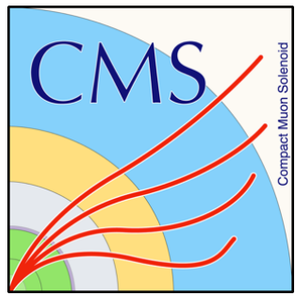
Highlights from CMS and LHCb

Shahram Rahatlou

On behalf of the CMS and LHCb collaborations



SAPIENZA
UNIVERSITÀ DI ROMA

LHC AFTER HIGGS DISCOVERY

- Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} D\psi$$

Precision Electroweak and QCD

$$+|D_\mu \phi|^2 - V(H)$$

Higgs properties
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \text{h.}c.$$

Higgs coupling to bosons and fermions
CKM matrix and CP Violation

- While keeping a wide open eye on new phenomena

$$+\mathcal{L}_{New}$$

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

OUTLINE

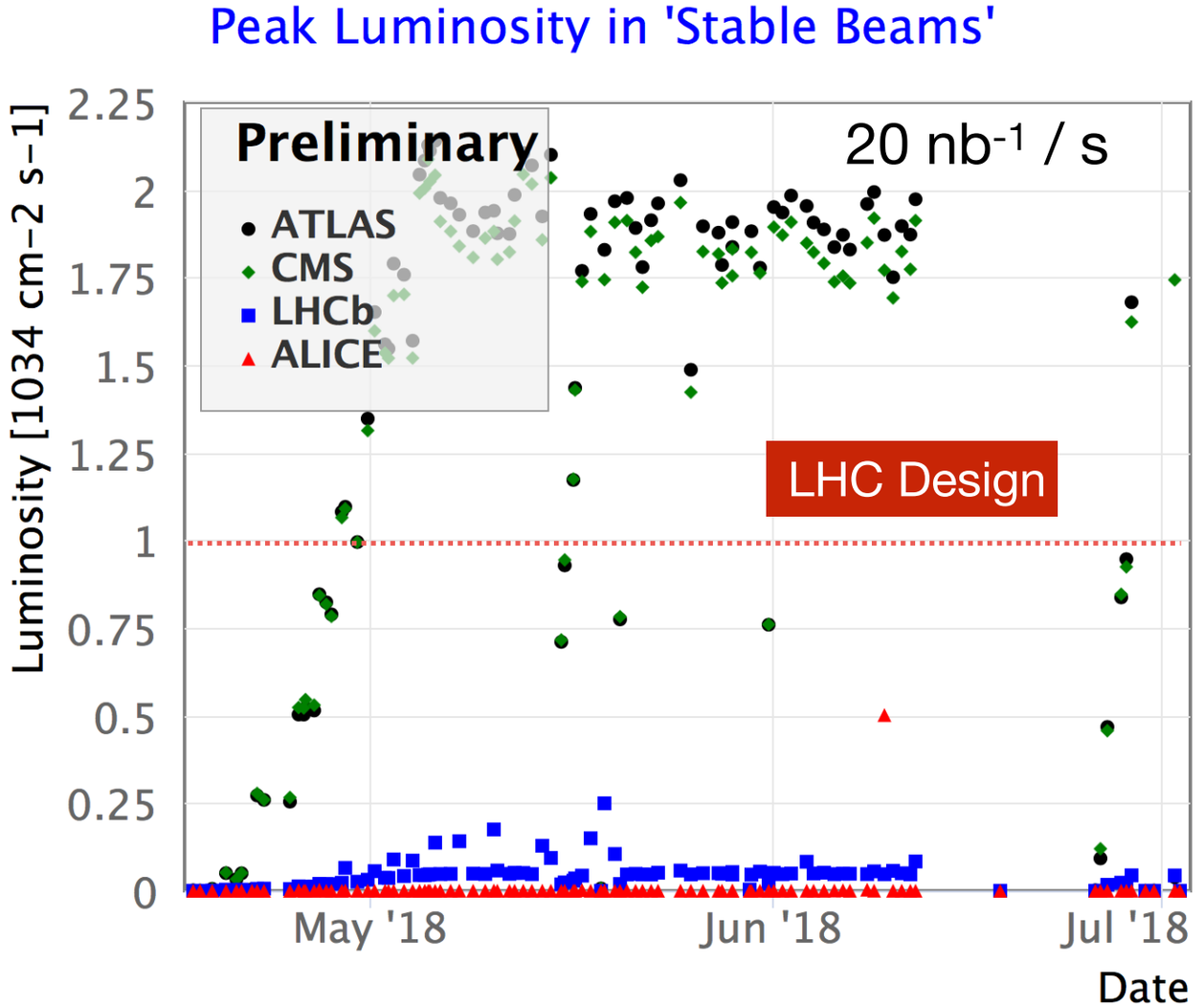
- CMS and LHCb have produced more than 100 results in a year
  - A lot more known about Higgs than just 2 years ago
  - Extensive and precise probe of CKM paradigm
  - Rich and diverse results at low energy in charm and beauty physics
  - Extensive search program at high mass for new phenomena
  - Differential measurements with top quark, Higgs, W and Z bosons
  - Probe of QCD in proton-proton and heavy ion collisions

See tomorrow's talks covering these results

New Results: http://cms.cern/news/ICHEP-2018

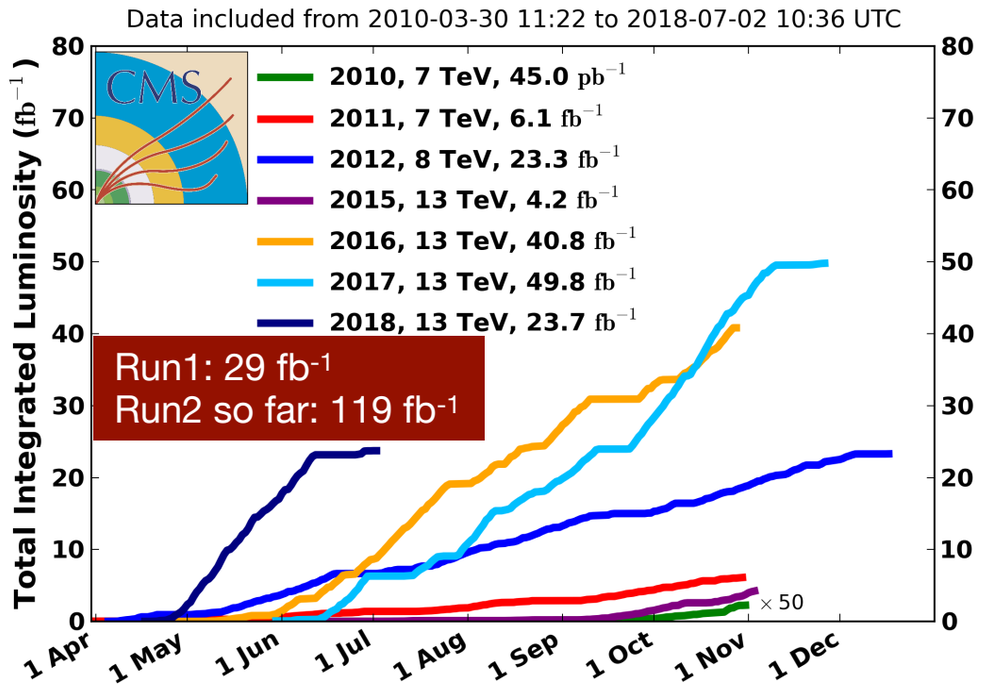
- A taste of CMS and LHCb programs and prospects for data to be collected starting in 2021 (Run3)

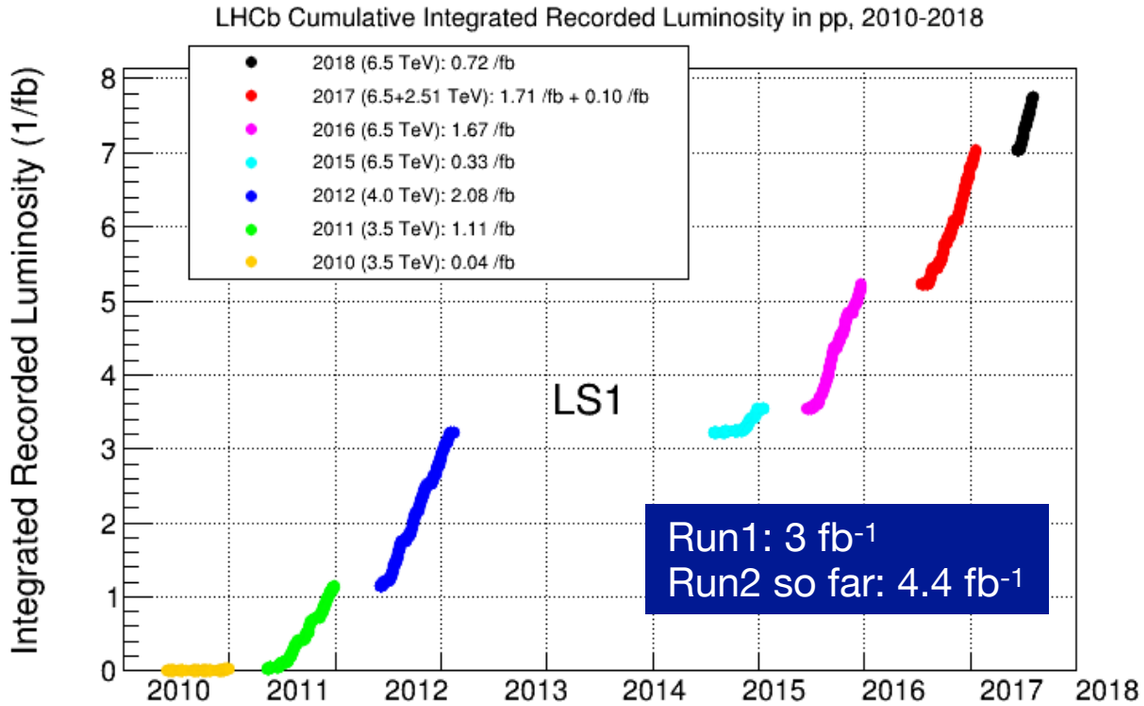
- *Special thanks to operations and accelerator teams of the LHC for sustained stellar performance*



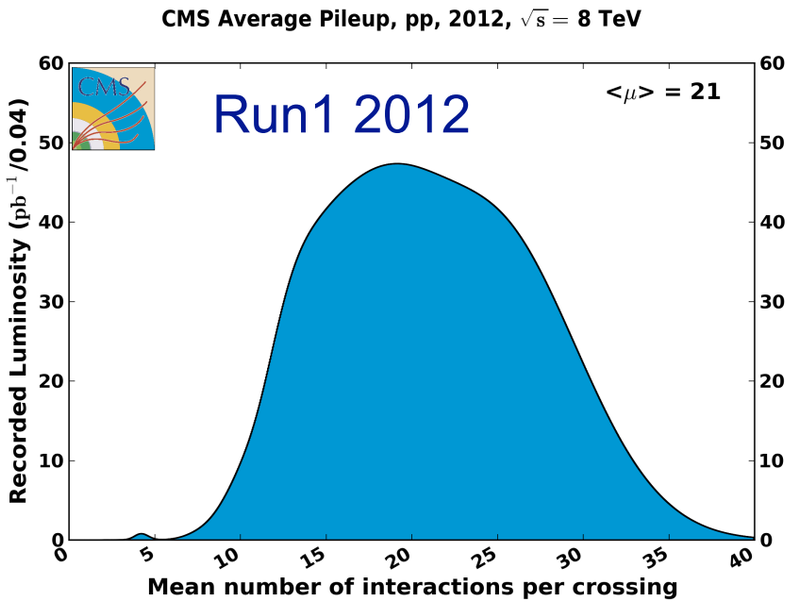
LHC PERFORMANCE

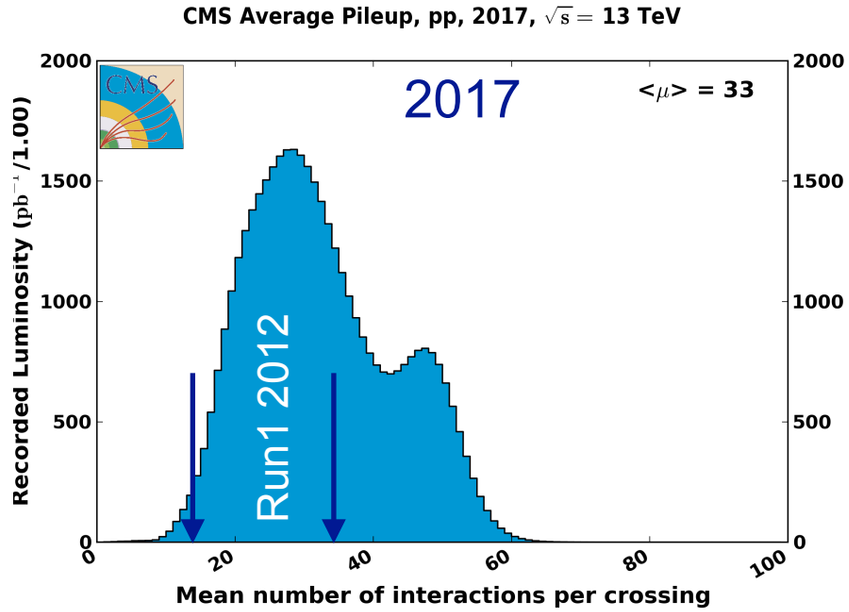
- LHC to provide 150 fb^{-1} to CMS and more than 5 fb^{-1} to LHCb in Run2



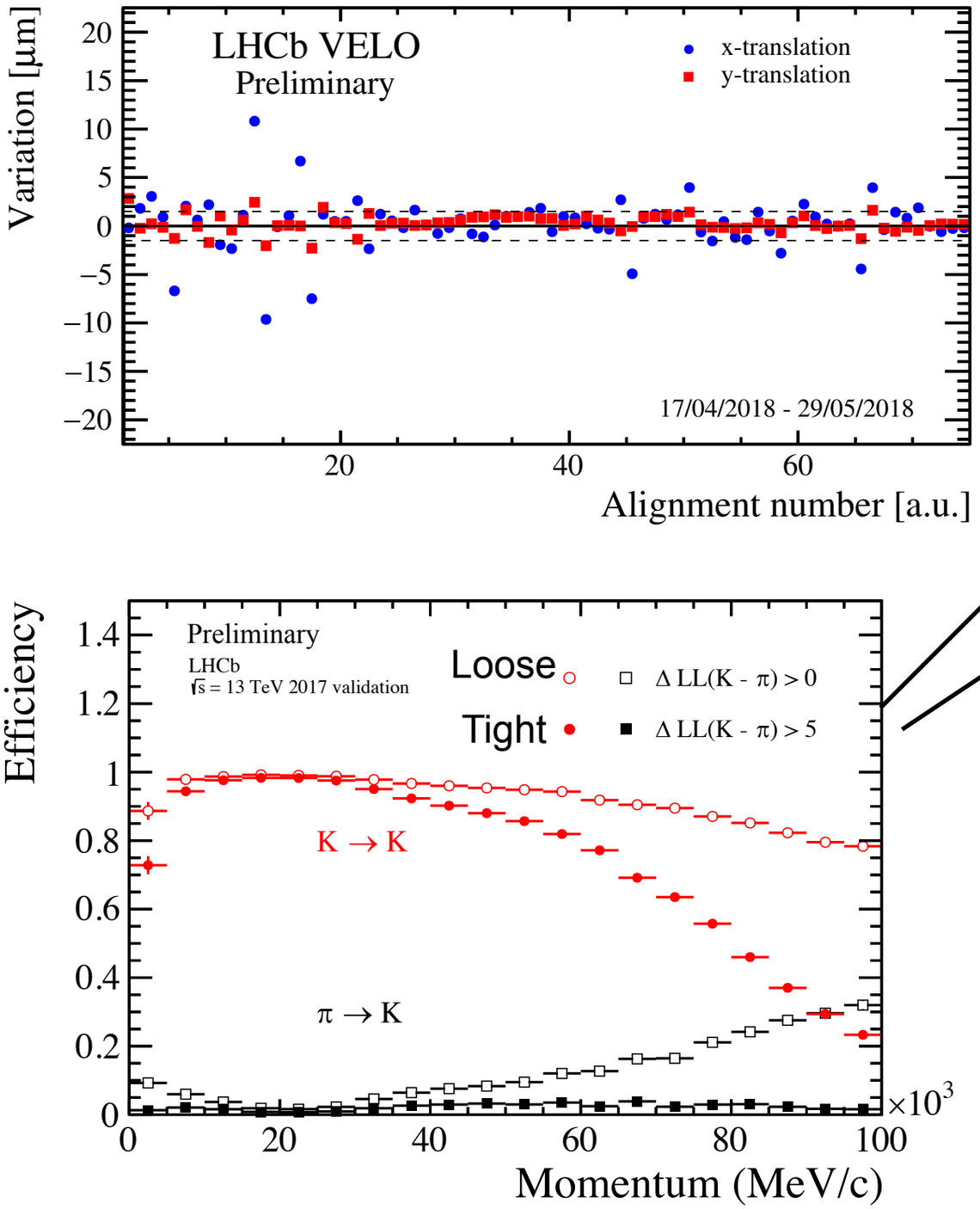


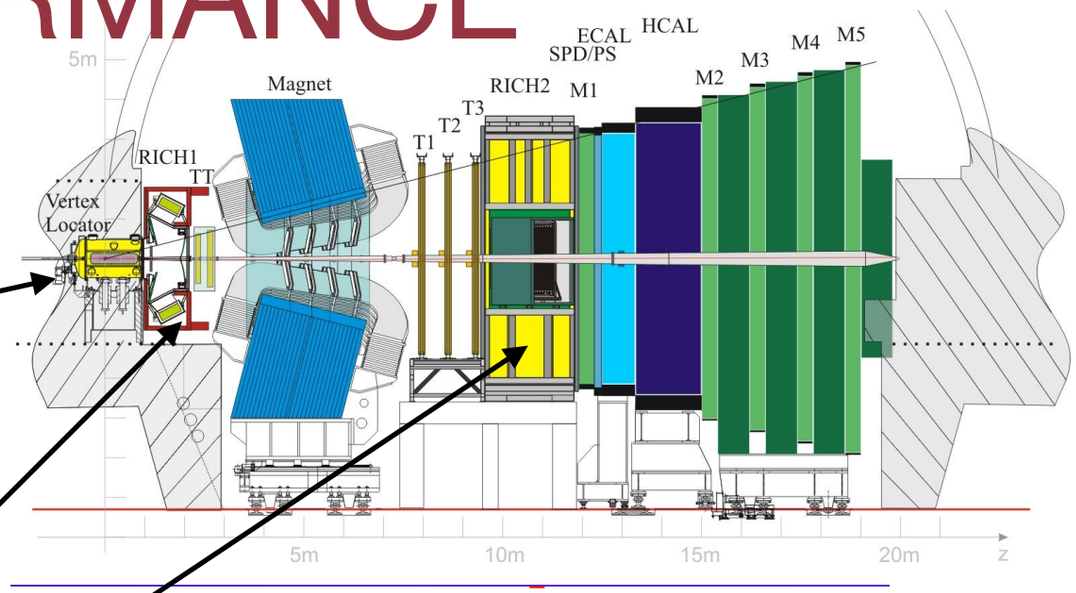
- More data and challenges for operation and physics analysis
  - increased number of simultaneous interactions
- Improved analysis techniques and operations key for successful program

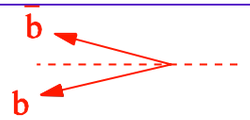


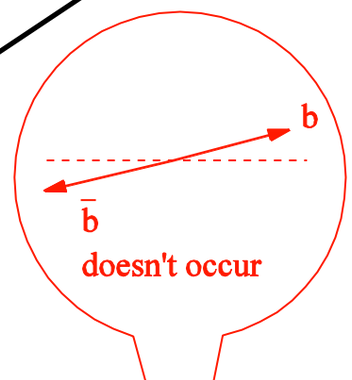


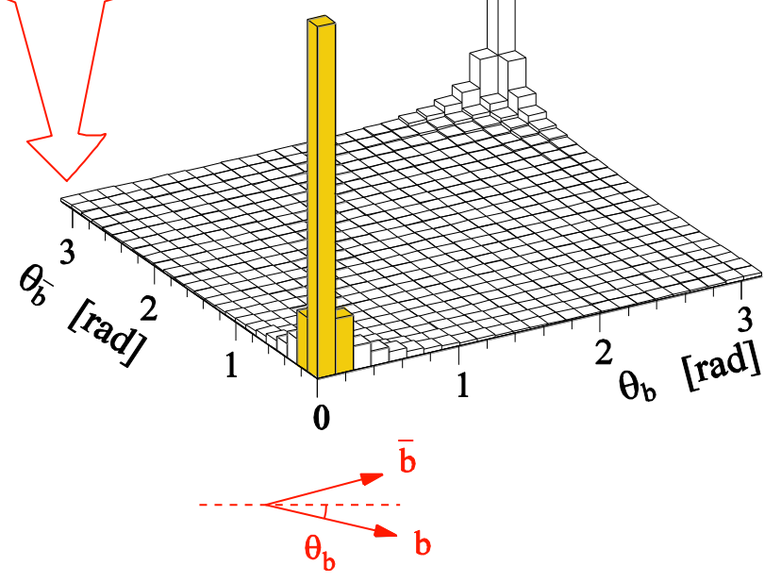
LHCb PERFORMANCE









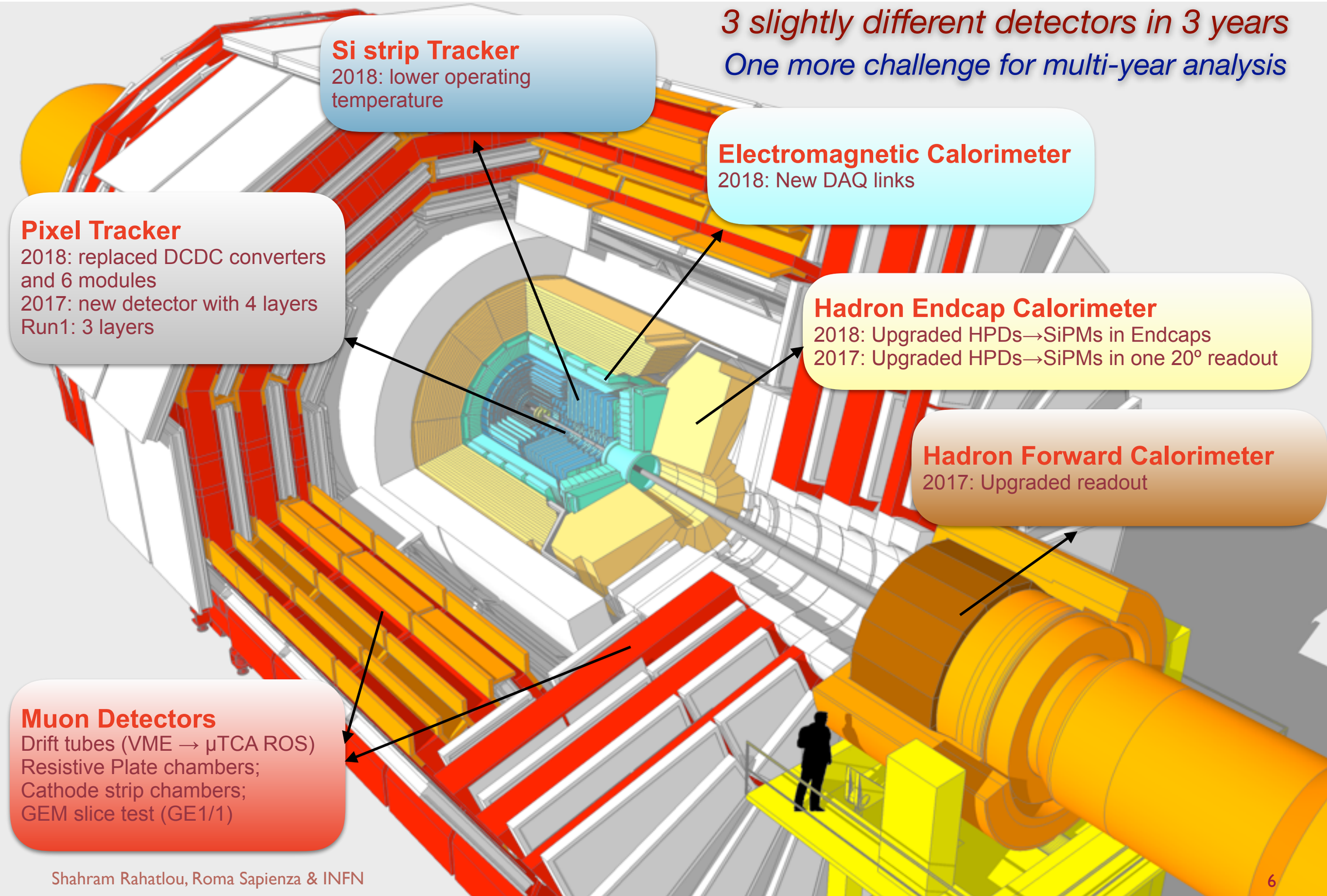


- Excellent tracking and superb particle identification key for flavor physics
  - Relative production ratio: $B_d/B_u/B_s/B_c$/b-baryons 4:4:1:0.01:1

