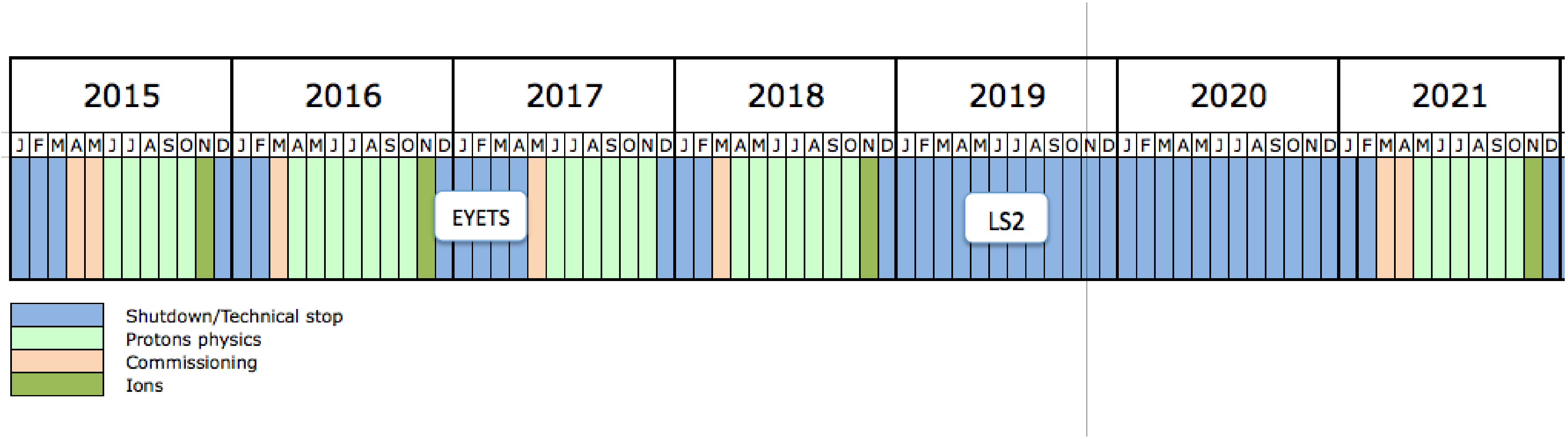
CMS+TOTEM experimental overview

S.Lehti, HIP

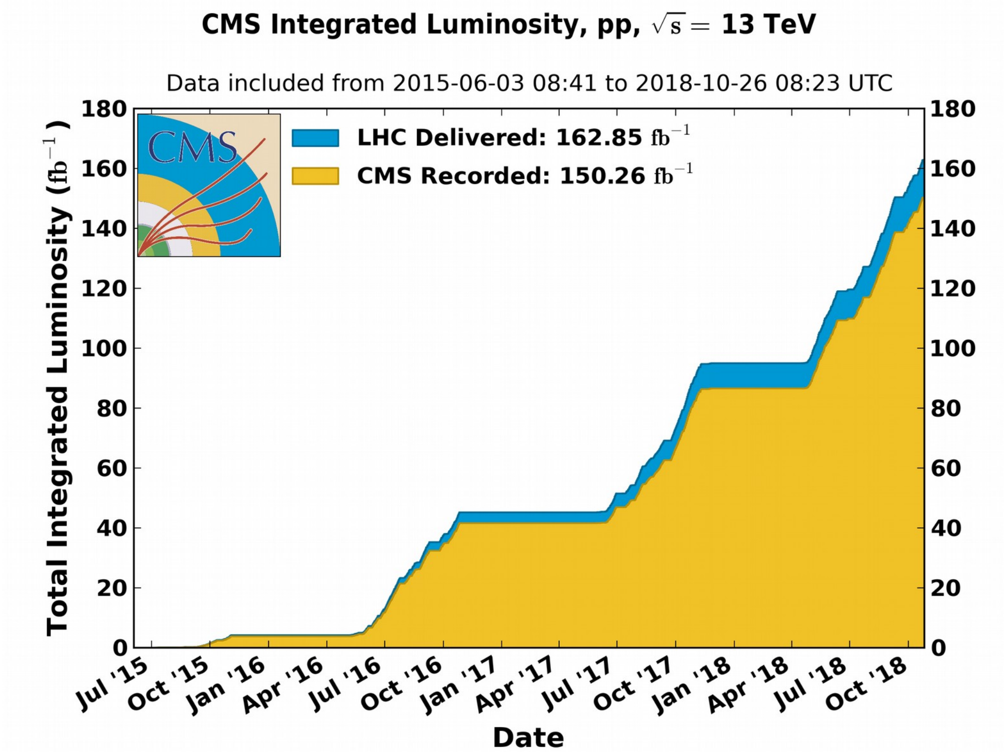
Long shutdown 2

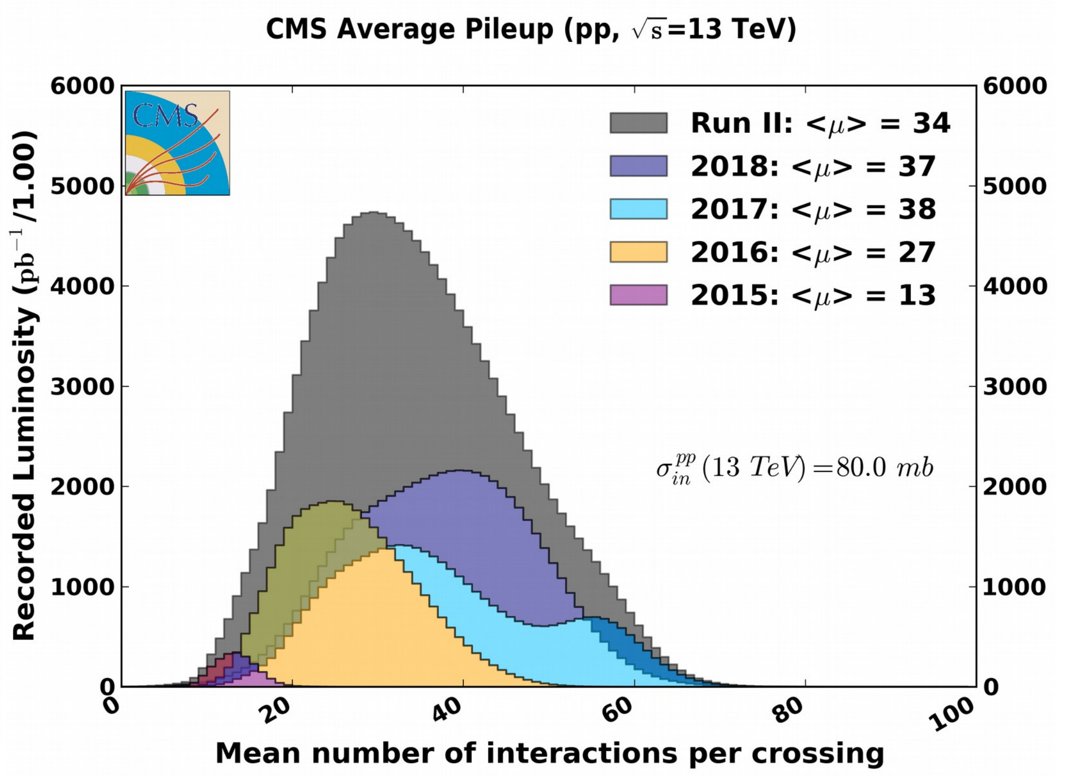


- Challenges in 2021-2023
  - High trigger rates
  - Large pileup over long time
  - Radiation damage

B.Vormwald

Run-2



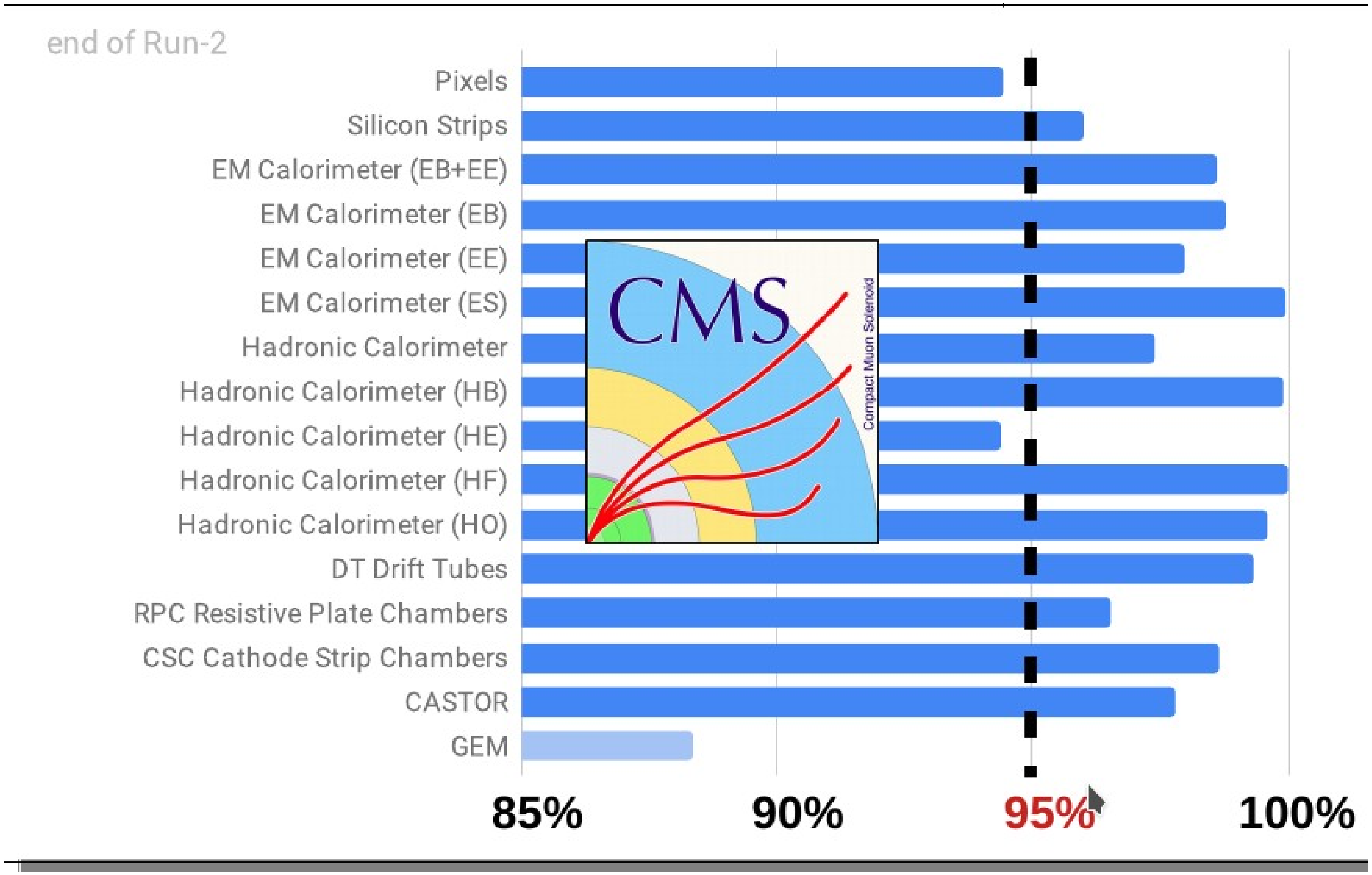


CMS	delivered	recorded	
2015	4.2 fb^{-1}	3.8 fb^{-1}	90%
2016	41.1 fb^{-1}	37.8 fb^{-1}	92%
2017	50.3 fb^{-1}	45.4 fb^{-1}	90%
2018	66.9 fb^{-1}	62.8 fb^{-1}	94%
	162.8 fb^{-1}	**150.2 fb^{-1}**	**92%**

- CMS data in Run-2
  - Excellent quality
    - Taken with evolving detector configuration (pixel, HCAL readout)

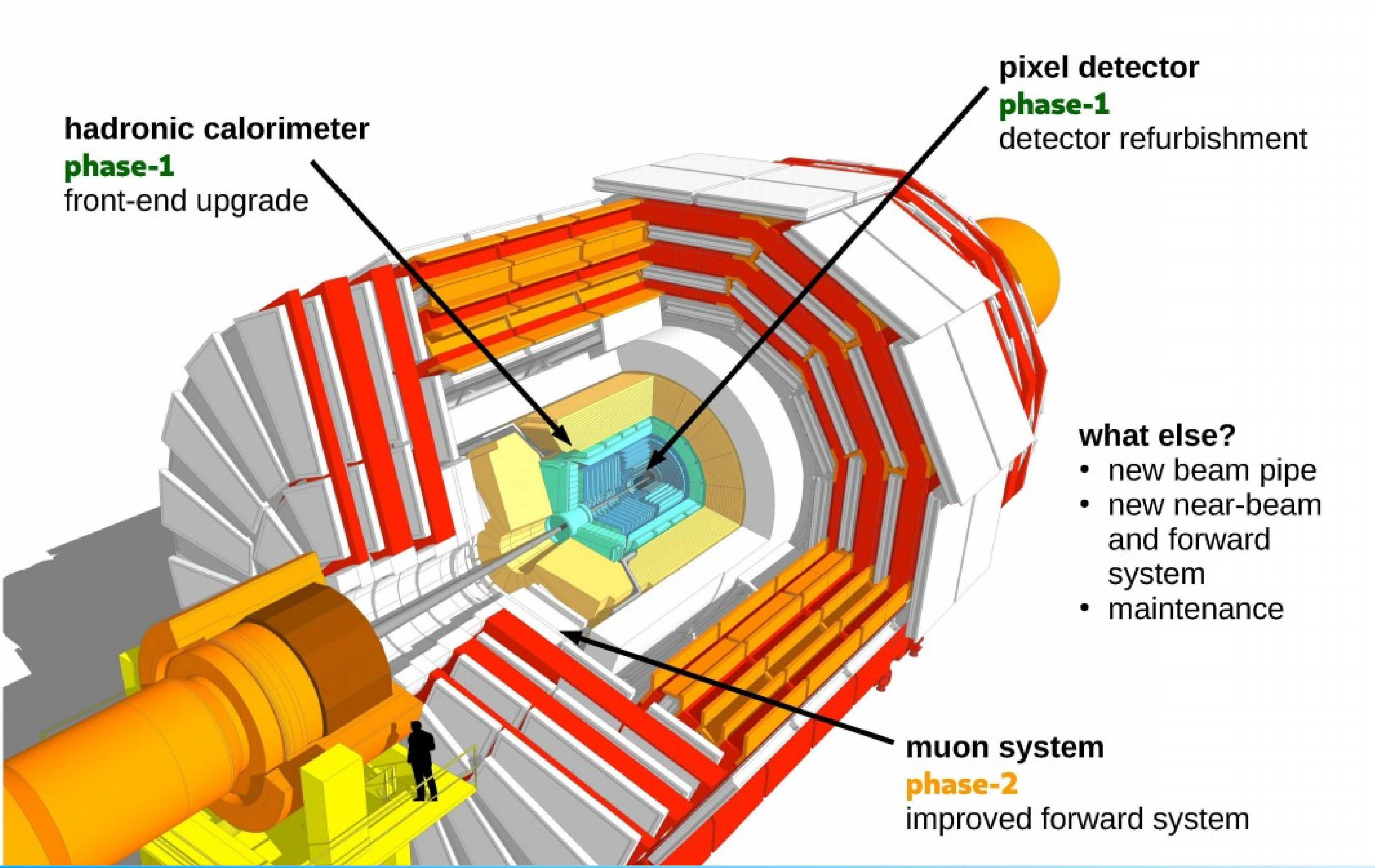
The detectors are alive...

