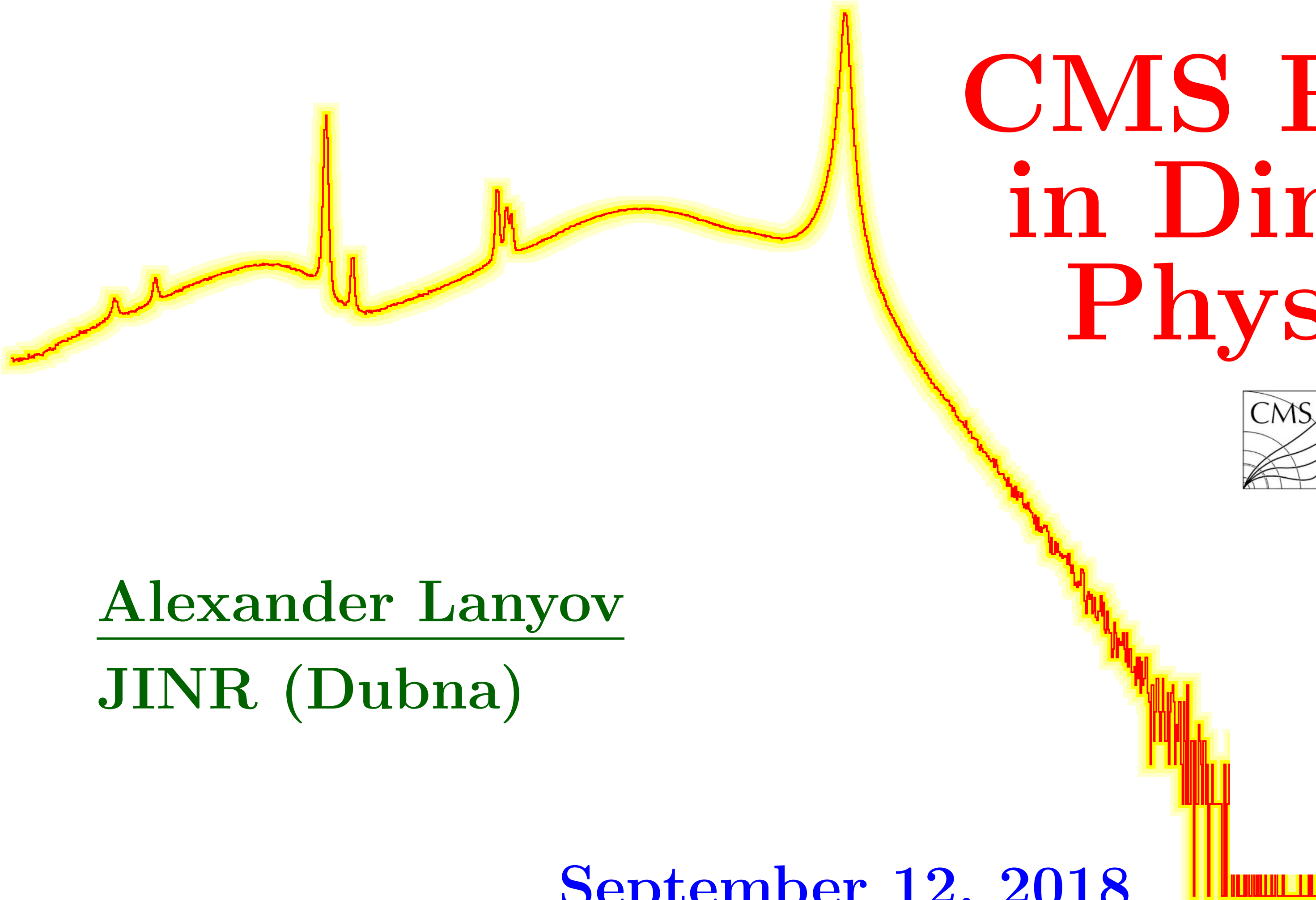
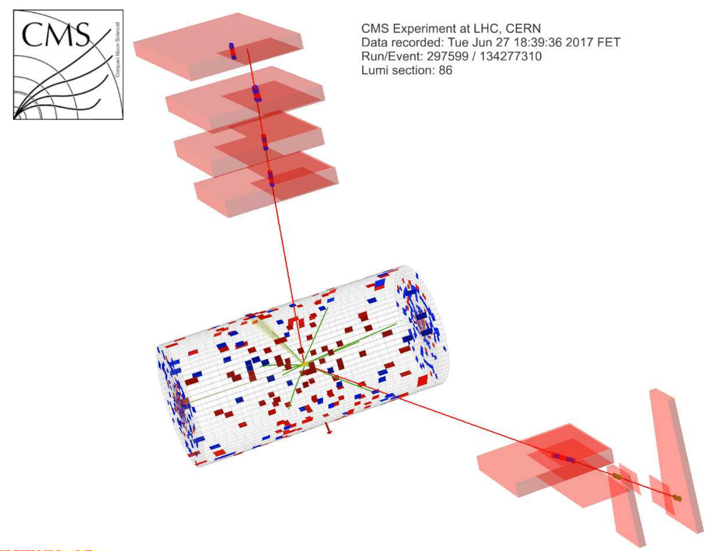
CMS Results in Dimuon Physics





Alexander Lanyov

JINR (Dubna)

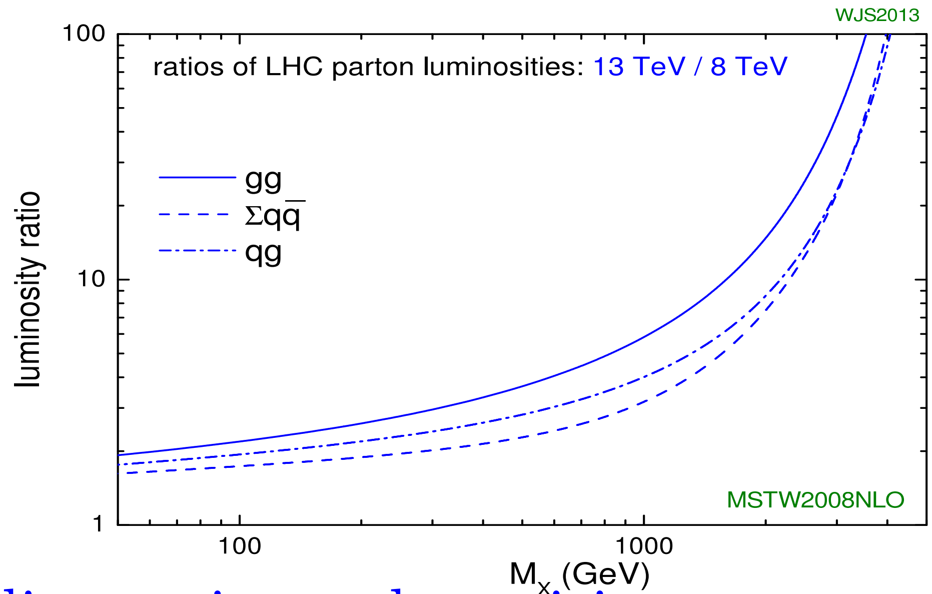
September 12, 2018

20th Annual RDMS CMS Collaboration Conference,

Tashkent, Uzbekistan

Introduction

- In Run 2 (2016–2018): rapid rise of integrated luminosity
  Expected total in Run 2 $\int \mathcal{L}\, dt \approx 150\,\mathrm{fb}^{-1}$.
- Transition to $\sqrt{s} = 13$ TeV



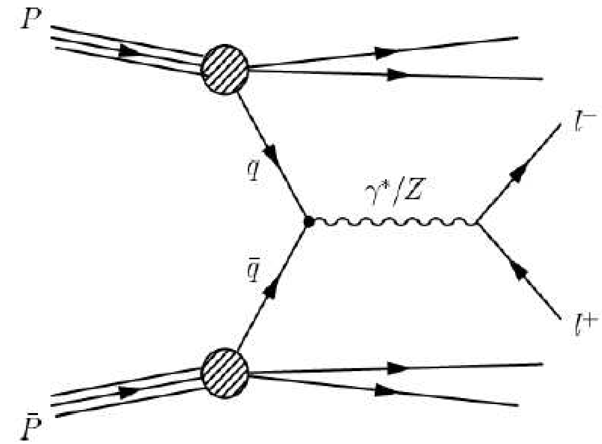
- New horizons are opening for discoveries and precision measurements.
- Therefore in this talk I would like to concentrate on some recent CMS public results with dimuon physics (SM and BSM),
  adding new interpretations,
  and reminding also some previous major results
  to be redone with the full Run 2 data.

Motivation to Study Dimuons at CMS

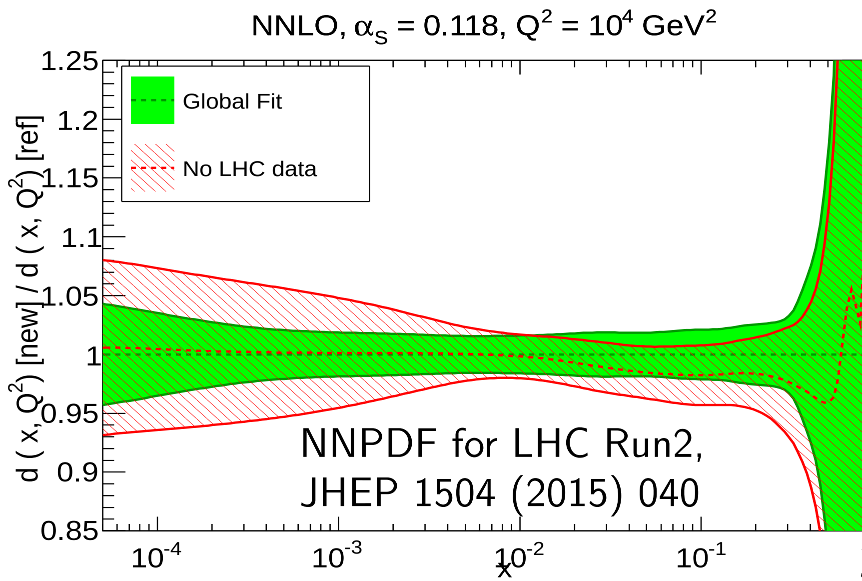
Many major discoveries were made before LHC in dimuon channel (J/ψ, Υ, Z, ...) — rather clean channel for finding new narrow resonances (often unexpected).

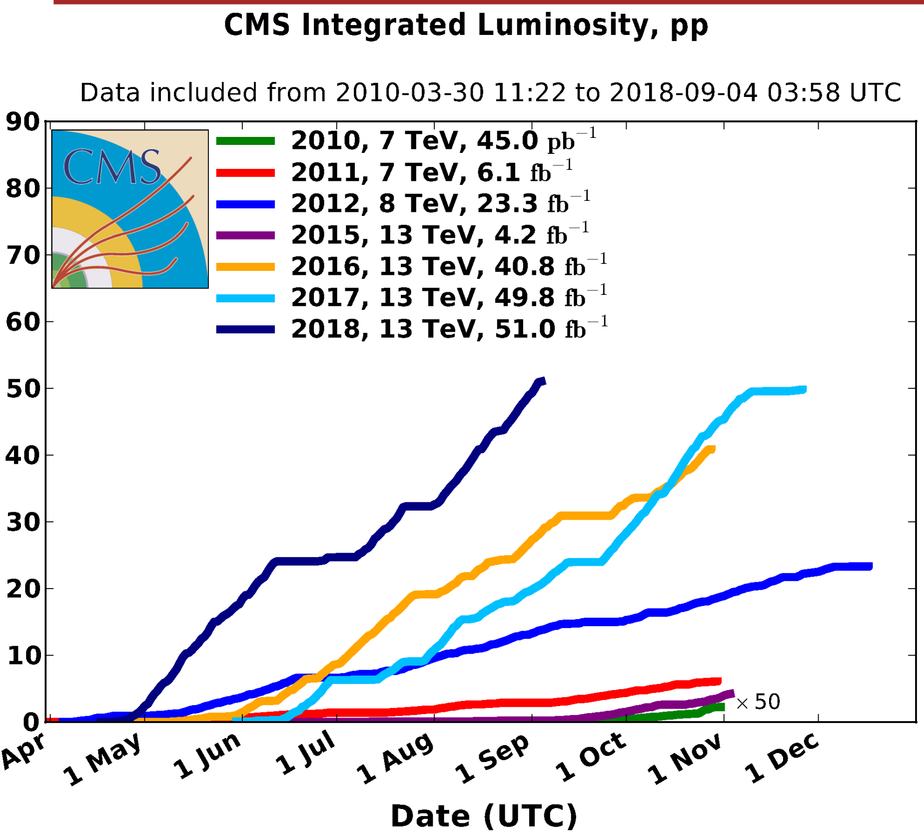
Why study dimuons at CMS?