CMS EVOLUTION

3 slightly different detectors in 3 years

One more challenge for multi-year analysis



Si strip Tracker
2018: lower operating temperature

Electromagnetic Calorimeter
2018: New DAQ links

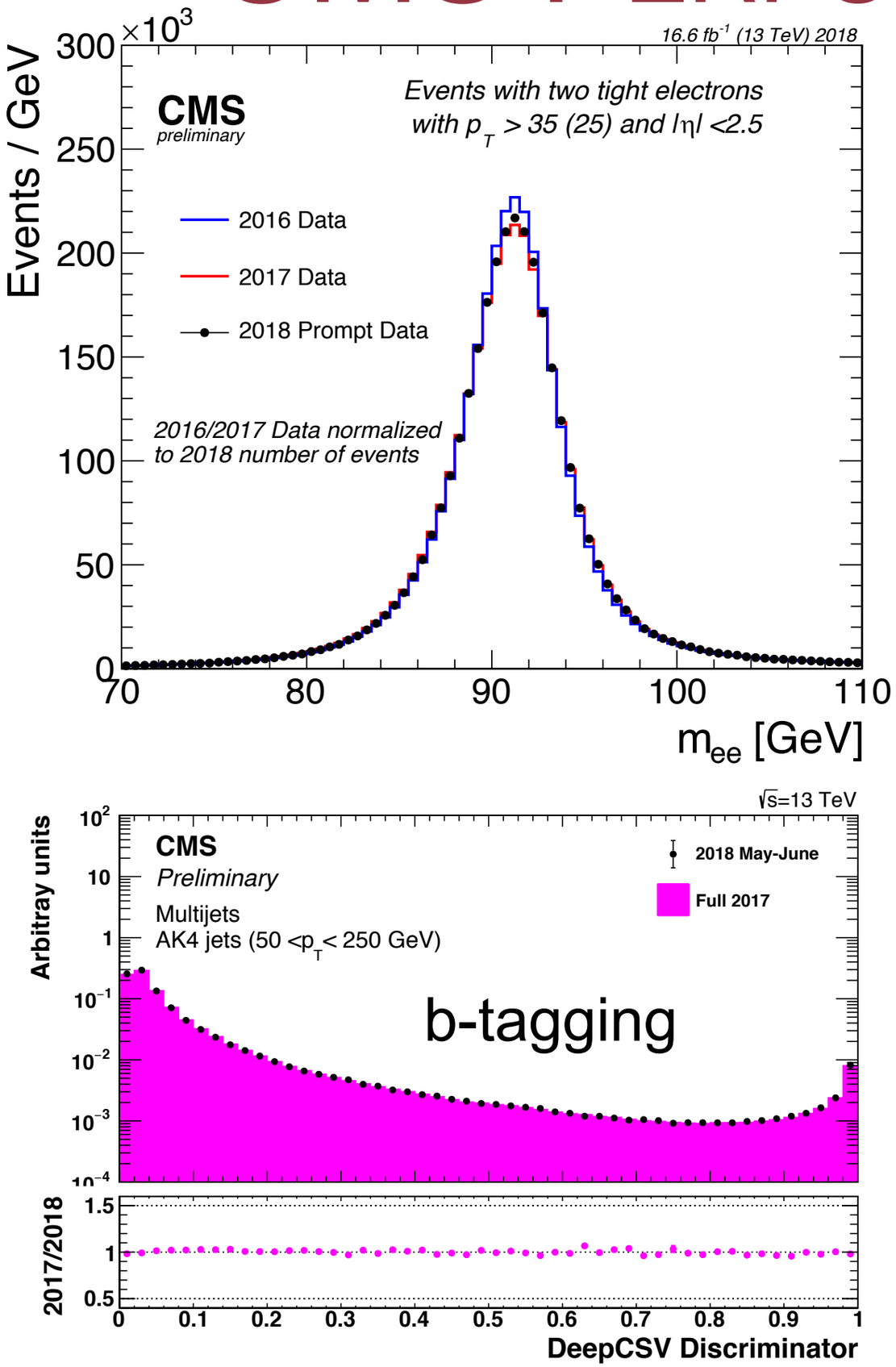
Pixel Tracker
2018: replaced DCDC converters and 6 modules
2017: new detector with 4 layers
Run1: 3 layers

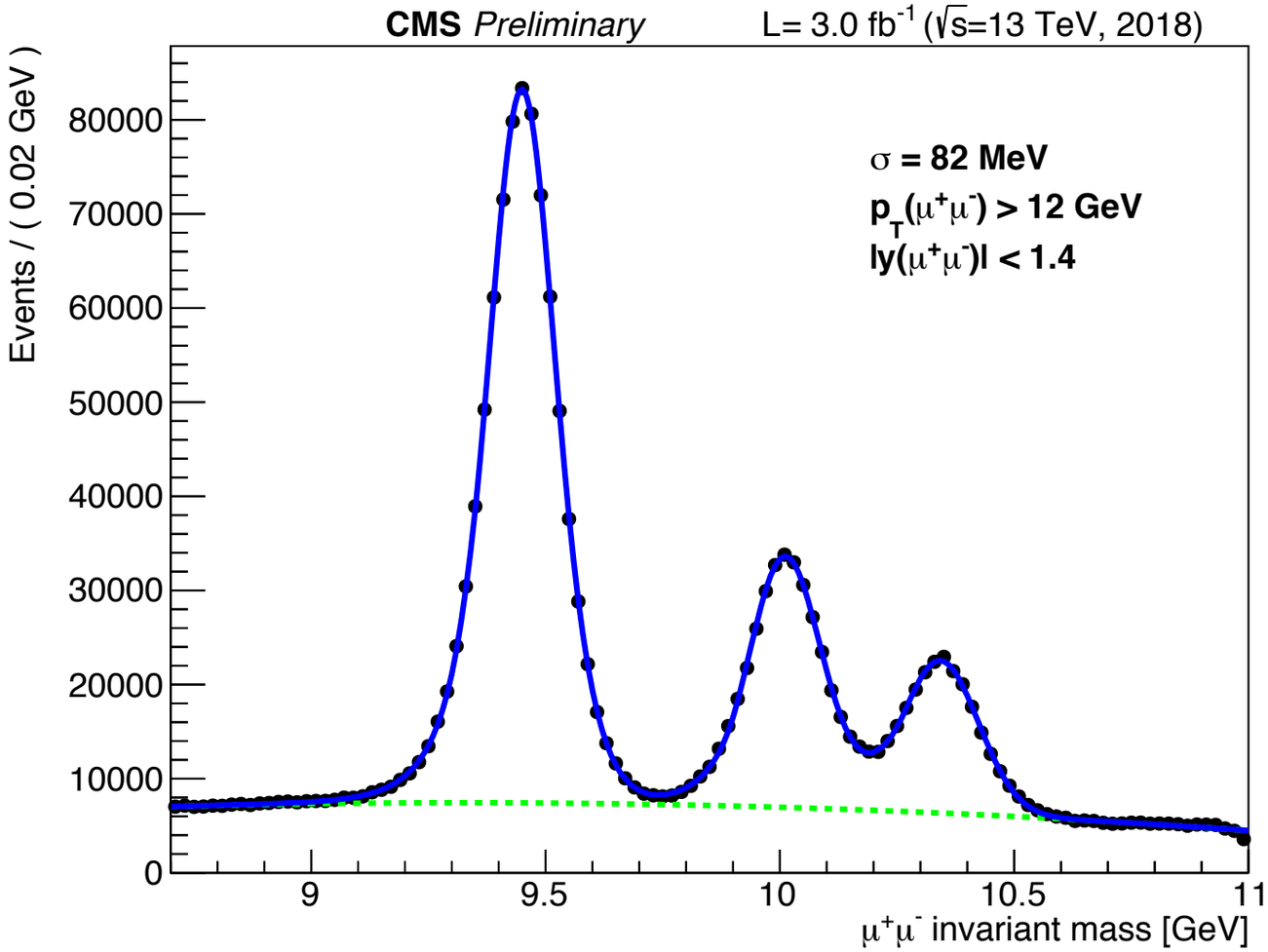
Hadron Endcap Calorimeter
2018: Upgraded HPDs→SiPMs in Endcaps
2017: Upgraded HPDs→SiPMs in one 20º readout

Hadron Forward Calorimeter
2017: Upgraded readout

Muon Detectors
Drift tubes (VME → µTCA ROS)
Resistive Plate chambers;
Cathode strip chambers;
GEM slice test (GE1/1)

CMS Performance in 2018





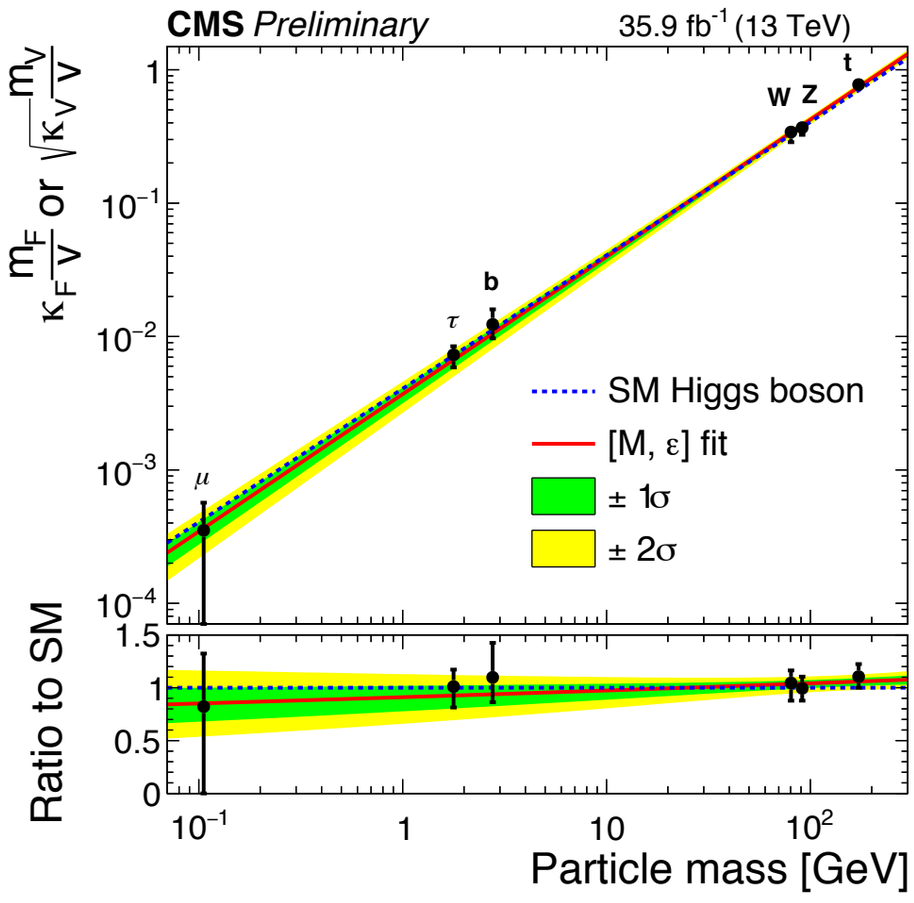
$$pp \longrightarrow t\bar{t}H$$

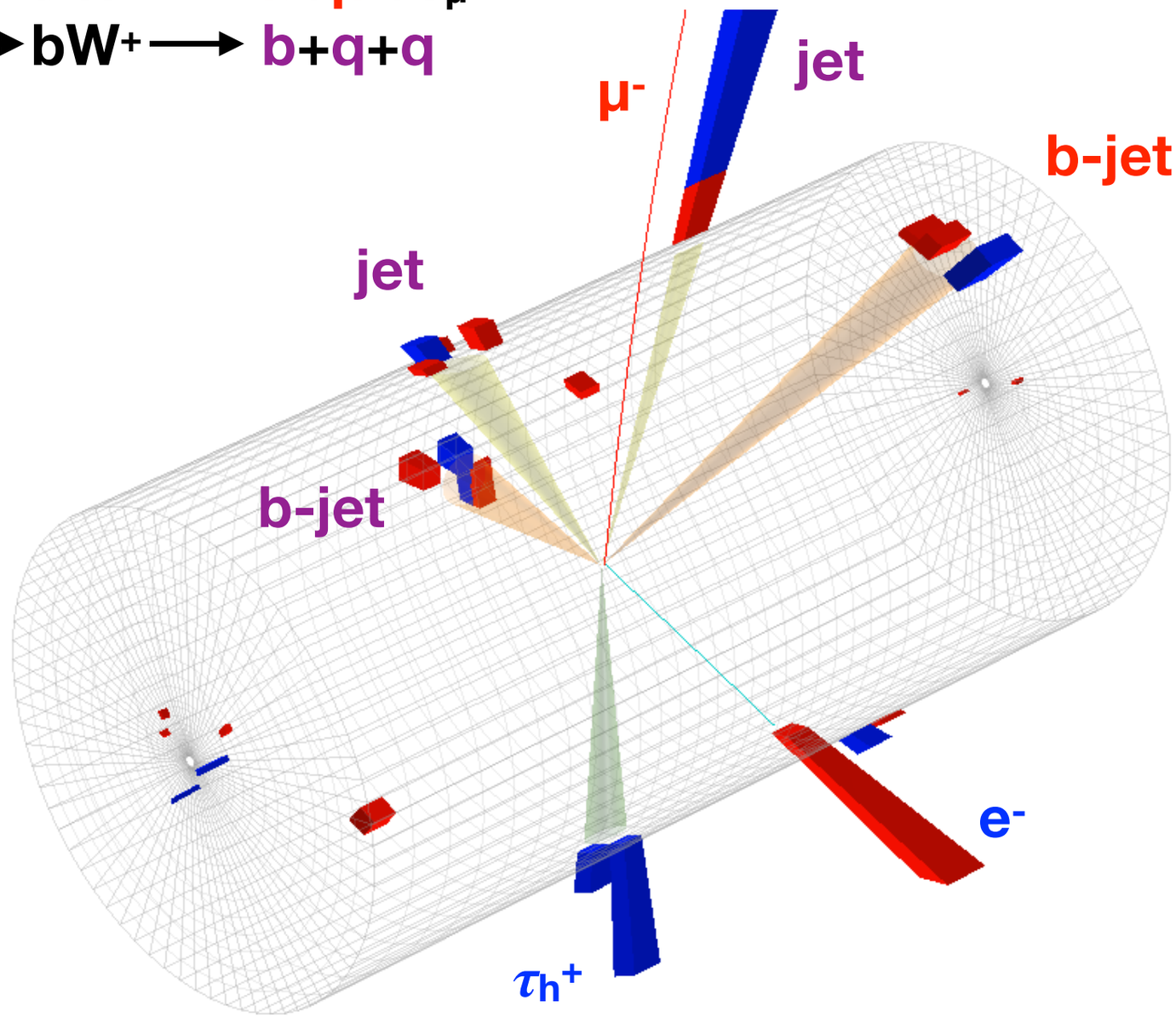
$$\tau\bar{\tau} \longrightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$$

$$\bar{b}W^- \longrightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$$

$$bW^+ \longrightarrow b + q + q$$

$$Y_{ij}\psi_i\psi_j\phi$$



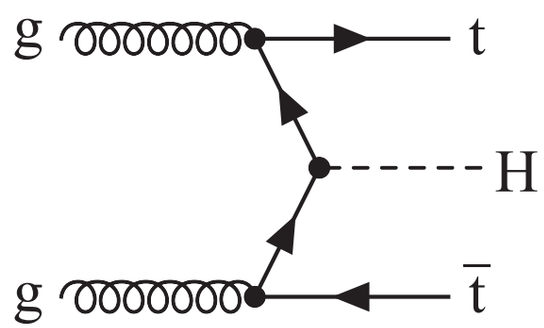


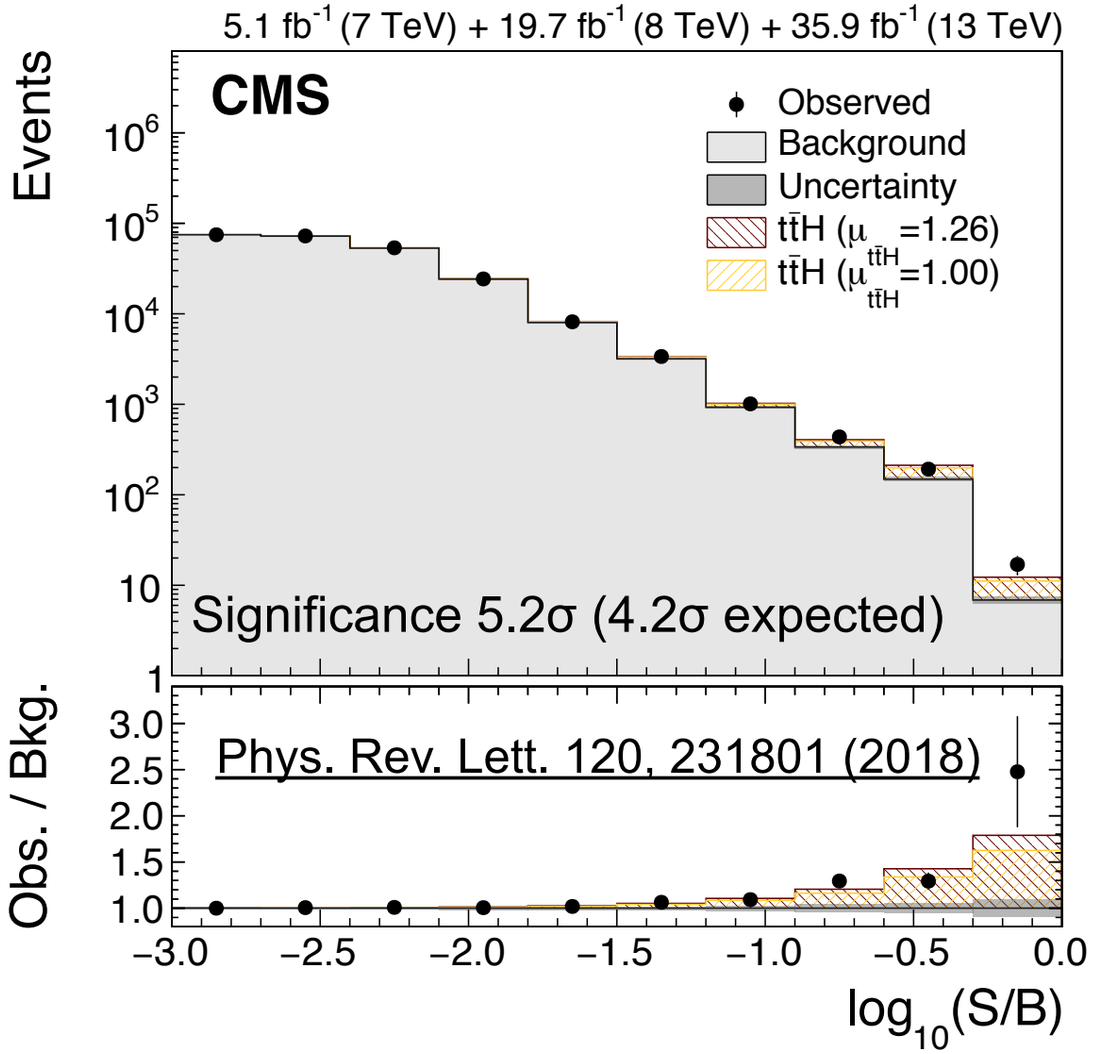
HIGGS

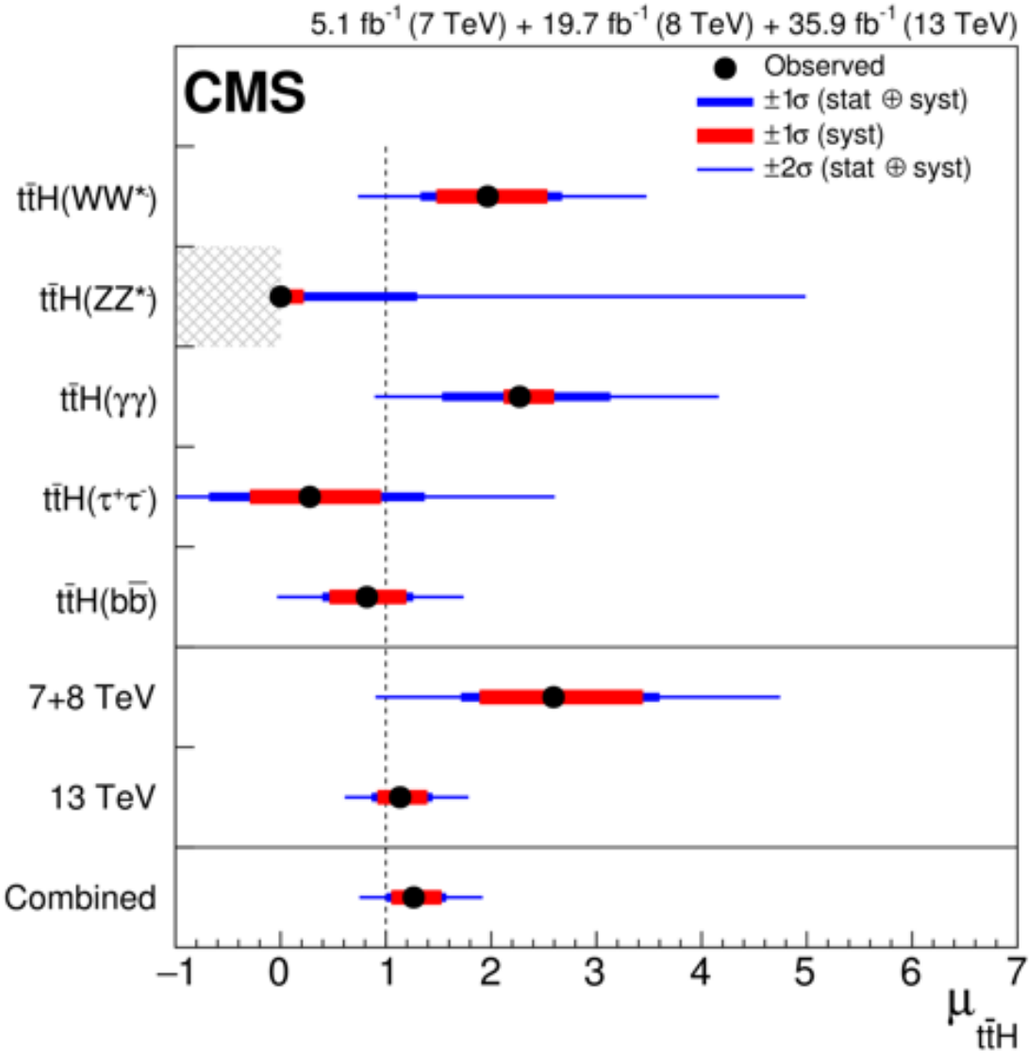
FROM DISCOVERY TO PRECISION

YUKAWA INTERACTION

- Observation of direct coupling of Higgs to top by CMS in April
  - Observation of H→ττ by CMS in 2017 Phys. Lett. B 779 (2017) 283
  - Evidence for H→bb also in 2017 Phys. Lett. B 780 (2017) 501
- Establishes direct tree-level coupling to up-type quarks
  - Additional data to be used for coupling to b quarks