Fraction of active detector channels in many subsystems at the end of LHC Run-2 still larger than 95%



B.Vormwald

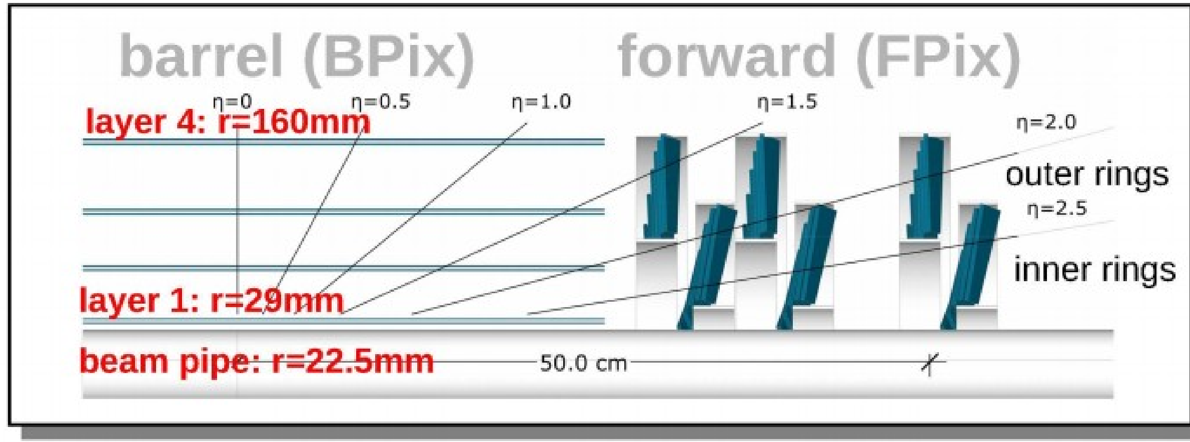
CMS Plans for LS2

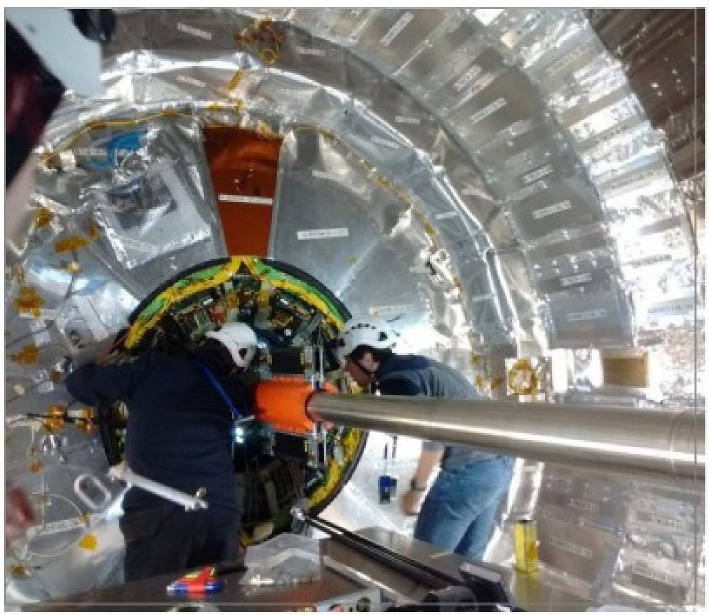


B.Vormwald

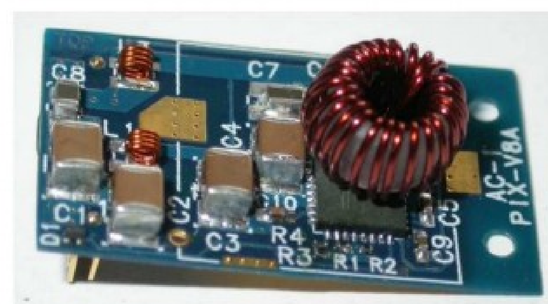
CMS Pixel

facts about CMS pixel
- installed in 2017
- powering via DC-DC converters
- DC-DC chip: CERN development, used in many phase-2 upgrade projects





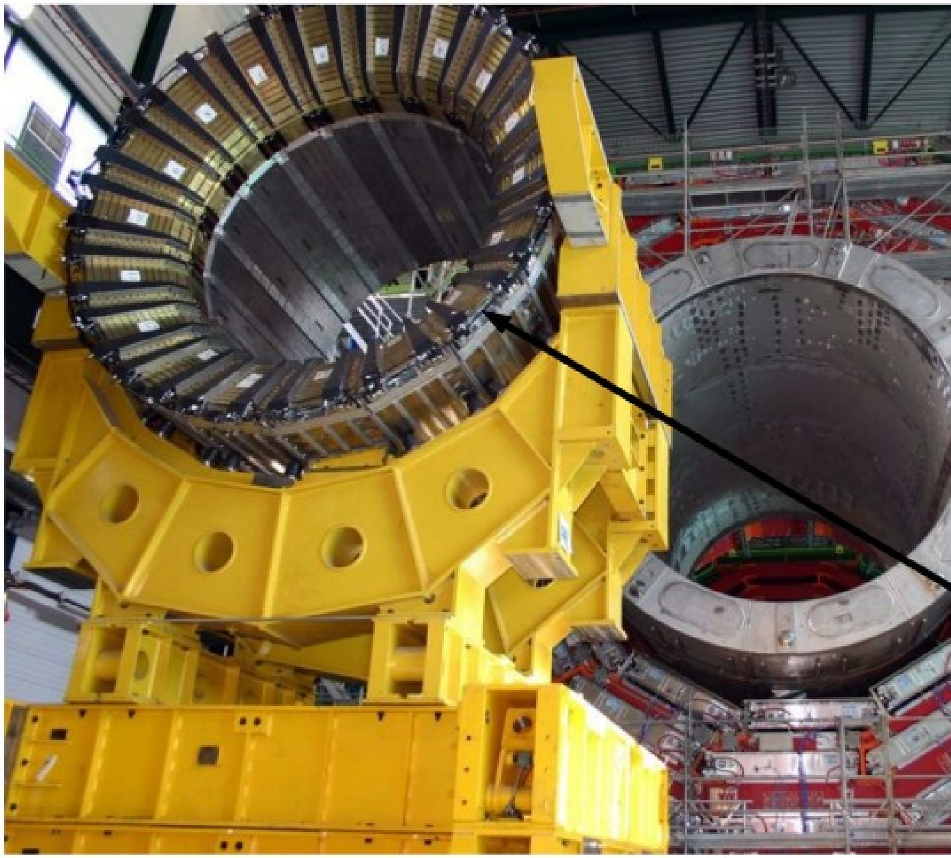
experience from last 2 years
- massive DC-DC converter failure end of 2017
- problem understood in 2018 and no problems until the end of Run-2



replacement of converters (among other activities) during LS2

B.Vormwald

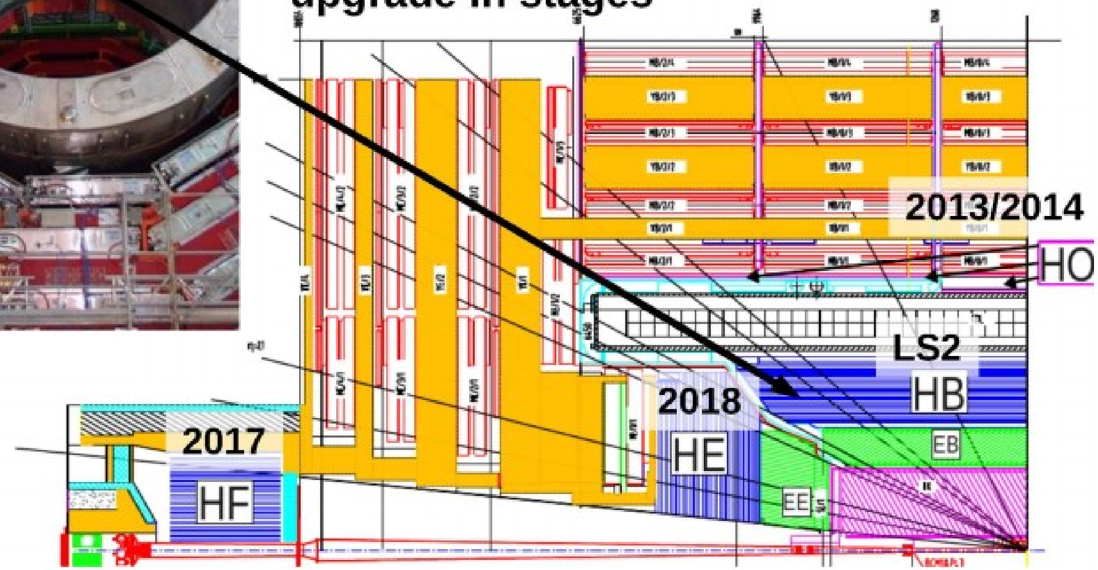
CMS Hadronic Calorimeter



facts about CMS hadronic calorimeter

- sampling calorimeter
  - absorber: brass or steel
  - scintillator: plastic
- fibers transport the light out of the absorber wedge to readout modules
- upgrade of readout modules in stages
  - barrel part (HB) only one missing

upgrade in stages



B.Vormwald

CMS Hadronic Calorimeter

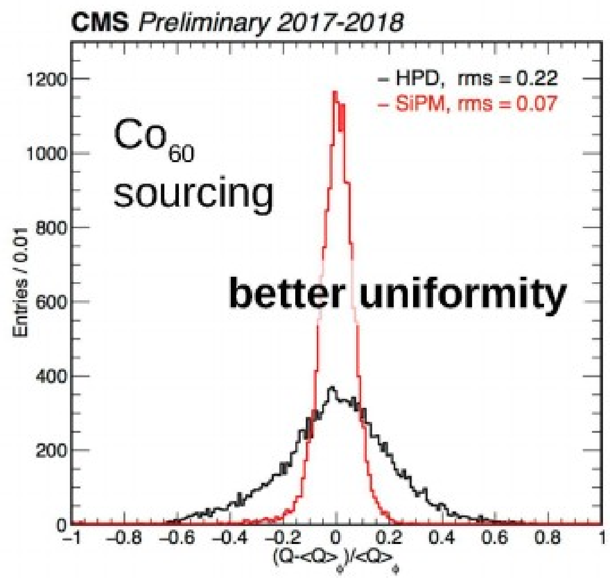
problems with photo detectors

phase 0

HV breakdowns of
hyprid photo detector
fake energetic showers

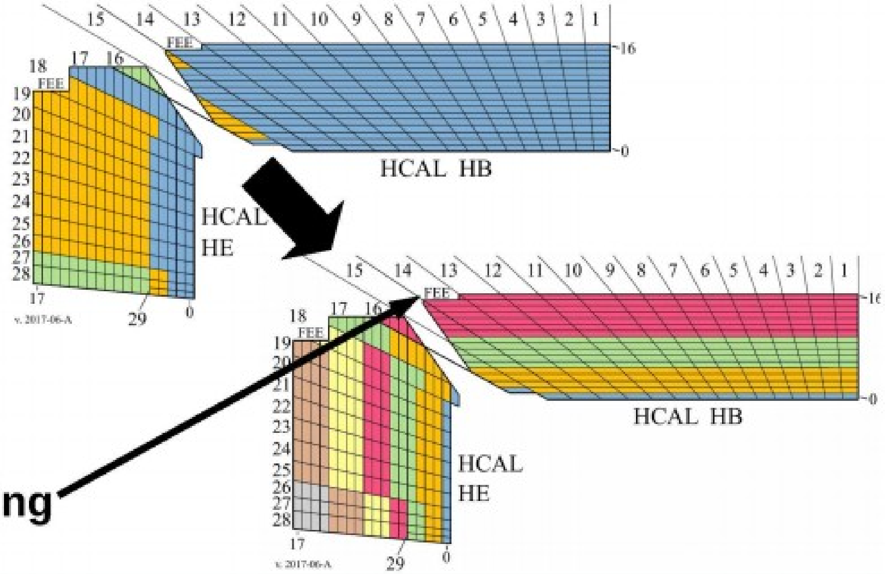
phase 1

SiPMs
- higher quantum efficiency
- better response



SiPMs – enabling technology
- longitudinal segmentation (1 → 4)
  - ➔ input to trigger & reconstruction
- better timing resolution
  - ➔ remove more efficiently background

