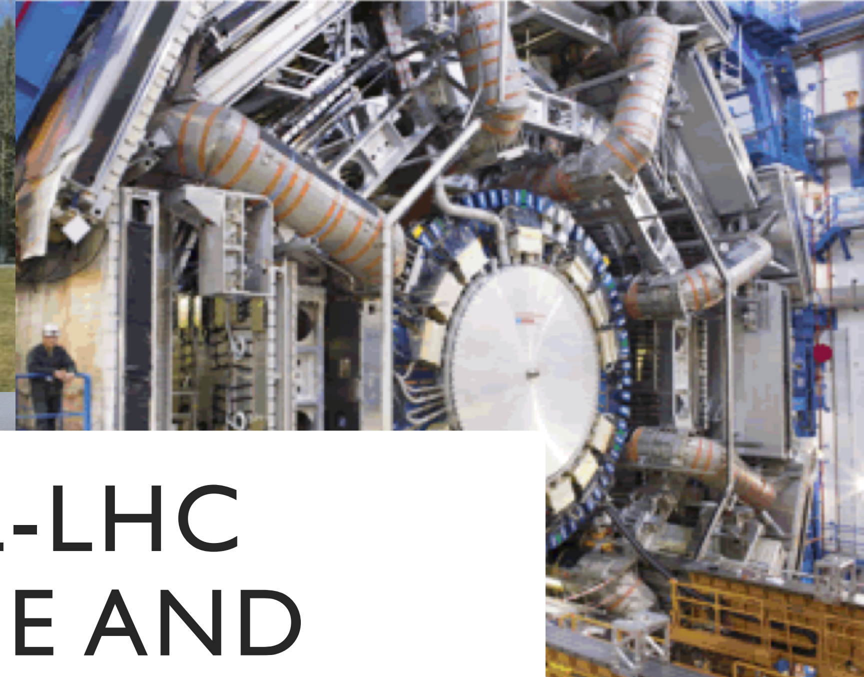
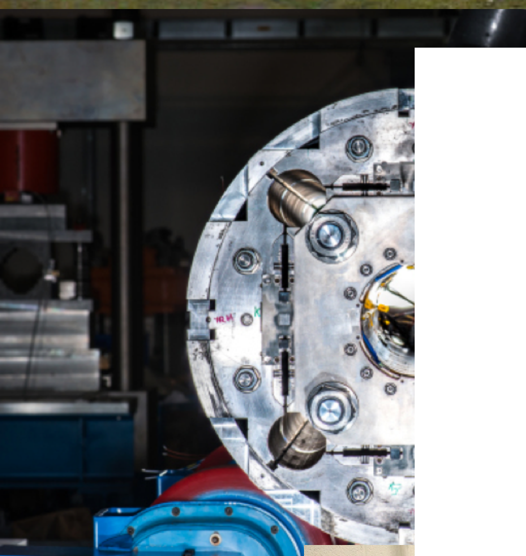
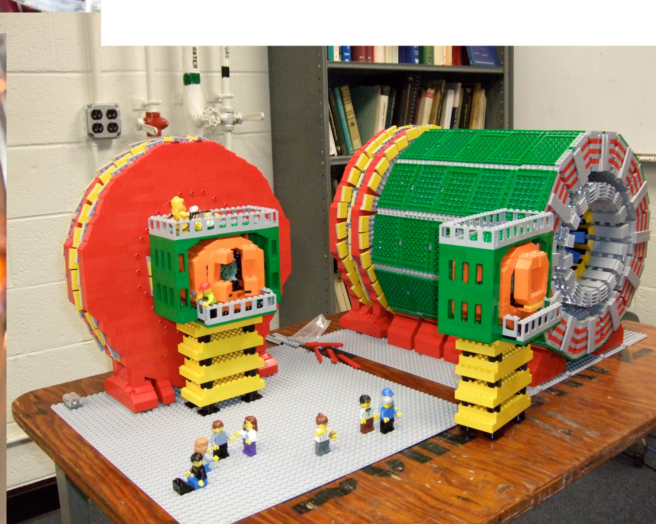


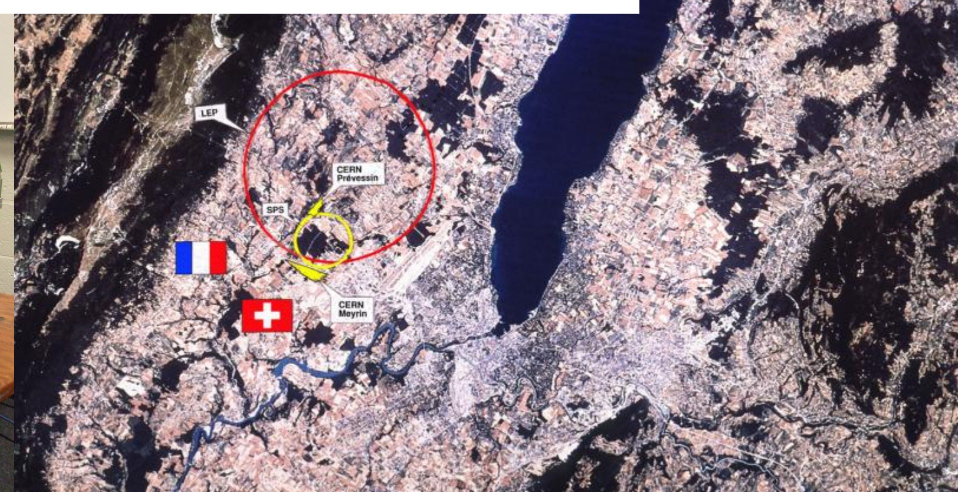


THE HL-LHC UPGRADE AND PHYSICS PROGRAM

SARAH ENO, U. MARYLAND

IASHEP 2019



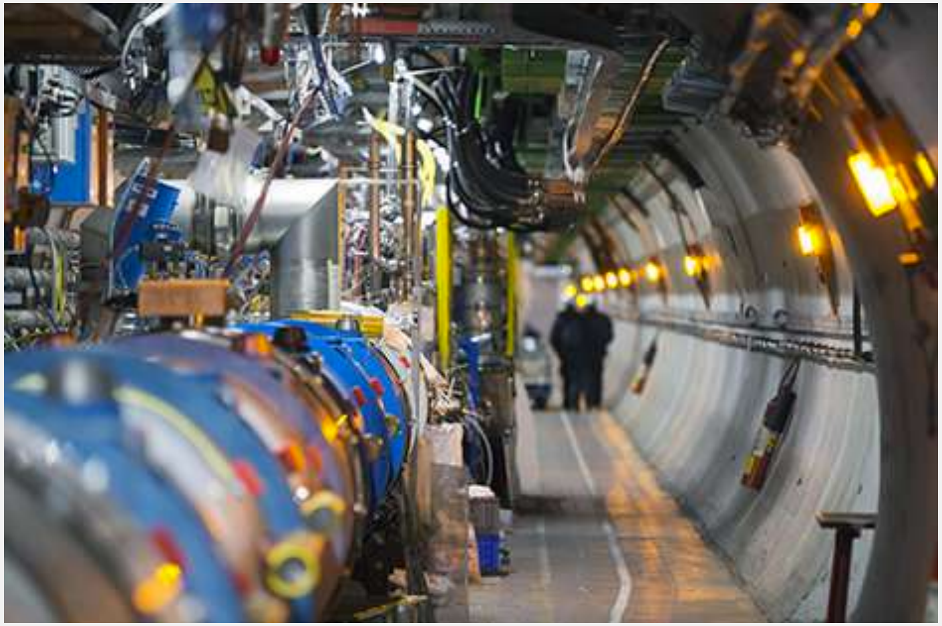


- Accelerator upgrades
- CMS and ATLAS physics program and upgrades❖

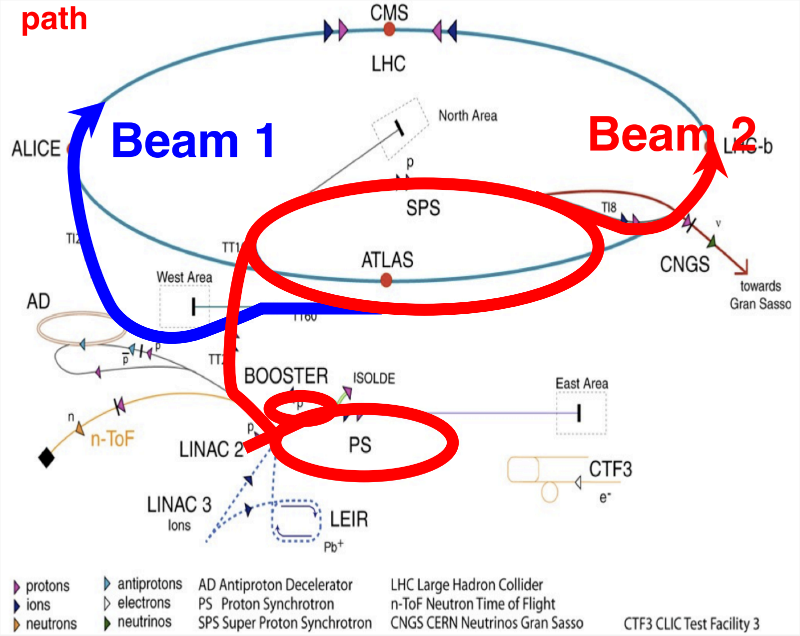
❖ Talk neglects LHCb, ALICE, heavy ion running
❖ I am a member of the CMS collaboration.

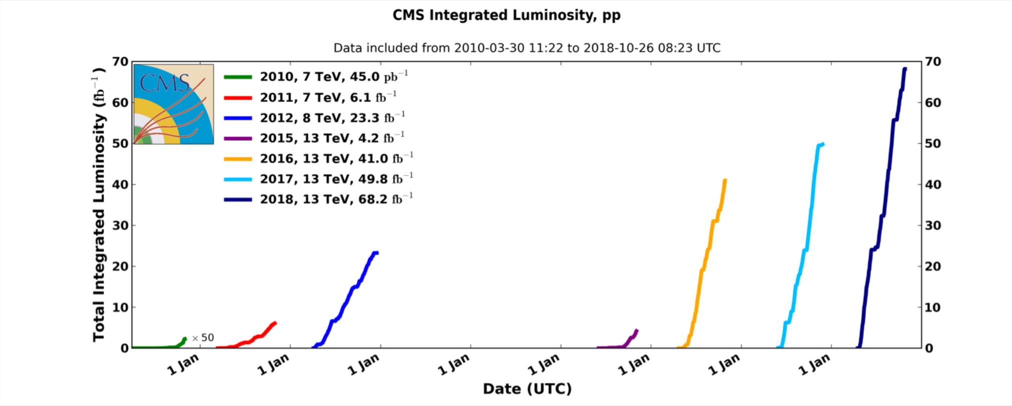
CELEBRATING THE LHC

- >10 years of exemplary running
- pp collisions at center-of-mass energies of 7,8, and 13 TeV
- >150 fb^{-1} at 13 TeV



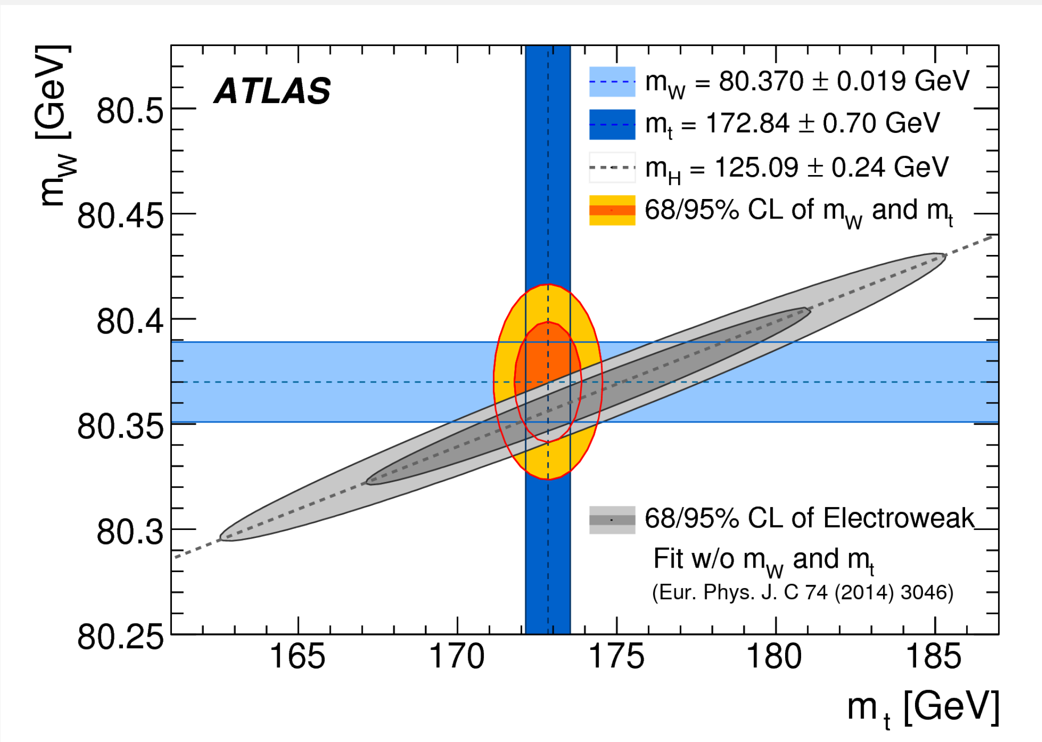
LHC proton path

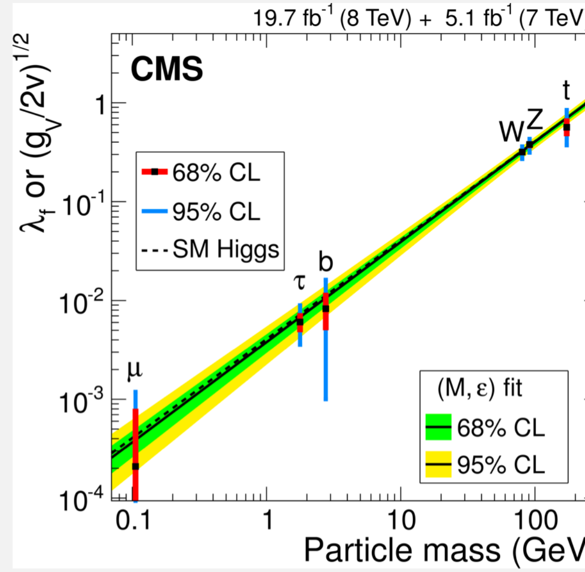


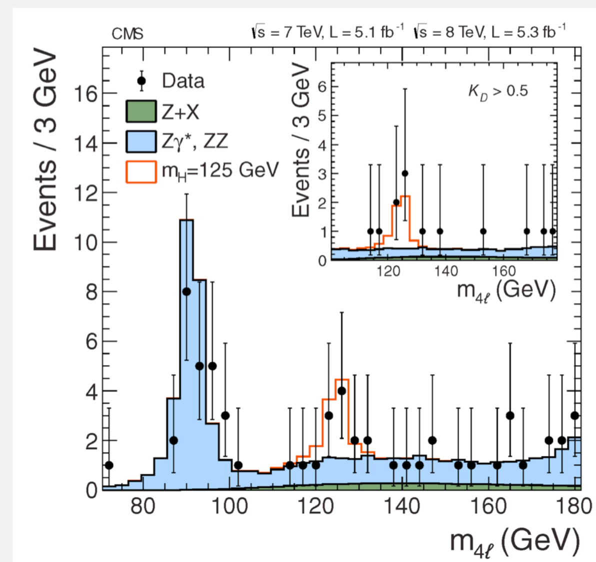


LHC PHYSICS ACCOMPLISHMENTS

- Higgs discovery
- Precision measurements of top and W masses

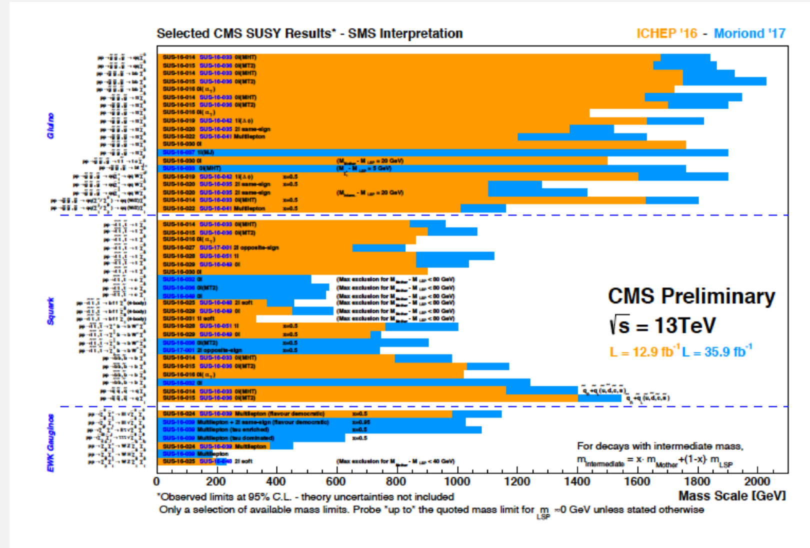


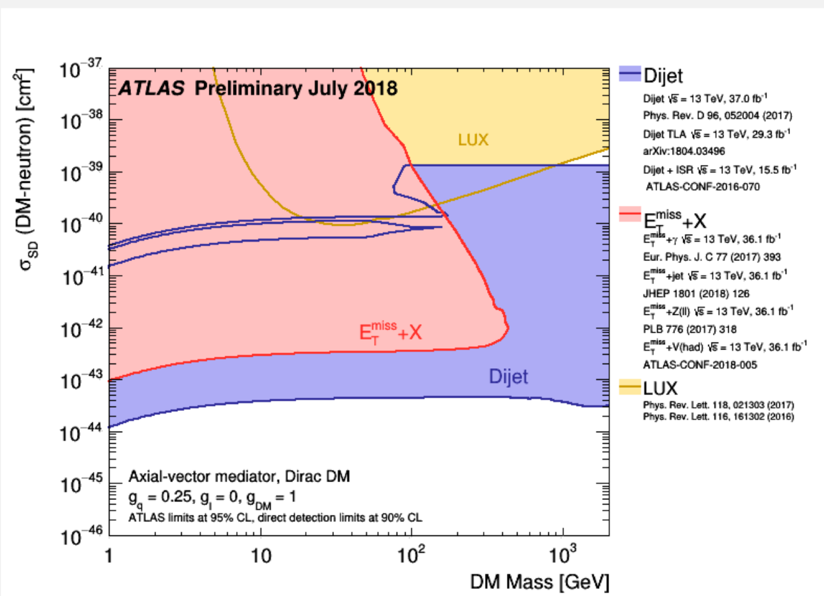


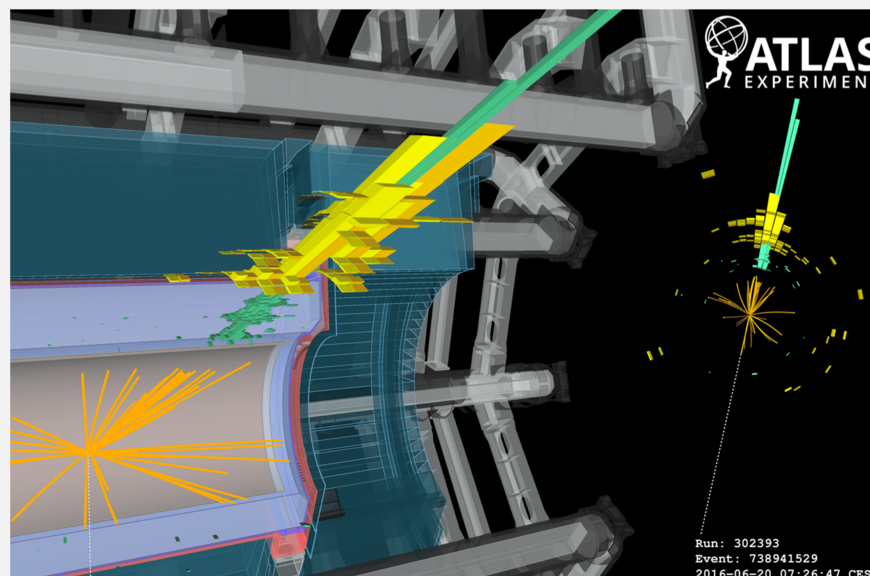


LHC PHYSICS ACCOMPLISHMENTS

- Competitive searches for dark matter
- Relegation of SUSY to an "also ran" as an explanation for the hierarchy problem