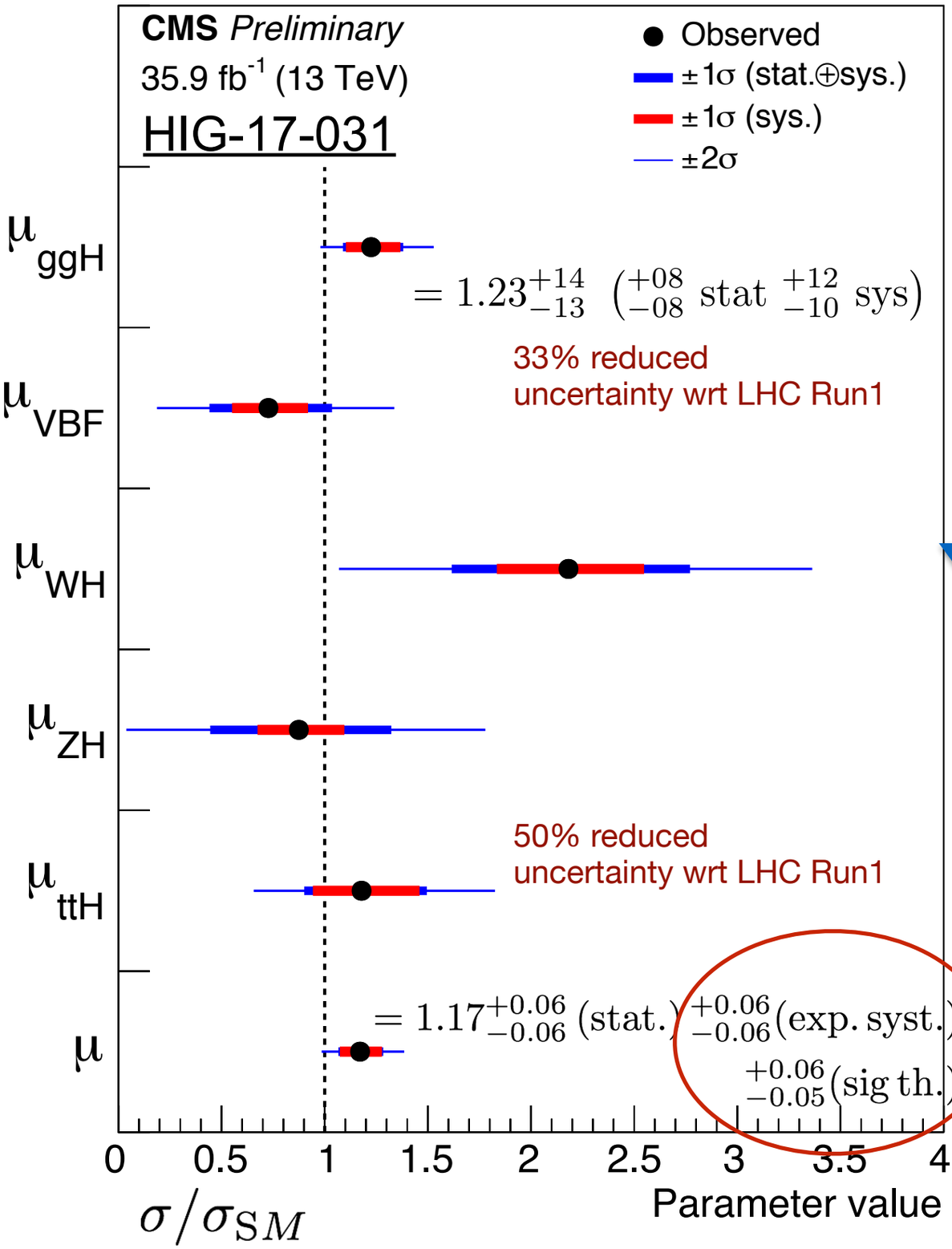


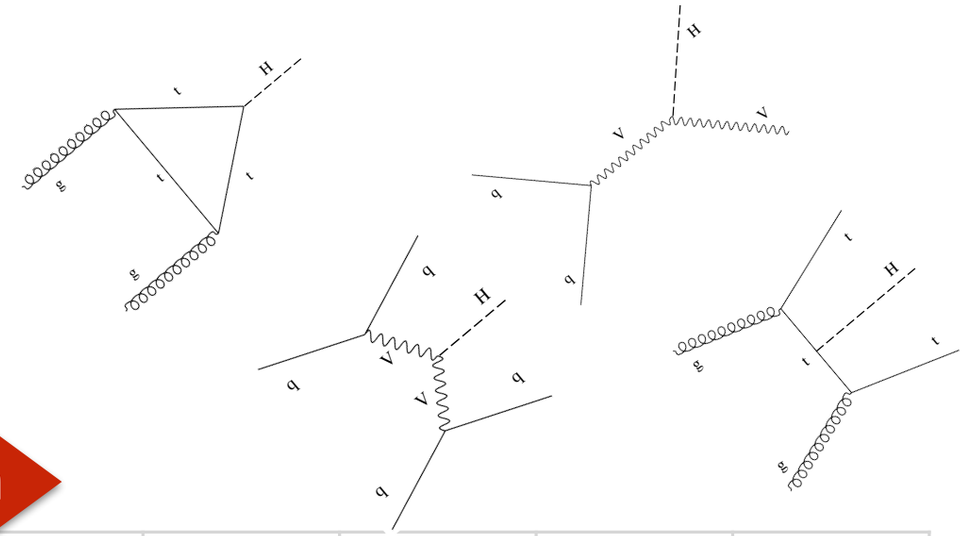




$$\sigma_{t\bar{t}H}/\sigma_{SM} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}\,(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg th.})\,^{+0.15}_{-0.07}(\text{sig th.})$$

Higgs Properties





Production

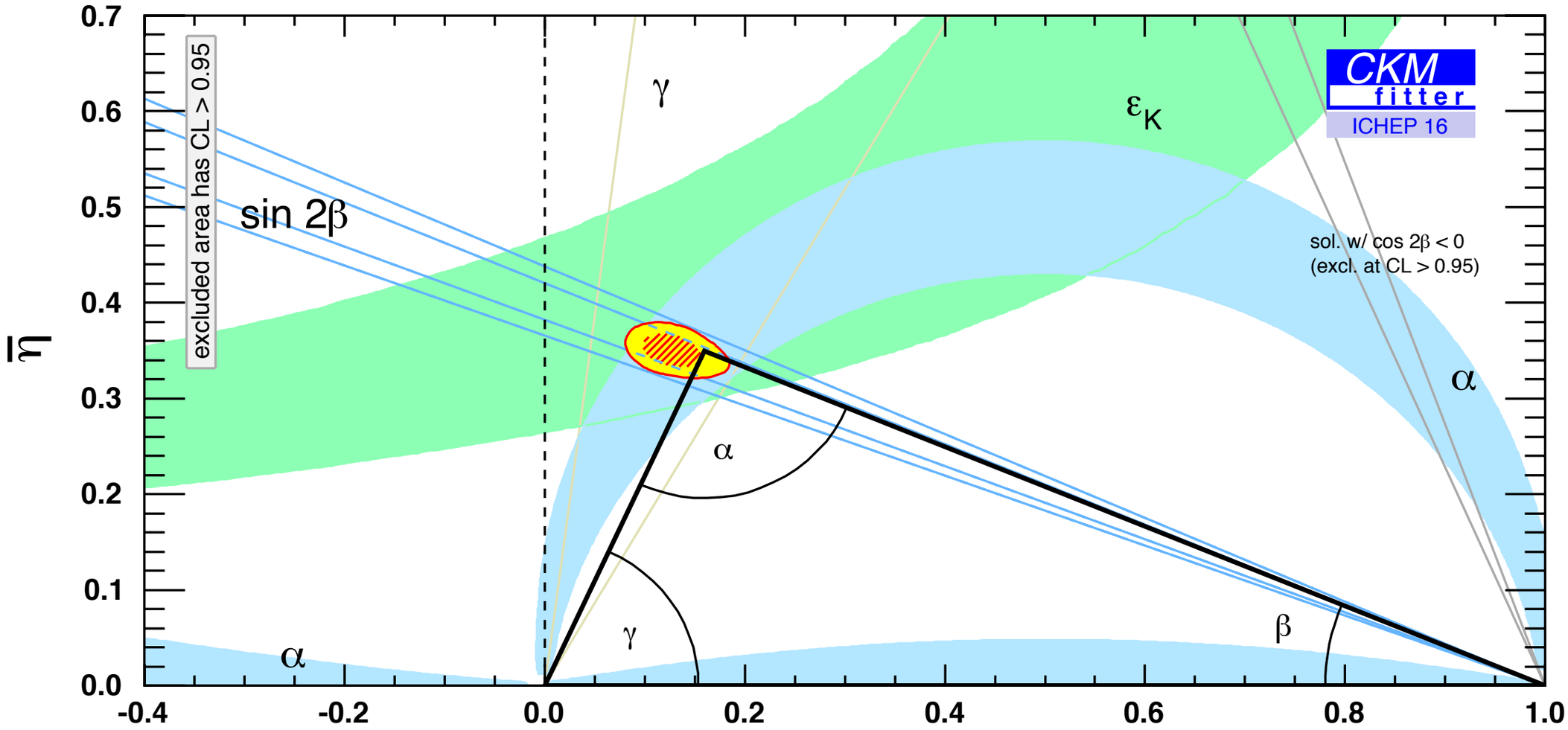
Decay

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

Total of 250 even categories

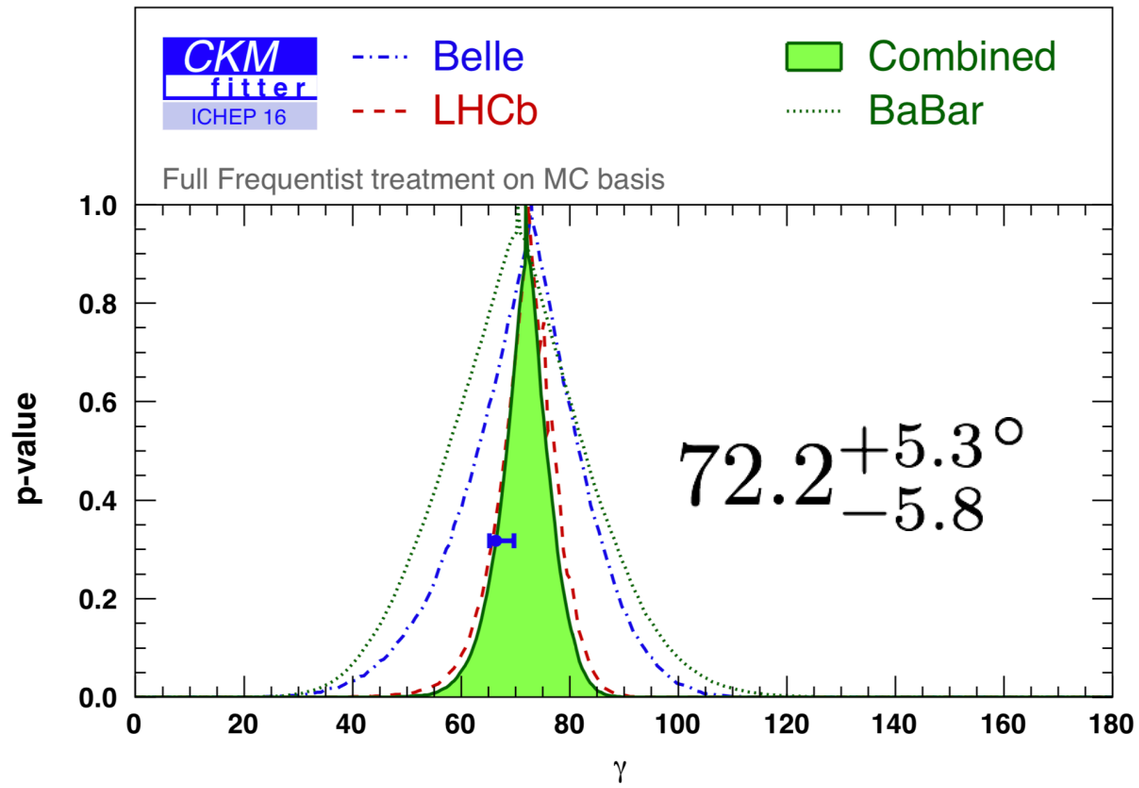
$$BF(H \to \text{inv.}) < 22\% \,@\, 95\%\,\text{C.L.}$$

- Nearing theory-limited territory with just 2016 data



$$Y_{ij}\psi_i\psi_j\phi$$

CP VIOLATION



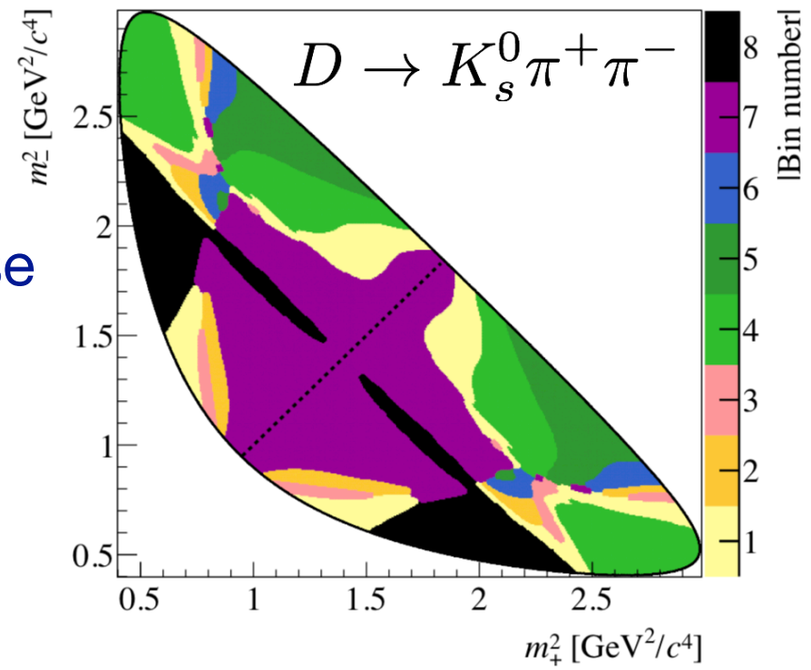
Most Precise γ

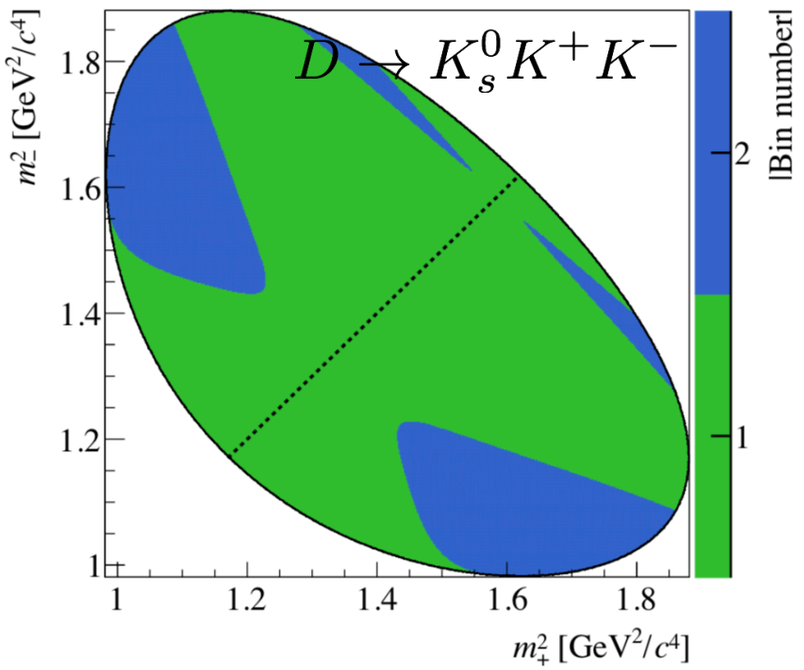
- Dalitz analysis of decays $B^- \to DK^-$

arxiv:1806.01202

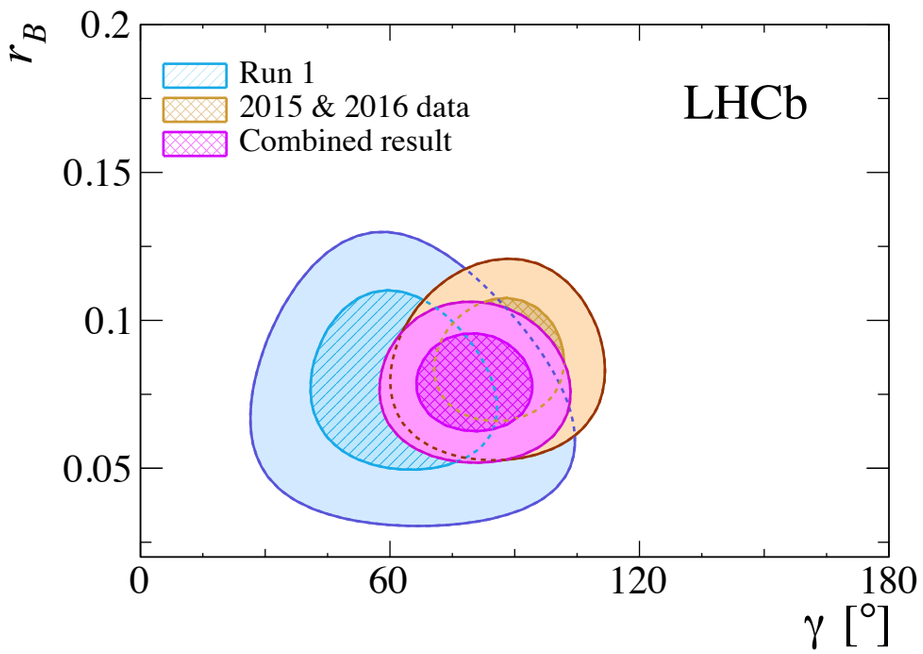
  - both kaons and pions
  - Intervals of D^0-D^0bar strong phase to maximise sensitivity
    - strong phase measured by CLEO-c

