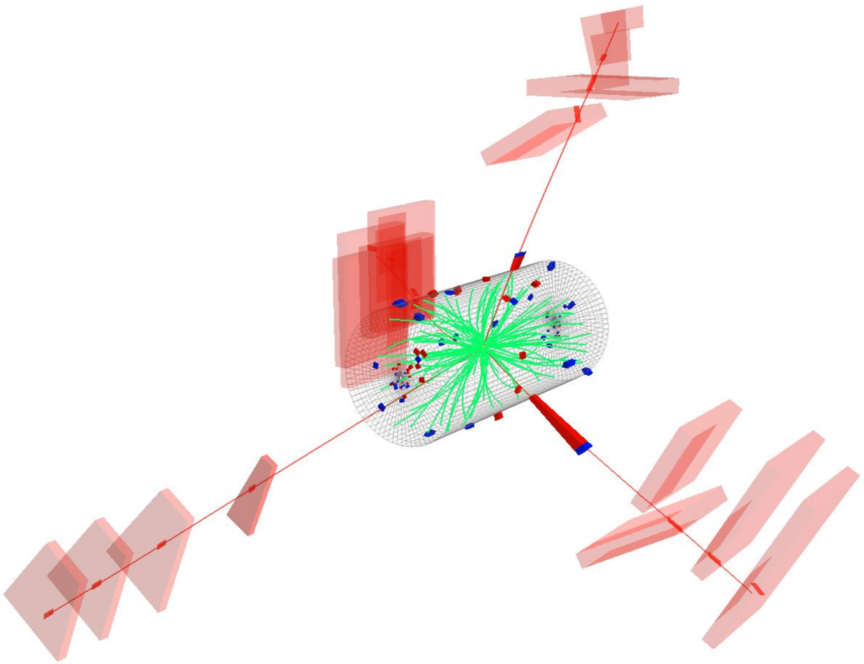


Mario Pellicciona
Istituto Nazionale di Fisica Nucleare - Torino

Physics at LHC

XXXII INTERNATIONAL SEMINAR of NUCLEAR and SUBNUCLEAR PHYSICS "Francesco Romano”

Otranto - June 2021

Today's topics

First class:

- Introduction & general considerations
- SM&BSM Higgs

Second class:

- Closing on the SM:

  Top, W, Z physics

CAVEAT

from the perspective of a an experimentalist working at CMS on Higgs & SM physics!

Third class:

- Flavor physics
- Exotic searches

Almost 70 years of SM

- 1954 Yang & Mills: construction of theory for massless particles. Particles interact with gauge fields
- 1961 Glashow: same origins for EM and Weak interactions, but EM has m=0 propagator and Weak has massive ones
- 1964 Englert/Higgs/al.: complex scalar doublet with two massless bosons → massive spin-1 bosons and a massive scalar
- 1967-68 Weinberg/Salam: gauge theory is spontaneously broken → SM of EWK interactions
- 1970 't Hooft/Veltman: EWK interaction is renormalizable

Experimental success of the SM

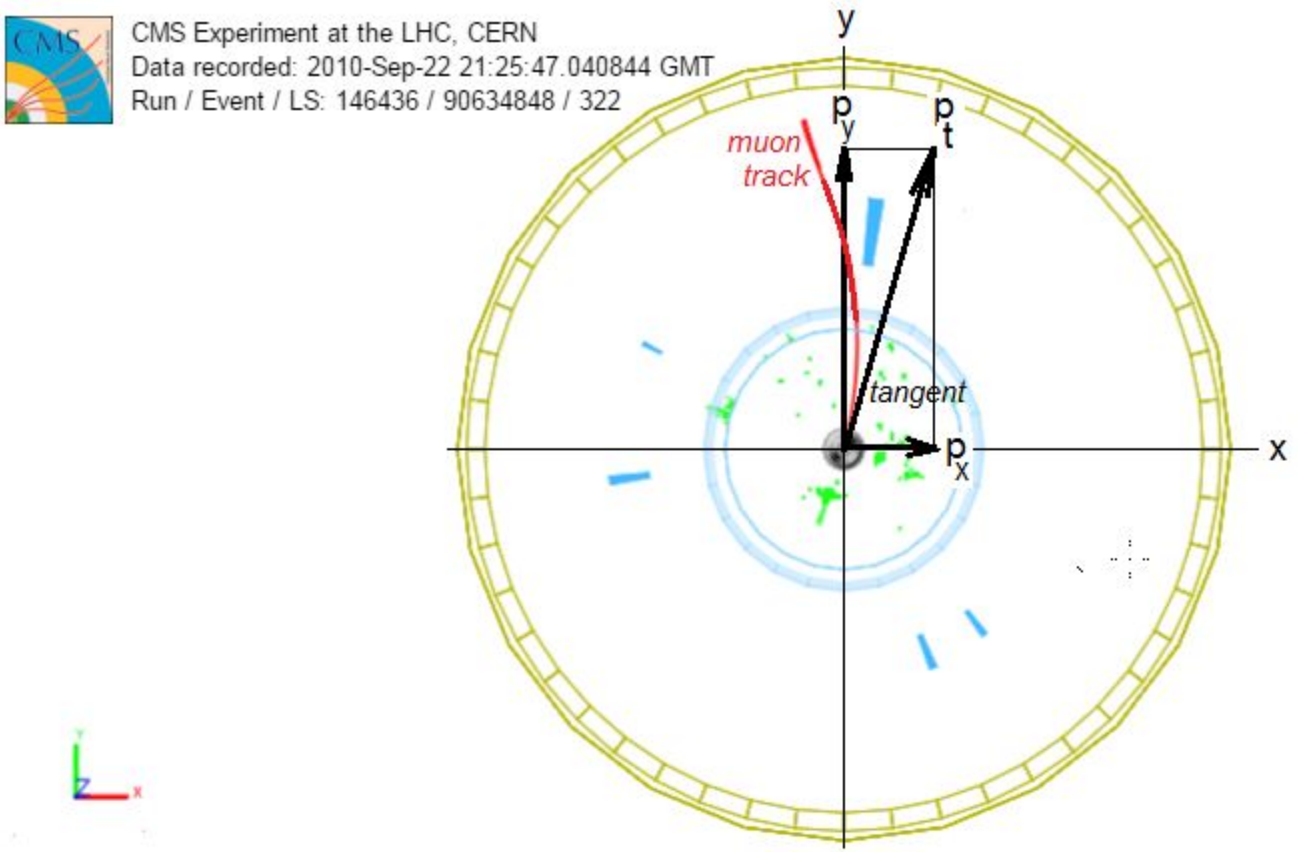
- 1973 Gargamelle: discovery of neutral current
- 1983 UA1 and UA2: discovery of W and Z bosons
- 1989-2000 LEP: SM gets its crown! Precision measurements show uncanny predictive power of theory
  - Couplings
  - W/Z mass
  - Test of non-abelian structure of EWK theory (and QCD!)

(plus very important results like the limit on the number of neutrino families)

- '83-'11 Tevatron: top discovery, m_{top} and m_W measurements
- 2012 LHC: 7-8 TeV energy, discovery of an Higgs-like particle by CMS and ATLAS

A few experimental considerations

It’s all about the transverse plane

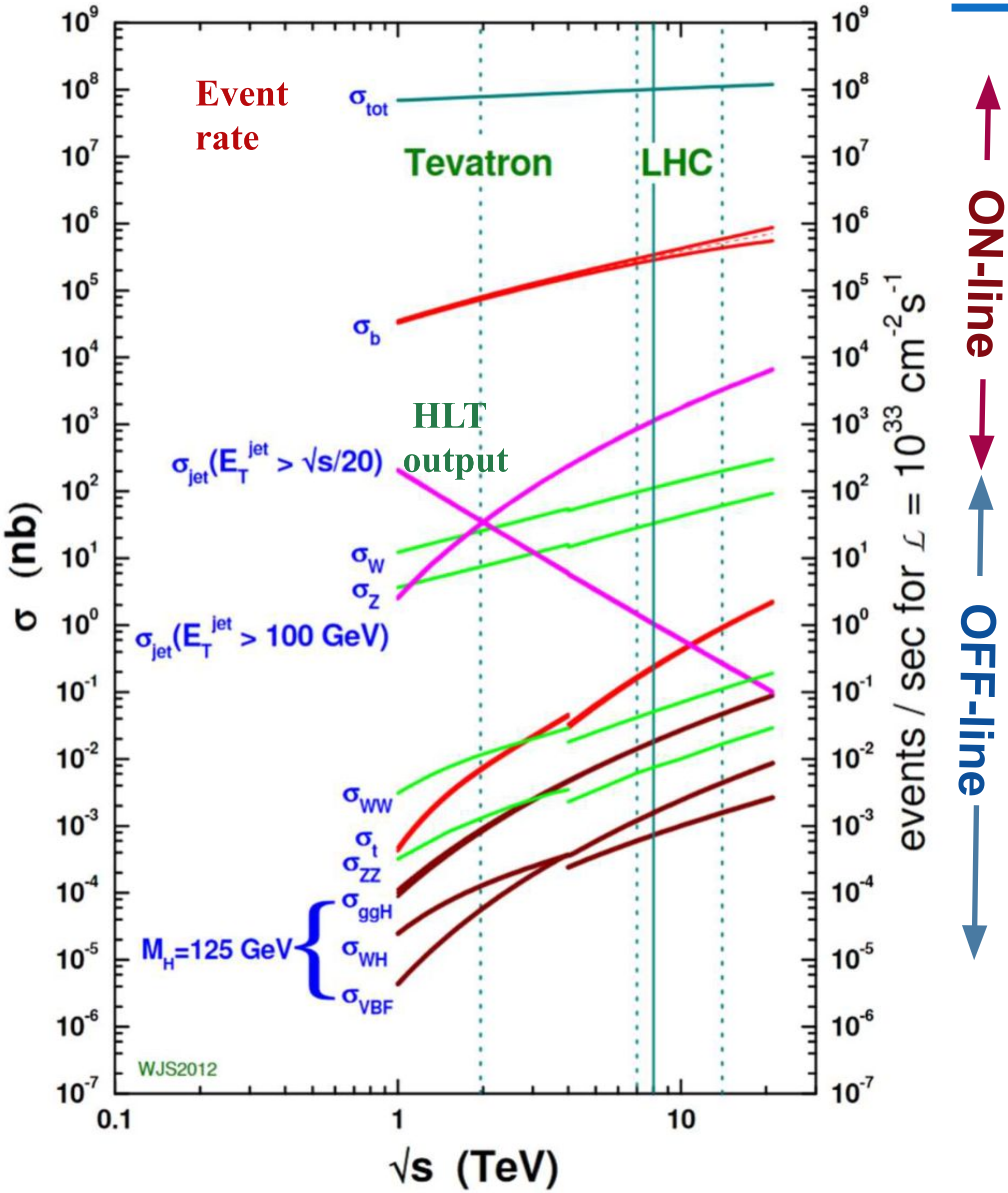


Initial state ~ known

Good to account for missing particles!

p_T is a relativistic invariant

Trigger rates and thresholds



LHC bunch crossing rate: 40 MHz

ATLAS & CMS:
Offline rate ~ 1 kHz

Typical "single particle" thresholds @ 13 TeV:

