RECENT HIGHLIGHTS FROM THE CMS EXPERIMENT

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Bormio, Italy, 21/1/19

57th Winter Meeting on Nuclear Physics

Outline

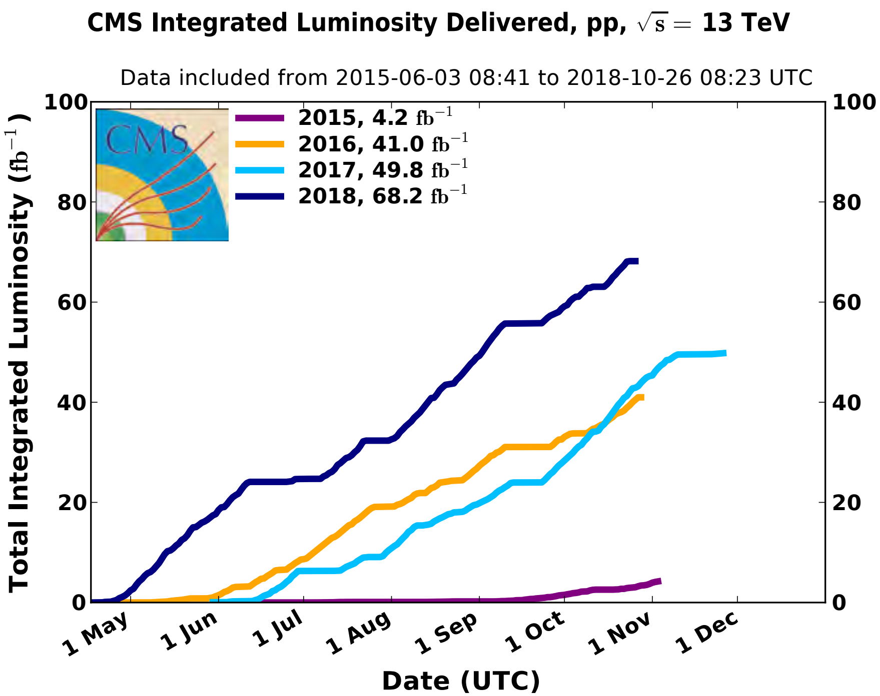
- LHC Performance: Three Machines in One
- 30,000 Feet Highlights:
  - Standard Model Measurements
  - Searches for New Physics
- Conclusions: Quo Vadis?

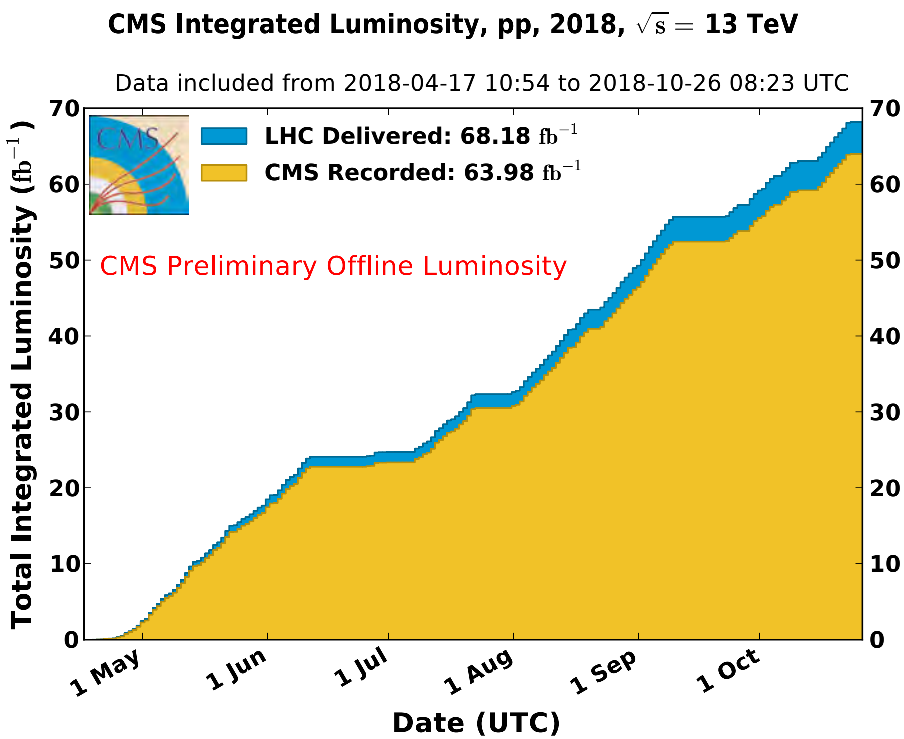
- Disclaimer: these are highlights of just a few of a large number of CMS results, with clear personal bias: they tell a story, rather than simply make up a shopping list...
- For the full physics analysis landscape in CMS, please refer to:
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/index.html
- P.S. And just because I am the first LHC speaker, it doesn't mean that things I'll be describing are unique to CMS - in fact you will hear about many exciting results from ALICE, ATLAS, and LHCb later this week!

The LHC Legacy

LHC Run 2 - Big Success

- 160/fb has been delivered by the LHC in Run 2 (2015-2018), at a c.o.m. of 13 TeV, exceeding the integrated luminosity projections
- Over 140/fb of physics quality data recorded
- Thank you, LHC, for a spectacular run!





Three Machines in One!

The LHC Legacy

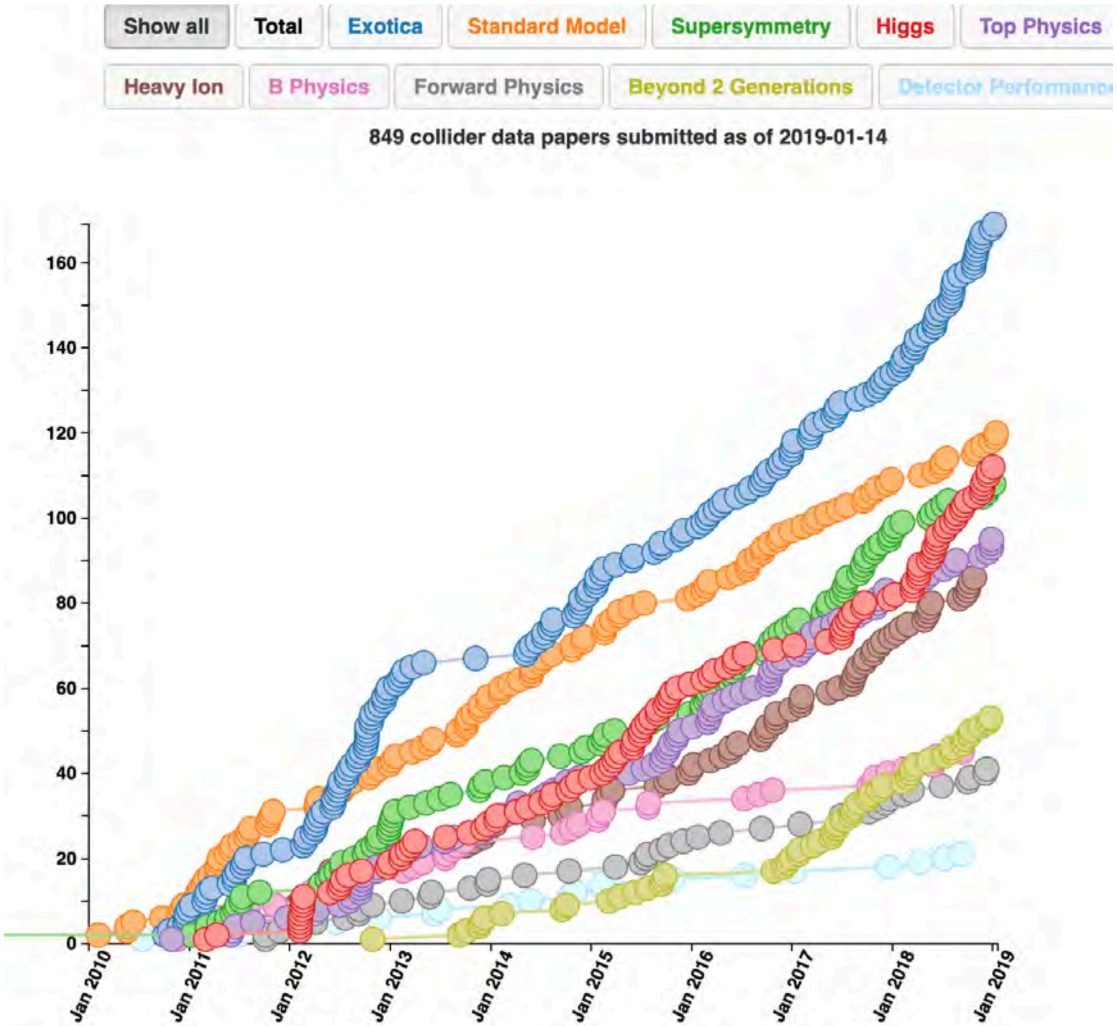
- The LHC has figuratively replaced three machines in one go:
  - Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
  - BaBar/Belle B factories (precision B physics)
  - RHIC (heavy-ion physics)
- The LHC experiments in general, and CMS in particular, are very successful in all these three areas
- Would not be possible without theoretical and phenomenological breakthroughs of the past decade:
  - Higher-order calculations ("NLO revolution"), modern Monte Carlo generators, reduced and better estimated PDF uncertainties
- Since it's impossible to cover all the aspects of this impressive program in one talk, I'll present a few highlights of recent CMS results in Higgs physics, SM physics, flavor physics, heavy-ion physics, and the discovery program, with the focus on the latter

Challenge: Big Data

- The amount of data produced by CMS is truly enormous: over 10 PB/year
- It takes some time to fully calibrate and align the CMS detector, and then reconstruct the data with the best possible calibrations
- As a result, most of the results presented in these talk are based on 2016 data, with a few also including 2017 data
- First results on the full Run 2 dataset at 13 TeV will be available by the 2019 Moriond conferences (~2 months)
  - Impressive, given that the 2018 run ended just 2 months ago!
- Overall, a very fast turn-around compared to earlier generations of HEP experiments!

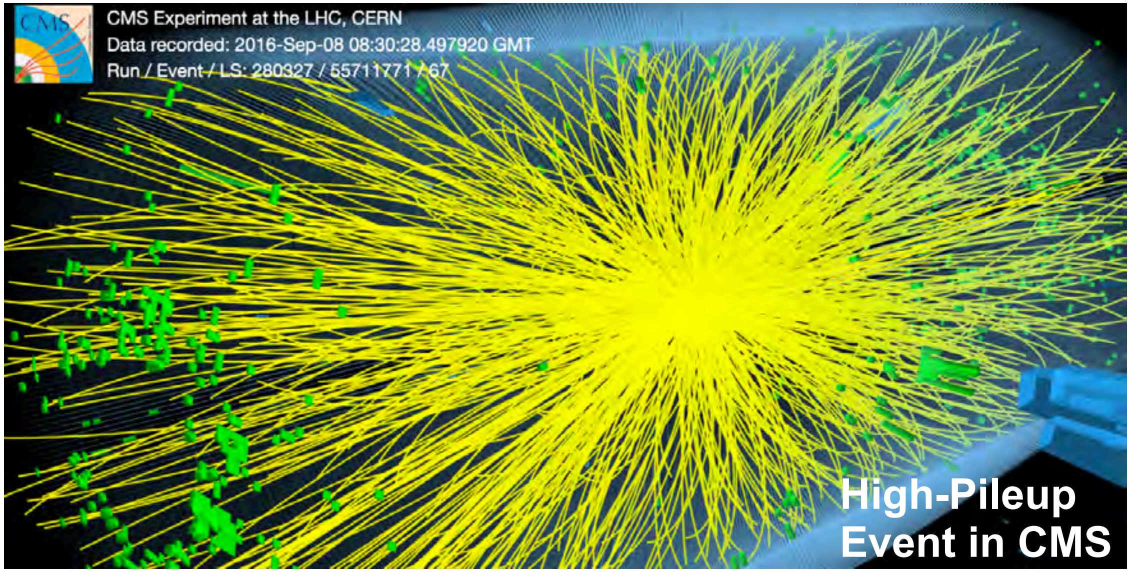
Publish or Perish!

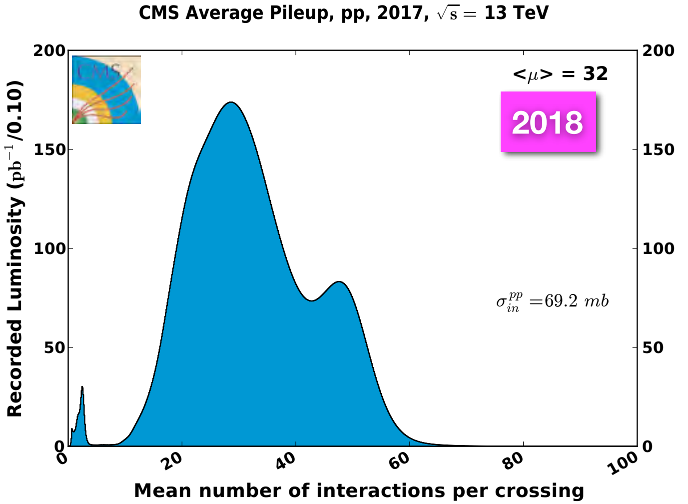
- As of today, we have submitted 849 pairs based on collision data - over a hundred/year!



Challenge: Pileup

- Every event is nearly as busy as a heavy-ion event!
- Average number of simultaneous interactions per bunch crossing (pileup, PU) was 32 in the latest, 2018 run
  - This exceeds the original LHC design PU number of 20
- Developed sophisticated tools to mitigate the effects of the PU: particle-flow reconstruction, MVA techniques





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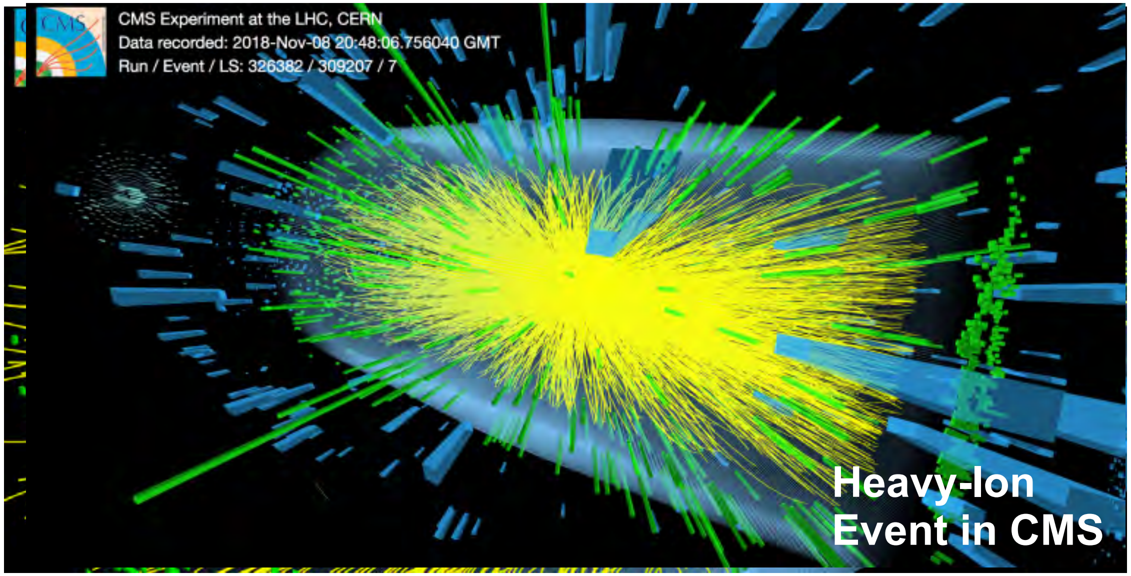
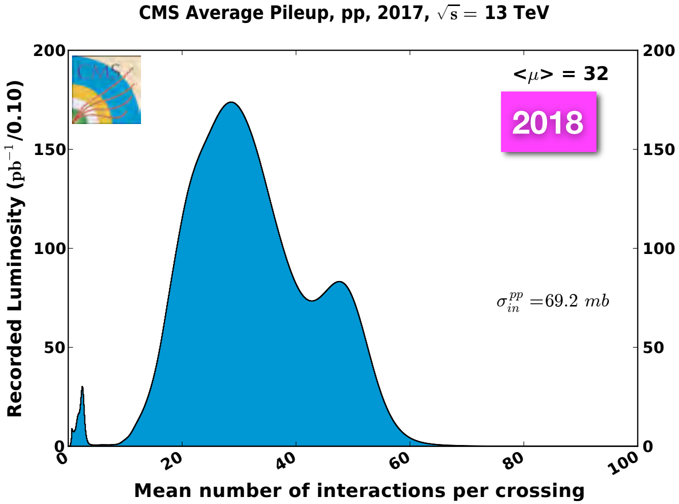




Higgs Physics Highlights

Higgs Factory

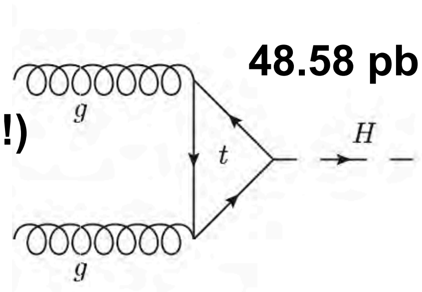
- LHC is the Higgs factory
- At 13 TeV, the production cross section for the Higgs boson, dominated by gluon-gluon fusion, is ~50 pb
  - 8M Higgs bosons delivered by the LHC in Run 2!
  - By now ATLAS and CMS could have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
- But: triggering is a big challenge:
  - Most of gg → H(bb) events were never put on tape, which is how half of the Higgs bosons are produced and decay
- Need to pursue aggressive triggering strategies and go for lower cross section production mechanisms to observe all possible Higgs boson decays and couplings

Standard Model Higgs Boson

- The properties of the SM Higgs boson are completely defined, once its mass is known
- Four production mechanisms: gluon fusion (ggF, a); vector boson fusion (VBF, b); associated production with a vector boson (VH, c) or a top quark pair (ttH, d)
- N.B. Tour de force state-of-the-art theoretical work in calculating cross sections

N^{3}LO (QCD) (!) + NLO (EW)

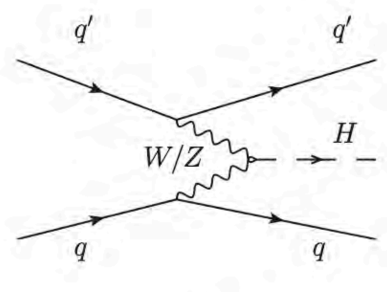
48.58 pb



a)

3.78 pb

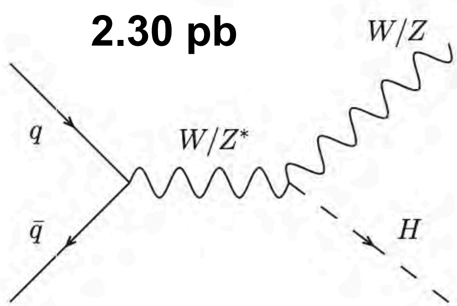
NNLO (QCD) + NLO (EW)



b)

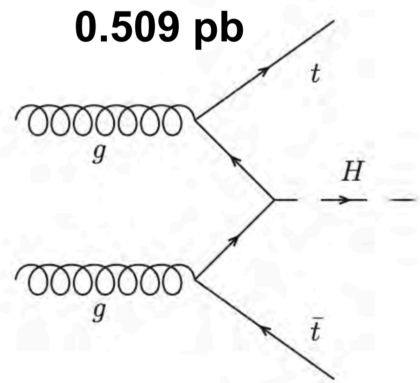
NNLO (QCD) + NLO (EW) except for gg → ZH @ NLO (QCD)

2.30 pb



c)

0.509 pb



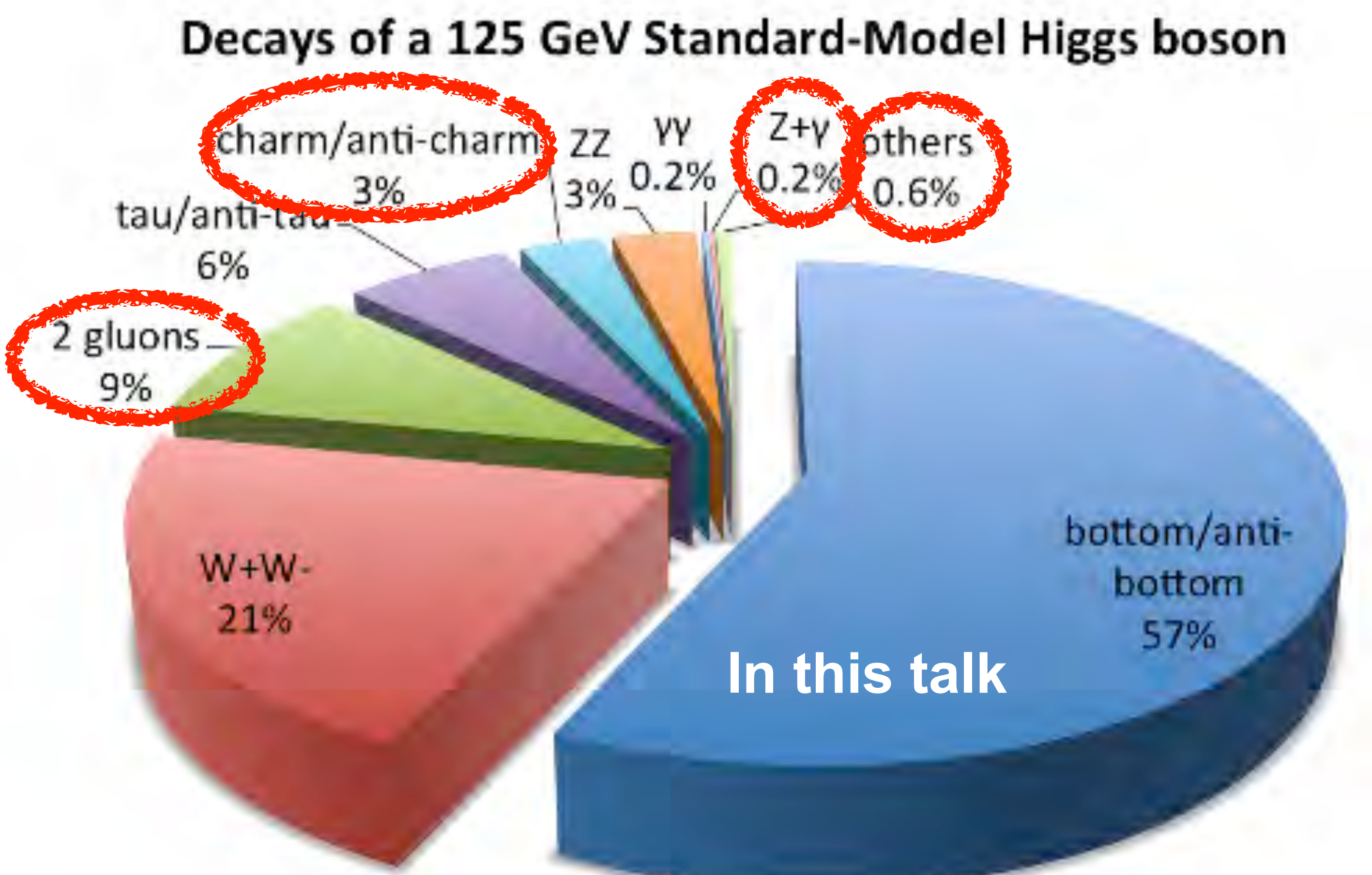
d)

NNLO (QCD)

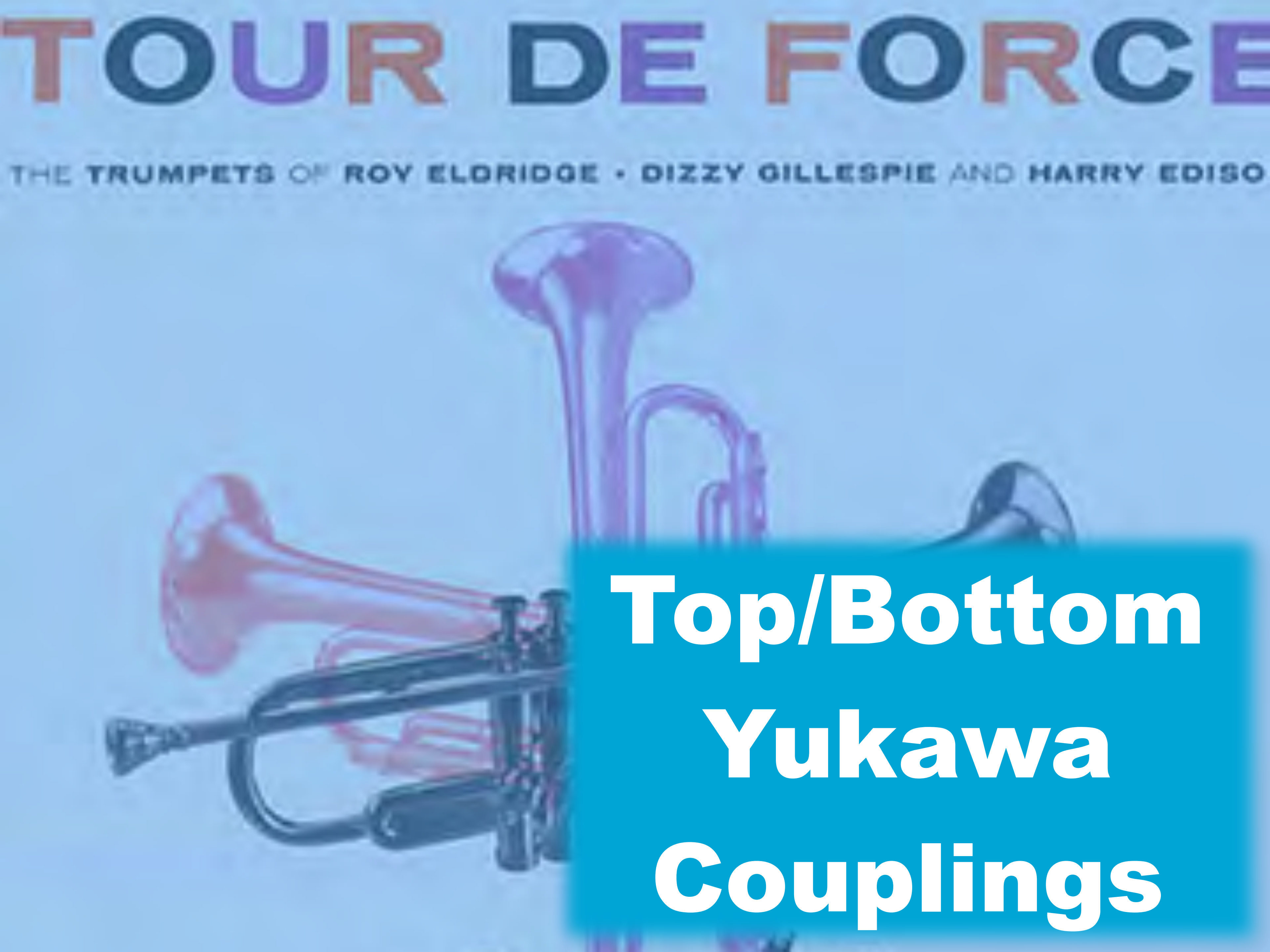
LHC Higgs XS WG arXiv:1610.07922

Higgs Boson Decays

- ✦ Decays circled in red have not been observed yet - 13% of the "pie" is still missing!