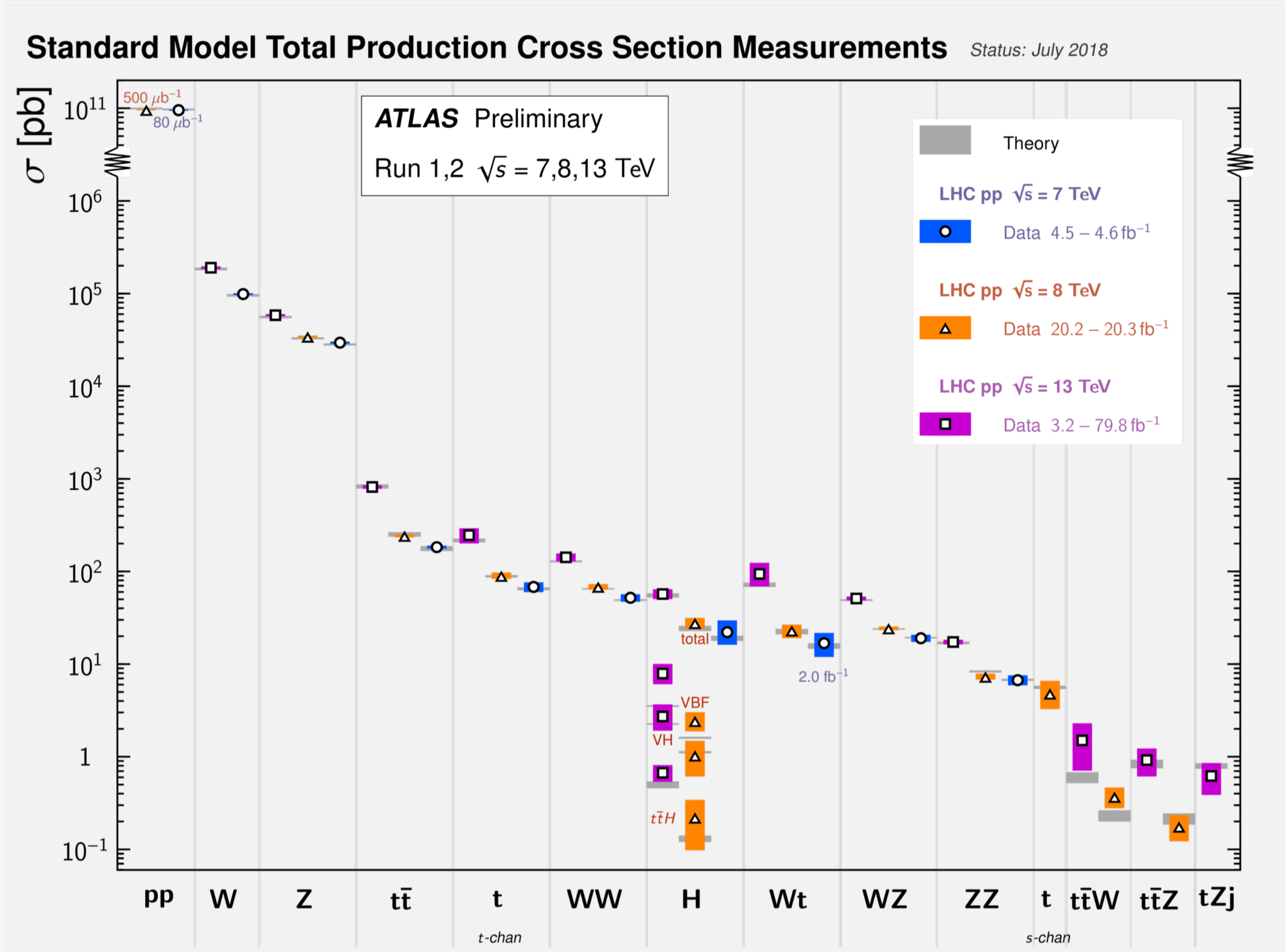






LHC PHYSICS ACCOMPLISHMENTS

Standard Model put to a wide variety of precision tests



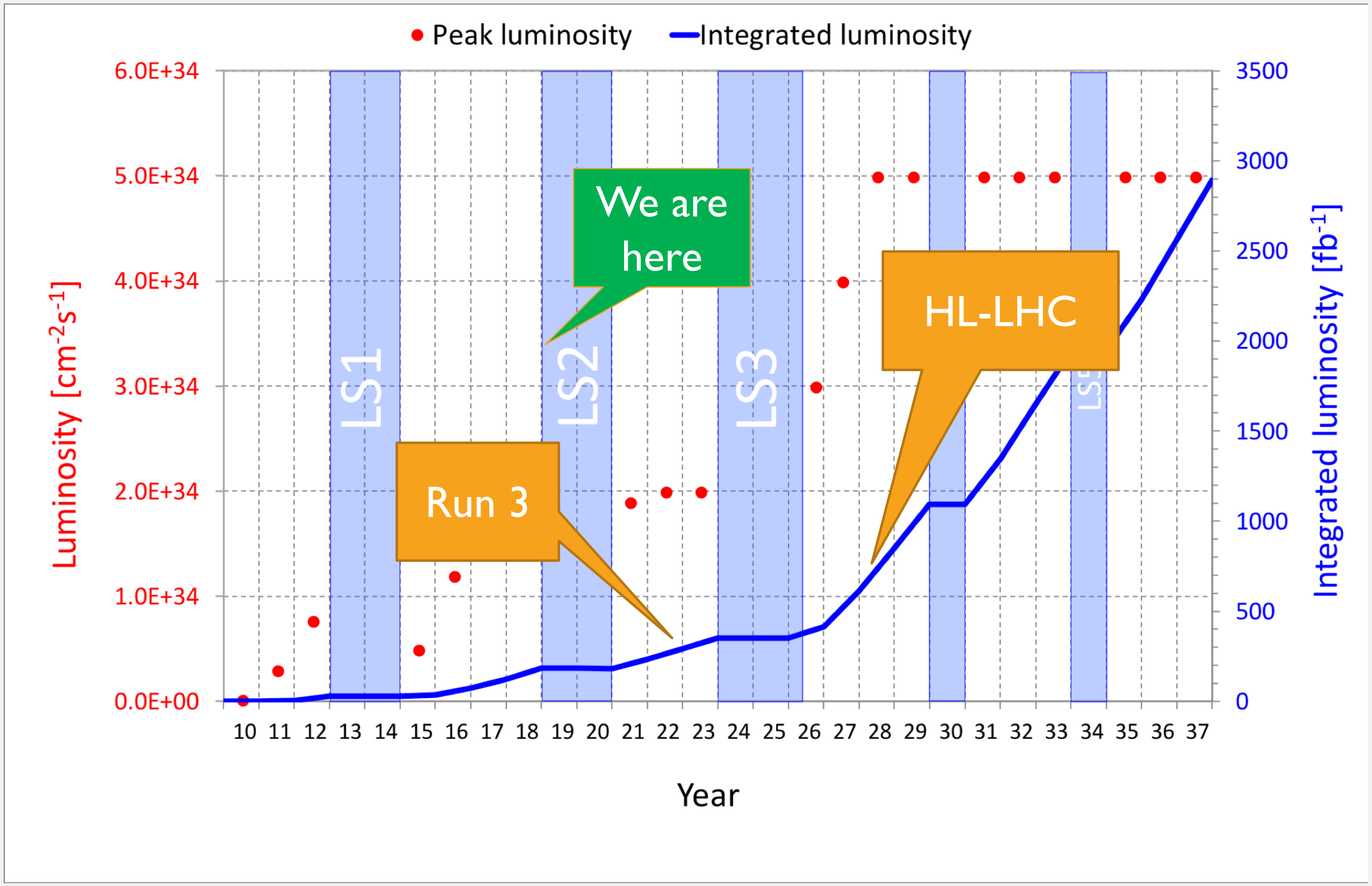
LHC FUTURE

Can the LHC give us more?

Expect 150 fb^{-1} more in Run 3

Beyond that, not as it is. Integrated luminosity doubling time is 10 years, and no student should be willing to do a 10 year thesis.

LHC UPGRADE PLANS

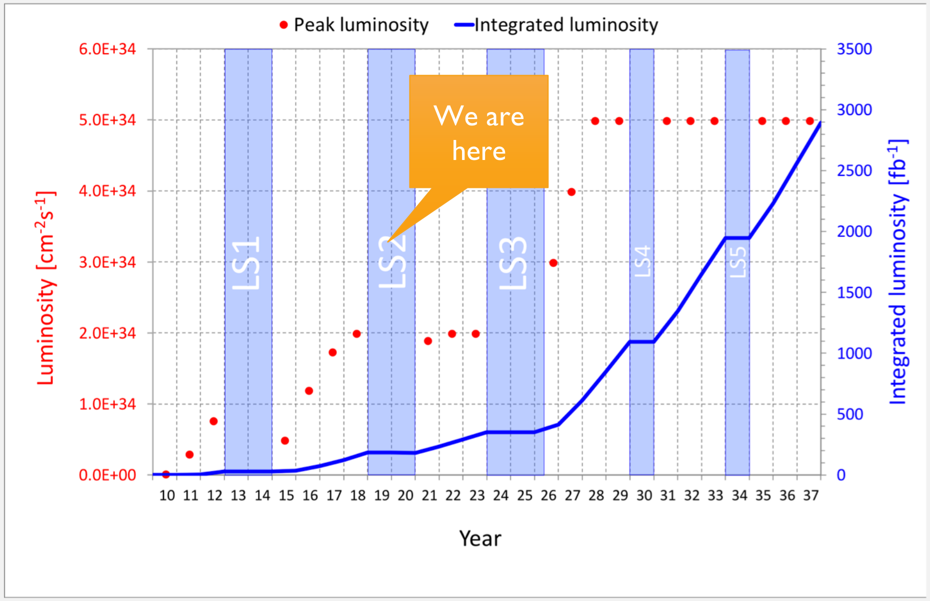


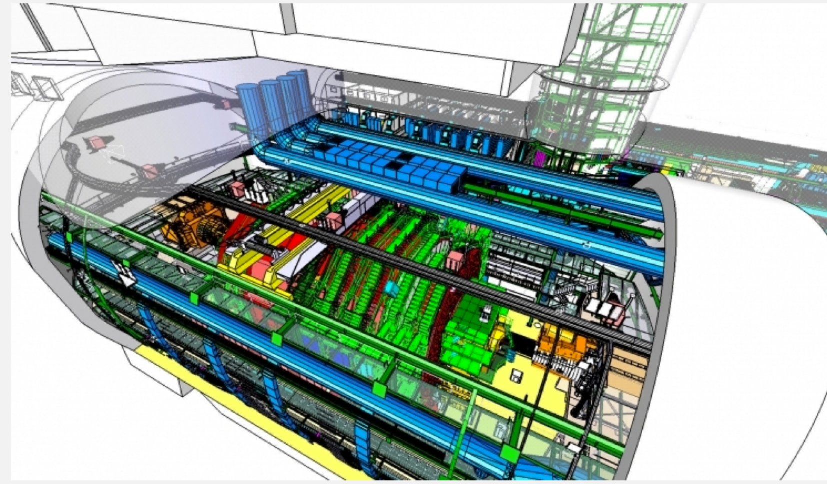
HE-LHC????

I’ll talk a little on Run 3, as these improvements also help HL-LHC running.

RUN 3

LS2

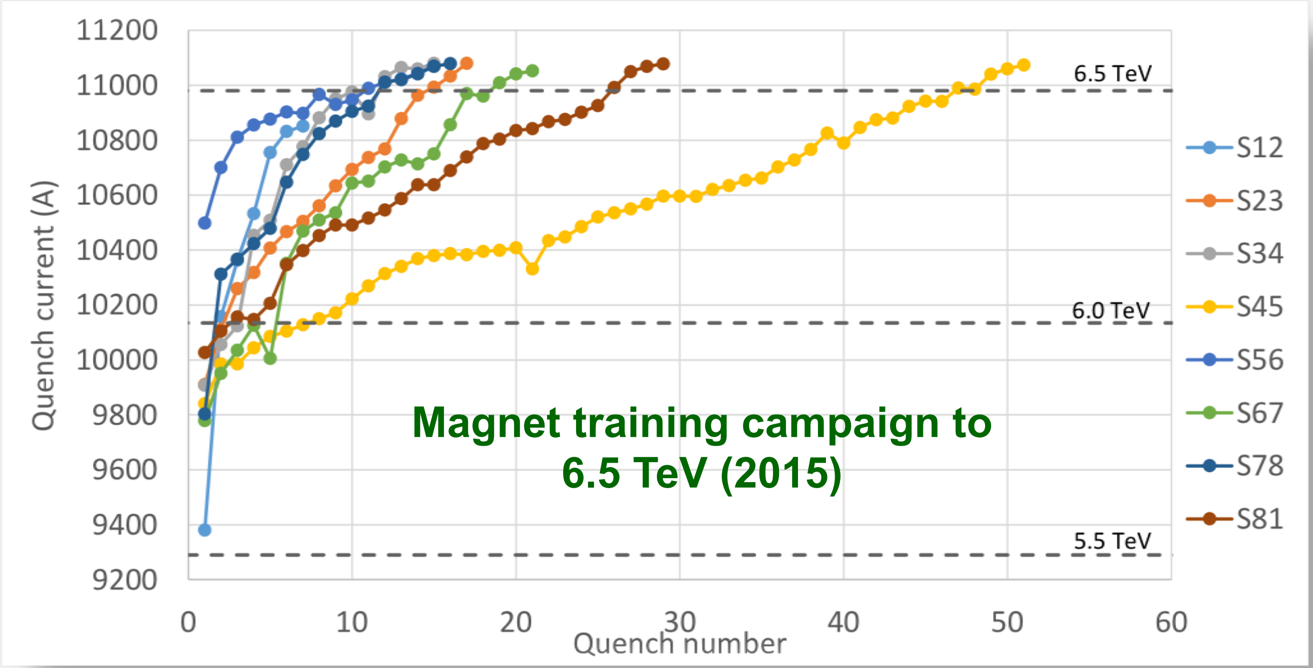




- Increase center of mass energy from 13 to 14 TeV
- 50% higher instantaneous luminosity
- Double size of sample in shorter time (300 fb^{-1})
- Upgrade detectors

MAGNETS

- All dipole magnets were trained for 6.5 TeV operation in 2015.
- Will be trained for 7 TeV during the shut down



HIGHER INTENSITY

$$L = \frac{kN^2 f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} F$$

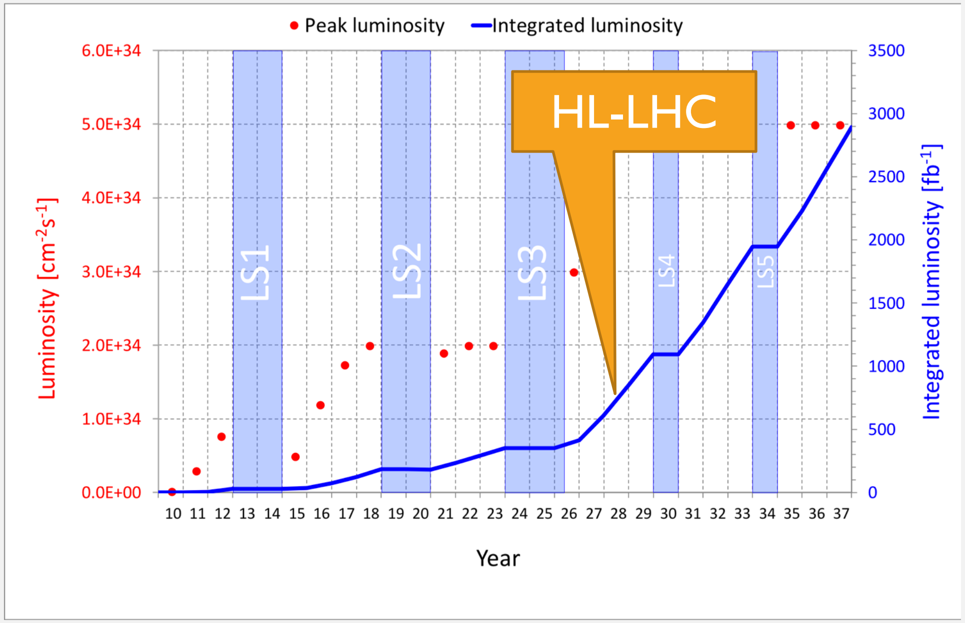
Parameter`	Design	2018	Run 3
Bunch population N_b (10^{11} p)	1.15	~1.1	~1.7
No. bunches k	2780	2556	~2600
Emittance ε (mm mrad)	3.5	~1.8	1.5 - 2
β* (cm)	55	30 / 25	100 - 25
Full crossing angle (μrad)	285	320 - 260	340 - 260
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.0	~2.1	3 - 4

Plans to ramp up the instantaneous luminosity during the 2021-2023 run
Limit on N_b of 1.7 due to limitations from RF system, beam dump system, heating of equipment, beam stability.

HL-LHC

HL-LHC

The groundbreaking ceremony for the launch of the civil engineering works took place on Friday 15 June 2018 with the presence of the CERN management, the French and Swiss Authorities and the CERN Council.

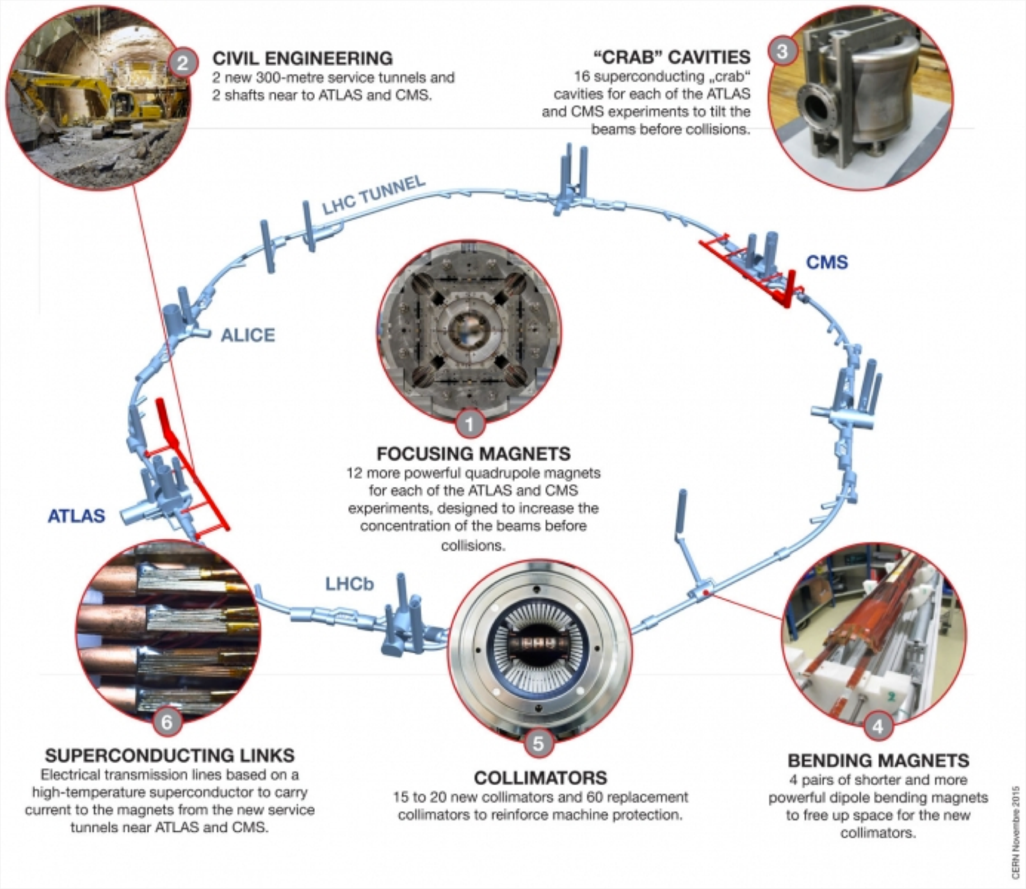


- 3-4E34→5E34 $cm^{-2}s^{-1}$(or maybe even 7-7.5E34 $cm^{-2}s^{-1}$)
- 250 fb^{-1}/year (300-350 fb^{-1})
- 3000-4000 fb^{-1}
- 25 → 140 (200) pileup

HL-LHC

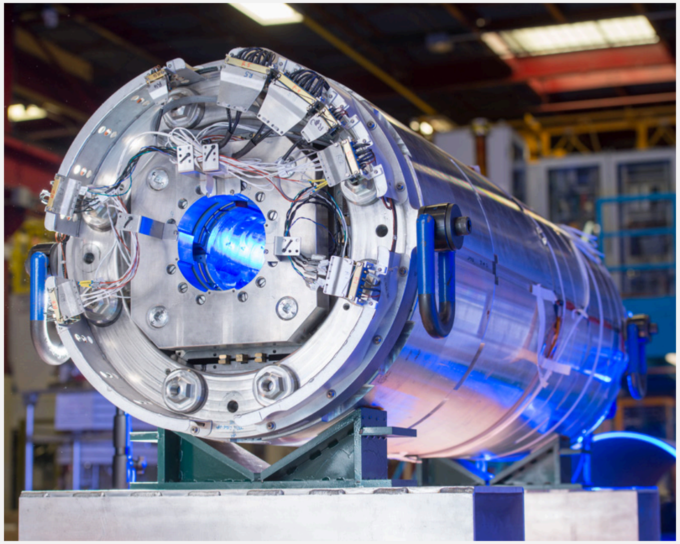
- 10 Tesla quadrupoles
- Crab Cavities

→ Higher intensity beams



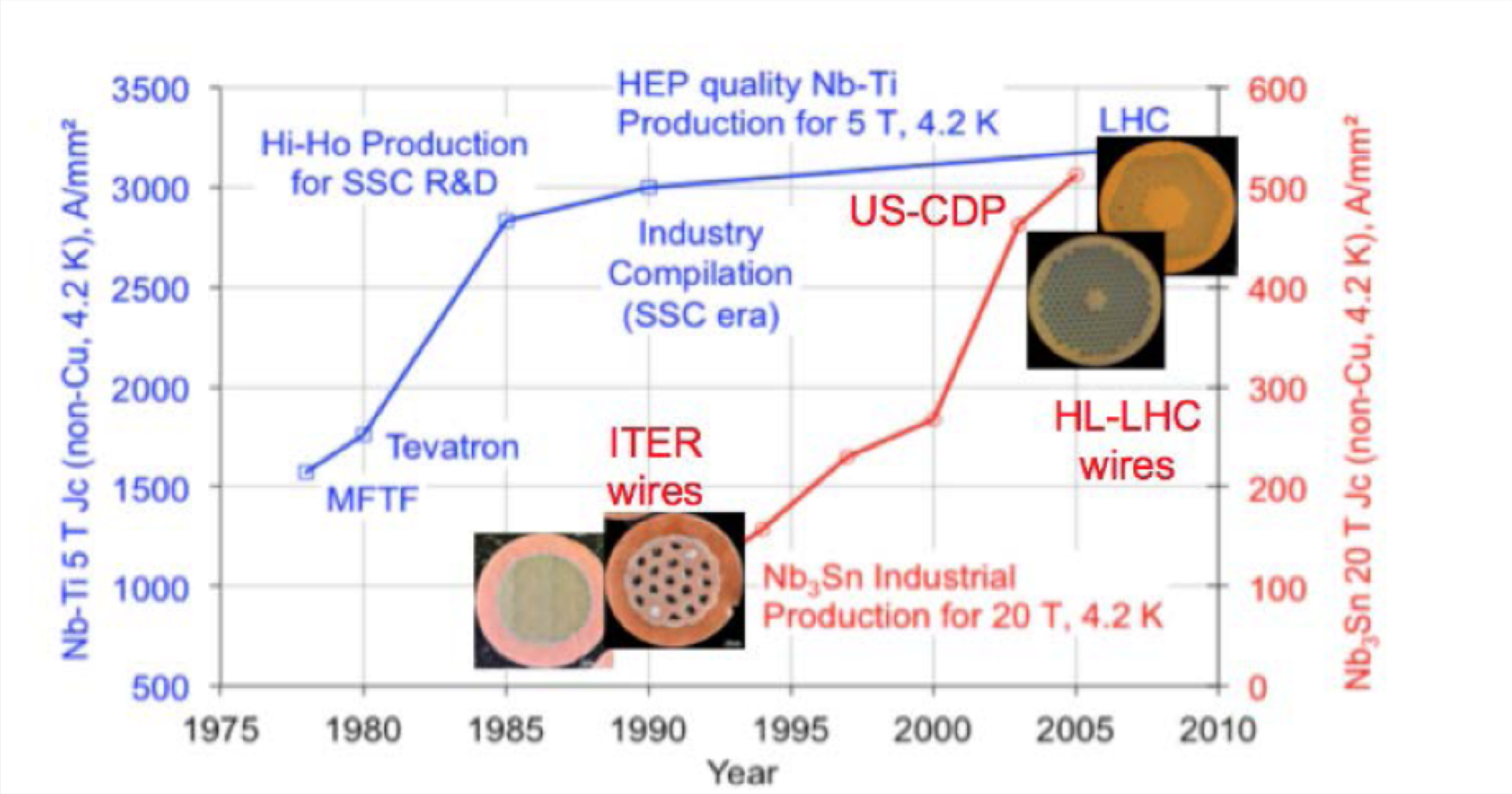
QUADRUPOLES

Need stronger focusing magnets to get higher instantaneous luminosities



In particular, the new main quadrupole magnets, that will sit in the insertion regions on either side of the ATLAS and CMS detectors, exploit a key innovative technology providing fields beyond 10 Tesla. They are built from niobium-tin (Nb_3Sn), using a unique design that allows the peak magnetic field strength to be increased by around 50% compared with the current LHC dipoles, bringing it from about eight to about 12 tesla (T).