installation of the 144 readout boxes ongoing

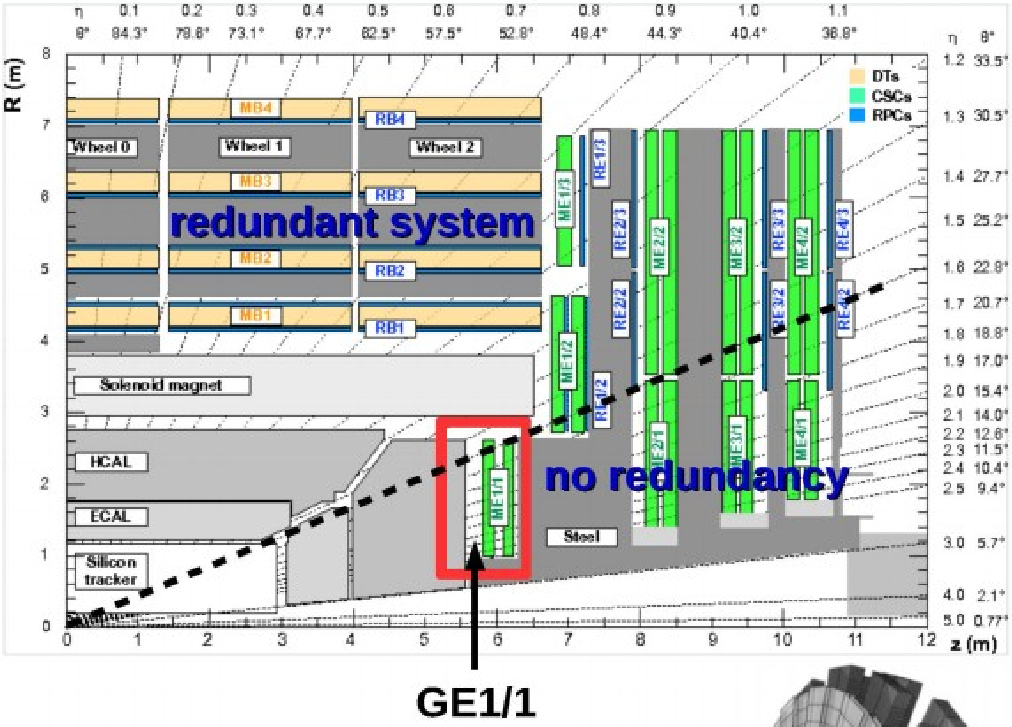


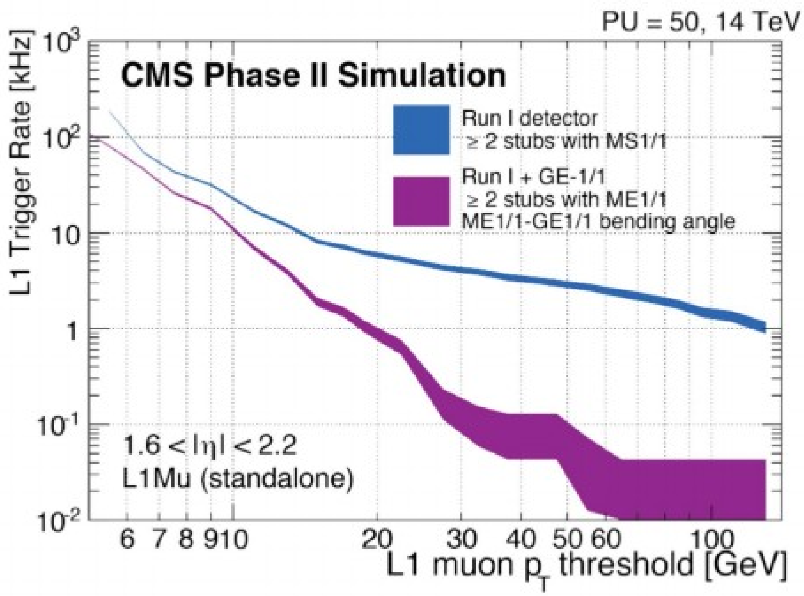
B.Vormwald

New GEM Detectors

redundant muon system

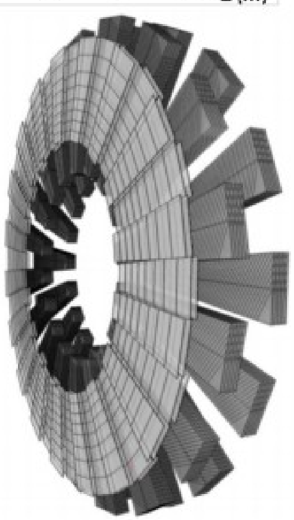
- GEM muon detectors complete redundancy in 1.6<|η|<2.2
- 72 detector chambers per detector endcap
- first stage of phase-2 muon upgrade in forward region





improvements

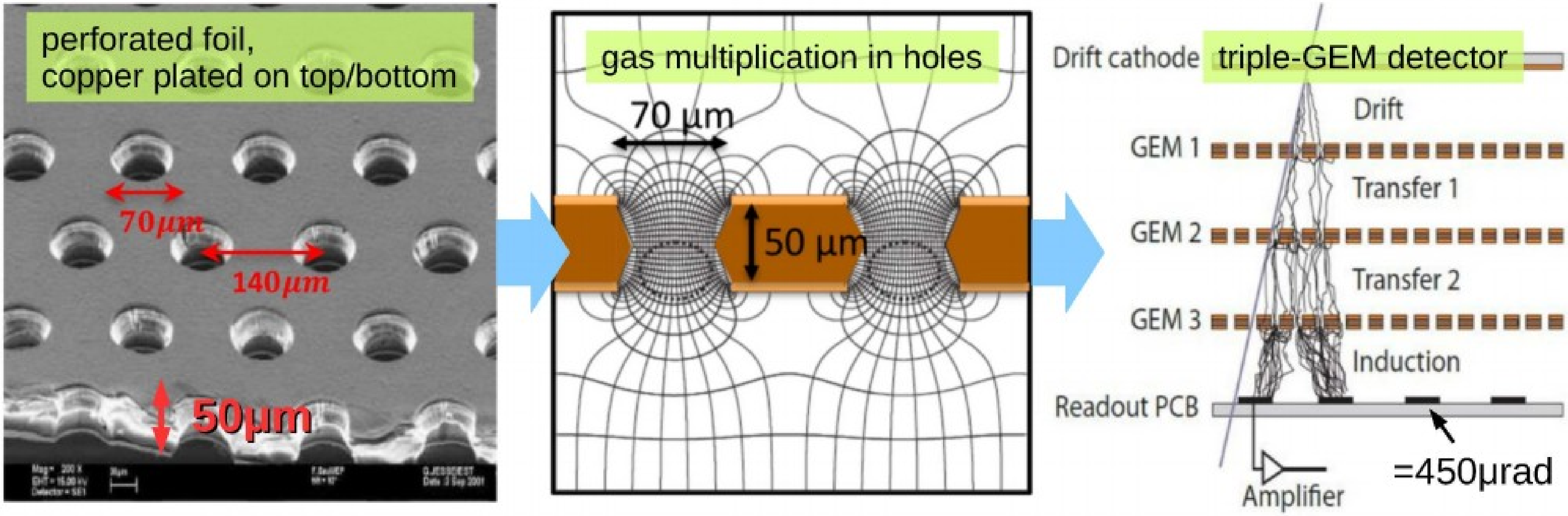
- CSC+GEM measure bending angle on trigger level → reduce fakes
- better tracking performance in region with reduced bending power (p||B)



B.Vormwald

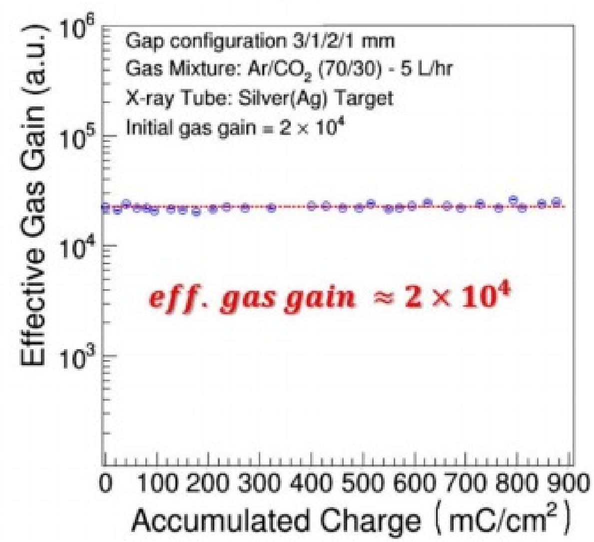
CMS Muon System

New GEM Detectors



advantages of GEM detectors

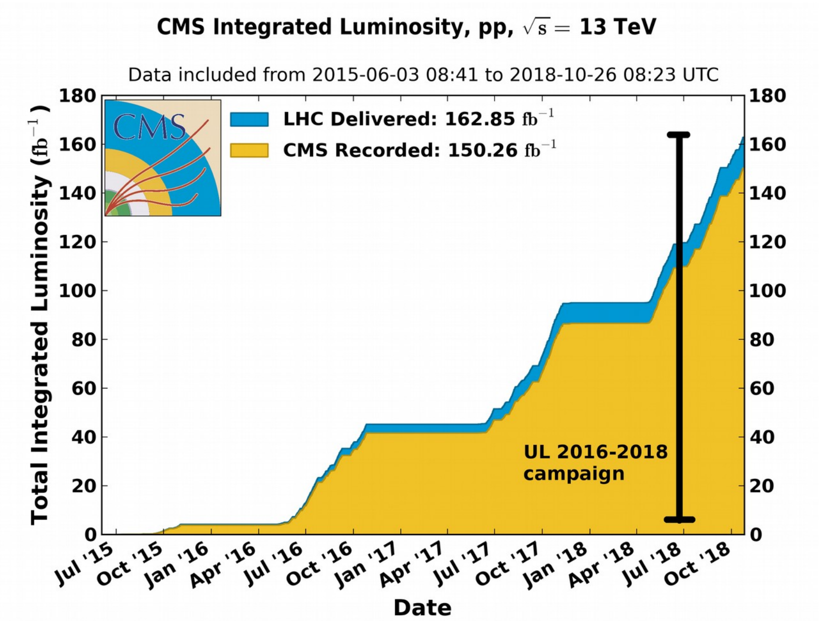
- thin
- can withstand very high particle fluxes O(MHz/cm^2)
- ε>97% for MIPs
- no aging (875mC/cm^2)
  - → irradiation up to 31y of HL-LHC!



B.Vormwald

Run 2 recalibration

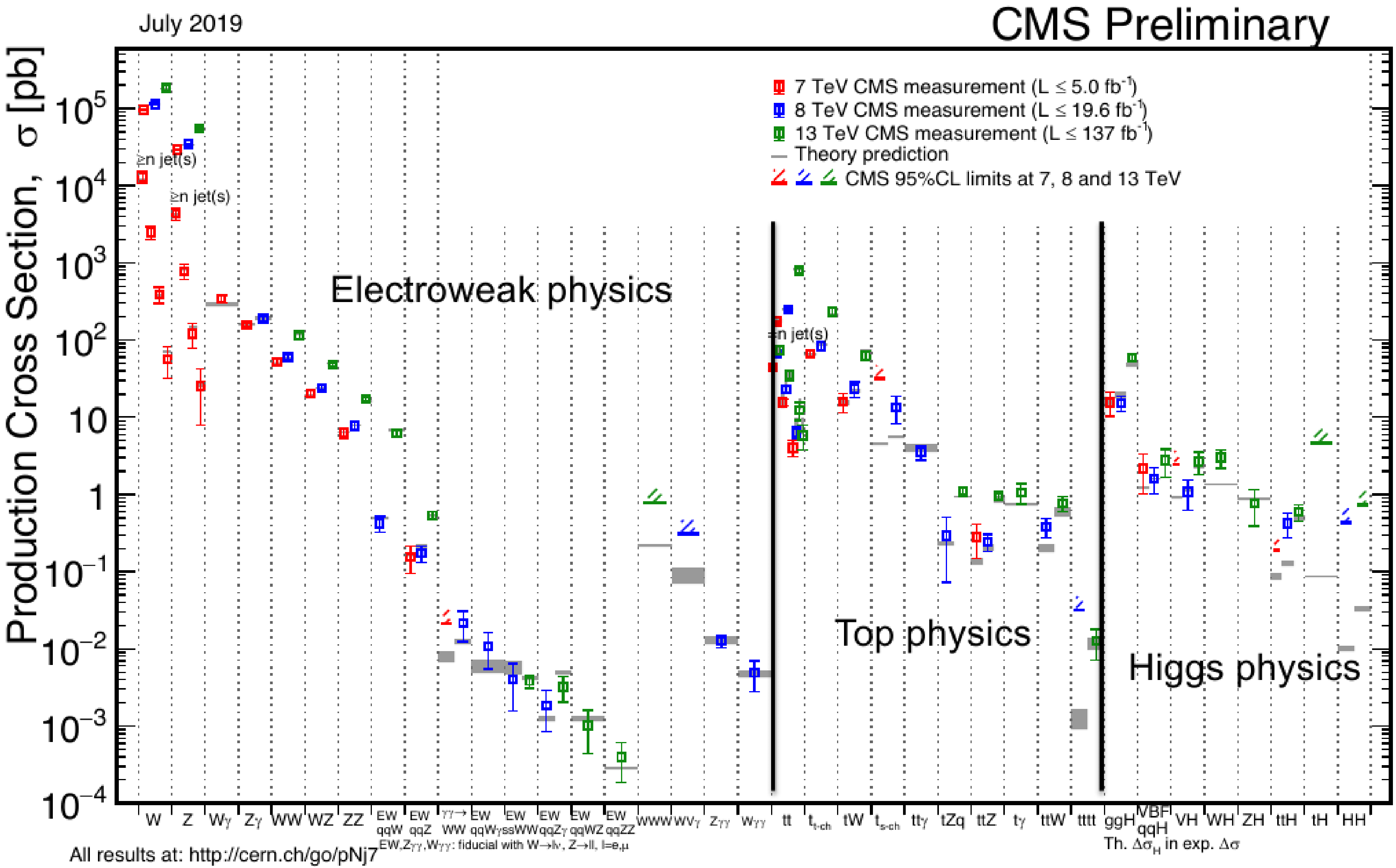
- Exhaustive recalibration of Run2 carried out in ***UltraLegacy*** *2016-2018* campaign
  - calibration and alignment of subdetectors
  - fine-tuning of reconstruction algorithms
- Data: complete reprocessing for 2016-2018, 97.5% of Run2 data (146fb-1)
- Simulation: new datasets are being produced
- Available for Physics analysis in Spring 2020



T.Lampen

Physics results from 2019

Standard Model Measurements



H_{125}

- LHC Run-1: discovery
- LHC Run-2: directly established couplings to 3rd generation fermions

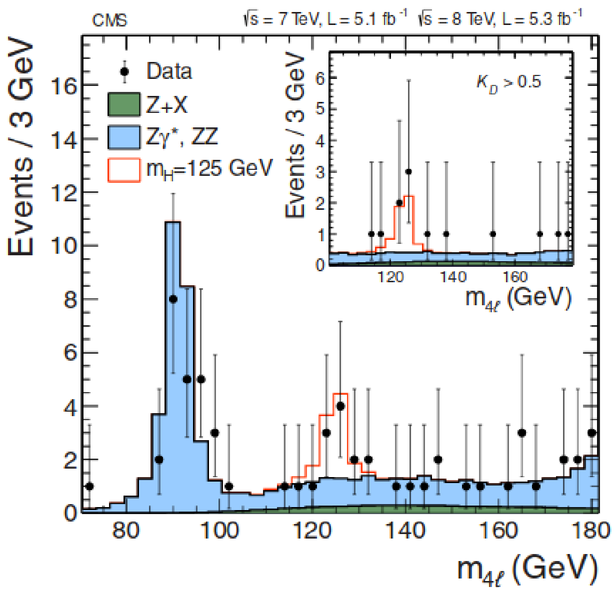
<table>
<tr><th></th><th>ggH</th><th>VBF</th><th>VH</th><th>ttH</th></tr>
<tr><td>H→ZZ</td><td colspan="4">HIG-19-001, Run 2</td></tr>
<tr><td>H→γγ</td><td colspan="2">HIG-18-029, ‘16+’17</td><td>HIG-16-040, ‘16</td><td>HIG-18-018, ‘16+’17</td></tr>
<tr><td>H→WW</td><td colspan="3">HIG-16-042, ‘16</td><td rowspan="2">HIG-18-019, ‘16+’17</td></tr>
<tr><td>H→ττ</td><td colspan="2">HIG-18-032, ‘16+’17</td><td>HIG-18-007, ‘16</td></tr>
<tr><td>H→bb</td><td>HIG-16-044, ‘16</td><td></td><td>HIG-18-016, 16+17</td><td>HIG-18-030, ‘16+’17</td></tr>
<tr><td>H→μμ</td><td colspan="2">HIG-17-019, ‘16</td><td colspan="2"></td></tr>
<tr><td>H→cc</td><td colspan="2"></td><td>HIG-18-031, ‘16</td><td></td></tr>
<tr><td>H→inv</td><td colspan="3">HIG-17-023, ’16</td><td></td></tr>
</table>

