Highlights from the CMS experiment

Wolfgang Adam

for the CMS collaboration

Ghent, BE

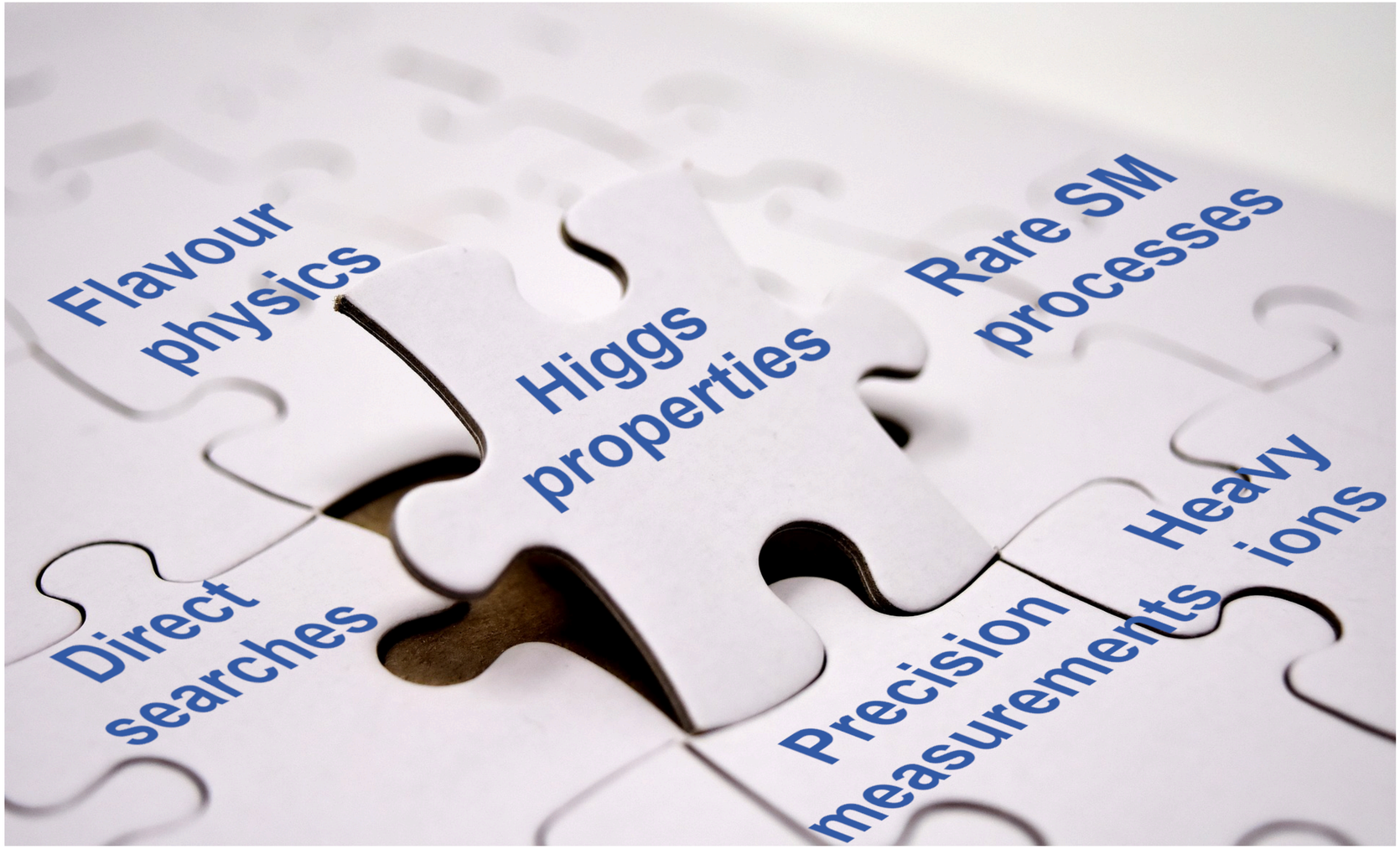
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

CMS

Physics goals & methods

Completing our picture

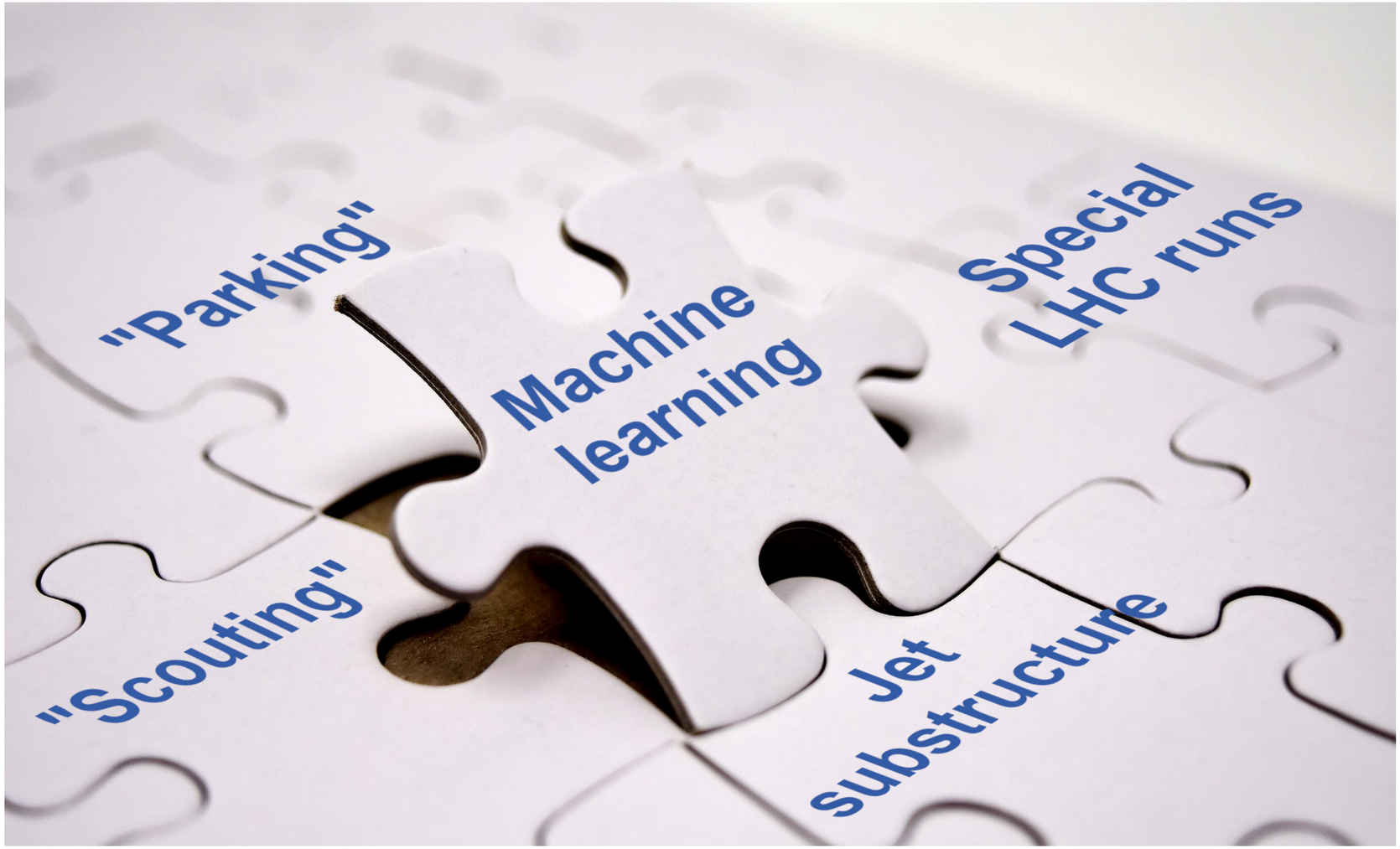


Physics goals & methods

How?

- New ideas for trigger, data processing, and analysis:

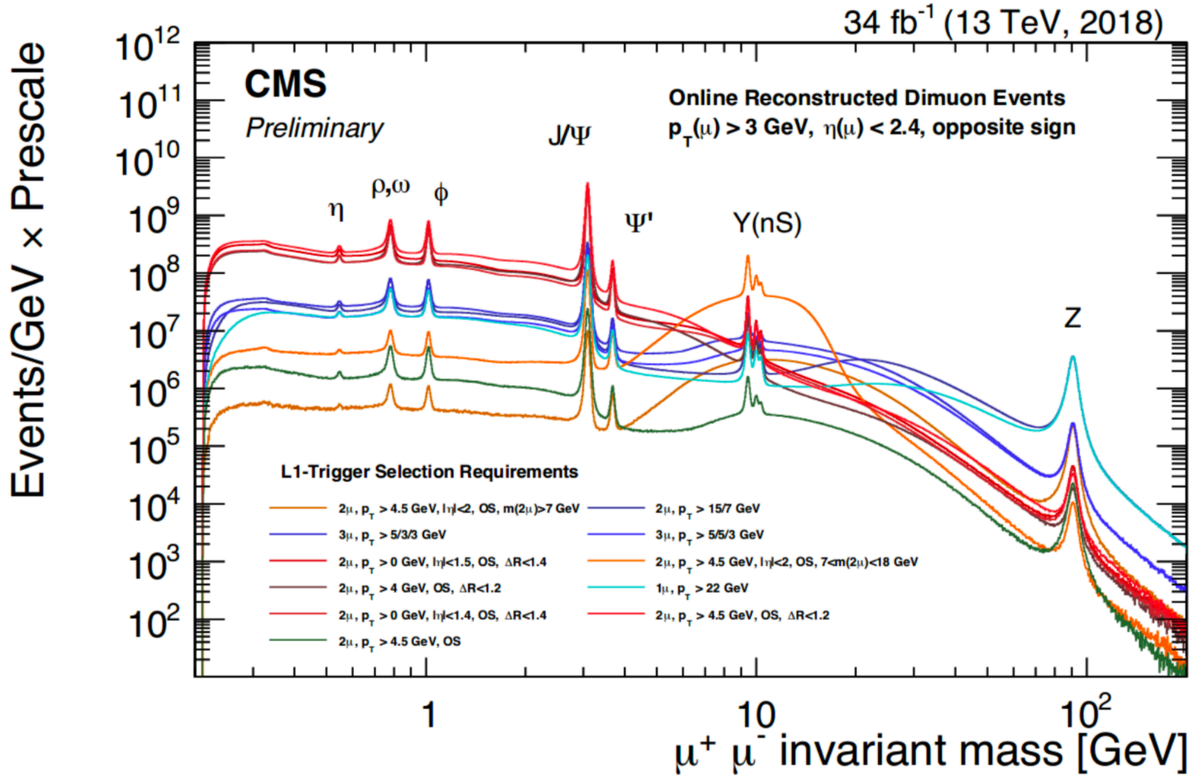
  continue improving analyses in terms of precision and sensitivity independently of increases in luminosity and collision energy



Physics goals & methods

"Scouting"

- Avoid bandwidth limitations in order to access lower p_T and mass regions where trigger rates are (too) high
  - reduction of event size to O(10kB) allows trigger rates of several kHz
- Reconstruct at the High Level Trigger (HLT) stage, drop RAW data and analyse using the HLT objects
  - needs adequate calibration at the HLT level and validation against full reconstruction
- Example: search for low-mass n-jet resonances



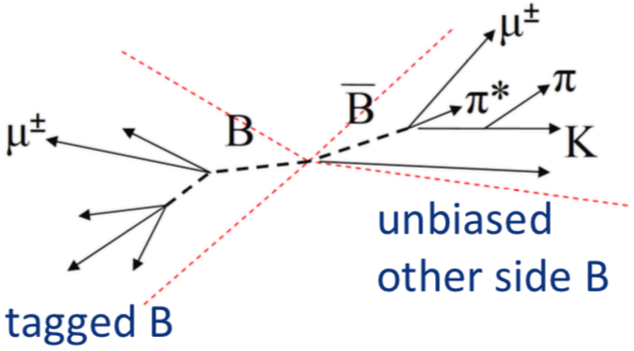
CMS DP-2018/055

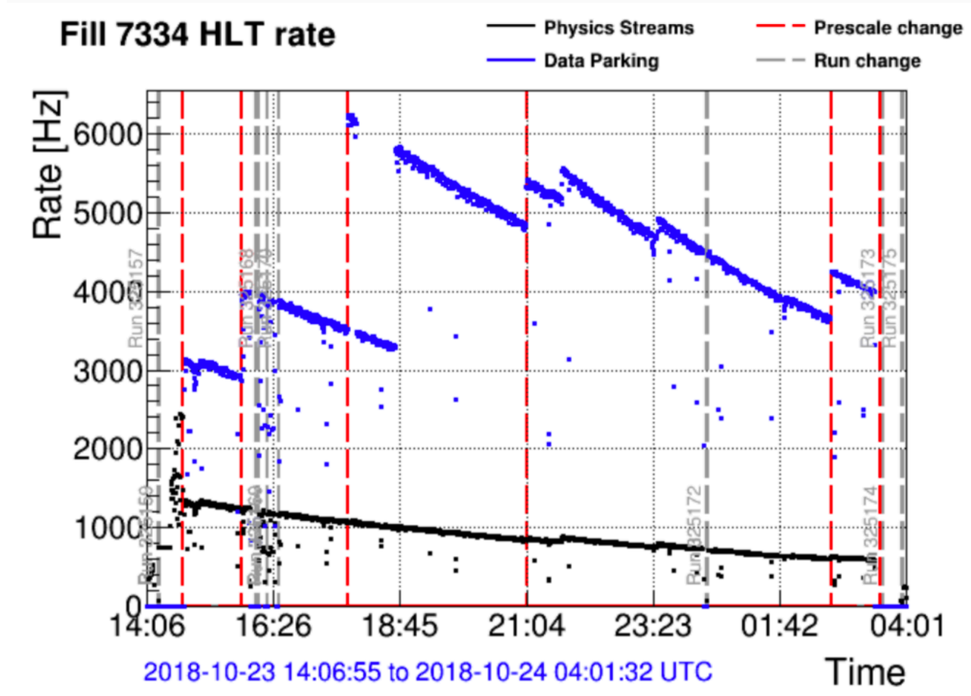
Physics goals & methods

"Parking"

- Avoid CPU limitations in prompt reconstruction
- Store additional datasets and delay processing to times of lower load on the computing system
  - needs careful planning taking into account data taking schedule and MC production

- Example: B-physics





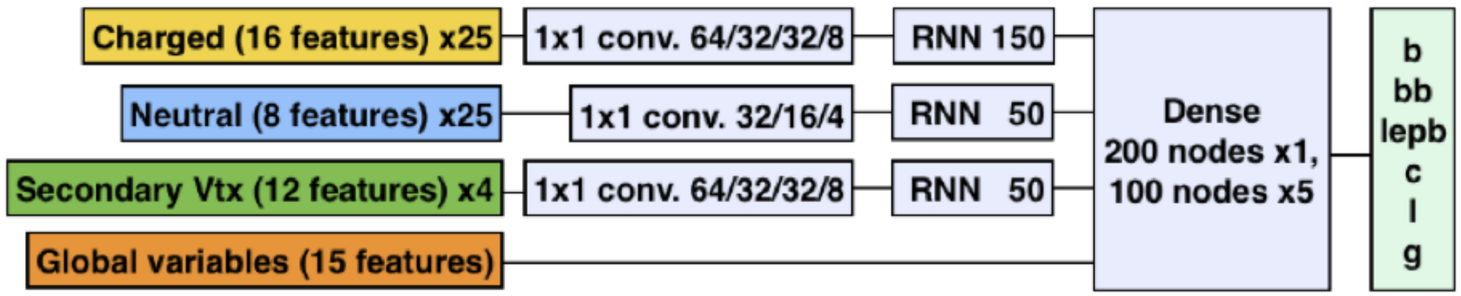
Use lower trigger rates at end of fill to store events at a rate of up to 6kHz

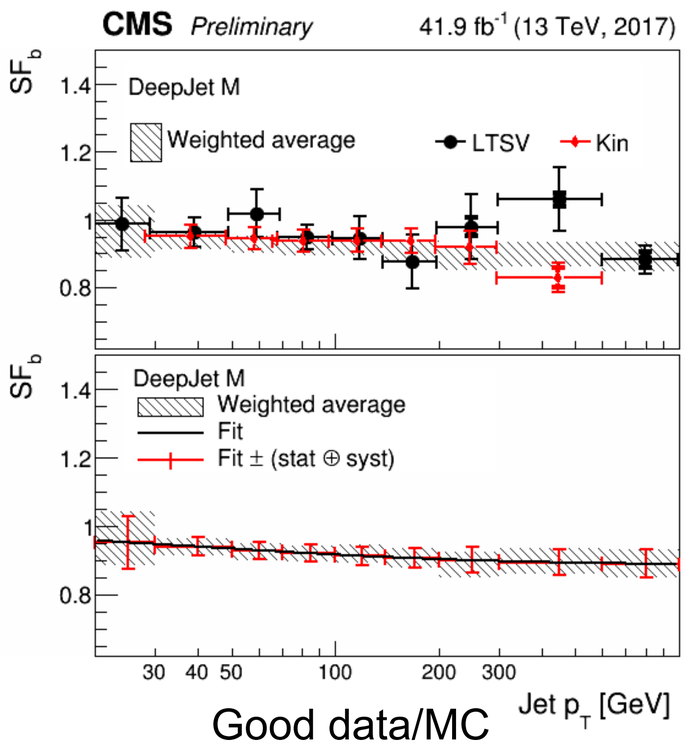
- displaced muon trigger → sample of unbiased B decays
- 12B events recorded

Physics goals & methods

Machine learning

- Use full power of multiple variables and reduce need for manual tuning
- Wide range of state-of-the-art algorithms used for solving combinatoric problems, regression, and classification
  - needs adequate control regions for performance measurements and (typically) large MC samples
- Examples: “DeepJet” b-tagging, neural networks for the ttH(H->bb) analysis





Good data/MC agreement at better performance

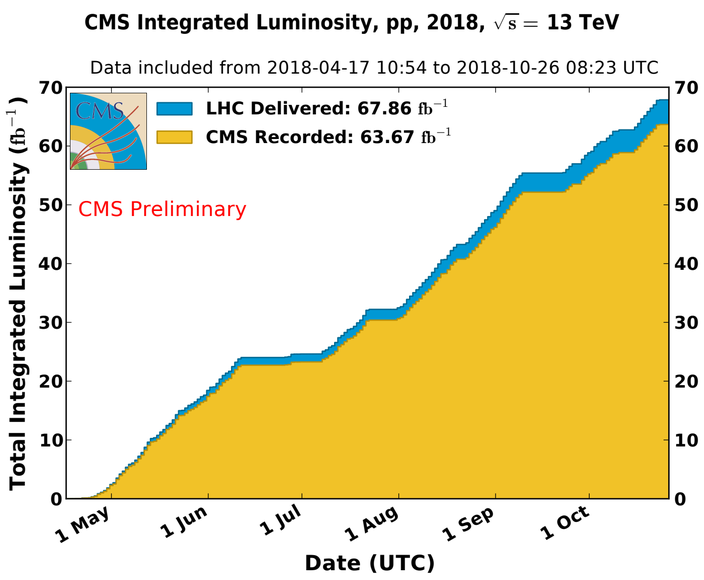
CMS DP-2018/058

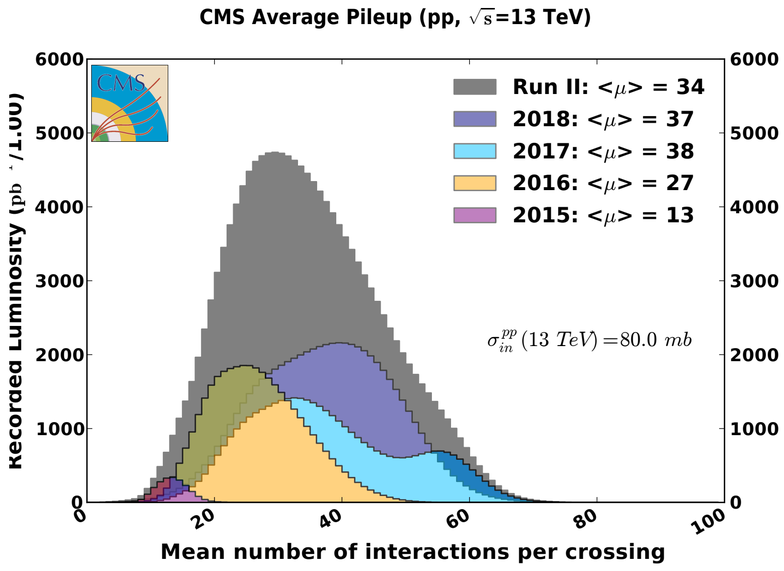
CMS data in Run 2

Excellent data quality

- Reminder: Run 2 data taken with an evolving detector configuration, in particular
  - upgrade of the pixel detector to 4 layers
  - upgrade of the HCAL readout (long. segmentation)

- 2018: largest dataset collected so far
  - uses nearly complete CMS Phase-1 configuration
  - pileup conditions similar to 2017





Properties of the Higgs boson

Higgs boson properties

Continuous work toward a global picture

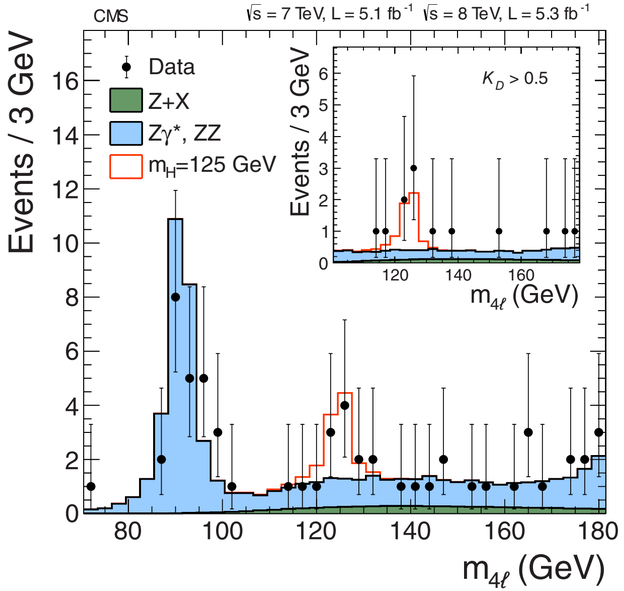
- LHC Run 1 led to discovery using decays to bosons
- LHC Run 2 directly established couplings to 3rd generation fermions
- LHC Run 3 will extend sensitivity to physics beyond the SM
- HL-LHC will allow to probe the Higgs self-coupling