USA LARP



HEP quality Nb-Ti
Production for 5 T, 4.2 K
Hi-Ho Production
for SSC R&D
LHC
US-CDP
Industry
Compilation
(SSC era)
HL-LHC
wires
Tevatron
MFTF
ITER
wires
Nb3Sn Industrial
Production for 20 T, 4.2 K
Nb-Ti 5 T Jc (non-Cu, 4.2 K), A/mm²
Nb3Sn 20 T Jc (non-Cu, 4.2 K), A/mm²
Year
3500
3000
2500
2000
1500
1000
500
600
500
400
300
200
100
0
1975
1980
1985
1990
1995
2000
2005
2010

LARP

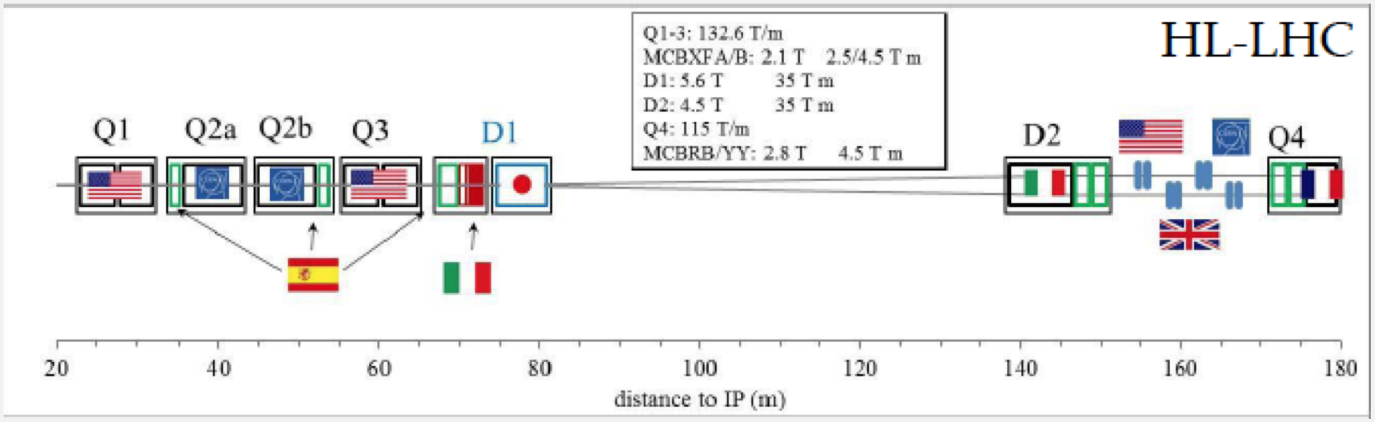
LARP prototype program
Coil test

- **MQXFPM1**
  - Vertical Test Facility @ BNL commissioned in September-October 2016
  - Test results at 1.9 K
    - **First quench**: 14387 A, **65%** of I_{ss} (22.1 kA)
      - Outer layer mid-plane block
    - **Second quench**: 16040 A, **73%** of I_{ss}
      - Inner layer pole turn straight section
  - Replacement of IGBT blown at discharge of quench 2 in progress
  - *Training resuming soon, but first long Nb_3Sn coil with HL-LHC design is behaving like the short models !*

Talk by Giorgio Apollinari at HEPAP meeting 2016

AND OTHER MAGNETS

About one hundred magnets of eleven different types



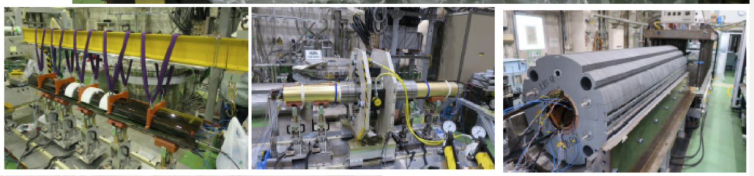
The dipole magnets at the interaction points, which divert the beams before and after the collision point, are being developed in Japan and Italy. One short model has been successfully tested at KEK in Japan and a second is in the process of being tested. INFN, in Italy, is also assembling a short model. Finally, progress is being made on the development of the corrector magnets at CERN and in Spain (CIEMAT), Italy (INFN) and China (IHEP), with several prototypes already tested. In 2022, a test line will be installed in hall SM18 in order to test a magnet chain at the interaction point.

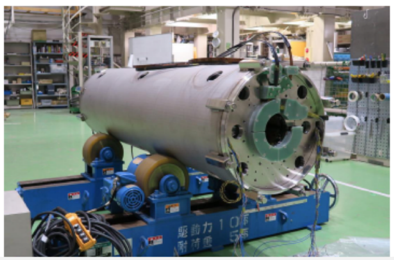
15-18 Oct 2018 https://home.cern/news/news/accelerators/halfway-high-luminosity

INTERNATIONAL CONTRIBUTIONS

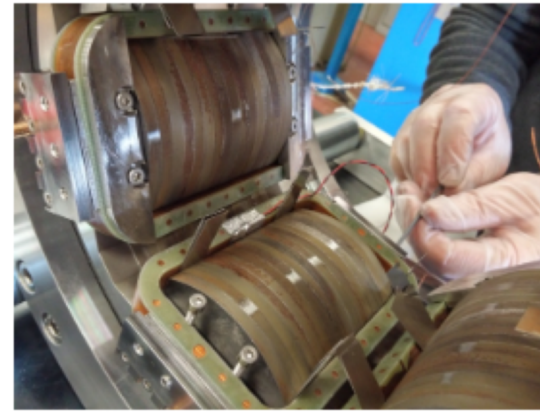
KEK
High Energy Accelerator Research Organization

Status of Model Magnet Development at KEK





Cold test of the 2nd model magnet is started at KEK in this week (from the 14th of October 2018).



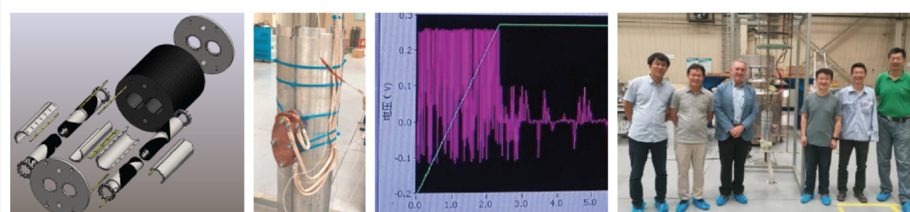
An expert in the LASA Laboratory (INFN Milan, Italy) works on assembling the first sextupole corrector of the HL-LHC. (Image: INFN Milan)

HL-LHC Collaboration – Accelerator technology

IHEP

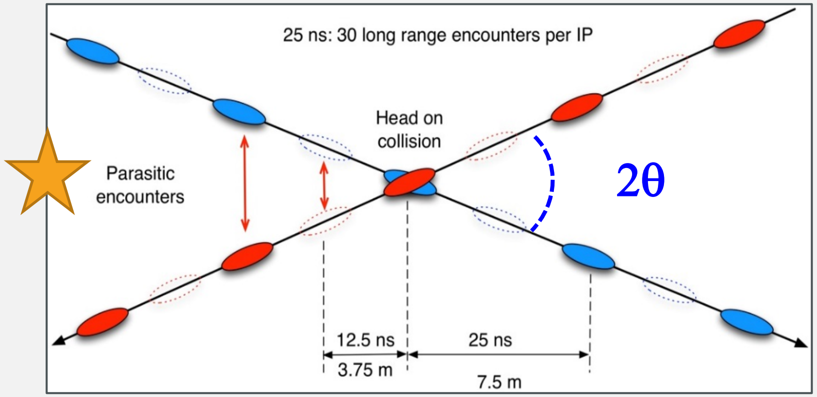
❖ **CCT magnet for HL-LHC**

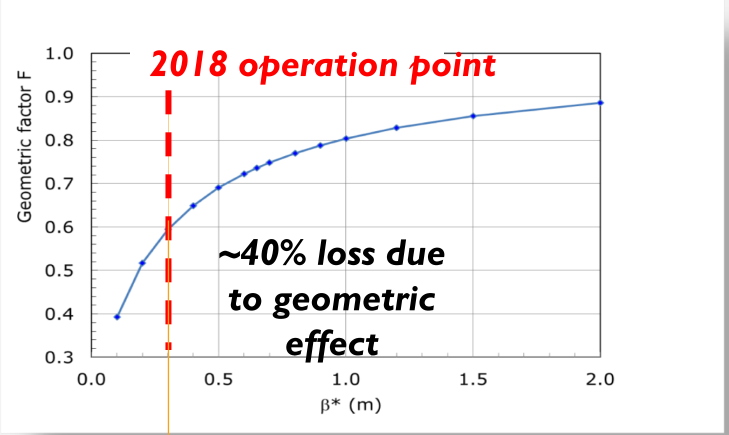
- China will provide 12 units CCT corrector magnets for HL-LHC before 2022
- A 0.5m model and 2.2m prototype to be fabricated and tested by June 2019



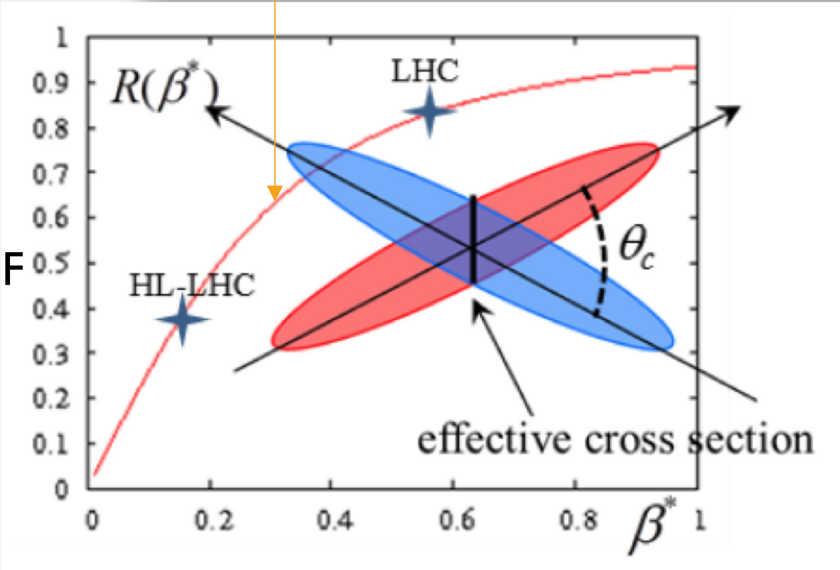
CROSSING ANGLE

Even now, the LHC needs a beam crossing angle to aviod parasitic encounters between bunches not in the interaction region





$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}F$$



This will just be worse at HL-LHC

CRAB CAVITY

DEVELOPMENT OF THE KEK-B SUPERCONDUCTING CRAB CAVITY

K.Hosoyama#, K.Hara, A.Honma, A.Kabe, Y.Kojima, Y.Morita, H.Nakai, K.Nakanishi, K.Akai, K.Ebihara, T.Furuya, S.Mitsunobu, M.Ono, Y.Yamamoto,
KEK, Tsukuba, Japan
K.Okubo, K.Sennyu, H.Hara, T.Yanagisawa
MHI Kobe Shipyard, Japan

Abstract

After more than 10 years of R&D efforts, two superconducting crab cavities for KEKB were constructed and installed into KEKB in January 2007. Effective head on collision of electron and positron has been achieved successfully. The crab cavities are operating stably for more than 1 year under high current operation condition. Design concept and R&D efforts of the superconducting crab cavity will be described. Construction of the crab cavity, including cryostat and tuning mechanism will be also discussed.

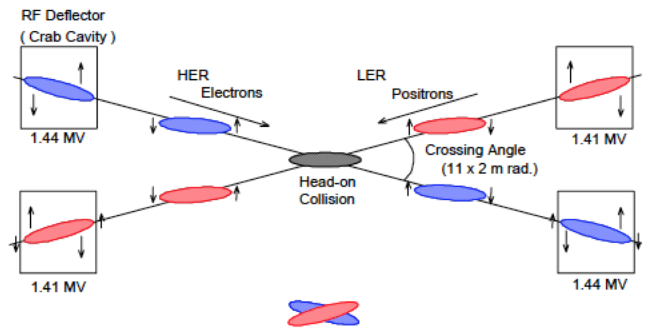


Figure 2: Crab crossing scheme for KEKB and non-crab crossing scheme case (lower)

INTRODUCTION

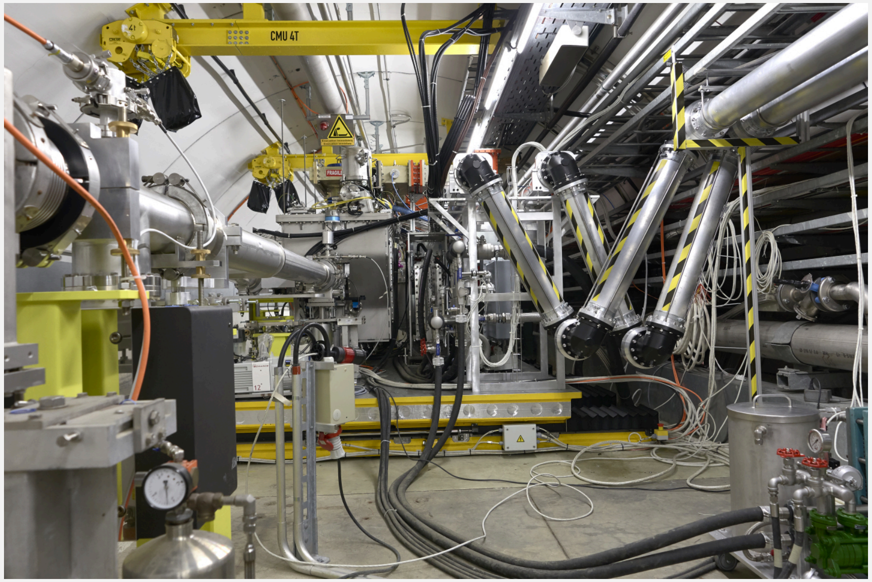
SLAC–PUB–4707
December 1988
(A)

ENERGY SCALING, CRAB CROSSING AND THE PAIR PROBLEM*

R. B. PALMER

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
and
Brookhaven National Laboratory, Upton, New York 11973

CRAB CAVITY



The crab cavities, used to rotate the beams of protons, have been successfully tested on 23 May 2018 – a world first. The test took place using a beam from the SPS and showed that bunches of protons could be tilted using these superconducting transverse radiofrequency cavities. These cavities will play an important role to increase the luminosity in the HL-LHC, which will be commissioned after 2025 and will increase the luminosity of the LHC by a factor of five to ten.

They are made of high-purity niobium superconducting material, operating at 2 kelvins (-271°C), in order to generate very high transverse voltage of 3.4 million volts.

https://home.cern/news/news/engineering/worlds-first-crabbing-proton-beam

LUMINOSITY LEVELING

Both the consideration of energy deposition by collision debris in the interaction region magnets, and the necessity to limit the peak pile-up in the experimental detector, impose an a priori limitation upon peak luminosity. The consequence is that HL-LHC operation will have to rely on luminosity levelling. As shown in Figure 1-3(a), the luminosity profile without levelling quickly decreases from the initial peak value due to 'luminosity burn' (protons consumed in the collisions). The collider is designed to operate with a constant luminosity at a value below the virtual maximum luminosity. The average luminosity achieved is almost the same as that without levelling, see Figure 1-3(b). The advantage, however, is that the maximum peak luminosity is lower.

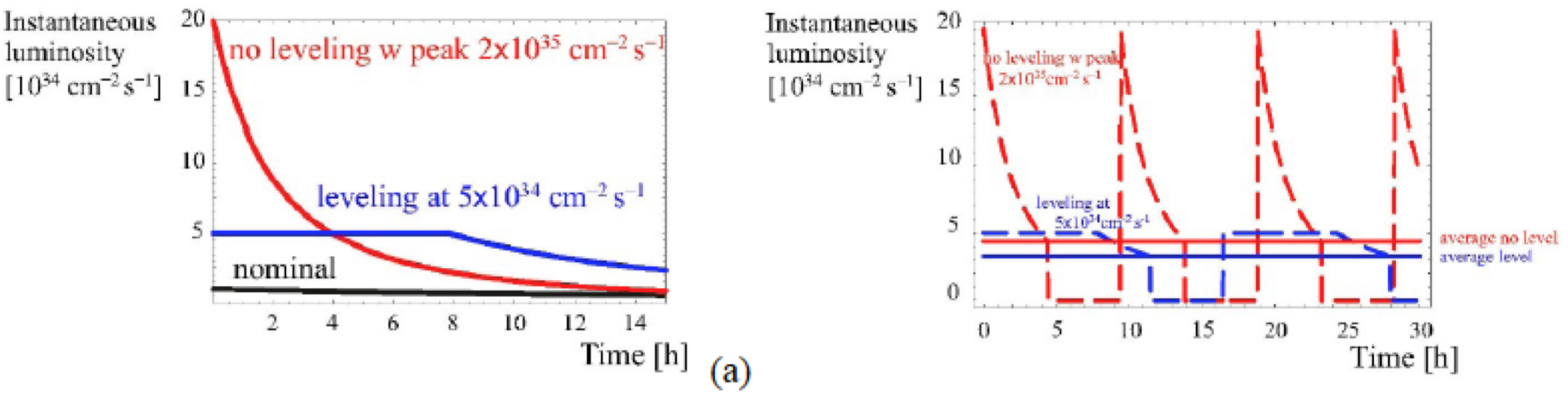
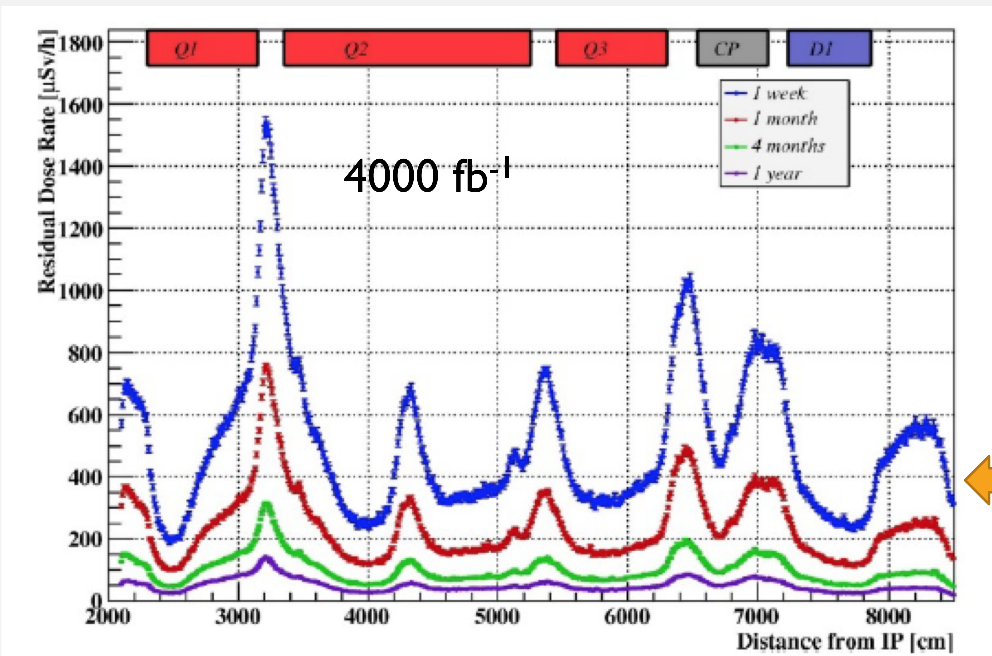
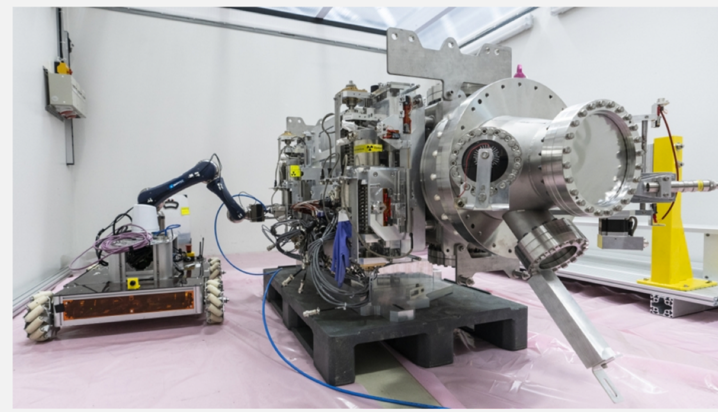


Figure 1-3: (a) Luminosity profile for a single long fill: starting at nominal peak luminosity (black line), with upgrade no levelling (red line), with levelling (blue line). (b) Luminosity profile with optimized run time, without and with levelling (blue and red dashed lines), and average luminosity in both cases (solid lines).

