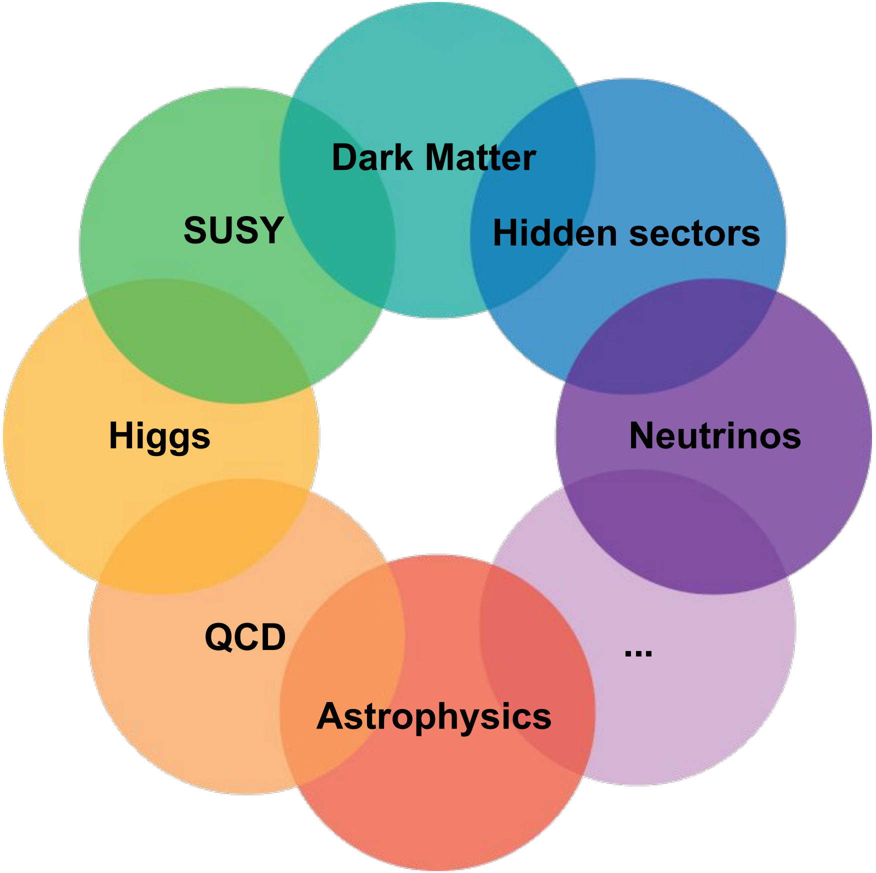
Physics at CMS

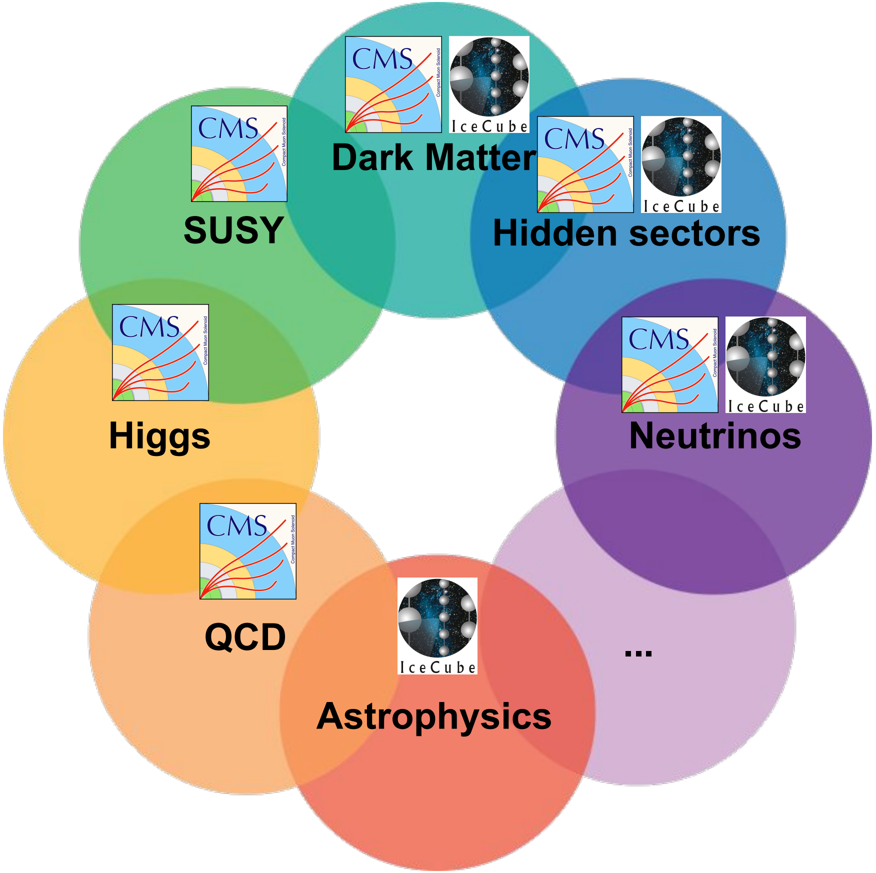
IIHE annual meeting meets HEP@VUB

Laurent Thomas and David Vannerom for the IIHE CMS community
November 16, 2021

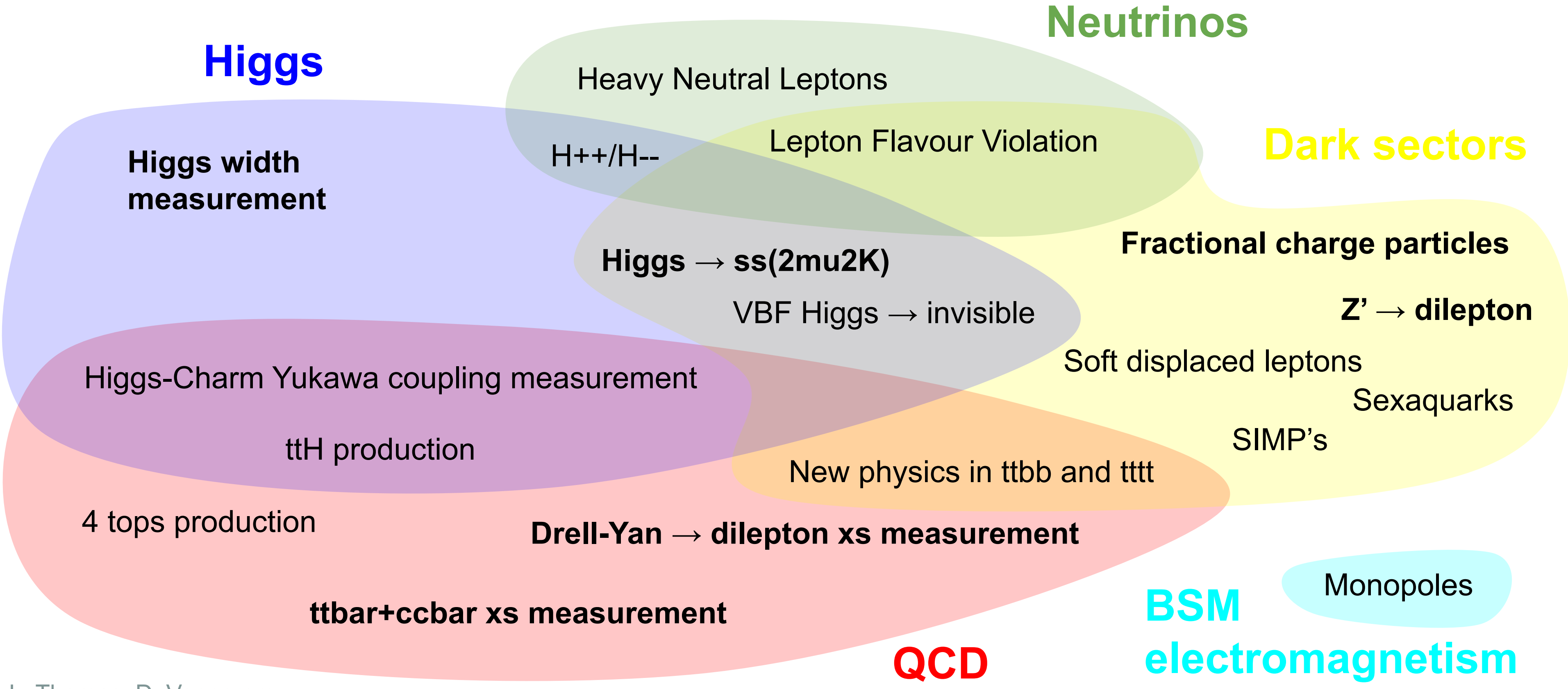
What is particle physics about today?



What is particle physics about today?



Recent/ongoing research projects at IIHE

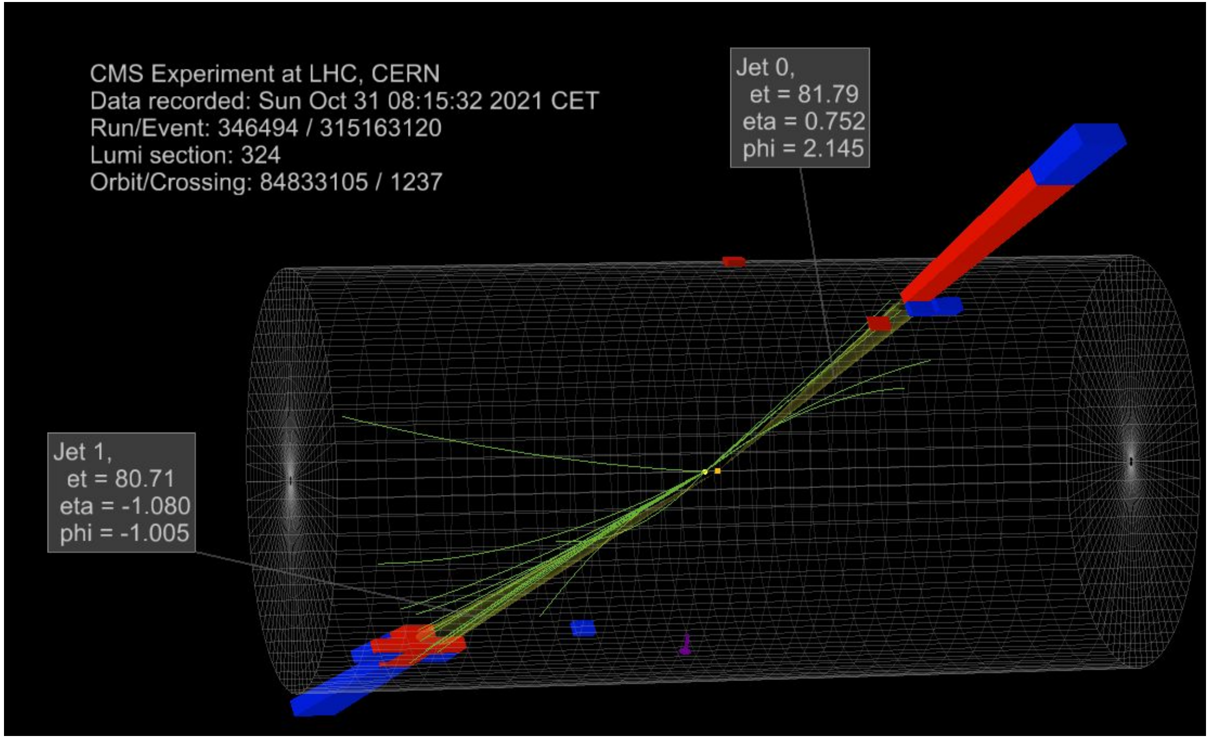


The LHC has restarted: CMS is ready!

Run-3 is just around the corner: **2022-2025**