PLB 779(2018)283
PRL 120(2018)231801
PRL 121(2018)121801

Production and decay modes covered by recent CMS results

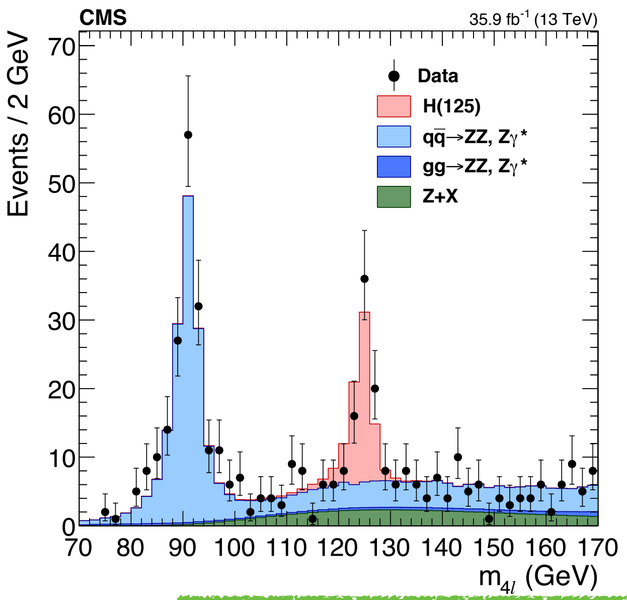
	ggH	VBF	VH	ttH
H→ZZ	HIG-19-001, Run 2			
H→γγ	HIG-18-029, '16+'17		HIG-16-040, '16	HIG-18-018, '16+'17
H→WW	HIG-16-042, '16			HIG-18-019, '16+'17
H→ττ	HIG-18-032, '16+'17		HIG-18-007, '16	
H→bb	HIG-16-044, '16		HIG-18-016, 16+17	HIG-18-030, '16+'17
H→μμ	HIG-17-019, '16			
H→cc			HIG-18-031, '16	
H→inv	HIG-17-023, '16			

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



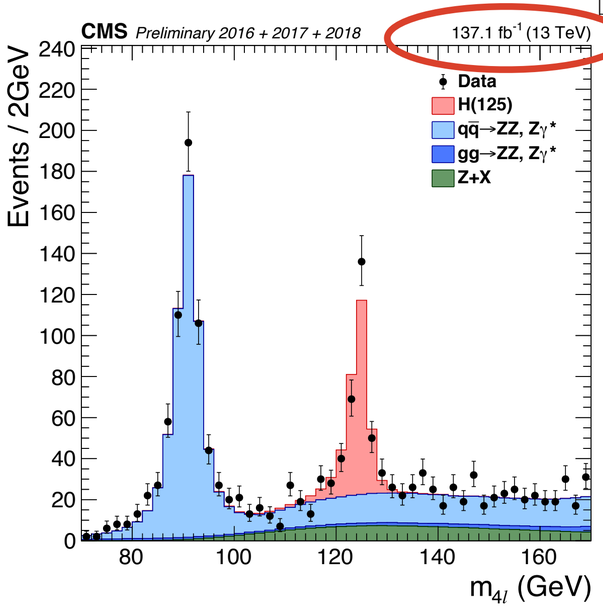
PLB 716(2012)30

Run 1



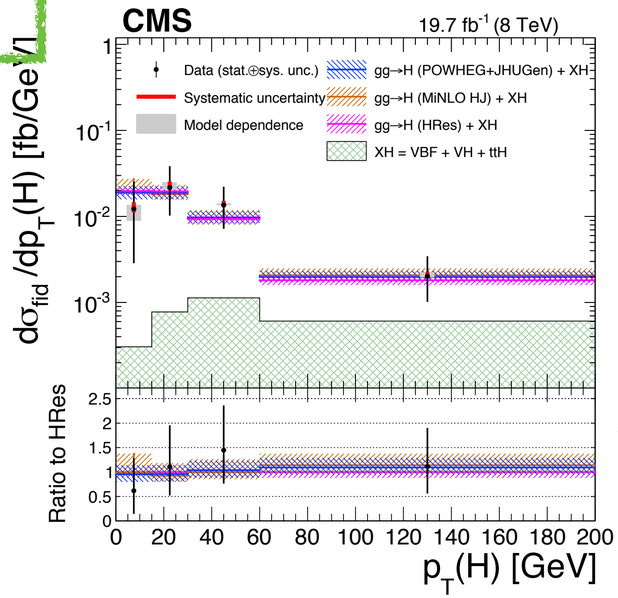
JHEP 11(2017)47

2016



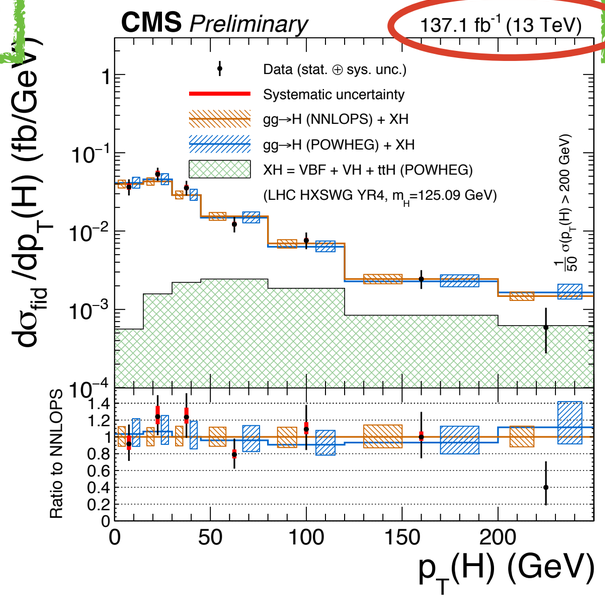
HIG-19-001

Run 2



JHEP 04(2016)5

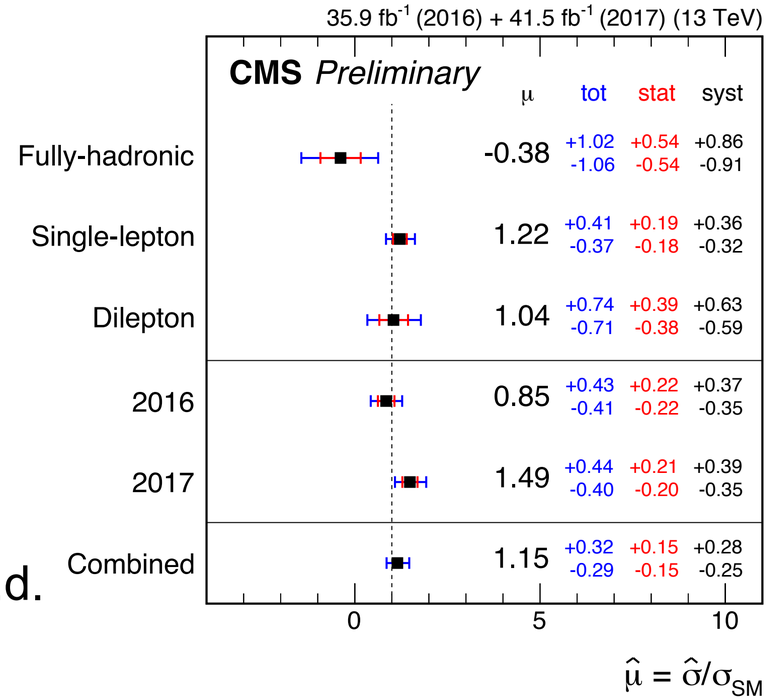
Run 1

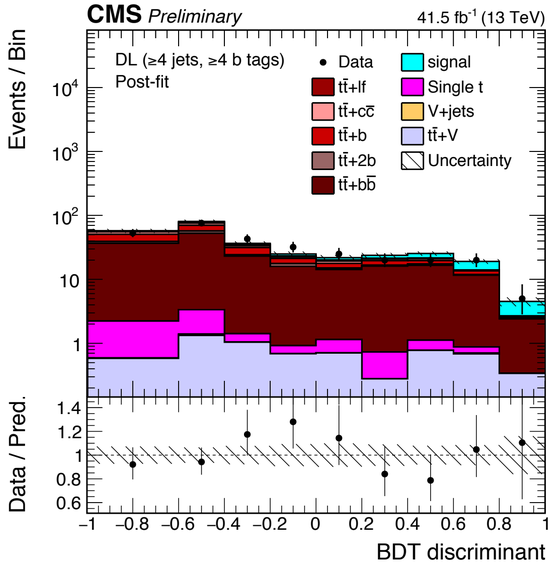


Decays to 3rd generation fermions

ttH (H→bb)

- Covers 0, 1, and 2l decay modes
- Improvements in particular for MVA techniques and b-jet identification



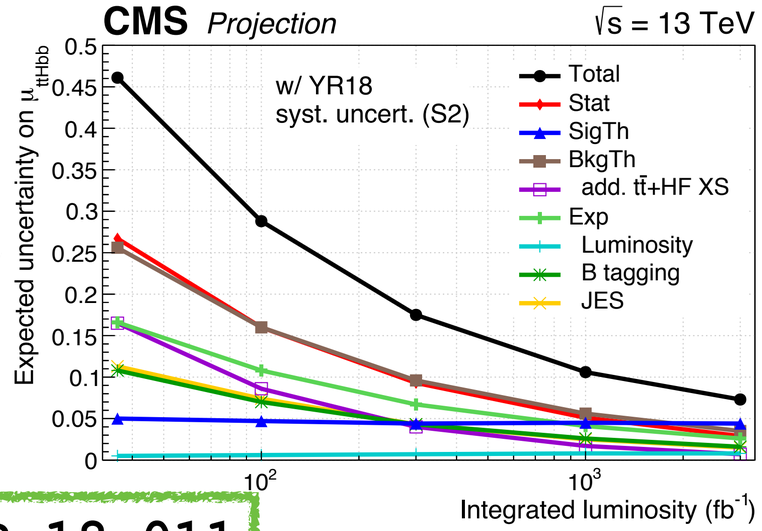


Achieved evidence for decays to bb based on ttH only:
obs (exp) significance = 3.9 (3.5) s.d.

$$\mu_{\text{comb}} = 1.15^{+0.32}_{-0.29}$$

HIG-18-030 NEW!

Comparison with HL-LHC projections
- already improved w.r.t. basis for projection
- large further potential for full HL-LHC luminosity



FTR-18-011

For reference:
Observation of H→bb by both ATLAS and CMS in 2018
CMS (multiple prod. modes): **PRL 121(2018)121801**

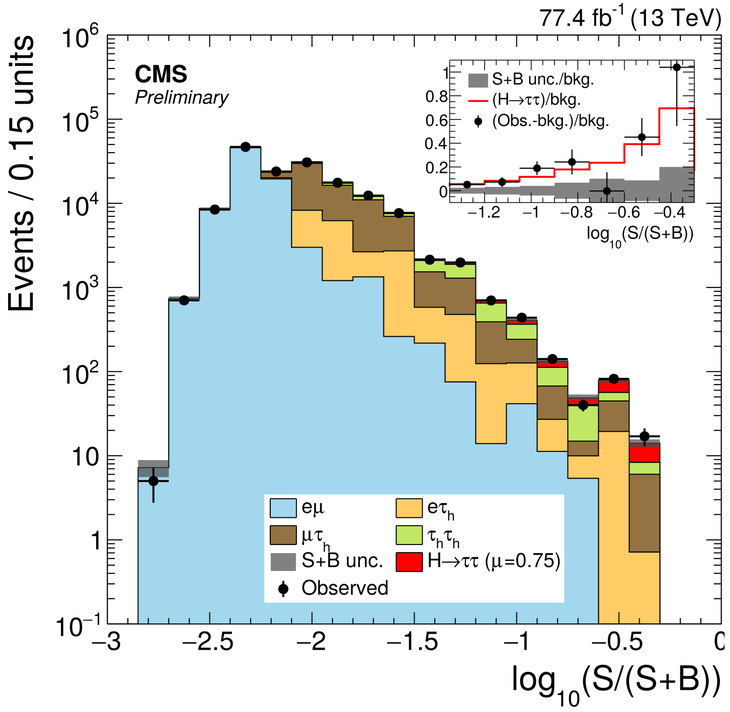
Decays to 3rd generation fermions

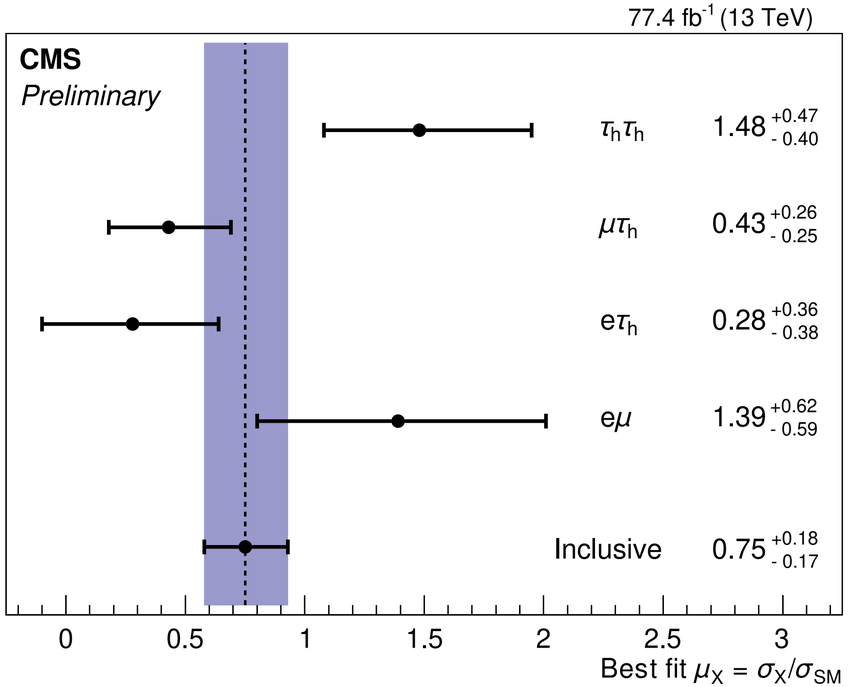
H→ττ

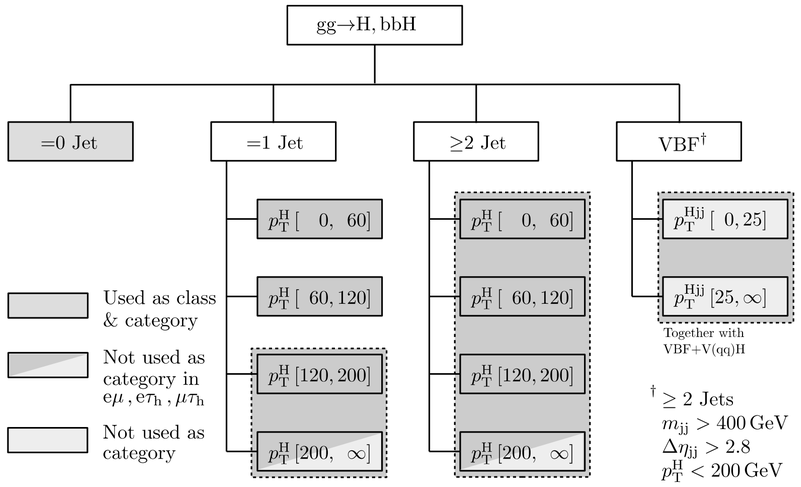
HIG-18-032

- Covers the eμ, eth, μτh, and τhτh channels
- New: use of NN classification to distinguish background and different signal categories

$$\mu_{\text{incl}} = 0.75^{+0.18}_{-0.17}$$





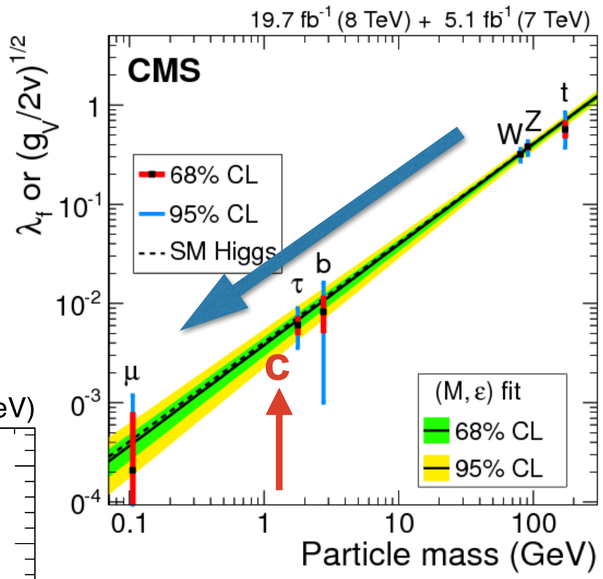


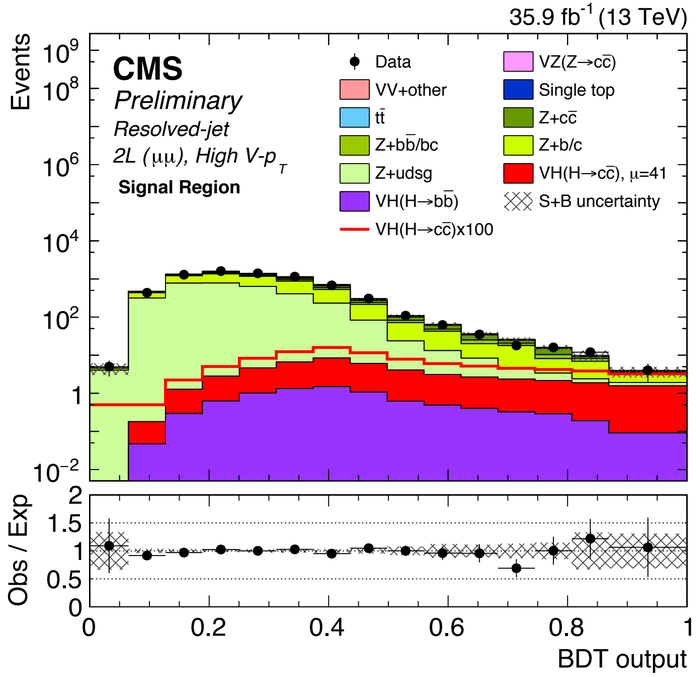
Includes detailed results on kinematic properties
(simplified template cross section stage 1 prescription)

Moving to the 2nd generation

First CMS result on VH, H→cc

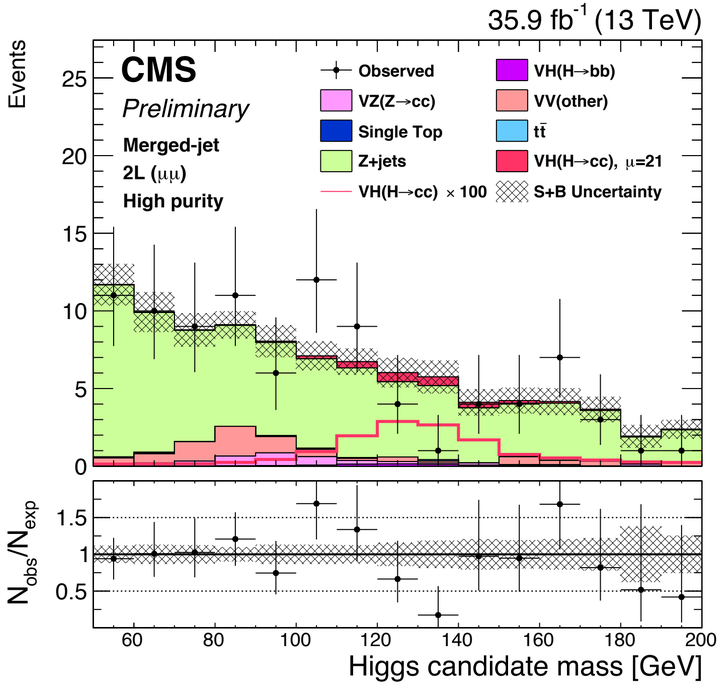
- highly challenging due to low cross section and need for c-tagging
  - categorisation according to lepton multiplicity of V decays
  - addressing resolved (2 c jets) and merged (1 cc jet) cases
  - use of ML and jet substructure for tagging and classification





BDT output for one category (resolved jets, $p_T(V)>150$GeV)

Jet mass for the high-purity category (merged jets)



HIG-18-031

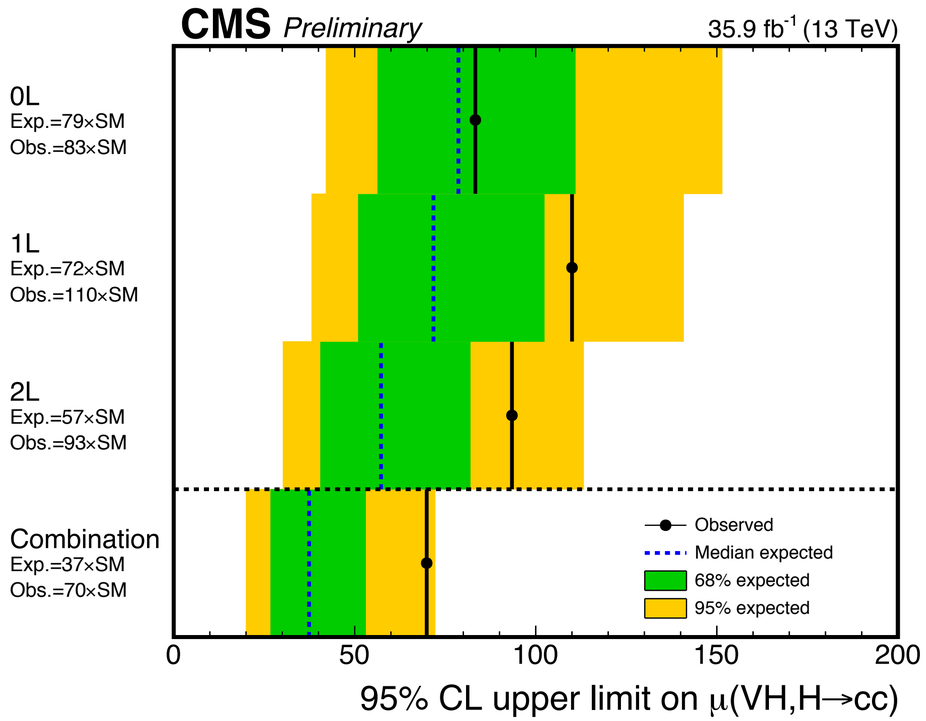
NEW!

Moving to the 2nd generation

HIG-18-031

First CMS result on VH, H→cc

- final results from combination of resolved & merged jet analyses



Combined results on signal strength:
- Obs (exp) exclusion: 70 (37)
- $\mu(\mathrm{VH}, \mathrm{H} \to c\bar{c}) = 36^{+20}_{-19}$

Validation using VZ production:
- $\mu(\mathrm{VZ}, \mathrm{Z} \to c\bar{c}) = 0.55^{+0.86}_{-0.84}$

For reference: current CMS results on H→$\mu\mu$ signal strength (data from 2016)
- obs (exp) exclusion: 2.92 (2.16)
- obs (exp) significance: 0.9 (1.0) s.d.