- Single Isolated Muon ~ 25 GeV
- Single Isolated Electron ~ 35 GeV
- Single Isolated Photon ~ 120 GeV
- Single Jet threshold ~ 140 GeV
- Transverse Missing Energy ~ 200 GeV

Importance of multiple objects triggers!
A bottleneck for many analyses

LHCb
Offline rate ~ 12 kHz (partly asynchronous)

- Single Muon ~ O(GeV)
- Use of topological triggers with MVAs

Particle isolation

Many processes studied at LHC involve electroweak production mechanisms

These are typically characterized by signatures with limited nearby "activity" (no hadronization)

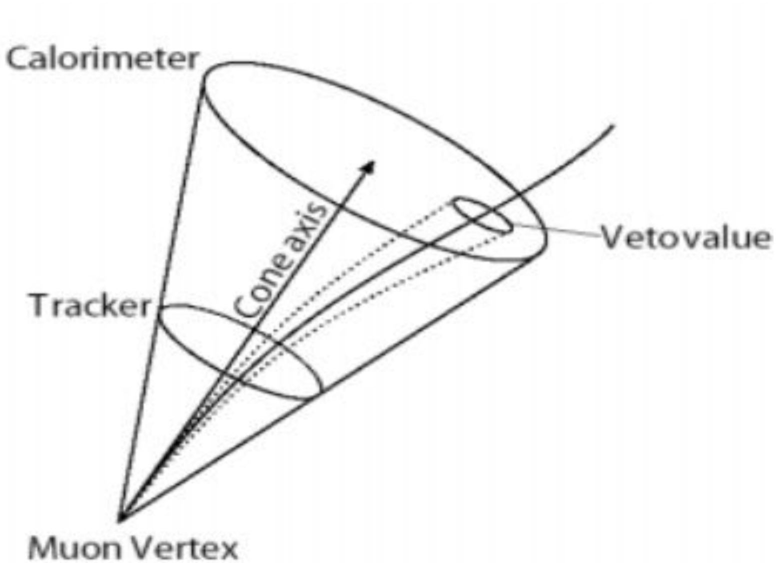
In hadron collider environment important to characterize these topologies

$\longrightarrow$ isolation!

For example: distinguish muons produced by W/Z decays from those inside jets (B/K decays for example)

Need to account for FSR

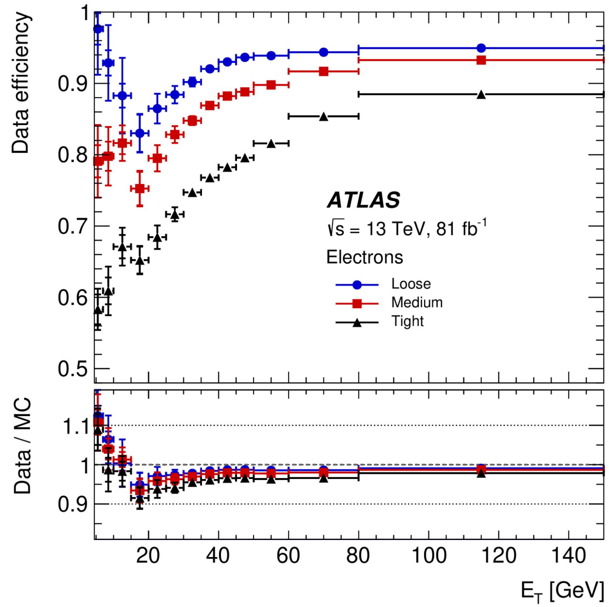
Heavily dependent on PU (but corrections can mitigate a lot)

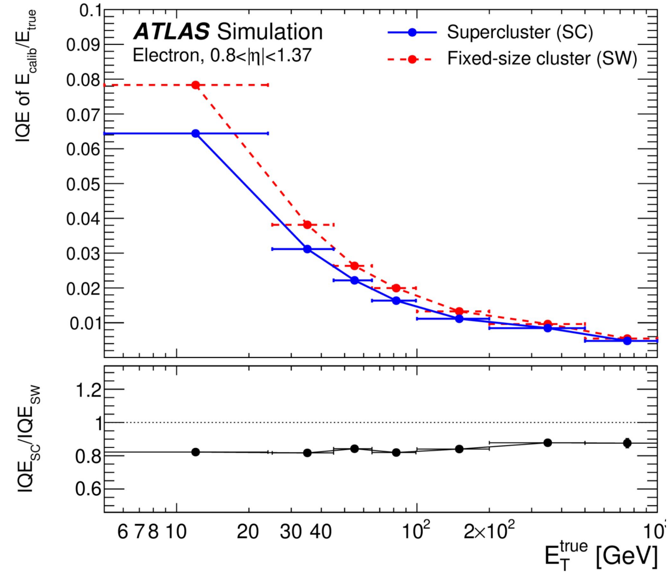


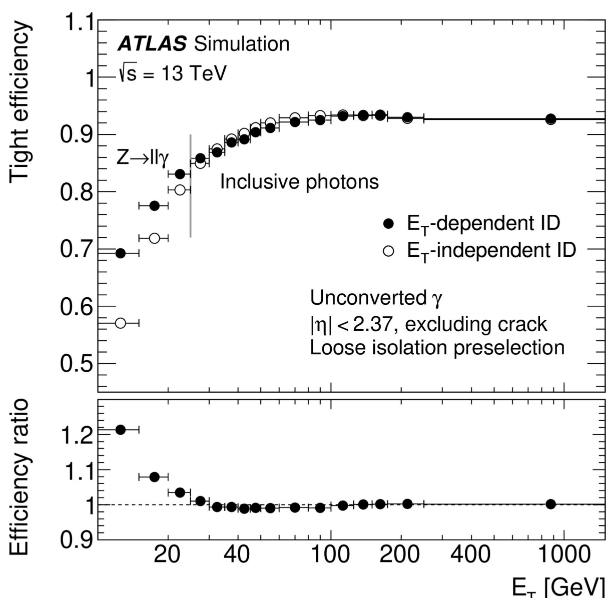
$$\mathcal{I}_{\mu,trk} = \frac{\sum\limits_{trk}^{cone} p_{T,trk}}{p_{T,\mu}}$$

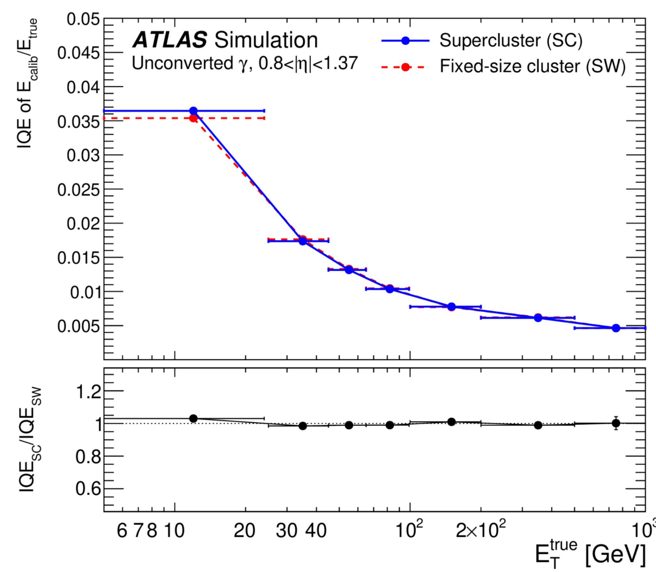
Typically used for leptons and photons, but in principle *any* EWK-mediated signature