2020 ONWARD NEED ROBOTS DUE TO HIGH ACTIVATION LEVELS

- Remote manipulation: the level of activation from 2020 onwards, and perhaps even earlier, requires careful study and the development of special equipment to allow the replacement of collimators, magnets, vacuum components, etc., according to the ‘as low as reasonably achievable’ (ALARA) principle. While full robotics is difficult to implement, given the conditions on the ground, remote manipulation, enhanced reality and supervision are the key to minimizing the radiation doses sustained during interventions.





Yearly dose limit of 5 rem in about 5 days work

PHYSICS

PHYSICS

ILC??

2018 LHC LS2 | 2023 LHC LS3 | 2026 HL-LHC | 2030 CEPC? | 2039 CEE-ee? | 2040 HE-LHC? | 2043 FCC-hh?

Right now, LHC primary* source of information on:

- Direct searches for new heavy particles (Fermi/Ice Cube/etc are currently direct competitors in this area, especially searches for dark matter particle)
- Precision measurements of the Higgs boson (has this field to itself until at least 2030?)
- Precision measurements of EWK parameters and closure test (W mass, top mass, Higgs mass). Has top mass to itself for a long time. (some information from AMO, etc).
- Some topics in rare b decays and other topics in b physics (CP-violation, etc) (SuperKEKB)

Provides important information on a host of other topics as well (proton structure, heavy ions, the tau lepton, the charm quark, etc)

* well, what do you expect somebody who has worked 20 years on LHC to say?

CERN YELLOW REPORT

Many new projections on physics reach came available in the past two months in anticipation of the CERN Yellow Report https://cds.cern.ch/record/2651134?ln=en

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Projected Physics Results

CMS-PAS-FTR-18-027	Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC with the CMS experiment		December 2018
CMS-PAS-FTR-18-036	Anomalous couplings in the ttZ final state at the HL-LHC		December 2018
CMS-PAS-FTR-18-029	Search for excited leptons in $\ell\ell\gamma$ final states in proton-proton collisions at the HL-LHC		December 2018
CMS-PAS-FTR-18-025	Performance of jet quenching measurements in pp and PbPb collisions with CMS at the HL-LHC		December 2018
CMS-PAS-FTR-18-032	High-p_{T} jet measurements at the HL-LHC		December 2018
CMS-PAS-FTR-18-015	Projection of differential $t\bar{t}$ production cross section measurements in the e/μ+jets channels in pp collisions at the HL-LHC		December 2018
CMS-PAS-FTR-18-014	Vector Boson Scattering prospective studies in the ZZ fully leptonic decay channel for the High-Luminosity and High-Energy LHC upgrades		December 2018
CMS-PAS-FTR-18-017	Projection of the Run 2 MSSM $H \rightarrow \tau\tau$ limits for the High-Luminosity LHC		December 2018
CMS-PAS-FTR-18-024	Open heavy flavor and quarkonia in heavy ion collisions at HL-LHC		December 2018
CMS-PAS-FTR-18-038	Prospects for the measurement of electroweak and polarized $WZ \rightarrow 3\ell\nu$ production cross sections at the High-Luminosity LHC		December 2018
CMS-PAS-FTR-18-026	Predictions on the precision achievable for small system flow observables in the context of the HL-LHC		December 2018
CMS-PAS-FTR-18-041	CP-violation studies at the HL-LHC with CMS using B_s^0 decays to $J/\psi\phi(1020)$		December 2018
CMS-PAS-FTR-18-013	Measurement of rare $B \rightarrow \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC		December 2018
CMS-PAS-FTR-18-006	Search for heavy composite Majorana neutrinos at the High-Luminosity and the High-Energy LHC		December 2018
CMS-PAS-FTR-18-031	Expected sensitivities for $t\bar{t}t\bar{t}$ production at HL-LHC and HE-LHC		December 2018
CMS-PAS-FTR-18-009	Search for $t\bar{t}$ resonances at the HL-LHC and HE-LHC with the Phase-2 CMS detector		November 2018
CMS-PAS-FTR-18-001	Searches for light higgsino-like charginos and neutralinos at the HL-LHC with the Phase-2 CMS detector		November 2018
CMS-PAS-FTR-18-018	First level track jet trigger for displaced jets at High Luminosity LHC		November 2018
CMS-PAS-FTR-18-020	Constraints on the Higgs boson self-coupling from ttH+tH, $H \rightarrow \gamma\gamma$ differential measurements at the HL-LHC		November 2018
CMS-PAS-FTR-18-010	Search for supersymmetry with direct stau production at the HL-LHC with the CMS Phase-2 detector		November 2018
CMS-PAS-FTR-18-016	Search for invisible decays of a Higgs boson produced through vector boson fusion at the High-Luminosity LHC		November 2018
CMS-PAS-FTR-18-011	Sensitivity projections for Higgs boson properties measurements at the HL-LHC		November 2018
CMS-PAS-FTR-18-005	Study of $W^{\pm}W^{\pm}$ production via vector boson scattering at the HL-LHC with the upgraded CMS detector		November 2018
CMS-PAS-FTR-18-008	Projection of searches for pair production of scalar leptoquarks decaying to a top quark and a charged lepton at the HL-LHC		November 2018
CMS-PAS-FTR-18-002	Search sensitivity for dark photons decaying to displaced muons with CMS at the high-luminosity LHC		October 2018
CMS-PAS-FTR-18-007	Projection of the Mono-Z search for dark matter to the HL-LHC		October 2018
CMS-PAS-FTR-18-004	Prospects for a search for gluon-mediated FCNC in top quark production using the CMS Phase-2 detector at the HL-LHC		September 2018
CMS-PAS-FTR-18-003	Search for vector boson fusion production of a massive resonance decaying to a pair of Higgs bosons in the four b quark final state at the HL-LHC using the CMS Phase 2 detector		July 2018

Obviously cannot cover all of these topics

Short Title	Document Number	Date	√s (TeV)
HL-LHC prospects for the measurement of ttgamma NEW	ATL-PHYS-PUB-2018-049	17-DEC-18	14
Prospects for jet and photon physics at the HL-LHC NEW	ATL-PHYS-PUB-2018-051	13-DEC-18	14
Prospect for 4top cross section HL LHC NEW	ATL-PHYS-PUB-2018-047	13-DEC-18	14
Electroweakinos, sleptons, 1lbb, 2L, 3L, 2 tau, upgrade NEW	ATL-PHYS-PUB-2018-048	15-DEC-18	14
Z to dilepton or tt, W to tb or lv 14 TeV HL-LHC NEW	ATL-PHYS-PUB-2018-044	09-DEC-18	14
HL-LHC prospect for top mass using J/Psi NEW	ATL-PHYS-PUB-2018-042	04-DEC-18	14
Prospects for MET+Jet NEW	ATL-PHYS-PUB-2018-043	05-DEC-18	14
Differential cross section measurement prospects at HL-LHC NEW	ATL-PHYS-PUB-2018-040	04-DEC-18	14
Prospects for $B_s \rightarrow J/\psi\phi$ at HL-LHC NEW	ATL-PHYS-PUB-2018-041	04-DEC-18	14
H/A->tautau prospects at HL-LHC NEW	ATL-PHYS-PUB-2018-050	19-DEC-18	14
Nuclear PDFs in Run 3 and 4 NEW	ATL-PHYS-PUB-2018-039	30-NOV-18	5.02/NN
Prospect for a measurement of the Weak Mixing Angle in p p --> Z/gamma* --> e+e- events with the ATLAS detector at the High Luminosity Large Hadron Collider NEW	ATL-PHYS-PUB-2018-037	29-NOV-18	14
Prospects for DM in VBF+MET and Photon+MET NEW	ATL-PHYS-PUB-2018-038	30-NOV-18	14
WIMP DM pair + HF quarks; 0, 2 leptons NEW	ATL-PHYS-PUB-2018-036	27-NOV-18	14
DV+MET prospects at HL-LHC	ATL-PHYS-PUB-2018-033	18-NOV-18	14
HL-LHC prospects for $\tau \rightarrow 3\mu$ NEW	ATL-PHYS-PUB-2018-032	20-NOV-18	14
Prospect studies for the production of three massive vector bosons with the ATLAS detector at the High-Luminosity LHC	ATL-PHYS-PUB-2018-030	14-NOV-18	14
Chargino-neutralino pair; disappearing track; soft leptons	ATL-PHYS-PUB-2018-031	15-NOV-18	14
Prospect study of electroweak production of a Z boson pair plus two jets at the HL-LHC	ATL-PHYS-PUB-2018-029	15-NOV-18	14
Prospects of HH->4b Resonance Search	ATL-PHYS-PUB-2018-028	13-NOV-18	14
Prospects for 4top Signatures (2HDM+a)	ATL-PHYS-PUB-2018-027	02-NOV-18	14
Prospects for the measurement of mW with the upgraded ATLAS detector	ATL-PHYS-PUB-2018-026	30-OCT-18	14
Prospects for Monotop Dark Matter	ATL-PHYS-PUB-2018-024	30-OCT-18	14
Prospective study of vector boson scattering in WZ fully leptonic final state at HL-LHC NEW	ATL-PHYS-PUB-2018-023	29-NOV-18	14
Prospects of VV Search and Measurement	ATL-PHYS-PUB-2018-022	30-OCT-18	14
3rd generation; 0 lepton; upgrade	ATL-PHYS-PUB-2018-021	30-OCT-18	14
Bulk properties of heavy ion collisions in Run 3 and 4	ATL-PHYS-PUB-2018-020	23-OCT-18	5.02/NN
Jet energy loss in heavy ion collisions in Run 3 and Run 4	ATL-PHYS-PUB-2018-019	23-OCT-18	5.02/NN
UPC with photons in Run 3 and 4	ATL-PHYS-PUB-2018-018	04-OCT-18	5.02/NN
Vh(125) h->cc prospects at HL-LHC	ATL-PHYS-PUB-2018-016	07-AUG-18	14
Theory uncertainty impact projection studies	ATL-PHYS-PUB-2018-010	16-JUL-18	14
h(125) -> mu mu prospects HL-LHC	ATL-PHYS-PUB-2018-006	24-MAY-18	14
Prospects for $\mathcal{B}(B^0_{(s)} \rightarrow \mu^+\mu^-)$ in Run-2 and HL-LHC.	ATL-PHYS-PUB-2018-005	10-MAY-18	13

PHYSICS AT HL-LHC WORKSHOP

Also see summary and combinations in Final Report of the Workshop on "Physics at HL-LHC, and perspectives on HE-LHC" at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop#Final_reports submitted to the European Strategy

https://cds.cern.ch/search?ln=en&p=reportnumber%3Acern-lpcc-2018-*+not+reportnumber%3Acern-lpcc-2018-01+not+reportnumb

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Articles & Preprints, **5** records found

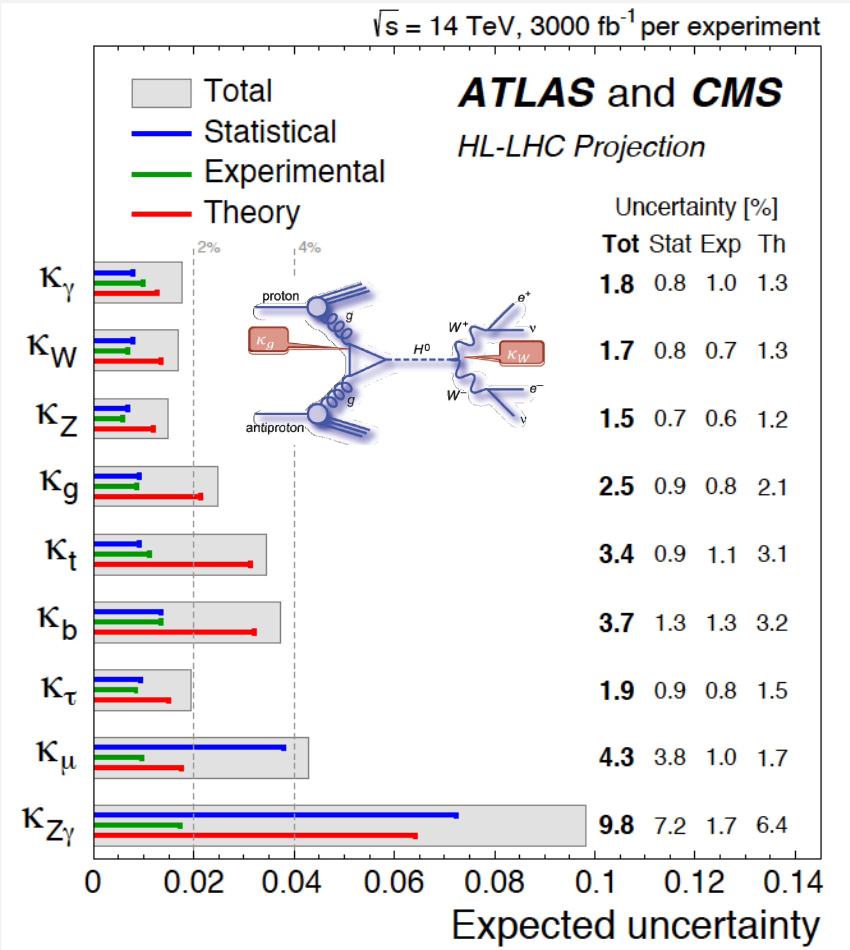
Articles & Preprints **5** records found

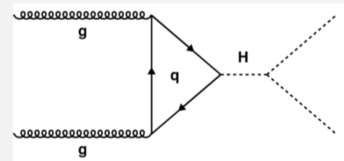
1. **Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams** / Citron, Z. (Ben Gurion U. of Negev) ; Dainese, A. (INFN, Padua) ; Gr Oetringhaus, J.F. (CERN) ; Jowett, J.M. (CERN) ; Lee, Y.-J. (MIT) ; Wiedemann, U.A. (CERN) ; Winn, M. (AIM, Saclay ; Orsay, LAL) ; Andronic, A. (Munster U.) ; Bellini, F. (CE Bruna, E. (INFN, Turin) *et al.*
The future opportunities for high-density QCD with ion and proton beams at the LHC are presented. [...]
arXiv:1812.06772 ; CERN-LPCC-2018-07. - 2018. - 207 p.
Full text - Fulltext
Detailed record - Similar records

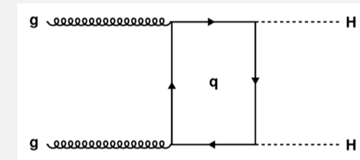
2. **Standard Model Physics at the HL-LHC and HE-LHC** / Azzi, Patrizia (Convenor) (INFN, Padova) ; Farry, Stephen (Convenor) (Liverpool U.) ; Nason, Paolo (Convenor) (IN Milan Bicocca) ; Tricoli, Alessandro (Convenor) (Brookhaven) ; Zeppenfeld, Dieter (Convenor) (KIT, Karlsruhe)
WG 1 report, from the Workshop on "Physics at HL-LHC, and perspectives on HE-LHC"..
CERN-LPCC-2018-03. - 2018. - 211 p.
Full text
Detailed record - Similar records

3. **Higgs Physics at the HL-LHC and HE-LHC** / Cepeda, Maria (Convenor) (Madrid, CIEMAT) ; Gori, Stefania (Convenor) (Cincinnati U.) ; Ilten, Philip James (Convenor) (Birmingham U.) ; Kado, Marumi (Convenor) (Orsay, LAL) ; Riva, Francesco (Convenor) (Geneva U.)

HIGGS IMPORTANT





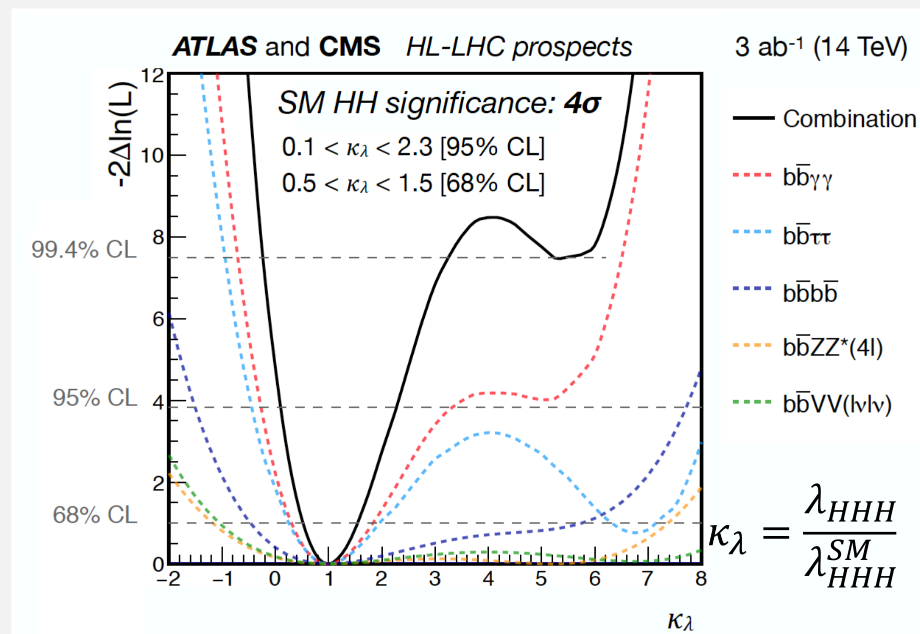


CMS-PAS-FTR-18-019

Table 16: Upper limit at the 95% confidence level, significance, projected measurement at 68% confidence level of the Higgs boson self coupling λ_{HHH} for the five channels studied and their combination. Systematic and statistical uncertainties are considered.

Channel	Significance [σ]	95% CL limit on $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$
bbbb	1.0	2.0
$bb\tau\tau$	1.4	1.5
$bbWW(\ell\nu\ell\nu)$	0.4	4.9
$bb\gamma\gamma$	1.8	1.1
$bbZZ(\ell\ell\ell\ell)$	0.4	6.6
Combined	2.5	0.8
Combined (stat. only)	2.7	0.7

+ ATLAS → 4σ



Combinations from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop#Final_reports

NEW CMS SEARCH PROJECTIONS

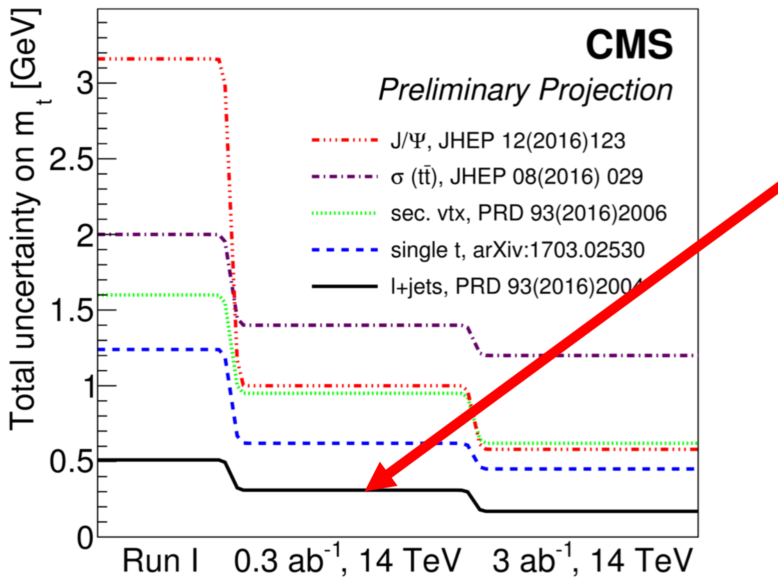
Particle	Current limit (TeV)	Reference (arXiv)	Reach (TeV)	reference
MSSM H→ττ, tanβ=26	1.25	1803.06553	2.0	CMS-PAS-FTR-18-017
Heavy composite majorana neutrino	4.6-4.7	1706.08578	8.0	CMS-PAS-FTR-006
Randall-Sundrum gluon	4.55	1810.05905	6.6	CMS-PAS-18-009
Higgsino-like charginos,neutralinos	O(160)	1801.01846	O(0.35)	CMS-PAS-18-001
direct $\tilde{\tau}$ production	0.1	LEP	0.65	CMS-PAS-FTR-18-010
Leptoquark → te and tμ	1.4	1809.05558 1803.02864	1.8	CMS-PAS-18-008
Dark matter-dark mediator mono-Z vector, 0.25,1	0.7-1.8	1711.00431 1712.02345	0.6-1.5	CMS-PAS-18-007

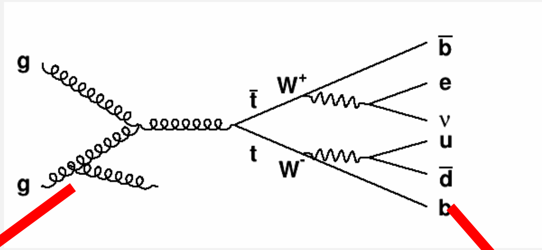
Similar laundry list from ATLAS, but I'm too lazy to turn it into a chart