PRL 122(2019)021801

Rare SM processes

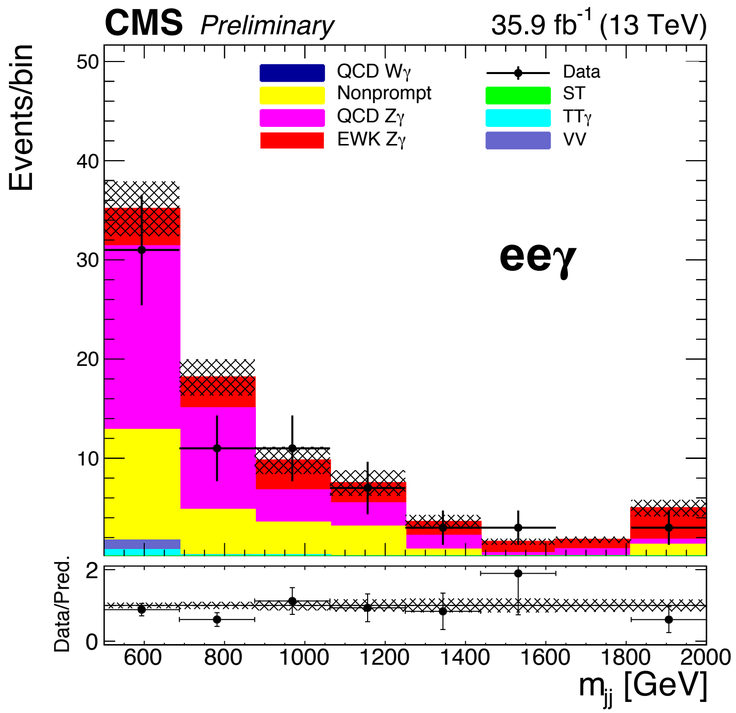
VBS: EWK Zγ production with two jets

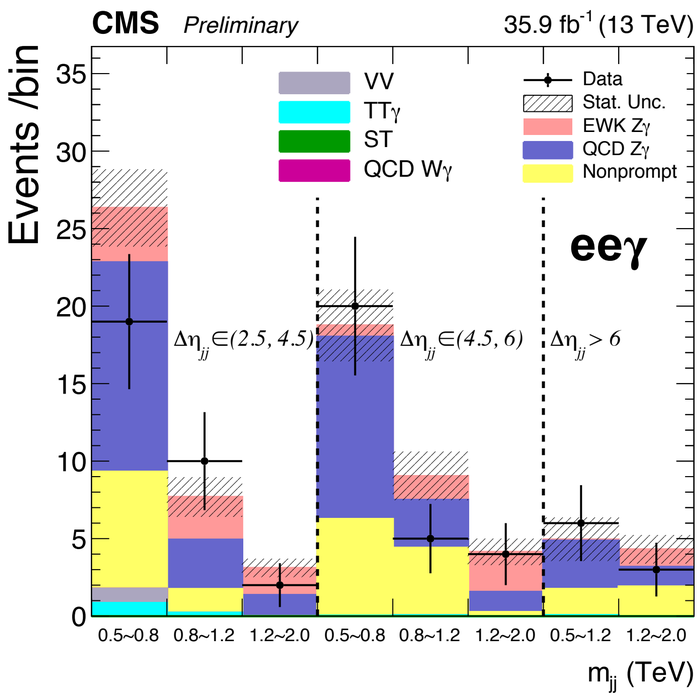
Vector boson scattering directly probes EWK SM gauge structure

- Selection reduces contribution from strong production
- Signal extracted from 2D fit to properties of the djiet system: m_{jj} and $\Delta\eta_{jj}$

SMP-18-007

NEW!





Obs (exp) significance
- this analysis: 3.9 (5.2) s.d.
- combination with 8TeV: 4.7 (5.5) s.d.

Signal strength (fid. region): $0.64^{+0.23}_{-0.21}$

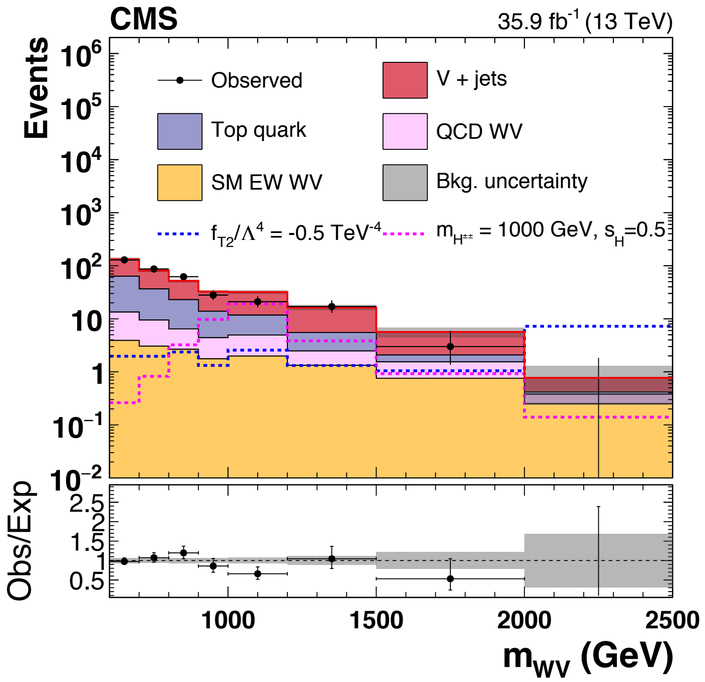
Limits on anomalous QGC parameters:
- the analysis sets the most stringent limits to date on two of these parameters ($F_{T,8}/\Lambda^4$ and $F_{T,9}/\Lambda^4$)

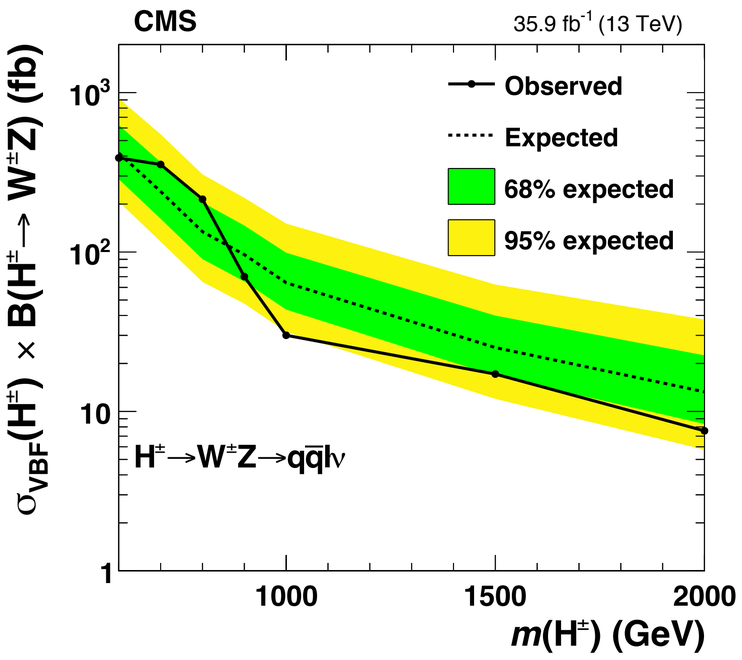
Other VBS measurements

Anomalous EWK VV production with two jets

- Using the WW, WZ, and ZZ channels
- Interpretation in EFT or as limits on $H^{\pm}$ production

arXiv:1905.07445





For reference:
Observation of EWK production of $W^{\pm}W^{\pm}$

PRL 120(2018)081801

Estimate ultimate precision of ~3% at HL-LHC: **FTR-18-005**

FTR-18-014

Ultimate goal: investigation of Z_L scattering → HL-LHC

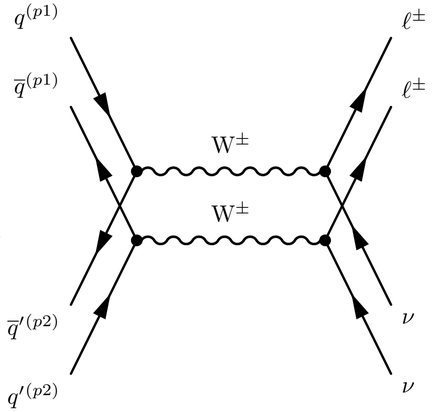
η coverage	significance	VBS $Z_L Z_L$ fraction uncertainty (%)
$\lvert\eta\rvert < 2.5(2.4)$	1.22σ	88
$\lvert\eta\rvert < 3.0(2.8)$	1.38σ	78
$\lvert\eta\rvert < 4.0(2.8)$	1.43σ	75

Double parton scattering

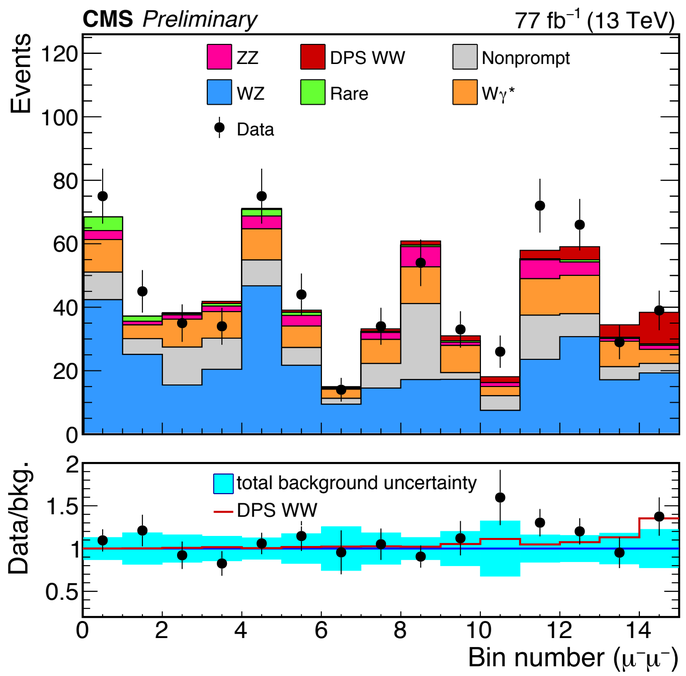
Evidence for the DPS process in same-sign WW events

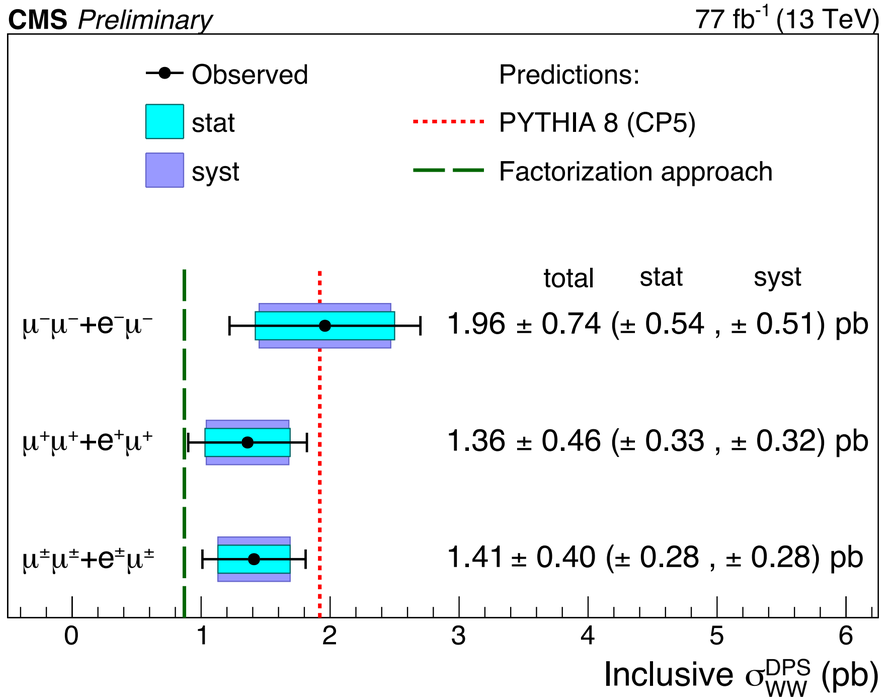
- Absence of extra jets @ LO can be used as a handle to distinguish DPS and single hard scattering
- Two multivariate classifiers discriminate signal from WZ backgrounds and events with mis-identified leptons

SMP-18-015



DPS cross section assuming factorisation: $\sigma_{\mathrm{DPS}} = \frac{n}{2}\frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$





First evidence for DPS WW production

- Significance = 3.9 s.d.

SM precision measurements

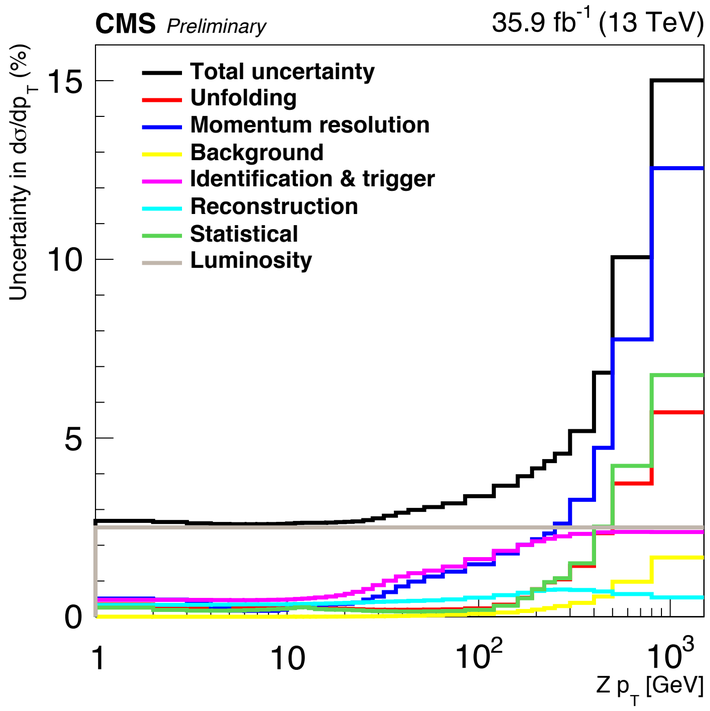
Precision measurements: Z+jets

Differential cross section measurement

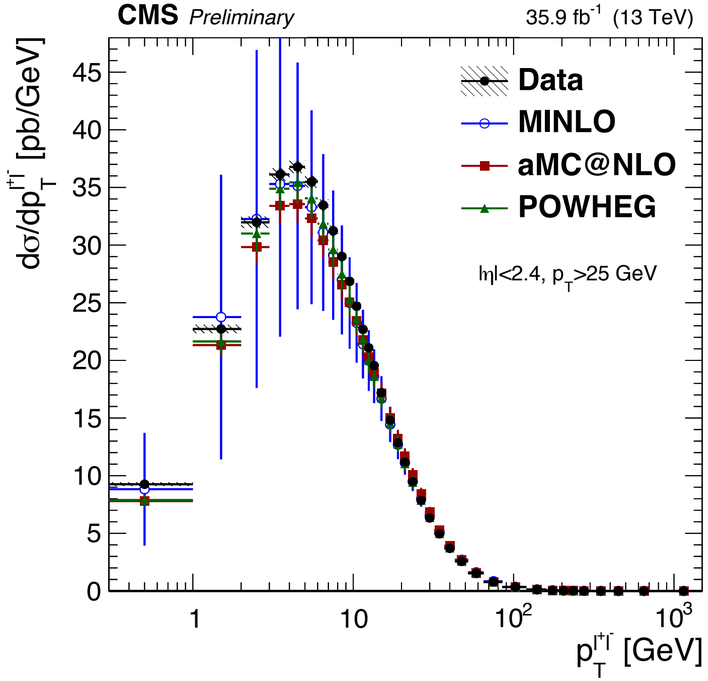
- Measured as function of $p_T(Z)$, $\eta(Z)$, and Φ^*
- Incl. cross section agrees with NNLO predictions
- Uncertainty on absolute cross section dominated by luminosity component for low $p_T(Z)$

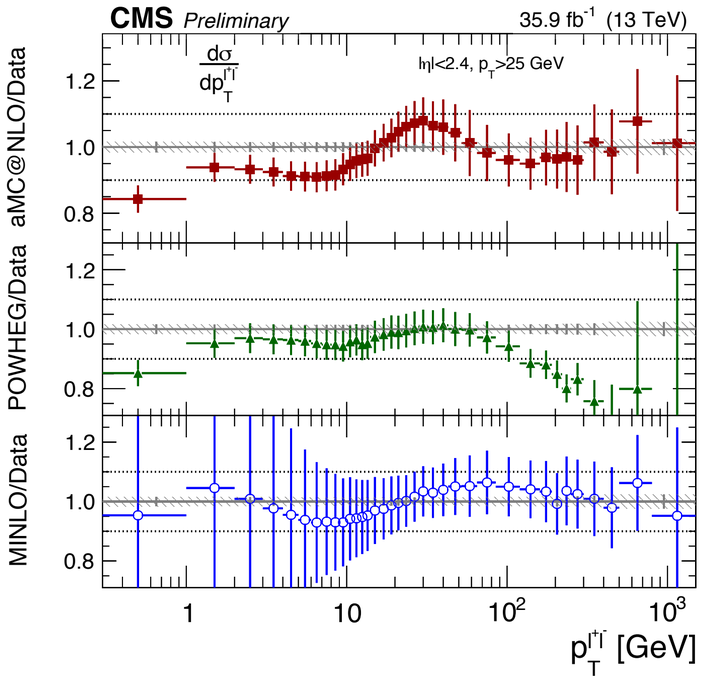
$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$



SMP-17-010



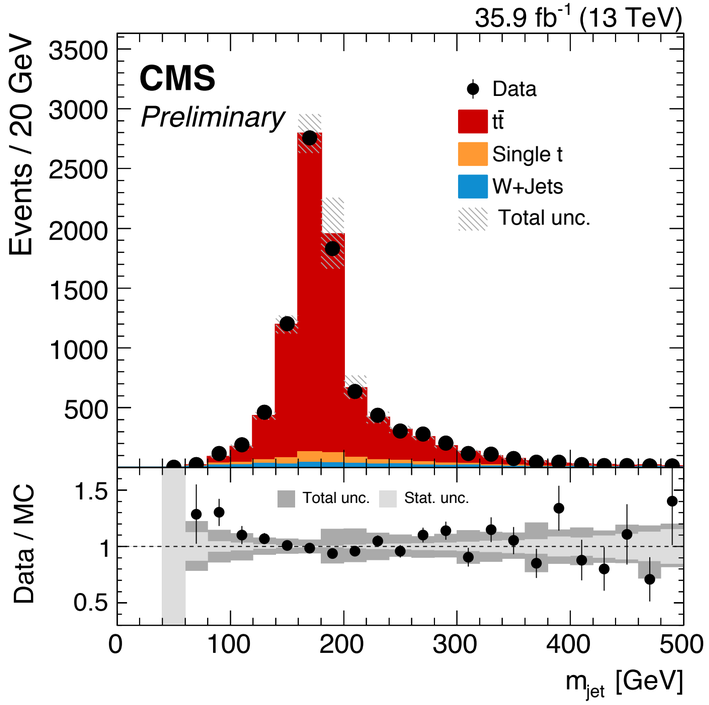


Achieves 0.5% uncertainty on normalised cross sections for $\Phi^*<0.5$ and $p_T(Z)<50$GeV

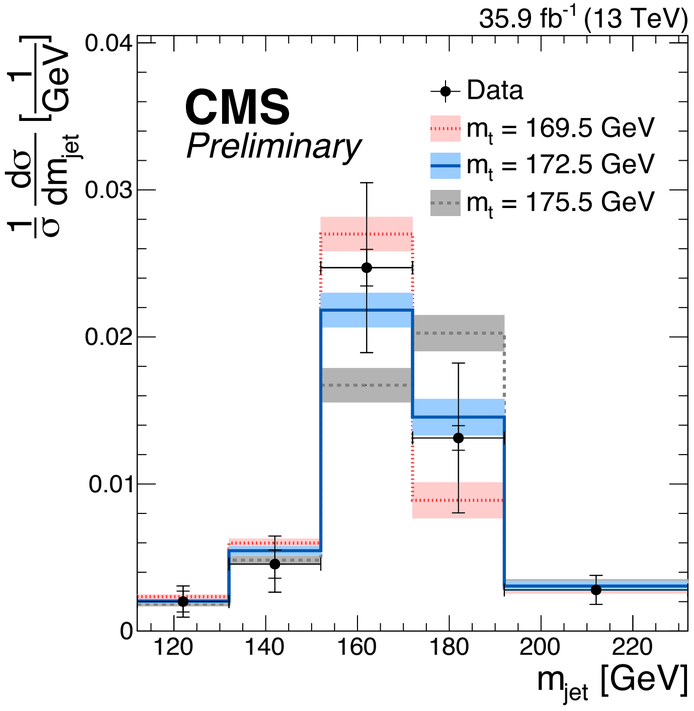
Measurement of m(jet) in top quark decays

Jet mass in decays of boosted top quarks

- Alternative approach to measuring m(t): jet mass of highly boosted top quarks (p_T>400GeV)
- Reconstruction of large (R=1.2) jets, and 3 subjets / jet using the XCone algorithm
  - one leptonic top decay is required, and jet with max. distance to lepton is chosen



Unfold to particle level



Extracted value for m(t) = 172.56 ± 2.47 GeV

Uncertainty similar to the ones from threshold production!

TOP-19-005 NEW!