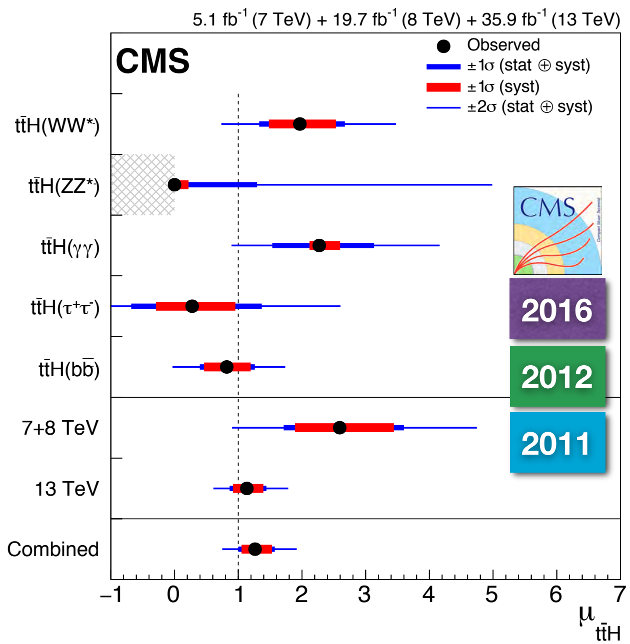


Top/Bottom Yukawa Couplings

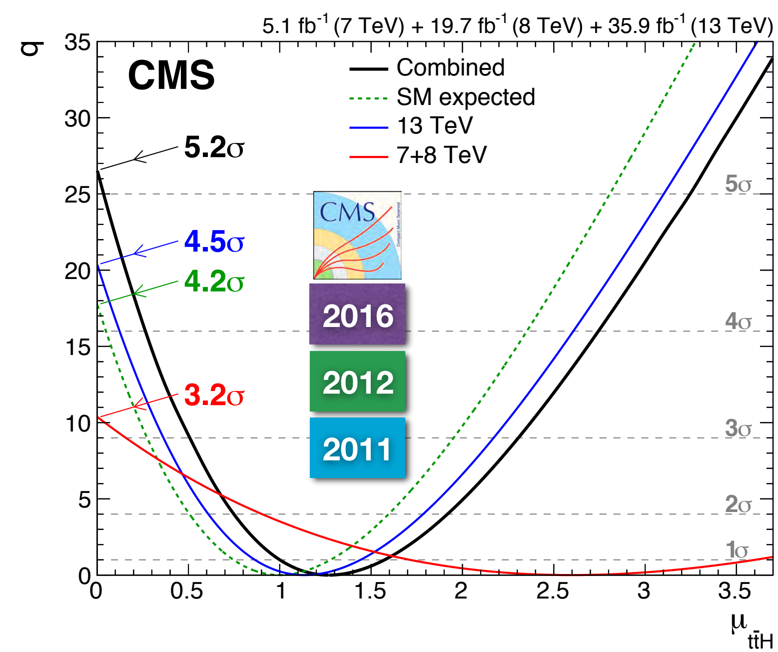


Observation of ttH Production

- Last April, CMS reported first observation of ttH production
  - Tour de force analysis, combining multiple channels (bb, ττ, γγ, multileptons), as well as 7, 8, and 13 TeV data
  - 5.2σ (4.2σ) observed (expected) significance, benefiting from an excess seen in Run 1 data
  - $\mu = \sigma_{exp}/\sigma_{th} = 1.26^{+0.31}_{-0.26}$, in agreement with the SM



CMS arXiv:1804.02610



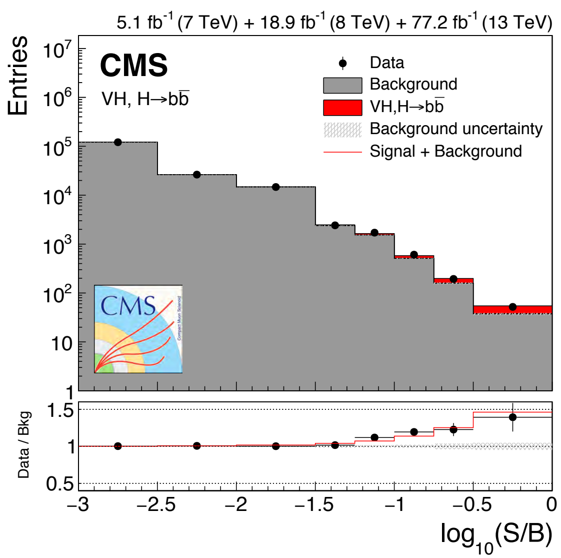
Observation of the H(bb) Decay

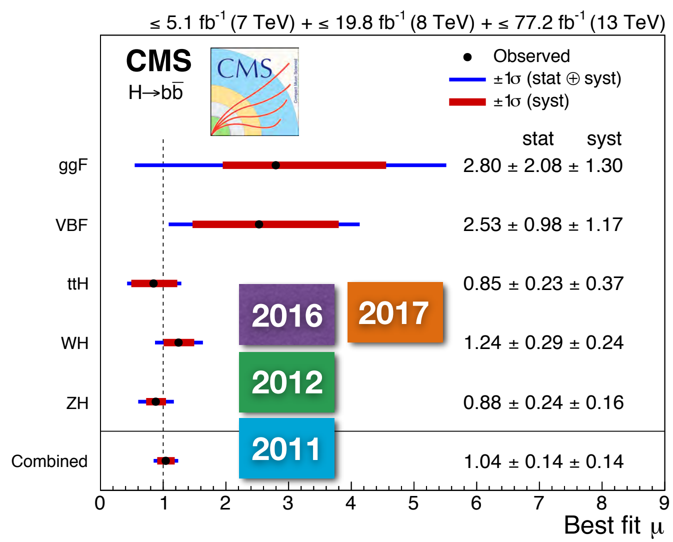
- Ironically, the dominant decay mode of the Higgs boson was the hardest to observe!
  - Took ATLAS and CMS over 6 years to publish first observation of the H(bb) decay
- Despite the large branching fraction, the dominant production mode is swamped by overwhelming QCD background
- Until recently the only viable channels were VH
  - But: there is a hope for observing H(bb) in ggF (see later) and even ttH(bb), as evident from the first ttH signal observation

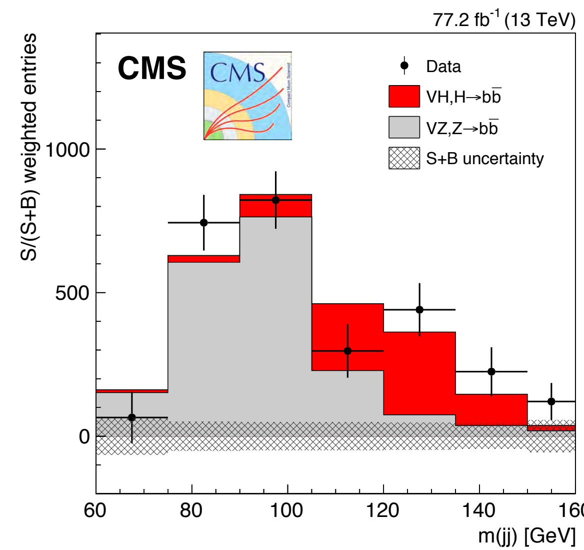
Observation of H(bb)

- Another tour-de-force analysis, using multiple event categories and MVA techniques, as well as advanced b tagging algorithms
  - Includes 2011, 2012, 2016, and 2017 data sets
  - The signal is evident in the b-tagged dijet mass distribution, weighted by the S/(S+B) ratio
- Observed (expected) significance: 5.6σ (5.5σ)
- $\mu = 1.04 \pm 0.20$

CMS arXiv:1808.08242





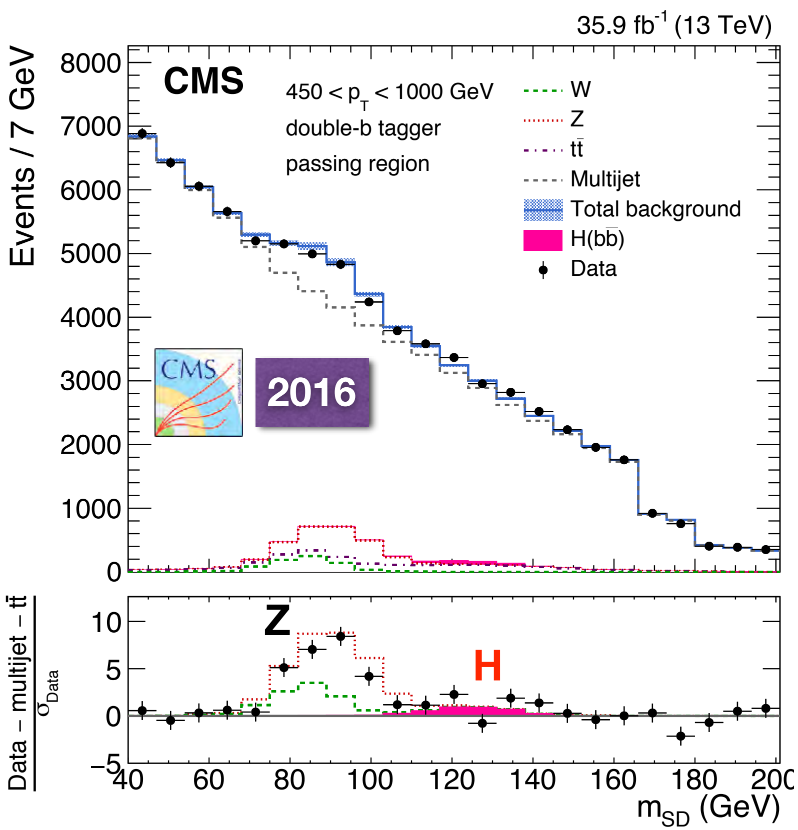


Towards ggF H(bb)

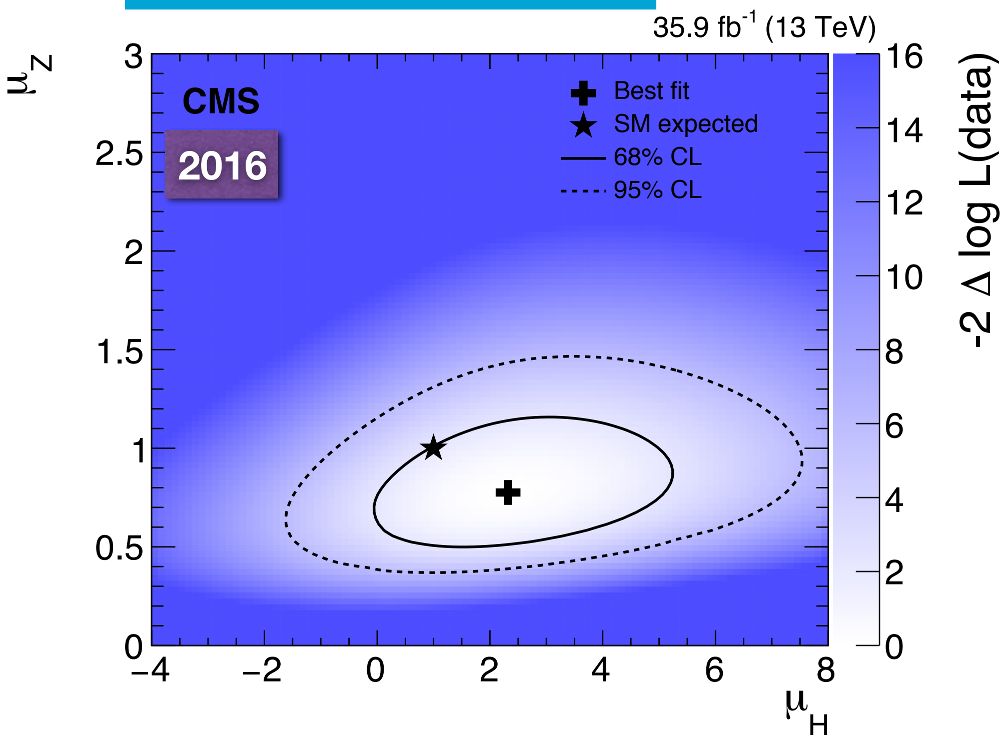
- Novel idea based on significant recent progress in the jet substructure techniques, allowing to reconstruct Lorentz-boosted Higgs bosons via a single, large-radius jet with the mass consistent with that of the Higgs boson
- Since jet mass generally depends on jet p_T (due to Sudakov double-logs, cf., e.g., "Sudakov Peak"), need to additionally decorrelate jet substructure variables from jet p_T
- Turns out that QCD backgrounds for high-mass large-radius jets are actually smaller than for the resolved topology, which provides a powerful method to look for low-mass resonances, e.g., the Higgs boson
- Additional use of b tagging techniques to see whether the jet is consistent with originating from a pair of b quarks, allow to maximize the sensitivity of this search

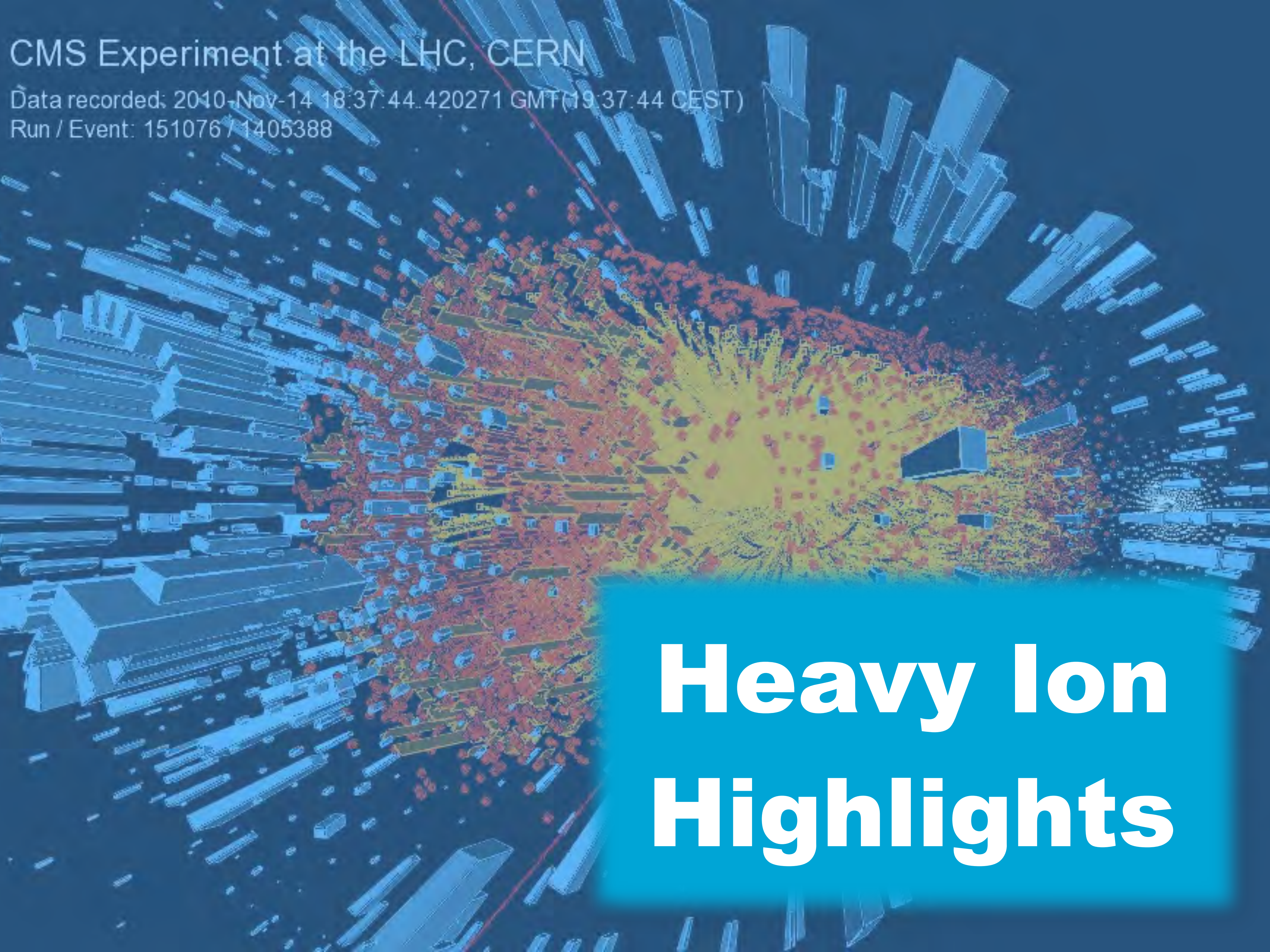
H(bb) in Boosted Channel

- First results are very promising: achieved ~1σ sensitivity w/ 2016 data alone
  - Finalizing the analysis on a full Run 2 data set now
- Ultimately would like to probe the H(gg) decay, which can't be seen otherwise at a hadron collider



CMS arXiv:1709.05543

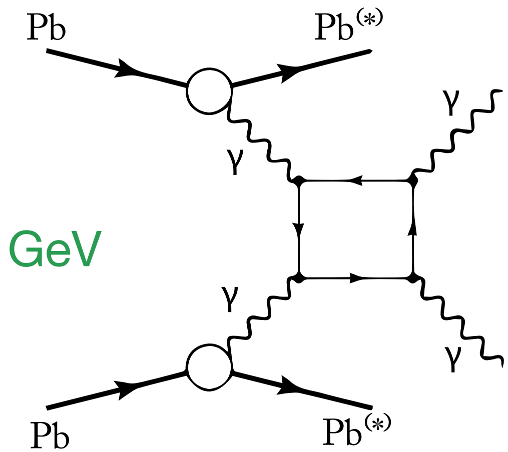


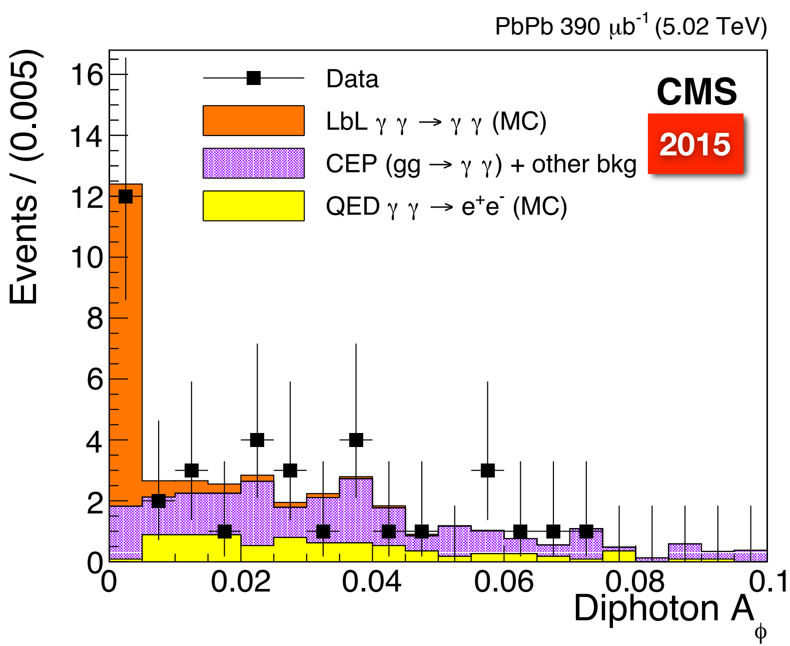


Heavy Ion Highlights

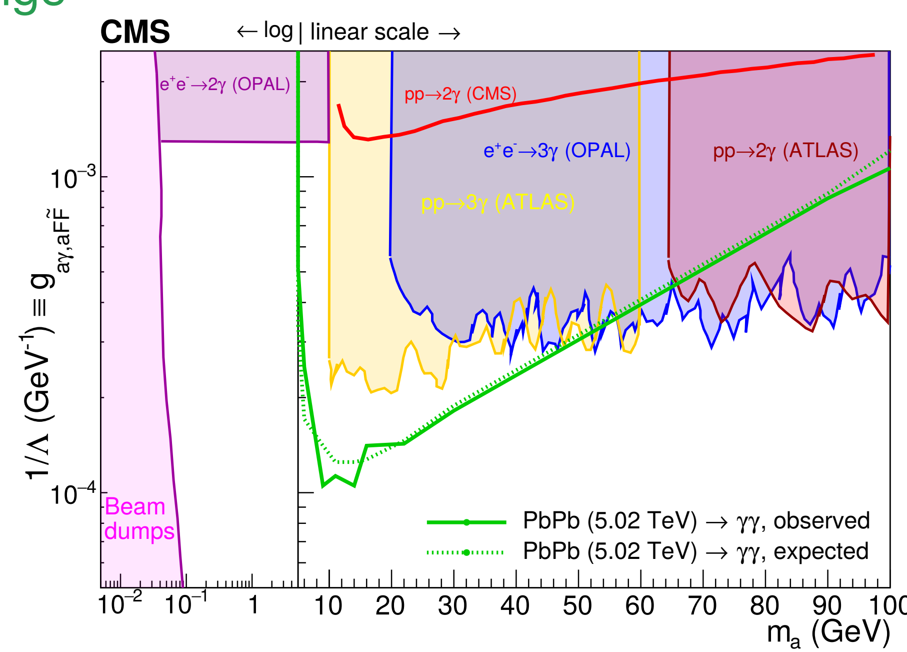
Light-by-Light Scattering

- Use ultraperipheral PbPb collisions to turn the LHC into a photon-photon collider!
  - Photon flux is enhanced by $Z^4 = 5 \times 10^7$ due to coherence!
- $\sigma_{fid}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46$ (stat.) ± 28 (syst.) ± 4 (th.) nb, in agreement with the prediction of 138 ± 14 nb for $m_{\gamma\gamma} > 5$ GeV
  - Observed (expected) significance of 4.1σ (4.4σ)
- Also interpreted as limits on axion-like particles via $\gamma\gamma \to a \to \gamma\gamma$; best limits in 5-50 GeV range





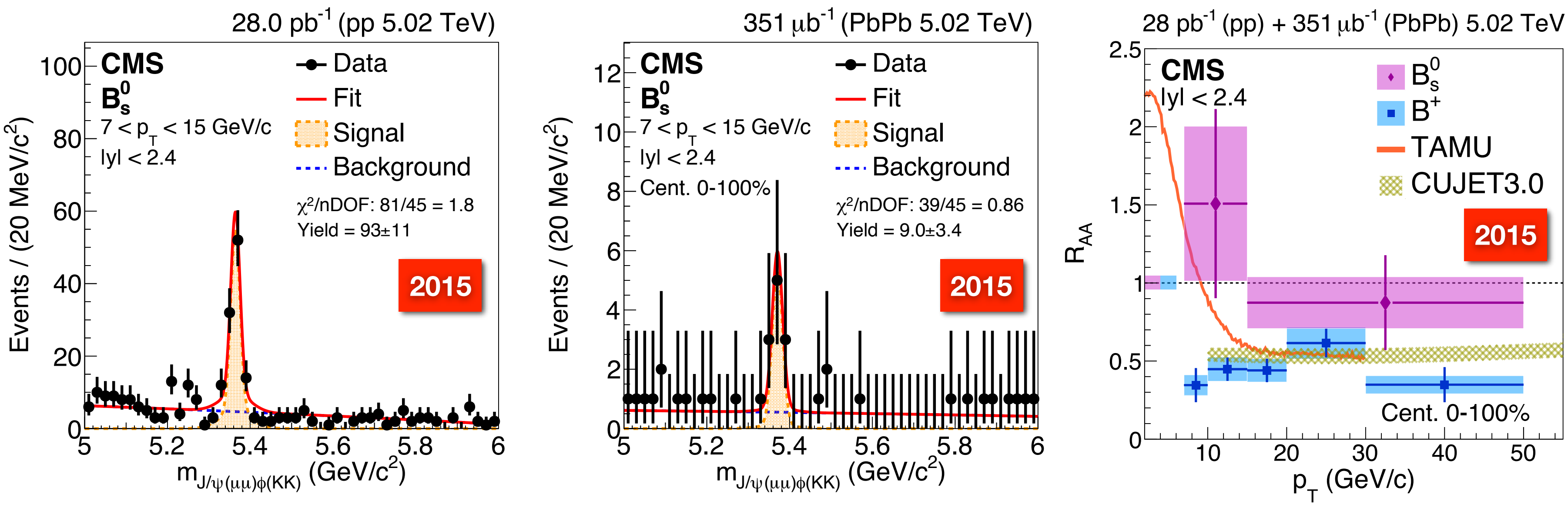
CMS arXiv:1810.04602



B_s Production in PbPb

- First observation of B_s production in heavy-ion collisions (PbPb) and a measurement of the differential cross section and a nuclear modification factor R_{AA}
  - B_s mesons are reconstructed via an exclusive $J/\psi(\mu\mu)\phi(KK)$ decay
  - Multivariate analysis techniques are used to extract signal in PbPb collisions
- The R_{AA} is enhanced at 2σ level relative to that for the B^+ mesons, consistent with theoretical predictions of enhanced strange quark production in hot nuclear medium due to recombination processes

