Searching for new physics @ CMS: with precision & innovation

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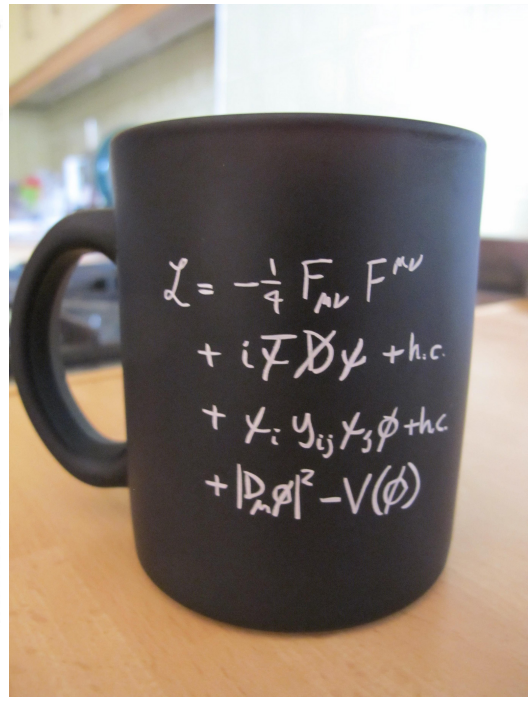
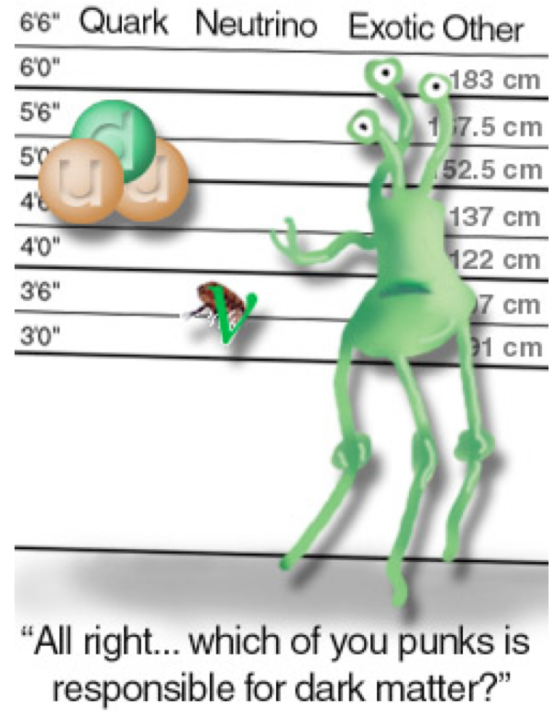
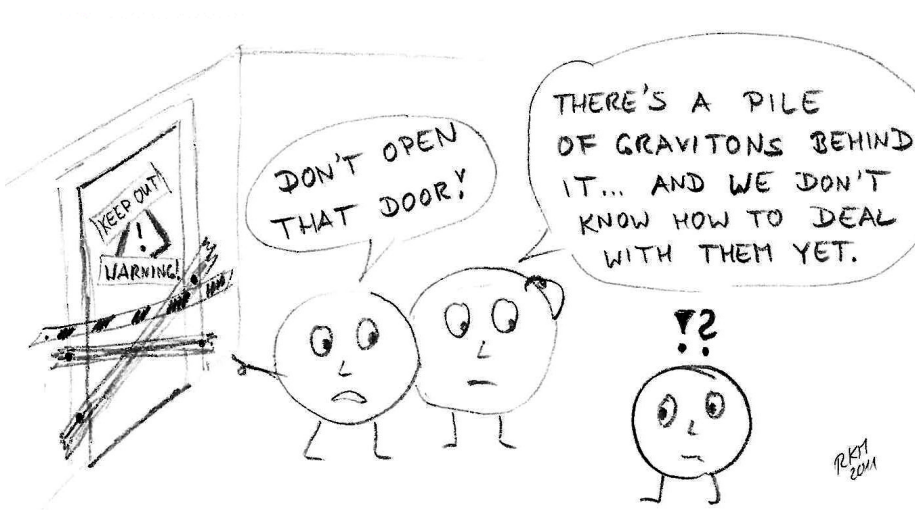
University of Wisconsin-Madison
(for the CMS Collaboration)

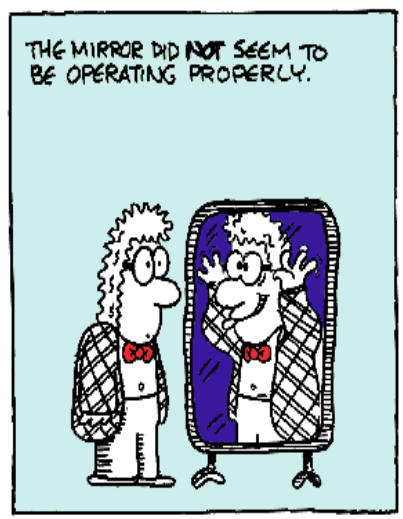
August 16th, 2019
Fermilab Joint Experimental-Theoretical Seminar

Goals of experimental particle physics









Achieved by…

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

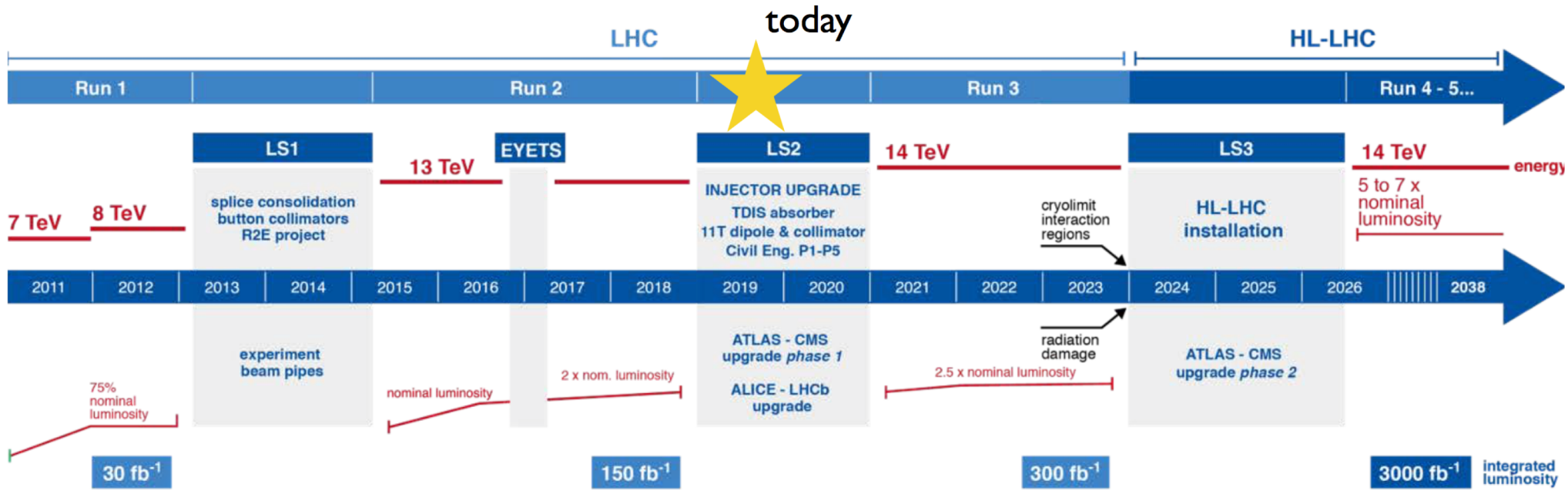
SM as a tool for discovery

- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space ➔ innovate!

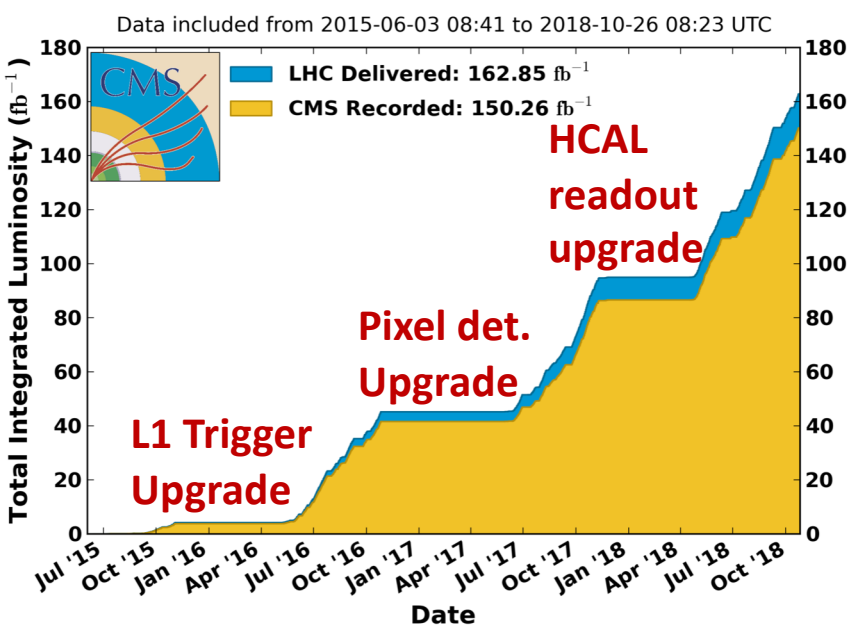
Exploring the unknown

Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

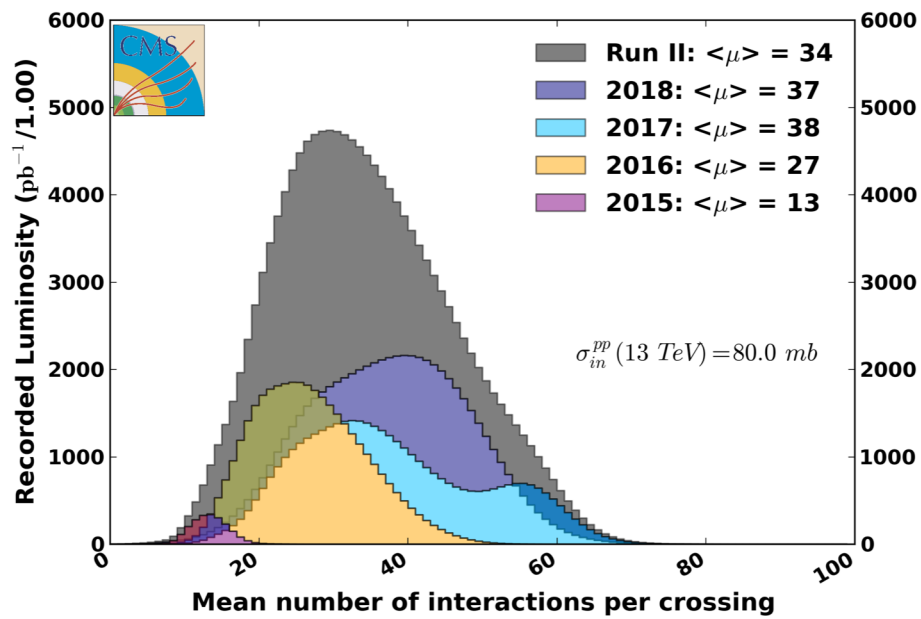
LHC/HL-LHC Program



CMS Integrated Luminosity, pp, $\sqrt{s} = 13$ TeV



CMS Average Pileup (pp, $\sqrt{s}$=13 TeV)



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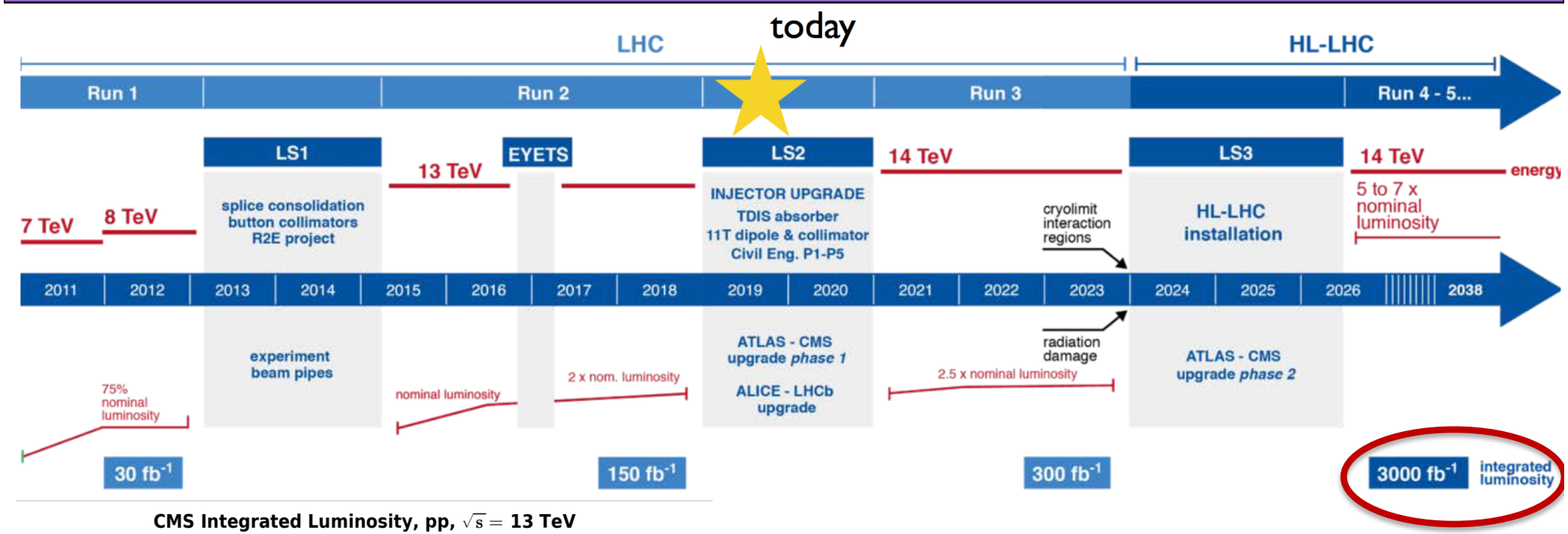
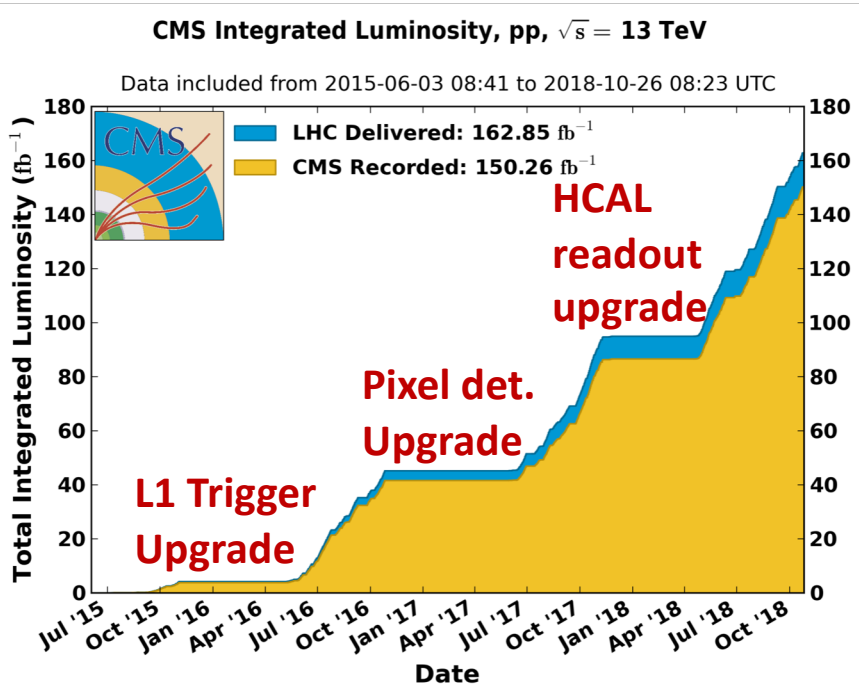




Excellent LHC (and CMS) performance: ~140 fb^{-1} good for analysis during Run 2

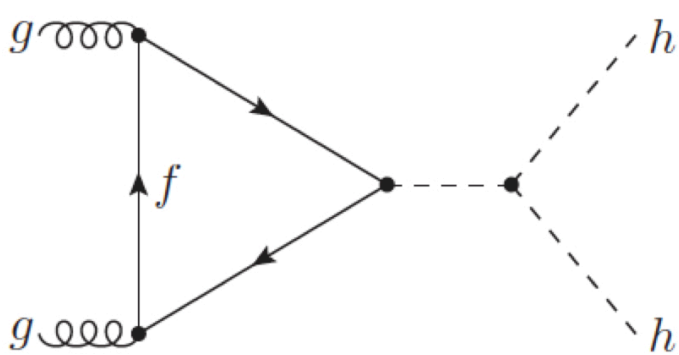
But 95% of the total LHC data still to come (and be studied)!

Higgs Physics

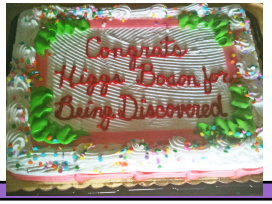
"Greetings Earth-people. We have been monitoring your progress. Now that you have discovered the Higg's boson you are qualified to join the Federation of Advanced Civilisations."

Key questions: post-discovery era

- Is it a Higgs boson or the Higgs boson ?
  - Is it elementary or composite ?
  - Does it interact with itself ?
  - Does it mediate a Yukawa force ?
- How does the Higgs couple to light particles (e.g. h → J/Ψ+γ)
- And how does it couple to muons ?
- Why is the Higgs so light ? Is m_H stabilized by ~TeV scale new physics or is it fine-tuned ?
- Are there additional Higgs bosons ?
- Are there exotic Higgs decays ?

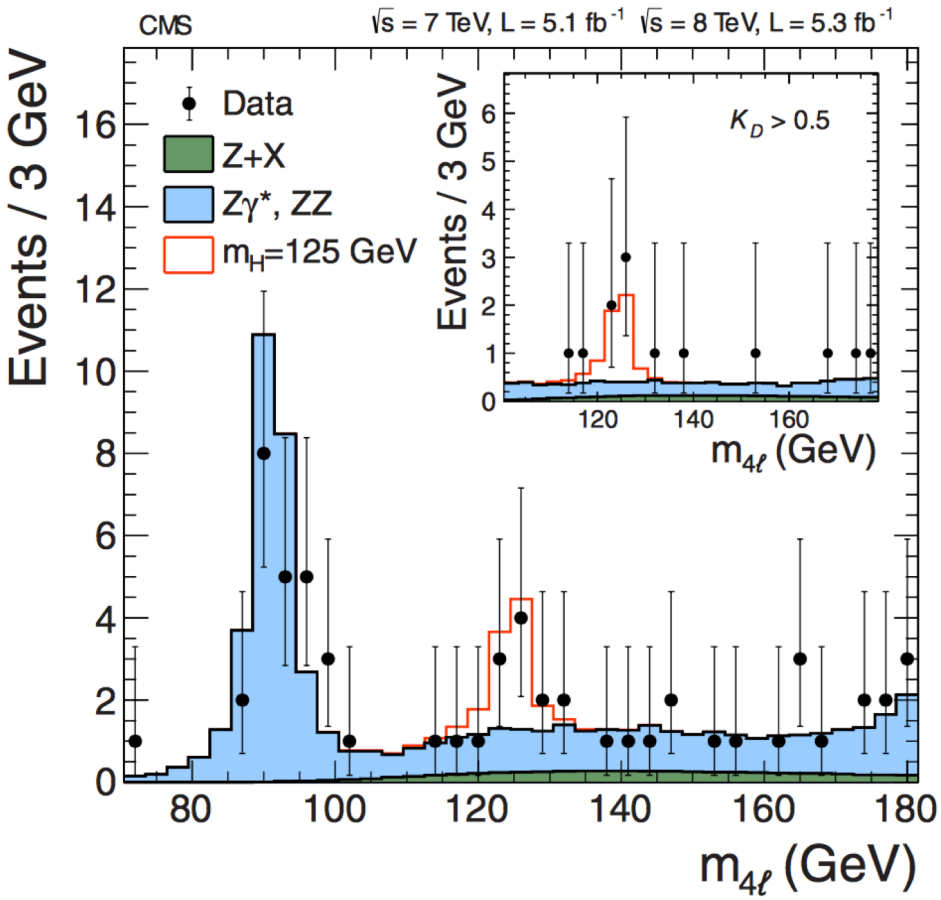


Higgs turns 7!



In the last ~7 years…

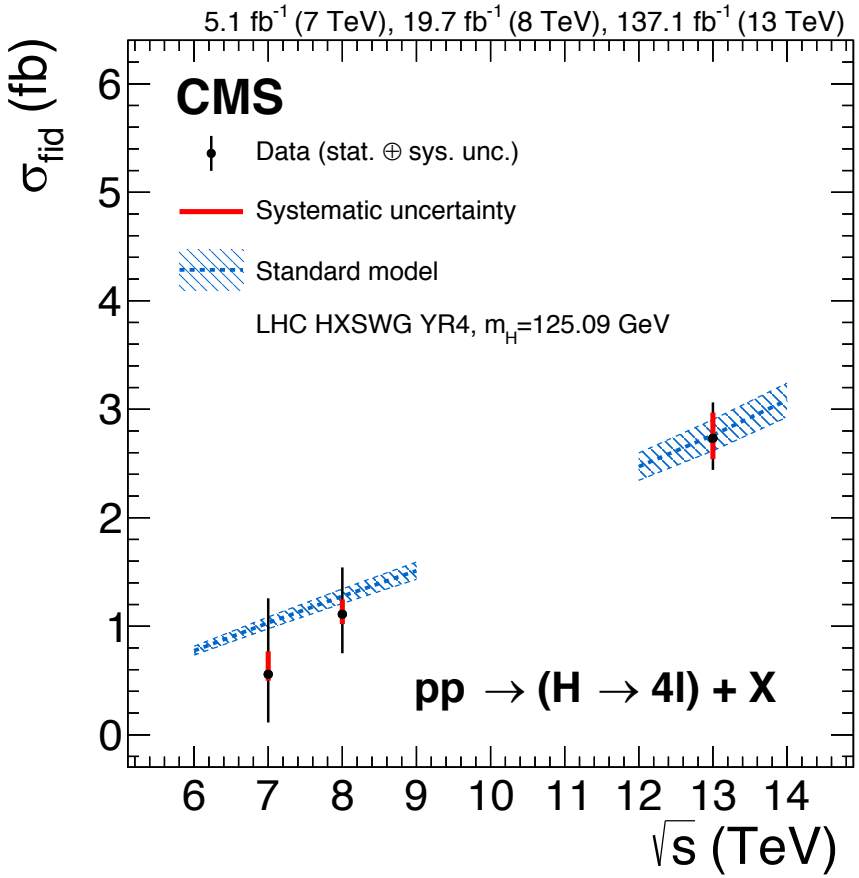
2012



Phys. Lett. B 716 (2012) 30

Discovery

2019



CMS-PAS-HIG-19-001

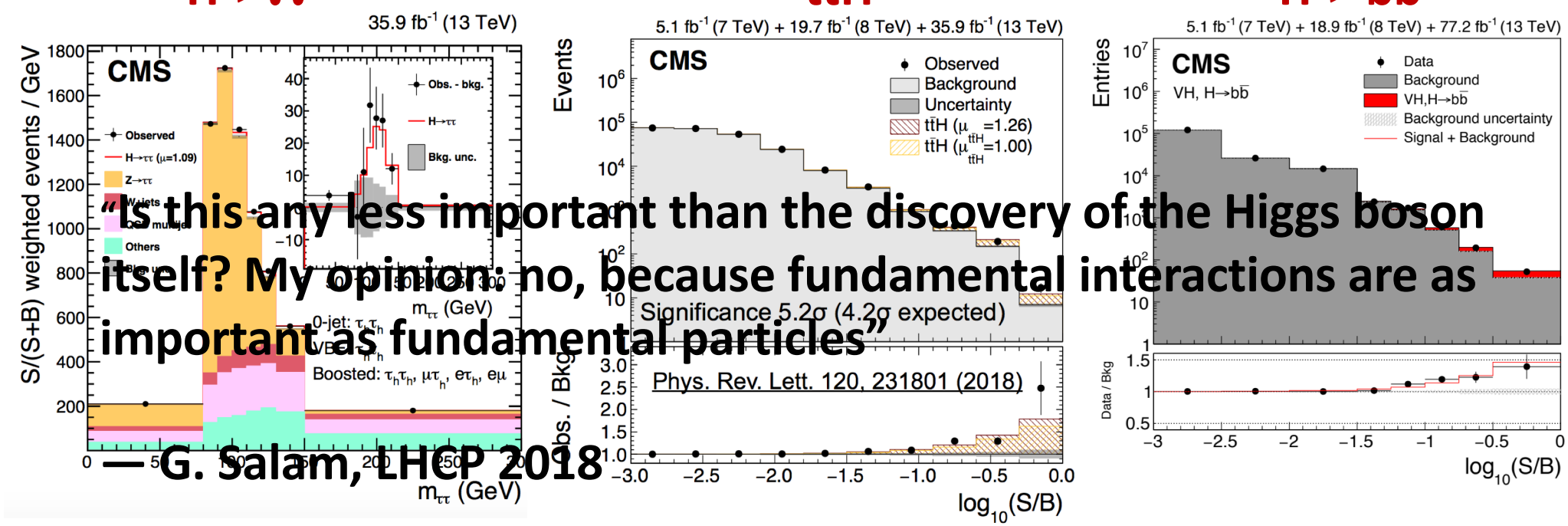
Precision

Establishing Higgs…

- Significant progress in the Higgs sector:
  - Firmly established $\gamma\gamma$, ZZ, WW decays
  - excellent mass measurement $m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}$