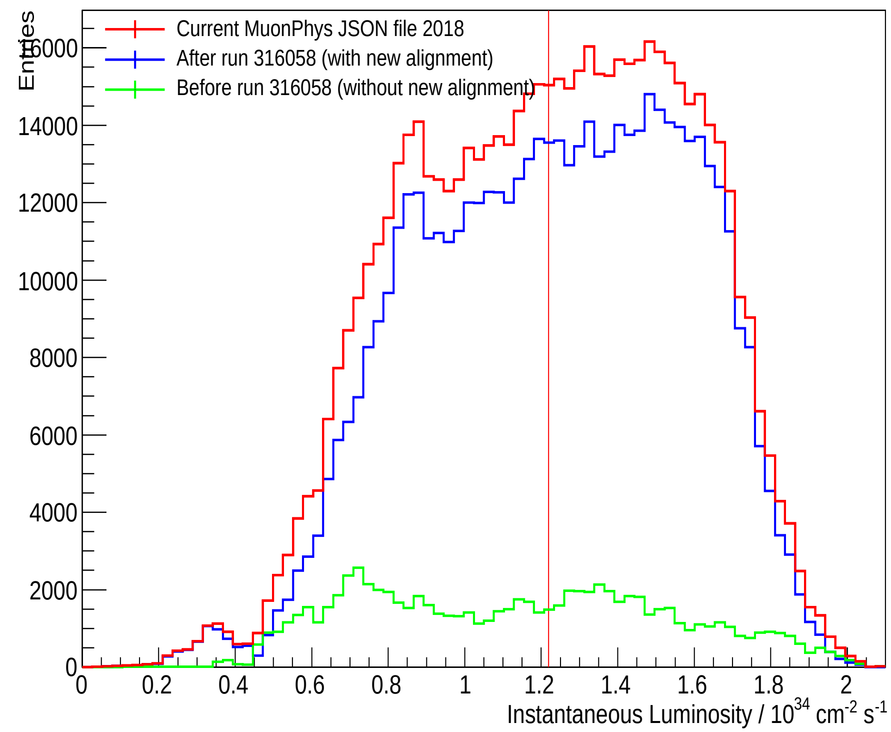
- Important Standard model benchmark channel
  Theoretical cross section calculated up to NNLO allowing tests of pQCD



- Many theoretical models predict contribution of New Physics in dimuon channel.
- Used to constrain PDFs
- Calibration and alignment, TnP
- Physics Processes produced in association with Z boson, $H \to ZZ$, $B \to \mu\mu$ discovery, $5\,\sigma$ discovery of $H \to b\bar{b}$ used also $Z \to \mu\mu$.

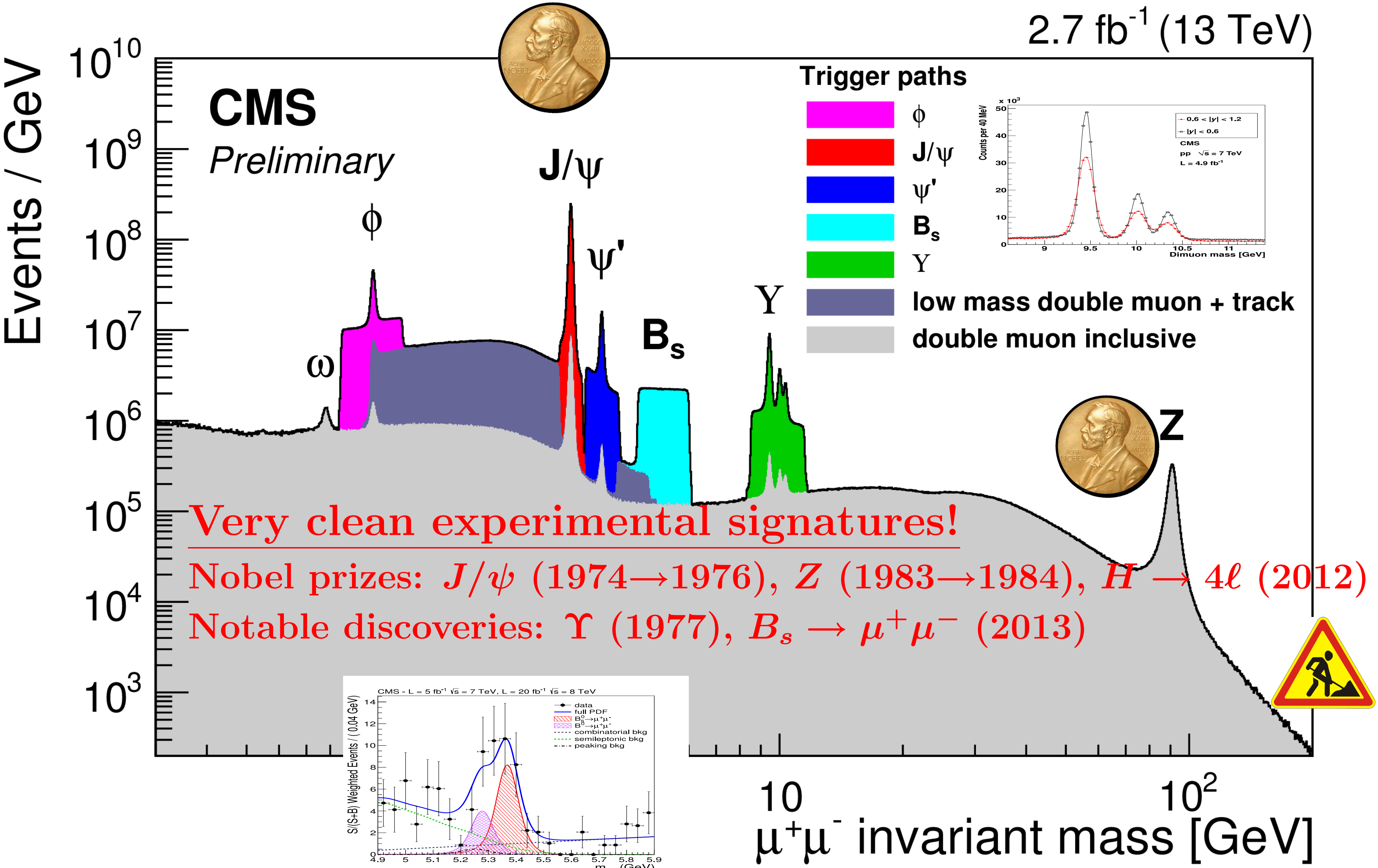






- Mean luminosity is more than $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (original nominal value for LHC)
- Rapid rise of integrated luminosity in 2016–2018 with $\sqrt{s} = 13$ TeV
- At the moment $\int \mathcal{L}\,dt$ is larger than 50 fb^{-1} in Run 2018
- Expected total in Run 2 $\int \mathcal{L}\,dt \approx 150\ \mathrm{fb}^{-1}$
- Data taking efficiency $> 90\%$

Dimuon Invariant Mass at CMS in Run 2



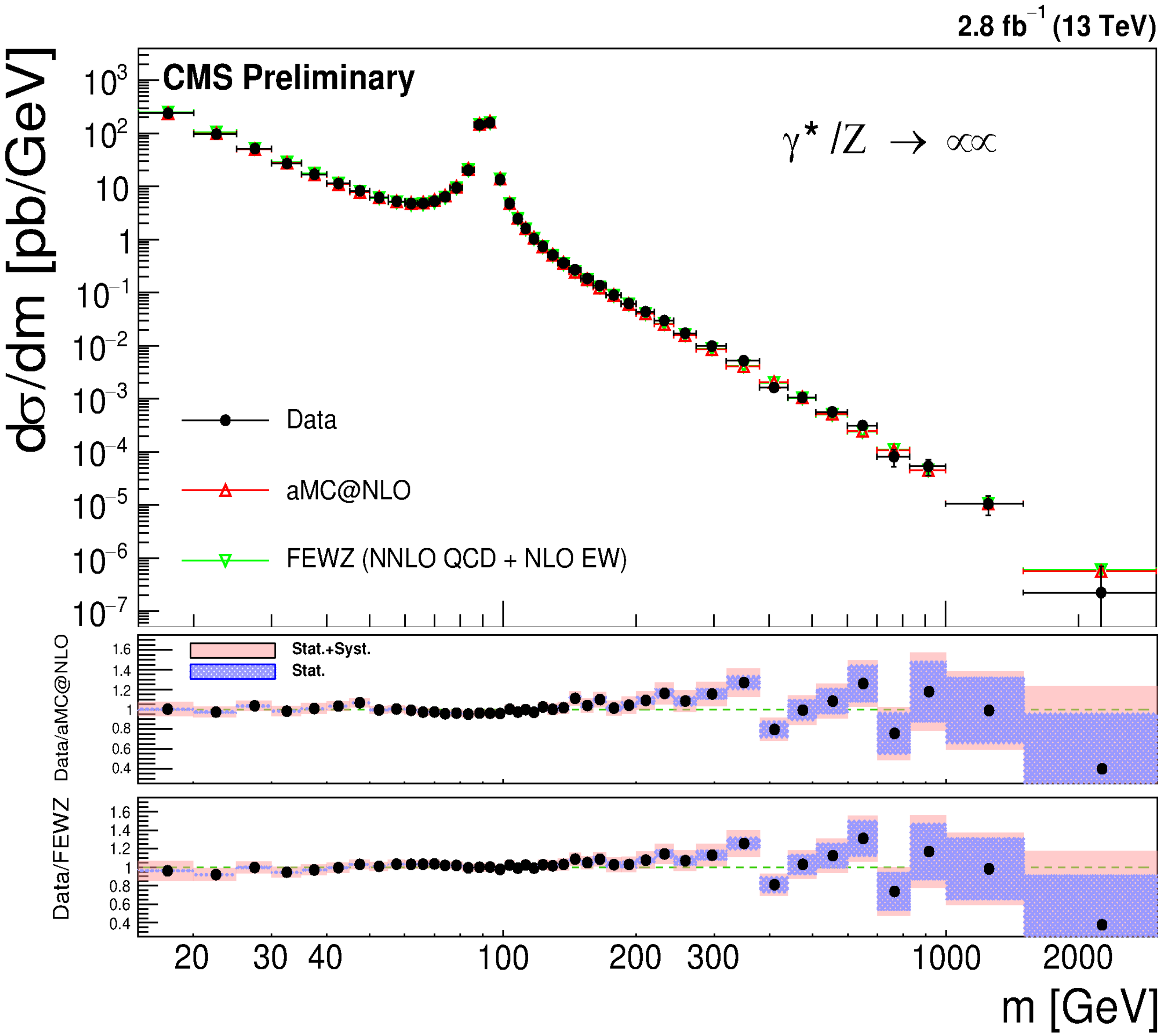
Very clean experimental signatures!

Nobel prizes: J/ψ (1974→1976), Z (1983→1984), $H \to 4\ell$ (2012)

Notable discoveries: ϒ (1977), $B_s \to \mu^+\mu^-$ (2013)

Drell-Yan process studies

Drell-Yan 1D Cross Section (CMS PAS SMP-16-009)

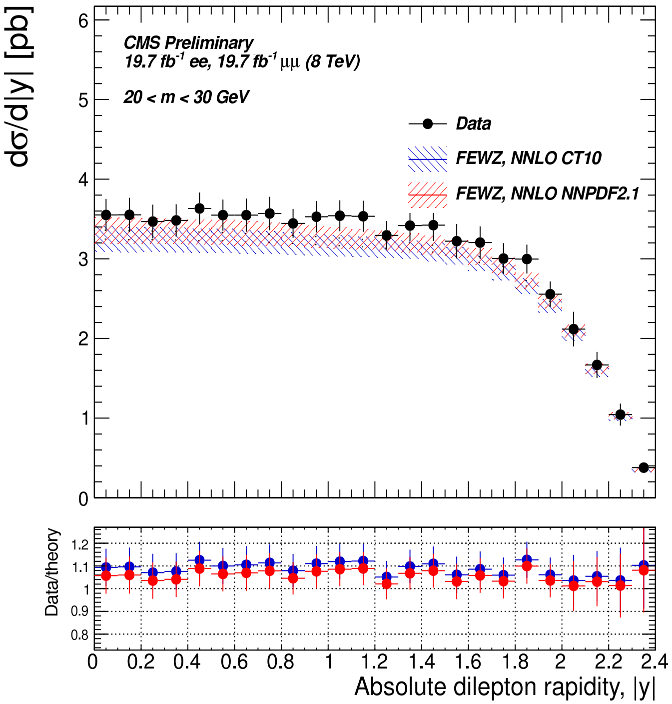


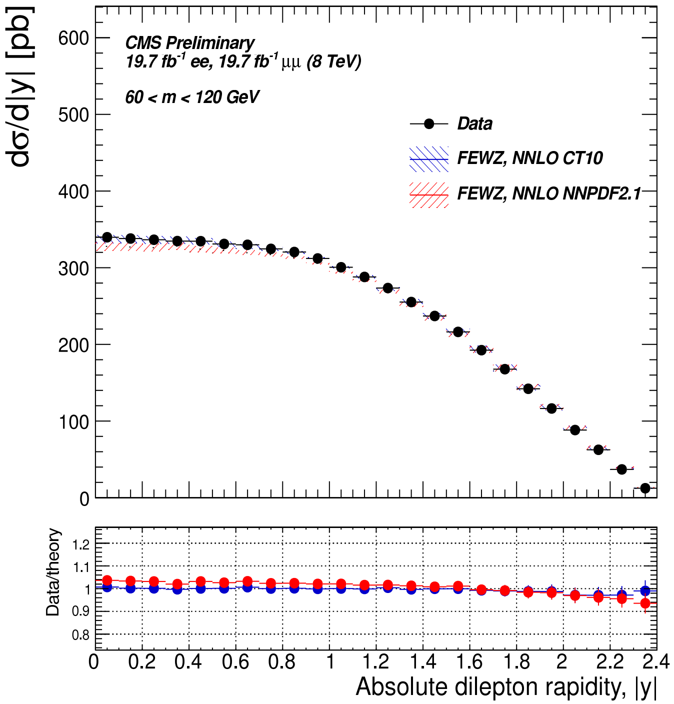
- $L = 2.8\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Mass range: 15—3000 GeV, divided by 43 bins
- Trigger: Isolated single muon trigger with $p_T > 20$ GeV
- Kinematic cut: $p_T^{\text{Lead}} > 22$ GeV, $p_T^{\text{Sub}} > 10$ GeV, $|\eta| < 2.4$
- Corrected to the full space
- Systematic uncertainty:
  Low-mass: Eff. SF $\sim 3\%$
  Z peak: FSR ($< 2\%$)
  High-mass: Det. Res. (up to 150%)