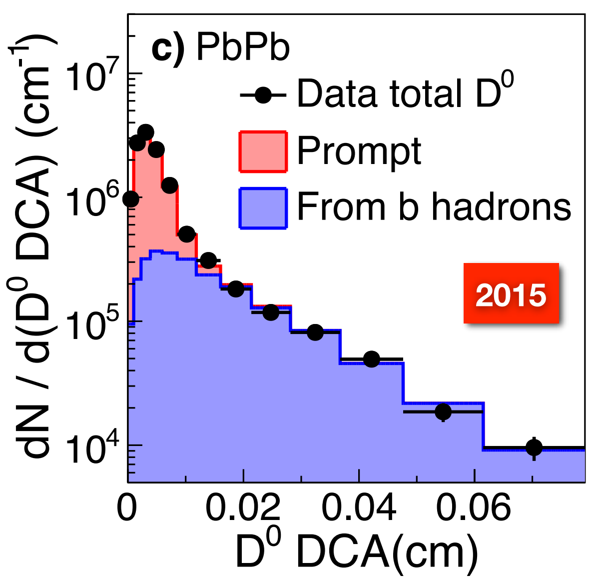
CMS arXiv:1810.03022

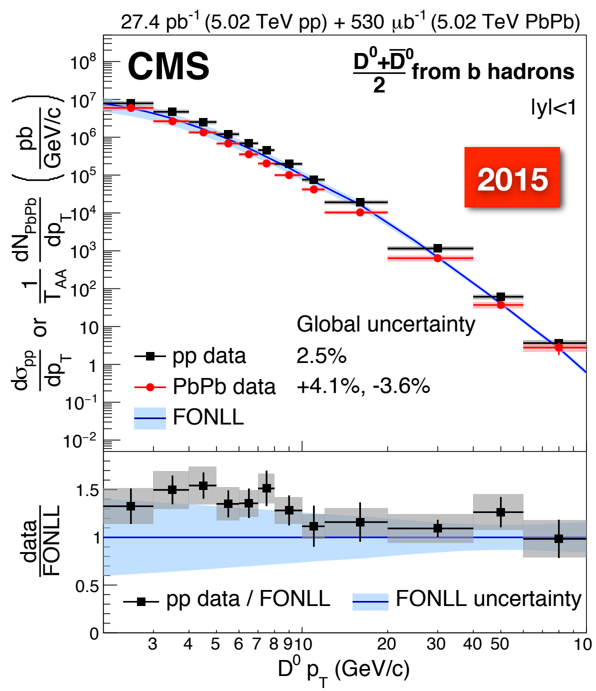


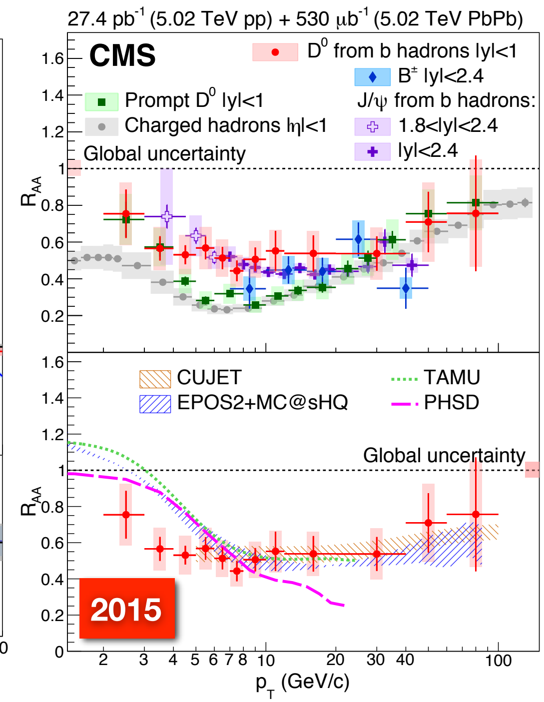
Beauty Suppression in PbPb

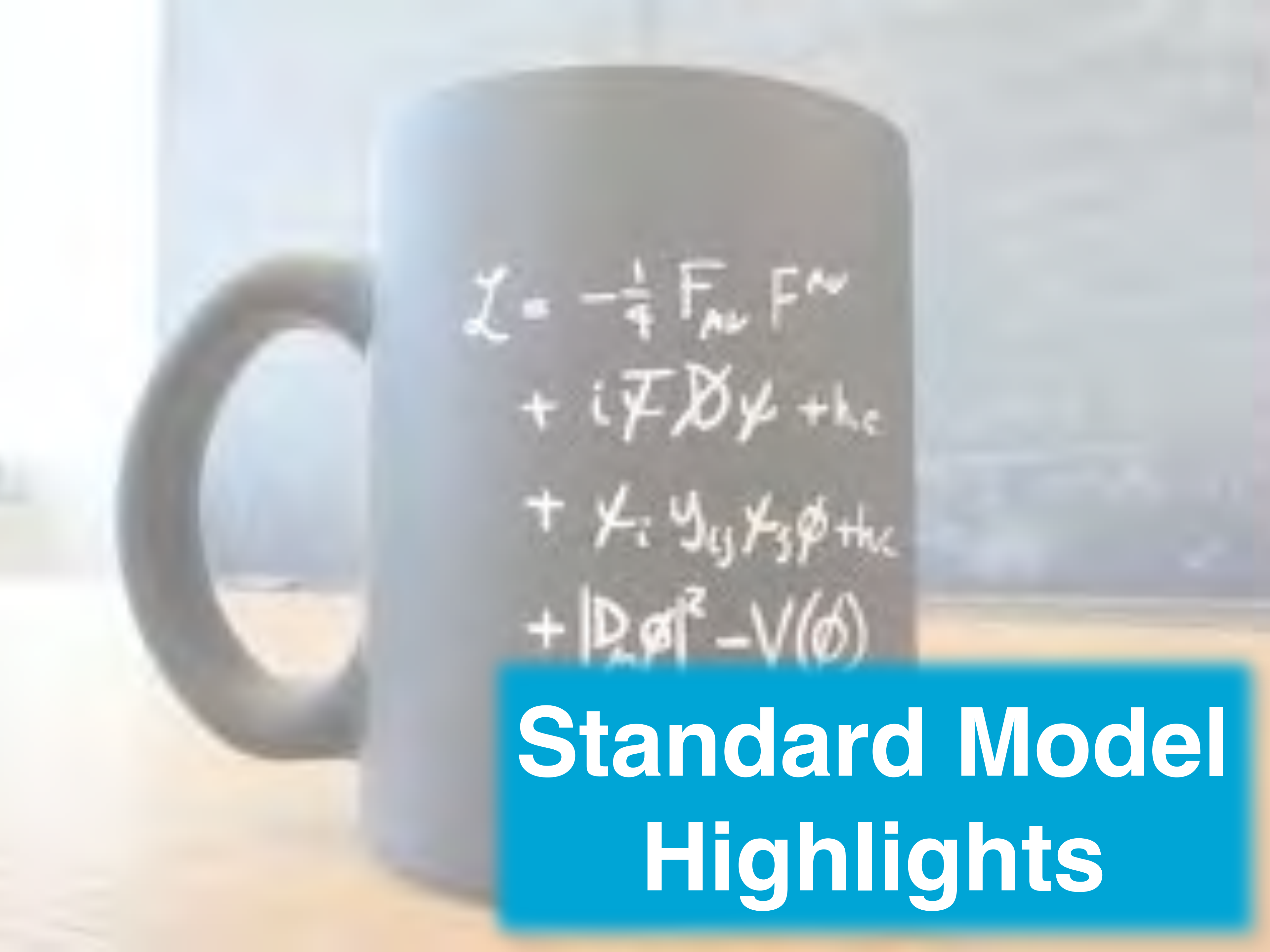
- Use non-prompt D^0 mesons to tag beauty production in PbPb collisions
  - Detect D^0 mesons via $K^-\pi^+$ decays and require significant displacement of the decay vertex to achieve high purity of b hadrons and lower the p_T range probed
- Measure nuclear modification factor as a function of D^0 p_T
- The measured R_{AA} is higher than for prompt D^0 mesons of generic charged hadrons for p_T < 10 GeV, consistent with the quark mass ordering of the suppression in QGP

CMS arXiv:1810.11102





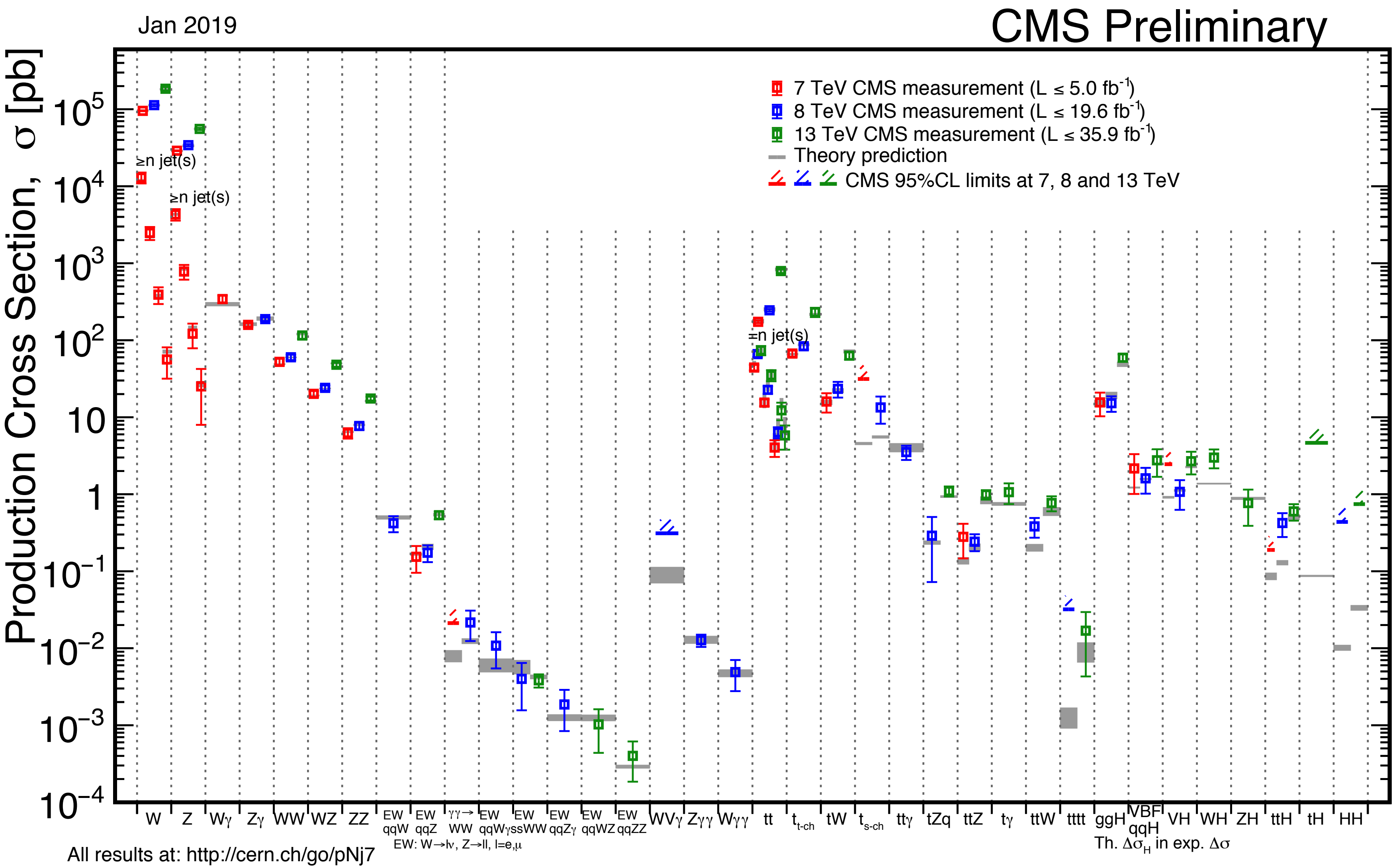




Standard Model Highlights

"Stairway to Heaven"

- ✦ Mind-boggling precision on so many SM processes!



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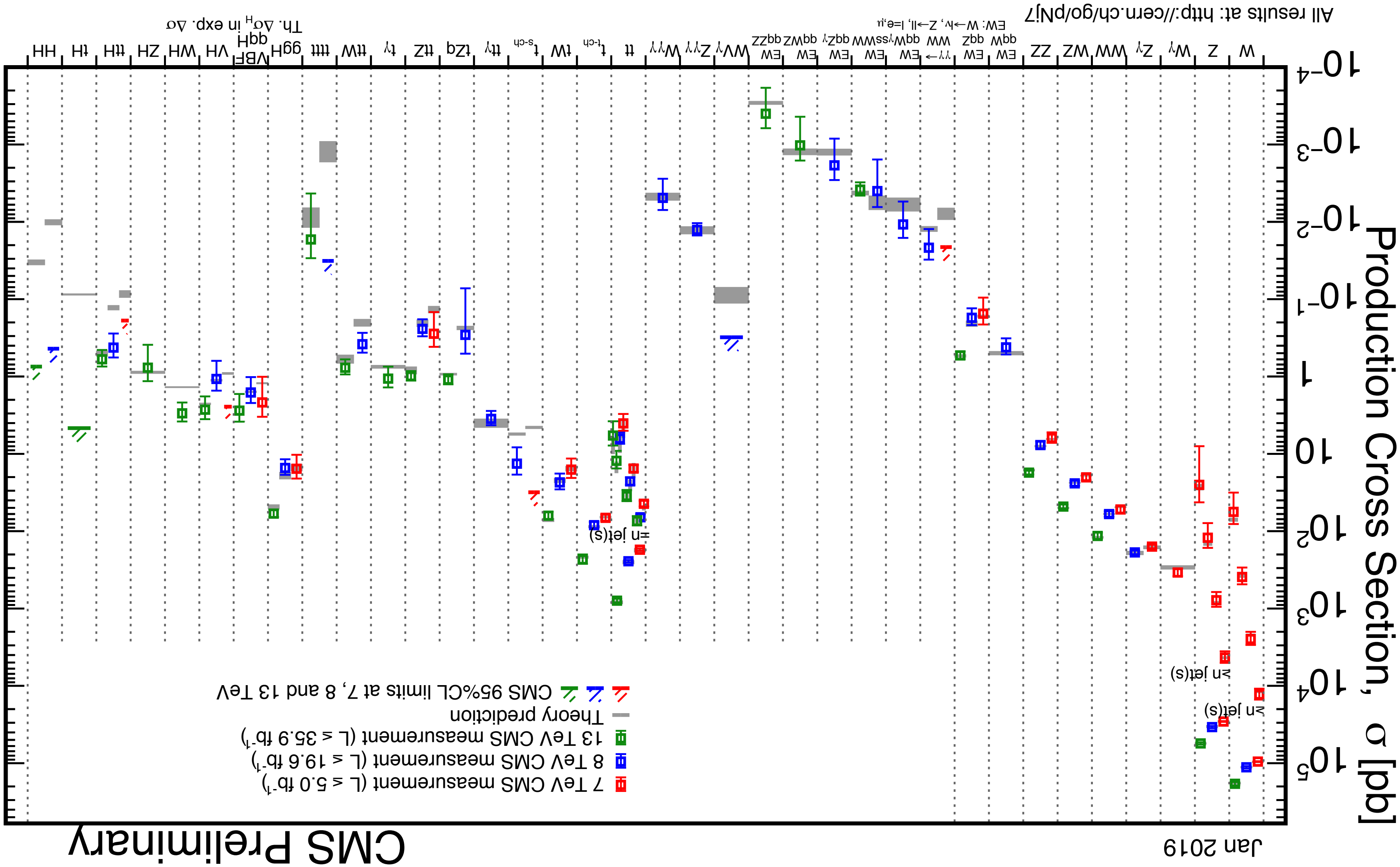
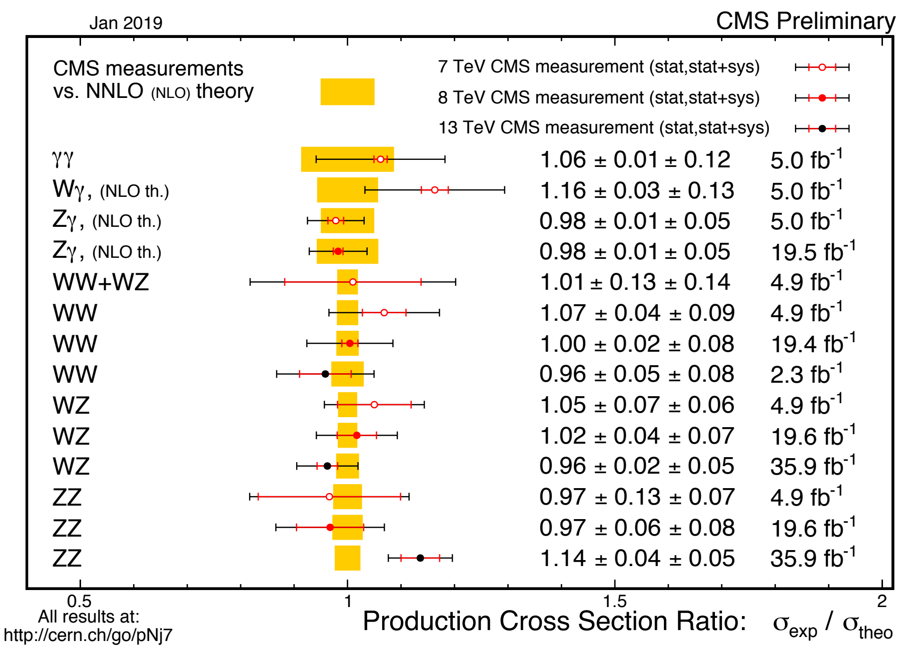
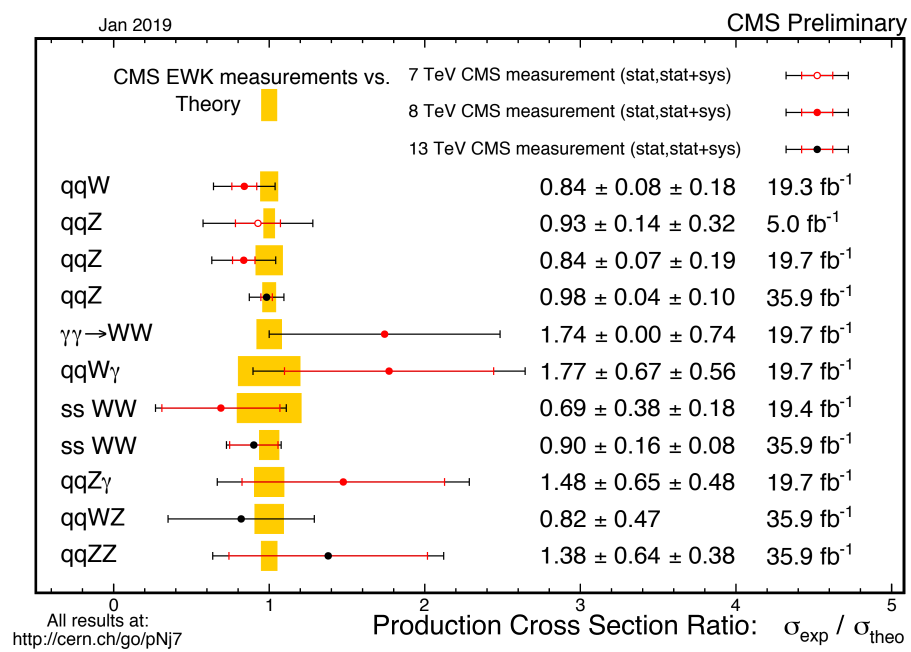


Vector Boson Measurements

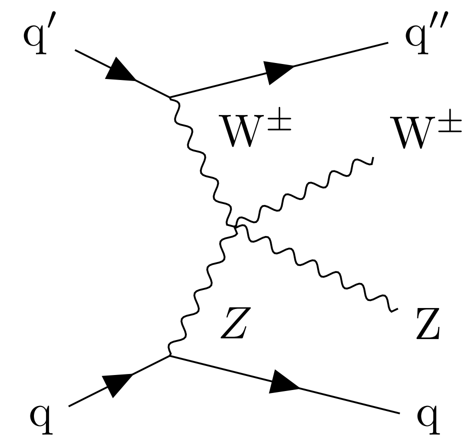
- Precision of diboson measurements broke the 10% threshold in a number of channels; in some it even rivals the precision of NNLO calculations
- For the first time entering the territory of precision probing of VBF/VBS and quartic vector boson couplings
- Most precise limits on triple gauge boson couplings, surpassing both LEP and the Tevatron

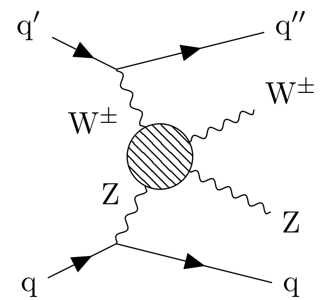


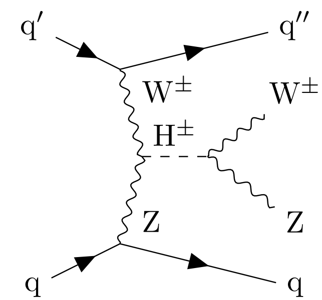


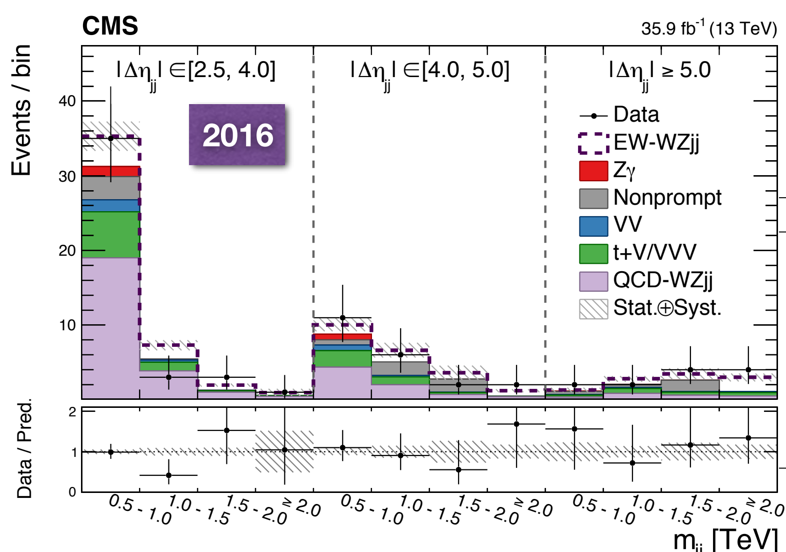
Measurement of WZ in VBF

- New measurement of the VBF WZ production in the trilepton channel at 13 TeV
- Several selections targeting various sources of potential new physics
- Measured cross sections are in good agreement with theoretical predictions, e.g., $\sigma^{\mathrm{fid}}_{\mathrm{WZjj}} = 3.18^{+0.57}_{-0.52}\,(\mathrm{stat})^{+0.43}_{-0.36}\,(\mathrm{syst})\,\mathrm{fb} = 3.18^{+0.71}_{-0.63}\,\mathrm{fb}$ to be compared with $3.27\,^{+0.39}_{-0.32}\,(\mathrm{scale}) \pm 0.15\,(\mathrm{PDF})\,\mathrm{fb}$.
- Sensitive variables: M_{jj} and $|\Delta\eta_{jj}|$ are used to set stringent limits on AQGC and charged Higgs boson production