- Couplings to 3rd generation fermions established in the last two years by the > 5σ observation of:

H->ττ **ttH** **H-> bb**



"Is this any less important than the discovery of the Higgs boson itself? My opinion: no, because fundamental interactions are as important as fundamental particles"

— G. Salam, LHCP 2018

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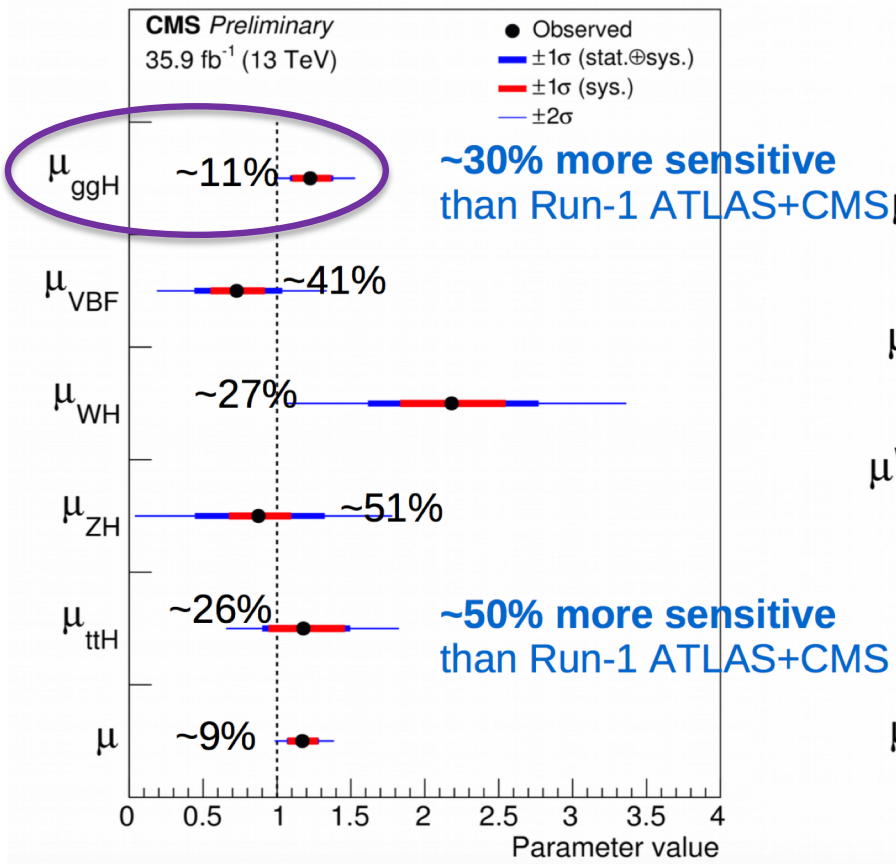
Higgs Properties

HIG-17-031

Surpassing Run 1 precision in key measurements with only 2016 data

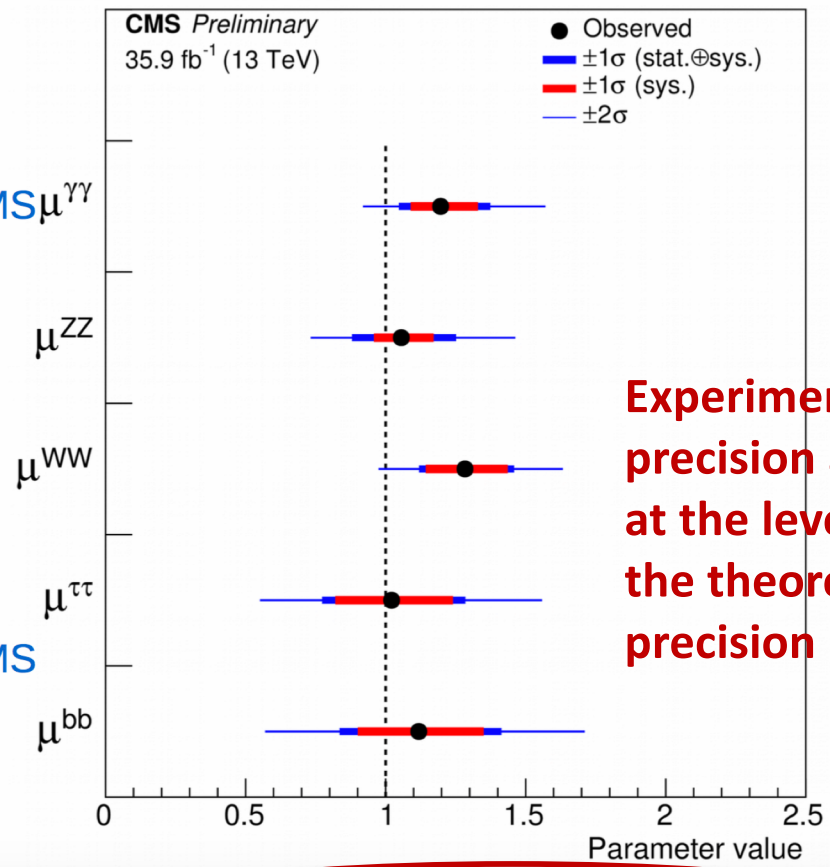
Per production mode



~30% more sensitive than Run-1 ATLAS+CMS

~50% more sensitive than Run-1 ATLAS+CMS

Per decay mode



Experimental precision already at the level of the theoretical precision

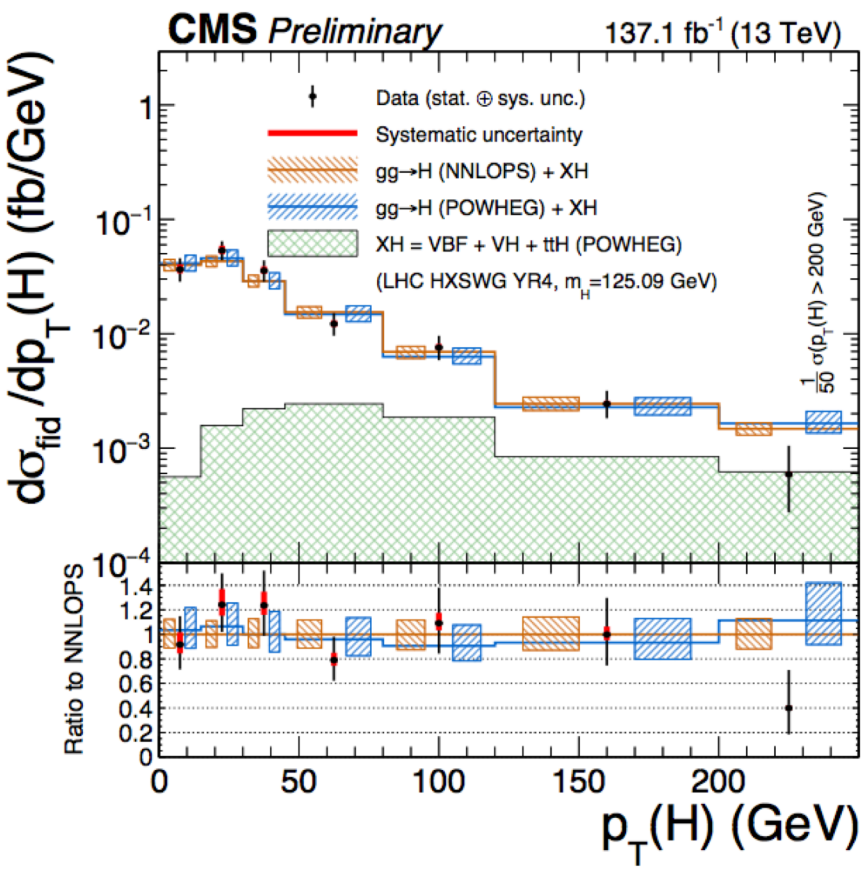
$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{sig. th.})\ ^{+0.06}_{-0.06}\ (\text{other sys.})$$

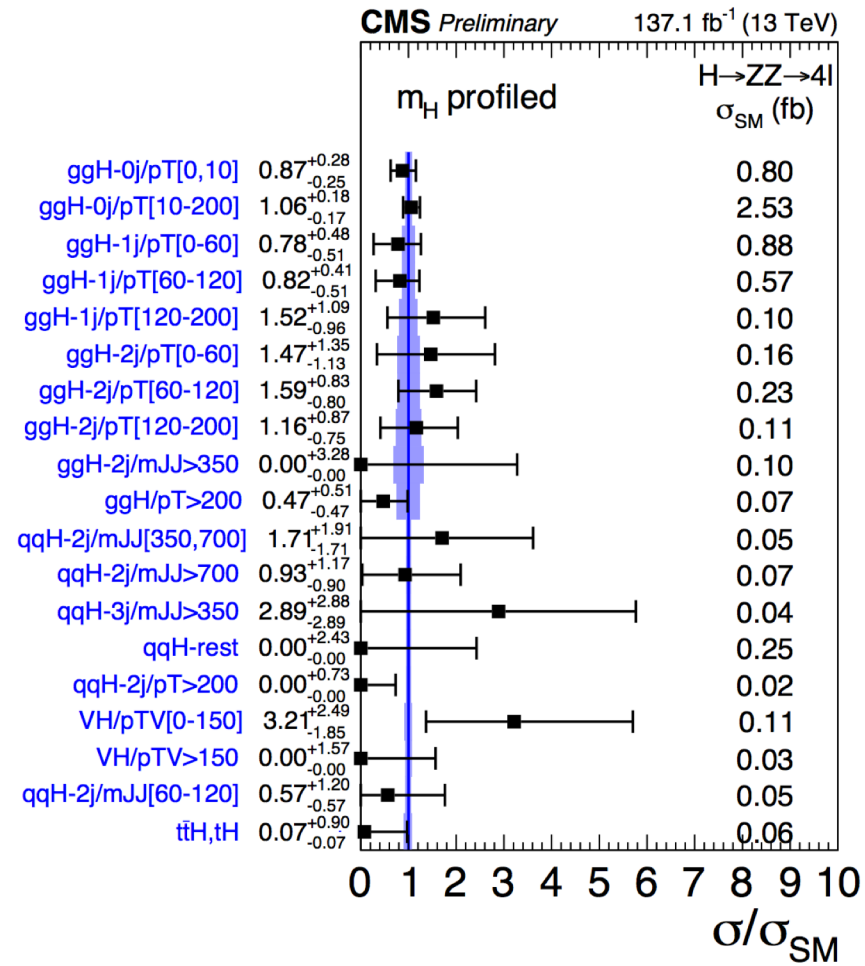
(ATLAS+CMS Run 1 combination: $\mu_{\text{ggH}} = 1.03^{+0.16}_{-0.14}$ **)**

Higgs Cross-sections

HIG-19-001

- Higgs physics has entered the ***precision*** era
  - Fiducial and differential cross section measurements comparing data to state-of-the-art calculations
  - Simplified template cross sections enable Higgs measurements that are less model dependent

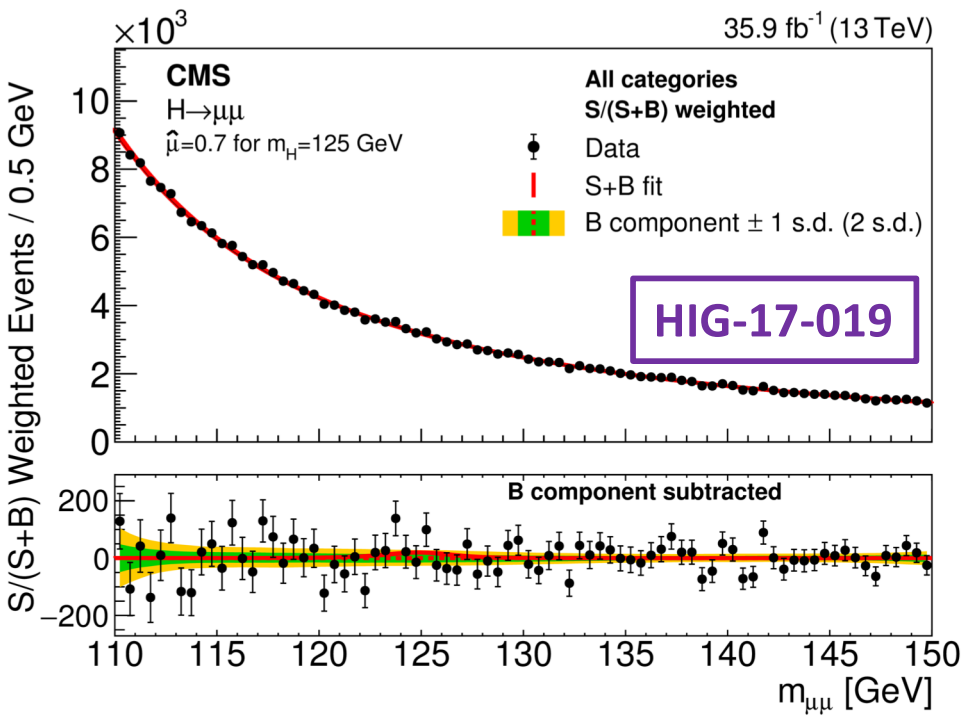


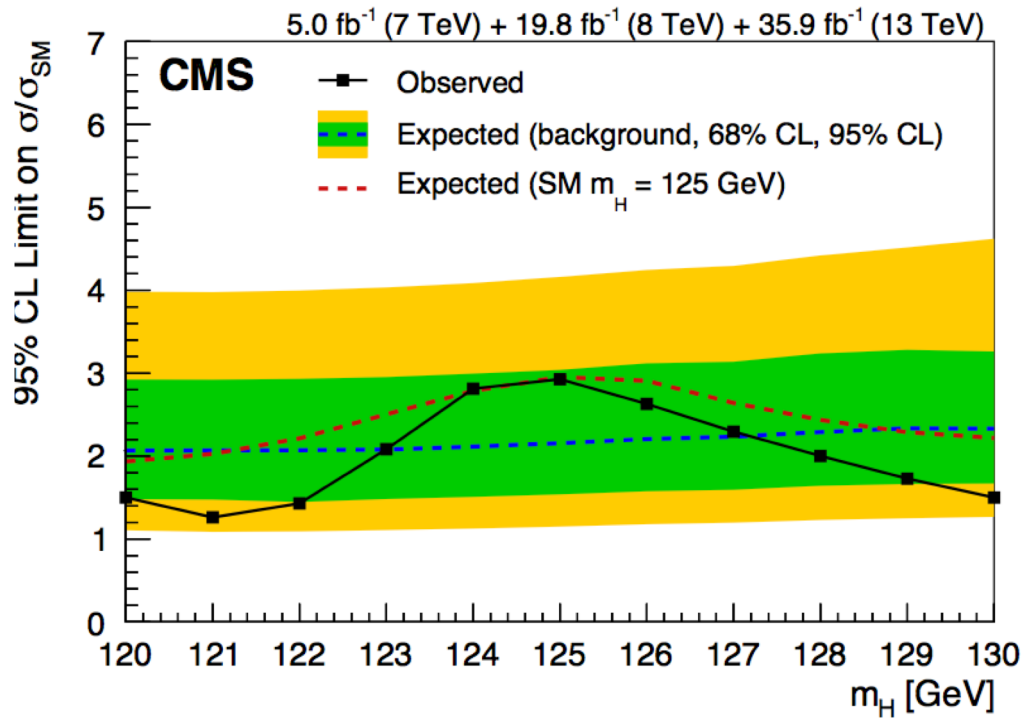


2nd generation: the next frontier ?

- Next important goal: establish Higgs couplings to 2nd generation fermions w/ H → μμ

  BR ($H \to \mu\mu$) ~ 2.2 x 10^{-4} : small but enhanced in some BSM scenarios





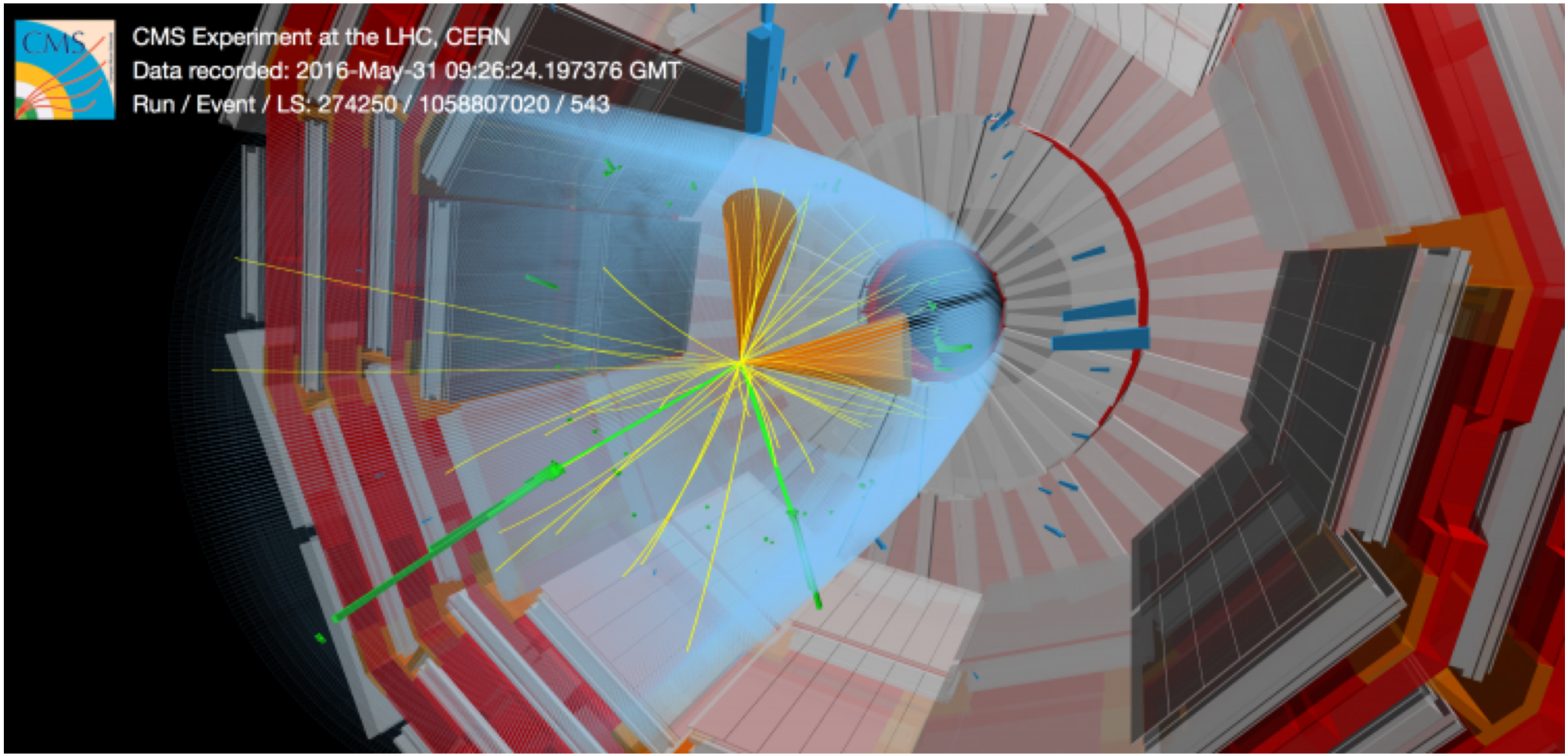
ATLAS w/ full Run 2:
μ_{ATLAS} = 0.5 ± 0.7
Obs. (exp.): 0.8σ (1.5σ)

CMS w/ Run 1 + 2016

μ_{CMS}=1.0 ± 1.0(stat) ± 0.1(syst) (RunI+2016)

Obs.(exp.): 0.9 σ (1σ)

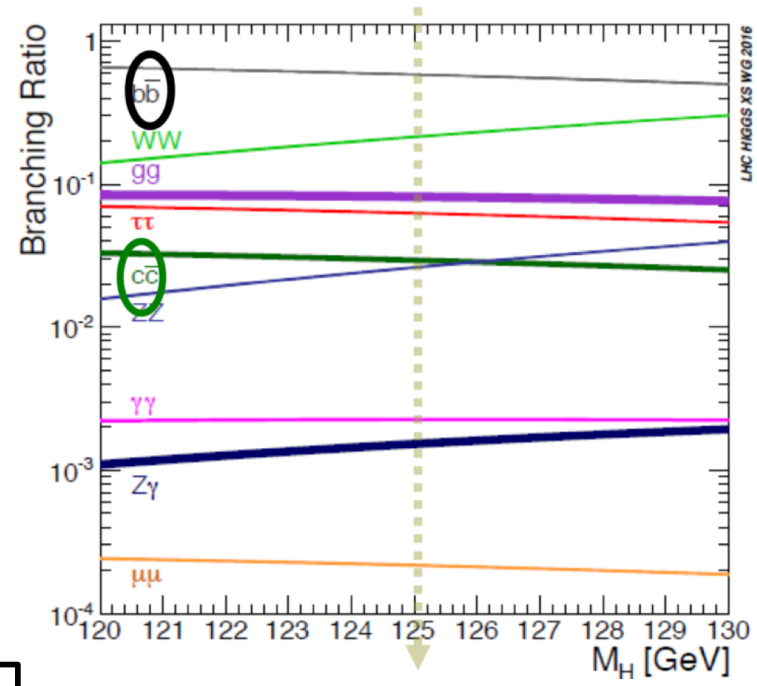
The charm of (Higgs) physics



Search for H->cc decays

HIG-18-031

- Motivation: establish Higgs couplings to up-type, 2nd gen. quarks
  - Higgs-charm coupling can be significantly modified by BSM physics
- H→cc: very challenging at the LHC
  - small BR: 2.9×10^{-2}
  - Very large backgrounds
    - H→bb is background in this search
  - **c-tagging** more challenging than b-tagging

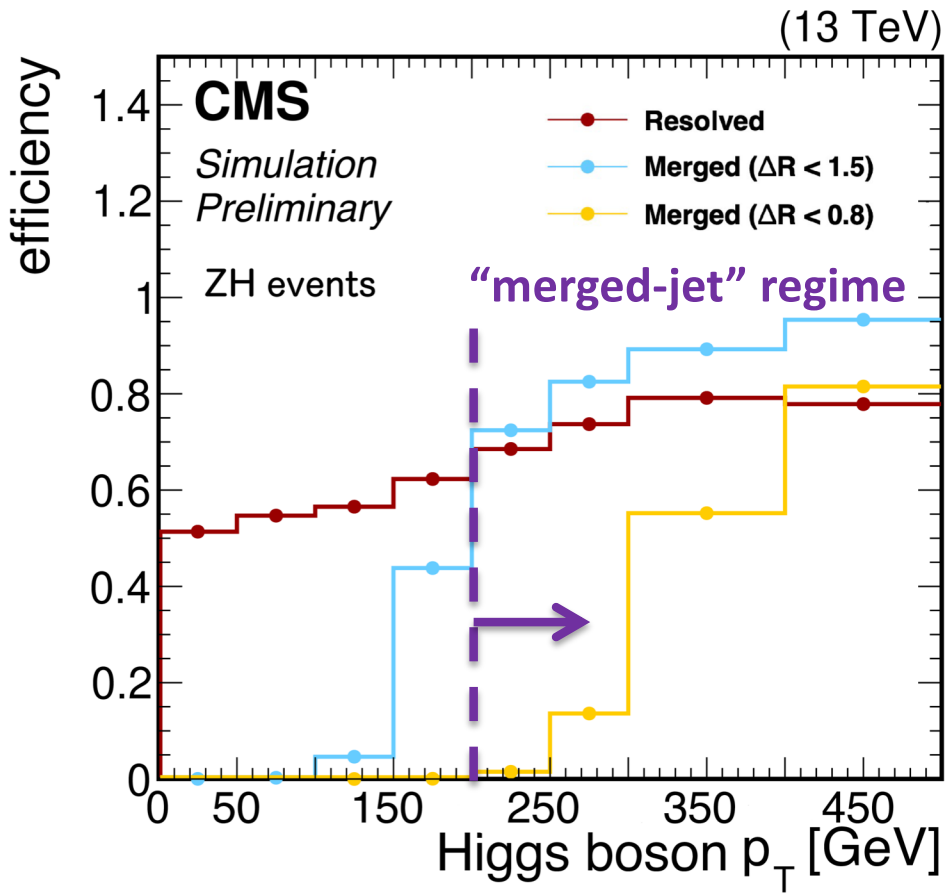


Need innovative tools and techniques!