Production and decay modes covered by CMS results

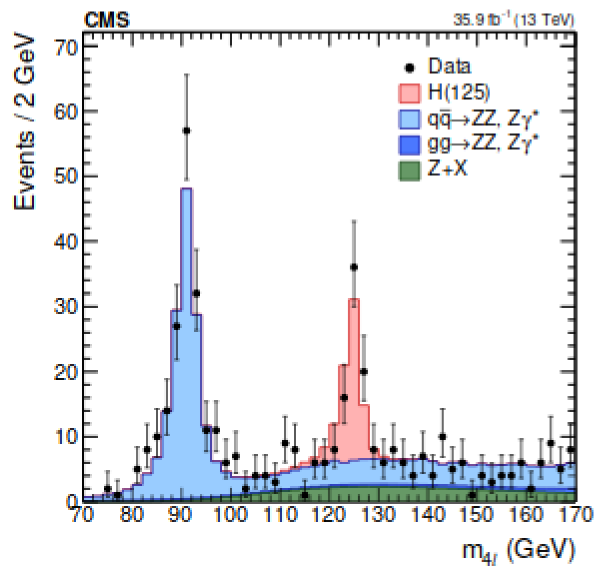
W.Adam

H$_{125}$

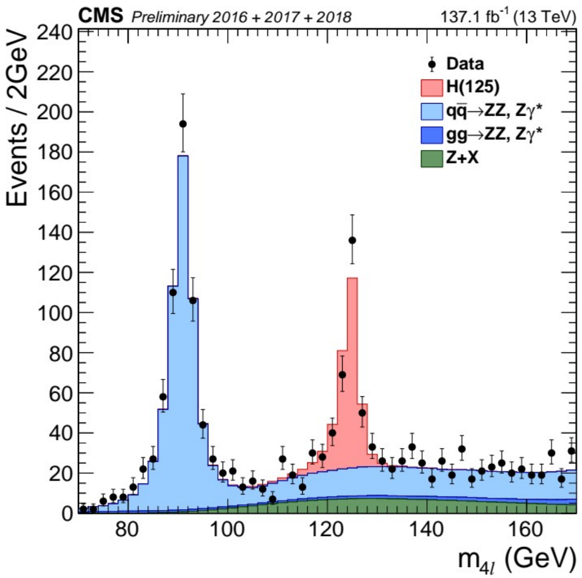
At discovery



2016



2016+2017+2018



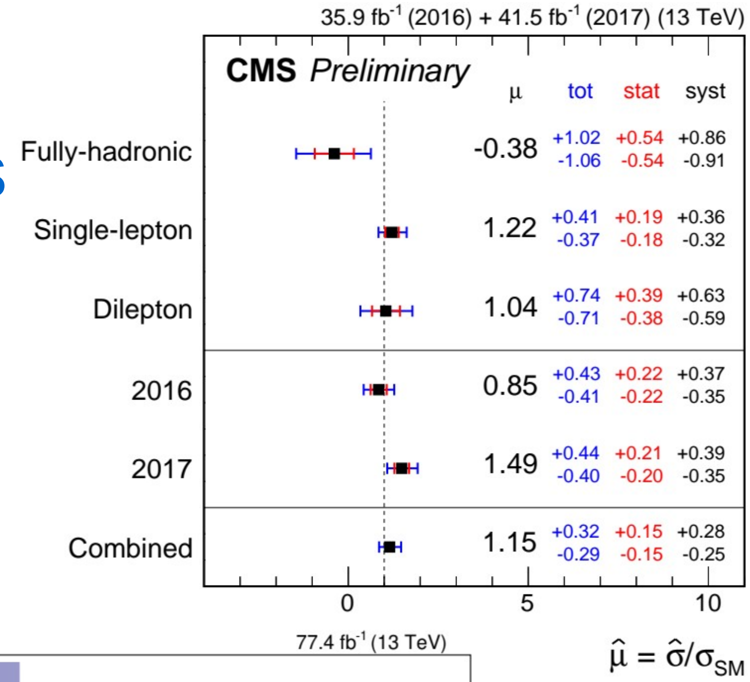
An illustration of progress in the past years: H → ZZ

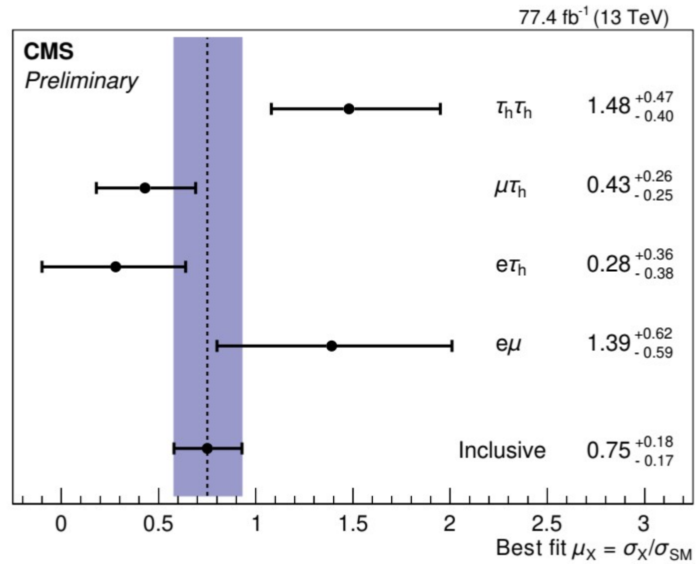
$$m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}$$

W.Adam

Decays to 3rd generation fermions

- ttH, H→bb
  - Covers 0,1,2-lepton decay modes
  - obs(exp) significance 3.9(3.5)σ
  - $\mu_{\text{comb}} = 1.15^{+0.32}_{-0.29}$
- H→ττ
  - Covers $e\mu/e\tau_h/\mu\tau_h/\tau_h\tau_h$
  - $\mu_{\text{incl}} = 0.75^{+0.18}_{-0.17}$

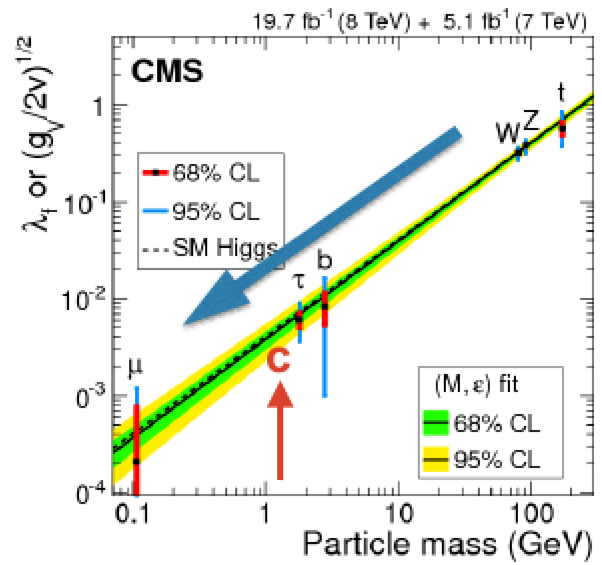


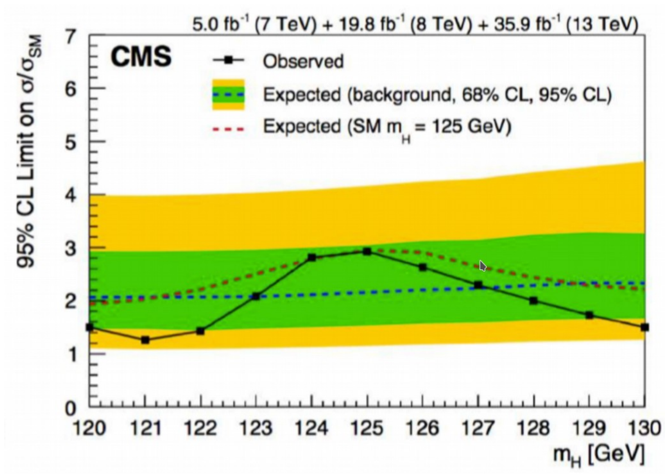


W.Adam

Moving to the 2nd generation

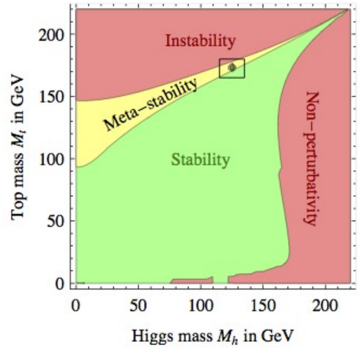
- First CMS results on VH, H→cc
  - Highly challenging due to low cross section and need for c-tagging
- CMS results on H→μμ (2016 data), small but enhanced in some BSM scenarios
  - obs(exp) exclusion: 2.92(2.16)
  - obs(exp) significance: 0.9 (1.0)σ

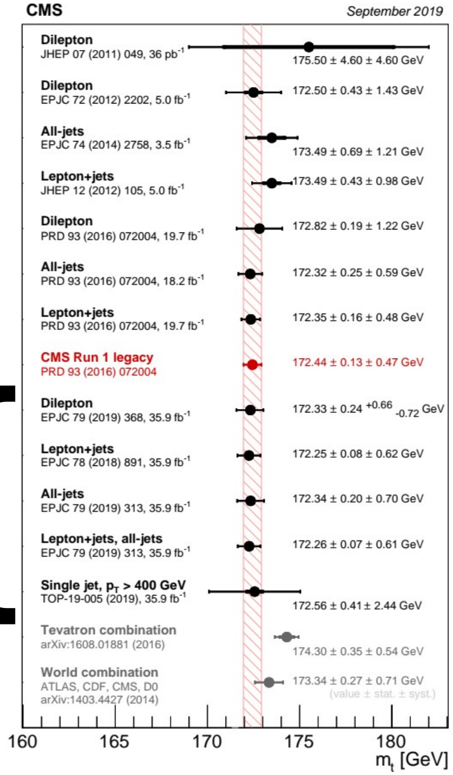




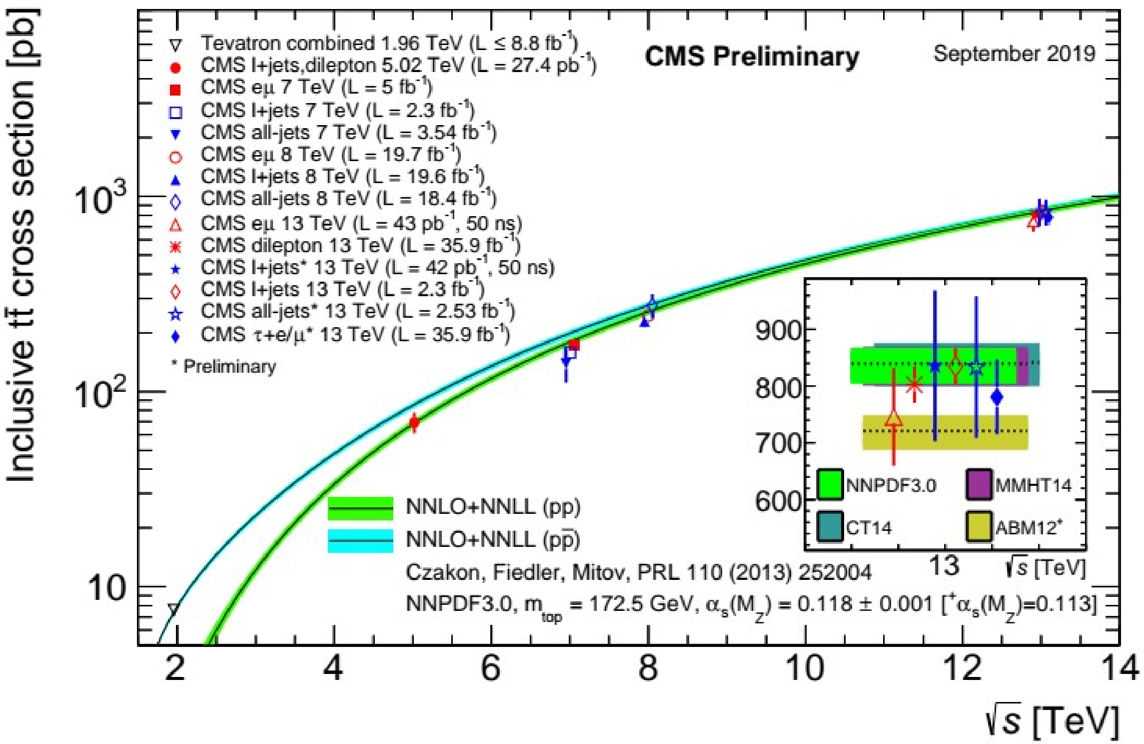
Top Quark Measurements

- After its discovery ~25 years ago, the top is still one of the hottest topics
- LHC: a top quark factory





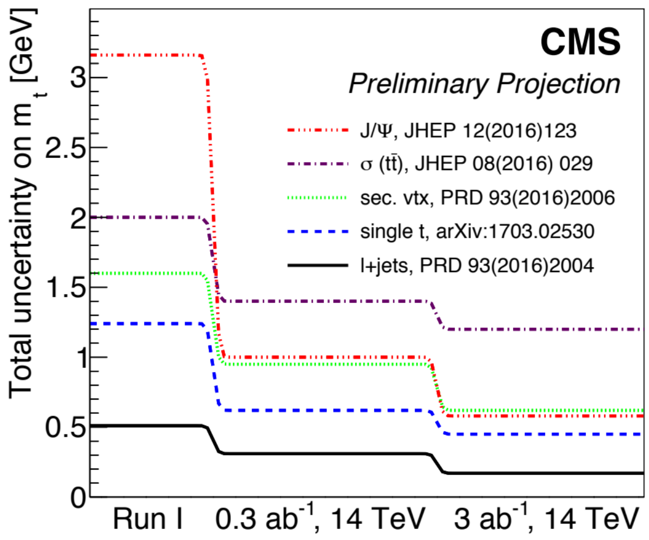
2018/2019 {



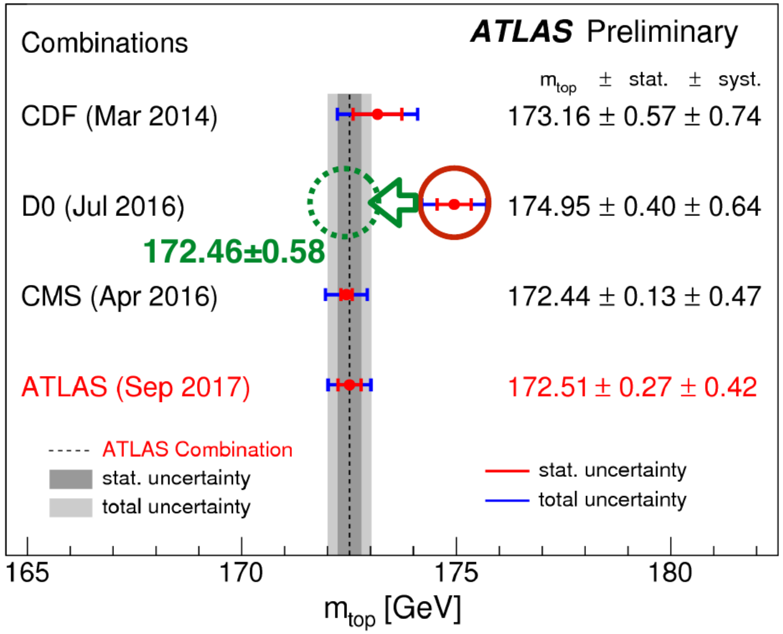
Z.Hu

Top quark mass

- Top quark mass
  - Key parameter in SM, for vacuum stability
  - Aiming at ***±0.2 GeV*** at CMS in l+jet channel
  - Address key systematics:b-JES,FSR,UE
- Progress on theory interpretation also important

