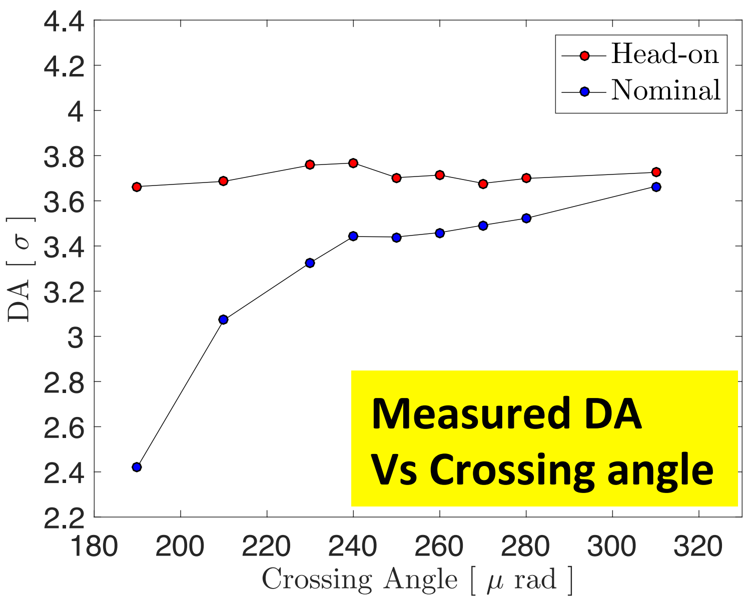
Can we translate losses in dynamic aperture?



Using the method proposed by M.Giovannozzi (Phys Rev Spec Top-AB, 15(2):024001, 2012)

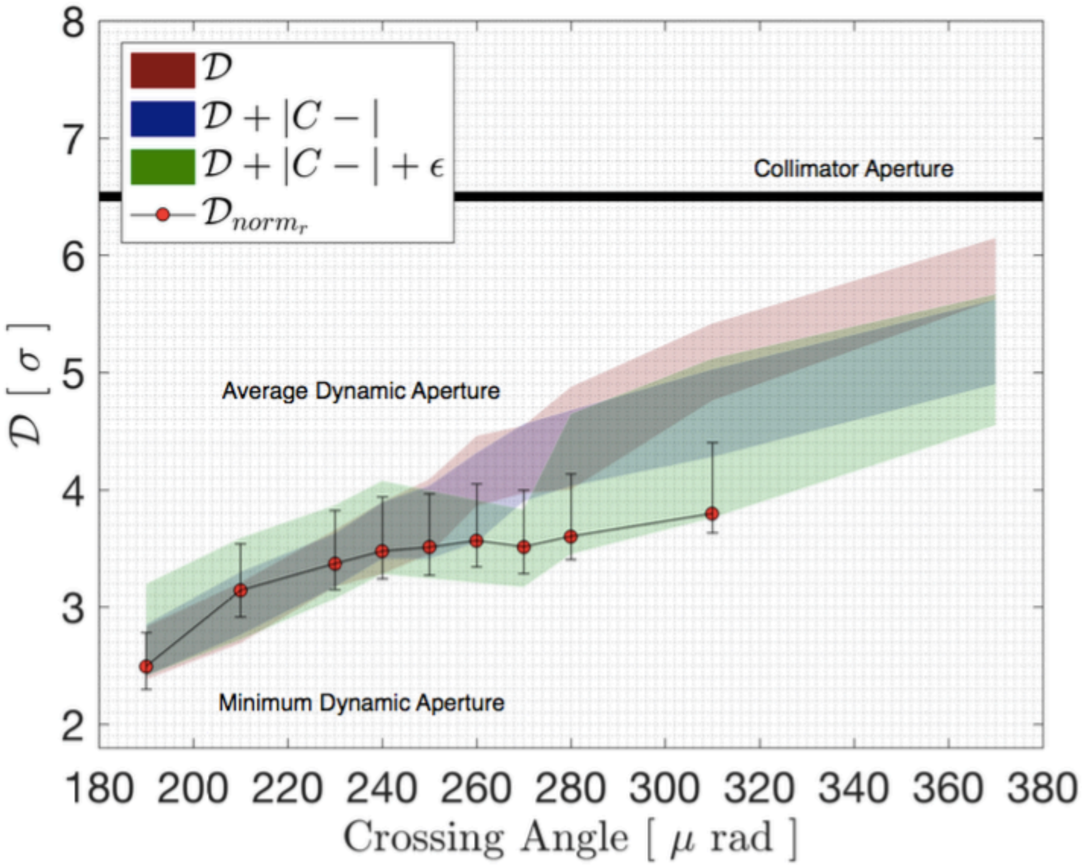
We applied to beam-beam experiments (lifetime evolution as a function of beam-beam parameters)





