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Beam-beam effects in a 100 TeV *p-p* Future Circular Collider

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- Beam-beam in FCC:
  - Beam and beam-beam parameters
- Beam-beam in Tevatron, RHIC and LHC:
  - Nature of the effects
- Expectations at 100 TeV:
  - simulations
- Counter-measures:
  - Compensation: e-lenses and wires
- R&D, studies needed:
  - Simulations
  - Beam studies

From the FCC-Note

EXTERNAL REFERENCES:

FCC-1401101315-DSC

$$L = \xi \frac{I}{e} \frac{\gamma}{\beta^*} \frac{1}{r_p} F$$

$\xi_t = 0.01$, Two IPs

Version 1.0 (2014-02-11)	**LHC**	**HL-LHC**	**FHC-hh**
c.m. Energy [TeV]	14		100
Number of bunches at - 25 ns - 5 ns	2808		10600 (8900) 53000 (44500)
Bunch population N_b $[10^{11}]$ - 25 ns - 5 ns	1.15	2.2	1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	3.75	2.5	2.2 0.44
Longitudinal emittance damping time [h]	12.9		0.54 (0.32)

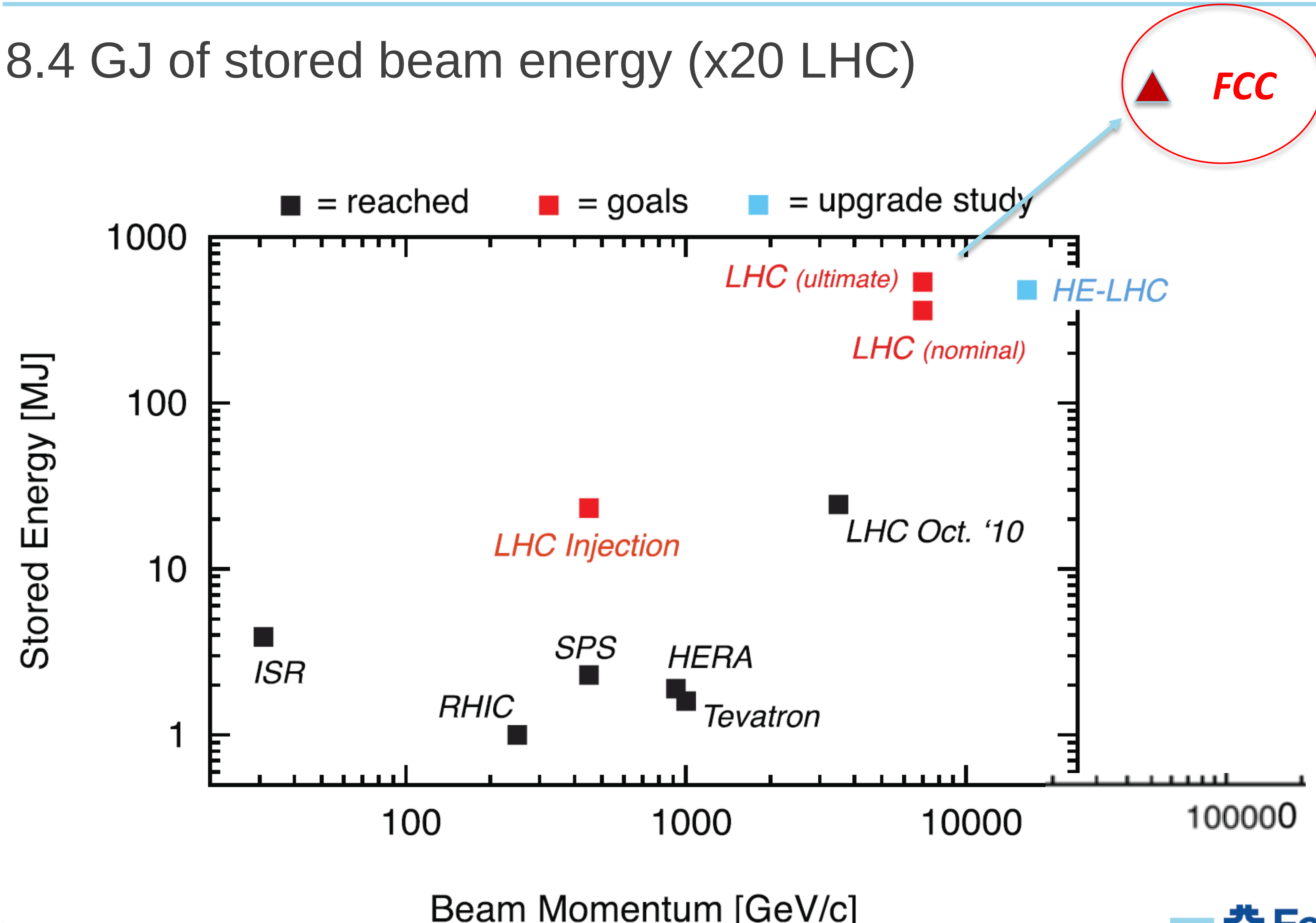
FCC beam-beam compared to other pp Colliders

