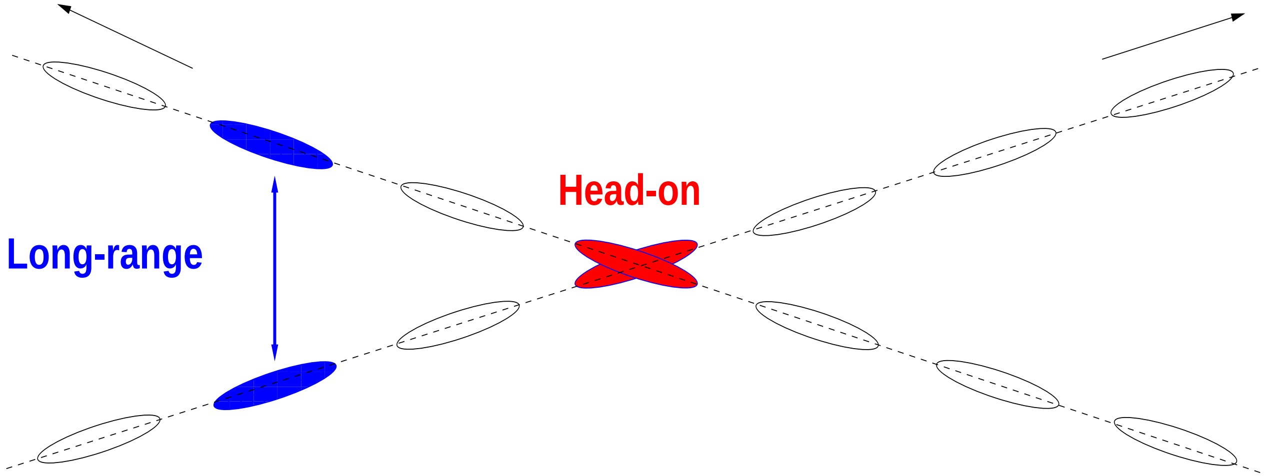
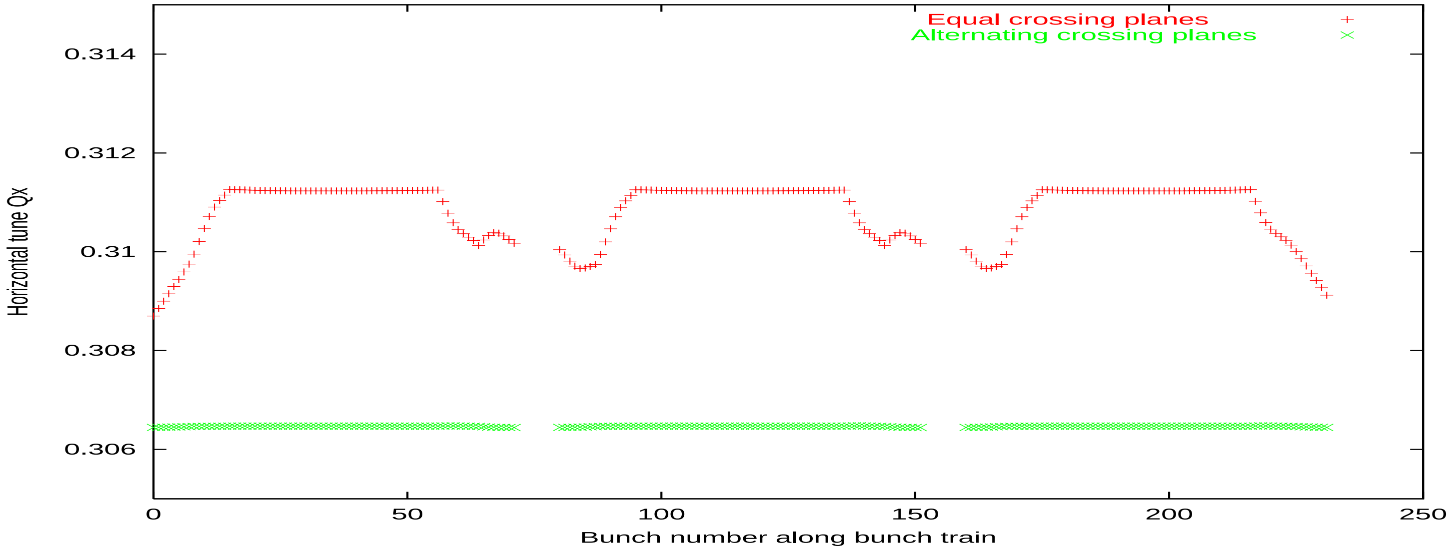
Long range beam-beam in LHC (W. Herr)