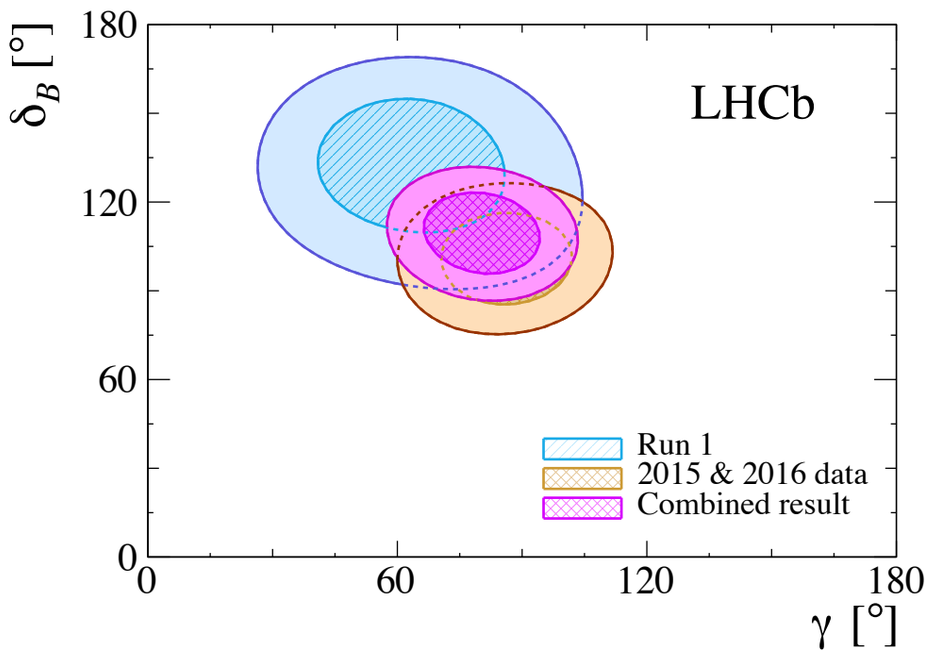
$$\gamma = (80^{+10}_{-9})^\circ$$





- Run2 data critical for this measurement

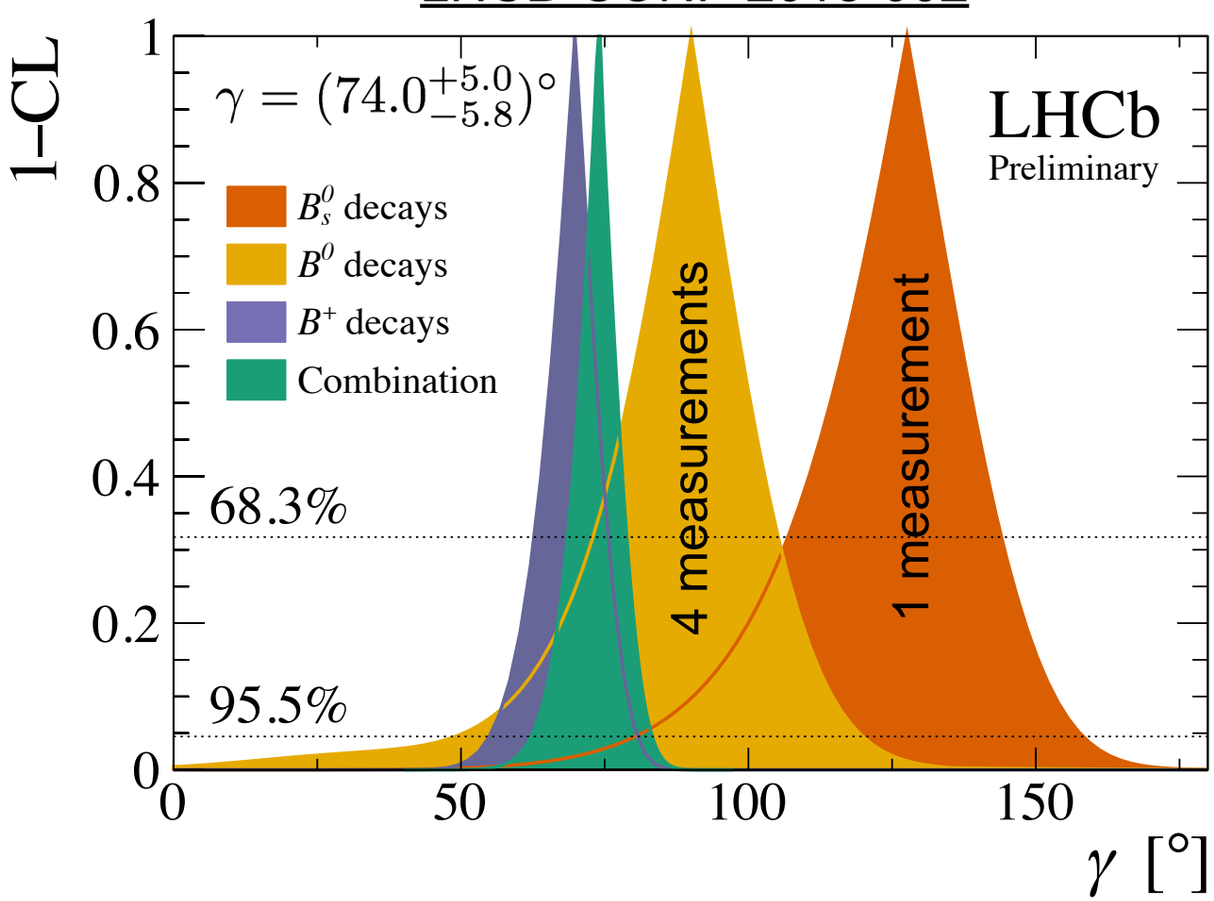


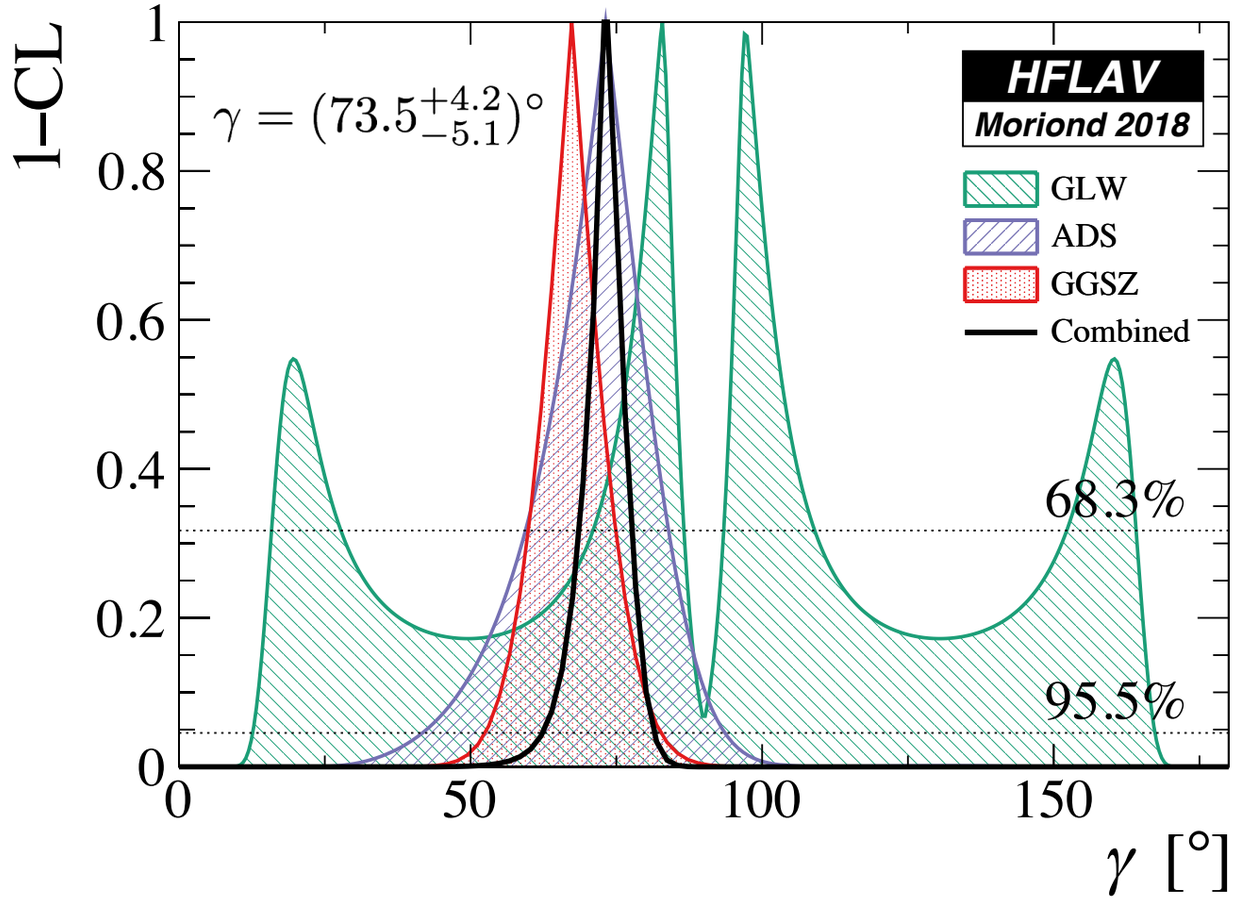


MEASUREMENT OF γ AT LHCb

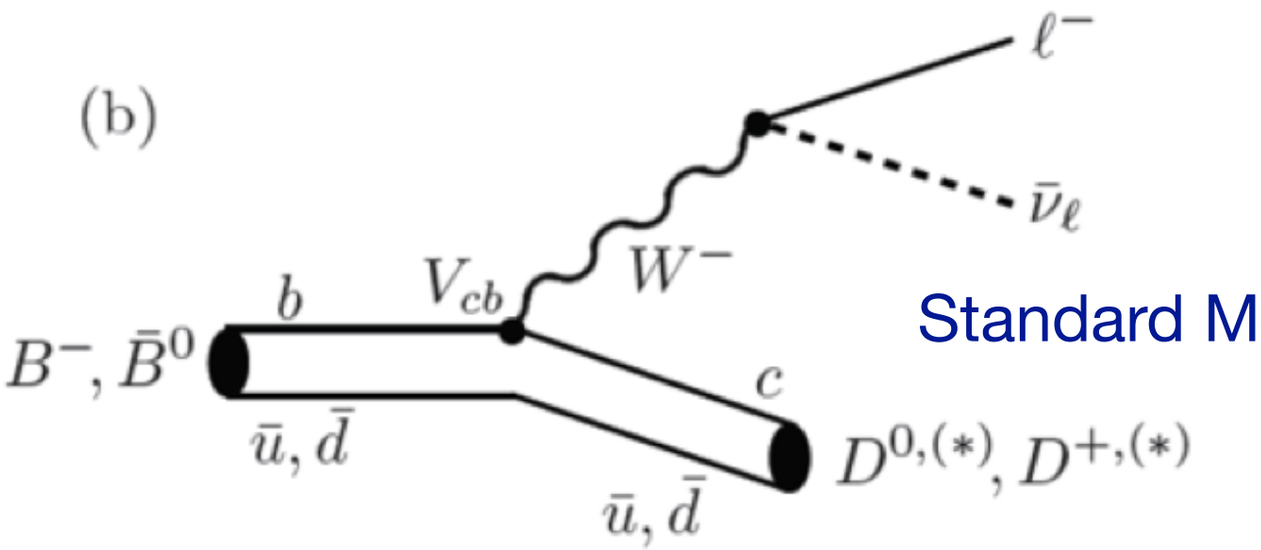
- Combination of 16 measurements from LHCb
  - 4 updated and 3 new measurements
  - 98 observables with 40 free parameters

LHCB-CONF-2018-002

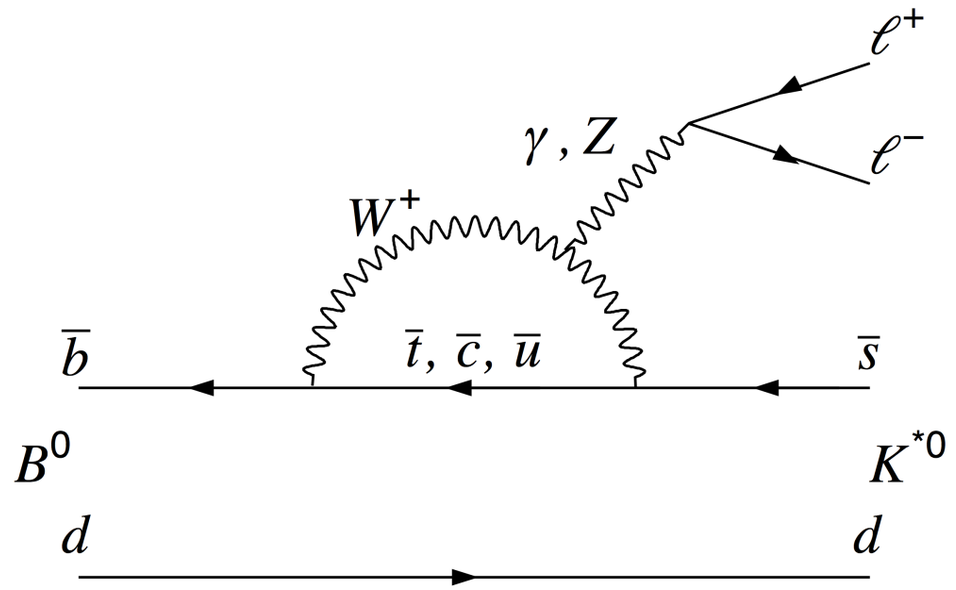


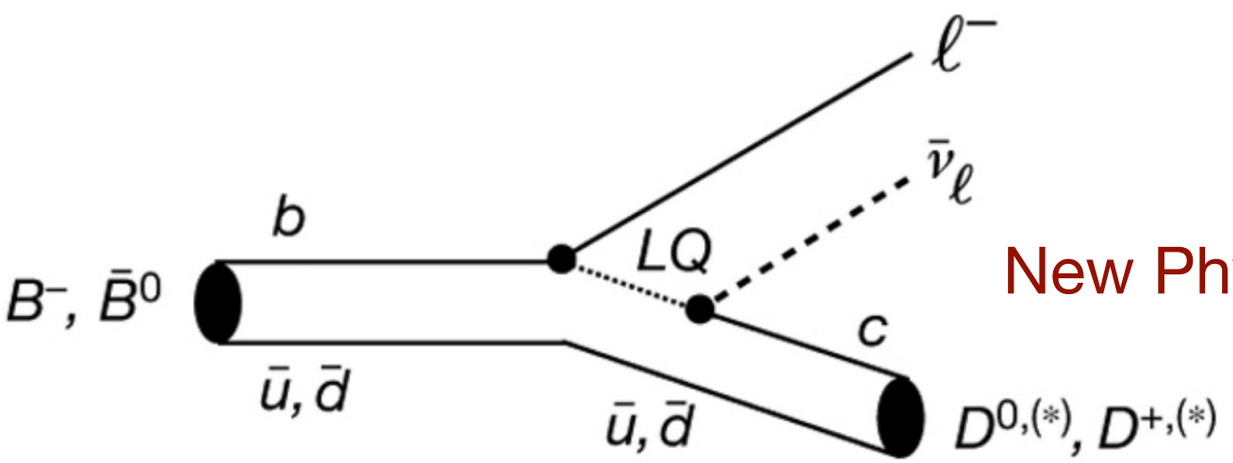


- Some tension between different decay modes

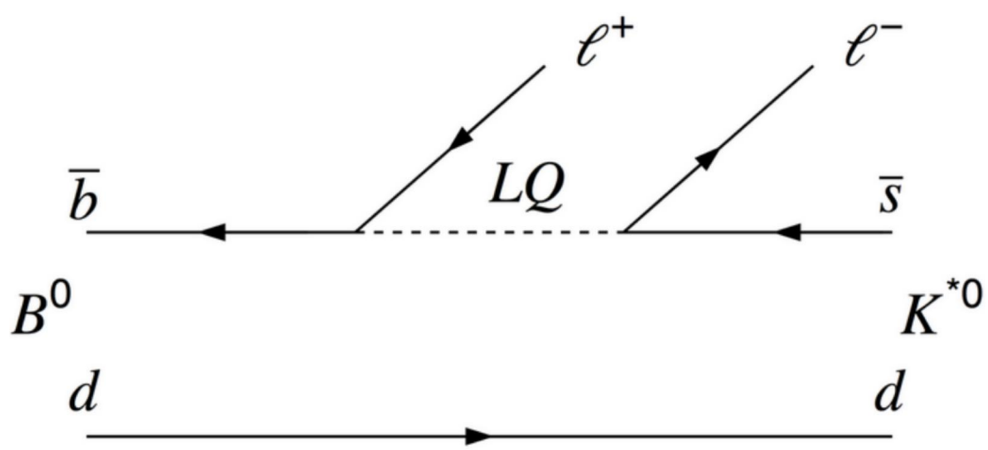


Standard Model





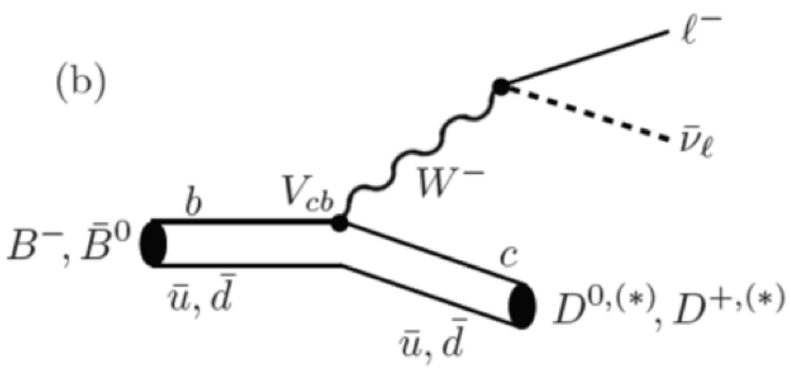
New Physics



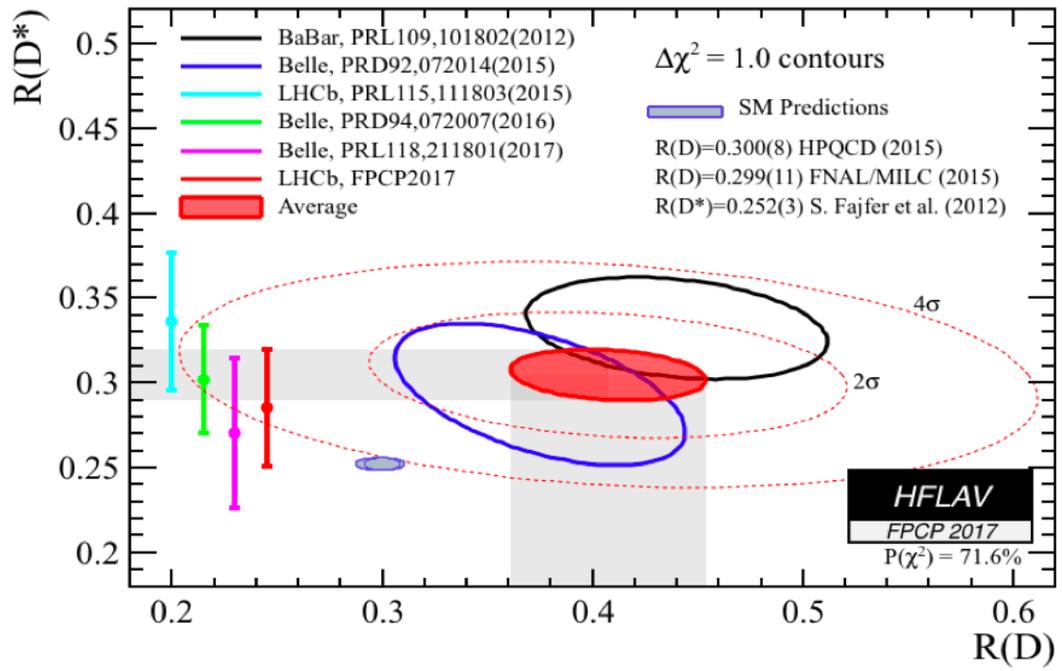
LEPTON FLAVOR UNIVERSALITY

INDIRECT NEW PHYSICS

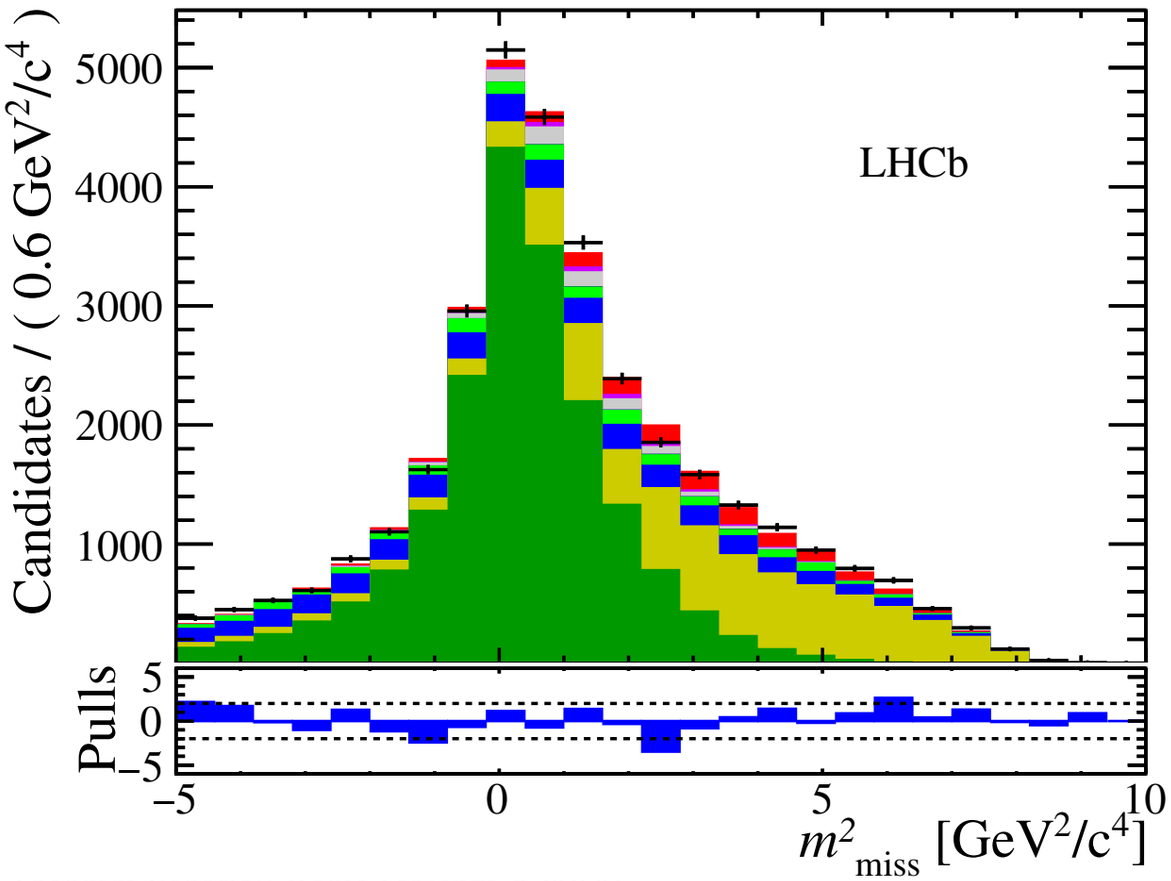
ANOMALIES AT TREE LEVEL



$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$



- Extending study of tree-level anomalies to B_c sector with J/psi



SM prediction: 0.25-0.28

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

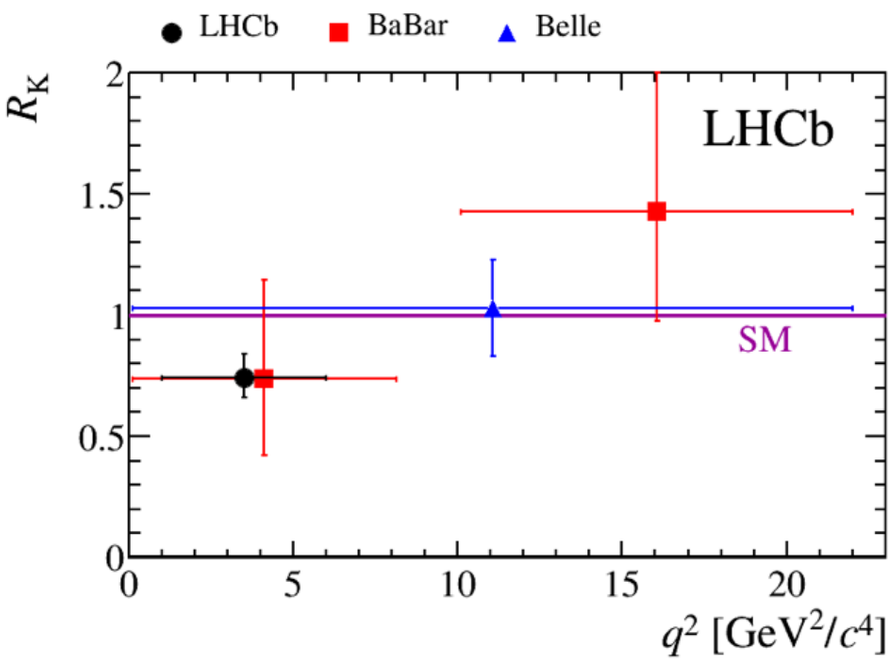
$$= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

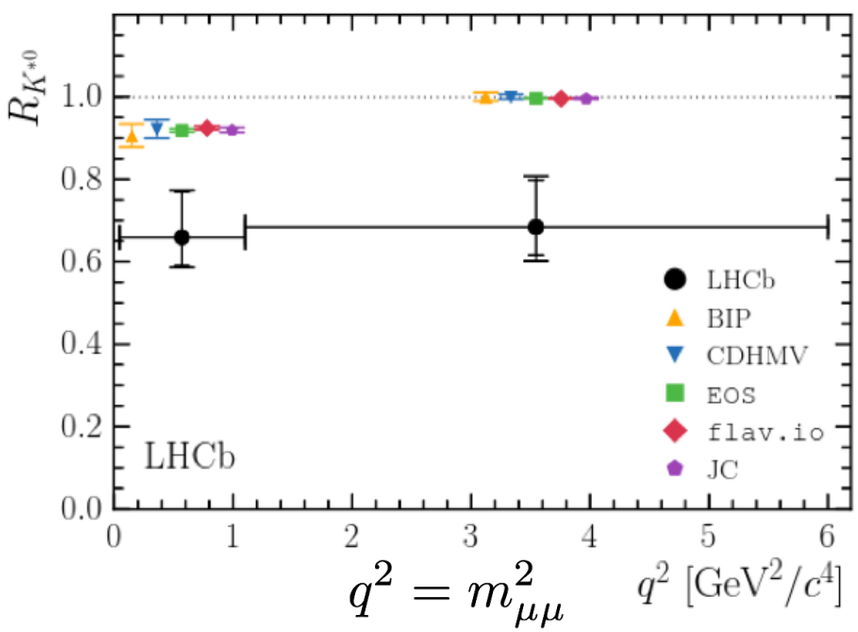
$B_c^+ \to J/\psi$ form factors

PRD 97 (2018) 072013,
PRL 120 (2018) 121801,
Run 1, 3 fb^{-1}

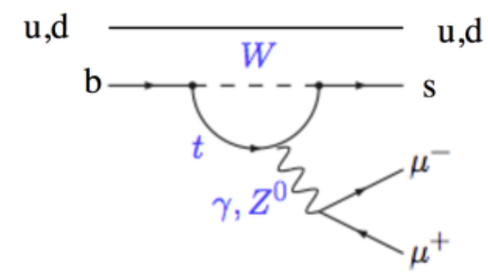
ANOMALIES IN PENGUINS

PRL 113 (2014) 151601, JHEP 08 (2017) 055, Run 1 data, 3 fb^{-1}





muons / electrons [b → s]