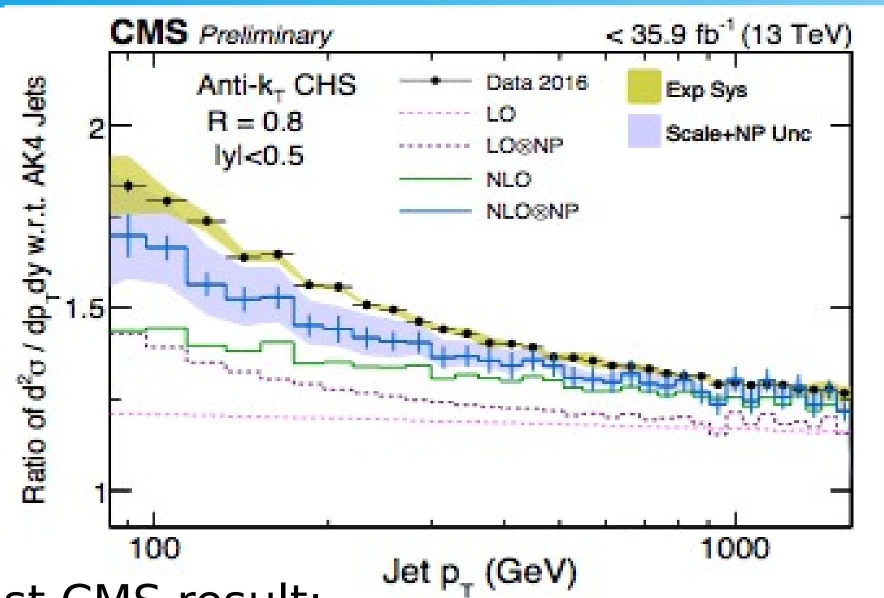


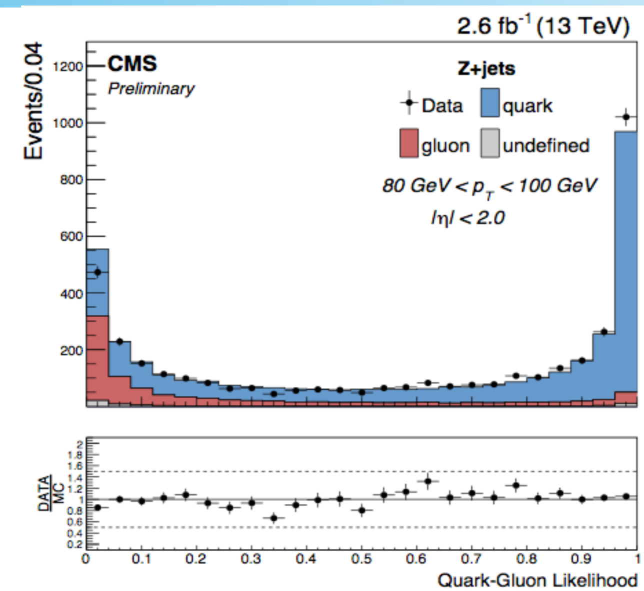
- MSc by T.Mäkelä re-anazysed D0 m_{top} results from 2014 using now public internal D0 notes on b-JES
  - Identified possible flaws in b-JES, correcting leads to lower mass
  - Method being implemented in CMS



M.Voutilainen

Jet cross sections

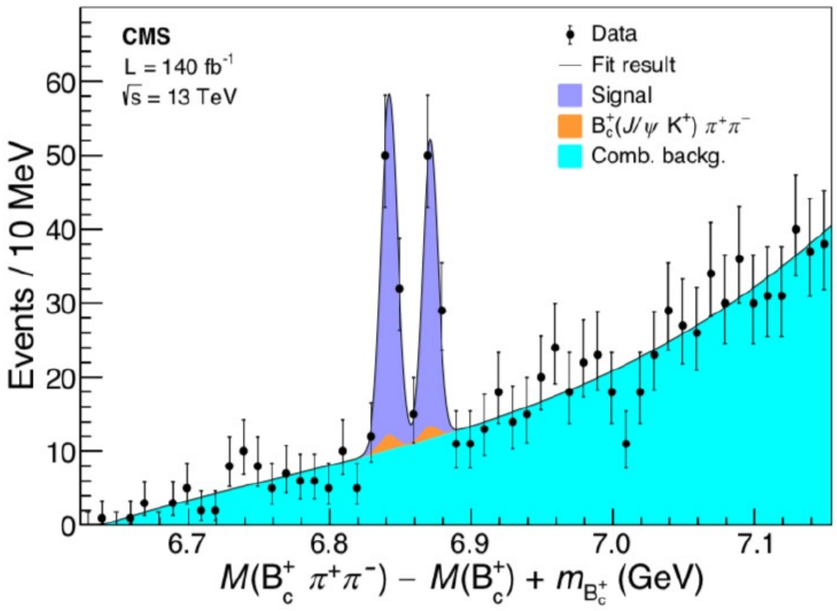




- Latest CMS result:
  - Dependence of inclusive jet production on anti-k_T distance parameter (2016 data)
- Ongoing work in Helsinki
  - Full Run 2 data ultimate precision analysis of inclusive jet cross section
    - Key input for parton distribution function (PDF) at high x and strong coupling (α_s) at high Q
  - Gluon cross section analysis as spin-of
    - Quark-gluon likelihood maintained by Helsinki PhD student
    - Collaboration with U. Marmara on gluon cross section measurement

H.Kirchenmann

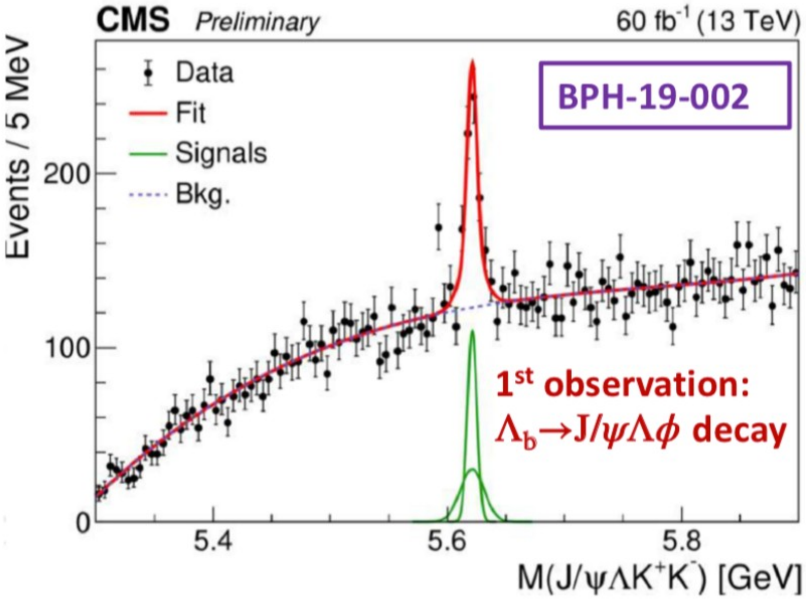
Observation of excited states



- Observation of Λ_b based on 2018 data
- Observation significance 9.7σ

- Observation of the $B_c(2S)^{\pm}$ and $B_c^{*}(2S)^{\pm}$ with full Run-2 data

Result confirmed by LHCb

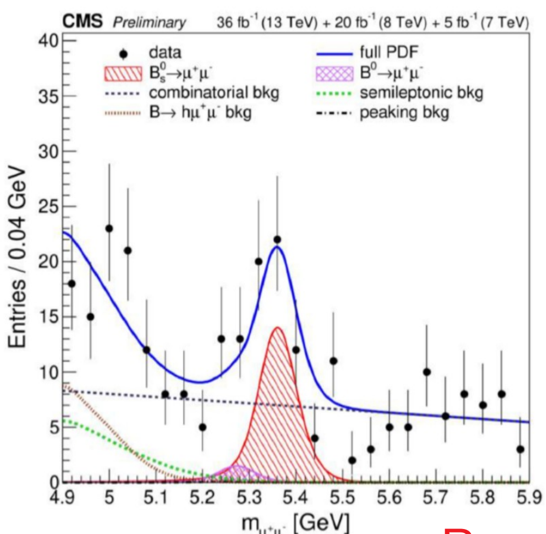


Z.Hu

Very rare decays

- $B_s^0 \rightarrow \mu\mu$ and $B^0 \rightarrow \mu\mu$
  - Forbidden at tree level, only through HO diagrams
  - Cabibbo suppressed, helicity suppressed
  - But not in models with extended Higgs sectors

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = [2.9^{+0.7}_{-0.6}\,(\mathrm{exp}) \pm 0.2(f_s/f_u)] \times 10^{-9}$$



$B^0 \rightarrow \mu^+\mu^-$ branching fraction:

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10}$ 95% C.L.

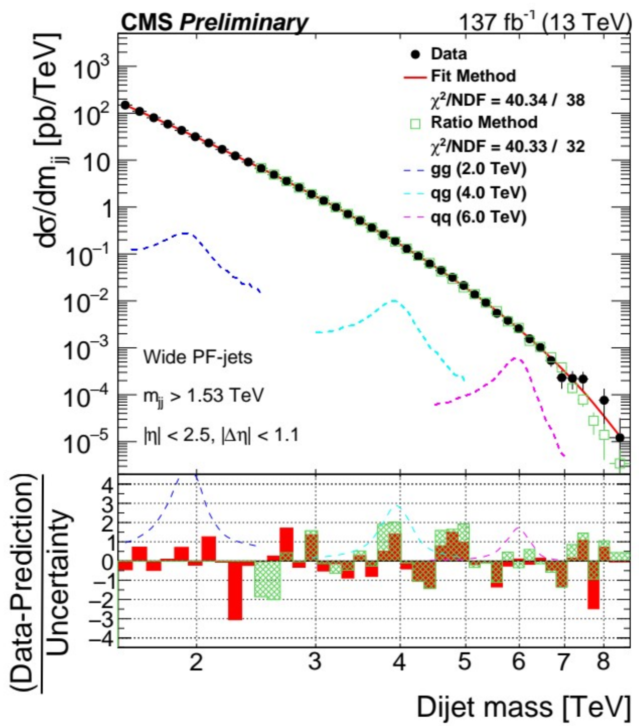
Previous CMS result:
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$
Phys. Rev. Lett. **111**, 101804

Z.Hu

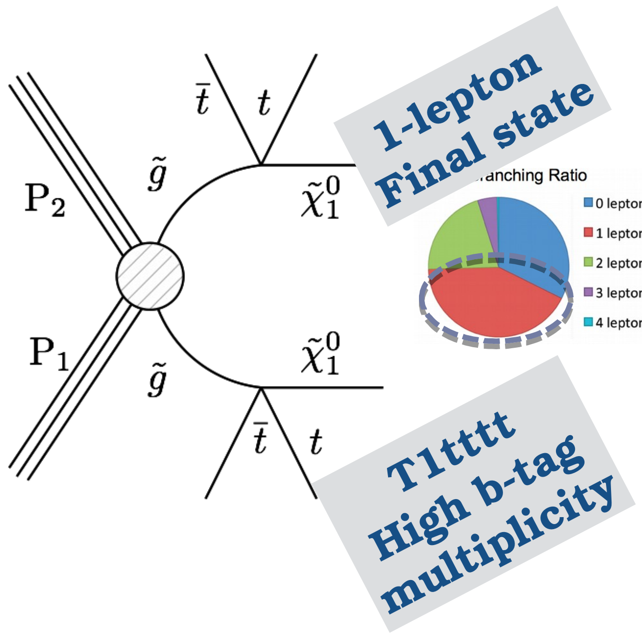
Results consistent with SM predictions

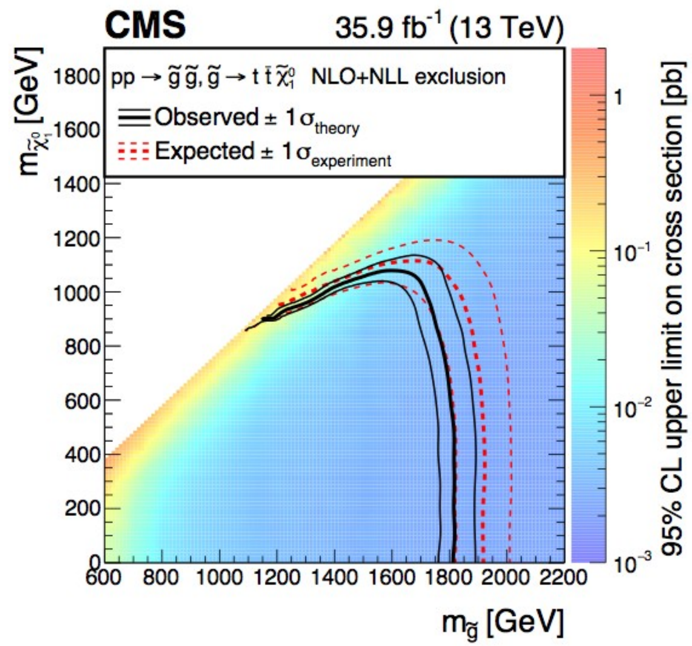
BSM Searches

- Resonant decays to two jets
  - Can be interpreted in a wide range of BSM models predicting particles decaying to gg,gq or qq
- SUSY searches
  - Searches for SUSY particles in R-parity conserving scenarios
    - Generic search for pair production of gluinos, squarks and stable LSP’s (multijet+MET signature)
    - Stop searches in a single lepton channel
    - Searches for staus