	E_{cm} TeV	Peak L, 10^{34} cm^{-2}s^{-1}	$N_{p(a)}$ 10^{11}	N_B	$\varepsilon_{p(a)}$ µm	β^* cm	ξ	W MJ
Tevatron	1.96	0.043	2.9/0.8	36	3/1.5	28	0.025	1.7
SSC	40	0.1	0.075	17,240	1	50	0.004	418
UNK	6	0.1	3	348	7.5	150	0.005	50
RHIC	0.5	0.025	1.9	111	3.1	65	0.018	0.8
LHC	14	1.0	1.15	2,808	3.7	55	0.01	360
FCC	100	5.0	1	10,600	2.2	110	0.01	8400

NB: FCC the 1st one hh collider to be dominated by SR damping

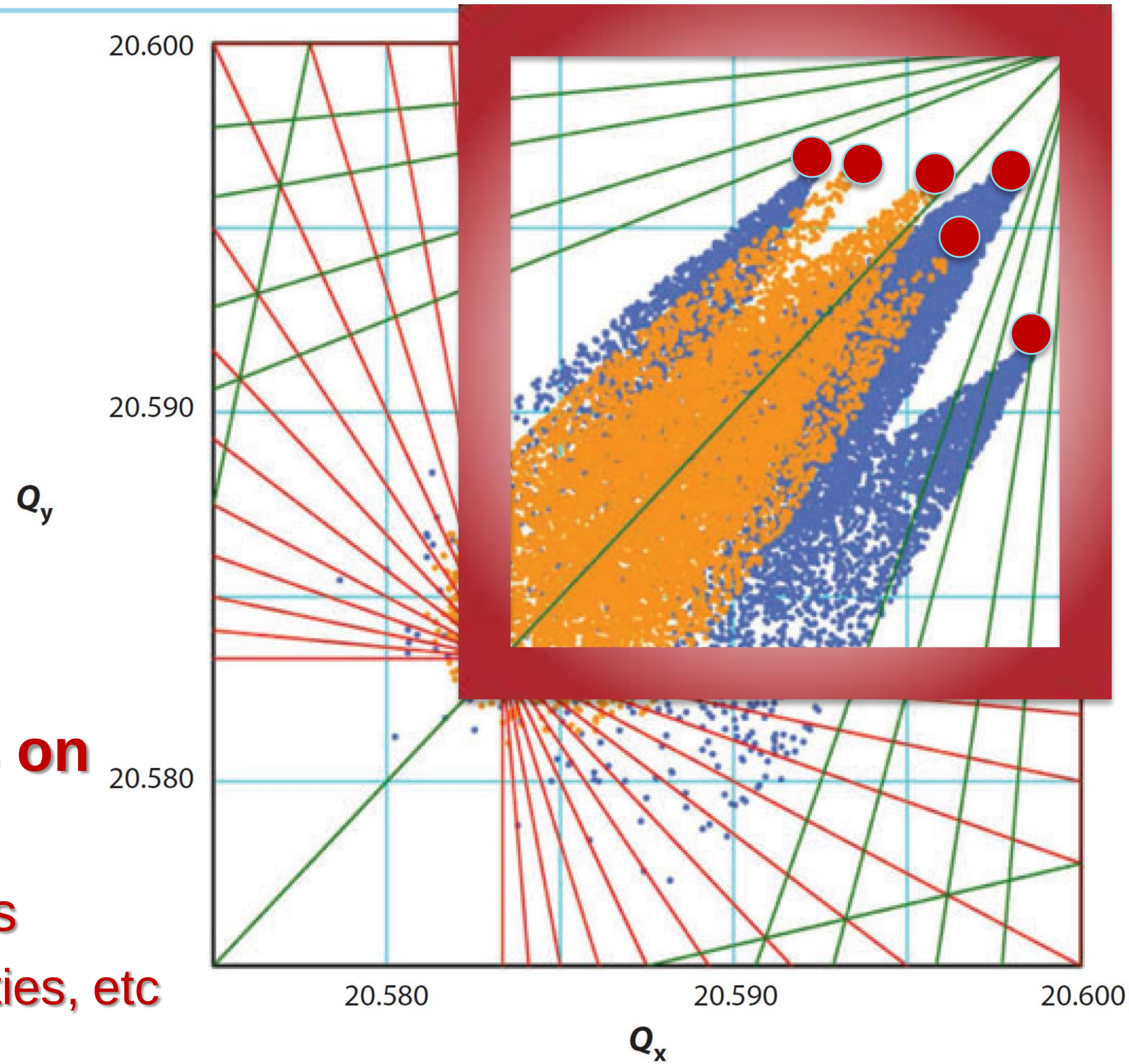
FCC beam dynamics challenge – beam power

8.4 GJ of stored beam energy (x20 LHC)



Types of beam-beam effects in FCC

- Head-on Effects
  - TeV, RHIC
- Long-Range effects
  - TeV, LHC
- Emittance growth
  - TeV. RHIC, LHC
- Particle losses
  - TeV, RHIC, LHC
- **Sensitivity depends on**
  - Beam parameters
  - Machine parameters
    - Tunes, chromaticities, etc
  - Collimation system