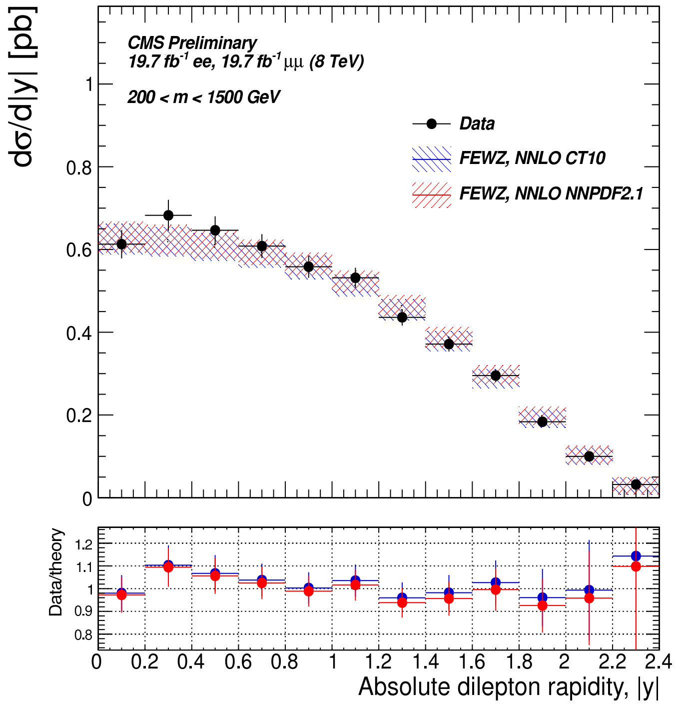
Generally good agreement between data and theory (aMC@NLO and FEWZ (NNLO QCD, NNPDF3.0))

Drell-Yan 2D Xsecs — M vs $|y|$ (Eur. Phys. J. C75 (2015) 147)

"Low mass"	Z region	"High mass"







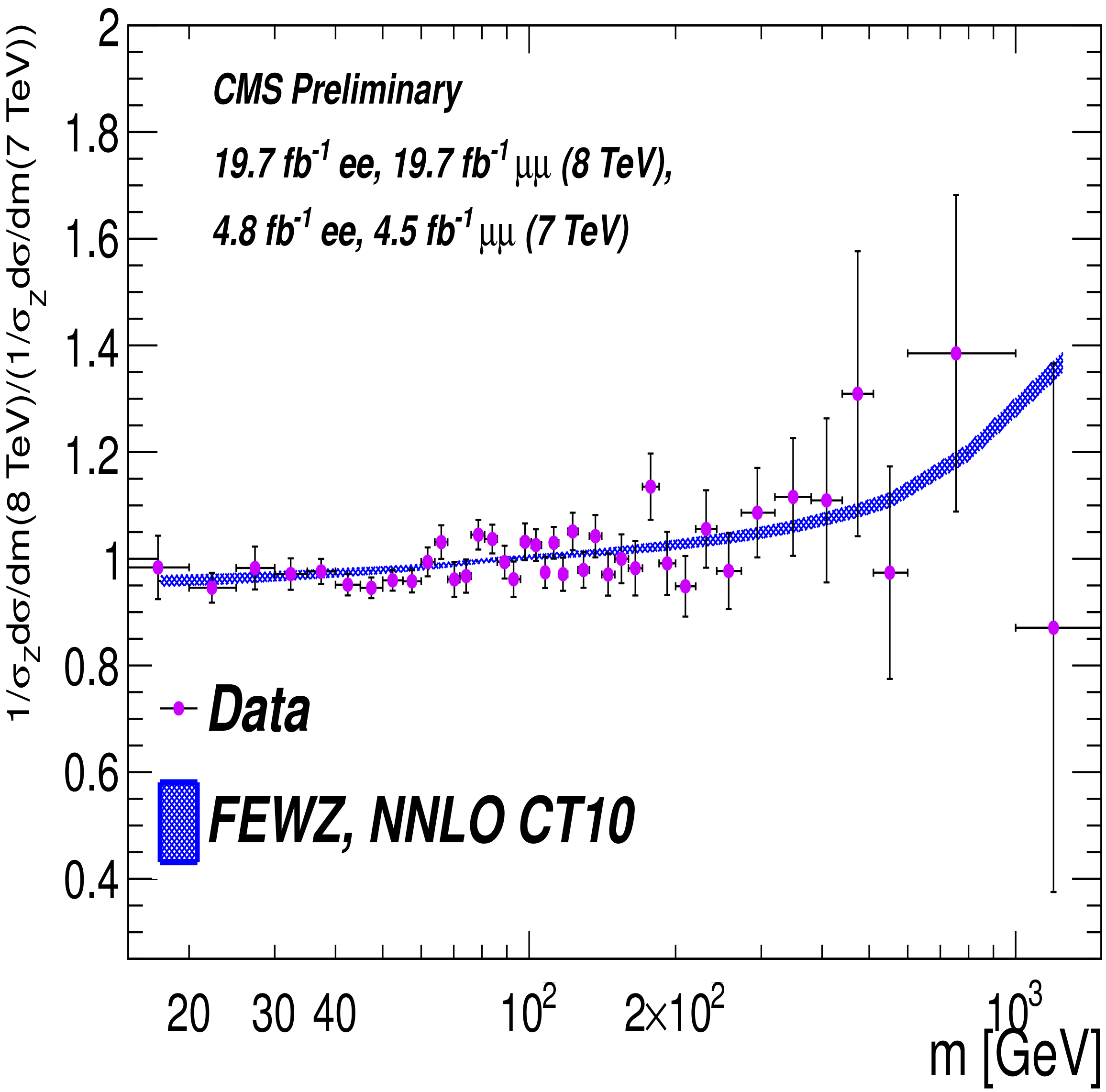
6 bins on $M_{\mu\mu}$ at 20, 30, 45, 60, 120, 200, 1500 GeV, $\quad$ 24 bins for $|y| = 0 - 2.4$
12 bins for $|y| = 2 - 2.4$

Within the detector acceptance to reduce the model dependence.

Good agreement with FEWZ but deviations exist at low and high mass regions.

The double ratio measurements provide a high sensitivity to NNLO QCD effects and could yield precise constraints on the PDFs

Measured ratio of DY xsecs between $\sqrt{s} = 8$ and 7 TeV



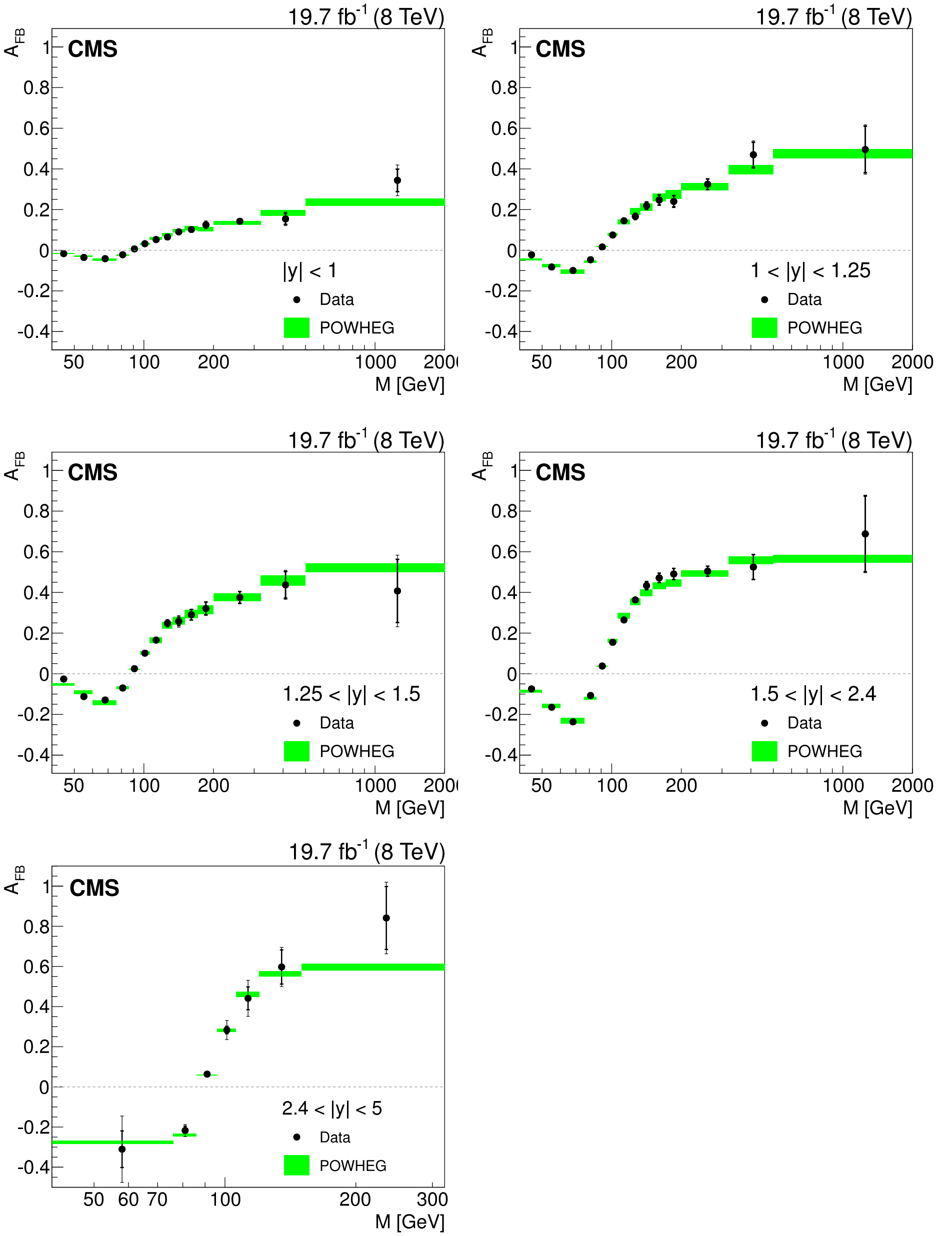
- Measurements of ratios of the normalized differential cross sections:

$$R_{8\,\mathrm{TeV}\,/\,7\,\mathrm{TeV}} = \frac{1/\sigma_Z\; d\sigma/dM(8\,\mathrm{TeV})}{1/\sigma_Z\; d\sigma/dM(7\,\mathrm{TeV})}$$

- Luminosity uncertainty is canceled out.
- Most of the theoretical uncertainties are reduced in such double ratio measurements due to correlations. (arXiv:1206.3557, M. Mangano, J. Rojo)
- Published in Eur. Phys. J. C75 (2015) 147

Also for 6 bins on $M_{\mu^+\mu^-}$ vs $|y|$. To be continued at higher energies...

Results for Drell-Yan Forward-Backward Asymmetry



$$A_{FB} = \frac{F - B}{F + B},$$

where F is $N(\cos\theta^* > 0)$, B is $N(\cos\theta^* < 0)$

$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}\cos\theta^*\right]$$

θ^* is angle between μ^- and quark direction in c.m.s. of dilepton.

- Quark direction is associated with the dilepton boost direction
- A_{FB} measured in different $|y|$ bins as a function of invariant mass $M_{\ell\ell}$
- CMS did the first measurement at hadron collider in $\mu^+\mu^-$ channel and combination of $\mu^+\mu^-$ and e^+e^- channels
- Good agreement to SM prediction
- $A_{\rm FB}$ can be used to measure Weinberg weak mixing angle $\sin^2\theta_W$

Eur. Phys. J. C76 (2016) 325

Angular coefficients of Z bosons as a function of p_T and Y (Phys. Lett. B 750 (2015) 154) at $\sqrt{s} = 8$ TeV

First measurement of Z boson angular coefficients in pp collisions and decaying to $\mu\mu$.

Coefficients A_i govern kinematics of the muons in $Z \to \mu\mu$. Their values follow from the vector and axial vector $(V - A)$ structure of boson-fermion couplings.

General structure of the lepton angular distribution in Z boson rest frame:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\mathrm{d}\phi^*} \propto \Big[(1+\cos^2\theta^*)+A_0\frac{1}{2}(1-3\cos^2\theta^*)+A_1\sin(2\theta^*)\cos\phi^*+A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*]$$

where θ^* and ϕ^* are the polar and azimuthal angles of the negatively charged lepton in the rest frame of the lepton pair.