Electron and photon performance

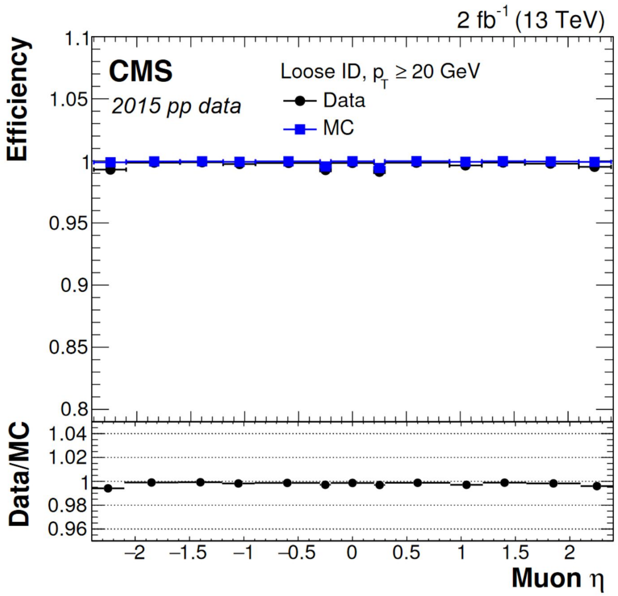


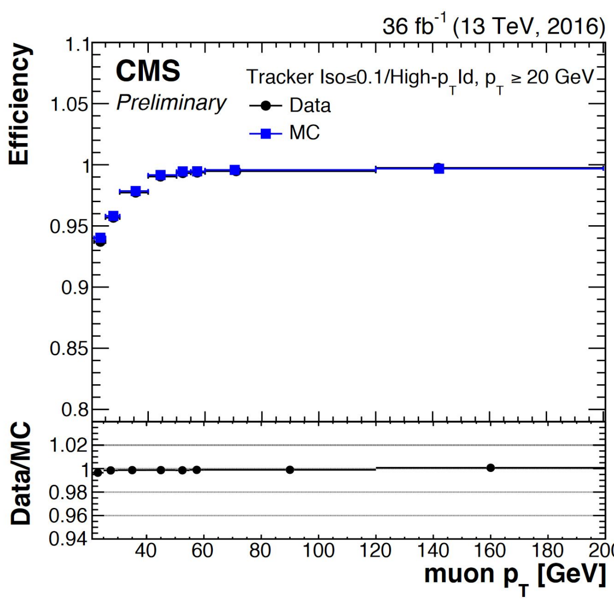


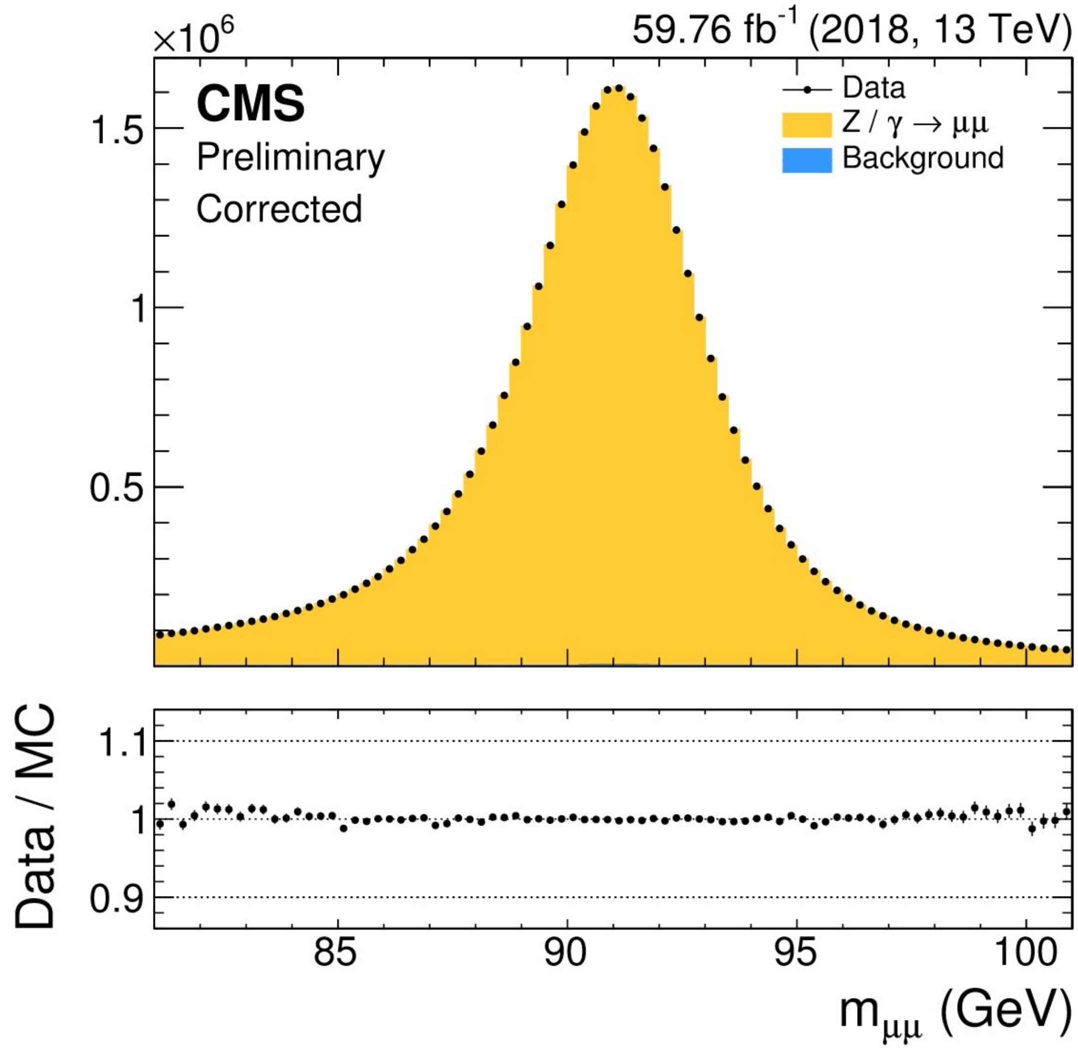




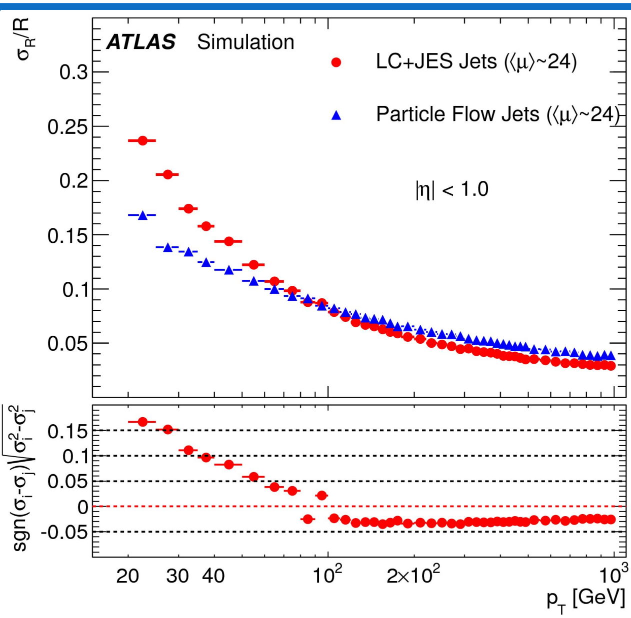
Muon performance

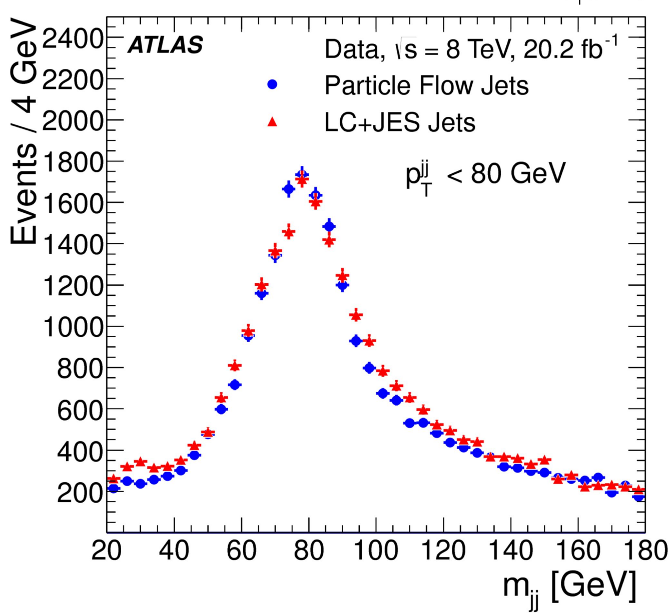


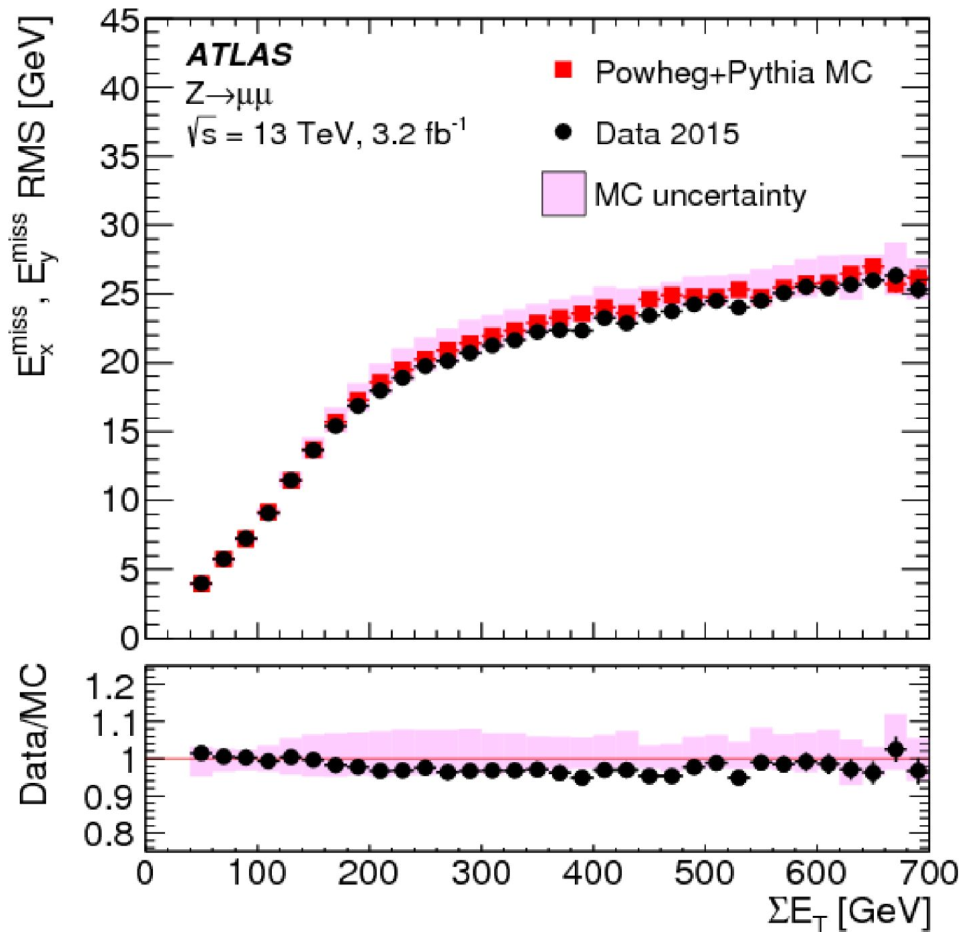




Jet/$E_{T,miss}$


ATLAS Simulation
LC+JES Jets (⟨μ⟩~24)
Particle Flow Jets (⟨μ⟩~24)
|η| < 1.0
σ_R/R
$\mathrm{sgn}(\sigma_i-\sigma_j)\sqrt{\sigma_i^2-\sigma_j^2}$
p_T [GeV]


ATLAS
Data, √s = 8 TeV, 20.2 fb^{-1}
Particle Flow Jets
LC+JES Jets
p_T^{jj} < 80 GeV
Events / 4 GeV
m_{jj} [GeV]


ATLAS
Z→μμ
√s = 13 TeV, 3.2 fb^{-1}
Powheg+Pythia MC
Data 2015
MC uncertainty
E_x^{miss}, E_y^{miss} RMS [GeV]
Data/MC
ΣE_T [GeV]

b-tagging

Importance of identifying b-jets

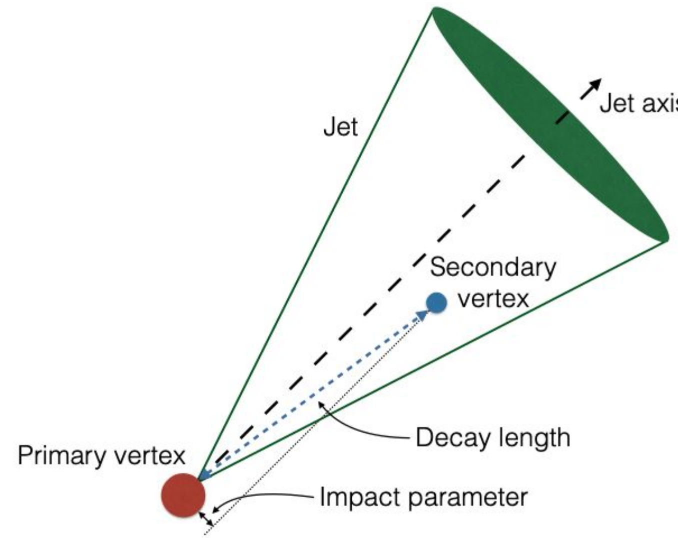
- Key of many EWK processes
- QCD backgrounds usually from light quarks

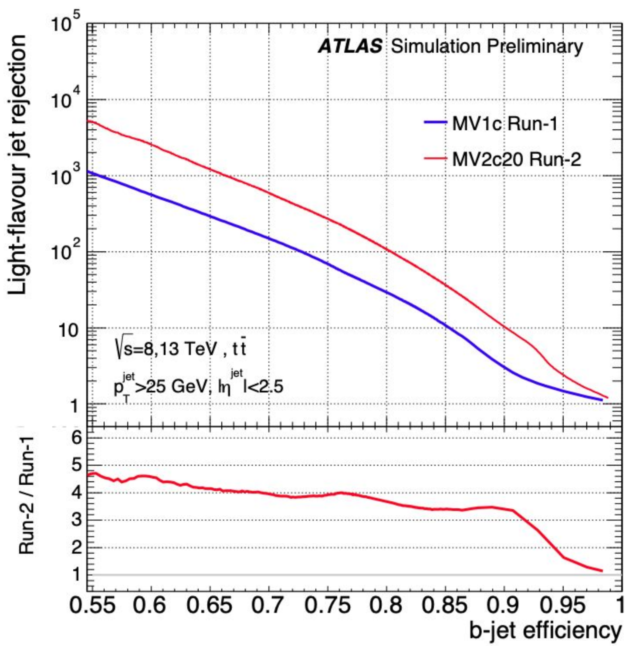
B decays have specific topologies

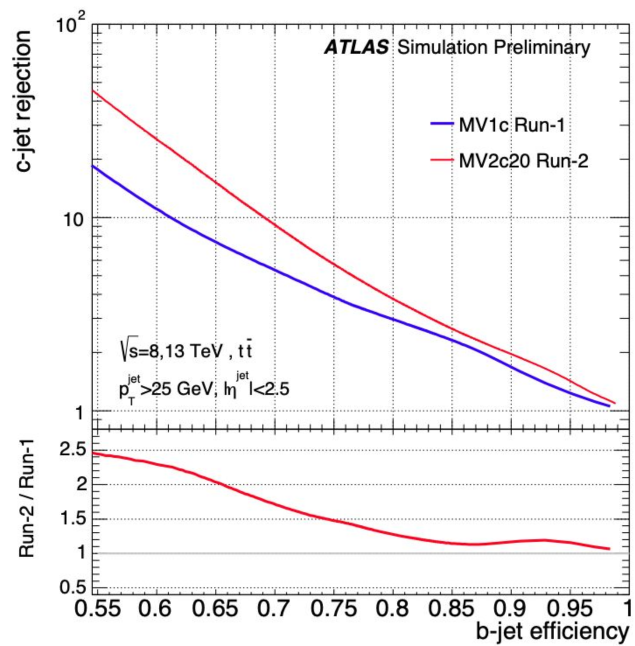
- Displaced charged particles
- Semileptonic decays

Several techniques

- Cut-based selection on tracks and secondary vertices
- MVA methods







Pile-up

Multiple proton-proton collisions in a single beam crossing

Evolved in time:

2012 <PU> ~ 20

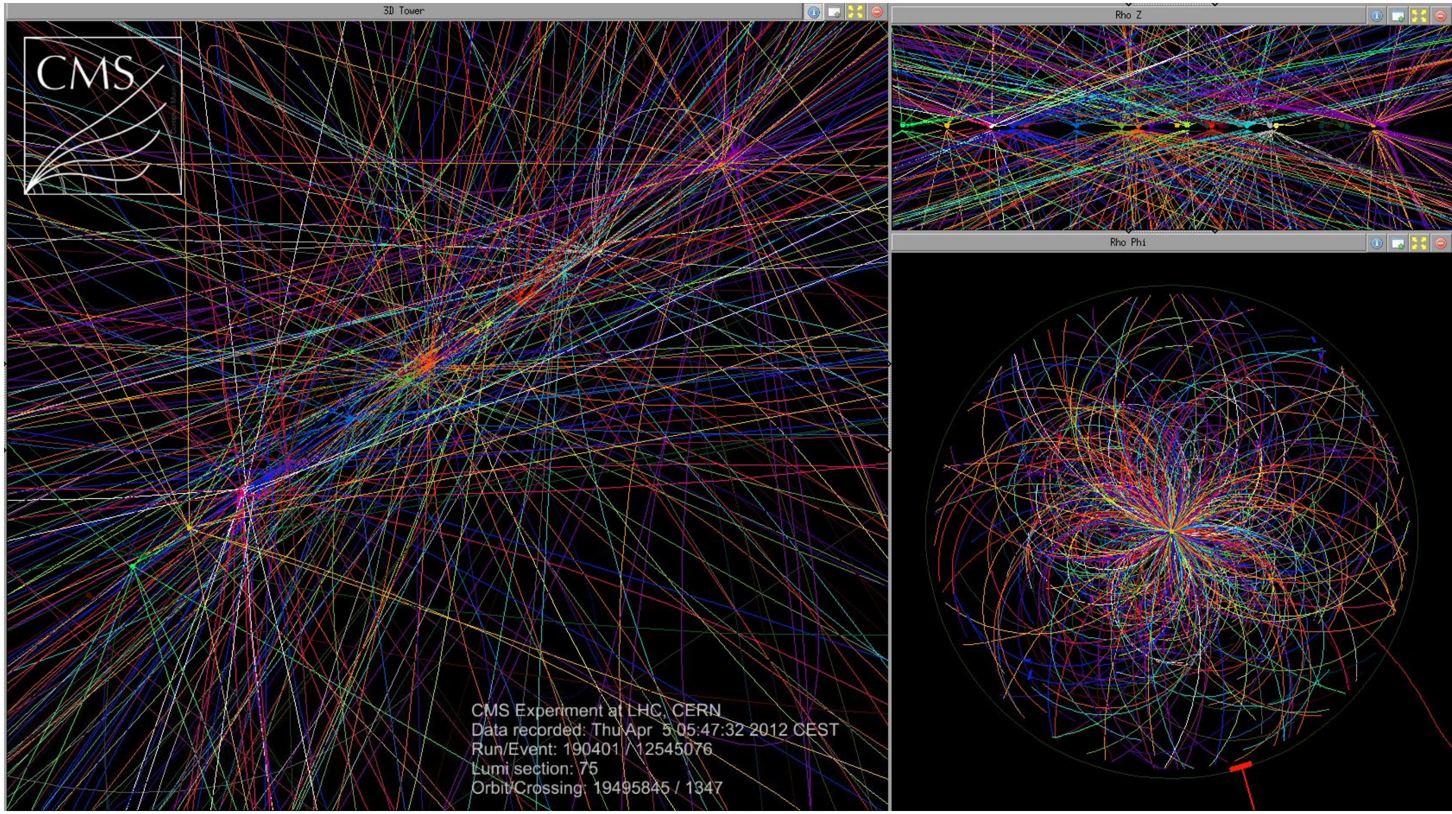
2016 <PU> ~ 20-40

2017 <PU> ~ 50

2018 <PU> ~ 40

Run3 <PU> ~ 50

HL-LHC <PU> 150-200



Major effect on performance (ID, reco, isolation, missing energy, etc.)

h_{125}

Dissecting the Higgs sector

Minimal request of the SM: one electroweak doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_0 + i\phi_3 \end{pmatrix}$$

- Most degrees of freedom absorbed to provide $W^{\pm}$ and Z mass (or L polarization)
- ϕ_0 remains as a scalar field $\longrightarrow$ Higgs boson

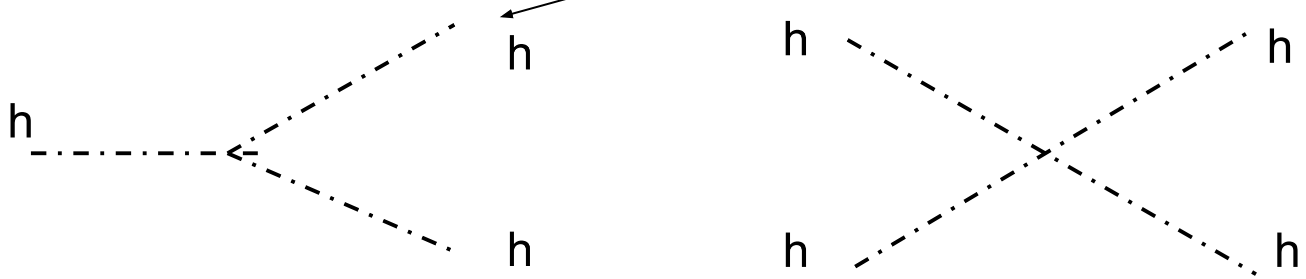
Reminder: fermions acquire mass through Yukawa interactions

The Higgs potential

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 = \frac{1}{2}m_h^2h^2 + \sqrt{\frac{\lambda}{2}}m_hh^3 + \frac{\lambda}{4}h^4$$

Mass

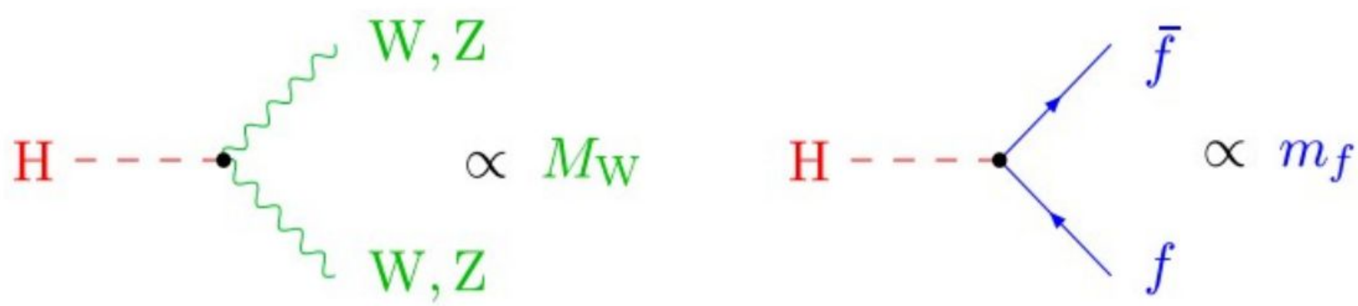
Self coupling



- We are normally taught to neglect the self-coupling terms (higher order)
- Within the SM, this is certainly true
- Enhancements possible in many BSM scenarios

Golden rule of Higgs phenomenology

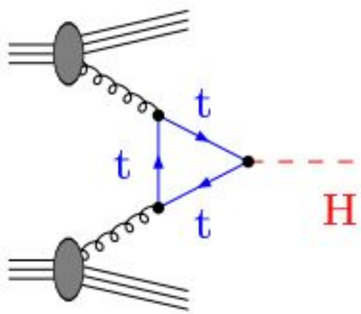
Coupling of Higgs to particles proportional to their masses



$\longrightarrow$ Higgs production (and decays) mostly via $W^{\pm}$, Z^0 and top quarks

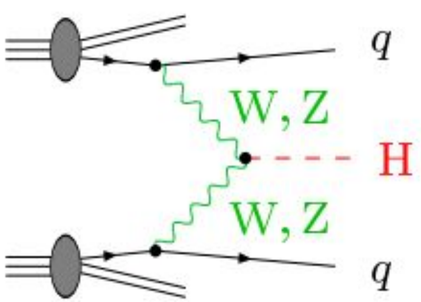
Higgs production at LHC

Production at hadron colliders:



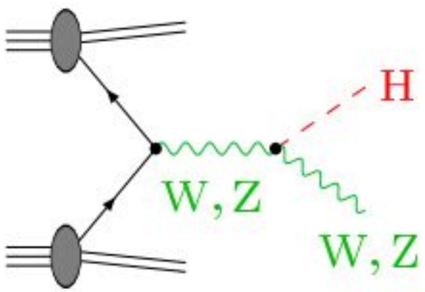
Gluon-gluon fusion

σ ~ 49 pb



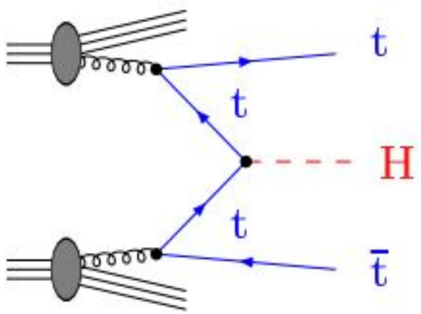
Vector boson fusion

σ ~ 4 pb



Associated production (Higgsstrahlung)

σ ~ 2 pb

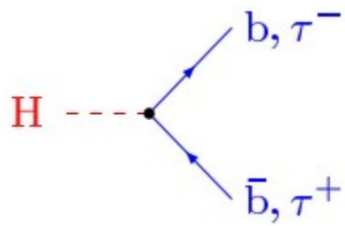


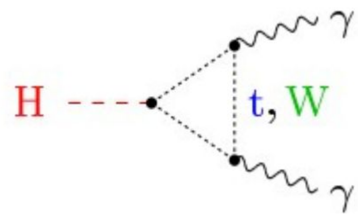
Top associated production

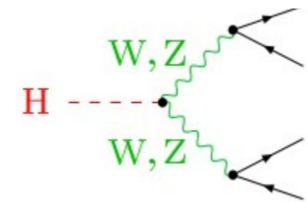
σ ~ 0.5 pb

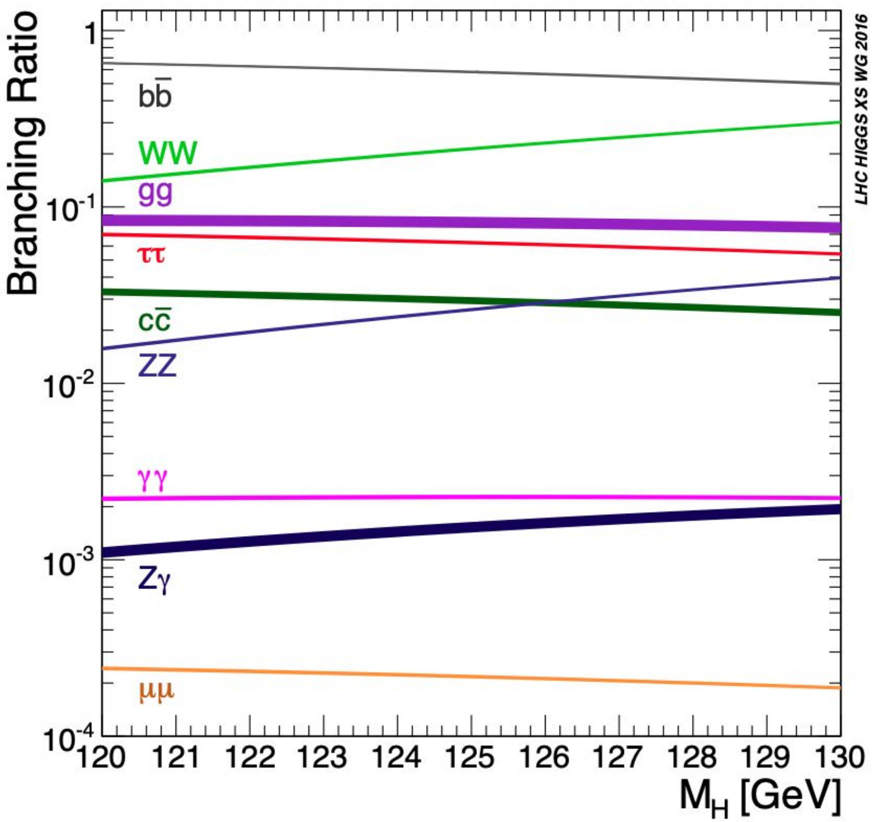
Higgs decays

Most relevant for h_{125}







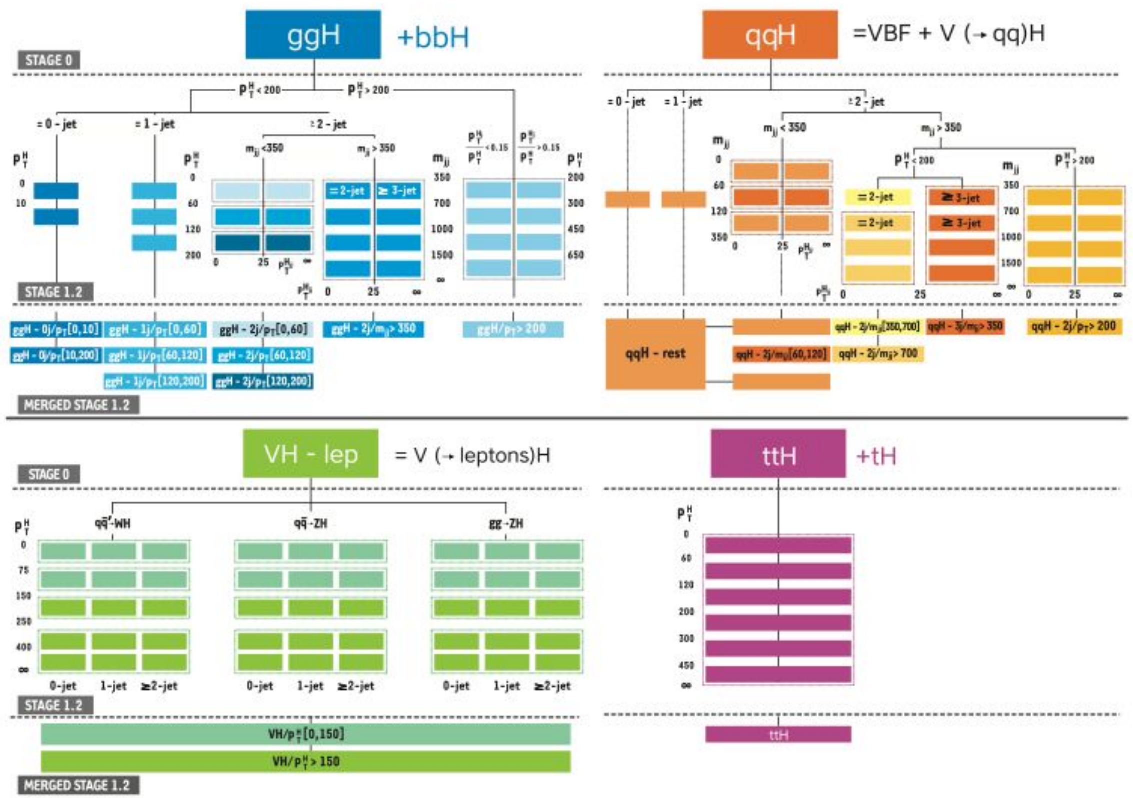


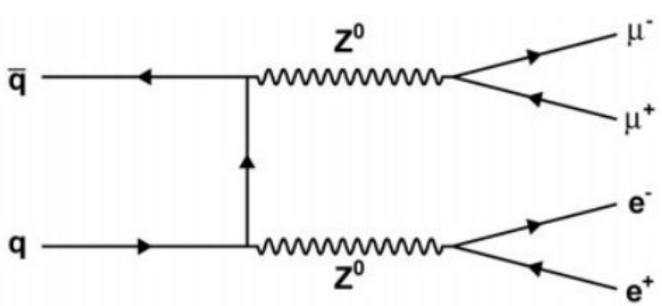
Synergy of CMS and ATLAS with the
LHC Higgs Cross Section Working Group
Main forum for information exchange between theory and experimental communities

$H \rightarrow ZZ \rightarrow 4l$

arXiv 2103.04956

- Very clean final state: four high momentum leptons
- Small number of events: BR($Z \rightarrow ll$) ~ 3%
  - Low statistic, high purity
- Final states con
  - $H \rightarrow \mu^+\mu^-$ μ
  - $H \rightarrow e^+e^-$ e
  - $H \rightarrow \mu^+\mu^-$ e
- Discrimination mechanisms
- Main backgrou $ZZ \rightarrow 4l$

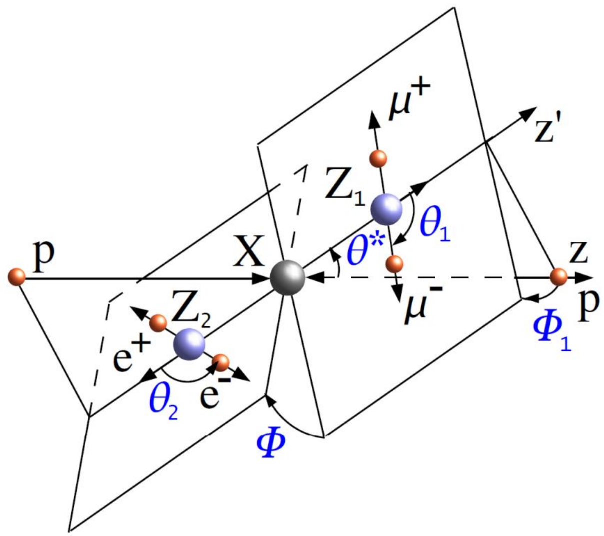




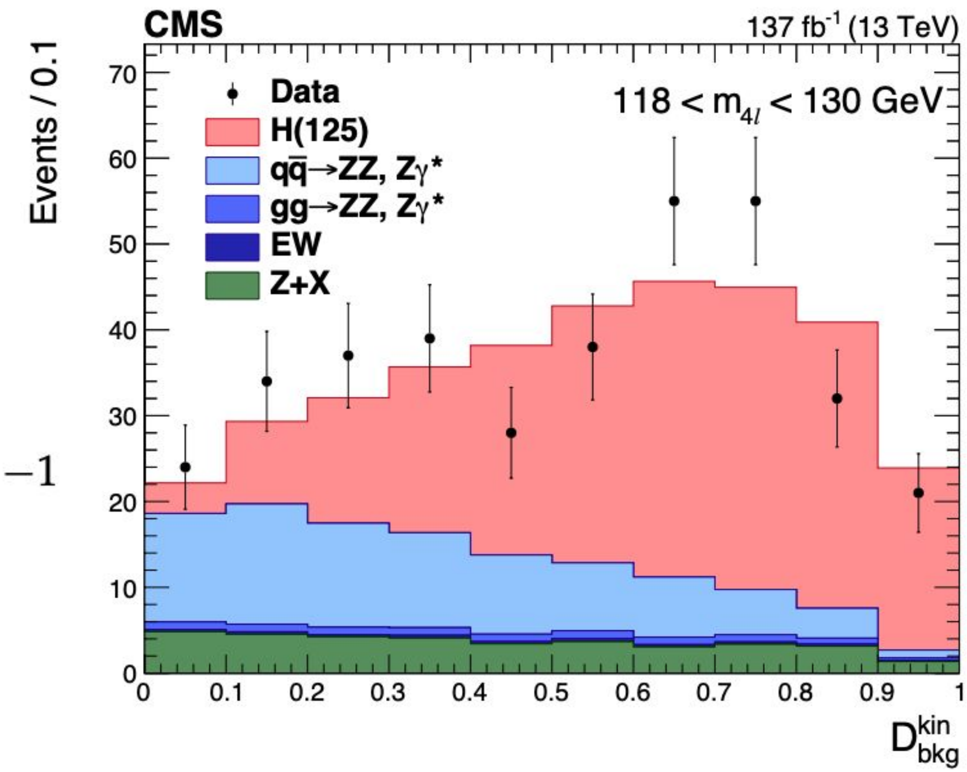
Kinematic discriminant

arXiv 2103.04956

Use kinematic properties of signal/background to construct a discriminant to fit

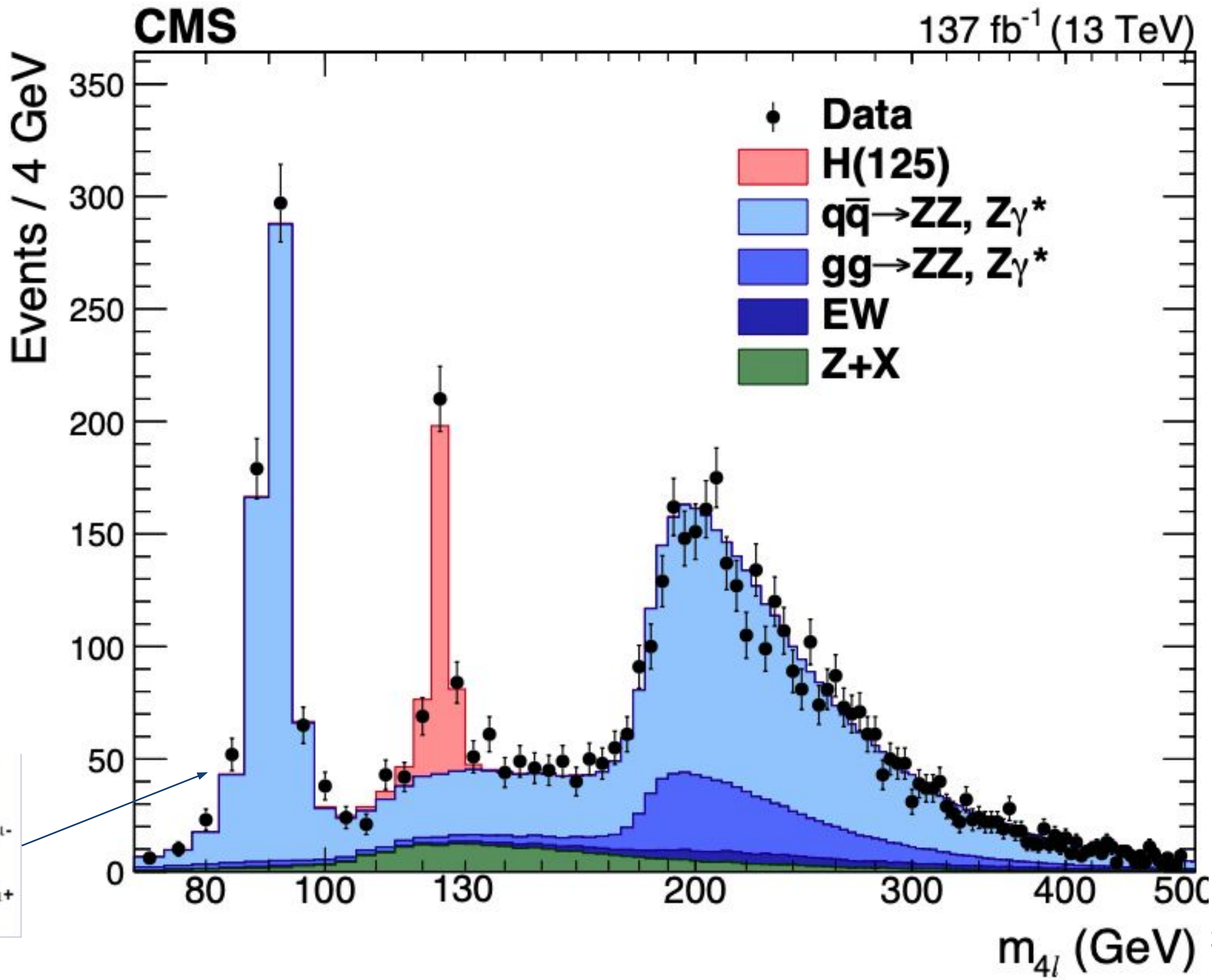


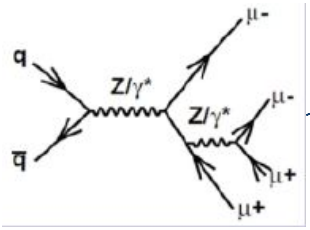
$$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}^{q\bar{q}}(\vec{\Omega}^{\mathrm{H}\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}^{gg}(\vec{\Omega}^{\mathrm{H}\to 4\ell}|m_{4\ell})}\right]^{-1}$$



m_{4L}

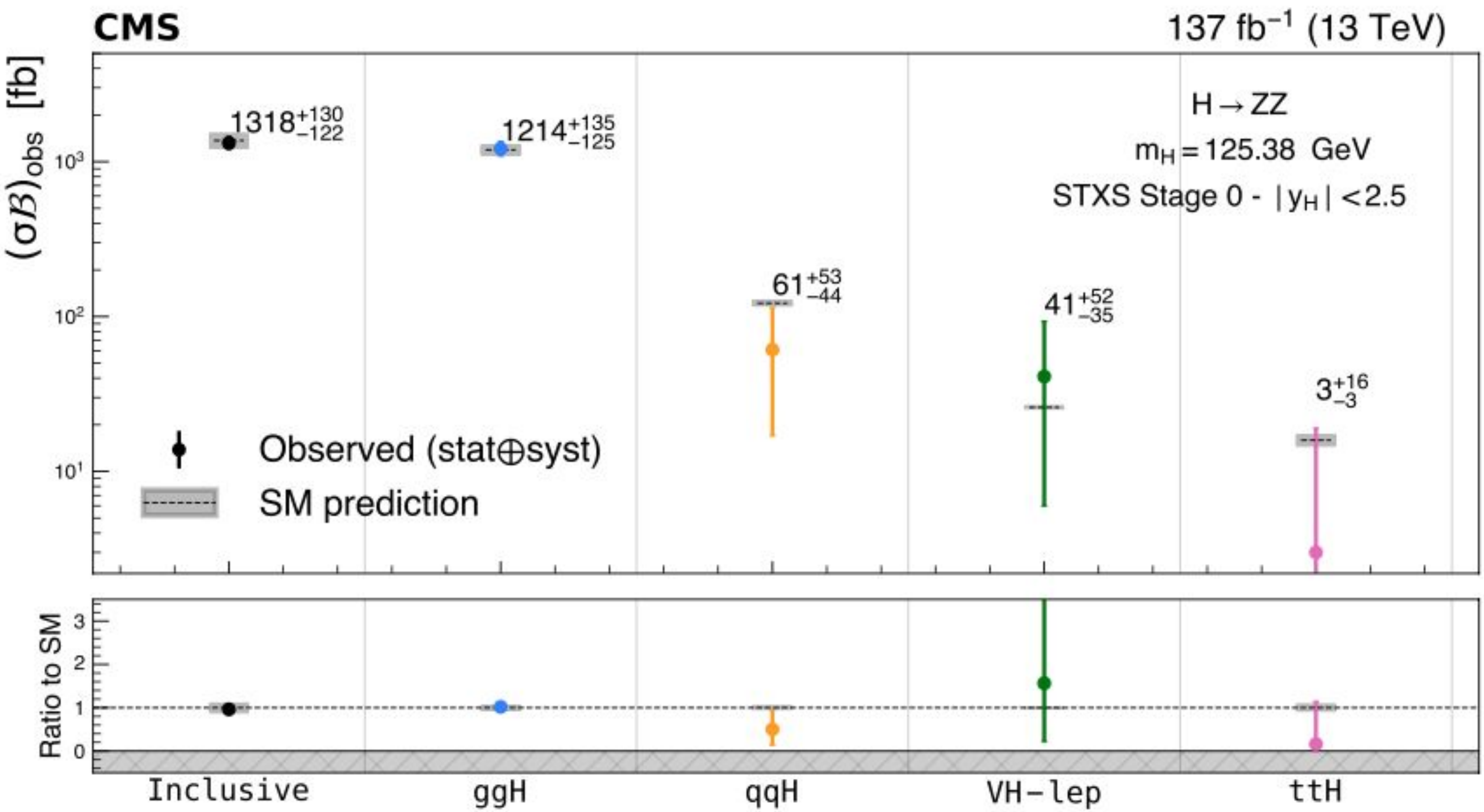
arXiv 2103.04956





Dissecting the signal

arXiv 2103.04956



Higgs mass measurement

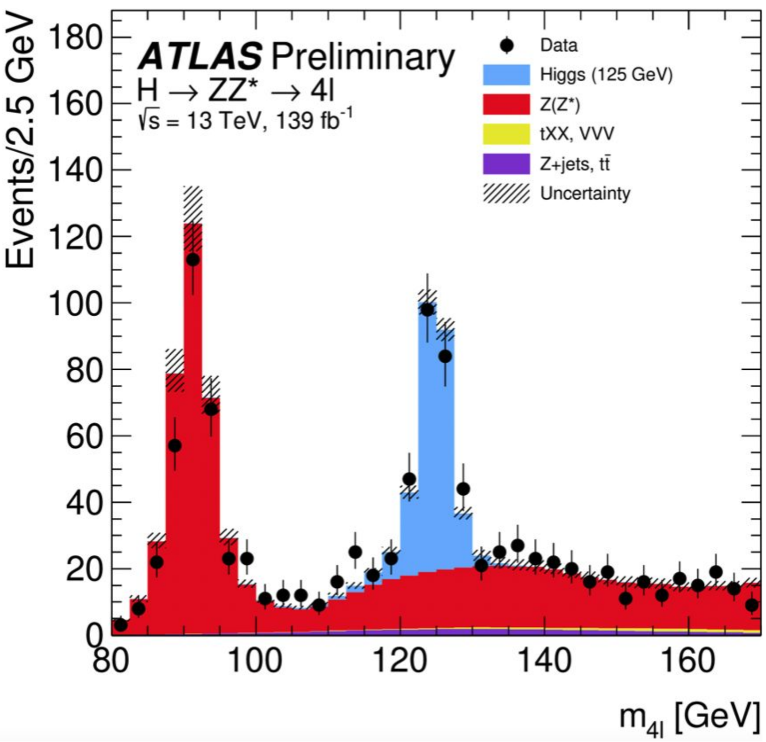
ATLAS-CONF-2020-005

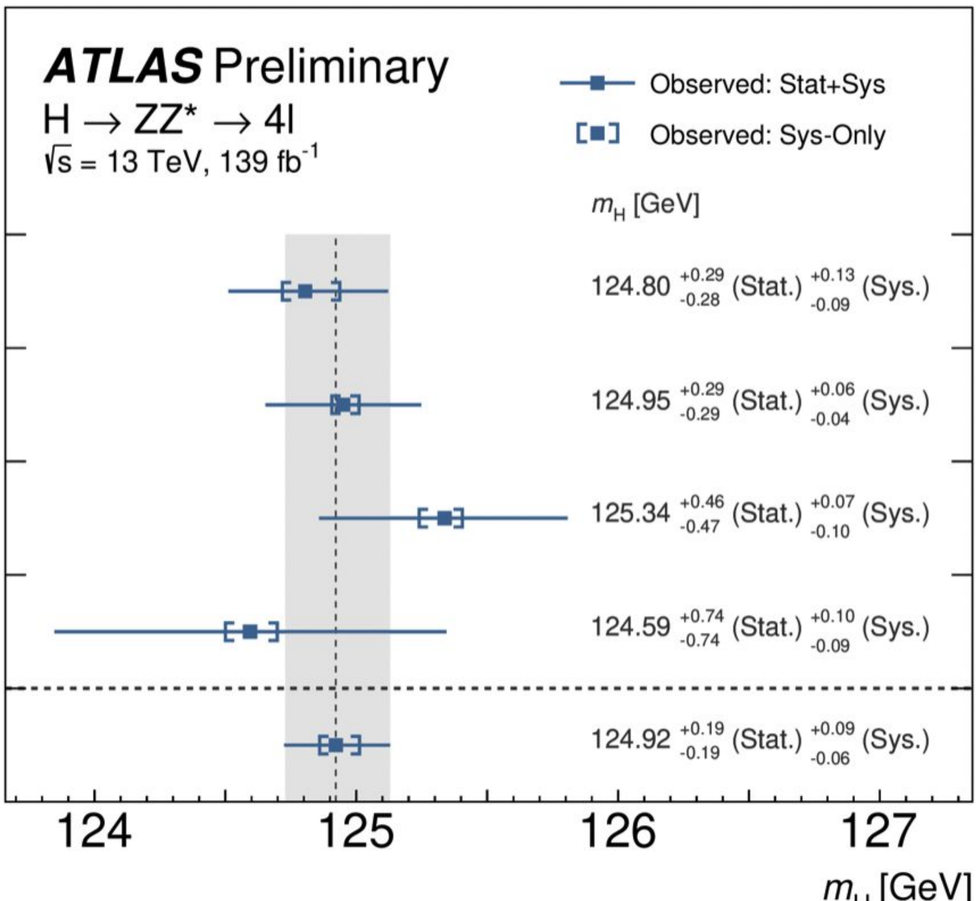
Full Run-2 mass measurement done by ATLAS in H⟶ ZZ ⟶ 4l