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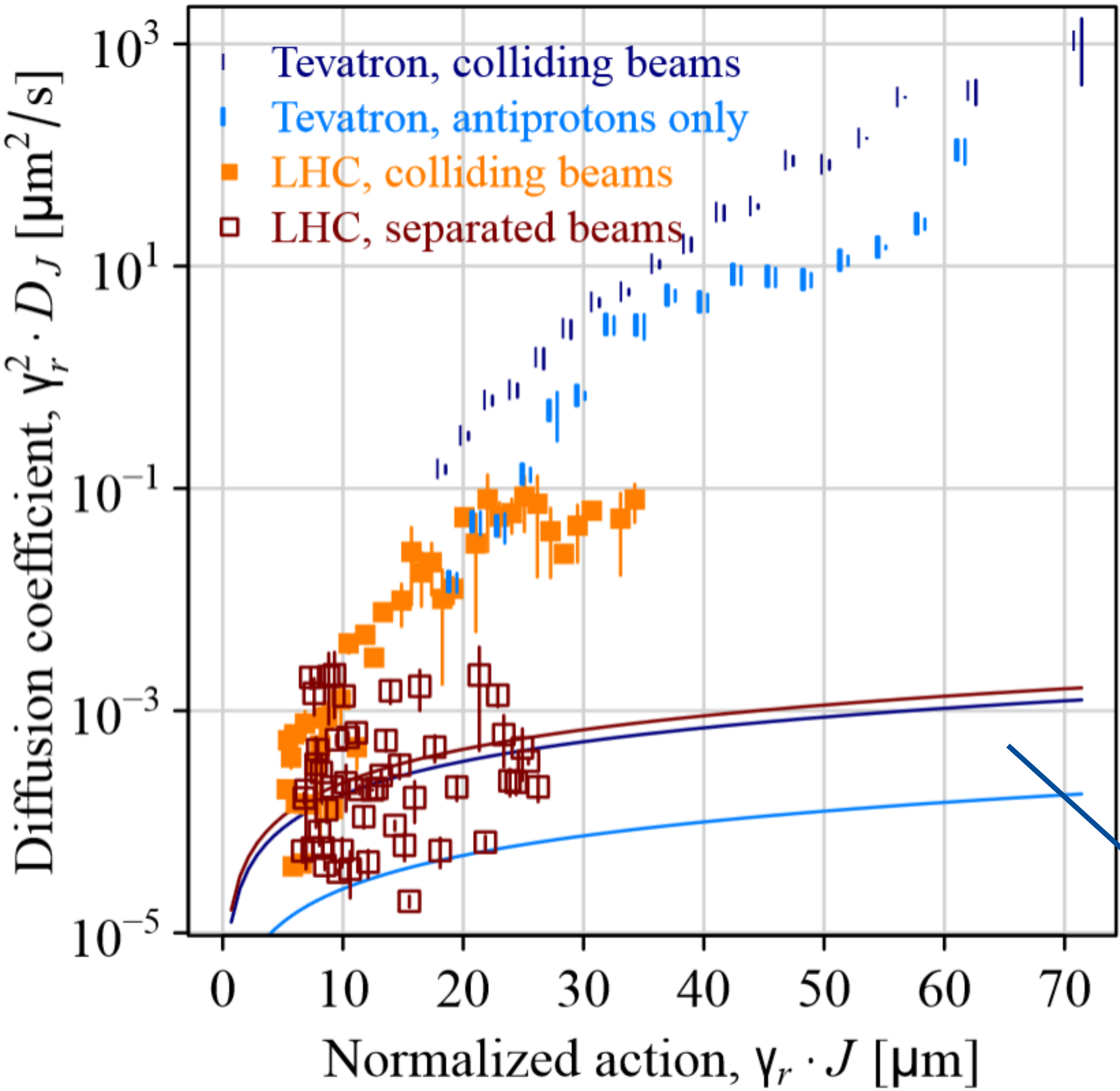
Beam halo diffusion rates in the Tevatron and in the LHC



Effect of beam-beam is 1-2 orders of magnitude bigger than dEmm/dt

curves from measured core emittance growth

$$D_J = \dot{\varepsilon} \cdot J$$

Courtesy G.Stancari

Seriousness of Beam-Beam Effects

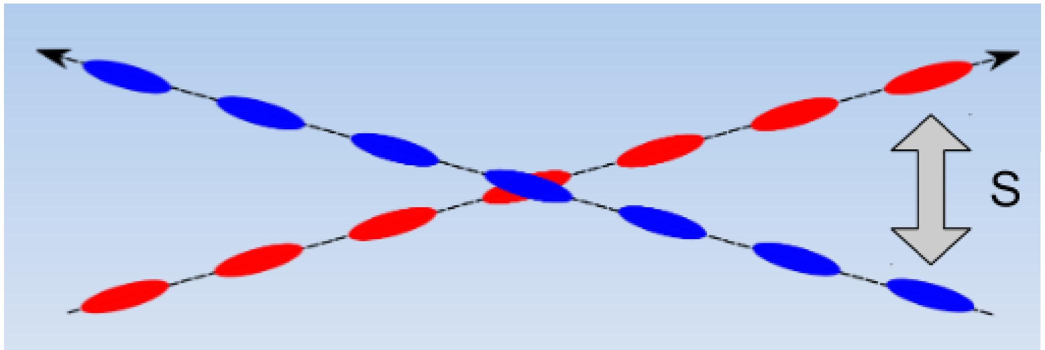
- Tevatron – end of Collider Run II conditions:
  - beam–beam-driven p and pbar losses at the injection energy …on the energy ramp … and in the low-beta squeeze together with in-store losses (ξ_{BB} ~0.02) - reduce the luminosity integral by 23–33 %
- RHIC – 200-500 GeV com *p-p* Runs:
  - BB-driven losses at ξ_{BB} ~0.018 → ~20-30% over few hours, limit the collider luminosity as injectors can provide x2 more beam
- LHC – 7-8 TeV com *p-p* Run I:
  - In typical stores with ξ_{BB} upto 0.015 (total) the beam-beam effects result in <~10% luminosity loss
  - In MDs ξ_{BB} upto 0.03 (total) were obtained with seemingly still tolerable losses