- Separation with crossing angle
- Up to 120 long range encounters
- Issues very different from Pretzl separation

PACMAN tune effects: calculation



- **Alternating crossing planes for passive compensation**
- **Minimizes PACMAN effects on tunes and chromaticities**
  - **Here example: tune along train with and without alternating crossing**

Which crossing angle do we need ?

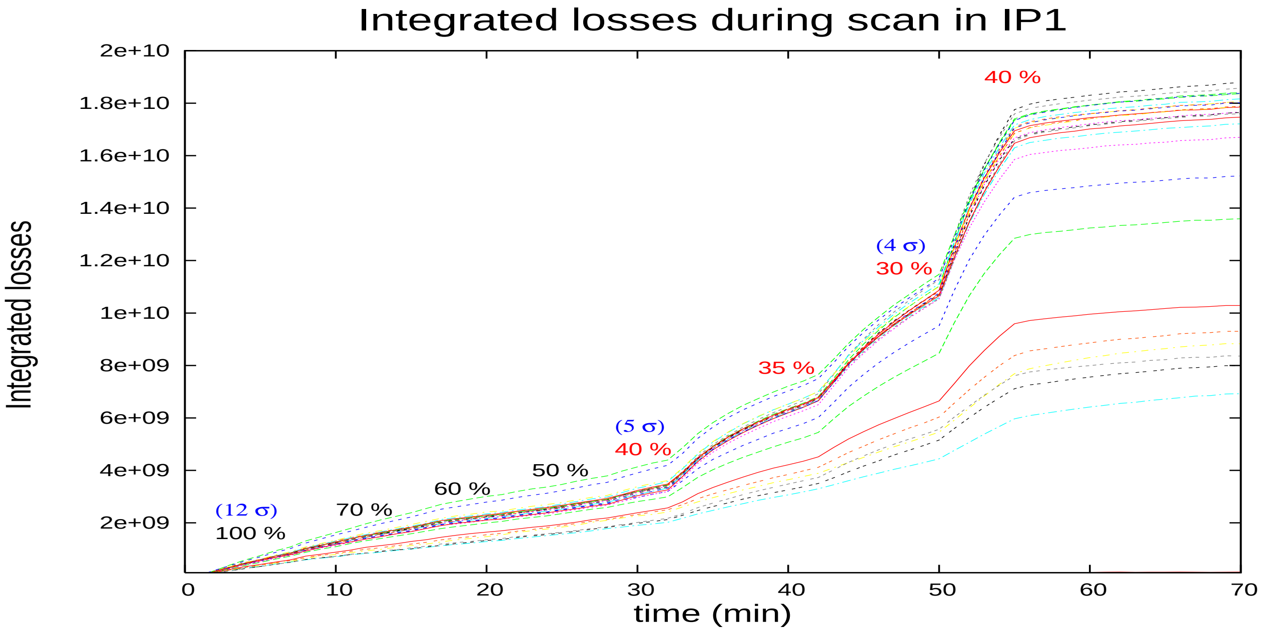
For comparison → normalized separation in the <u>drift space</u>:

$$d_{sep} \approx \frac{\sqrt{\beta^*} \cdot \alpha \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}}$$