Minimal target luminosity: 160/fb (Run-2 was 140/fb)

Next step: HL-LHC
Target lumi/year: 250/fb
Target lumi (total): 3000/fb



900 GeV pp collisions (Oct 31st, 2021)

Computing and secretariat

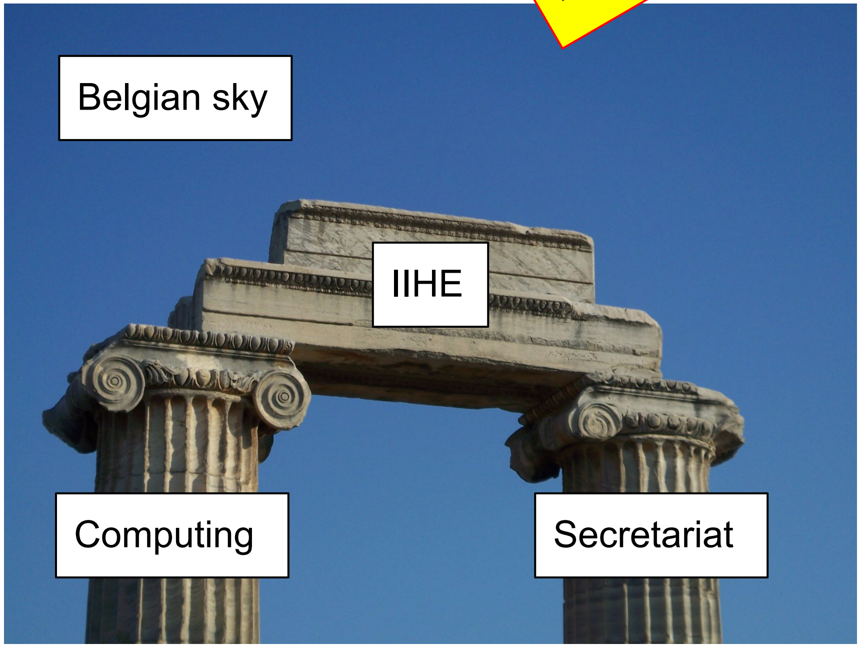
All of this would not be possible without a strong IT team:

- Olivier Devroede
- Denis Dutrannois
- Stéphane Gérard
- Romain Rougny
- Shkelzen Rugovac
- Adriano Scodrani

And a dedicated secretariat:

- Audrey Terrier
- Sofie Van Den Bussche

Many thanks!