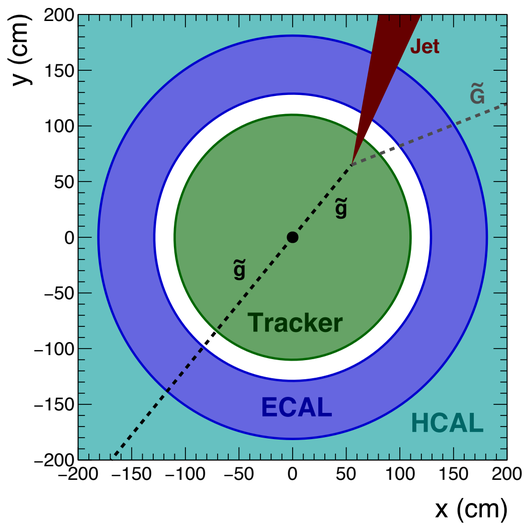
Long-lived particles

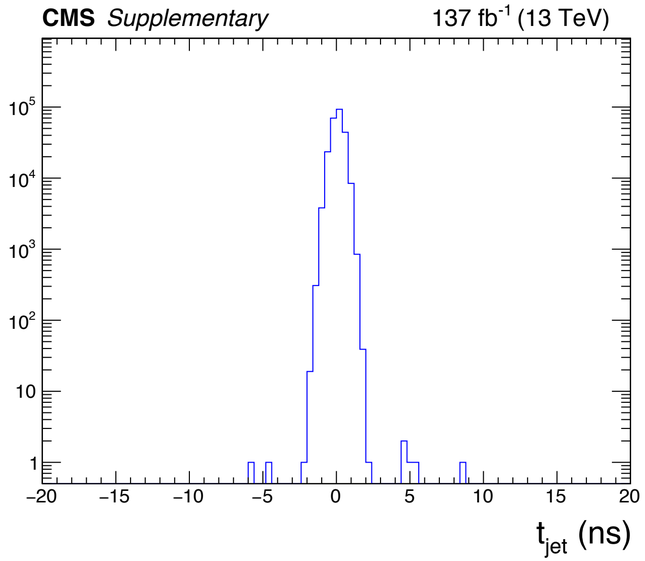
Delayed jets

arXiv:1906.06441

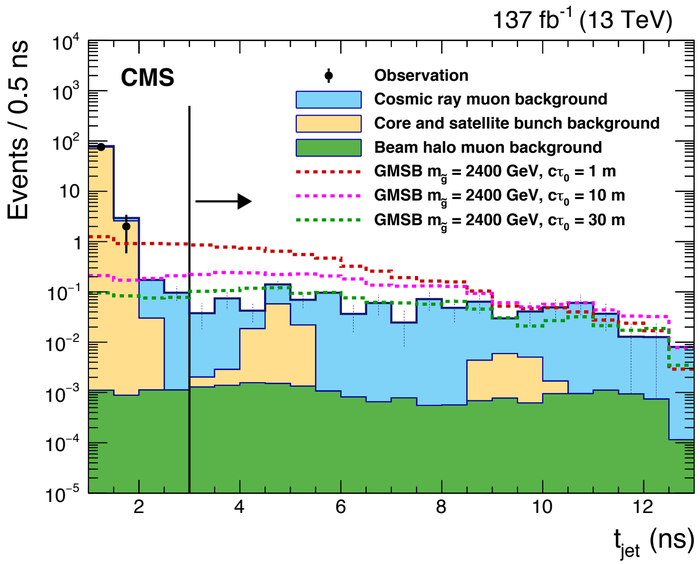
Jet timing using ECAL

- Long-lived gluinos give rise to jets from displaced vertex
  - Delay due to differences in velocity and in path length
- uses median time of all ECAL cells in the jet cone

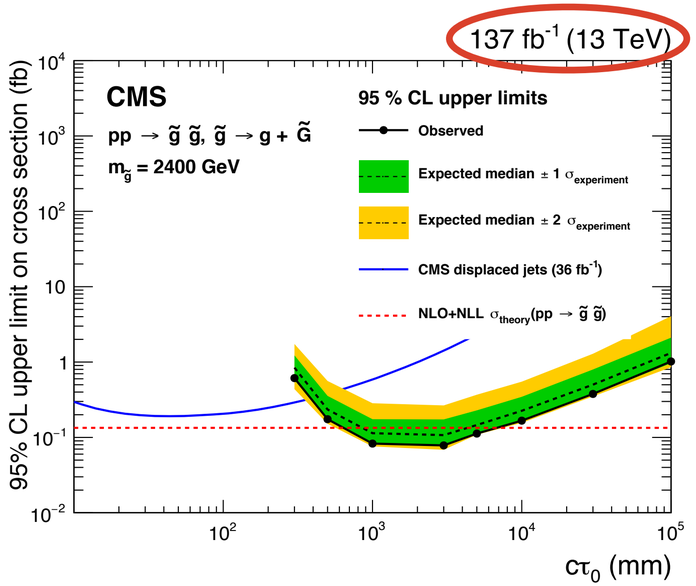




median time of ECAL cells in cone - background jets



main backgrounds from cosmics & satellite bunches



significant extension of sensitivity w.r.t. tracker-based searches

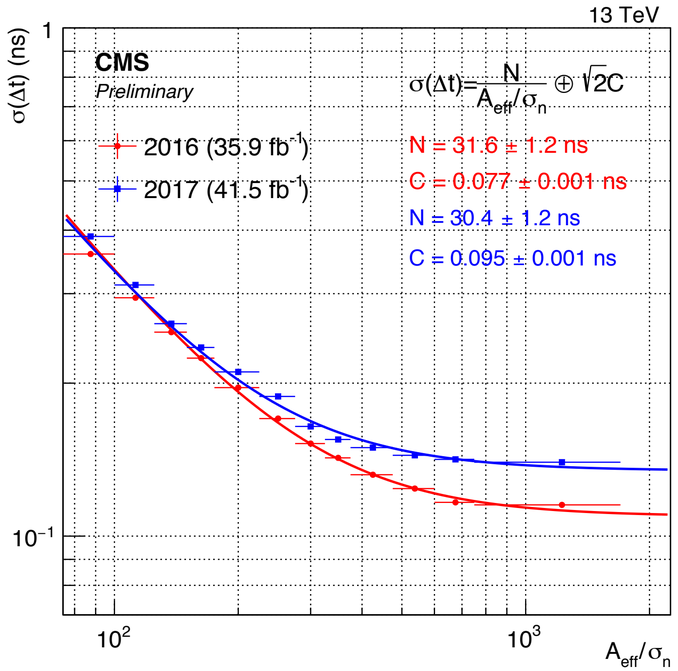
Delayed photons

Photon timing using ECAL

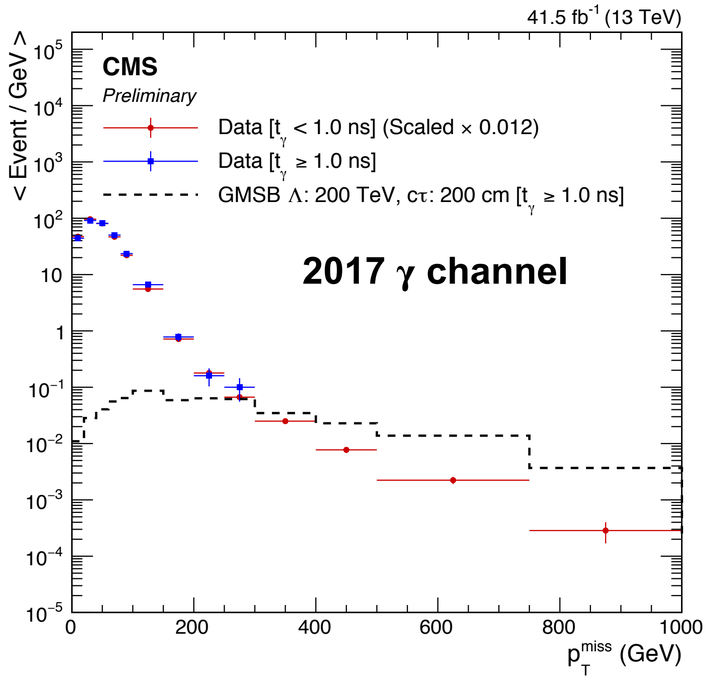
- Long-lived neutralinos decay to a photon and a graviton
- requires precise calibration of ECAL timing and resolution

EXO-19-005

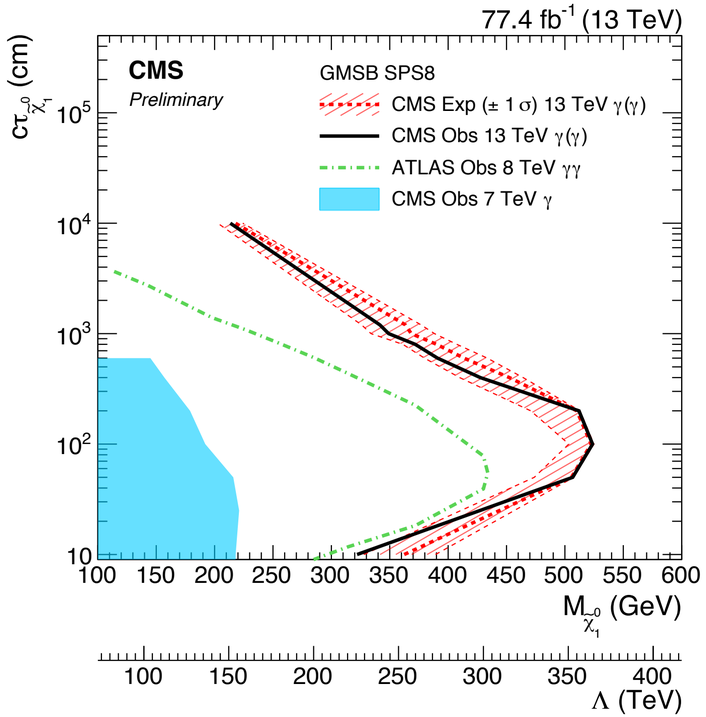
NEW!



Time resolution for photons



Spectra for prompt and delayed selections, and signal



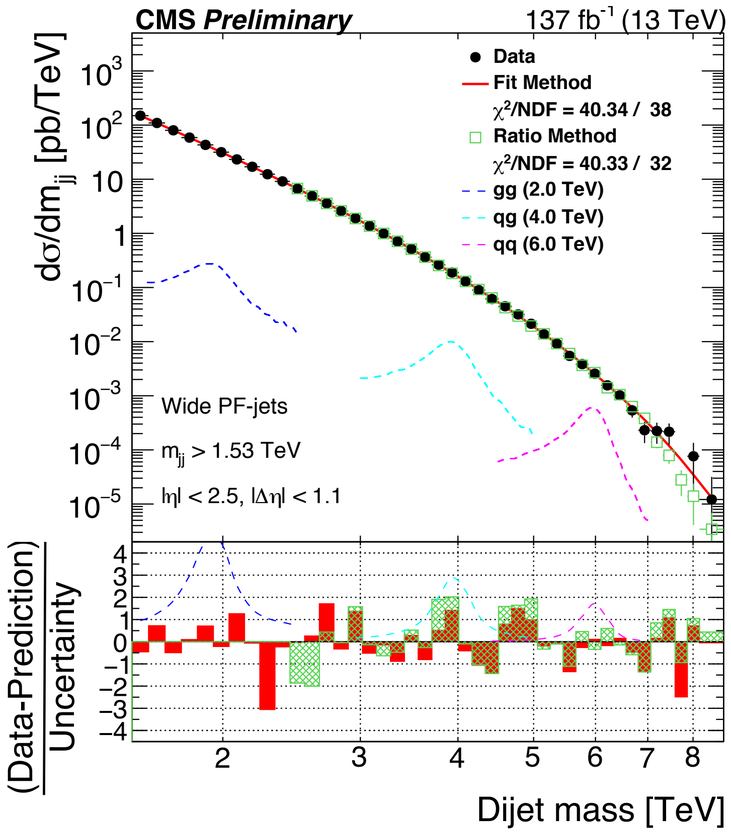
Substantial improvement w.r.t. early Run 1 search

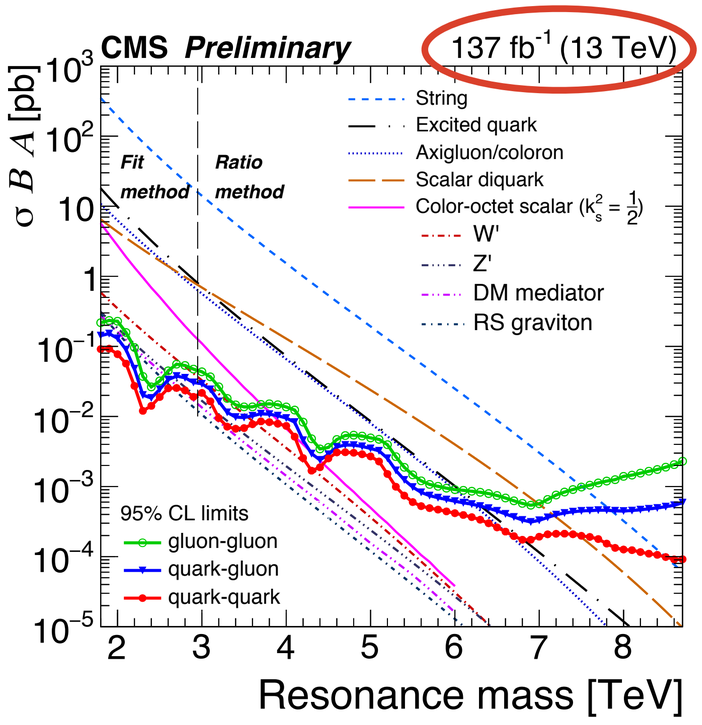
(High-mass) direct searches

Resonant decays to two jets

Classical high-mass resonance search

- can be interpreted in a wide range of BSM models predicting particles decaying to gg, gq, or qq
- keep to improve analysis with new techniques:
  - replace parameteric background shape by measurement in data sideband region
  - consistent predictions, higher sensitivity for masses > 3TeV



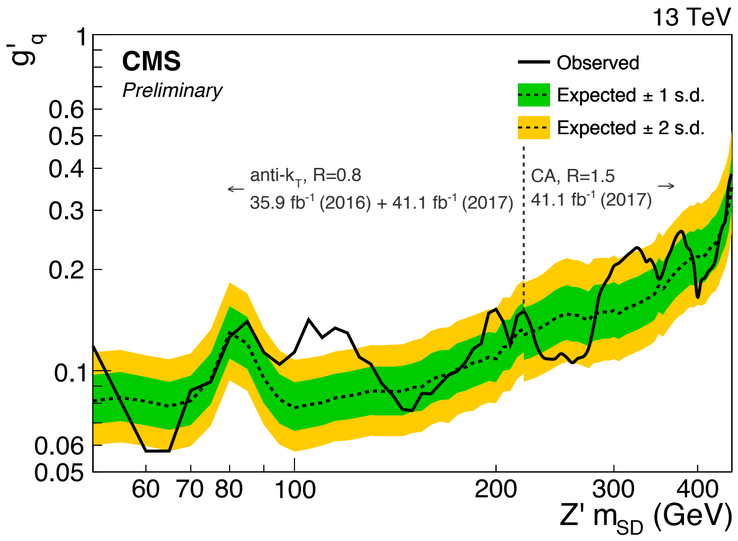


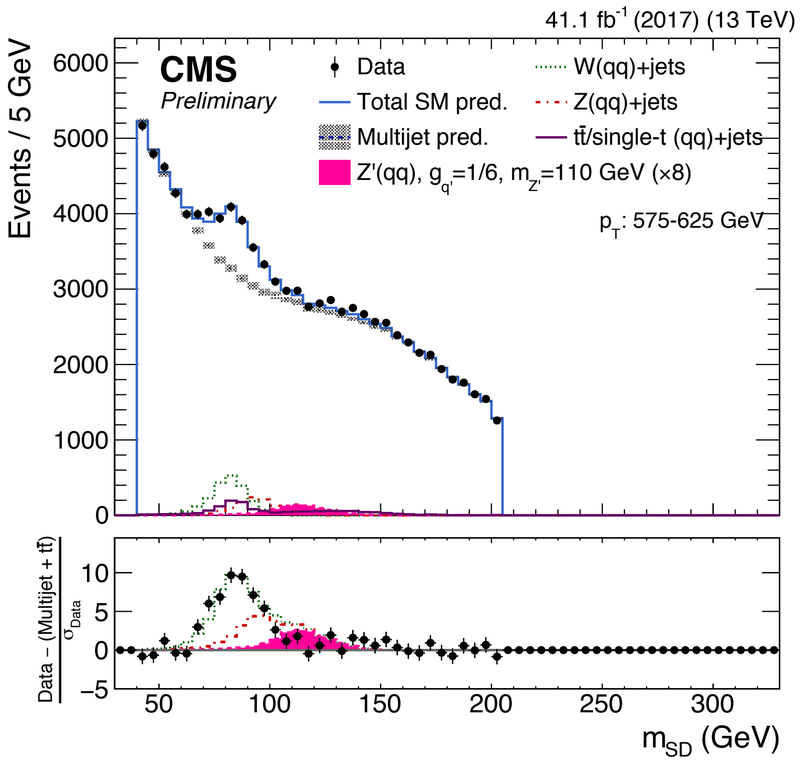
EXO-19-012 NEW!

Resonant decays to jets (boosted)

But no strong indications at high masses

- investigate low mass range in more detail:
  - here: looking for light vector resonances coupling to quark pairs
- need to overcome trigger restrictions; two approaches:
  - “scouting” for masses between 450 and 1000 GeV
  - here: use a hard ISR jet → boosted di-jet systems
- use of large-radius jets and jet substructure leads to an extension of sensitivity up to 450 GeV





EXO-18-012

SUSY searches

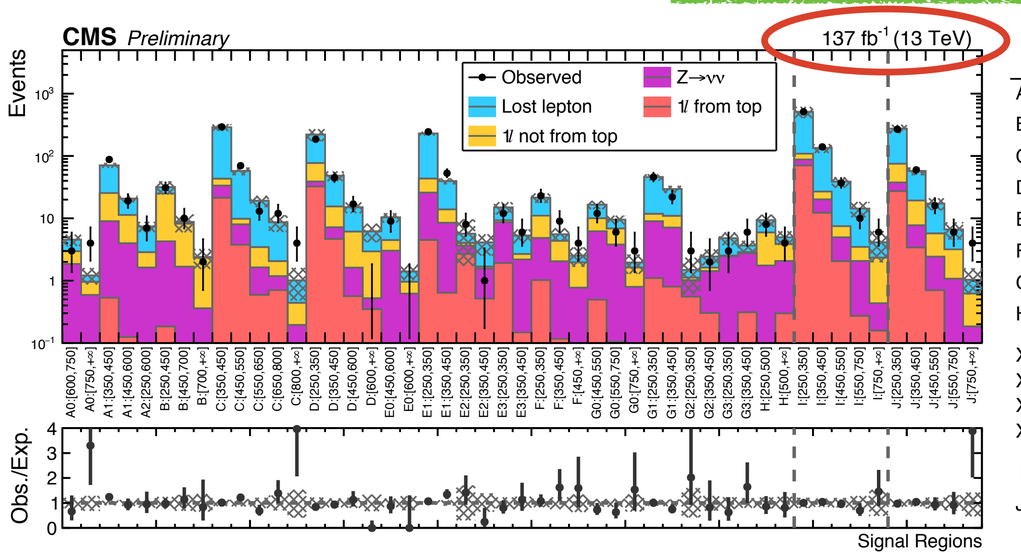
Recent searches for strongly produced SUSY particles in R-parity conserving scenarios

- Generic search for pair production of gluinos and squarks, stable (undetected) lightest SUSY particle
  - striking multijet + MET signature

SUS-19-006 NEW!

- Targeted search for top squark production
  - single-lepton channel

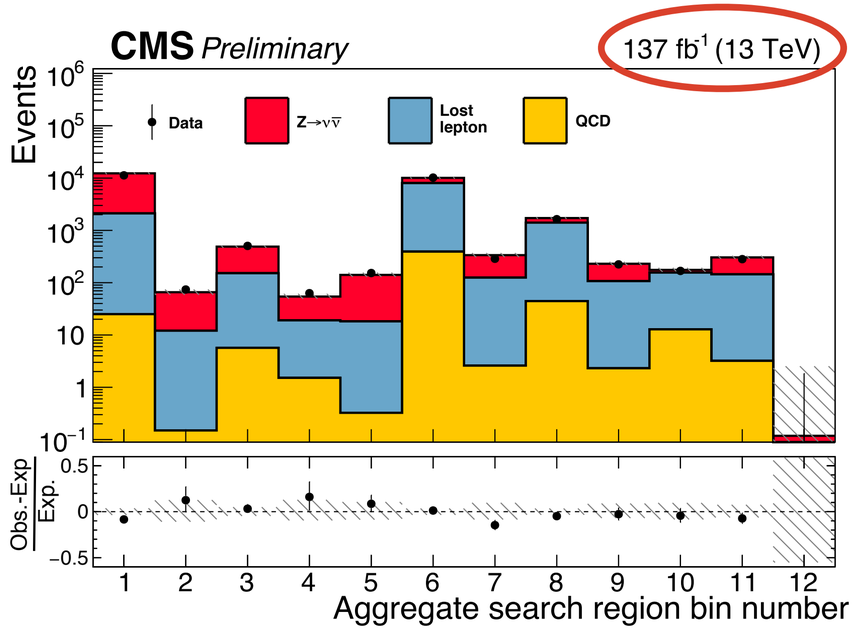
SUS-19-009 NEW!



	N_J	t_{mod}	$M_{l/b}$ [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$



Sensitivity in terms of mass limits in simplified model interpretations increased by ~150 GeV for gluinos and ~200GeV for top squarks.

Optimiziation for long-lived scenarios (disappearing tracks) leads to largely enhanced mass reach **SUS-19-005**

And many more …

PRL 122(2019)132001

Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

TOP-18-011

Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13$ TeV

SMP-19-001

Measurement of the $pp \to ZZ$ production cross section at $\sqrt{s} = 13$ TeV with the Run 2 data set

arXiv:1906.3322

Production of Λ_c^+ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Observation of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

PRL 122(2019)132003

SMP-18-013

Measurement of the associated production of a W boson and a charm quark at $\sqrt{s} = 8$ TeV

Search for charged Higgs bosons decaying into a top quark and a bottom quark in the fully hadronic final state at 13 TeV

HIG-18-015

Measurement of the dependence of inclusive jet production cross sections on the anti-k_T distance parameter in proton-proton collisions at $\sqrt{s} = 13$ TeV

SMP-19-003

Search for the resonant production of a pair of Higgs bosons decaying to the $b\bar{b}ZZ$ final state

HIG-18-013

Search for anomalous couplings in semileptonic WW and WZ decays at $\sqrt{s} = 13$ TeV

SMP-18-008

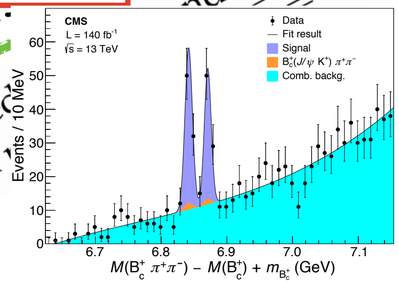
Measurement of total and differential cross sections of central exclusive $\pi^+\pi^-$ production in proton-proton collisions at 5.02 and 13 TeV

FSQ-16-006

First LHC paper using the full Run 2 dataset!

PRL 122 (2019) 1

Observation of two excited
the $B_c^+(2S)$ mass in



nd measurement of
= 13 TeV

TOP-18-011

First measurement of ttbb in the hadronic channel

Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13$ TeV

M asurement of the $pp \to ZZ$ production cross section at $\sqrt{s} = 13$ TeV with the Run 2 data set

SMP-19-001

arXiv:1906.3322

Production of Λ_c^+ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV

First observation of tZq production

n in association
s at $\sqrt{s} = 13$ TeV

Observation of single top
with a Z boson in proton-proton c

PRL 122 (2019) 132003

SMP-18-013

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HIG-18-015

Measurement of the dependence of inclusive jet production cross sections on the anti-k_T distance parameter in proton-proton collisions at $\sqrt{s} = 13$ TeV

SMP-19-003

CMS has published almost 900 papers based on LHC collision data !