- **Proposed (minimum) separation $\approx$ 12 σ**
- **Crossing angle α depends on β^* (in crossing plane) !**

→ **<u>Smaller</u> β^* requires <u>increased</u> crossing angle α**

Experiment 1: scan of crossing angle - losses

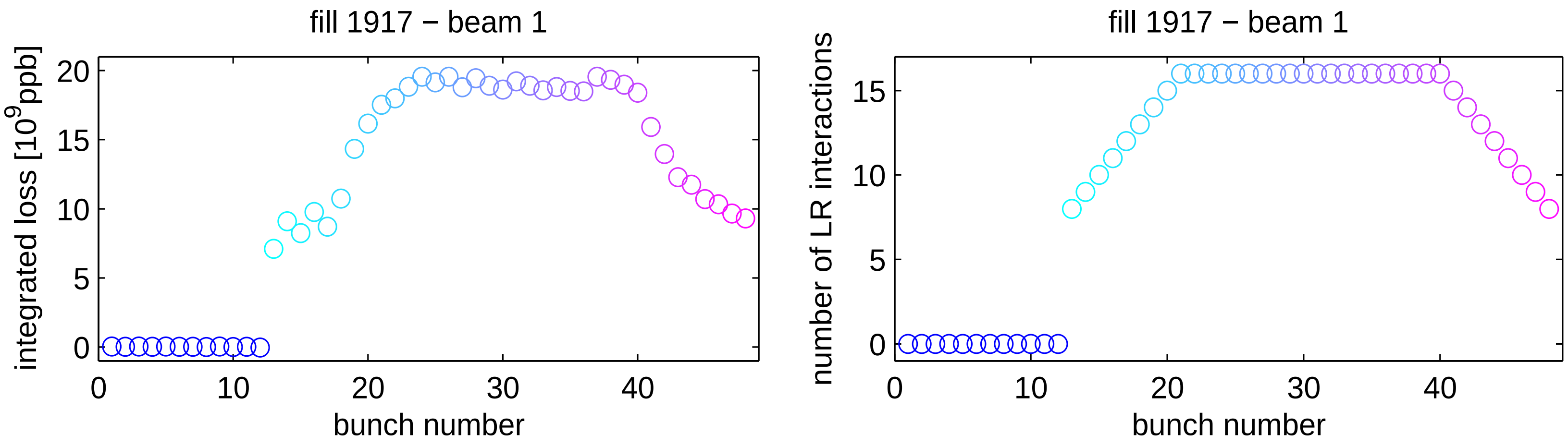


- **First test (2011) with $\beta^* = 1.50$ m, intensity: 1.2 10^{11} p/b, emittance: 2.0 - 2.5 μm**

→ **Bunch by bunch loss as function of crossing angle in IP1**

→ **Different behaviour of the bunches in the train**

PACMAN effects along train



- **Integrated losses and number of long range interactions**
- **'PACMAN' effects clearly visible, and exactly reproducible !!**

Can we understand the observations ?