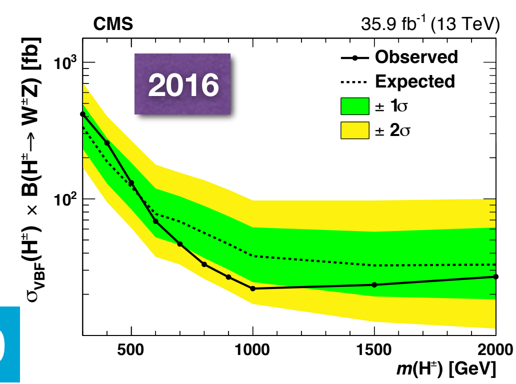








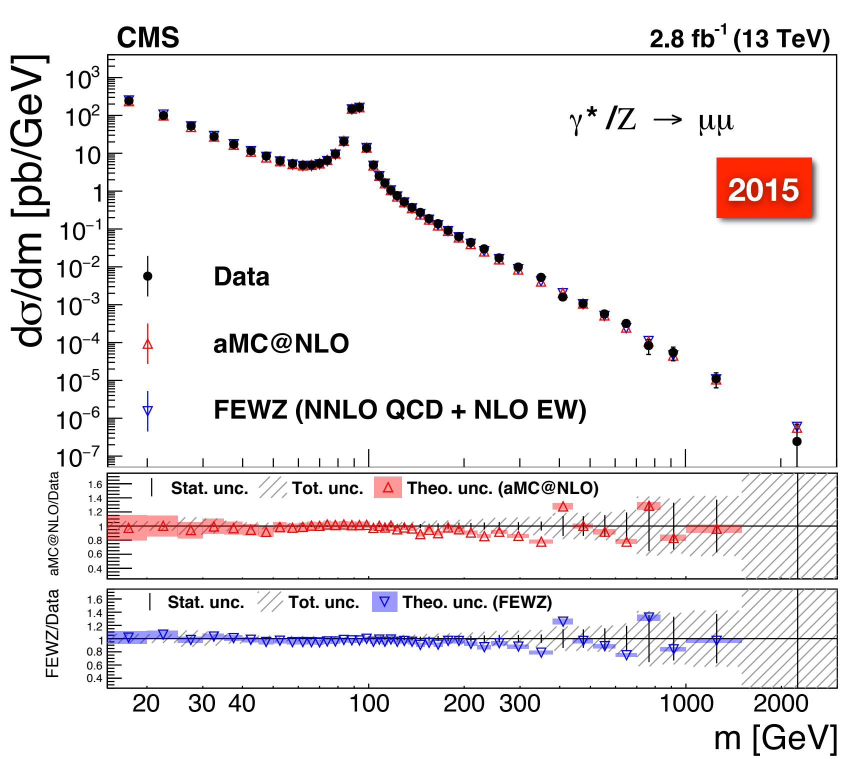
Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	$[-11.2, 11.6]$	$[-9.15, 9.15]$
f_{M1}/Λ^4	$[-10.9, 11.6]$	$[-9.15, 9.45]$
f_{S0}/Λ^4	$[-32.5, 34.5]$	$[-26.5, 27.5]$
f_{S1}/Λ^4	$[-50.2, 53.2]$	$[-41.2, 42.8]$
f_{T0}/Λ^4	$[-0.87, 0.89]$	$[-0.75, 0.81]$
f_{T1}/Λ^4	$[-0.56, 0.60]$	$[-0.49, 0.55]$
f_{T2}/Λ^4	$[-1.78, 2.00]$	$[-1.49, 1.85]$



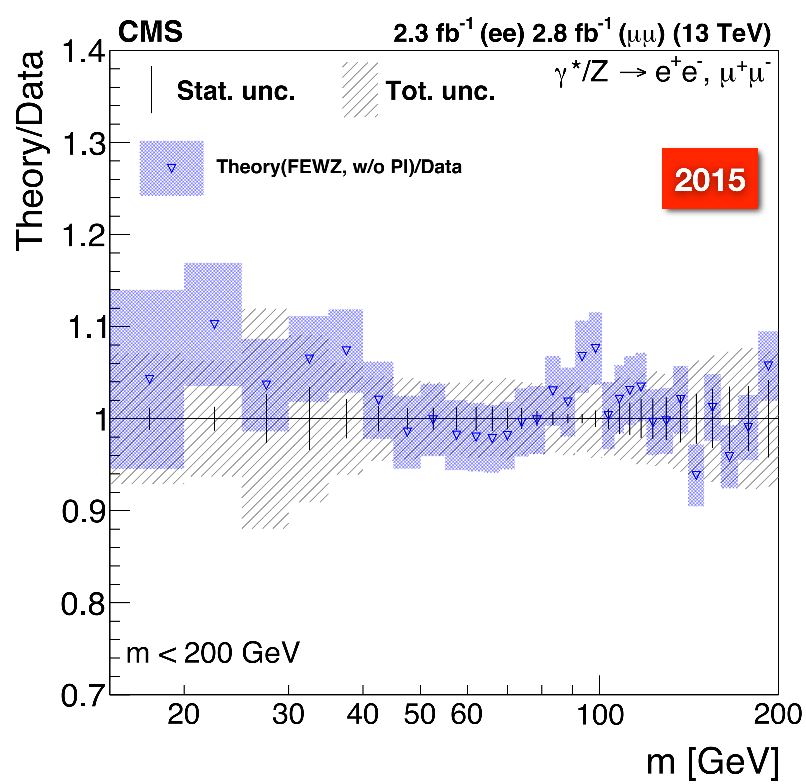
CMS arXiv:1901.04060

Differential Drell-Yan Cross Section

- New, high-precision measurement of the differential dσ/dm DY cross section at 13 TeV in the 15-3000 GeV mass range
  - Uncertainties are as low as a few percent!
  - Excellent agreement with the state-of-the-art NNLO QCD + NLO EW predictions, including photon-induced contributions

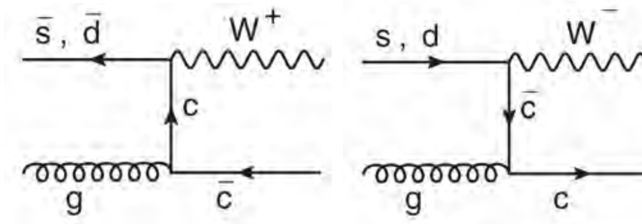


CMS arXiv:1812.10529

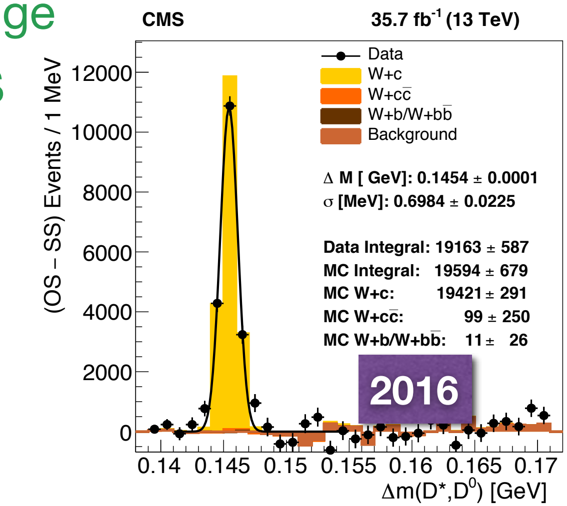


W+c Production

- Measurement of W+c cross section at 13 TeV, using exclusive $D^{*\pm} \rightarrow D^0\pi^\pm \rightarrow K^\mp\pi^\pm\pi^\pm$ decays
  - Gives direct access to the strange quark PDFs

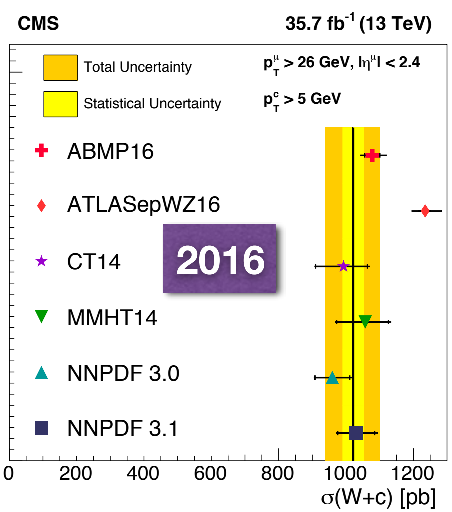


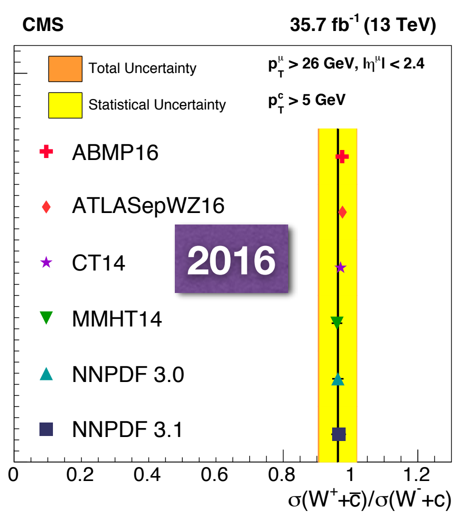
- The new result improves on the precision of the strange quark PDF extraction compared to the previous CMS analysis at 7 TeV

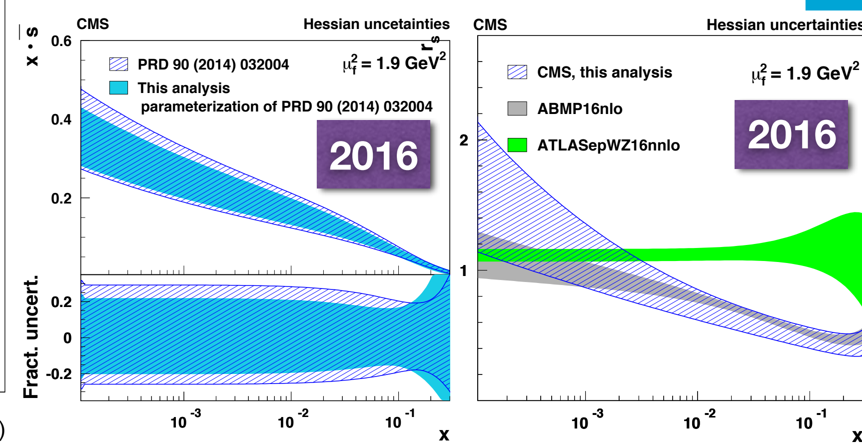


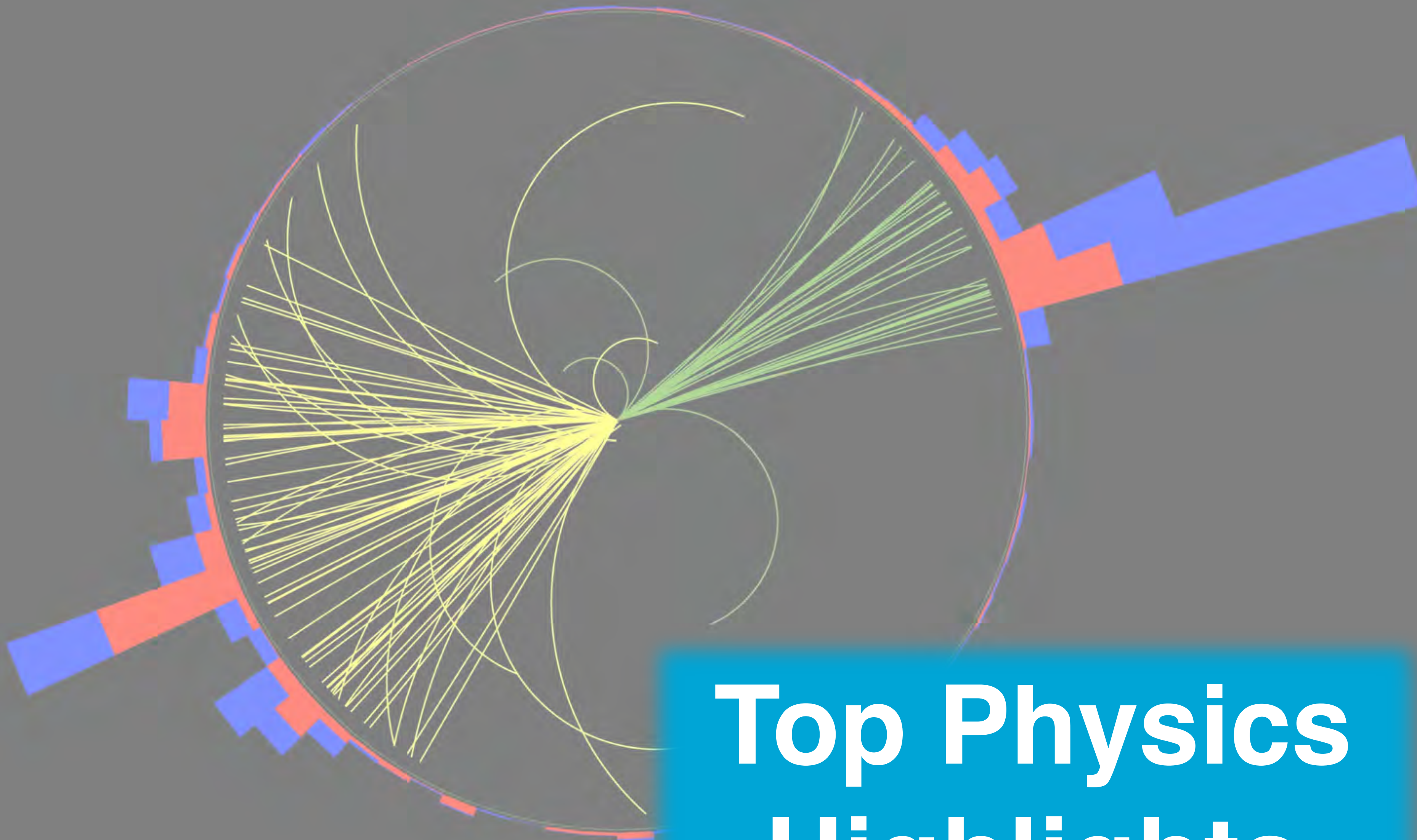
CMS arXiv:1811.10021

- CMS results do not support the recent ATLAS claim [arXiv:1612.03016] on an enhanced strange quark contribution to the proton sea at high x







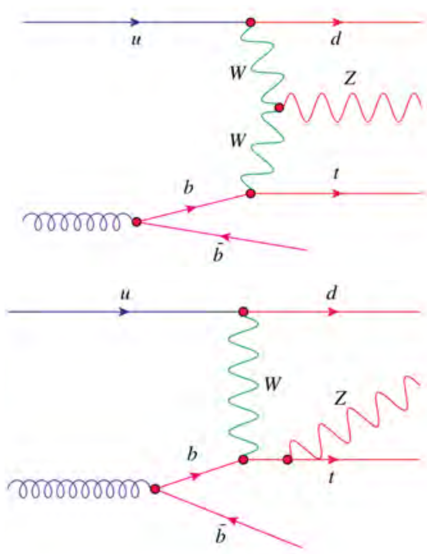


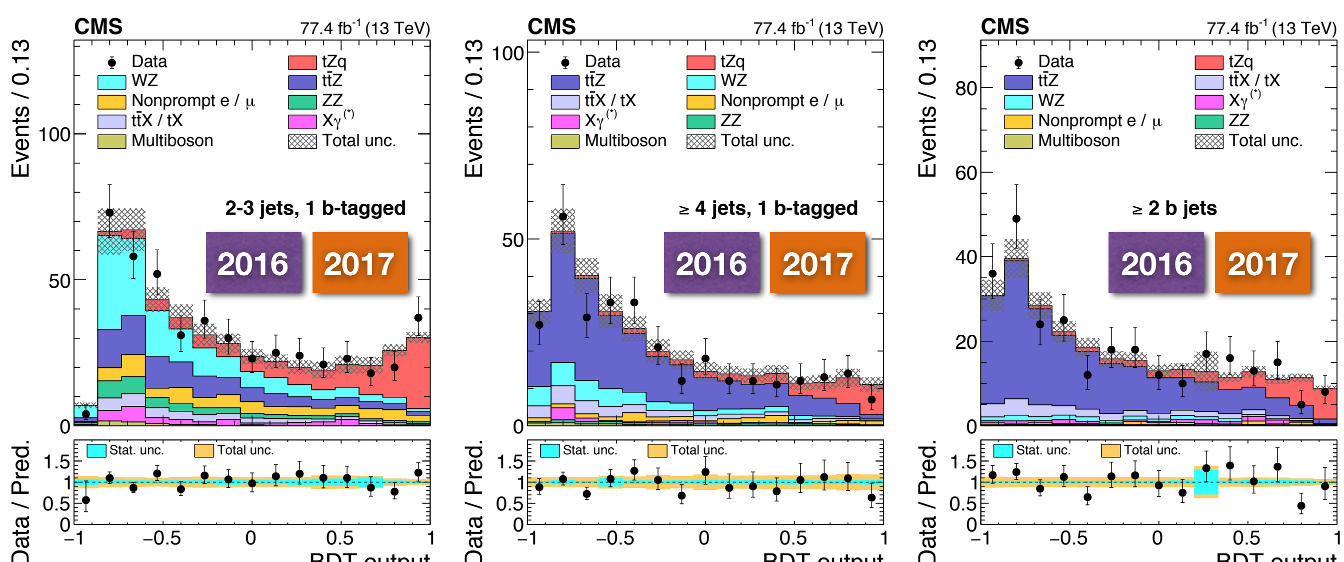
Top Physics Highlights

Observation of tZq Production

- Interesting SM process sensitive to contributions from new physics, including FCNC interactions
- Highly optimized analysis in the Z(ll) channel, based on 2016 & 2017 data, with three event categories defined by the number of jets and b-tagged jets, with MVA selection in each category
  - Observed (expected) signal significance: 8.2σ (7.7σ)
- Measured fiducial cross section: $\sigma(\mathrm{pp} \to \mathrm{tZq} \to \mathrm{t}\ell^+\ell^-\mathrm{q}) = 111 \pm 13\,(\mathrm{stat})\,^{+11}_{-9}\,(\mathrm{syst})\,\mathrm{fb}$
  - Agrees w/ theoretical prediction of 94.2 ± 3.1 fb

CMS arXiv:1812.05900

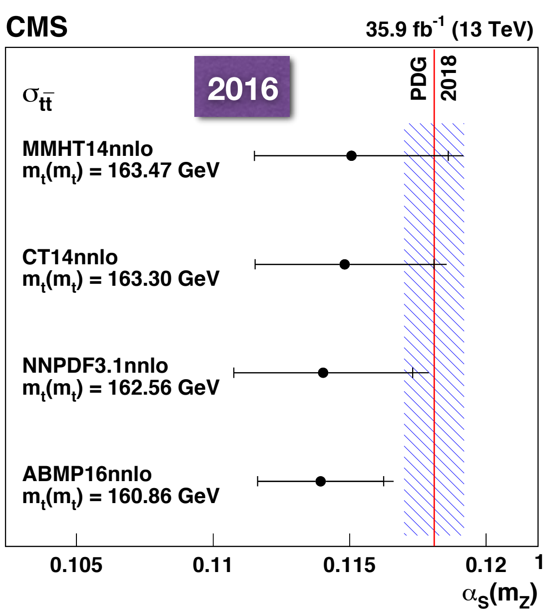


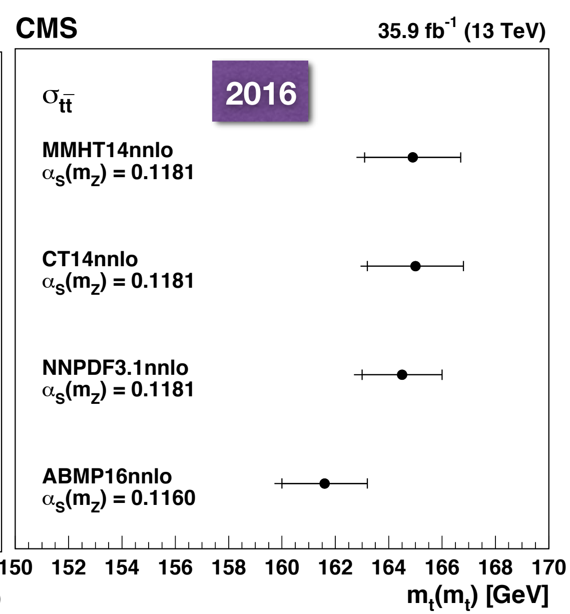


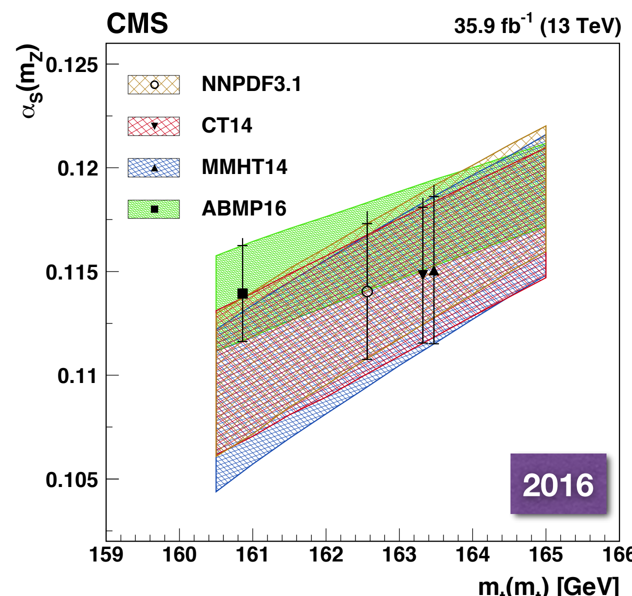
Top Quark Mass, σ, α_s

- Clever alternative way of extracting top quark mass and α_s from a precision measurement of top quark pair production cross section in the dilepton channel
  - Use MS scheme and NNLO PDFs and accuracy to simultaneously extract α_s and m_t from subscription, taking into account correlation with PDFs
  - Using m_{lb}^{min} as a variable sensitive to m_t, get:

$$\sigma_{t\bar{t}} = 815 \pm 2\,(\mathrm{stat}) \pm 29\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb},$$
$$m_t^{\mathrm{MC}} = 172.33 \pm 0.14\,(\mathrm{stat})\,^{+0.66}_{-0.72}\,(\mathrm{syst})\,\mathrm{GeV}.$$







PDF set	m_t^{pole} [GeV]
ABMP16	169.9 ± 1.8 (fit + PDF + α_S) $^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	173.2 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.3}$ (scale)
CT14	173.7 ± 2.0 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)
MMHT14	173.6 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)

CMS arXiv:1812.10505

B Physics Highlights

Study of Excited B_s States

- New analysis based on 2012 data @ 8 TeV studying p-wave, in particular B_{s1} ($j_s = 3/2$, $J^P = 1^+$), B^*_{s2} ($j_s = 3/2$, $J^P = 2^+$) [observed by CDF, D0, and later LHCb]
  - First observation of $B^*_{s2} \to B^0 K_s^0$ is observed for the first time with 6.3σ significance; a 3.7σ evidence for $B_{s1} \to B^{*0} K_s^0$ is also seen
  - The following branching fraction ratios were measured:

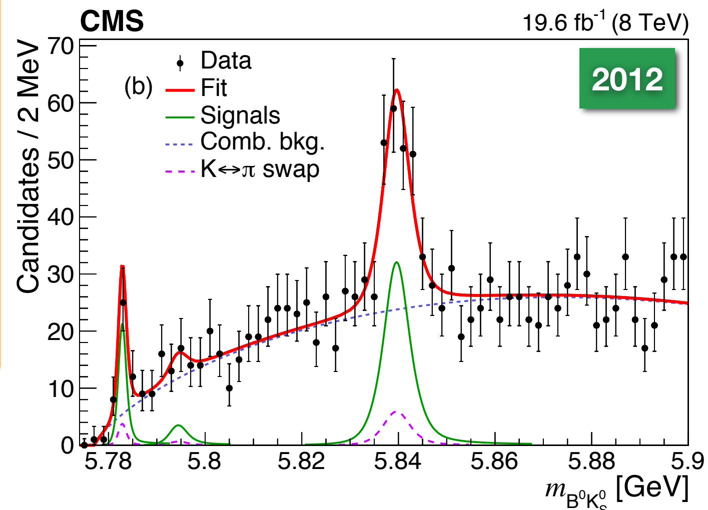
$$R_2^{0\pm} = \frac{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^0\mathrm{K}^0_S)}{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^+\mathrm{K}^-)} = 0.432 \pm 0.077 \pm 0.075 \pm 0.021$$

$$R_1^{0\pm} = \frac{\mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}^0_S)}{\mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)} = 0.49 \pm 0.12 \pm 0.07 \pm 0.02,$$

$$R_{2*}^{\pm} = \frac{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^{*+}\mathrm{K}^-)}{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^+\mathrm{K}^-)} = 0.081 \pm 0.021 \pm 0.015,$$

$$R_{2*}^{0} = \frac{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^{*0}\mathrm{K}^0_S)}{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^0\mathrm{K}^0_S)} = 0.093 \pm 0.086 \pm 0.014.$$

CMS arXiv:1809.03578



$$M(\mathrm{B}^*_{s2}) = 5839.86 \pm 0.09 \pm 0.07 \pm 0.15\,\mathrm{MeV},$$
$$M(\mathrm{B}_{s1}) = 5828.78 \pm 0.09 \pm 0.06 \pm 0.28\,\mathrm{MeV}.$$

  - Also measured mass differences:

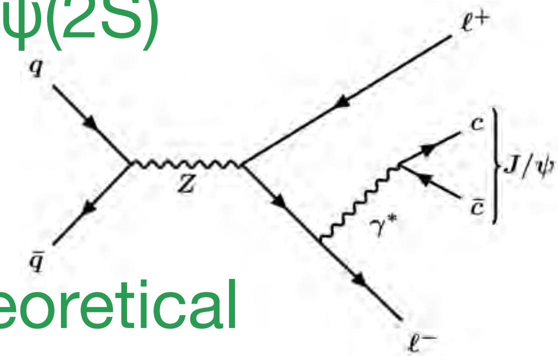
$$M_{\mathrm{B}^0} - M_{\mathrm{B}^+} = 0.57 \pm 0.49 \pm 0.10 \pm 0.02\,\mathrm{MeV},$$

First meas. → $$M_{\mathrm{B}^{*0}} - M_{\mathrm{B}^{*+}} = 0.91 \pm 0.24 \pm 0.09 \pm 0.02\,\mathrm{MeV}.$$

Observation of a Rare Z Decay

- Observation of the $Z \rightarrow \psi l^+l^-$, $\psi = J/\psi + \psi(2S)$ decay in the 4μ + 2μ2e modes