A_4 is proportional to A_{FB}.

These measurements provide comprehensive information about the Z boson production mechanisms, compared to the QCD predictions.

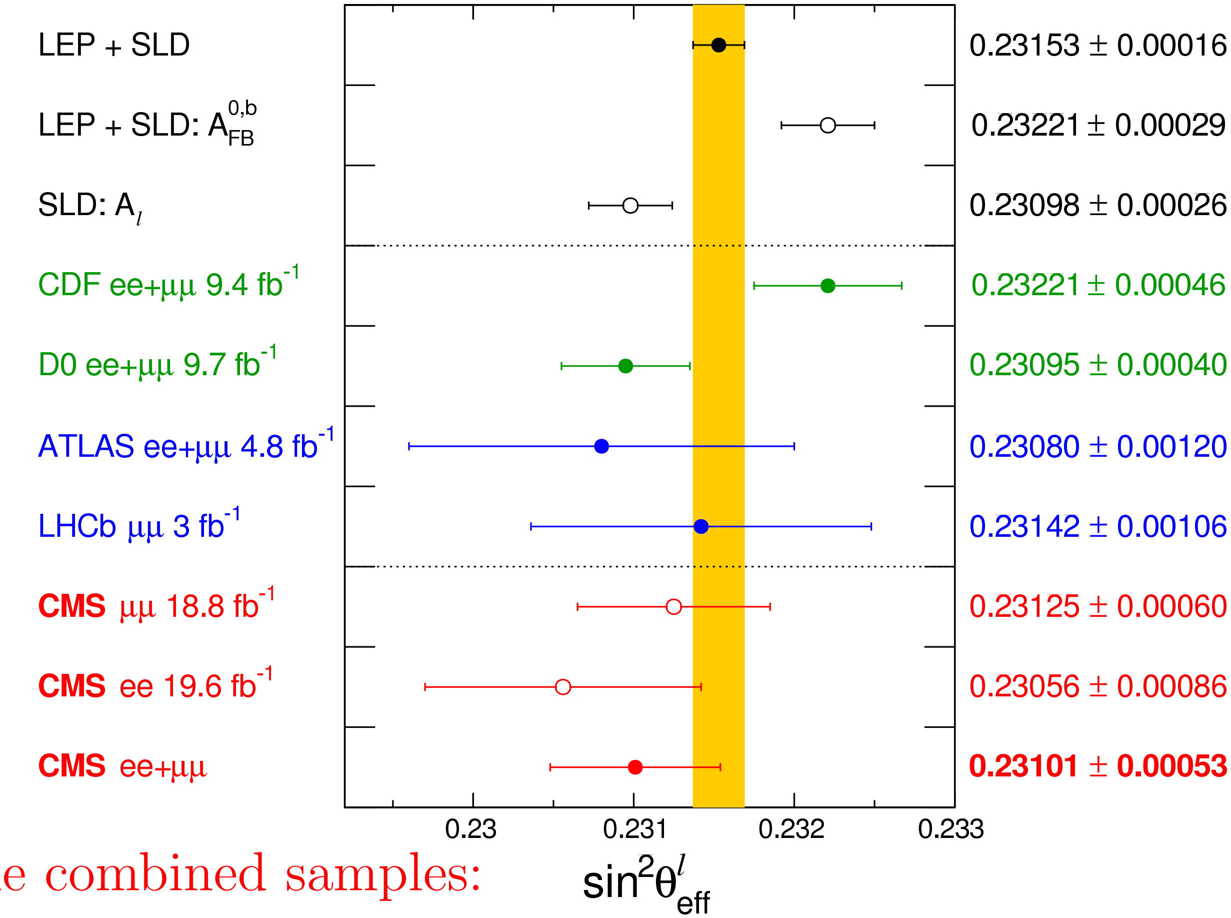
See details in the next talk by Ilya Gorbunov.

Measurement of Weak Mixing Angle with A_{FB} (arXiv:1806.00863)

Measurement of the leptonic effective weak mixing angle $\sin^2\theta_{\rm Eff}$ by fitting the mass and rapidity dependence of the observed A_{FB} in dilepton events.

$\sin^2\theta_{\rm Eff}$ is defined by relation for vector and axial-vector couplings of Z boson:

$v_f/a_f = 1 - 4\,|Q_f| \times \sin^2\theta_{\rm Eff}$



Effective weak mixing angle from the combined samples:

$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf}) =$
$= 0.23101 \pm 0.00052$

Uncertainties are significantly reduced compared to our previous measurement.

The common value for LHC measurements is dominated by the CMS measurement.

The results are consistent with the most precise measurements.

Further improvement is expected at HL-LHC (CMS PAS FTR-17-001).

Search for Higgs $\rightarrow \mu^+\mu^-$ (HIG-17-019 = arXiv:1807.06325)

Rare decay: $Br(H \rightarrow \mu^+\mu^-)_{SM} = 2.2 \times 10^{-4}$

New paper arXiv:1807.06325 (HIG-17-019):

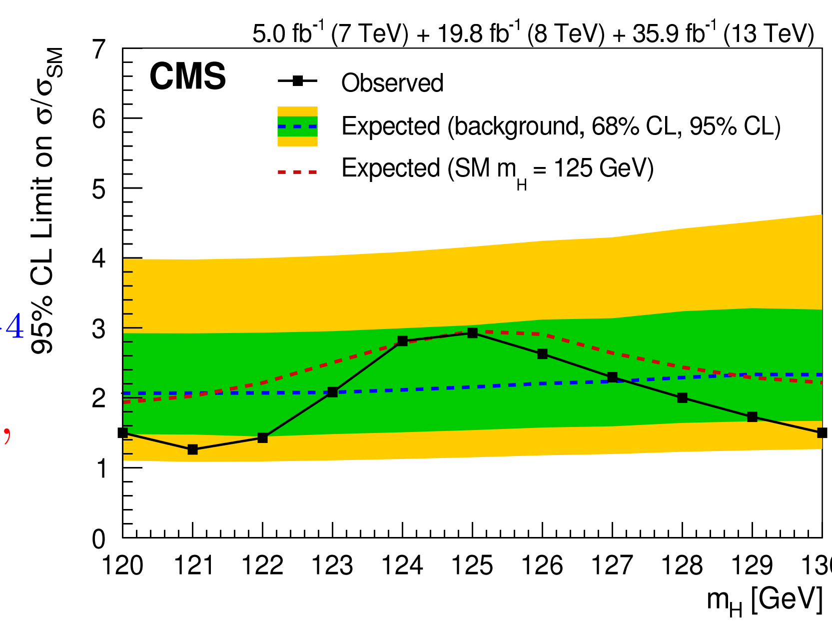
Observed μ limit: $2.92 \times$ SM value (95 % C.L.)

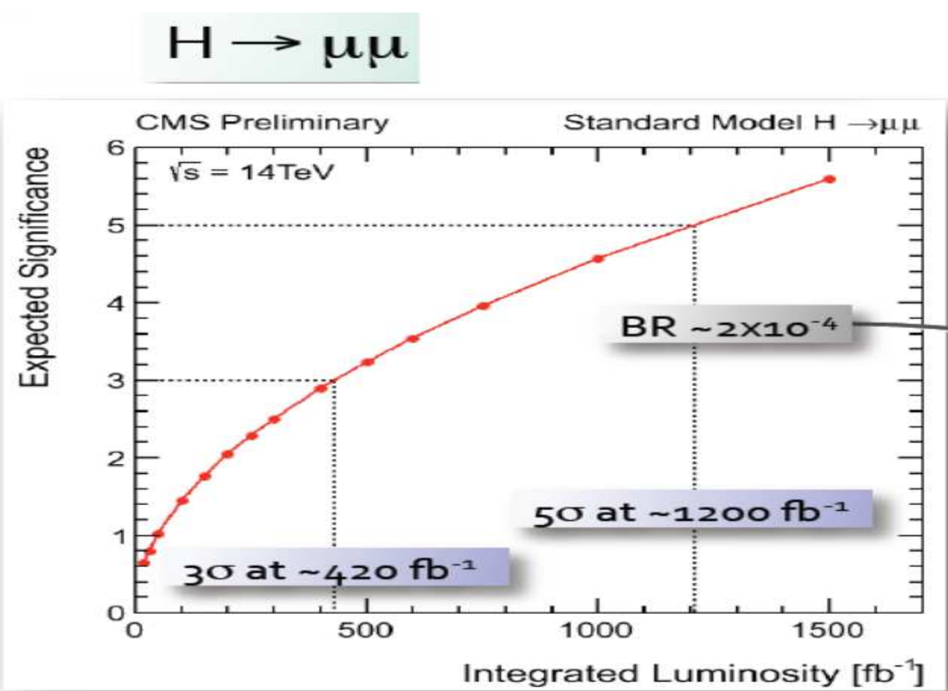
Expected μ limit: $2.16 \times$ SM value (95 % C.L.)

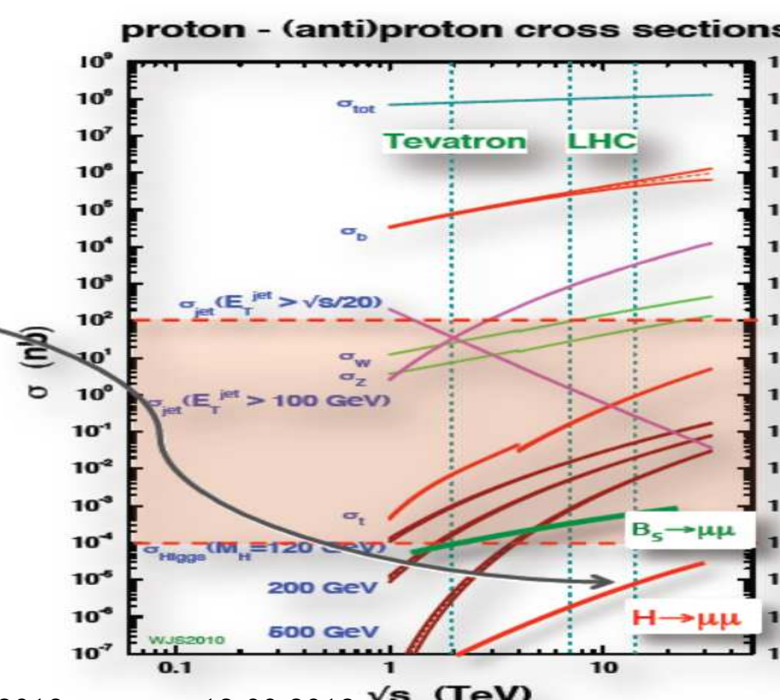
$\Rightarrow$ Limit on SM Higgs: $Br(H \rightarrow \mu^+\mu^-) < 6.4 \times 10^{-4}$

Signal strength $\hat{\mu}^{comb} = 1.0 \pm 1.0$ (stat) ± 0.1 (syst),

Observed combined significance is 0.9 s.d.







Exotica

Models Beyond Standard Model

Many theories beyond Standard Model developed to address SM omissions.

New heavy resonances appear naturally in various extensions of Standard Model:

- E_6 models Z'_ψ, Z'_χ, Z'_η arise in different ways of breaking E_6 symmetry group $E_6 \to SO(10) \times U(1)_\psi$; $SO(10) \to SU(5) \times U(1)_\chi$; $Q_{Z'} = Q_\psi \sin(\theta_6) + Q_\chi \cos(\theta_6)$
- SSM (Sequential Standard Model) or "reference" model — The same coupling constants for Z' as for the SM
- Heavy graviton resonances are predicted by RS1 (Randall-Sundrum) model of TeV-scale gravity with one additional warped extra dimension: coupling constant $c = k/\bar{M}_{Pl}$

Non-resonant models such as ADD and Contact interactions:

- ADD (Arkani-Hamed–Dimopoulos–Dvali) — large flat extra dimensions, $N_{ED} = 2 - 7$, low-energy effective string scale M_s
- Contact interactions model comes from idea of quark and lepton compositeness. Conventional benchmark — 4-fermion interaction model $\mathcal{L} \sim \dfrac{4\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{l}_L\gamma_\mu l_L)$. Λ — the energy scale parameter for the contact interaction.

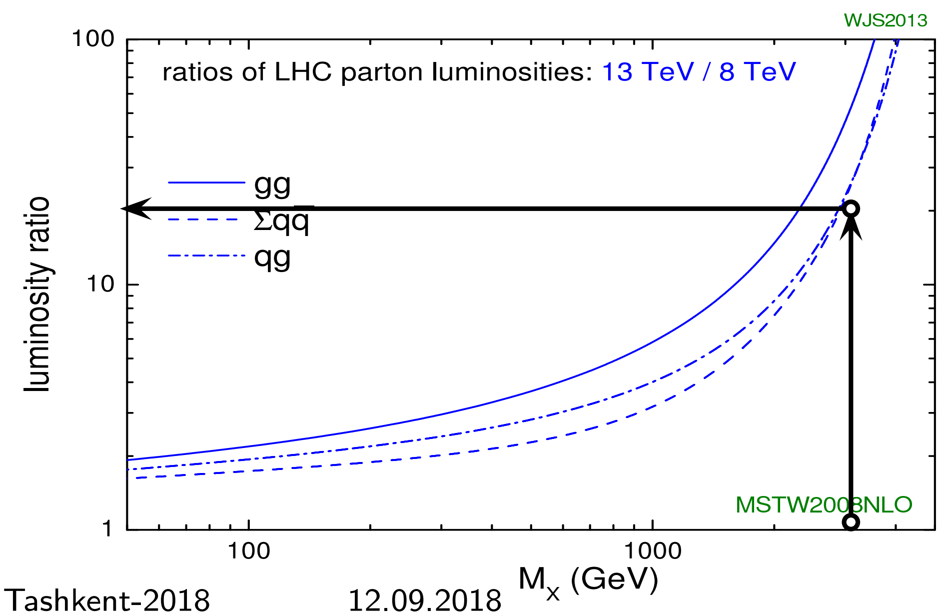
There exist also other models in which heavy dileptons appear.