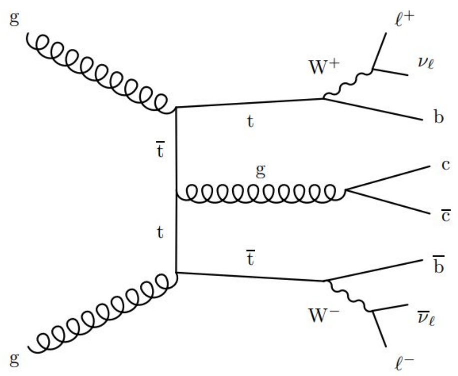


Review of some IIHE-CMS analyses

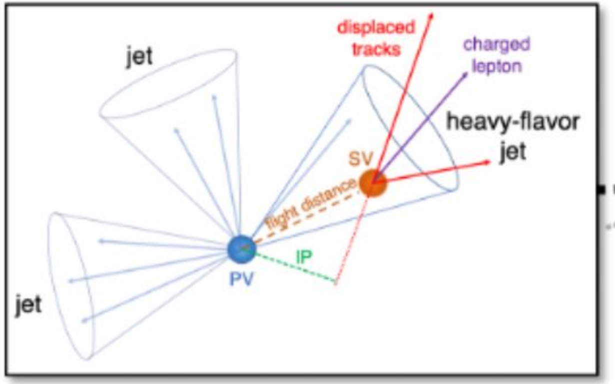
Measurement of the ttbar+ccbar cross-section

J. D'Hondt
S. Moortgat, E. Bols, A. De Moor

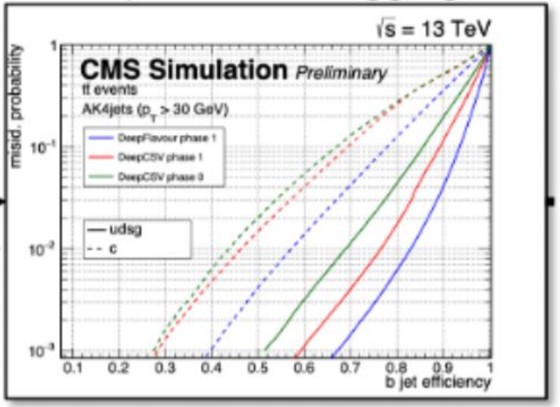
In processes with b and c jets, it is important to be able to identify them: **c- and b-tagging algorithms**



① c, b and t quarks require jets and heavy flavor tagging (new c-tagger)



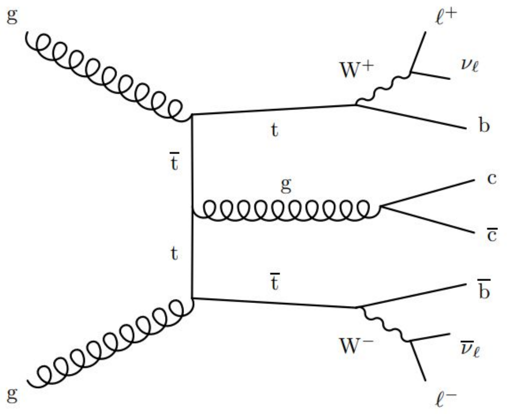
② Improved Machine Learning techniques for HF tagging



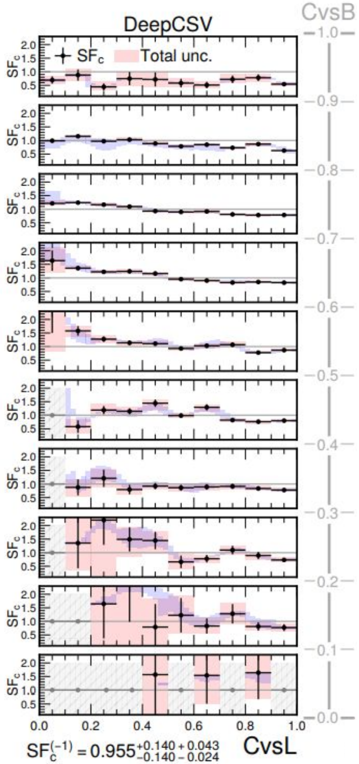
Measurement of the ttbar+ccbar cross-section

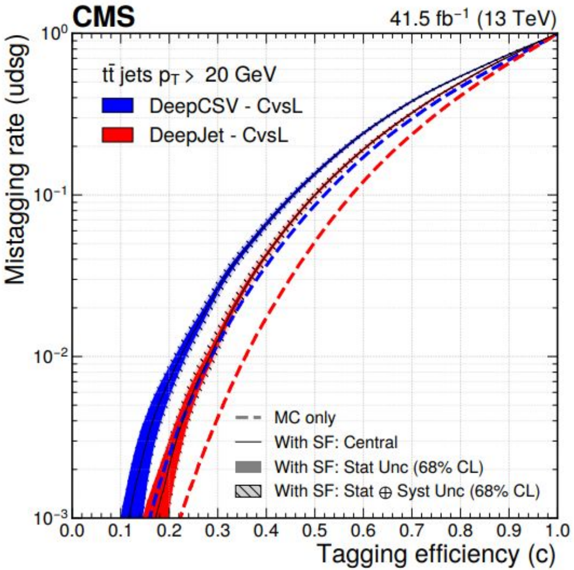
J. D’Hondt
S. Moortgat, E. Bols, A. De Moor

Challenge: separate light-flavoured jets from b AND c jets simultaneously



Scale factors derived to correct c- and b-taggers for data/MC disagreements





CMS-BTV-20-001
2111.03027 [hep-ex]

Aparté: the technical work you won't hear about in this talk

- "Technical" work **critical** for the success of CMS physics program
- Instrumentation is a big part of it (see previous talk)
- This can take other forms too:
  - Detector alignment/calibration
  - Data certification
  - Physics object/event reconstruction
  - Triggering
  - Event generation studies
  - Computing operations
- IIHE heavily involved in all these areas
- No time to go through them here
- Focusing on a few physics highlights

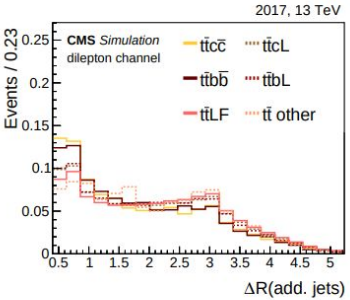
Measurement of the ttbar+ccbar cross-section

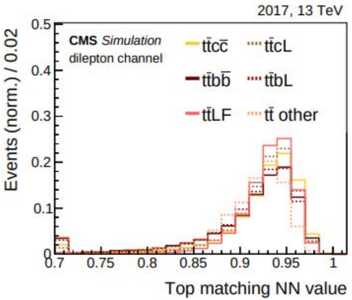
J. D'Hondt
S. Moortgat, E. Bols, A. De Moor

Using these advanced tools, compute the cross-section:

Data : 2017 (41.5/fb)
Selection (ttbar + ≥ 2 jets):
- 2 OS leptons, pT > 25 GeV, |eta| < 2.4
- ≥ 4 jets, pT > 30 GeV
- 2 b-jets
- Missing ET > 30GeV in SS leptons events
- 2-leptons invariant mass outside Z peak

Train a NN with the following 6 variables:
- CvsL and CvsB for each additional jet
- ΔR between the two additional jets
- NN score for best jet-parton permutation





Design discriminators based on NN outputs:

$$\Delta_{b}^{c} = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}b\bar{b})},$$

$$\Delta_{L}^{c} = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}LL)}.$$

Measurement of the ttbar+ccbar cross-section

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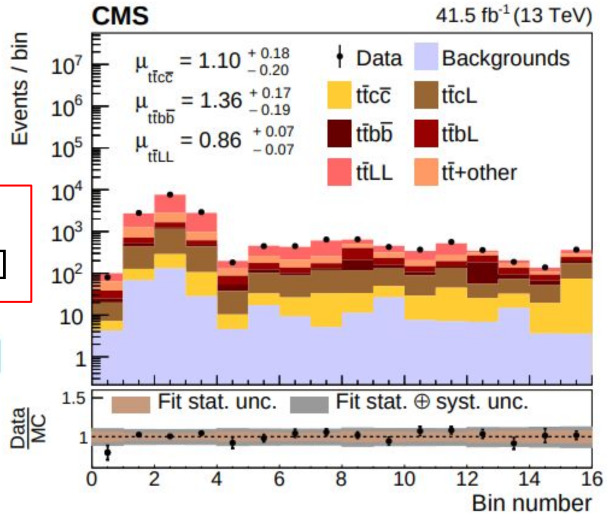
CMS-TOP-20-003
2012.09225v2 [hep-ex]

16 bins:

$\Delta_L^c \otimes \Delta_b^c : [0, 0.55, 0.65, 0.85, 1.0] \otimes [0, 0.35, 0.5, 0.6, 1.0]$

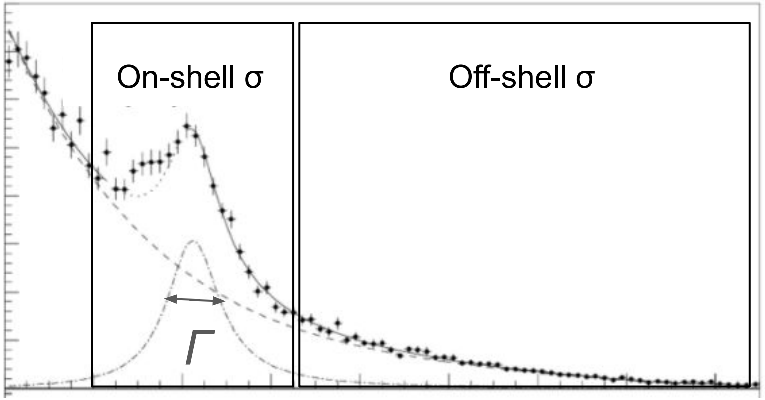


	Result	POWHEG	MADGRAPH5_aMC@NLO
	Fiducial phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$0.207 \pm 0.025 \pm 0.027$	0.187 ± 0.038	0.189 ± 0.032
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$0.132 \pm 0.010 \pm 0.015$	0.097 ± 0.021	0.101 ± 0.023
$\sigma_{t\bar{t}LL}$ [pb]	$5.15 \pm 0.12 \pm 0.41$	5.95 ± 1.02	6.32 ± 0.94

P. Vanlaer
N. Postiau , M. Mahdavikhorrami, H. Wang

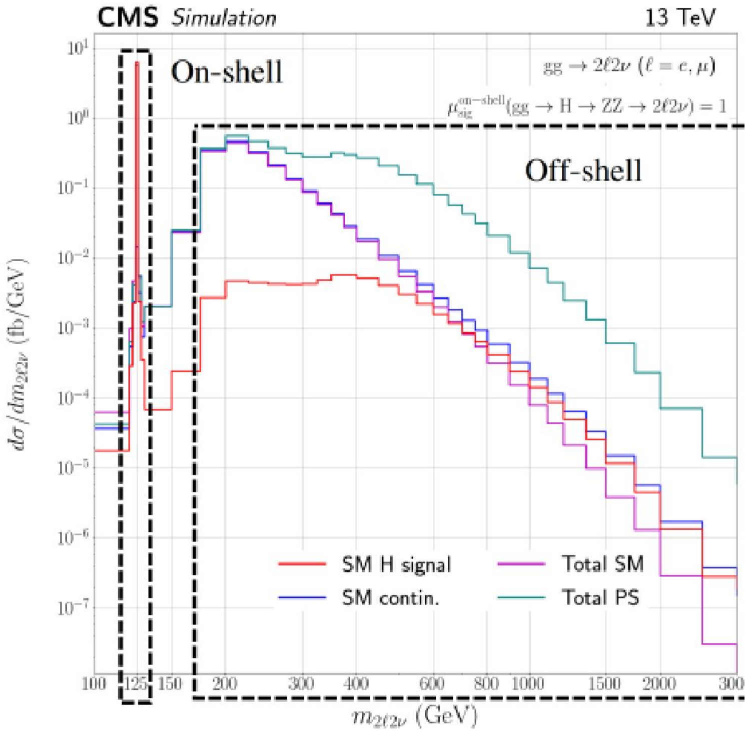
Measurement of the SM Higgs width

Particle width (Γ) = Planck constant (ħ) / Particle lifetime (τ)



$$\sigma^{\text{on-shell}} \propto \frac{g^2_{\text{prod}} g^2_{\text{dec}}}{\Gamma_{\text{H}}} \propto \mu_{\text{prod}}$$

$$\sigma^{\text{off-shell}} \propto \int \frac{g^2_{\text{prod}} g^2_{\text{dec}}}{\left(q^2_H - m^2_H\right)^2} dq^2_H \propto \mu_{\text{prod}} \cdot \Gamma_H$$



Measurement of the SM Higgs width

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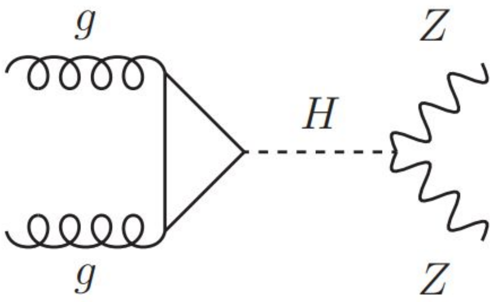
N. Postiau , M. Mahdavikhorrami, H. Wang

$gg \to H \to ZZ:$



Two closely related challenges:

1. Evidence for **off-shell Higgs** production in the ZZ → 2l2nu channel
2. Measurement of the **Higgs width**, which is:
   - ~200 times too small to be resolved by CMS
   - ~10^9 times too large to yield an observable decay length

This measurement is (spoiler alert: *was*) still missing from the characterization of the Higgs boson since its discovery in 2012

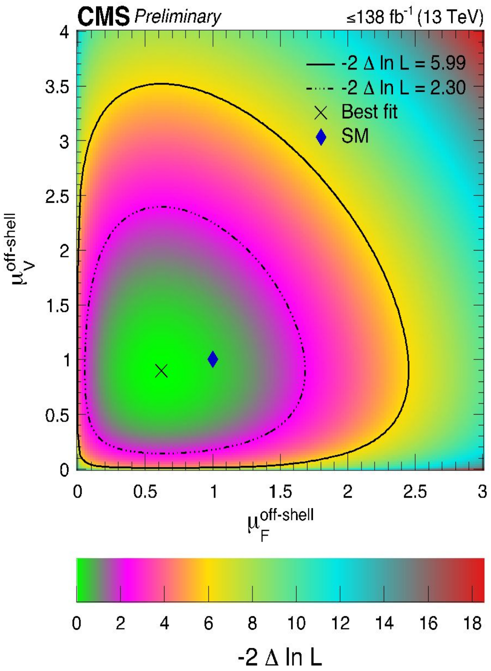
Measurement of the SM Higgs width

P. Vanlaer
N. Postiau , M. Mahdavikhorrami, H. Wang

Measurement of the width from the ratio of off-shell/on-shell cross-sections

Data : Run-2 (140/fb)
Selection (Z(2l)Z(2nu)):
- 2 same flavour OS leptons, pT ≥ 25 GeV
- Missing ET ≥ 125 GeV
- Categories: 0, 1 and ≥ 2 jets with pT > 30 GeV

Discriminants:
- H transverse mass
- Missing ET



CMS-HIG-21-013

CMS preliminary result out October 18:
Evidence for offshell production !
First two-sided measurement of Γ_H

Param.	Cond.	Observed 68% | 95% C.L.	Expected 68% | 95% C.L.
Γ_H (MeV)	SM-like	$3.2^{+2.4}_{-1.7} \|^{+5.3}_{-2.7}$	$^{+4.0}_{-3.48} \|^{+7.2}_{-4.065}$

In agreement with standard model prediction Γ_H = 4.1 MeV

CERN seminar Nov 30th on Higgs width and search for invisible decays

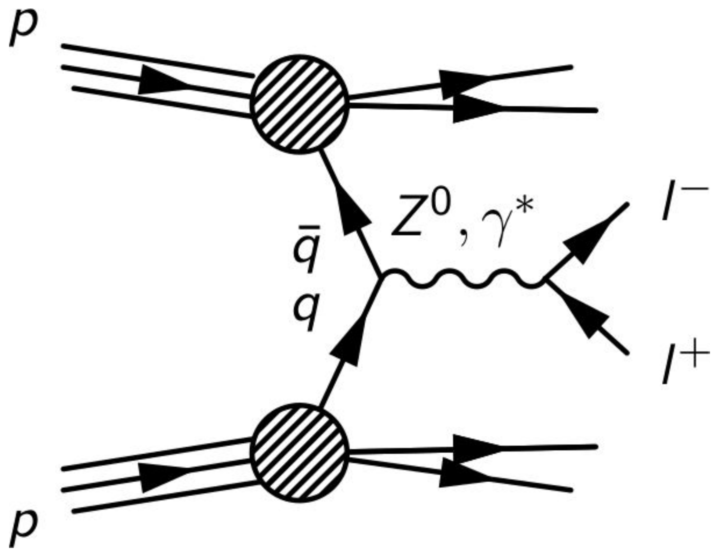
Laurent Favart
Bugra Bilin, Louis Moureaux

Mass-dependent pT distribution in DY events

We need accurate QCD models to help us predict the cross-section of the processes we study.

Goal and challenges:

- Scanning down to low pT allows to **probe non-perturbative QCD regimes** (soft gluon resummation) + increases sensitivity to intrinsic parton pT within colliding hadrons
- Resummation functions scale with m(ll): this analysis can **test the validity and precision of the different models**



Besides the pT, an angular (more precise) variable is studied:

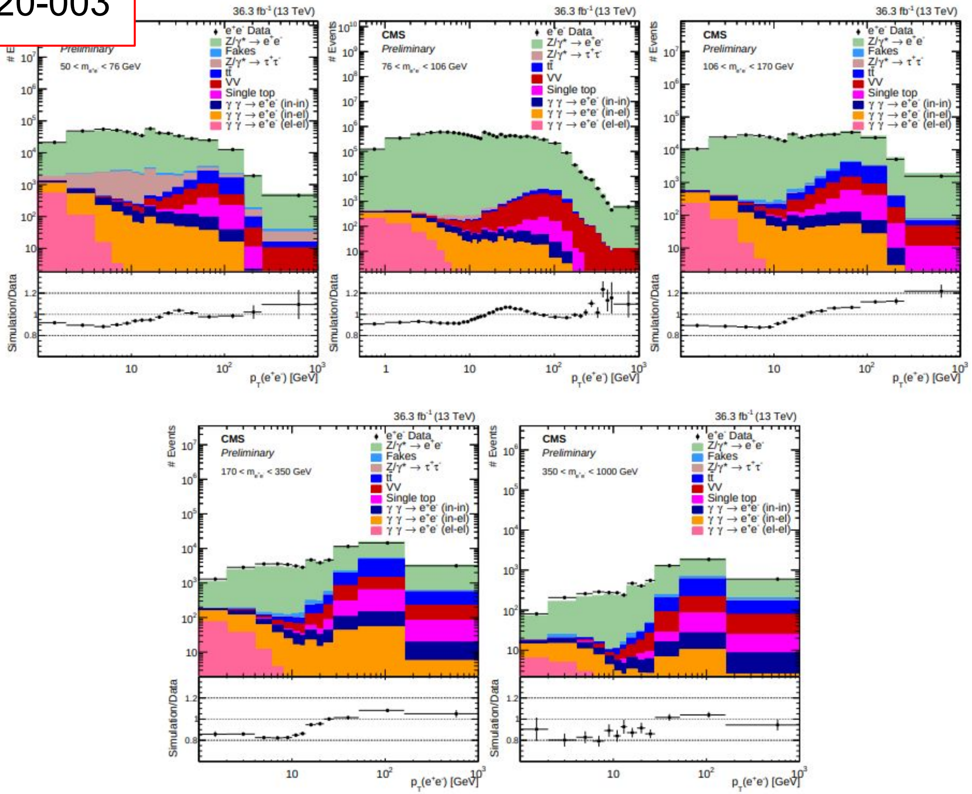
$$\varphi^* \equiv \tan(\pi - \Delta\varphi) \cdot \sin(\theta^*_\eta) \quad cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$$

Laurent Favart
Bugra Bilin, Louis Moureaux

Mass-dependent pT distribution in DY events

CMS-SMP-20-003

Mass regions:



Data : 2016 (36.3/fb)

Selection (2 leptons):

- Exactly 2 OS leptons, pT > 25 (20) GeV, |eta| < 2.4
- PU mitigation for jets: MVA + pT > 30 GeV
- b-jets veto

Laurent Favart
Bugra Bilin, Louis Moureaux

Mass-dependent pT distribution in DY events

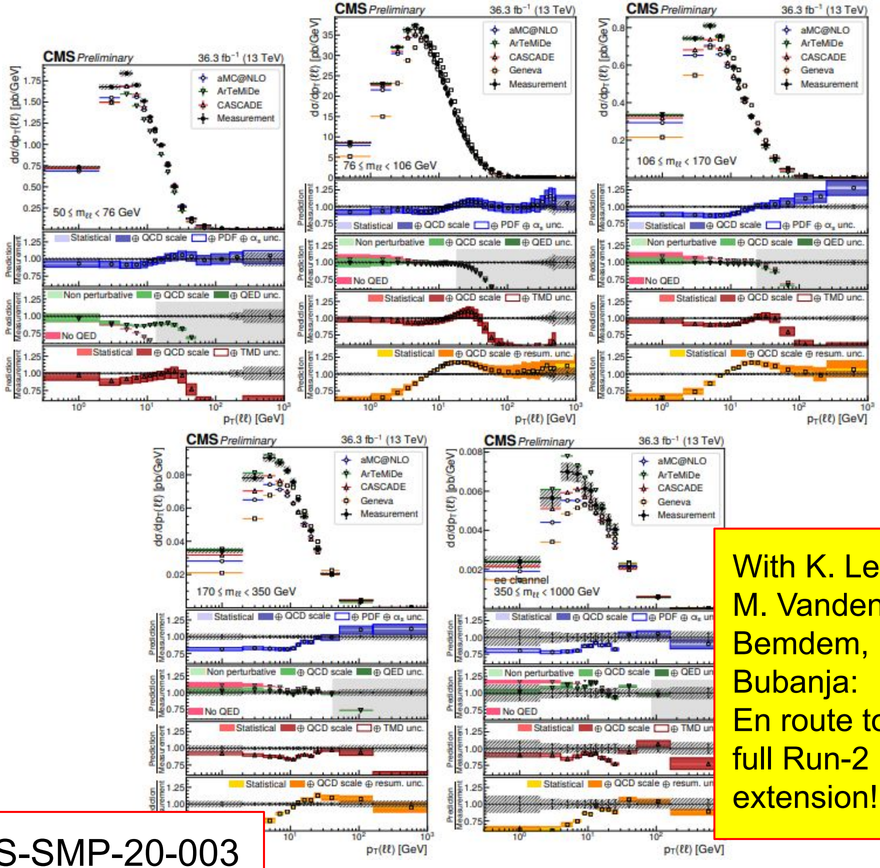
Results

- aMC@NLO: overall good but prediction too high at low pT (where gluon resummation applies)
- GENEVA: α_S choice yields a harder spectrum

Transverse Momentum Dependent (TMD) - based:

- arTeMiDe: very good agreement where applicable
- CASCADE: similar but worse at transition because lack of higher fixed-order calculations

These results are needed to assign correct systematics on predictions (e.g. for the Higgs pT)



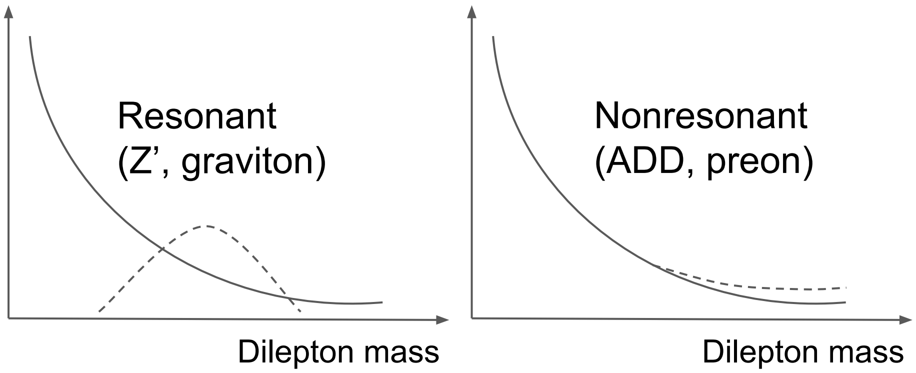
With K. Lee, M. Vanden Bemdem, I. Bubanja:
En route to the full Run-2 extension!

CMS-SMP-20-003

Barbara Clerbaux
M. Draguet, W. Fang, X. Gao, R. Goldouzian, A.K. Kalsi, L. Thomas

New physics in the dilepton final state

Many different models predict new physics in the dilepton (e+e-/mu+mu-) invariant mass spectrum.



Also interesting is to compare those two final states to look for flavour violating behaviours:

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$

New physics in the dilepton final state

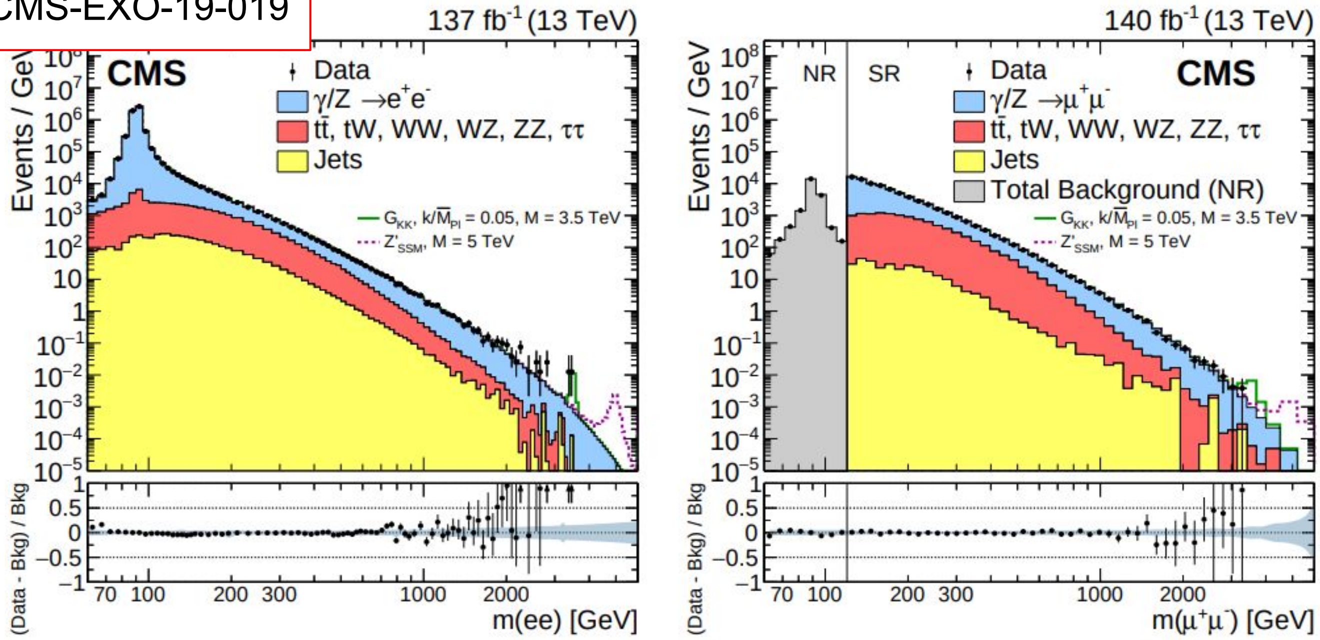
Barbara Clerbaux
M. Draguet, W. Fang, X. Gao, R. Goldouzian, A.K. Kalsi, L. Thomas

Data: Run-2 (137 or 140/fb)

Selection (electrons):
- 2 iso. electrons, pT > 35 GeV, |eta_c| < 1.44 OR 1.57 < |eta_c| < 2.5
- Lateral energy spread quality cut
- H/E < 5%

Selection (muons):
- 2 iso. Muons, pT > 53 GeV, |eta| < 2.4
- Opposite sign

CMS-EXO-19-019

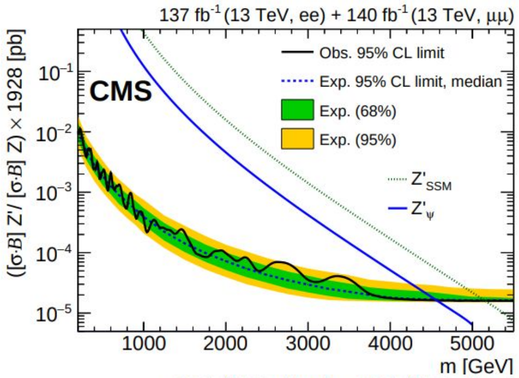


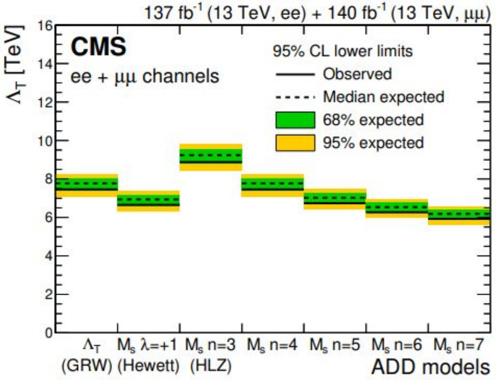
Backgrounds are normalized to data around the Z peak

New physics in the dilepton final state

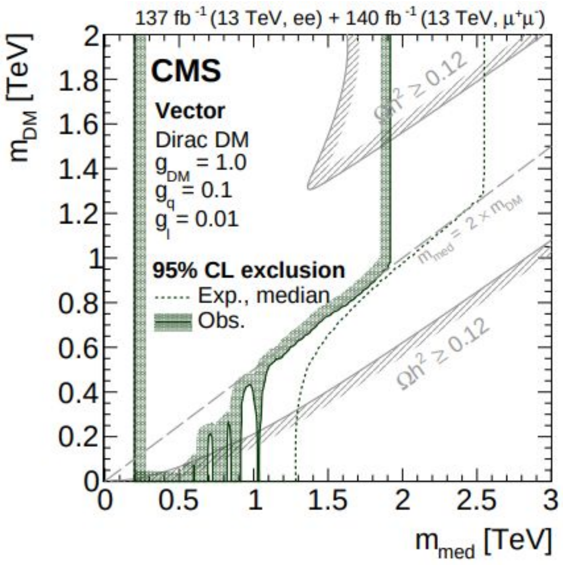
Barbara Clerbaux
M. Draguet, W. Fang, X. Gao, R. Goldouzian, A.K. Kalsi, L. Thomas

Limits on the Z'



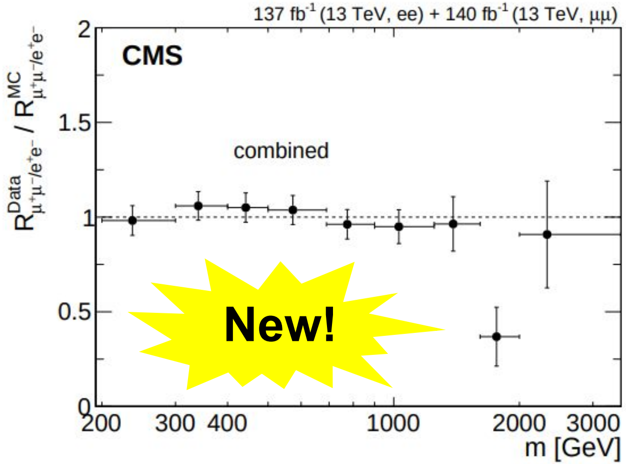


Limits on the DM mediator



Limits on ADD models

mu/e ratio



CMS-EXO-19-019

S. Lowette, B. Clerbaux
D. Vannerom

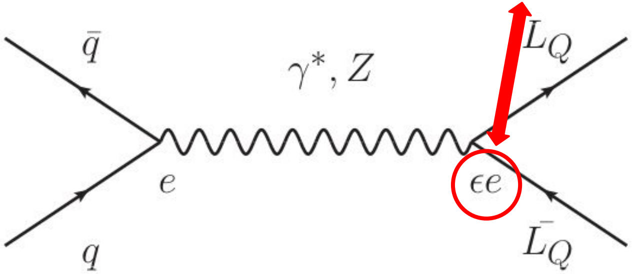
Search for low charge particles

All known free-propagating particles carry an EM charge 0 or +/- n x *e* (n: integer). Is this always true or **do particles exist that carry an arbitrary (low) charge?**

It is somewhat straightforward to build a model for a new particle with an arbitrary electromagnetic charge:

1. A new U’(1)
   a. Kinetic mixing with SM Hypercharge U(1)
2. A new fermion field charged under this new U’(1)

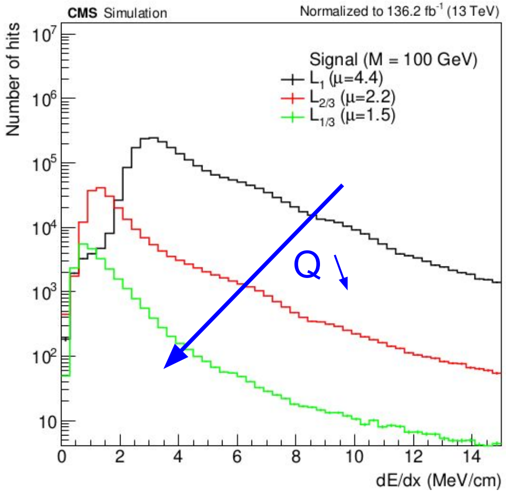
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'A\!\!\!/' - ie'\kappa B\!\!\!/ + iM)\psi$$