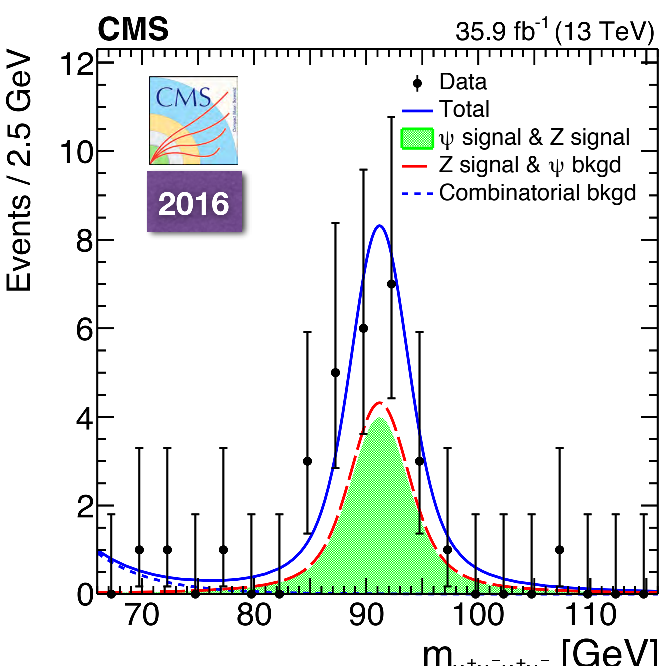
$$\frac{\mathcal{B}(Z \to J/\psi\, \ell^+\ell^-)}{\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} = 0.67 \pm 0.18\,(\text{stat}) \pm 0.05\,(\text{syst})$$

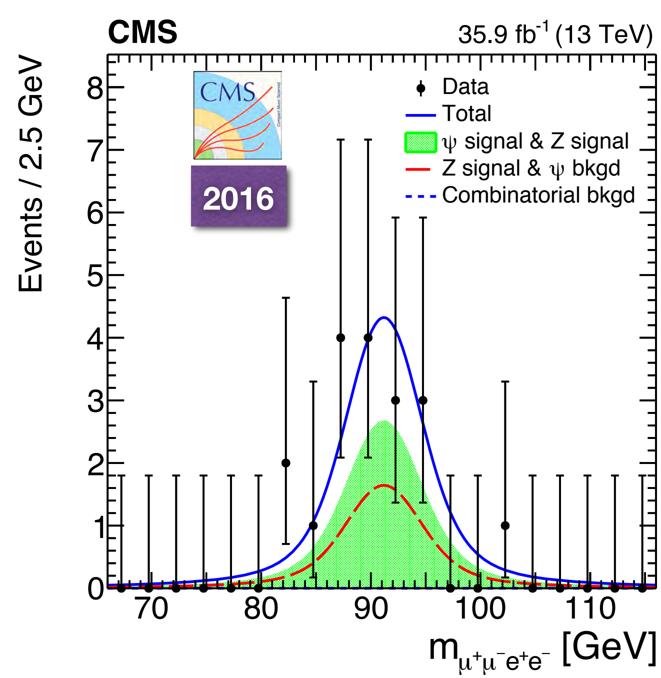


- $B(Z \rightarrow \psi l^+l^-) \approx 8 \times 10^{-7}$, consistent w/ theoretical predictions of $(6.7\text{-}7.7) \times 10^{-7}$

Combined significance: 5.7σ

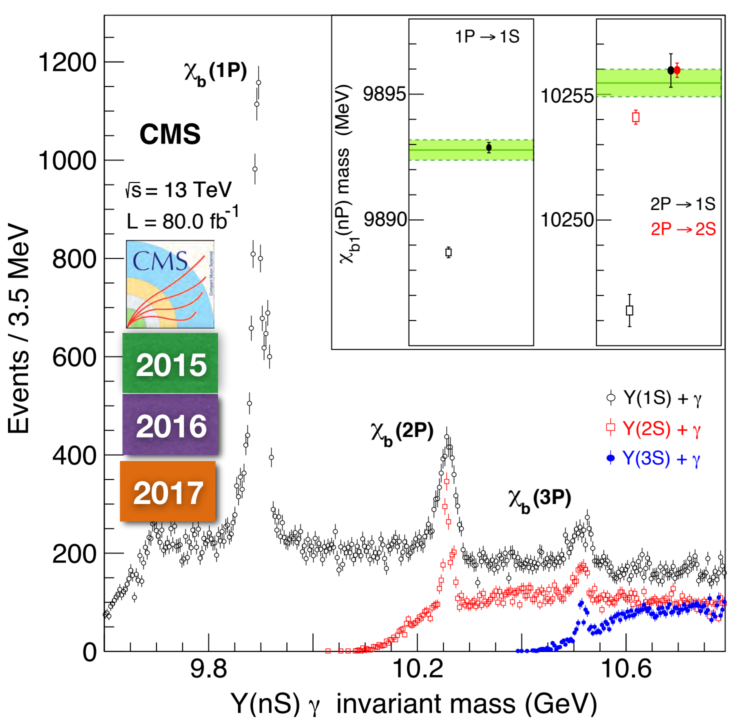
CMS arXiv:1806.04213



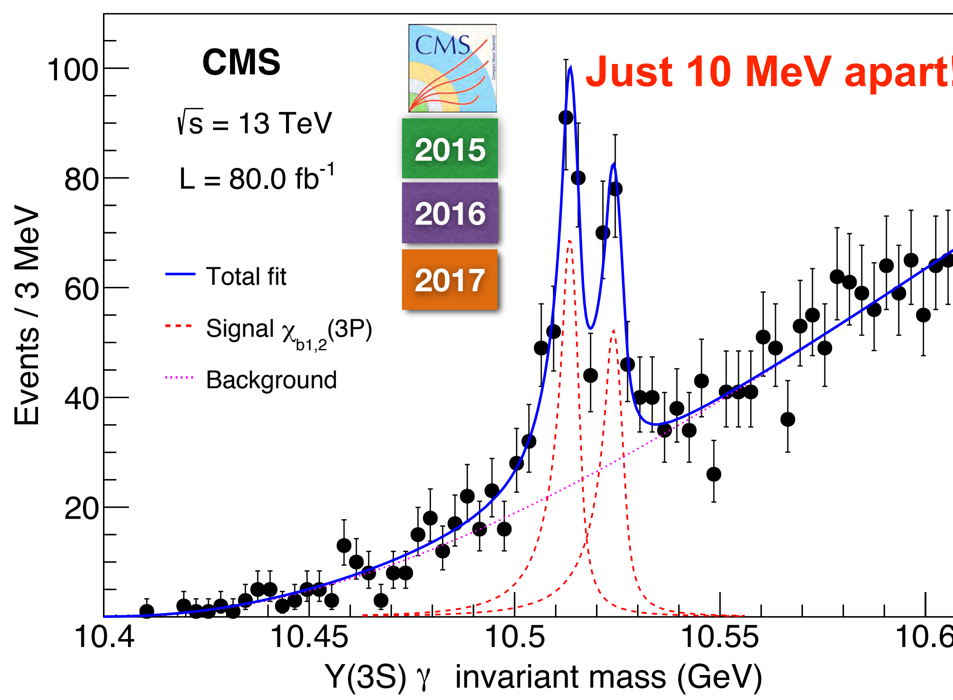


Observation of $\chi_{bJ}(3P)$

- First observation of excited, 3P χ_{bJ} states, J = 1, 2 via $\Upsilon(3S)\gamma$ decays using 2015-2017 data
- Detect low-p_T photons using conversions into e^+e^- pairs
- Achieved an unprecedented 5 MeV resolution in mass, and measured mass difference to be: $\Delta M = 10.60 \pm 0.64 \pm 0.17$ MeV



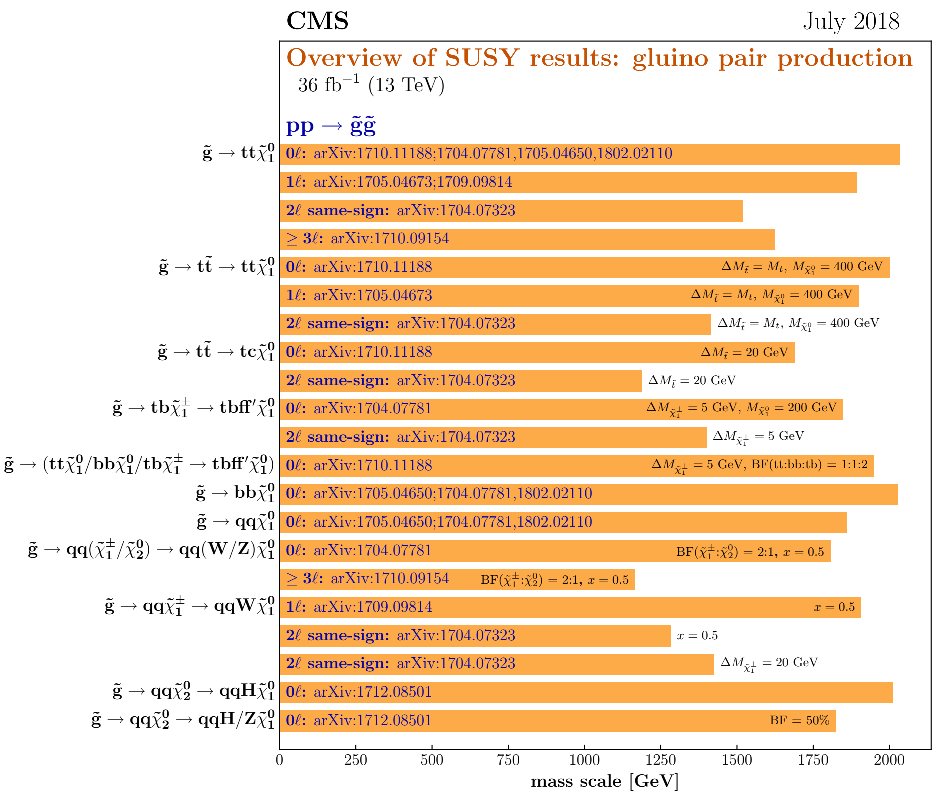
CMS arXiv:1805.11192



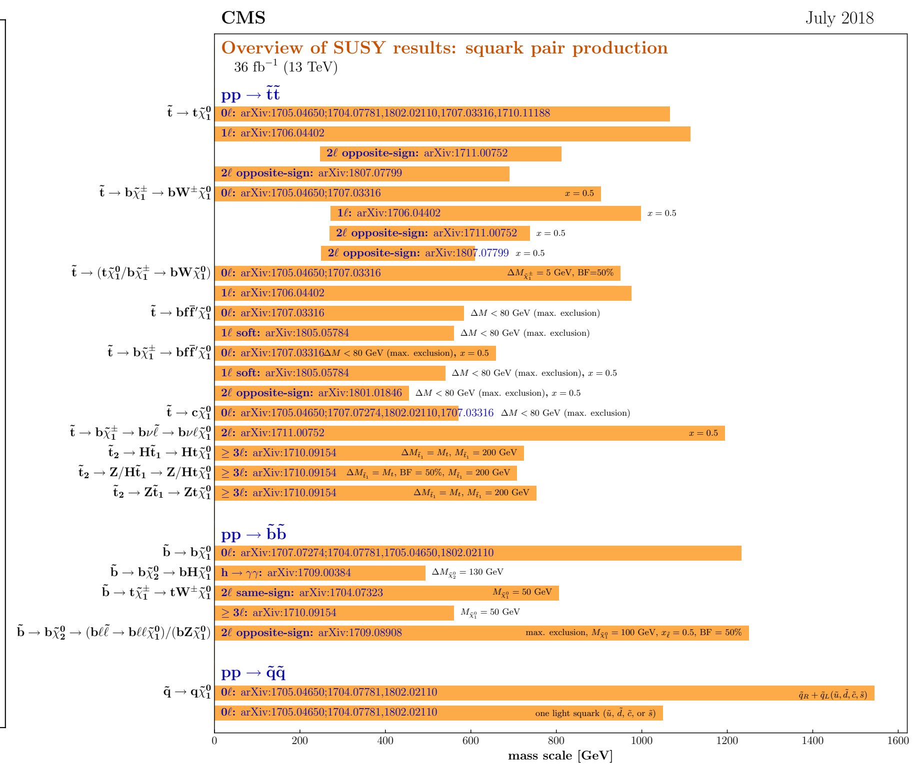
SUSY Searches

Supercemetery?

- At first glance, the TeV scale SUSY is simply not there: strongly produced superpartners of gluons and quarks, gluinos and squarks, have been excluded to ~2 and ~1 TeV, respectively...



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.



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Read the Fine Print!

- Keep in mind that:
  - Searches typically assume 100% branching fraction in a particular channel
  - Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
  - Interpretation is usually done via simplified model framework, not in the full model

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  - Searches typically assume 100% branching fraction in a particular channel
  - Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
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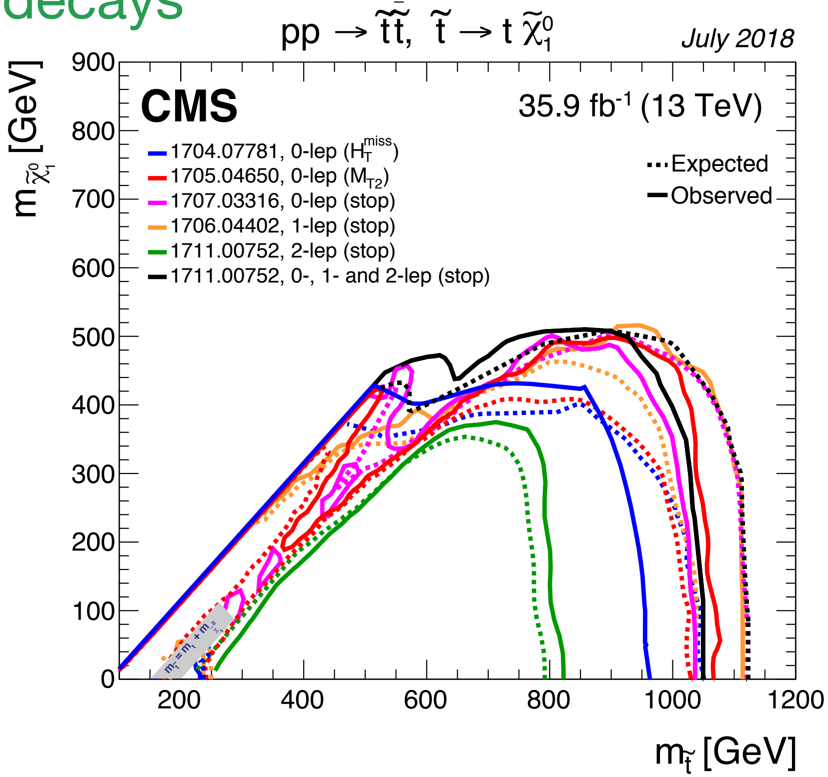
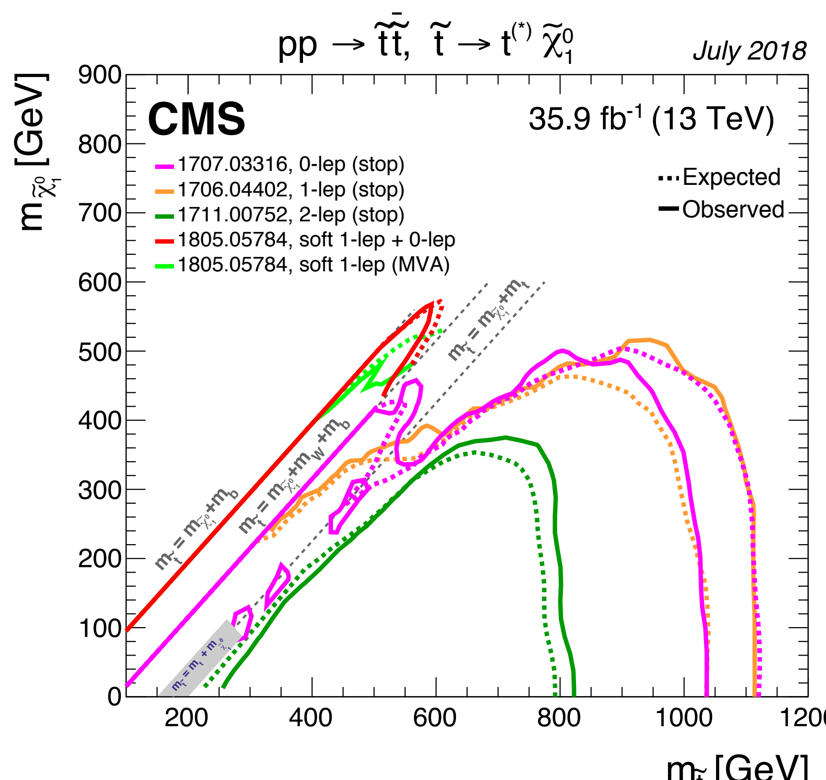
Pulling all the Stops!

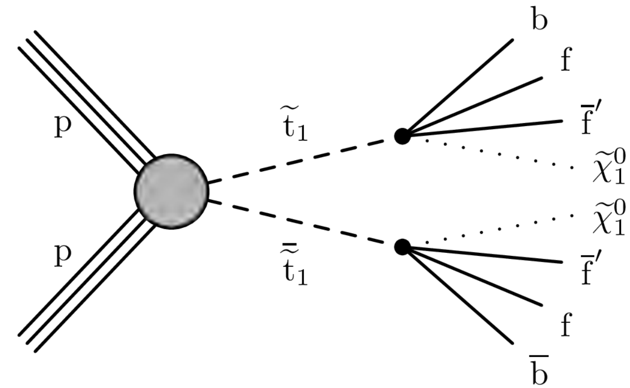
- Top quark partner ("stop") is expected to be light, if SUSY offers a natural solution to the hierarchy problem
  - Not surprisingly, a lot of effort went into top squark searches
- With the top squark masses excluded as high as ~1 TeV, a paradigm shift in filling gaps at low masses, via challenging 3- and 4-body decays

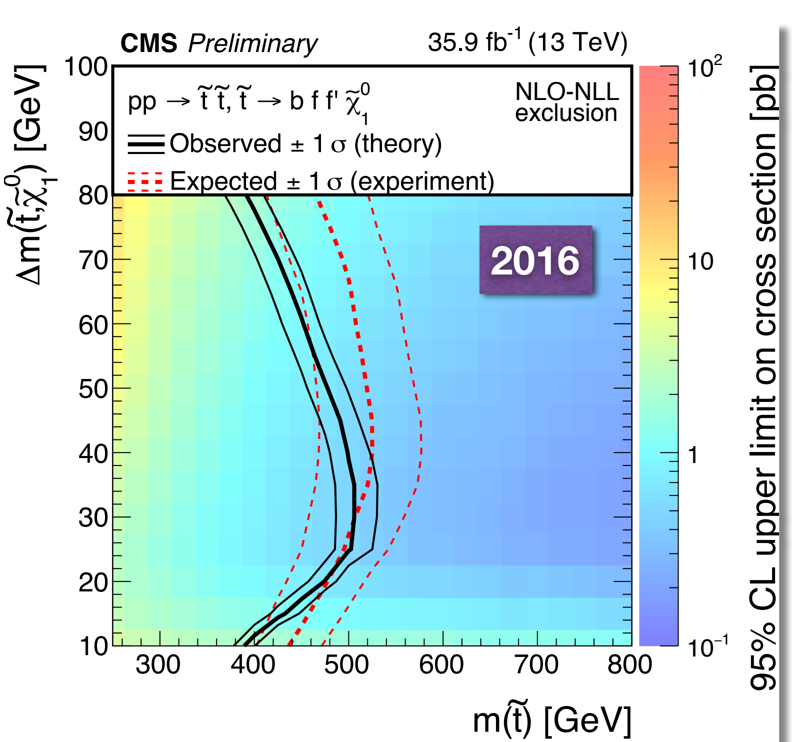


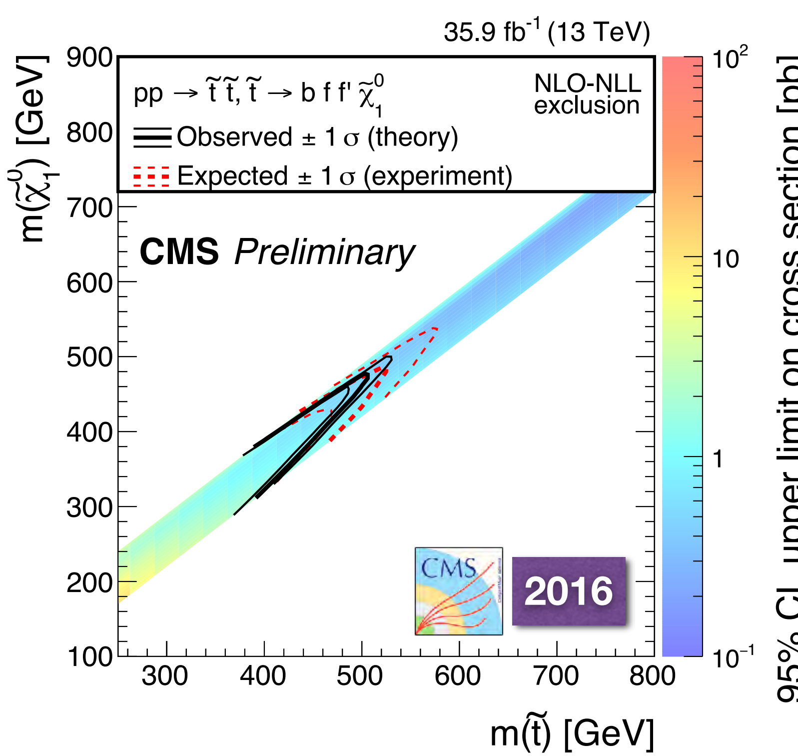


Search for 4-body Stop Decays

- Require at least one soft lepton (30 > p_T > 3.5-5 GeV) and a hard ISR jet to aid the efficiency and triggering



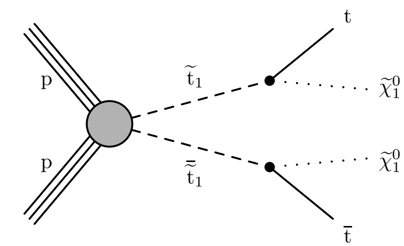




CMS Collaboration
SUS-16-052

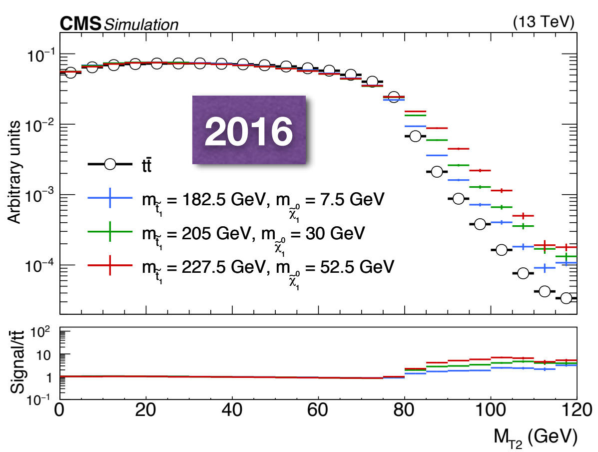
Search for Light Top Squarks

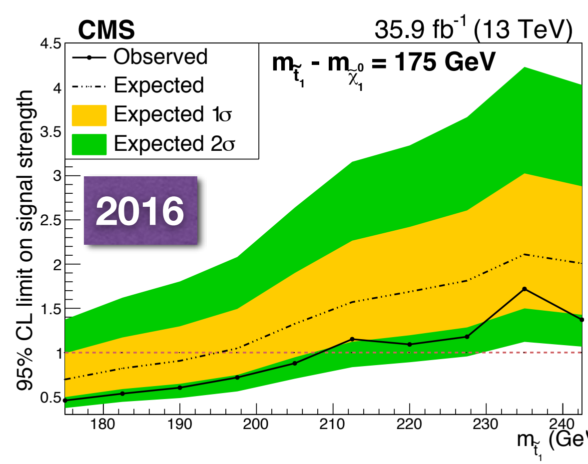
- A particularly challenging case is when the mass of the top squark is nearly degenerate with the sum of the top quark and neutralino masses: $(m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t)$

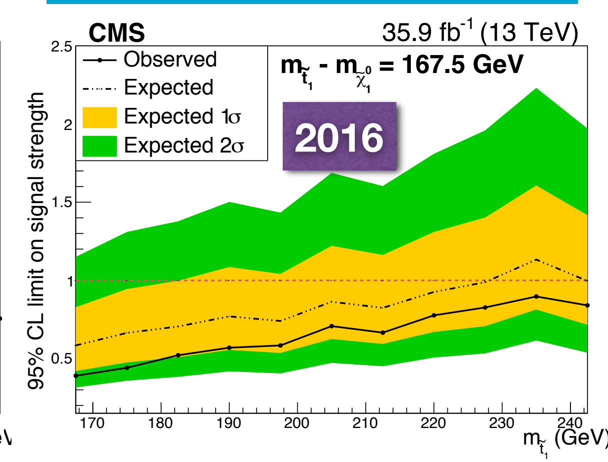


- In this case the neutralino is produced nearly at rest and not being detected, does not contribute to the missing transverse momentum
    - Consequently, the process looks just like top quark pair production!
- The new analysis in the dilepton channel looks for an excess of events above the dominant background using shape differentiation offered by an M_T-like variable (M_{T2})