History and CMS Publications on Searches for Heavy Dilepton Resonances

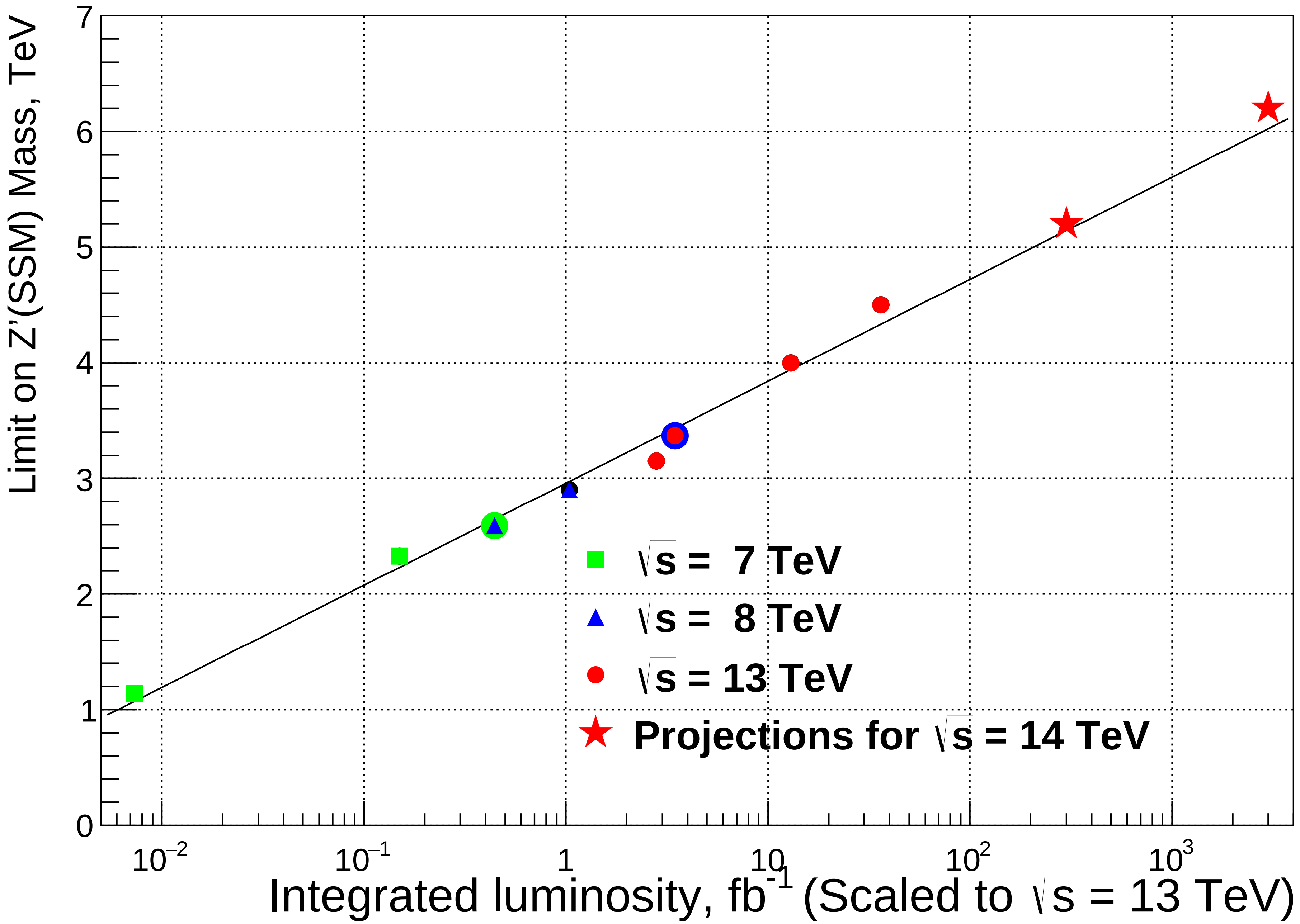
Publications and Results on Searches for Heavy Dilepton Resonances:

Date	Paper: Reference	Paper: arXiv	$\sqrt{s}$, TeV	L, fb^{-1}	Z' Models: SSM	Z' Models: Z'_ψ	RS1 Model: $c = 0.1$	RS1 Model: $c = 0.05$	RS1 Model: $c = 0.01$
03.2011	JHEP 05 (2011) 093	1103.0981	7	0.040	1.14	0.89	1.08	0.86	
06.2012	PL B714 (2012) 158	1206.1849	7	5	2.33	2.00	2.14	1.81	
12.2012	PL B720 (2013) 63	1212.6175	7+8	5.3+4.1	2.59	2.26	2.39	2.03	
12.2014	JHEP 04 (2015) 025	1412.6302	8	20.6	2.90	2.57	2.73	2.35	1.27
12.2015	CMS PAS EXO-15-005		13	2.8	3.15	2.60			
09.2016	EXO-15-005 paper	1609.05391	8+13	20.6+2.9	3.37	2.82	3.11		1.46
08.2016	CMS PAS EXO-16-031		13	13.0	4.00	3.50			
03.2018	JHEP 1806 (2018) 120	1803.06292	13	36	4.50	3.90	4.25	3.65	2.10

Need to rescale integrated luminosities of measurements at $\sqrt{s} = 7$ and 8 TeV to $\sqrt{s} = 13$ TeV using Stirling plot



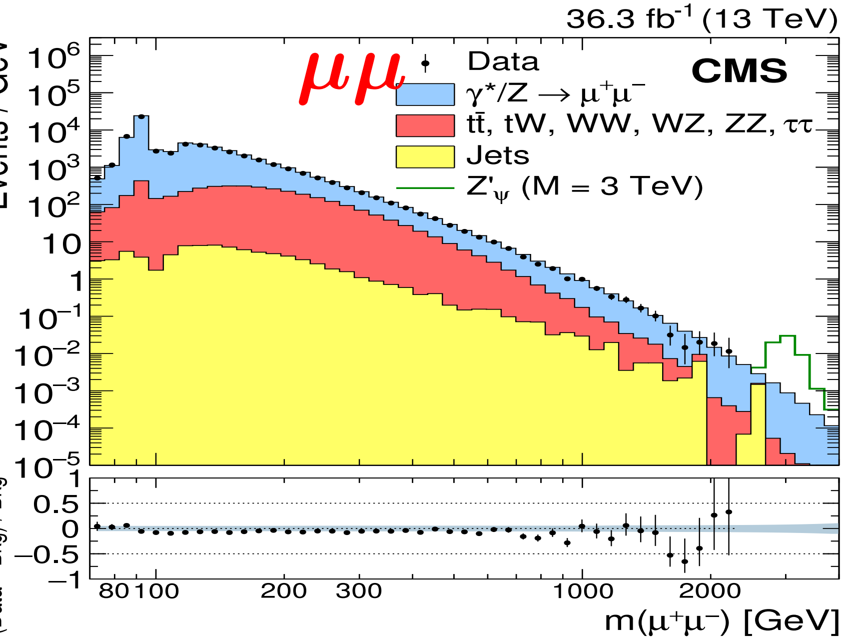
CMS Z' Dilepton Limits vs Integrated Luminosity

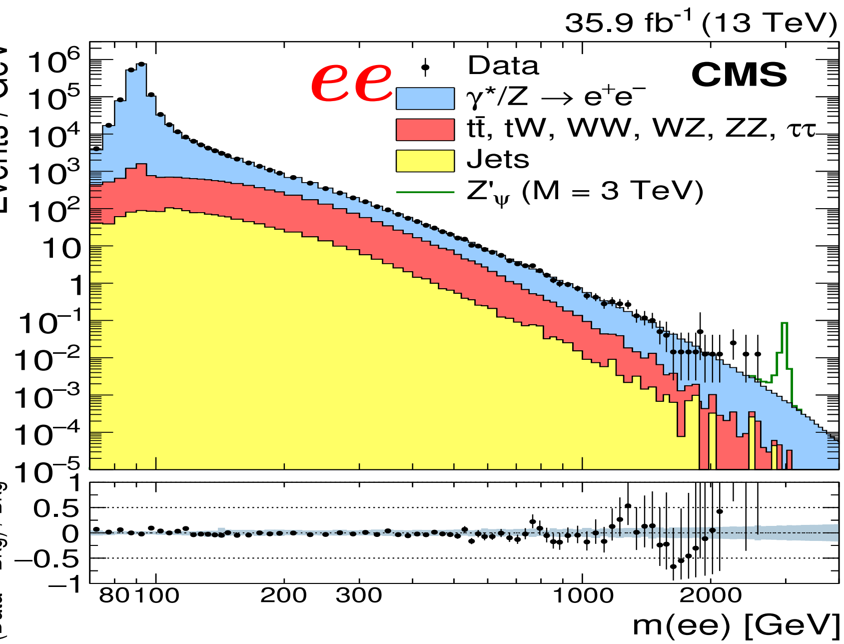


Search for Heavy Resonances in Dilepton Channels

JHEP 1806 (2018) 120; arXiv:1803.06292

Dilepton Mass Spectrum at 13 TeV (JHEP 1806 (2018) 120)





- Offline cut $p_T > 53$ GeV
- Single muon trigger $p_T > 50$ GeV
  Double electron trigger $E_T > 33$ GeV.
- Good Data / MC agreement,
  No obvious bumps seen.
- Largest mass found: 2.3 TeV ($\mu^+\mu^-$), 2.6 TeV (ee)
- To impose mass limits, we normalize to $\sigma(Z)$:

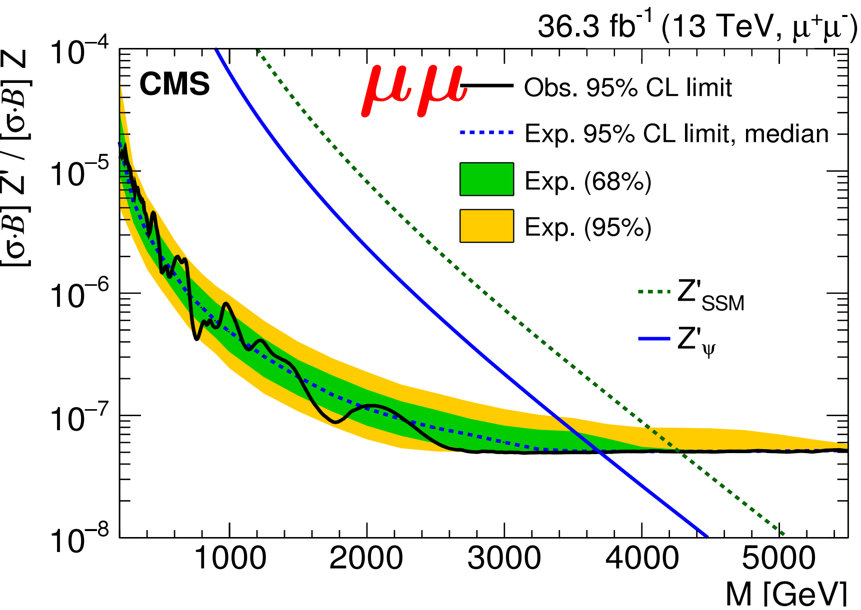
$$R_\sigma = \frac{\sigma(Z' \to \ell^+\ell^-)}{\sigma(Z \to \ell^+\ell^-)} = \frac{N(Z')}{N(Z)} \times \frac{A(Z)}{A(Z')} \times \frac{\varepsilon(Z)}{\varepsilon(Z')}$$

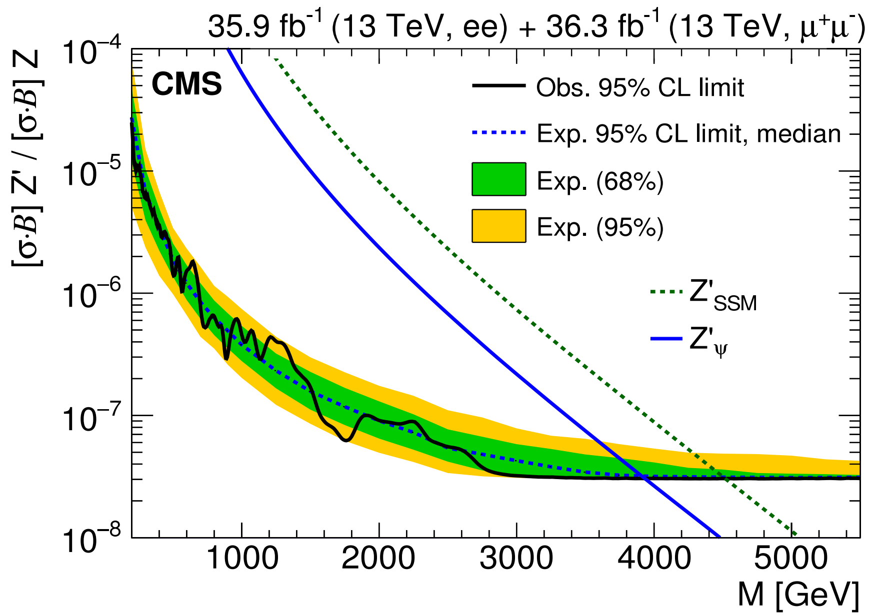
- Removed luminosity uncertainty,
  other systematic effects reduced.
- Existence (or lack) of a signal is established by performing unbinned maximum likelihood fits to the observed spectrum.
- Added interpretations in various models.