Sear mileptonic WW and WZ decays at $\sqrt{s} = 13$ TeV

Search for the resonant production of a pair of Higgs bosons decaying to the $b\bar{b}ZZ$ final state

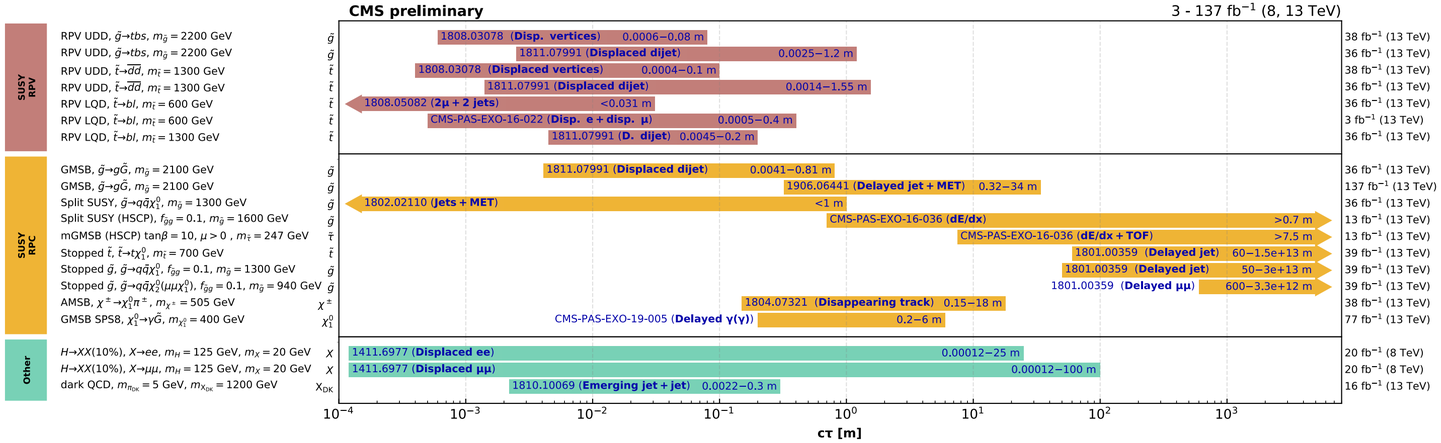
HIG-18-013

SMP-18-008

Measurement of total and differential cross sections of central exclusive $\pi^+\pi^-$ production in proton-proton collisions at 5.02 and 13 TeV

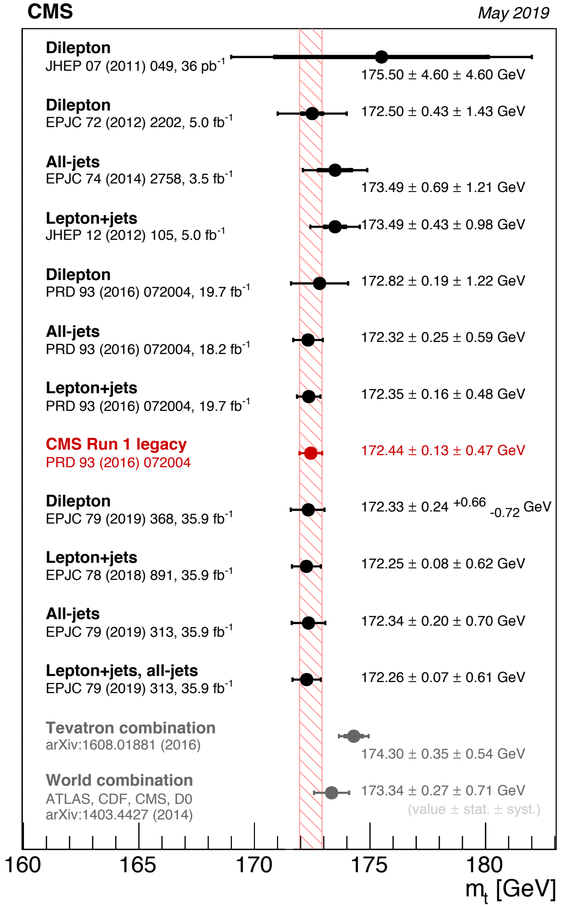
FSQ-16-006

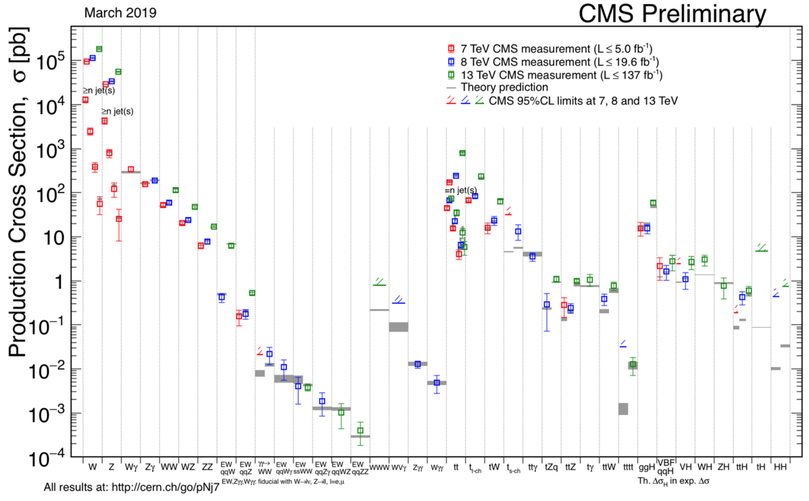
Overview of CMS long-lived particle searches



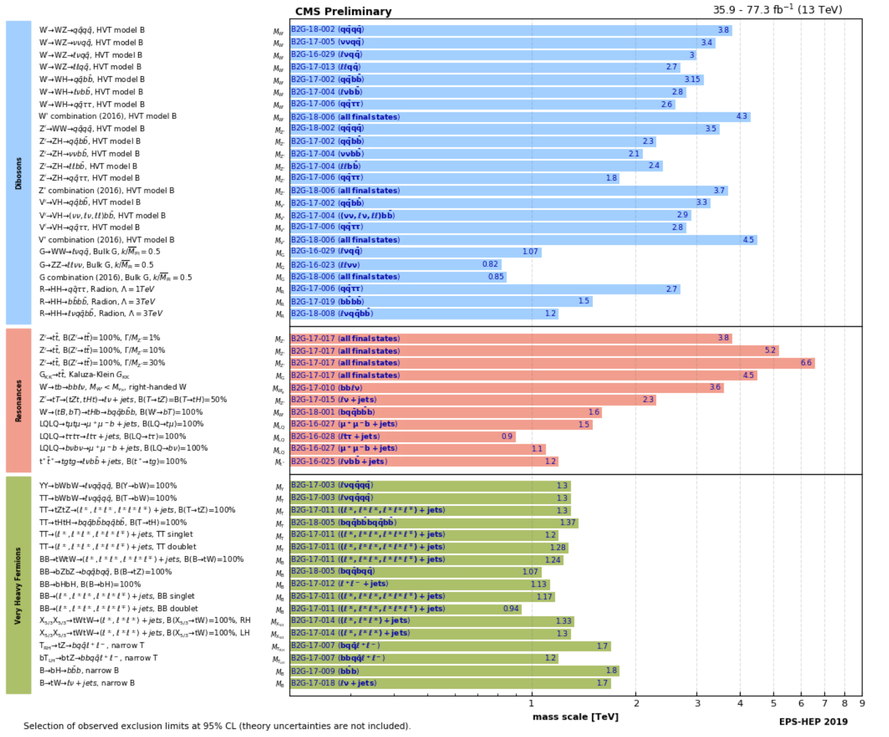
). The y-axis tick labels indicate the studied long-lived particle.

July 2019

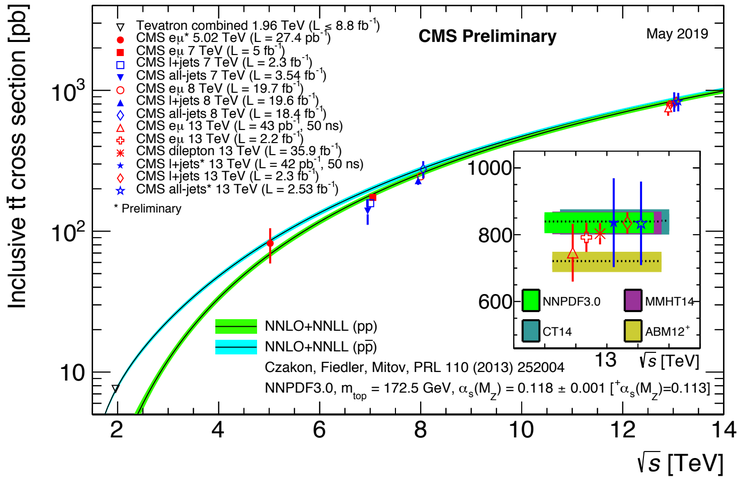




Overview of CMS B2G results



Selection of observed exclusion limits at 95% CL (theory uncertainties are not included).



Upgrades

Preparing for LHC Run 3 …

"Phase-1" upgrades of CMS

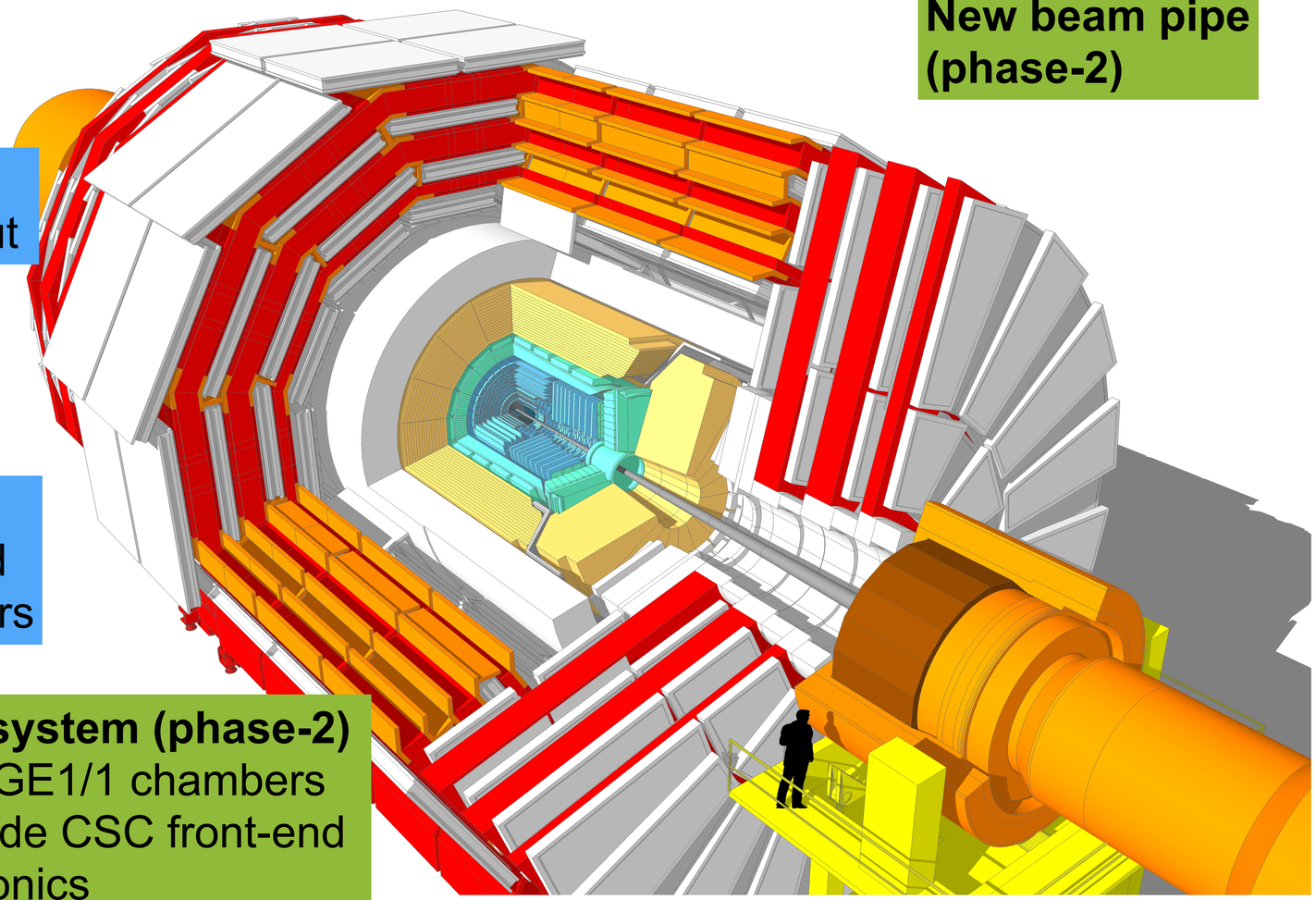
- Majority of the upgrades have been done in the past years
- Last step:

HCAL barrel
- install new 5Gbps readout

Pixel
- replace layer 1 and all DCDC converters

Muon system (phase-2)
- GEM GE1/1 chambers
- Upgrade CSC front-end electronics

New beam pipe (phase-2)



(small) selection of activities in long shutdown 2 (2019/2020)

The road to high luminosity

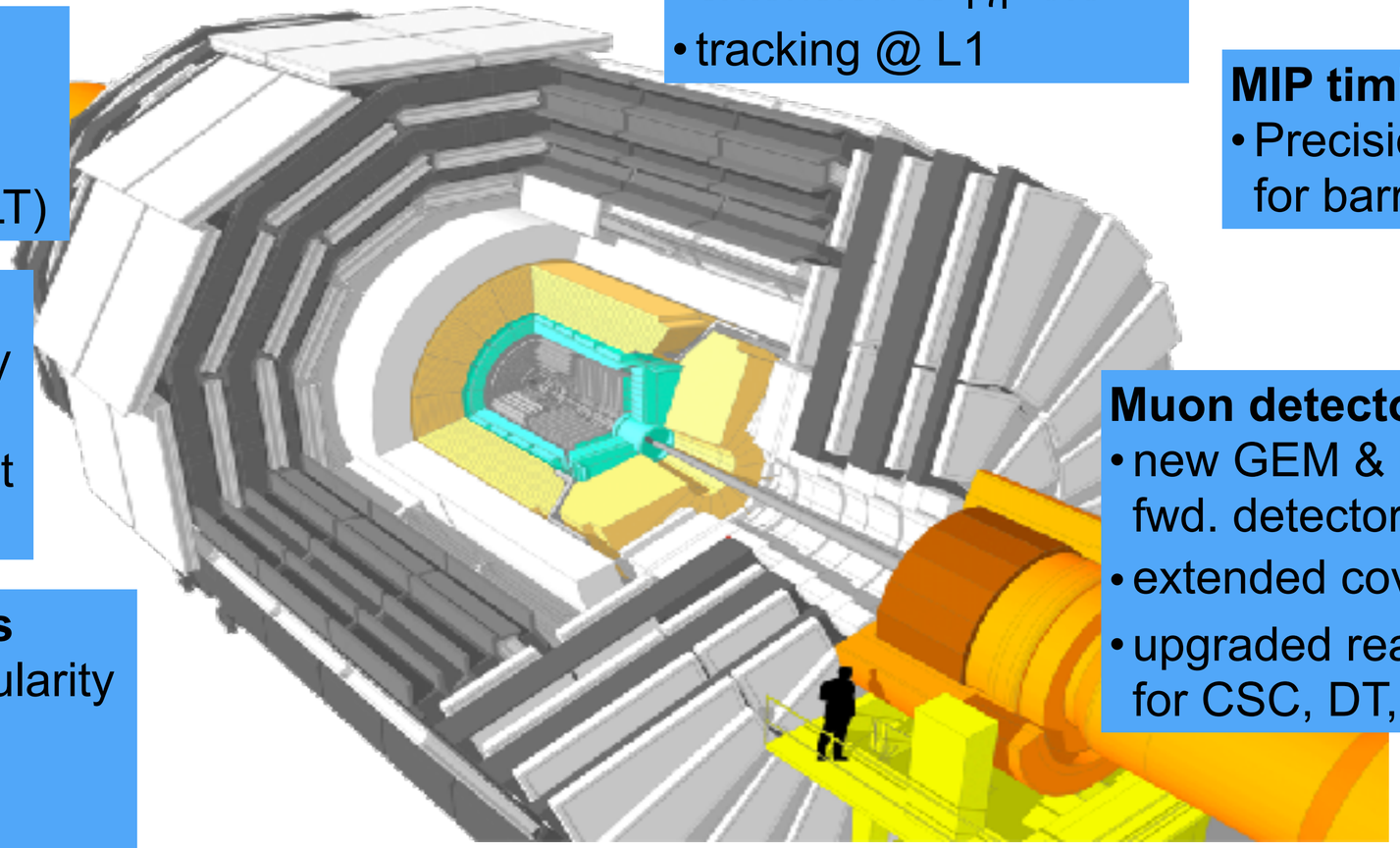
EPS-HEP
2019

Upgrades for HL-LHC

Tracker
- increased granularity & extension to $|\eta|$=3.8
- tracking @ L1

Trigger
- incl. tracker at 40MHz
- increase max. rate to 750kHz (L1) /7.5kHz (HLT)

MIP timing detector
- Precision timing for barrel & endcaps



Calorimeter endcaps
- Si-based high-granularity calorimeter
- 3D shower measurement + timing

Muon detectors
- new GEM & RPC fwd. detectors
- extended coverage to $|\eta|$=3
- upgraded readout for CSC, DT, RPC

Barrel calorimeters
- ECAL crystal-granularity readout @ 40MHz
- new ECAL&HCAL backend boards

Upgrades for HL-LHC

Tracker
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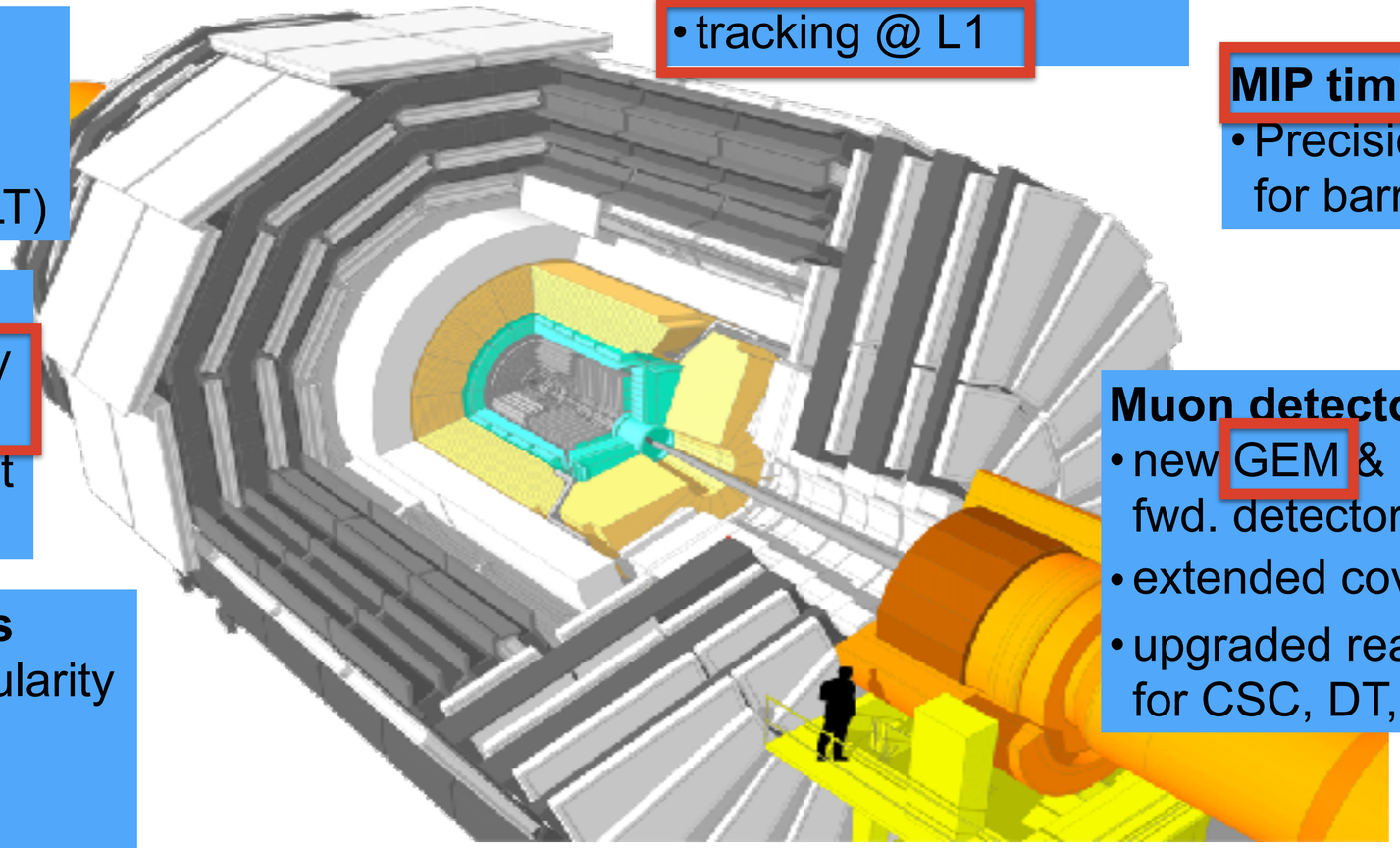


Muon detectors
- new GEM & RPC fwd. detectors
- extended coverage to $|\eta|$=3
- upgraded readout for CSC, DT, RPC

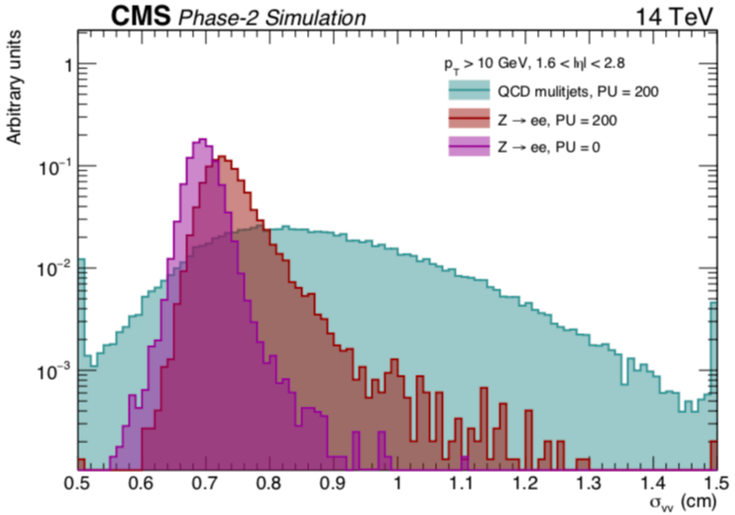
Barrel calorimeters
- ECAL crystal-granularity readout @ 40MHz
- new ECAL&HCAL backend boards

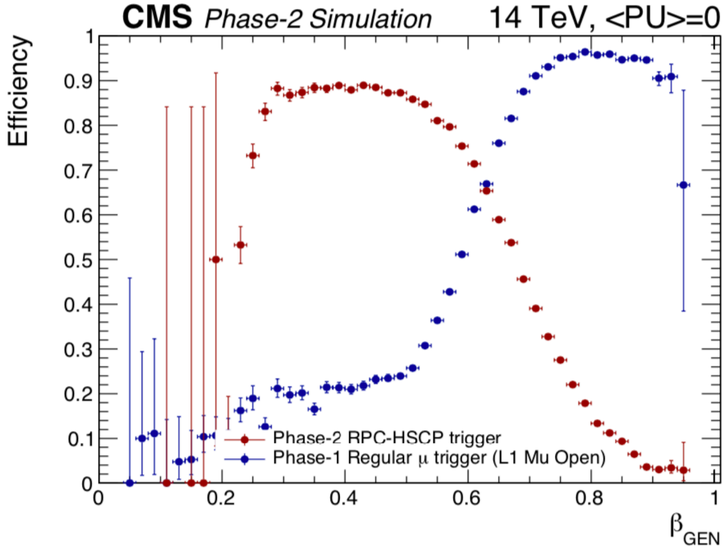
Many new & Innovative elements!