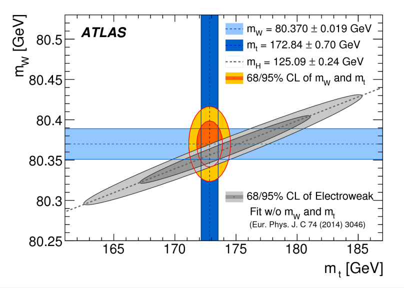
TOP MASS

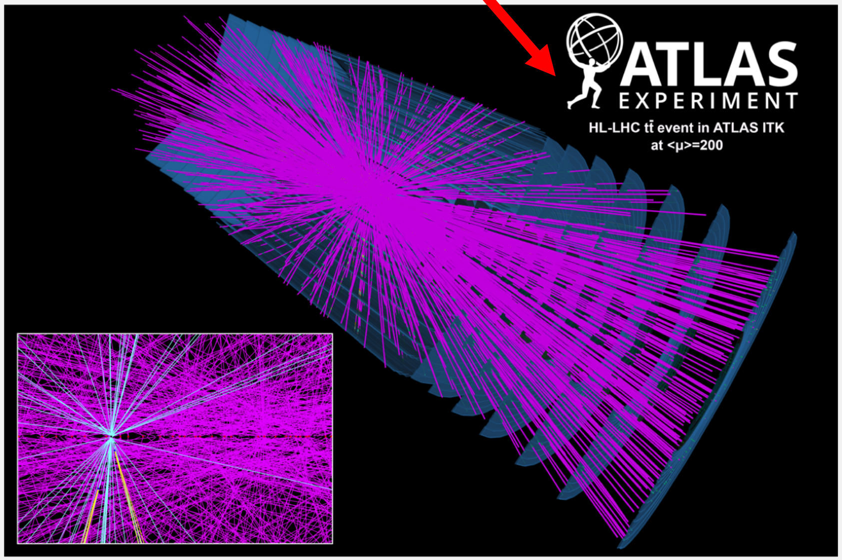
Older result, but fun to look at, as it will last a long time even if a new machine is built but also because it challenges the detector

CMS-PAS-FTR-16-006









Lepton+jets 0.51→0.31 → 0.17 GeV uncertainty

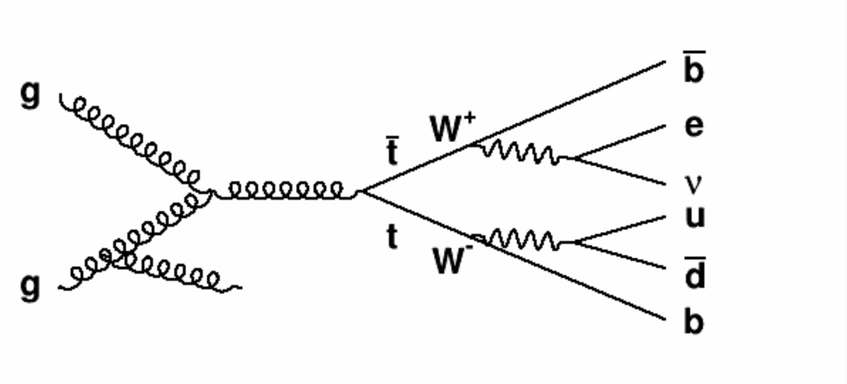
0.17/173=0.001

See also challenging W mass projection by ATLAS ATL-PHYS-PUB-2018-026

TOP MASS

Conceptually simple

- Pick out jets from top decay (not trivial due to extra jets)
- Pair up the right jets to each top
- Calculate mass

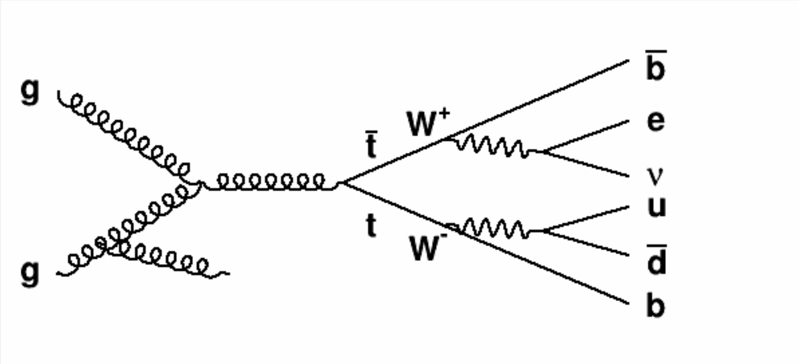


Challenges

- Need very well understood jet energy scale, neutrino (MET), and lepton energy scale
- Need efficient b tagging to reduce combinatorics of jet assignment and reduce backgrounds
- Need to get events that where the objects all have moderate p_T to tape

These challenges become even more challenging in the presence of pileup.

UNCERTAINTY DETAILS

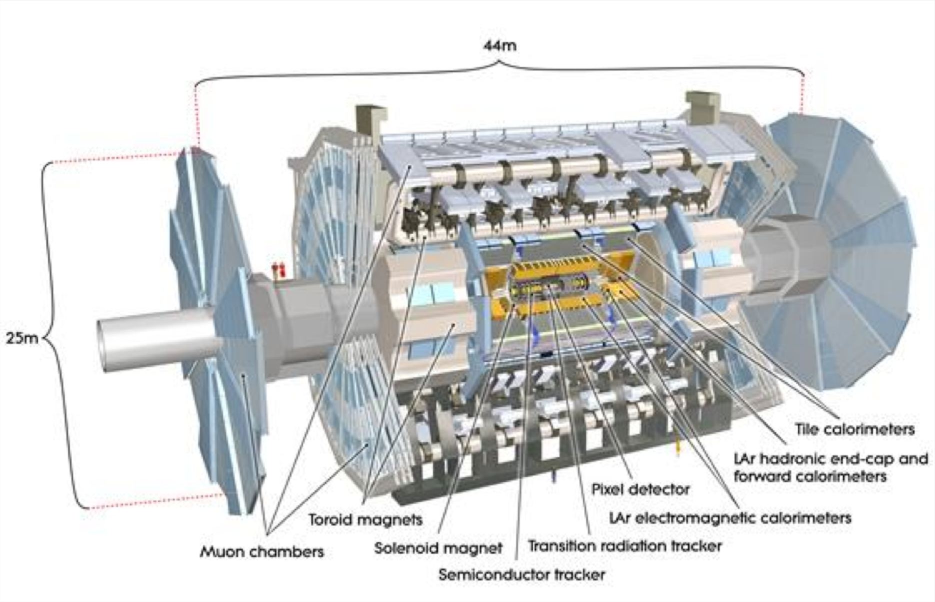


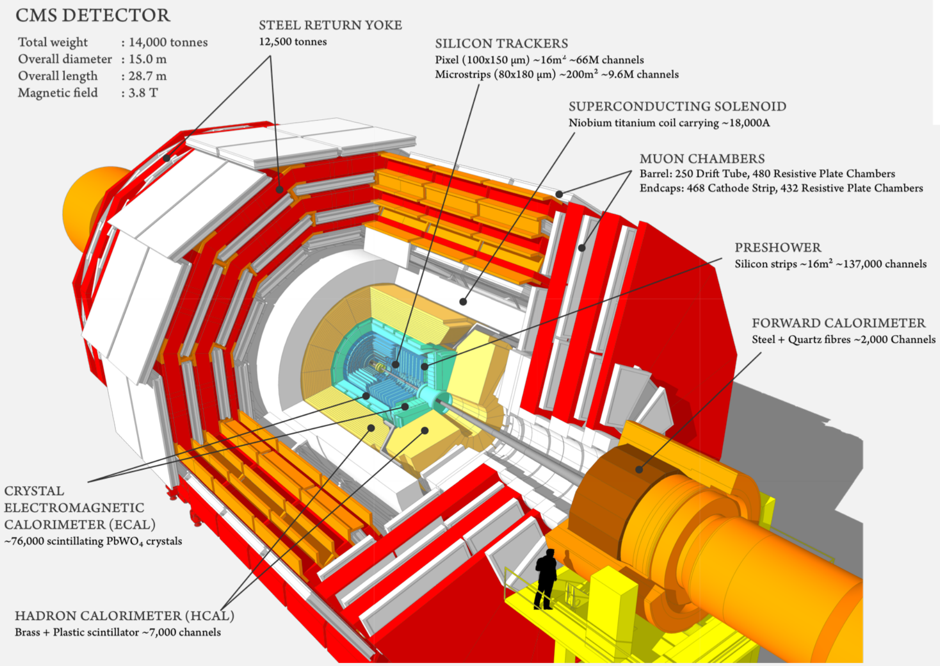
Source	Value (GeV) 8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	Comment
Method calibration	± 0.04	± 0.02	± 0.02	MC stat. $\times 4$
Lepton energy scale	$+0.01$	± 0.01	± 0.01	unchanged
Global JES	± 0.13	± 0.12	± 0.04	3D fit, differential
Flavor-dependent JES	± 0.19	± 0.17	± 0.06	3D fit, differential
Jet energy resolution	-0.03	± 0.02	< 0.01	differential
E_T^{miss} scale	$+0.04$	± 0.04	± 0.04	unchanged
b tagging efficiency	$+0.06$	± 0.03	± 0.03	improved with data
Pileup	-0.04	± 0.04	± 0.04	unchanged
Backgrounds	$+0.03$	± 0.01	± 0.01	cross sections
ME generator	-0.12 ± 0.08	–	–	NLO ME generator
Ren. and fact. scales	-0.09 ± 0.07	± 0.06	± 0.06	NLO ME generator, MC stat.
ME-PS matching	$+0.03 \pm 0.07$	± 0.06	± 0.06	MC stat.
Top quark p_T	$+0.02$	< 0.01	< 0.01	improved with data
b fragmentation	< 0.01	< 0.01	< 0.01	unchanged
Semileptonic b hadron decays	-0.16	± 0.11	± 0.06	improved with data
Underlying event	$+0.08 \pm 0.11$	± 0.14	± 0.09	improved with data, MC stat.
Color reconnection	$+0.01 \pm 0.09$	± 0.05	< 0.01	improved with data
PDF	± 0.04	± 0.03	± 0.02	improved with data
Systematic uncertainty	± 0.48	± 0.30	± 0.17	
Statistical uncertainty	± 0.16	± 0.04	± 0.02	
Total	± 0.51	± 0.31	± 0.17	

CURRENT DETECTORS

ATLAS

- Rad hard liquid argon calorimeter
- Several different tracker technologies

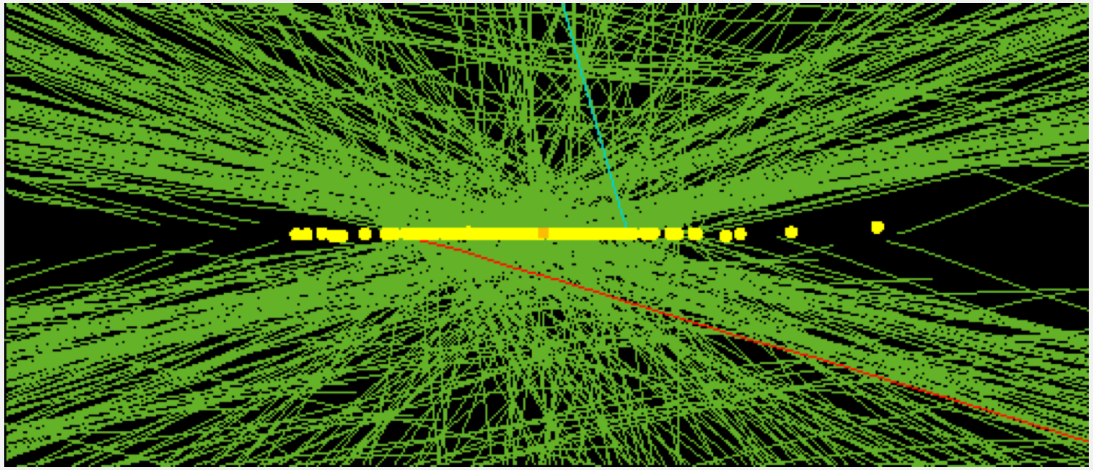




CMS

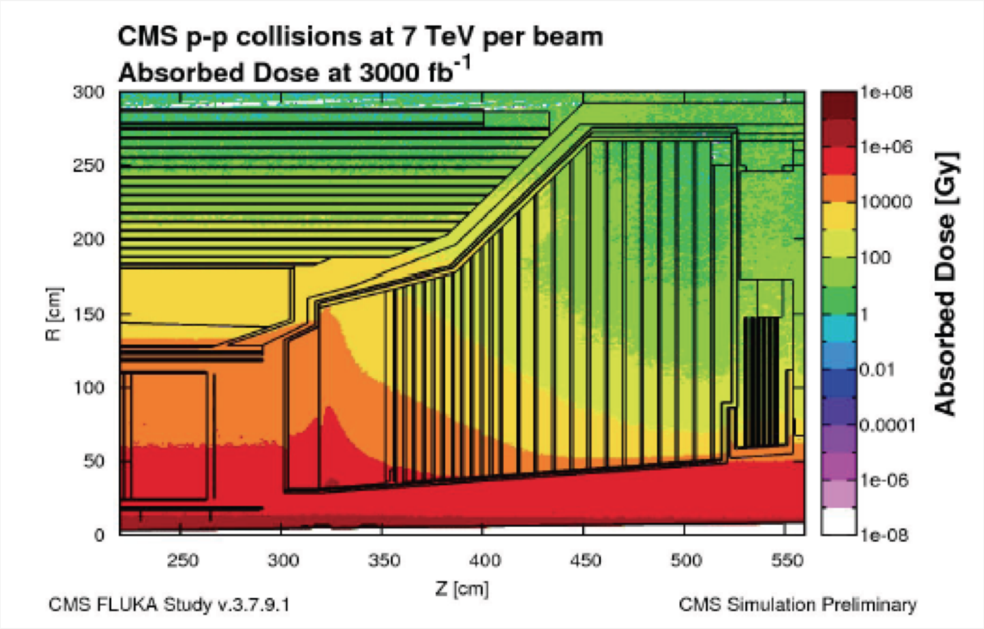
- Crystal ECAL, scintillator-based sampling HCAL
- All silicon tracker

YIKES!!!



23→200 pileup

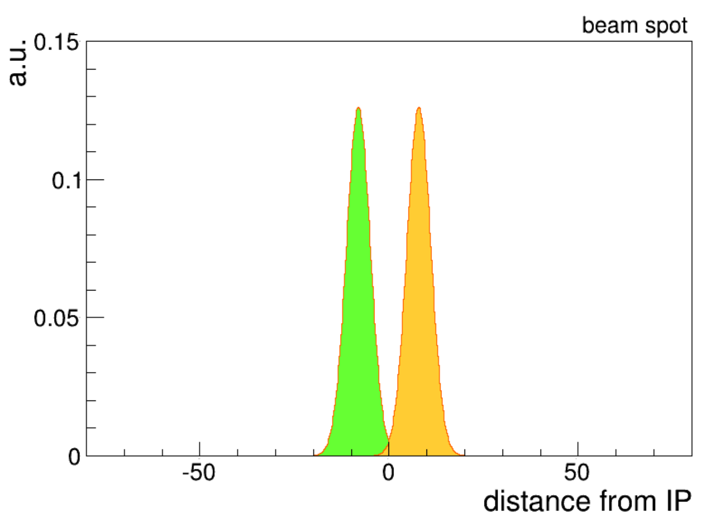
It won't quite melt, but…



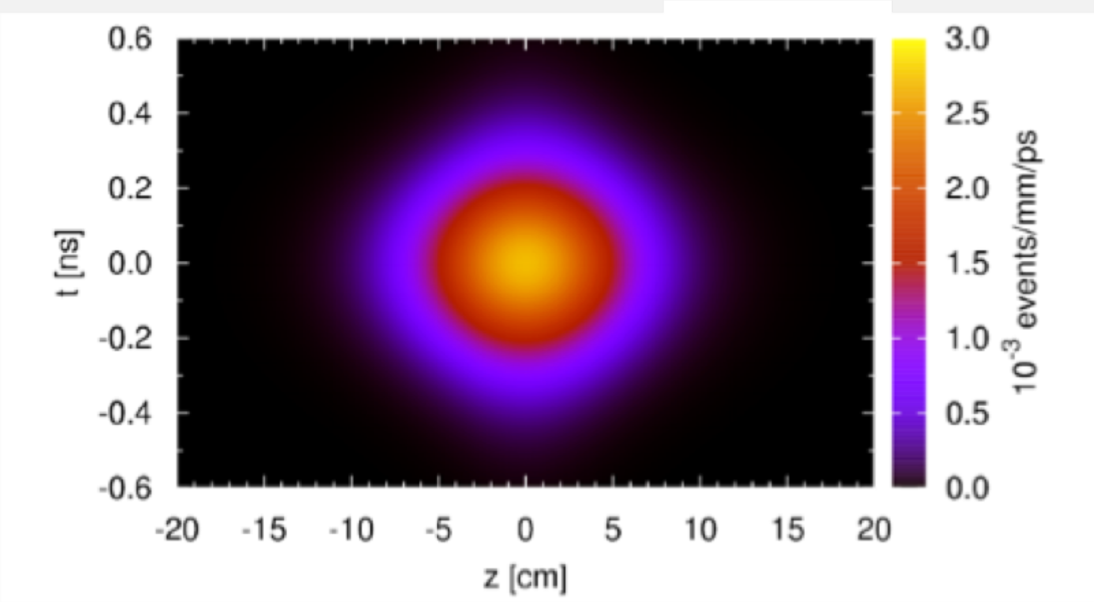
UPGRADES

- Add timing detectors to cope with increased pileup, which affects lepton identification (via isolation), b tagging effectiveness (via primary vertex reconstruction and combinatorics), JES
- Increase granularity of tracker to preserve reconstruction efficiency in high pileup environment. While replacing everything, extend angular coverage and reduce material (ATLAS moving to all silicon)
- Increase trigger capabilities to preserve trigger thresholds. Especially add fast tracking in trigger
- Replace fried detectors (endcap calorimeters for CMS) and improve them while at it.

VERTEX TIME



As the bunches pass through each other, collisions occur at different times as well as positions



Two vertices with the same position can have creation times that different by 10s of ps.

TIMING DETECTORS

ATLAS

For charged particles

- Coverage 2.4<eta<4
- 2 layers of Silicon sensors (LGAD)

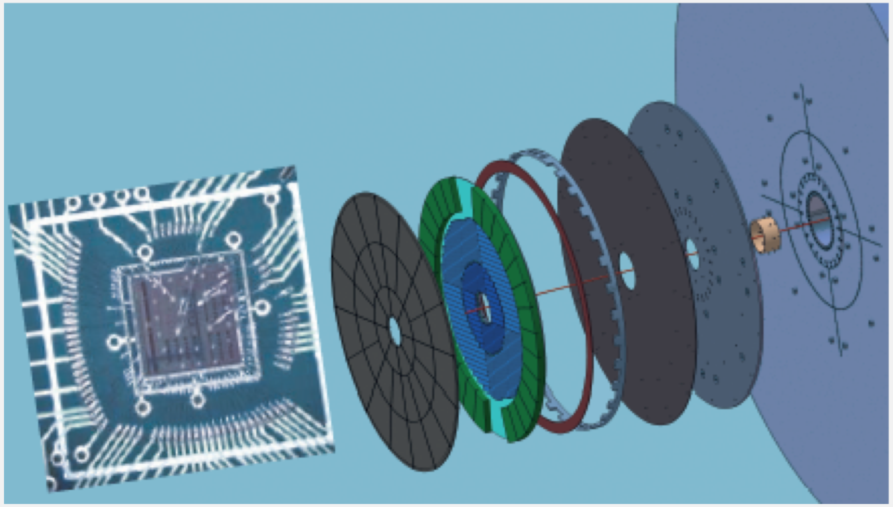
CMS

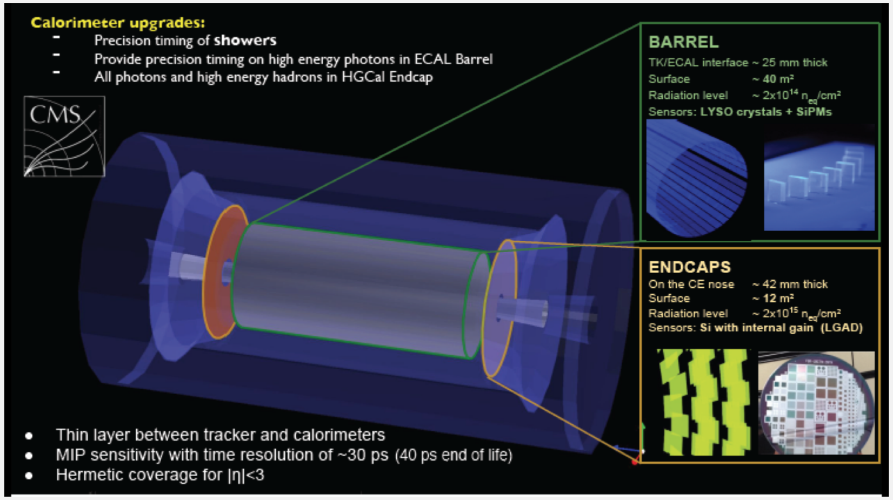
For charged particles

- coverage eta<3
- Barrel LYSO:Ce crystals + SiPMs
- Endcaps Silicon sensors (LGAD)