⟶ All production modes included

⟶ Kinematic fit to mass-constrain the first lepton pair to Z mass

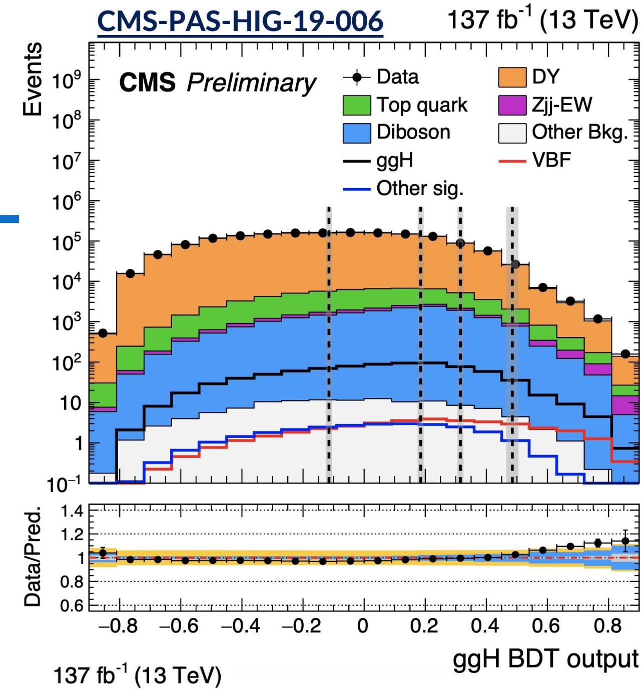
⟶ Per-event m_{4l} resolution



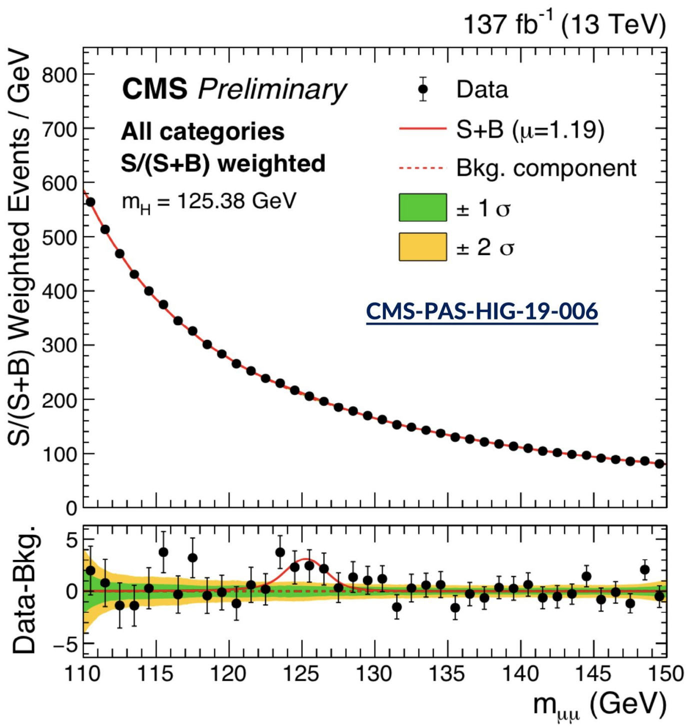


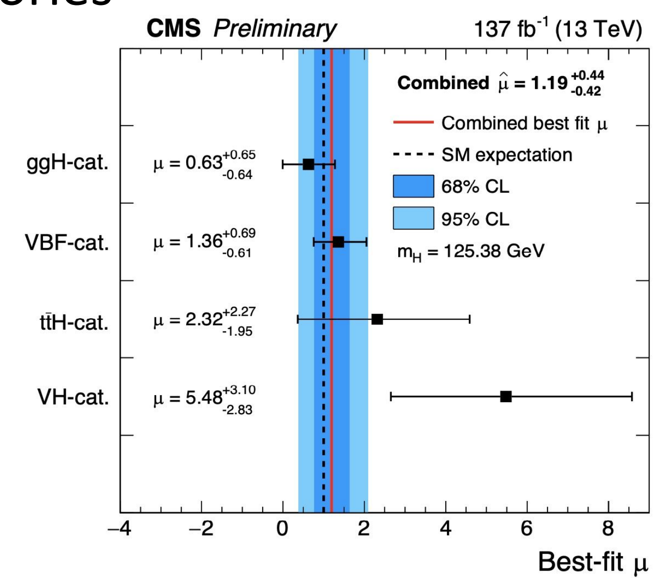
$H \rightarrow \mu\mu$

arXiv:2009.04363
sub. JHEP



- Test 2nd generation coupling
- In SM BR($H \rightarrow \mu\mu$) ~ $2*10^{-4}$
- High p_T isolated muons
- Production categories
  - ggH, VBF, ttH, VH
  - VBF from DNN fit
- Separation in MVA score categories





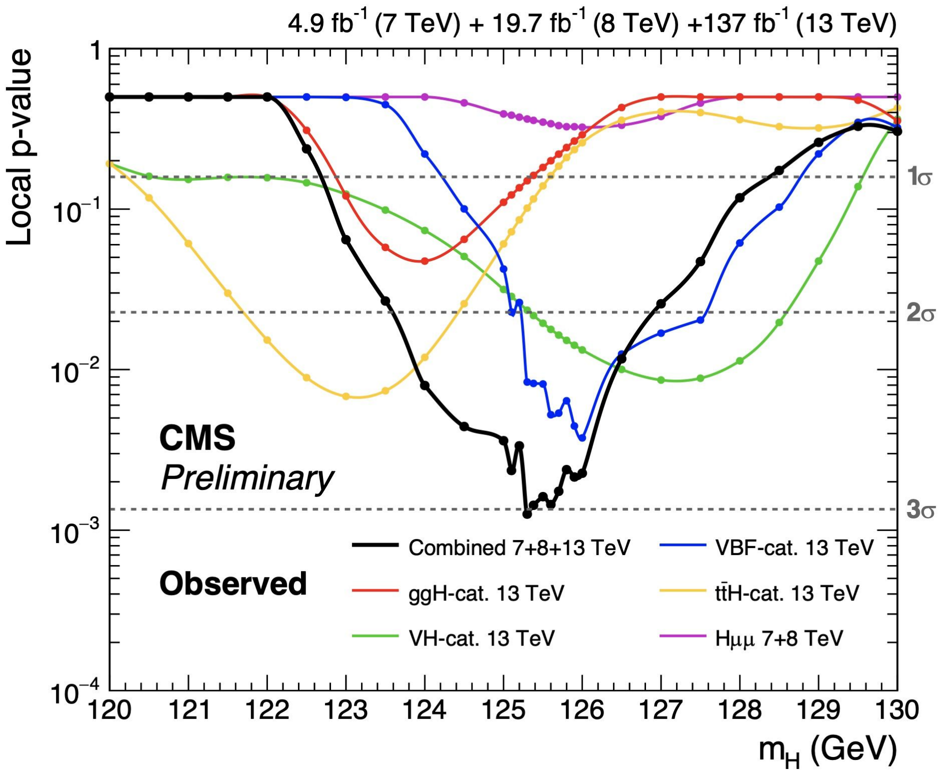
Signal strength

$$\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$$

$$\mu = 1.19^{+0.41}_{-0.39}(stat)^{+0.17}_{-0.16}(syst)$$

per m_H = 125.38 GeV

$H \rightarrow \mu\mu$: first evidence



Prod. Category	Obs. (exp.) significance (m_H = 125.38 GeV)
VBF	2.40 (1.77)
ggH	0.99 (1.56)
ttH	1.20 (0.54)
VH	2.02 (0.42)
Comb. 13 TeV	2.95 (2.46)
Comb Run 1+2	2.98 (2.48)

Uncertainty source	$\Delta\mu$	
Total uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.39
Total systematic uncertainty	+0.17	−0.16
Size of simulated samples	+0.07	−0.06
Total experimental uncertainty	+0.12	−0.10
Total theoretical uncertainty	+0.10	−0.11

Limited by statistical uncertainty
→ Run3 fundamental for discovery

Measuring(-ish) the width

Direct measure of the Higgs width not possible at LHC

- Theory prediction ~ 4 MeV
- Experimental resolution ~ O(GeV), under best conditions

Use a trick: measure $\sigma_{\text{on-shell}}/\sigma_{\text{off-shell}}$

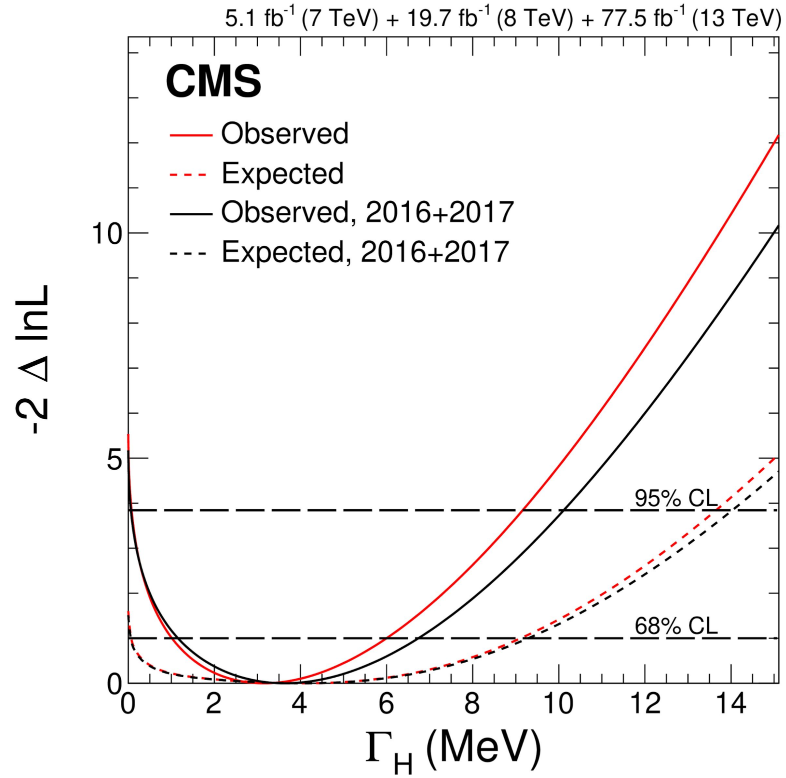
- $\sigma_{\text{on-shell}}$ depends on width, $\sigma_{\text{off-shell}}$ doesn't
- Only works if couplings scale in the same way, also with new physics
- Usually measured in 4l final state