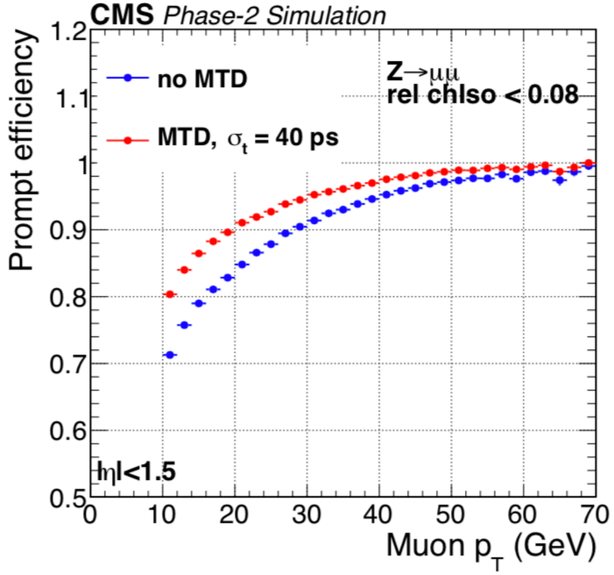
Phase-2 upgrade starts now!

Upgrades for HL-LHC

What are the benefits? Some examples







Endcap calorimeters
- fine segmentation provides powerful discriminating variables for e-ID

Muon system
- L1 trigger on delayed signals with upgraded RPC readout

MIP timing detector
- Improved efficiency of the isolation selection for leptons

CERN-LHCC-2017-023

CERN-LHCC-2017-012

CERN-LHCC-2019-003

Summary

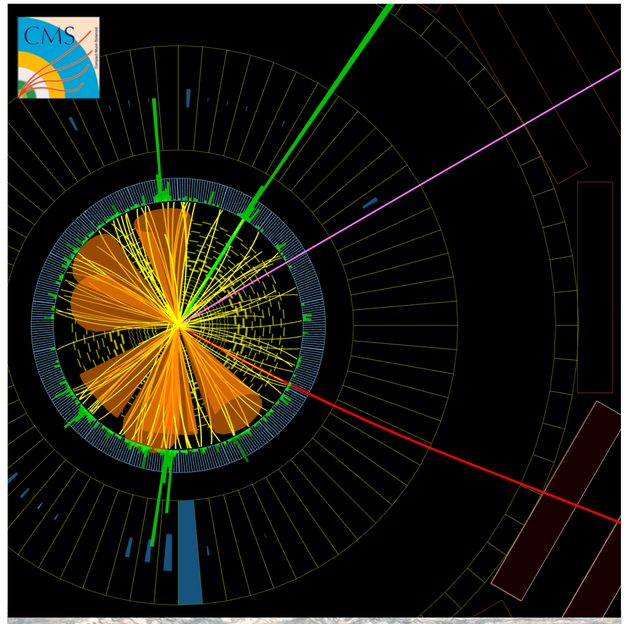
Summary

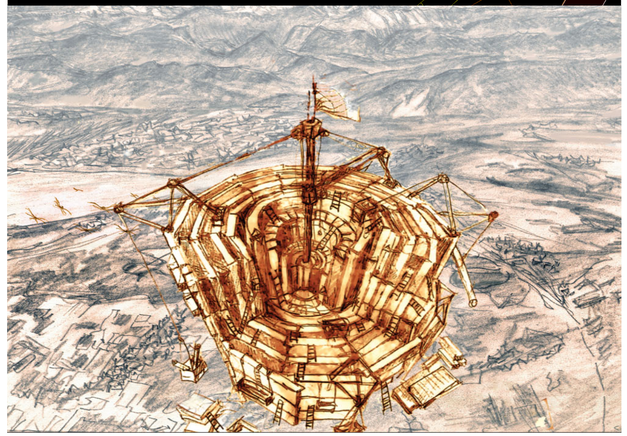
Continuing the harvest based on the LHC Run 2 dataset

- Many results using the full dataset of 137fb^{-1} have been shown
  - currently mainly focusing on searches and rare processes
  - can expect many more results in the next months
- Also progressing in precision measurements
  - currently using early data
  - full Run 2 results will use ultimate calibrations with a legacy reconstruction of Run 2 datasets

Preparing for the future

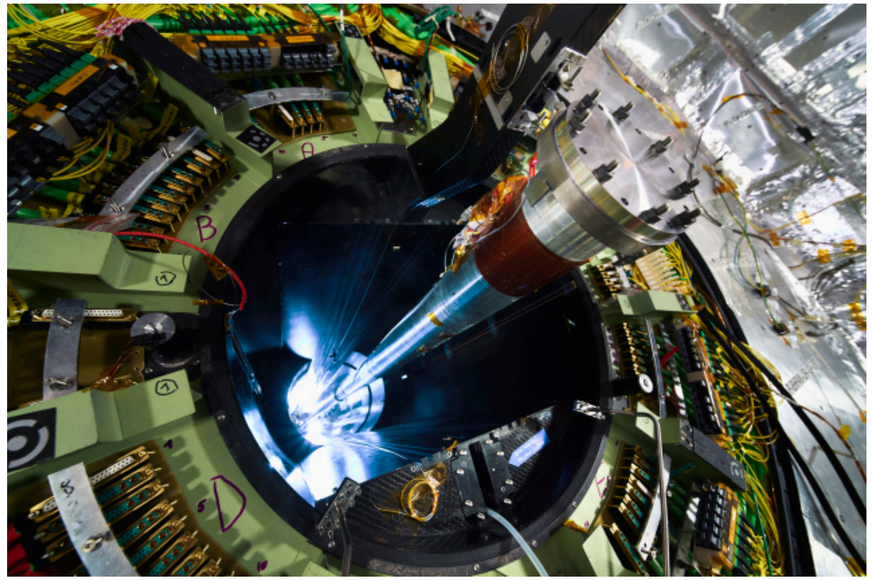
- First round of upgrades is terminating now
- Starting first extensions and modifications in view of HL-LHC
- Current results show that we are on track for Run 3 and beyond
  - HL-LHC projections show the large gains expected with the upgraded detector and an integrated luminosity of 3ab^{-1}





Additional material

Preparing for LHC Run 3 ...

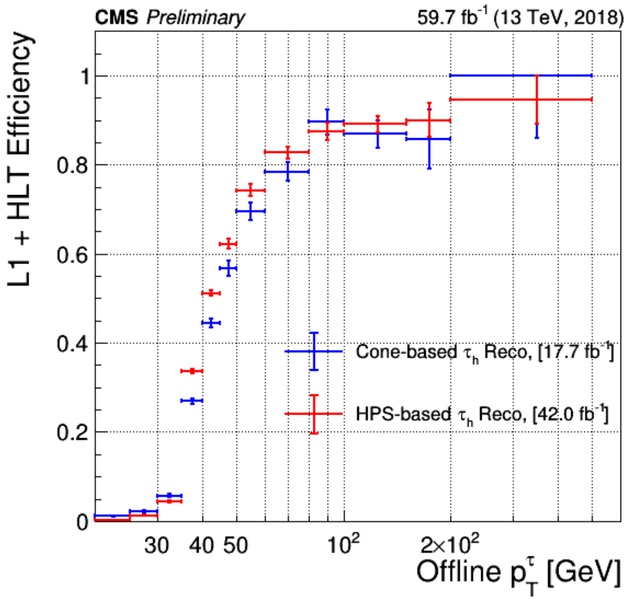


(small) selection of activities in long shutdown 2 (2019/2020)

Detector performance in 2018

Improved τ triggers

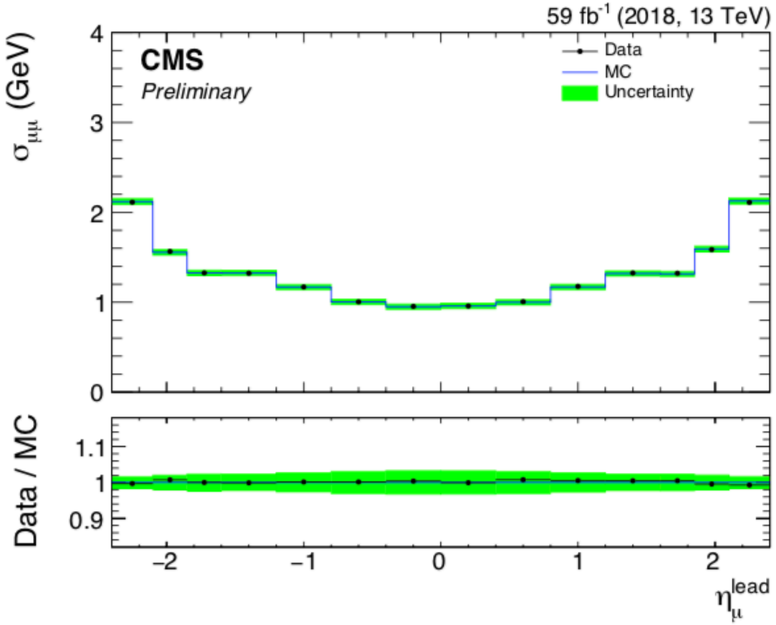
- Use of offline "HPS" algorithm
  - sharper turn-on
  - lower rates



CMS DP-2019/012

Excellent muon performance

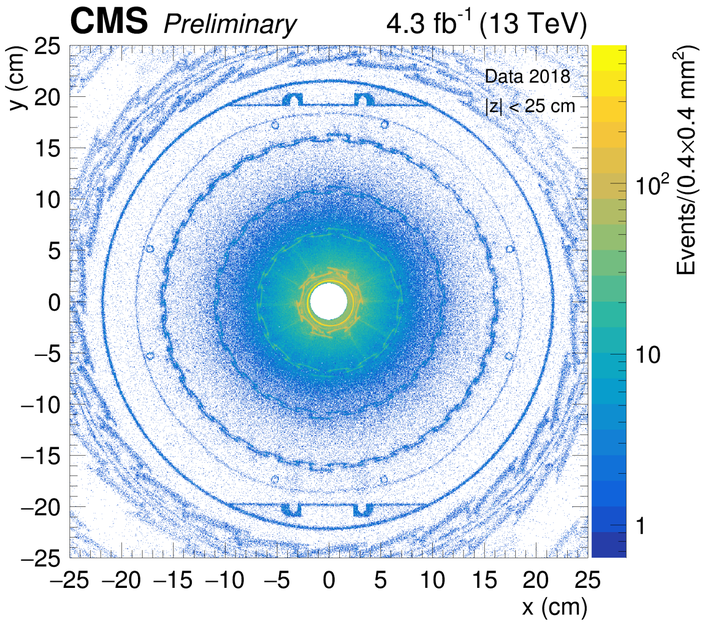
- Compatible with previous years
- MC reproduces data well
  - e.g., dimuon mass resolution



CMS DP-2019/022

Tracker "radiography"

- Reconstructed hadronic interactions show structure of "Phase-1", 4-layer pixel detector



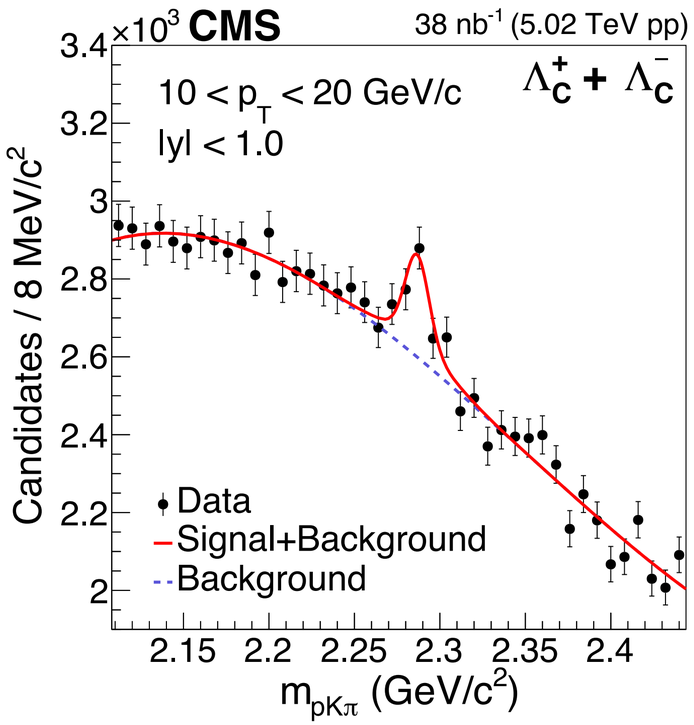
CMS DP-2019/001

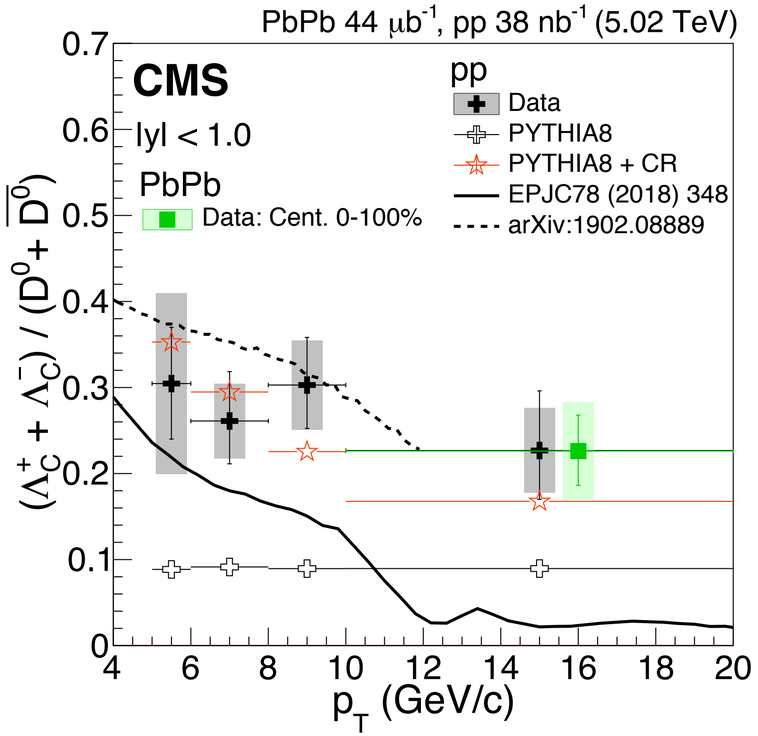
Heavy Ions

Λ_c^+ production in pp and PbPb at $\sqrt{s_{NN}}$=5.02TeV

arXiv:1906.03322

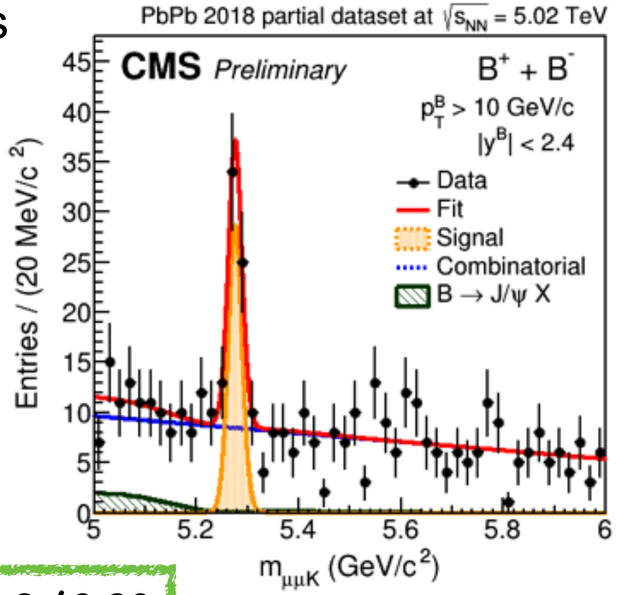
- Ratio w.r.t. D_0 production
  - pp: well described by model including colour reconnection
  - pp and PbPb consistent with current precision





Performance in the 2018 PbPb run

- collected luminosity: ~ 1.80 nb-1
- dataset includes ~4.5B min. bias events
  - transferring up to 7GB/s to offline
- excellent data quality



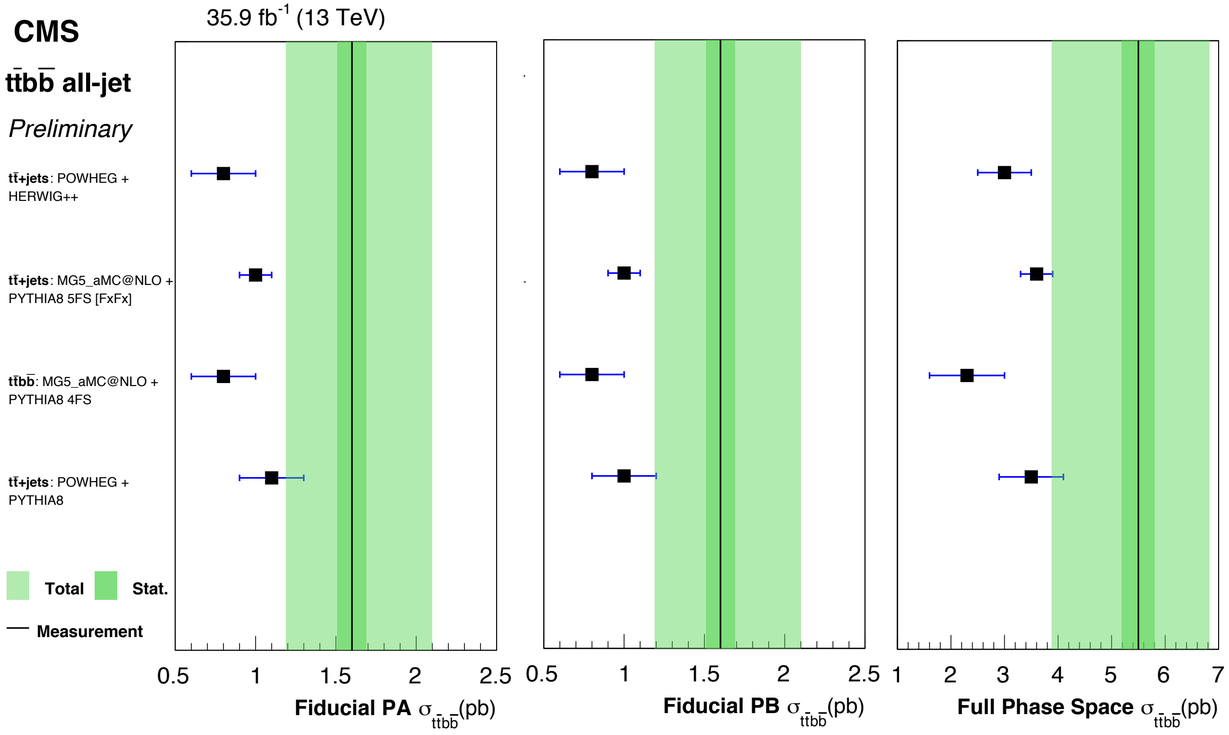
CMS DP-2018/060

Top-quark pairs + bb / jj

One of the main backgrounds for ttH(H→bb) measurement

- first measurement of σ(ttbb) in the hadronic channel

TOP-18-011



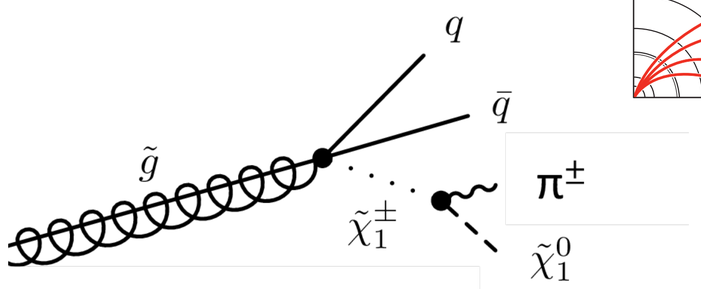
Predictions underestimate measured σ(ttbb)

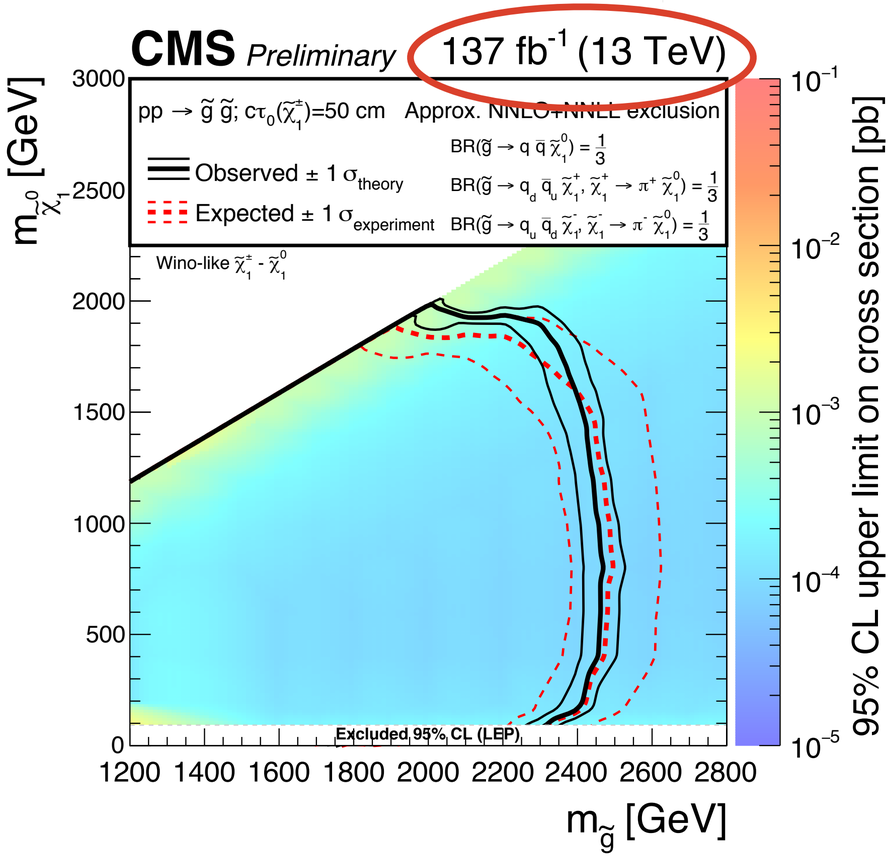
SUSY searches

But we (can) do more!