Strong-production SUSY search



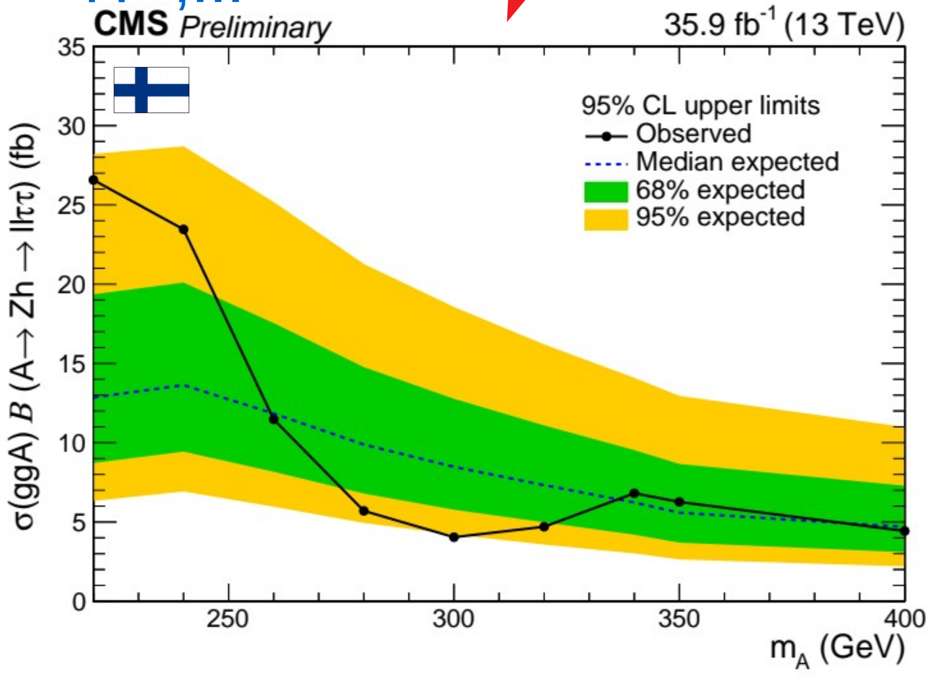


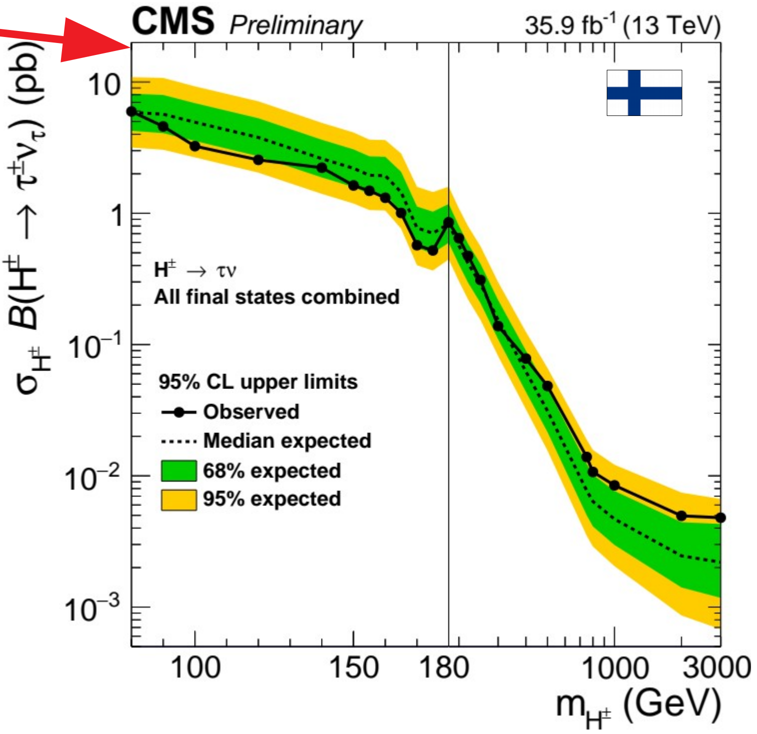
- Searching for gluino pair production, decaying to four top quarks
- Among the most sensitive analyses in final state with a single lepton; collaboration with Athens, CERN, DESY
- Plan to publish full Run 2 analysis with 2016-18 data in 2020

H.Kirchenmann

BSM Searches

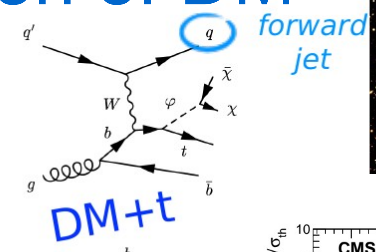
- Neutral and charged Higgs searches in many different final states
  - H→Z(ll)A(bb), A→Z(ll)h(ττ), H→μτ/eτ, H→tt,...
  - H^+→τν, H^+→WA, H^+→tb, H^+→WZ,...
  - H^{++},...

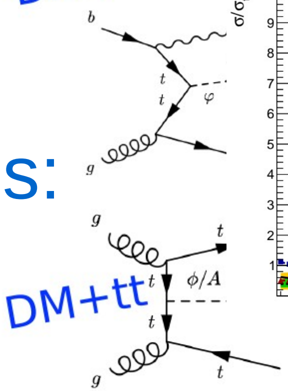


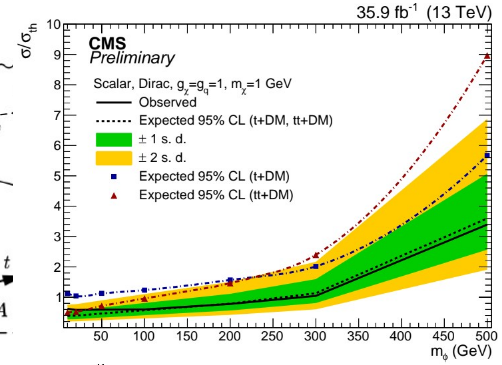


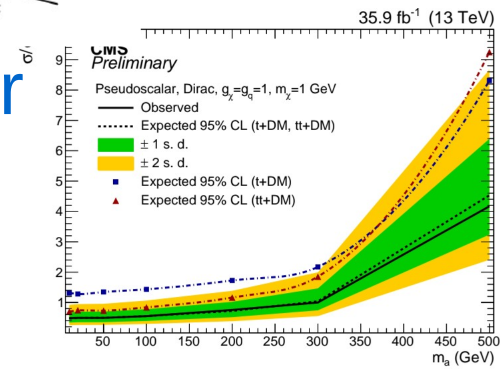
Dark Matter

- Dark matter at colliders: production of DM particles and mediators
- Signatures
  - DM particles as missing Et
  - Trigger on recoiling SM particles: mono-X signature
  - Or long-lived particles, new resonances, models with a dark sector









I. De Bruyn

SM particle	Publication	Integrated luminosity
Higgs	CMS-PAS-EXO-18-011	36 fb-1
Top quark(s)	CMS-EXO-18-010, JHEP 03 (2019) 141 CMS-EXO-16-051, JHEP 06 (2018) 027	
Photon	CMS-EXO-16-053, JHEP 02 (2019) 074	
Jets or hadronic Z/W	CMS-EXO-16-048, Phys Rev D 97 (2018) 092005	

Totem

- **Low luminosity part of TOTEM** including vertical RPs & their equipment **continue as a separate running experiment** until 2021-22 focusing on physics of high runs aiming for a σ_{tot} at sqrt(s) = 14 TeV (in 2021-22).

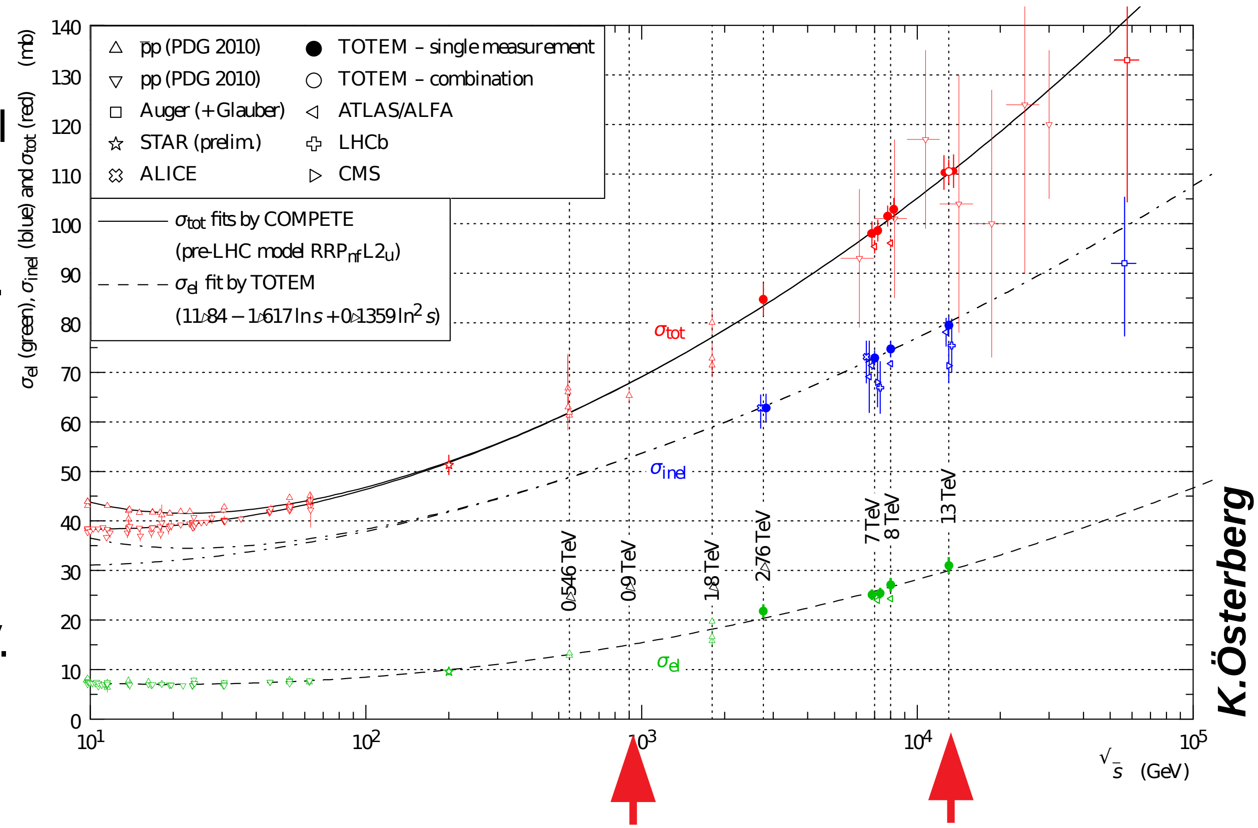
Physics priorities:

- Confirm & characterize t-channel exchange of a colourless C-odd 3-gluon compound state ("Odderon") in elastic scattering.
- Glueball candidate studies (with CMS).

Detector upgrades:

new T2 telescope for measurement of σ_{tot} @ = 14 TeV.

Event counter at 5.3 < eta < 6.5



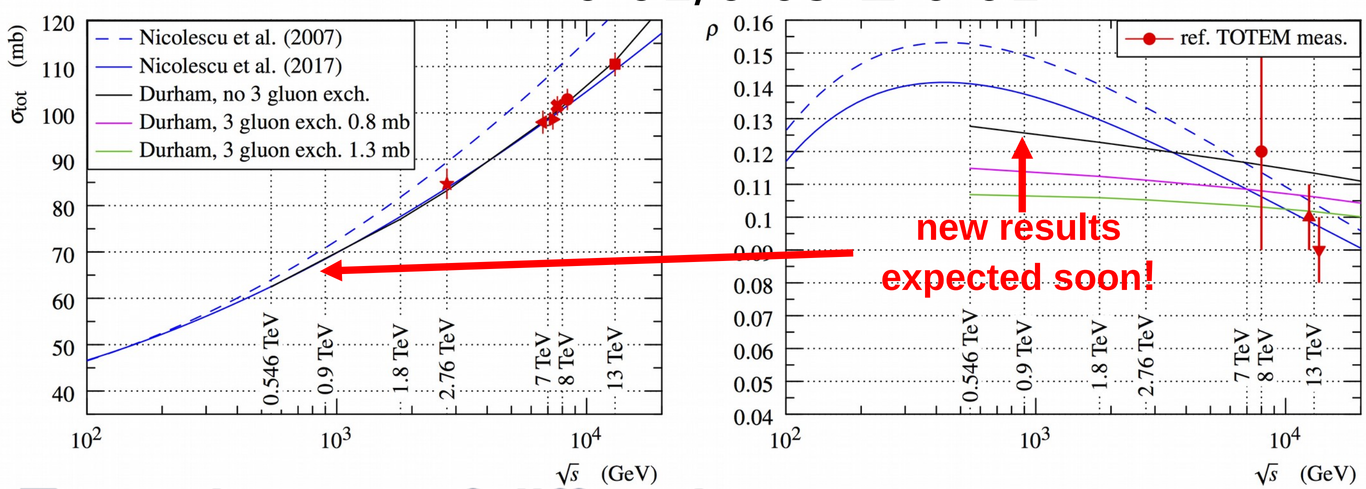
new results
expected soon!

Colourless C-odd 3-gluon compound

- **rapidly increasing σ_{tot} & decreasing ρ in pp scattering at high energies**

TOTEM@√s = 13 TeV: σ_{tot} = 110.5 ± 2.4 mb, ρ = 0.10 ± 0.01/0.09 ± 0.01

EPJC 79 (2019) 785



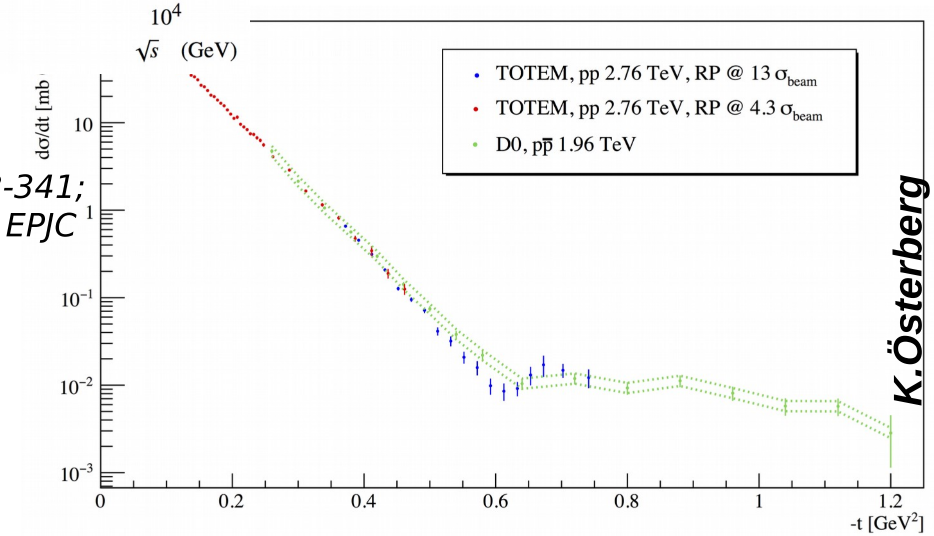
Adding t-channel exchange of colourless C-odd 3-gluon compound ("Odderon") improves model description of the TOTEM σ_{tot} & ρ

E. Martynov & B. Nicolescu, PLB 778 (2018) 414; V.A. Khoze, A.D. Martin & M.G. Ryskin, PRD 97 (2018) 034019

- **persistency of diffractive minimum in pp scattering for TeV energies** (= gluon exchange dominance) **& absence in p$\bar{p}$**

CERN-EP-2018-341; submitted to EPJC

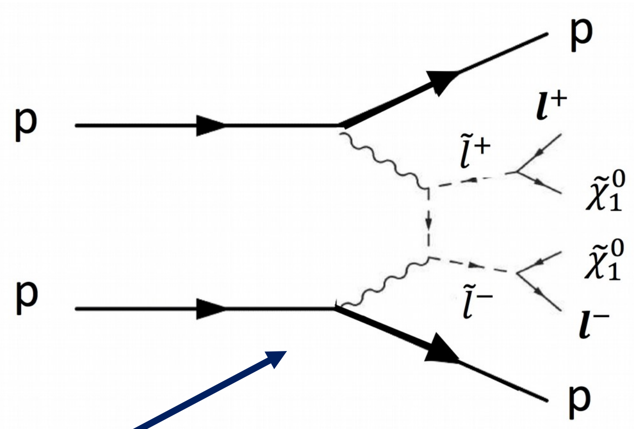
Next: model-independent extrapolation of TOTEM elastic pp $d\sigma/dt$'s to $\sqrt{s}$ = 1.96 TeV for direct comparison (joint D0-TOTEM analysis)