Beam-Beam Effects in FCC

- All of the above at ξ_{BB} ~0.01 or more :
  - losses at the injection energy, on the energy ramp, and in the low-beta squeeze
  - in-store losses (transverse and longitudinal) due to head-on + long-range + other nonlinearities + instabilities + external noises + SR damping + feedback systems + collimation + etc
- Can be simulated or studied in LHC and RHIC (some):
  - additional complications:
  - Eg due to larger circumference lower betatron frequencies and typically much stronger external noises (GM, ripples, vacuum chamber fluctuations, etc) → need FB
  - More long-range encounters → bigger orbit separations at IP bunch-by-bunch

$$\frac{1}{\epsilon_0}\frac{d\epsilon}{dt}=\frac{\Delta^2(1-s_0)}{4\left(1+\frac{g}{2\pi\xi}\right)^2}$$

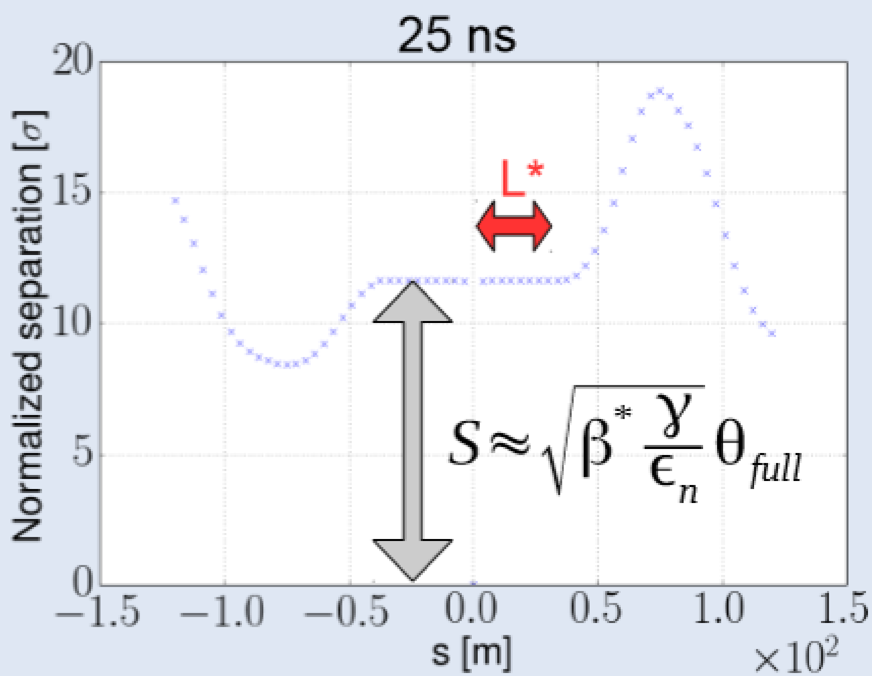
Long-range Interactions → "Clothed" Orbits

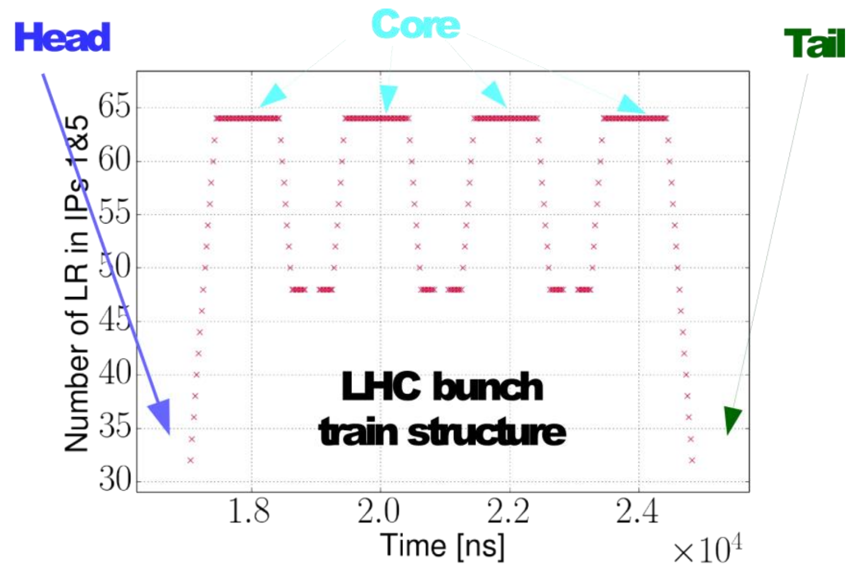


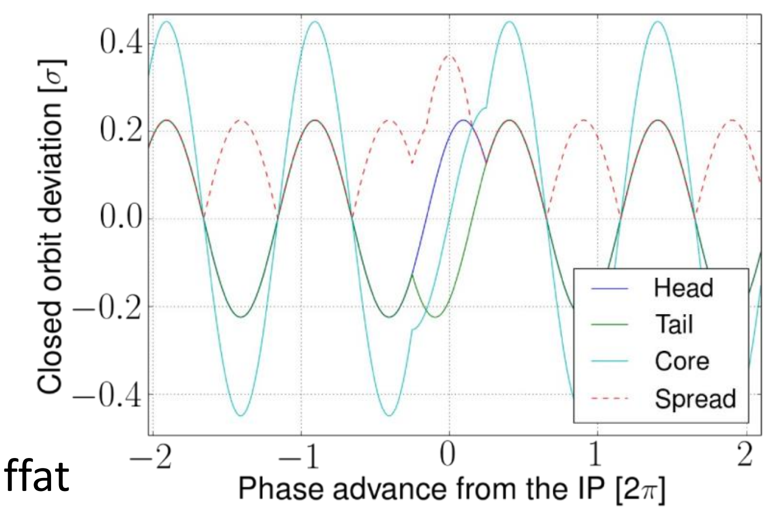
Δt_{bb}=25 ns → spread of ~0.2 σ

Δt_{bb}=5 ns → spread of ~2 σ

- a common chamber of 120 m around the IP (2xLHC
- TOY_V1 optics with L* = 36 m





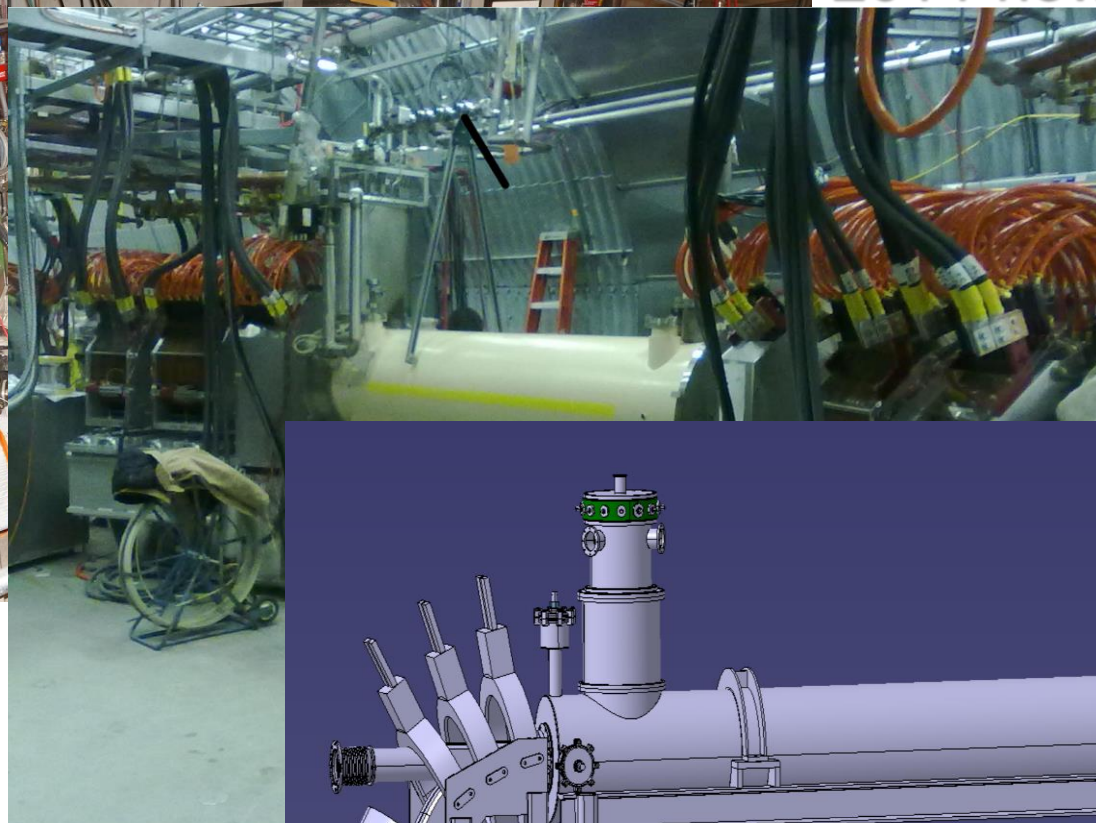


Courtesy X.Buffat

Countermeasures

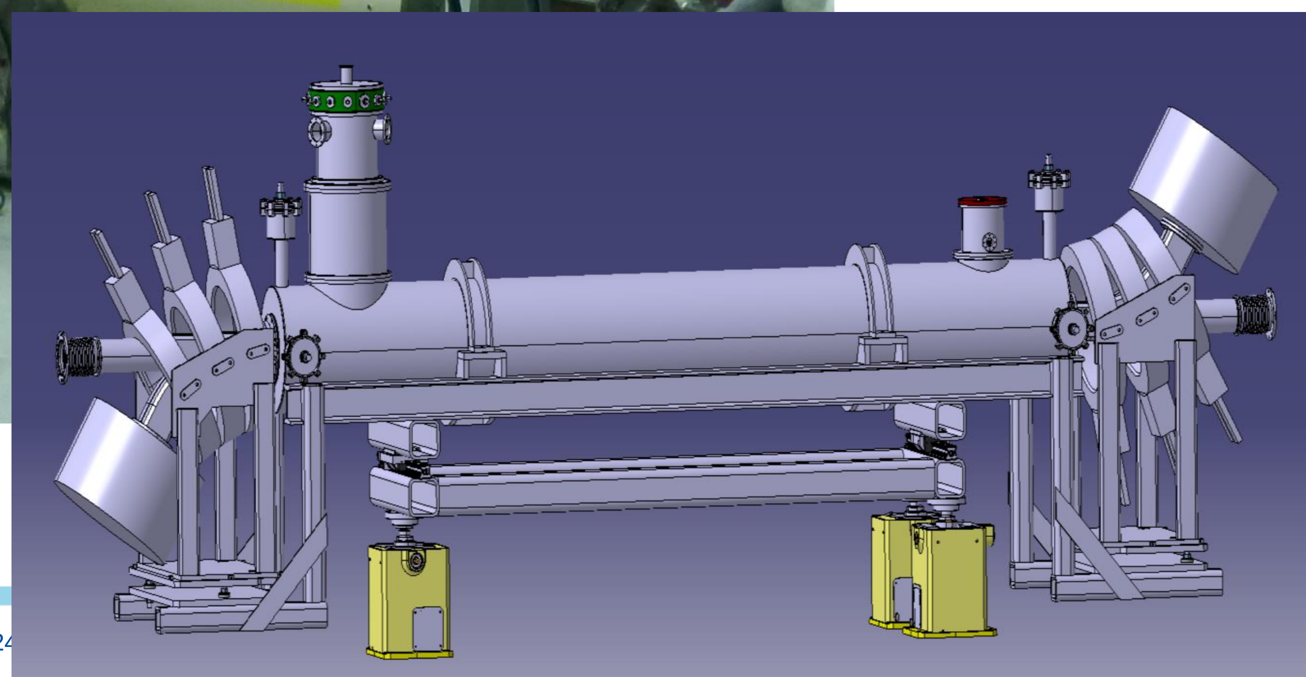
- Keep the beam-beam interaction parameters small, e.g. ξ_{BB} <0.02, $\Delta X_{separation}$ >10σ, etc
- Choice of the WP, reduce *Q'* and *Q"*, minimize other nonlinearities
- (More) effective beam collimation system
- Active beam-beam compensation:
  - Compensation of tuneshifts (linear, eg bunch-by-bunch)
  - Compensation of tunes spread and NL-driving terms (head-on)
  - Compensation of all effects at once when possible ("wire compensation of LR effects")
  - Electron Lenses and Compensating Wires