Target VH production: very clear signature
- Vector boson recoiling against Higgs boson
- Main BKG: V+jets and ttbar
  - QCD significantly suppressed
- Very little activity in the event

Events categorized based on leptonic decays of V boson: 0L, 1L, 2L {L=e, μ}

H->cc search strategy



"Resolved-jet topology"

- Higgs decay products resolved in two AK4 (R=0.4) jets (di-jet)
- Probe larger fraction of the available signal cross-section

"Merged-jet topology"

- A single AK15 (R=1.5) jet to reconstruct the H->cc decay
  - R=1.5: good balance between purity and acceptance
- Potentially allows to better exploit the correlation between the two charm quarks

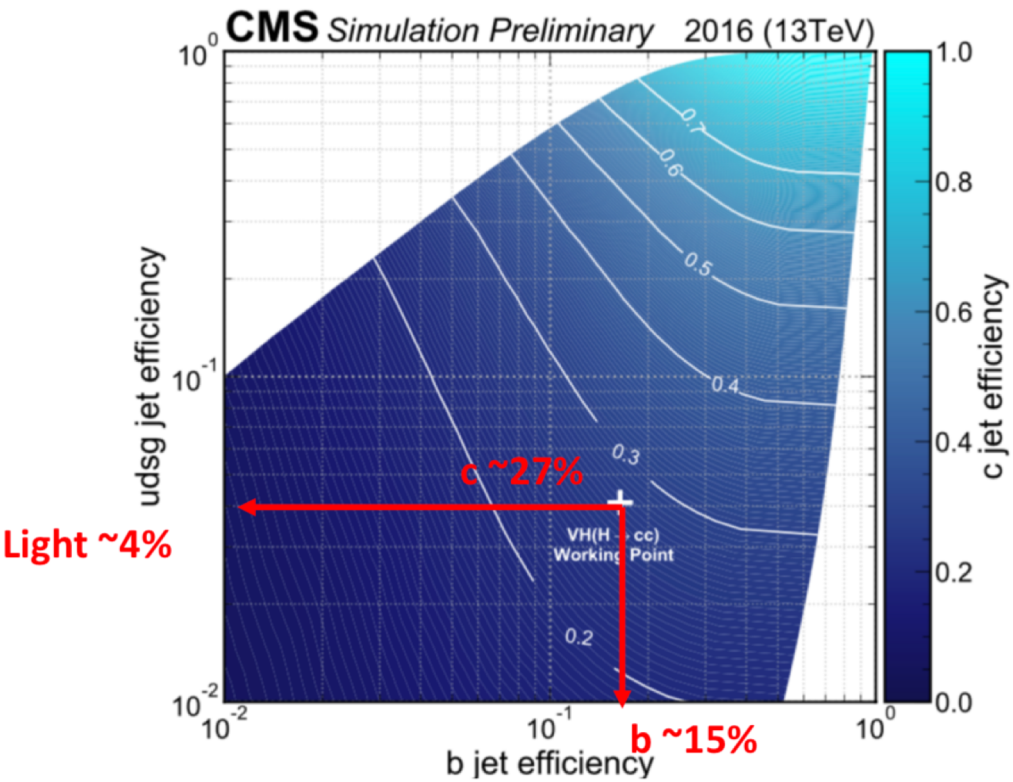
Final result: combination of the two topologies based on $p_T(V)$

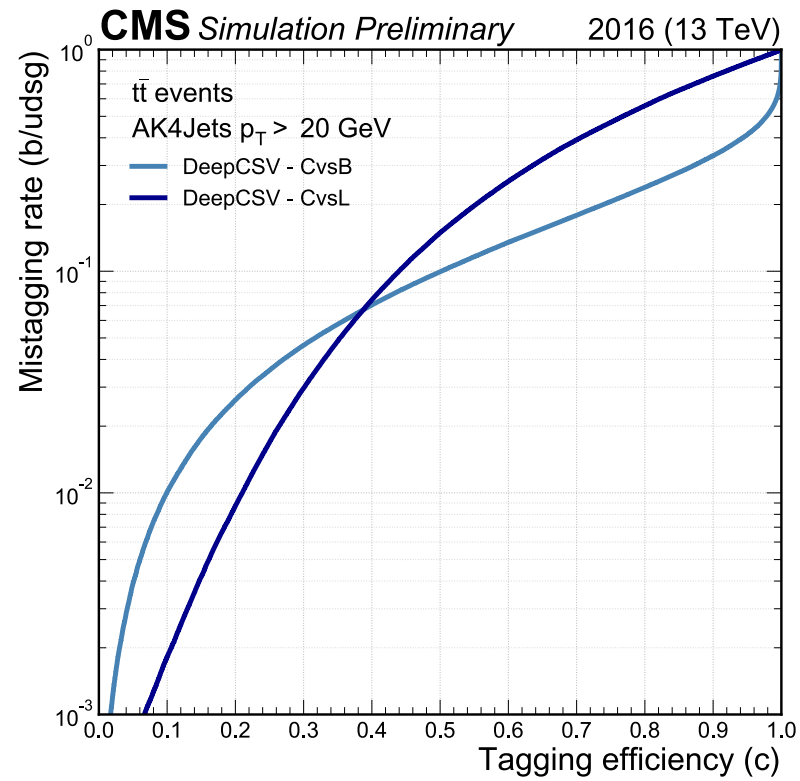
Charm-tagging

- Challenge: charm has intermediate properties b/w light and b-jets
  - Exploit Deep Neural Networks

"Resolved-jet" case: *JINST* **13** (2018) P05011

- Multi-classifier output with weights p(c), p(b), p(udsg)
- Define two discriminants to separate c-jets from light and b-jets
  - **CvsL**: p(c)/[p(c)+p(udsg)] and **CvsB**: p(c)/[p(c)+p(b)]



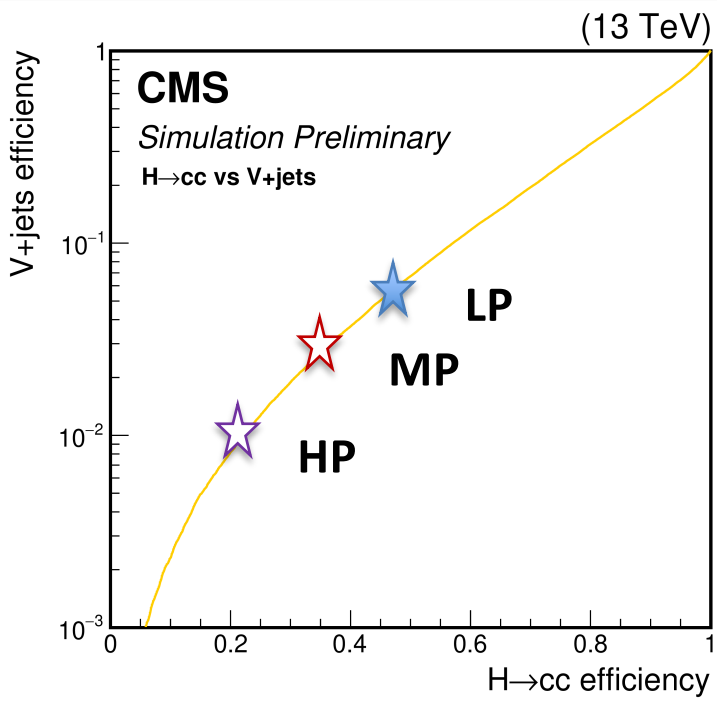


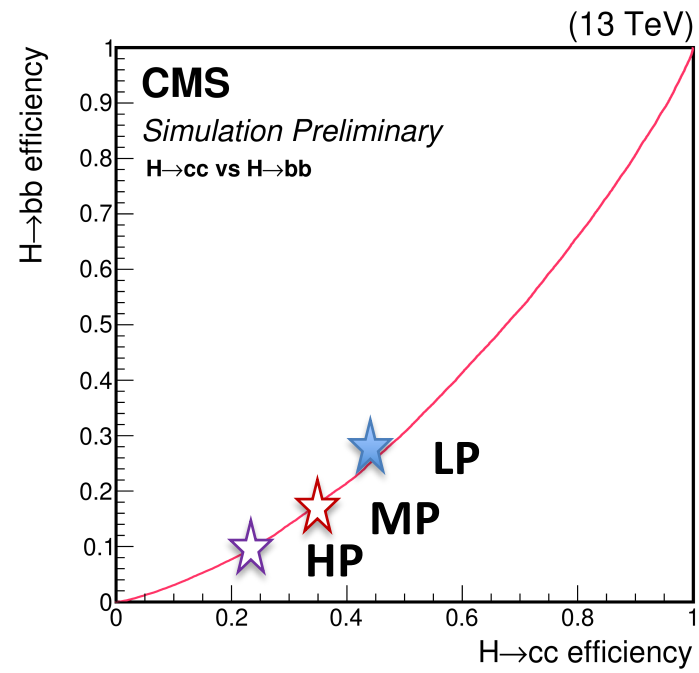
Charm-tagging

- Challenge: charm has intermediate properties b/w light and b-jets
  - Exploit Deep Neural Networks

"Merged-jet" case: *CMS-PAS-JME-19-002*

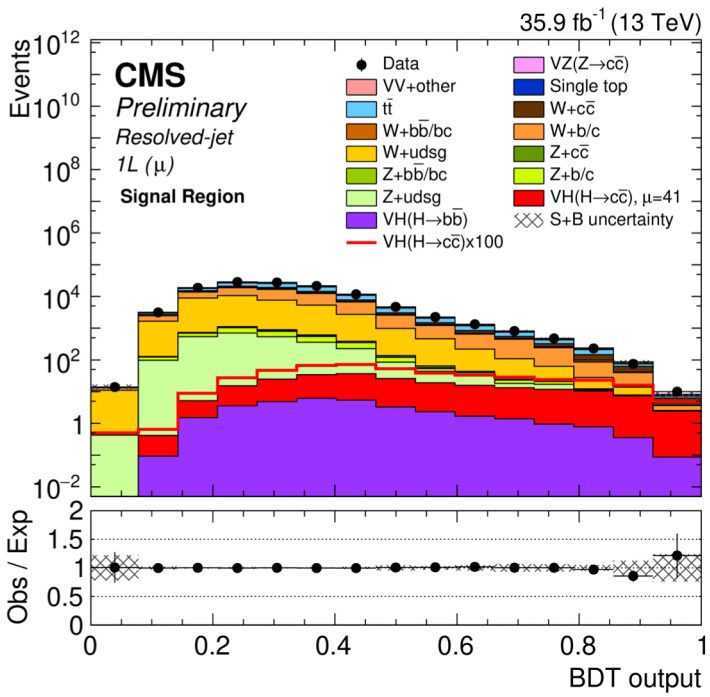
- Advanced boosted jet tagger "DeepAK8" adapted on AK15 jets
- multi-class classifier for top, W, Z, Higgs, and QCD jets
  - subdivided based on decay modes (e.g. H->bb, H->cc, ..)
  - can be aggregated for flavor tagging (e.g., bb vs cc vs light)
  - Decorrelated with mass to prevent mass sculpting





Search strategy

- Impose requirements on Higgs candidate
  - Resolved topology:
    - Primary req: two highest "CvsL" AK4 jets
  - Merged topology:
    - highest pT AK15 jet [pT>200 GeV, 50 < jet (mass) < 250 GeV]
- **Event level separation:** Maximize sensitivity by developing BDTs to separate signal from background



- Main backgrounds (i.e. V+jets, ttbar) estimated from data control samples
- Simultaneous fit to signal regions (SR) & control regions (CR)

Resolved topology:
Fit c-tagging discriminant shape in CRs and BDT shapes in SR

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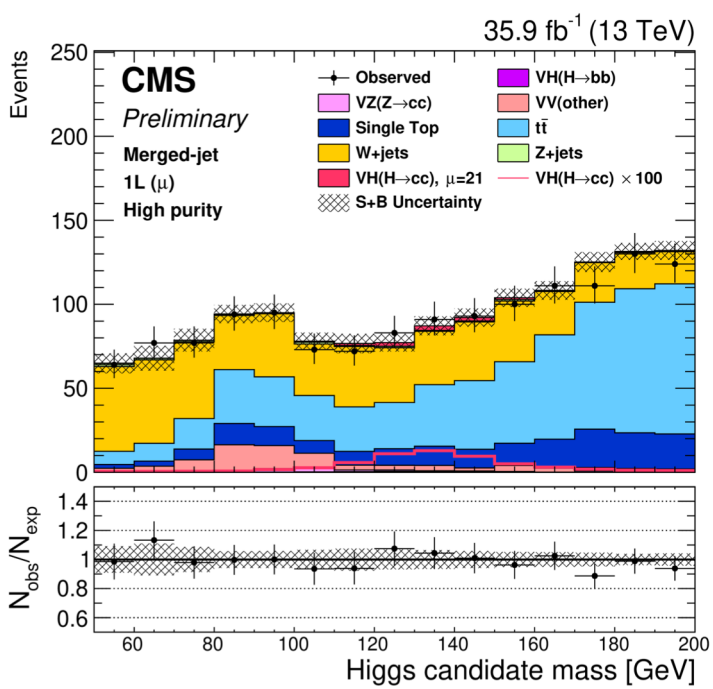


- Main backgrounds (i.e. V+jets, ttbar) estimated from data control samples
- Simultaneous fit to signal regions (SR) & control regions (CR)

Merged topology:
BDT> 0.5; m(Hcand) final fitted variable for signal extraction

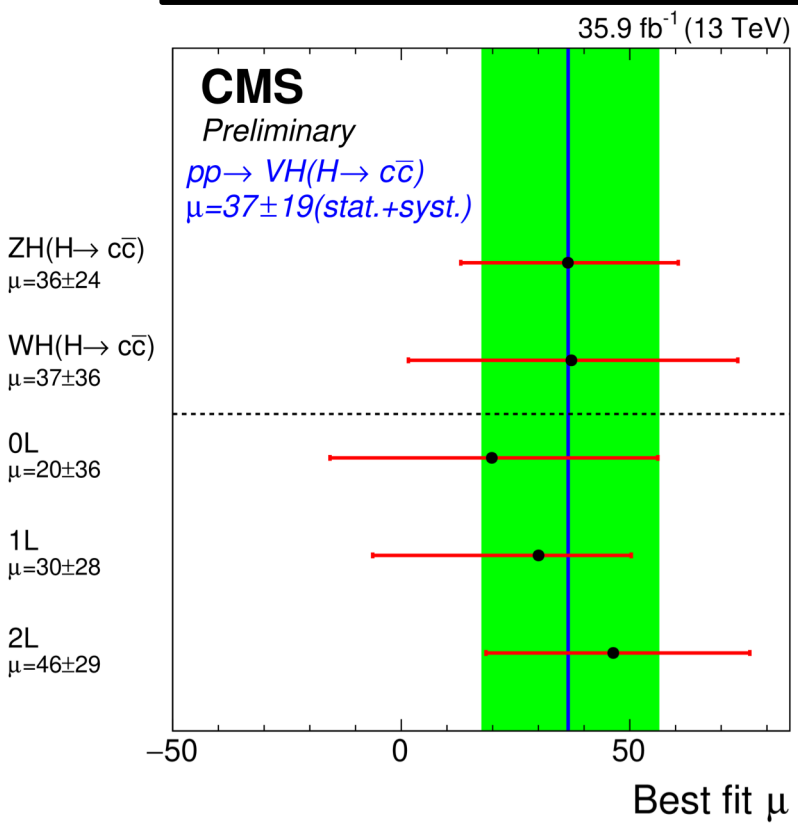
Search results

- Validate search by measuring the VZ→cc process
  - Results consistent with SM within expectations
- Combine (V)H->cc results from resolved-jet &merged-jet topologies

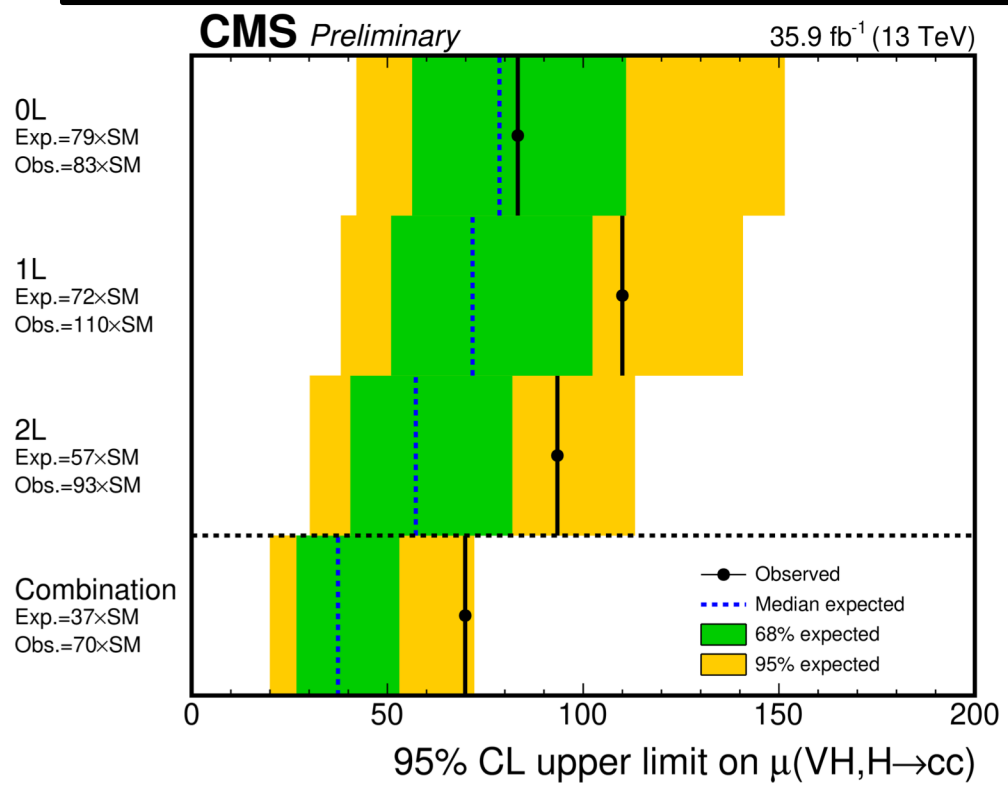
$$\mu < 70 \text{ obs. } \left(37\left(^{+16}_{-10}\right)\left[^{+35}_{-17}\right]\right) \text{exp.}(1\sigma)[2\sigma]$$

Strongest limit to date

Best fit signal strength



95% C.L. exclusion limit on $\mu_{VH(cc)}$

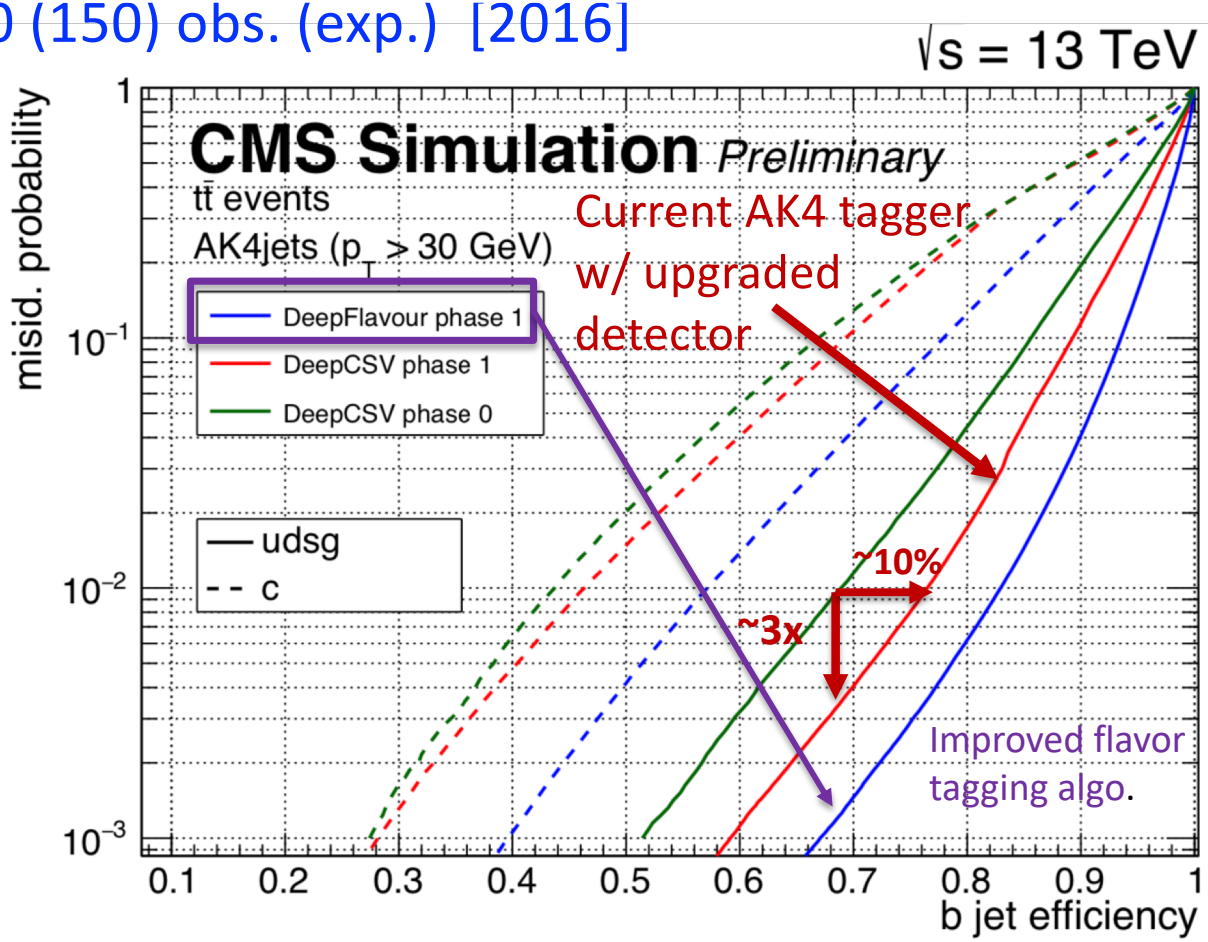


VH(cc) outlook

- 1st direct search conducted for H->cc in CMS w/ 35.9 fb^{-1} (2016 data)
- Advanced techniques for charm tagging and analysis methods are helping to set the stage
  - Strongest limit to date $\mu < 70$ obs. $\left(37\left(^{+16}_{-10}\right)\left[^{+35}_{-17}\right]\right)$ exp.$(1\sigma)[2\sigma]$
  - ATLAS Z(ll)H search: 110 (150) obs. (exp.) [2016]
- HL-LHC is critical

Expected improvements:

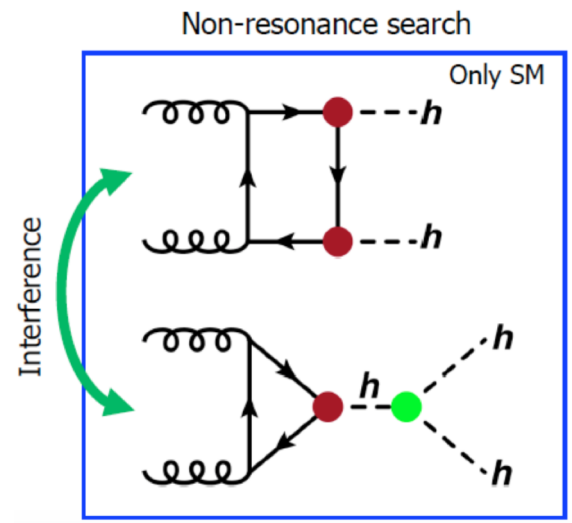
- Charm tagging:
  - upgraded pixel det.
  - improved algorithms
- Improved signal extraction techniques
- Full Run 2 data



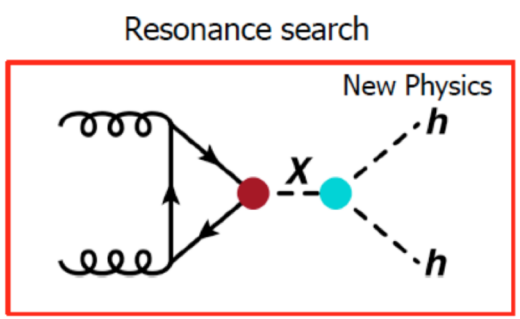
See talk by L. Gouskos @ HH2019 for details