For neutral

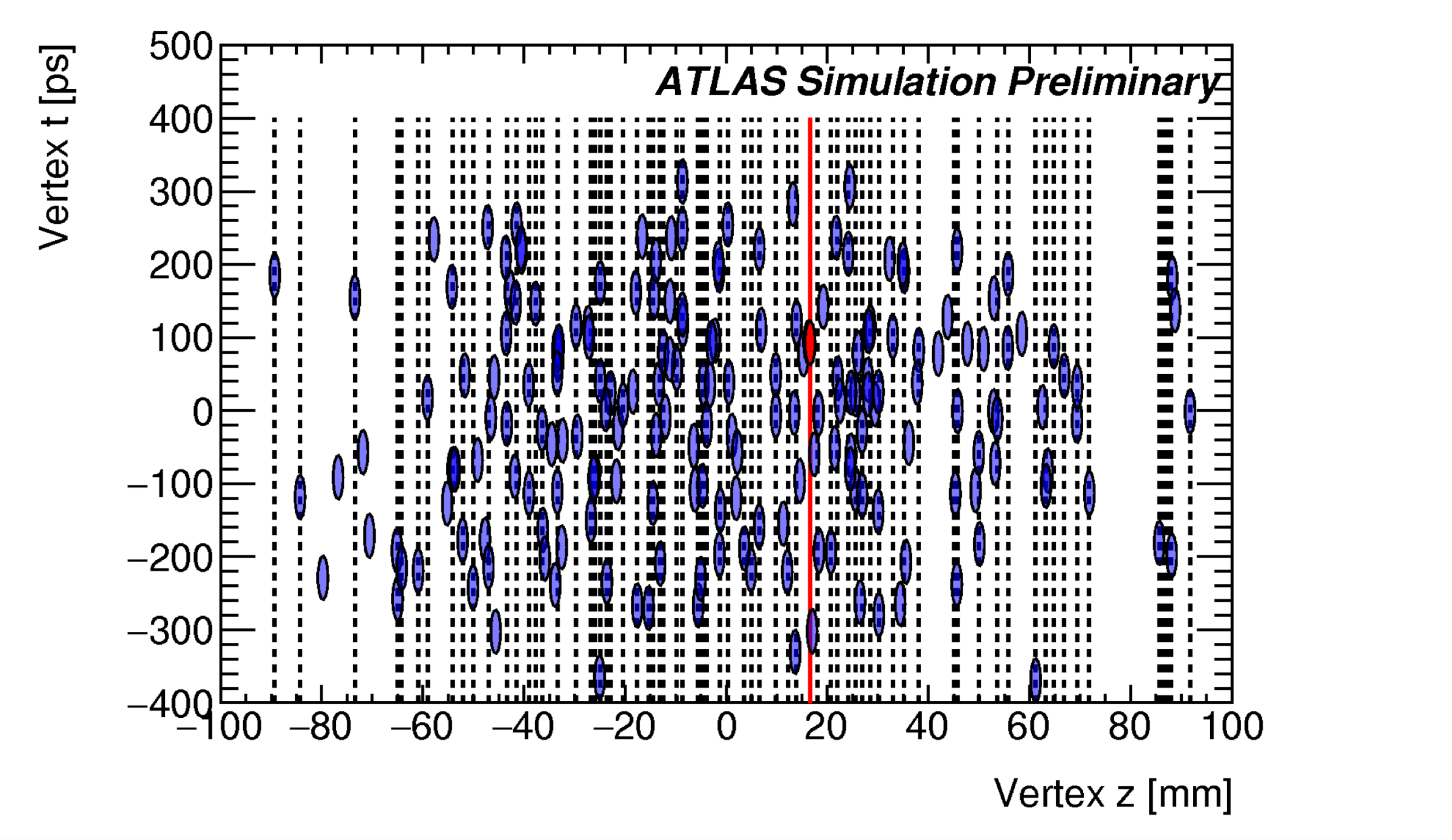
- Improved timing in Barrel EM calorimeter (<30 ps E>25 GeV start of run)
- Improved timing in new endcap calorimeter (15 ps for 12 MIPS)





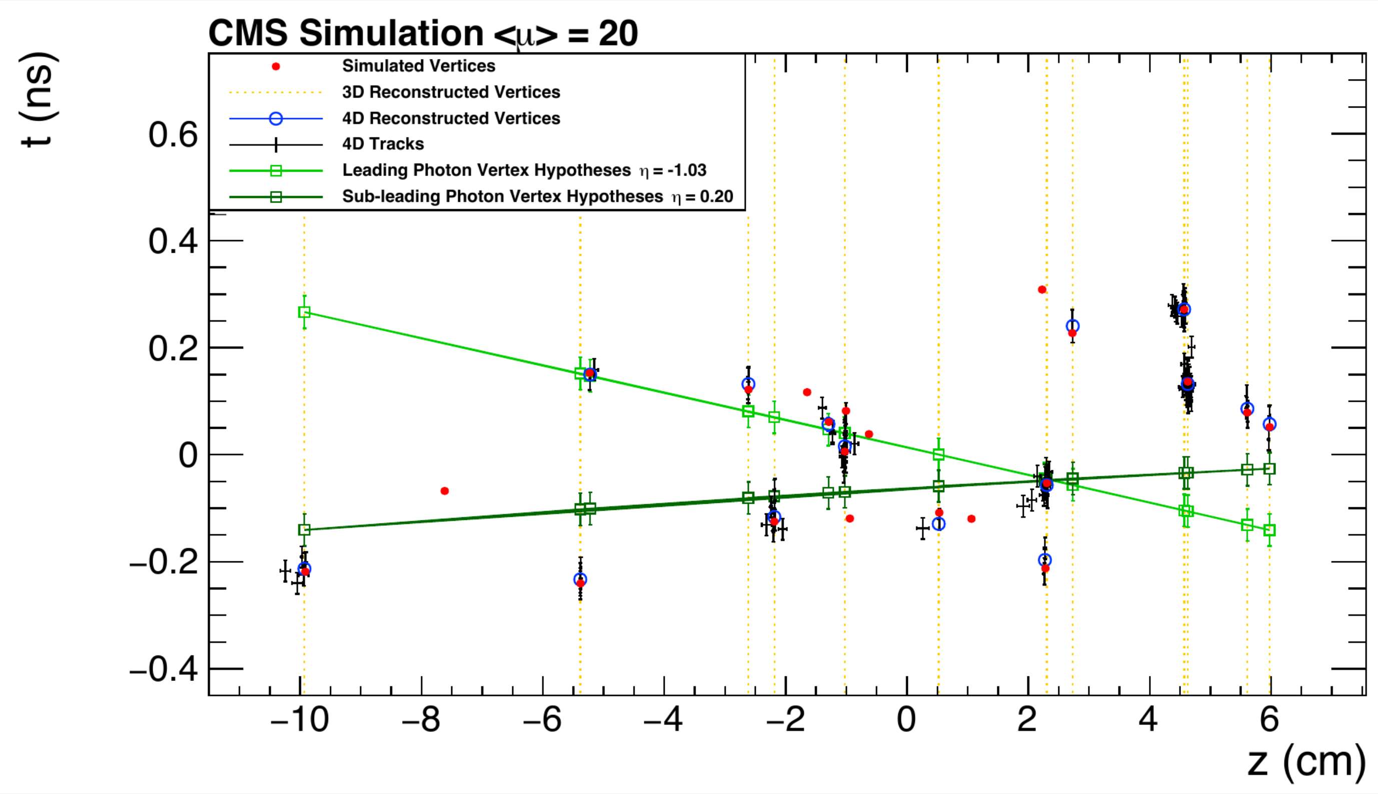
REDUCING PILEUP VIA TIMING

- Most pileup for charged tracks can be removed using z
- However, some additional part can be removed using t



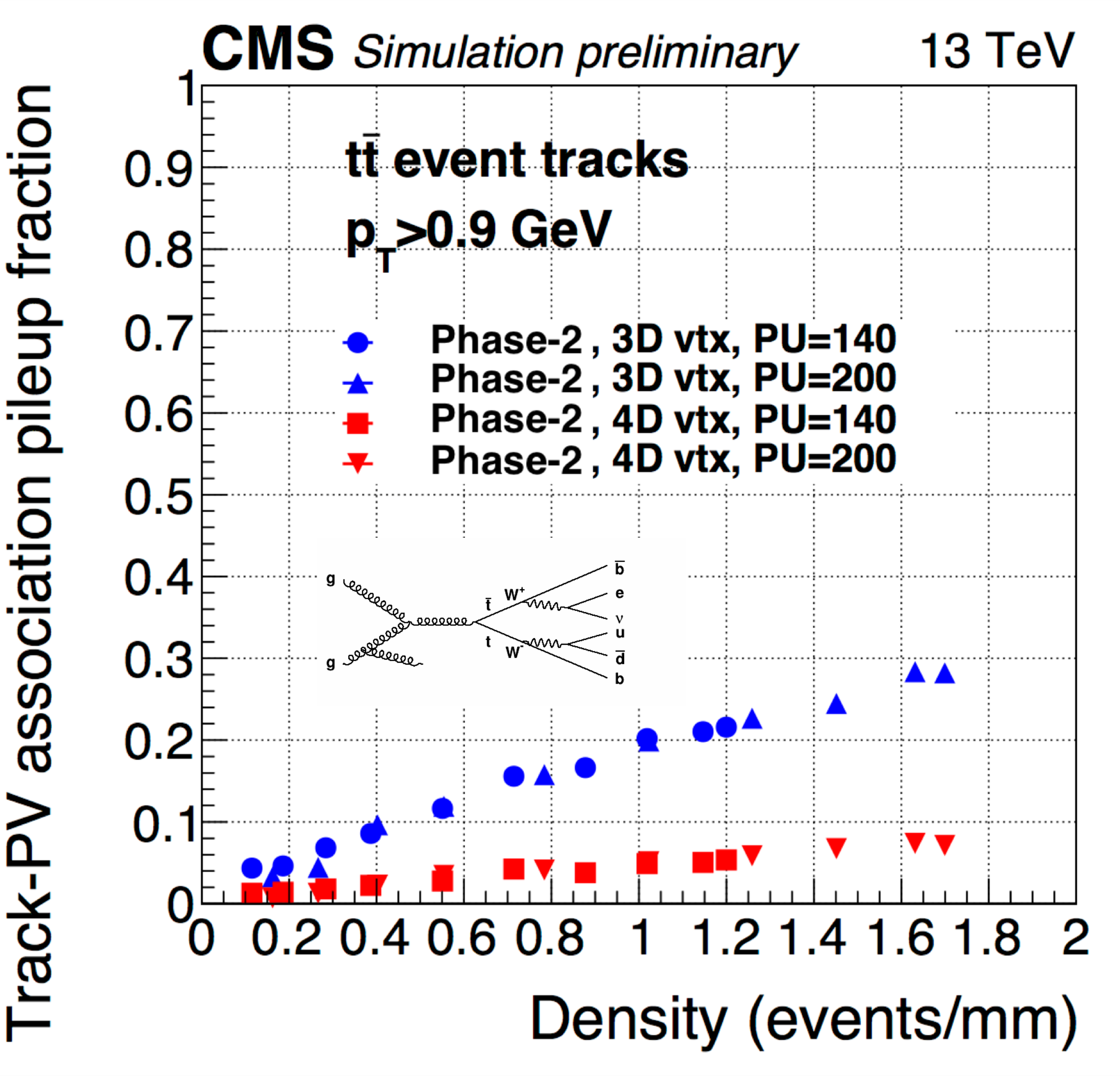
NEUTRALS?

Can even use this technique to find the vertex for the photons in Higgs $\rightarrow \gamma\gamma$ events. For each cluster, for each z position, calculate the creation time that goes with it and the cluster time. Look for vertex that gives same creation time for both clusters.

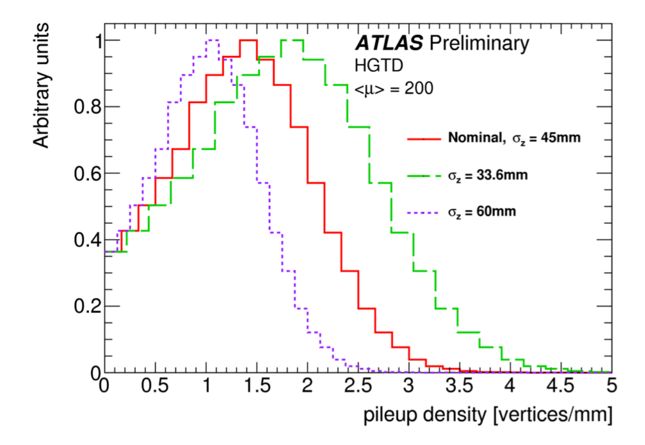


This can be used to improve the resolution of the Higgs $\rightarrow \gamma\gamma$ peak.
Not useful for neutrals from pileup events.

PILEUP



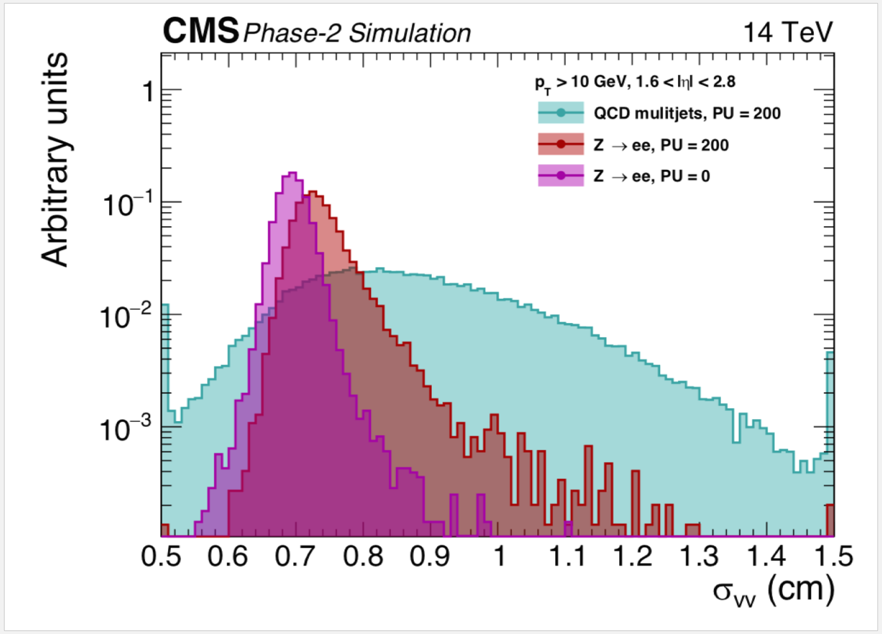
Can reduce pileup from charged particles from about 30% to about 8% at highest pileup density

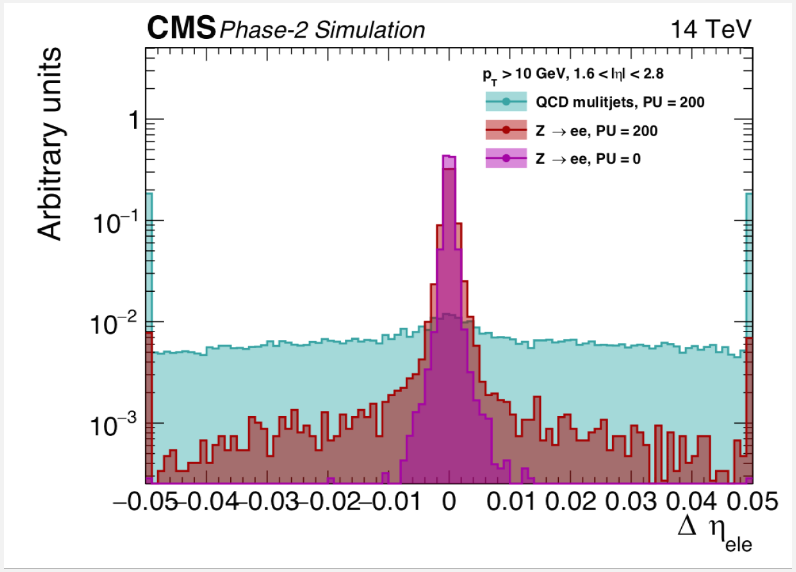


LEPTON IDENTIFICATION

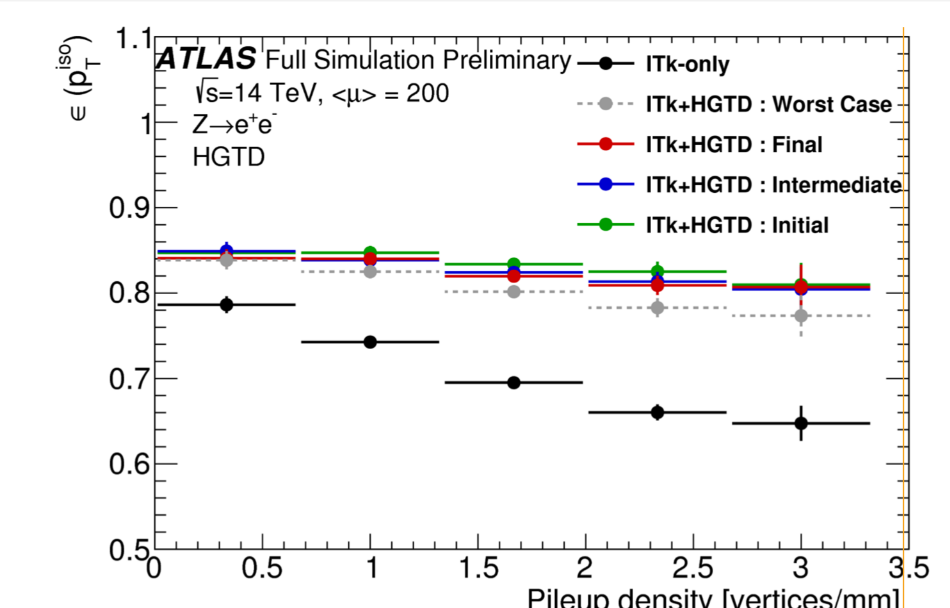
Vulnerability of lepton identification variables to pileup.

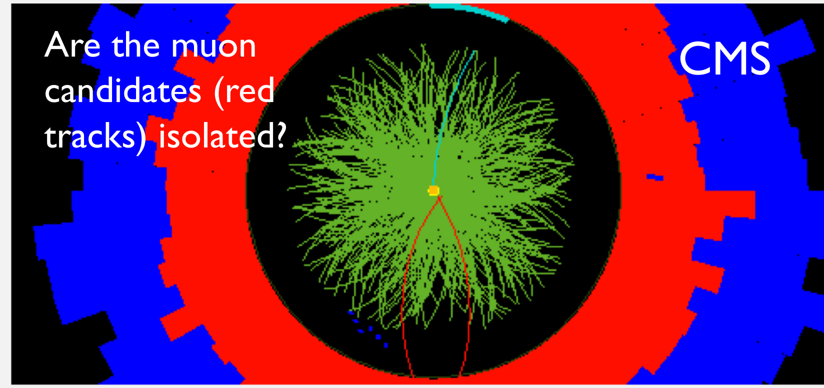
- Purple=no pileup,
- brown is with 200 pileup (endcap calorimeter)

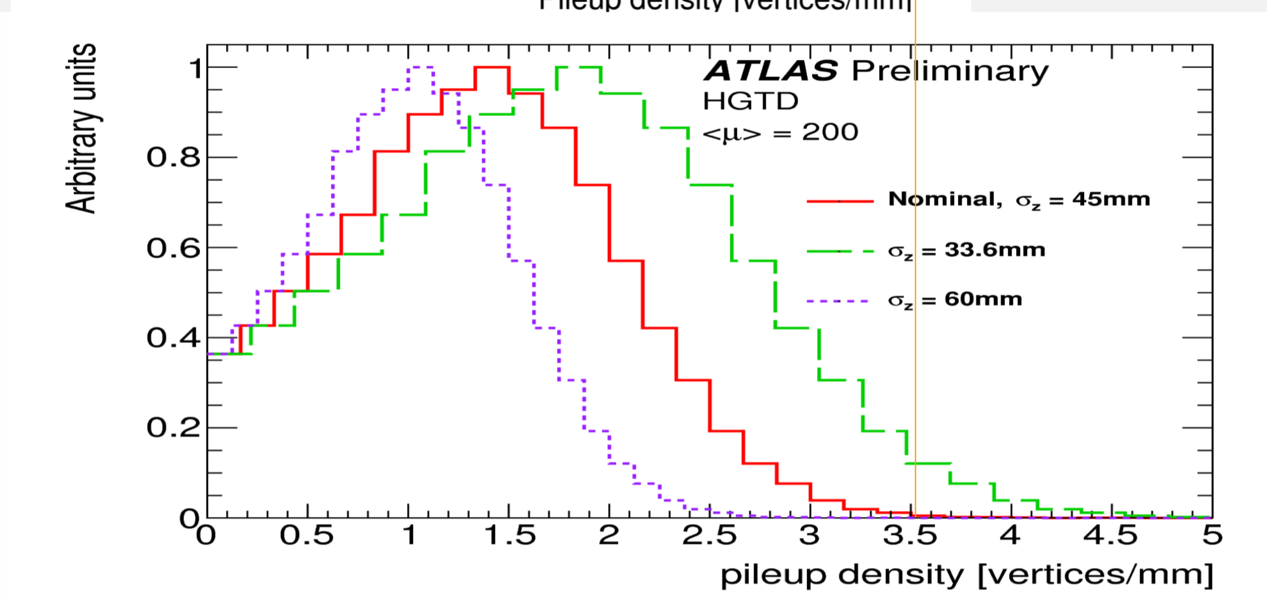




LEPTON ISOLATION

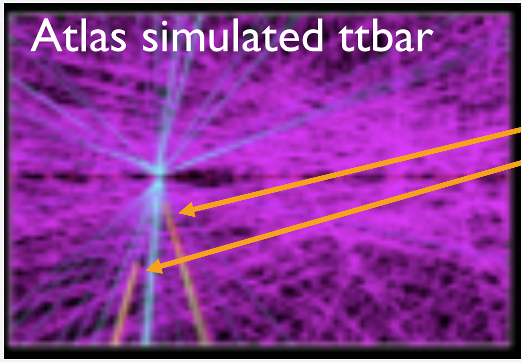




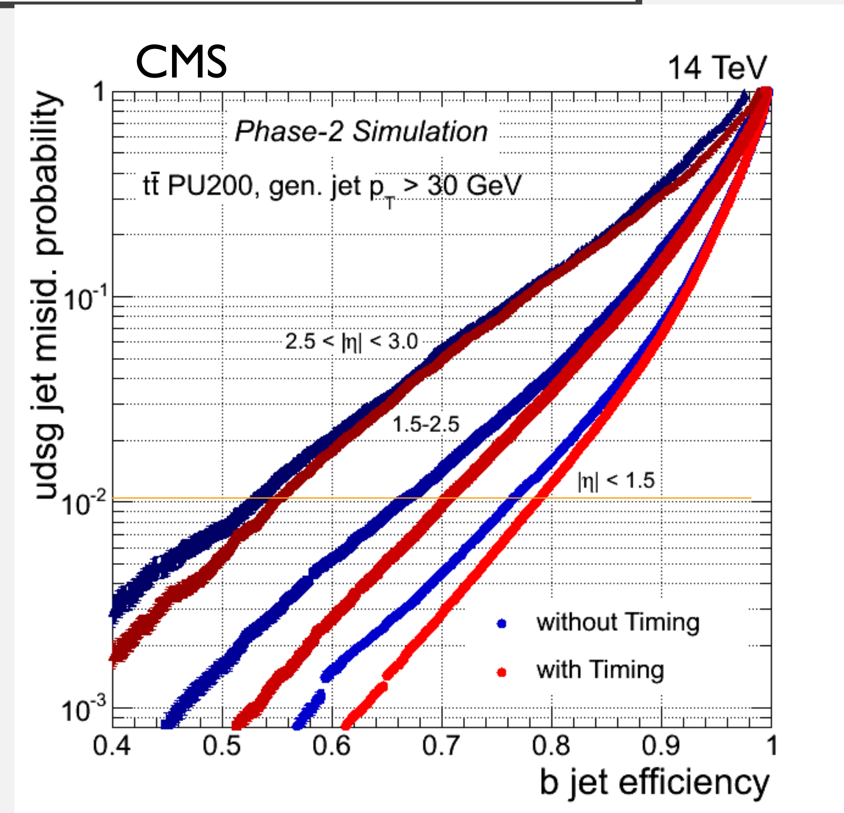


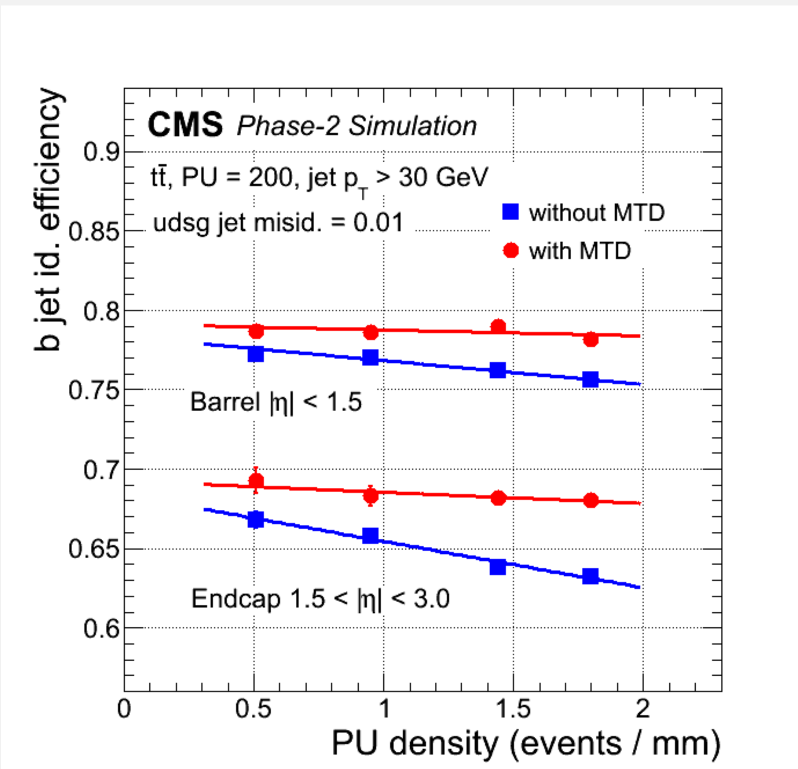
At fixed rejection, improvement in efficiency especially at high pileup density