CMS arXiv:1901.01288



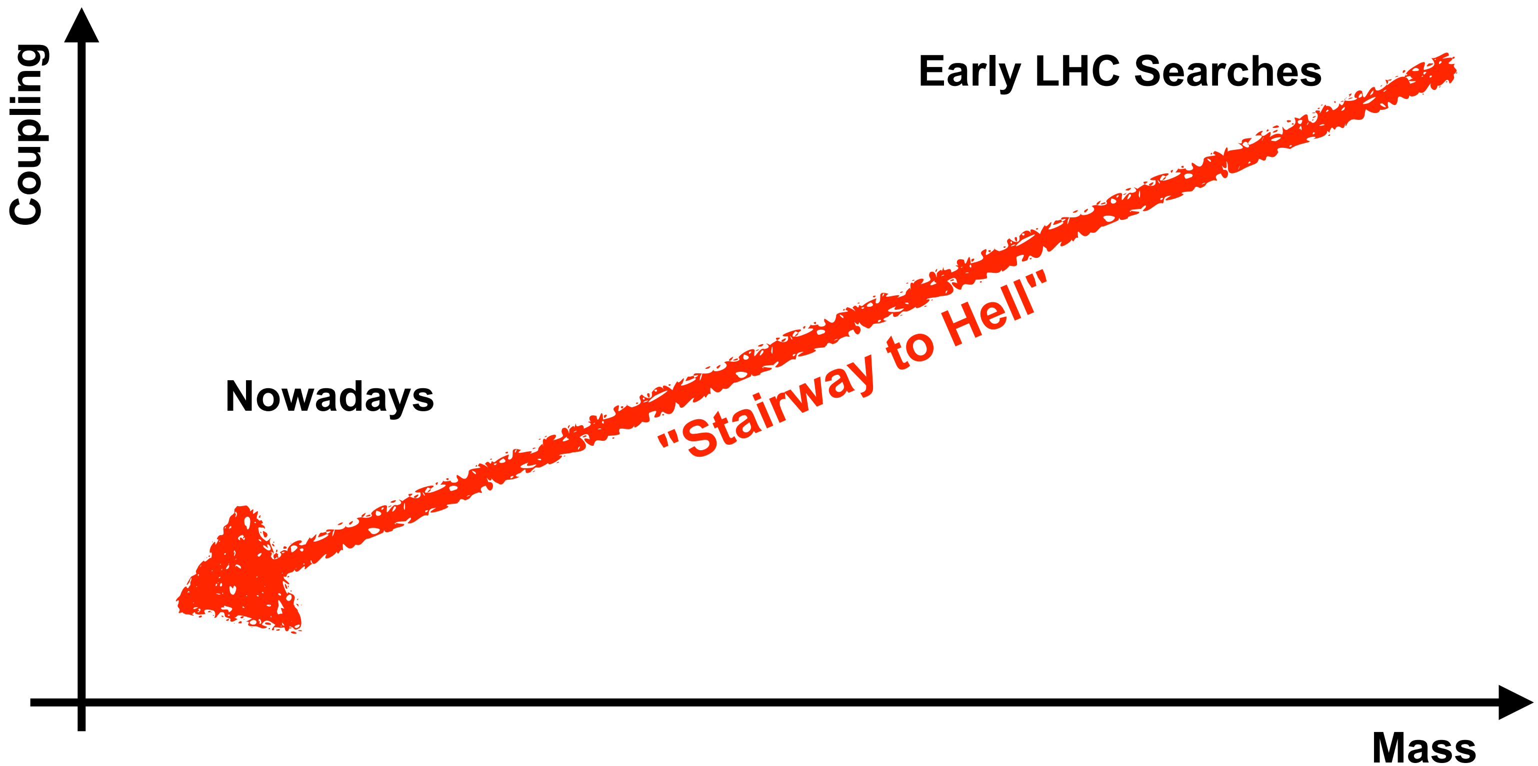




Exotica Searches

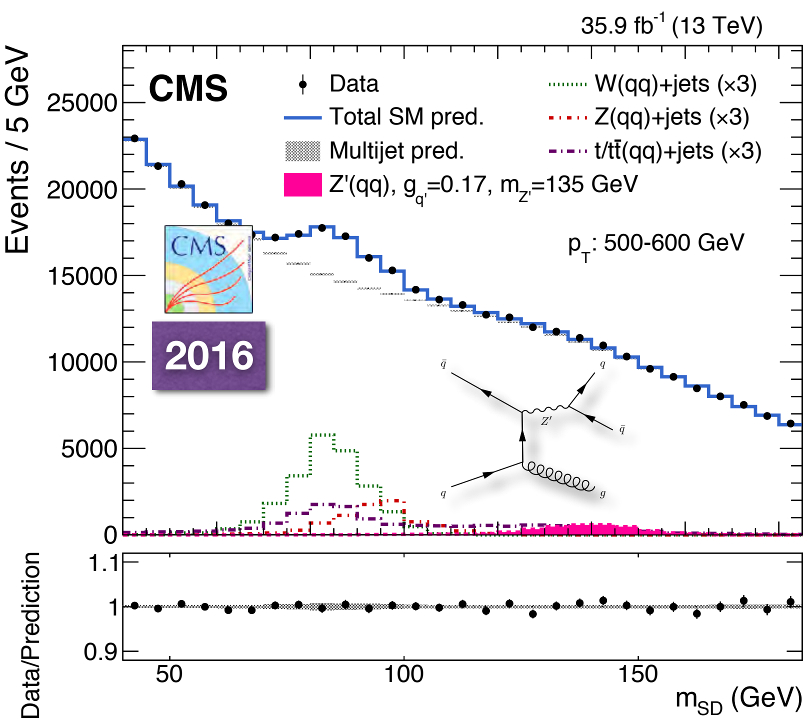
Shift of Paradigm

- At first, we were looking at the highest masses, which opened up due to record high machine energy
- These are low-background searches, but only sensitive to large couplings
- Last few years marked a shift in paradigm: we are going for high-background, experimentally challenging searches for low couplings and low masses - something that earlier machines may have missed!

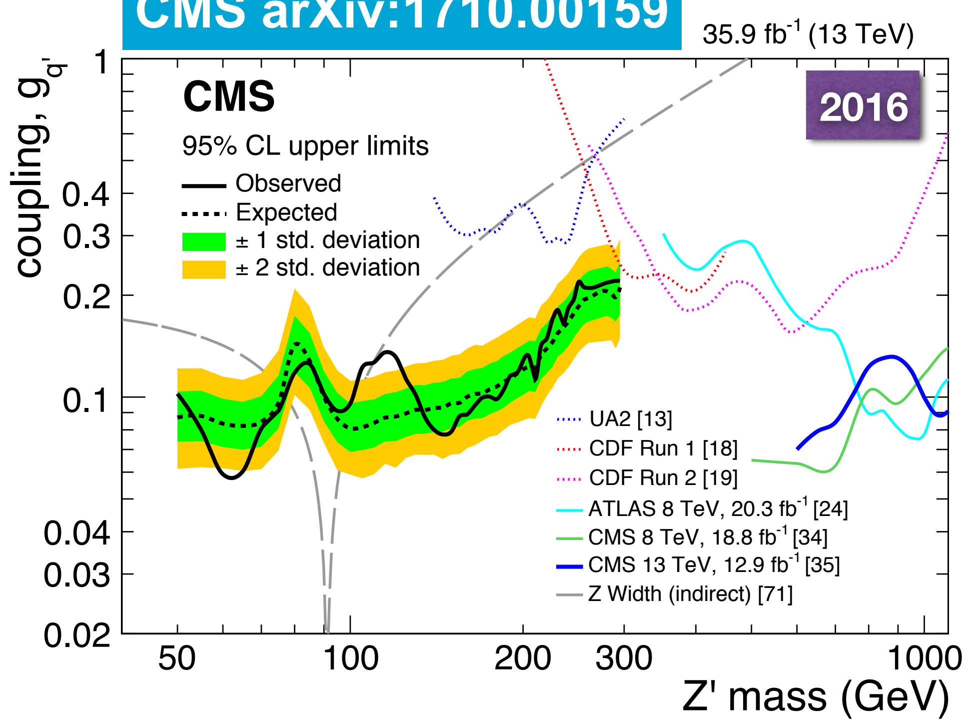


Low Mass Dijet Analysis

- Use ISR to trigger, similar to the H(bb) search and look for resonances in the jet mass
- Allows to lower the dijet mass reach to 50 GeV, as demonstrated with the W/Z peak observation in CMS
- Goes well beyond the only available 30-year old UA2 limits in terms of mass reach and couplings!



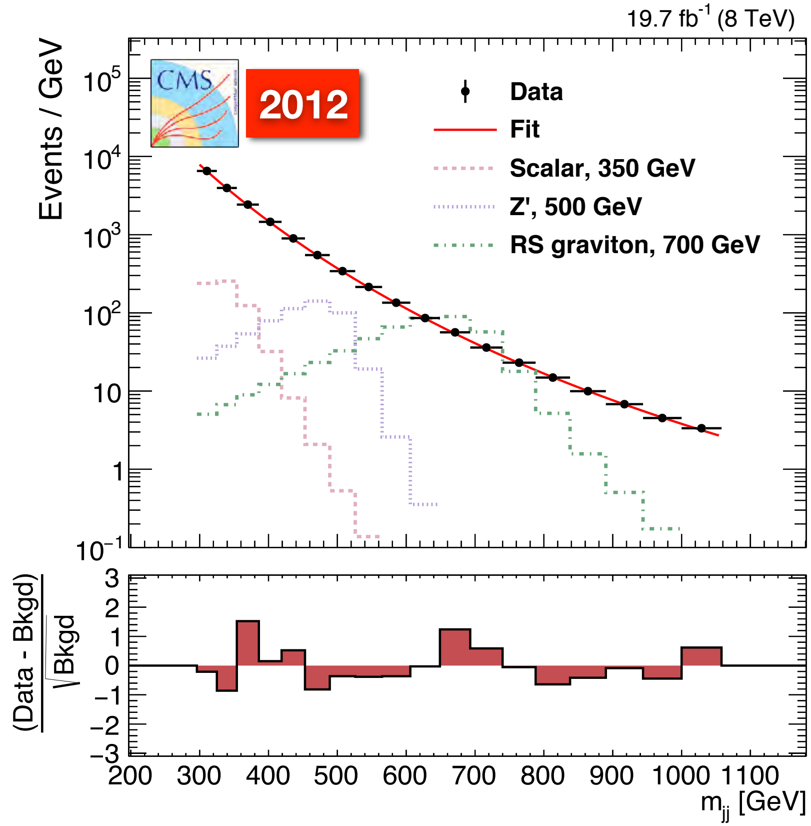
CMS arXiv:1710.00159

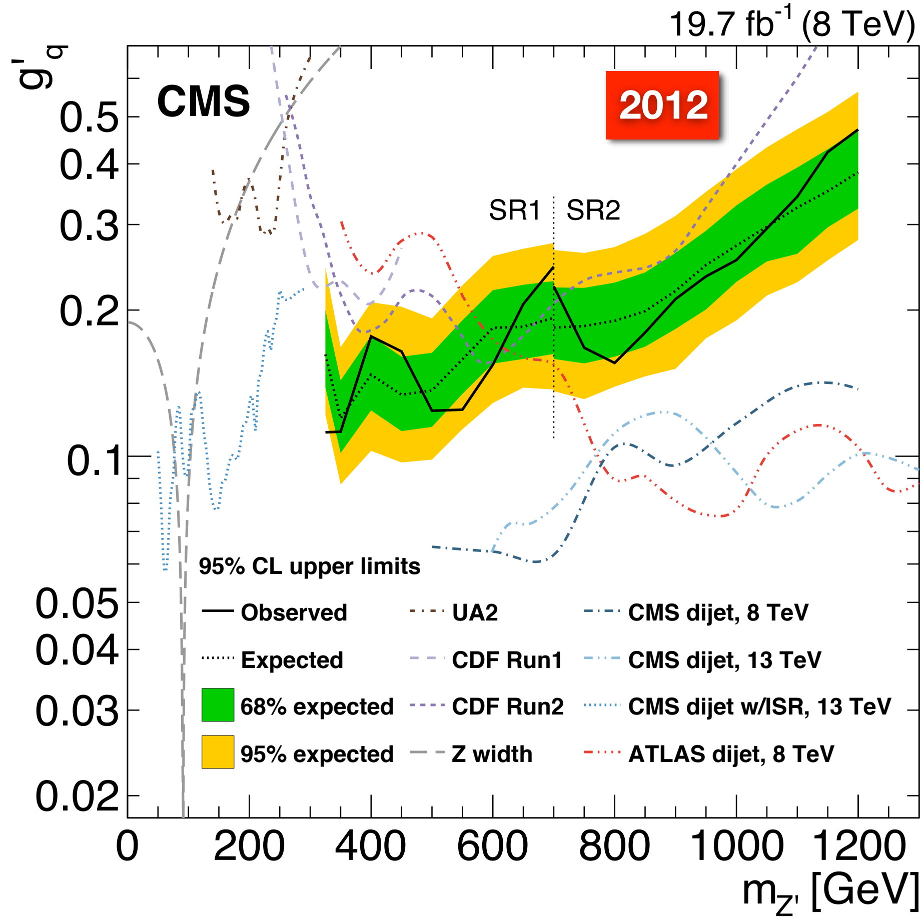


Low-Mass bb Dijet Search

- Likely the last search analysis based on 2012 data
- Uses dedicated b-tagged trigger, allowing for the first time to probe bb masses below the tt threshold

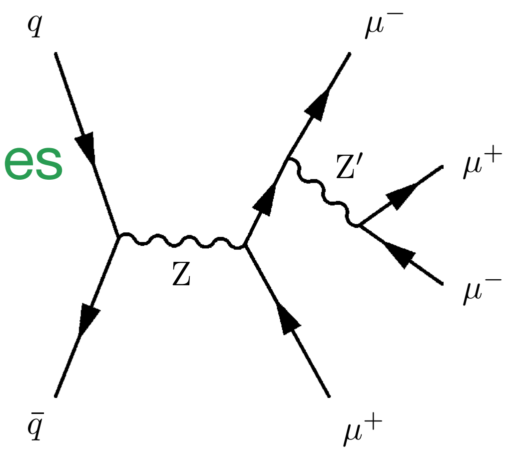
CMS arXiv:1802.06149





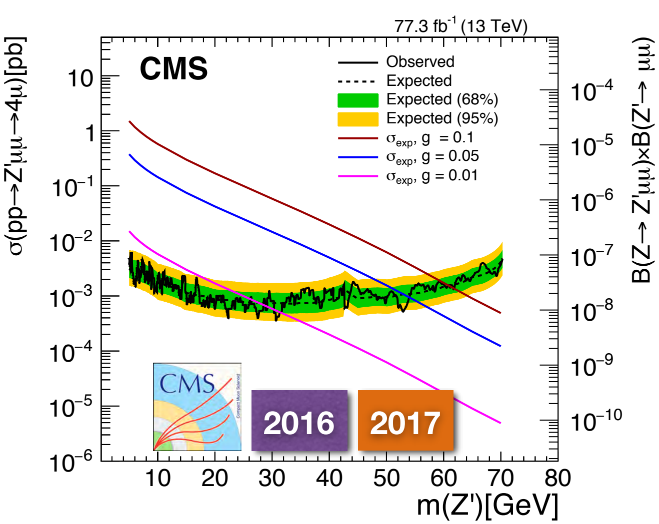
Search for Z' in Z → 4μ decay

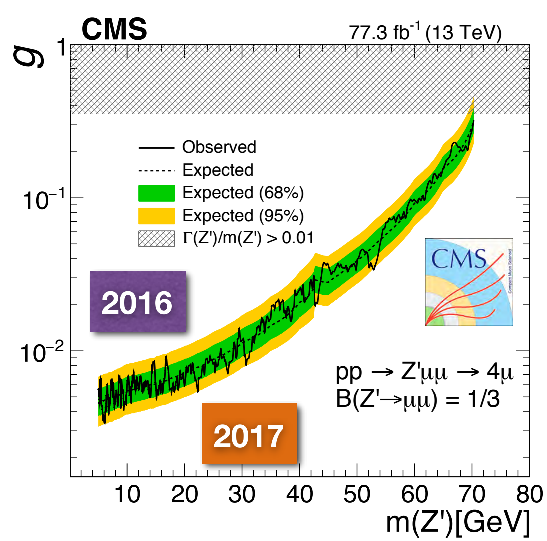
- Search for Z' with preferential coupling to second-generation particles, suggested as possible explanation of b → sμμ flavor anomalies
- Based on the H(ZZ) → 4μ analysis, using 2016+2017 data
- Closed significant fraction of the allowed parameter space in the L_μ - L_τ models

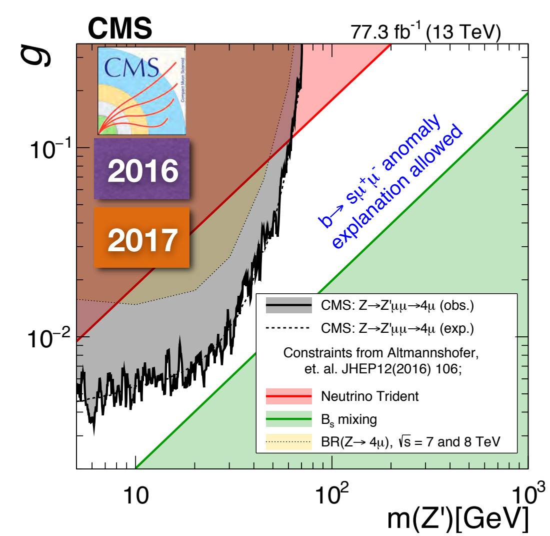


Altmannshofer et al. arXiv:1609.04026

CMS arXiv:1808.03684

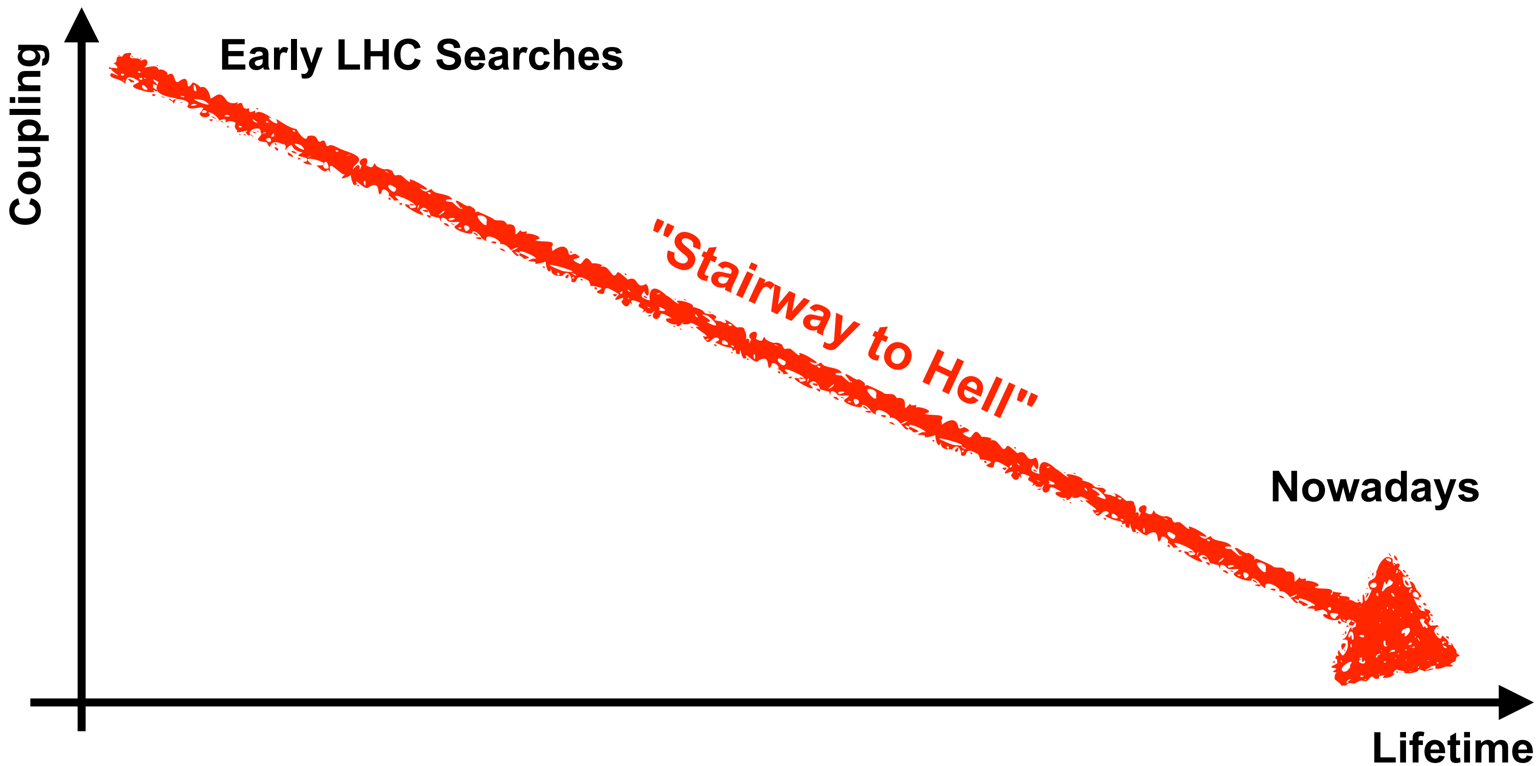






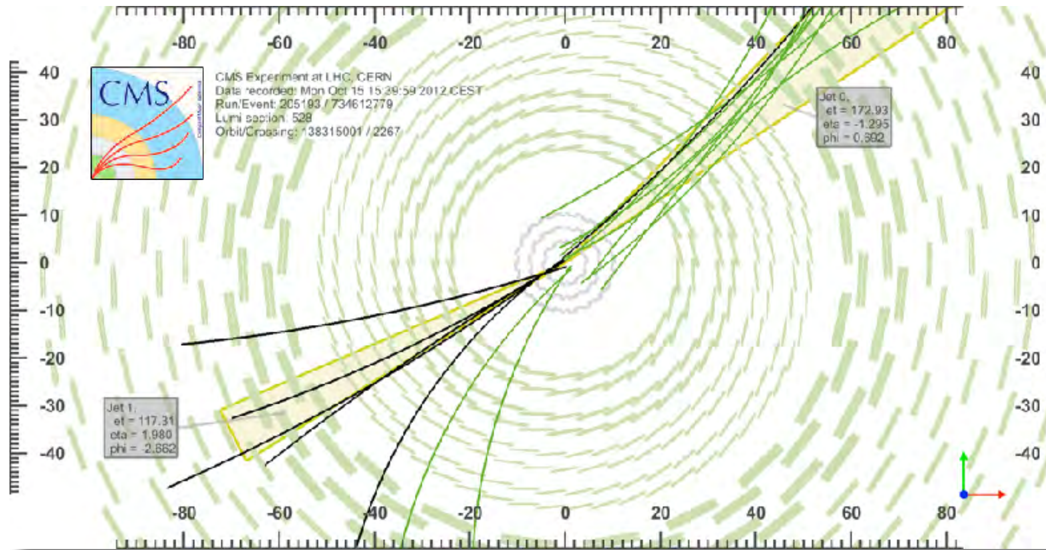
Long-Lived Particles

- Continuing with a quest for small couplings, at certain point weakly-coupled particles become long-lived and can decay in the middle of the detector
- Requires considerably different experimental techniques and often dedicated triggers to look for such signatures

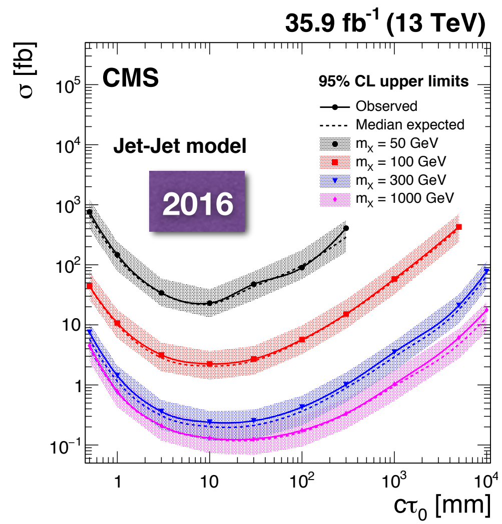


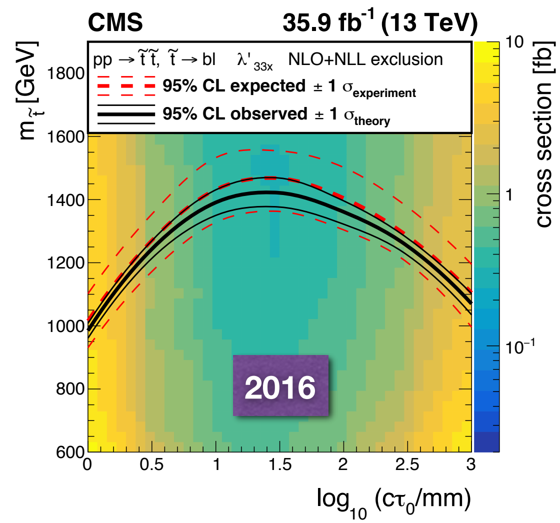
Search for Displaced Jets

- CMS search based on dedicated triggers requiring at least two jets with low number of prompt tracks
- Special MVA displaced jet tagging based on the angular and displacement information for the tracks (e.g., 2D IP_{sig})
- Offers high sensitivity to objects decaying into a pair of non-prompt jets, as QCD background is small



CMS arXiv:1811.07991

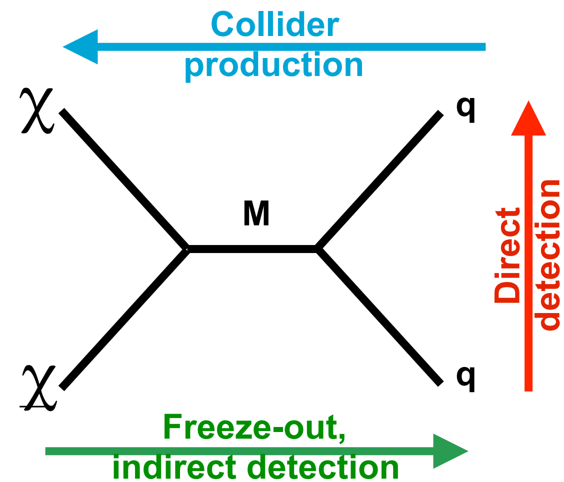


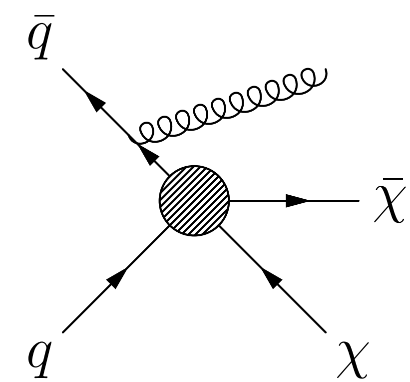


Dark Matter Searches

Make It, Break It, or Shake It!