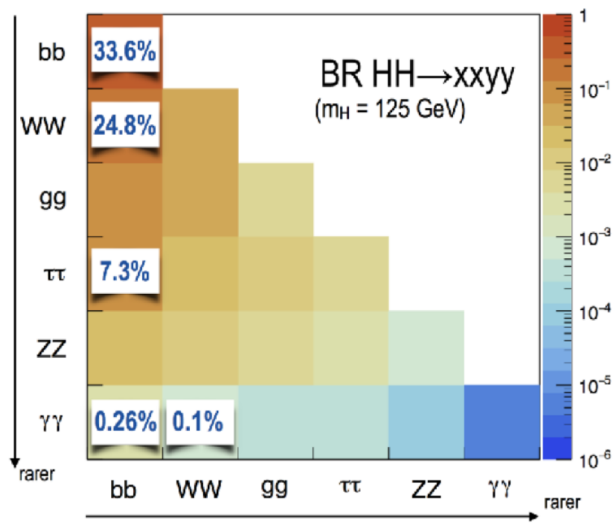
HH

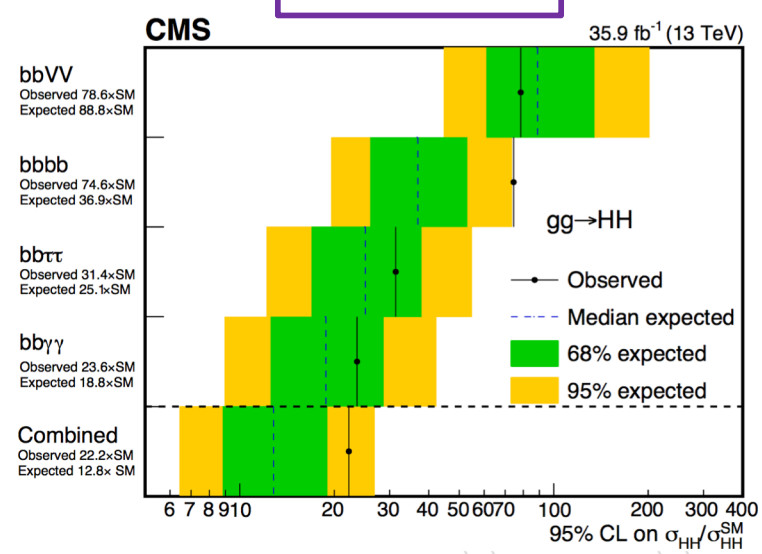
- Directly probes Higgs field potential (sensitive to the self-coupling **λ**)
- Small cross section, destructive interference with box diagram
- Puts constraints on several new-physics scenarios
  - **Non-resonant:** New/modified vertices contributing to hh production
  - **Resonant:** new narrow width particle decaying into two SM Higgs



HIG-17-030



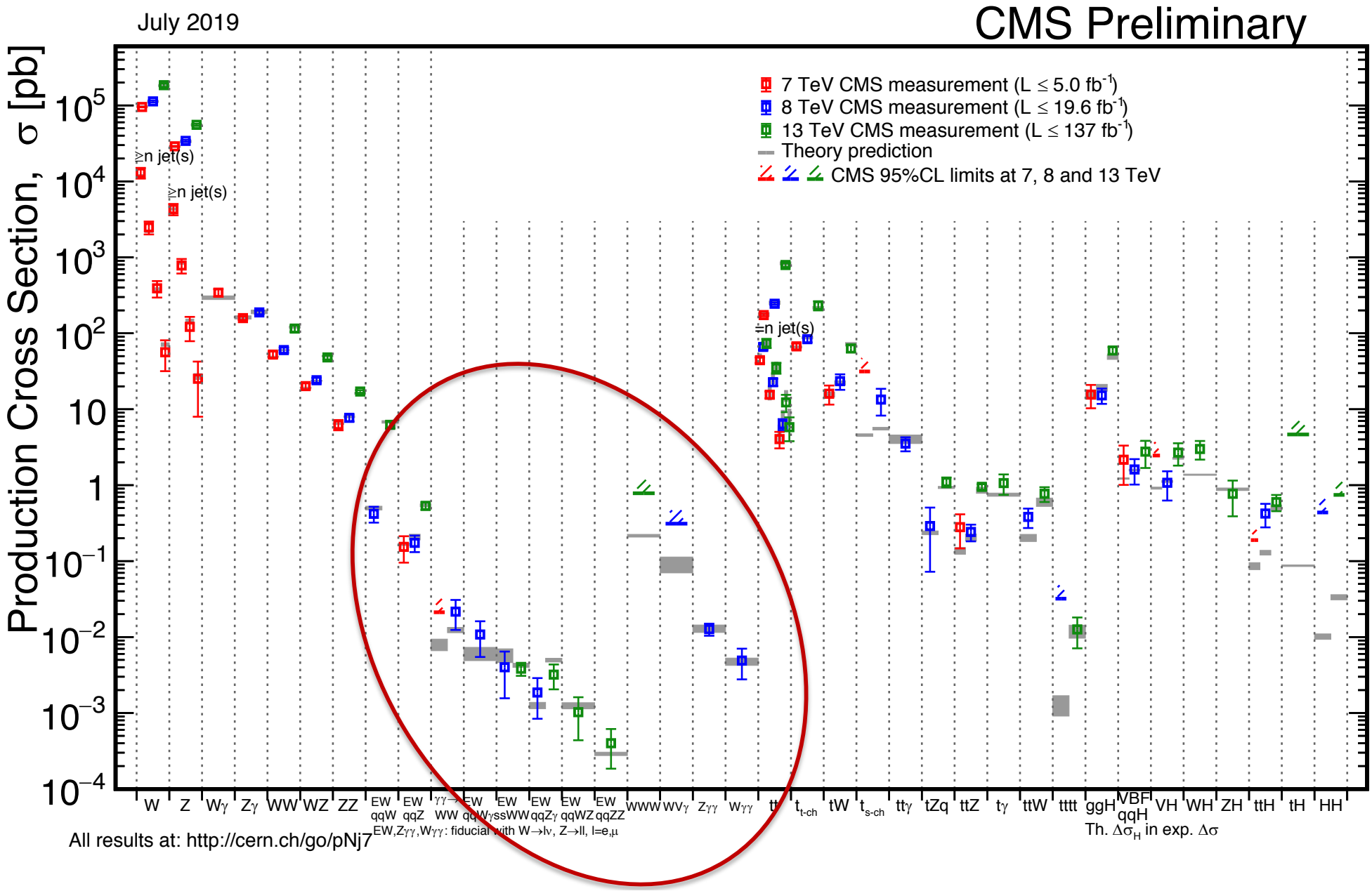




ATLAS+CMS HH significance @ HL-LHC: 4σ

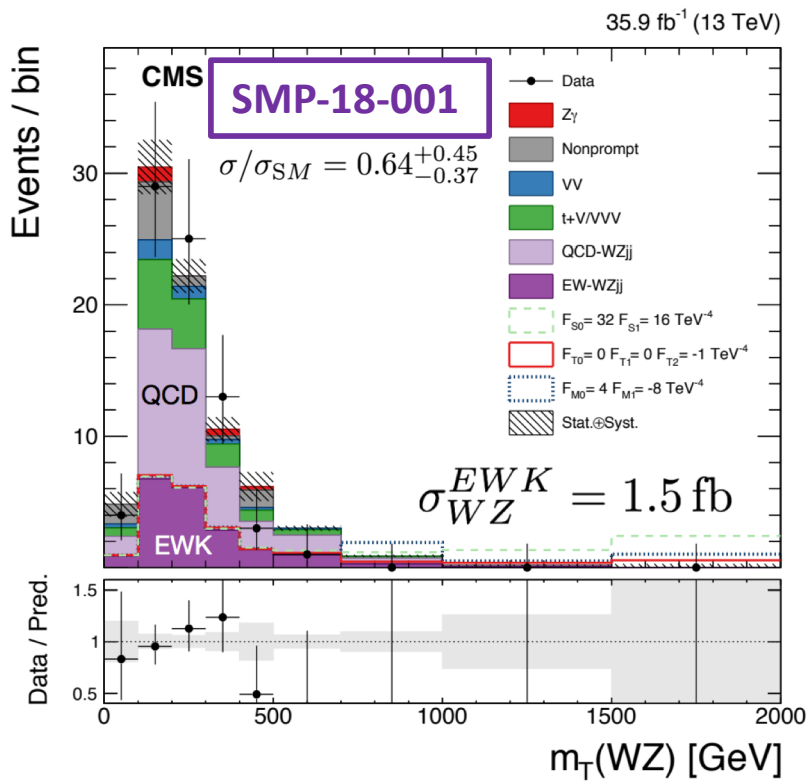
combination probes ~10 times the SM prediction

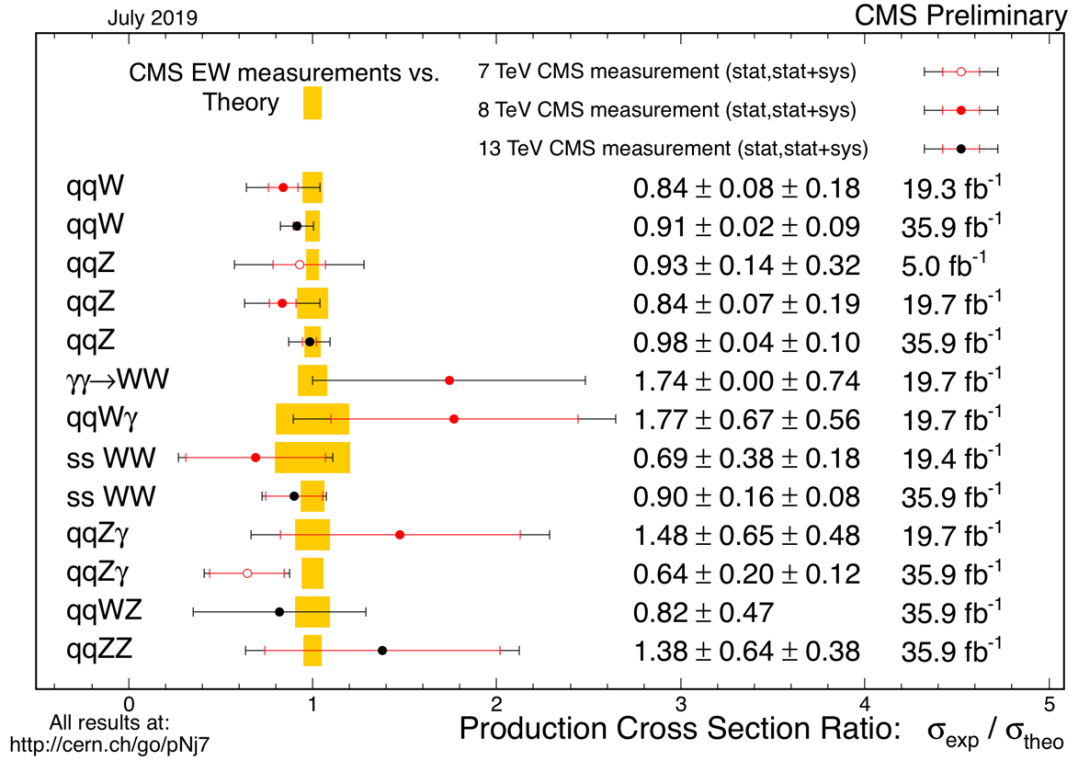
Standard Model reigns supreme



Measurements of “rare” processes

- Large datasets allow us to test SM in complementary ways
  - multi-differential cross-section measurements
  - First-time sensitivity to rare multi-boson final states and production mechanisms



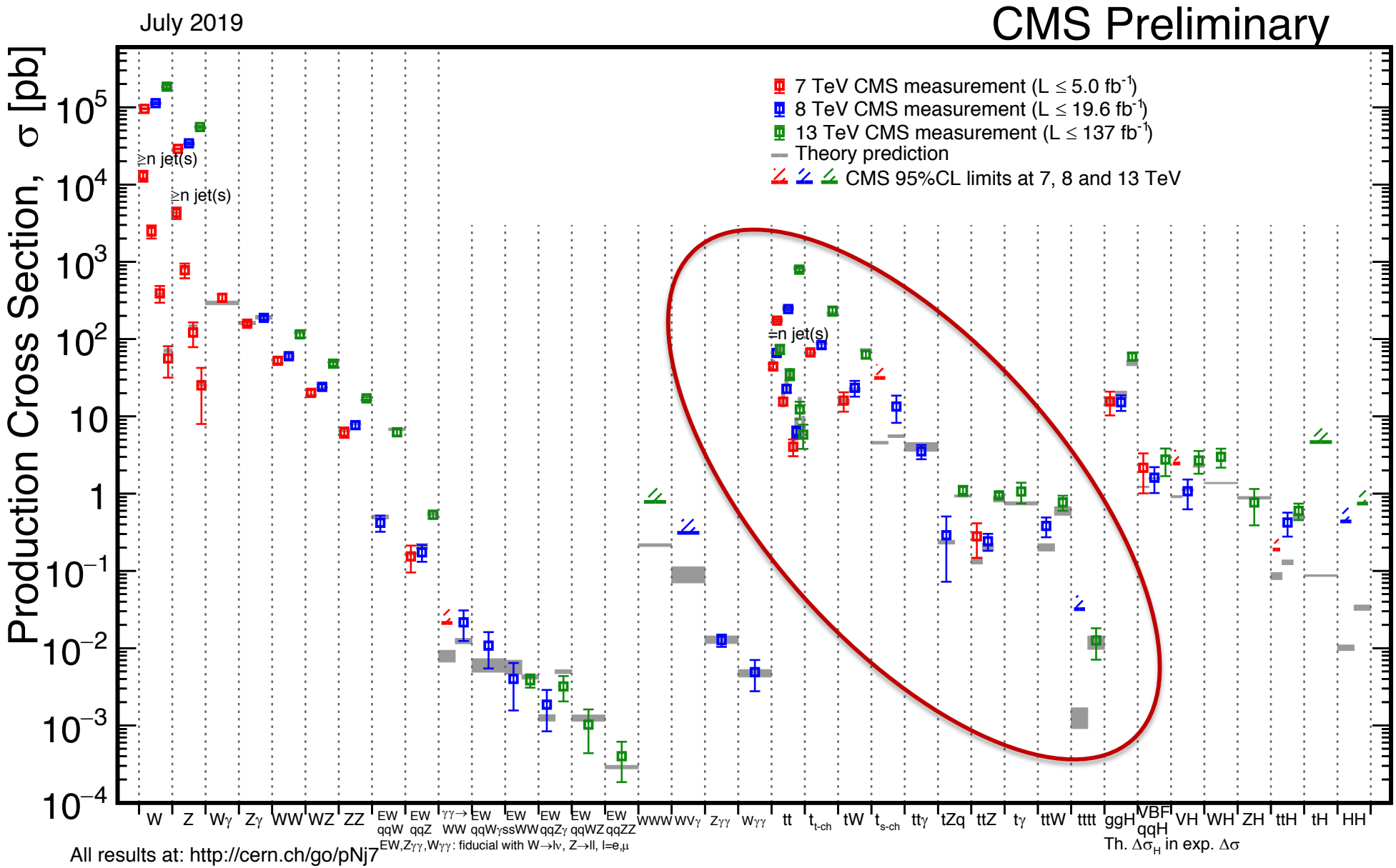


Still room for surprises!

Quartic gauge couplings known exactly in SM and sensitive to new physics

Starting to be sensitive to NNLO corrections;

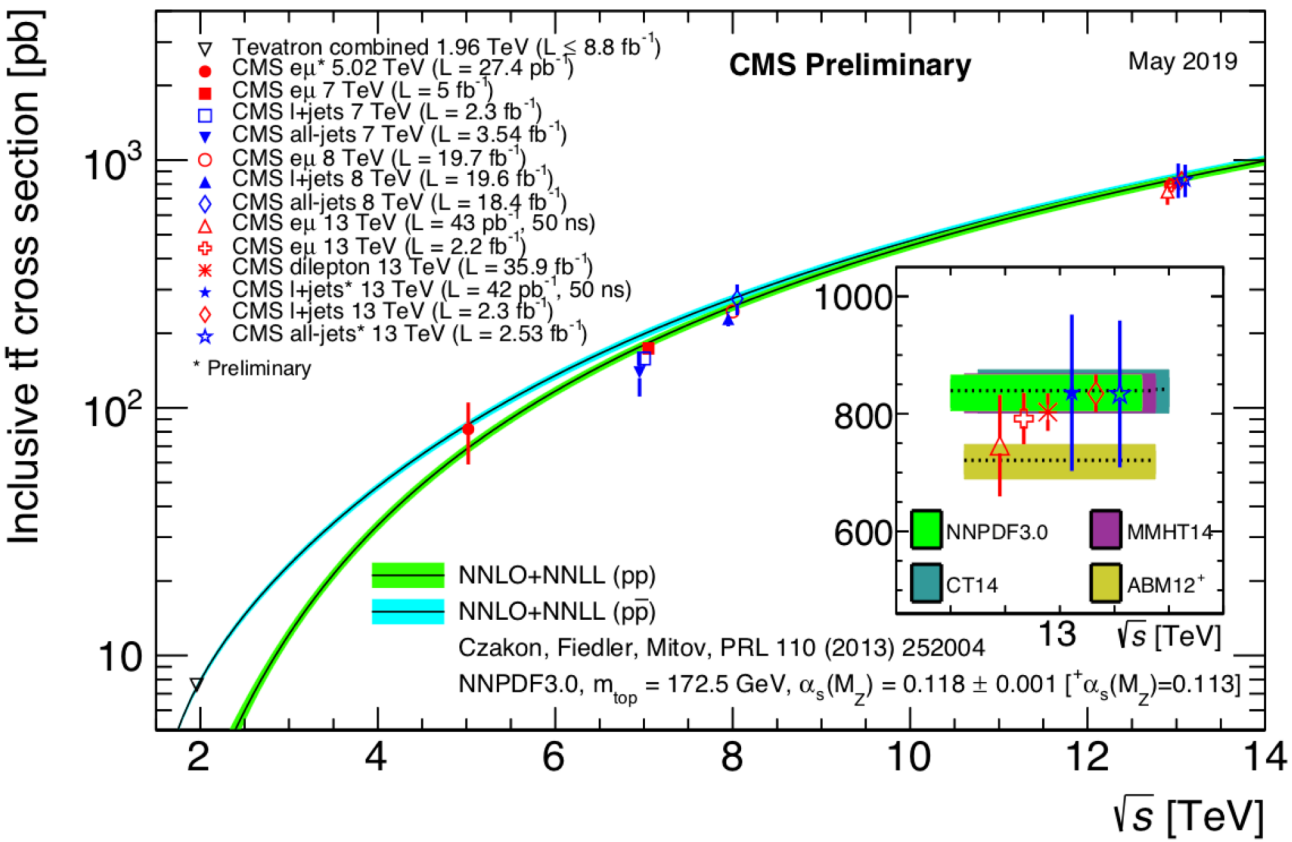
NLO corrections available for practically all diboson final states, combined EWK and QCD NLO corrections?


July 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ WWW WVγ Zγγ Wγγ tt t t-ch tW t s-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

Precision Top Quark Physics

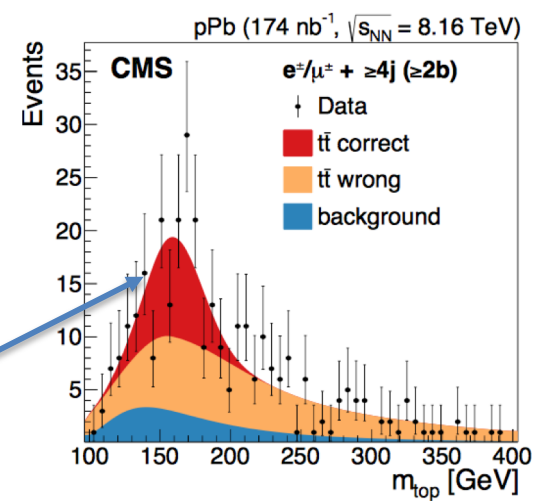
Over ~25 years since its discovery, the top quark is still one of the hottest topics…

LHC: a top quark factory!



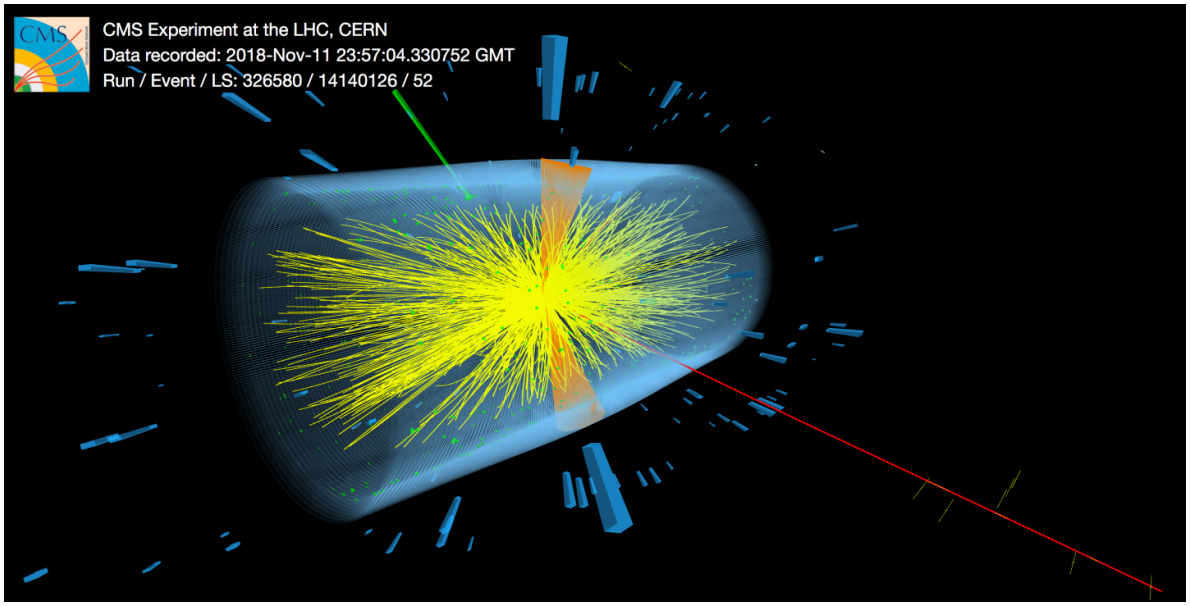
Inclusive cross section well understood; agrees with NNLO predictions

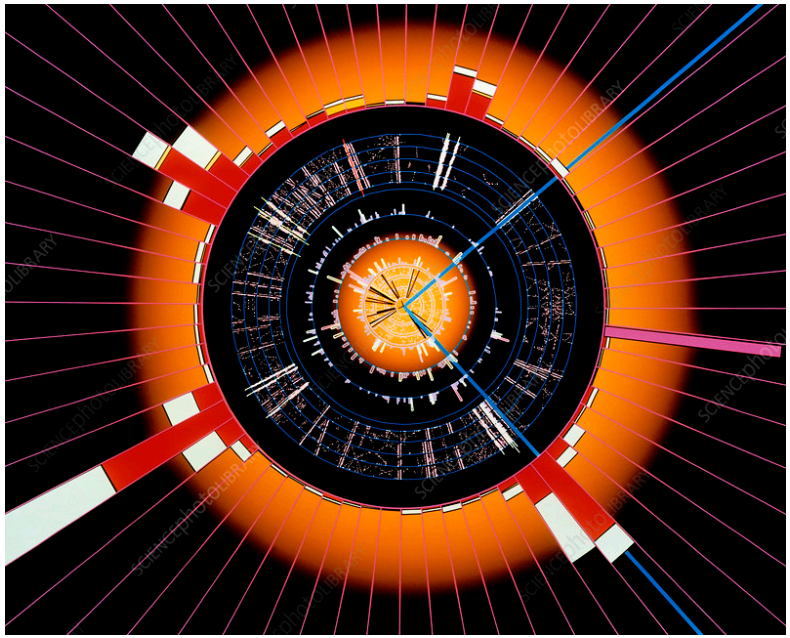
PRL 119, 242001

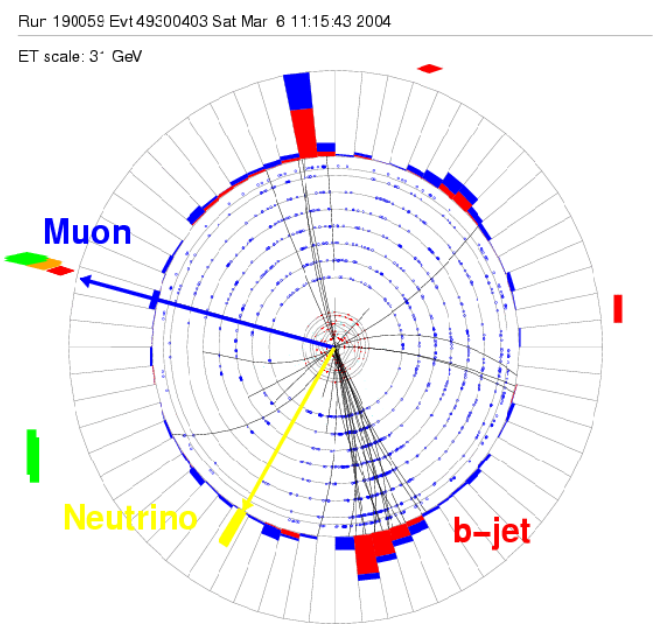


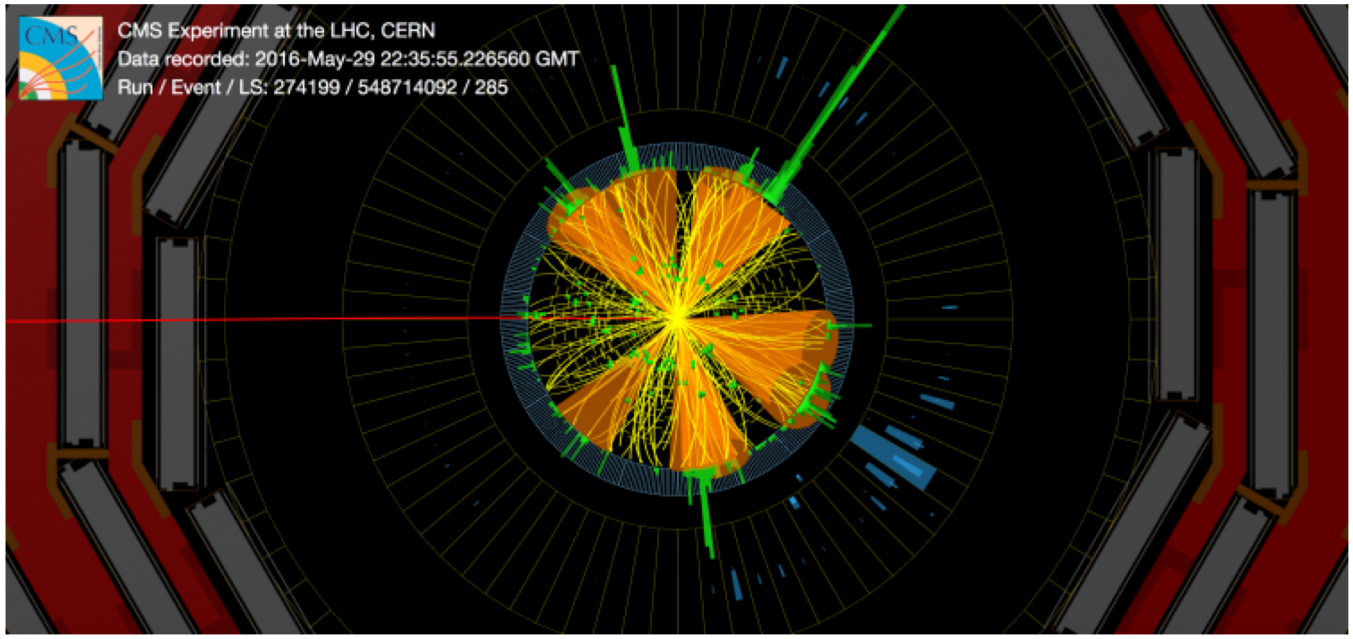
Observation of top quarks in heavy-ion collisions!