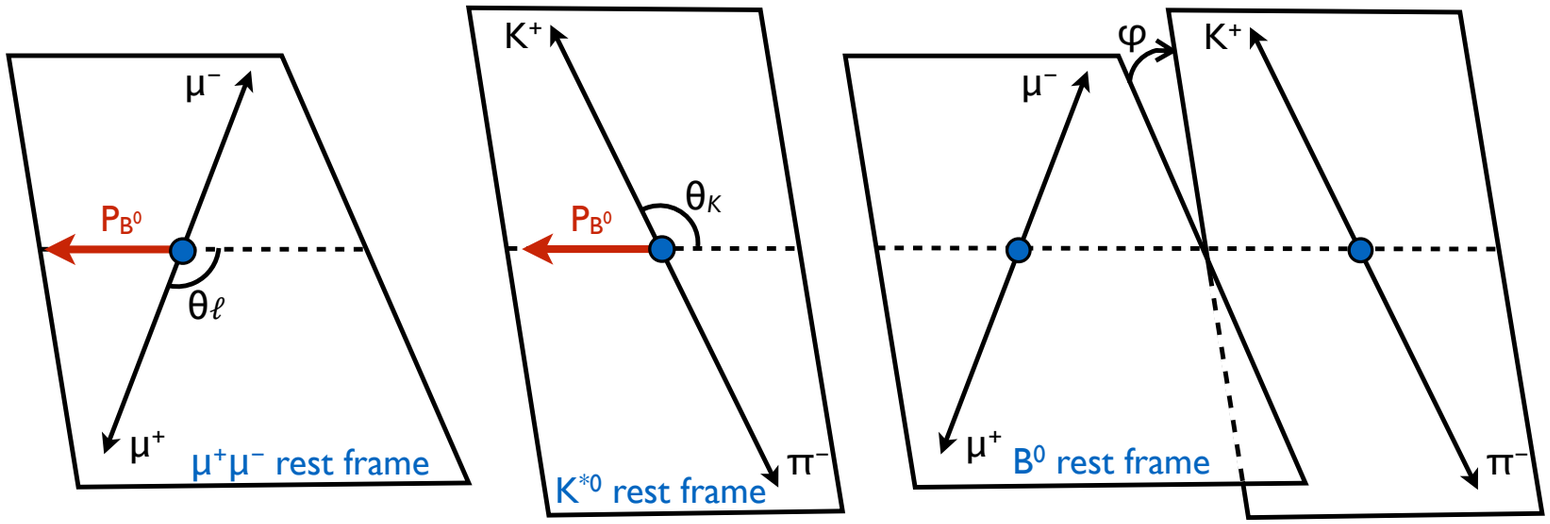
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

Analogously: R_{K^*}

- Discrepancies in b →sll transitions at BaBar, Belle, and LHCb
  - Differential branching fractions
- Analysis with Run2 data underway at LHCb
  - challenging precision analysis over multi-year data sample
  - Also adding new final states, e.g. $B_s \to \phi\, l^+ l^-$
- Plan to perform measurement at CMS with improved low-momentum electron reconstruction

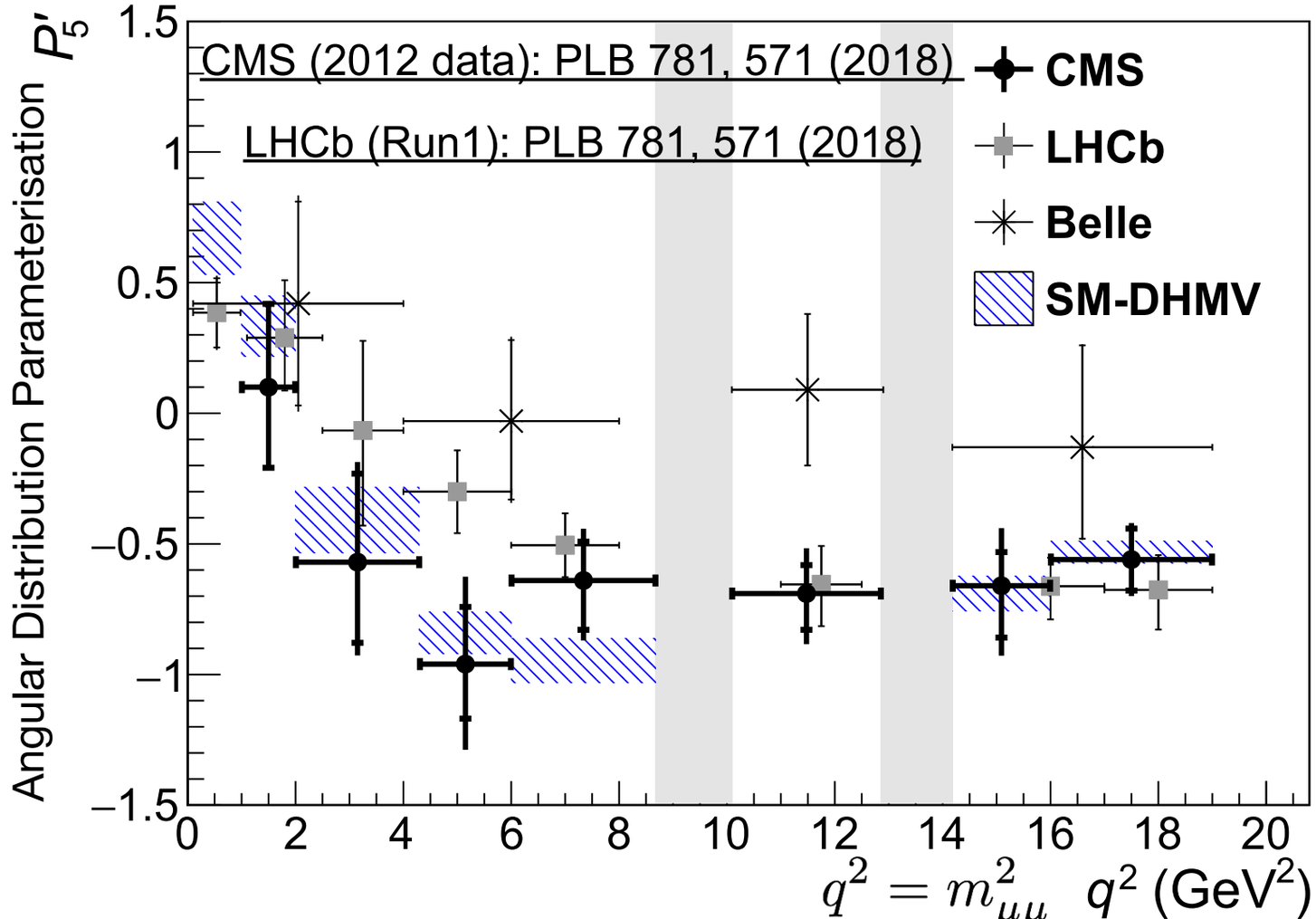
Anomalies in Angular Distributions

$$\bar{B^0} \to K^{*0}(K^+\pi^-)\mu^+\mu^-$$



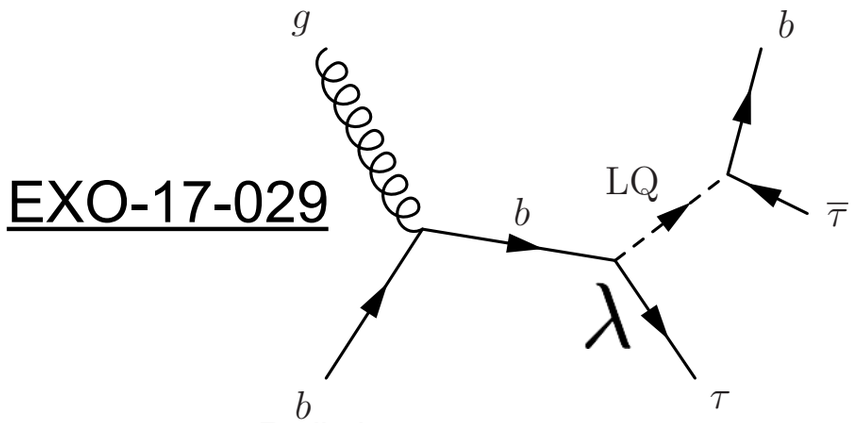
- Some discrepancy observed also in angular distributions
  - Not as compelling as in rates
  - Very large uncertainties
  - requires full Run2 statistics

- Dedicated triggers in CMS in 2017 to increase statistics for analysis at end of Run2

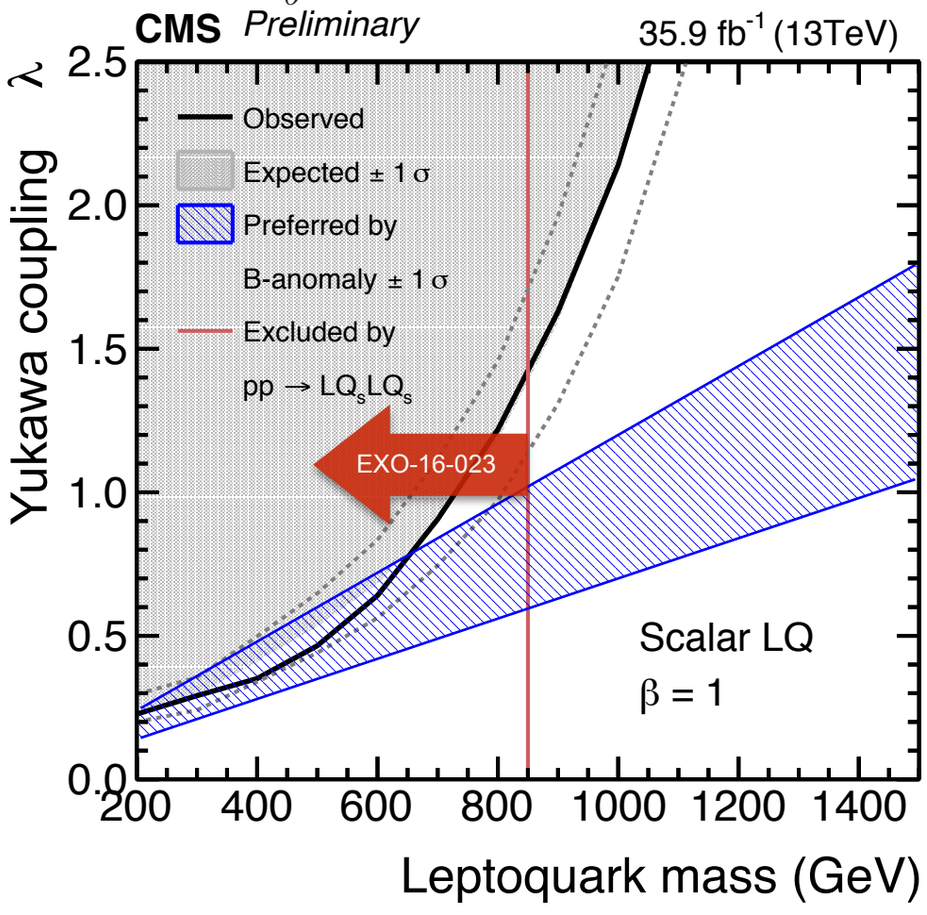


TACKLING ANOMALIES AT HIGH MASS

- Tree-level explanation of B anomalies with preferred coupling to 2nd and 3rd generations
  - Pair- and single-production of leptoquarks
  - Also with DM candidate emission

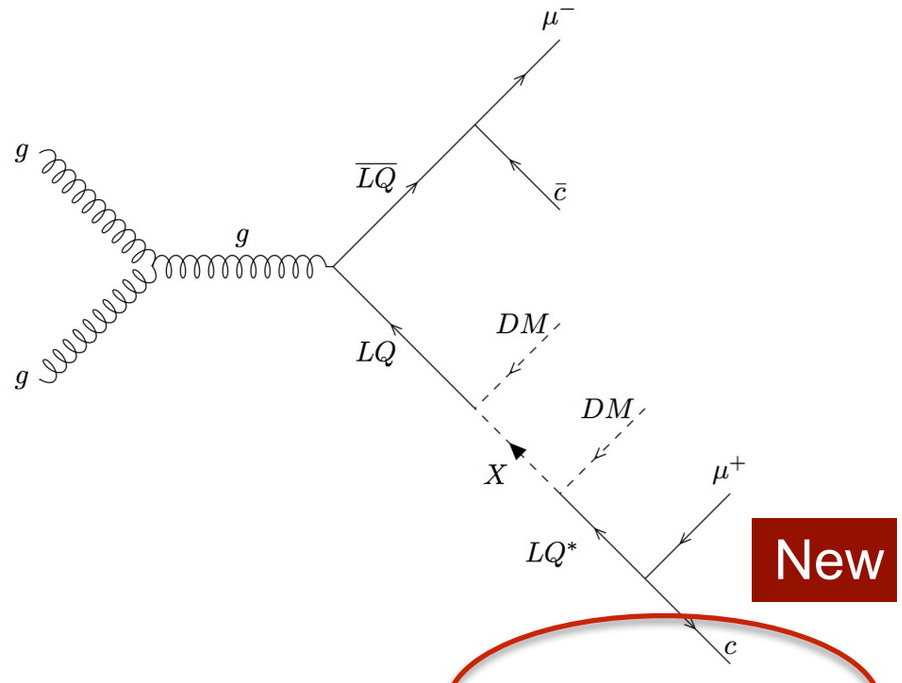


EXO-17-029

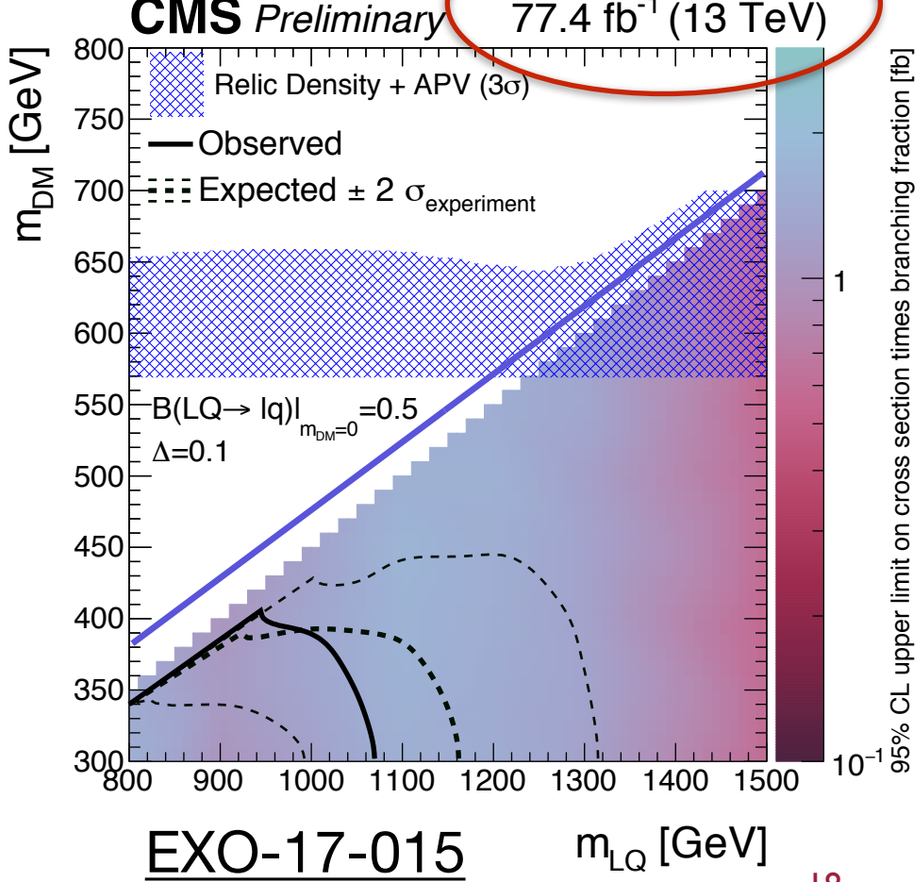


$M_{LQ,\,lim}$ (GeV)	β=1	β=0
1st gen.	*ee qq* 1130	*νν qq* 980 V: 1790 (q=udsc)
2nd gen.	*μμ qq* 1530	
3rd gen. (q=b)	*ττ bb* 850	*νν tt* 1020 V: 1780
3rd gen. (q=t)	*ττ tt* 900	*νν bb* 1100 V: 1810
	μμ tt 1420	
3rd gen. single	*τ τb* λ=1: 740	