- There are three main approaches to detect dark matter (DM):
  - DM-nucleon scattering (direct detection, or DD)
  - Annihilation (Indirect detection, or ID)
  - Pair production at colliders
- All three processes are nothing but topological permutations of one and the same Feynman diagram:
  - But: how to trigger on a pair of DM particles at colliders?
  - Initial-state radiation (ISR: g, γ, W/Z, H, …) to rescue!
- Original idea - to use ISR - appeared eight years ago:
  - Beltran, Hooper, Kolb, Krusberg, and Tait, “Maverick Dark Matter at Colliders” arXiv:1002.4137 (299 citations)

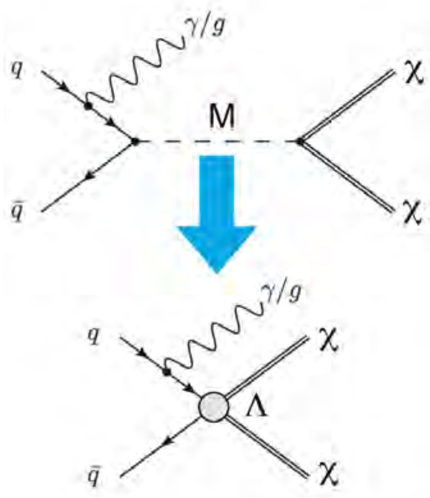




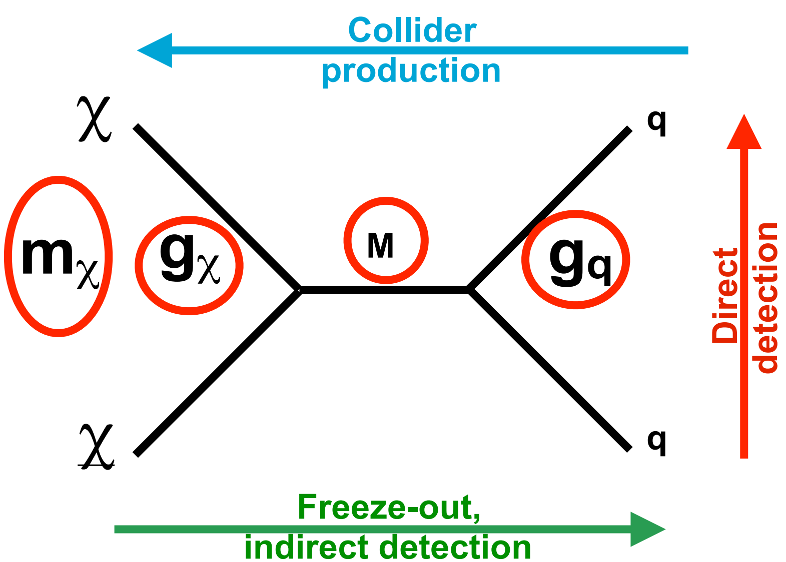
Monojet + MET

Dark Matter Interactions

- Early DM searches: EFT based
  - Since then understood the fundamental limitations of EFT and moved to simplified models
- Moving away from EFT allows for a more fair LHC vs. DD/ID experiments comparison and emphasizes the complementarity of the two approaches



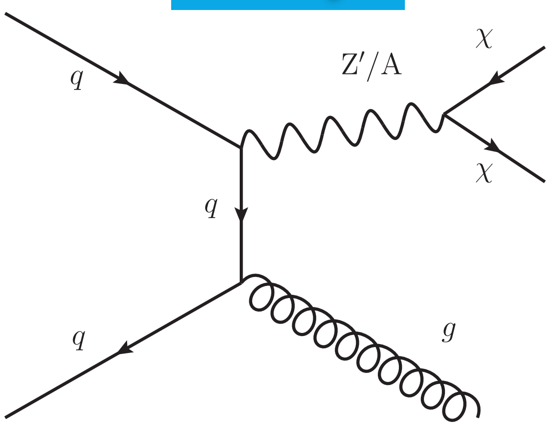
Fundamentally 4D problem!



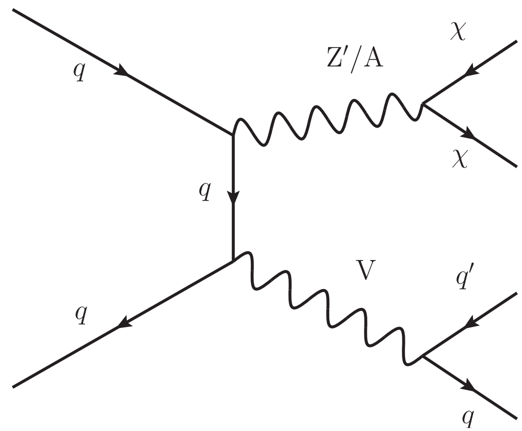
Simplified Models to Rescue

- Combined monojet and mono-V(jj) (boosted) analysis
- Probes scalar and pseudoscalar mediators, in addition to (axial) vector ones

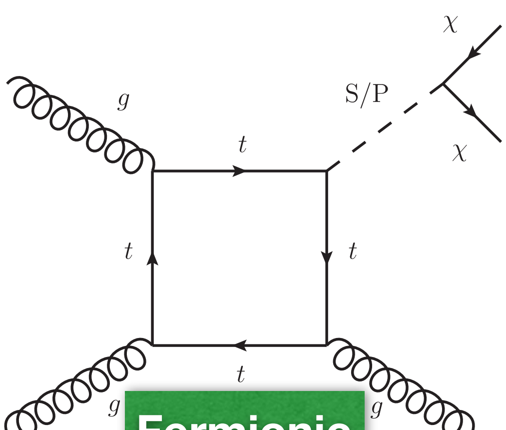
Monojet



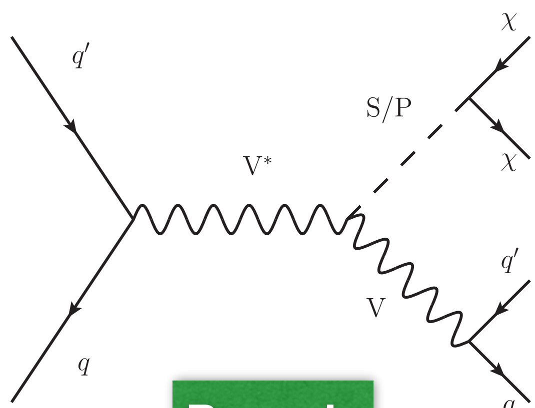
Mono-V



(Axial) Vector



Fermionic



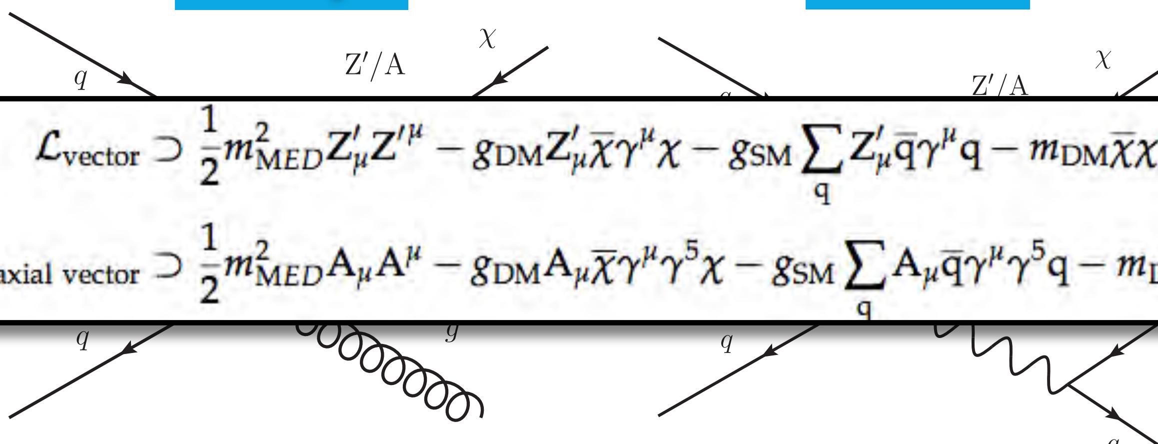
Bosonic

(Pseudo) Scalar

Simplified Models to Rescue

- ✦ Combined monojet and mono-V(jj) (boosted) analysis
- ✦ Probes scalar and pseudoscalar mediators, in addition to (axial) vector ones

Monojet **Mono-V**

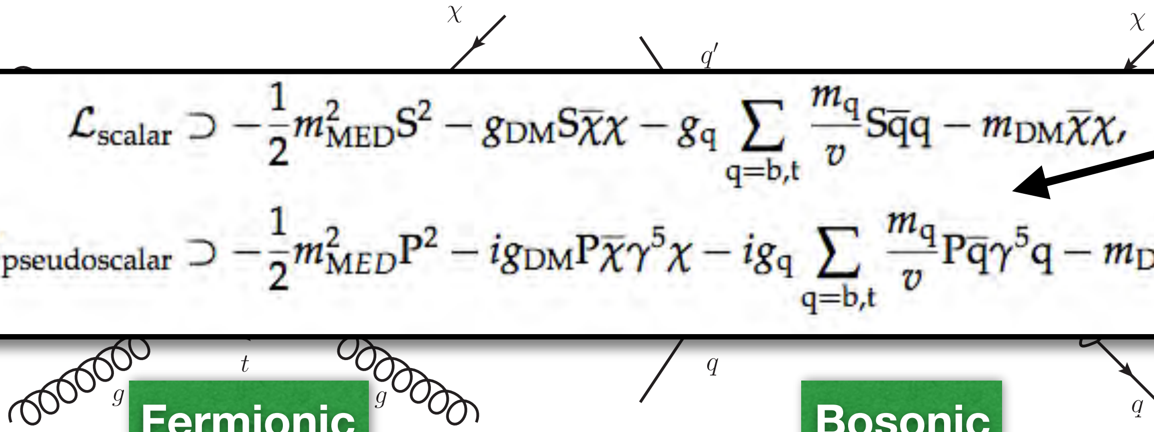


$$\mathcal{L}_{\text{vector}} \supset \frac{1}{2} m_{\text{MED}}^2 Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_{\text{SM}} \sum_{\text{q}} Z'_\mu \bar{\text{q}}\gamma^\mu \text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{axial vector}} \supset \frac{1}{2} m_{\text{MED}}^2 A_\mu A^\mu - g_{\text{DM}} A_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - g_{\text{SM}} \sum_{\text{q}} A_\mu \bar{\text{q}}\gamma^\mu\gamma^5 \text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

(Axial) Vector

Higgs-like couplings to SM fields



$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\bar{\chi}\chi - g_{\text{q}} \sum_{\text{q=b,t}} \frac{m_{\text{q}}}{v} S\bar{\text{q}}\text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{pseudoscalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 P^2 - i g_{\text{DM}} P\bar{\chi}\gamma^5\chi - i g_{\text{q}} \sum_{\text{q=b,t}} \frac{m_{\text{q}}}{v} P\bar{\text{q}}\gamma^5 \text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

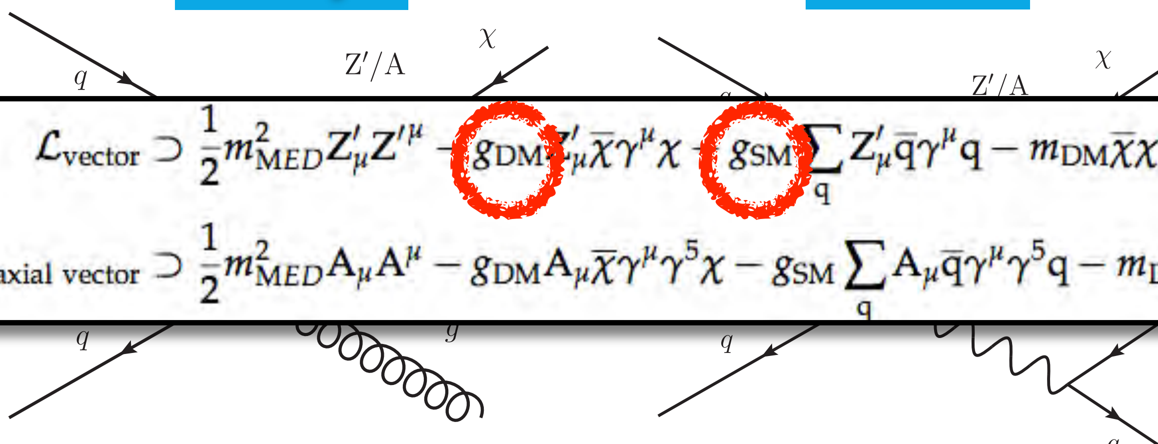
(Pseudo) Scalar

Fermionic **Bosonic**

Simplified Models to Rescue

- ✦ Combined monojet and mono-V(jj) (boosted) analysis
- ✦ Probes scalar and pseudoscalar mediators, in addition to (axial) vector ones

Monojet **Mono-V**



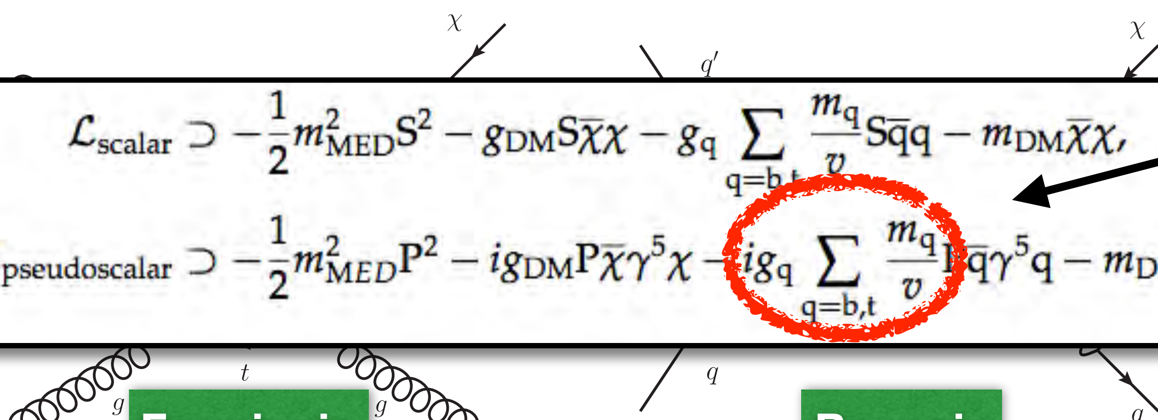
$$\mathcal{L}_{\text{vector}} \supset \frac{1}{2} m^2_{\text{MED}} Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_{\text{SM}} \sum_{\text{q}} Z'_\mu \bar{\text{q}}\gamma^\mu \text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{axial vector}} \supset \frac{1}{2} m^2_{\text{MED}} A_\mu A^\mu - g_{\text{DM}} A_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - g_{\text{SM}} \sum_{\text{q}} A_\mu \bar{\text{q}}\gamma^\mu\gamma^5 \text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

(Axial) Vector

$g_q = 0.25$, $g_\chi = 1$

Higgs-like couplings to SM fields



$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2} m^2_{\text{MED}} S^2 - g_{\text{DM}} S\bar{\chi}\chi - g_{\text{q}} \sum_{\text{q=b,t}} \frac{m_{\text{q}}}{v} S\bar{\text{q}}\text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{pseudoscalar}} \supset -\frac{1}{2} m^2_{\text{MED}} P^2 - i g_{\text{DM}} P\bar{\chi}\gamma^5\chi - i g_{\text{q}} \sum_{\text{q=b,t}} \frac{m_{\text{q}}}{v} P\bar{\text{q}}\gamma^5\text{q} - m_{\text{DM}}\bar{\chi}\chi,$$

(Pseudo) Scalar

Yukawa couplings

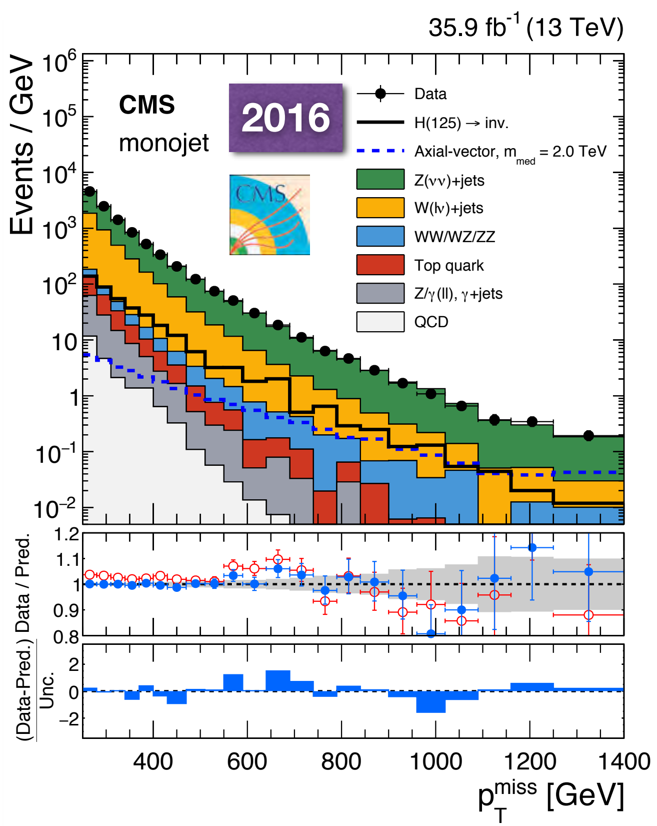
Fermionic **Bosonic**

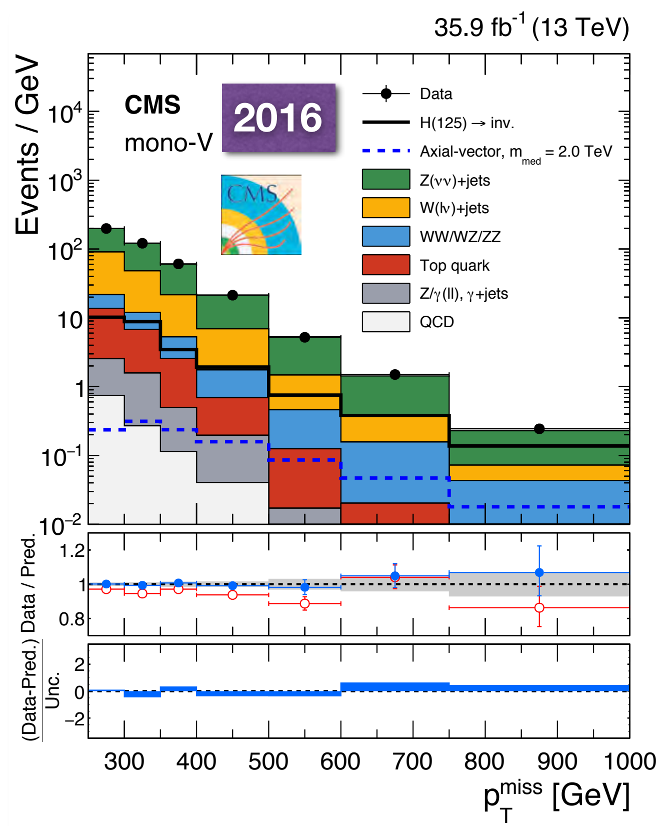
Monojets: the Classics

CMS Monojet/Mono-V Analysis

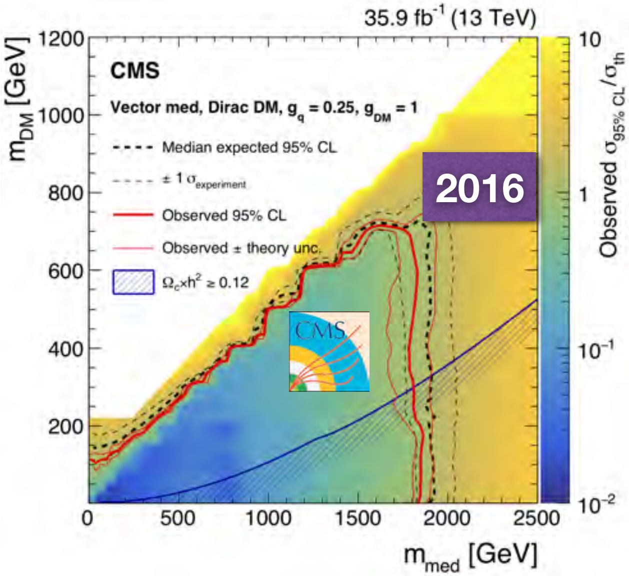
- ✦ The latest Run 2 analysis is built on the Run 1 techniques
  - Combines "massless" (monojet) and massive (mono-W/Z) jets
  - State-of-the-art treatment of NLO EW/QCD corrections to SM V+jets processes, after Lindert et al., arXiv:1705.04464