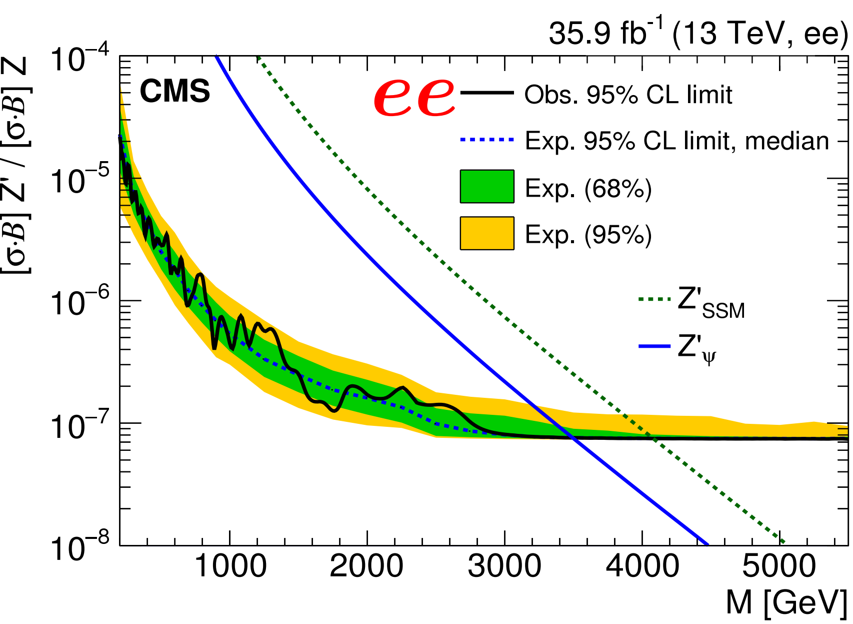
Z' Mass Limits (JHEP 1806 (2018) 120; arXiv:1803.06292)

Dileptons channels

Combined $\mu\mu + ee$



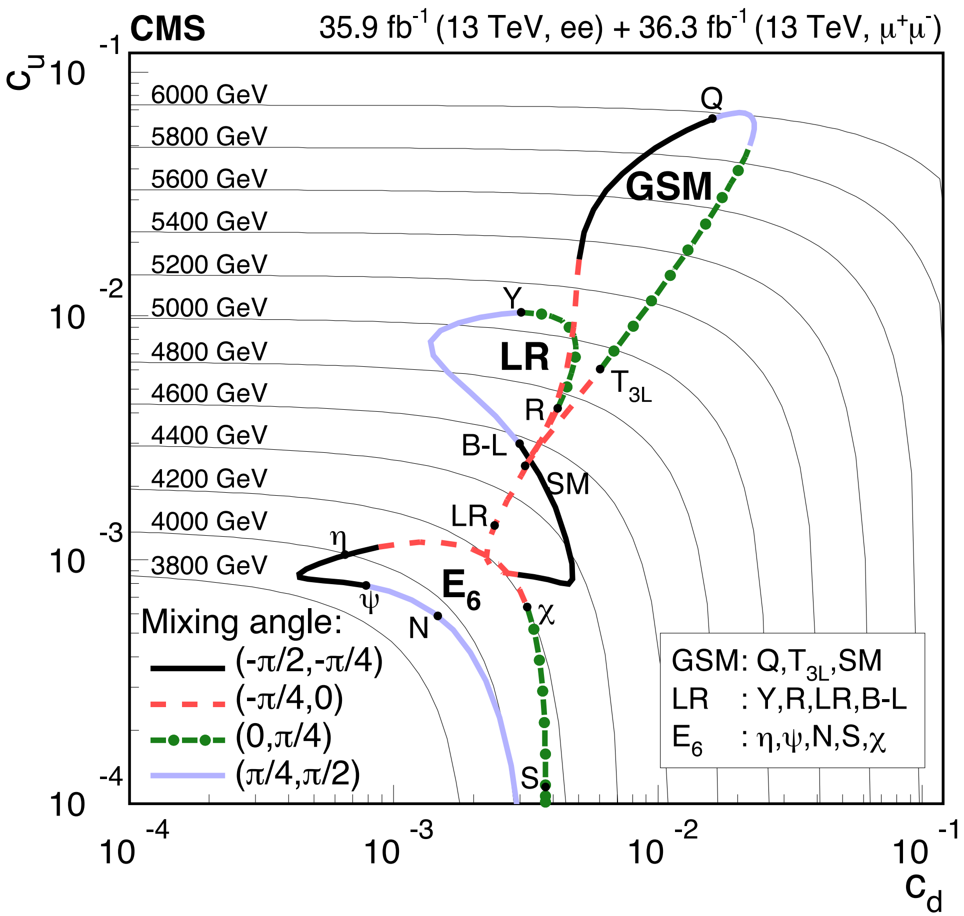




Limits at 95% C.L. on the ratio of Z' cross section to Z cross section, assuming a narrow resonance

The limit exclude a Z'_{SSM} with a mass less than 4.5 TeV and Z'_{ψ} with a mass less than 3.9 TeV. For $\mu^+\mu^-$ — 4.25 (Z'_{SSM}) & 3.7 TeV (Z'_{ψ}).

Generalizing to Other Z' Models — Plot c_u–c_d



Z' cross section can be expressed in terms of quantity $[c_u w_u + c_d w_d]$ (arXiv:1010.6058):

$$\sigma_{l^+l^-}^{Z'} = \frac{\pi}{48s}\left[c_u w_u(s, M_{Z'}^2) + c_d w_d(s, M_{Z'}^2)\right]$$

c_u, c_d contain information from the model-dependent couplings to fermions in the annihilation of charge 2/3 and -1/3 quarks, respectively.

w_u, w_d contain information about PDFs for the annihilation at a given mass.

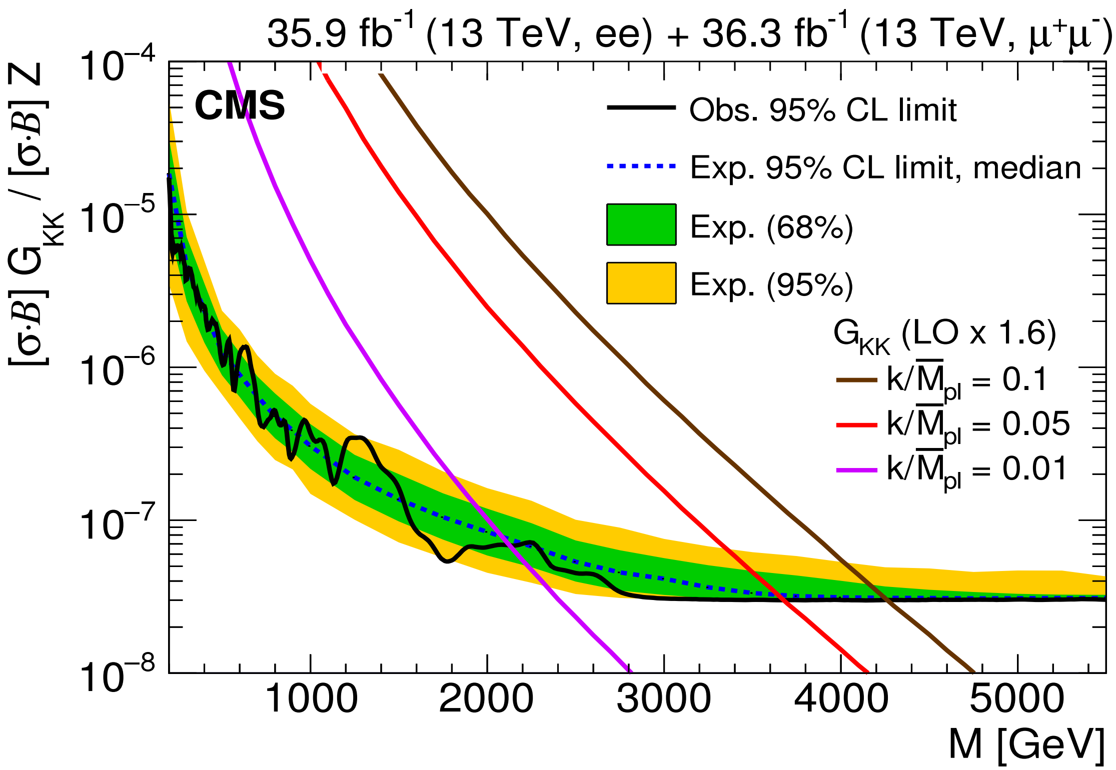
Z'_{SSM} is a special case of generalized sequential standard models (GSM),
Z'_ψ is one of the E_6 models,
generalized L-R models can also be included.

Plot shows iso-contours of cross section with constant $c_u + (w_d/w_u)c_d$.

Changing this combination (or $\int L\,dt$) by 1 order of magnitude moves the mass limits by ≈ 1 TeV.

JHEP 1806 (2018) 120; arXiv:1803.06292 (EXO-16-047) at $\sqrt{s} = 13\,\mathrm{TeV}$

RS1 Model (arXiv:1803.06292) $\sqrt{s} = 13$ TeV



The measured dilepton mass spectra are consistent with predictions from Standard Model.

An RS1 graviton with coupling $c = 0.10$ is excluded below 4.25 TeV.

An RS1 graviton with coupling $c = 0.05$ is excluded below 3.65 TeV.

An RS1 graviton with coupling $c = 0.01$ is excluded below 2.10 TeV.

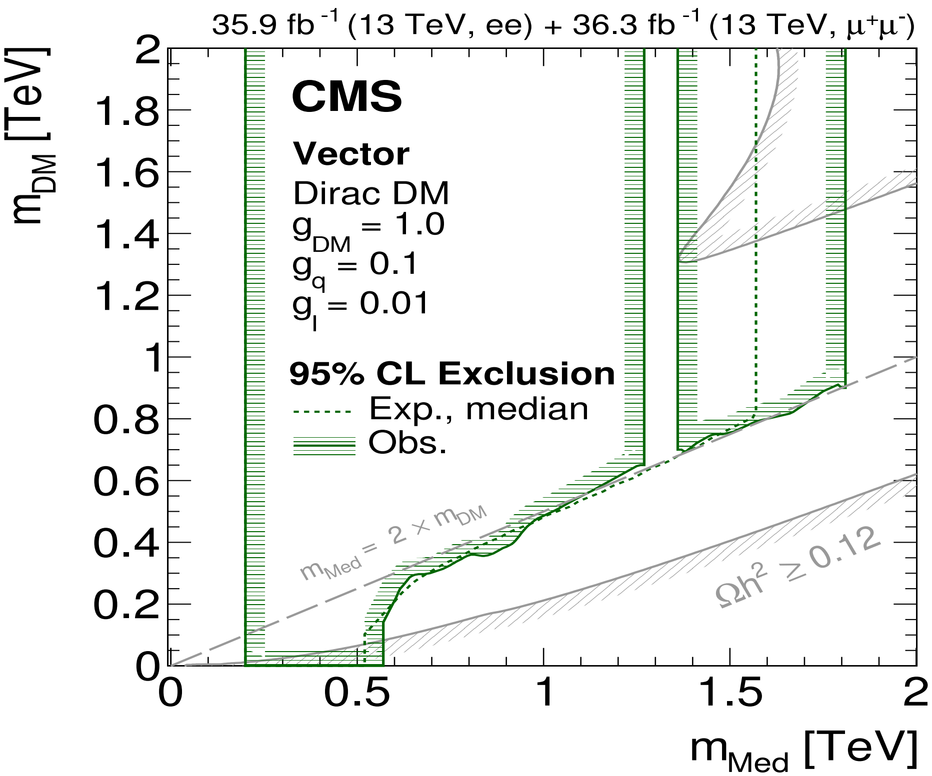
Dark matter interpretation (arXiv:1803.06292)