pair production



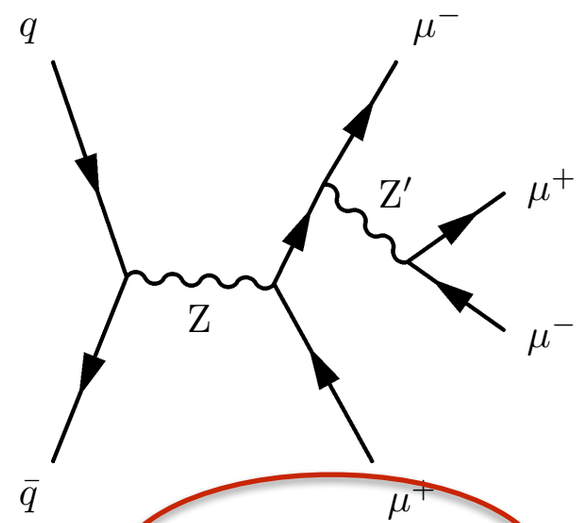
New



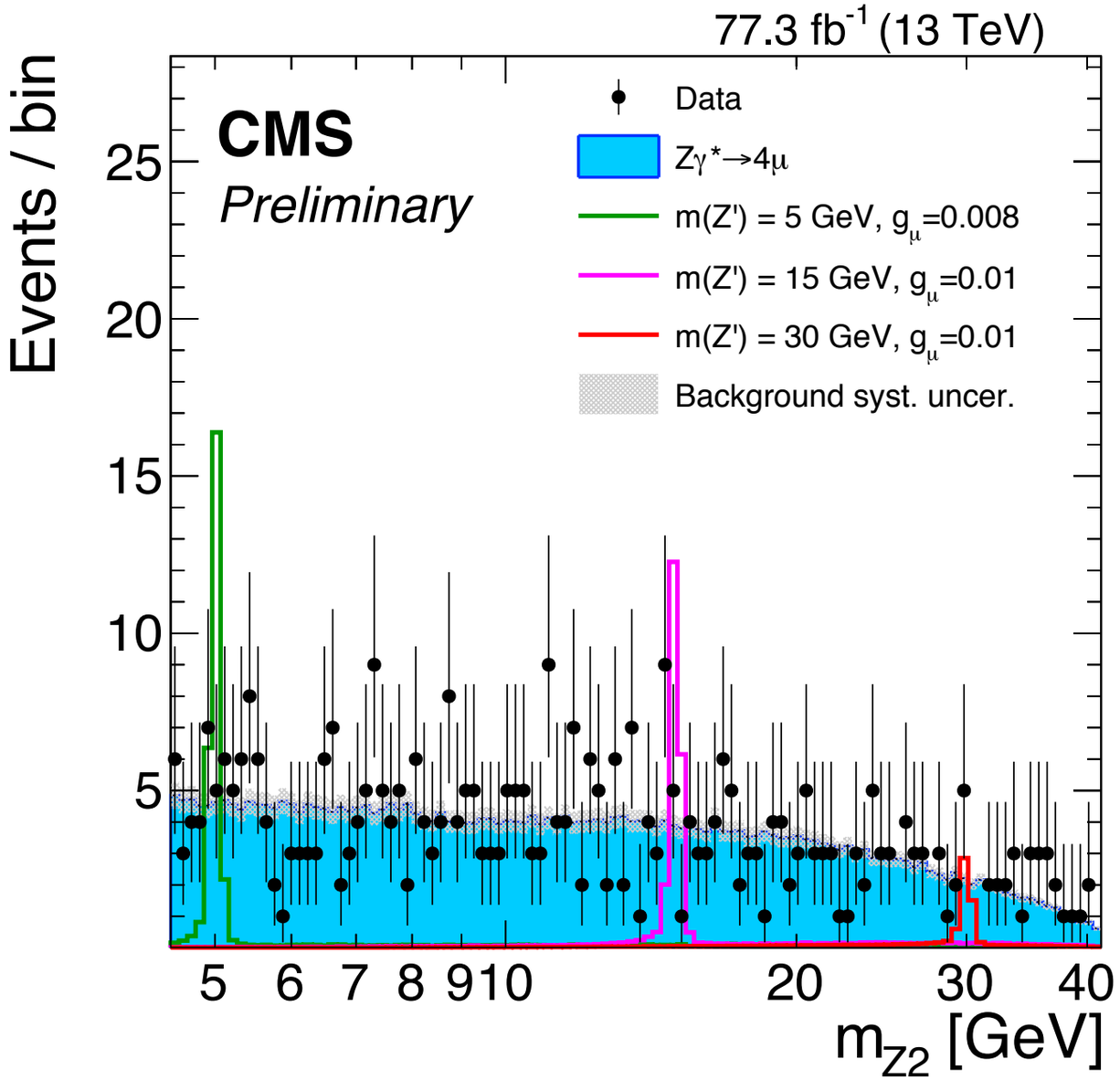
EXO-17-015

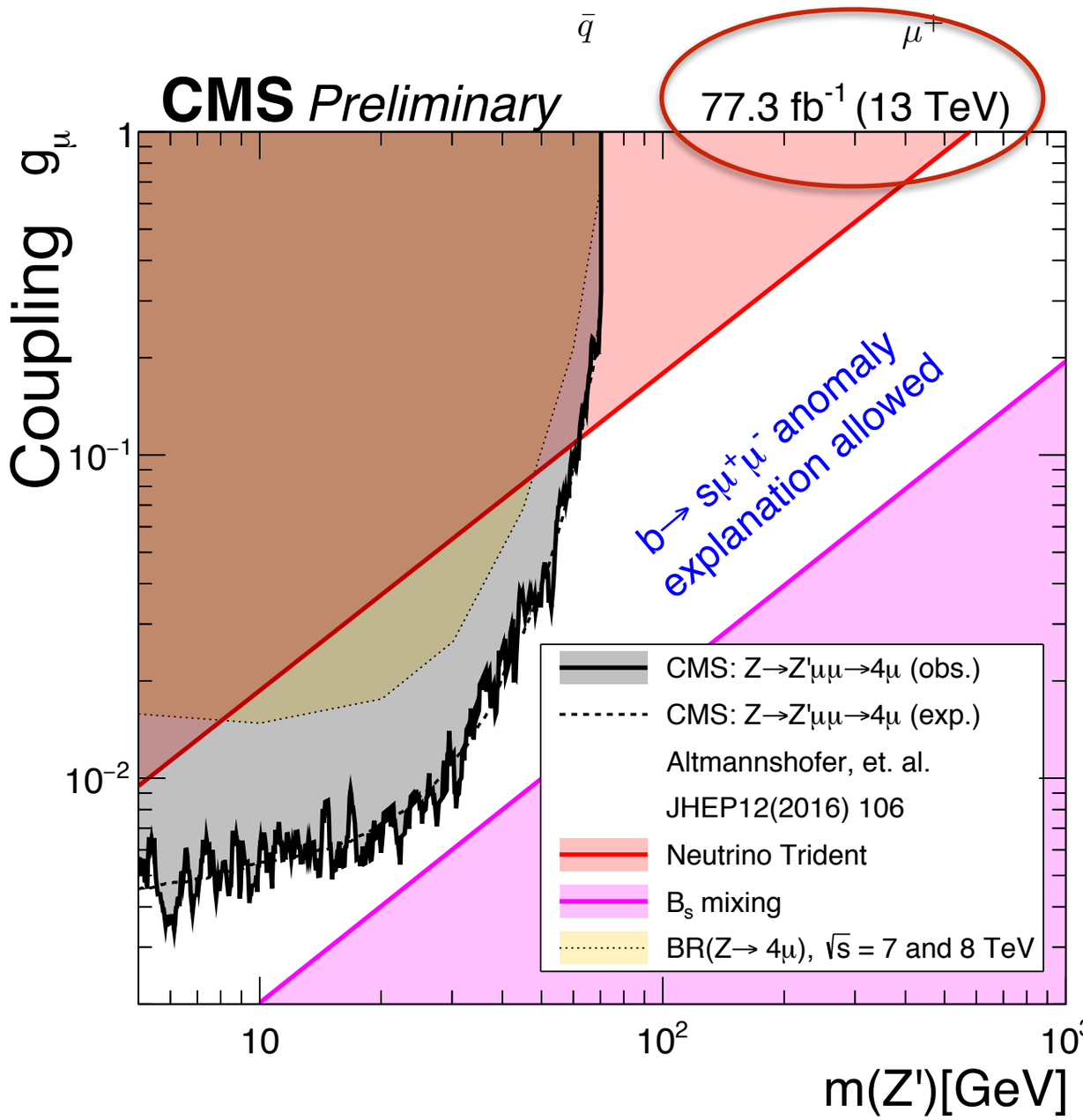
LIGHT Z' BOSON

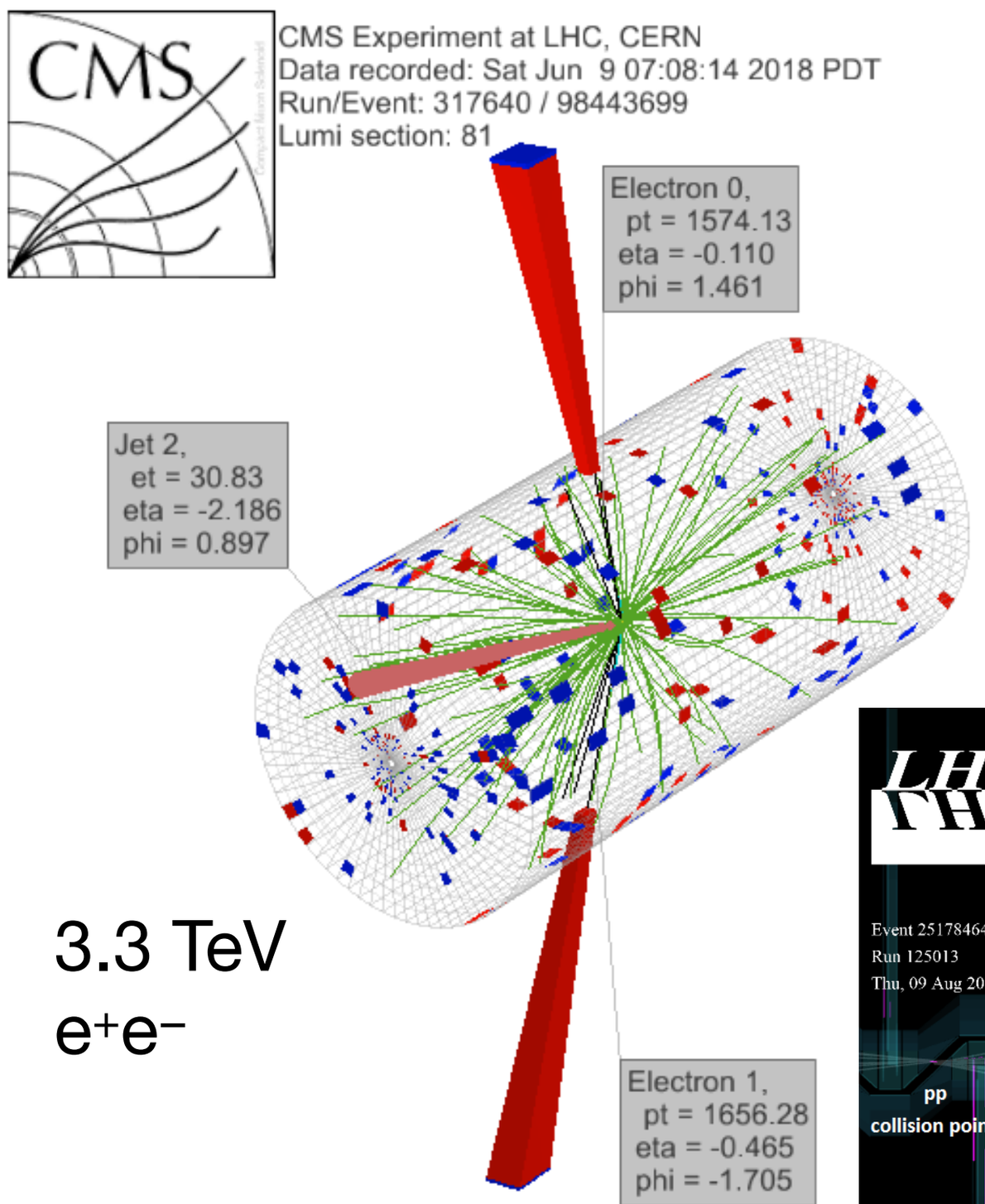
- Search for new gauge boson below the Z mass
  - New ideas taking advantage of 2017 data



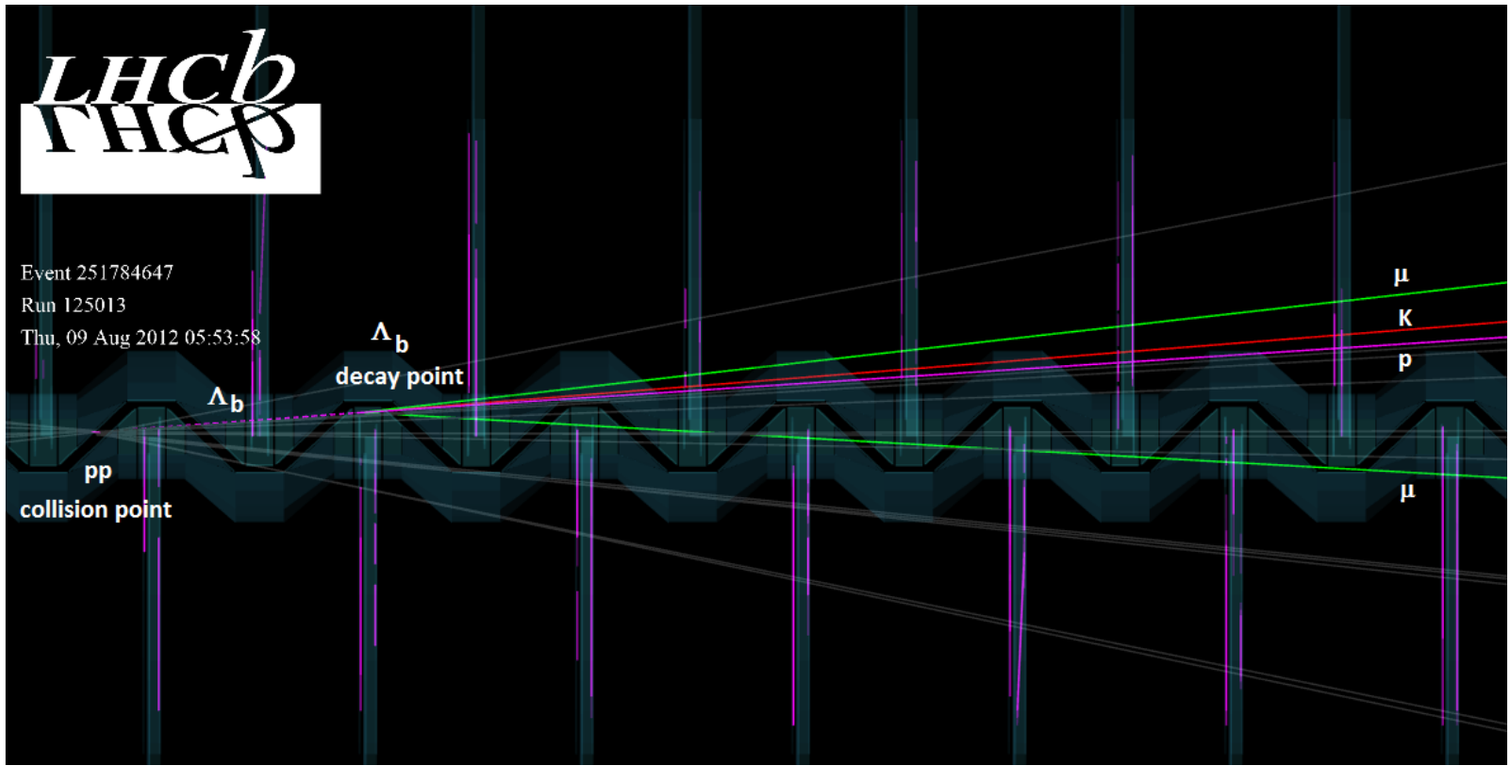
EXO-18-008







3.3 TeV
e^+e^-



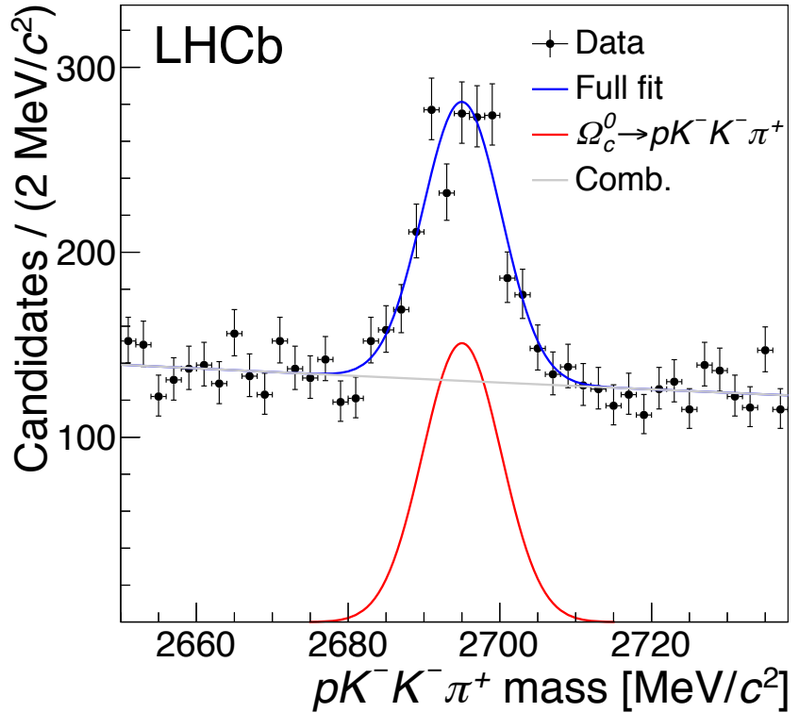
EXOTICS AND SPECTROSCOPY

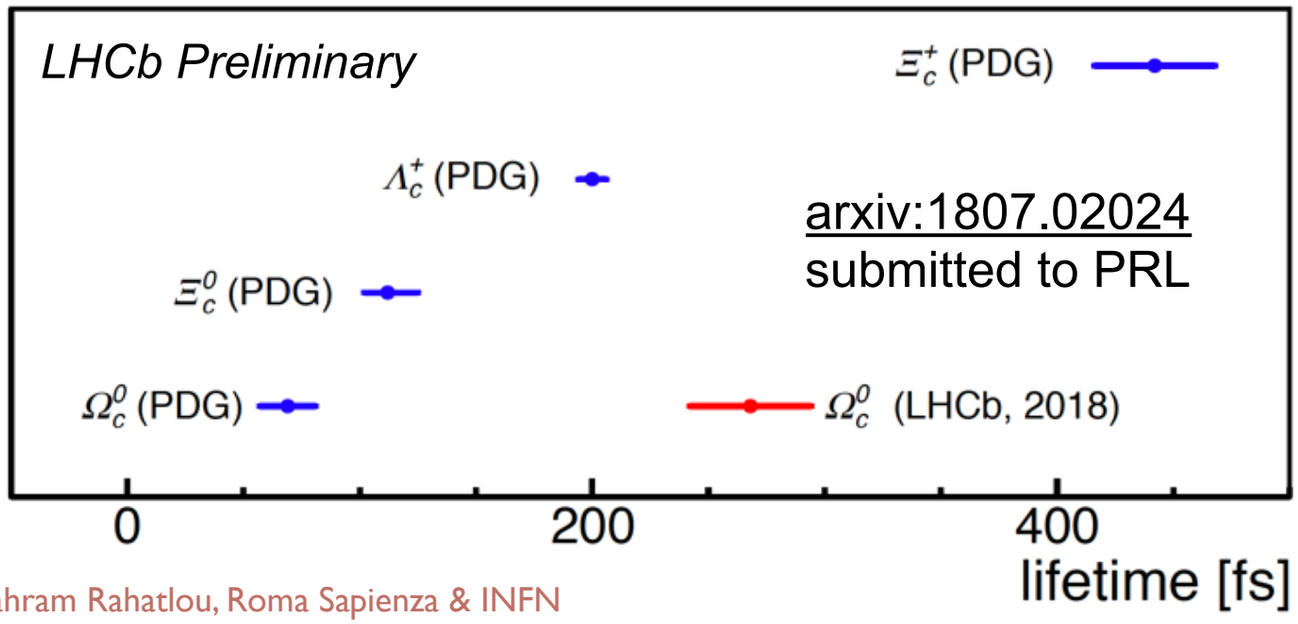
LIFETIME OF Ω^0_c

- Measurement of Ω^0_c lifetime with respect to well measured D^+ lifetime
  - copious reference sample $B \to D^+(\to K^-\pi^+\pi^+)\mu\nu_\mu X$
  - measurement with $\Omega_b^0 \to \Omega_c^0(\to pK^-K^-\pi^+)\mu\nu_\mu X$
  - Critical role of particle identification
- Measurement 4 times larger than PDG average
  - 69 ±12 fs
  - dominated by FOCUS experiment

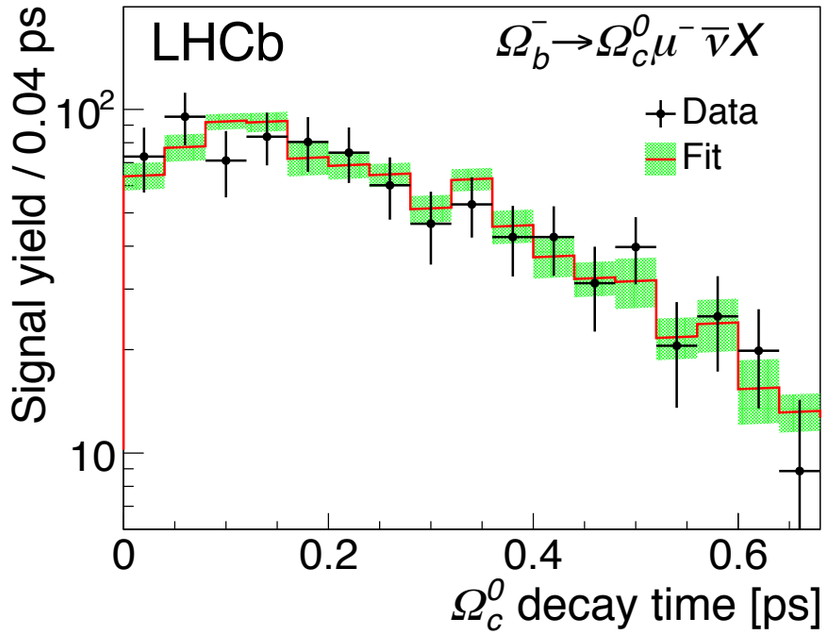
$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$





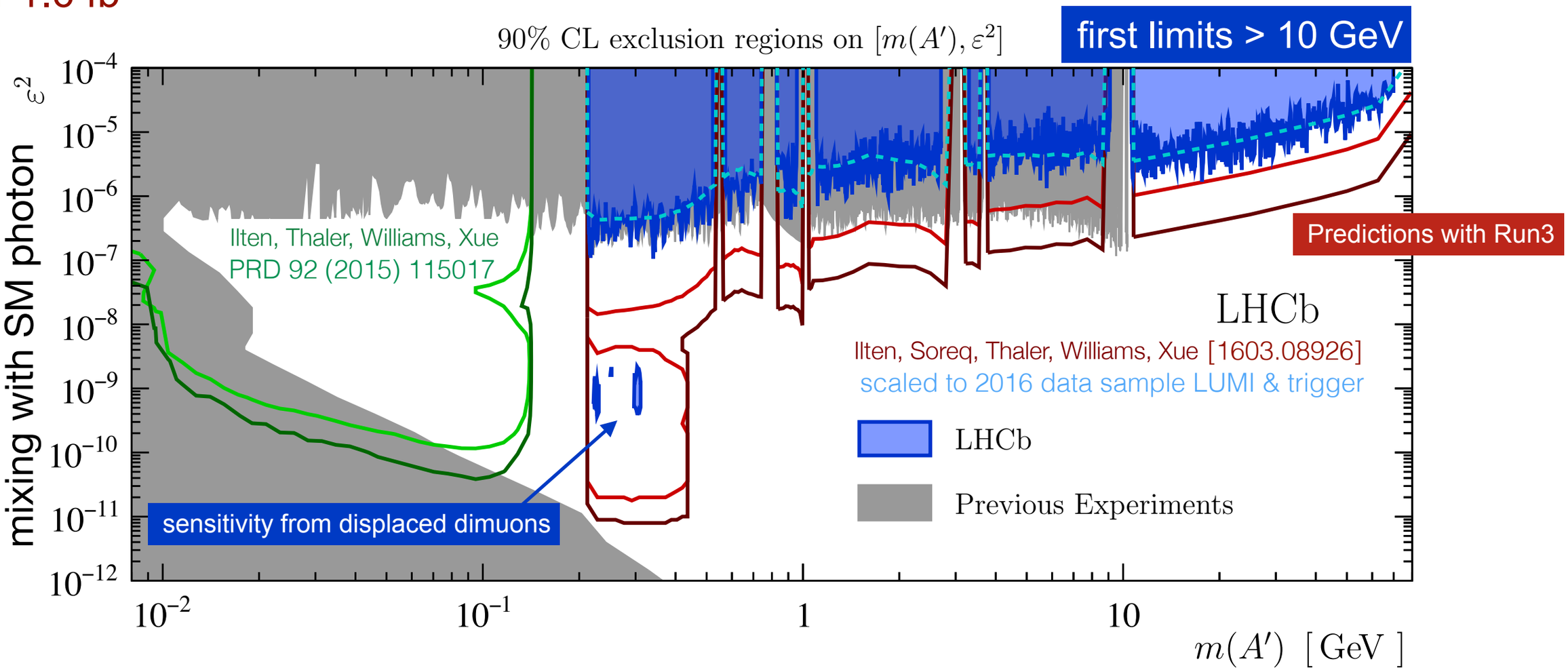
New



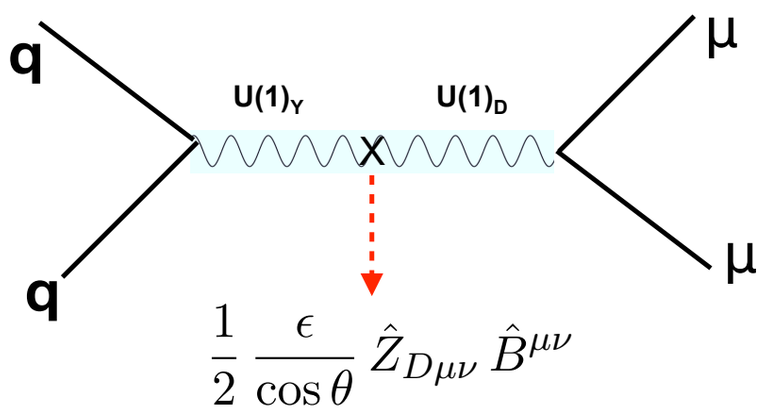
DARK PHOTON

PRL 120, 061801 (2018)

Run1 1.6 fb^{-1}

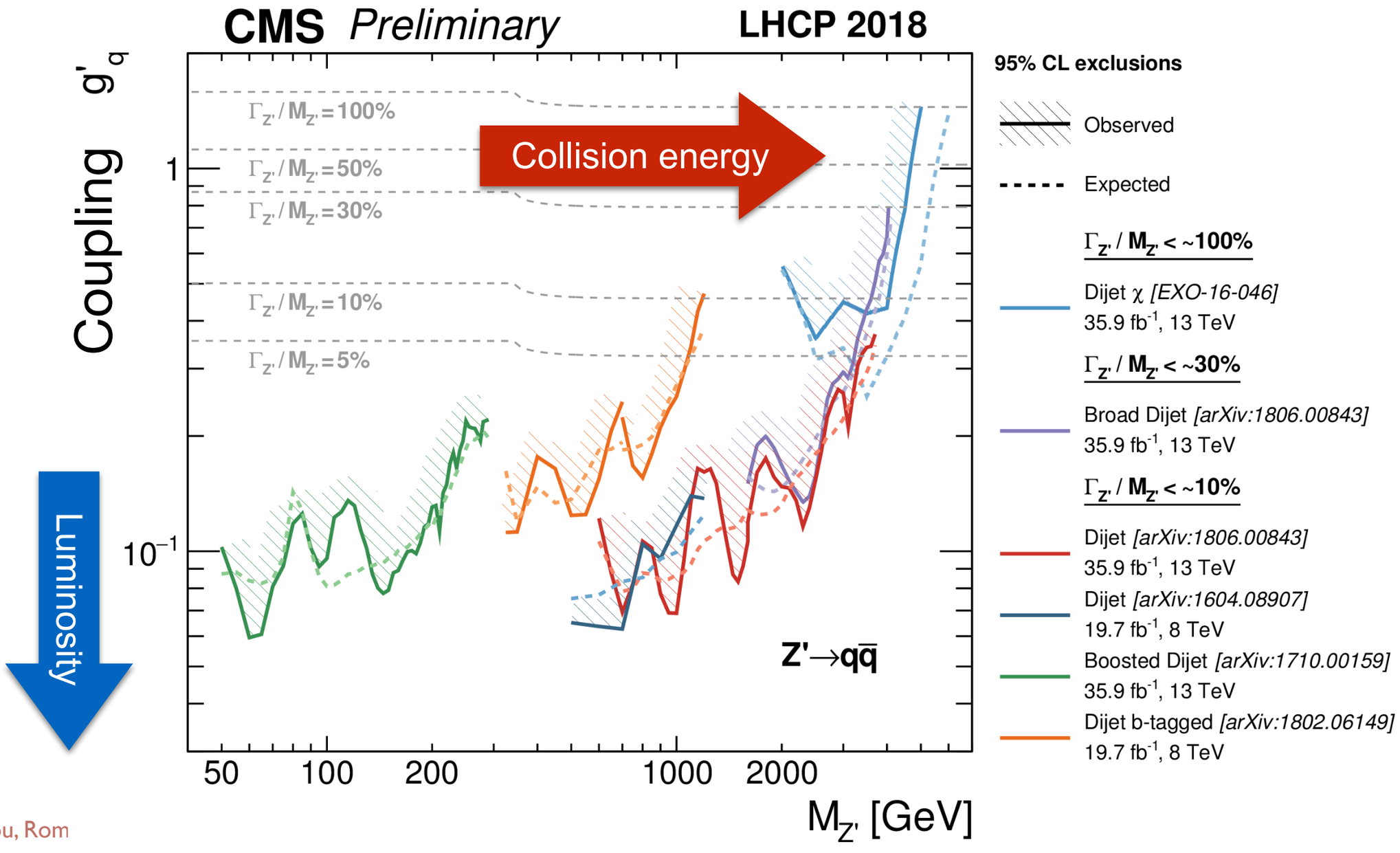


- Kinetic mixing of Dark Photon and a virtual photon
- Clean experimental signature
  - Prompt bump or displaced di-muon pair
- Great potential with data collected in 2017
  - dedicated low-mass triggers for increased sample
  - Addition of di-electron final state