B TAGGING



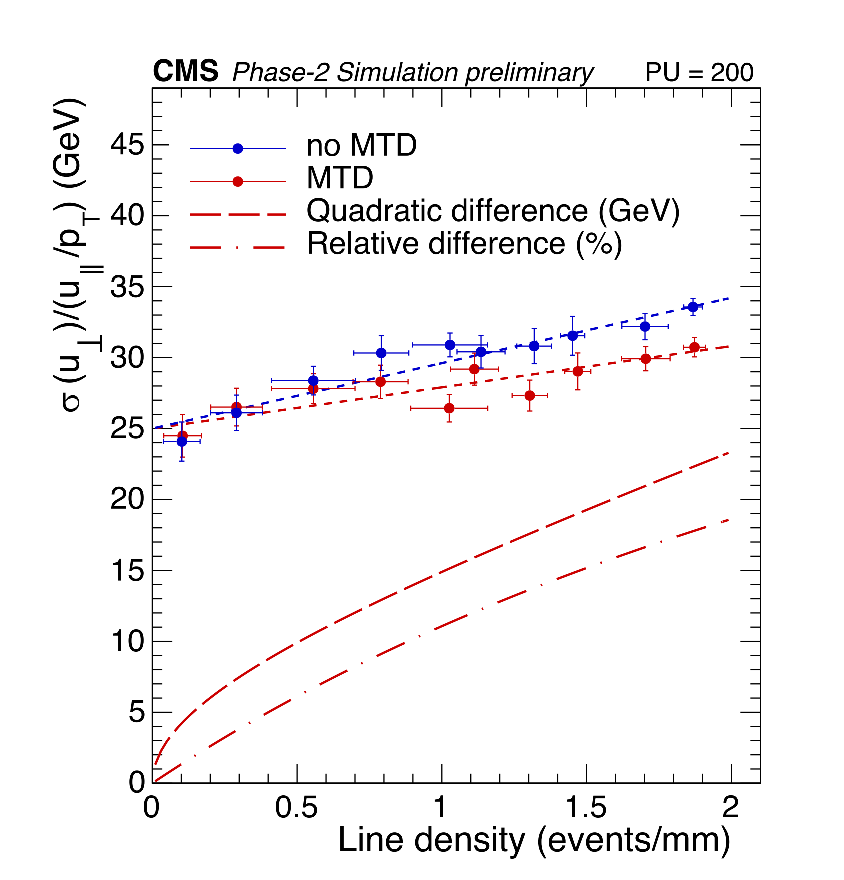
Are
these b's?

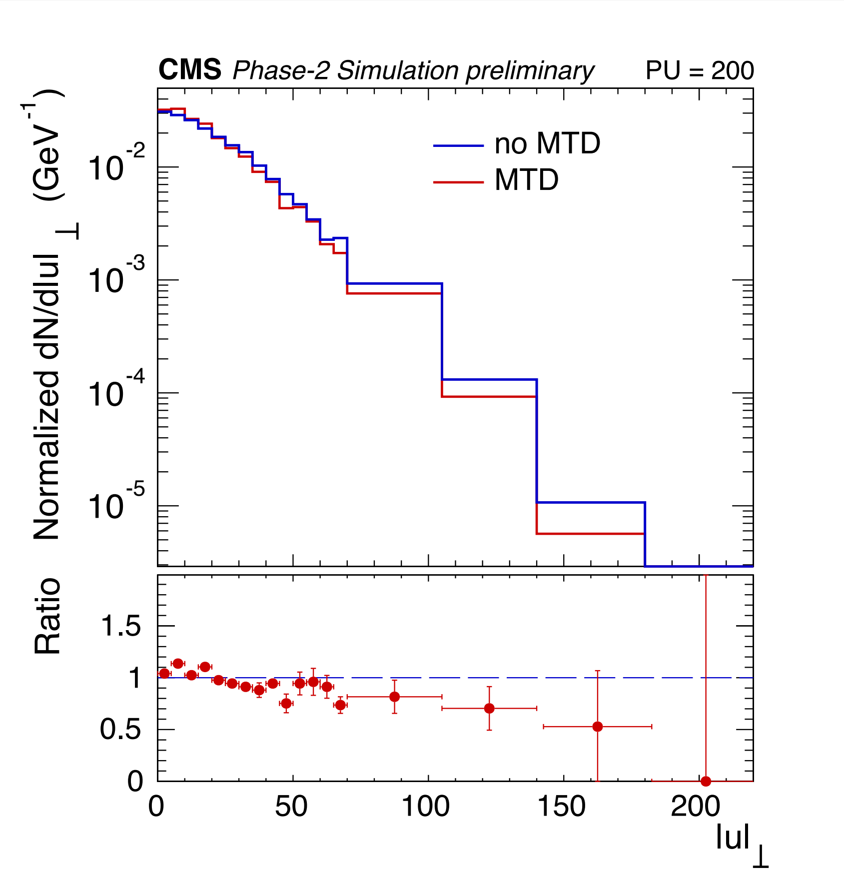




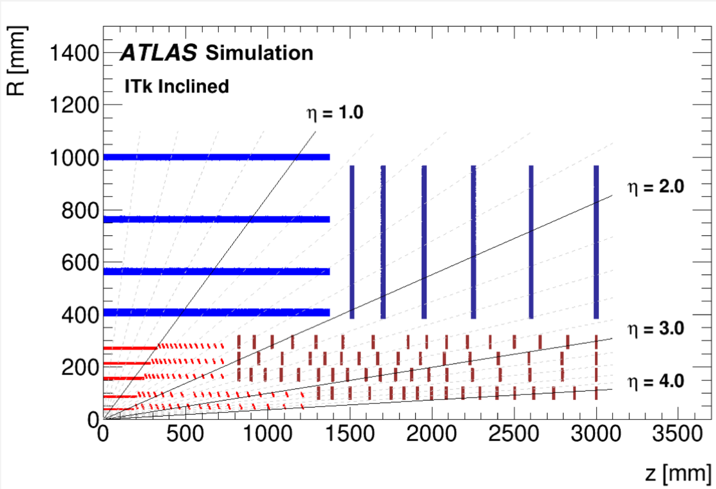
Again, at fixed rejection, improvement in tagging efficiency

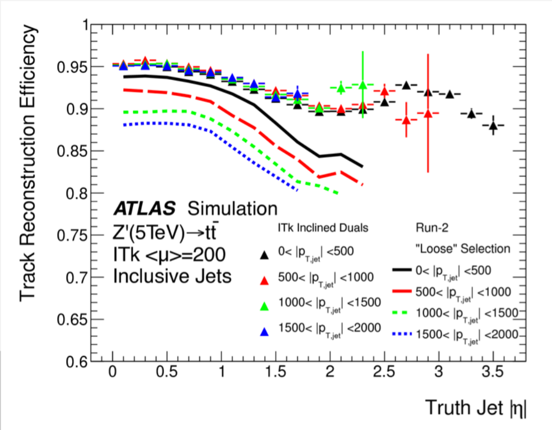
MET

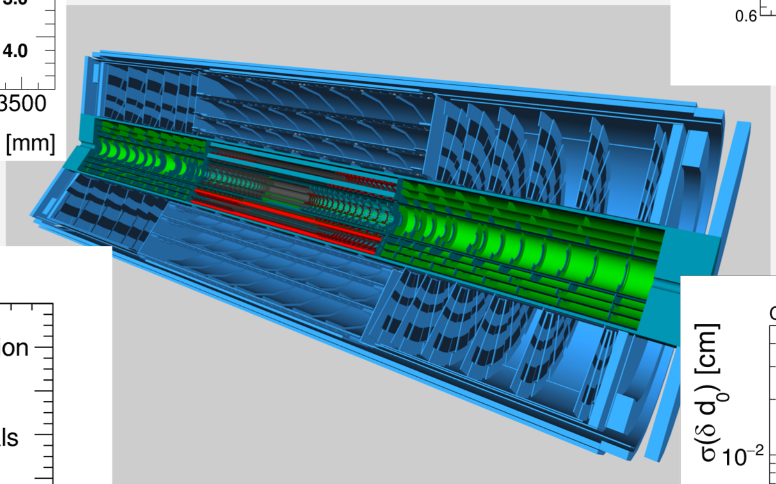

CMS Phase-2 Simulation preliminary
PU = 200
no MTD
MTD
Quadratic difference (GeV)
Relative difference (%)
σ (u⊥)/(u∥/pT) (GeV)
Line density (events/mm)

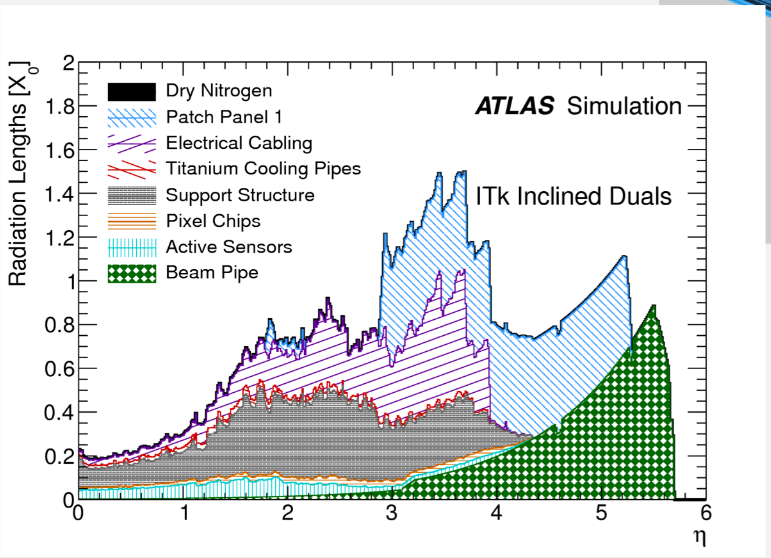

CMS Phase-2 Simulation preliminary
PU = 200
no MTD
MTD
Normalized dN/d|u|⊥ (GeV⁻¹)
Ratio
|u|⊥

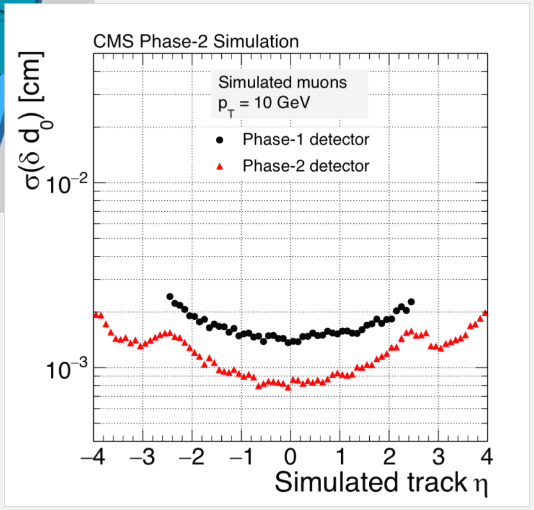
TRACKER UPGRADE





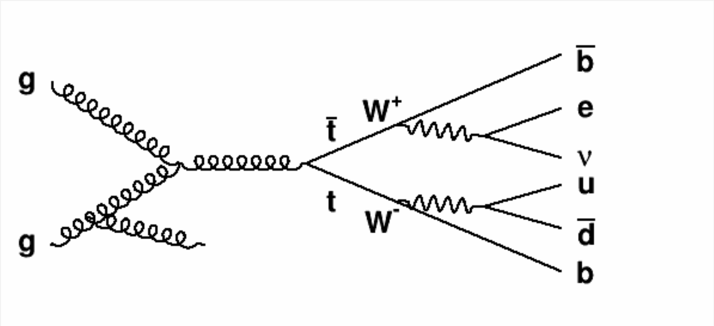




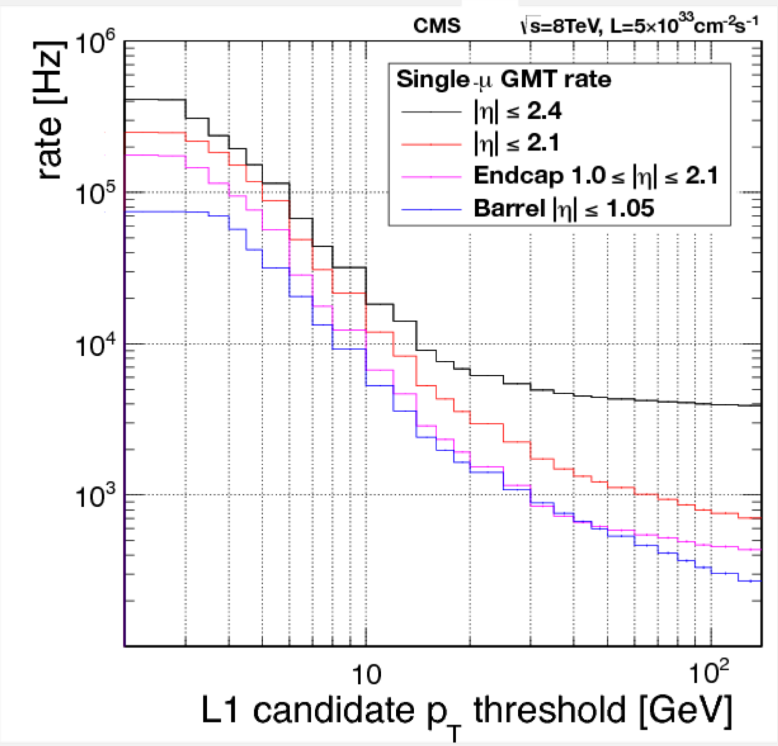


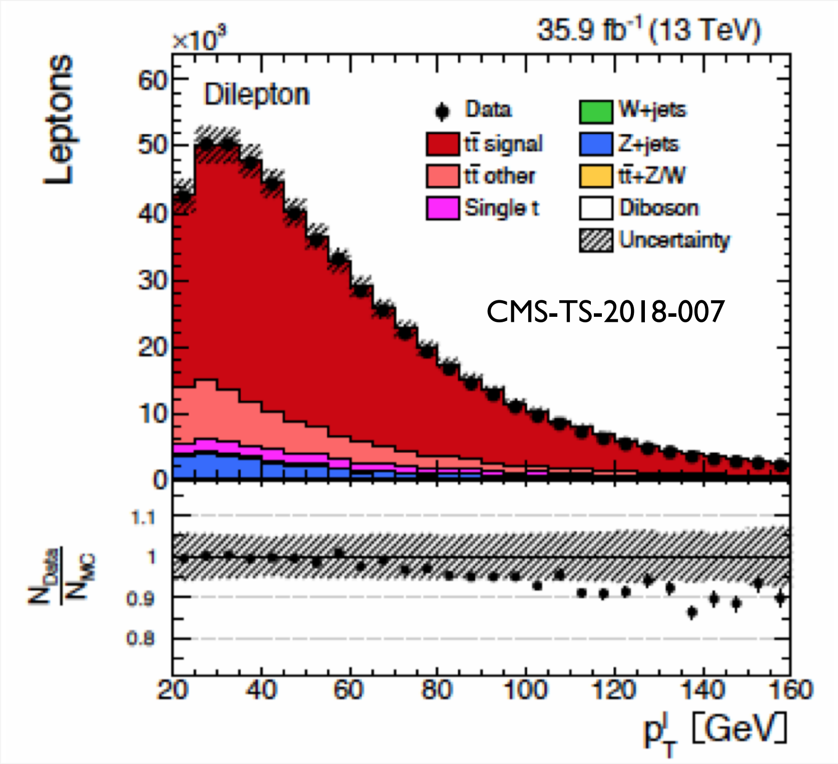
CMS looks similar if you take off your glasses

TRIGGER



Many improvements to the trigger. Perhaps the most interesting is the addition of tracking trigger.

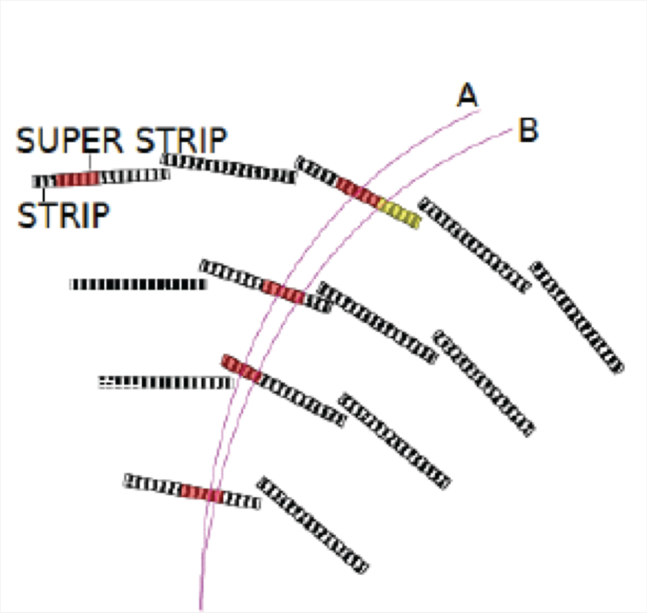


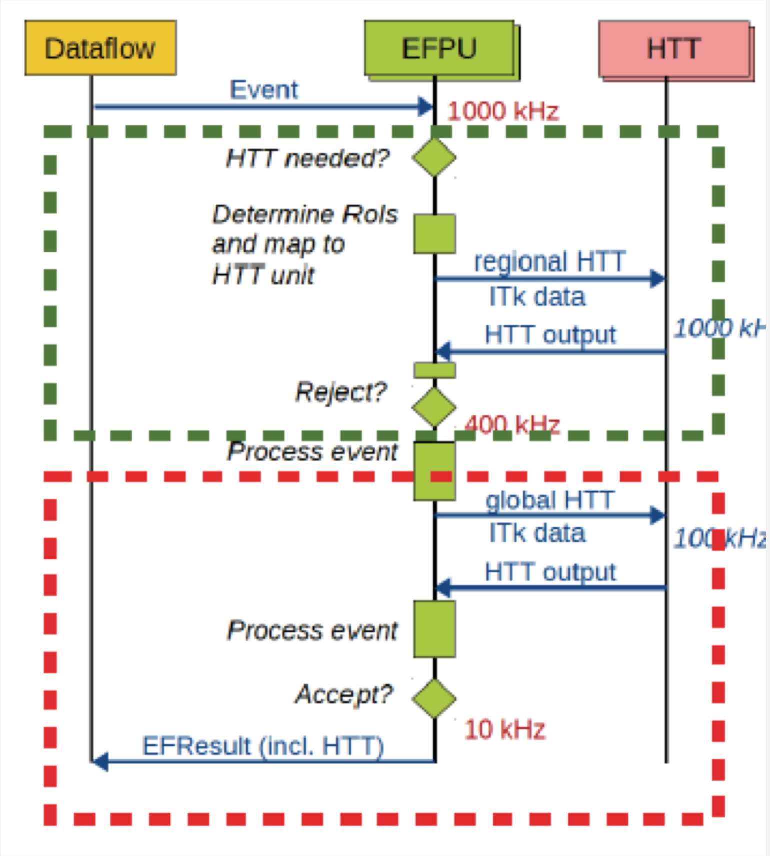


TRIGGER

ATLAS

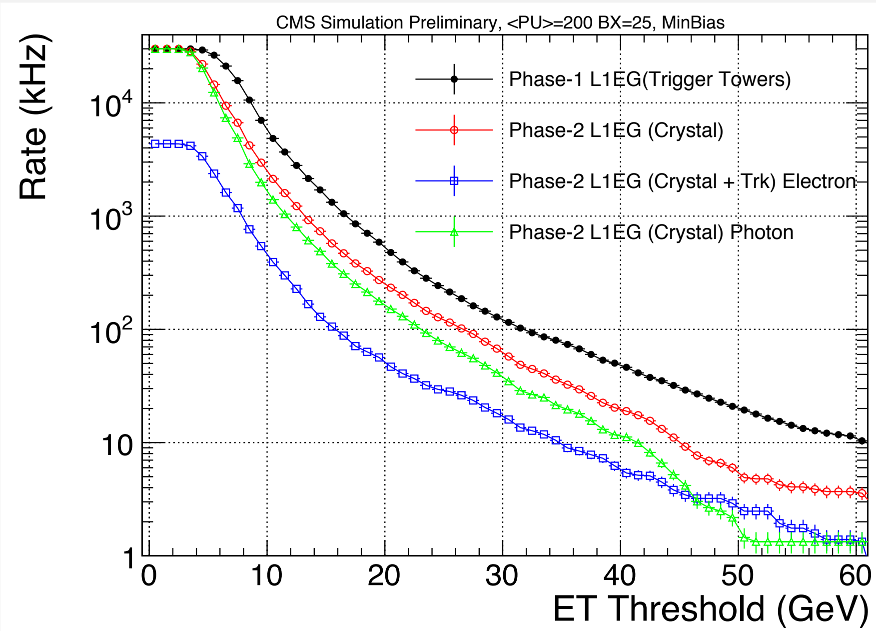
- Hardware trigger after level 1 after **LS2**
- Hardware tracking using full silicon readout after level 1 after **LS3**
- Possible regional tracking at L0
- Full calorimeter granularity at level 1