- models with small mass differences between the two lightest sparticles predict long-lived, charged particles with an invisible decay:
  - disappearing tracks

- extension of a search for strong SUSY production leads to long-lived signatures leads lower backgrounds and increased sensitivity
  - for large $c\tau$, the mass limit for gluinos increases by up to 400GeV with respect to the standard search

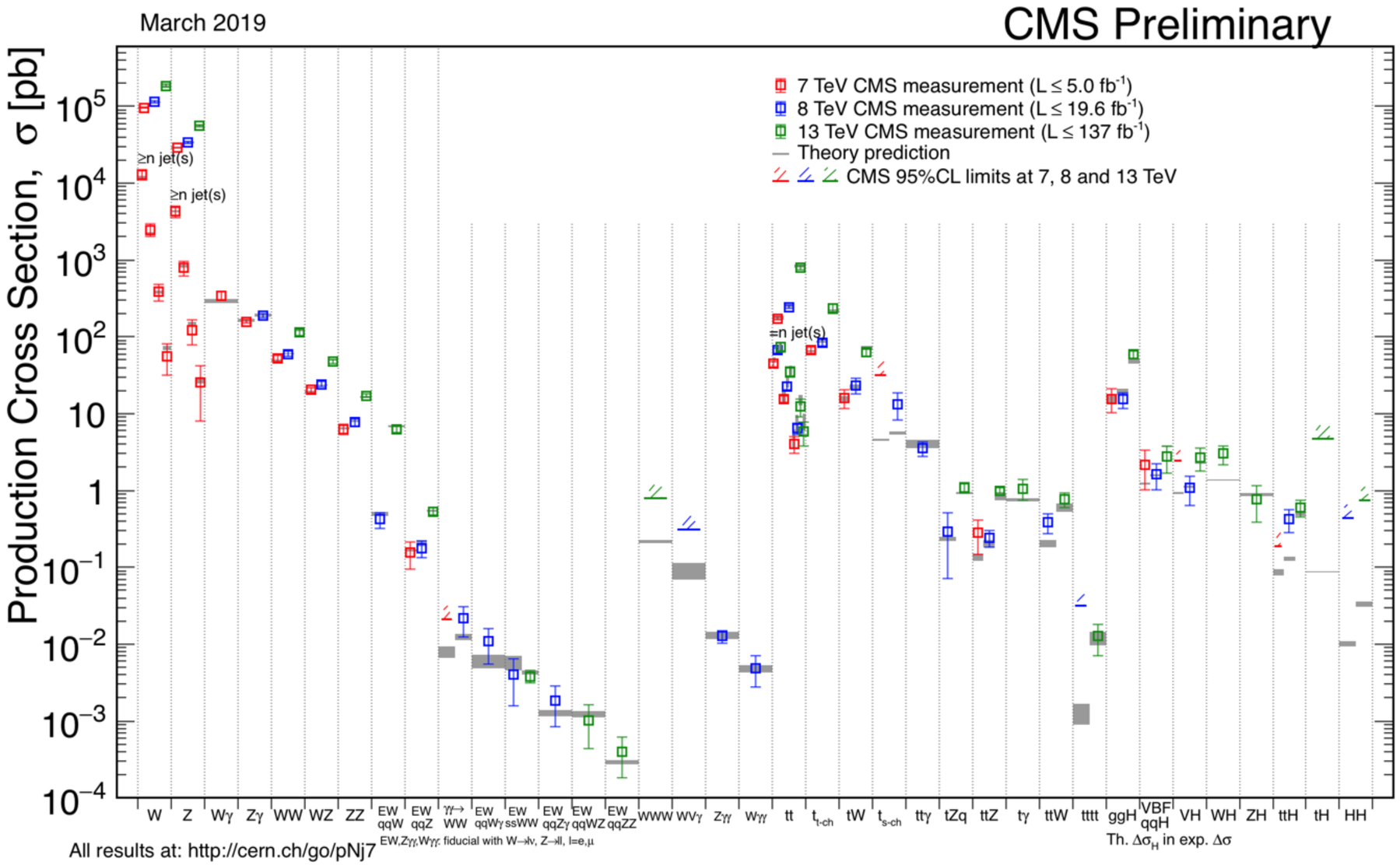




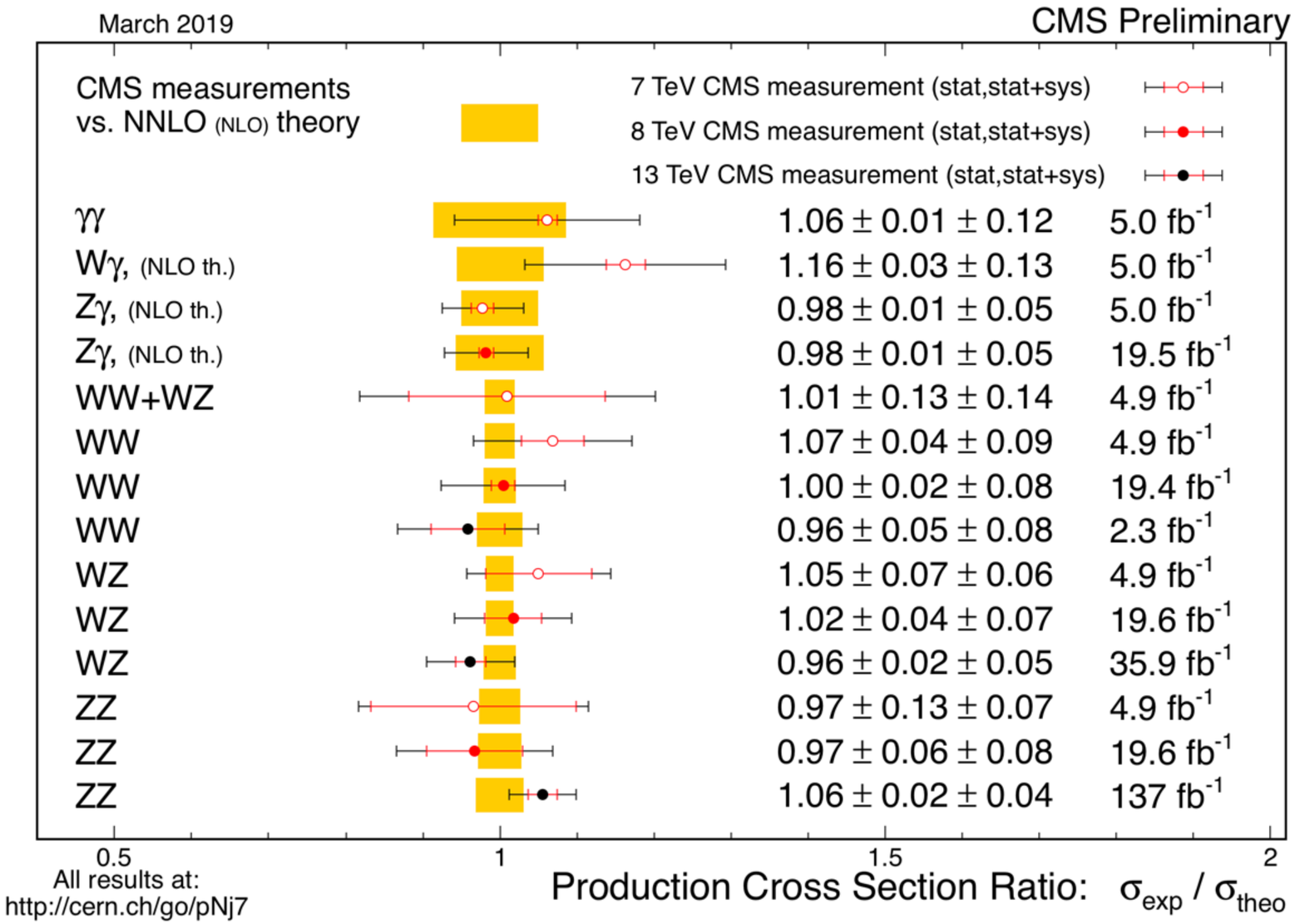
SUS-19-005

Summary plots

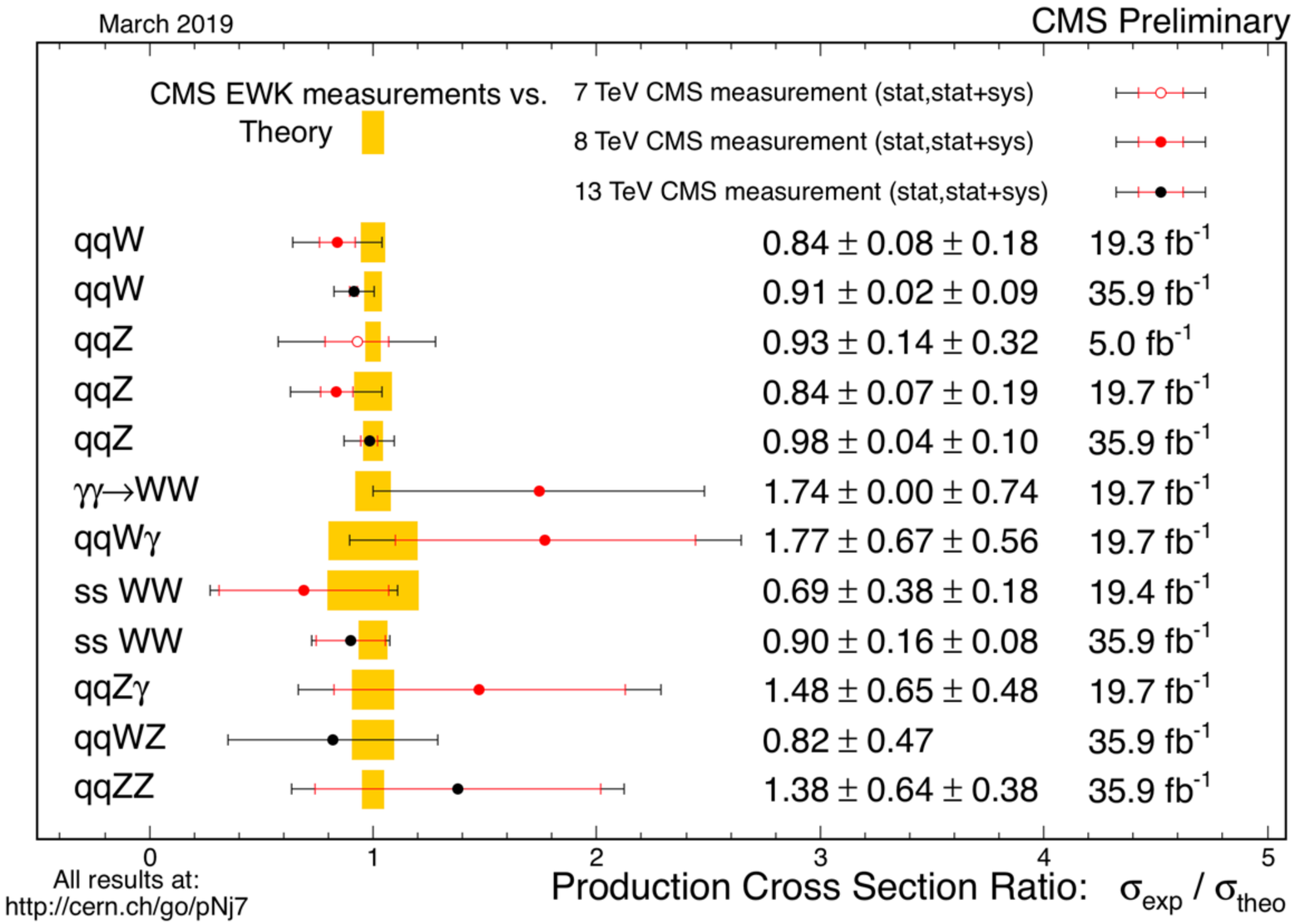
Summary SM cross sections



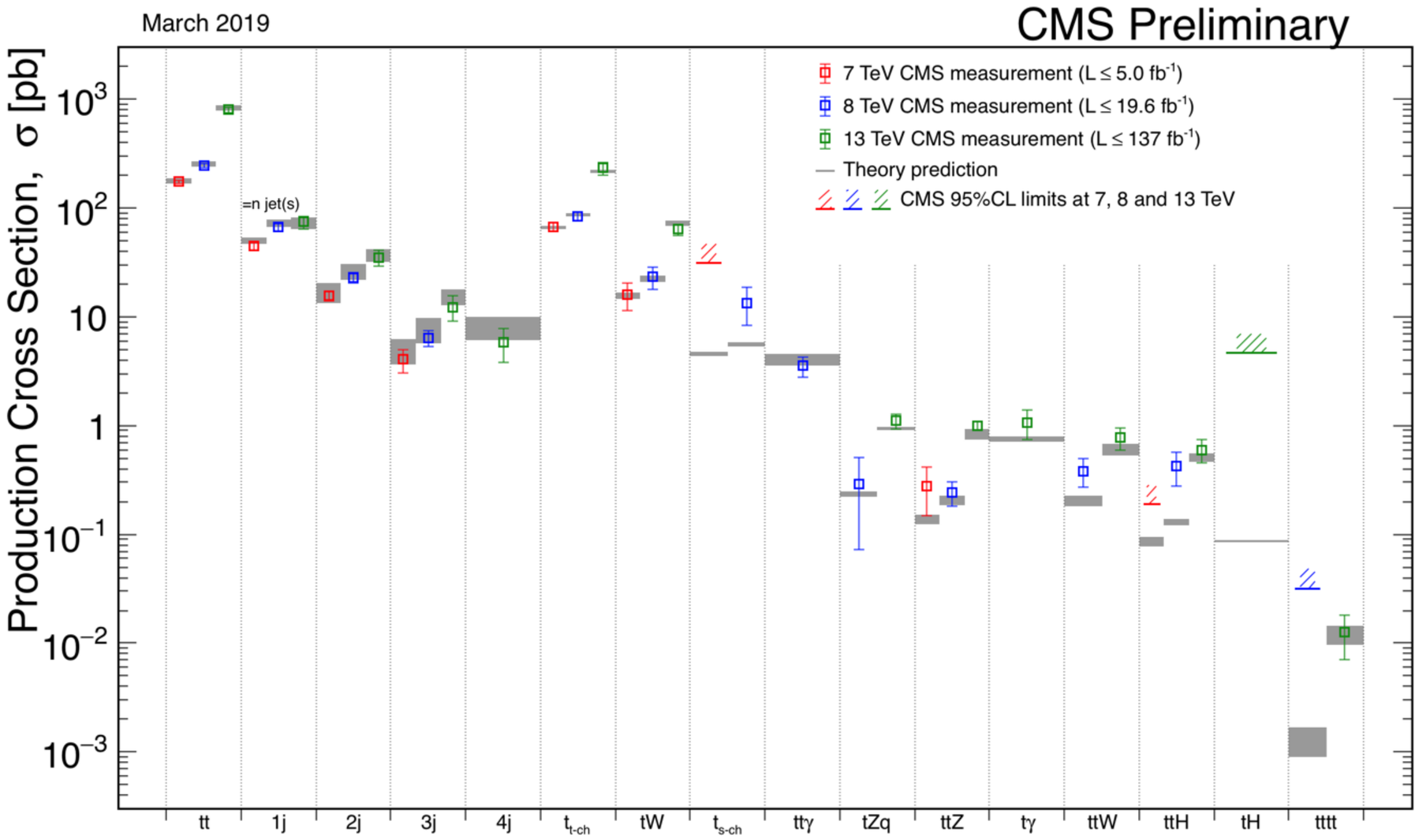
Summary SM cross sections



Summary SM cross sections

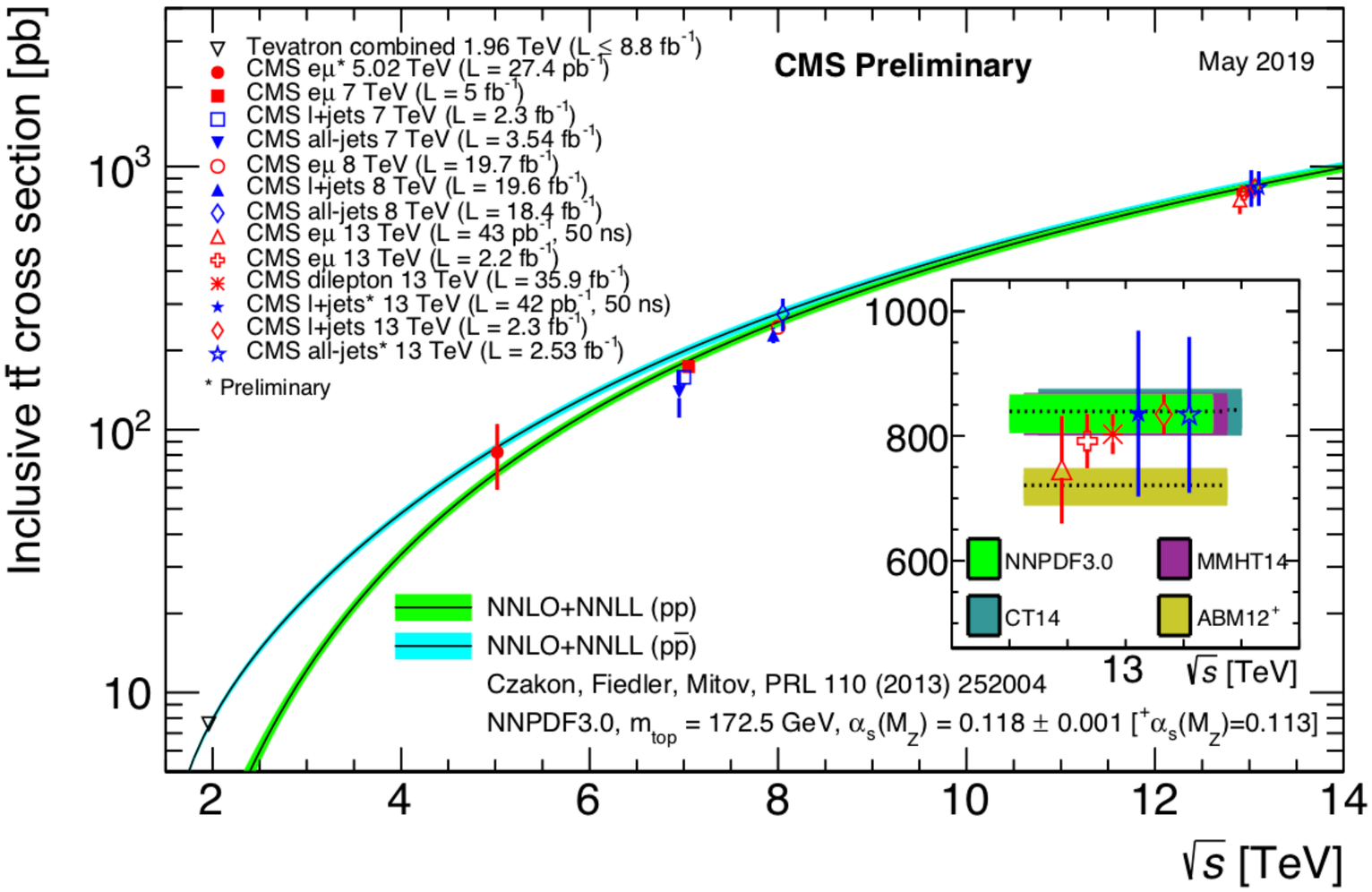


Summary top quark cross sections