Electron Lenses: Tevatron, RHIC, LHC



RHIC “Blue” and “Yellow”
2014-now

LHC e-Lens for
High-Lumi
ca 2023

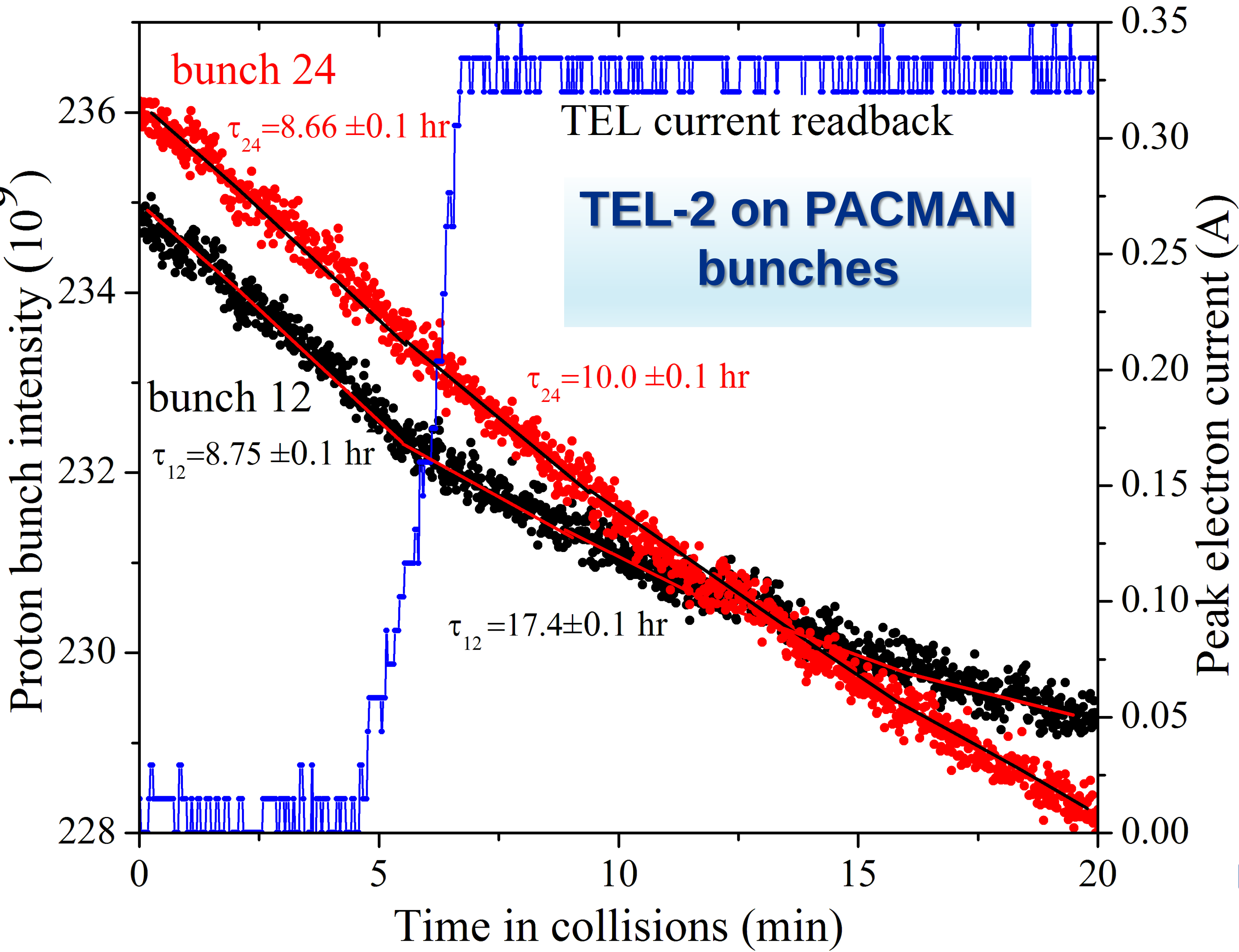


Tevatron

TEL-1 &
TEL-2

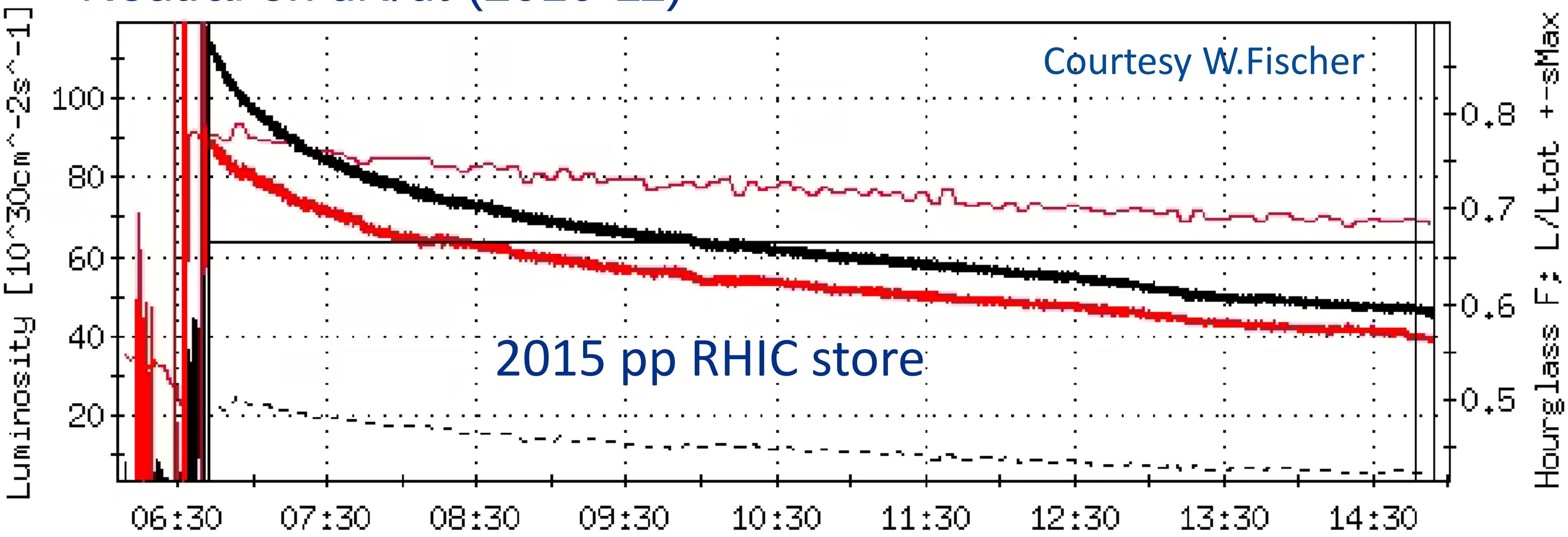
2001-2011

Tune-shift Compensation in Tevatron → x 2 in Lifetime

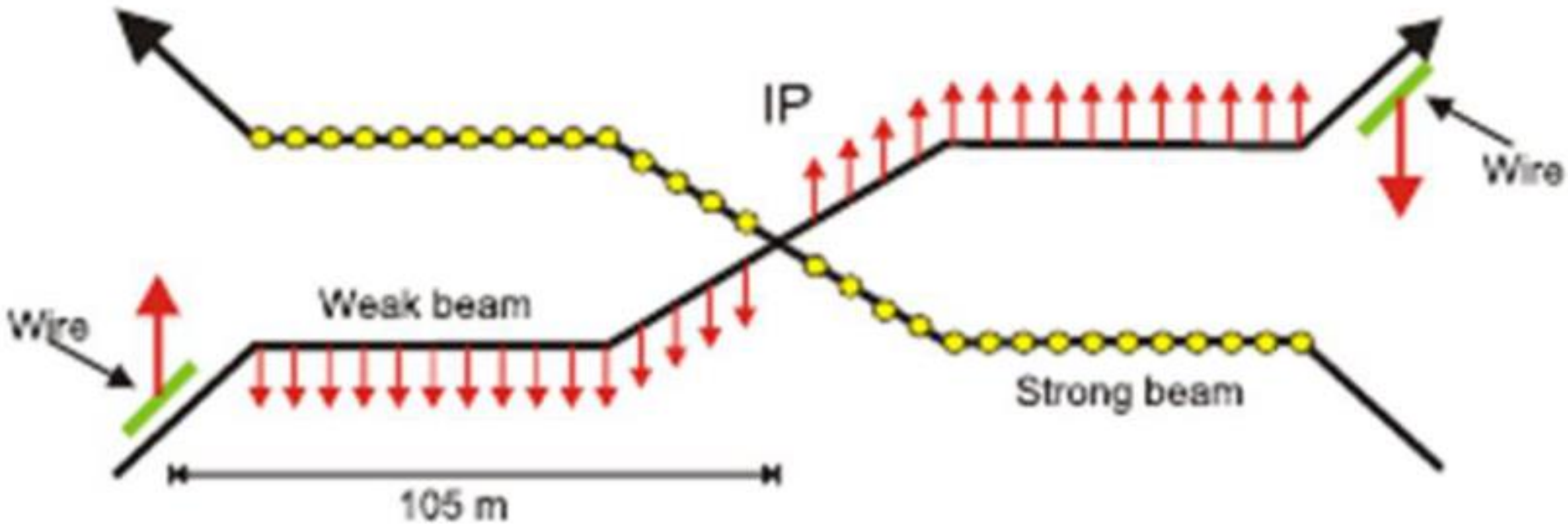


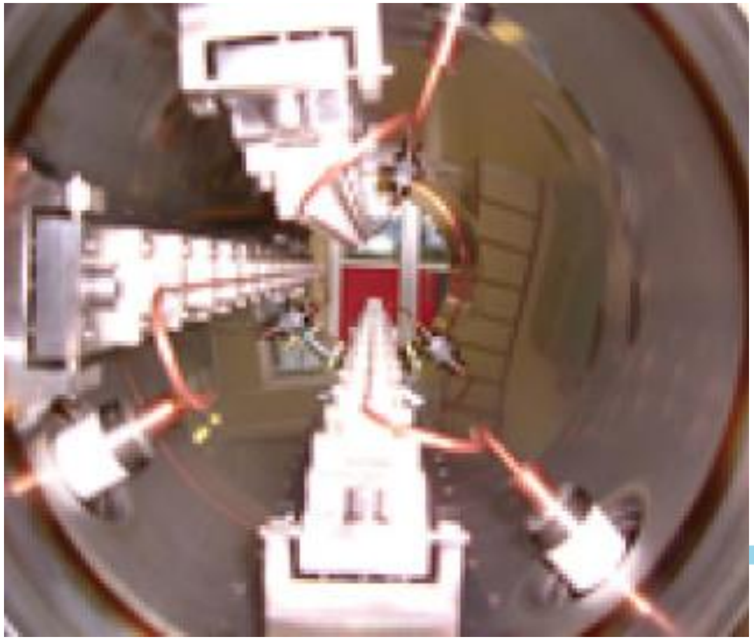
Head-On Compensation: Tevatron and RHIC

- Tevatron: *p-a* 1.96 TeV
  - TELs used in stores
  - ξ_{BB} ~ + 0.02 *p* on *pbars*
  - ξ_{EL} ~ - 0.003 *e* on *pbars*
  - × ½ emit growth (2003)
  - Neutral on *dN/dt* (2010-11)
- RHIC: 2015 p-p 200 GeV
  - RELs used for ~1hr in stores
  - ξ_{BB} ~ - 0.02 *p* on *protons*
  - ξ_{EL} ~ + 0.008 *e* on *protons*
  - +150% increase in *peak Lumi*
  - +90% increase in *avg. Lumi*



“Wire“ Compensation of Long-Range Beam-Beam Effects





Proposed in 2001 by JP Koutchouck
Tests in RHIC and SPS encouraging but not decisive. Test in LHC launched in 2014 to get assessment by **2016 -2017.**
However the technology of “wire embedded in collimation” should be **replaced by e-beam wires**

Summary

- Beam-beam effects might appear "not bad" in FCC:
  – ξ_{BB} ~0.01 is "conservative"… visible SR damping…
- But they can/will be worse than in the Tevatron, RHIC and LHC due to:
  – Enormous beam power → very low loss tolerances
  – Lower betatron frequencies → larger noises
  – Longer IRs and L* → more long-range beam-beam
- We are at the very beginning of comprehensive beam studies:
  – "trustable" simulations checks vs LHC/RHIC realities
- Counter-measures must be in the FCC design:
  – Compensation: e-lenses and e-wires