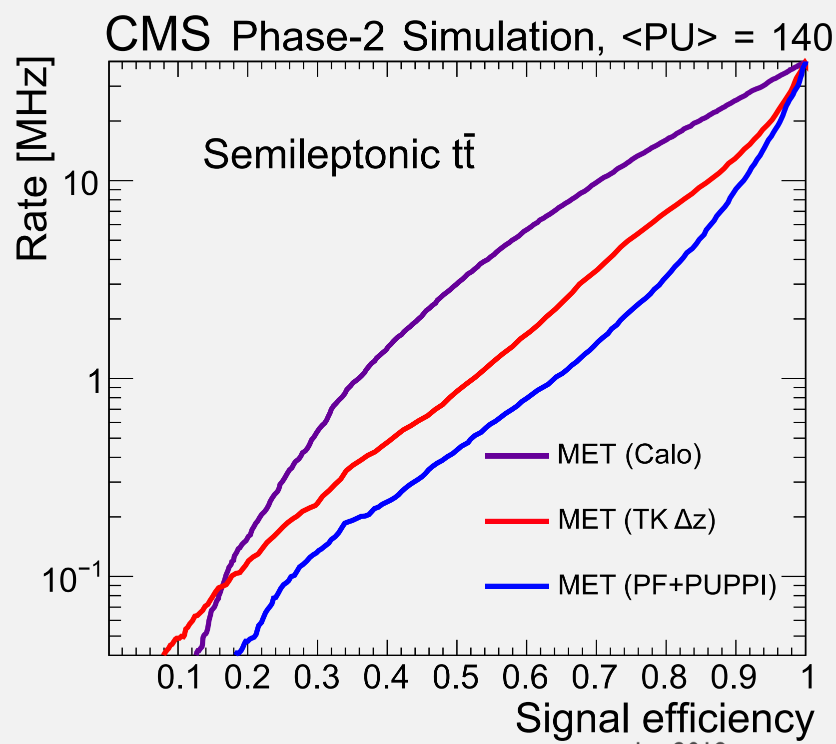
CMS will have one as well after LS3.

RATES



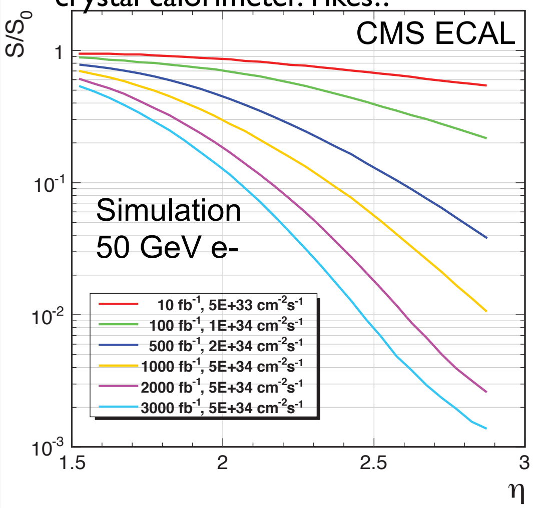
Track trigger can bring substantial improvements to electron and MET triggers.

Red is track only

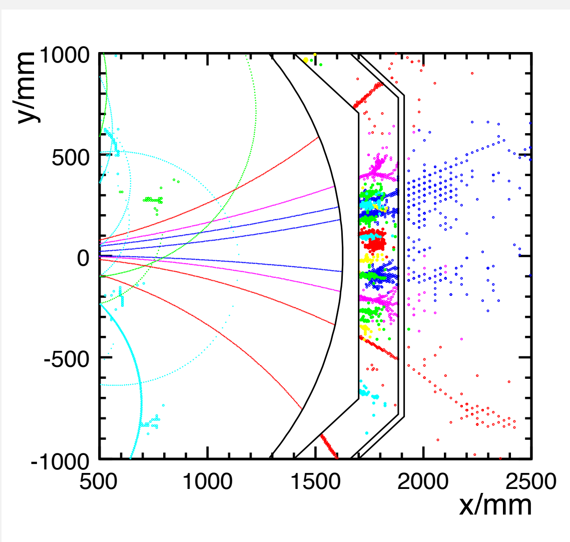


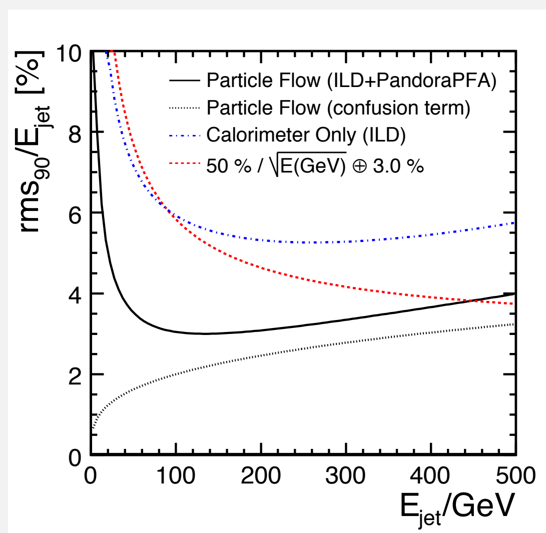
CMS ENDCAP CALORIMETER

Light output reduction of crystal calorimeter. Yikes!!



Replace with a detector inspired by work of CALICE collaboration (https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome) and "Particle Flow Calorimetry and the PandoraPFA Algorithm arXiv:0907.3577





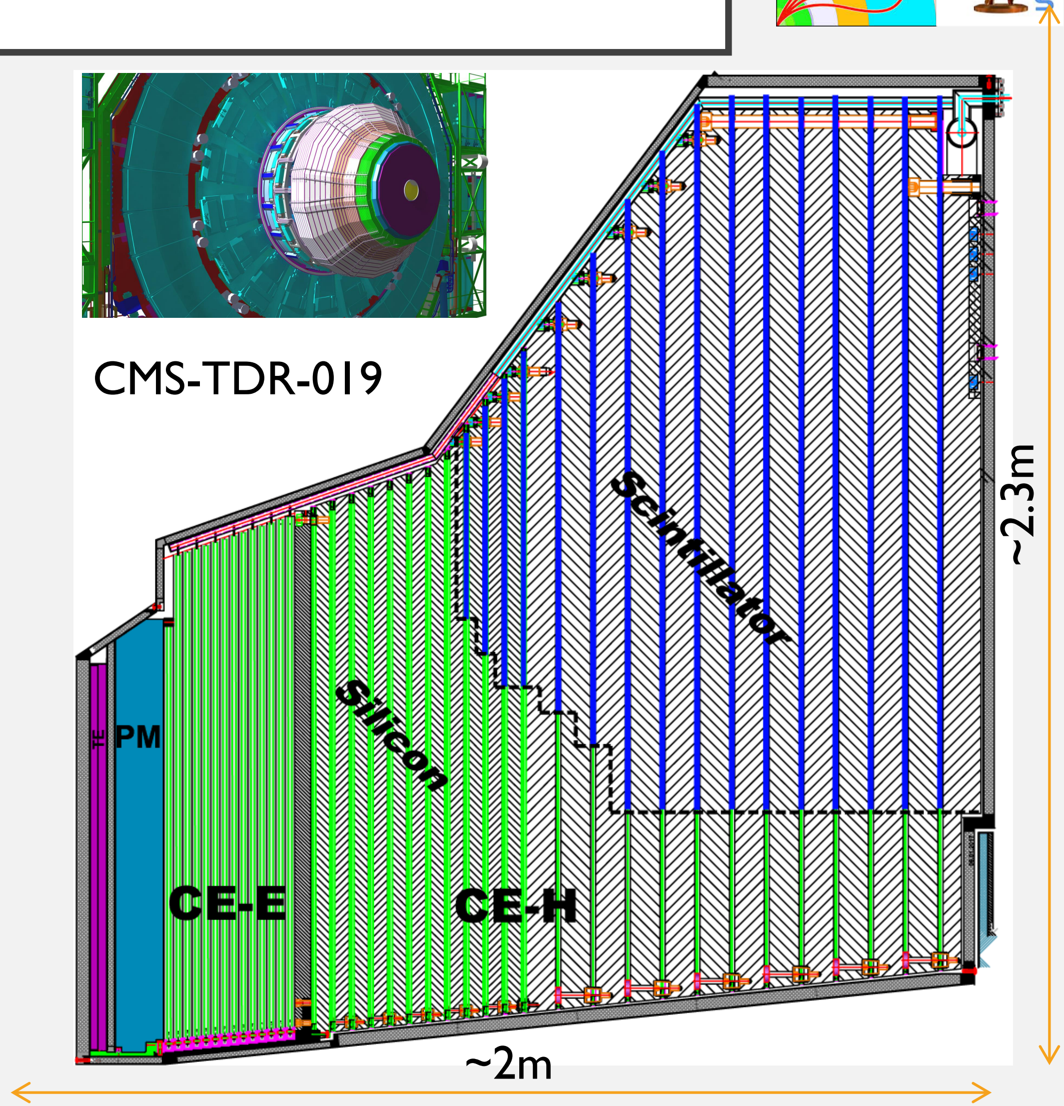
HGCAL

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:

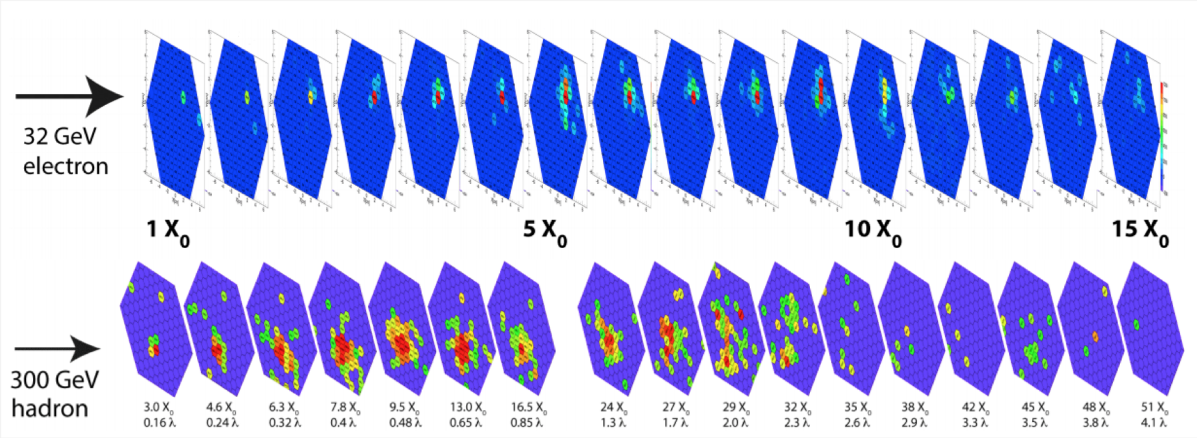
- CE covers $1.5 < \eta < 3.0$
- ~215 tonnes per endcap
- Full system maintained at -30°C
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M si channels, 0.5 or 1 cm^2 cell size
- ~27000 si modules
- Power at end of HL-LHC: ~110 kW per endcap

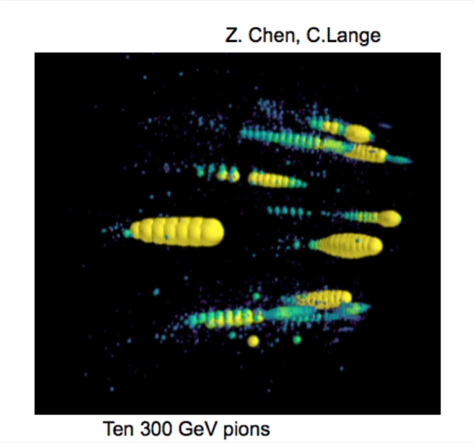


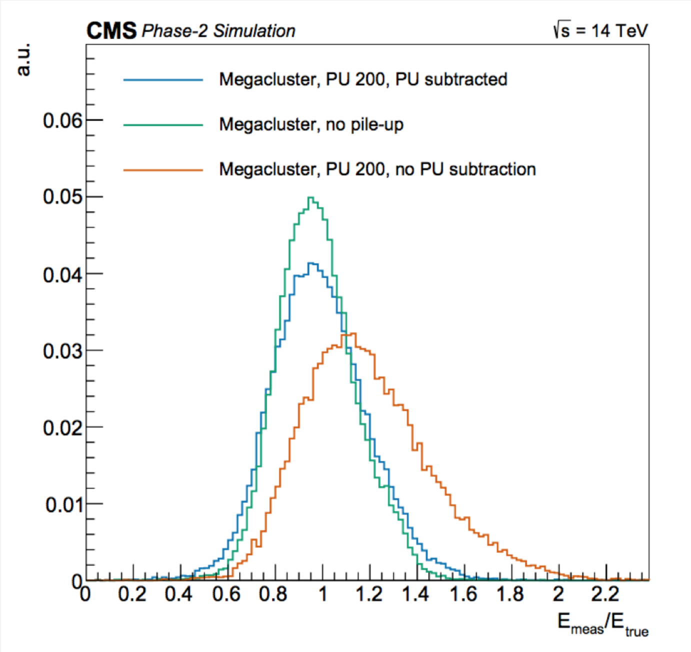
Electromagnetic calorimeter (C**E-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ

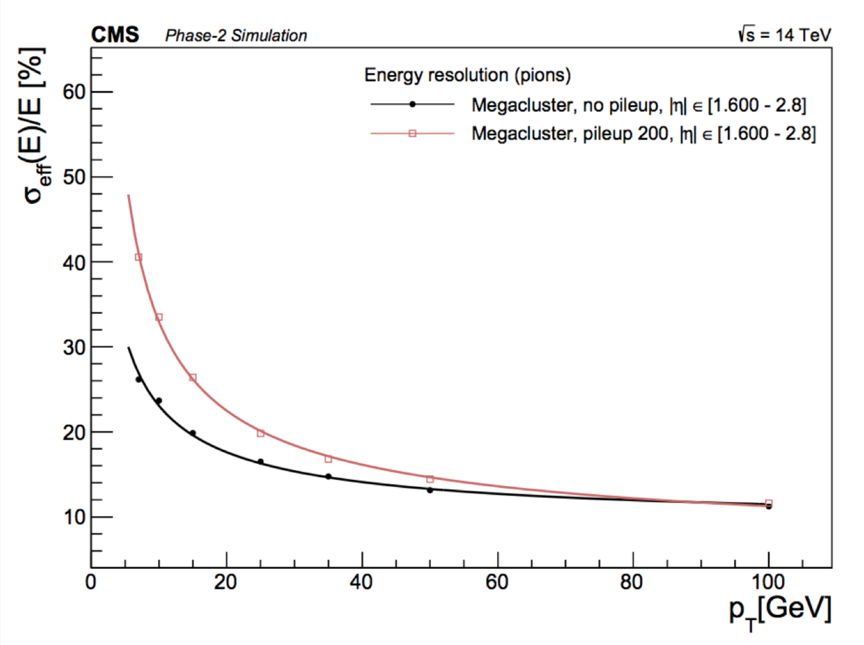
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 24 layers, ~8.5λ

HGCAL PERFORMANCE







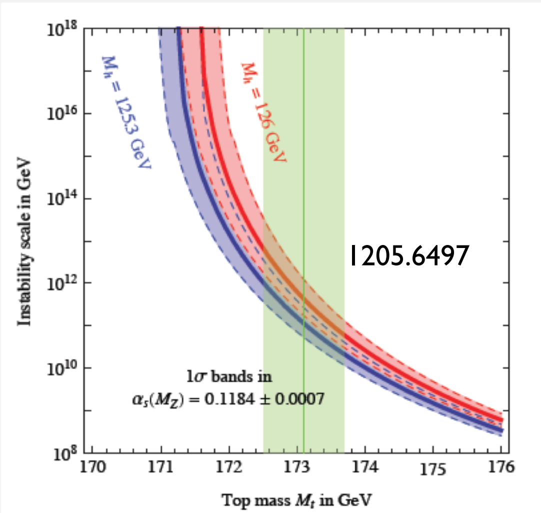


CONCLUSIONS

- HL-LHC
  - Many prototypes of HL-LHC magnets already working well.
  - Crab cavity rotation of proton beam demonstrated this summer
  - HL-LHC construction started.
  - A coordinated international effort is making HL-LHC possible
- Experiments
  - Will have exciting new timing detectors for pileup reduction
  - Track triggers will maintain thresholds and allow triggering of new signatures
  - Extended tracking coverage will improve particle ID close to beam pipe
  - A high granularity calorimeter will be part of CMS
- Physics
  - HL-LHC will enable more precise tests of standard model and significant improvement of reach for new physics

BACKUP

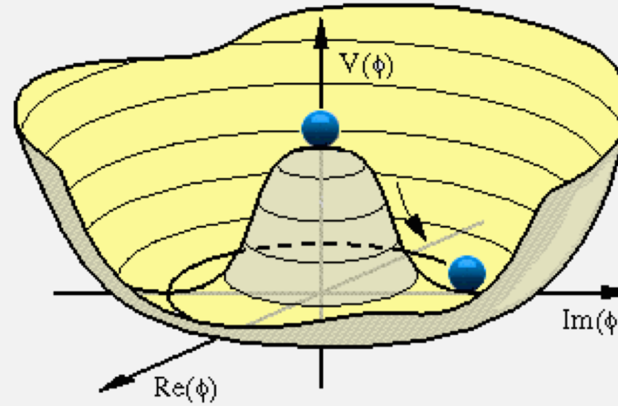
TOP MASS



$$V = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$M_W = \frac{1}{2}gv \quad M_Z = \frac{1}{2}g_Z v \quad m_H = \sqrt{-2\mu^2}$$



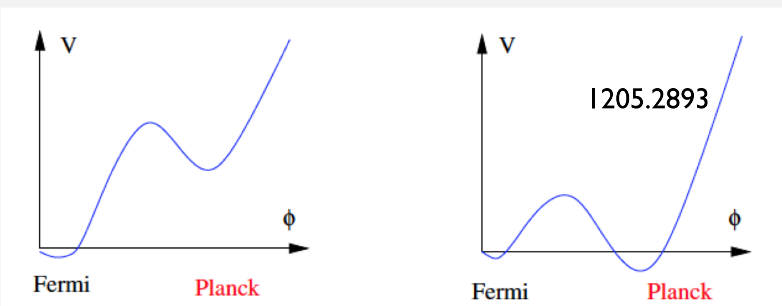
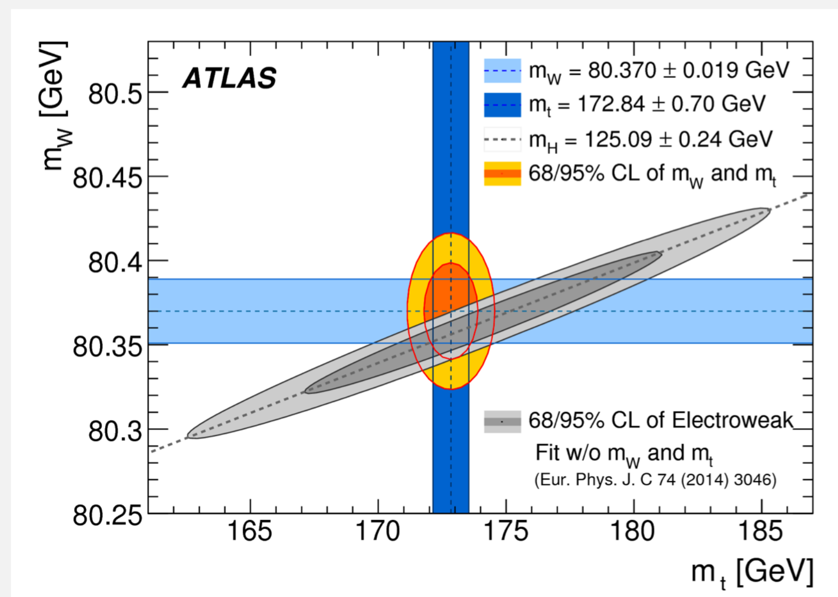


Figure 2. Schematic depiction of the SM effective potential V for the Higgs field for $M_H > M_{\min}^{\text{stability}}$ (left) and $M_H < M_{\min}^{\text{stability}}$ (right).



Systematic uncertainty relating MC top mass used in fitting to one corresponding to a well defined renormalization scheme/pole mass O(few hundred Mev)

HE-LHC

MAGNETS

What if the new high field technology (16 Tesla field) developed for the HL-LHC quadrupoles were used for dipoles?

$$p \propto B$$

$$\sqrt{s} = \left(\frac{16}{8.4}\right) 14 = 27\ TeV$$

- And, while you are replacing everything, upgrade instantaneous luminosity by x4
- So can shoot for 14 ab^{-1} over 20 years
- *Technically*, could start in 2040

HE-LHC

FCC-pp collider 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		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	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	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36