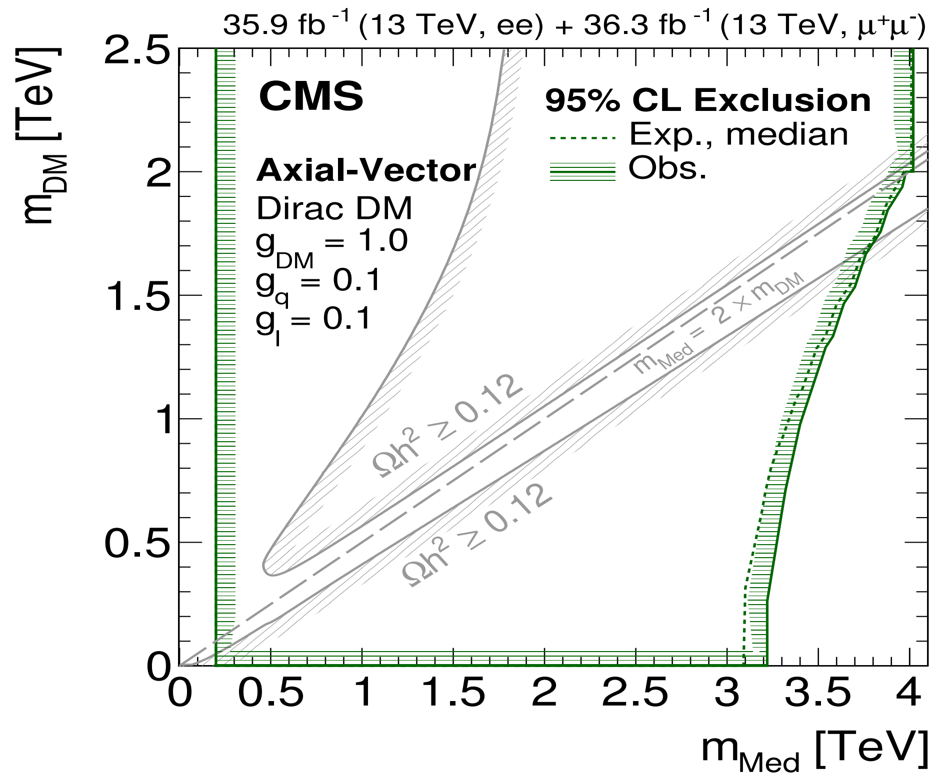
Simplified model of dark matter production via a mediator particle in s channel,

Used 2 sets of benchmark coupling values from "Recommendations of the LHC Dark Matter Working Group" (arXiv:1703.05703, CERN-LPCC-2017-01):

- Vector mediator with small couplings to leptons: $g_{\mathrm{DM}} = 1.0$, $g_{\mathrm{q}} = 0.1$, $g_{\ell} = 0.01$;
- Axial-vector mediator with equal couplings to q and ℓ: $g_{\mathrm{DM}} = 1.0$, $g_{\mathrm{q}} = g_{\ell} = 0.1$.

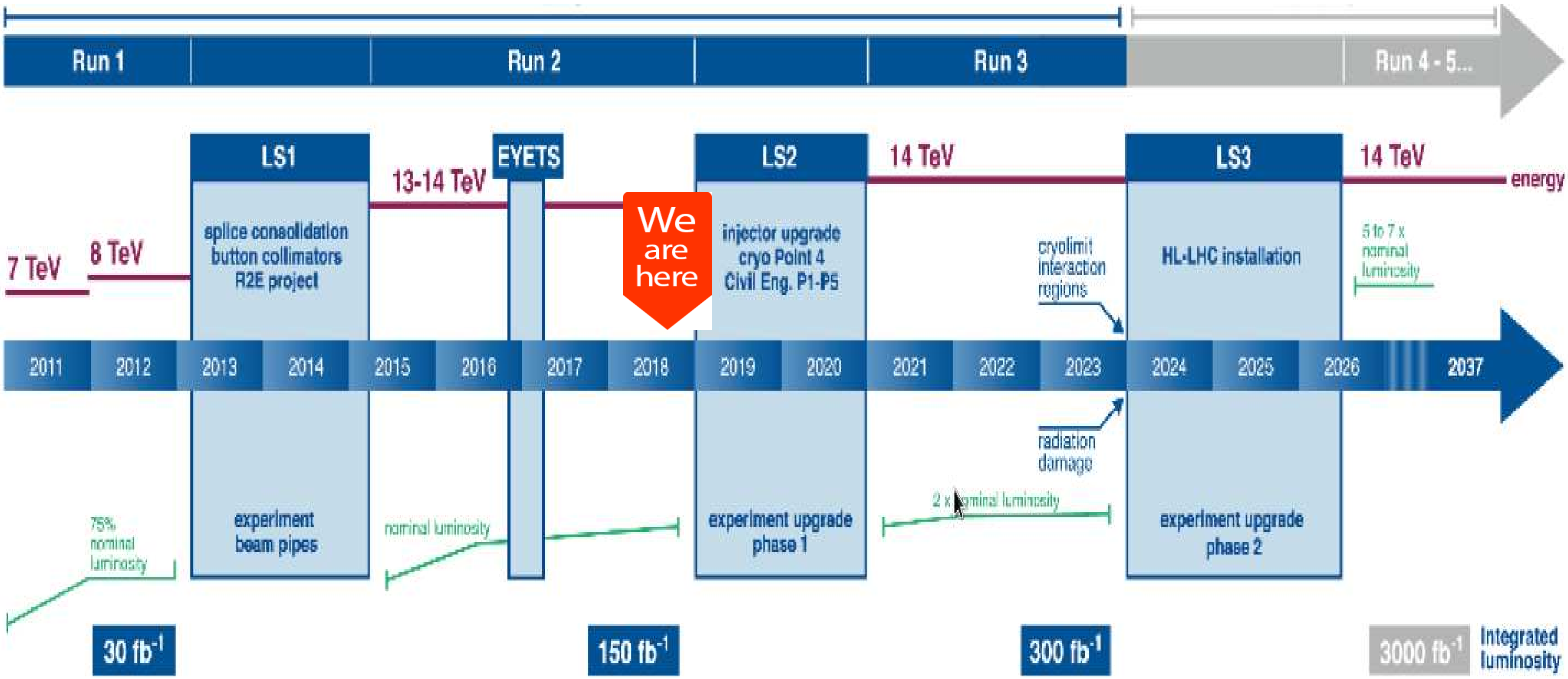
Limits at 95% confidence level are obtained for masses of DM particle and mediator.