Top evolution









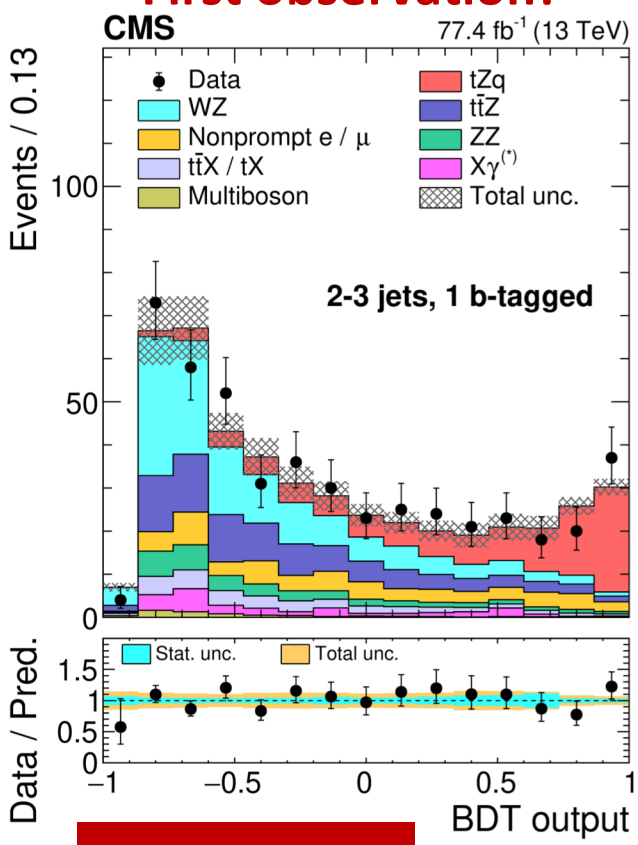
TOP-18-008

Rare top

TOP-18-003

- tZq: sensitive to tZ coupling and WWZ coupling, FCNC
  - rare process: $\sigma_{tZq} \approx 1$ pb

First observation!



15% precision

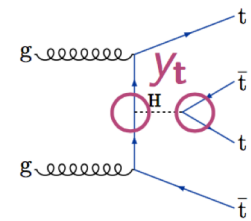
$m_{ll} > 30$ GeV

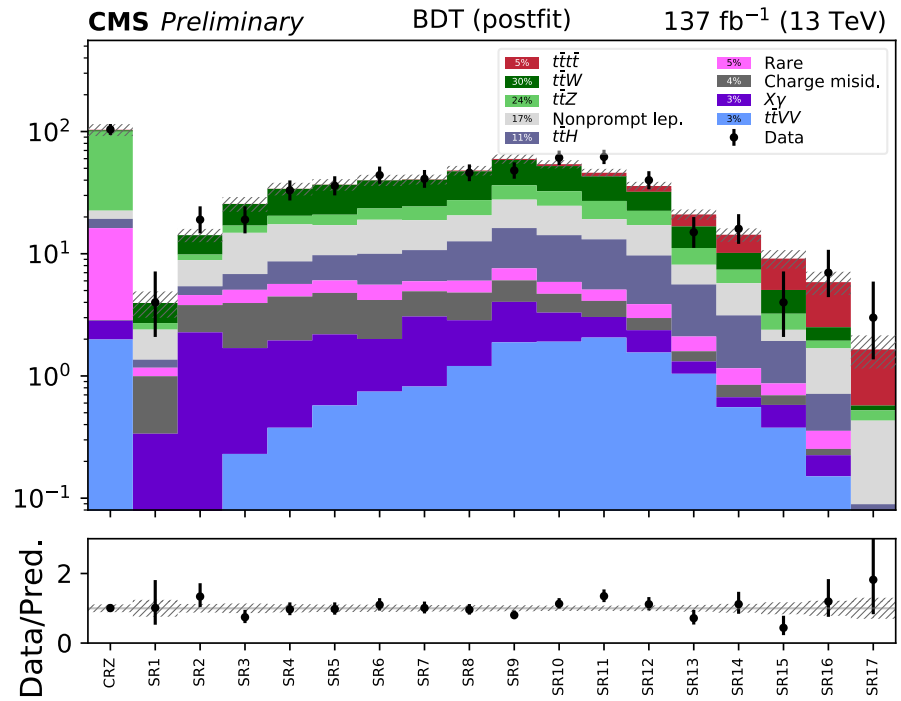
$$\sigma(\mathrm{pp} \to \mathrm{tZq} \to \mathrm{t}\ell^+\ell^-\mathrm{q}) = 111 \pm 13\,(\mathrm{stat})\,^{+11}_{-9}\,(\mathrm{syst})\,\mathrm{fb}$$

- tttt: unobserved very rare process ($\sigma_{tttt} \approx 0.01$ pb)
  - Sensitive to top yukawa coupling

$$|y_t/y_t^{SM}| < 1.7,$$

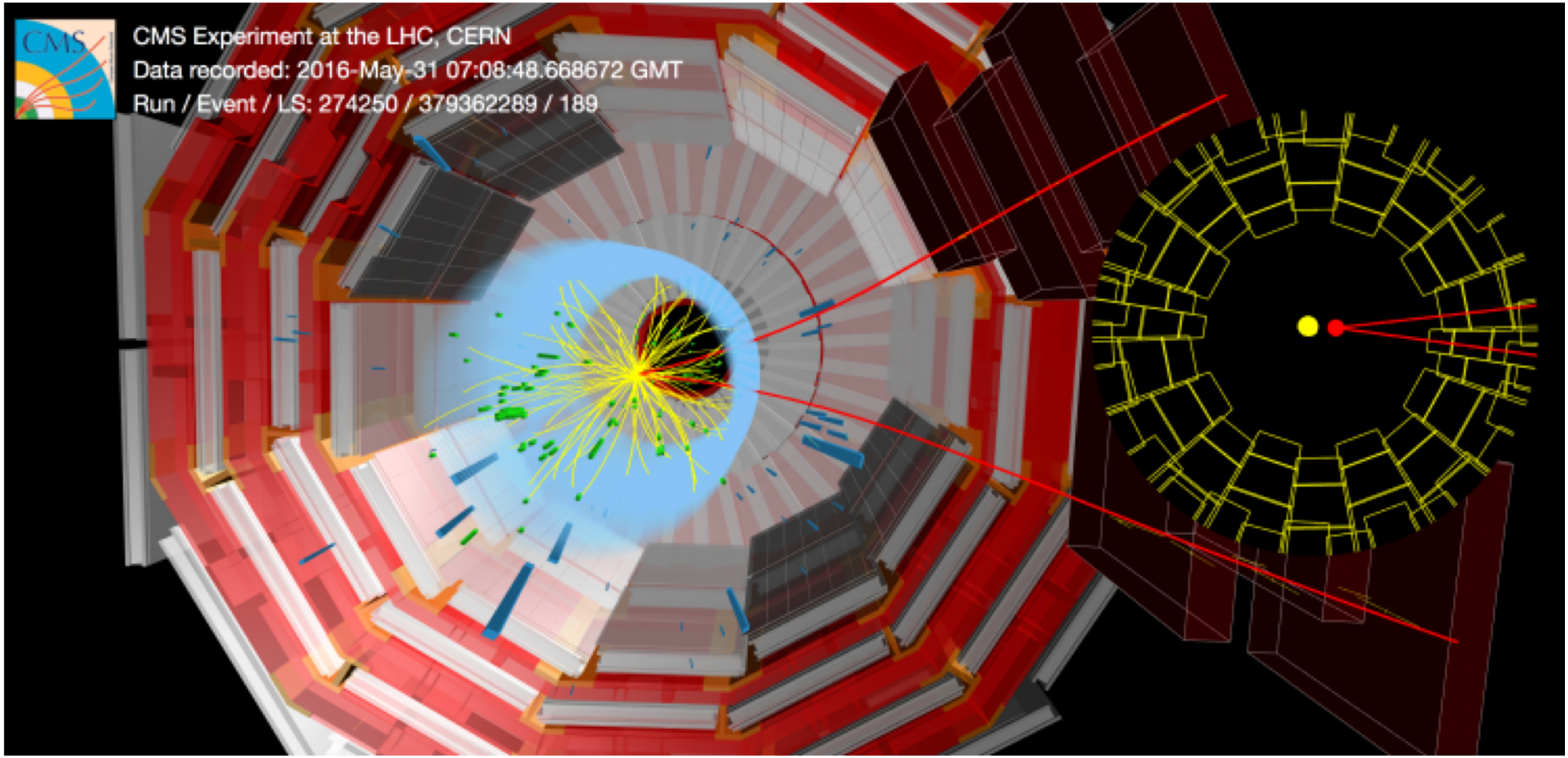
@ 95% CL



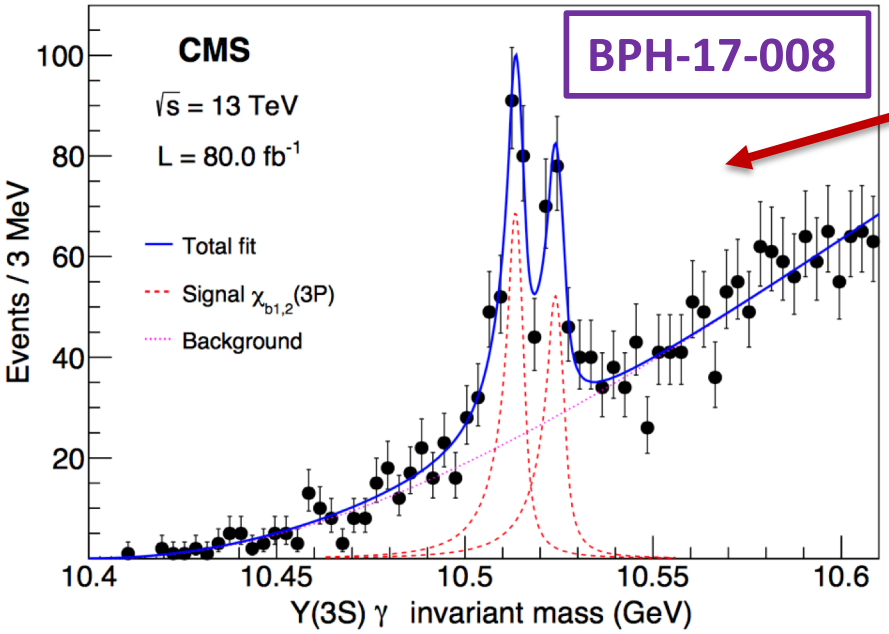


Approaching sensitivity to 4-top: obs. (exp.): 2.6 (2.7) σ

The beauty of physics

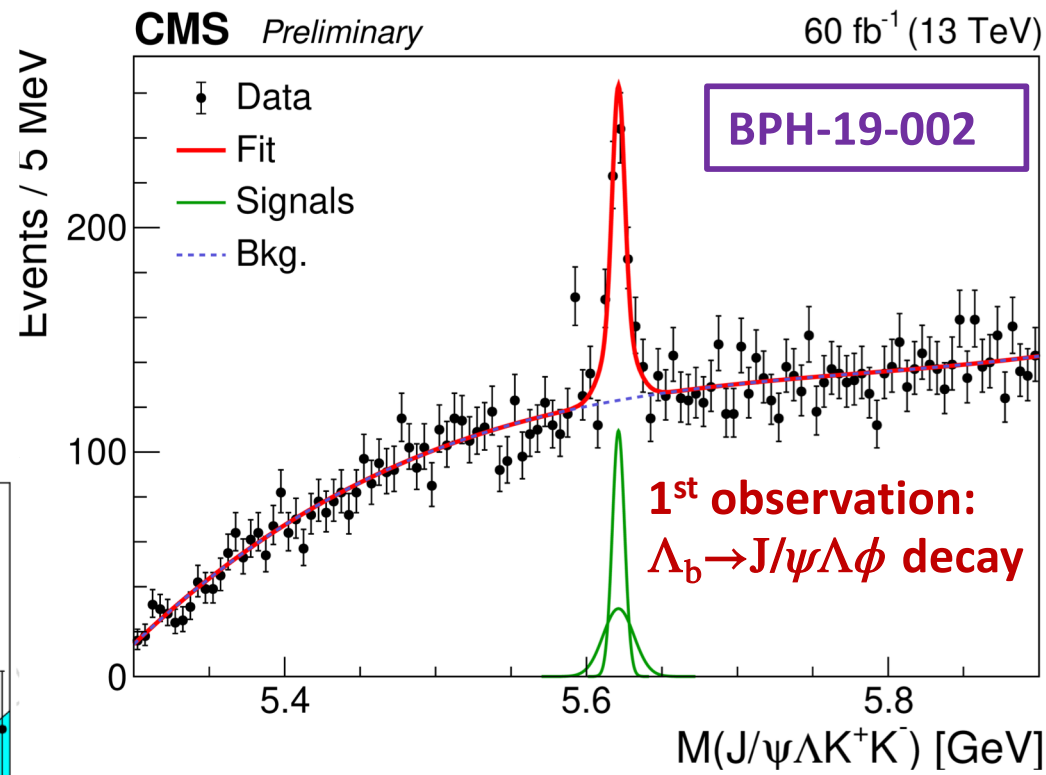


Flavor sector



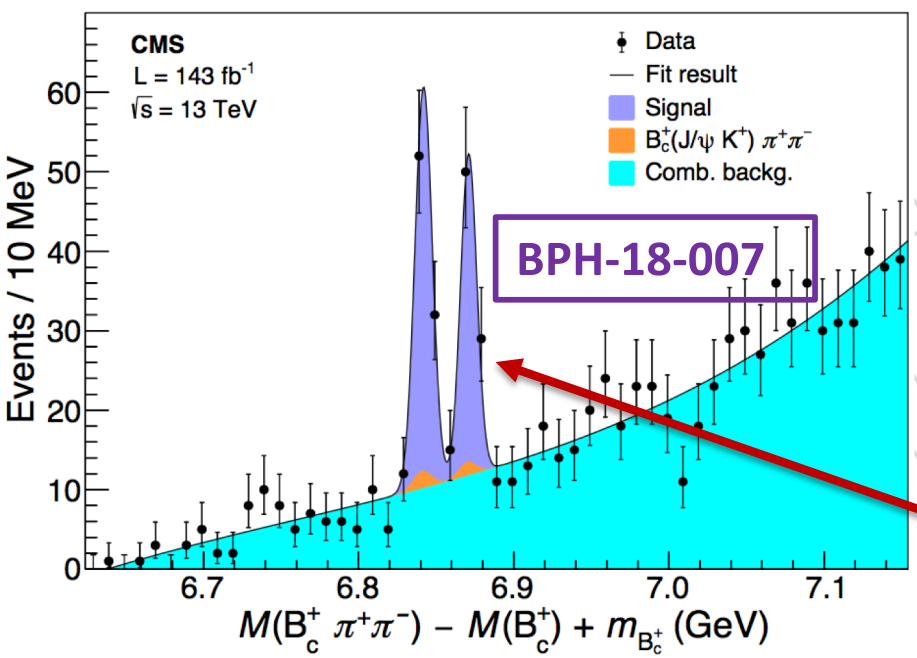
BPH-17-008

1st observation: doublet structure of $\chi_b(3P)$ resonance



BPH-19-002

1st observation: $\Lambda_b \to J/\psi \Lambda \phi$ decay



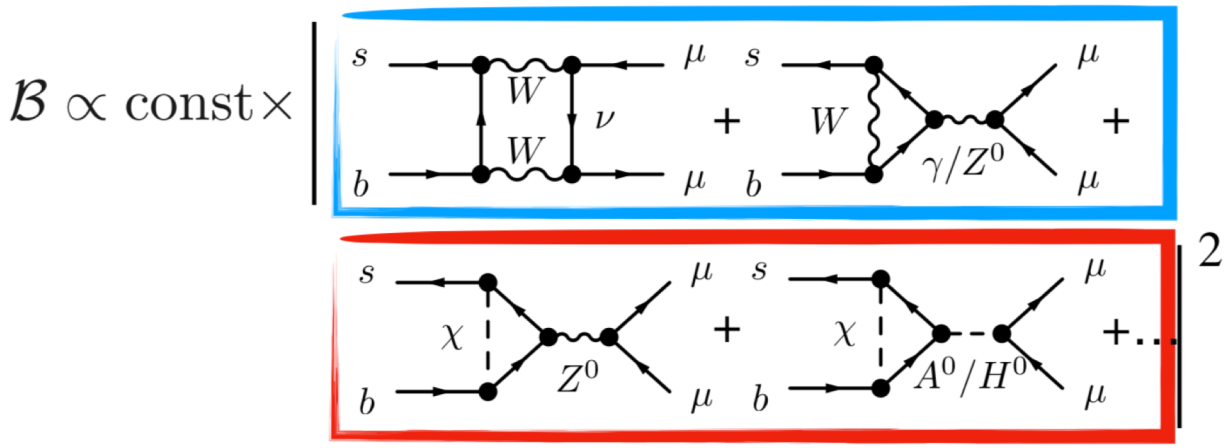
BPH-18-007

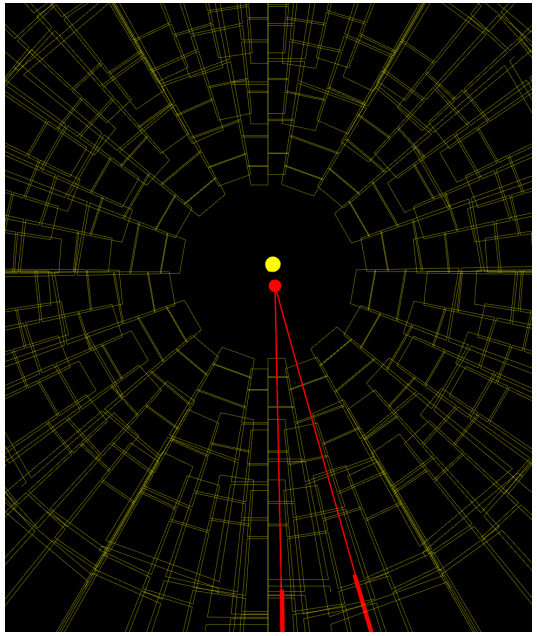
1st observation: well-resolved $B_c(2S)^{\pm}$ & $B_c^*(2S)^{\pm}$ peaks (first LHC full Run 2 paper)

B → $\mu^+\mu^-$

BPH-16-004

- Very rare B → $\mu^+\mu^-$ decays
  - effective FCNC, helicity suppressed in the SM
  - but: not in models with extended Higgs sectors





- SM prediction:

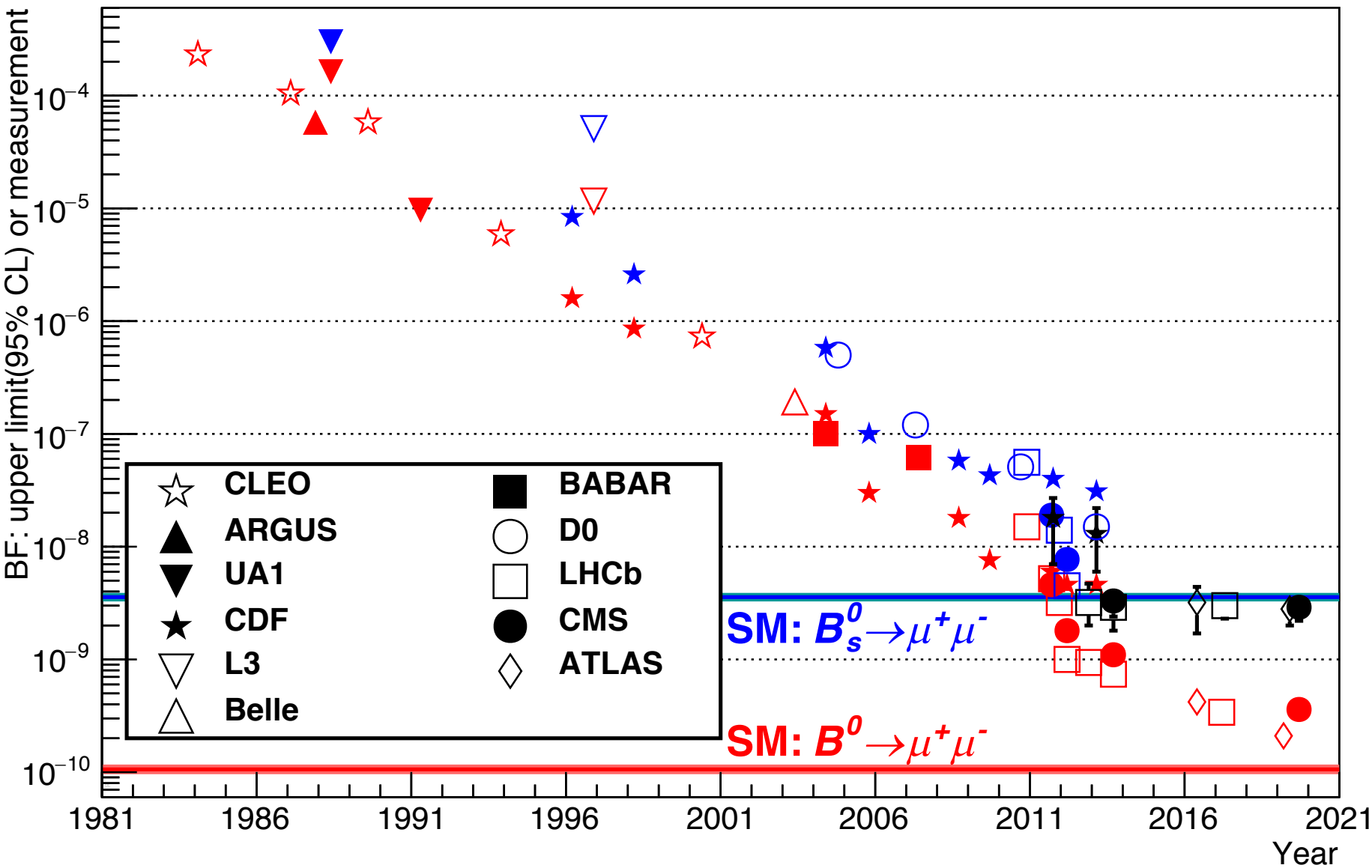
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

PRL 112 (2014) 101801

- Measurement of the B_s effective lifetime is a complementary probe in new physics searches
  - SM: only the heavy mass eigenstate decays to $\mu^+\mu^-$

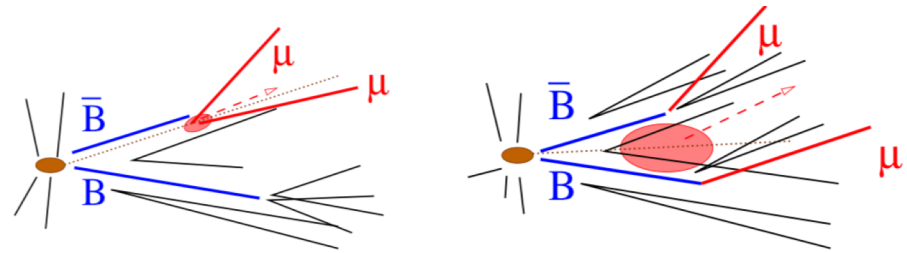
$$\tau^{SM}_{\mu^+\mu^-} = 1.615\,\text{ps}$$

A rich history…



Experimental strategy

- Signal B → $\mu^+\mu^-$
  - two muons from one decay vertex



- Background:
  - combinatorial (from sidebands)
    - two semileptonic (B) decays (gluon splitting)
    - one semileptonic (B) decay and one misidentified hadron
  - rare hadronic and semileptonic B decays (MC simulation)

- Ratio measurement for cancellation of many systematic uncert.

