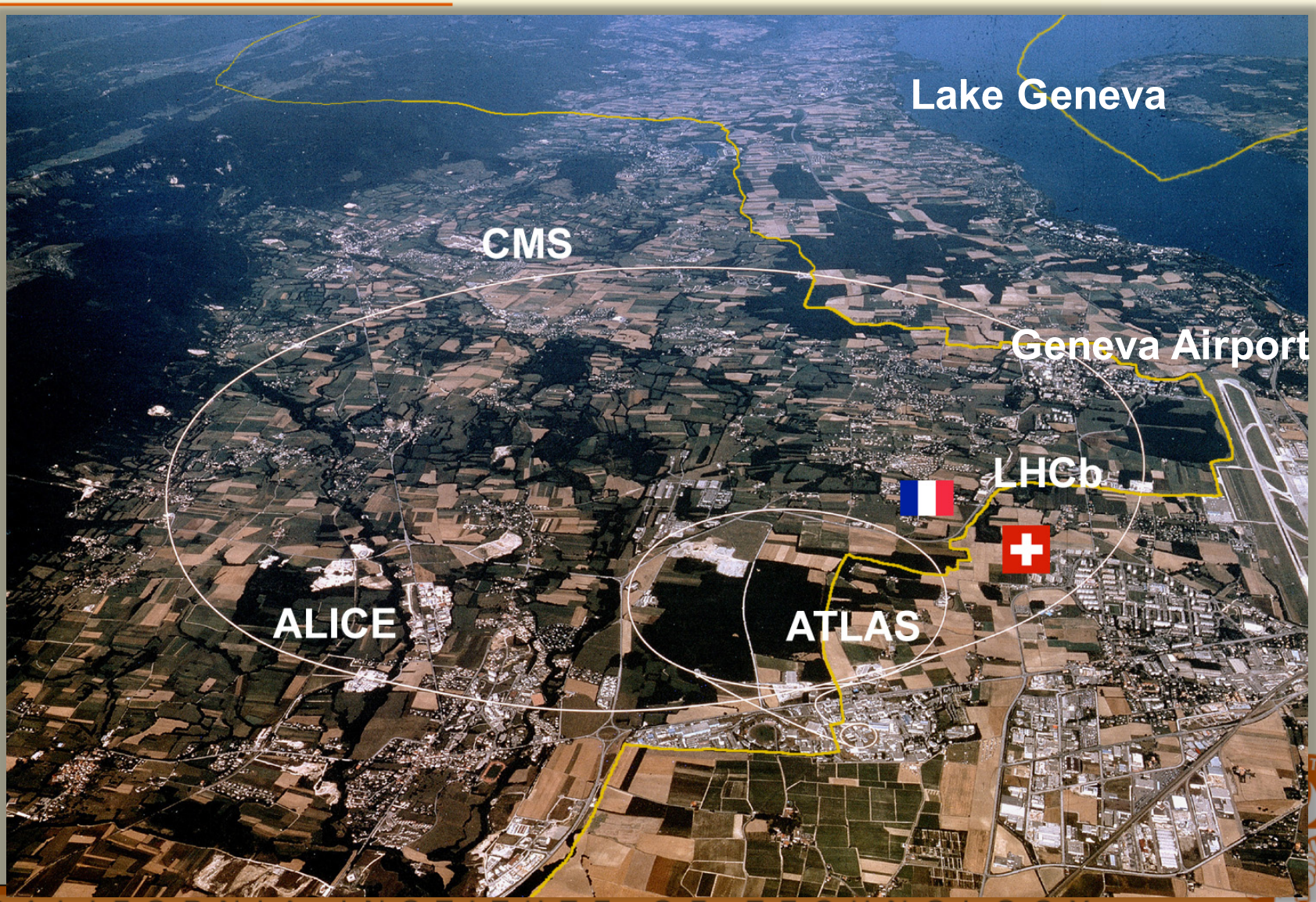
First Results and Prospects from CMS at 13 TeV

Artur Apresyan

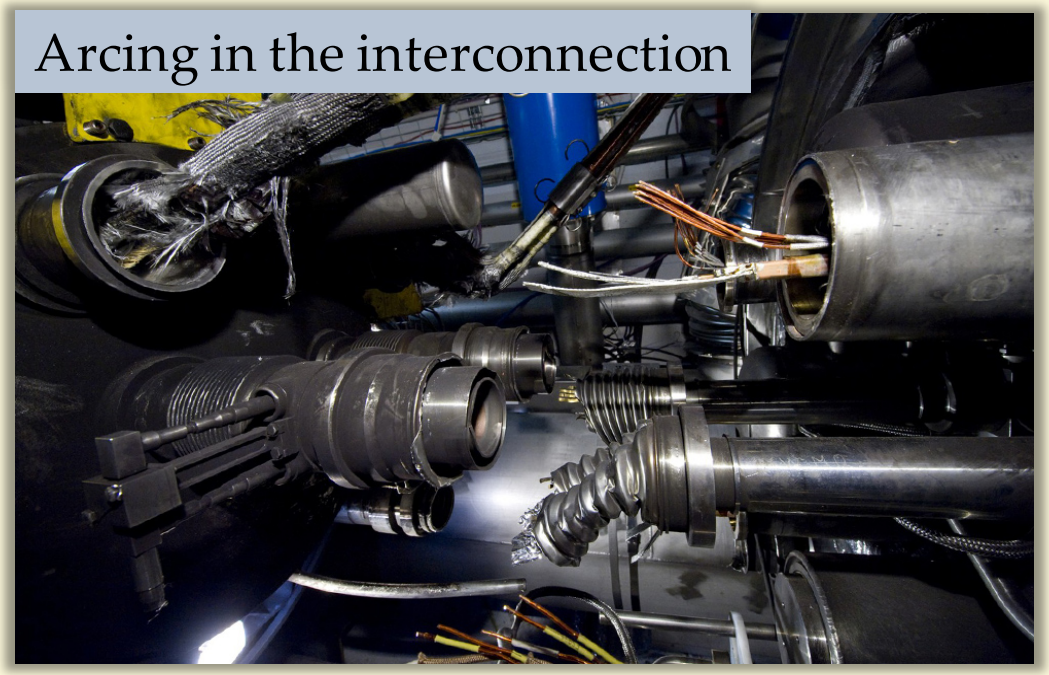
California Institute of Technology

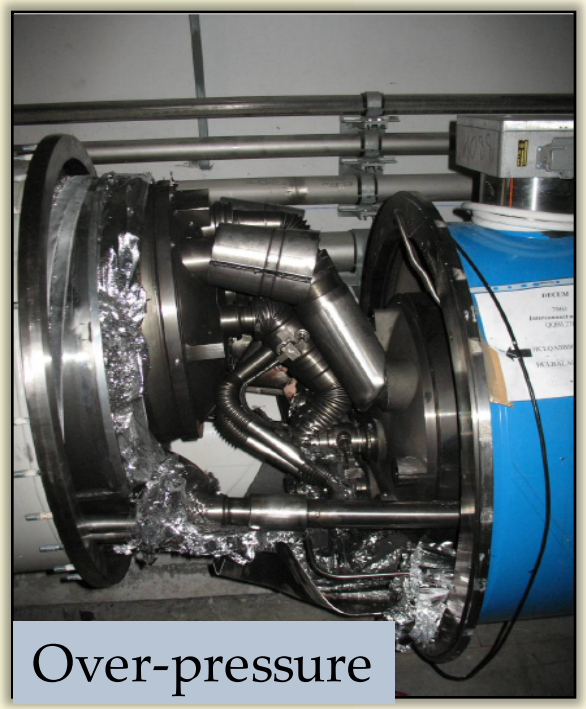
Large Hadron Collider



Large Hadron Collider

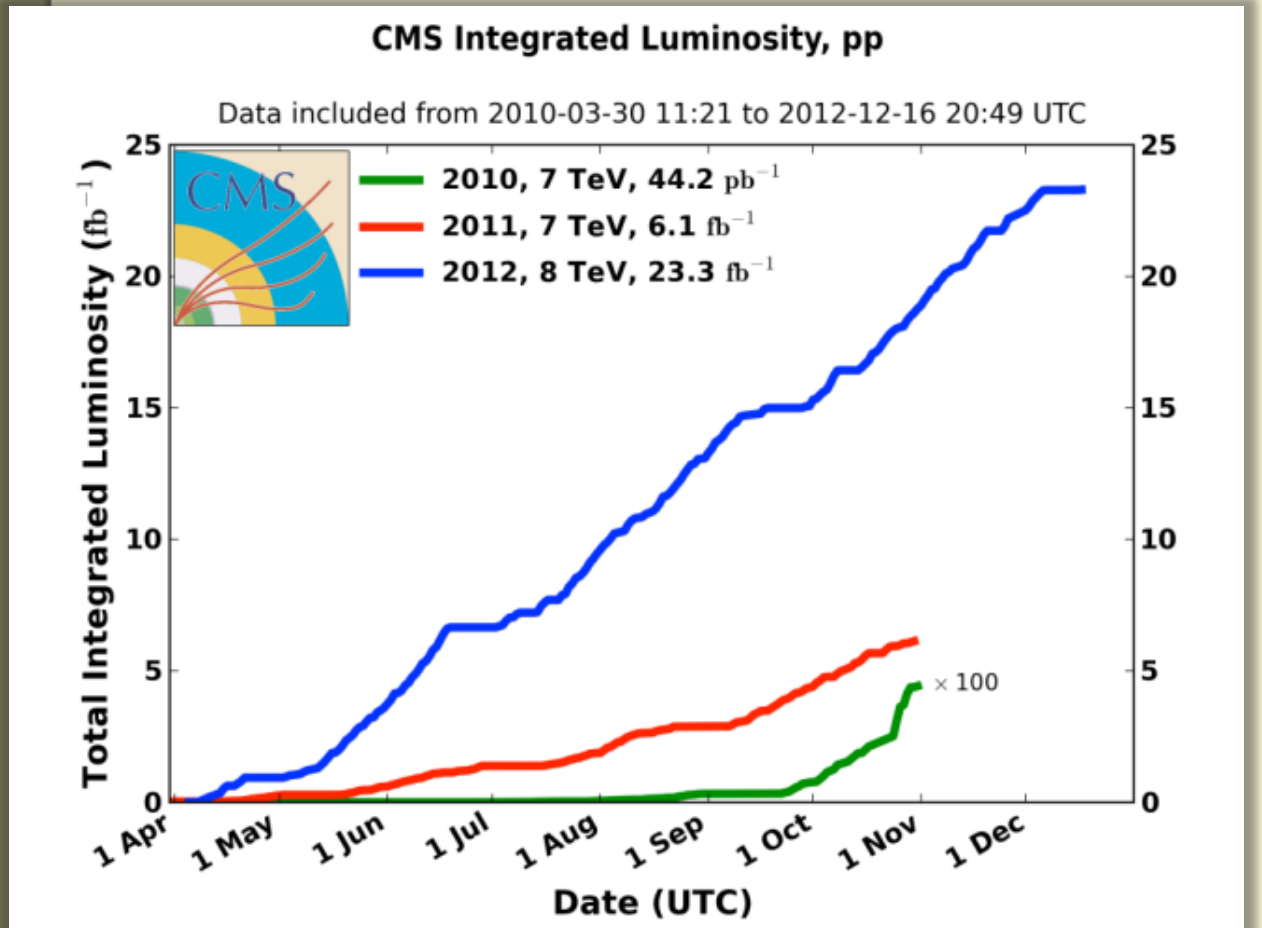
- The LHC started operations in September 2008


Arcing in the interconnection


Over-pressure

- **After ~ 1 year of repairs, LHC restarts in 2010**
  - **$\sqrt{s}$ = 7 TeV in 2010, 2011, and $\sqrt{s}$=8 TeV in 2012**

LHC 2010-2012



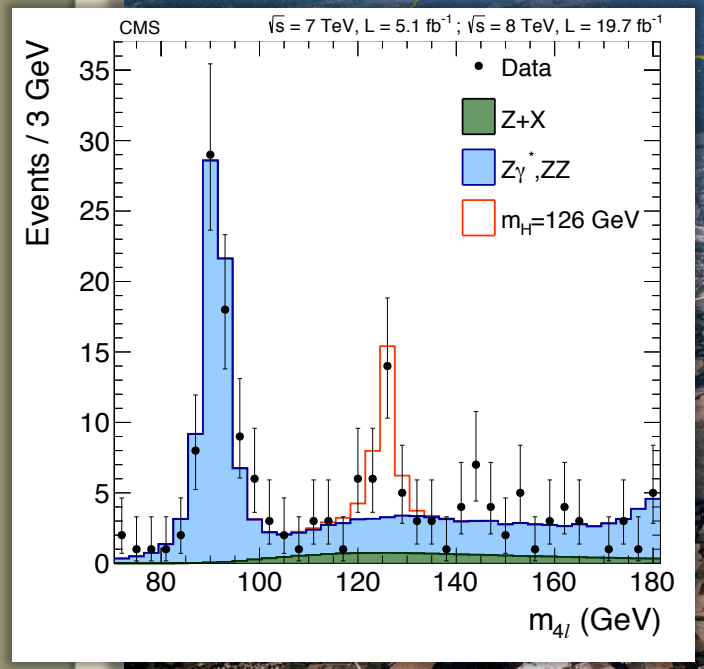
2010: 0.04 fb^{-1}
$\sqrt{s}$ = 7 TeV
commissioning

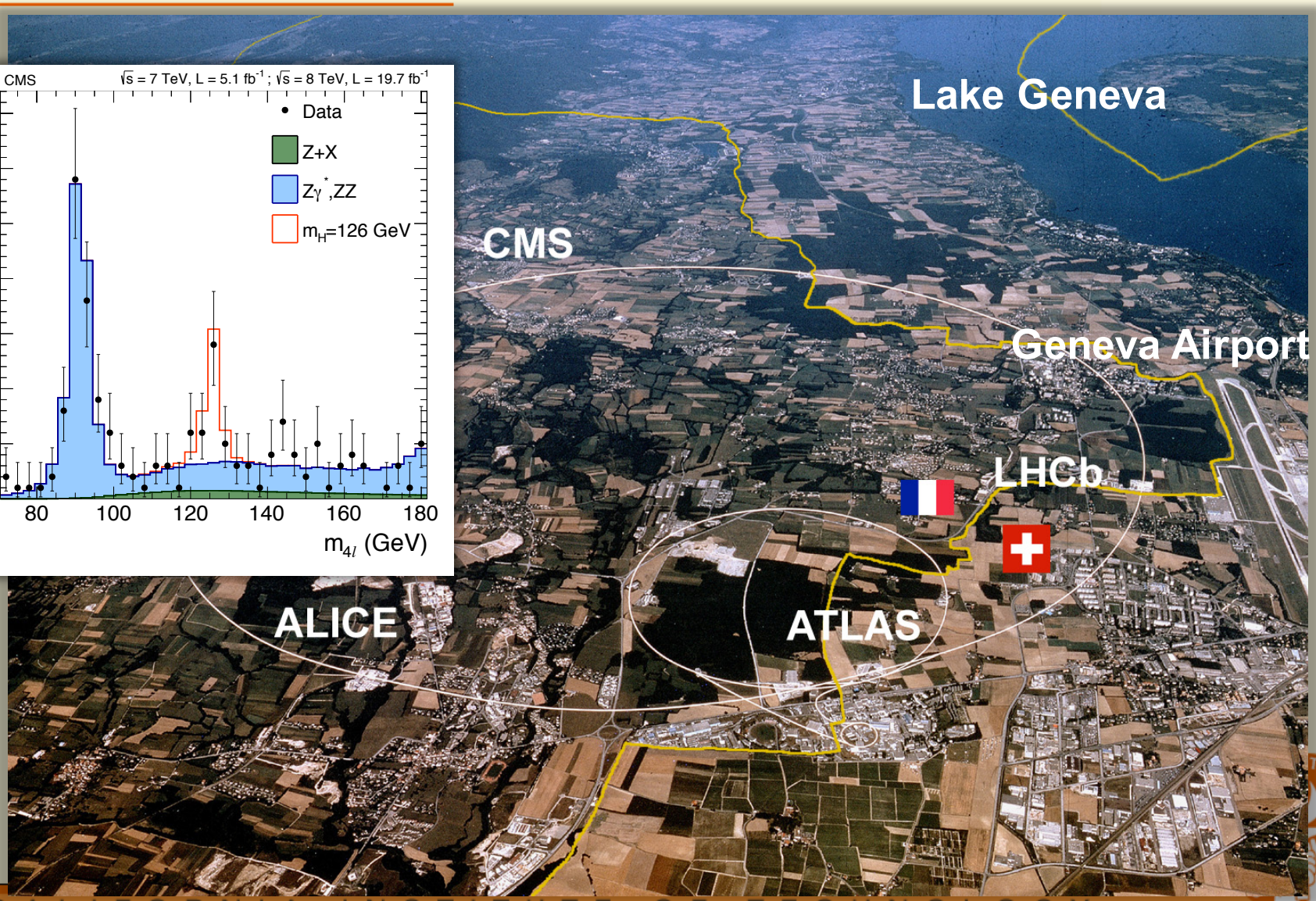
2011: 6.1 fb^{-1}
$\sqrt{s}$ = 7 TeV
… exploring limits

2012: 23.3 fb^{-1}
$\sqrt{s}$ = 8 TeV
… production

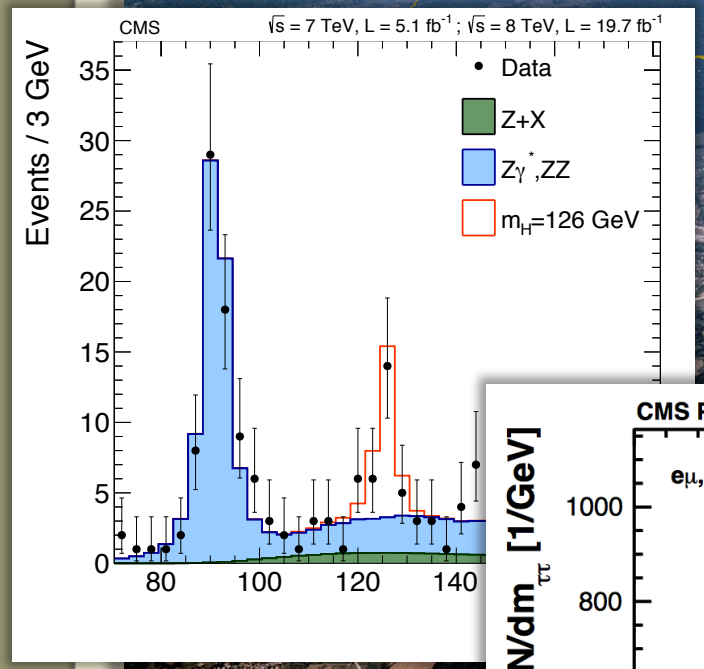
Peak luminosity: **~280 pb^{-1}/day**

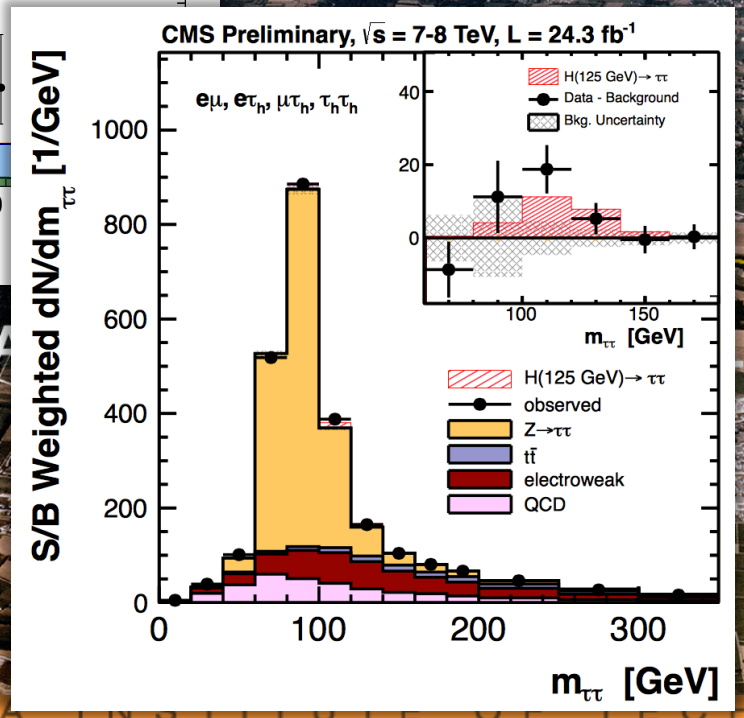
Discoveries at CMS



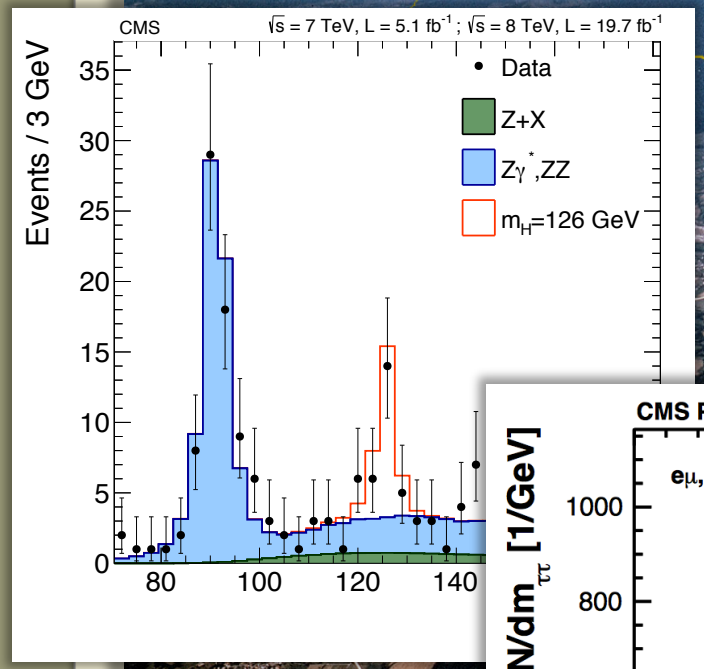


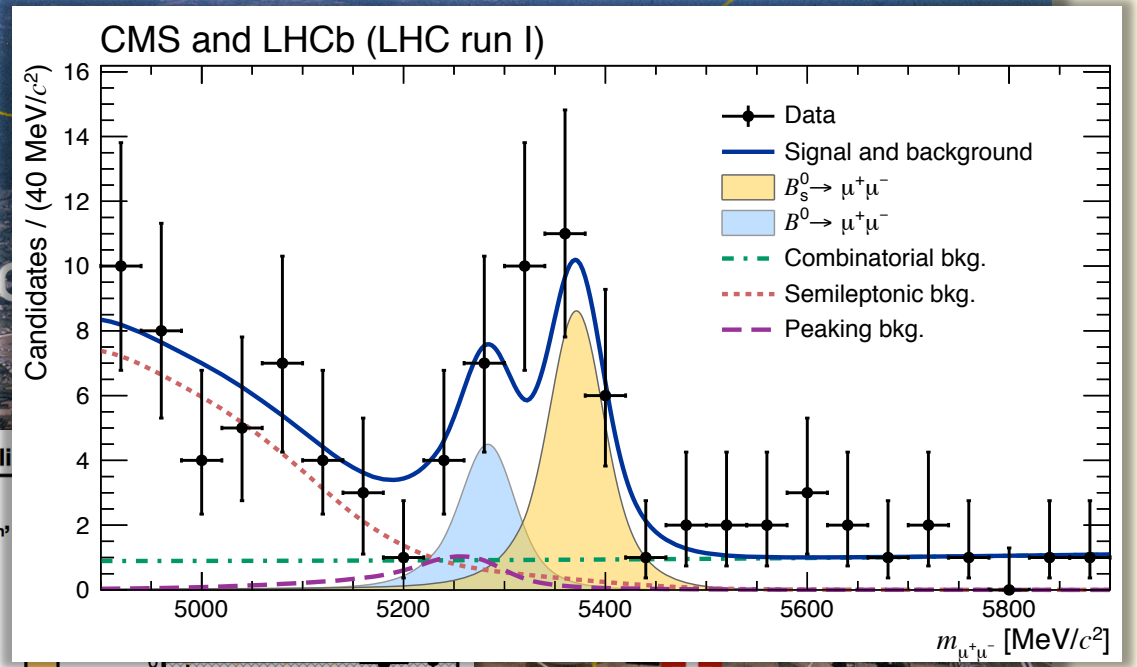
Discoveries at CMS

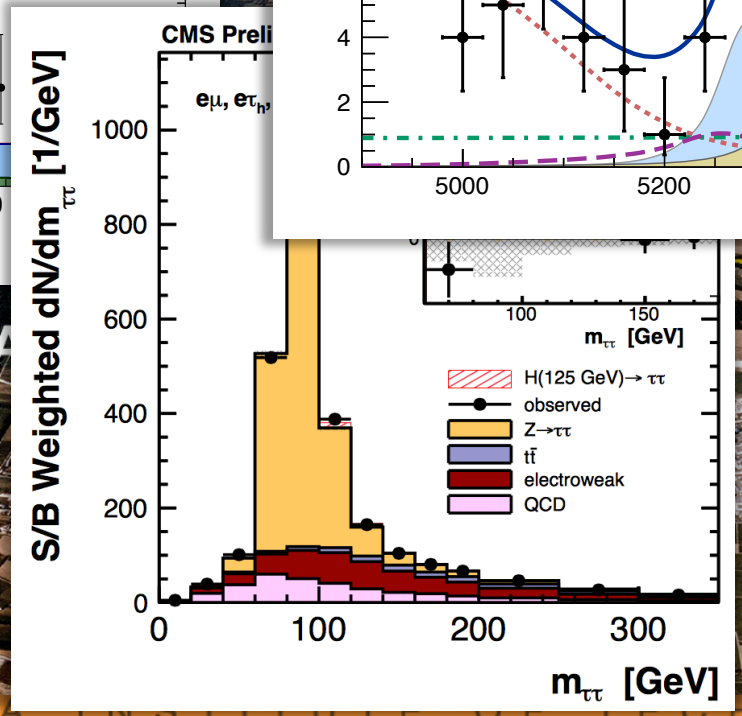




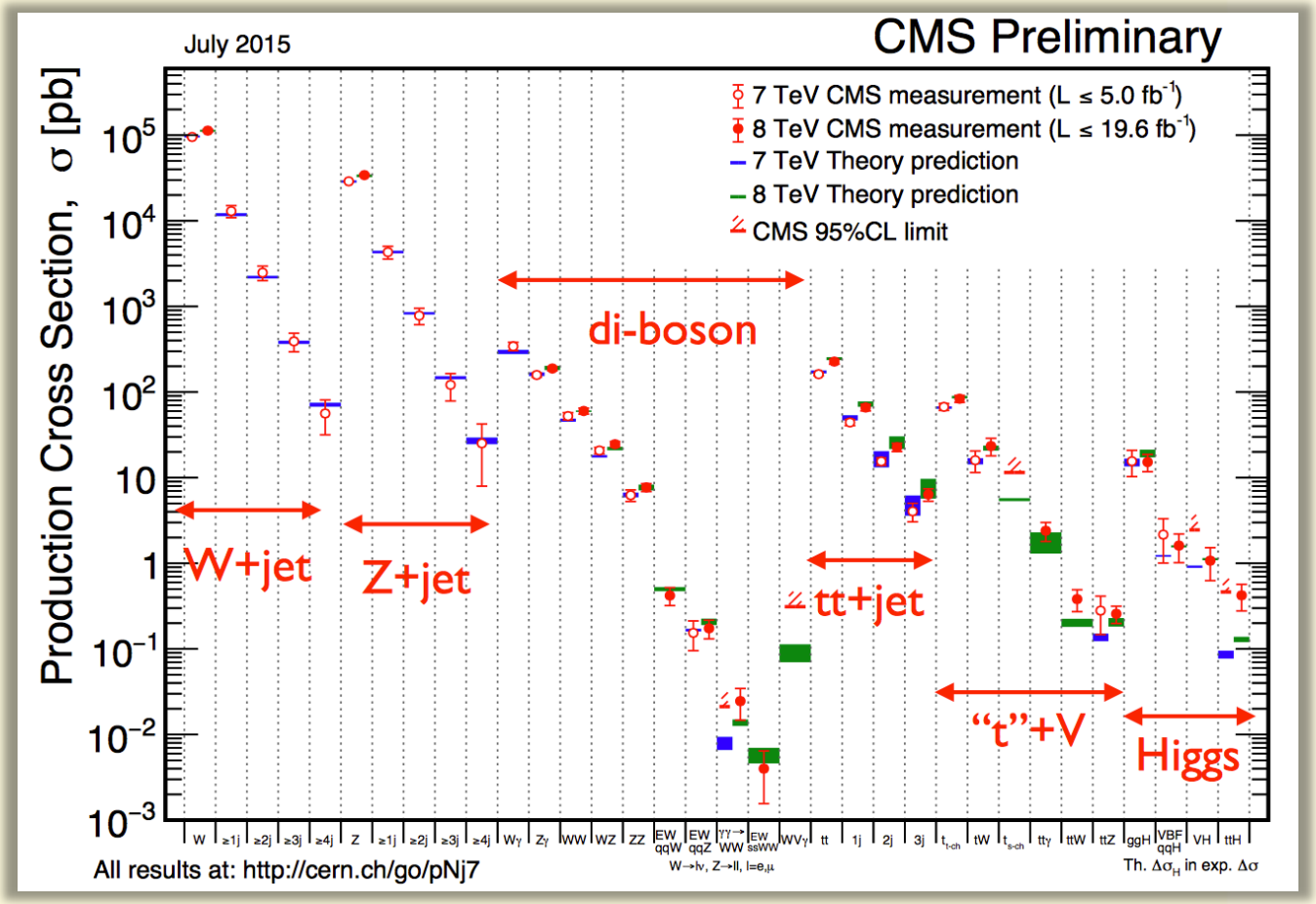
Discoveries at CMS





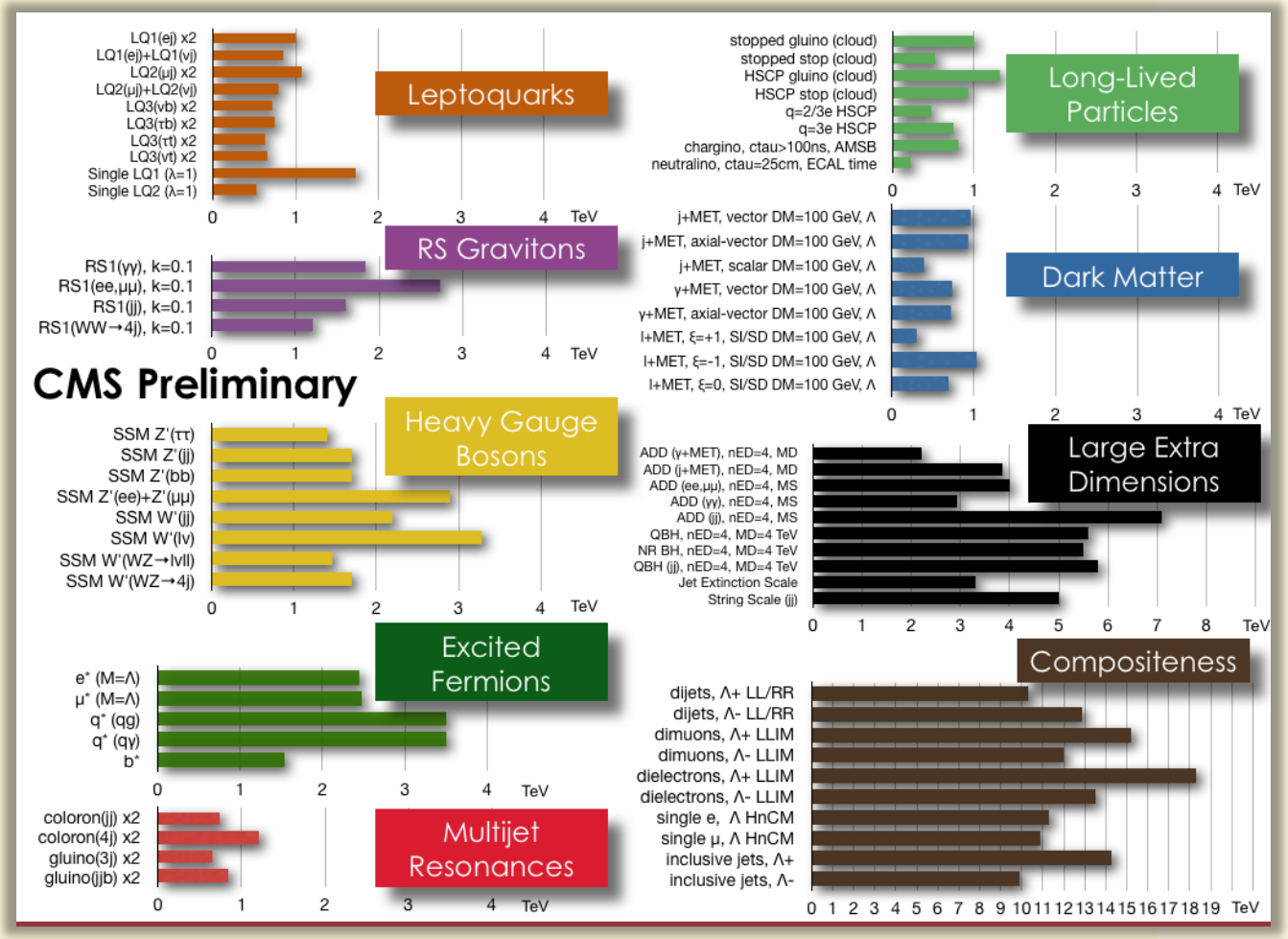


CMS Run 1 Legacy



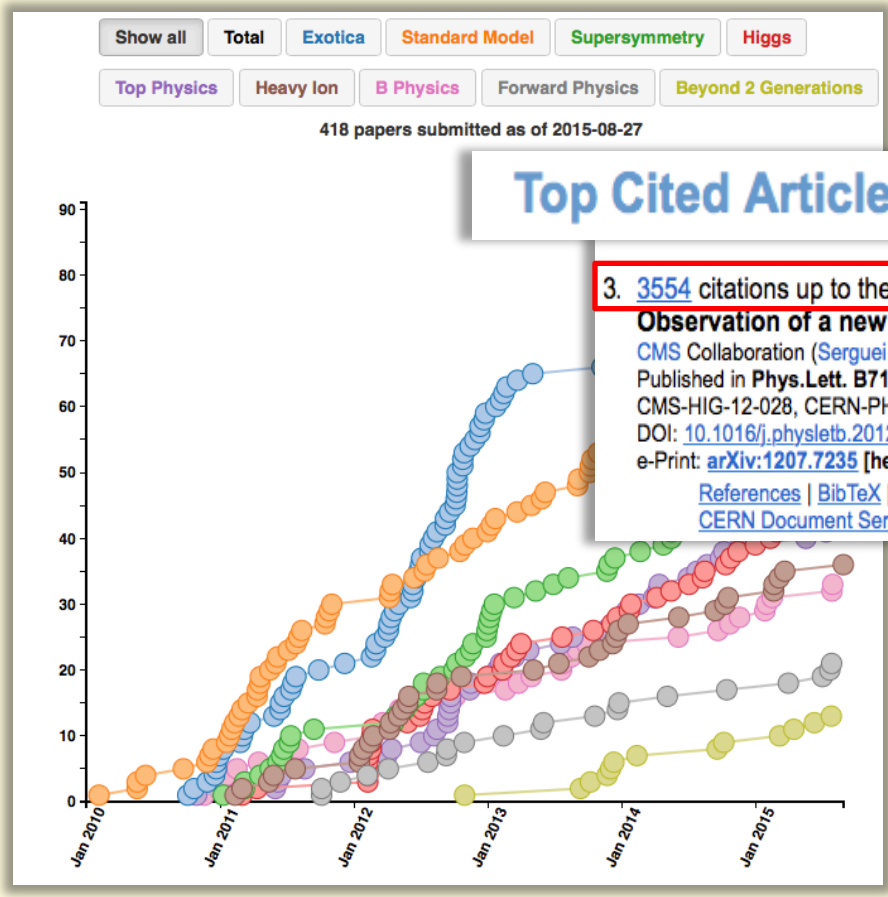
Standard Model tested over a large range

CMS Run 1 Legacy



A broad program of BSM searches

CMS Run 1 Legacy



Top Cited Articles of All Time (2014 edition) in hep-ex

3. 3554 citations up to the end of 2014

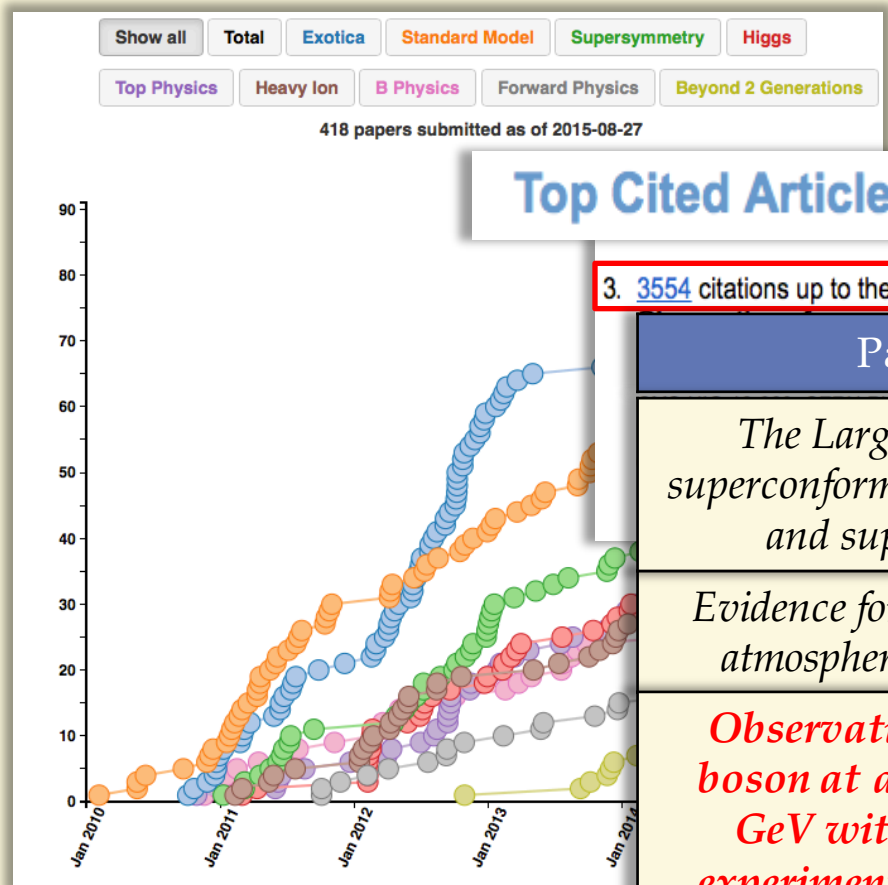
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 42 pp.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE; Interactions.org article

More than 400 publications on √s=7+8 data, and counting

CMS Run 1 Legacy



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Paper	Year	Citations/Age
The Large N limit of superconformal field theories and supergravity	1999	10,193
Evidence for oscillation of atmospheric neutrinos	1998	3,942
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC	**2012**	**3,533**

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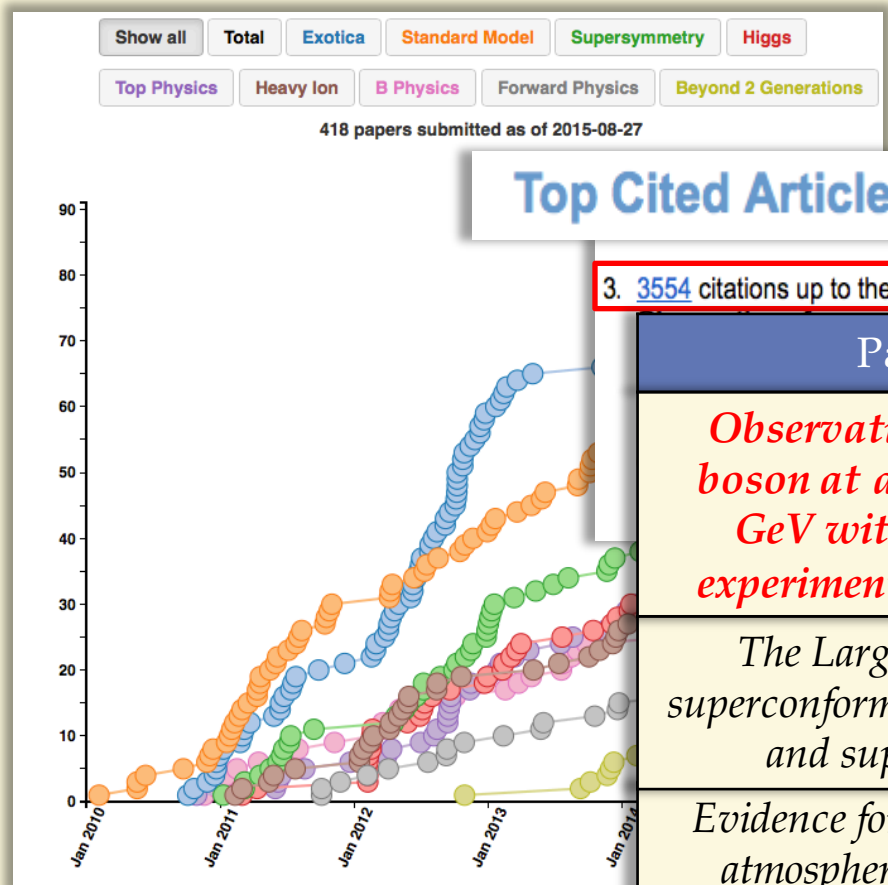
CMS Run 1 Legacy



Top Cited Articles of All Time (2014 edition) in hep-ex

3. 3554 citations up to the end of 2014

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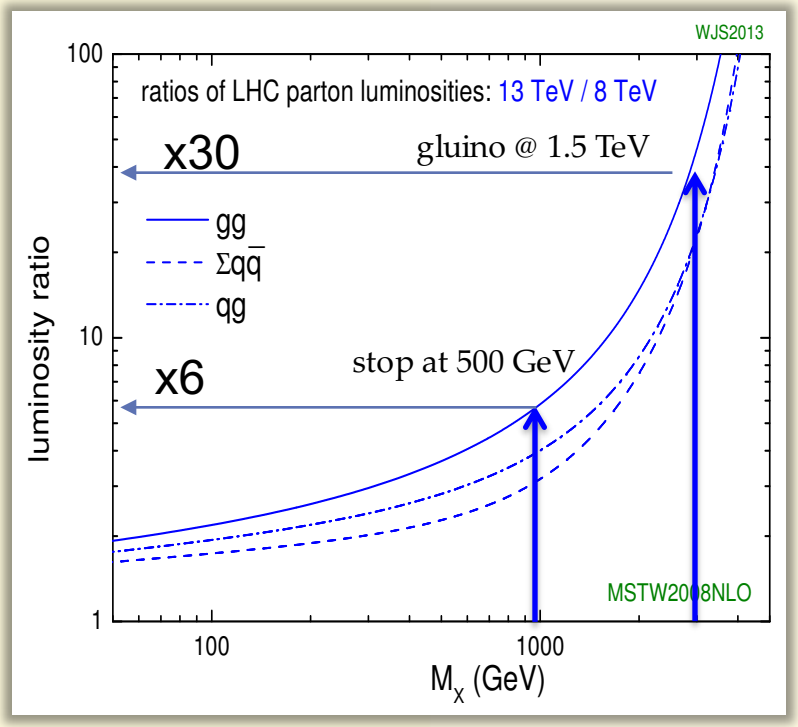
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC	**2012**	**3,533 /3 = 1178**
The Large N limit of superconformal field theories and supergravity	1999	10,193 /16 = 637
Evidence for oscillation of atmospheric neutrinos	1998	3,942 /17 = 232

More than 400 publications on √s=7+8 data, and counting

What's new in Run 2

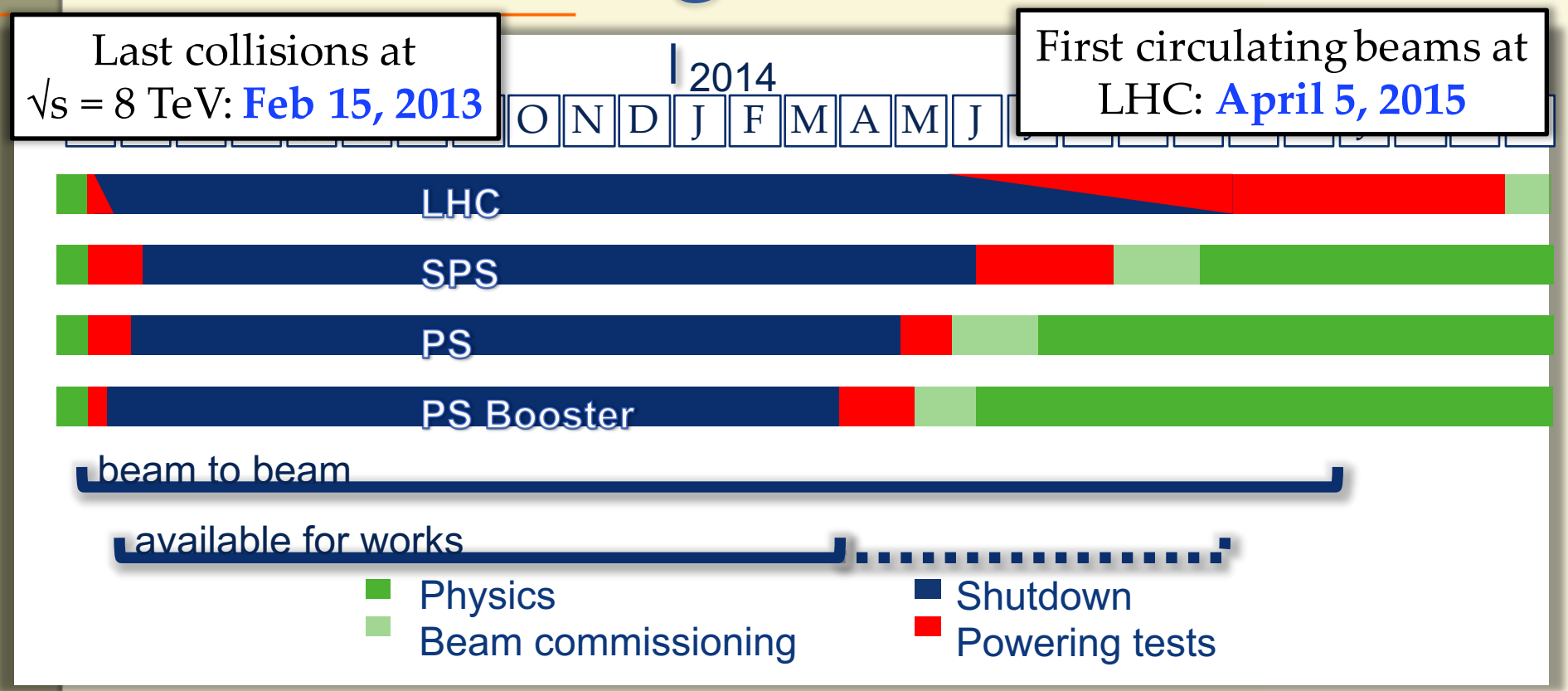
- Bring LHC to design parameters
  - Increase **√s to 14 TeV**
  - **25ns** bunch spacing, compared to **50 ns** in Run 1
  - Collect **~100fb^{-1}** by end of 2018



- Dramatically increase physics potential
  - **massive objects, SUSY, W'/Z'…**
  - Observe rare processes: **ttH, VBF…**
  - Precision studies: **Higgs, top…**

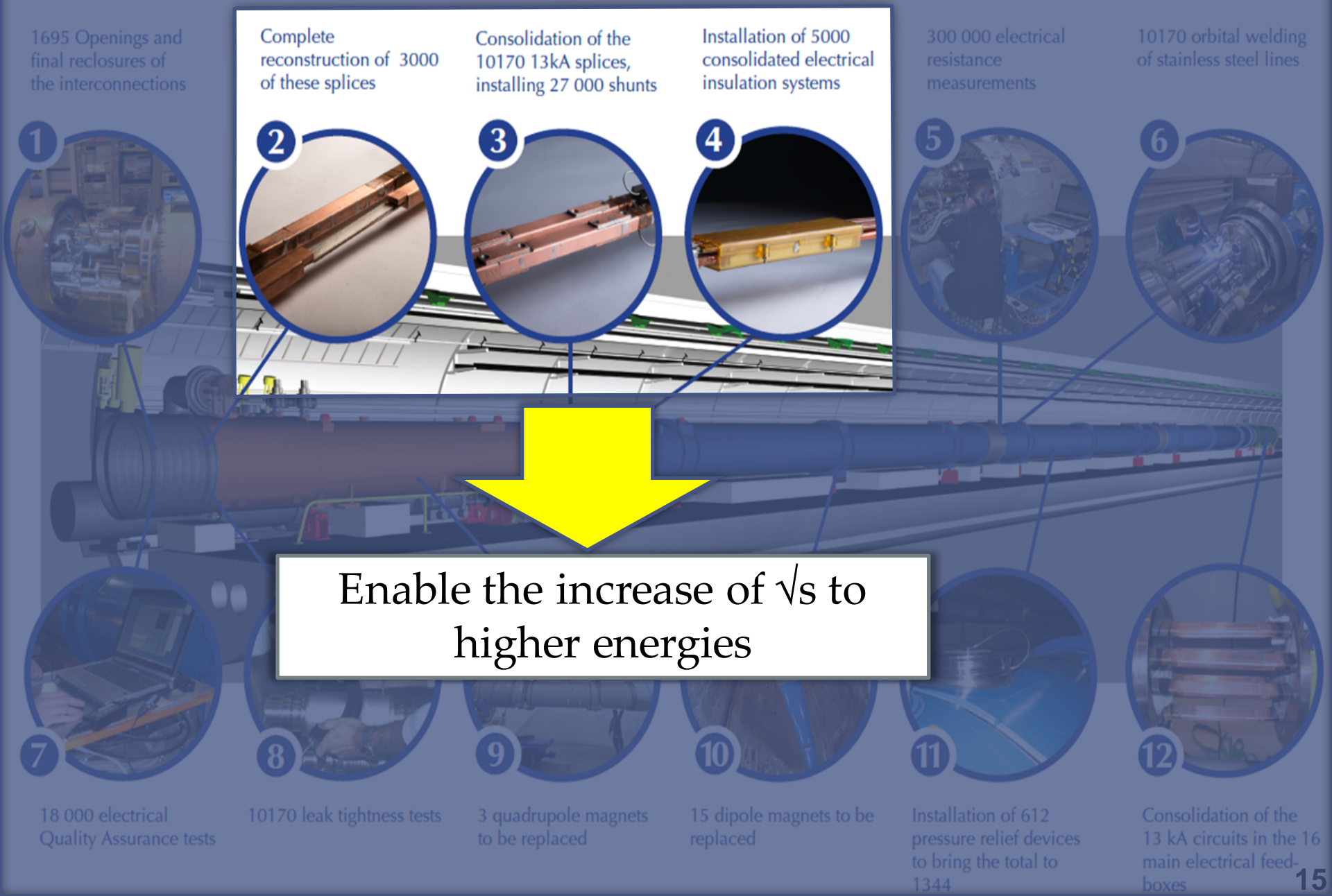
Major efforts across machine and experiments to exploit the full potential

LHC Long Shutdown 1



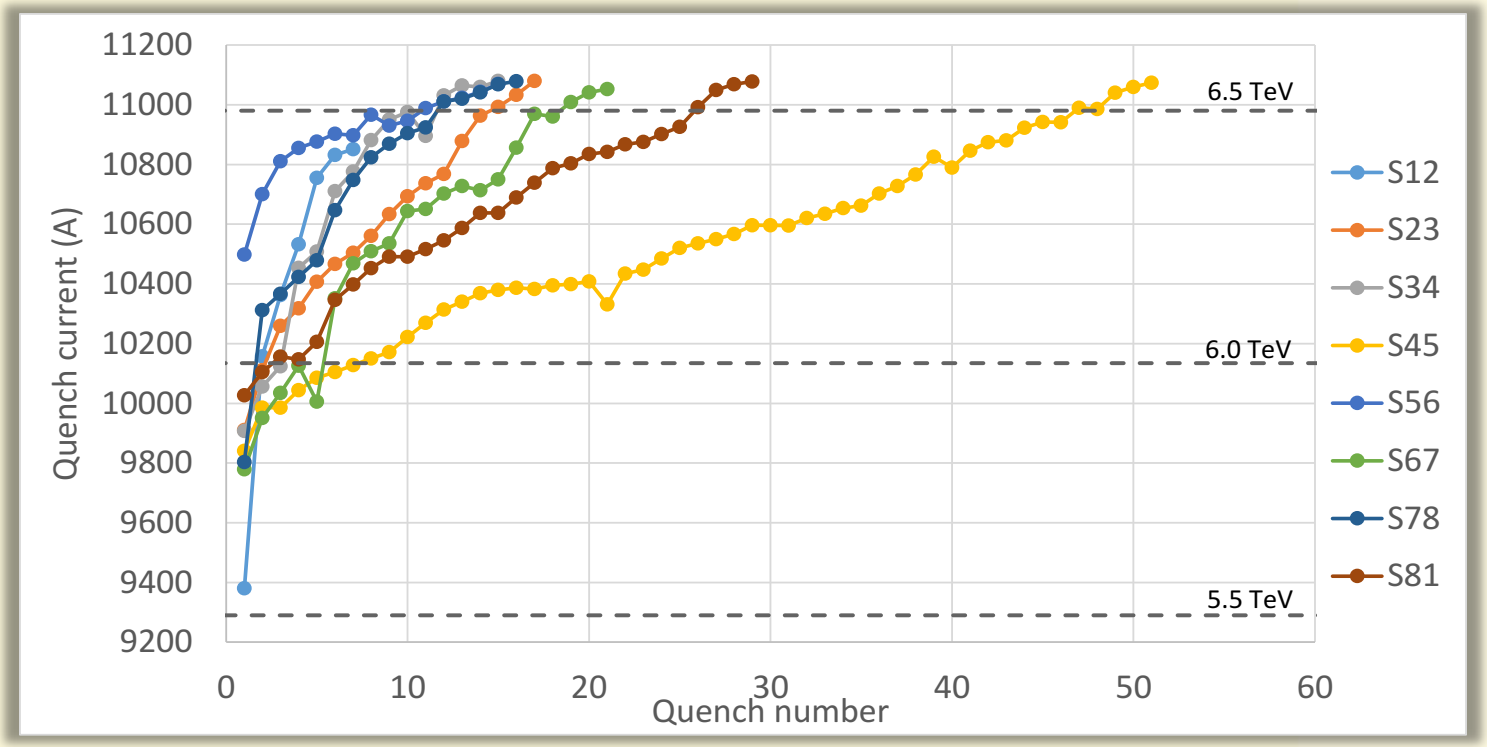
Prepare LHC for nominal operation at 14 TeV
Consolidate, upgrade the LHC and injector performance

The main 2013-14 LHC consolidations



Enable the increase of √s to higher energies

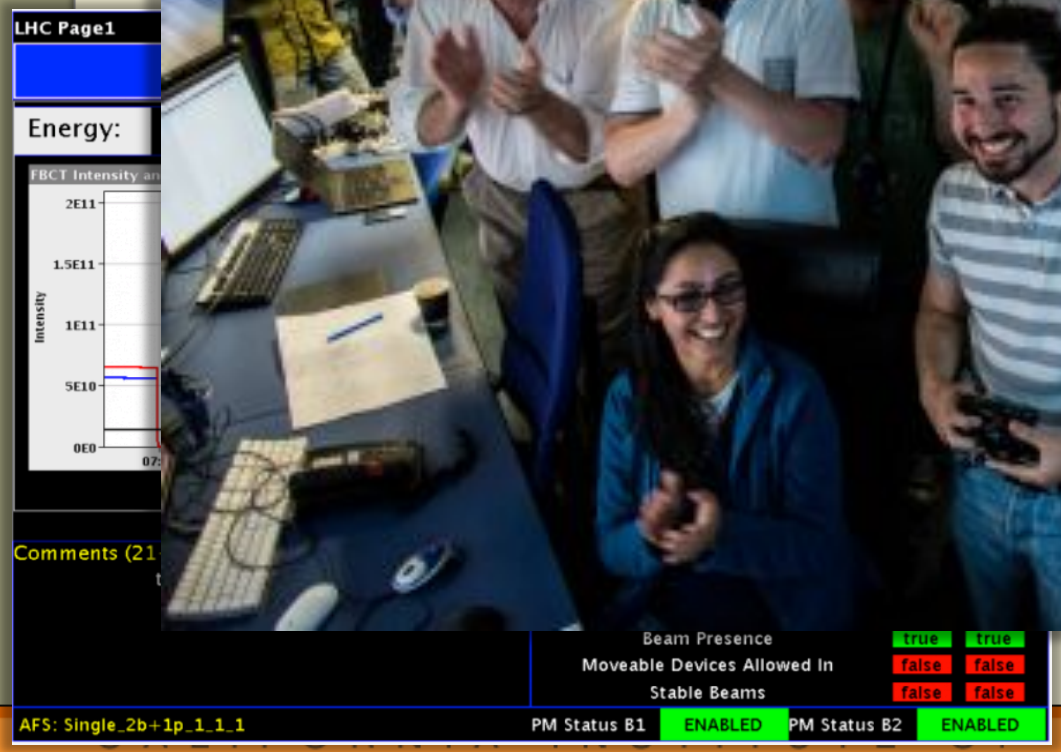
Dipole training



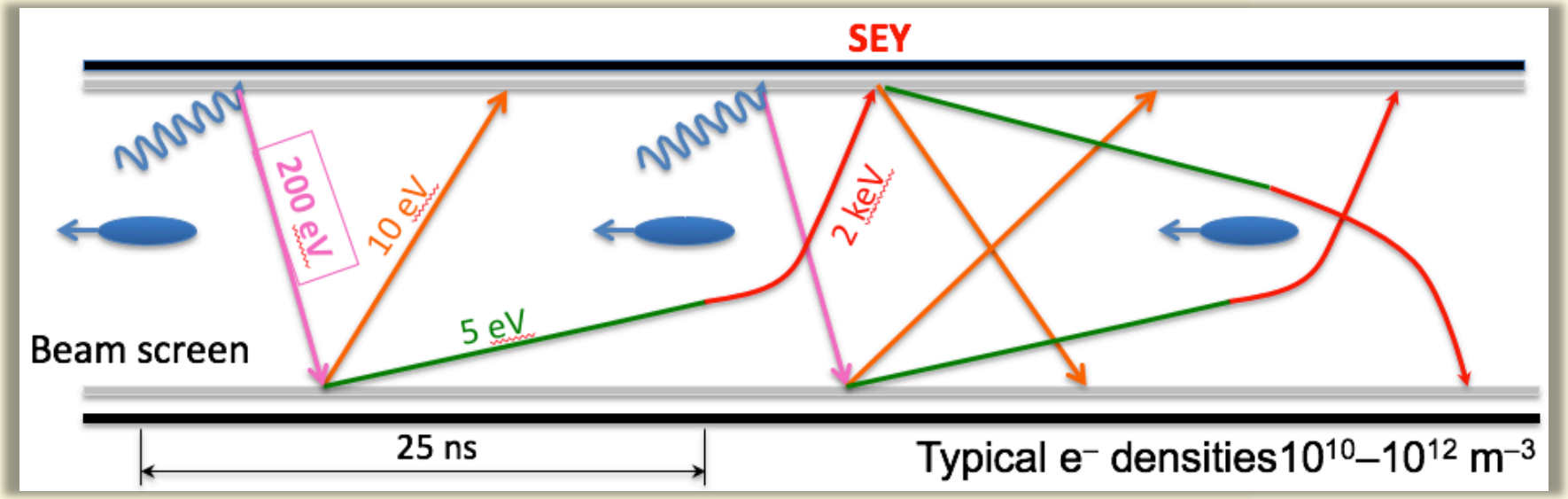
- Each sector is trained to **6.55TeV** (11080A)
  - 100 A above the operational field

LHC operations in 2015

- *
-



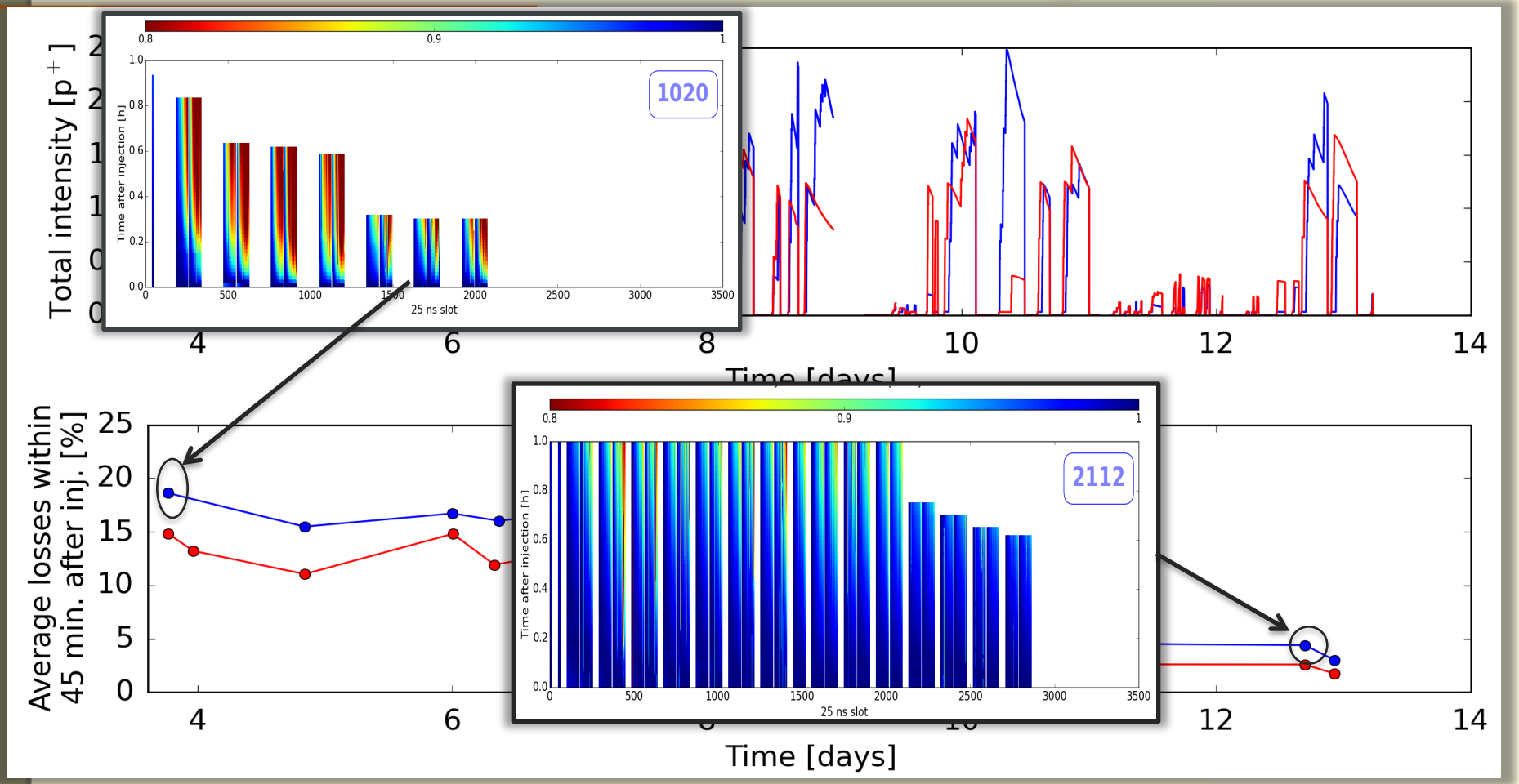
Electron cloud



- Leads to beam instabilities, emittance growth, excessive energy deposition in the cold sectors

- *Scrubbing*: electron bombardment of a surface to reduce the **secondary electron yield (SEY)** of a material.

LHC Scrubbing



Improved beam quality after scrubbing: much reduced losses

Present beam quality at 450 GeV OK for up to ~1500 bunches

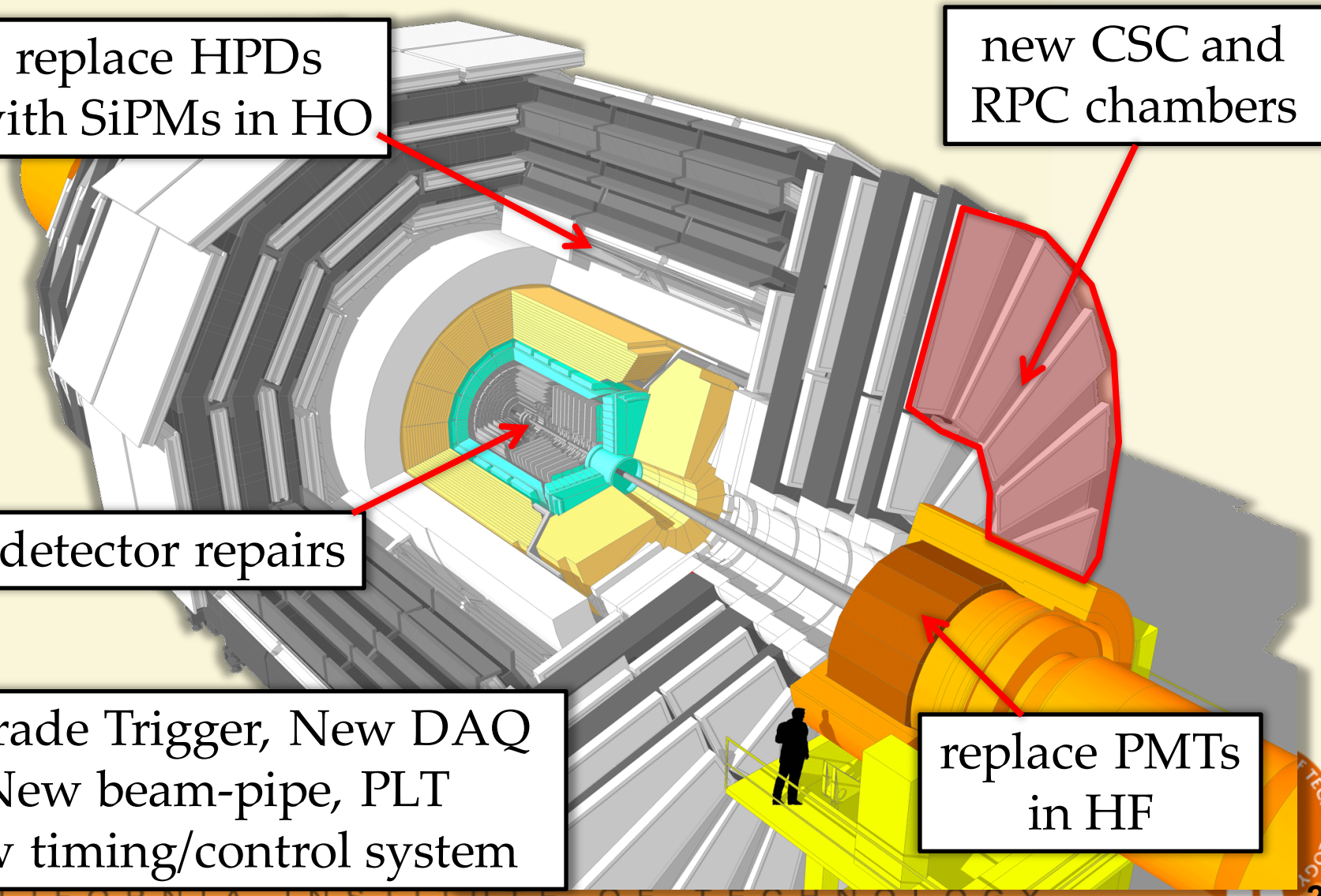
LHC 2015 performance

- **LHC successfully started highest energy collisions**
  - Fundamental parameters of the machine perform well

- Some issues were identified
  - Quench Protection System: SEU sensitive, will be replaced soon
  - Electron cloud: to be improved
  - Injection protection devices: limit N_{bunch}~1200, to be replaced in YETS

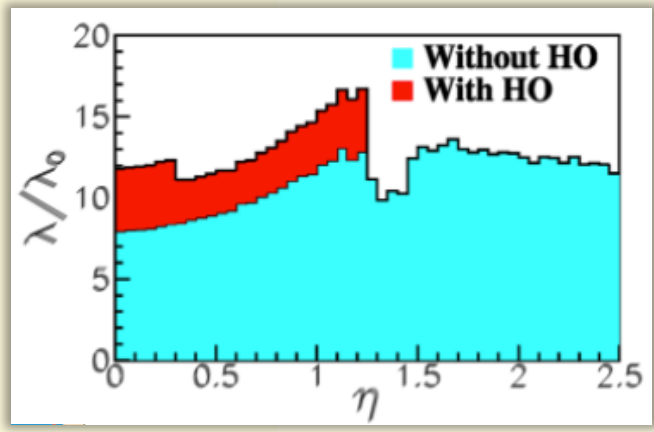
	Nc	β*	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	476	80	1.1e11	1.8	1.6e33	14	0.1 fb^{-1}	27
2015.1	1200	80	1.2e11	3.5	3.6e33	50	~2.3 fb^{-1}	21
2015.2	1200	60	1.2e11	2.3	5.6e34	47	~3.4 fb^{-1}	33

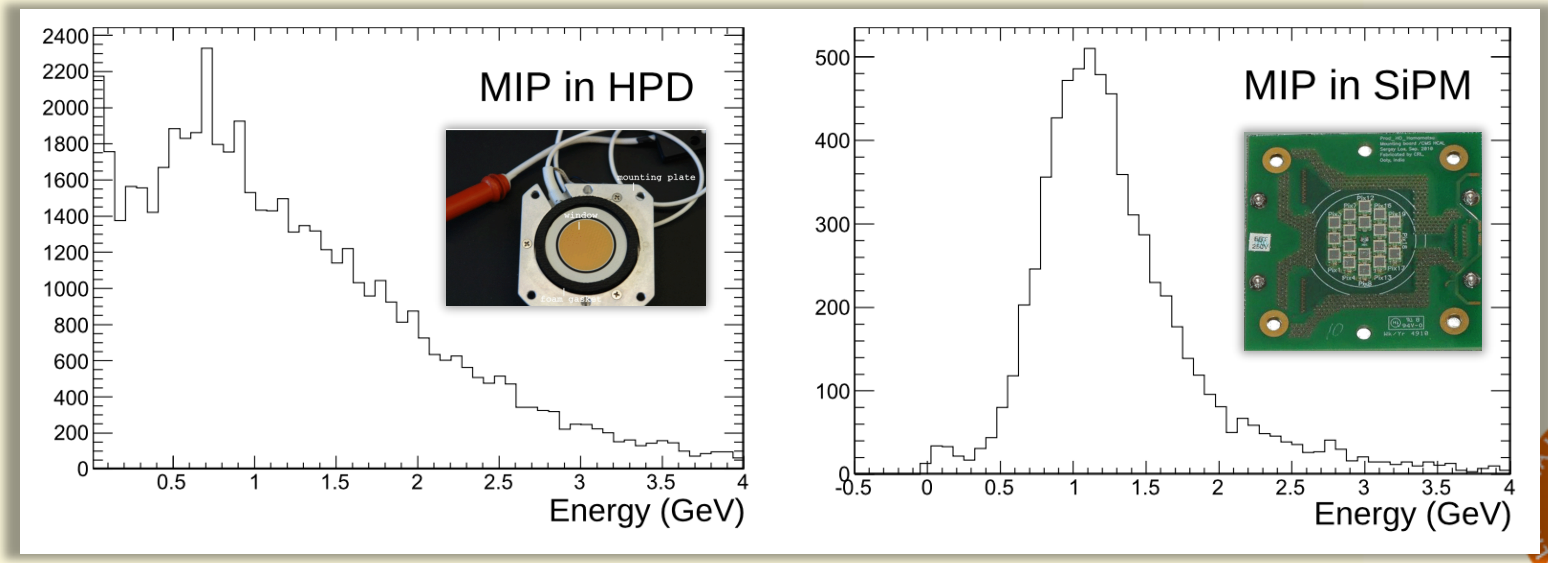
CMS LS1 Upgrades (2013-15)



LS1: HCAL Outer (HO)

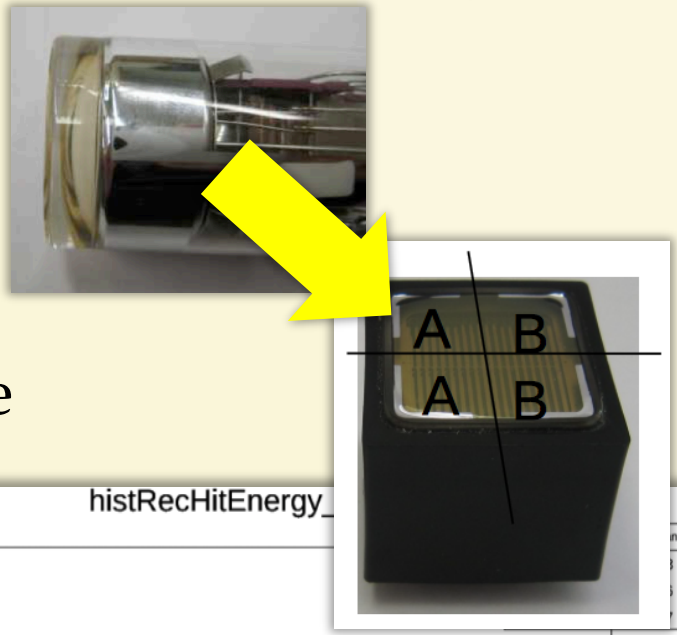
- Replace HPD photodectors in HO
  - Problems with running in fringe field of the CMS magnet
  - Low gain and photo detection efficiency
- SiPM advantages
  - **Excellent S/N**, high **rad-tolerance,** no sensitivity to B-field, **wide dynamic range**

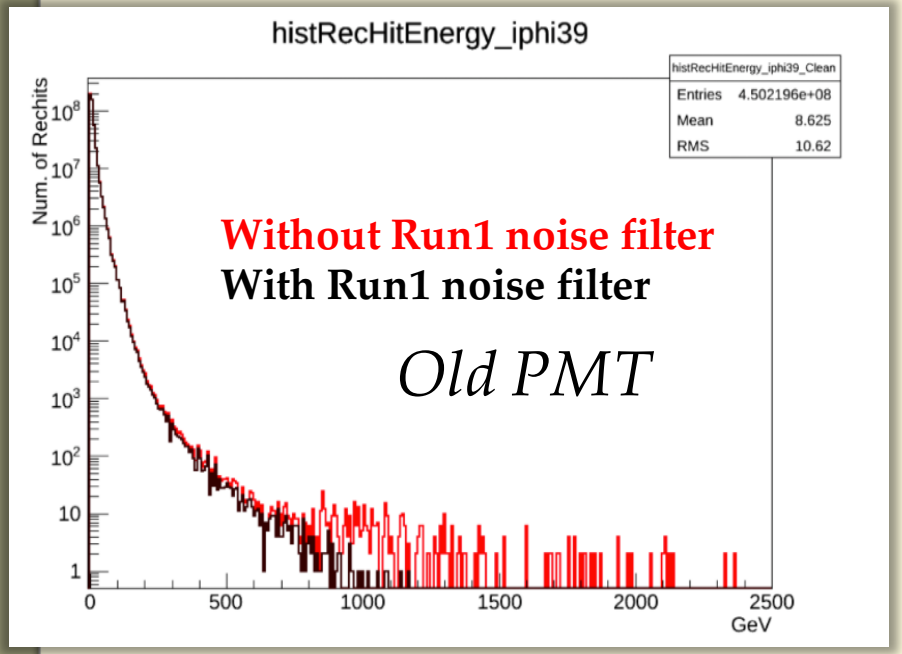


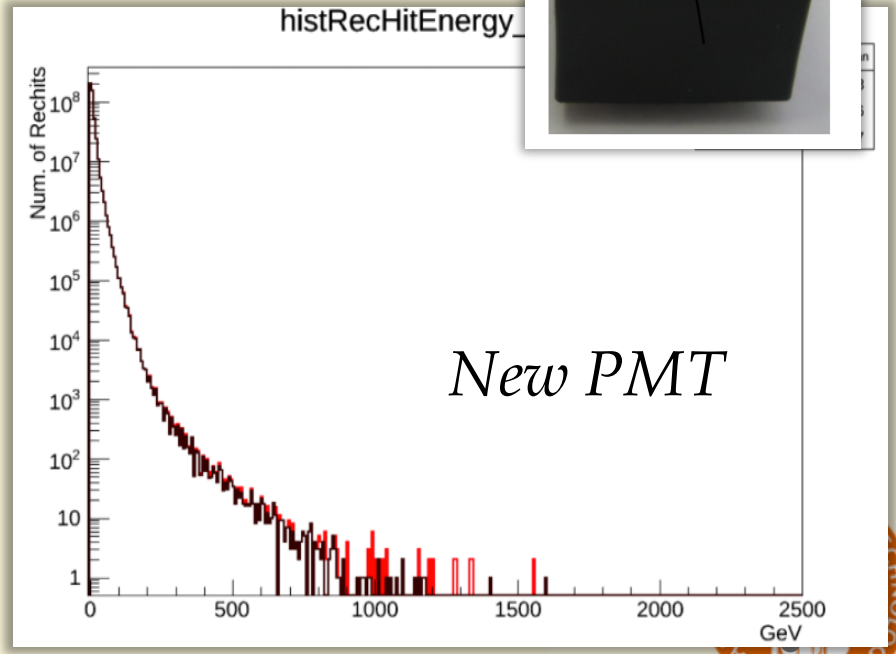


LS1: HCAL Forward (HF)

- *Multianode*, *thin-window* PMTs
  - Reduction in anomalous signals
- New back-end electronics for HF
  - Pilot project for Phase-1 upgrade

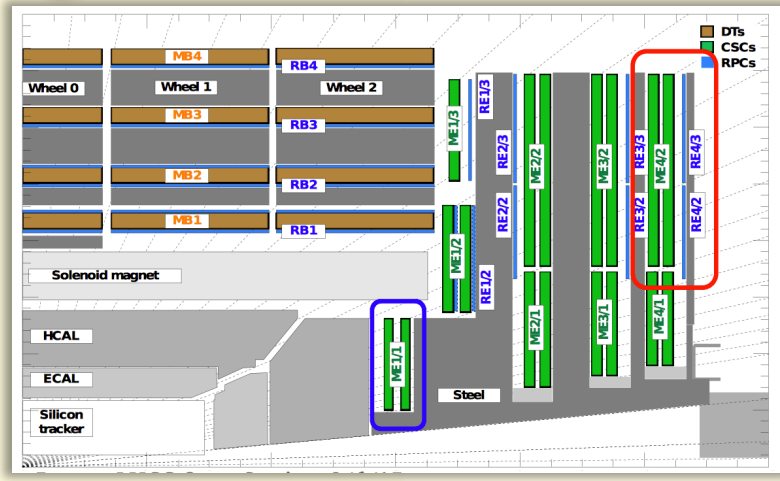


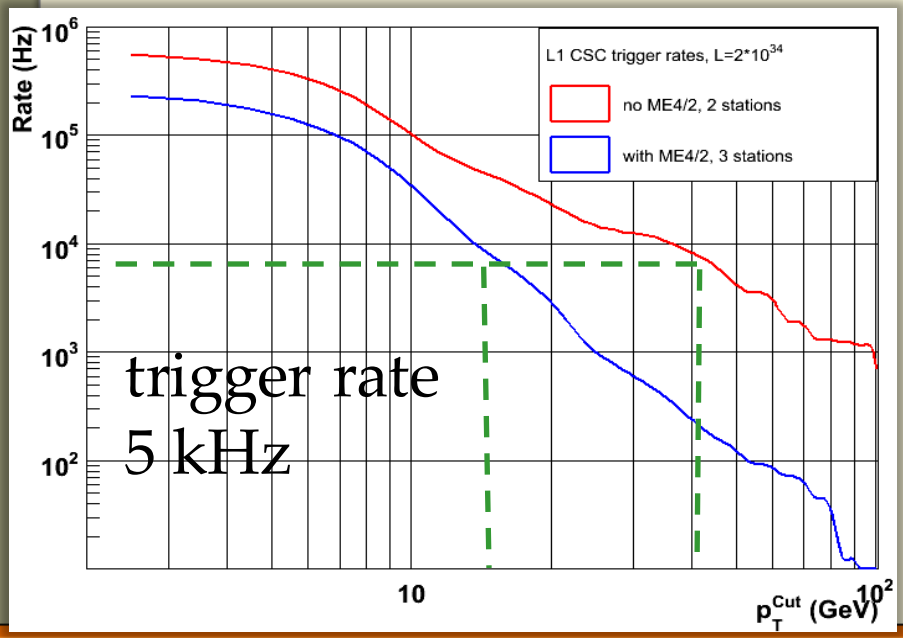


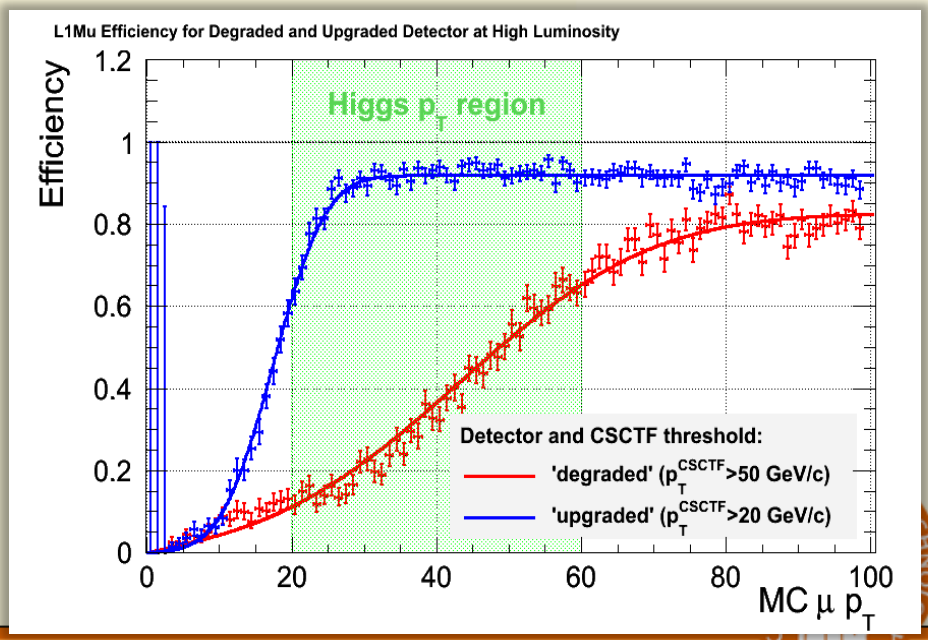


LS1: Muon upgrades

- ME1/1 chambers: new digital boards and trigger cards
- ME4/2: **72** (**144**) new **CSC** (**RPC**) chambers
- Maintain trigger rates at a lower P_T threshold

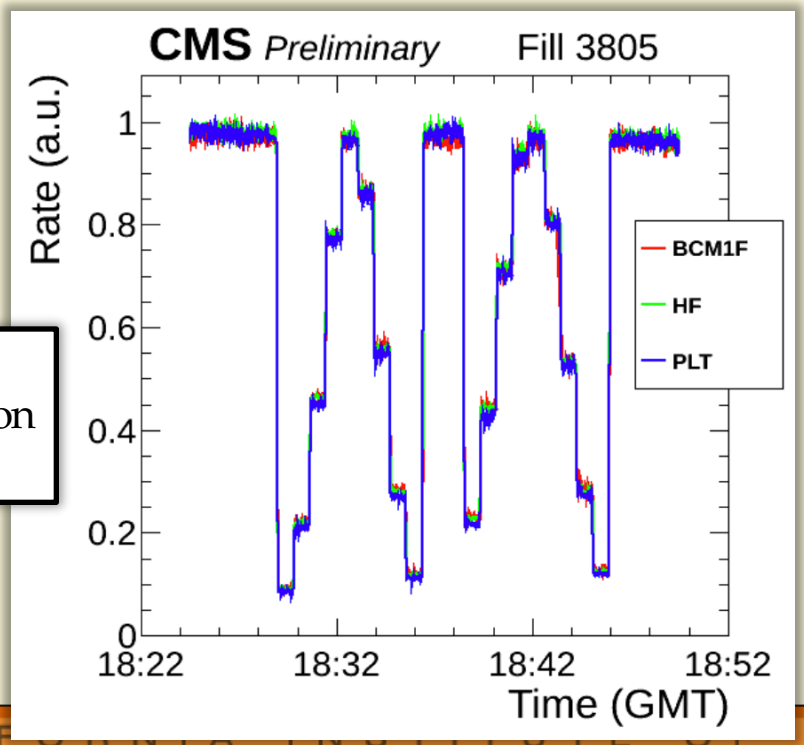




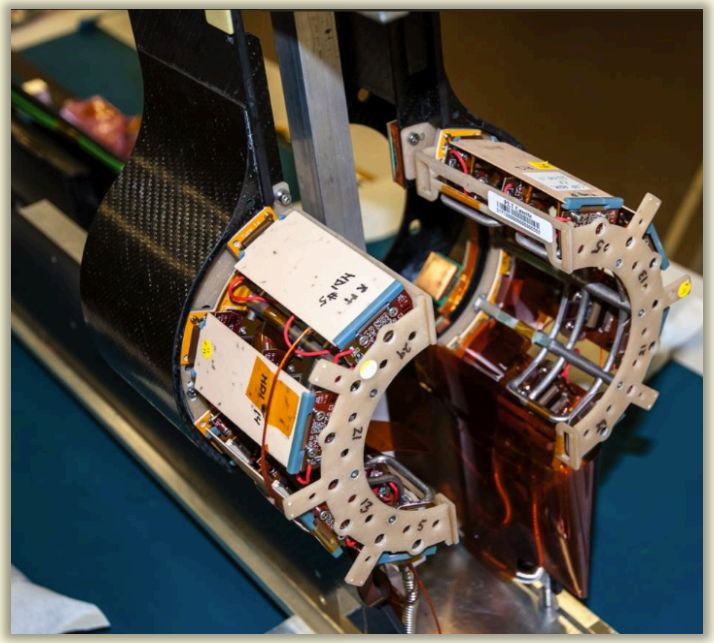


Pixel Luminosity Telescope

- High precision, **real-time** luminosity measurement
- Immediate feedback to LHC to optimize the beam conditions for CMS ➔ **more lumi to analyze**

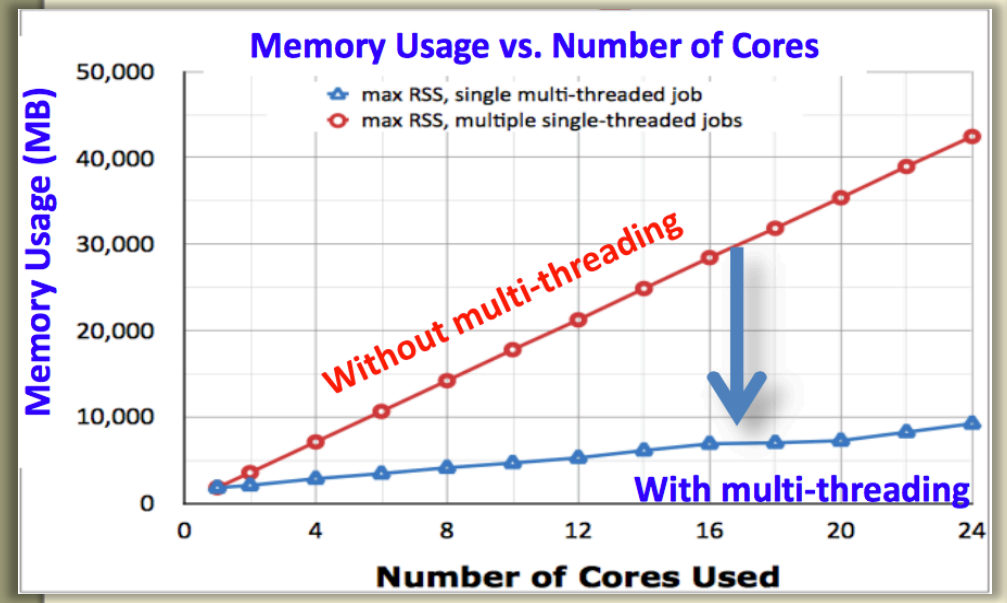


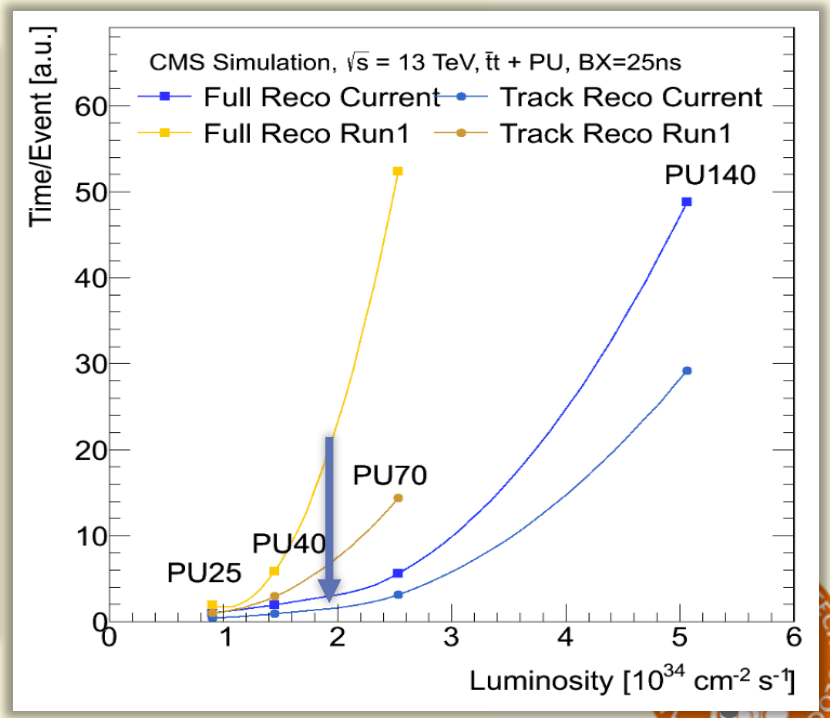
Beam Optimization Scan



Software and Computing

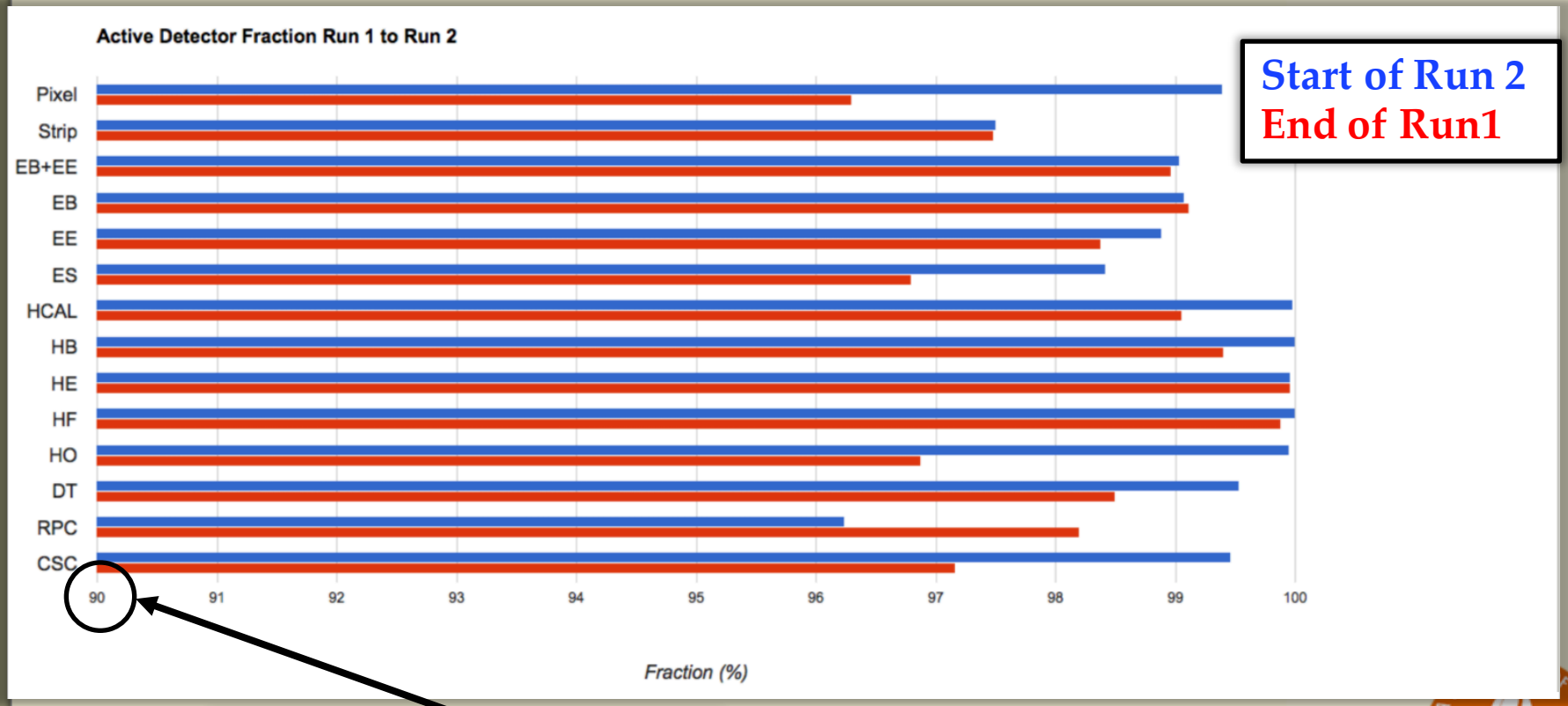
- Significant overhaul during shutdown
  - Multithreading in simulation/reconstruction: **x4 improvement**
  - Improve **reconstruction time** at high PU
  - **Any Data, Anywhere, Anytime (AAA)**
  - New data format (miniAOD): reduce analysis time **by x10**





Detector readiness

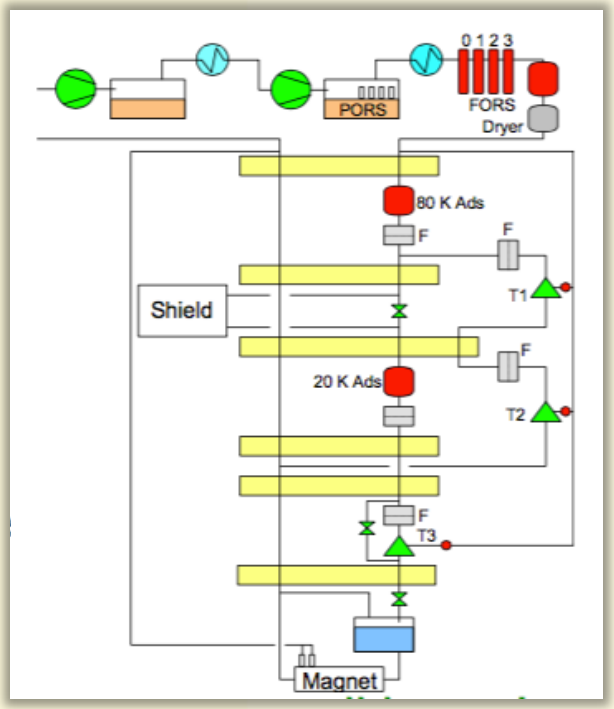
- Several recovery campaigns
- Active channels fraction is **higher than at the end of Run 1**



Note: starts at 90%

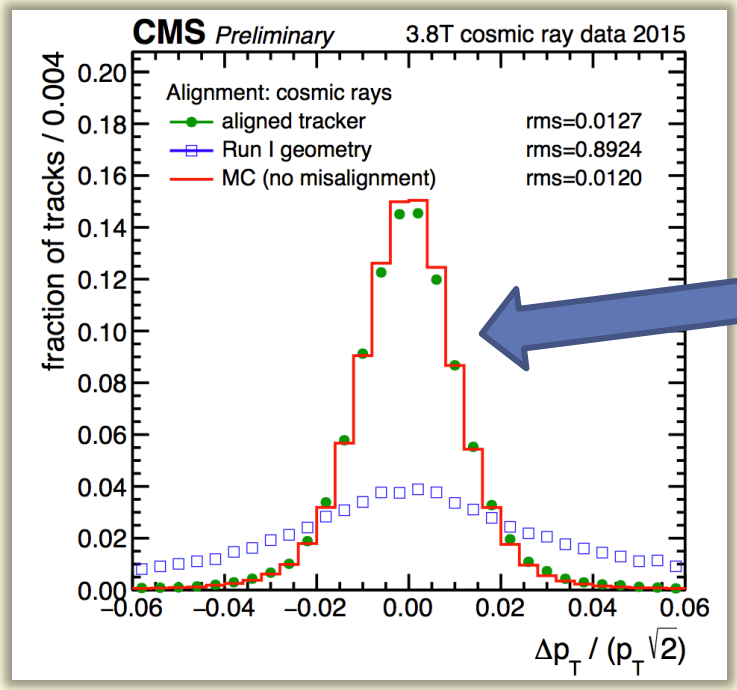
CMS magnet

- Inefficiencies of the oil separation system of the compressors
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system
- A comprehensive program to re-establish its nominal performance is underway.

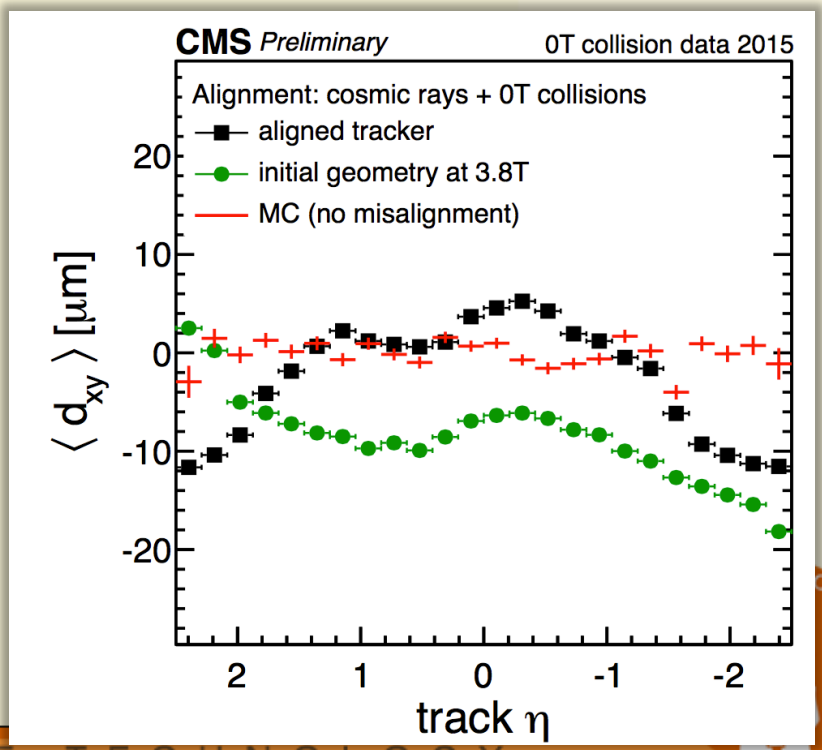


All 13 TeV results in the following are at 3.8 T, unless otherwise specified

Detector commissioning: alignment

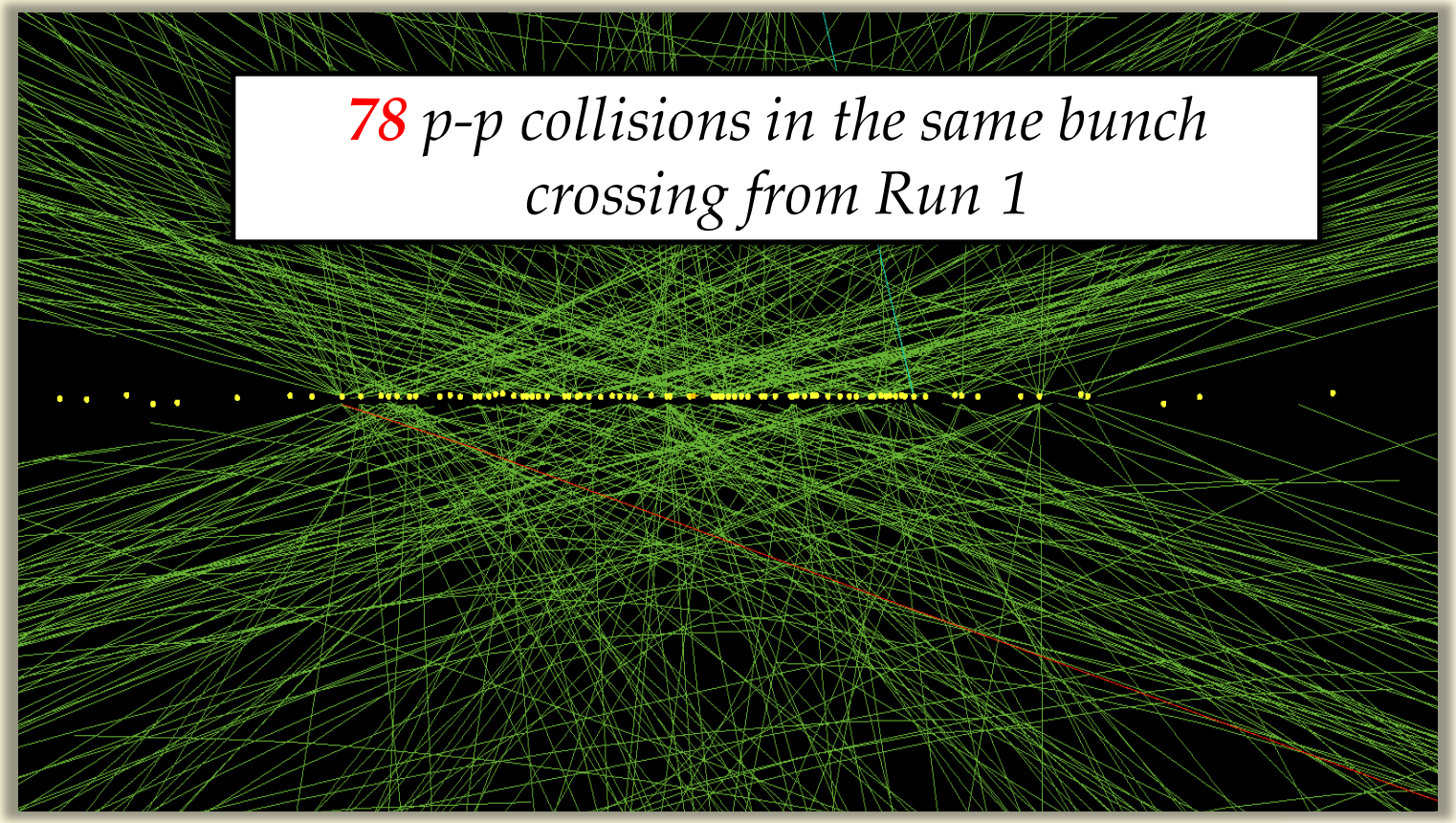


- Tracker alignment with cosmic rays
  - Refit tracks with various alignments constants
  - Precision **very close** to ideal MC



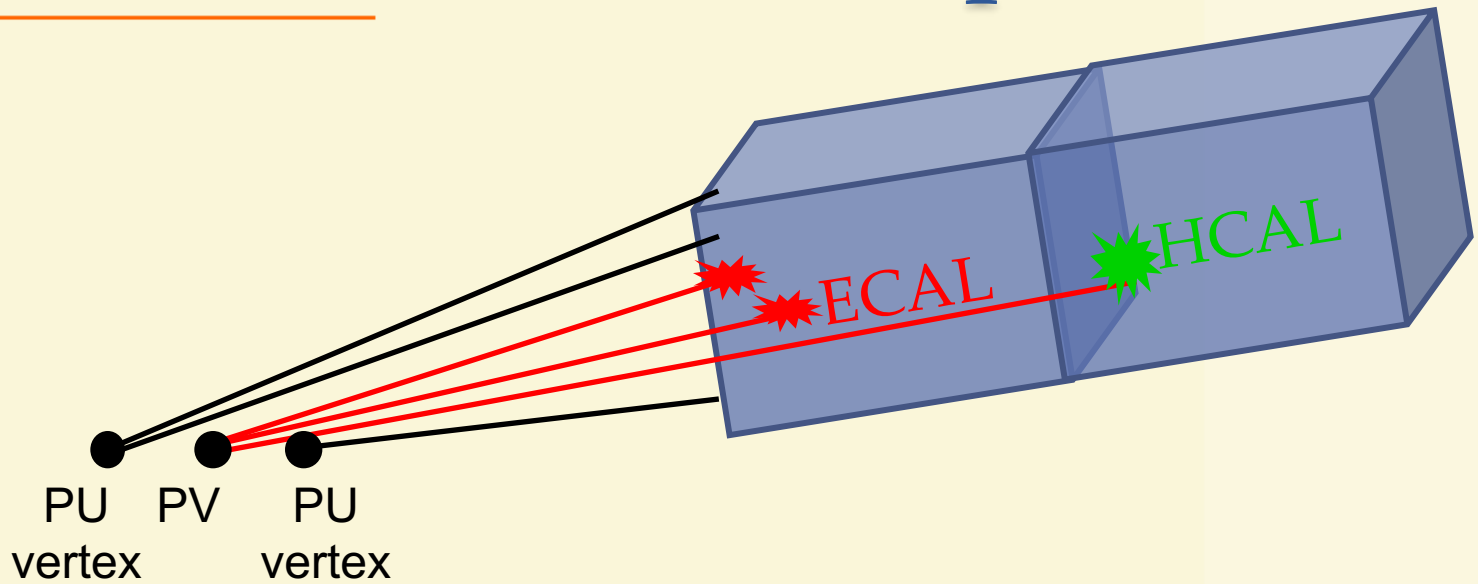
- **Well aligned** central part
- Forward region lacks statistics, will improve with more data

Pileup in CMS



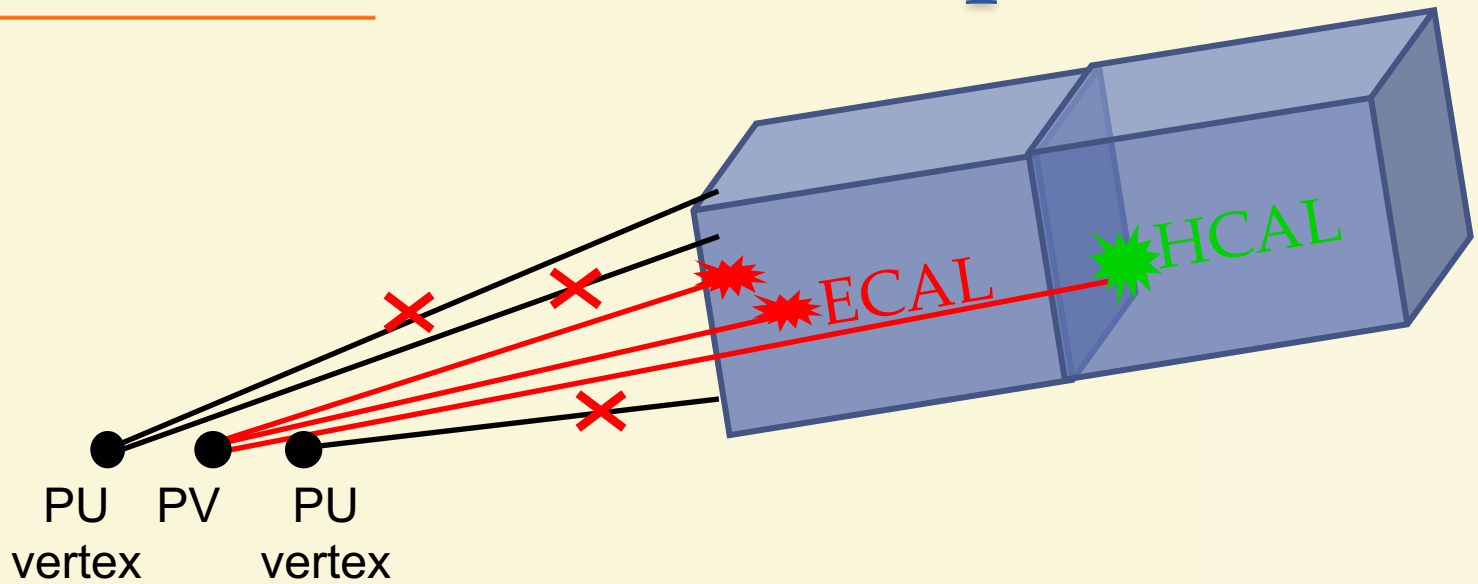
- Maximize the integrated luminosity ➔ large pileup

In Time Pileup



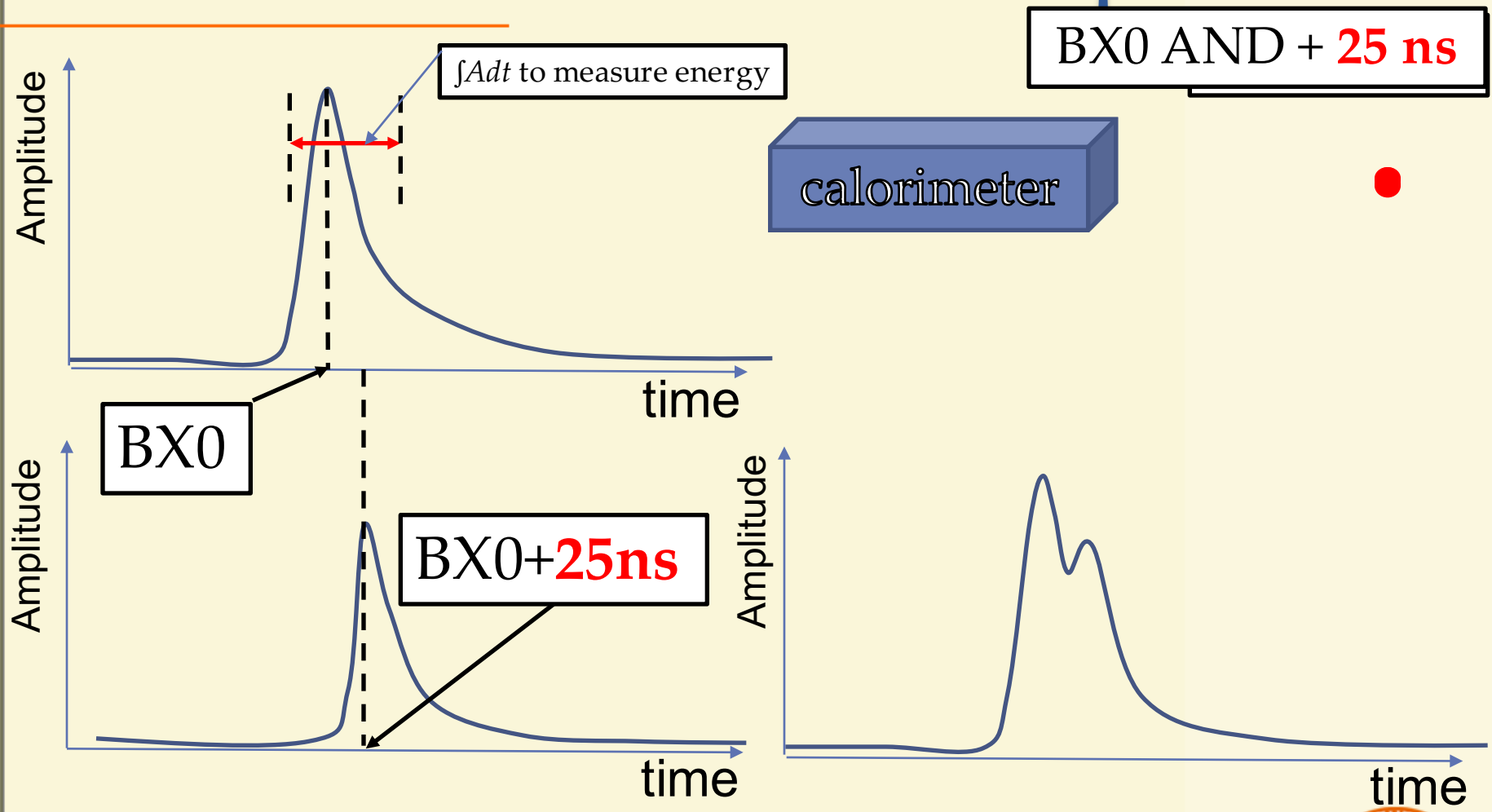
- We want to measure energies of particles produced in the **primary collision (PV)**

In Time Pileup



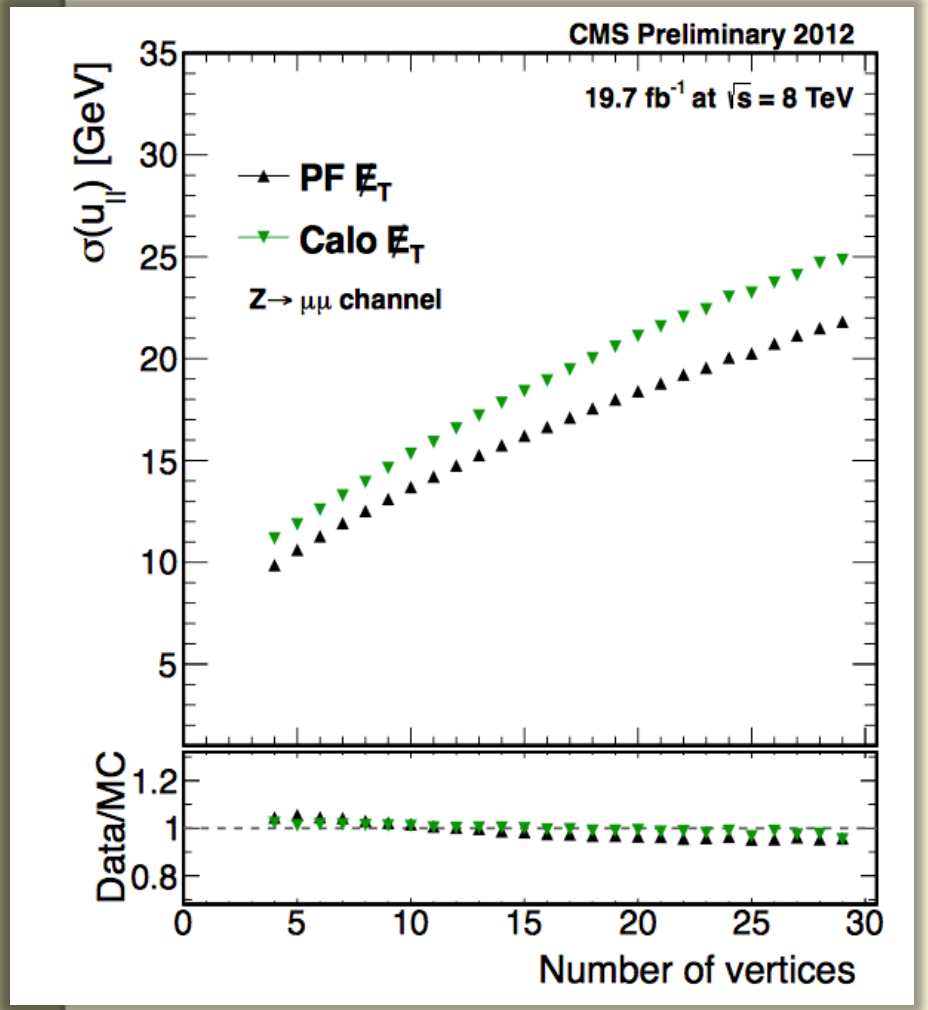
- We want to measure energies of particles produced in the **primary collision (PV)**
- Energies from PU collisions **can be subtracted** by taking out the charged tracks that come from **PU vertex**

Out of Time Pileup



No tracks to subtract the OOT PU deposits!

Out of Time Pileup

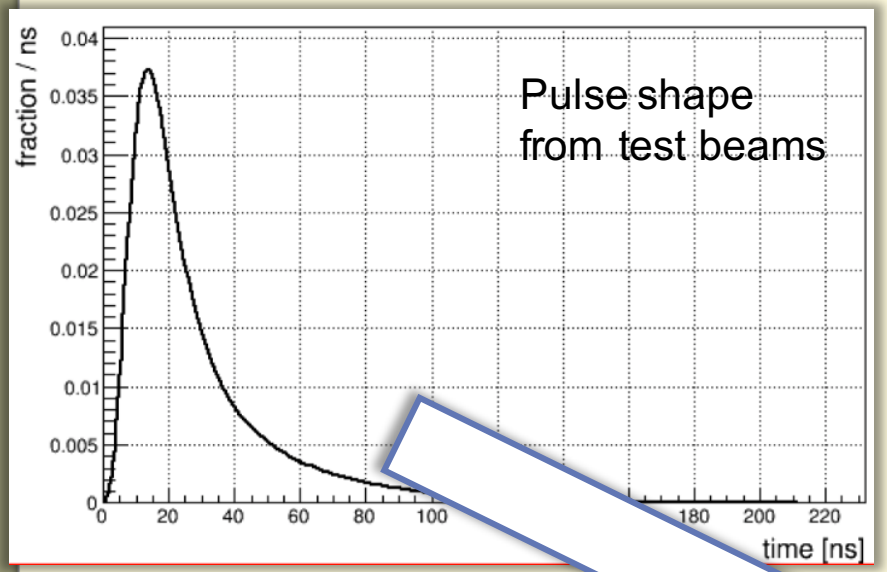


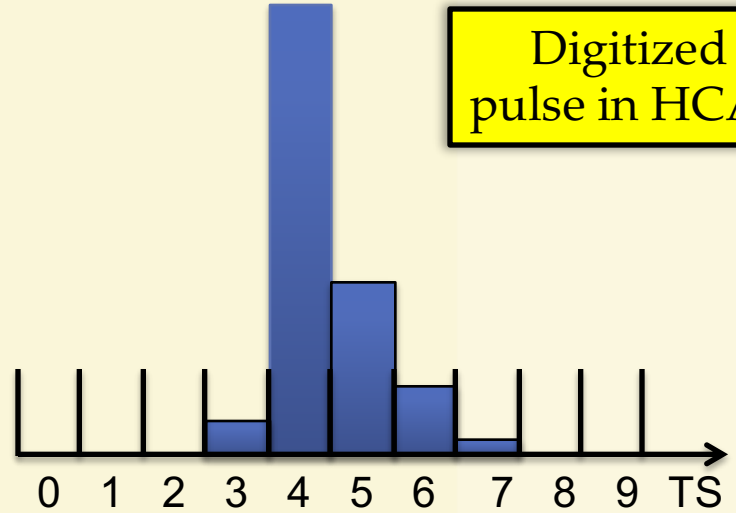
Extra neutral energy ➔ Jet/MET resolutions worsened

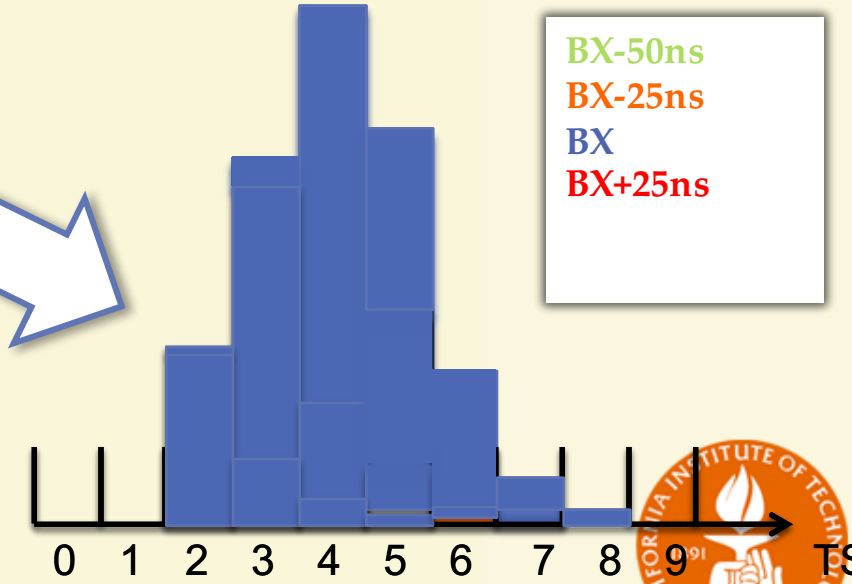
OOT PU generally worsens the resolutions by ~20-30%

$$\sigma_{MET} = \sigma_{MET}(N_{PU}) \oplus \sigma_{MET}(N_{OOT})$$

OOT PU Removal

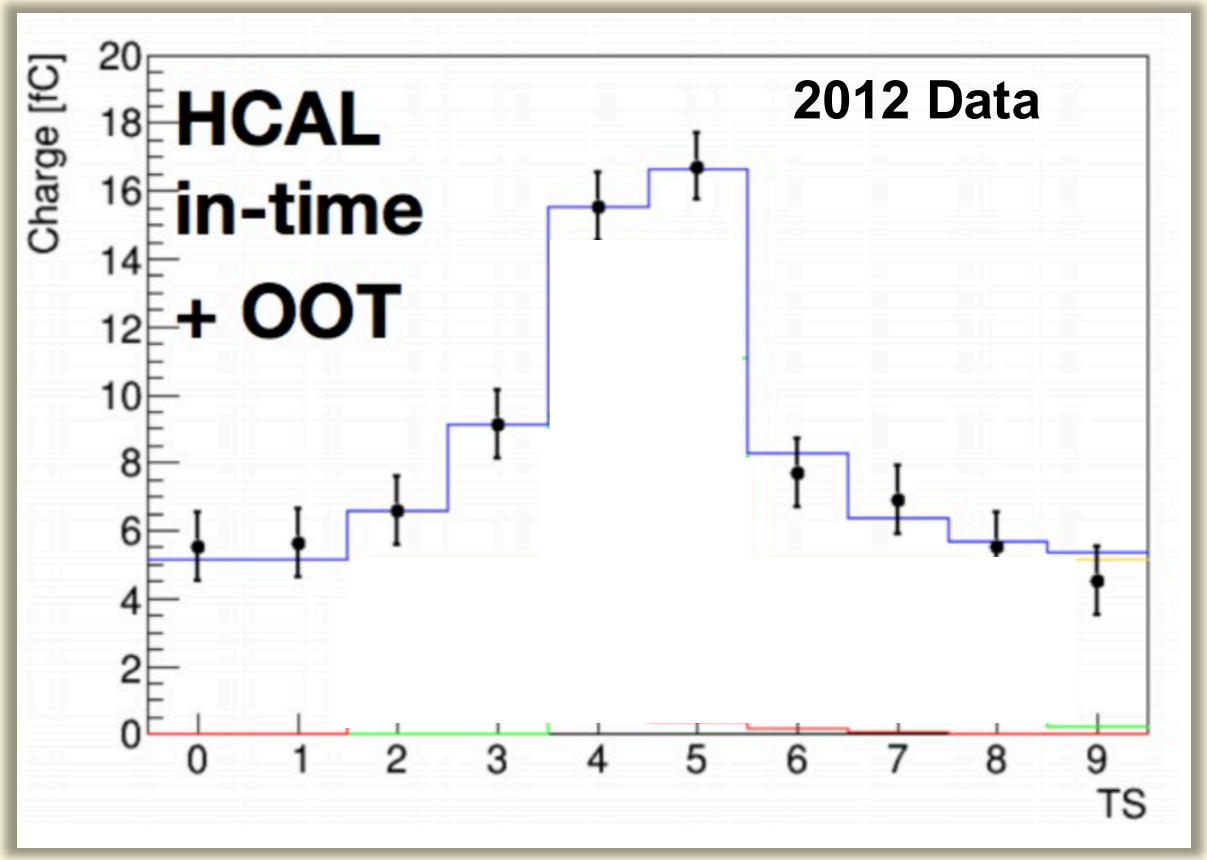






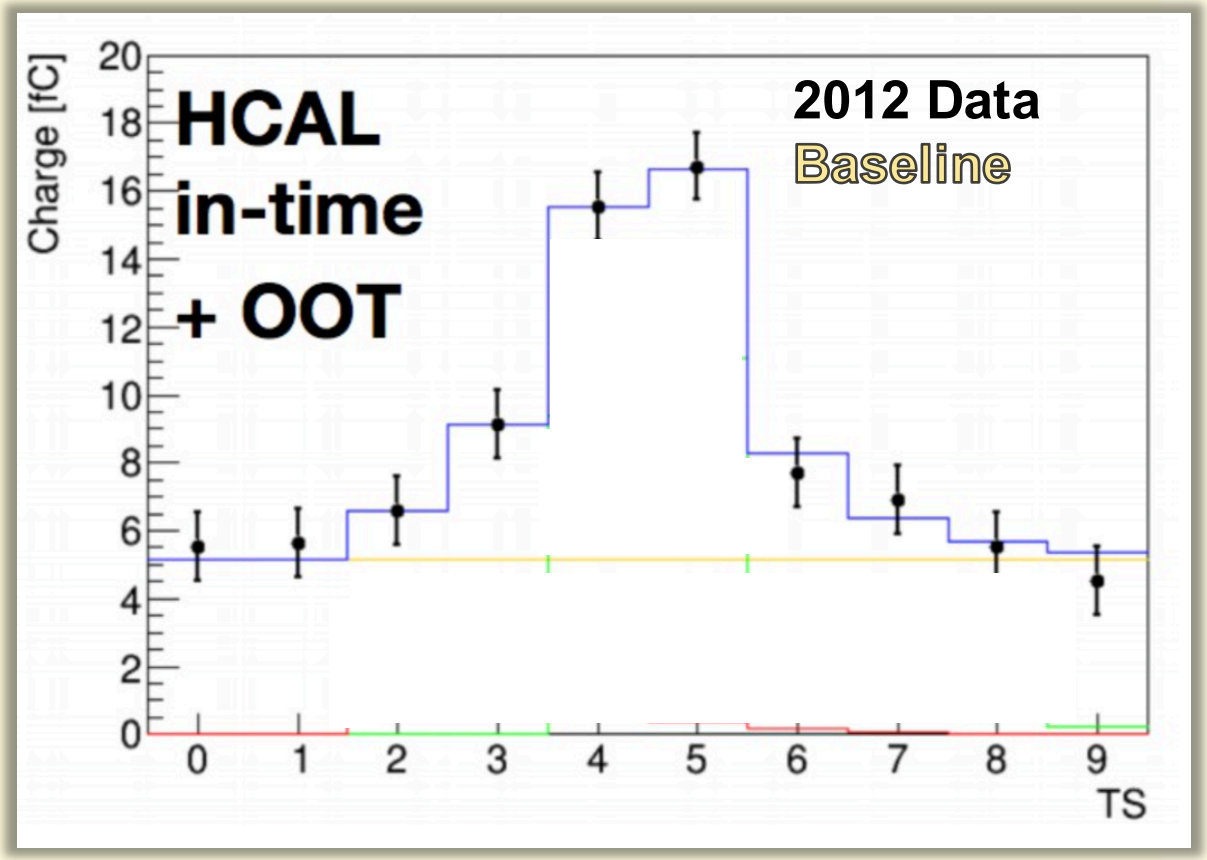
Fit measured data for the known pulse shape from past test beams

OOT PU removal in HCAL



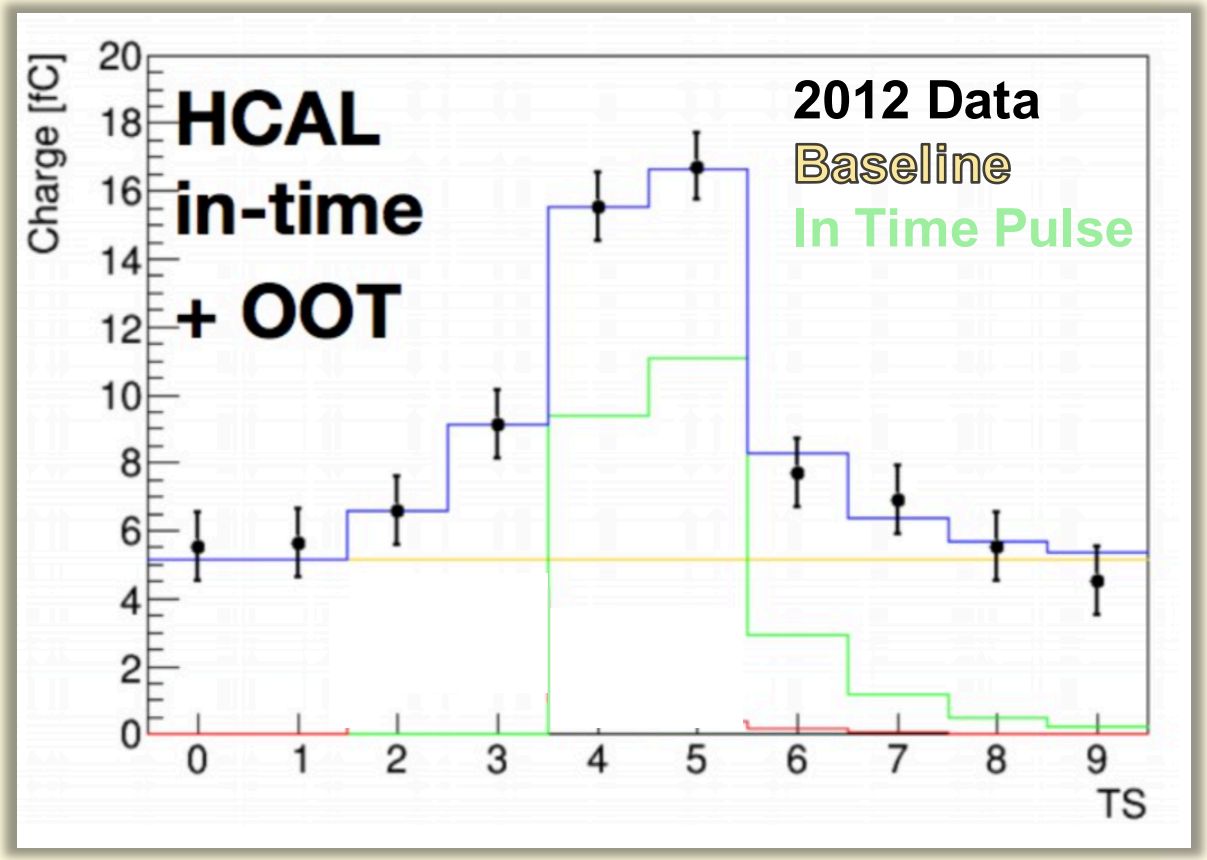
In Time Pulse

OOT PU removal in HCAL



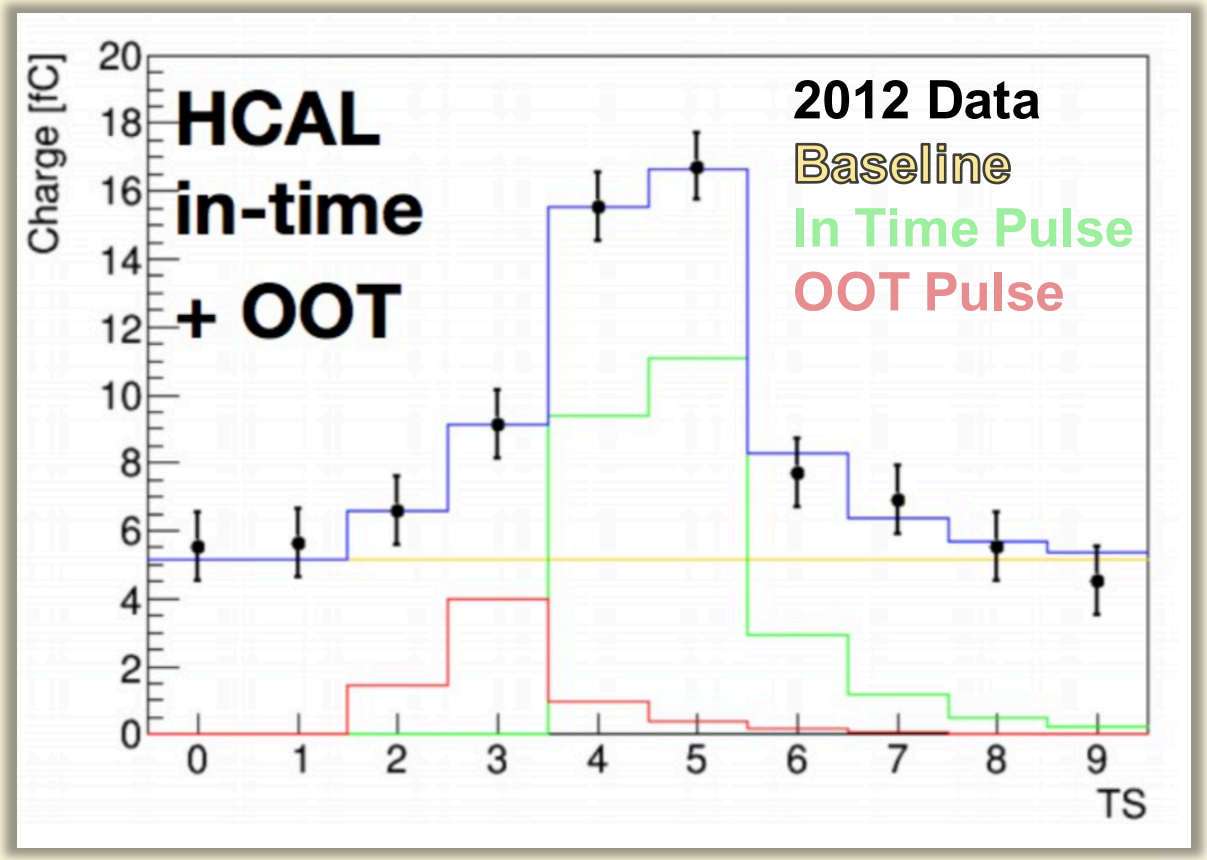
In Time Pulse

OOT PU removal in HCAL



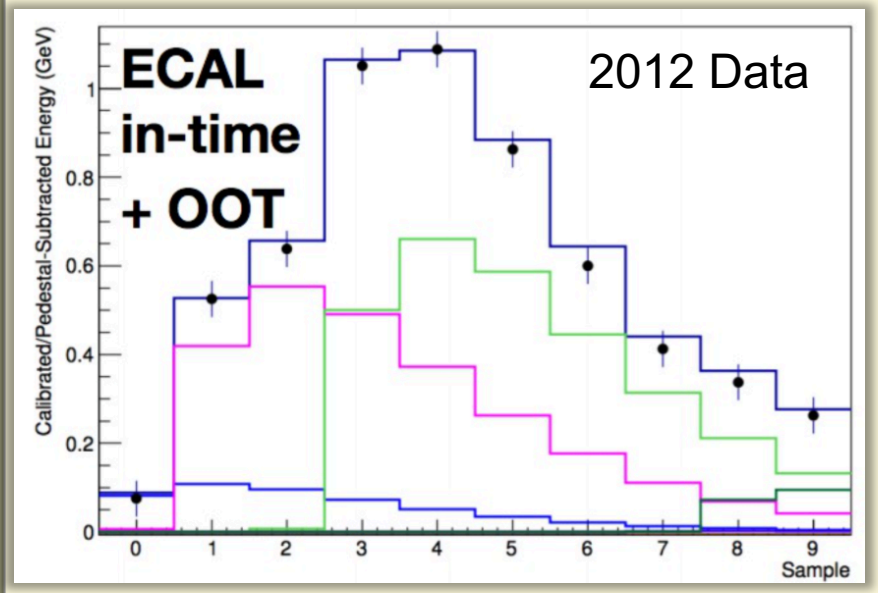
In Time Pulse

OOT PU removal in HCAL

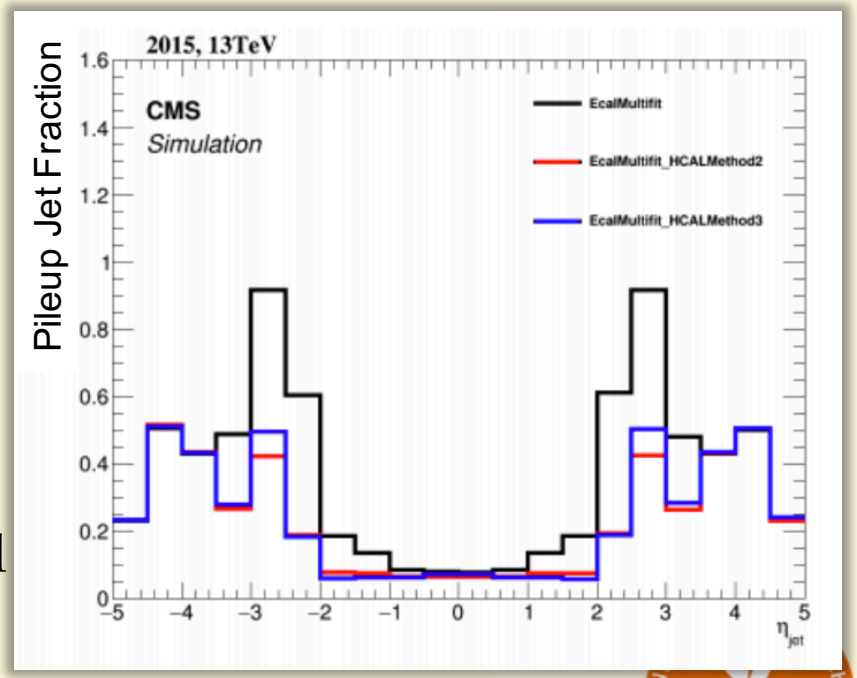


In Time Pulse

OOT PU removal in ECAL



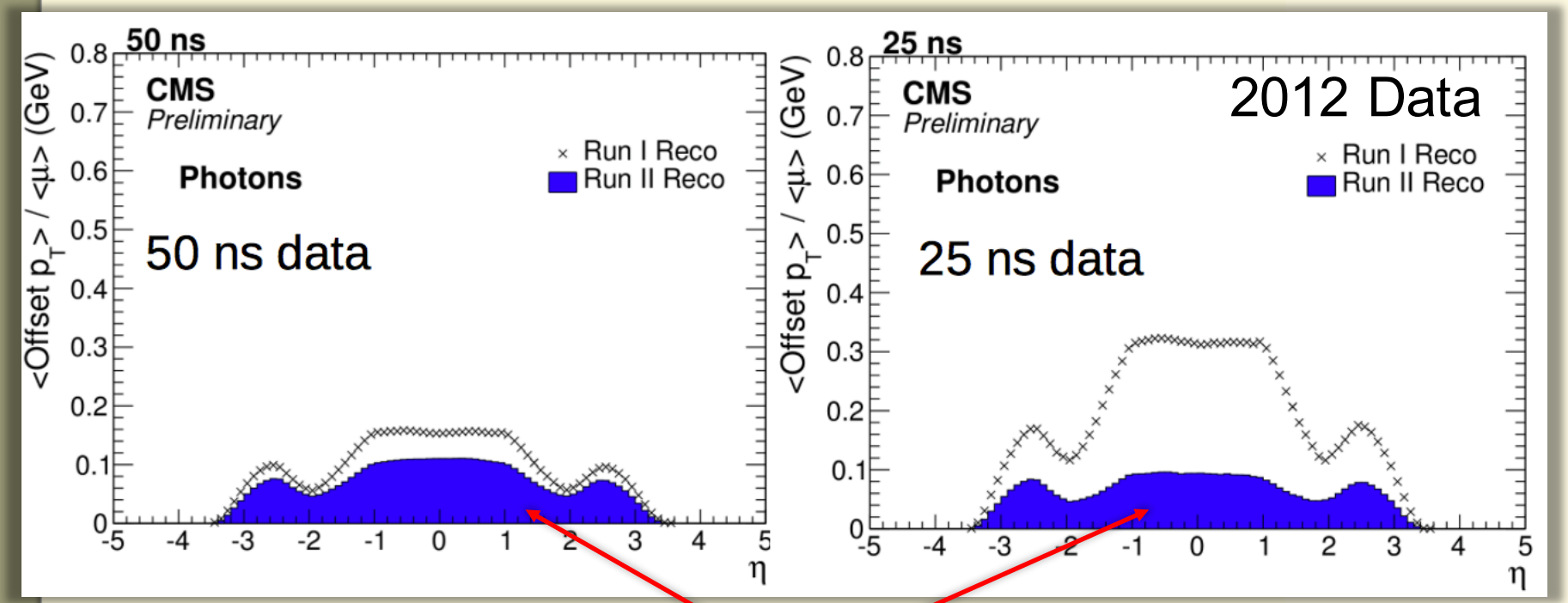
Similar strategy performed in ECAL: fit all pulses



- Both ECAL and HCAL do a faster version at HLT
  - Roughly **50% reduction** in pileup background rate at same threshold with no loss in performance

Jet improvement

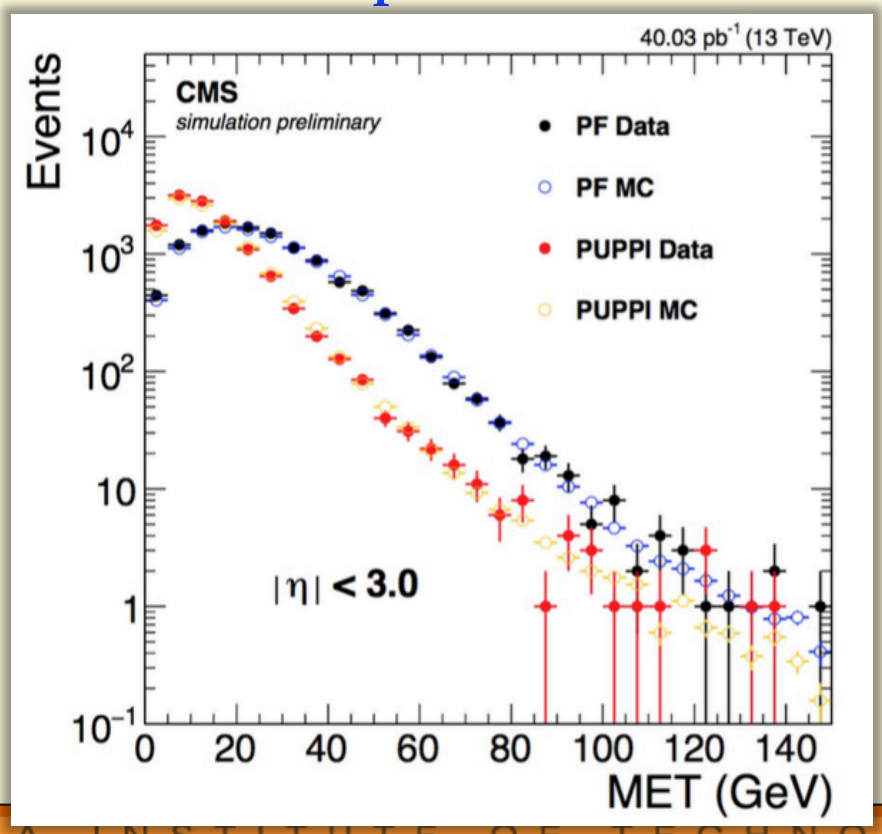
- Effects of OOT Pileup almost entirely removed!



Jet PT offset same in 50 and 25ns collisions

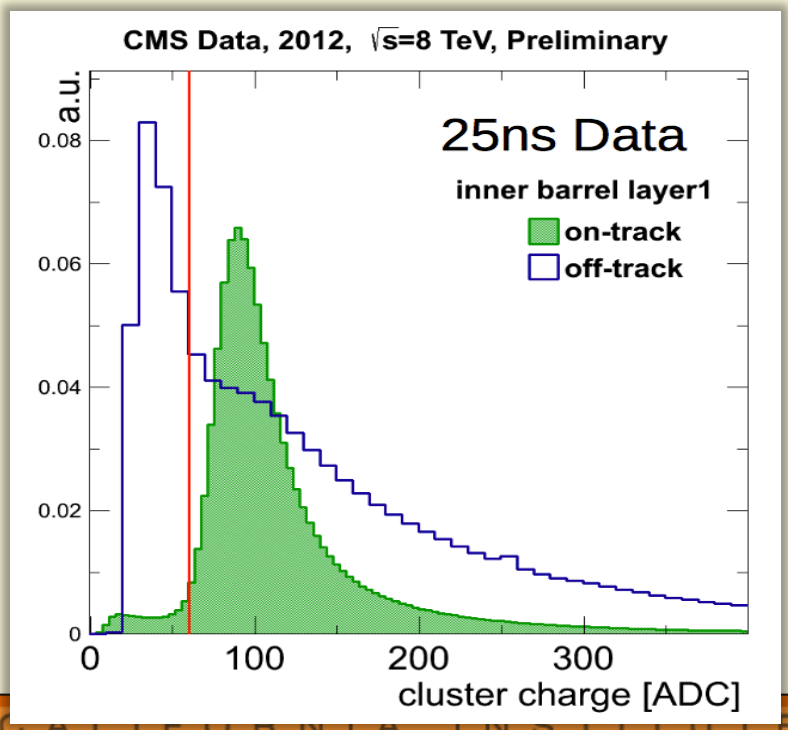
MET improvement

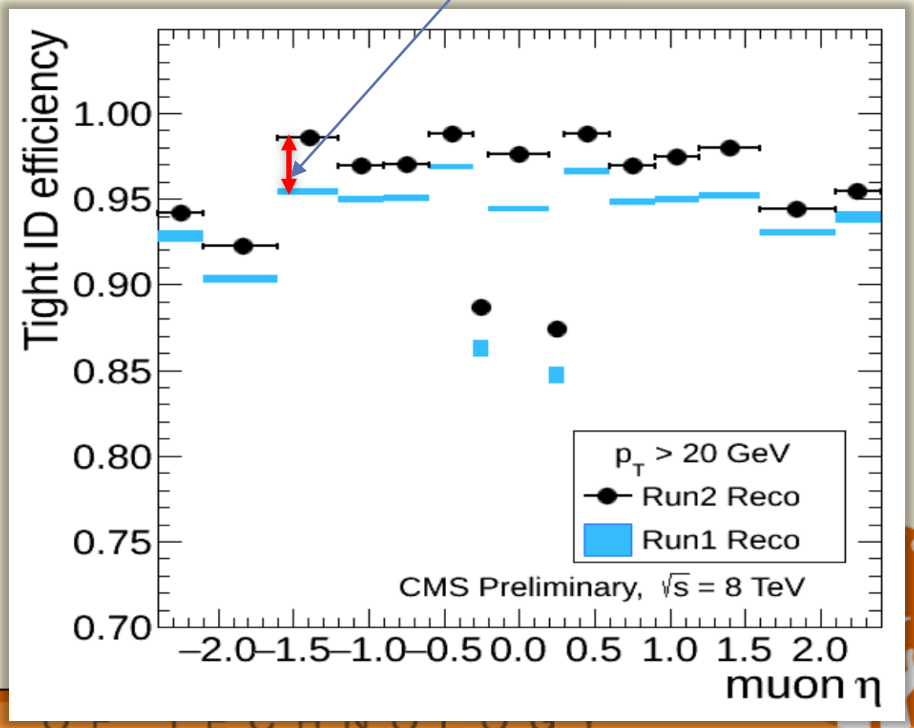
- Improves MET reconstruction as well
- PUPPI: **Pile Up Per Particle Identification**
  - Weight particle flow candidates according to the surrounding activity ➔ **discriminate particles from hard scattering vs PU**



Track reconstruction

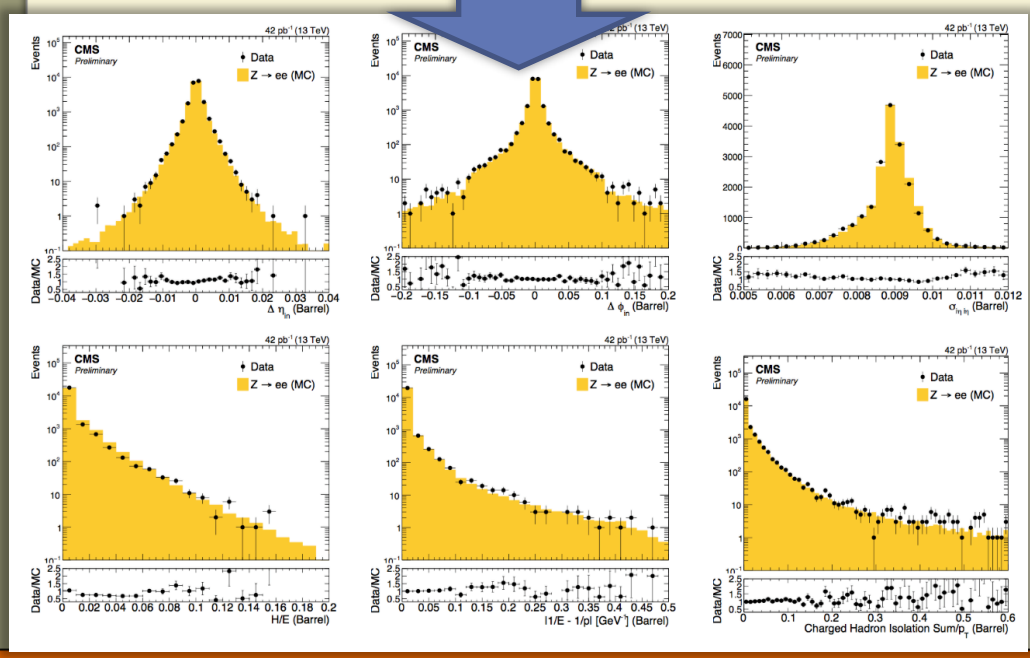
- Improved track reconstruction
  - **2x faster** at the same PU, **lower fake rate**
  - Use of cluster charge to **reduce OOT hits**
- New, muon specific tracking: **increased efficiency**
  - Recovering lost tracks and non associated hits

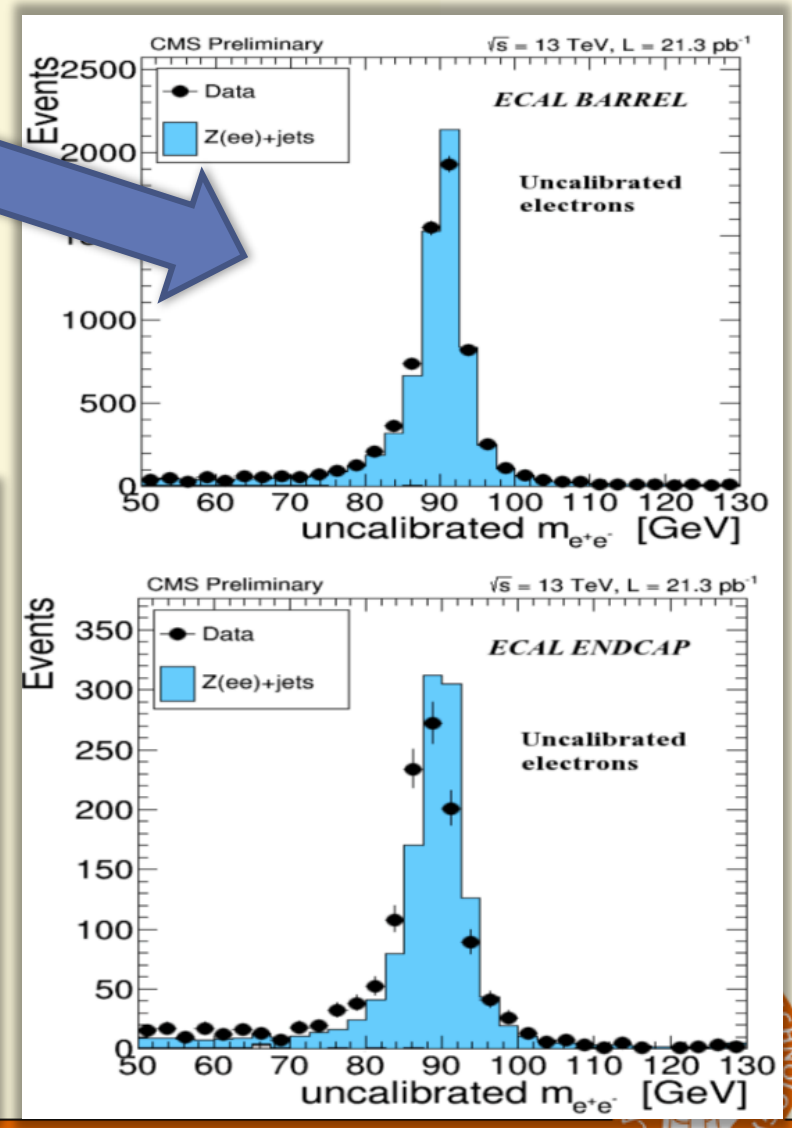




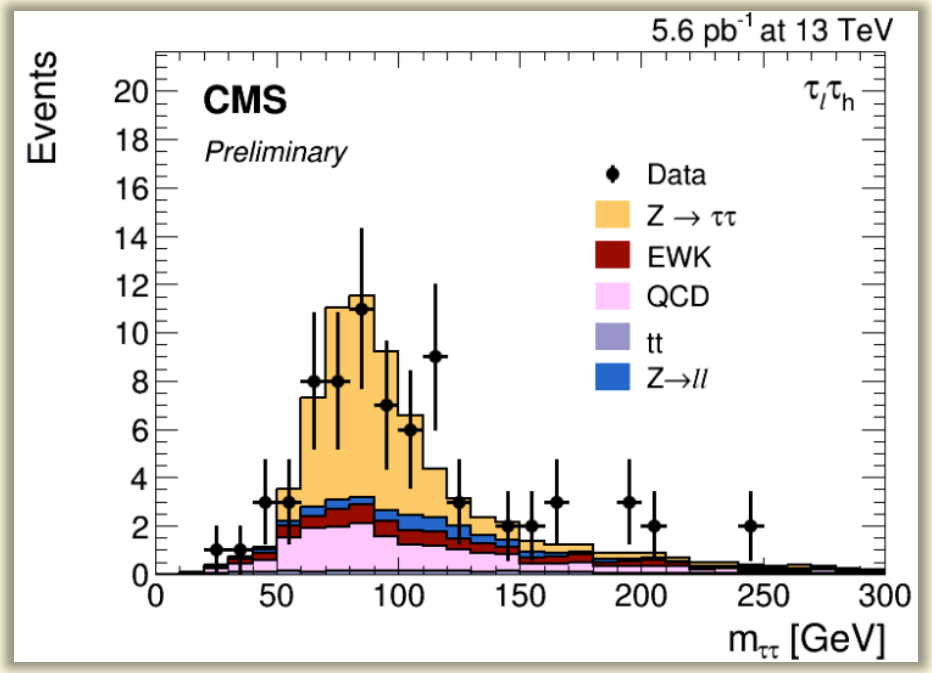
Electron reconstruction

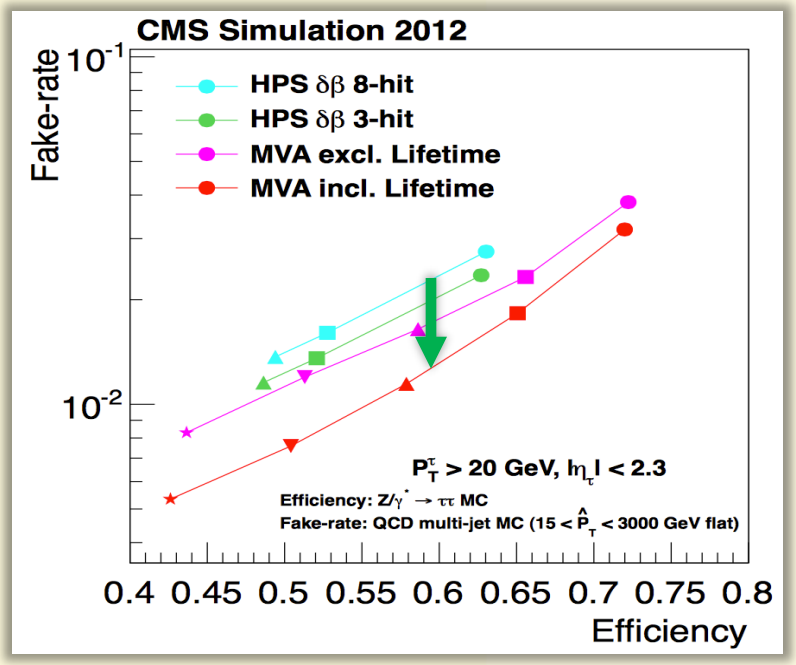
- The uncalibrated energy scale is already quite good
- All variables used for electron ID agree well with simulation





τ reconstruction

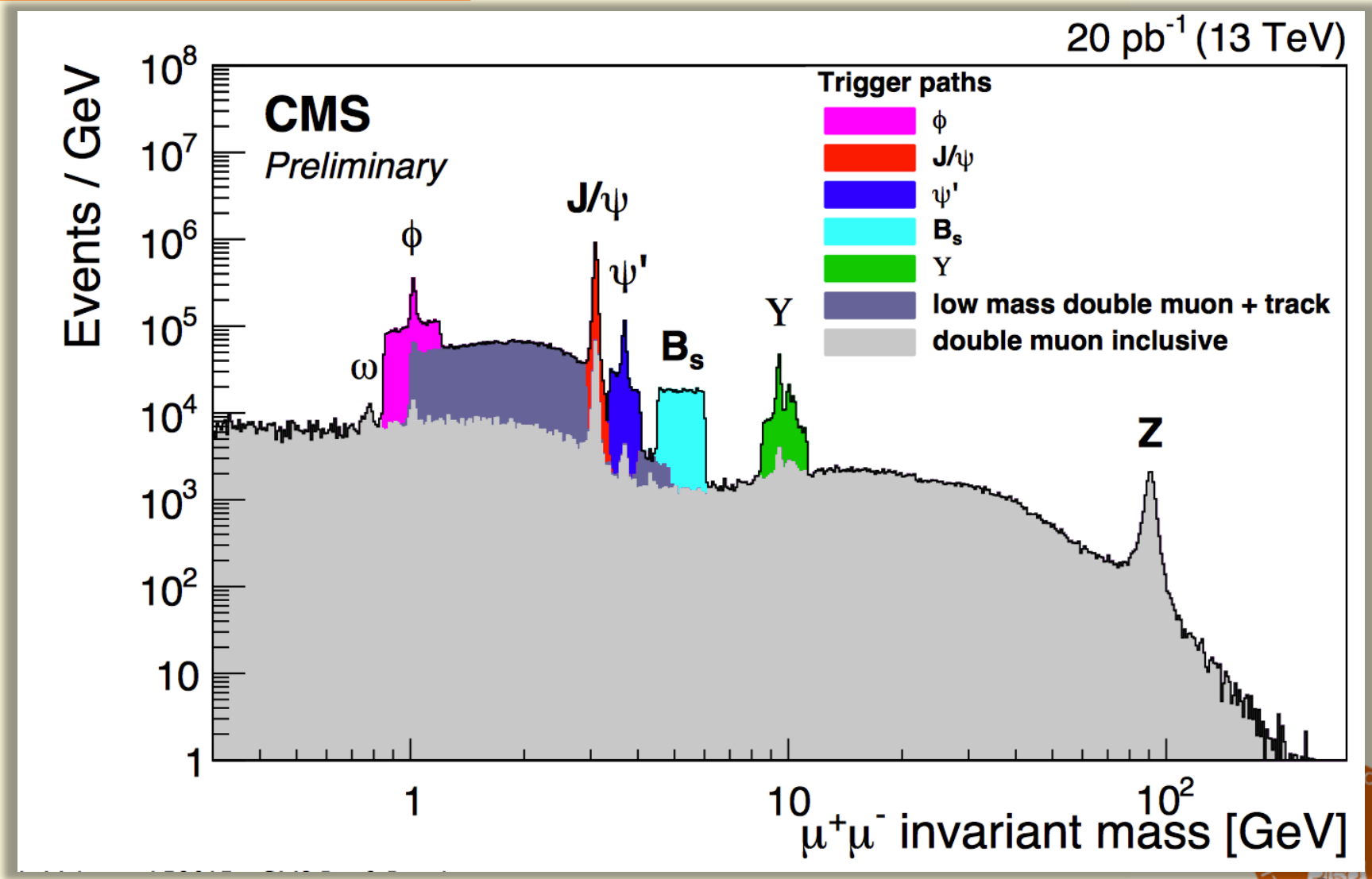




- New MVA –based τ ID uses as input information lifetime
  - Reduce the jet → tau fake-rate **down by 40-50%** compared to cut-based tau ID
  - **About 60% efficiency** with ~1-2% fake rate

CMS-DP-2015-018

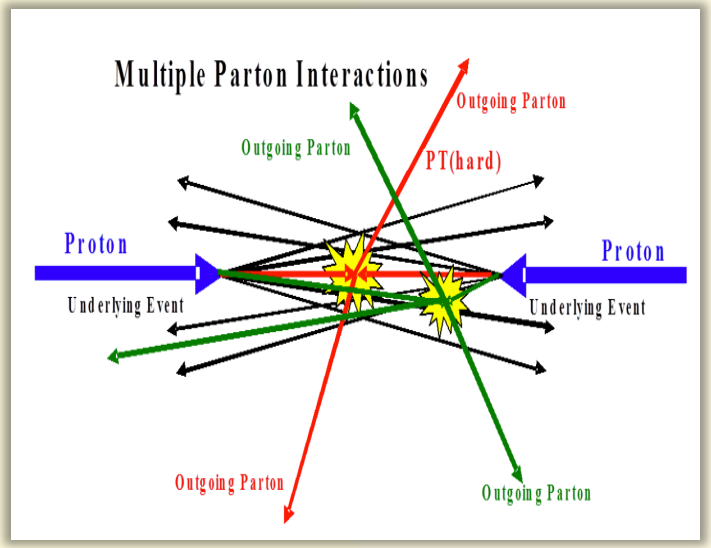
Rediscover the SM



$dN_{ch}/d\eta$

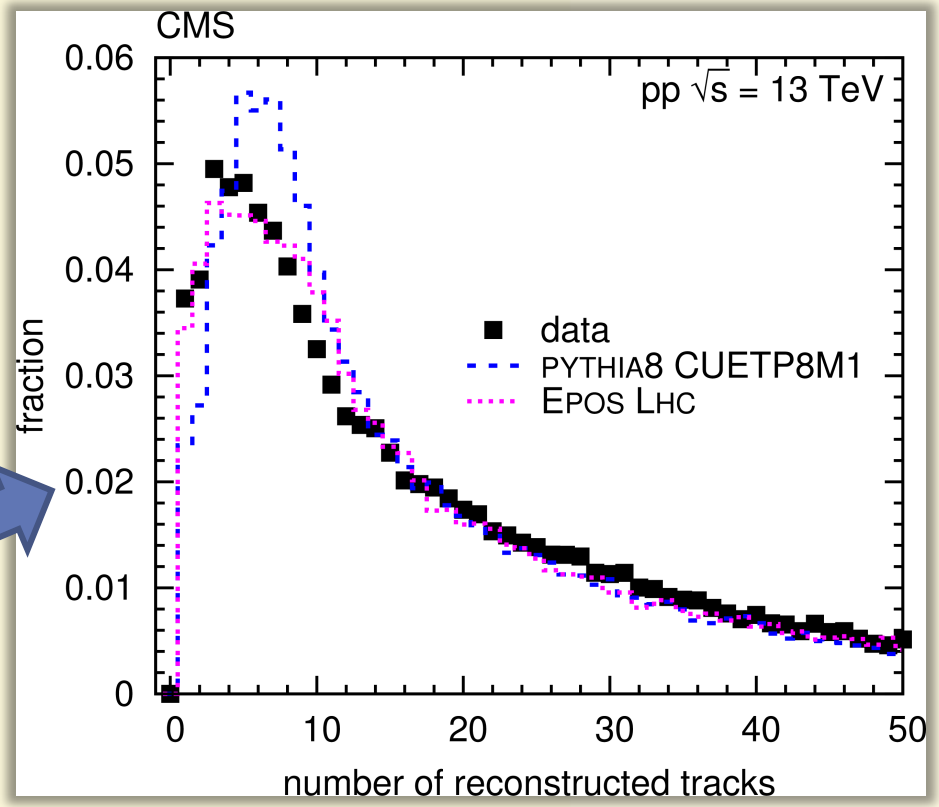
First CMS paper on 13 TeV: arXiv:1507.05915
submitted to PLB

- One of the most basic physical observables in collider physics
- Reflects *relative roles* of **soft-** and **hard-scattering** contributions
- Soft contributions are predicted phenomenologically ➔ **measure in data to adjust the MC simulation**

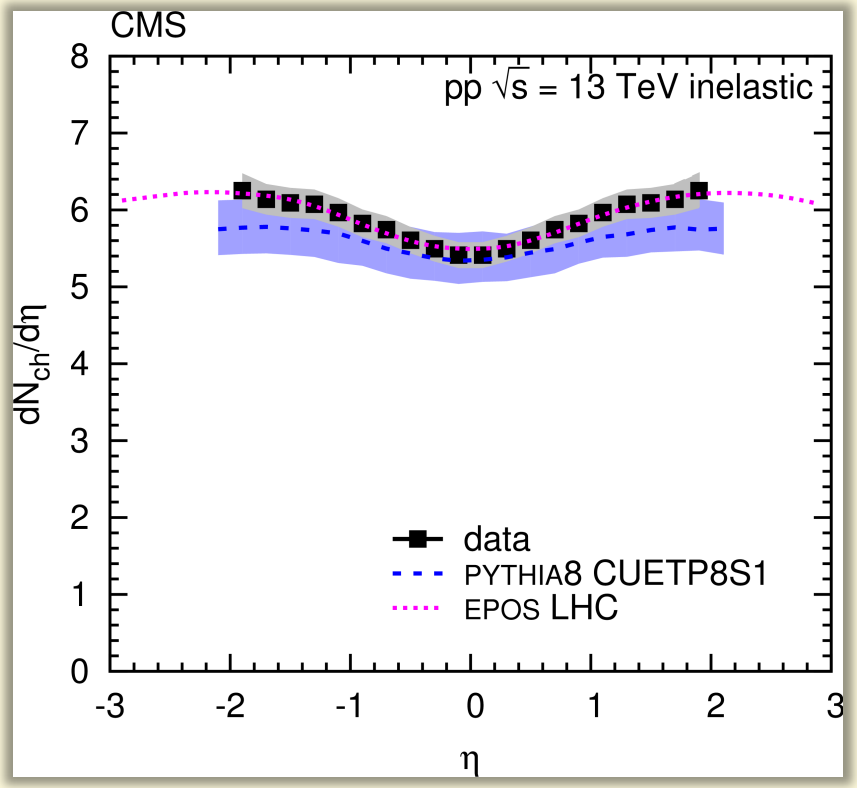


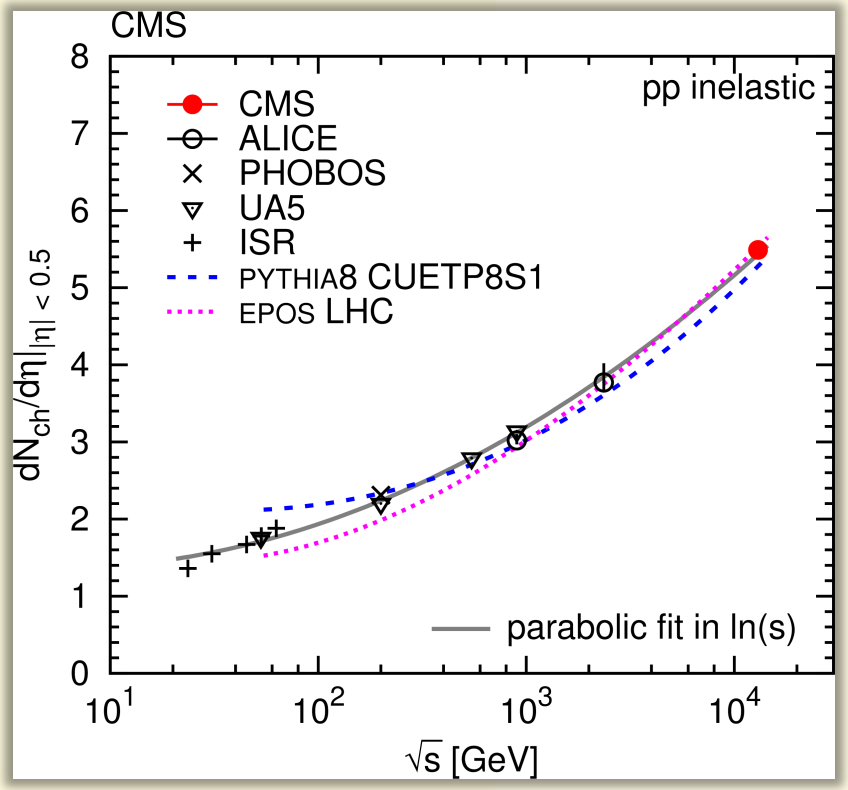
$dN_{ch}/d\eta$

- Use special low-PU data collected at 0T field
  - **PU is 0.2-5%** due to 3σ separation between beams
- **Good agreement** between data and MC, especially at high multiplicities
- All charged particles with $|\eta|<2$
  - Secondary interactions and prompt leptons excluded



$dN_{ch}/d\eta$

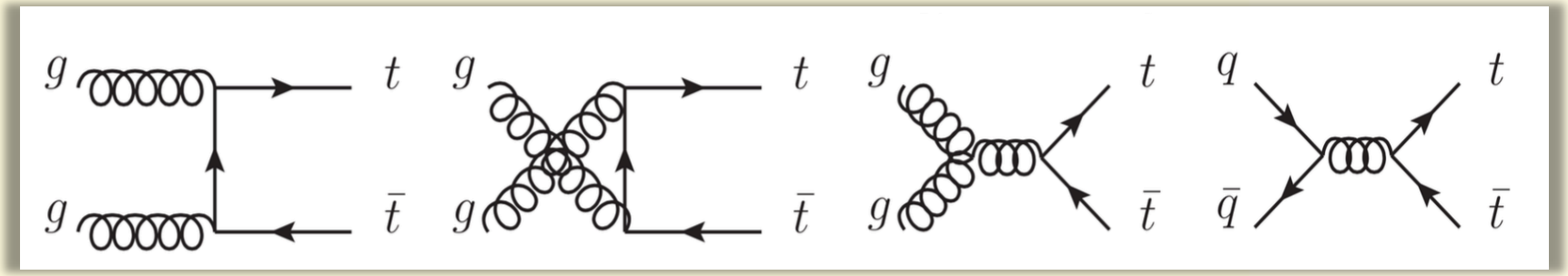




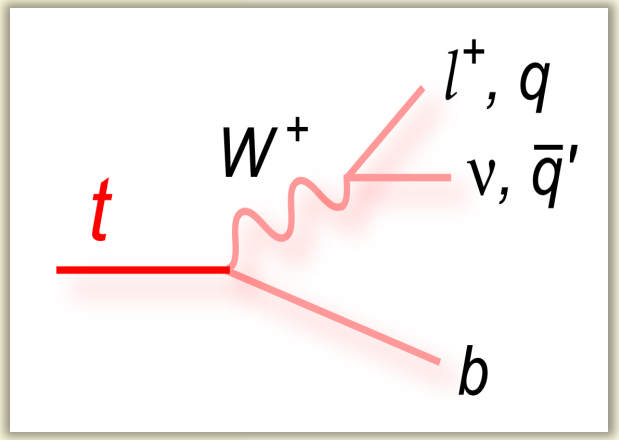
- EPOS and PYTHIA8 CUETP8S1 agree with data in $|\eta| < 0.5$
- EPOS LHC describes data better at higher $|\eta|$ regions

$$dN_{ch}/d\eta_{|\eta|<0.5} = 5.49 \pm 0.01\ (\text{stat}) \pm 0.17\ (\text{syst})$$

Top quark production

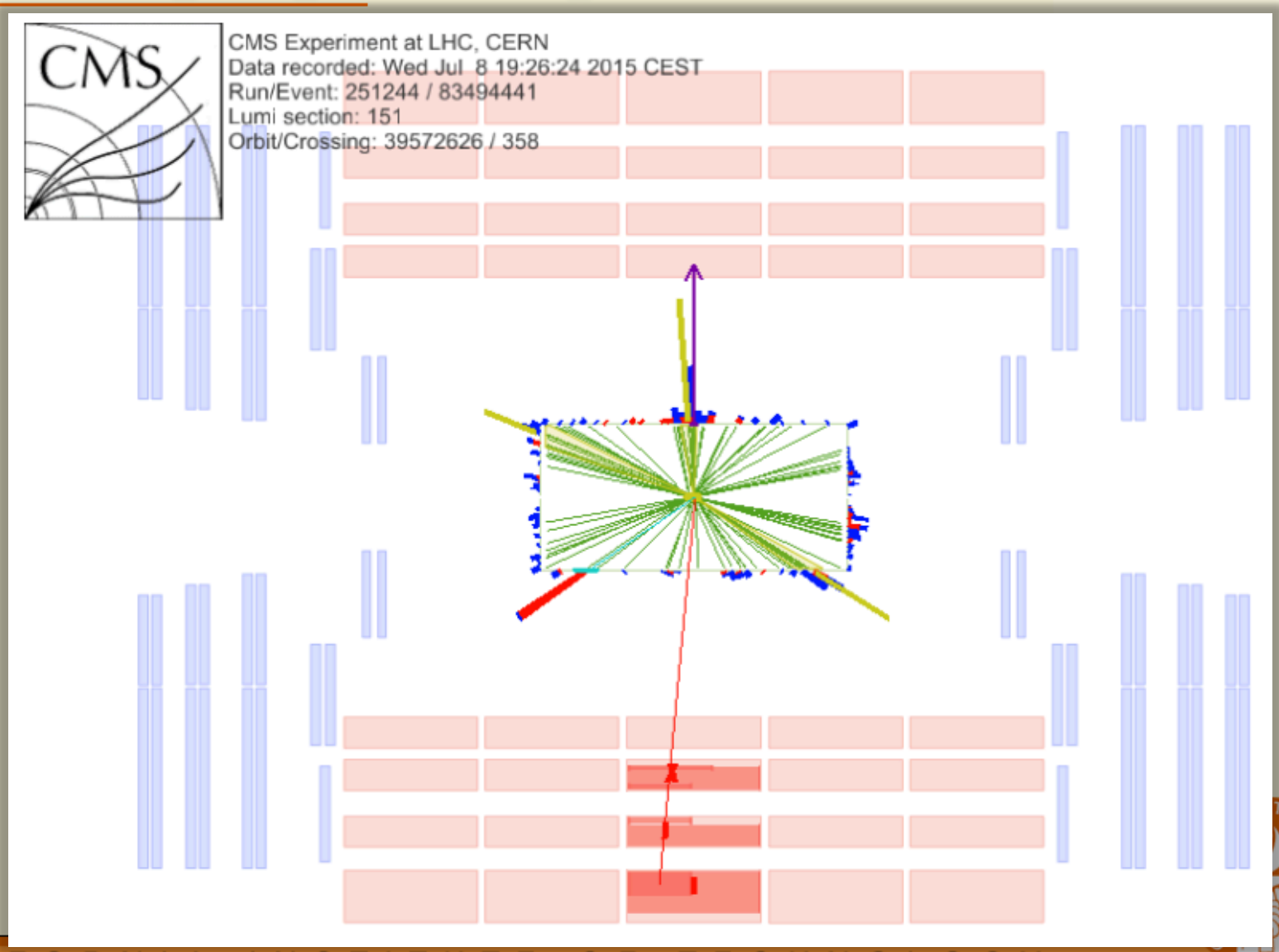


- An ideal final state to test many of the ingredients needed for various NP searches:
  - Relatively high **MET**, **b-tagging**, several **jets**, charged **leptons**
  - Commission new algorithms developed for Run 2
  - Modeling of the PU, underlying event, event generators, PDFs



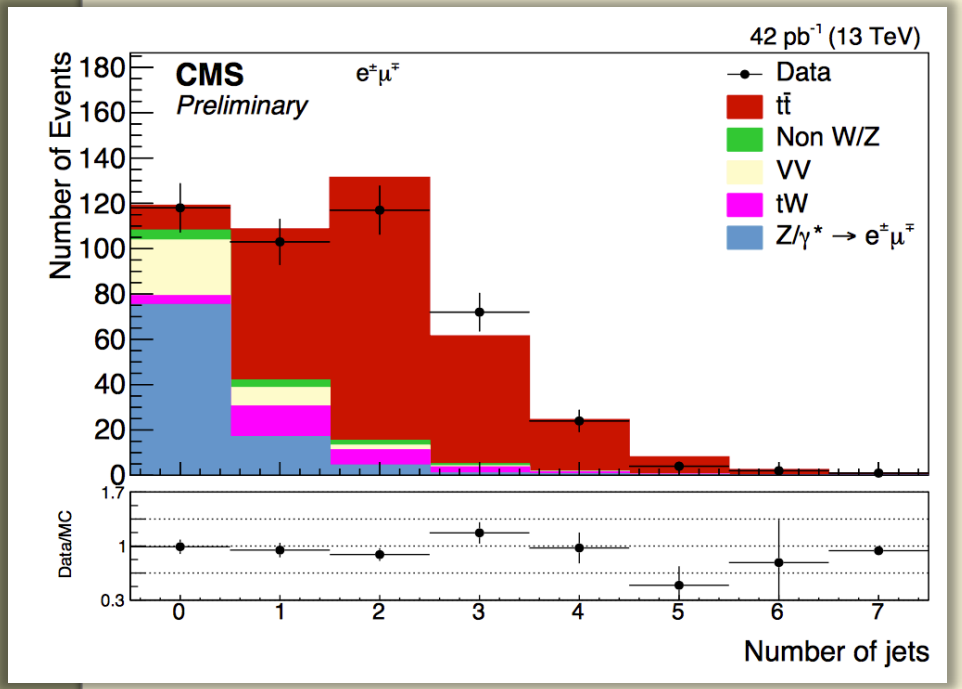
CMS-PAS-TOP-15-003

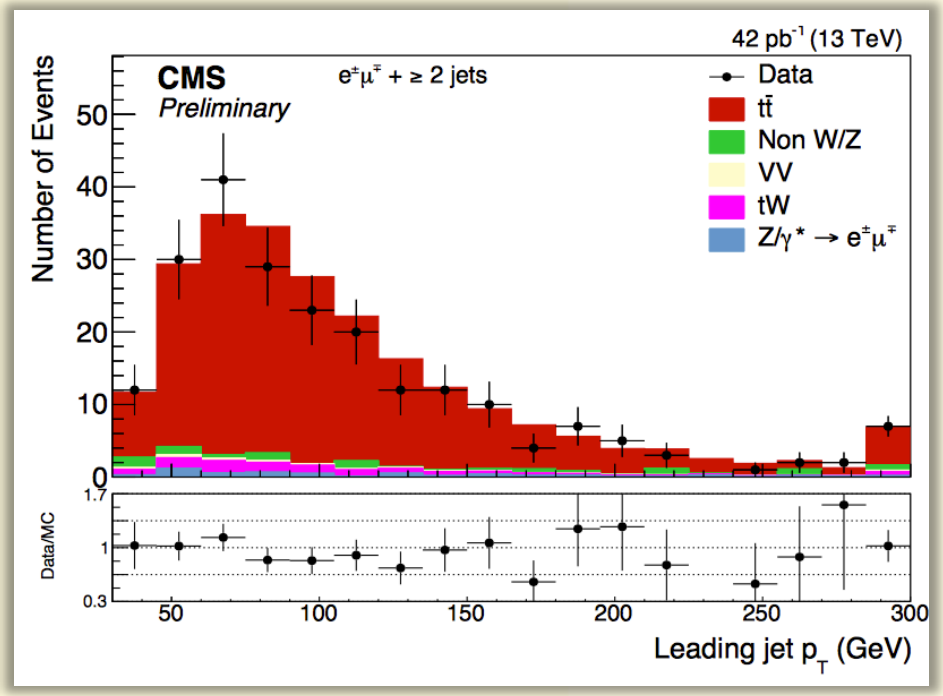
Top quark production



CMS-PAS-TOP-15-003

Top quark production

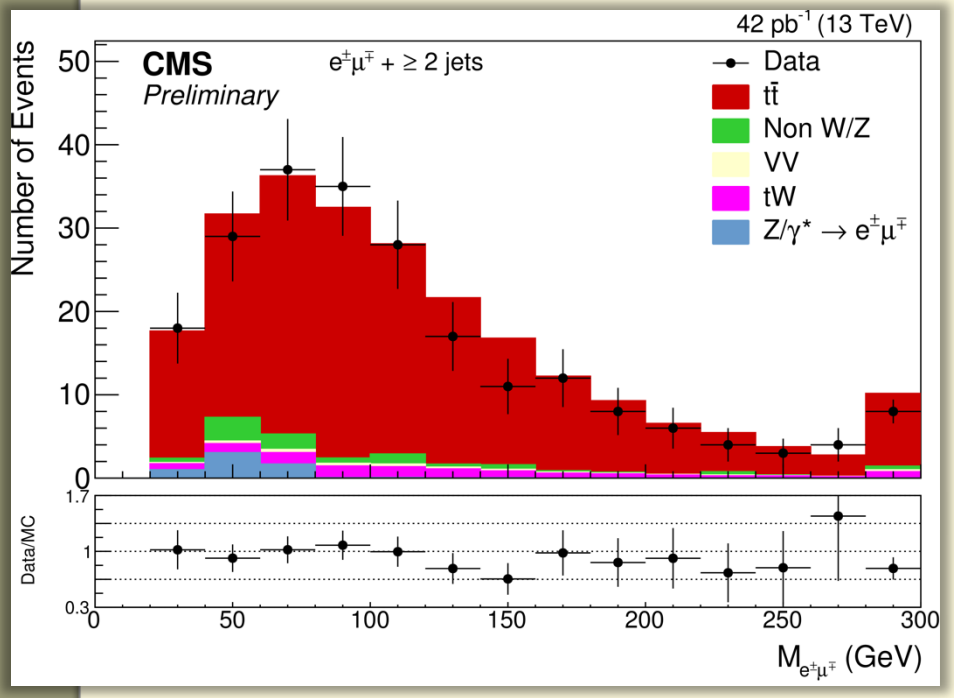


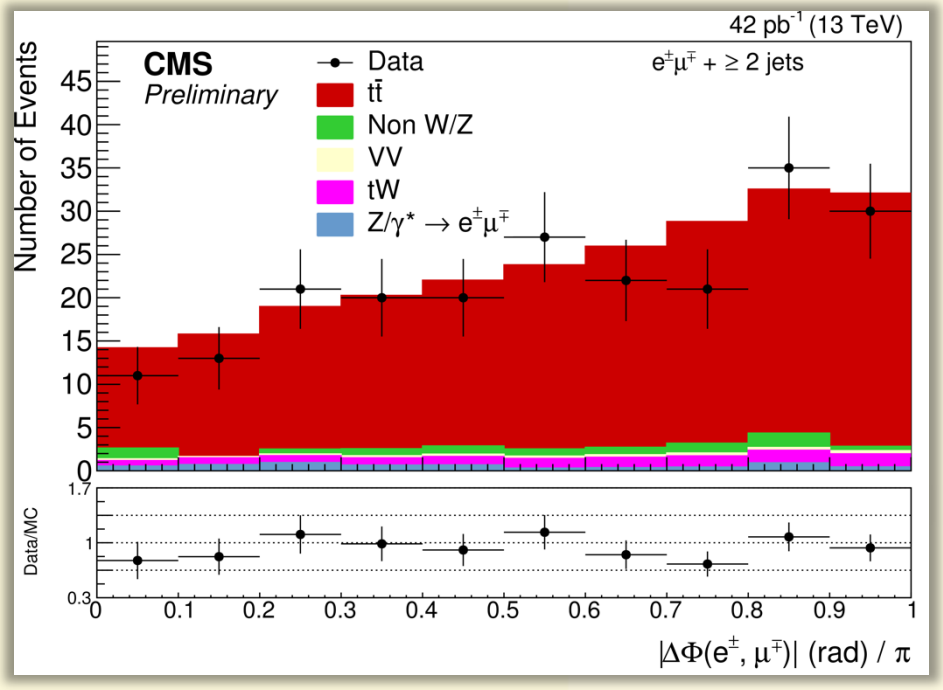


- A clean sample of top quark pairs: **OS electron+muon+jets**
- Leptons: **P_T> 20 GeV, $|\eta|$< 2.4**; Jets: **P_T> 30 GeV, $|\eta|$< 2.4**
- Signal: PowhegV2+Pythia8, normalized to **NNLO+NNLL**
  - Systematics studies with MG5_aMC@NLO, Powheg + Herwig++

CMS-PAS-TOP-15-003

Top quark production

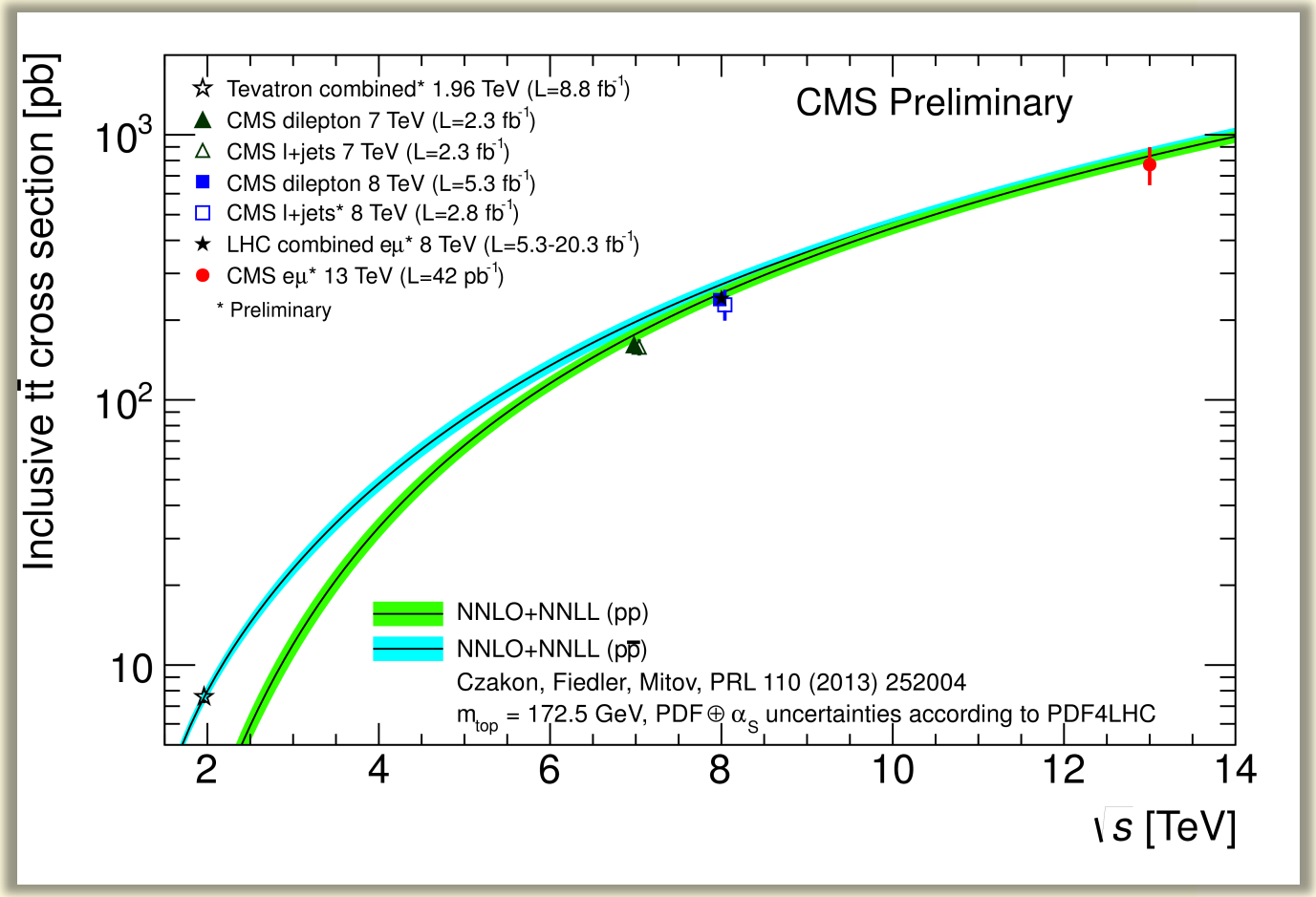




- New particles could show up in these distributions: we are starting exploring the **new regime**!
- Data is well modeled by simulation; gives confidence in **detector and trigger performance**

CMS-PAS-TOP-15-003

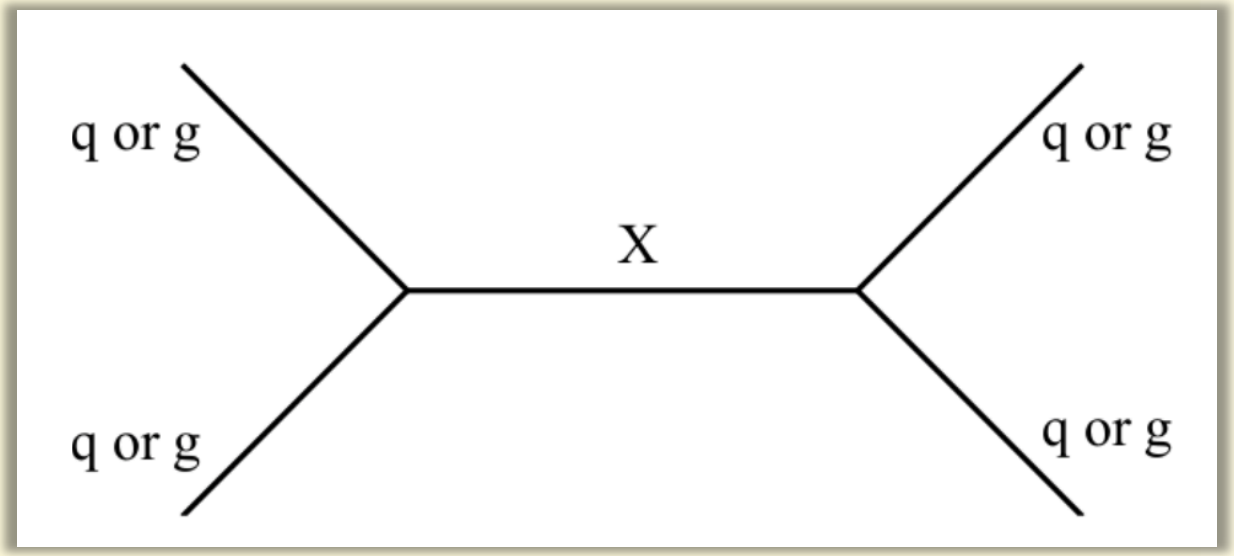
Top quark production



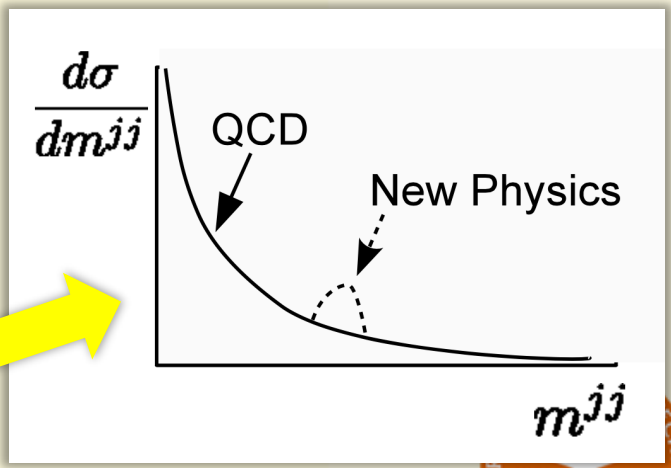
Inclusive σ_{tt}= 772 ± 60 (sta) ± 62 (sys) ± 93 (lum) pb

Large increase in cross section: **σ(13 TeV)/σ(8 TeV)~3**

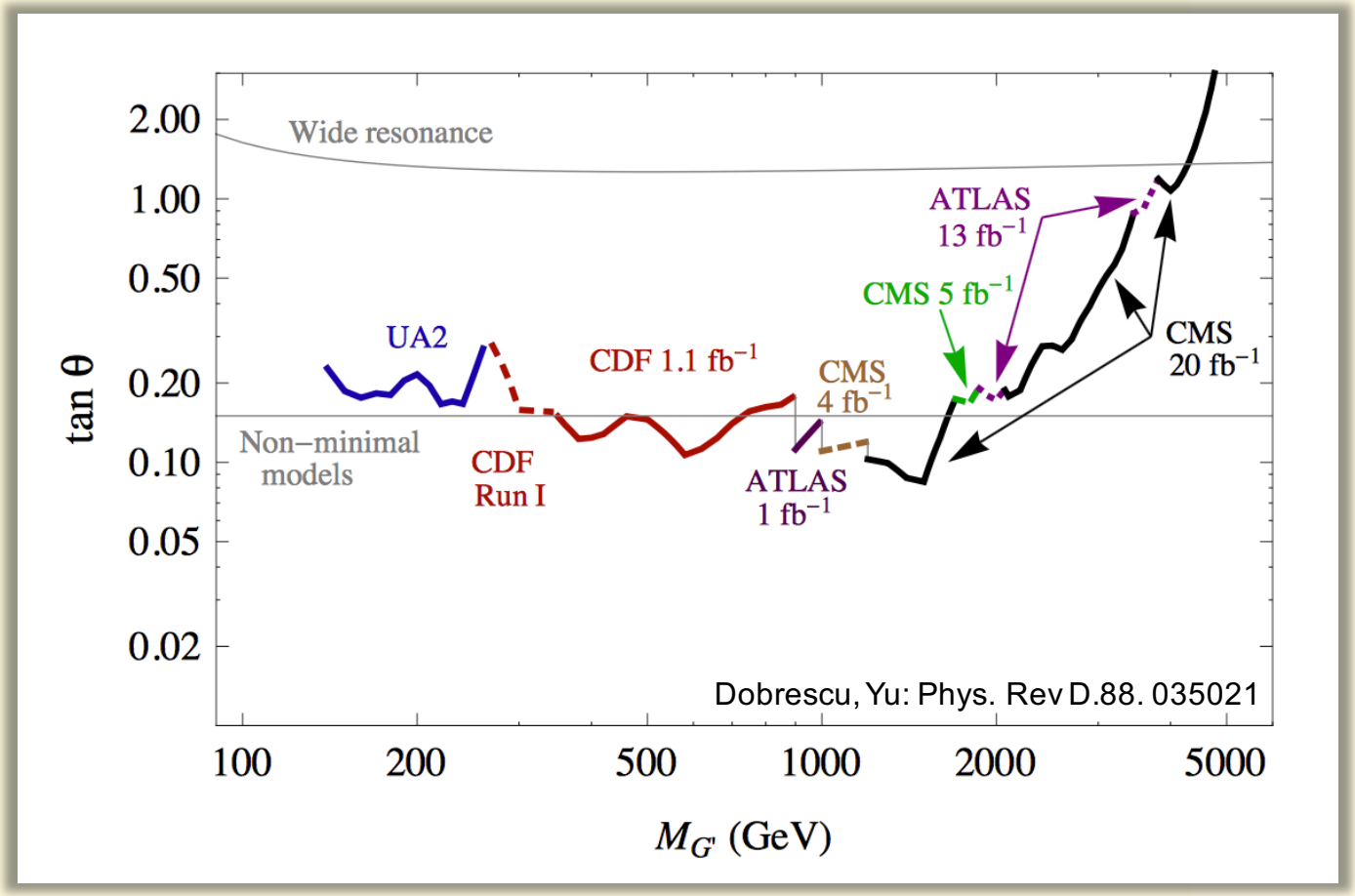
Dijet resonances



- Hadronic final states sensitive to many extensions of the SM
- Strong production: dijets provide an early discovery potential
  - Look for **bumps in dijet mass**

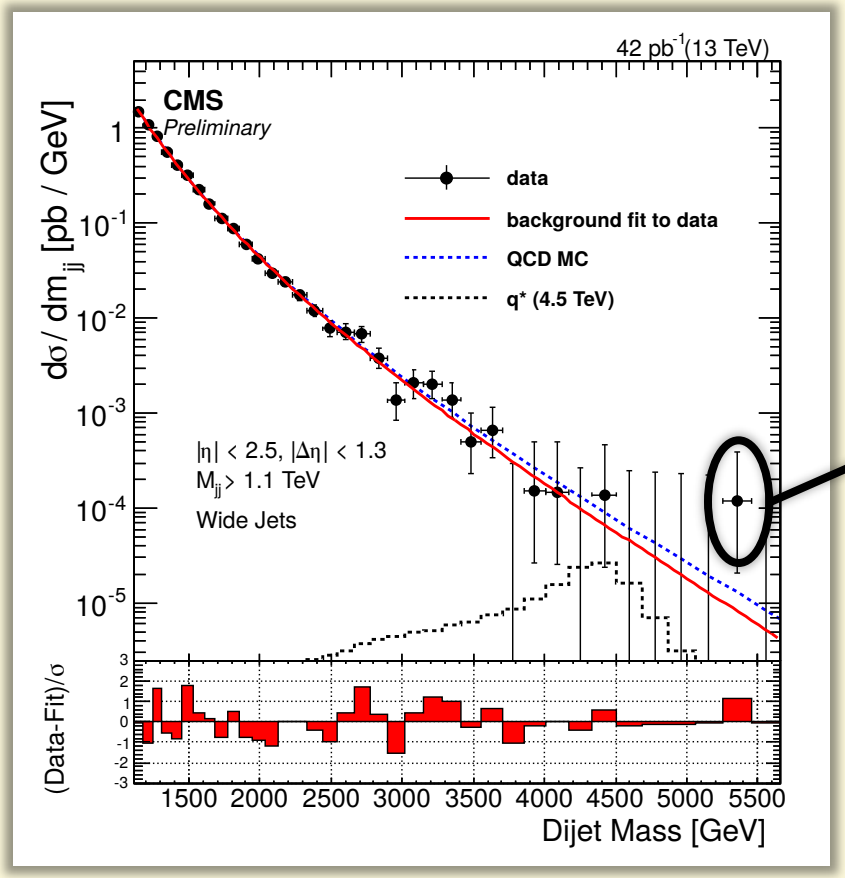


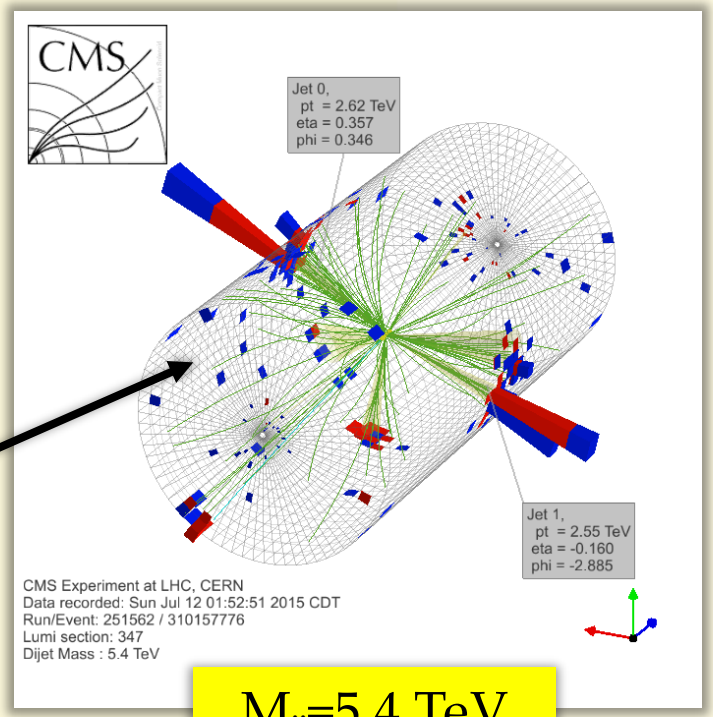
Dijet resonances



- Searches for s-channel production performed over the past **three decades:** limits up to **~5 TeV**

Dijet resonance





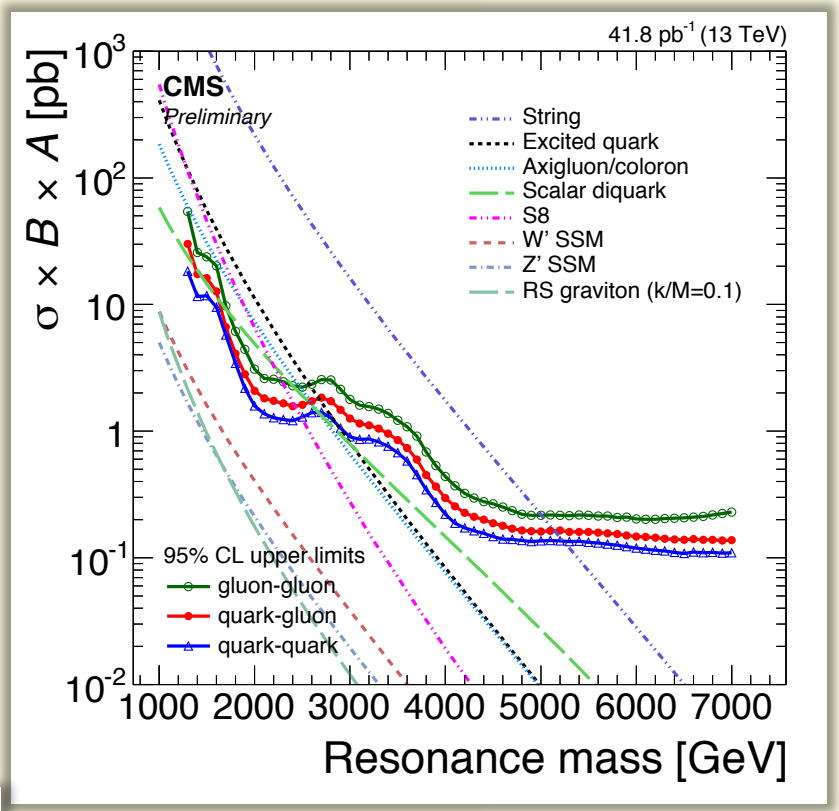
M_{jj}=5.4 TeV

- Background model:
  - Don't rely on background MC
  - Fit a smooth function to the data

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2}}$$

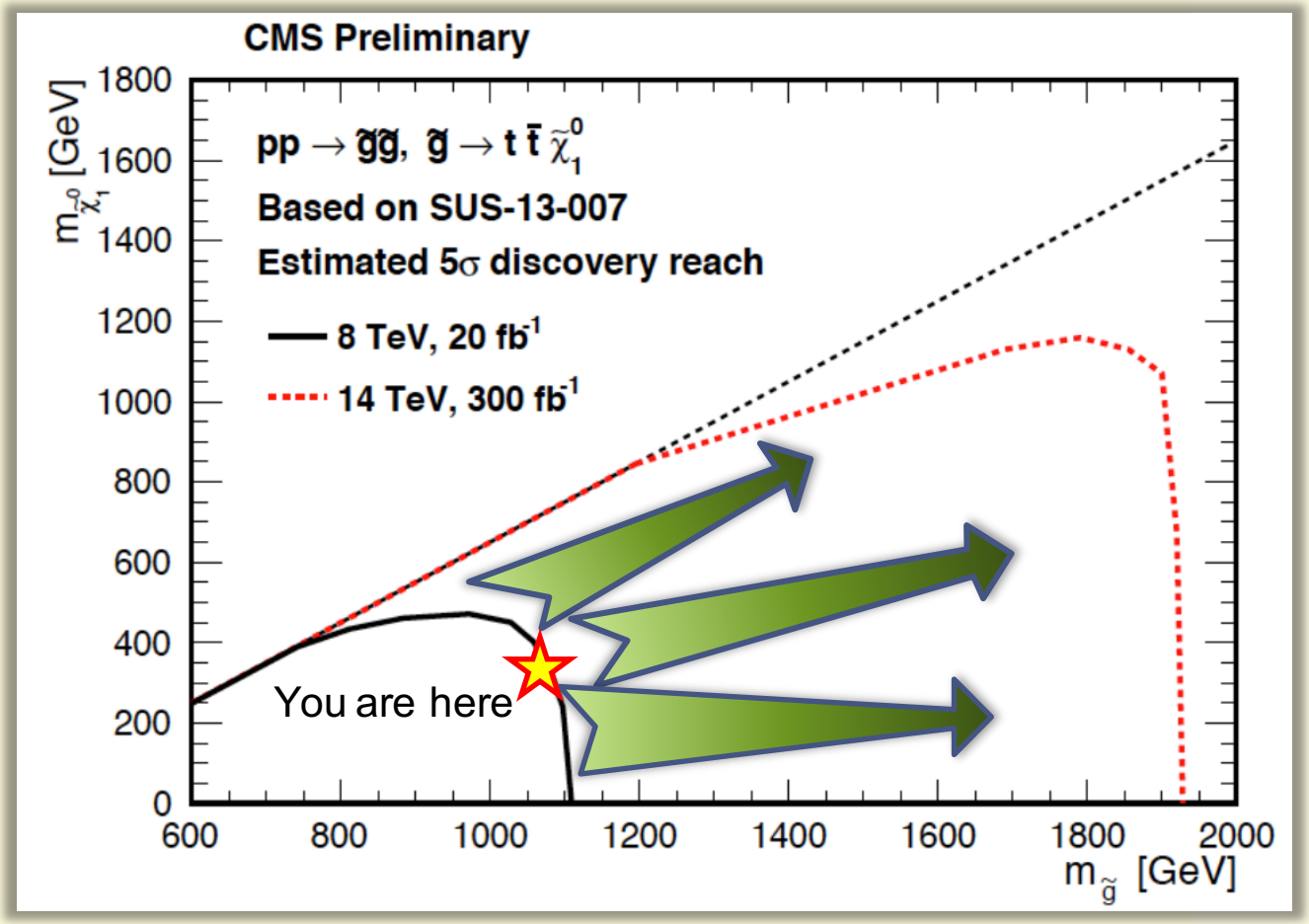
Dijet resonance

- Set 95% CL upper limits are set on $\sigma \times Br \times A$
- Interpret the results as limits on several signal models
  - Narrow resonances with width smaller than CMS M_{jj} resolution
- **Best Run 1 limit was 5.0 TeV**

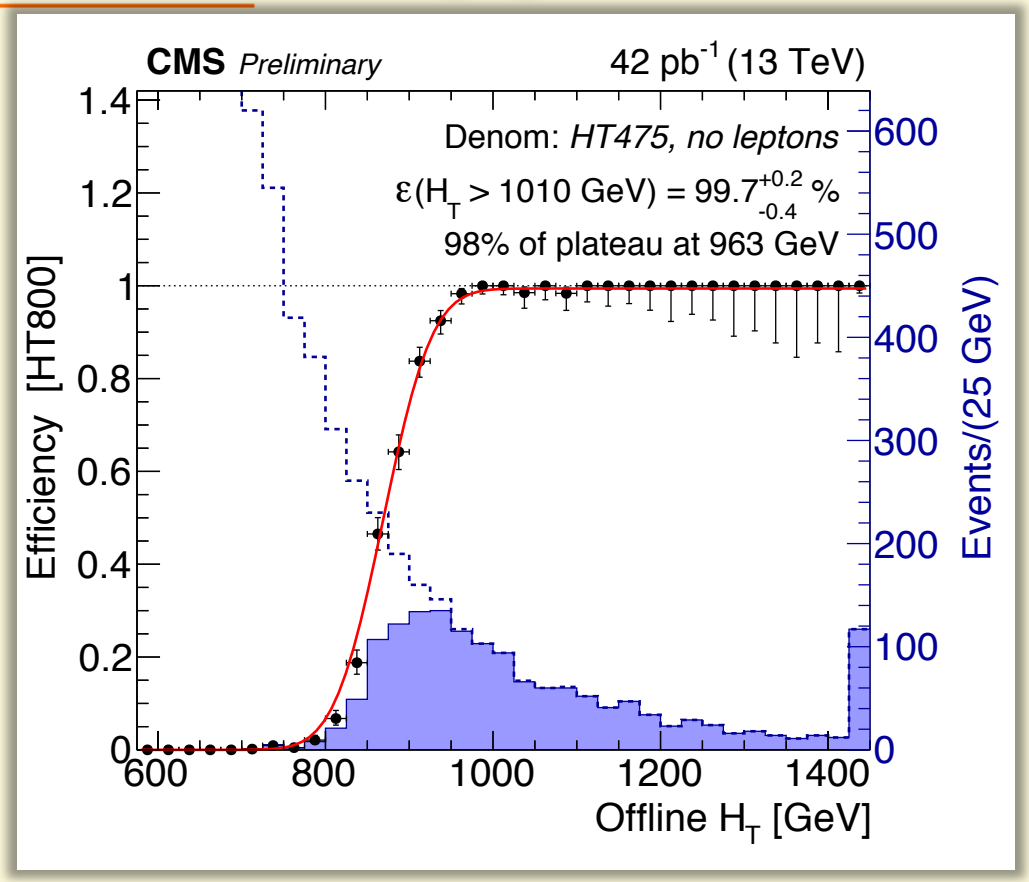


Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String Resonance (S)	qg	5.1	5.2
Excited Quark (q*)	qg	2.7	2.9
Scalar Diquark (D)	qq	2.7	3.3
Axigluon (A)/Coloron (C)	$q\bar{q}$	2.7	2.9
Color Octet Scalar (s8)	gg	2.3	2.0

A new front of attack



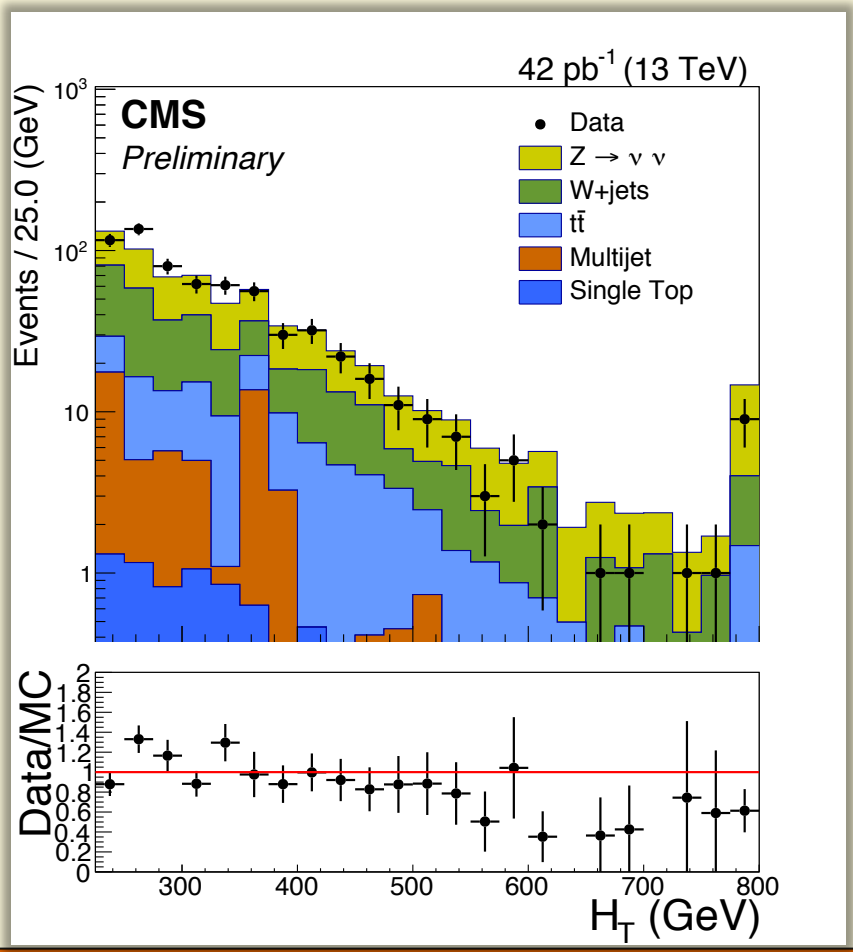
Triggers

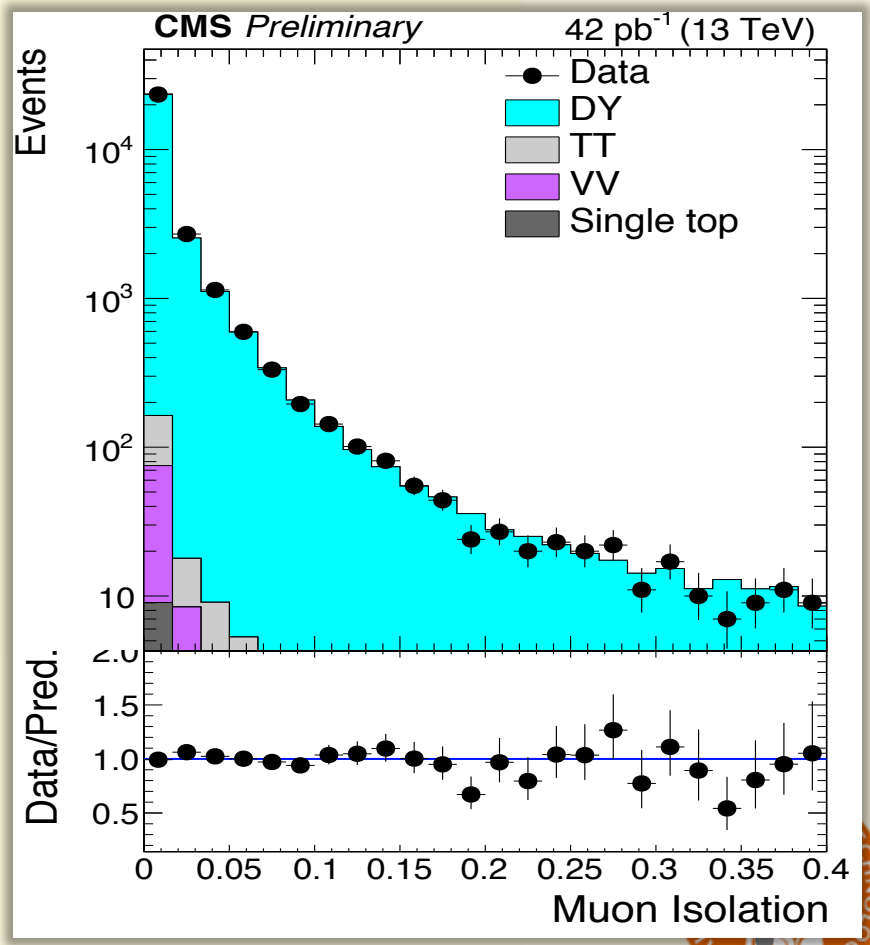


- First line of attack is to **collect signals with high efficiency**
- Trigger efficiency measurements show **good control** of the online and offline reconstruction

Background estimation

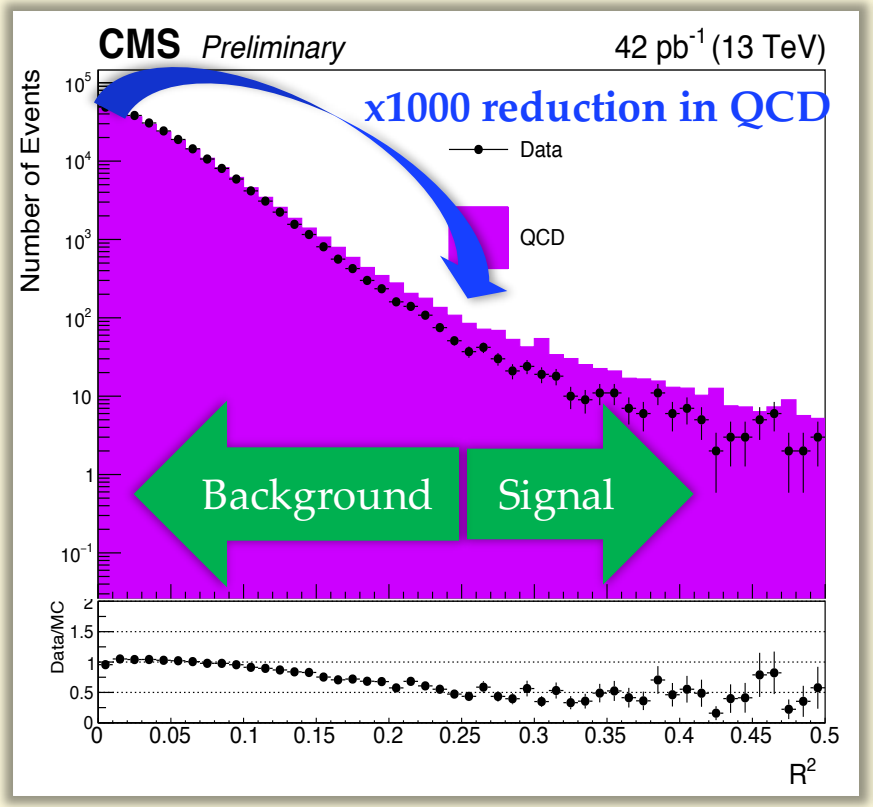
- A whole new energy regime: do our background estimation methods still work?

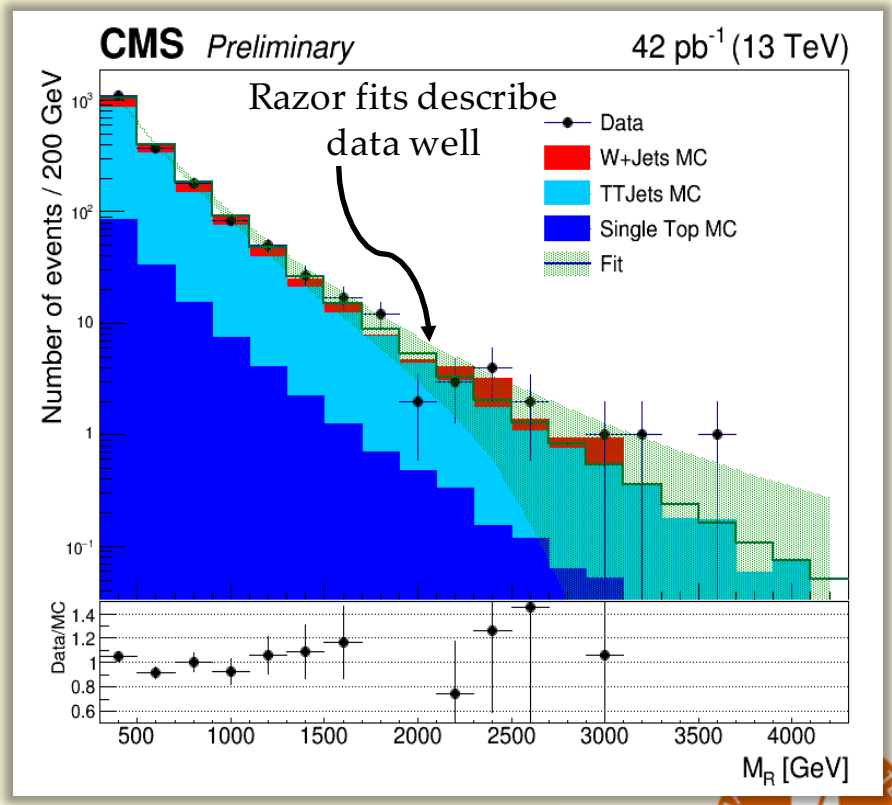




Background estimation

- A whole new energy regime: do our background estimation methods still work?

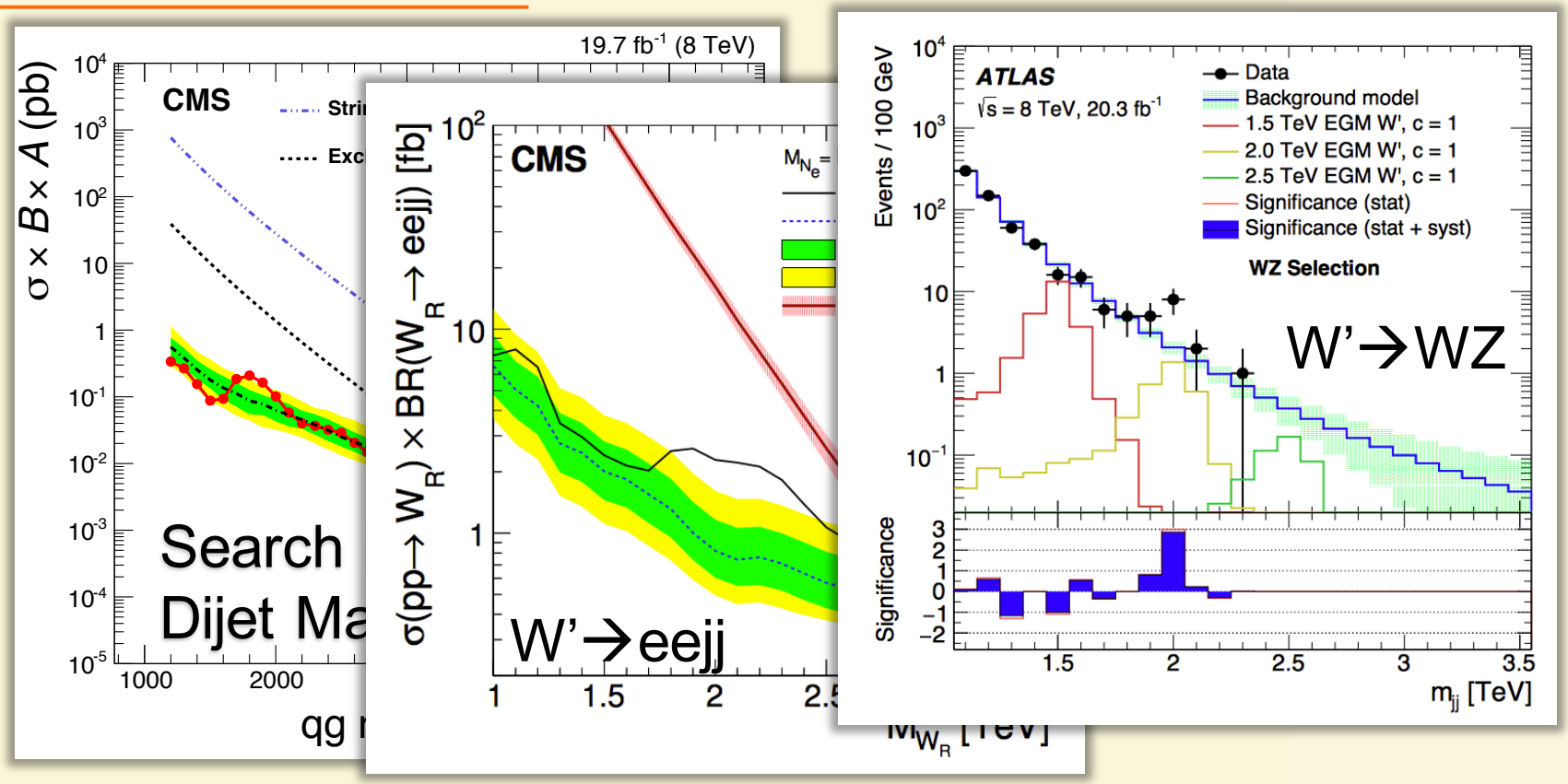




What to keep an eye on?

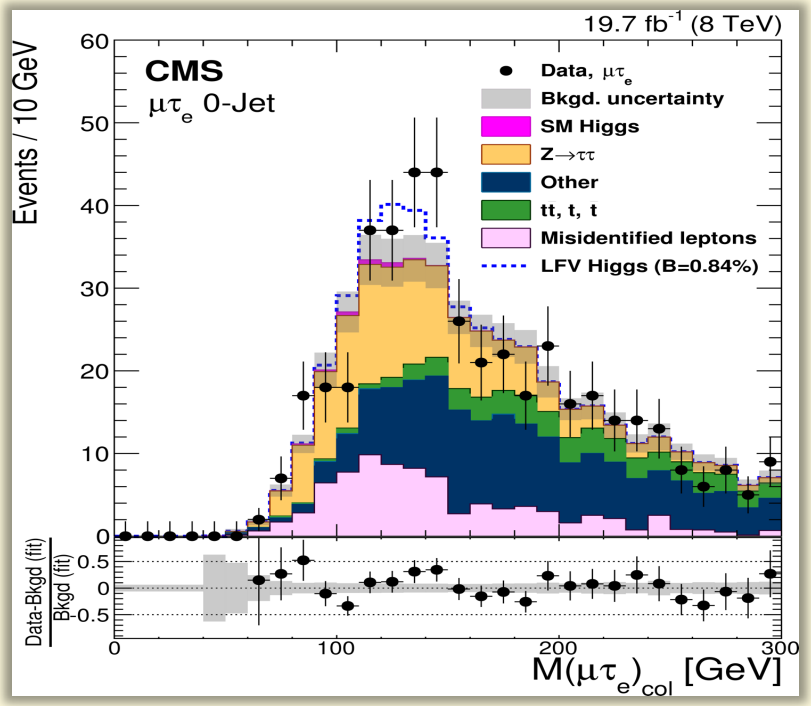
- A few intriguing excesses from Run 1
  - A "resonance" around 2 TeV??
  - Excess $H \rightarrow \mu\tau$
  - $H \rightarrow \gamma\gamma$ with Razor
  - ttH
  - The dilepton "edge"
  - others…

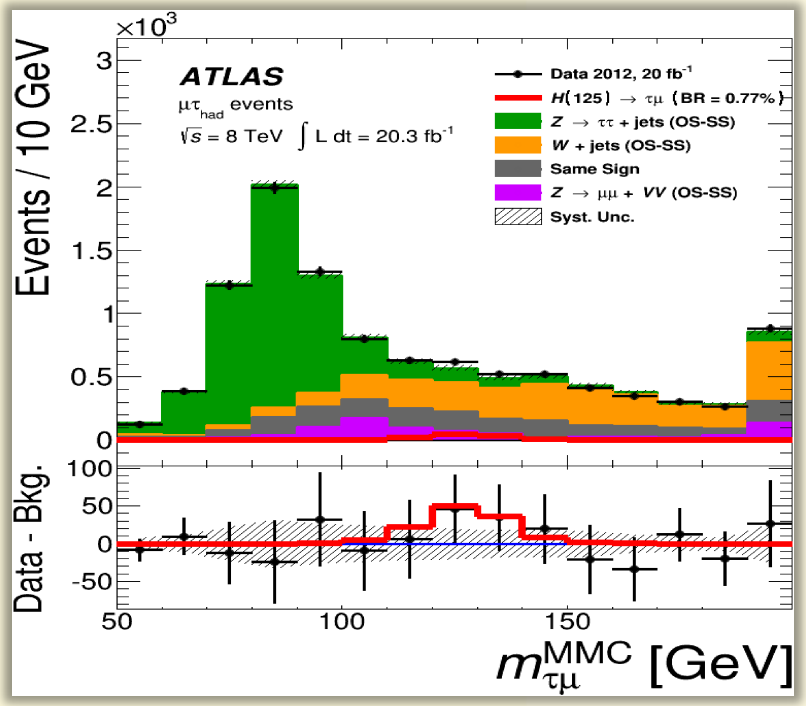
2TeV excess



- Excess around 2 TeV seen in both CMS and ATLAS
  - Not always consistent in the same channels…
- Need 3-5 fb^{-1} to confirm or dispel the intrigue

H→μτ

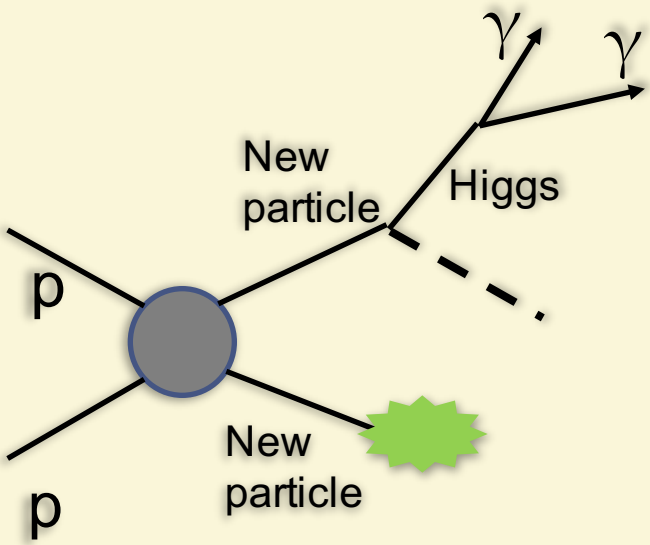


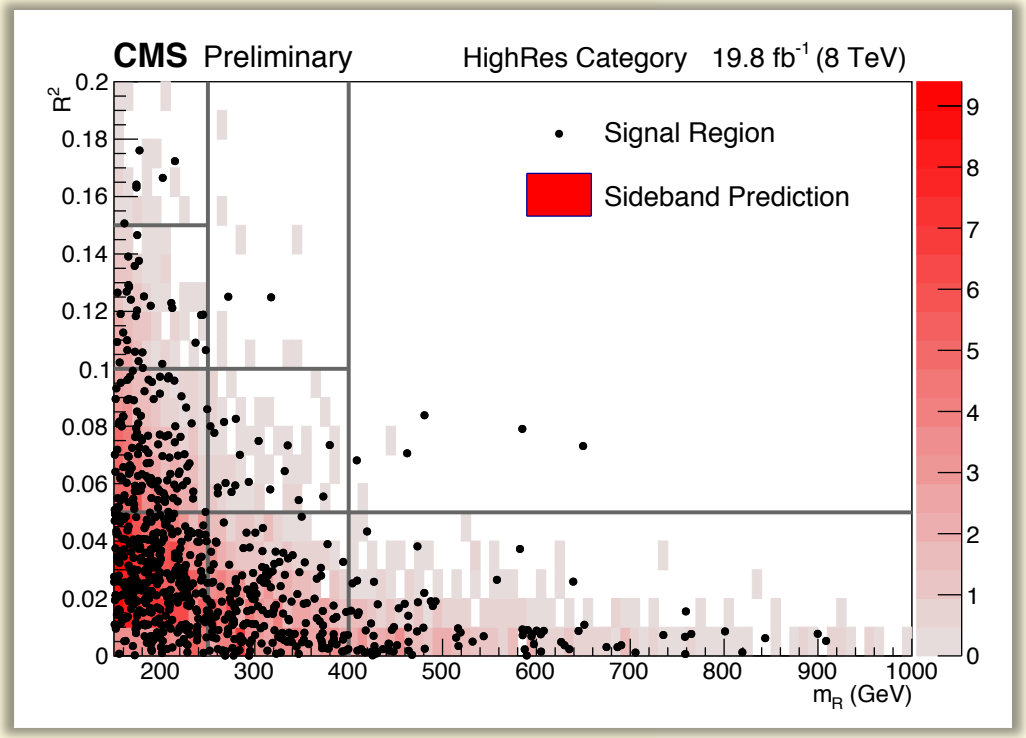


- LFV Higgs decays: Models with >= 1 Higgs doublet, composite Higgs, RS models, etc…
- Best fit value for Br(H → μτ)= **0.84±0.4% @ CMS**, and **0.77±0.62% @ATLAS**
- Excess in **CMS ~ 2.84σ**, at **ATLAS ~2.2σ**

New

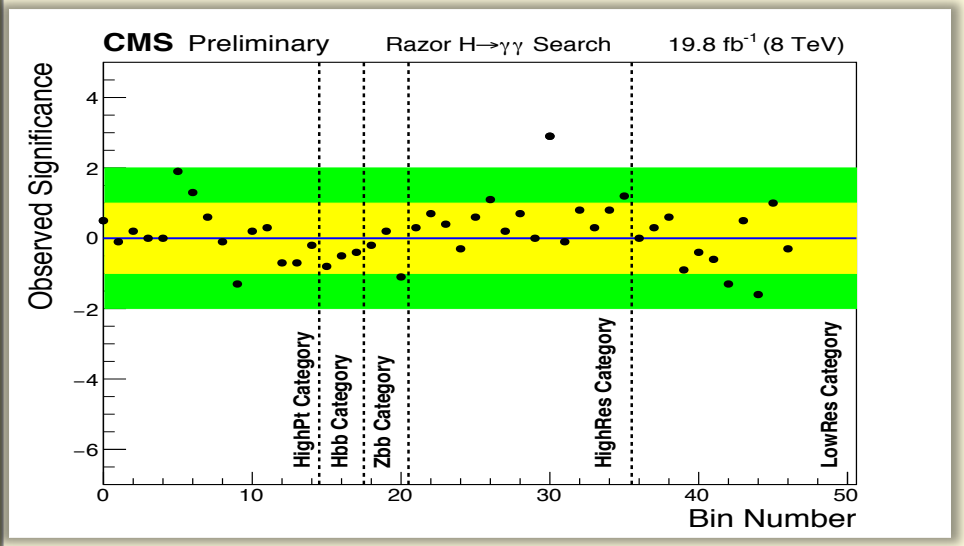
H→γγ with Razor





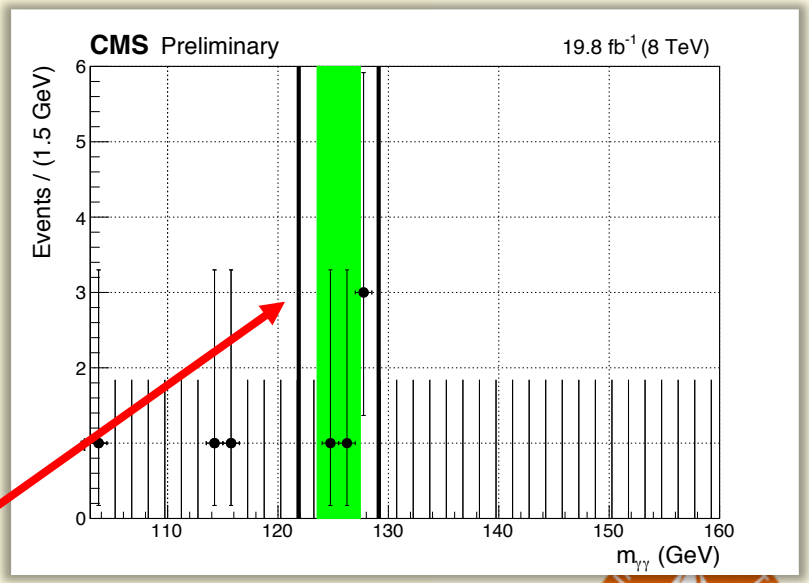
- Search for new physics using the **Higgs as an event *"tag"***
- Reconstruct events with the "Razor" variables
- Backgrounds estimated from **$m_{\gamma\gamma}$ sidebands**

H→γγ with Razor



- Good agreement with background expectation
- One signal box has ~3σ local significance

M_R region	R^2 region	observed events	expected background	p-value	significance (σ)
150 - 250	0.00 - 0.05	363	$357.6^{+9.6}_{-9.4}$(syst.)	0.40	0.3
150 - 250	0.05 - 0.10	149	$139.4^{+5.6}_{-5.4}$(syst.)	0.23	0.7
150 - 250	0.10 - 0.15	35	$32.5^{+3.4}_{-3.1}$(syst.)	0.34	0.4
150 - 250	0.15 - 1.00	7	$8.0^{+1.7}_{-1.4}$(syst.)	0.40	-0.3
250 - 400	0.00 - 0.05	218	$207.9^{+7.0}_{-6.8}$(syst.)	0.27	0.6
250 - 400	0.05 - 0.10	20	$14.7^{+2.5}_{-2.1}$(syst.)	0.13	1.1
250 - 400	0.10 - 1.00	3	$2.7^{+0.8}_{-0.6}$(syst.)	0.43	0.2
400 - 1400	0.00 - 0.05	109	$101.6^{+5.0}_{-4.8}$(syst.)	0.26	0.7
400 - 1400	0.05 - 1.00	5	$0.5^{+0.4}_{-0.2}$(syst.)	0.002	2.9
1400 - 3000	0.00 - 1.00	0	$0.9^{+0.5}_{-0.3}$(syst.)	0.44	-0.1



Summary

- Accelerator and the detector perform very well, with many improvements on all fronts
  - Sub-detectors, DAQ, computing, etc…
- The LHC and CMS have successfully entered the new era of explorations of the terascale
- The search season is starting, and many new results will come soon

Backups

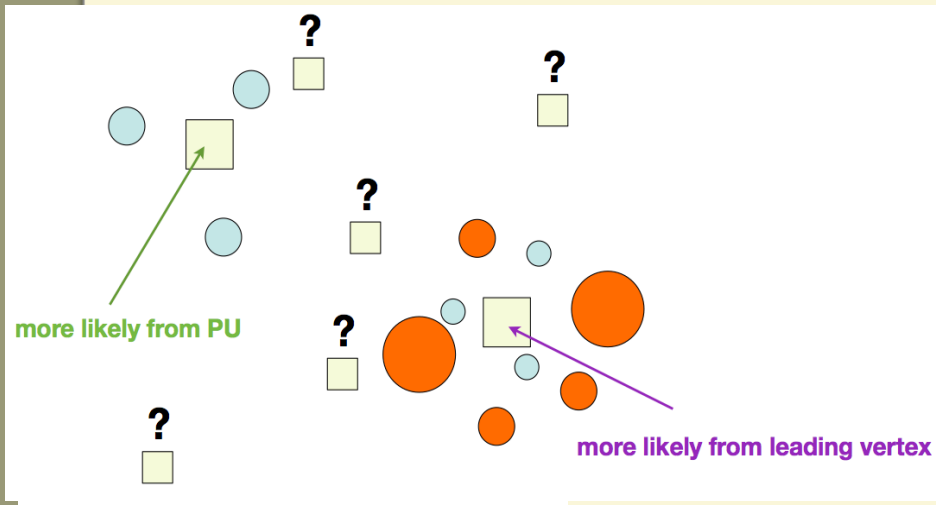
Uncertainties in σ_{tt}

Table 1: Summary of the individual contributions to the systematic uncertainty on the $\sigma_{t\bar{t}}$ measurement. The uncertainties are given in pb and as relative uncertainties. The statistical uncertainty and the total uncertainty on the result are also given.

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	60	7.7
Trigger efficiencies	39	5.0
Lepton efficiencies	33	4.3
Lepton energy scale	< 1	≤ 0.1
Jet energy scale	20	2.6
Jet energy resolution	< 1	≤ 0.1
Pileup	2.8	0.4
Scale (μ_F and μ_R)	1.5	0.2
$t\bar{t}$ NLO generator	15	1.9
$t\bar{t}$ hadronization	14	1.8
PDF	12	1.5
Single top quark	14	1.8
VV	3.5	0.5
Drell–Yan	3.9	0.5
Non-W/Z leptons	8	1.0
Total systematic (no integrated luminosity)	62	8.0
Integrated luminosity	93	12
Total	126	16.4

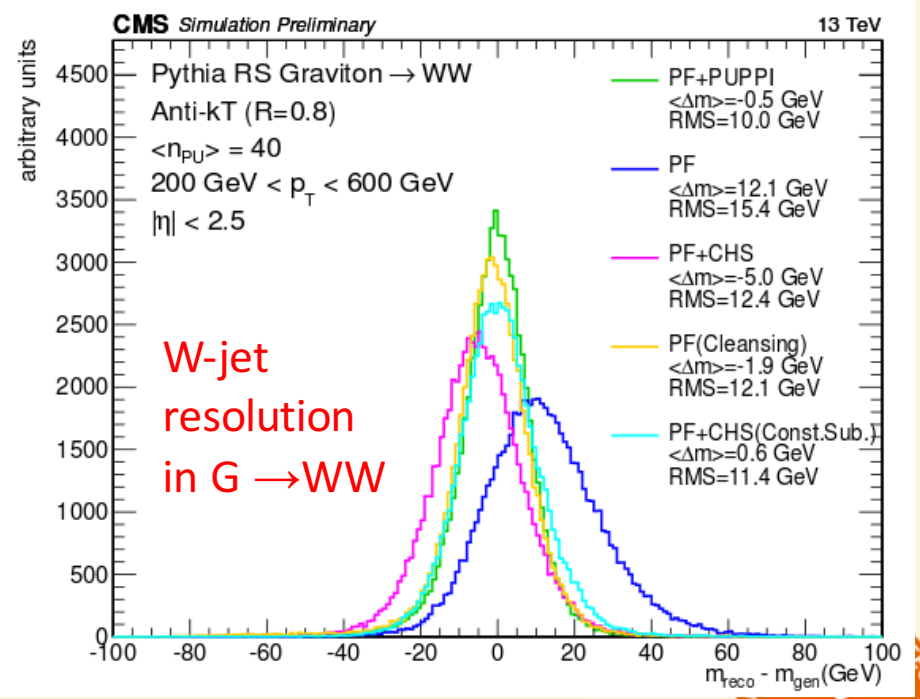
PUPPI

- PUPPI* technique uses per-particle PU subtraction. First results based on full reconstruction look promising
  - Can also be used on lepton isolation



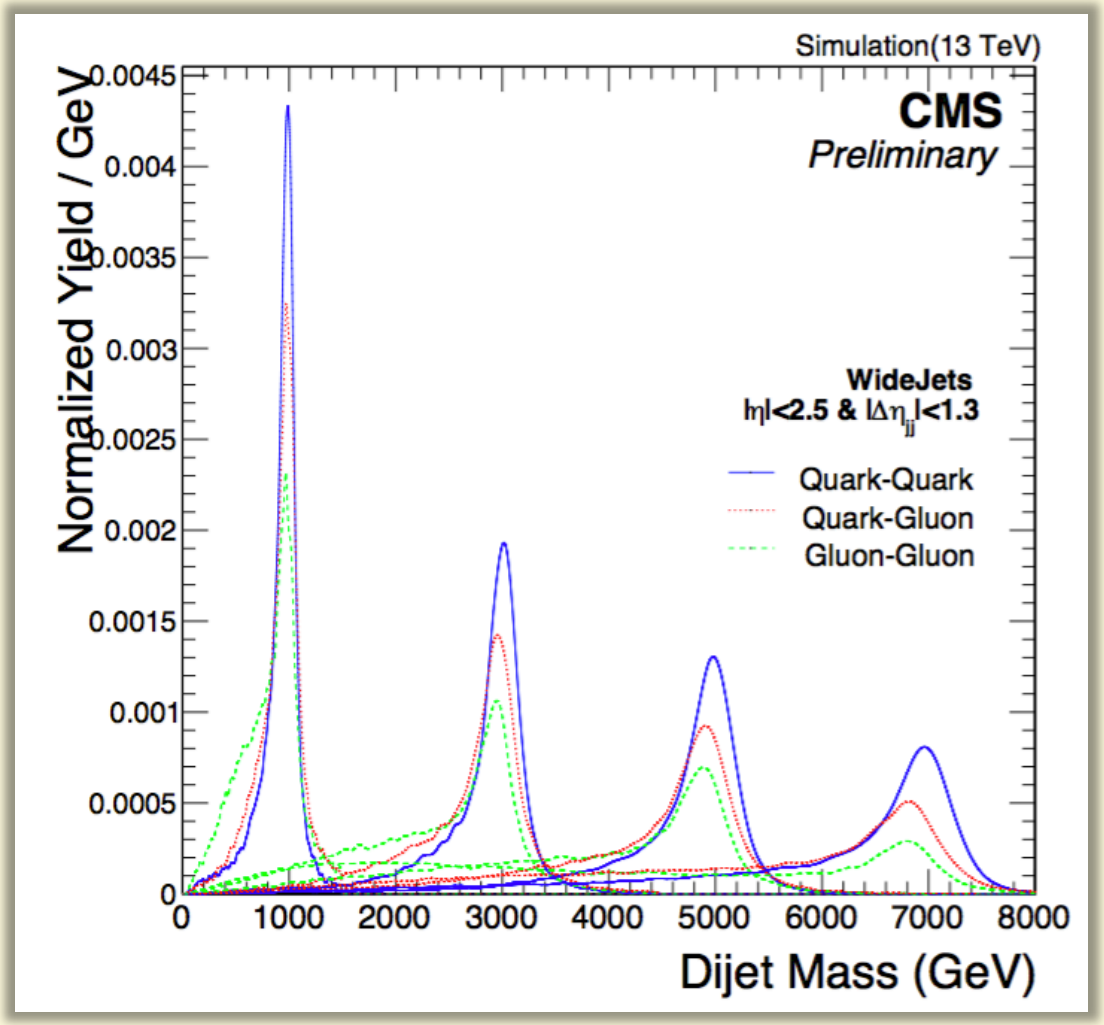
$$\alpha_i = \log \sum_{j \in \text{event}} \frac{p_{Tj}}{\Delta R_{ij}}$$

$$R_{\min} \leq \Delta R_{ij} \leq R_0$$

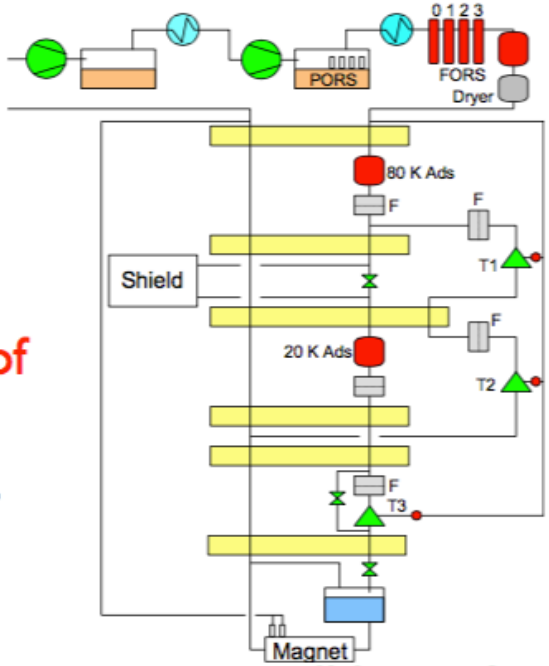


*Pile-Up Per Particle Id, http://arxiv.org/abs/1407.6013

Resonance Spectrum



Magnet cryogenics issues



- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The data delivered during the first two weeks of LHC re-commissioning with beams at low luminosity have been collected with B=0
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.