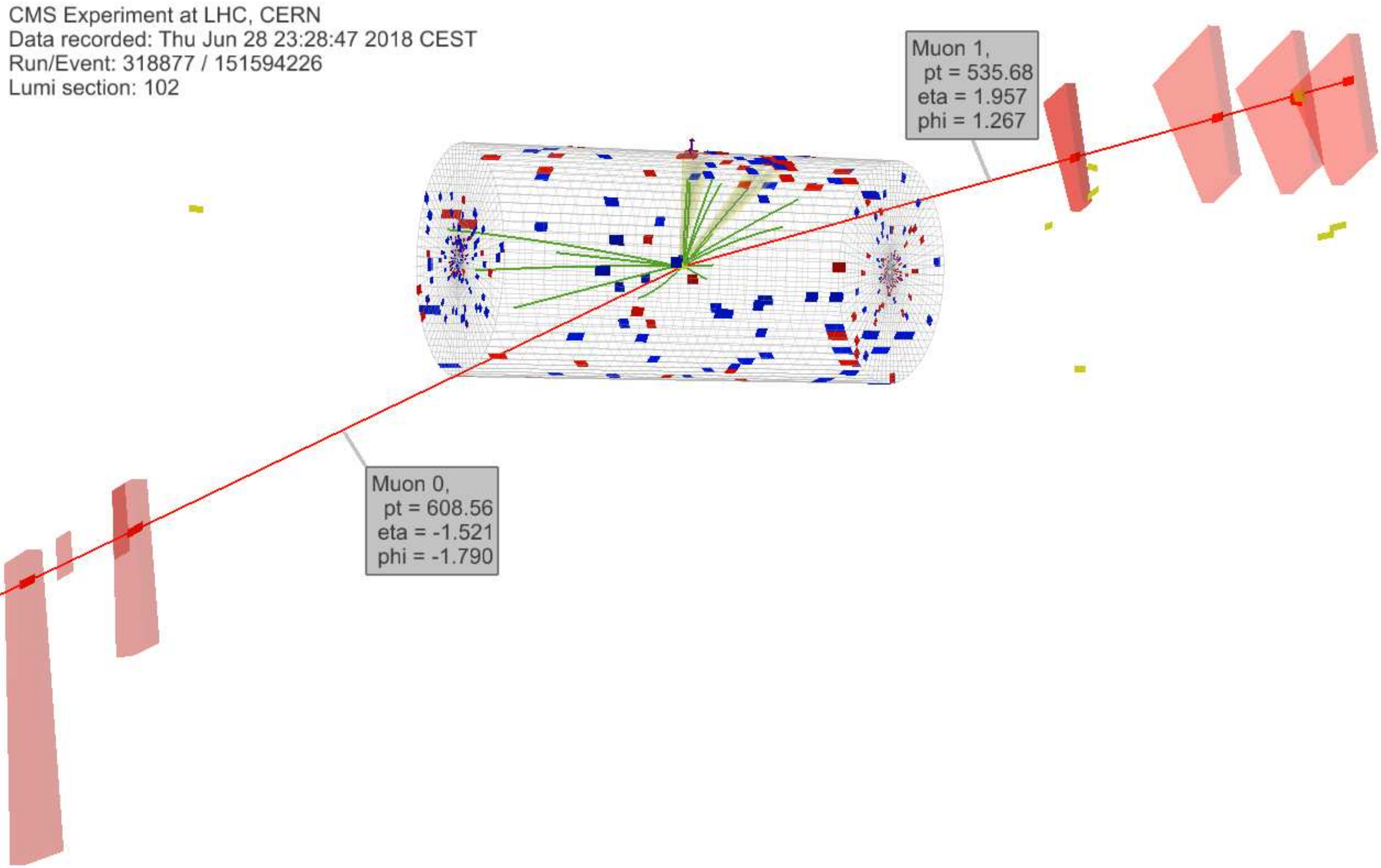
Future perspectives

LHC Long-turn Road Map

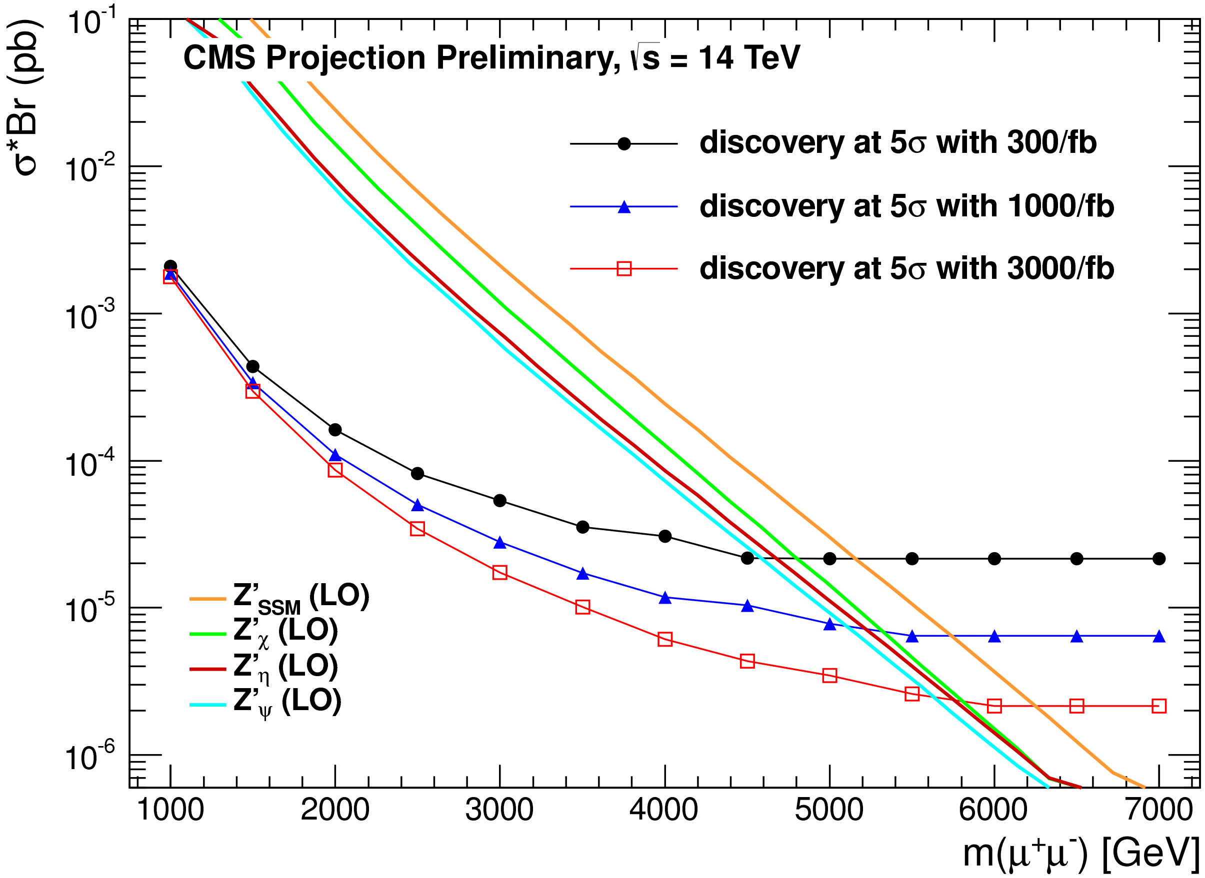


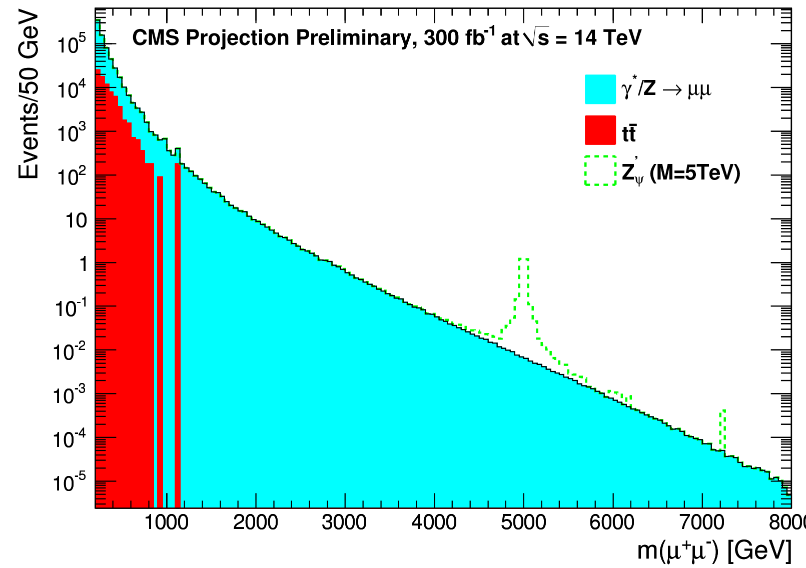
$M = 3.3$ TeV

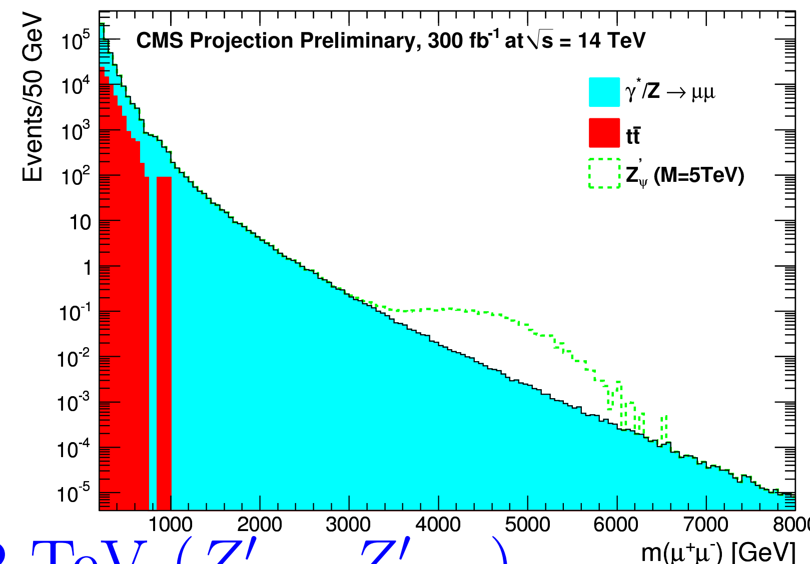
Muons: $p_T = 610,\ 540$ GeV, $\eta = -1.52,\ +1.96$



Proj. for $Z' \to \mu\mu$ at $\sqrt{s} = 14$ TeV (arXiv:1307.7135)



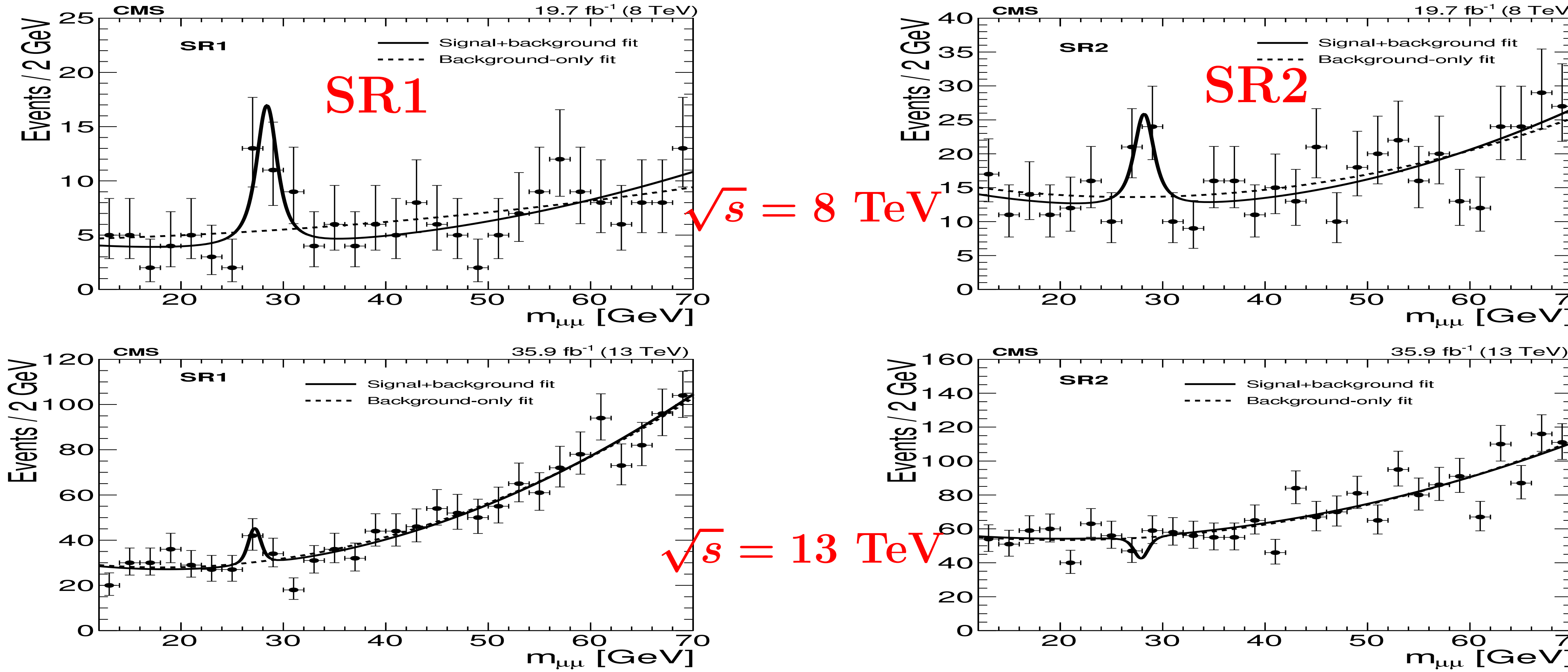




Projections for dimuons at $\sqrt{s} = 14$ TeV:

- at $\int L\,dt = 300\ \mathrm{fb}^{-1}$ — up to 4.6 – 5.2 TeV (Z'_ψ – Z'_{SSM})
- at $\int L\,dt = 3000\ \mathrm{fb}^{-1}$ — up to 5.6 – 6.2 TeV.

Search for $\mu^+\mu^-$ resonances produced in association with b-jets (arXiv:1808.01890 = HIG-16-017)



Details in talk by V. Gavrilov earlier today

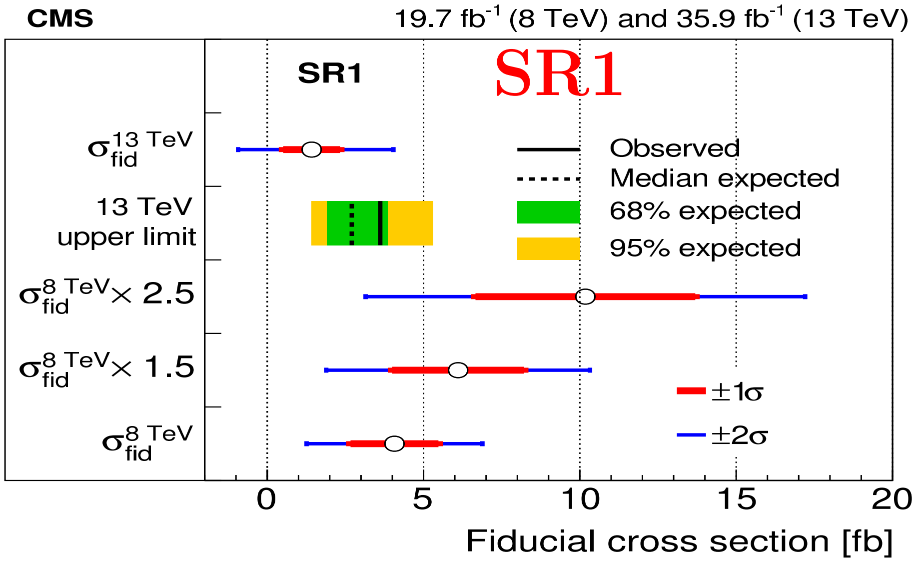
High-p_T muons + 2 mutually exclusive event categories in 2 "signal regions":

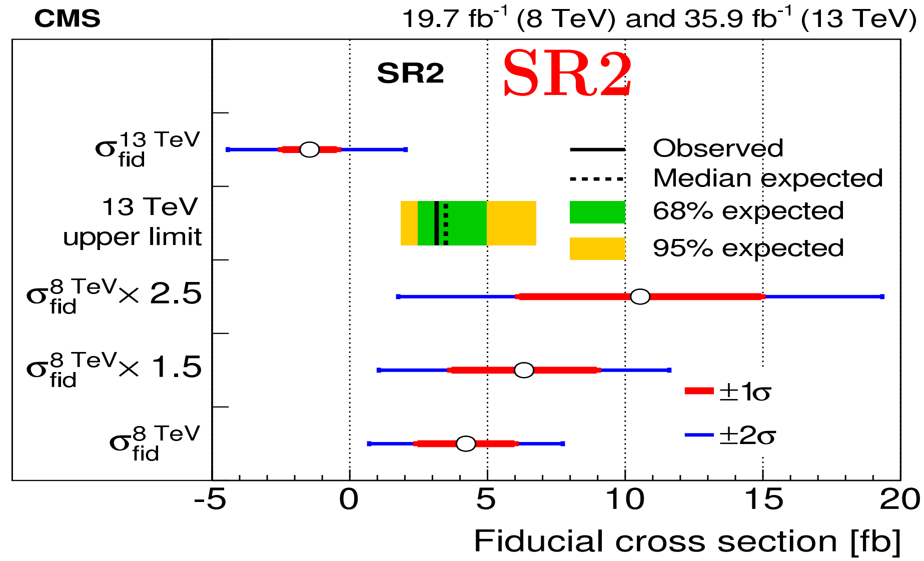
- SR1 — b quark jet in central region ($|\eta| \leq 2.4$) and ≥ 1 jet in forward region ($|\eta| > 2.4$).
- SR2 — 2 jets in the central region, ≥ 1 b-tag, no jets in the forward region, and small MET.

An excess of events above the background near a dimuon mass of 28 GeV is observed in the 8 TeV data, corresponding to local significances of $4.2\,\sigma$ (SR1) and $2.9\,\sigma$ (SR2).

A similar analysis conducted with 13 TeV data results in a mild excess corresponding to a local significance of $2.0\,\sigma$ (SR1), while SR2 results in a $1.4\,\sigma$ deficit.

Search for $\mu^+\mu^-$ resonances produced in association with b-jets (arXiv:1808.01890 = HIG-16-017)





If we assume not a large increase of the signal cross section (e.g. factor 1.5 from qq initiated productions), and take into account that the dominant $t\bar{t}$ background is increased by 3.
the 8 and 13 TeV results are compatible within $2\,\sigma$.

In the lack of a realistic signal model, the 13 TeV results are not sufficient to make a definitive statement about the origin of the 8 TeV excess.

⇒ More data and additional theoretical input are required.

Conclusions

- CMS performed studies of dimuons
  contributing to better understanding of Standard Model physics,
  and making most restrictive limits for New Physics.

- Mass limits for new resonances have been improved:
  4.5 TeV (SSM model), 3.9 TeV (Z'_ψ model) at 95% C.L.,
  New interpretations and generalizations have been considered:
  RS1 model: 4.25–2.1 TeV (for coupling $c = 0.1 - 0.01$),
  Dark matter: $M_{\mathrm{Med}} < 1.8$–4 TeV (for couplings: Vector / Axial-Vector).

- Expected integrated luminosity $\int L\,dt = 150$ fb^{-1} in Run 2.
  First dileptons with $M > 3$ TeV were seen.
  Much data to analyze, potentially leading to discoveries
  or better understanding of the dynamics.

- Projections for Z' discovery potential in the dimuon channel at $\sqrt{s} = 14$ TeV:
  up to 5.6 – 6.2 TeV at $\int L\,dt = 3$ ab^{-1}.

- New unexpected signal found from dimuons at $M \approx 28$ GeV, produced in
  association with a b quark jet and another jet.
  Local significances up to $4.2\,\sigma$ at $\sqrt{s} = 8$ TeV, still unclear at $\sqrt{s} = 13$ TeV.
  $\Rightarrow$ More data and additional theoretical input are required.