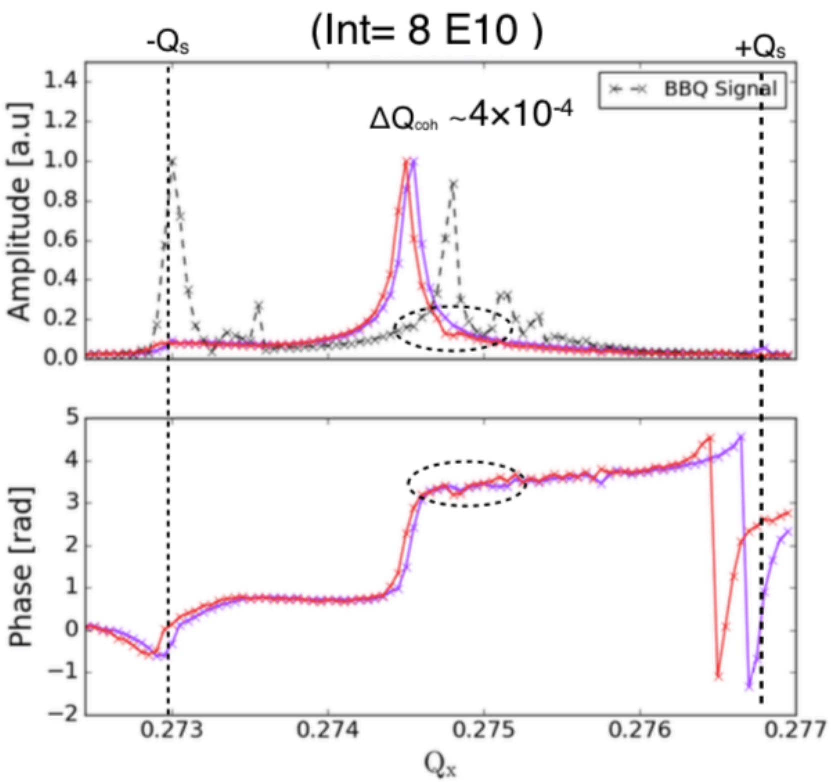
Use the Dynamic Aperture simulation to predict the losses expected per scenario…

How far are models from reality?



Include in luminosity models losses expected from Dynamic Aperture, to have estimates on impact to collimation system

Beam Transfer Function measurements of Landau damping



Collective effects change the beam response and makes it very difficult to reconstruct the Stability Diagram by using an analytical fitting function.

Models are available but benchmark with data can highlight effects of impedance, beam-beam, electron cloud, external noise…

Probe impact of longitudinal plane on the transverse stability diagram

Impedance studies: 2 beam impedance effects

Target:

The aim is to benchmark predictions with measurements. Understanding the impact of the impedance of two beams (especially power loss) and the proton dynamics. There are not many places in the world where such measurements are possible. DAFNE-TS 2 beams in common pipes and impedance in common region.

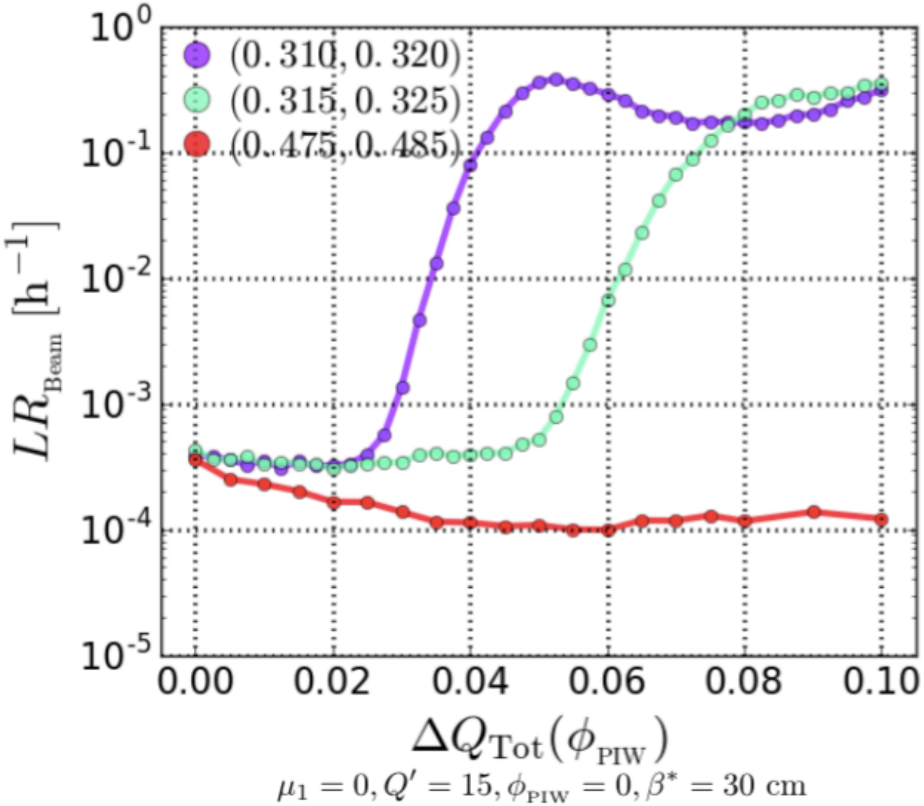
- Use existing devices in common beam pipes (i.e. Y-chamber and bellow in the DAFNE IR SIDDARTA) to predict and measure the power loss with one and two beams.
- Measurements can be performed with existing monitoring or new installation (temperature of the device and the cooling water, EM field probe, vacuum gauge for heating, tune shift for stability). Might require installation of temperature probes on the outside of the chamber.
- 1 beam measure heat-load dependence on beam parameters(intensities, bunch length, filling patter) and benchmark to simulations results and models.
- Same procedure but with two beams to benchmark the scaling laws for two beams
- Second part will be to explore the dependency on the impedance it self. This will require a tuneable device (i.e. a collimator or a special pick-up with bad termination…)
- Perform dedicated heat load and temperature measurements with one and two beams and various beam parameters, with varying impedance. Requires modifications of the IR layout and new devices. Or optics changes to make larger betas at the impedance locations.
- The set-up will be useful to test impedance detection technique

Head-on Limit: Losses and Emittance growth

Working point optimization could increase the beam-beam maximum tune shift (0.046)

Further optimization with dynamic aperture cross check in the presence of long-range beam-beam are foreseen

Noise effects to be explored



Further studies needed to explore flat option and real limit with long-range beam-beam effects