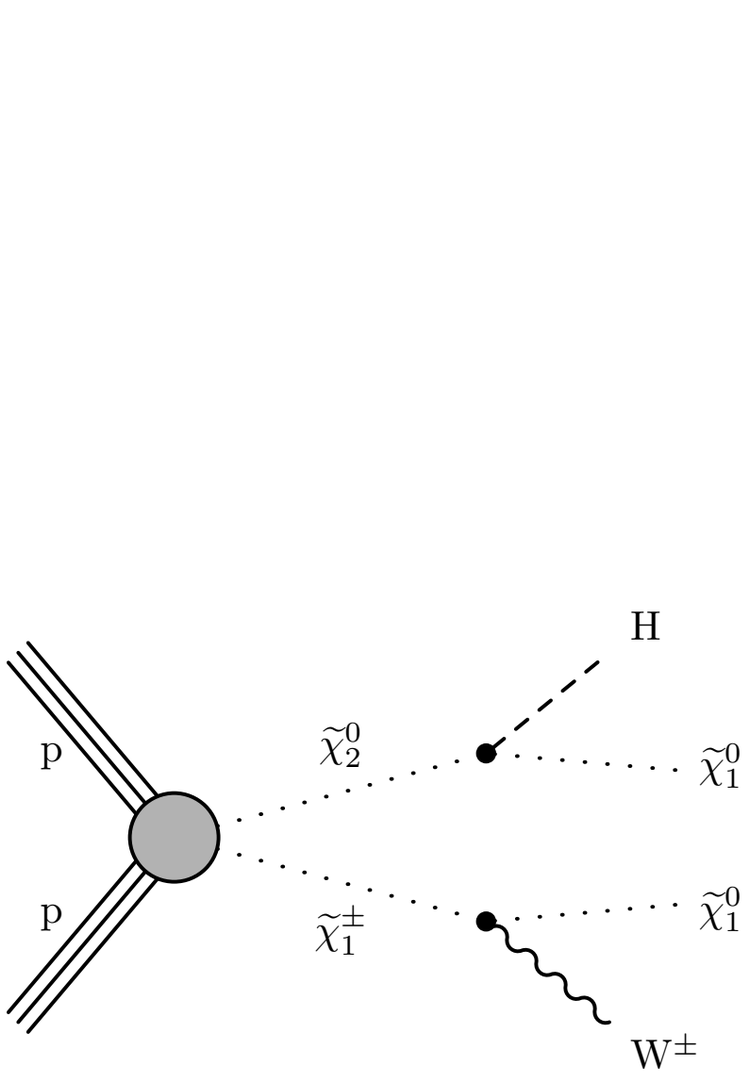
SEARCHES

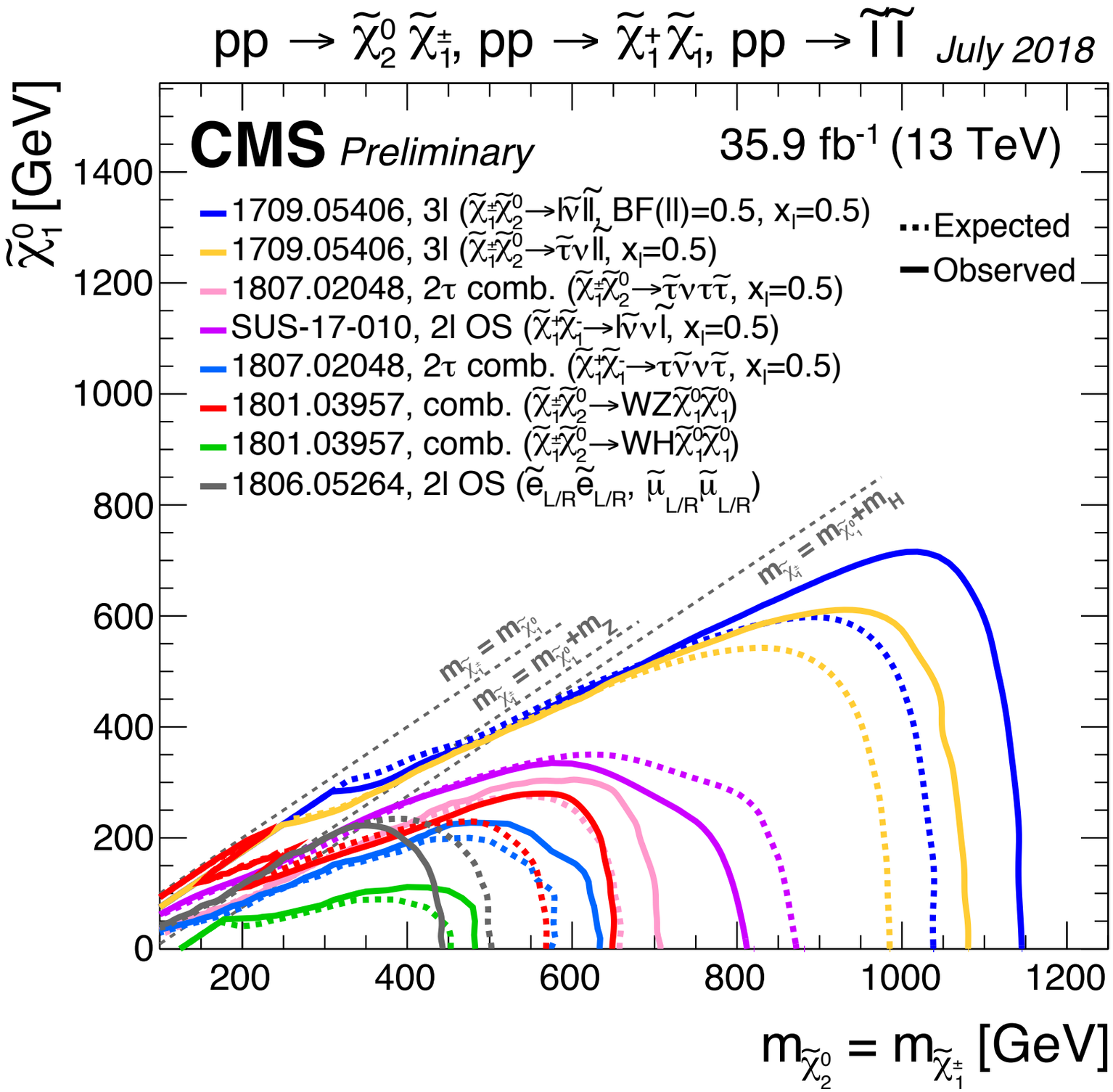
- Biggest jump in mass limits with increased energy at start of Run2
  - Assuming maximal coupling to SM particles
  - Most searches published with 36 fb-1 of data
- With full Run2 data focus on exploring weakly coupled phenomena
  - Expect new publications with 150 fb^{-1}

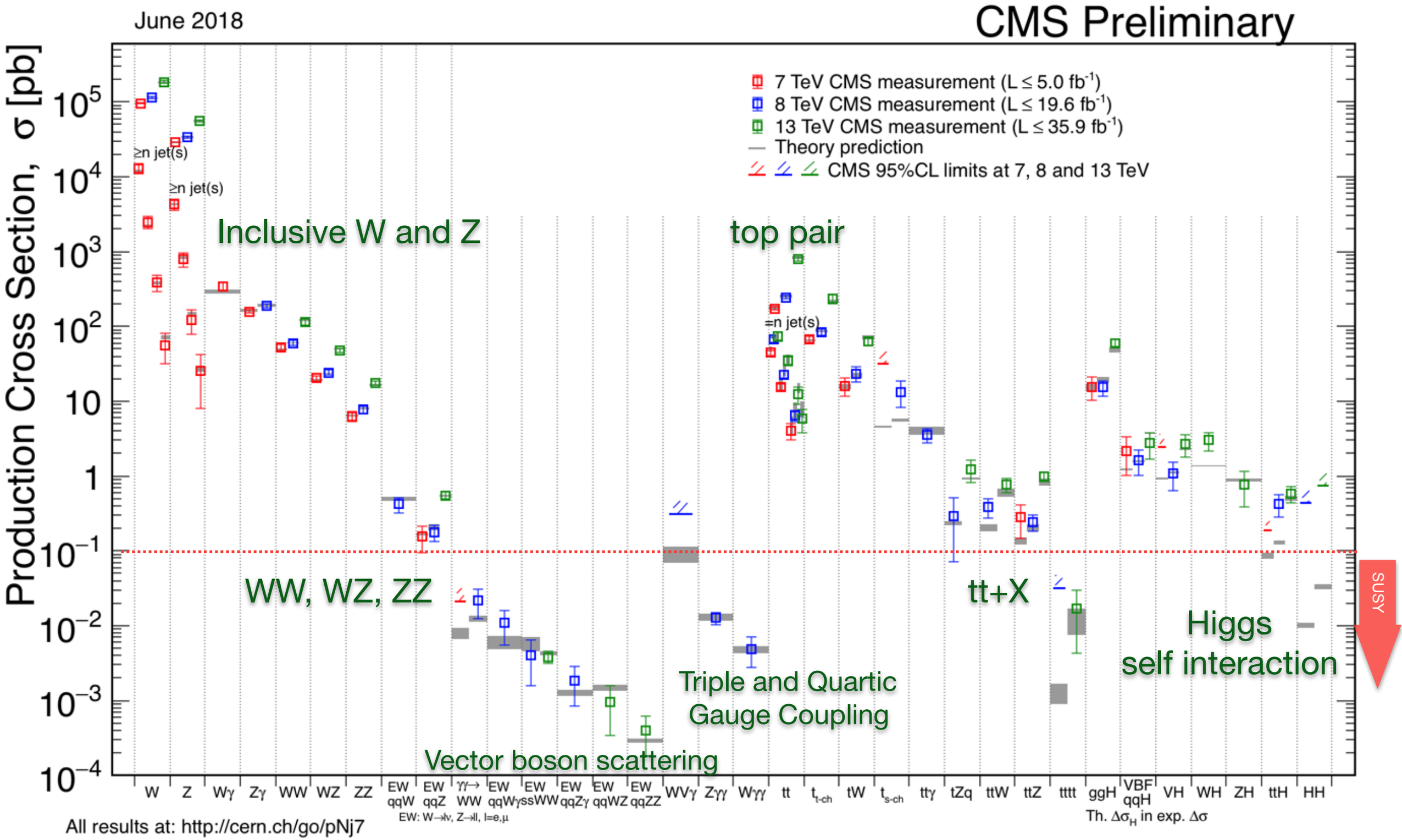


SUPERSYMMETRY

- Higgs now used to probe electroweak production of supersymmetry
  - In just 6 years from discovery to Higgs tagging



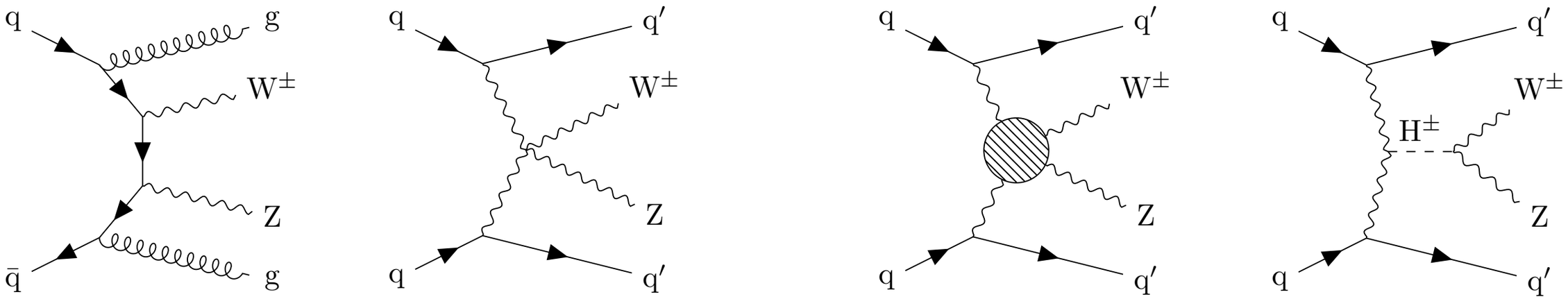




STANDARD MODEL

NEW PHYSICS THROUGH PRECISION

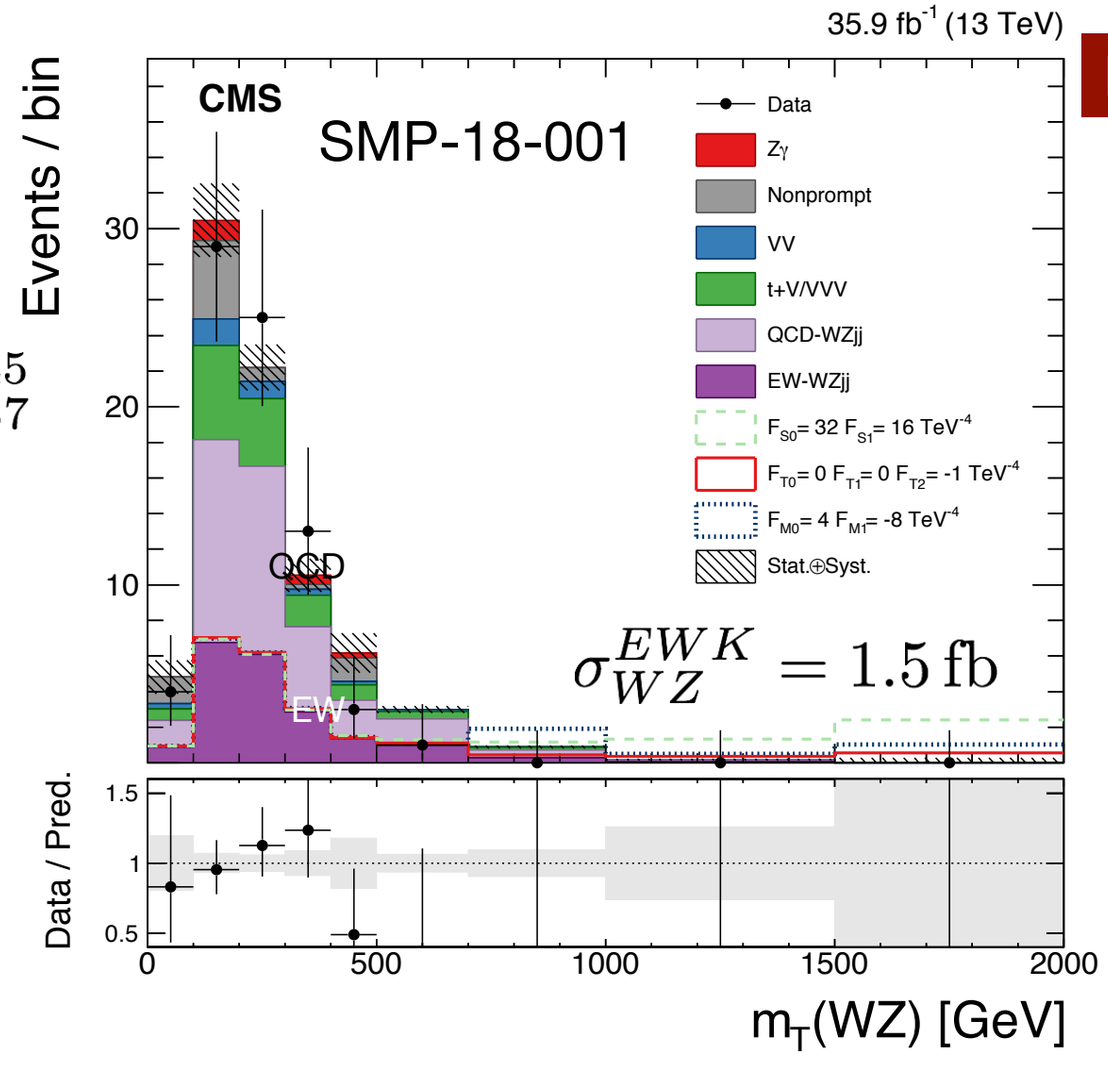
VECTOR BOSON SCATTERING

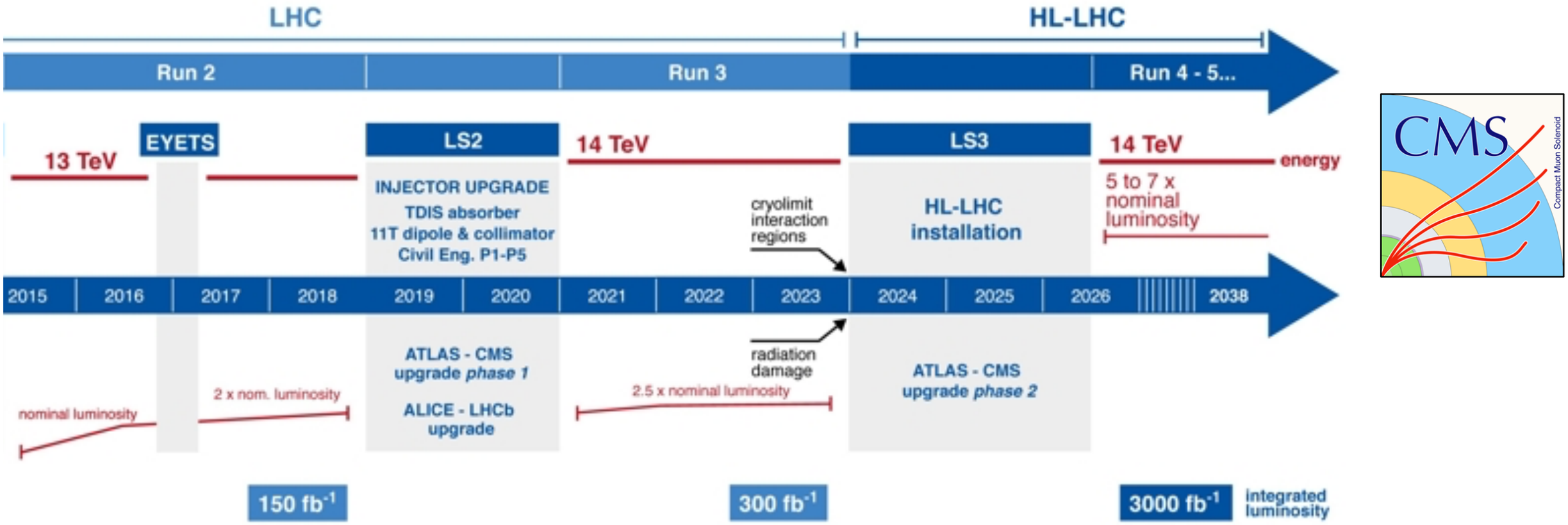


- Quartic gauge couplings known exactly in SM and sensitive to new physics contributions
  - Disentangle QCD and EW contribution through jet kinematics
- Observed significance: 1.9σ
  - expected 2.7σ $\sigma/\sigma_{SM} = 0.64^{+0.45}_{-0.37}$
- Important milestone for Run2 and longterm LHC program towards study of WW scattering
  - Evidence for same-sign WW already published in 2017

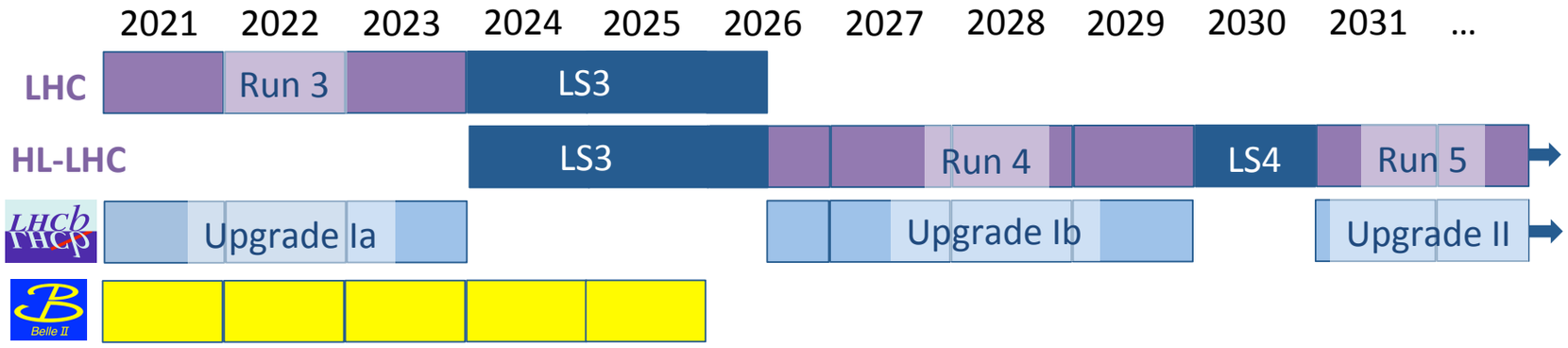
Phys. Rev. Lett. 120, 081801

New





x5 Run1 x2 Run2 x10 Run3



TOWARDS HIGH LUMINOSITY

WITH UPGRADED DETECTORS

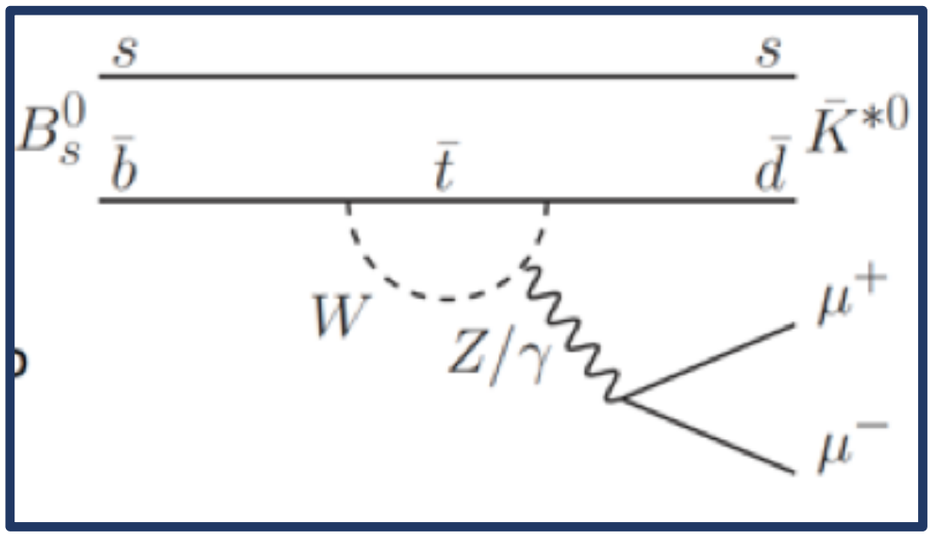
LFUV WITH $B^0_s \to K^{*0}\,\mu^+\mu^-$

