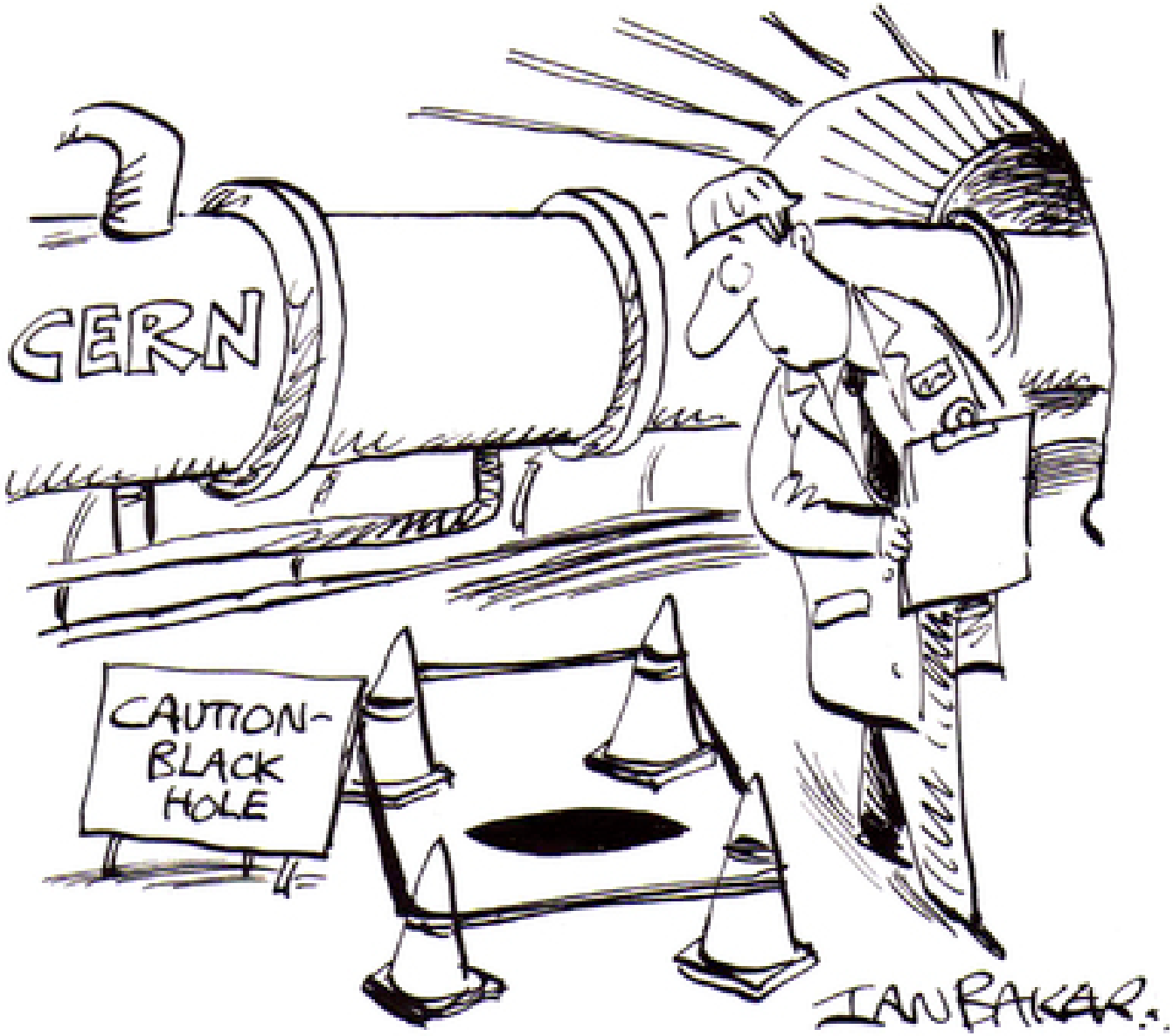
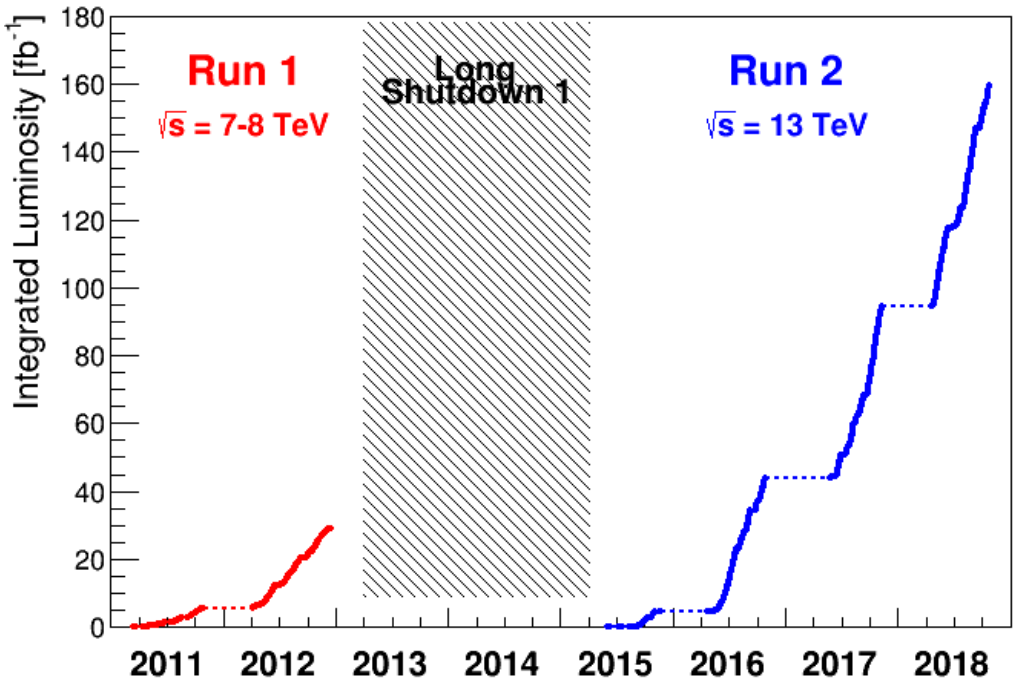