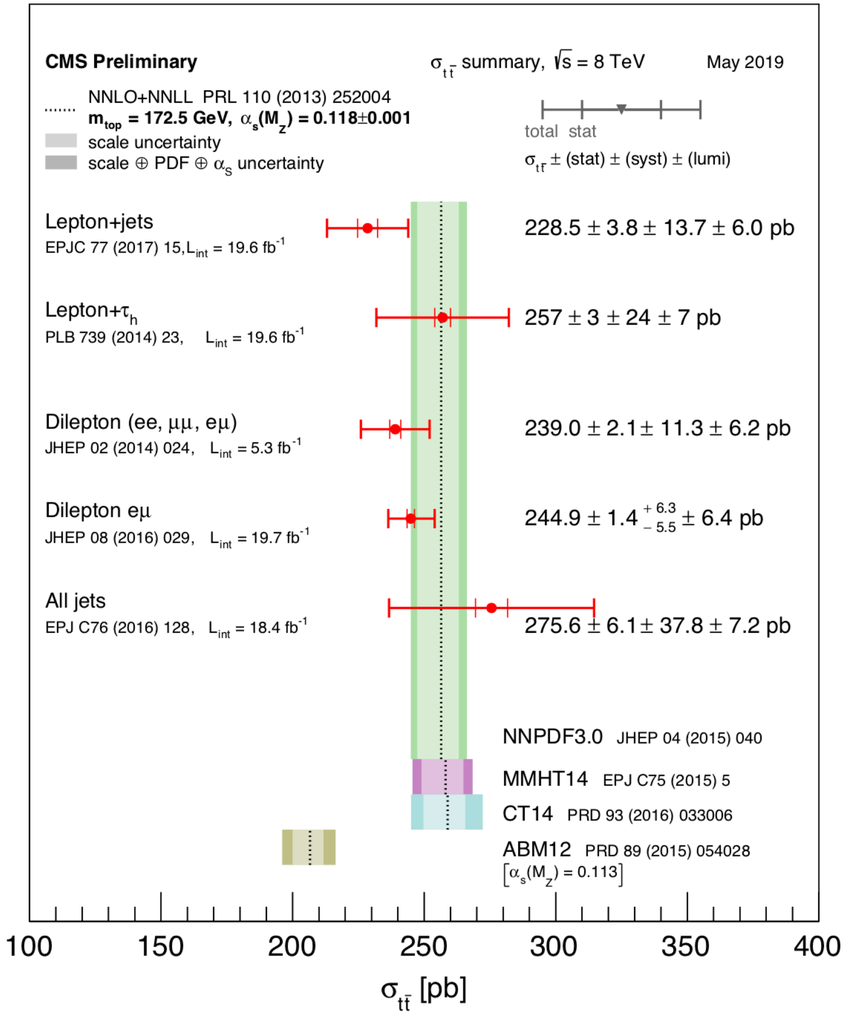


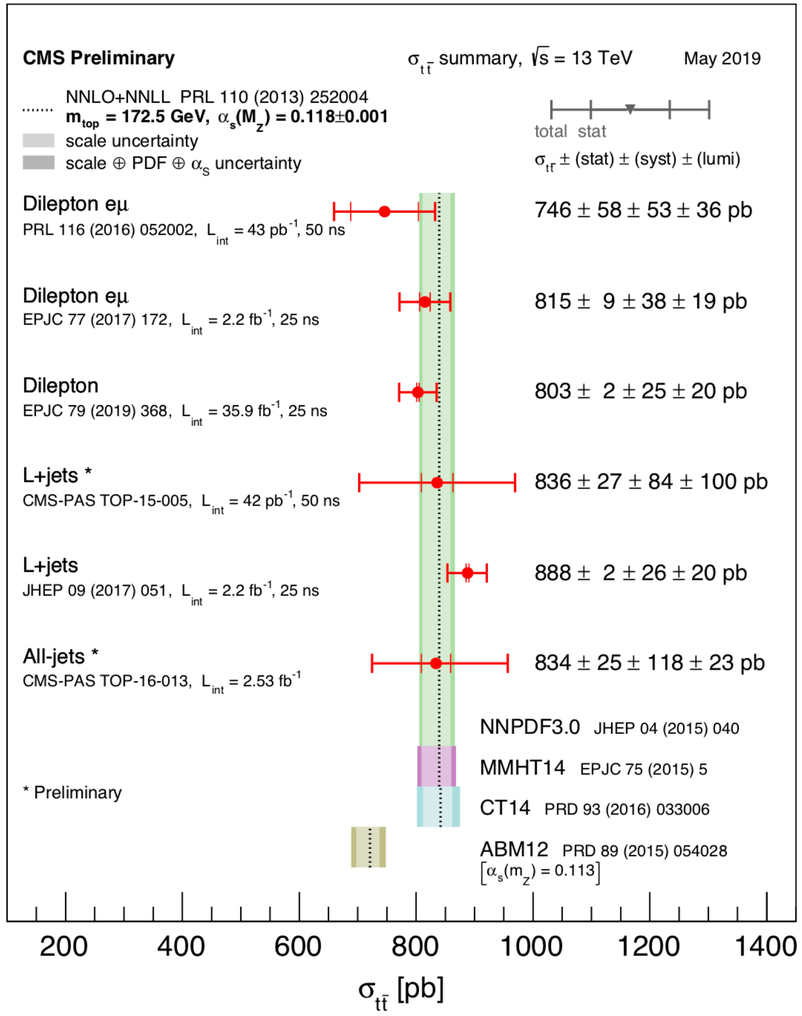
All results at: http://cern.ch/go/pNj7

Top-quark pair cross section summary

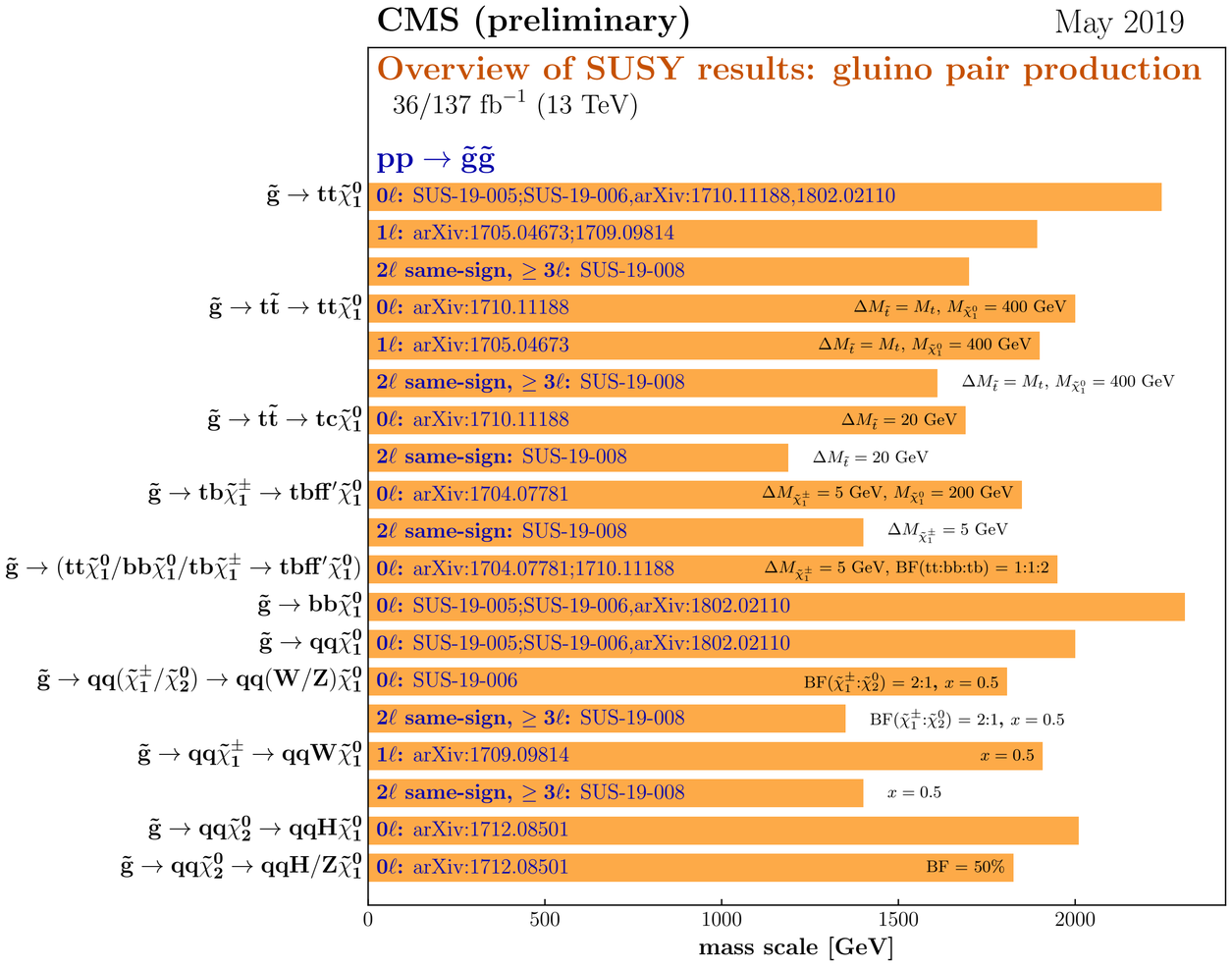


Top-quark pair cross section summary

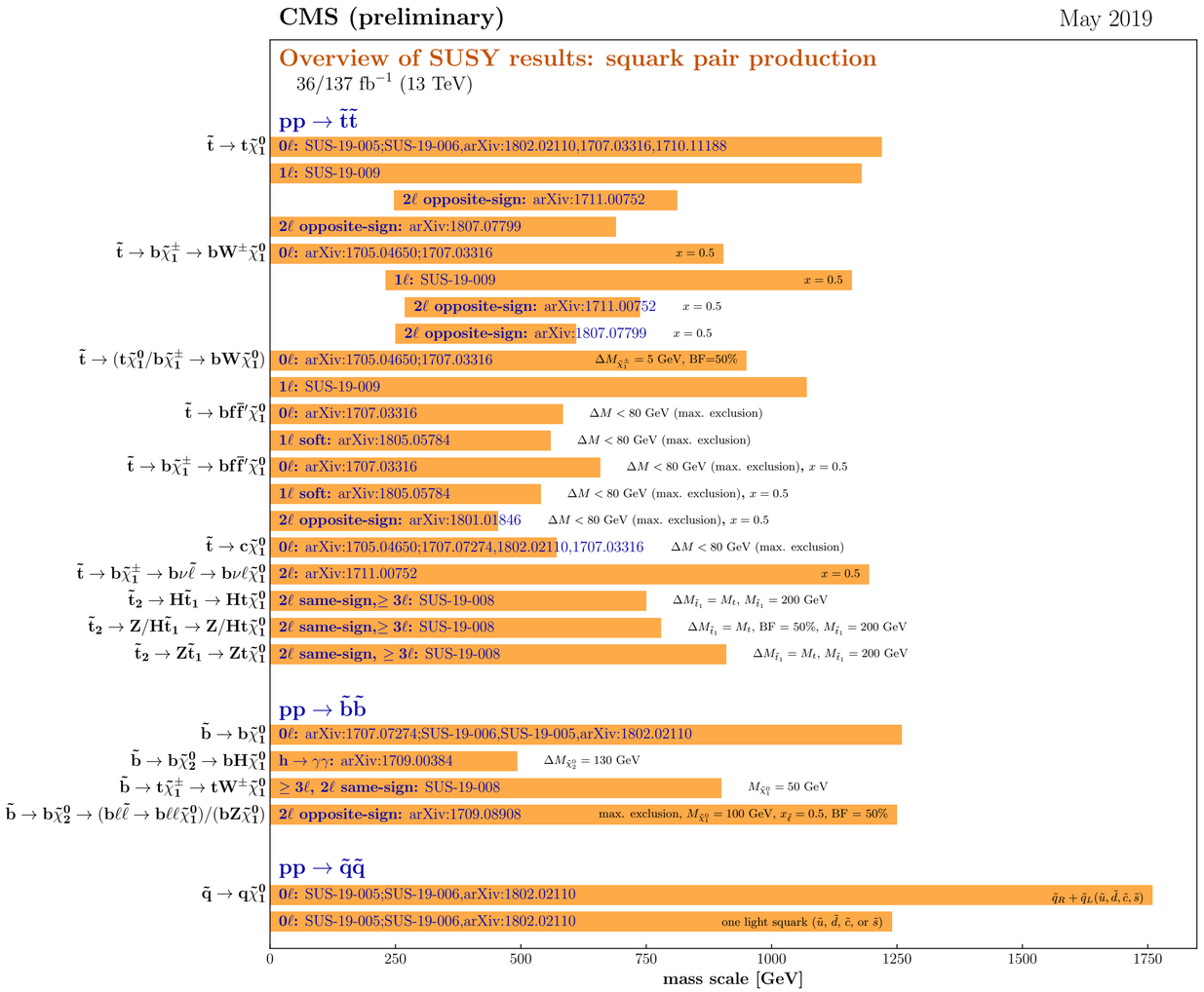




SUSY summaries



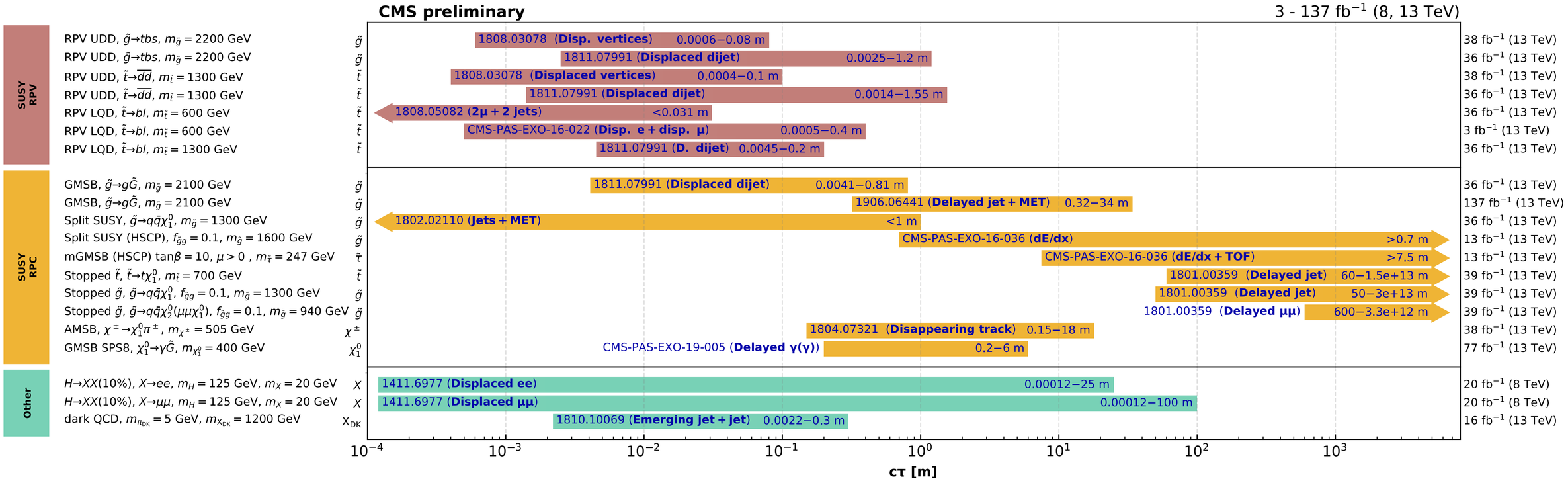
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Summary long-lived particles

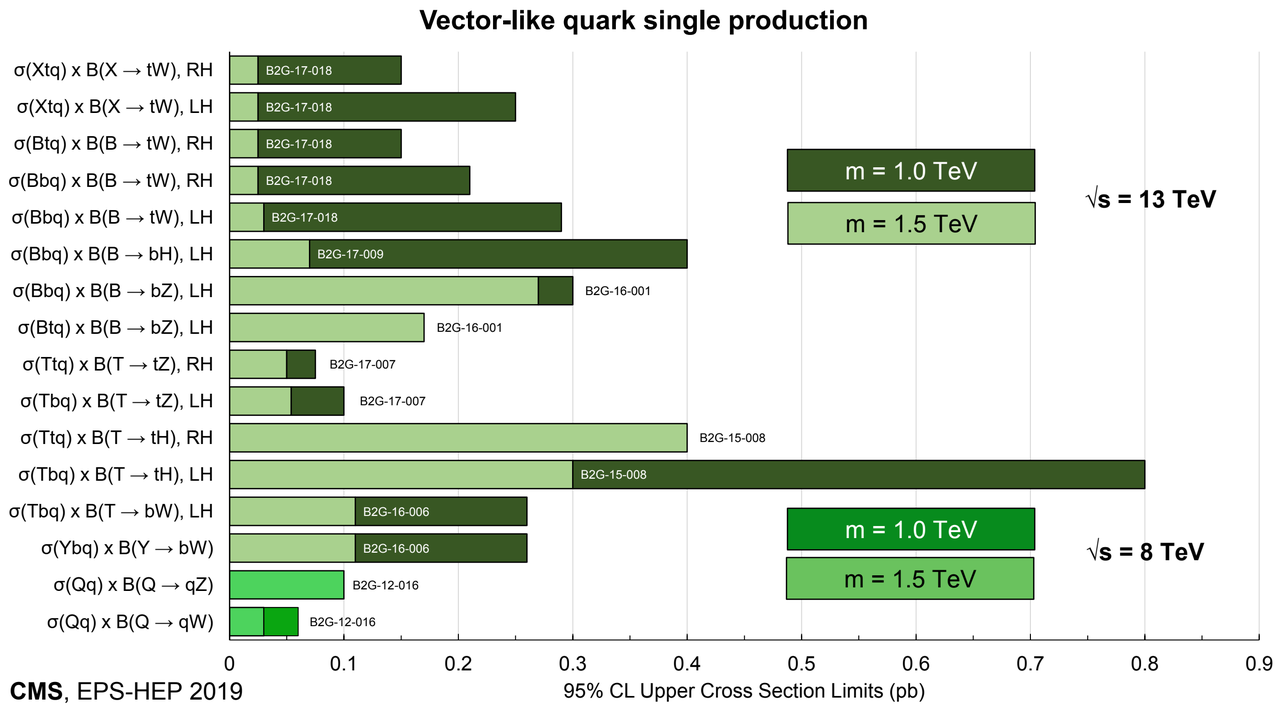
Overview of CMS long-lived particle searches

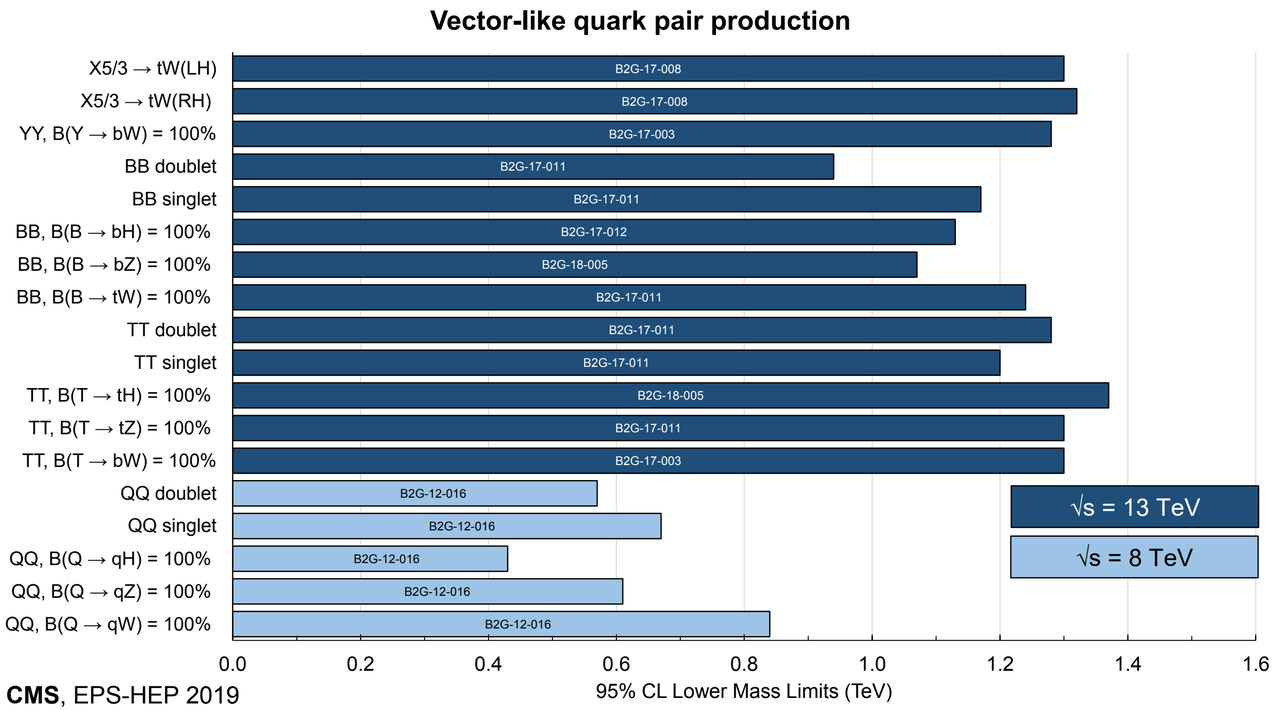


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

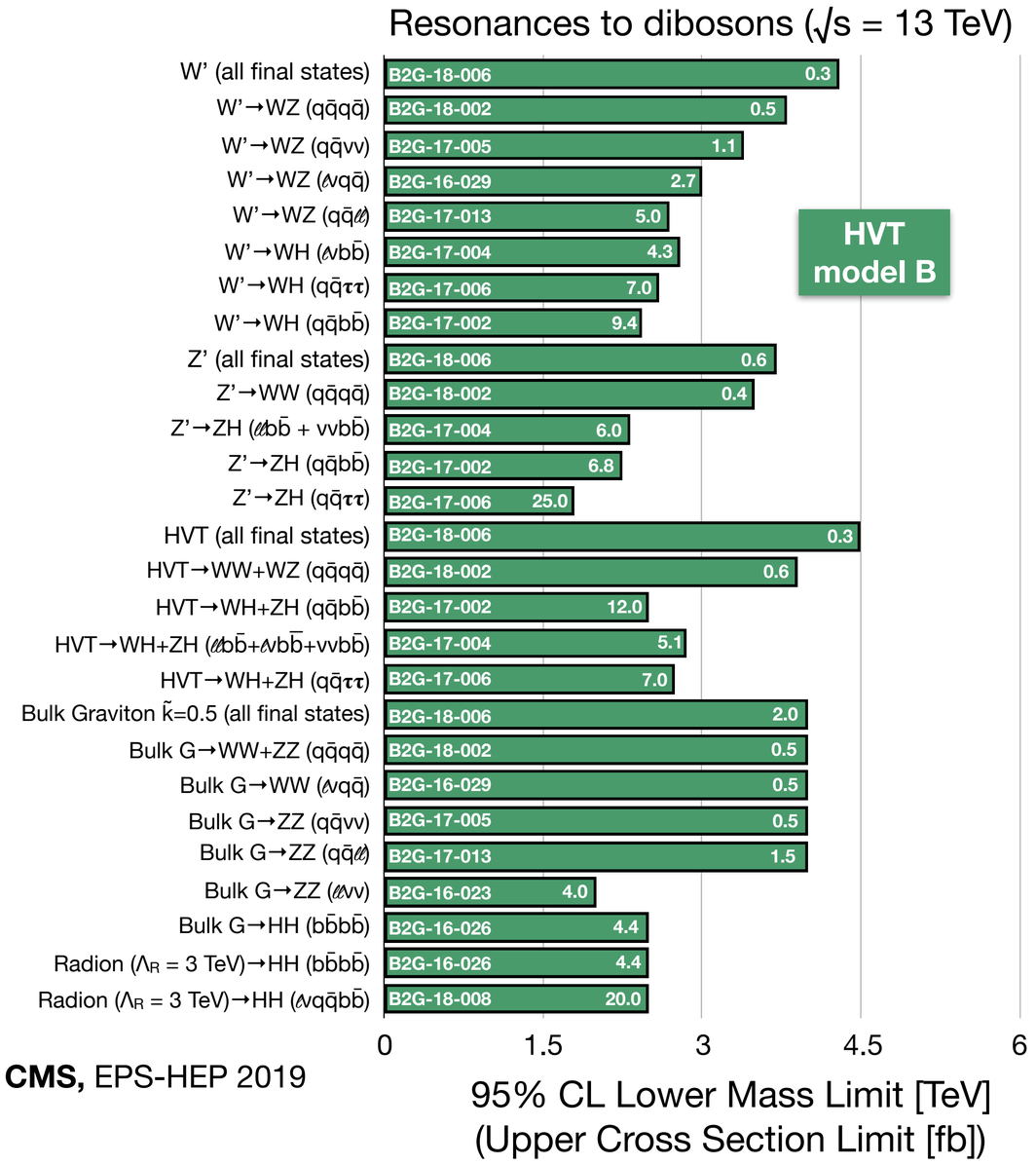
July 2019

Summaries vector-like quarks





Summary di-boson resonances



CMS, EPS-HEP 2019