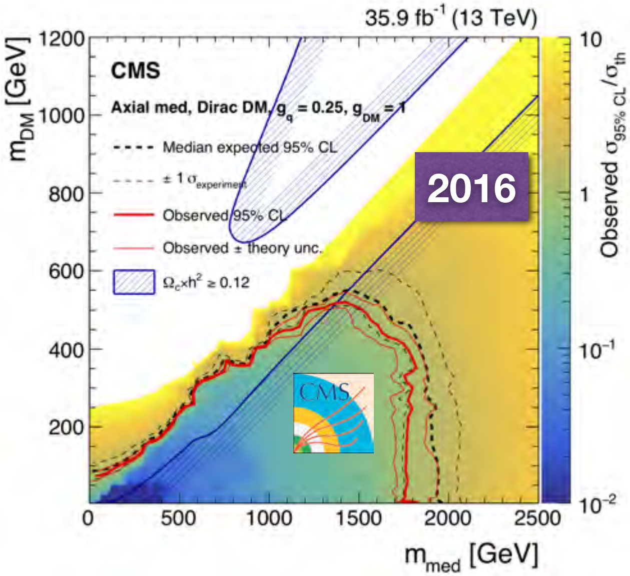
CMS arXiv:1712.02345

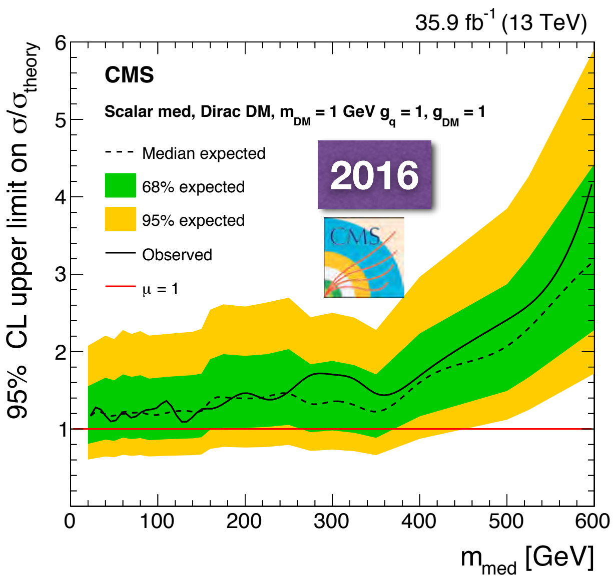


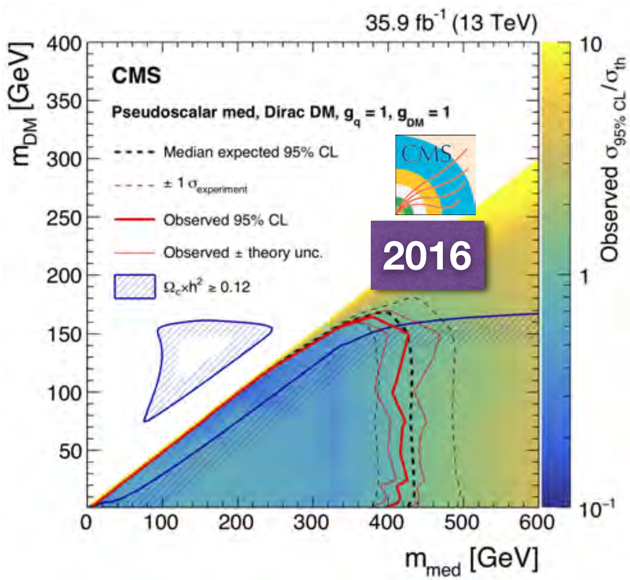


DM Interpretation





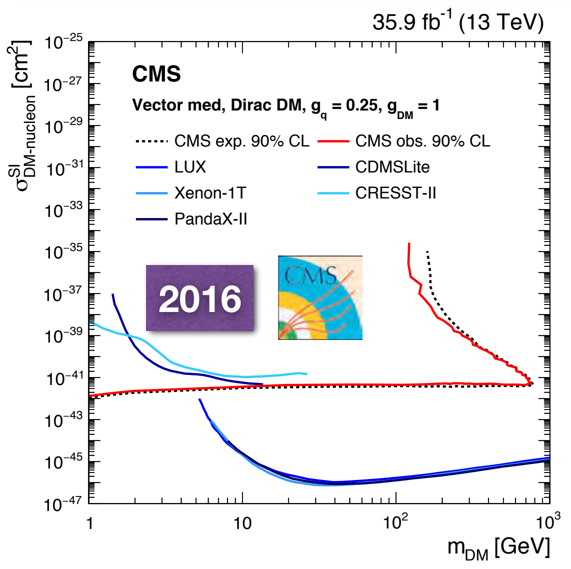


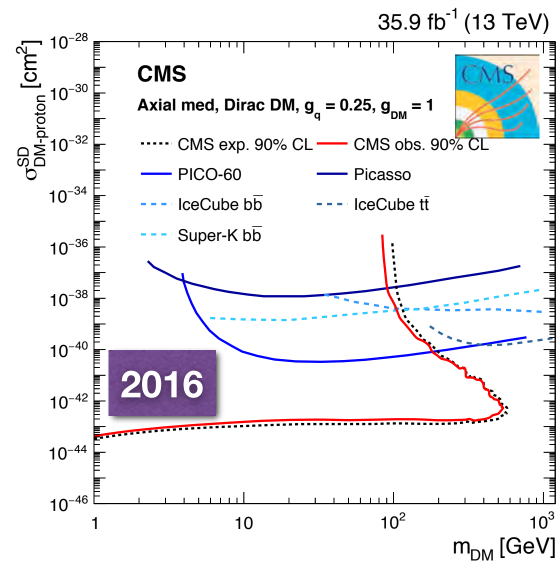


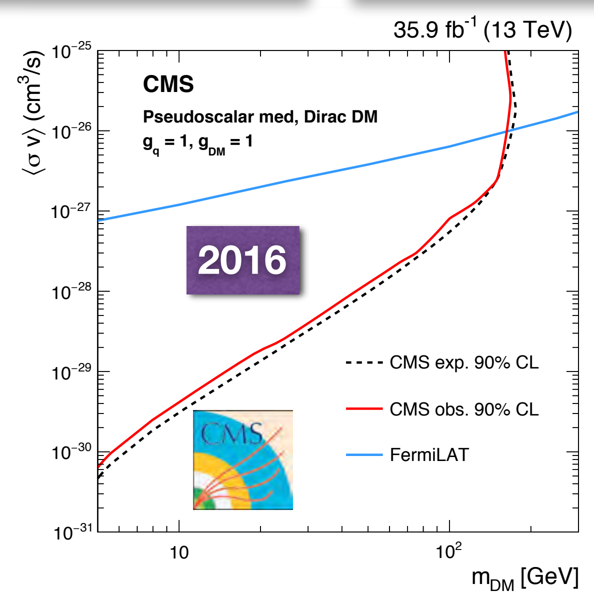
CMS arXiv:1712.02345

Complementarity w/ I/DD

CMS arXiv:1712.02345

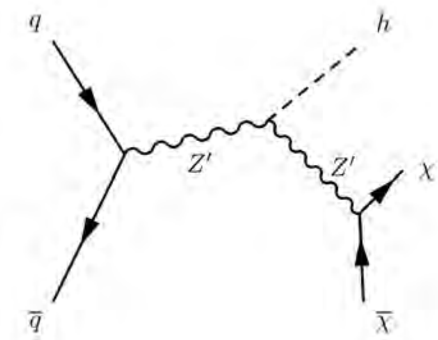




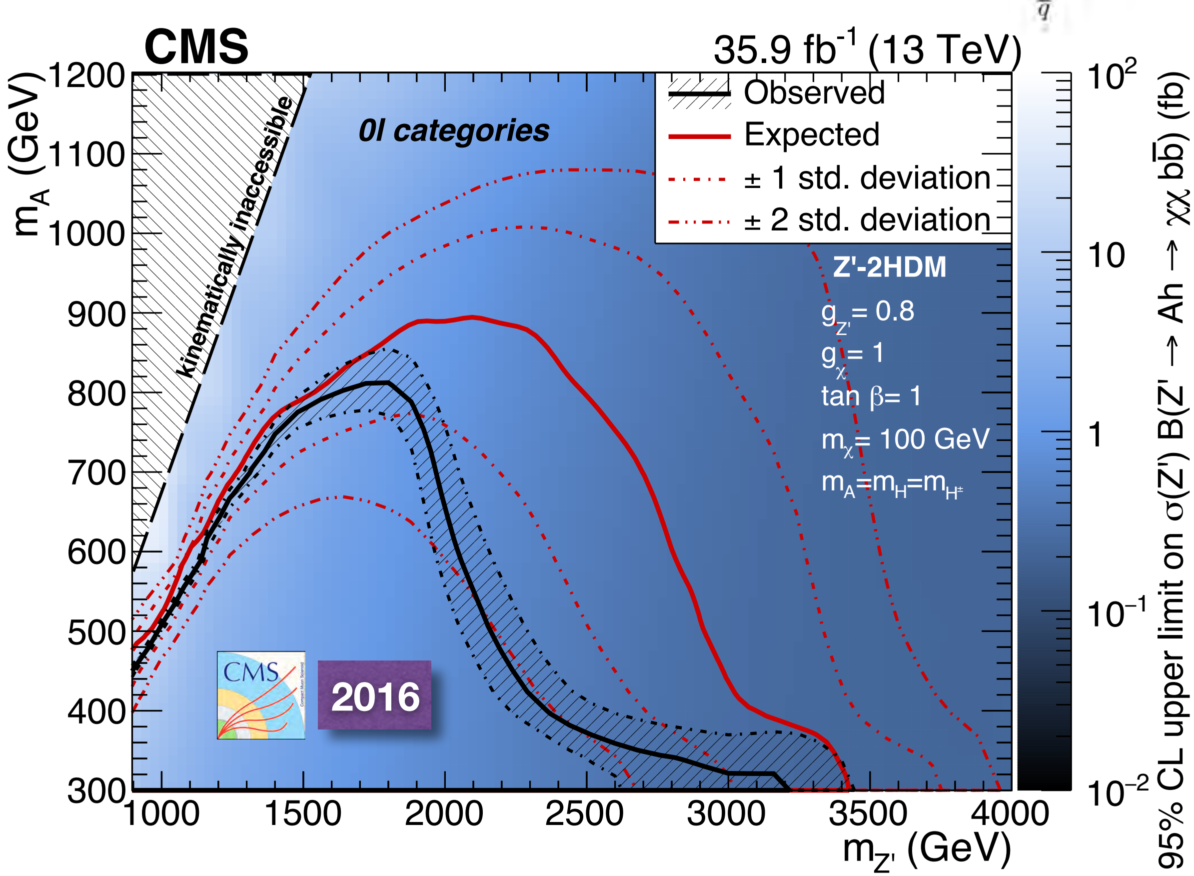


Mono-Higgs Search

- Newly discovered Higgs boson could be produced in association with DM!
- Looking for the dominant decay mode: H(bb) (+ MET)
- By far most restrictive limits on the model to date, even despite a slight excess observed



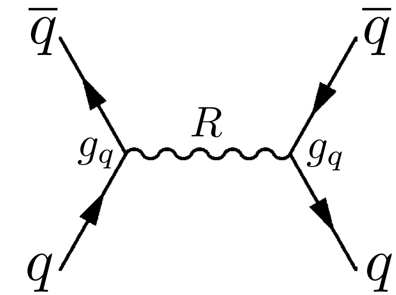
CMS arXiv:1807.02826



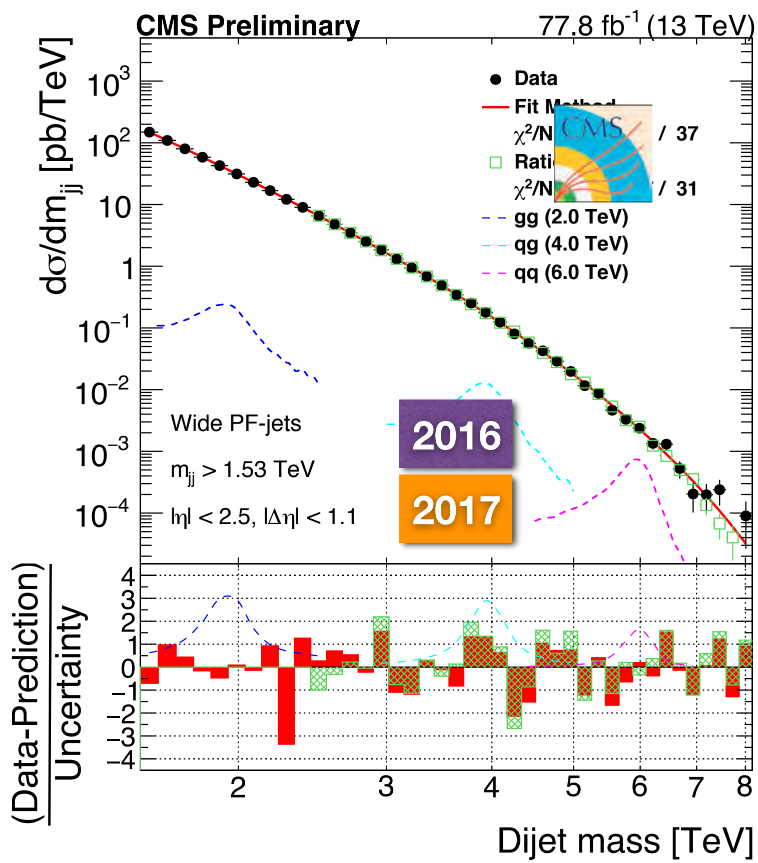

Searches for
a Mediator

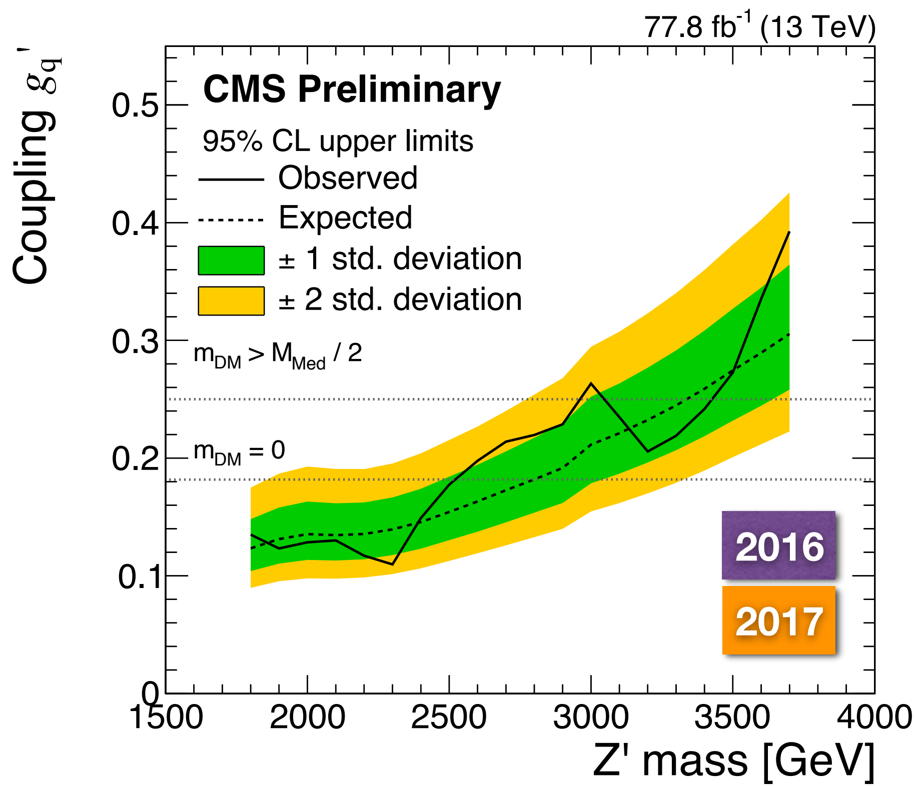
Search for a Mediator

- One doesn't need to produce DM at the LHC to look for a mediator
- Since it's coupled to the initial state, one could look for dijet decays of the mediator by "recycling' various dijet resonance searches



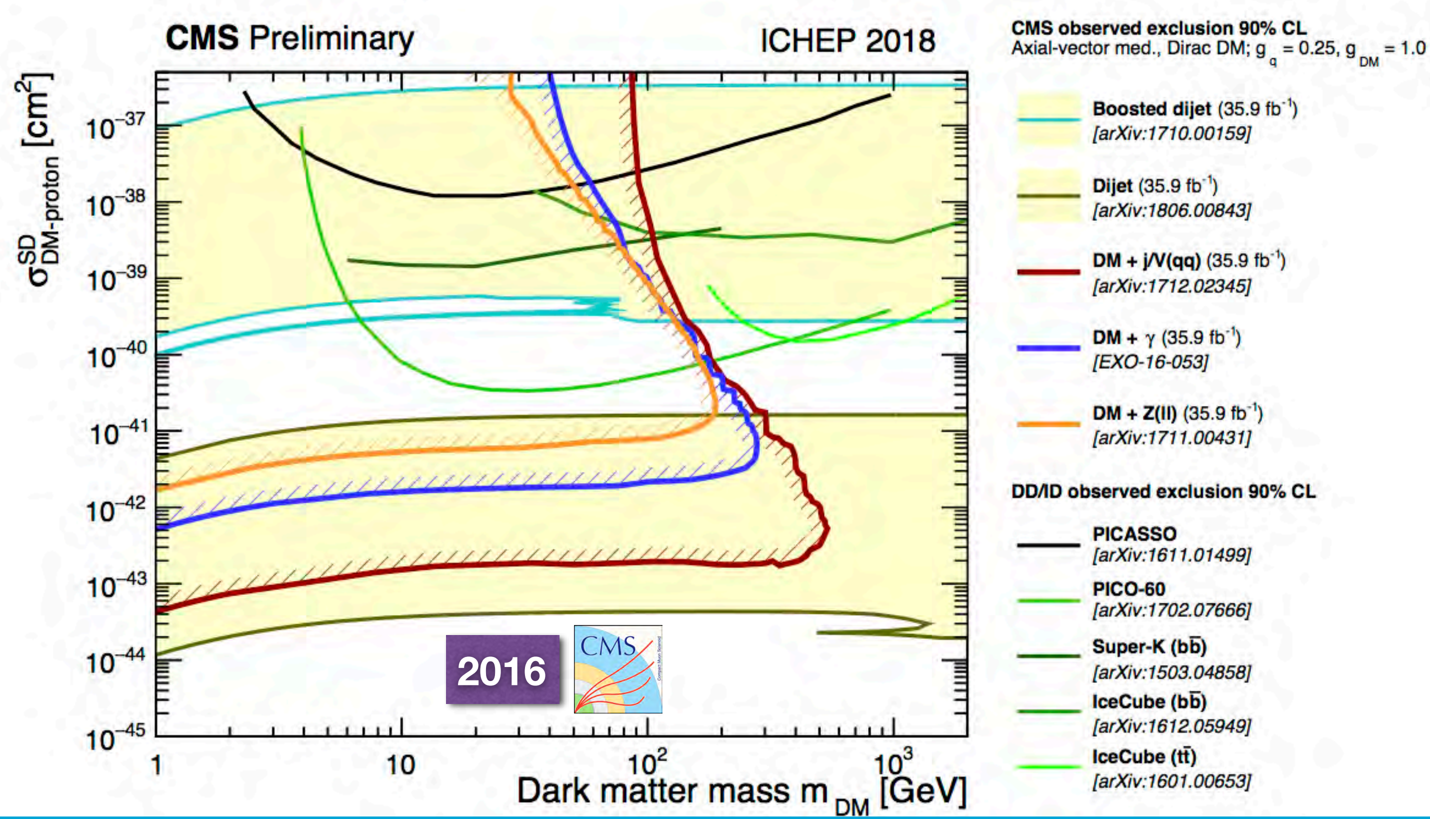
CMS PAS EXO-17-026





Big Picture: LHC vs. DD

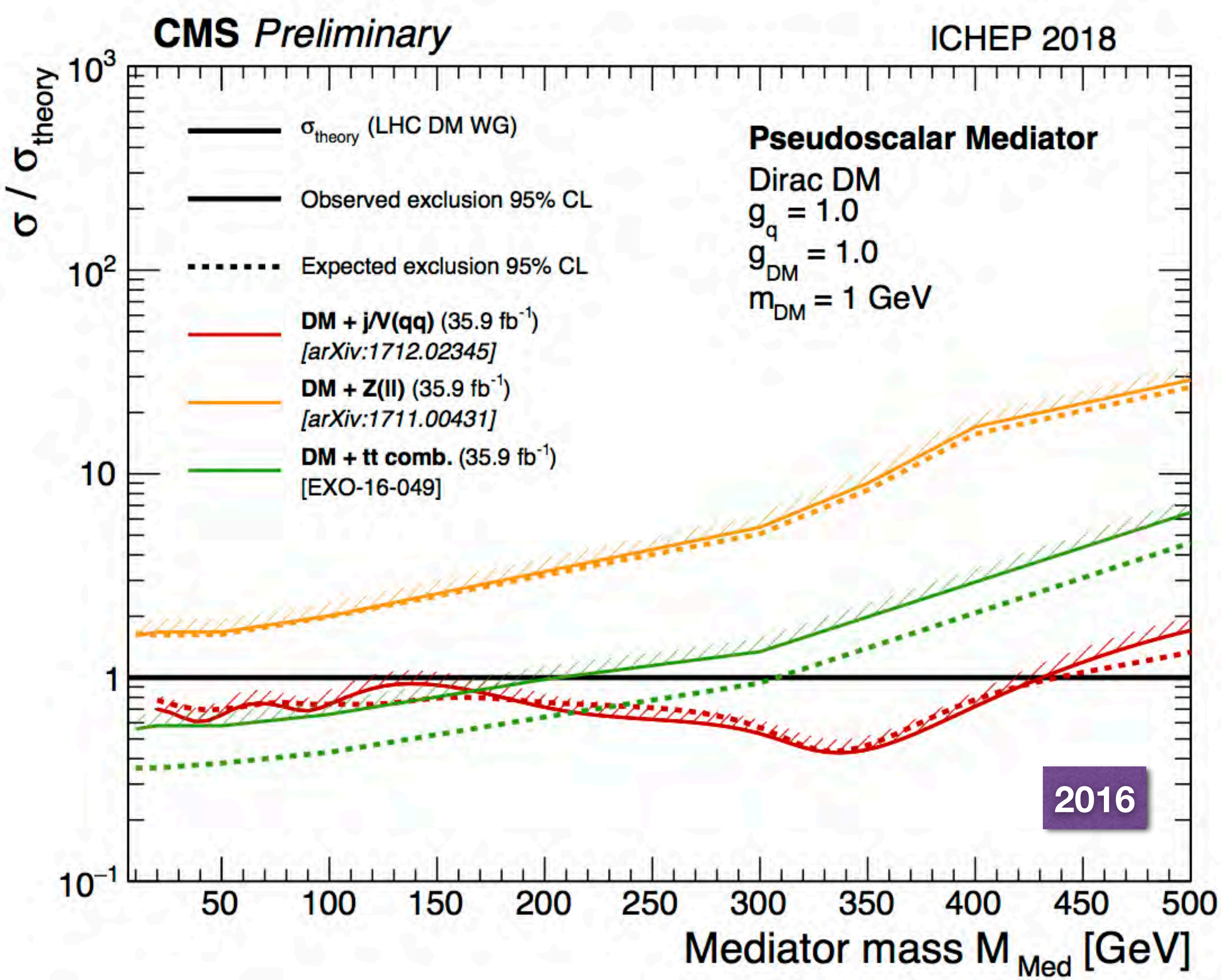
- Axial vector mediators
  - No resonant enhancement due to spin-dependent cross section
  - Colliders typically win over the DD experiments up to a few hundred GeV DM masses



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Dark_Matter_Summary_plots

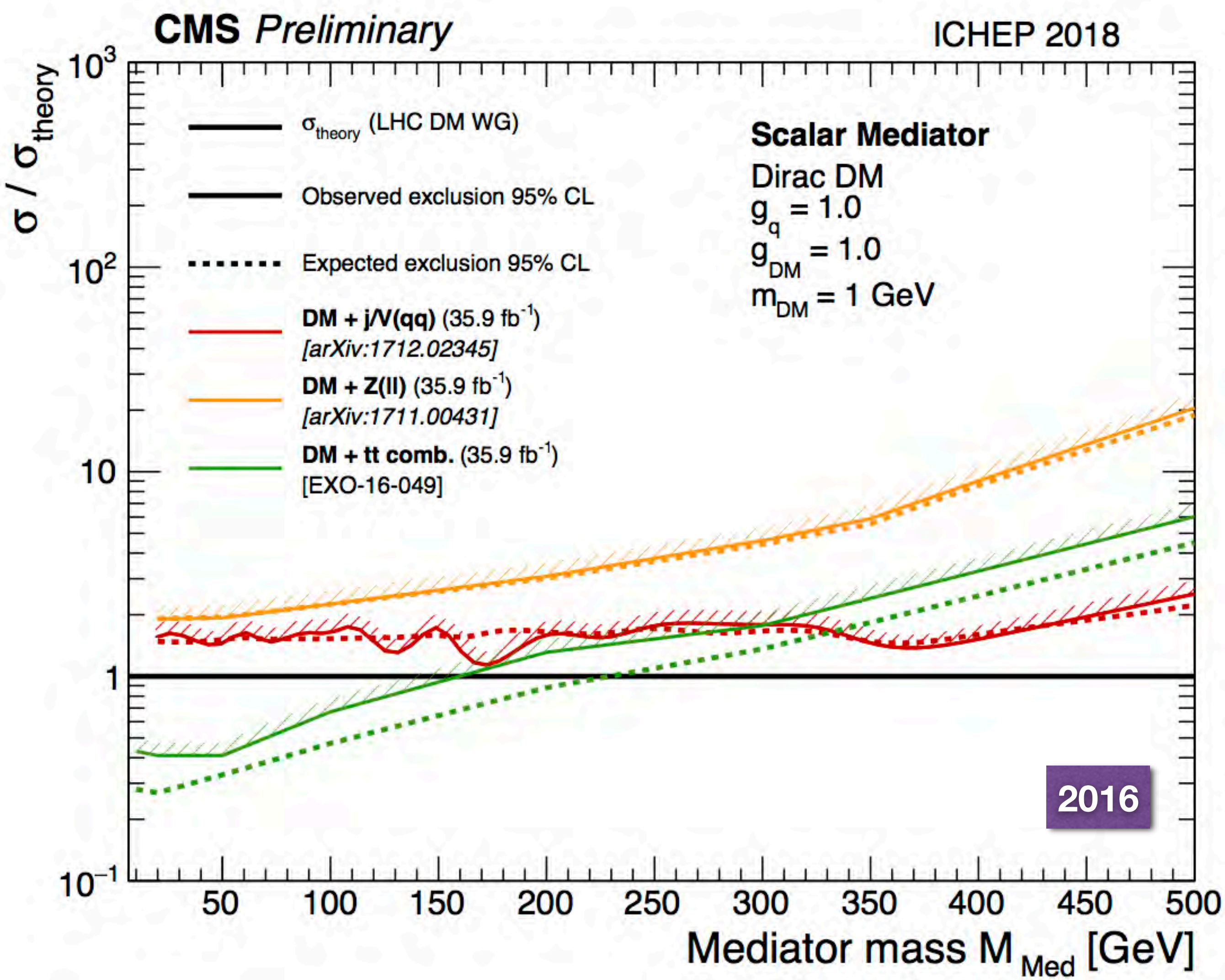
Big Picture: Spin 0

✦ For the first time started probing spin-0 mediators



Big Picture: Spin 0

✦ For the first time started probing spin-0 mediators



Future Run 2 Searches

- Parton luminosity arguments shaped the searches program in 2015-2018:
  - Look for high-mass singly or pair-produced objects:
    - Gluinos, squarks (SUSY)
    - Z', W', dijet, tt, and diboson resonances, vector-like quarks, leptoquarks, black holes (Exotica)
- The situation has finally changed after 2016, since the data doubling time from now on for the first time would exceed 1 year, approaching a "lifetime" of a graduate student in CMS
- Expect more sophisticated searches in complicated final states that haven't been explored before, using advanced analysis techniques, ISR and VBF probes, etc.
- The LHC searches are moving away from the lampposts (both theoretical and experimental) and enter really unprobed territory

Conclusions: Quo Vadis?

- LHC is an amazing machine, with a spectacular performance by far exceeding the expectations, despite a few birth pains
- Discovery of the Higgs boson in 2012 has completed the standard model of particle physics and paved an avenue to decades of exploration
    - Cf. the richness of top quark physics now, nearly a quarter century after the discovery!
- Precision standard model measurements, supported by the latest theory developments continue to be very exciting and important
- Direct searches for new physics have unexpectedly failed so far, but not for the lack of trying!
    - Redirect searches away from theoretical lampposts, and toward challenging signatures and most sophisticated analysis techniques
    - If all fails: LHC will do for dim-6 operators what LEP did for the SM dim-4 ones (SMEFT approach)!
- It's too early to throw a towel in: there are still hints for BSM physics (e.g., in the flavor sector) and we will follow up on them diligently
- Stay tuned for many new results from full Run 2 data later this year!


NON SEQUITUR
I'VE GOT A FEELING SOMETHING BIG IS JUST AROUND THE CORNER FOR US AND THINGS WILL FINALLY START FALLING OUR WAY...

Thank You!