Heavy ions at LHC: A brief introduction to challenges and achievements so far

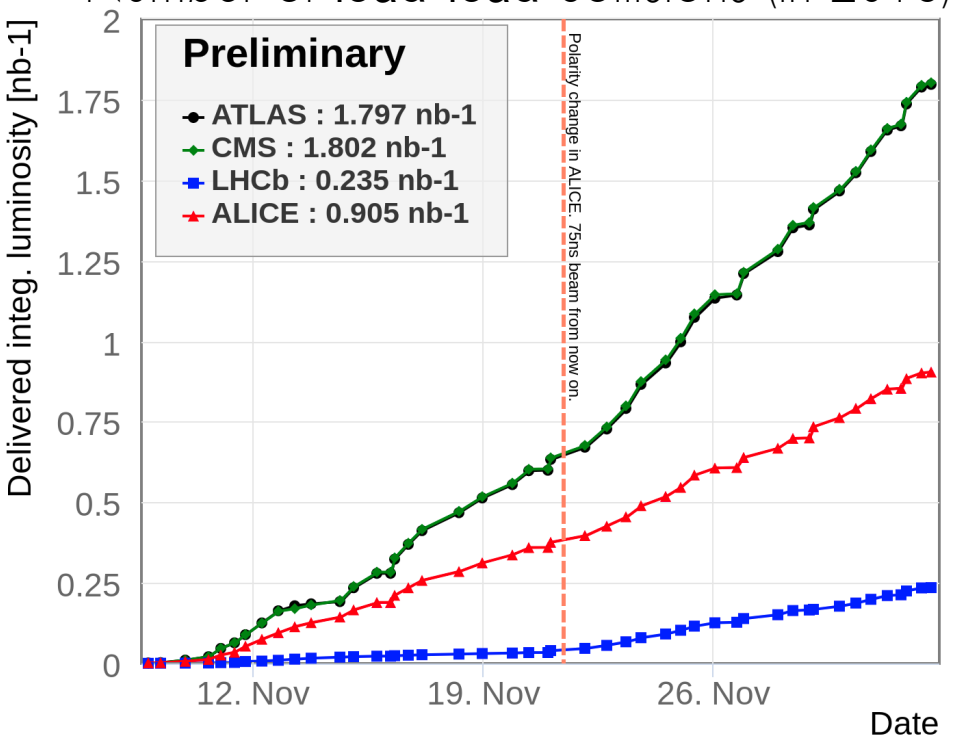
G.K. Krintiras

A lot of progress in the accelerator forefront

Number of **proton-proton** collisions



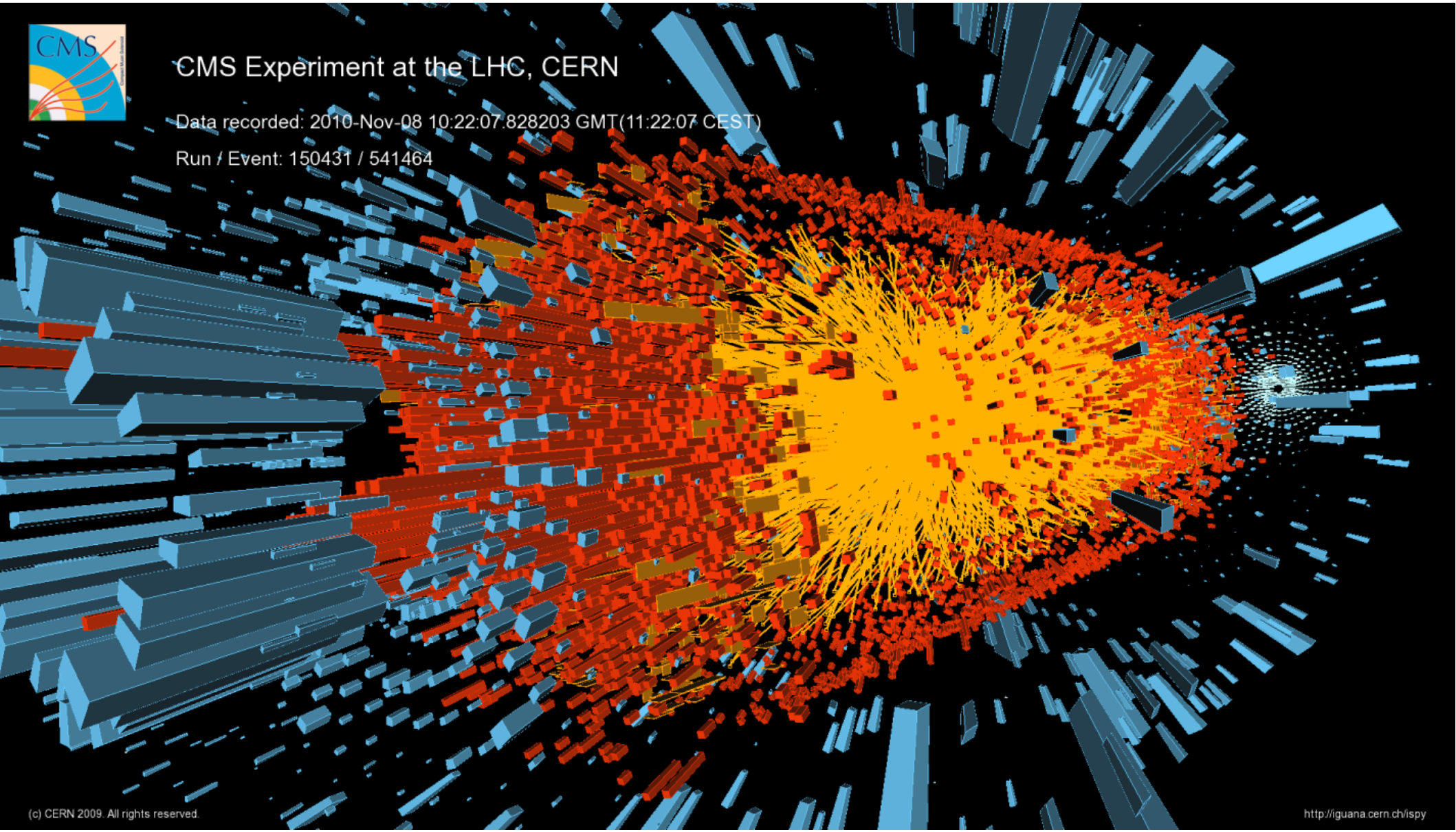
Number of **lead-lead** collisions (in 2018)



Plots from the LHC Coordination Info page

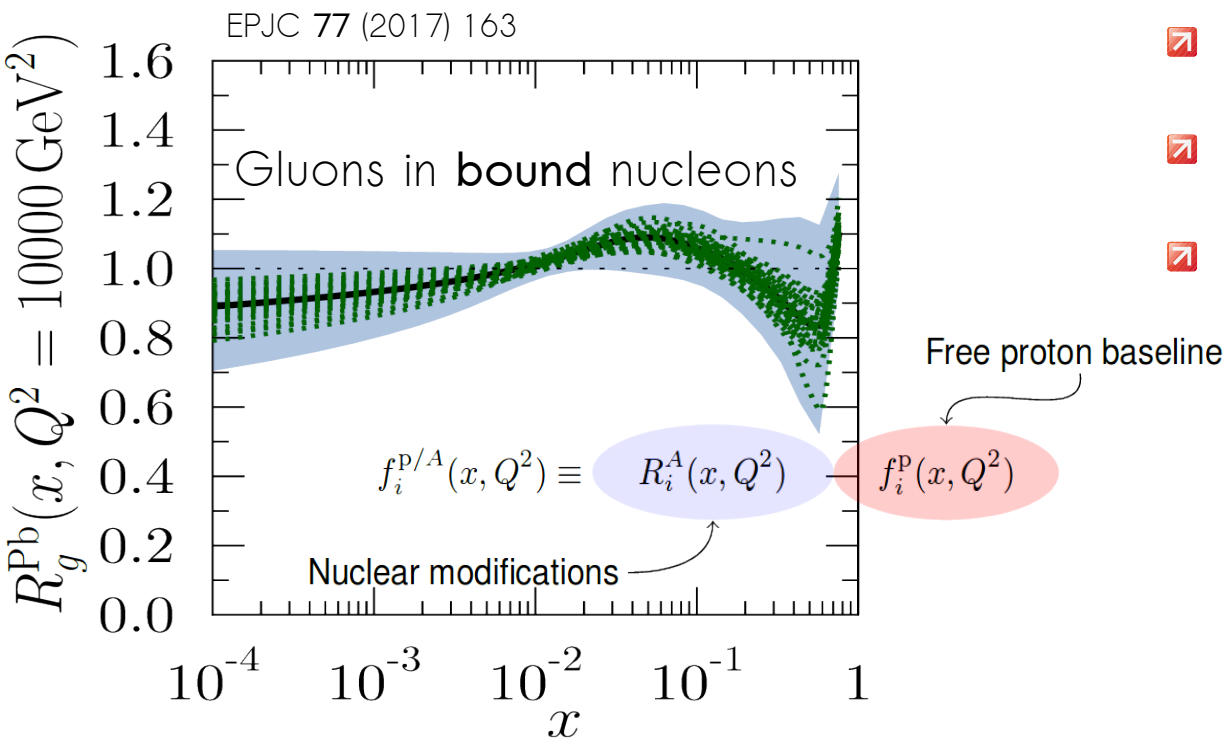
- Luminosity is collider **FOM** for delivering statistically significant data samples
  - We have about 2000 times **less** nuclear (lead-lead or proton-lead) than proton-proton data
  - Mainly due to acceleration limitations and partly due to running time: 4 months **vs** > 4 years!