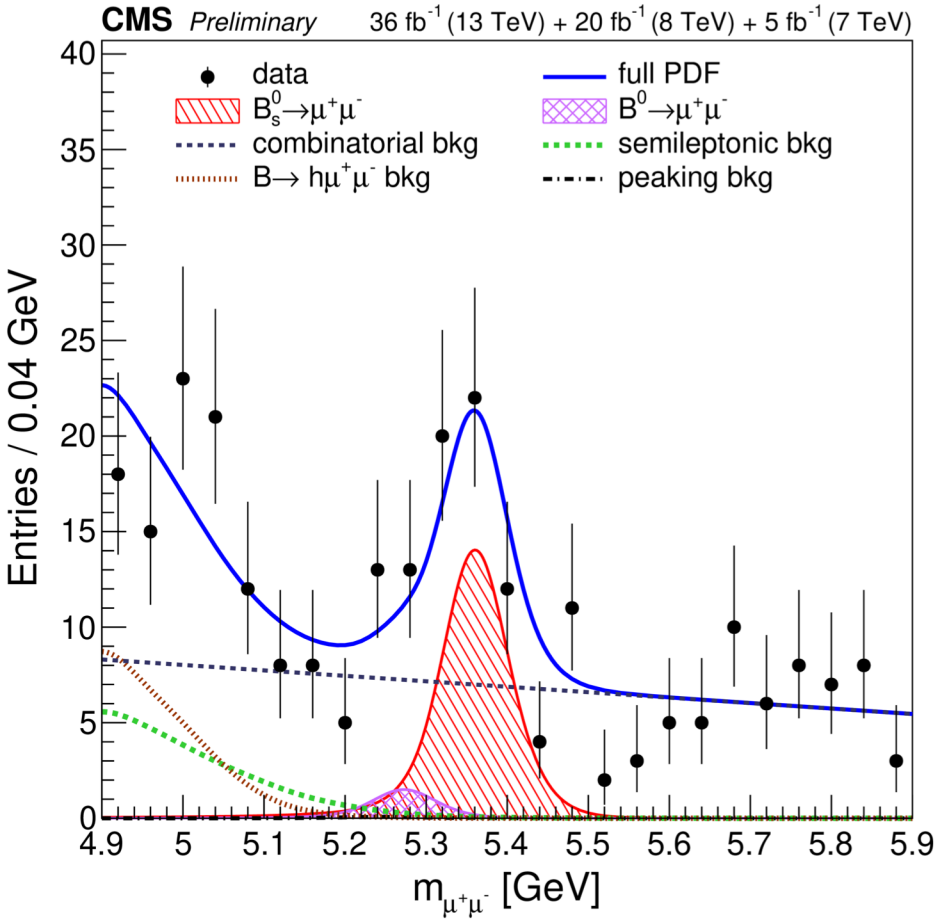
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\epsilon_{tot}^{B^+}}{\epsilon_{tot}} \mathcal{B}(B^+ \to J/\psi K^+)\, \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

  - Result depends on the ratio of the fragmentation functions f_u/f_s
    - Use PDG value: f_s/f_u = 0.012 ± 0.012 (exp) ± 0.015 (additional uncertainty assigned for p_T and energy dependence)

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- Use Run 1 (7, 8 TeV) + Run 2 (2016 13 TeV) datasets
- $B_s^0 \to \mu^+\mu^-$ branching fraction:

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



Significance:
5.6 (6.5) σ obs (exp)

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

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

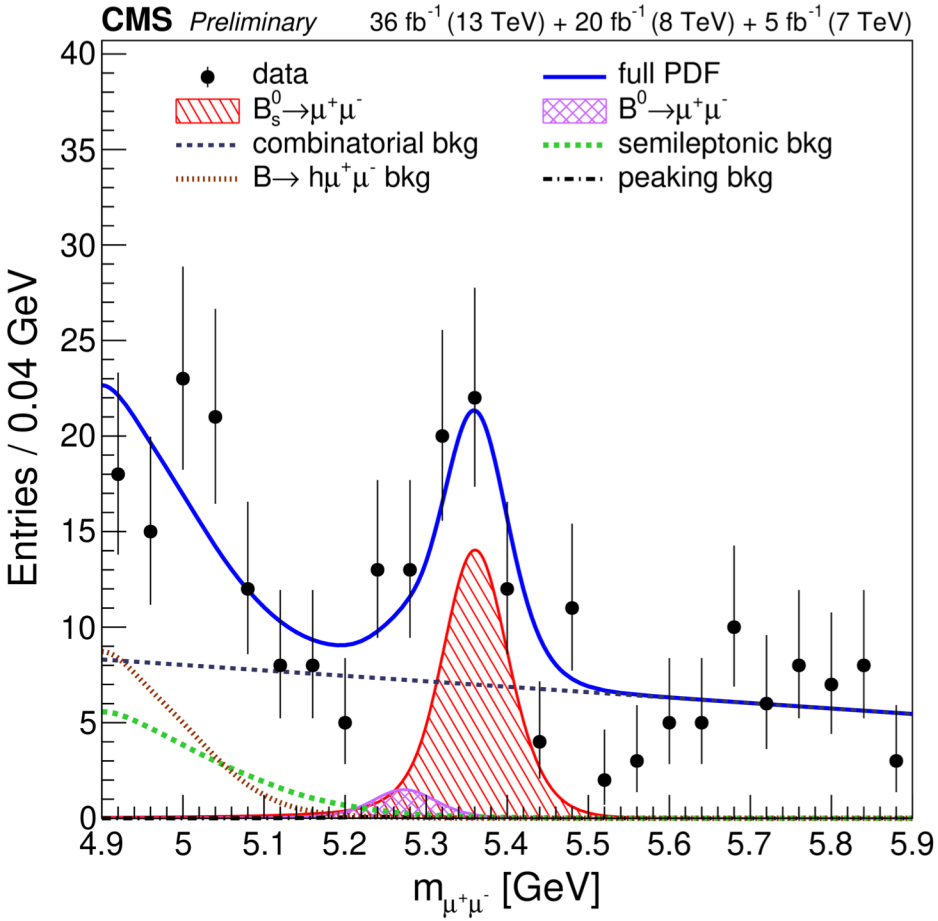
Previous CMS result:
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$
Phys. Rev. Lett. **111**, 101804

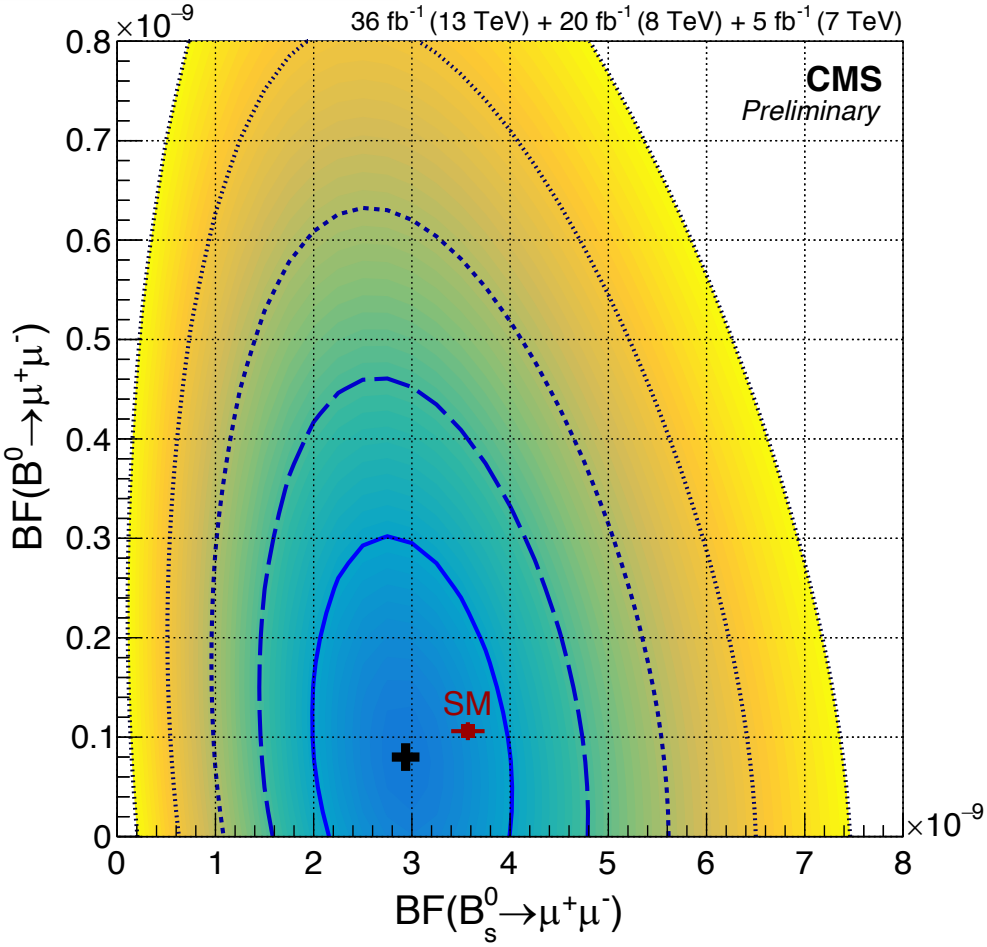
Results consistent with SM predictions

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- Use Run 1 (7, 8 TeV) + Run 2 (2016 13 TeV) datasets
- $B_s^0 \to \mu^+\mu^-$ branching fraction:

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

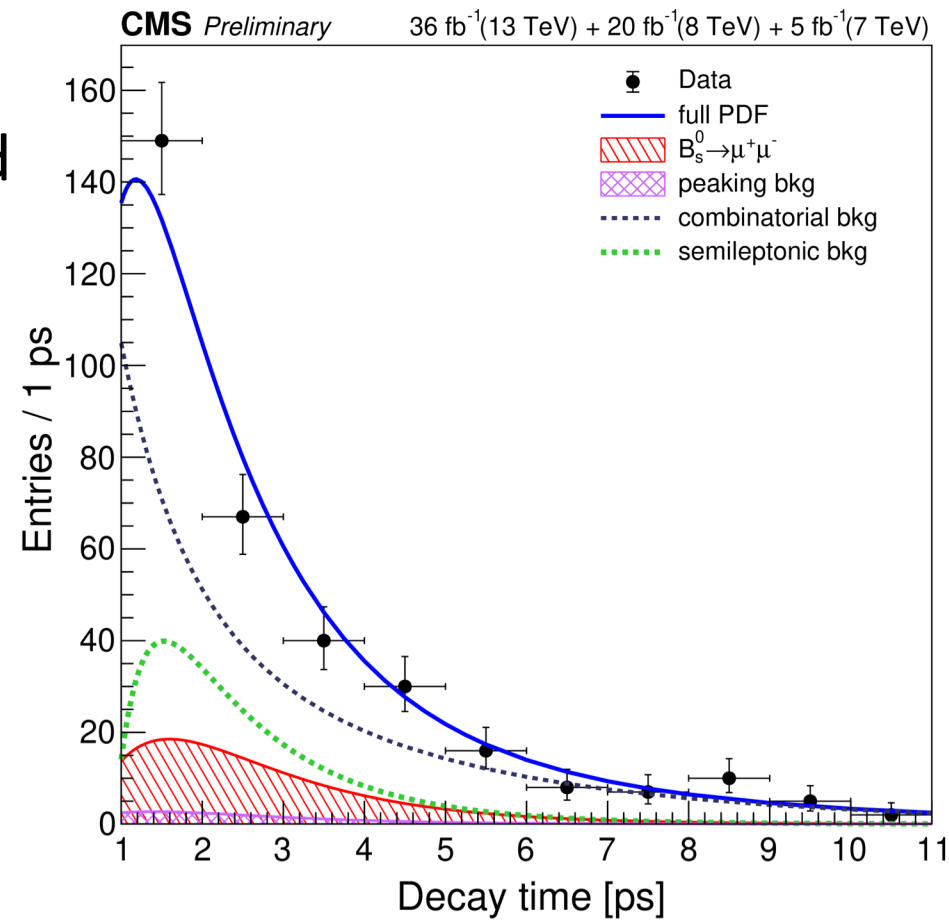




B_s^0 effective lifetime

- $B_s^0 \rightarrow \mu^+\mu^-$ effective lifetime is determined using an 2D unbinned maximum likelihood fit
  - Result consistent with SM expectations and with an earlier measurement from LHCb.

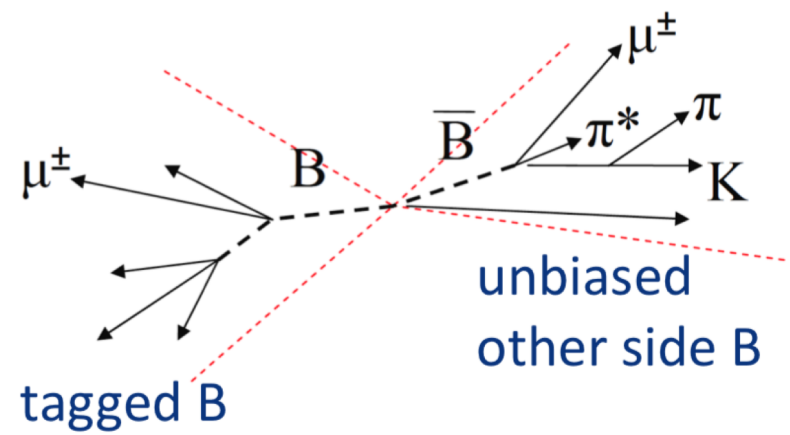
- Prospects for full Run 2 dataset:
  - Resolve B^0 and enable precision comparisons to the SM for B_s^0
  - New physics could show up in the lifetime with improved precision.



$$\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44}\ \text{ps}$$

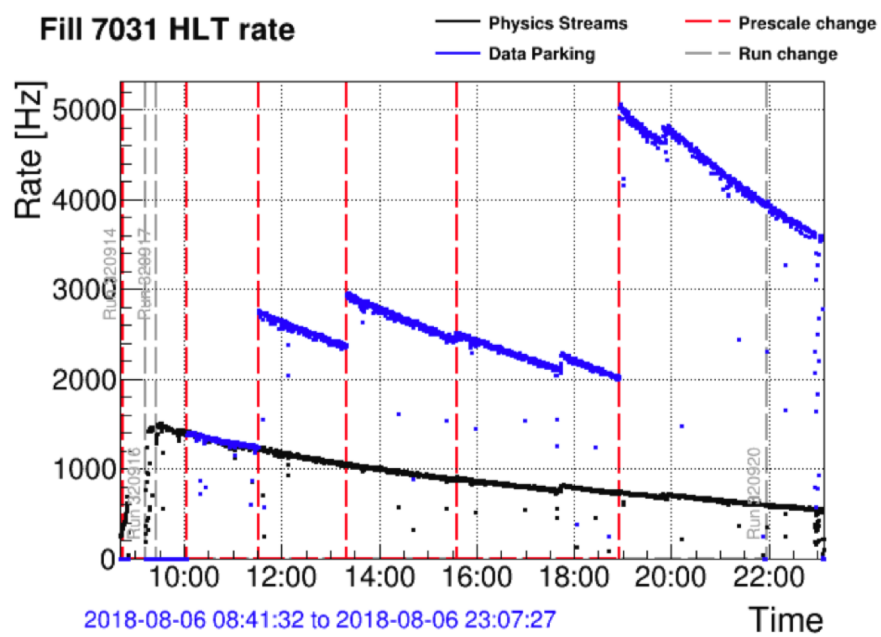
Data parking and B physics

- During Run 2, CMS stored a large unbiased B hadron sample by tagging on the "opposite-side" B
  - 12 B events recorded
  - Up to 6 kHz additional rate to tape

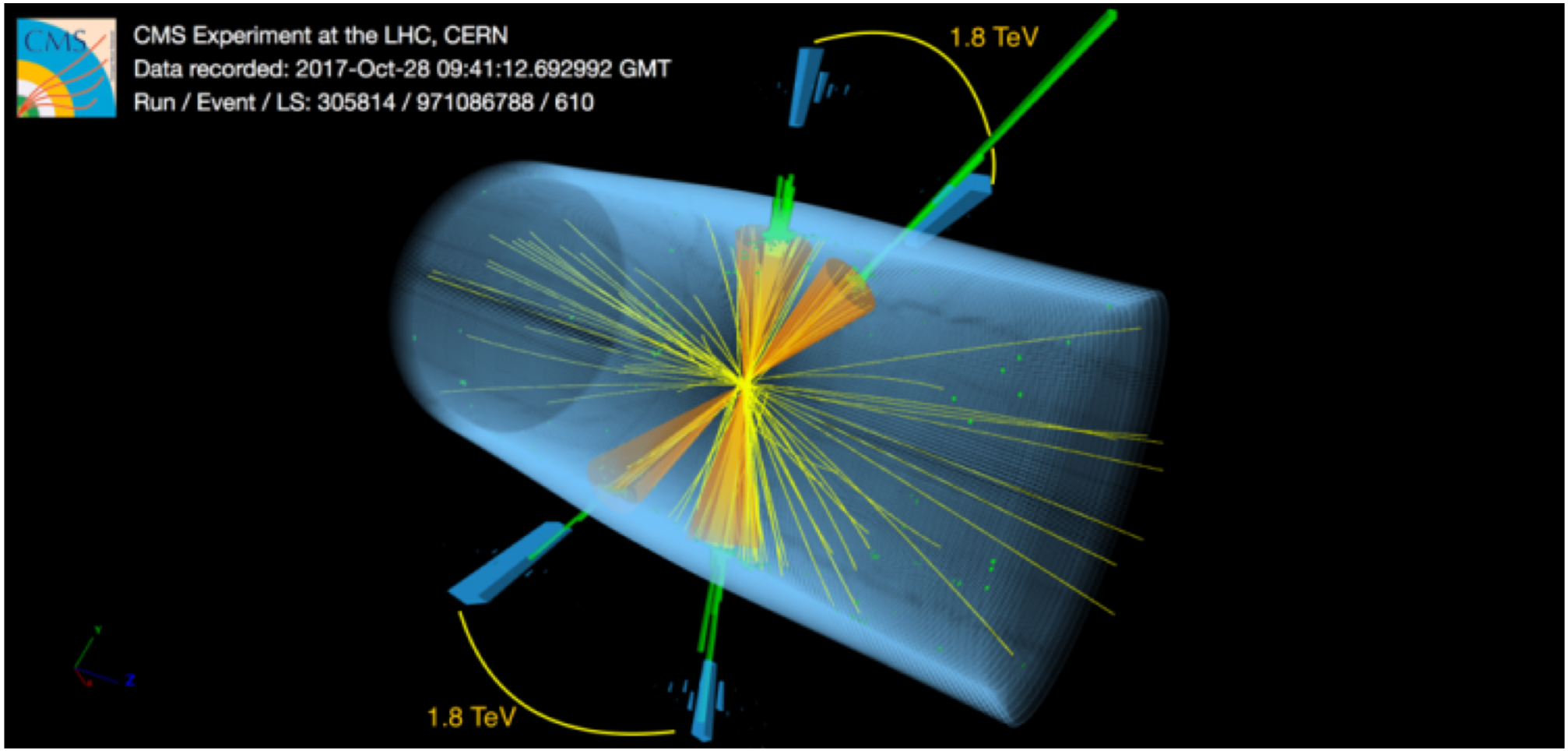


- Data was "parked" (→ no prompt reconstruction) and processing delayed to times of lower load on the computing system

- Potential resource for investigating B flavor anomalies and searches for other exotic phenomena