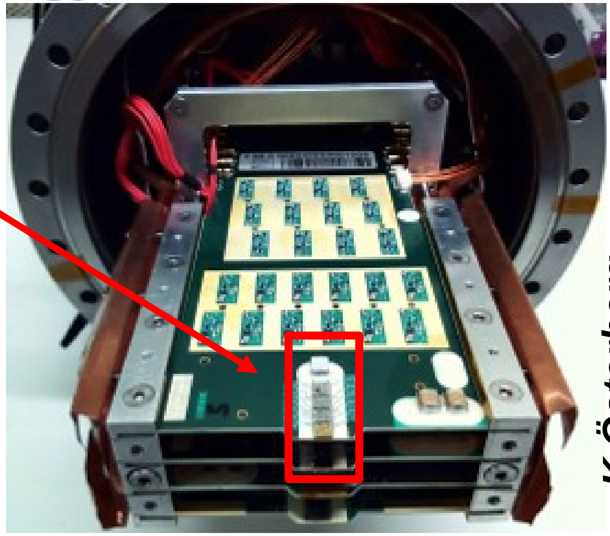
K.Österberg

CMS forward proton precision timing

- **Increase the CMS sensitivity to central exclusive processes in Run 3 (& HL-LHC?)**
  - precise proton arrival time measurement in CMS Proton Precision Spectrometer (PPS) allows reconstruction of proton longitudinal vertex position & associate it with particle vertices in central part (to mitigate pile-up)



- **Physics:** anomalous quartic gauge couplings, axion-like particles, **low-mass SUSY searches…**
- **Technology: single-crystal CVD diamonds**

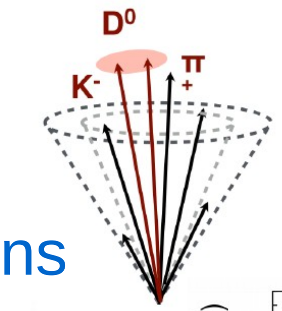


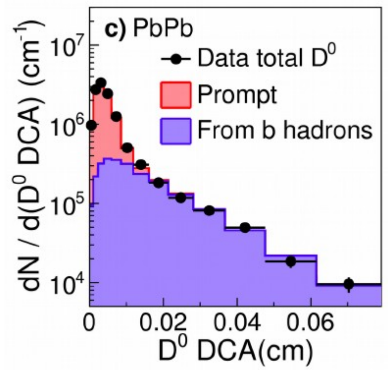
K.Österberg

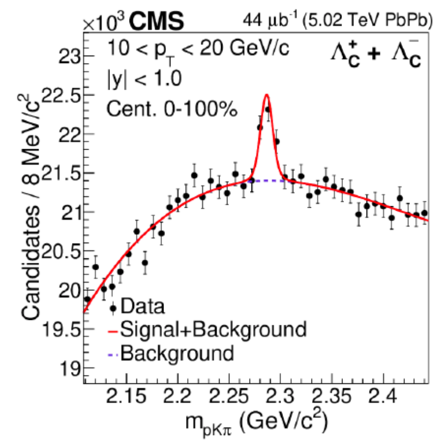
- **Finnish responsibilities include:**
  - detector procurement, metallization & QA
  - detector module testing & assembly
- **PPS @ HL-LHC ?**
  - A completely new system with increased radiation tolerance & timing precision requirements
  - Expression of Interest to be submitted to CMS 2019

Heavy Ions

- CMS has a versatile heavy flavor program in A+A
  - Quarkonia and open charm and beauty
- Redistribution of D^0 mesons in jets
  - Observed for the first time in Pb+Pb collisions
  - J/ψ in jets (p+p) much softer than models
- D^0 mesons from b-hadron decays
  - Strong b-quark energy loss at low pT
- Λ_C^+ (udc) baryons suppressed, disagree with the model

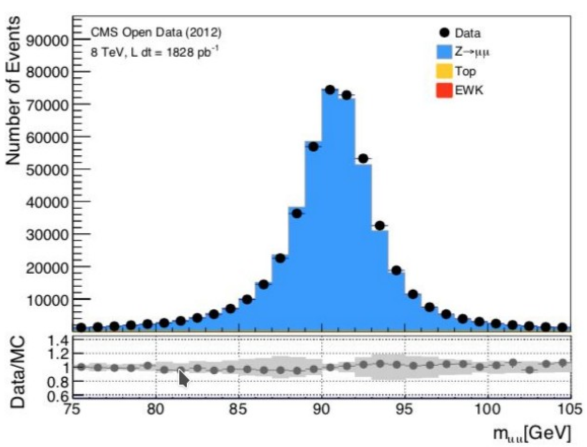






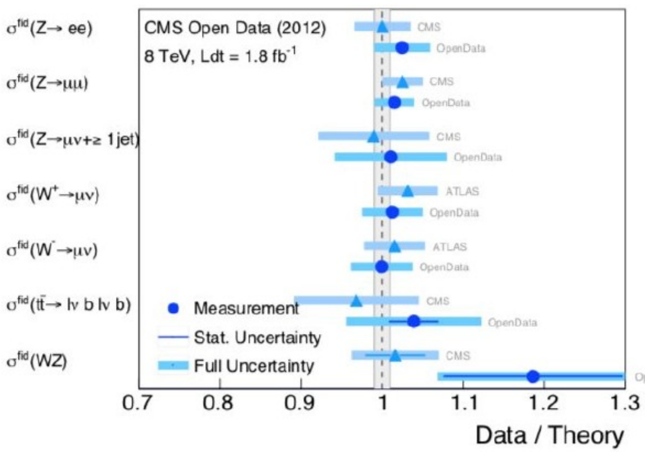
Open Data

- First re-measurement of SM cross sections at 8 TeV using CMS Open Data
  - Precision of 2-6% reached
  - Consistent with official measurements and SM predictions
- Full 2011 and 2012 datasets available
- Analysis software: public analysis framework ‘Bacon’ in github



Lepton momentum scale calibrated using
the Z boson invariant mass spectrum

Process	cross section [pb] (stat. ± sys. ± lumi.)	Prediction [pb] (signal MC)
$Z/\gamma^* \to e^+e^-$	$\sigma^{fid} = 461 \pm 17$ $(1 \pm 13 \pm 11)$	$\sigma^{fid.} = 450 \pm 0.02$
$Z/\gamma^* \to \mu^+\mu^-$	$\sigma^{fid} = 406 \pm 12$ $(1 \pm 6 \pm 10)$	$\sigma^{fid.} = 400 \pm 0.01$
$Z/\gamma^* \to \mu^+\mu^- + \geq 1$ jet	$\sigma^{fid} = 77.1 \pm 5.5$ $(0.4 \pm 5.1 \pm 1.9)$	$\sigma^{fid.} = 76.3 \pm 5.0$
$W^+ \to \mu^+\nu$	$\sigma^{fid} = 3052 \pm 124$ $(1 \pm 98 \pm 76)$	$\sigma^{fid.} = 3015 \pm 100$
$W^- \to \mu^-\nu$	$\sigma^{fid} = 2103 \pm 86$ $(1 \pm 69 \pm 52)$	$\sigma^{fid.} = 2105 \pm 60$
$t\bar{t} \to \mu^\mp e^\pm \nu\bar{\nu}b\bar{b}$	$\sigma^{fid} = 4.54 \pm 0.35$ $(0.14 \pm 0.30 \pm 0.11)$	$\sigma^{fid.} = 4.37 \pm 0.35$
$W^\pm Z \to l^\pm \nu l^+ l^-$	$\sigma^{fid} = 28.1 \pm 3.3$ $(3.1 \pm 0.9 \pm 0.7)$	$\sigma^{fid.} = 23.7 \pm 0.4$



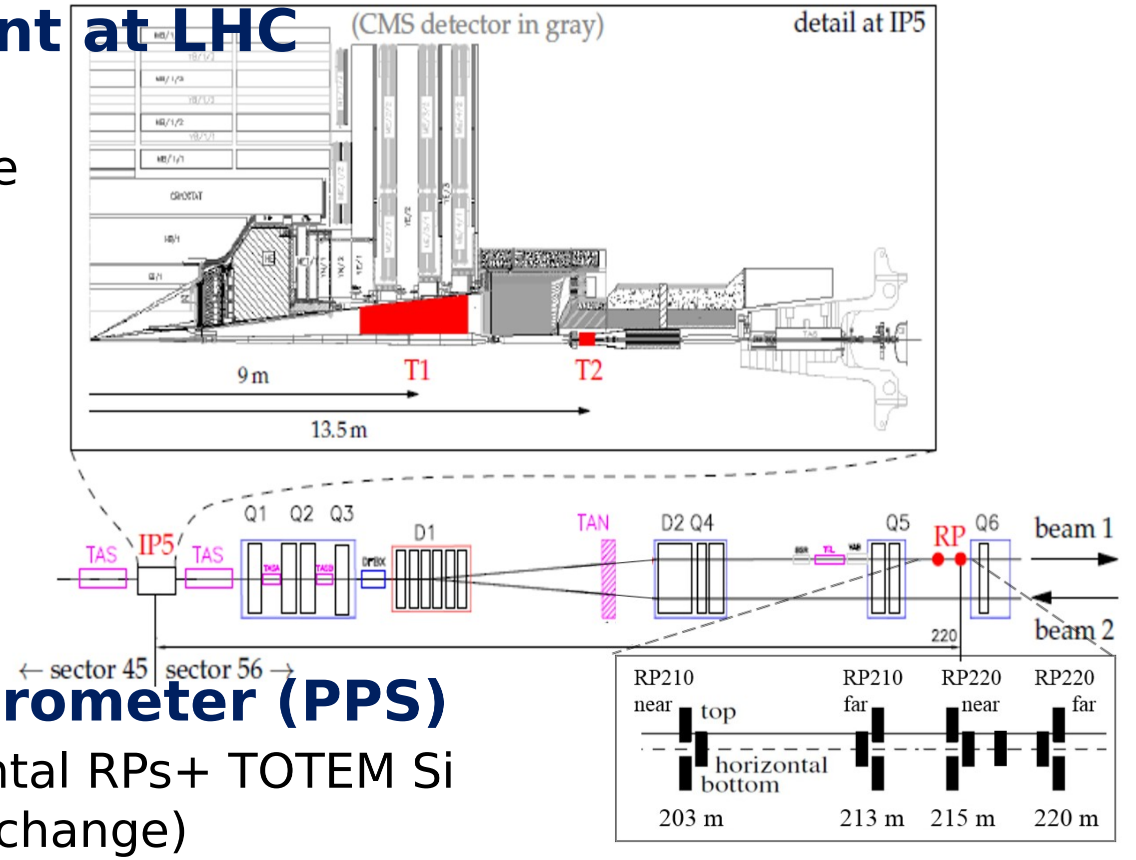
M.Schott

Summary

- Upgrade of the detectors aiming partially already for HL-LHC conditions
- CMS had a very successful Run-2 with record data taking efficiency in 2018
  - H_{125} precision measurements
  - SM precision measurements
- ..but no new physics found
- Continuing the harvest based on the full LHC Run-2 dataset

Backup

TOTEM (& CMS forward physics)



✓ Forward physics experiment at LHC

- total cross-section (σ_{tot})
- elastic scattering over wide |t|-range
- diffractive & exclusive processes

✓ Detectors

- T1 & T2 for charged particles
- Roman Pots (RP) for leading protons with tracking & TOF

✓ CMS Precision Proton Spectrometer (PPS)

- proton tracking detectors in horizontal RPs+ TOTEM Si μstrips ⇒ CMS 3D Si pixels (gradual change)
- proton timing detectors in new cylindrical RP + TOTEM (double-layered) diamond detectors adapted for PPS

- TOF = Time-Of-Flight
- β^*= beam proton oscillation amplitude ∝ transverse IP size

✓ Run scenarios:

- Special high β^*, vertical RPs ⇒ σ_{tot}, elastic, & low mass exclusive & diffractive processes
- Standard low β^*, horizontal RPs ⇒ **high mass exclusive processes & BSM searches**

continuous high luminosity data taking as integral part of CMS: fb^{-1} in 2016-18

Helsinki detector contributions

- **GEM-detectors for T2:** services radiation damaged ⇒ T2 removed during YETS 2017-18

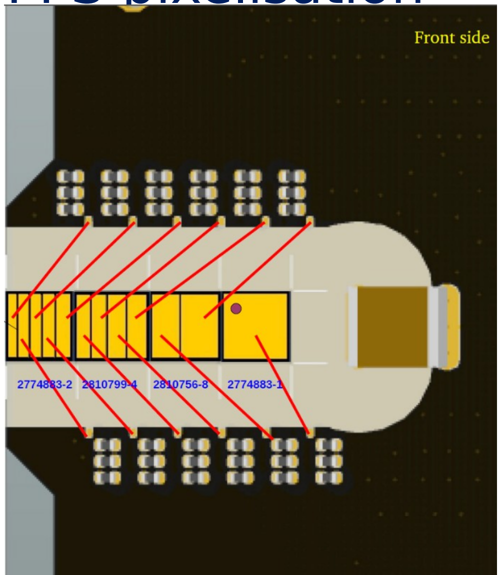
- **scintillators & fibers for nT2**

During LS2 new pipe beam installed in T2 region (not compatible with current T2 anyway). Prepare new scintillator-based inelastic detector ("nT2") to be installed for a = 14 TeV σ_{tot} & measurement run (expected 2021 or 2022) ⇒ TDR submitted to LHCC in June

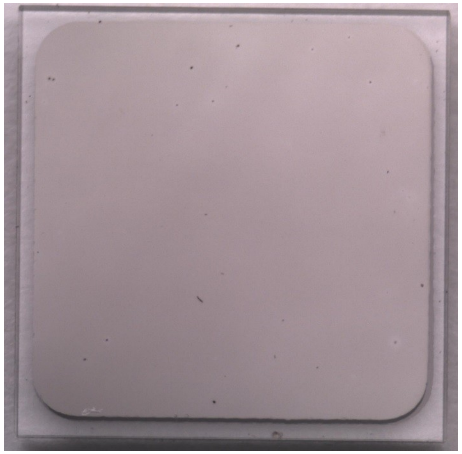
- **diamonds for proton TOF detectors including radiation hardness characterisation**

Prepare a 2nd set of double-layered diamond detectors for 2 additional timing RPs to be installed for Run 3 (one RP/side of IP) ⇒ to improve TOF measurement to achieve 20-30 ps

PPS pixelisation



Diamond detector

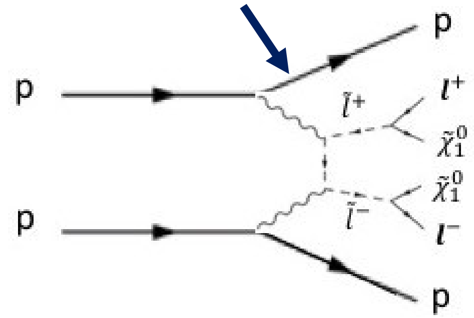


PPS diamond TOF module

beam

Helsinki CMS-TOTEM priorities 2019-22

- **σ_{tot} & ρ measurements** at $\sqrt{s}$ = 0.9 (2018 data) & 14 TeV (2021 data?) with their interpretation with respect to C-odd 3-gluon compound state t-exchange
- **Studies of glueball candidates (f_0 & f_2 resonances)** in central exclusive production at $\sqrt{s}$ = 13 TeV in 2015 & 2018 special run data
- **Exclusive $\gamma\gamma$ production** with PPS using full 2016-18 PPS statistics of $\sim$110 fb^{-1} (sensitive to anomalous quartic $\gamma\gamma\gamma\gamma$ couplings & high mass axion like particles)
- **Low mass SUSY searches** (especially small $|\text{m}_{\text{LSP}} - \text{m}_{\text{nLSP}}|$) with PPS using full 2016-18 PPS statistics & improve CMS PPS capability for Run 3 SUSY searches



e.g. slepton production in compressed SUSY scenarios

N. Schul & K. Piotrzkowski, NP Proc. 179-180 (2008) 289; L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin & M. Tasevsky, JHEP 1904 (2019) 010

- **Extension of diamond based CMS PPS proton TOF detector** for high luminosity running after LS2 in Run 3 (physics motivation: BSM searches)
- **Building of TOTEMs new scintillation based T2 ("nT2")** for inelastic rate measurements at $\sqrt{s}$ = 14 TeV to determine σ_{tot} & ρ after LS2 (in 2021?)