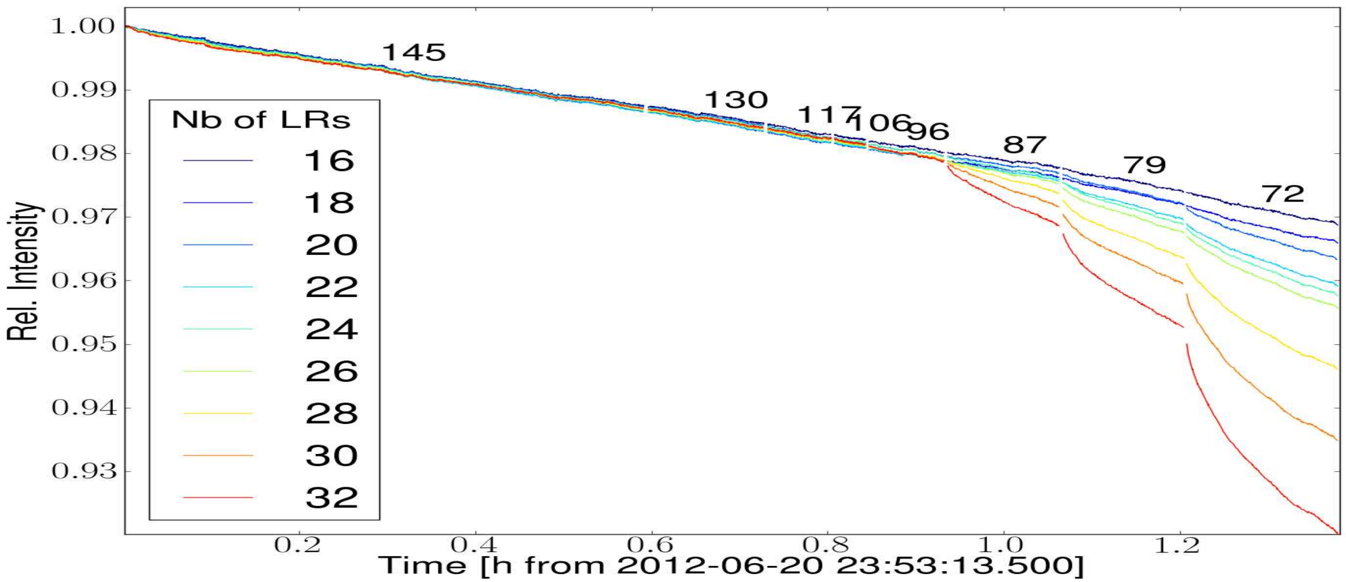
- **Try an analytical model (allows to study parametric dependencies)**
- **Based on computation of beam-beam invariants and smear (W.Herr, D.Kaltchev; IPAC09) → D. Kaltchev, this session**
- **Can compute invariants for individual long range encounters**
  - **Derive scaling laws for dynamic aperture (losses) etc.**
  - **Find the "critical" long range encounters**
  - **Estimate effects for future machine (in finite time, i.e. without tracking) HL-LHC, HE-LHC**

Test of parametric dependence (separation, intensity)

experiment	emittance	β^*	Intensity
2011 (50 ns)	2.0 - 2.5 μm	1.5 m	1.2 10^{11}
2012 (50 ns)	2.0 - 2.5 μm	0.6 m	1.2 10^{11}
2012 (50 ns)	2.0 - 2.5 μm	0.6 m	1.6 10^{11}
2012 (25 ns)	3.5 - 4.0 μm	1.0 m	1.2 10^{11}

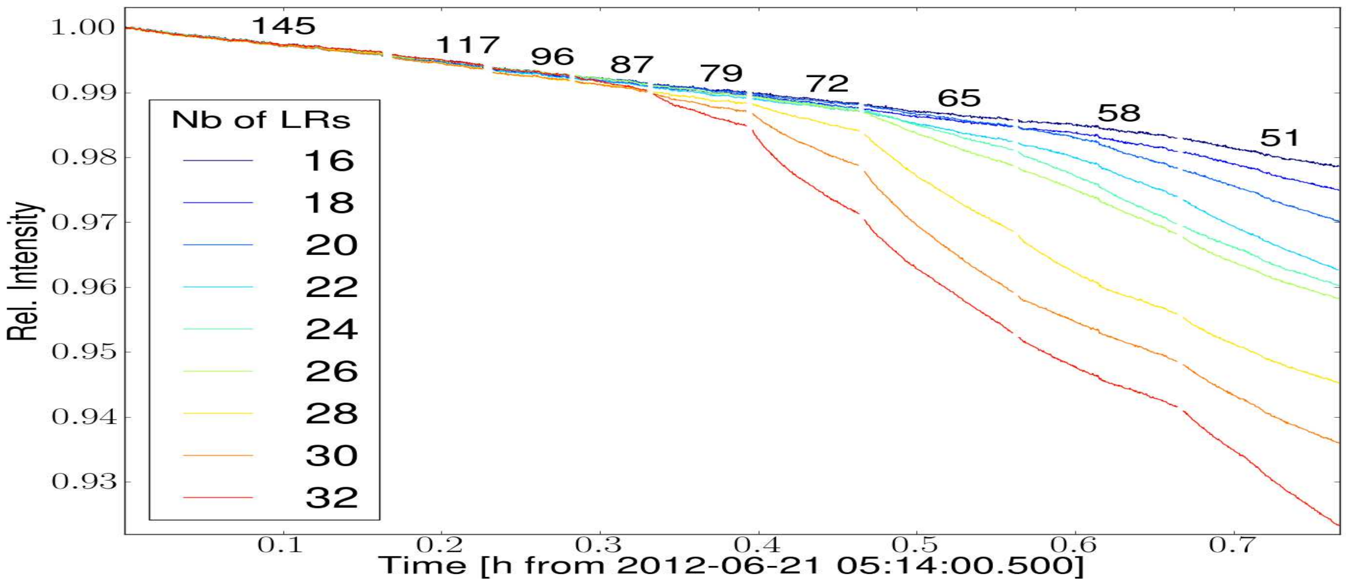
- **Combination of parameters allows parametric studies**
- **Normalized separation adjusted with β^* and crossing angle:** $\sqrt{\beta^*} \cdot \alpha \;=\;$ **const.**

Test of parametric dependence (separation, intensity)



- **Recent test (2012) with $\beta^* = 0.60$m, intensity: 1.6 10^{11} p/b**
- **Initial separation $\approx$ 9 - 9.5 σ**
- **Losses start $\approx$ 6 σ separation ($\alpha = 96\ \mu$rad)**

Test of parametric dependence (separation, intensity)



- **Recent test (2012) with $\beta^* = 0.60$m, intensity: 1.2 10^{11} p/b**
- **Initial separation $\approx$ 9 - 9.5 σ**
- **Losses start $\approx$ 5 σ separation ($\alpha = 87$ μrad)**

Analysis of long range experiments (D. Kaltchev)

Idea:

- **Long range beam-beam on a particle at amplitude n_σ depends on set of parameters:**

  $n_\sigma, N_b, n_{lr}, \alpha, \epsilon_n, \gamma, ..$

- **Find a (analytical) model ($\mathcal{M}$) to parametrize non-linear long range beam-beam strength**

  $\mathcal{M}(n_\sigma, N_b, n_{lr}, \alpha, \epsilon_n, \gamma, ..)$

- **To allow comparison and extrapolation**

Analysis of long range experiments (D. Kaltchev)

Try a model with smear $S(n_\sigma)$

- **Procedure to find analytical expression $S(n_\sigma)$:**
  - **Use Lie-algebraic method to derive generalized invariant**
  - **Smear $S(n_\sigma)$ is "r.m.s." of invariant (integrated over Φ)**
- **Valid for multiple IPs, long range interactions**
- **Compare with tracking, estimate where comparison breaks down**

Analysis of long range experiments (D. Kaltchev)

How do we use that ?

Ideally we would have for two configurations a and b:

$$S(n_\sigma, N_b^a, n_{lr}^a, \alpha^a, \epsilon_n^a, \gamma^a, ..) = S(n_\sigma, N_b^b, n_{lr}^b, \alpha^b, \epsilon_n^b, \gamma^b, ..)$$

If the smear is the same, the behaviour should be the same

To compare two of our experiments:

$$S(n_\sigma, 1.2\ 10^{11}, n_{lr}^a, \alpha^a, \epsilon_n^a, \gamma^a, ..) = S(n_\sigma, 1.6\ 10^{11}, n_{lr}^b, \alpha^b, \epsilon_n^b, \gamma^b, ..)$$

If α^a is known $\Rightarrow$ **we computed expected α^b**

In our case: $\alpha^a = 96\ \mu rad$ theory says $\alpha^b = 86\ \mu rad$, found 87 μrad

Similar procedure should apply to other parameters

Analysis of long range experiments (D. Kaltchev)

- **Start of losses (critical angles) can be explained with analytical smear formula**
- **Can be used (for after LS1 and HL-LHC, etc..):**
  - **compare different configurations (without tracking)**
  - **extrapolate between 50 ns and 25 ns spacing**
- **Optimization of collisions scenarios much easier with this technique**

Expected scaling laws: dynamic aperture

- **This allows to derive scaling laws**
- **Scaling laws for long-range dynamic aperture DA**

$$
\begin{aligned}
DA &\propto \frac{1}{n_b} \quad \text{(number of bunches)} \\
DA &\propto \frac{1}{\sqrt{\epsilon}} \\
DA &\propto d_{sep} \propto \alpha \\
DA &\propto d_{sep} \propto \sqrt{\beta^*} \\
DA &\propto \frac{1}{N} \quad \text{(Intensity)}
\end{aligned}
$$

- **Can make estimates for parameters for future machines (HL-LHC, ..)**

Summary - long range beam-beam in the LHC

- **Plenty of experience in two years and significant progress understanding**
- **Long range interactions main source of dynamic aperture**
- **PACMAN effects very visible - require attention**
- **Scaling laws have been established, can serve for extrapolation for new configurations**

The long range problem

Some answers from beam-beam studies (experiments and theory):

- **Effect on dynamic aperture ? Yes**
- **What is the required separation ? $\geq$ 10 σ**
- **Do we have PACMAN effects ? Yes**
- **Do alternating crossing schemes help ? Yes**
- **Can we collide with offset beams ? Yes**
- **Can we predict anything ? Yes**

Tevatron Long-Range Summary

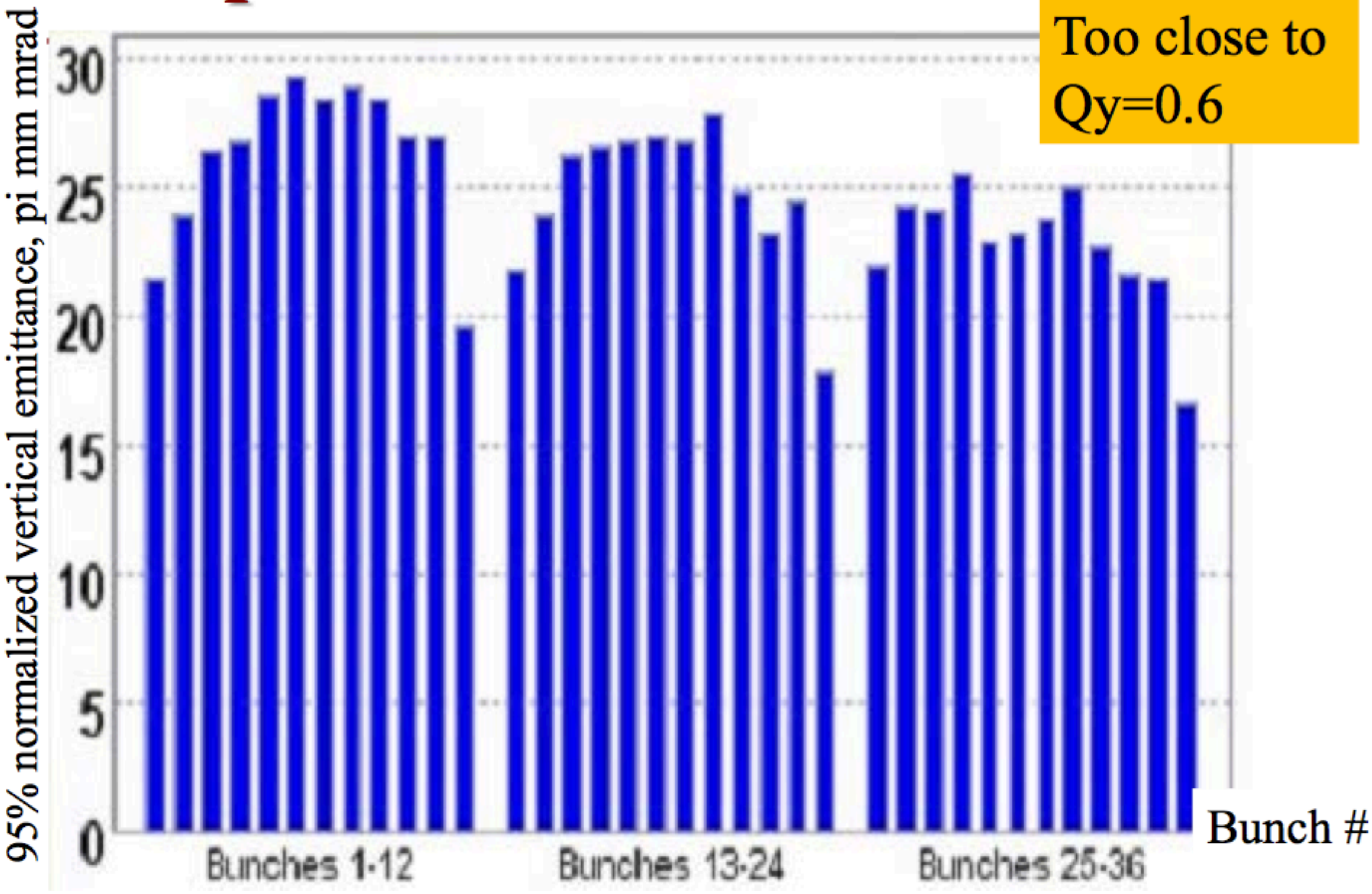
A.Valishev for V.Shiltsev

- In the Tevatron Run II, 36x36 bunch collisions made for 72 crossings per revolution per bunch. The total number of interaction points was 138.
  - – Several steps in longitudinal cogging during antiproton injection created additional complication of the collision pattern.
- Long-range beam-beam effects manifested themselves in reduction of beam lifetime and accelerated emittance growth.
  - – This accounted for as much as 50% luminosity loss early in Run II down to ~5-10% at the end.
- No coherent effects attributed to beam-beam

- At injection energy, LR beam-beam was the dominant factor for intensity losses both in proton and antiproton beams.
  - Especially noticeable for off momentum particles, and strongly related to the tune chromaticity (strength of sextupoles).
- During low-beta squeeze and collisions, LR also caused transverse emittance growth.
  - In squeeze beams briefly (2s) came within 2-2.5σ at 1 point. This caused sharp loss spikes.
  - At collisions 4 crossings at 5.8-6σ separation were essential. The rest LR's were at 8-10σ

- Bunch-to-bunch (pacman) effects were significant - particle losses AND fast differential emittance growth.
  - Differences in tunes, coupling and chromaticity were essential due to the confined space in tune diagram.
  - Orbit difference did not have adverse effect on performance.

“Scallops” in Pbar Bunch Emittances



Too close to Qy=0.6

- Dedicated beam experiments were conducted to identify problematic locations.
- Day-by-day careful analysis of beam data (and especially bunch-by-bunch data) from HEP stores was key to understanding beam-beam performance and scaling.
- Extensive modeling
  - Weak-strong particularly useful.
  - Very practical was computation of RDT’s

- LR effects were mitigated by:
    - Increase of separation by installation of extra separators.
    - Rearrangement of helical orbits.
    - Optimization of machine optics – linear and nonlinear.
    - Pulsed e-lense
    - Large number of incremental improvements, no “silver bullet”.