That's a mess ☺



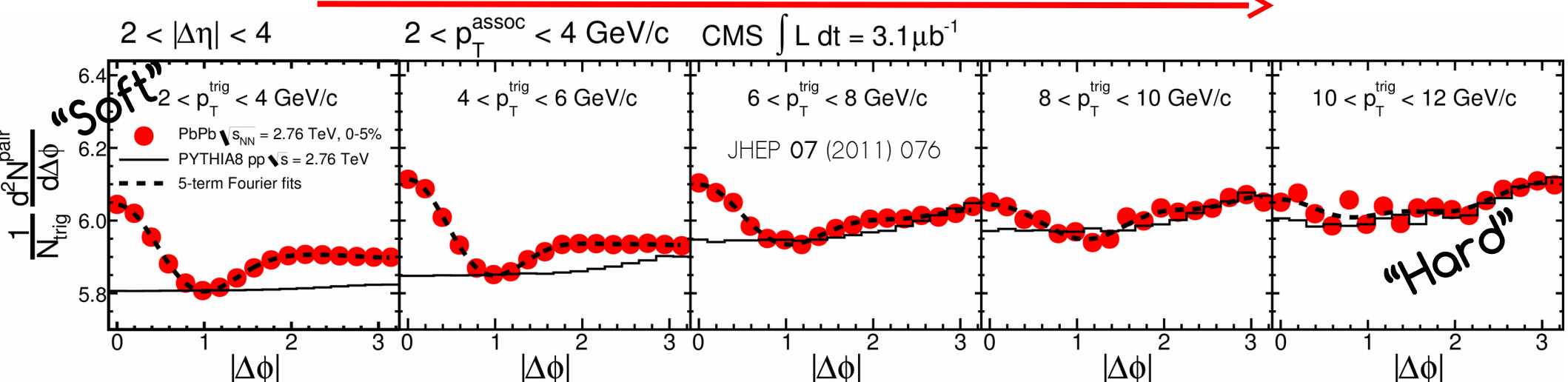
CMS-PHO-EVENTS-2010-002-51

What is the primordial form that early Universe existed in?



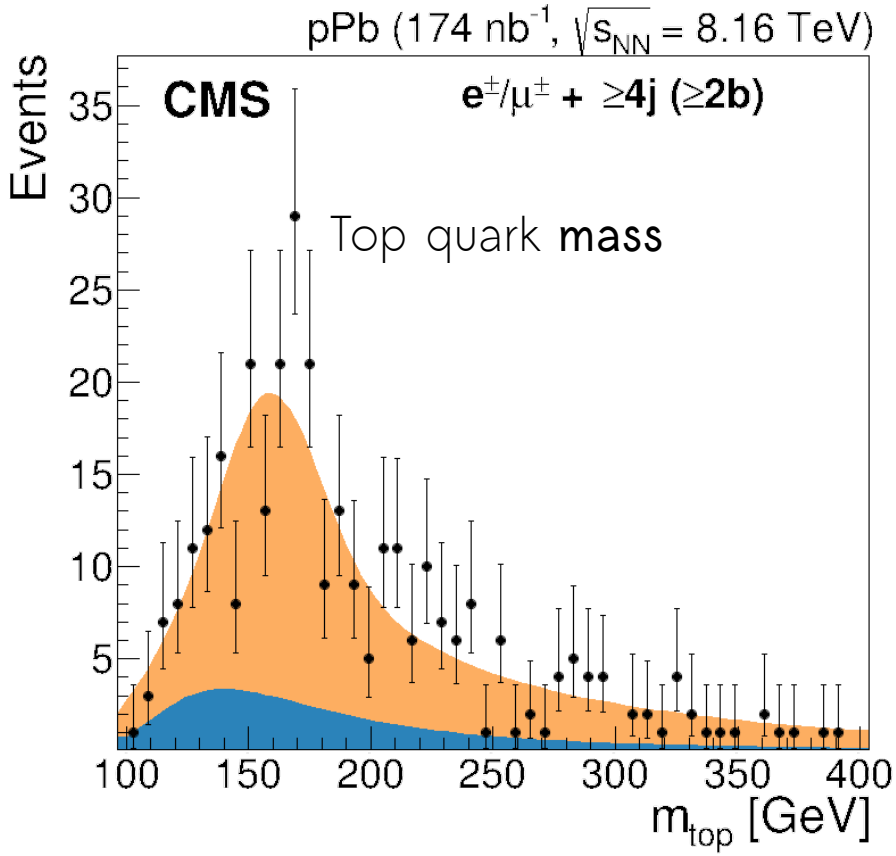
- It was very much in the state of a "soup"
- Disproving the liquid hypothesis is **easy**
- Validating the liquid hypothesis is **tricky**
  - What happens to bound nucleons?

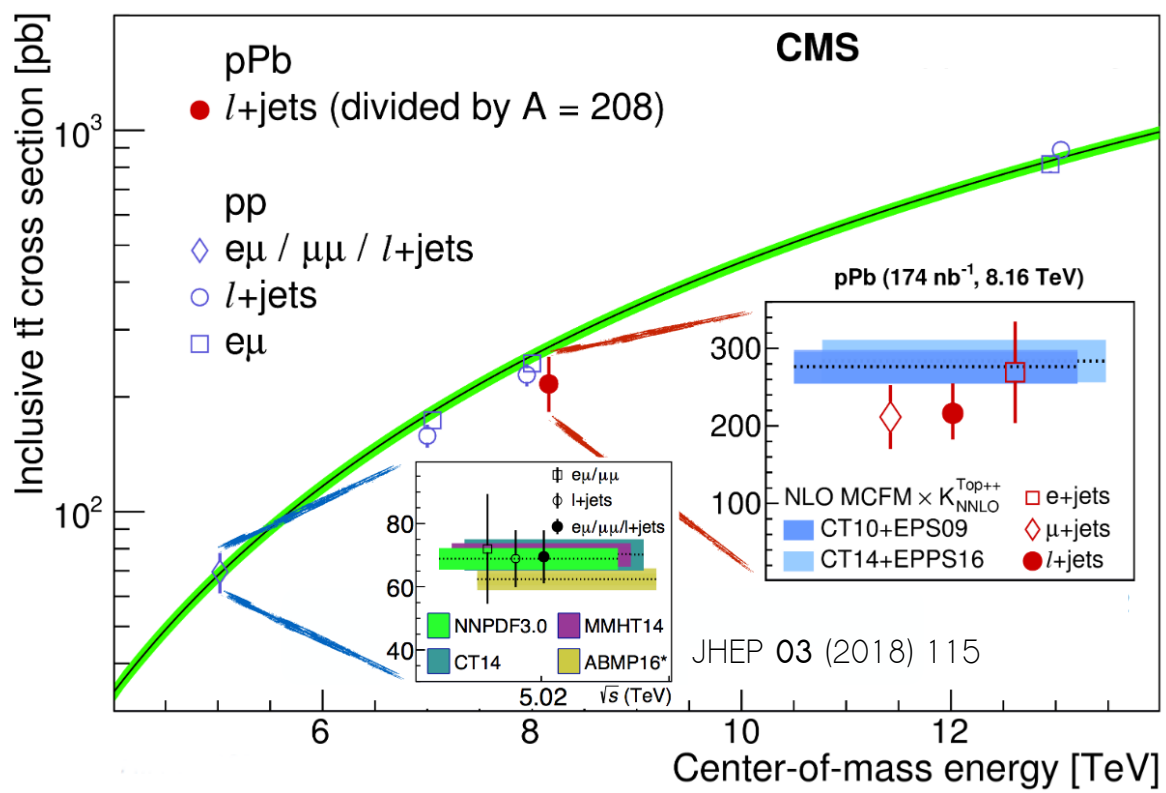
A fluid that retains its QCD **asymptotic freedom** character!



A novel and theoretically precise probe @ LHC !

- First experimental **observation** of the top quark in nuclear (proton-lead) collisions
  - **consistent** with pQCD calculations as well as the proton-proton data
- **Minimally** rely on assumptions from event simulations
  - paves the way for the study in lead-lead collisions

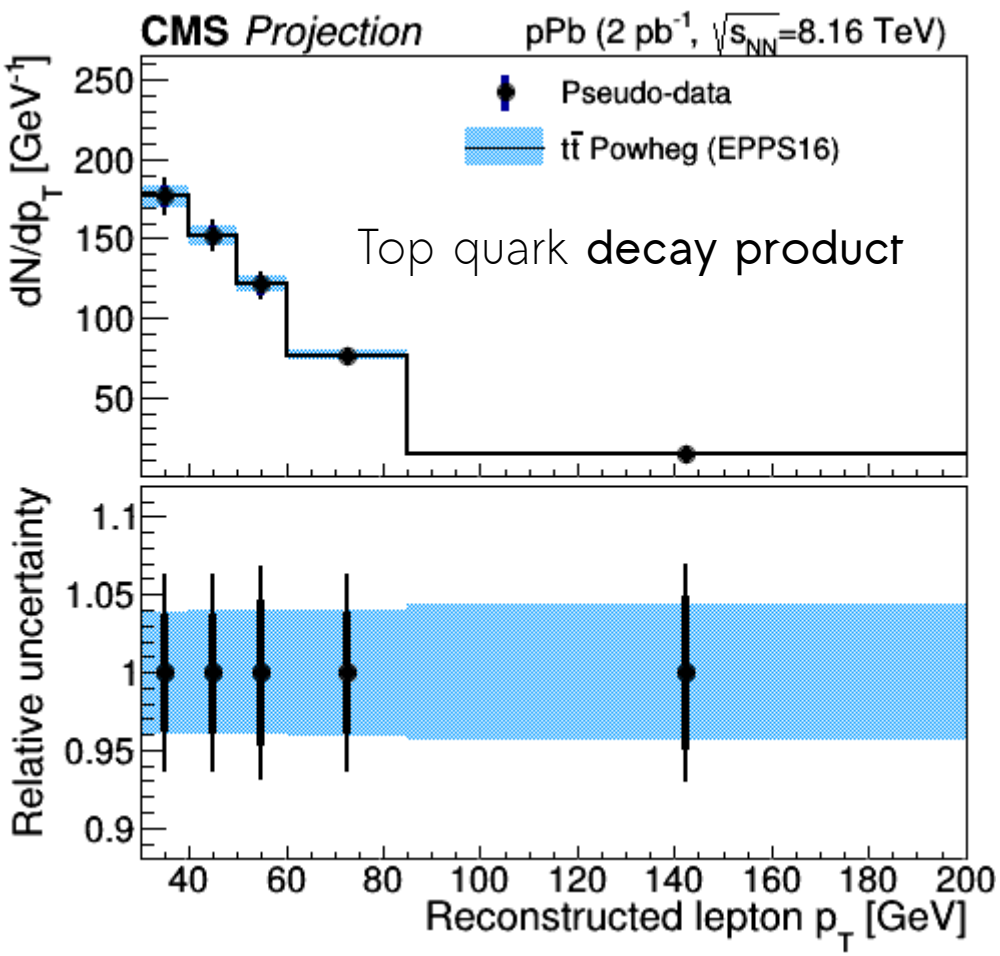


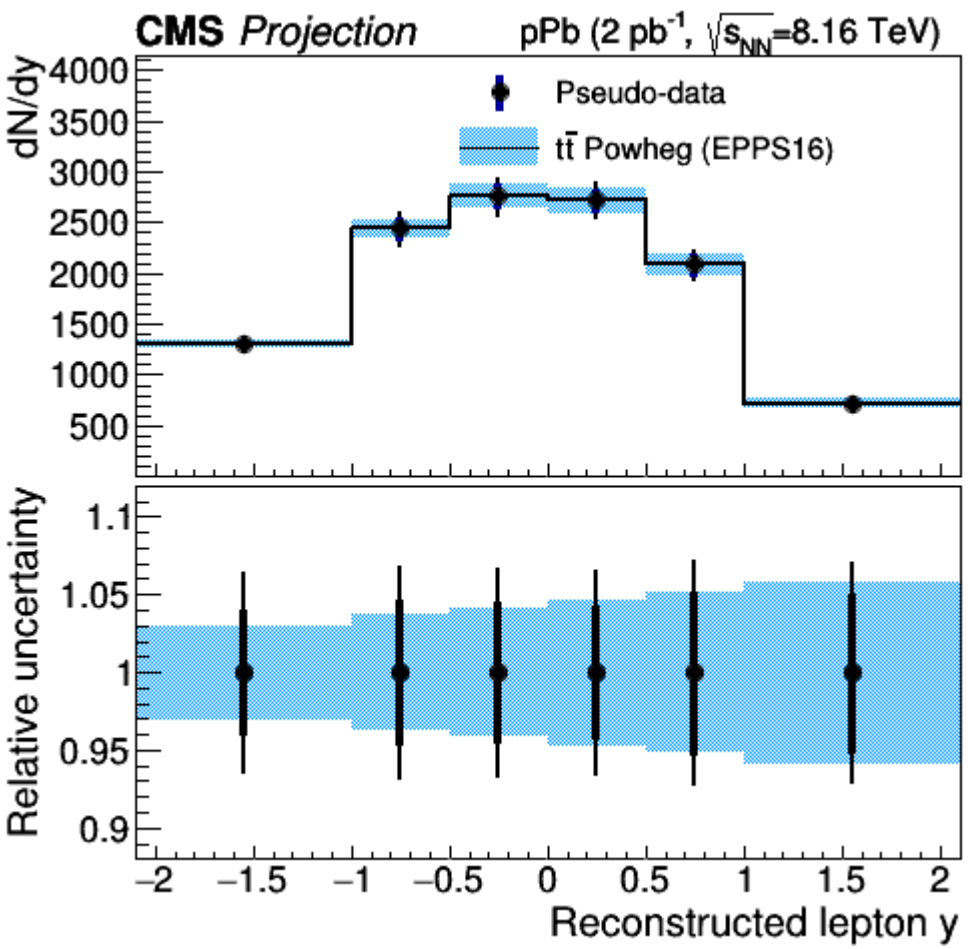


Phys. Rev. Lett. **119** (2017) 242001

Future physics opportunities for high-density QCD

- We can get better constraints with more data
  - Runs 3+4 and High-Luminosity LHC era in the near future, i.e., >=2026
    - to substantially reduce the statistical uncertainty in the measurement





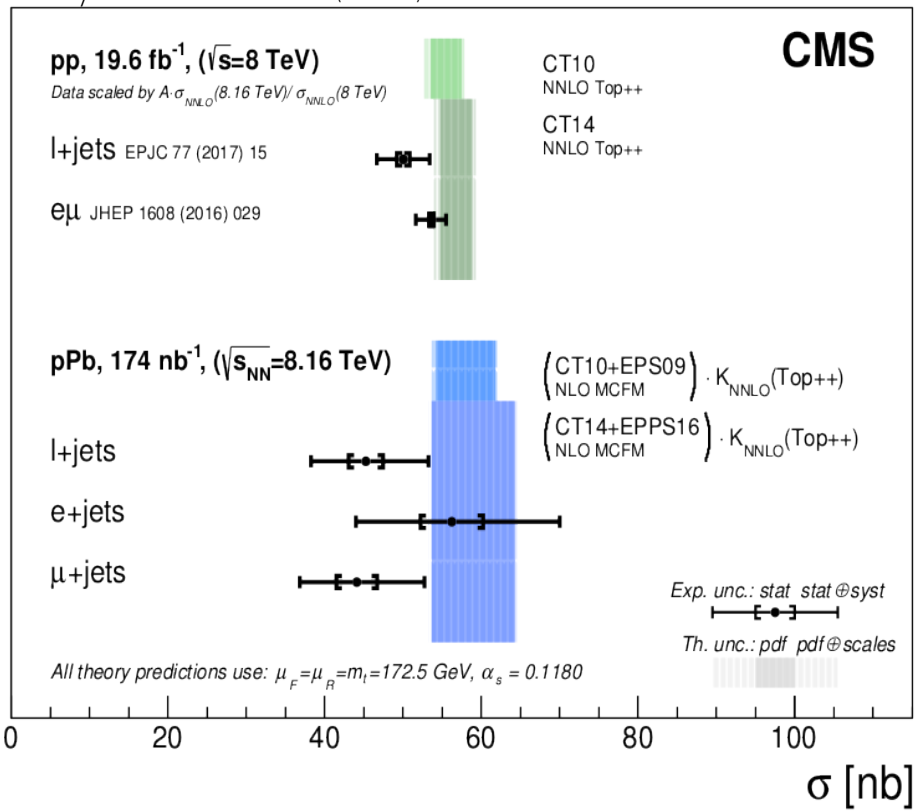
CMS-PAS-FTR-18-027

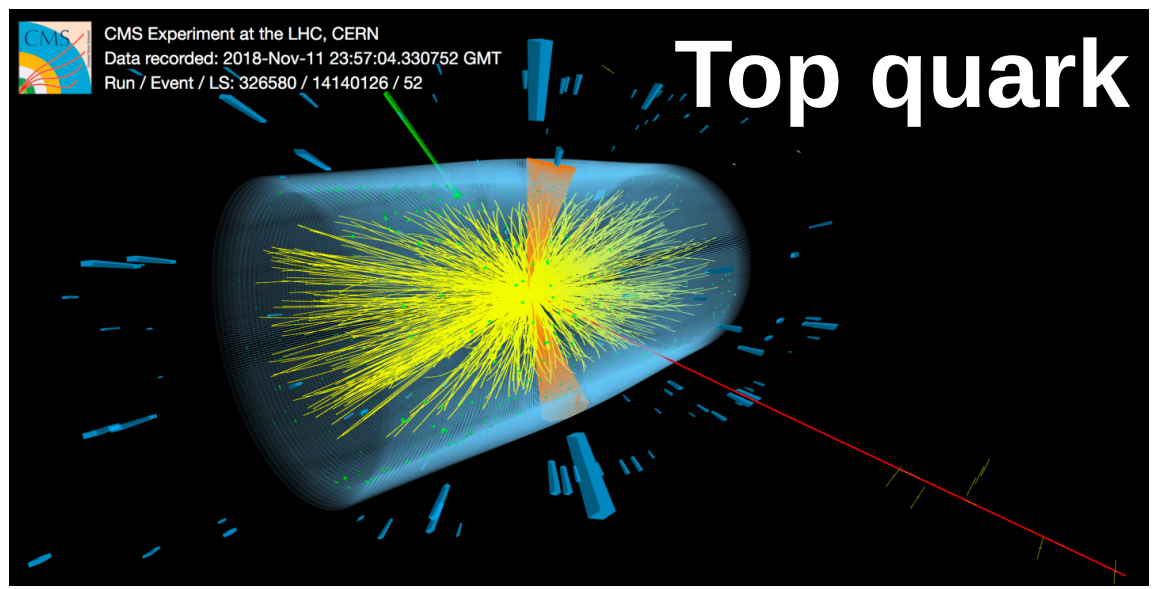
(High-Luminosity LHC Yellow Report)

Outlook

- **First** study of top quark in nuclear collisions
  - A novel tool to probe the nucleon constituents in nuclear environment
    - paving the way for **dedicated** future studies, and
    - contributing to the **longevity** of nuclear collision program @ LHC and post-LHC

Phys. Rev. Lett. **119** (2017) 242001





CMS-PHO-EVENTS-2018-010-21


Thank you for the attention
and Merry Christmas!

slides

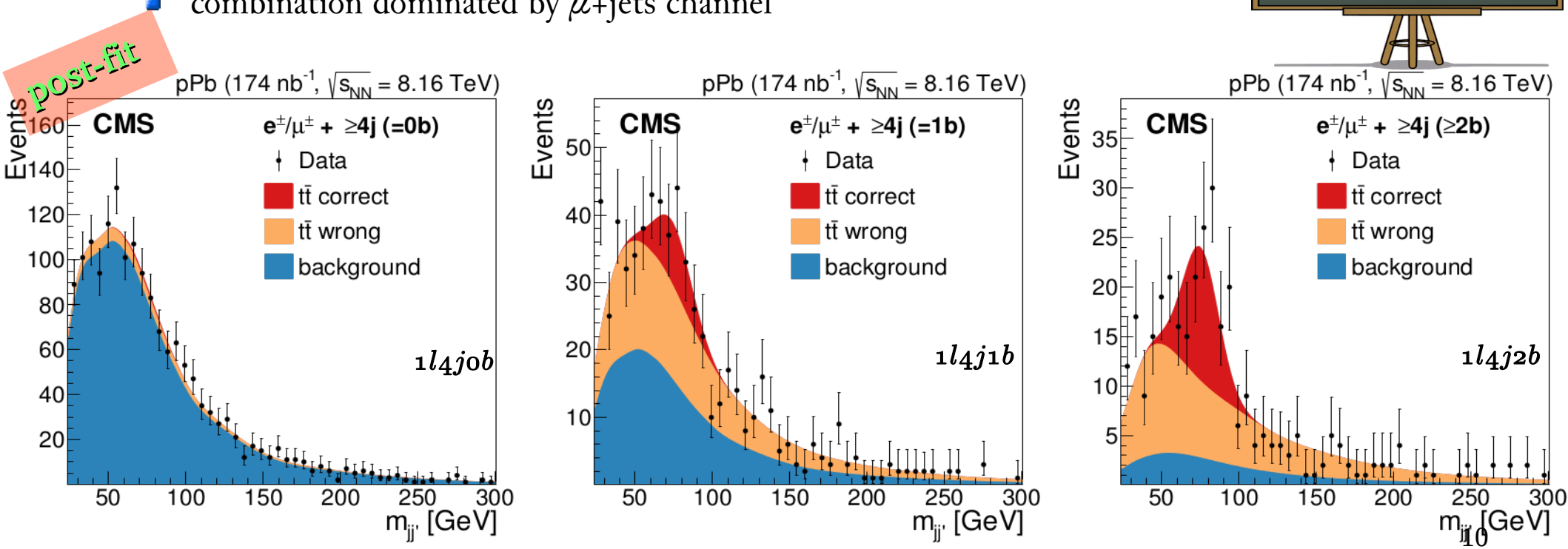
Measuring the tt production cross section (l+jets)

- Basic ingredients: **acceptance** (A) and **efficiency** (ε)
  - A = 0.060±0.002(tot) (0.056±0.002(tot)) in μ(e)+jets channel
    - determined @ NLO with **POWHEG** (v2) in the fiducial region
  - ε = 0.91±0.04(tot) (0.63±0.03(tot)) in μ(e)+jets channel
    - measured in data with "tag-and-probe" method (Z boson candle)
- Total number of signal (S) events in all 6 cats. : **S = 710 ± 130(tot)**
    - combination dominated by μ+jets channel

$\mathcal{L}_{int}$ =174 nb-1

σ_{tt} = 45±8(tot) nb

$d\sigma_{tt} / \sigma_{tt}$ = 17 % (!)

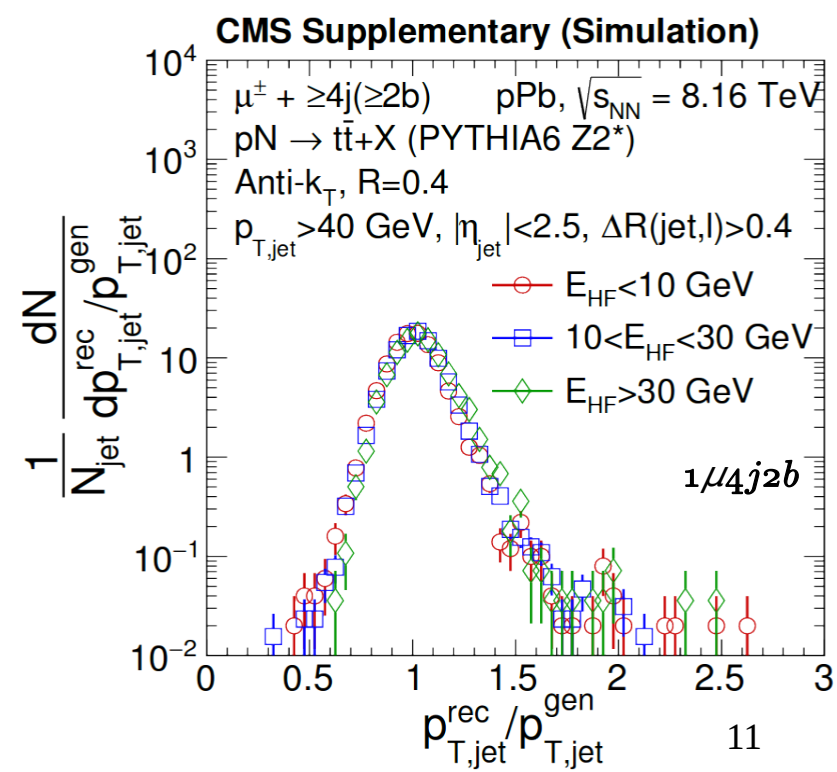


Background completely determined from data!

Splitting uncertainty in a stat & syst component

- Neither trivial nor unique task
  - **stat:** fix nuisances to post-fit values and refit with floating σtt
  - **syst:** $\sqrt{(tot^2 - stat^2)}$
- effect of identified sources for systematic variations
  - fix all other nuisances to post-fit values and refit within $\pm 1\sigma$

UNCERTAINTY DESCRIPTION	EFFECT (%)
EVENT COUNT σtt floats in the fit and all other parameters fixed to their post-fit values	5
b FINDING EFFICIENCY the probability that a b jet passes both the kinematic and the b tagging selections	13
BACKGROUND Shape and normalization uncertainties	7
LUMINOSITY Preliminary offline calibration for pPb data taking 2016 period	5
JET ENERGY SCALE 3%-level non-closure of the jet energy corrections in MC events and a 3% residual calibration uncertainty from data	4
LEPTON EFFICIENCY Dominated by the underlying event dependence	4
ACCEPTANCE QCD, strong coulping and PDF⊗nPDF (POWHEG)	4



Careful treatment of UE dependence

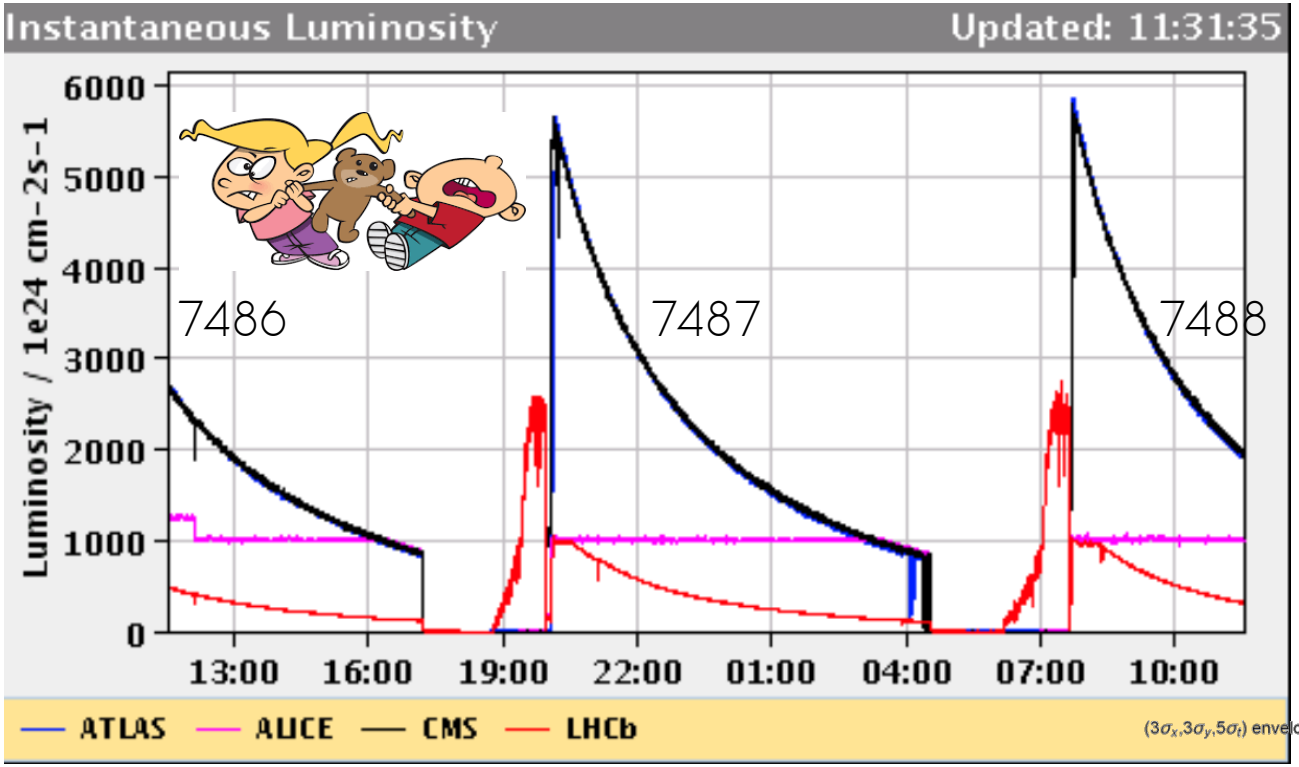
Summary (PbPb)

- Since 2010 LHC devoted ~4 (2+2) months of its operating time with PbPb collisions
- Peak PbPb luminosity is now **6 times** the design and $\mathcal{L}_{int}$ surpassed the initial goal of 1/nb
- All 4 (major) LHC experiments **participate fully** in the heavy-ion program

M. Schaumann *et al.* (136th LHCC Meeting)

	Heavy-Ions (2018 achieved)	Heavy-Ions (Design)	Protons (2018)
Energy [TeV]	**6.37 Z**	7 Z	6.5
Particle Charge Z	**82**	82	1
β^* at IP 1/2/5/8 [m]	**0.5 / 0.5 / 0.5 / 1.5**	0.5 / 0.5 / 0.5 / -	0.25 / 10 / 0.25 / 3
Emittance [μm]	**~4 (proton equiv.)**	3.75 (proton equiv.)	~1.8
Bunch **Intensity** [10^{11} charges]	**0.2 (= 2.4x10^8 ions)**	0.06 (= 0.7x10^8 ions)	1.1
No. Bunches	**733**	592	2556
Bunch Spacing	**100ns → 75ns**	100ns	25ns
Peak **Luminosity** at IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	**6 / 1 / 6 / 1**	- / 1 / 1 / -	

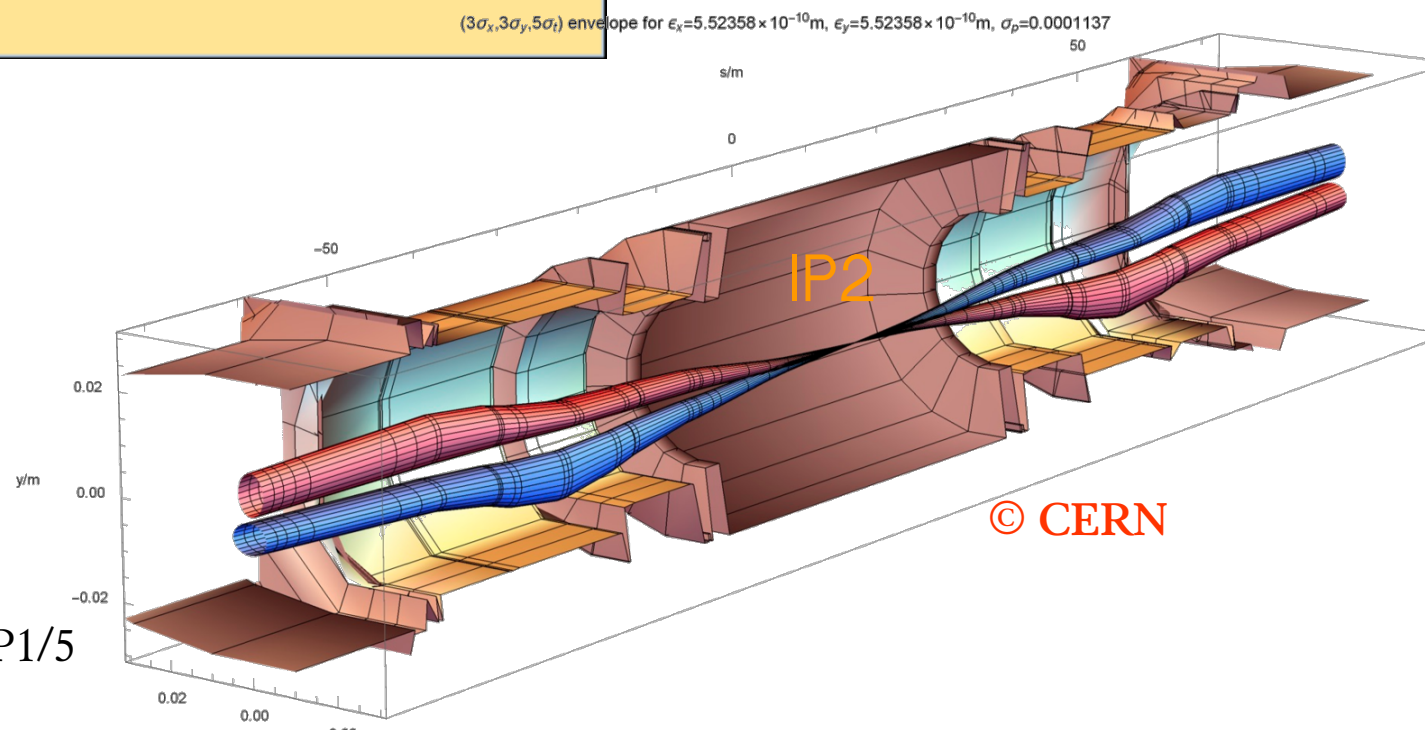
Luminosity sharing is puzzling



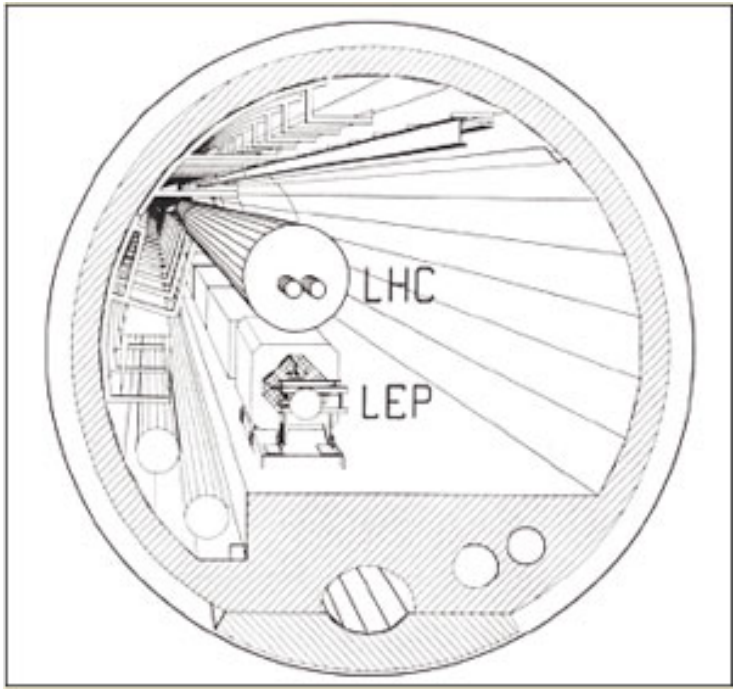
- Short time frame to fulfill all goals
  - ATLAS/CMS ≫ 10^27Hz/cm2
  - ALICE = 10^27Hz/cm2
  - LHCb ≥ 10^27Hz/cm2

    → ×10 than 2015

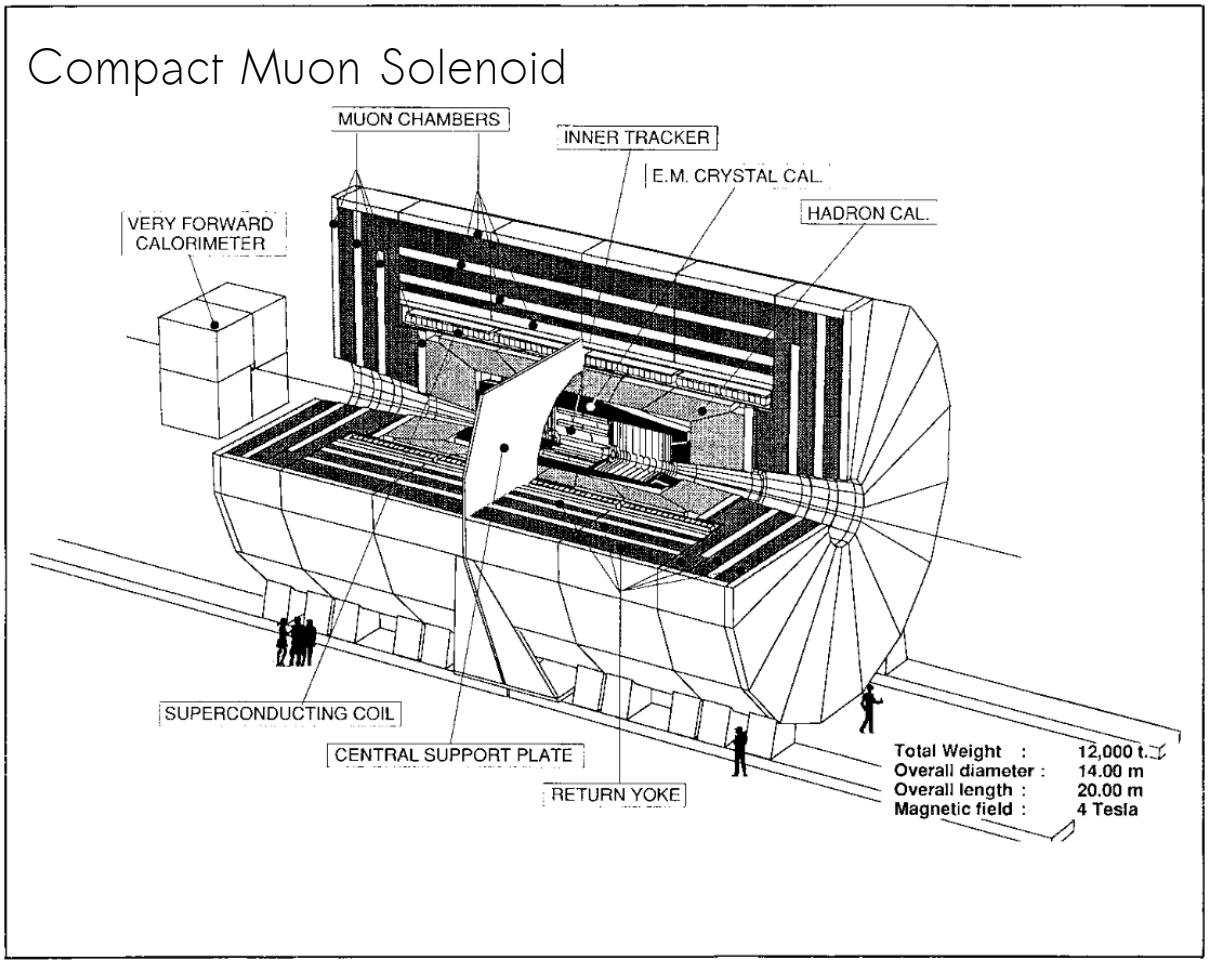
- Completely new optics cycle
  - β^*=(0.5, 0.5, 0.5,1.5)
- Beam size at IP2 ×2
  - reduce peak luminosity at IP1/5



What's after the Large Electron-Positron Collider (1989-2000)?



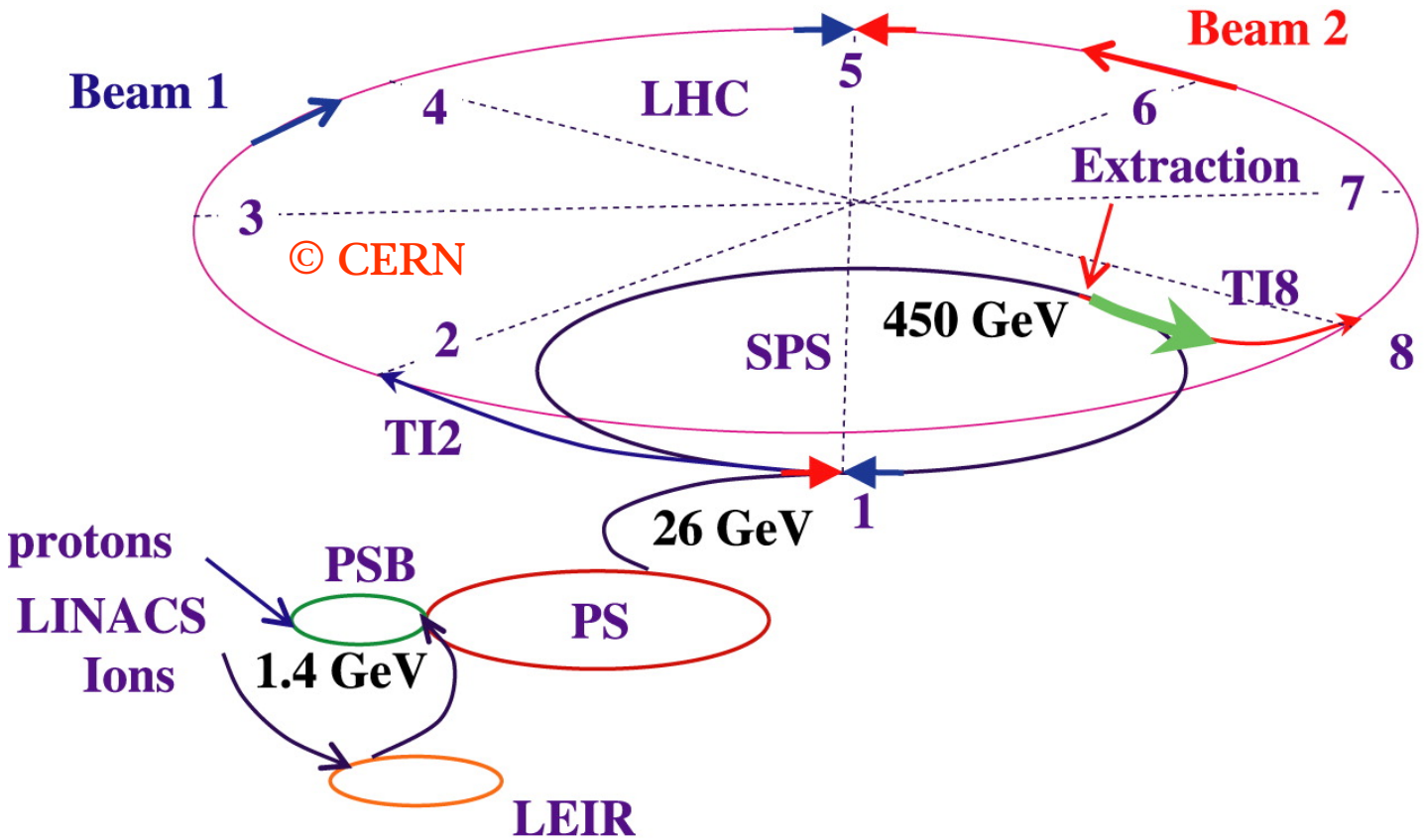
Lausanne LHC workshop (1984)



Evian debut (1992)

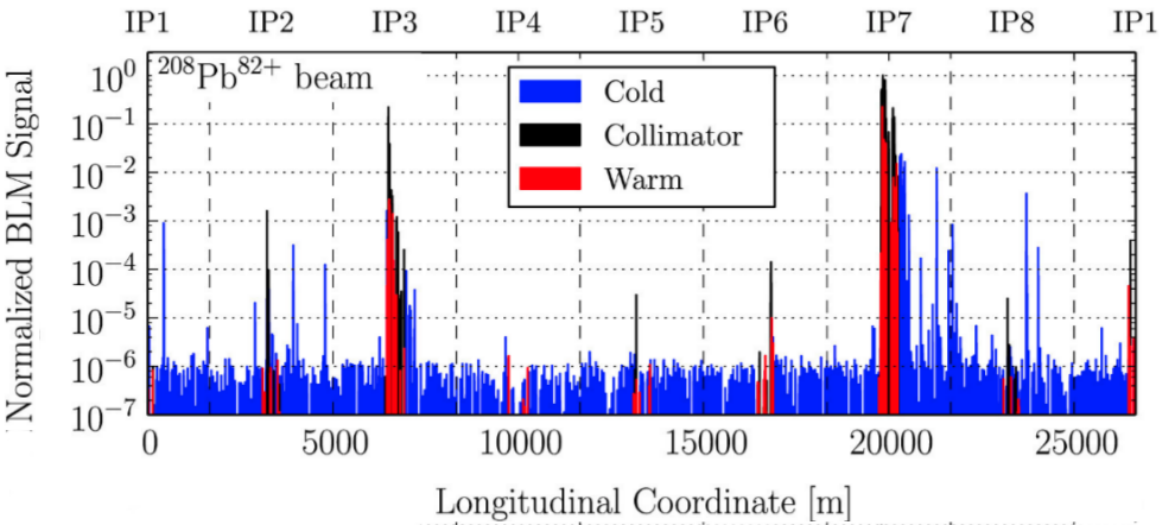
- The infrastructure for a **Large Hadron Collider** (LHC) would be limited by
  - the existed tunnel (radius and size) and its injectors: "Multipacket" collider + **10 T** magnets
  - *Expressions of Interest* in 1992: LHC to handle proton and lead **ions**

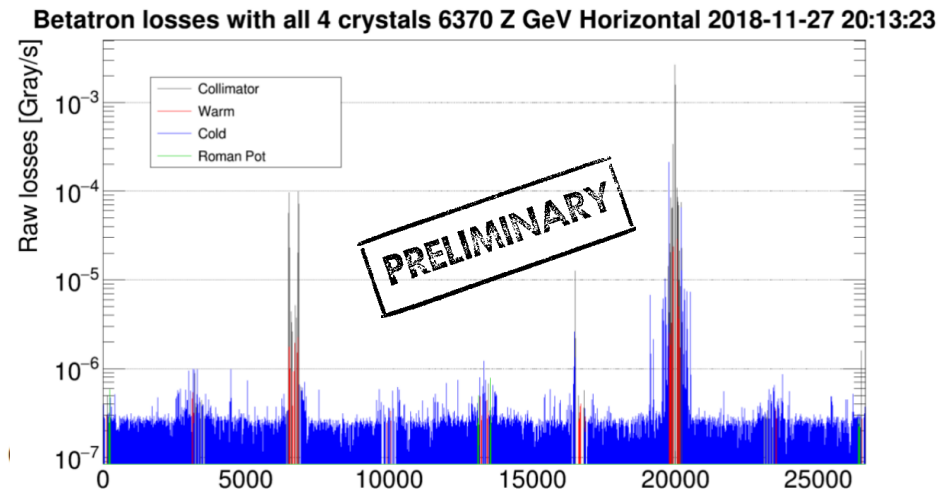
LHC success is also based on its injectors



- The original LHC design foreseen **only** proton-proton and lead-lead collisions
  - Slight different path for Pb ions up to to a certain point (SPS)
  - Novel modes **established:** proton-lead (2011) and Xenon-Xenon (2017)

Tests on crystal collimation and quench limit





- Control the power of the secondary beams emitted from the IP by the bound-free pair production (BFPP)
  - The risk of quenching is mitigated by displacing and spreading out these losses
  - Test postponed with Pb beams in 2018 (too low intensity from injectors)

CERN-ACC-NOTE-2016-0024