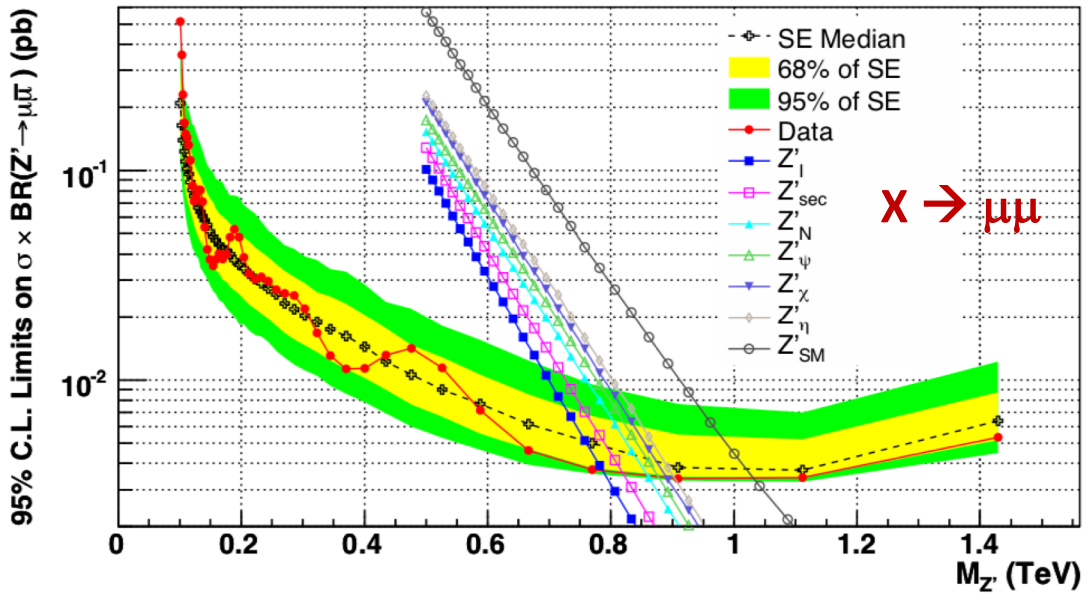
Exploring the unknown



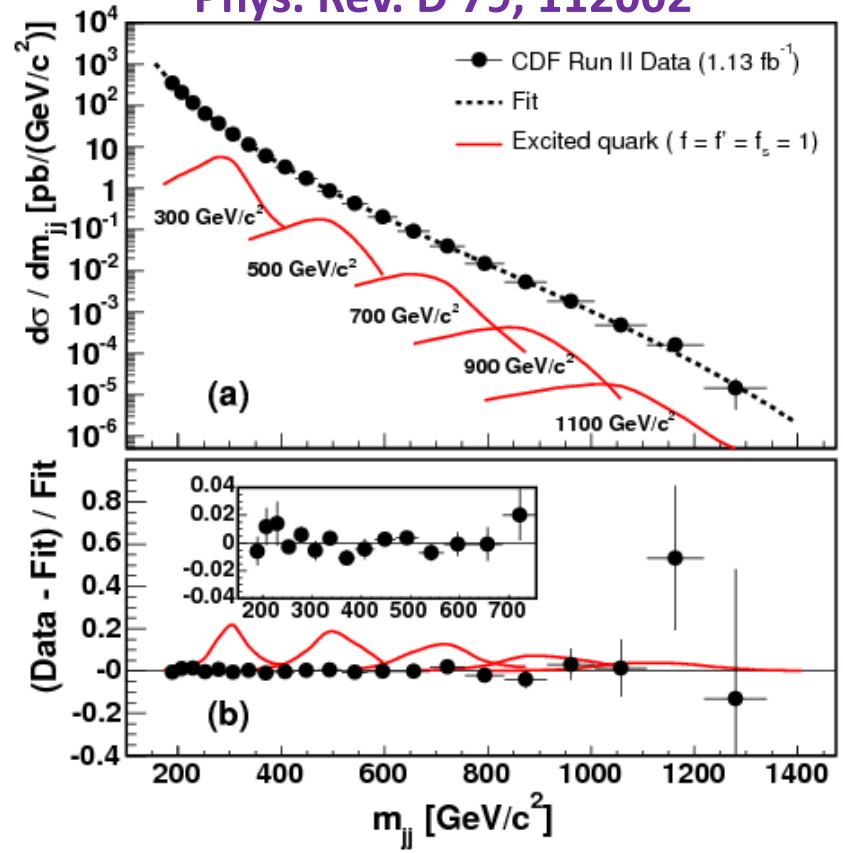
Exotic landscape ~10 years ago

PRL 102:091805,2009

CDF, L=2.3 fb^{-1}



Phys. Rev. D 79, 112002

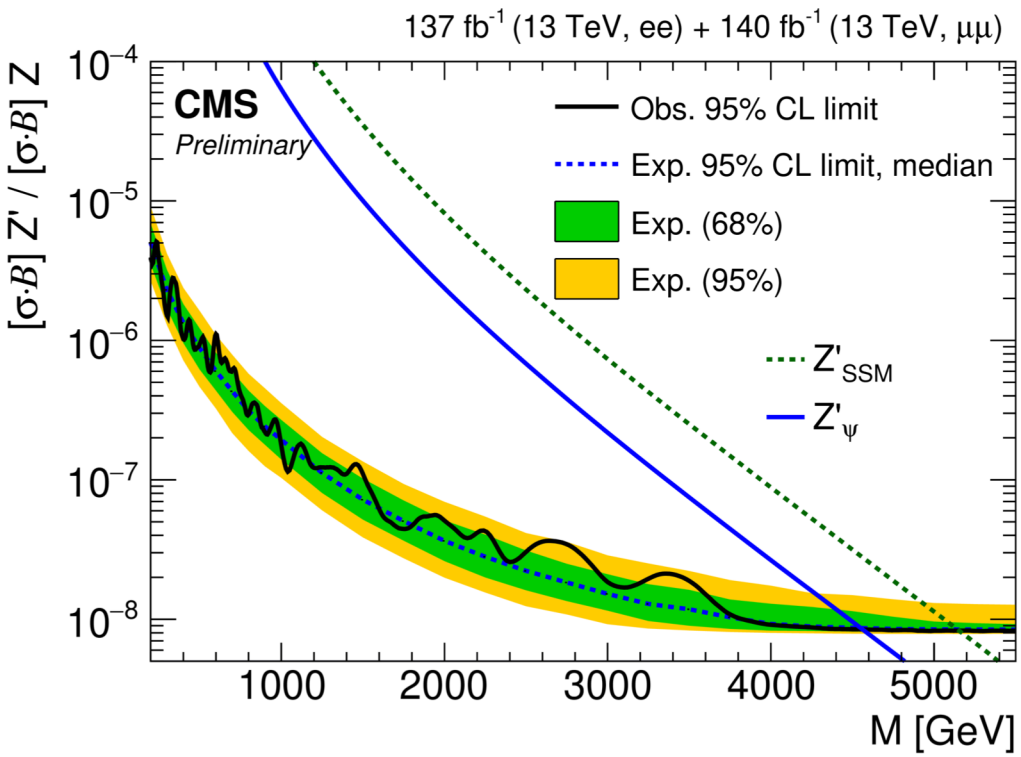


Searches for new massive resonances (di-leptons), di-jet resonances approaching ~ 1TeV

Exotic landscape circa 2019

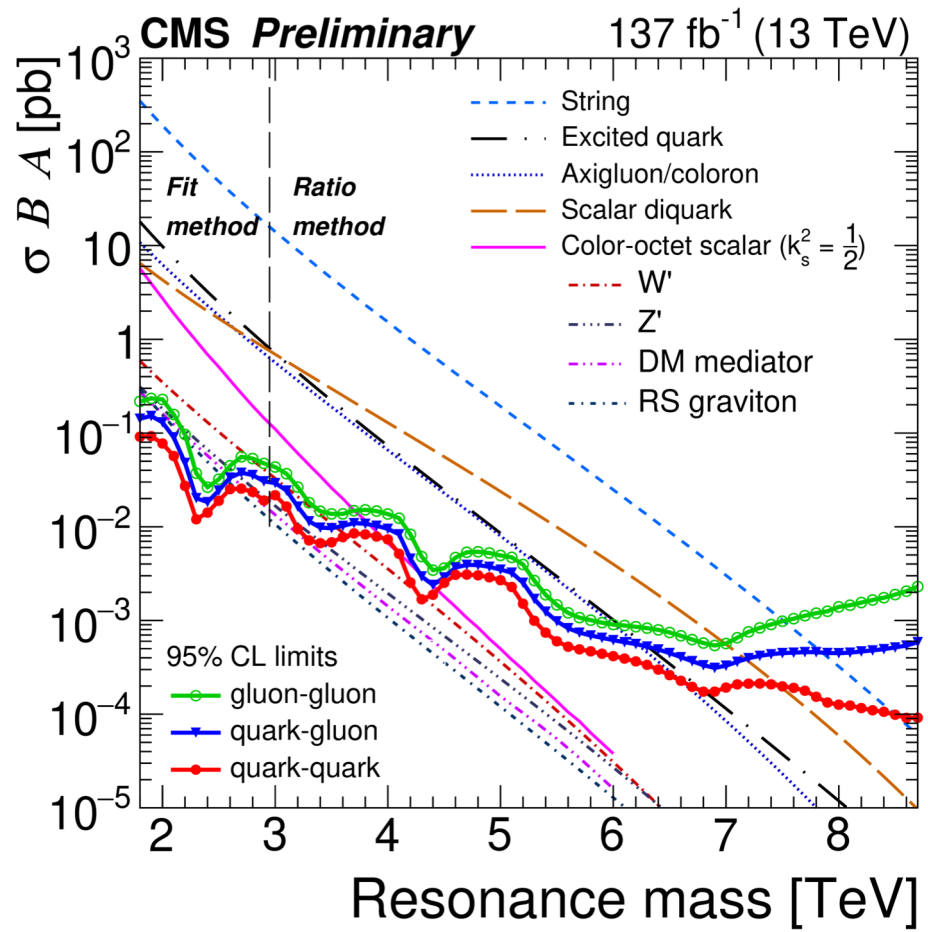
Dilepton resonance search

EXO-19-019



Dijet resonance search

EXO-19-012



Excluding particles w/ mass ~5 TeV

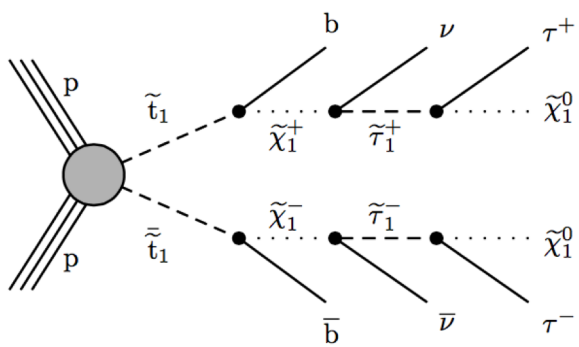
i.e. > 5 times the reach from 10 years ago

Focus now on complex topologies and weakly coupled phenomenon

Direct search strategies @ CMS

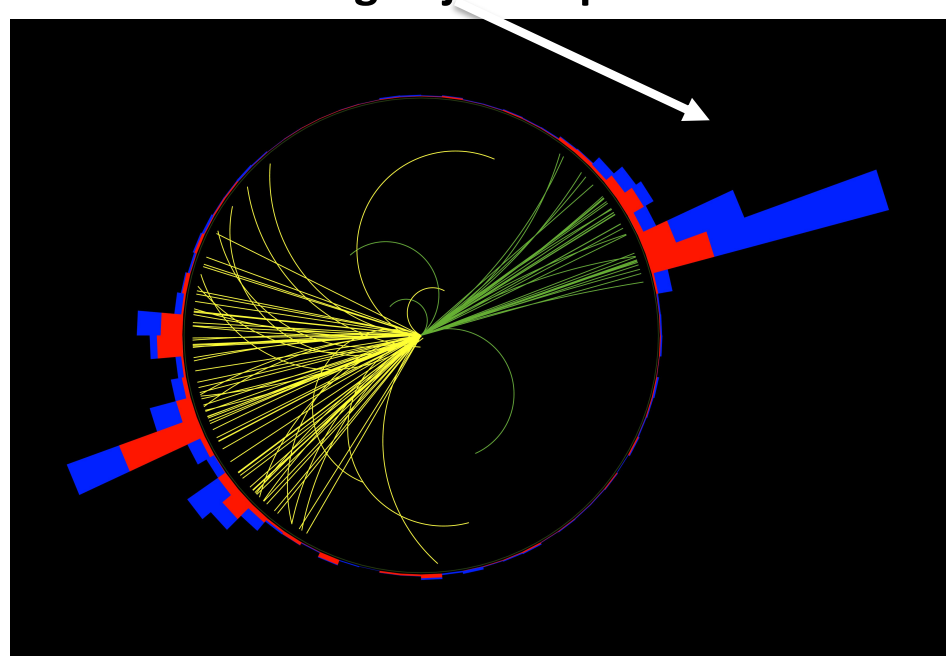
Rich and diverse search landscape

- Big inclusive searches complemented by dedicated searches that target gaps in coverage
- Incorporate machine learning for Higgs, b, charm, top tagging
- Improve lepton reconstruction/ID for compressed spectra w/ low pT leptons; improve analysis techniques, jet substructure
- Challenging topologies
- Unconventional analyses
- Longer decay chains



e.g. consider taus in stop decay chains (traditional searches veto taus or don't focus on them

Z'→ttbar candidate event w/ "merged jet" top candidate



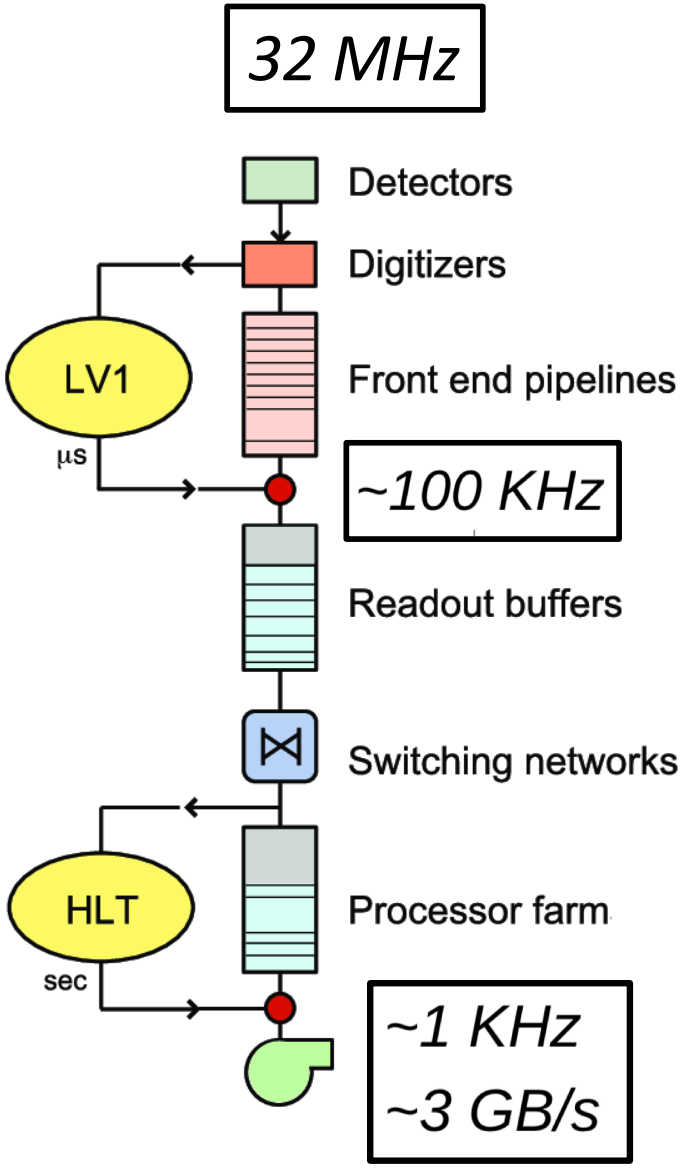
SUSY results in A. Ovcharova's seminar; Boosted searches in S. Rappachio's seminar

CMS Trigger

CMS has a 2 level trigger system for selecting interesting collision events

1. Level 1 (L1) trigger: algorithms running on custom electronics boards
   - Coarse calo & muon info, no tracking info.
   - Hard limits on latency (on-detector buffer size) and total accept rate (readout electronics design)

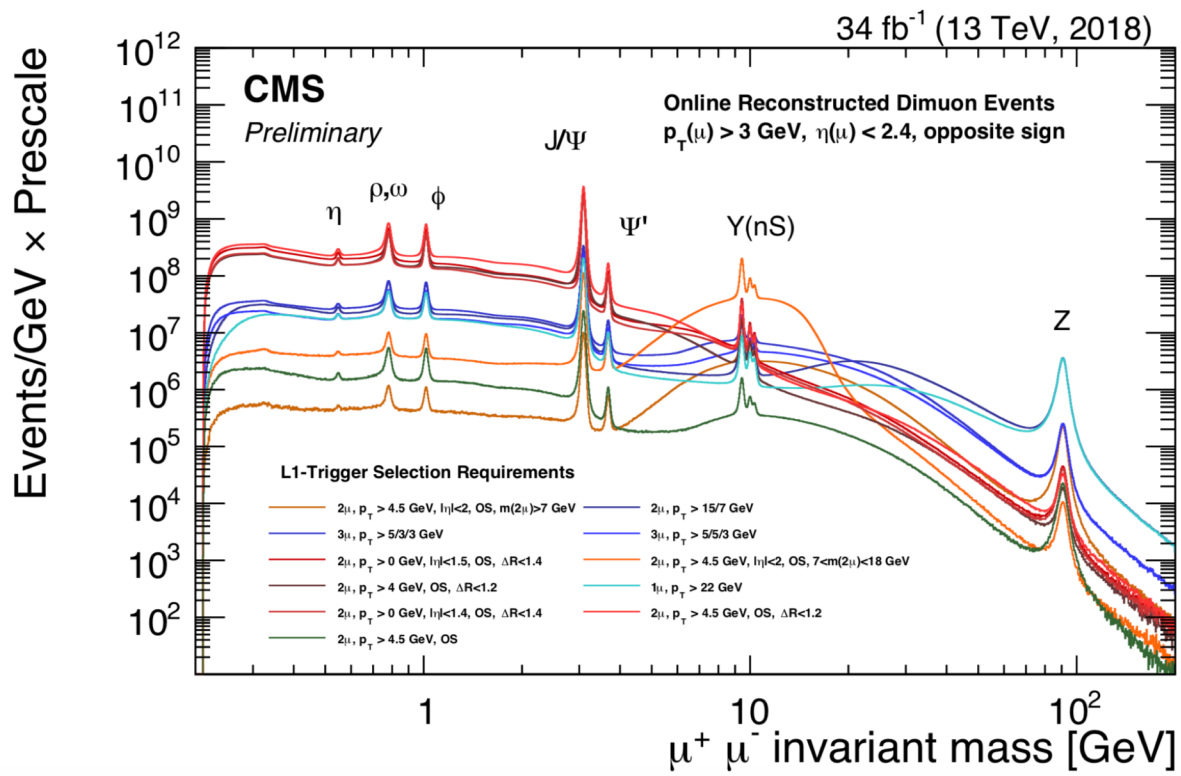
2. High Level Trigger (HLT): algorithms running on commercial CPUs
   - Hard limit on latency (CPU power) and total bandwidth (transfer data from online file system to storage)
   - *No hard limit on the total rate*



“Scouting”

Traditional trigger algorithms usually require high thresholds (e.g. on p_T and mass) to reduce the event rate, and then readout the full event info.

- The limit is the total bandwidth
  - Can reduce the event size to collect events at a higher rate (i.e. lower thresholds)
  - reduction of event size to O(10kB) allows trigger rates of several kHz
- Reconstruct at the HLT stage, keeping limited information (HLT objects)
  - needs adequate calibration @ HLT and validation against full reconstruction



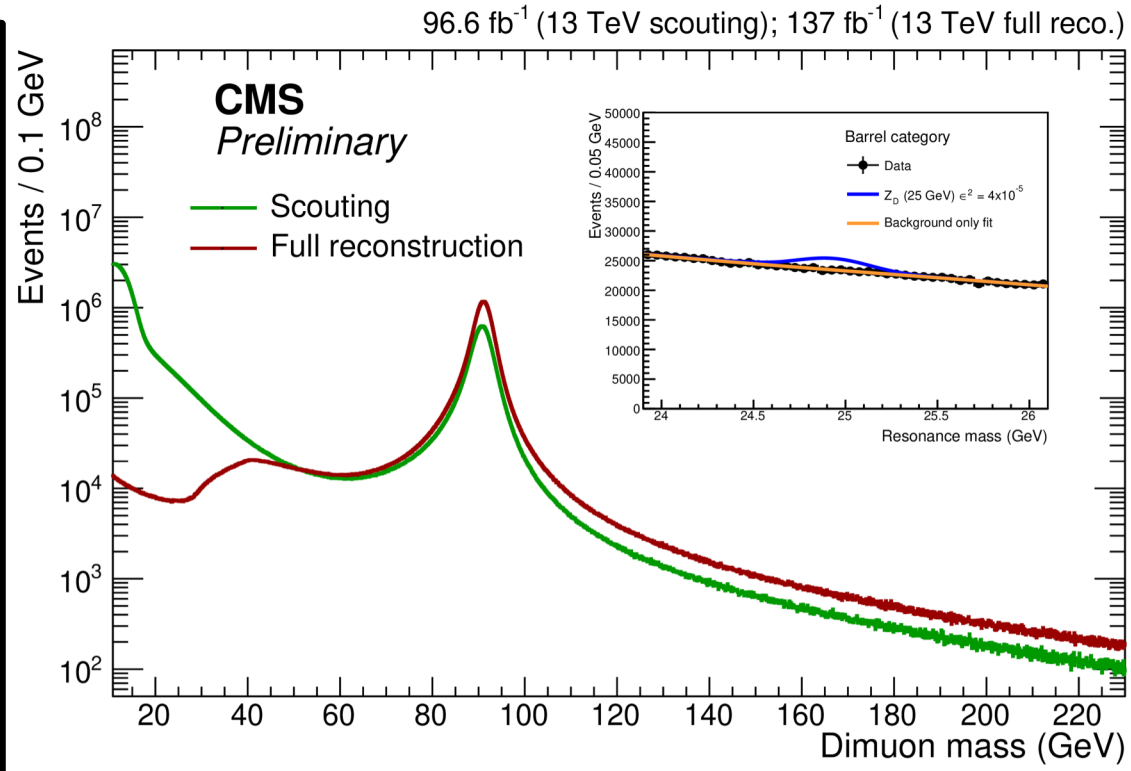
CMS-DP-2018/055

Dimuon resonances

EXO-19-018

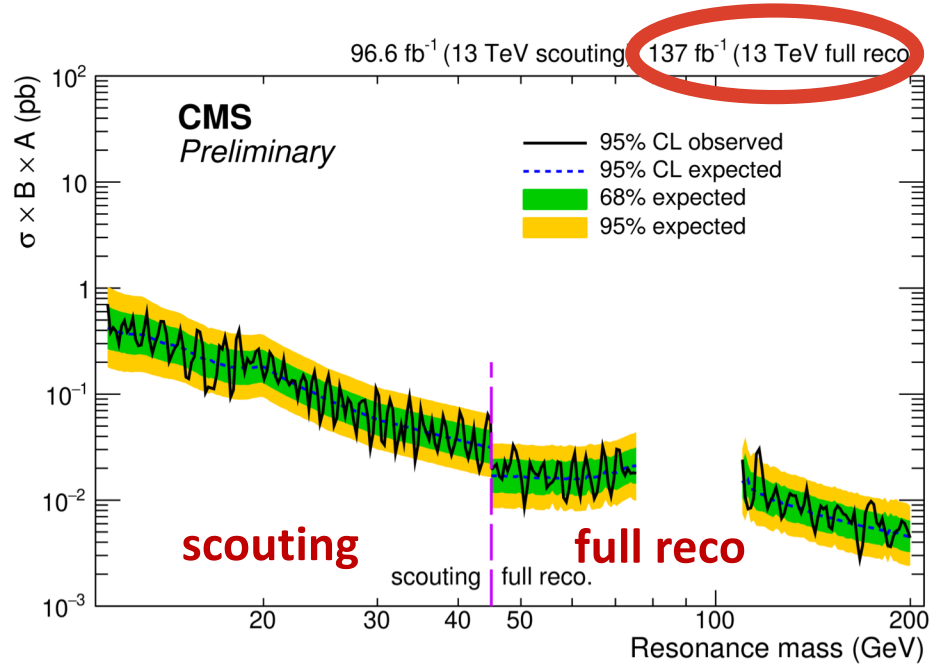
- Search for dimuon resonances in **12.5-75 GeV and 110-200 GeV mass range**
  - For mass range > 45 GeV search, "standard" muon triggers are used
    - Dimuon HLT trigger thresholds 17, 8 GeV
  - For masses < 45 GeV, use high rate dimuon data scouting triggers

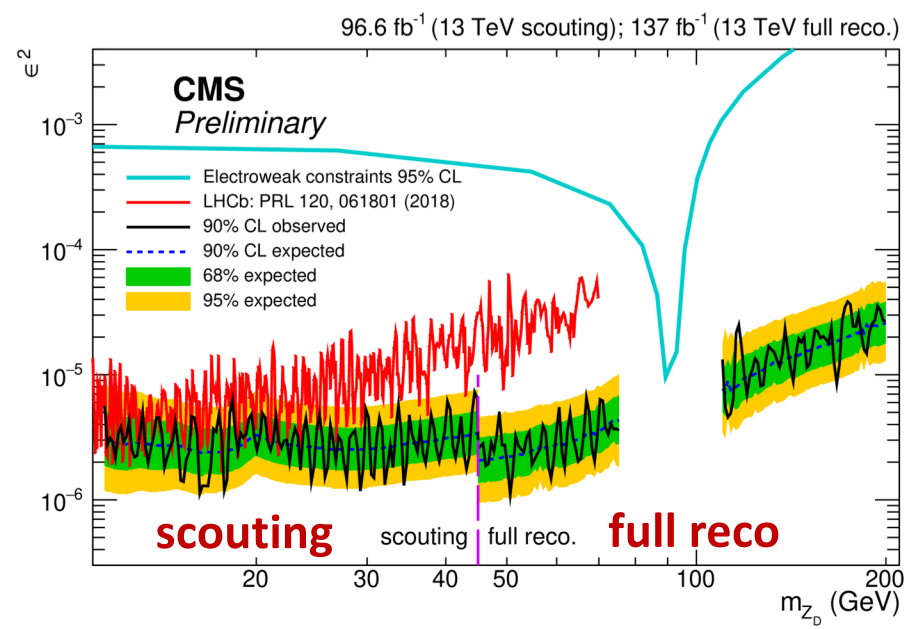
- 2 muons w/ $p_T > 4$ (4.5) GeV in 2017 (2018)
- keep info about the kinematic properties, quality of the muons reco'd at HLT, discard most everything else
- Ave. HLT rate: 5.6 (4.4) kHz in 2017 (2018)



Dimuon resonances

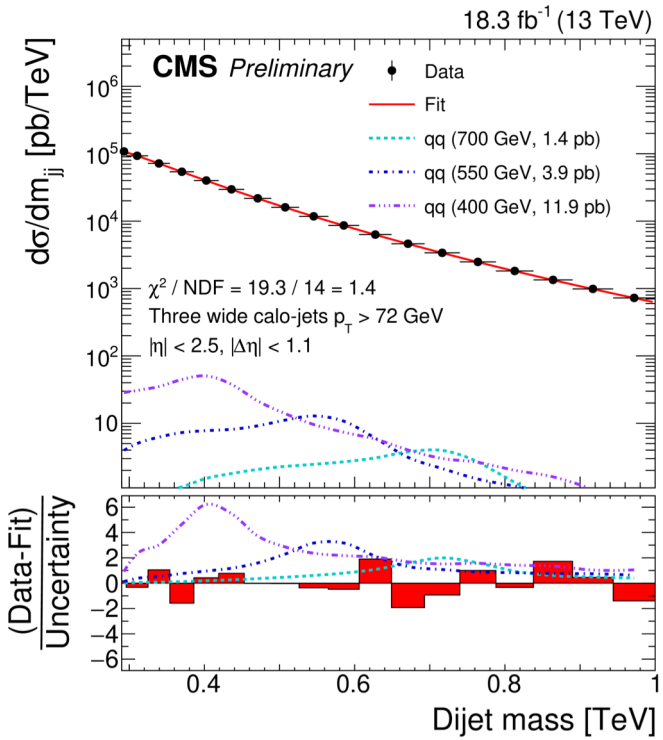
- Results can be interpreted as a **dark photon (Z_D)** that that may feebly couple SM particles to to a hidden, dark sector of particles.
- The strength of the coupling with SM fermions is determined by the kinetic mixing coefficient ϵ.
- Strongest constraints to date on the kinetic mixing coefficient of a dark photon with mass greater than 11.5 GeV.