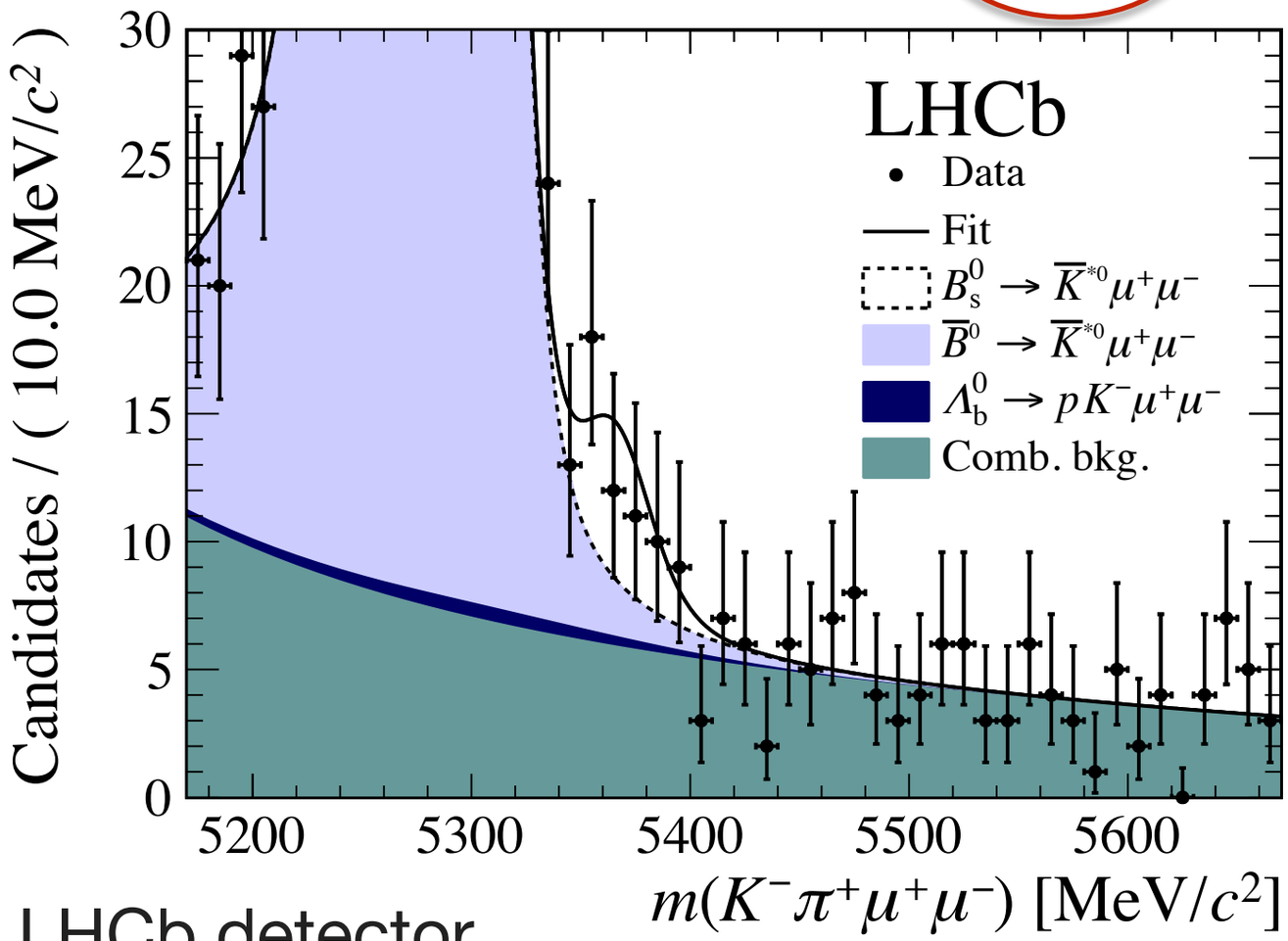
- Heavily suppressed b → dll transition in Standard Model
  - complementary to b → sll transitions in B^0_d decays

arXiv:1804.07167,
Run 1+2, 4.6 fb^{-1}

- Evidence of 3.4σ (38 ± 12 events) consistent with prediction

$$\mathcal{B}(B^0_s \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$

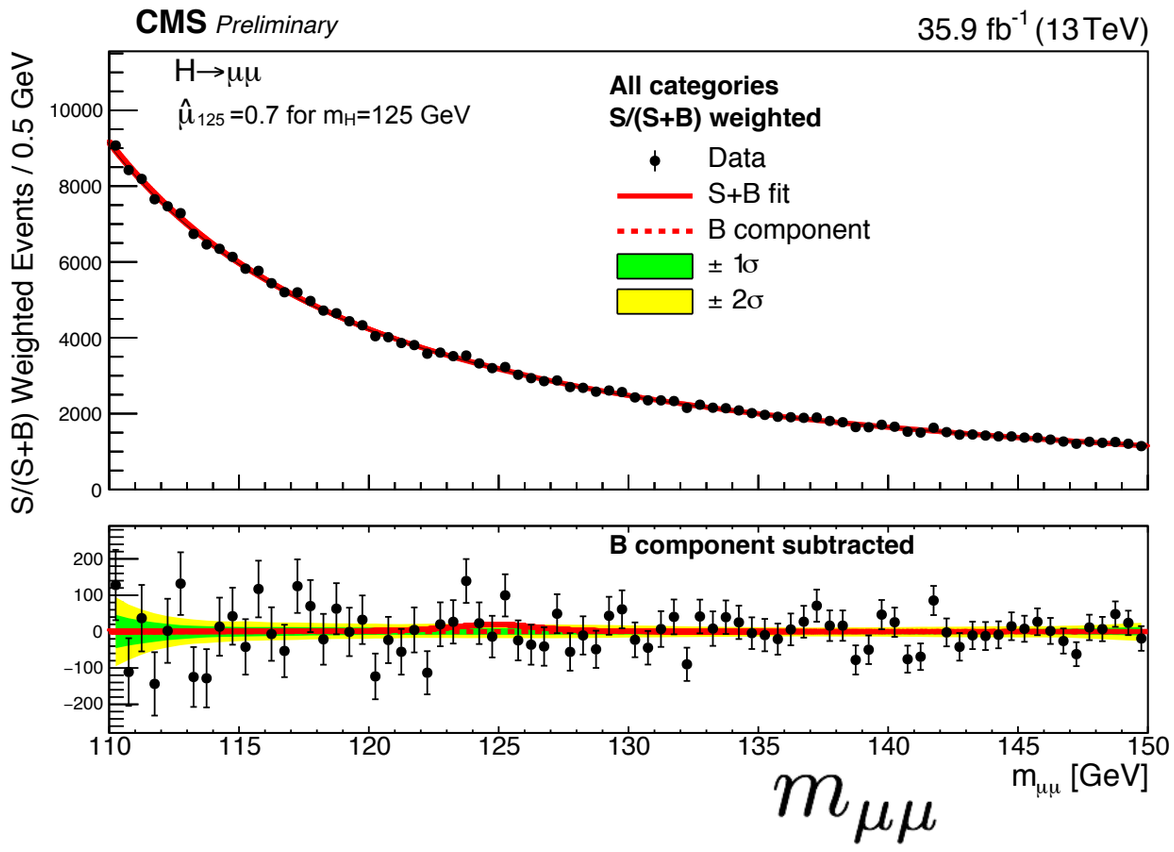


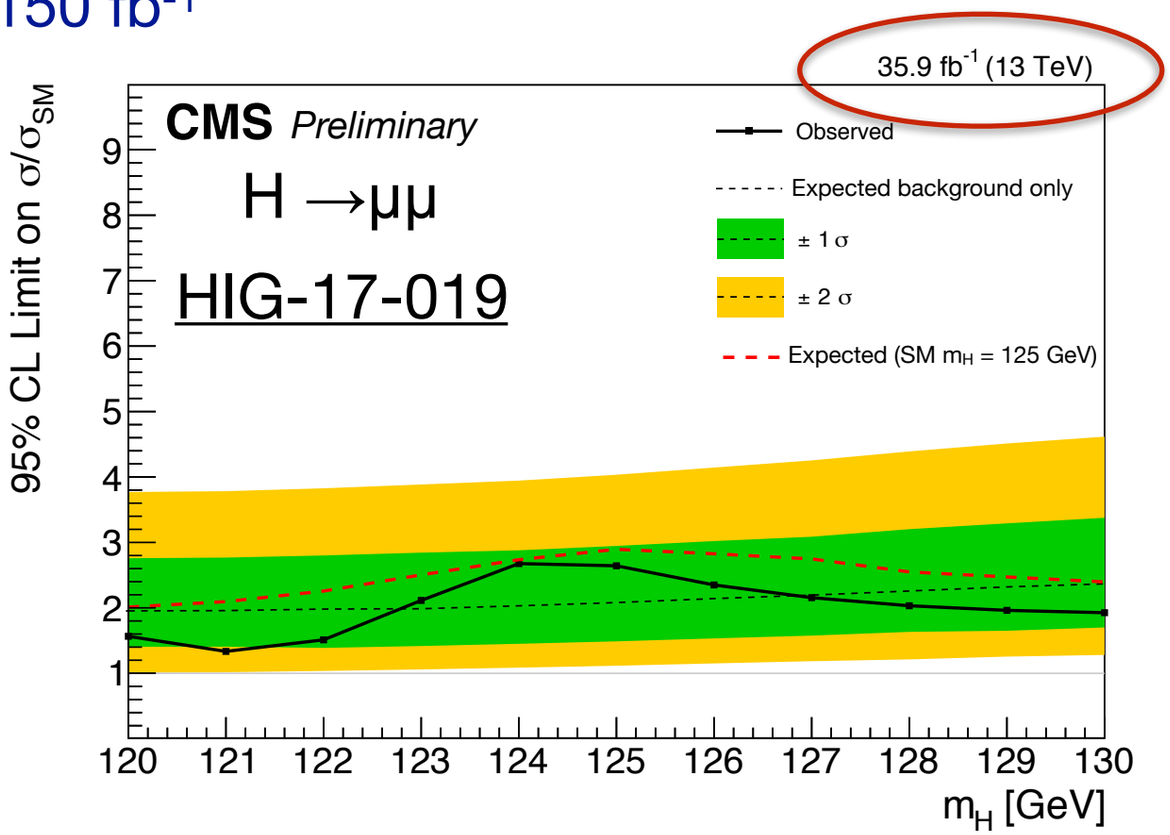


- Angular analysis with upgraded LHCb detector
  - Sensitivity with Run3 possibly better than current B_d measurement

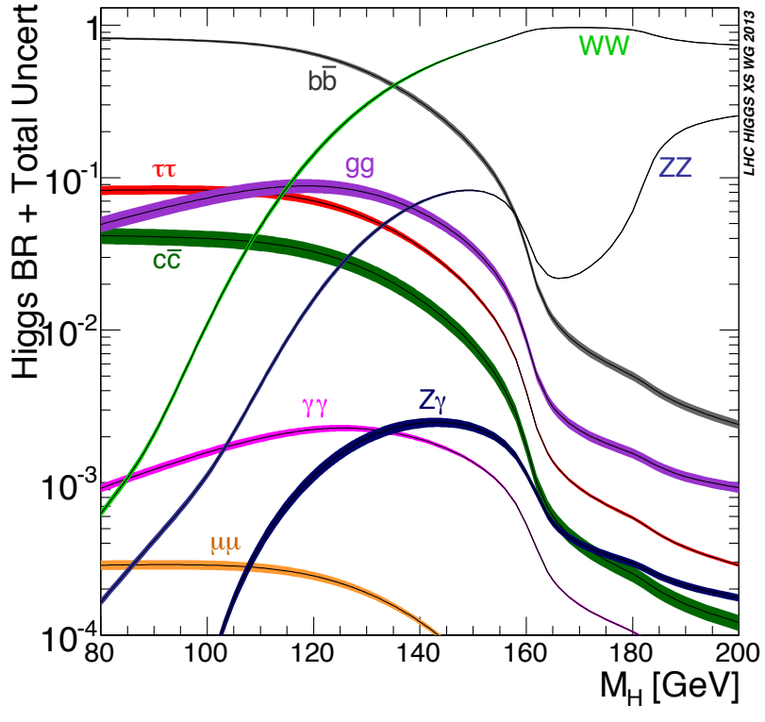
RARE HIGGS DECAYS

- Already tackling H →μμ thanks to excellent detector performance
  - Looking forward to updated result with 150 fb^{-1}





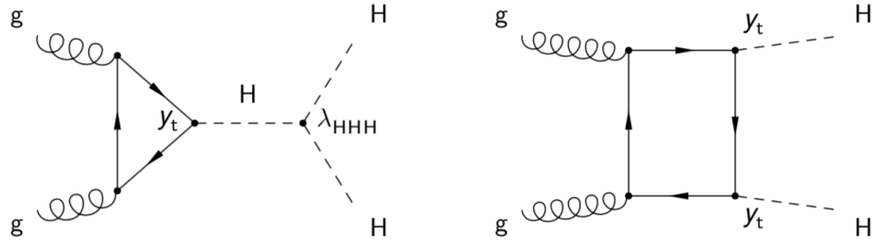
- First results now also on more challenging decay modes
  - Higgs to Zγ
- Run3 and HL-LHC needed for first evidence of rare decays
  - Higgs to charm



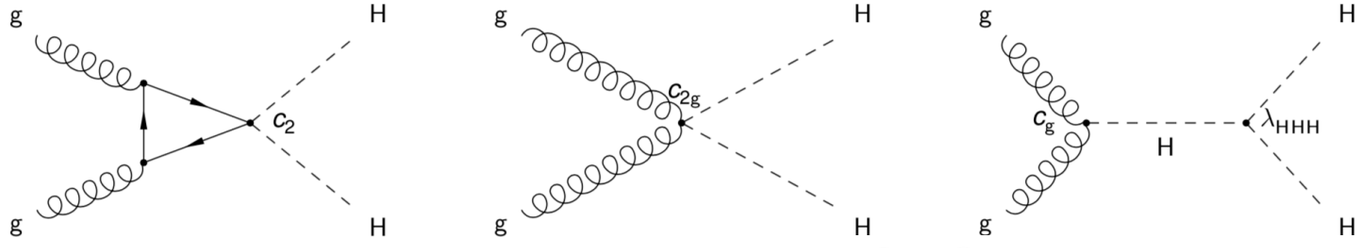
HIGGS SELF-INTERACTION

- Understanding Higgs sector requires measurement of its self-interaction

Standard Model

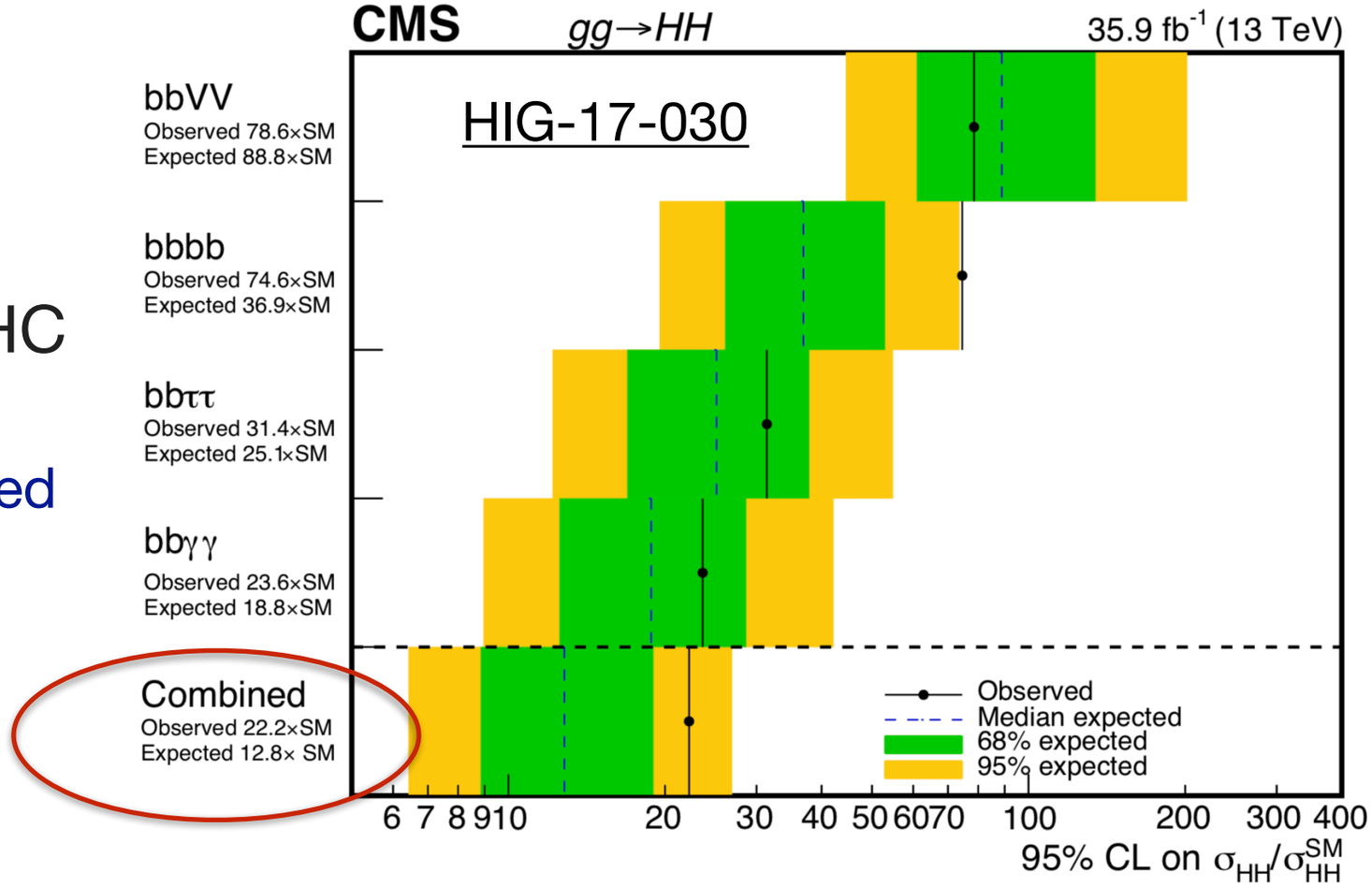


New Physics



New

- Promising for Run3 and HI-LHC
  - currently limited by statistics
  - room for even more sophisticated analysis techniques



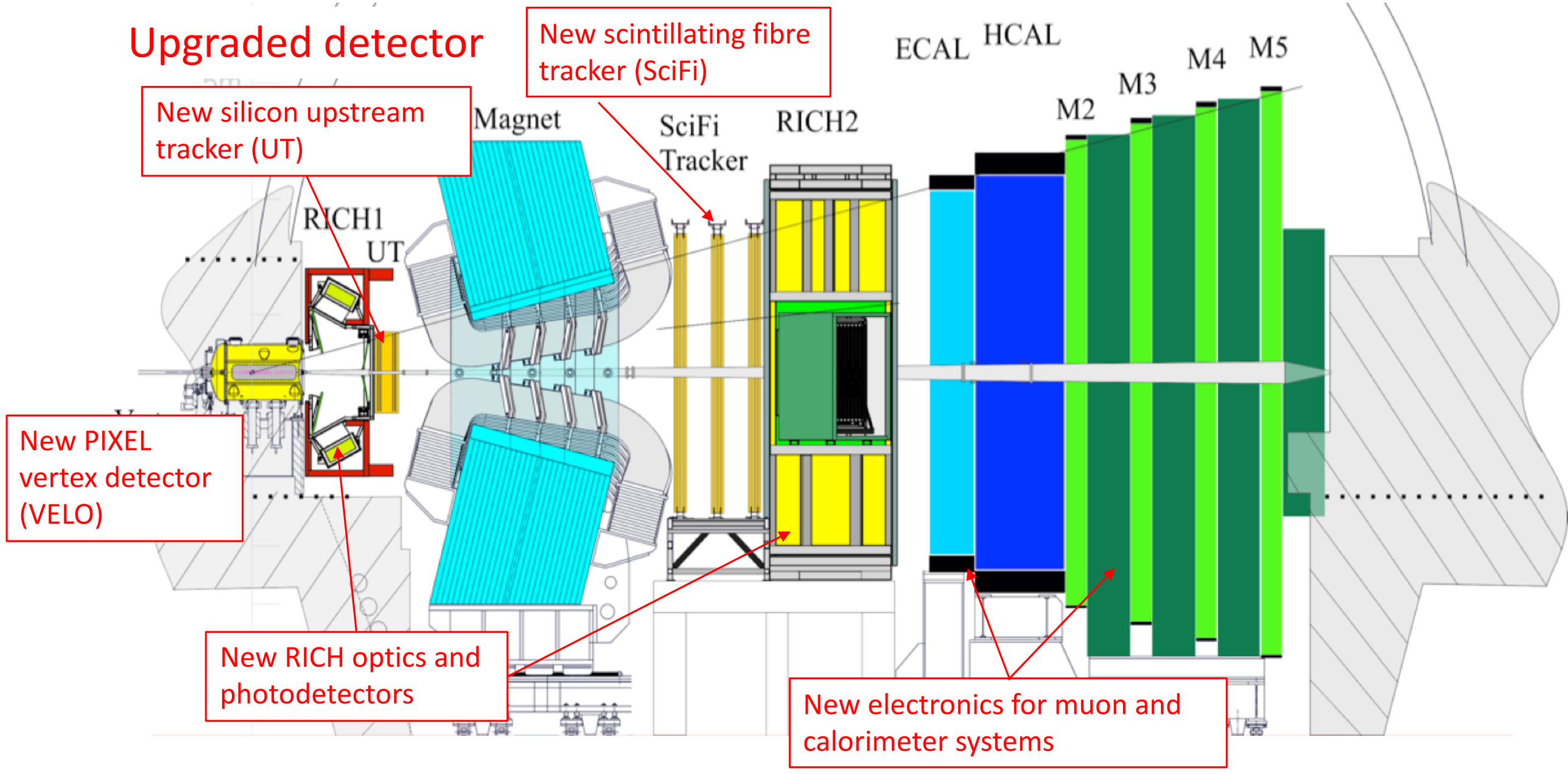
OUTLOOK

- CMS getting close to establishing Yukawa interaction for third generation fermions
  - Run 2 data should provide first hint for 2nd generation
  - First results paving the way for Run3 and HL-LHC program
- LHCb entering precision measurement territory for angle γ
  - Also extending systematic study of CP violation to rare B decays
  - Tremendous advancement also in charm and beauty spectroscopy
- Both experiments investigating intriguing flavor anomalies
  - Adding new final states at low mass
  - Tackling possible sources of anomalies at high mass
- Run2 an opportunity to bridge the gap between Searches and Standard Model physics
  - Precision top and electroweak measurements sensitive to new physics
- ***Upgraded*** *detectors* ***key*** *for a* ***successful*** *physics* ***program*** *at high luminosity*

Extra Material

LHCb UPGRADE FOR RUN 3 IN A SNAPSHOT

All sub-detectors read out at 40 MHz for a **fully software trigger**



CERN-LHCC-2012-007

CMS Phase II Upgrade

L1-Trigger/HLT/DAQ

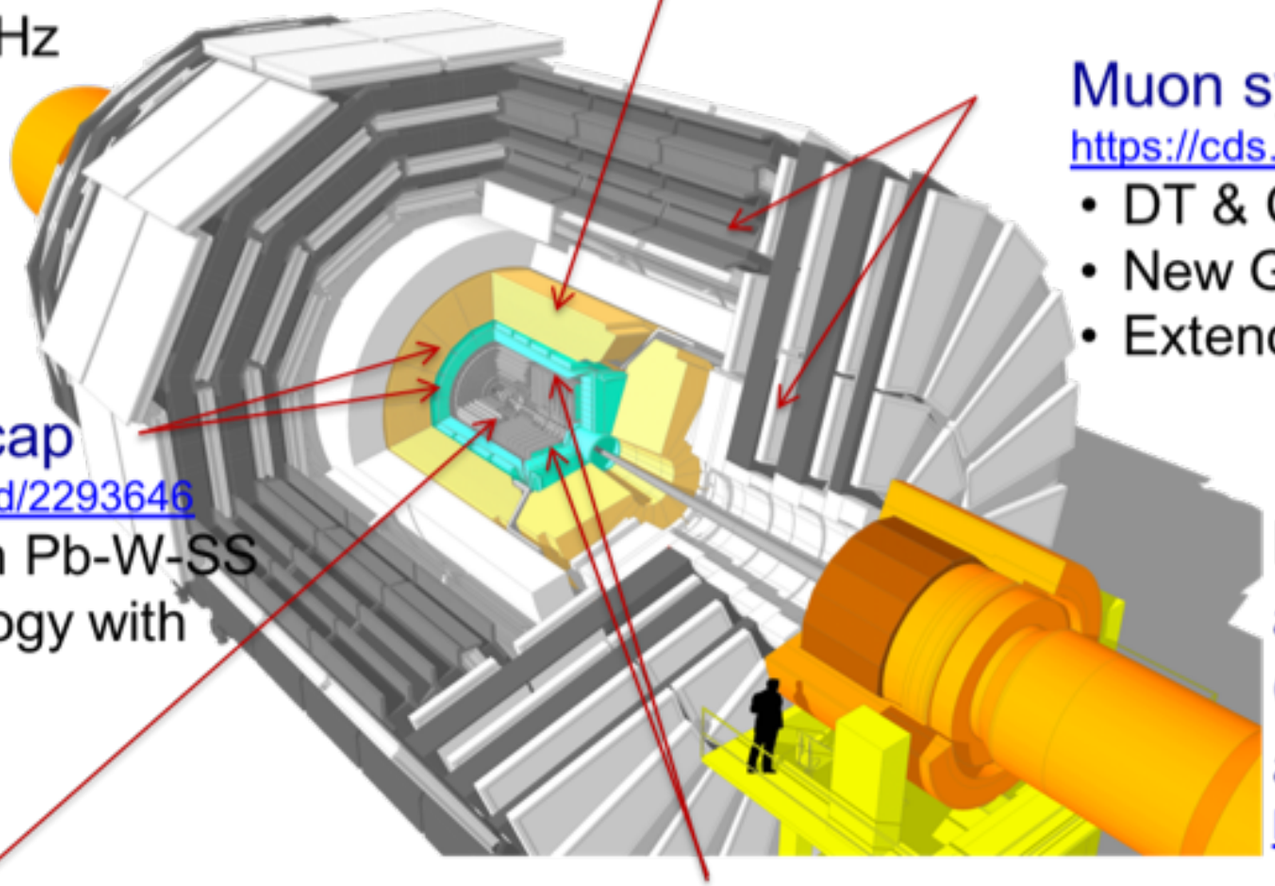
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Calorimeter Endcap

https://cds.cern.ch/record/2293646

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2296612

- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes