Optimum Filling Scheme for Ions in the LHC

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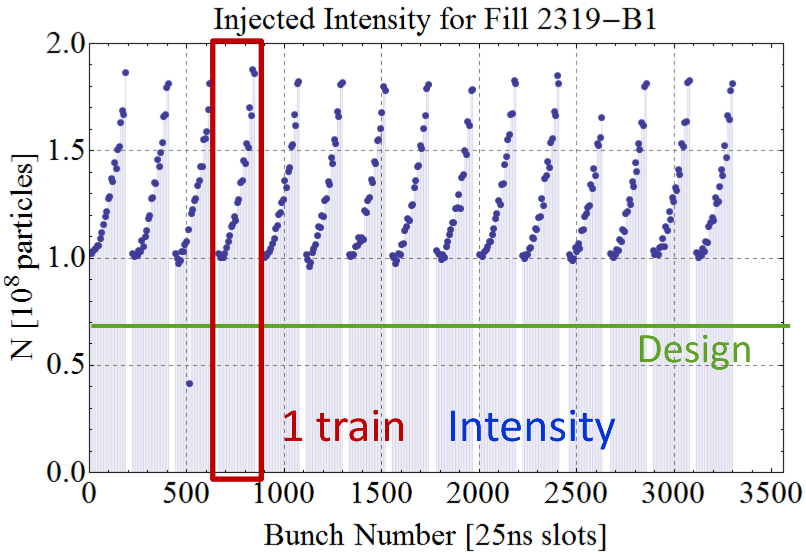
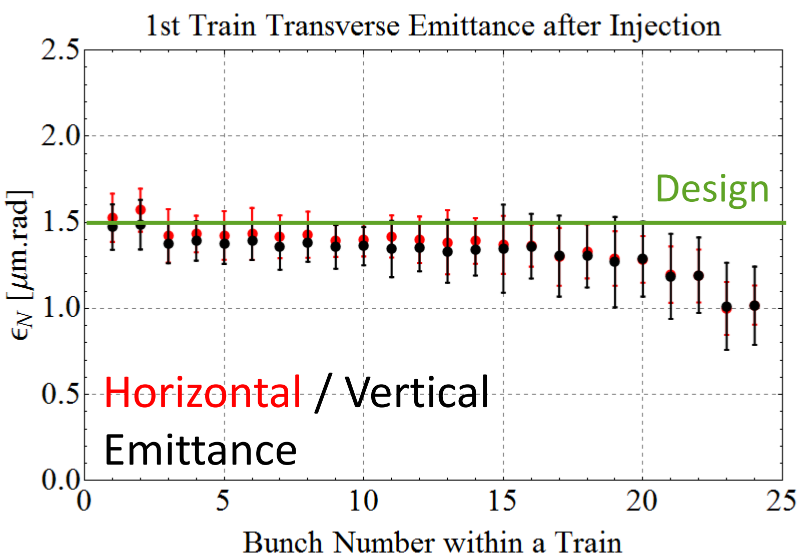
Outline

- Bunch-by-Bunch Differences in the LHC.
- Empirical Model to Predict Peak Luminosities per Bunch.
- Optimum Filling Schemes for after LS1 and LS2.
- Instantaneous and Integrated Luminosity Evolution for Selected Scenarios.

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV

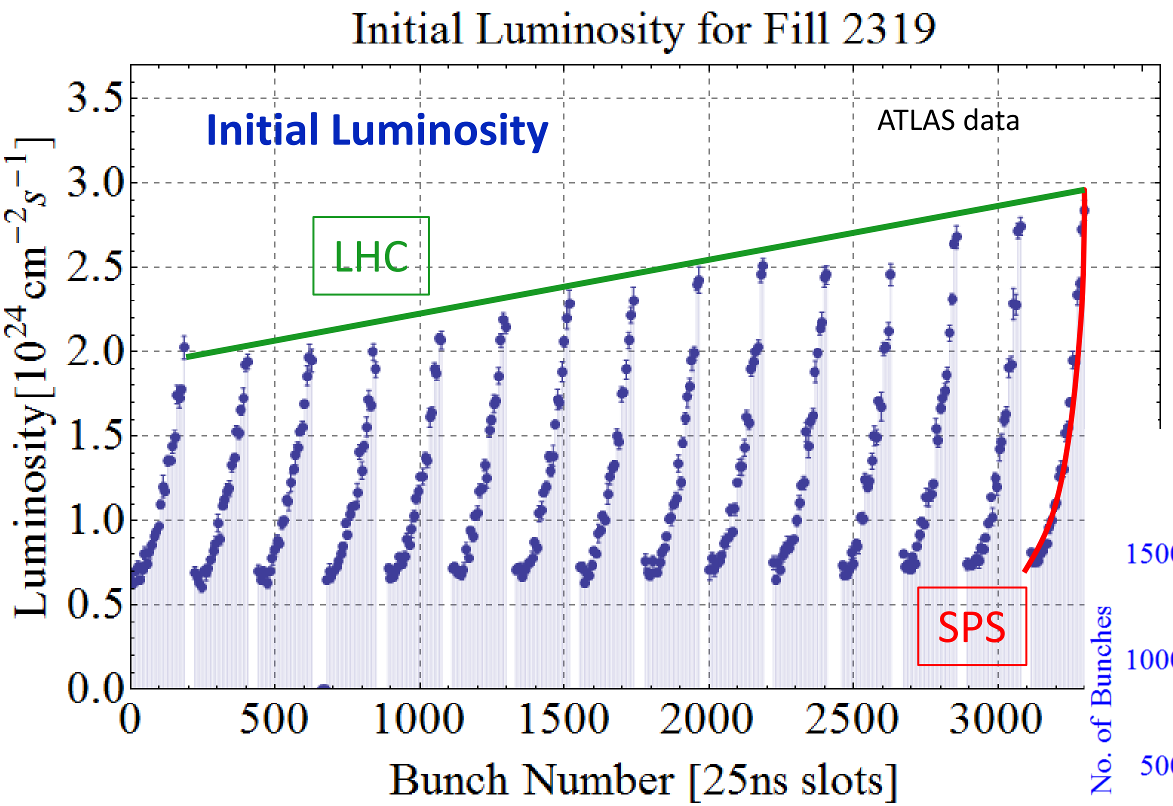


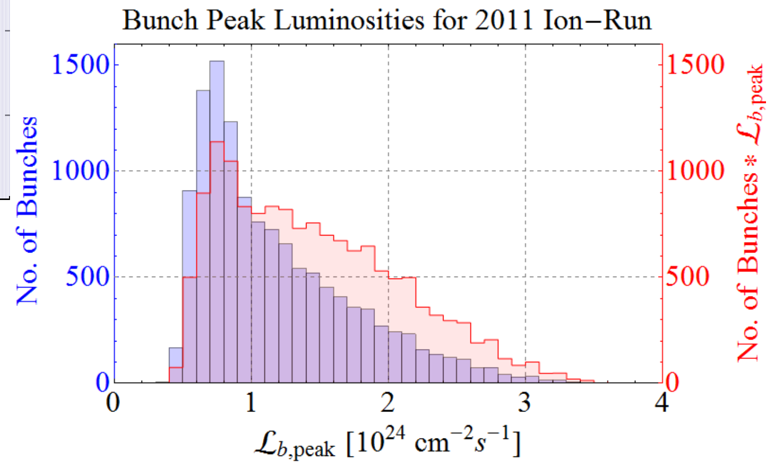


- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.
- IBS at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low energy → strong IBS, → emittance growth and particle losses.

Bunch-by-Bunch Luminosity

E = 3.5Z TeV





Two effects:

Slope imprinted by SPS injection plateau.

Slope imprinted by LHC injection plateau.

→ Last train does not see degradation due to LHC injection plateau.

→ Cleanest picture of what happens “to the luminosity” in the SPS.

Parametrisation of Degradation in the SPS

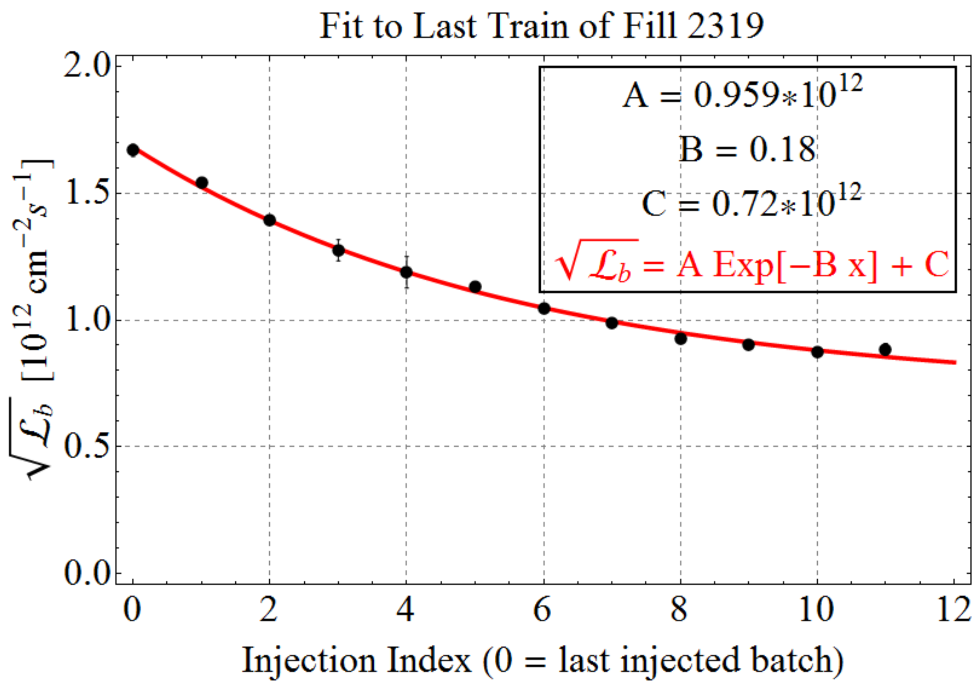
- Take ATLAS bunch-by-bunch luminosity data of last train injected into LHC.
- Invert order of the bunches. → time evolution
- Average over bunches of one PS batch.
- Take square root of the data, since: $\sqrt{\mathcal{L}} \propto N_b/\sqrt{\epsilon}$

  for equal colliding bunches (as is approx. the case in ATLAS):

$$N_b = N_{b1} = N_{b2}$$
$$\epsilon = \epsilon_1 = \epsilon_2$$

- Fit an exponential of the form:

$$\sqrt{\mathcal{L}} = A \exp[-B\, x] + C$$



Average over all proper fills of 2011

$$\begin{aligned}
\sqrt{\mathcal{L}_{\mathrm{SPS}}} &= \bar{a}\exp[-\bar{b}\,x] + \bar{c} \\
\bar{a} &= 1.04 * 10^{12}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2} \\
\bar{b} &= 0.19 \\
\bar{c} &= 0.71 * 10^{12}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2}
\end{aligned}$$

Parametrisation of Degradation in the LHC

- Group bunches of equivalent PS batches (n^{th} PS batch) from all trains, which saw the same SPS injection plateau length.
- Invert the order → time evolution.
- Fit an exponential of the same form as before: $\sqrt{\mathcal{L}} = A \exp[-B\, x] + C$

- Result: 12 fits with different decay speed due to different brightness's of the bunches.
- Simplification: 1 curve that describes all of them.
- Two possibilities:
  1) Average fit parameters of all curves.
  2) Take fit of average bunch.
- Number 2) is in better agreement with the data.

Average over all proper fills of 2011

$$\begin{aligned}
\sqrt{\mathcal{L}_{\mathrm{LHC}}} &= \bar{A} \exp[-\bar{B}\, x] + \bar{C} \\
\bar{A} &= 7.74 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2} \\
\bar{B} &= 0.0012 \\
\bar{C} &= -6.53 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2}
\end{aligned}$$

Complete Parametrisation

$$\sqrt{\mathcal{L}_{\mathrm{b}}} = F_{Nb}\, F_{norm} (\bar{a} \exp[-\bar{b}\, n_{\mathrm{PSbatch}}] + \bar{c})(\bar{A} \exp[-\bar{B}\, n_{\mathrm{LHCtrain}}] + \bar{C})$$

Intensity scaling factor

Normalisation factor

$$F_{norm} = 8.27 * 10^{-13}$$

$$\begin{aligned}
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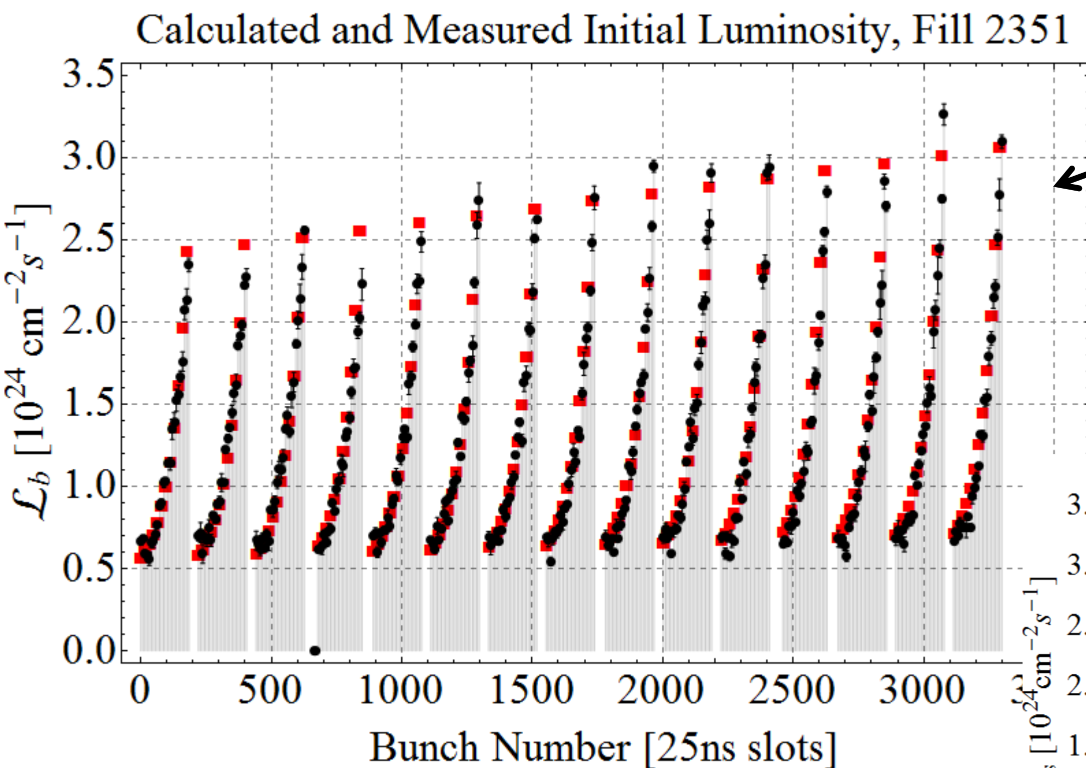
\end{aligned}$$

Only takes variations due to SPS and LHC into account.
LEIR, PS are assumed to have cycles similar as in 2011.

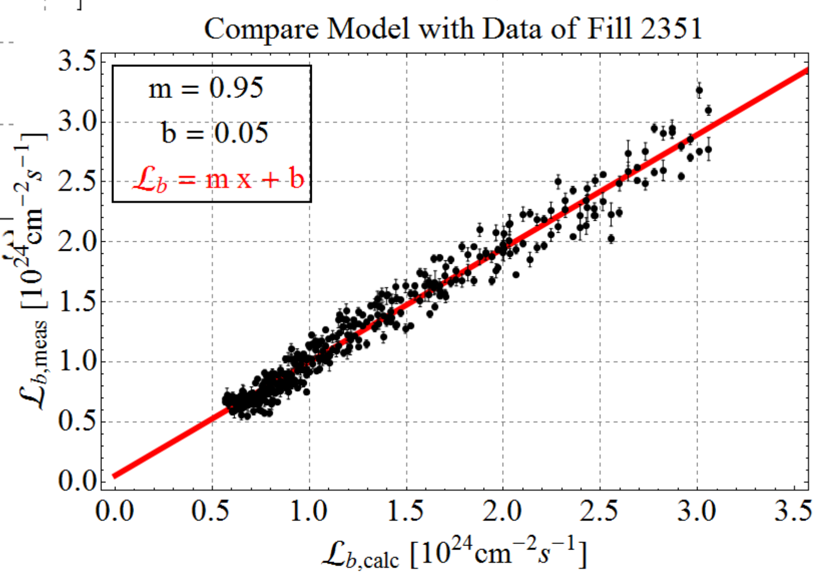
Validation of the Parametrisation

$$\sqrt{\mathcal{L}_\mathrm{b}} = F_{Nb}\,F_{norm}(\bar{a}\exp[-\bar{b}\,n_{\mathrm{PSbatch}}]+\bar{c})(\bar{A}\exp[-\bar{B}\,n_{\mathrm{LHCtrain}}]+\bar{C})$$



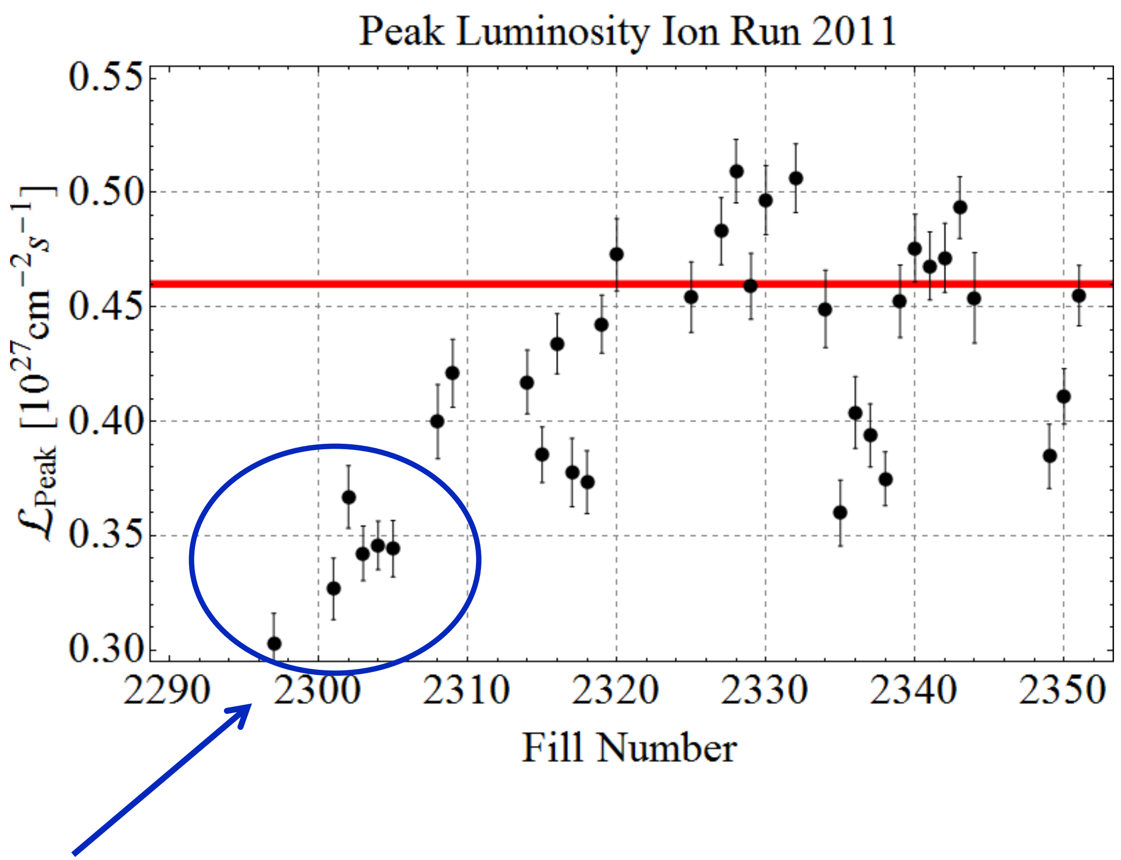
Calculation compared to data of the last fill from 2011.

Data vs. calculation



Validation of the Parametrisation

Peak Luminosity per fill: Sum over all single bunch luminosities.



Not taken into account
for building the model.

Estimates

Linear parameter scaling w.r.t. 2011 parameters:

1. Number of particles per bunch N_b
2. Energy E
3. β^*

Vary injection scheme:

Free parameters:

1. Number of bunches per PS batch. (*Constrain: 2011 PS cycle length*)
2. Spacing PS.
3. Spacing SPS.
4. *Spacing LHC: assumed to be 900ns.*

} Given by hardware constrains.

Parameters to be optimised:

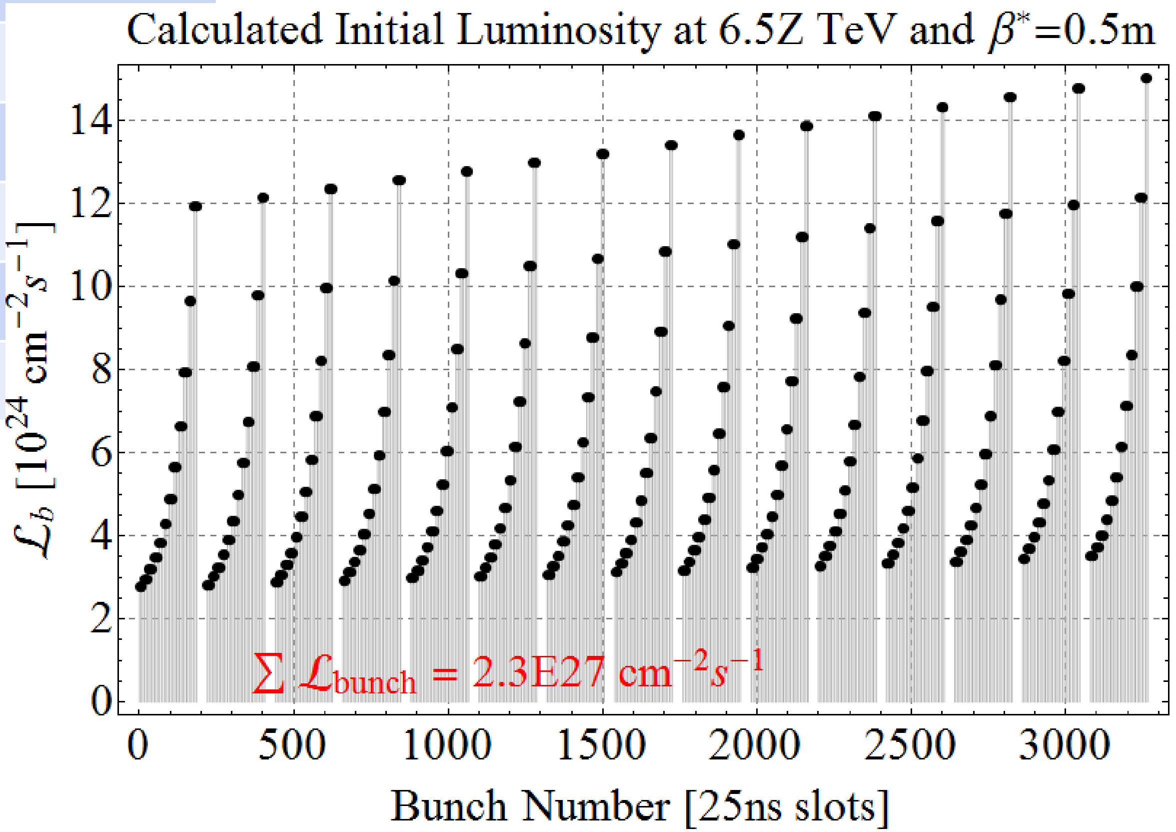
1. Set number of PS batches per LHC train.
2. Set number of LHC trains.

} Optimise to achieve max. peak luminosity.

Estimates for after LS1 – 2011 Scheme

E = 6.5 Z TeV

2011 Filling Scheme	@ E = 6.5Z TeV β^*= 0.5m F_{Nb} = 1.15
Spacing PS [ns]	200
Spacing SPS [ns]	200
No. bunches/PS batch	2
No. PS batches/train	12
No. LHC trains	15
No. bunches/beam	358



2011 filling scheme with 2013 bunch performance.

Max. peak luminosity
$2.3 \times 10^{27} \text{cm}^{-2}\text{s}^{-2}$

Estimates for after LS1 – Batch Compression

Batch Compression	**@ E = 6.5Z TeV** **β^*= 0.5m** **F_{Nb} = 1.15**
Spacing PS [ns]	100
Spacing SPS [ns]	225
No. bunches/PS batch	2
No. PS batches/train	7 / 9
No. LHC trains	29 / 24
No. bunches/beam	406 / 432

max. Luminosity

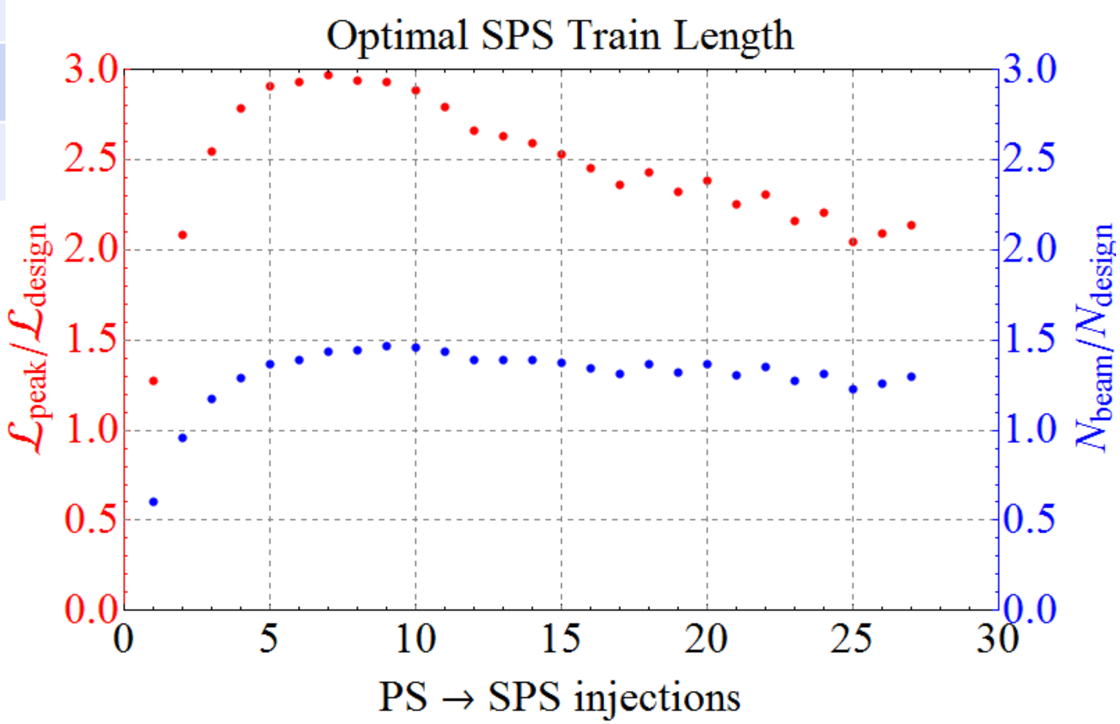
max. Intensity

Max. peak luminosity
$3 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-2}$

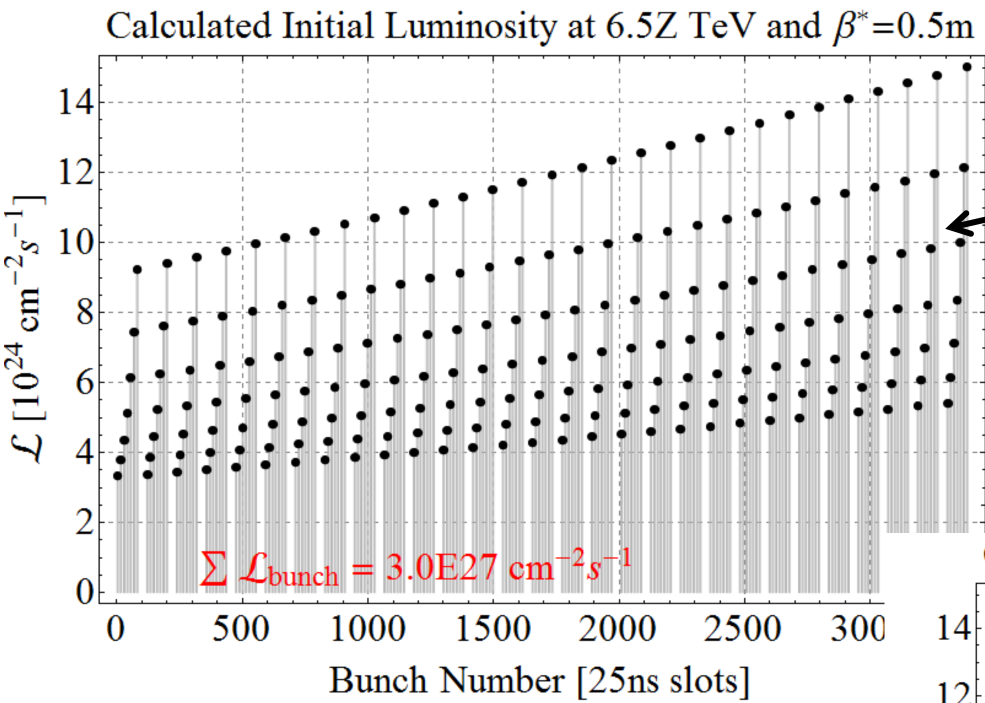
Filling schemes are not exact!

Takes into account:

- Not more than 40% of the SPS is filled.
- 3.3μs abort gap.
- 900ns LHC kicker gap.
- All bunches are colliding with an equal partner.



Estimates for after LS1 – Optimisation

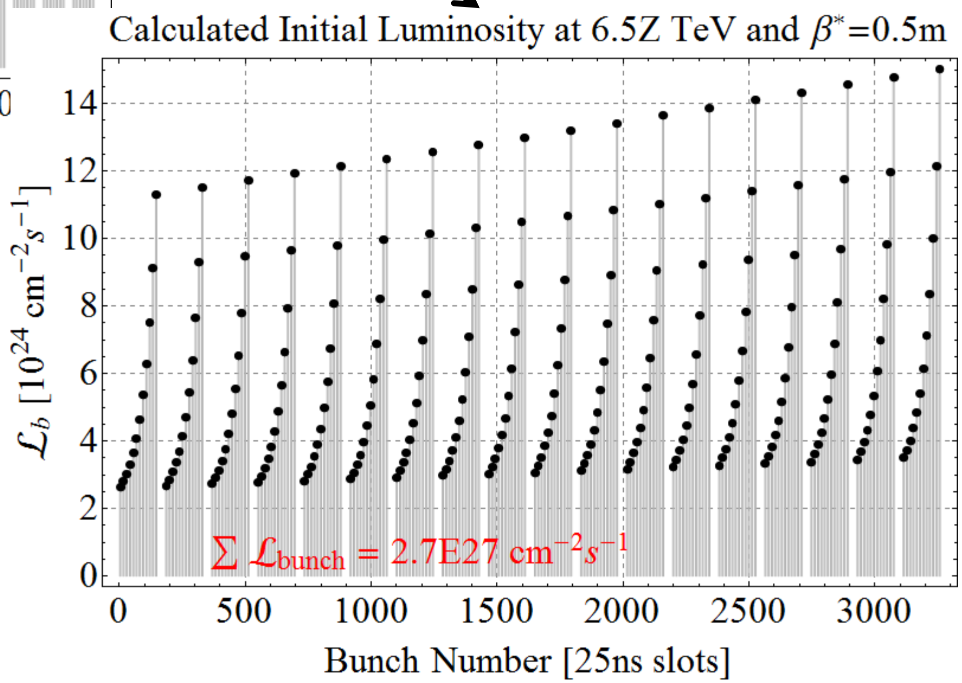


Scheme with max. peak luminosity

7 batches & 29 trains = 406 bunches

Scheme similar as in 2011

12 batches & 18 trains = 432 bunches



- ~15% improvement in peak luminosity due to batch compression in the PS.
- Another ~10% by shortening the trains.

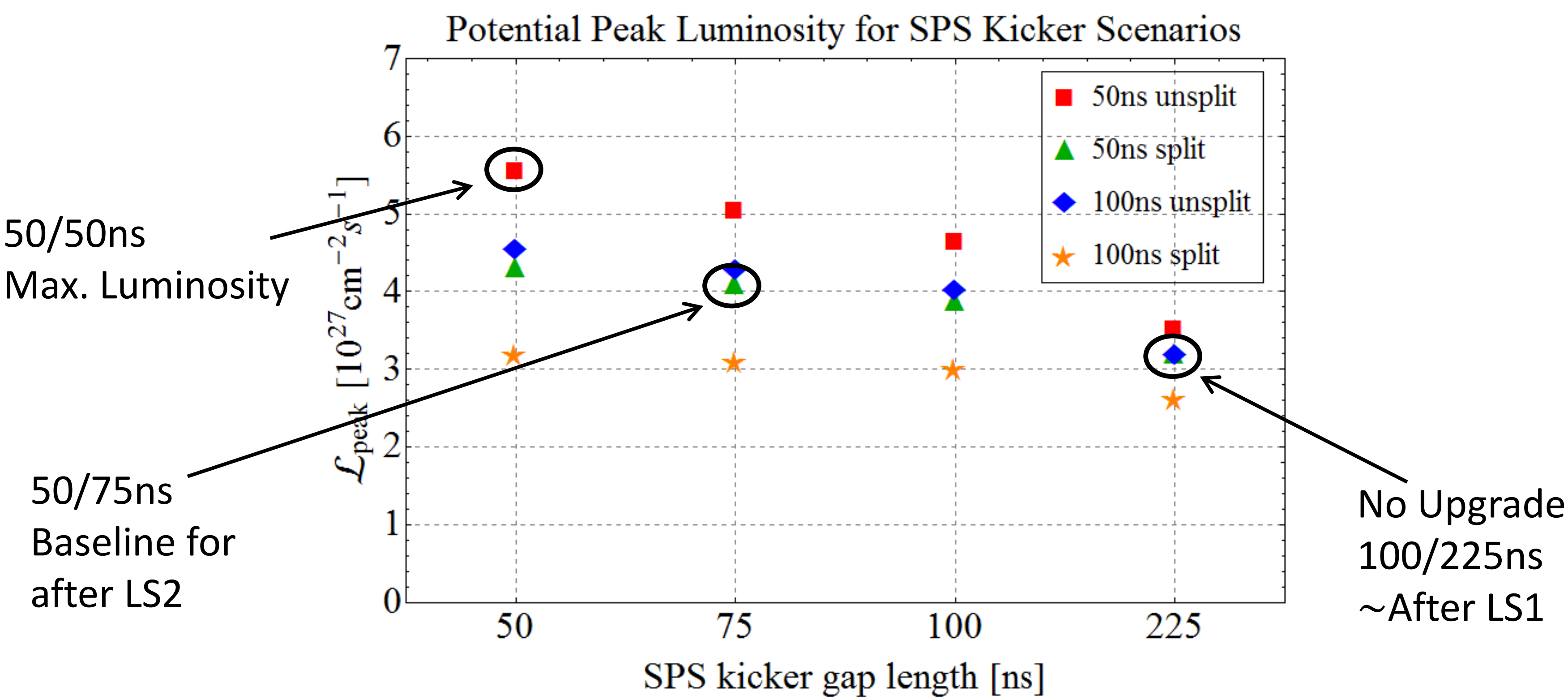
→ 30% more as for 2011 scheme.

Estimates for after LS2

SPS Spacing [ns]	PS Spacing [ns]	No. Bunches/PS Batch
50	50 or 100	2 (unsplit) or 4 (split)
75	50 or 100	2 or 4
100	50 or 100	2 or 4
225	50 or 100	2 or 4

E = 7 Z TeV

Intensity scaling:
unsplit: F_{Nb} = 1.15
split: F_{Nb} = 0.85

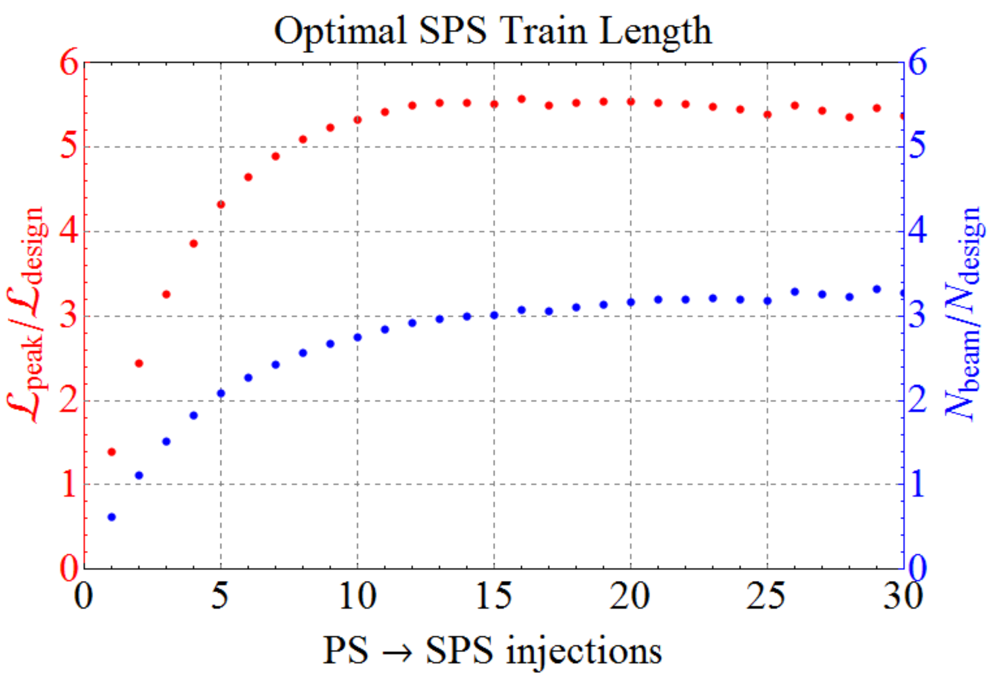


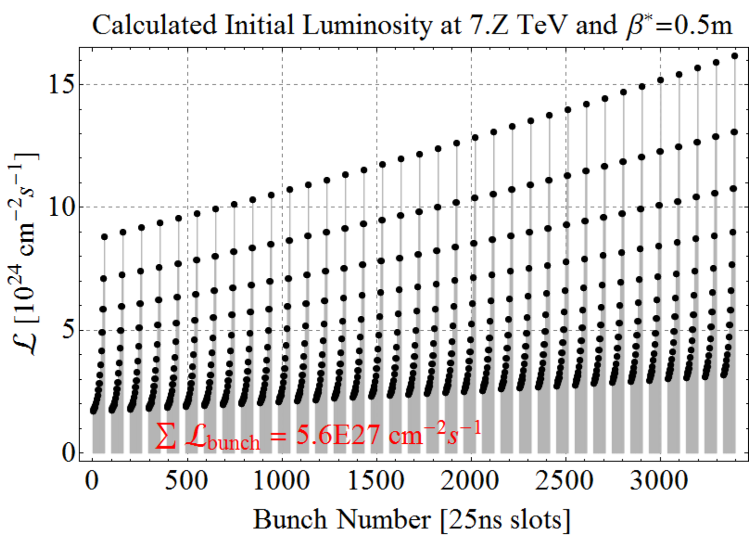
Estimates for after LS2 – 50/50ns Scheme

50/50ns Scheme PS Bunch Splitting	@ E = 7Z TeV β^* = 0.5m F_{Nb} = 1.15
Spacing PS [ns]	50
Spacing SPS [ns]	50
No. bunches/PS batch	2
No. PS batches/train	16
No. LHC trains	35
No. bunches/beam	1120

Option with highest luminosity achievable!

$$L_{peak} = 5.6 \times 10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-2}$$



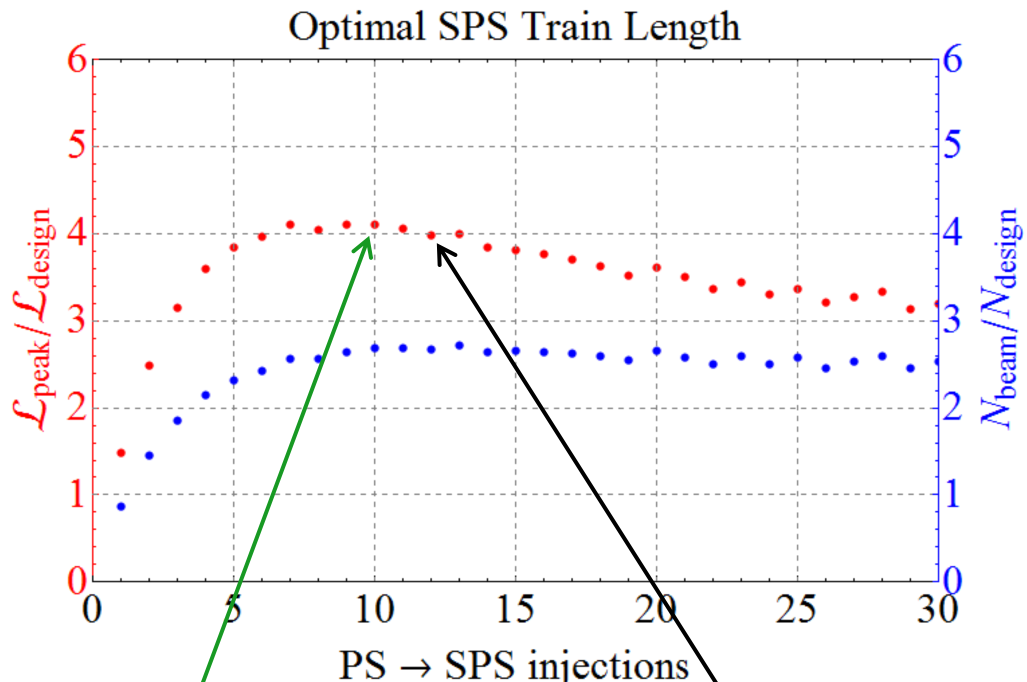


Flat Peak Luminosity Evolution for more than 12 batches/train.

Estimates for after LS2 – 50/75ns Scheme

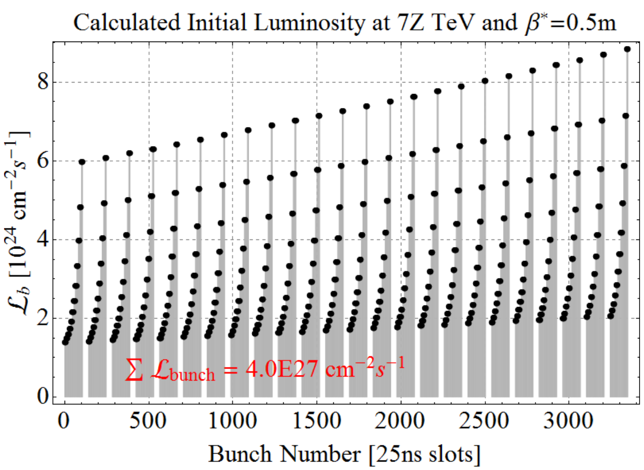
50/75ns Scheme PS Bunch Splitting	@ E = 7Z TeV β^*= 0.5m F_{Nb} = 0.85
Spacing PS [ns]	50
Spacing SPS [ns]	75
No. bunches/PS batch	4
No. PS batches/train	12
No. LHC trains	24
No. bunches/beam	1152

$$L_{peak} = 4 \times 10^{27} \text{cm}^{-2} \text{s}^{-2}$$



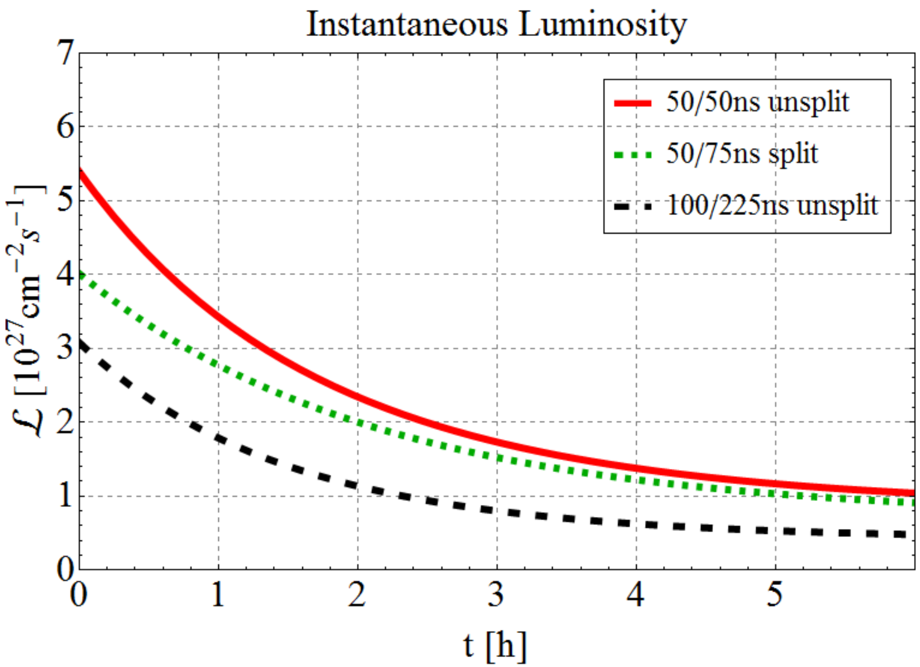
Optimal Injection Scheme:
10 PS batches, 28 LHC trains
→ ~1120 bunches/beam

Django's Proposal:
12 PS batches, 24 LHC trains
→ ~ 1152 bunches /beam



However, only minor differences in expected peak luminosity!

Luminosity Evolution w/wo SPS Kicker Upgrade

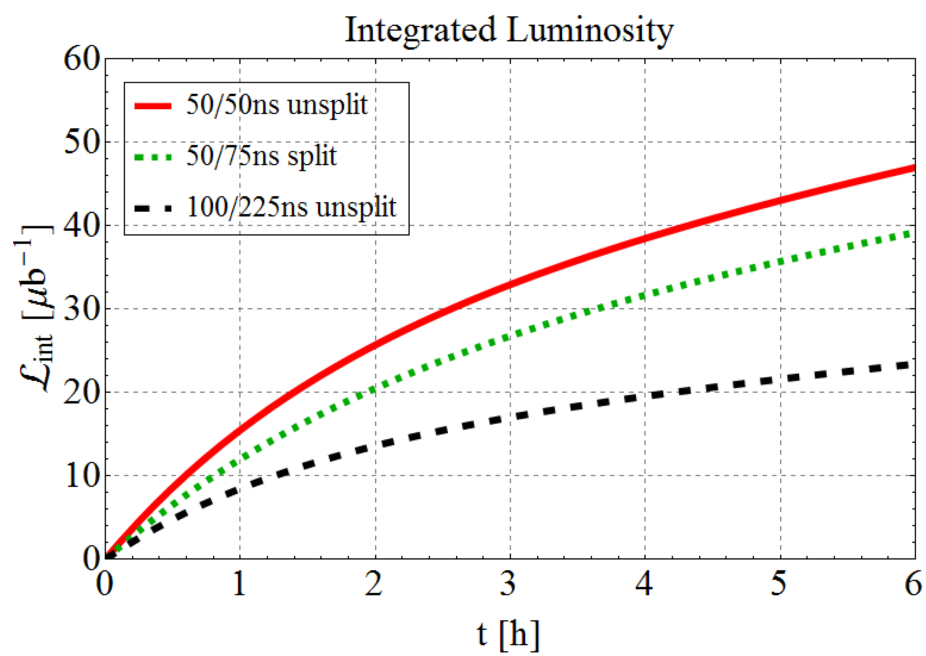


Takes into account different

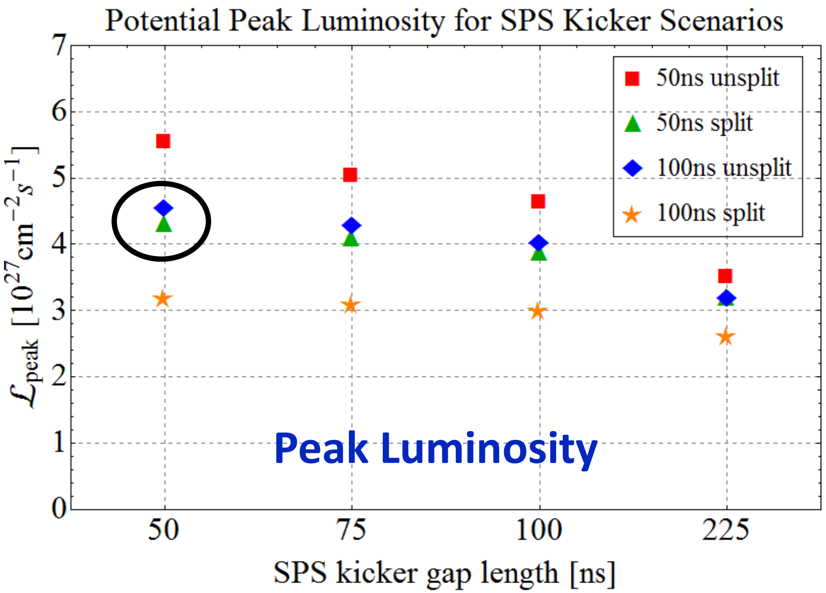
- initial bunch luminosities,
- bunch luminosity decay times.

Without any upgrade (black curve):

- Almost 50% integrated luminosity less (after 5h) compared to 50/50ns case.
- 40% less compared to 50/75ns cases.

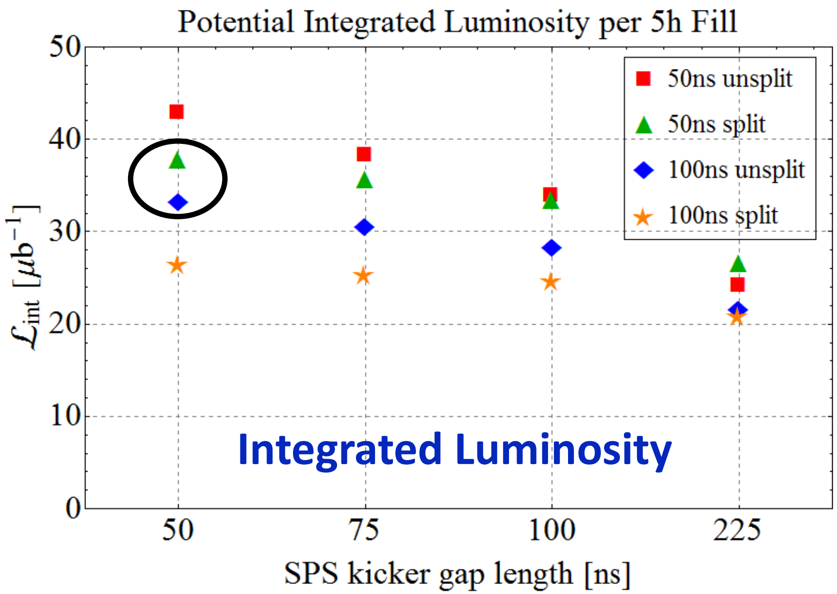


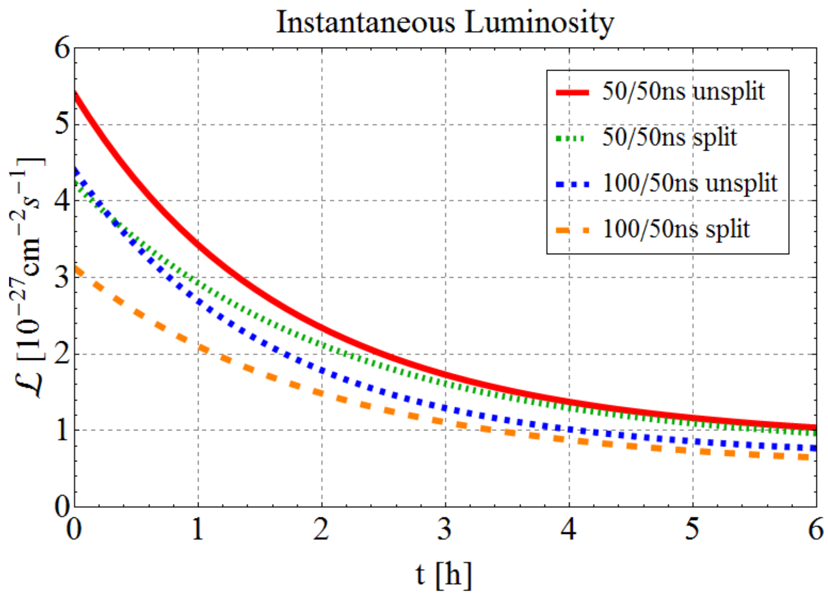
Luminosity Evolution: Splitting



Peak luminosity higher for 100ns PS spacing with unsplit bunches.
→ Higher brightness bunches decay faster.
→ Higher integrated luminosity for 50ns PS spacing with split bunches.

50/50ns split → 1200 bunches/beam
100/50ns unsplit → 748 bunches/beam





Conclusions

- Strong bunch degradation in the SPS/LHC, due to accumulation process of the bunches/trains.

- Empirical model for the $L_{b,peak}$ depending on the bunch position inside the train/beam (i.e. SPS/LHC injection plateau length per bunch) was built based on 2011 ATLAS luminosity data.

- After LS1: A batch compression scheme with 100/225ns spacing and shorter trains is expected to deliver $L_{peak} = 3 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-2}$.

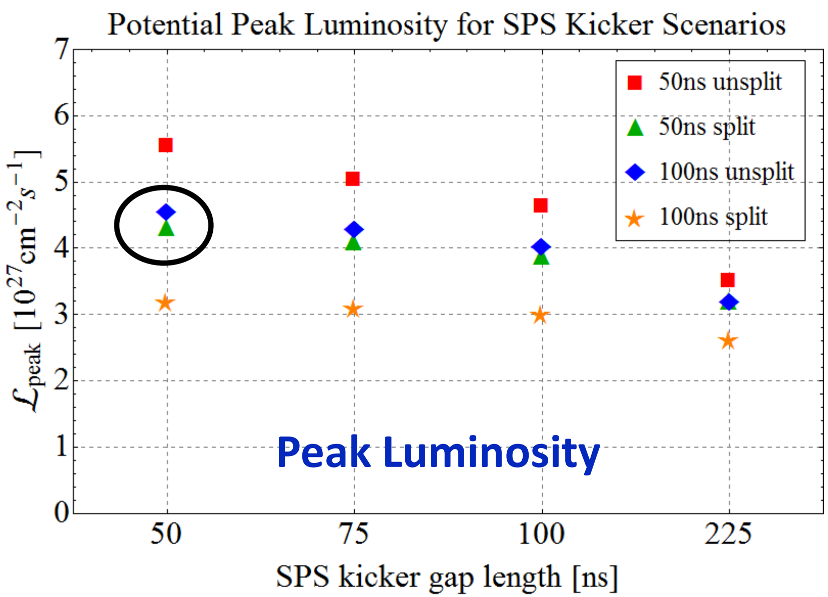
- After LS2 *(depending on intensity scaling)*:
  - Max. luminosity with 50/50ns spacing: $L_{peak} = 5.6 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-2}$ (44$\mu\mathrm{b}^{-1}$/5h).
  - Alternatively with 50/75ns spacing: $L_{peak} = 4 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-2}$ (36$\mu\mathrm{b}^{-1}$/5h) .
  - Without upgrade and 100/225ns spacing: 22$\mu\mathrm{b}^{-1}$/5h.

- For final decision integrated luminosity has to be investigated as well.

- Model can be refitted to SPS and LHC performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains.

THANK YOU
FOR YOUR ATTENTION

Luminosity Evolution w/wo SPS Kicker Upgrade



Peak luminosity higher for 100ns PS spacing with unsplit bunches.
→ Higher brightness bunches decay faster.
→ Higher integrated luminosity for 50ns PS spacing with split bunches.

50/50ns split → 1200 bunches/beam
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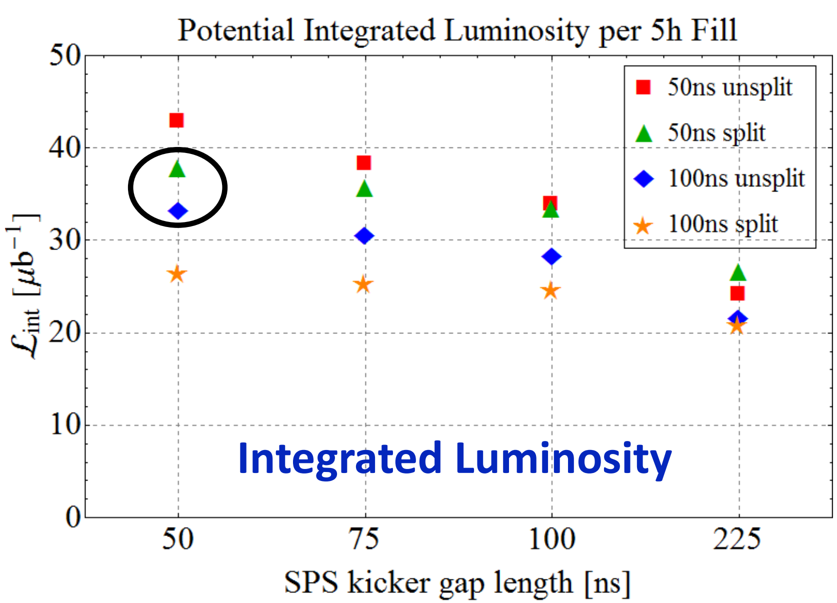

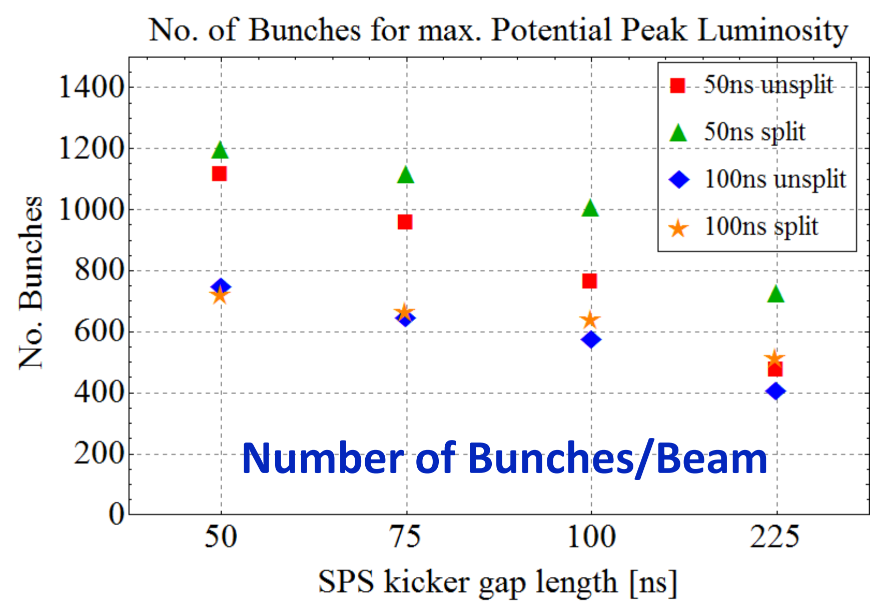

Design & Current Performance

	Collision (Design)	Injection (2011)	Collision (2011)	Injection (2013)	Collision (2013)
Beam Energy [Z GeV]	7000	450	3500	450	4000
No. Ions per bunch [10^8]	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance [μm. rad]	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	---
RMS bunch length [cm]	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	9.8 ± 0.1
Peak Luminosity [10^{27} cm^{-2}s^{-1}]	1	---	$\mathbf{0.4 \pm 0.1}$	---	p-Pb

Bunch-by-Bunch Differences after Injection (450Z GeV)