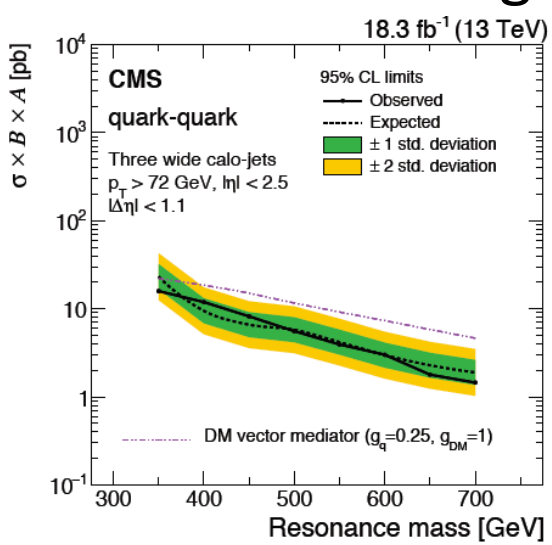




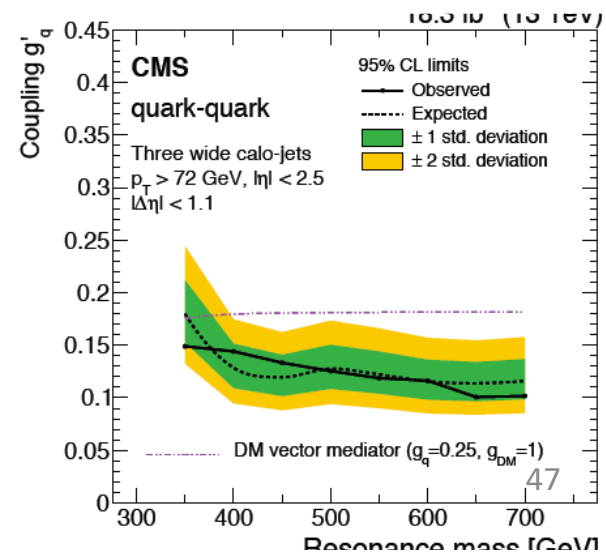
Low mass dijet resonances

- Search for vector resonances decaying into two jets in the mass range 350 – 700 GeV
  - 2016 data scouting w/ low H_T triggers
    - 240 (250) GeV at L1 (HLT)
    - Rate 4 kHz at 1E34
  - selection: Require 3 wide jets p_T > 72 GeV
- Set 95% CL upper limits on the coupling to quarks $g_{q'}$ in the range 0.10 – 0.15 for a vector resonance interacting only w/ quarks



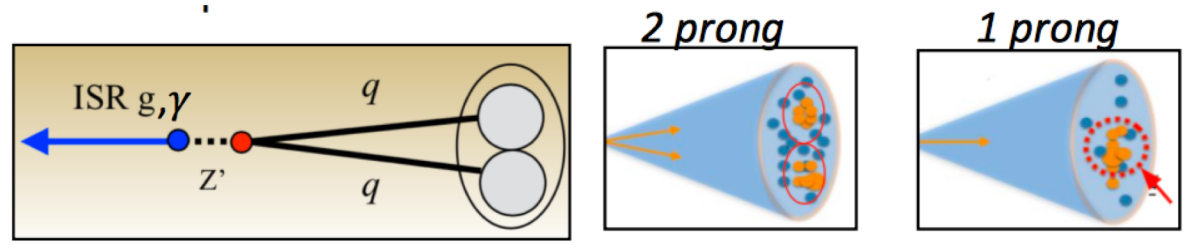


EXO-19-004



Dijet Resonance Searches

Other novel trigger strategies for probing lower masses;

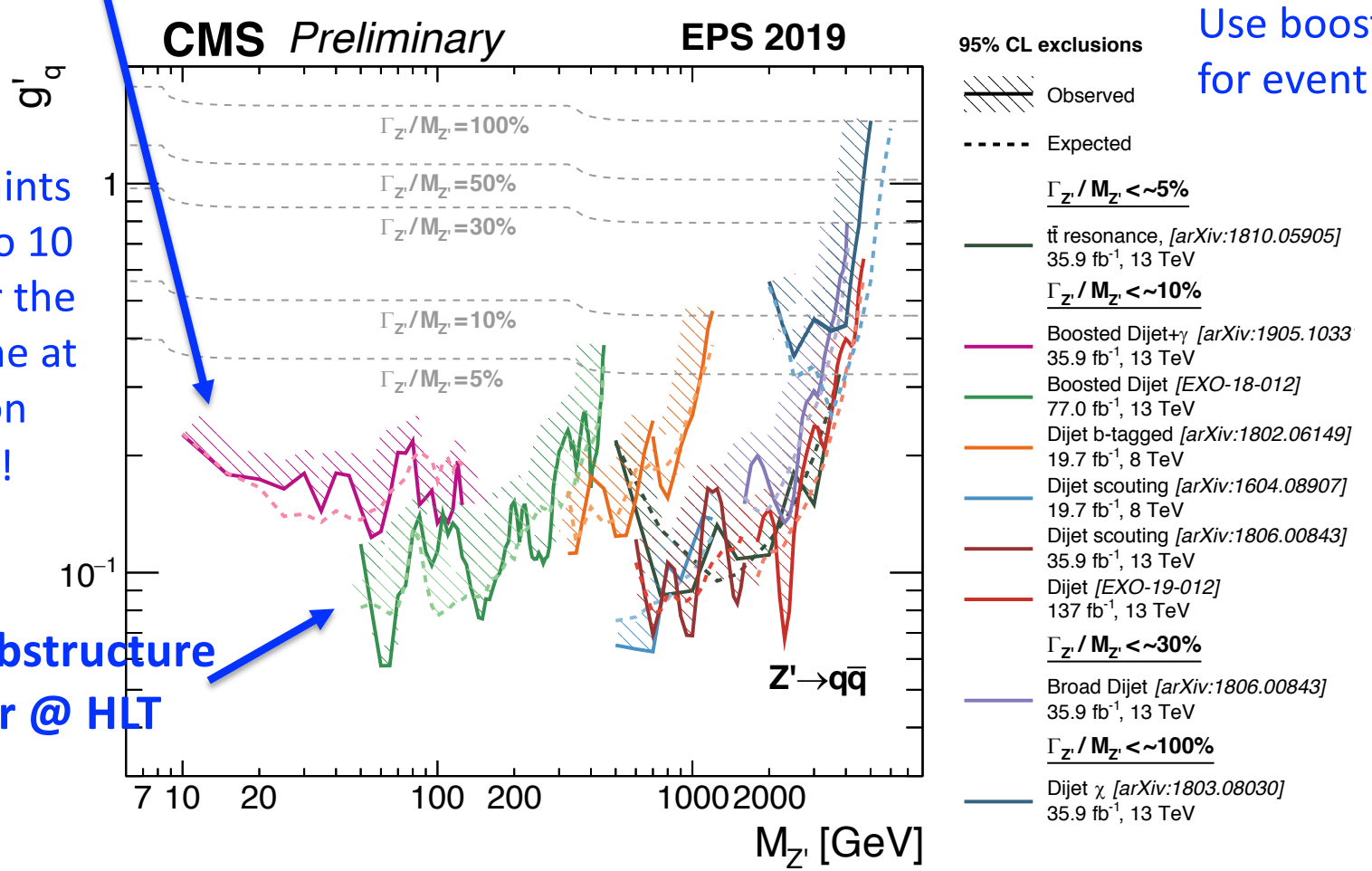


Use boosted techniques for event reco.

ISR photon tag @ HLT

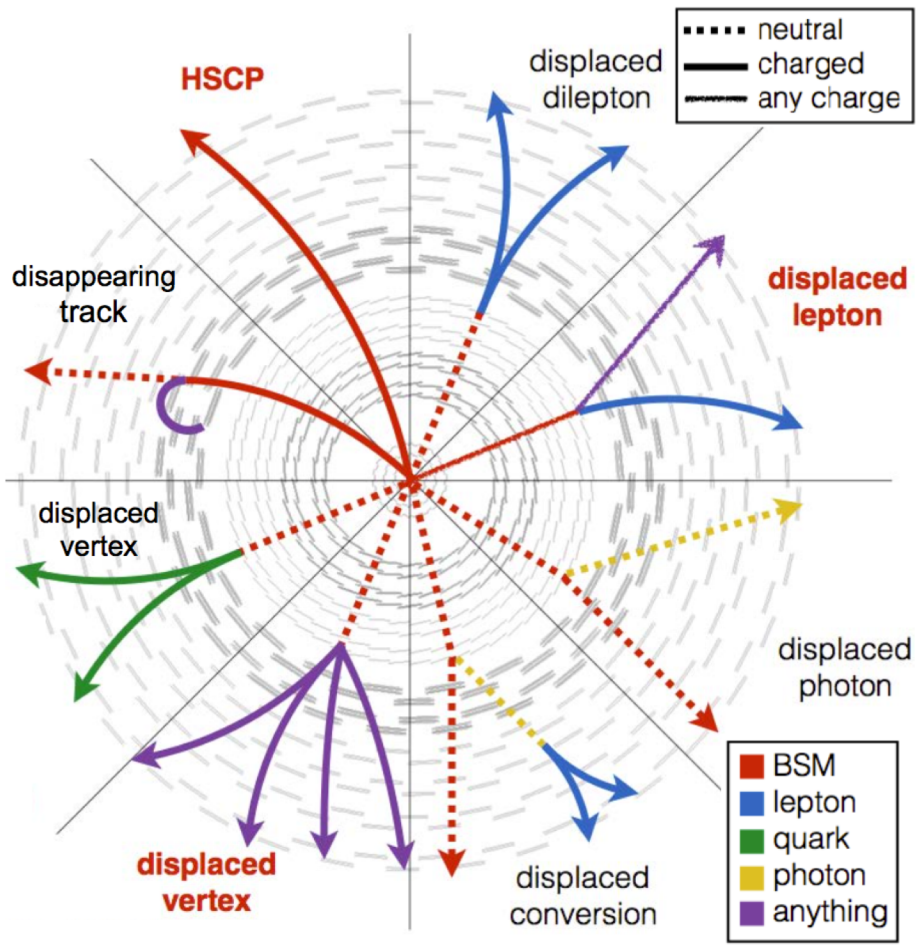
Constraints down to 10 GeV for the first time at a hadron collider!

Jet substructure trigger @ HLT



Long-lived particle searches

Long-lived and other exotic particles with striking signatures predicted by many BSM models



Credits: J. Antonelli

Searches need to often overcome challenges in trigger, reconstruction, & background estimation

Excellent detector understanding is absolutely critical

Taking advantage of several topologies currently

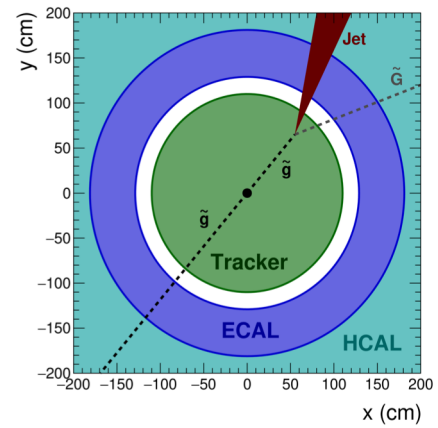
HL-LHC upgrades will provide improved sensitivity

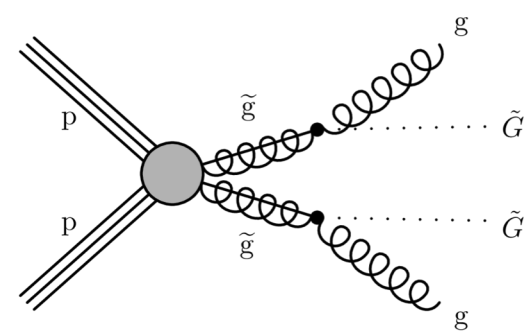
EXO-19-001

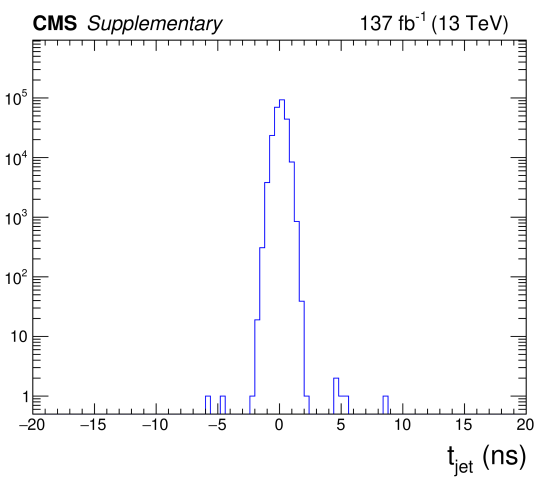
Search for delayed jets

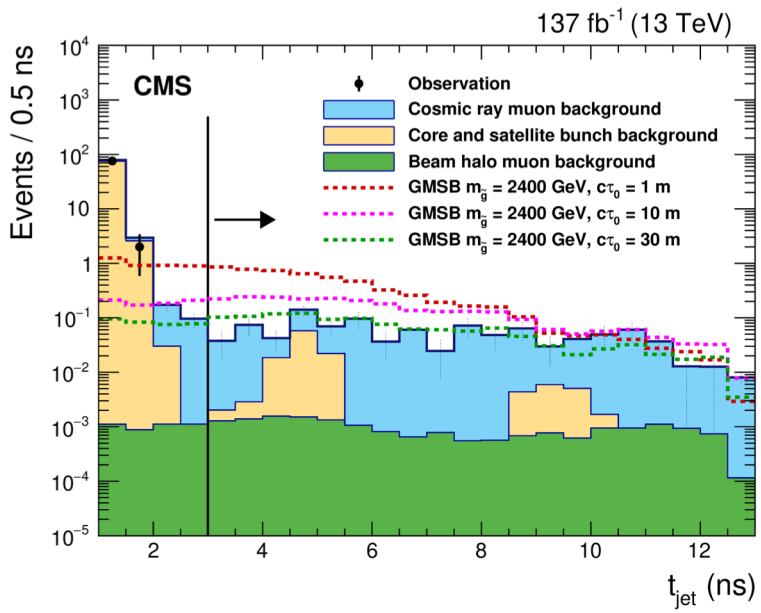
Long-lived gluinos give rise to jets from displaced vertex

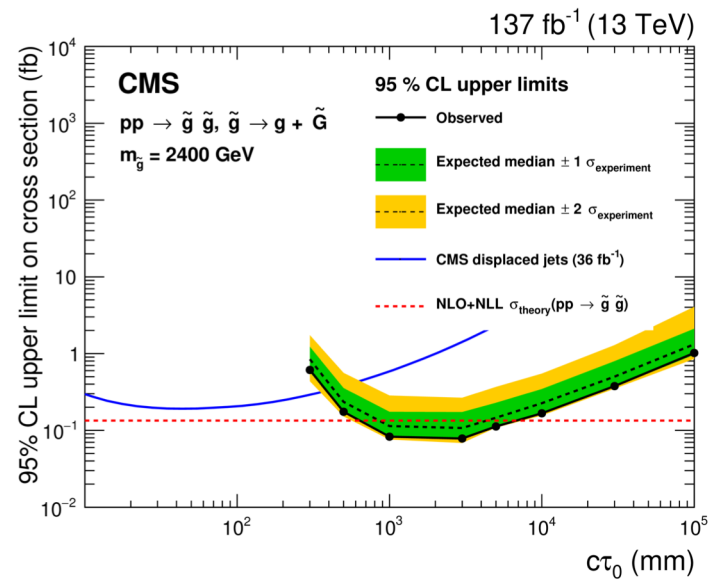
- Interpreted in a model of gauge mediated SUSY breaking
- uses timing info from ECAL









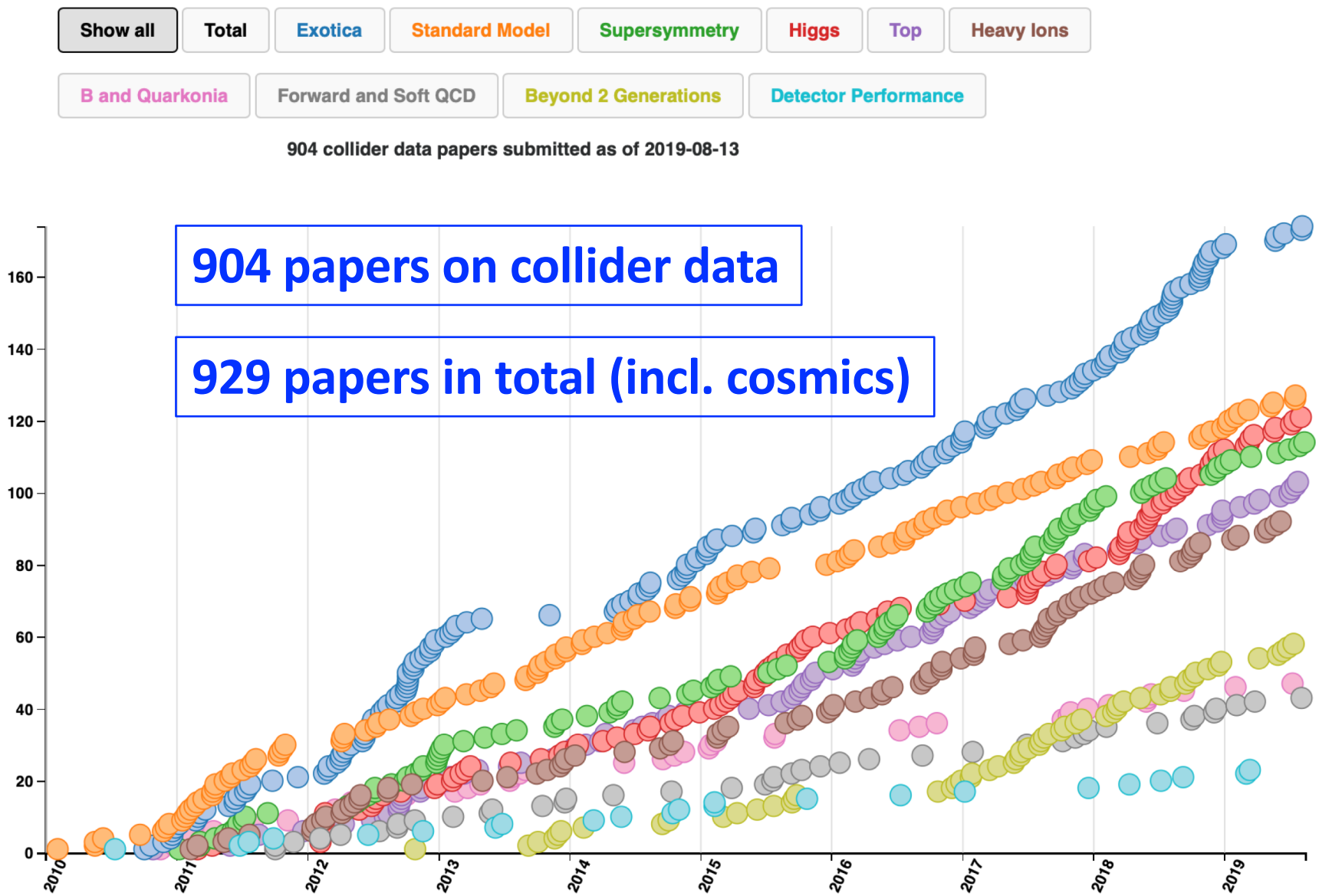


median time of ECAL cells in jet cone: background jets

main backgrounds from cosmics & satellite bunches

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

Publications



http://cms-results.web.cern.ch/cms-results/public-results/publications/

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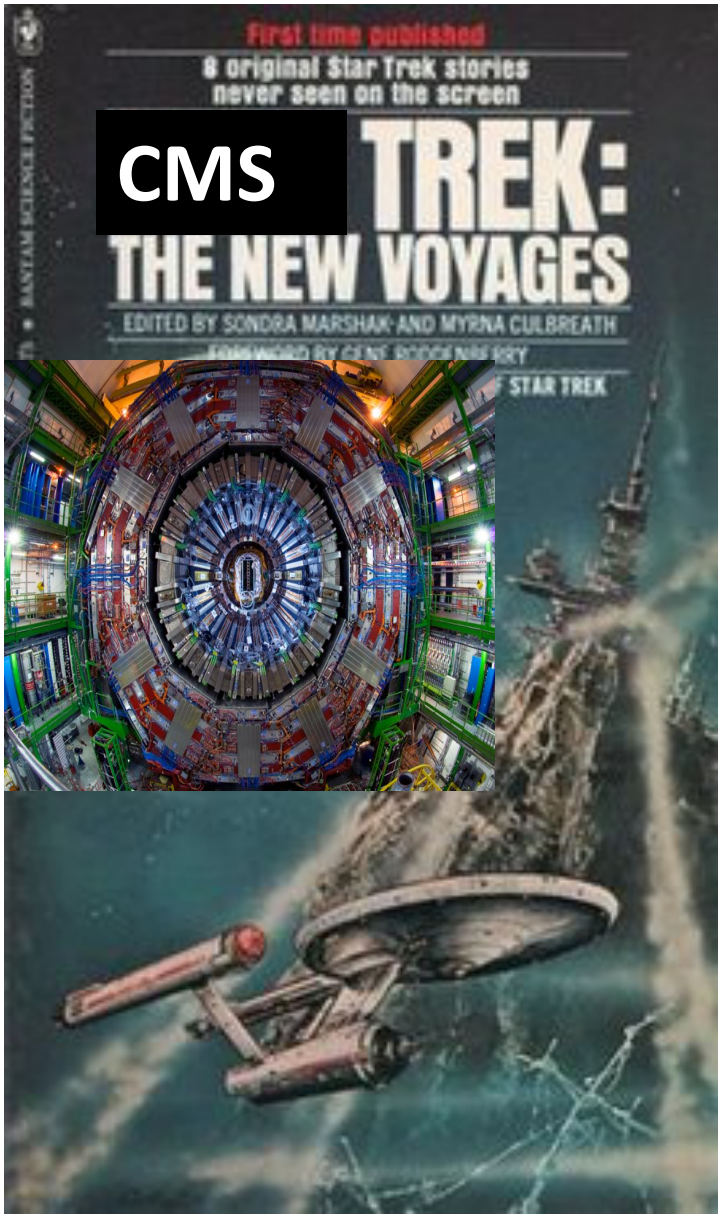
Summary & Outlook

- The ~10 years of LHC operation has been one amazing ride!
  - Discovery of the Higgs boson
  - Using the Higgs as a tool for discovery
    - Characterization of its properties via precision measurements
    - Measurements of rare/exotic Higgs decays
    - Higgs tagging in searches
  - Huge amounts of BSM parameter space ruled out
  - At the same time, innovative strategies for triggering, data-taking and analysis are providing access to previously unexplored territory!
- An exciting time to develop and implement new ideas
  - Go in directions where no one has gone before!
- 95% of the total LHC data still to come (and be studied)!

Outlook

LHC: the energy frontier.

These are the voyages of the CMS *Enterprise*.

Its twenty five-year mission: to explore strange new dimensions, to seek out new particles and new forces, to boldly go where no (wo)man has gone before.