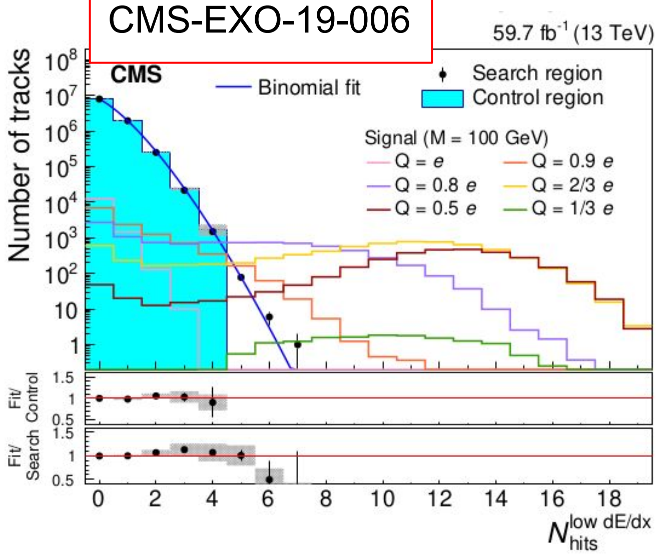
S. Lowette, B. Clerbaux
D. Vannerom

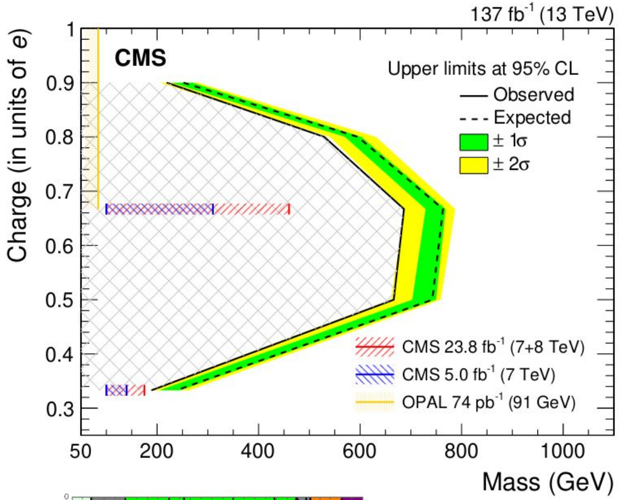
Search for low charge particles

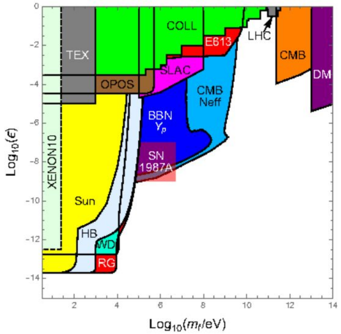
Search strategy: signal tracks show many low dE/dx measurements in the tracker

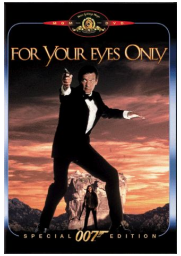


CMS-EXO-19-006





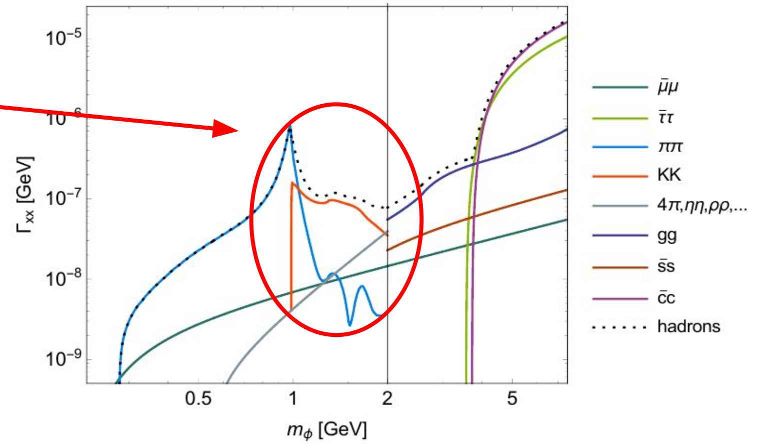




Exotic Higgs decay to long-lived light scalars

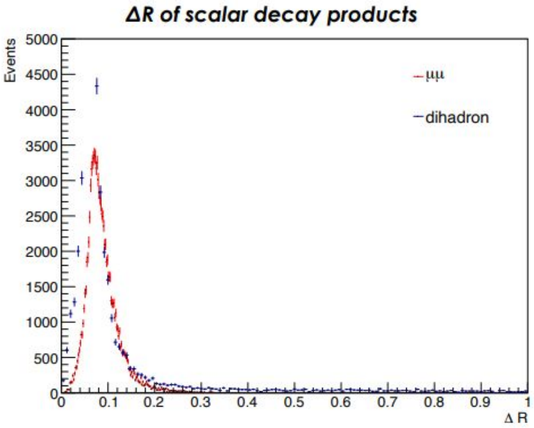
S. Lowette, B. Clerbaux
S. Dansana, A. Morton

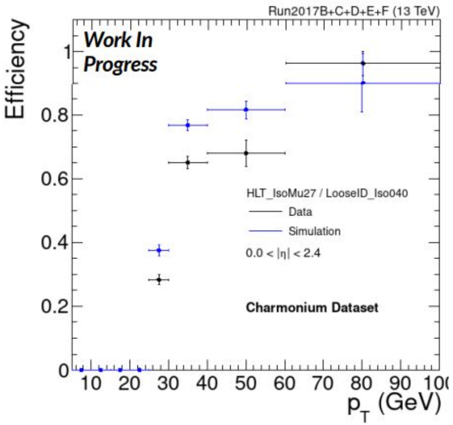
Search for: h → ss → 2mu + 2K



Data: Run-2
Selection:
- Trigger on collimated muons
- K± identification possible at low momenta ~1GeV
- Displaced vertex

Early-stage effort!





I did not tell you about...

- Doubly-charged Higgs boson (B. Clerbaux, L. Thomas, S. Paredes Saenz)
- VBF Higgs to invisible (L. Thomas)
- LFV processes in emu, mutau and etau (B. Clerbaux, D. Beghin, B. Dorney, X. Gao, R. Goldouzian, A.K. Kalsi, G. De Lentdecker)
- LFV in top production (B. Clerbaux, X. Gao, R. Goldouzian)
- Monopoles (P. Vanlaer, M. ElSawy)
- Higgs-Charm Yukawa coupling (J. D'Hondt, N. Breugelmans)
- 4 top production (J. D'Hondt, F. Blekman, D. Müller)
- New physics in tttt/ttbb (J. D'Hondt, F. Blekman, D. Müller)
- Sexaquarks (S. Lowette, J. De Clercq)
- SIMP's (S. Lowette, I. De Bruyn)
- Soft displaced leptons (F. Blekman, A.R. Sahasransu)
- ...

Thank you!

Stay tuned...