*

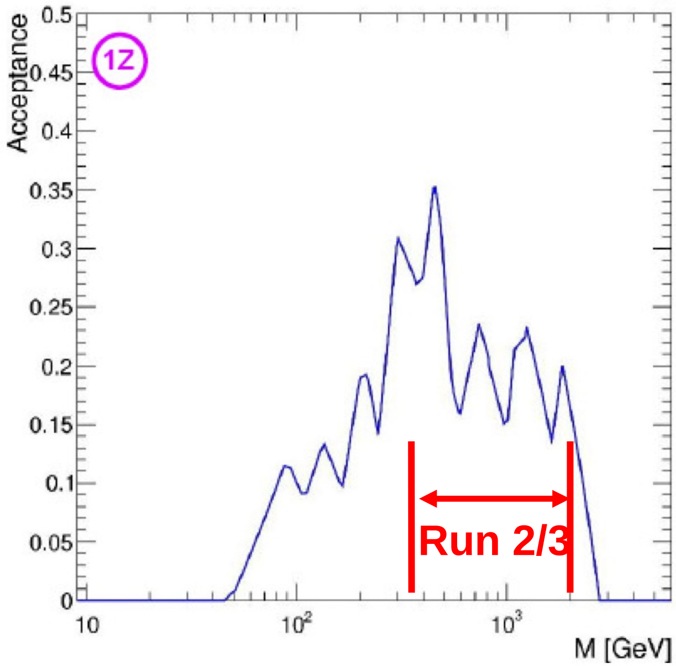
*Academy of Finland FIRI infrastructure funding 330 k€ to cover HIP part of costs

Proton tagged physics @ HL-LHC

Physics motivations (300 $\mathrm{fb}^{-1} \leftrightarrow$ 3000 fb^{-1}, improved low mass acceptance)

- High-mass searches: increased sensitivity to anomalous couplings ($\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$ ...) by $\sim$ a factor 10 & to couplings of axion like particles ("ALPs") by $\sim$ a factor 4
- Higgs/EWK: measure Higgs quantum numbers in a completely independent way
- Low-mass searches: extend SUSY searches in compressed scenarios to lower masses

e.g. HL-LHC mass acceptance assuming proton detectors at 210-250 m & 400-450 m; β_x^* = 0.15 m & vertical crossing



Completely new system: new (compact?) Roman Pots @ 400 m, improved radiation hardness of the tracking detectors (3D Si detectors?), radiation hard timing detectors with $\sim$ 5 ps timing resolution (?) $\Longrightarrow$ R&D required to find adequate solutions

The CMS Proton Precision Spectrometer at HL-LHC – Expression of Interest

(intended to be submitted for CMS internal review)

Physics highlight: colourless C-odd 3-gluon compund state

- **rapidly increasing σ_{tot} & decreasing ρ in pp scattering at high energies**

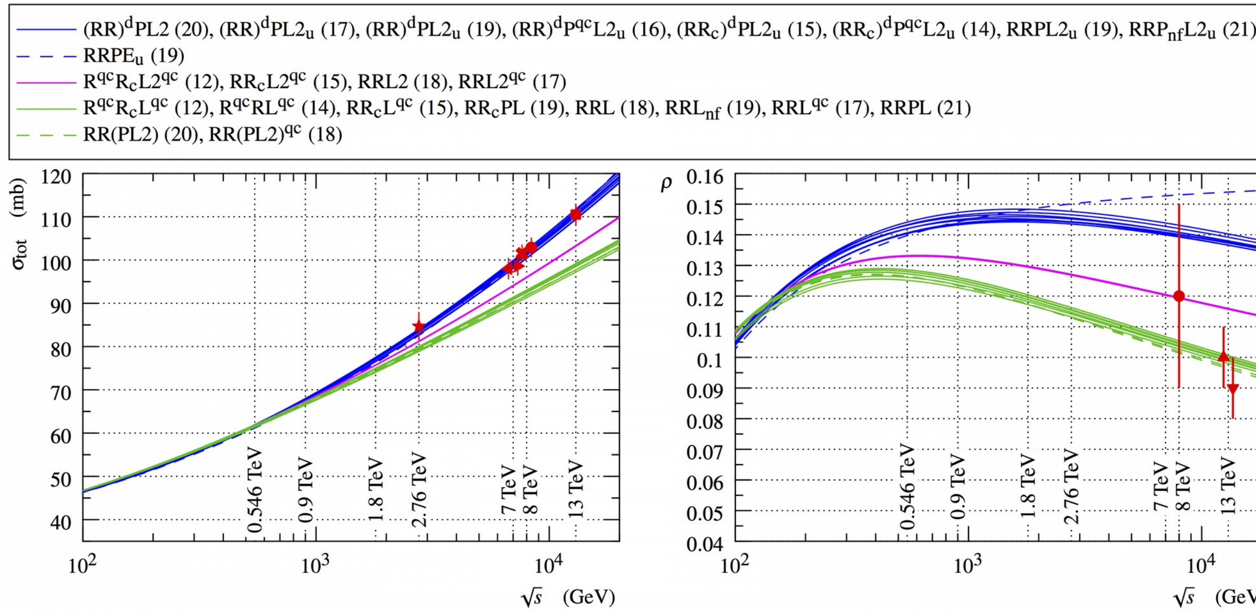
TOTEM@√s = 13 TeV: **σ_{tot} = 110.6 ± 2.4 mb, ρ = 0.10 ± 0.01/0**

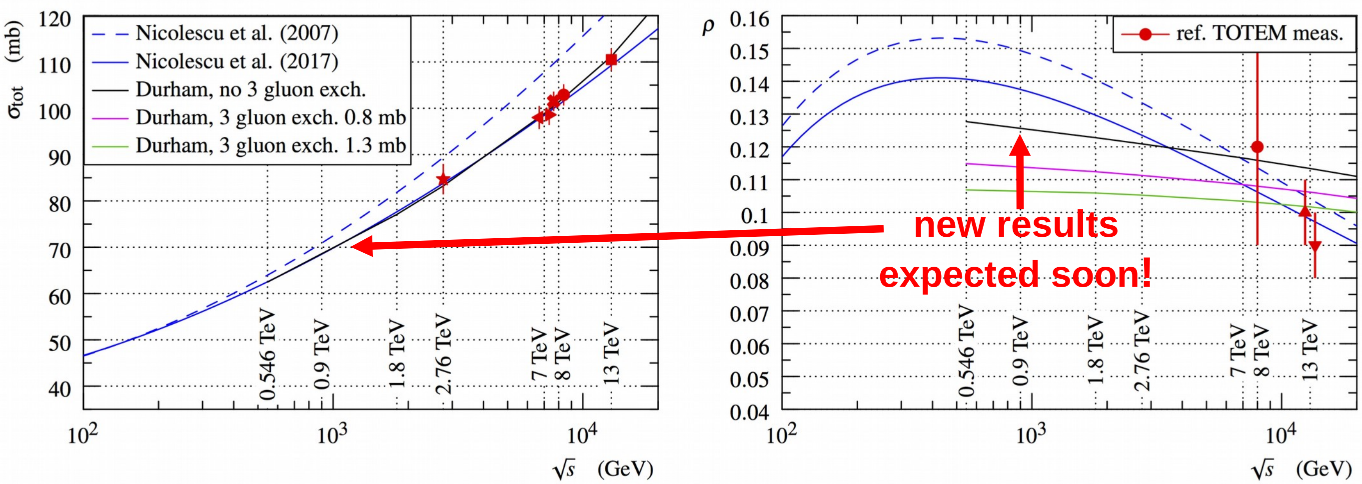
CERN-EP-2017-335; accepted by

Comparison with pre-LHC models (without 3-gluon exchange):

J.R. Cudell et al., PRL 89 (2002) 201801

No model able to describe simultaneously TOTEM σ_{tot} & ρ measurements





Comparison with models including 3-gluon exchange:

E. Martynov & B. Nicolescu, PLB 778 (2018) 414; V.A. Khoze, A.D. Martin & M.G. Ryskin, PRD 97 (2018) 034019

Adding Odderon/3-gluon t-exchange improves model descriptions of TOTEM σ_{tot} & ρ

Alternative: decrease of σ_{tot} growth beyond LHC energies

Physics highlight: colourless C-odd 3-gluon compound state?

- **Persistency of diffractive minimum in scattering at TeV energies** (gluon dominance) **& absence in**

ISR: √s = 52.8 GeV

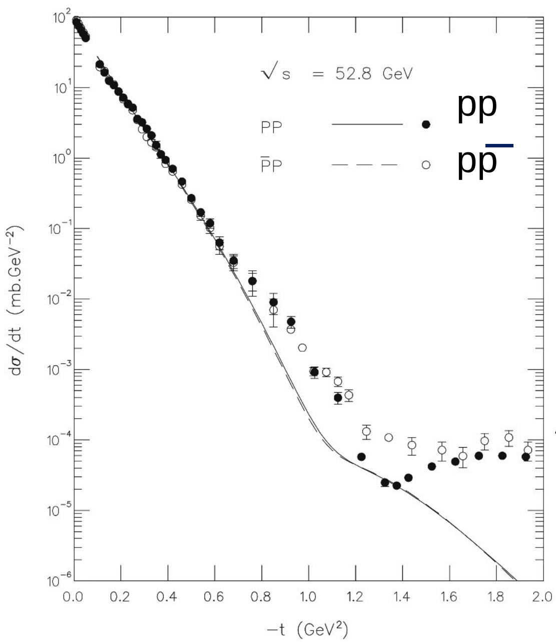
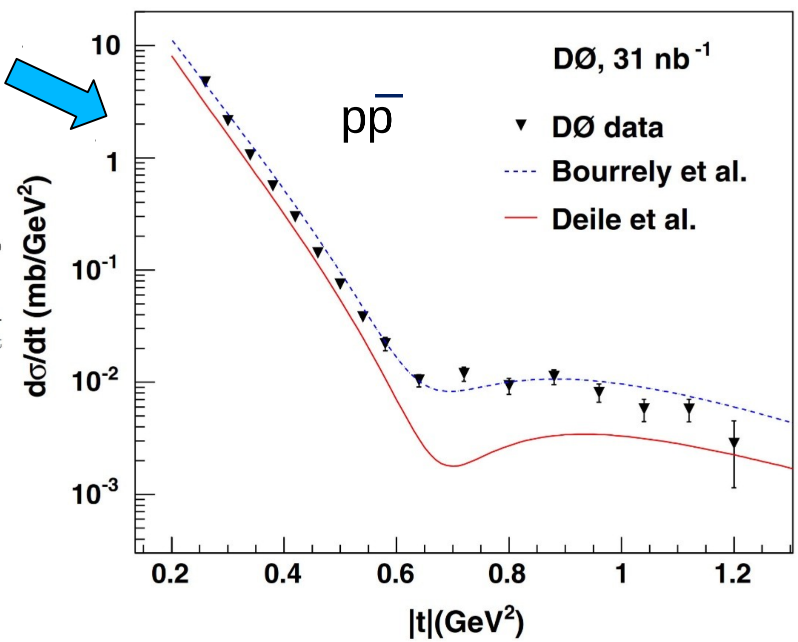


Fig. 1. pp and $\bar{p}p$ $d\sigma/dt$ predictions for the case without the odderon, together with the experimental points, at $\sqrt{s} = 52.8$ GeV

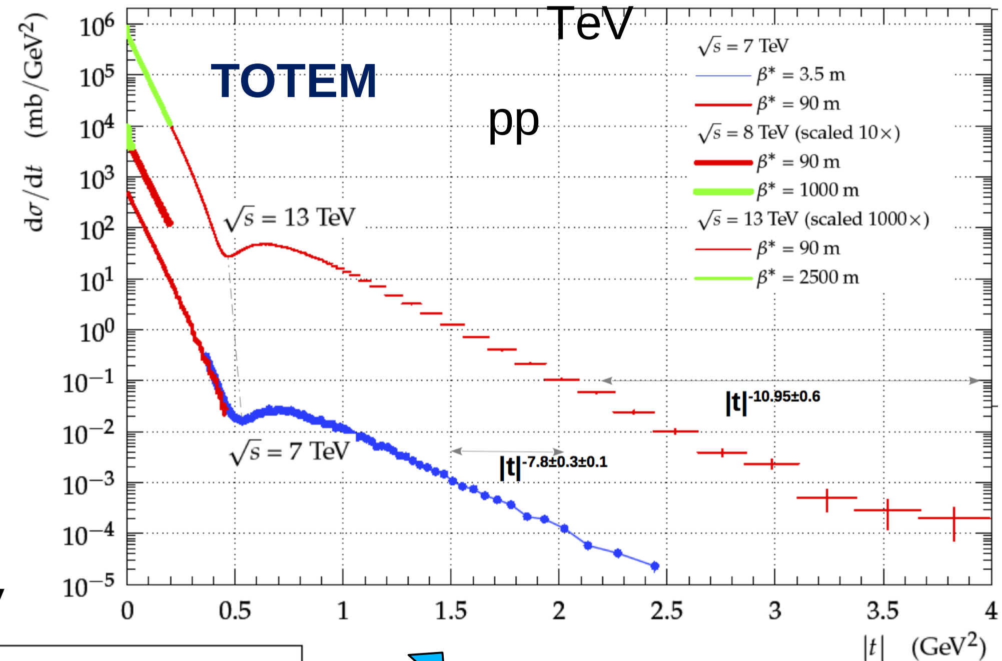
A. Breakstone et al., PRL 54 (1985) 2180

Tevatron: √s = 1.96 TeV



D0 Collaboration, PRD 86 (2012) 012009.

LHC: √s = 7 & 13 TeV



TOTEM Collaboration, EPL 95 (2011) 41001 & CERN-EP-2018-338

pattern follows expectation from t-channel exchange of colourless C-odd bound 3-gluon compound !