$$\Gamma_H = 3.2^{+2.8}_{-2.2}\ MeV$$

[0.08, 9.16] 95% CL

Systematic uncertainties ~ 0.5 MeV

PRD 99 (2019) 112003



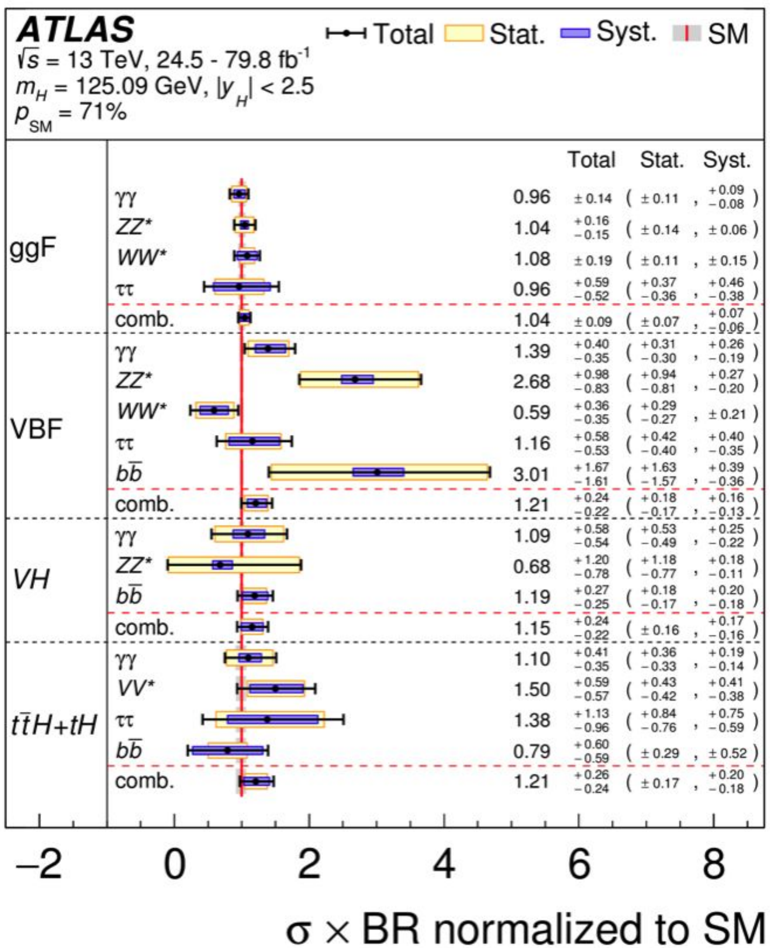
Putting it all together

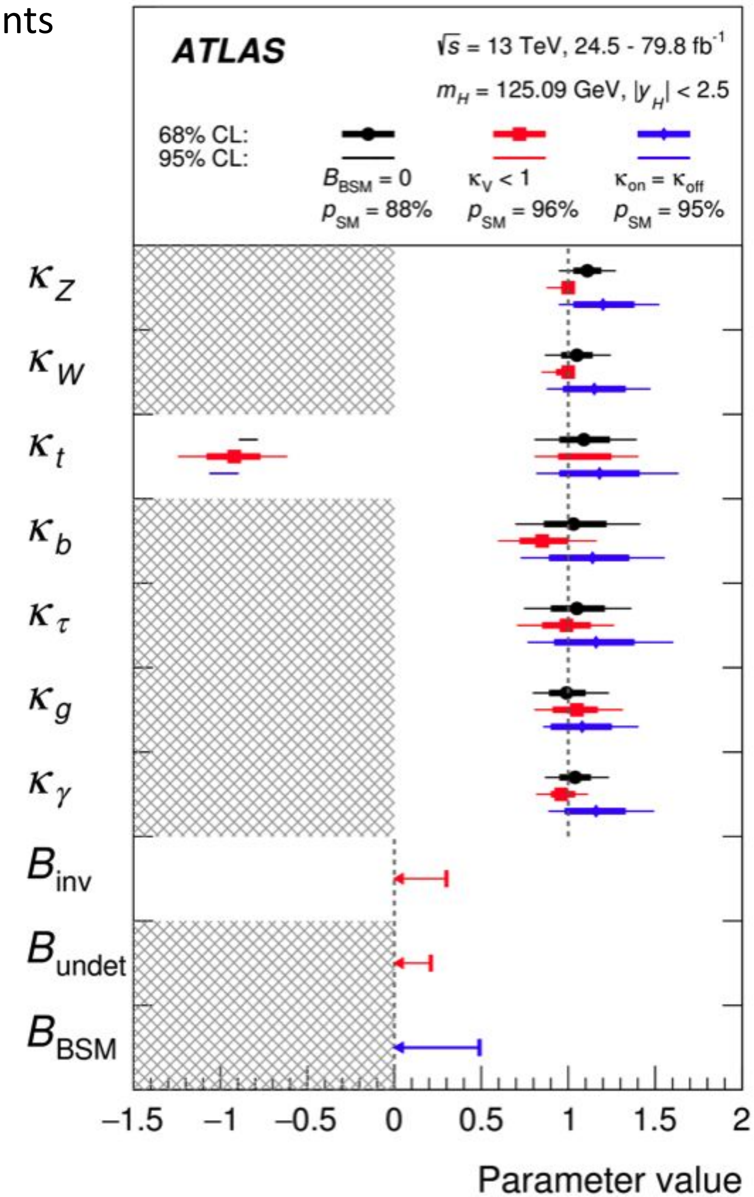
$$\kappa = \frac{g_{meas}}{g_{SM}}$$

Measurements of *BR translated into coupling measurements

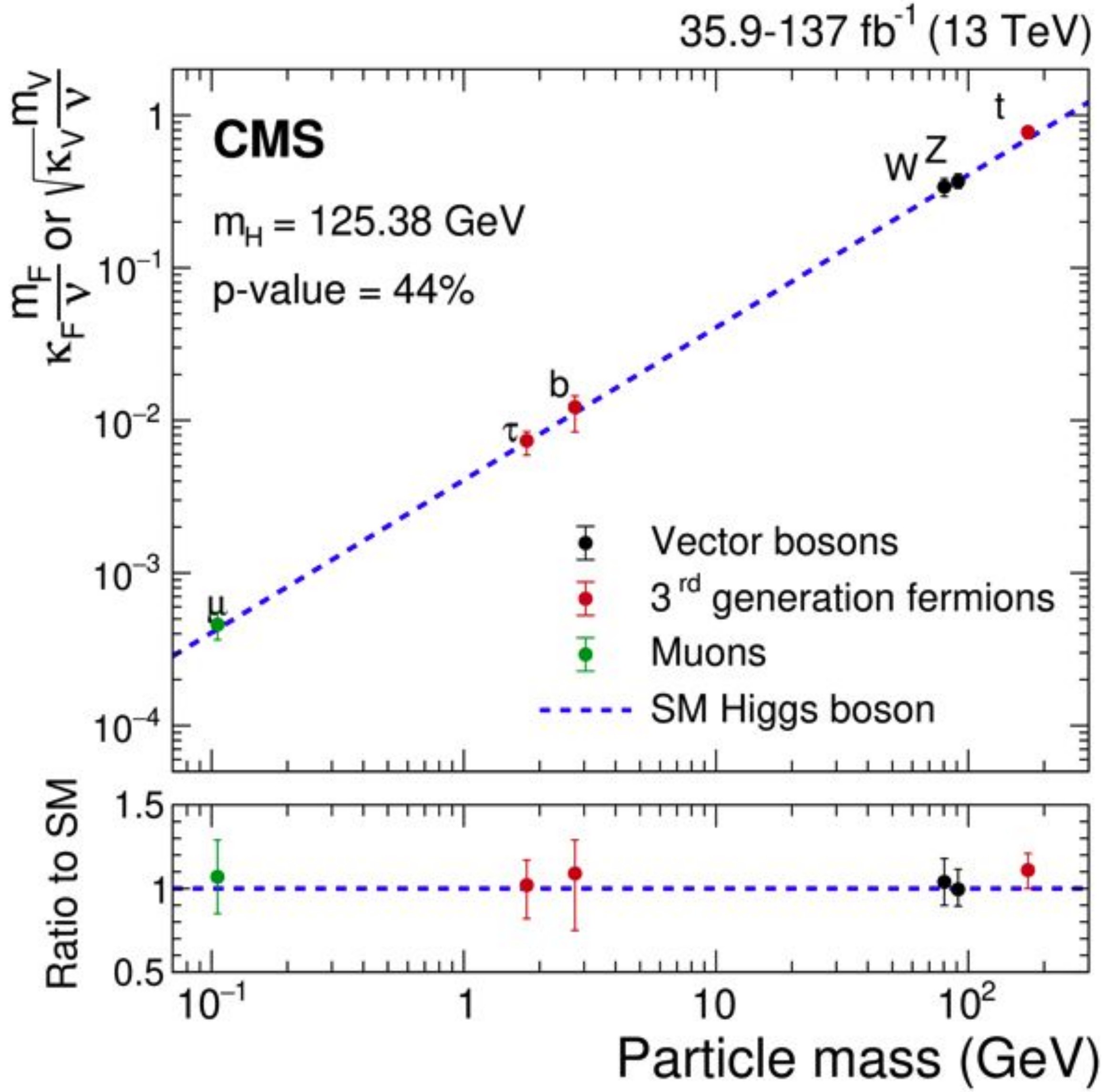
The “kappa framework”

Correlations between POIs (and systematics)





An interesting exercise



BSM Higgs

Next-to-minimal-ish: 2HDM

Additional electroweak doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad \phi' = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}$$

5 degrees of freedom available

➔ **CP-even (h, H) CP-odd (A), $H^{\pm}$**

With few assumptions, free parameters of the theory: m_h, m_H, m_A, $m_{H\pm}$, tanβ, α

α is the mixing parameter between h and H

$$\tan(\beta) = \frac{<\varphi>_0}{<\varphi'>_0}$$

Somewhat problematic to produce common benchmarks with all these parameters

→ Extensive work of theory/experiment within the LHC HXSWG

Parameters can be constrained in particular incarnations of 2HDM

→ In MSSM, d.o.f. reduced to two parameters → m_A and tanβ

Personal note: very “mild” BSM if no SUSY → sideways SM!

Couplings in 2HDM

All mass eigenstates couple to both h and H in all configurations, but couplings depend on model

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
		Different scaling of up and down fermions	Different scaling of leptons and quarks	Different scaling of up and down quarks, leptons flipped

$$g_{h,VV} \propto \sin(\beta-\alpha) \qquad g_{H,VV} \propto \cos(\beta-\alpha)$$

Typical topologies

Signatures depend on mass hierarchy

High mass:

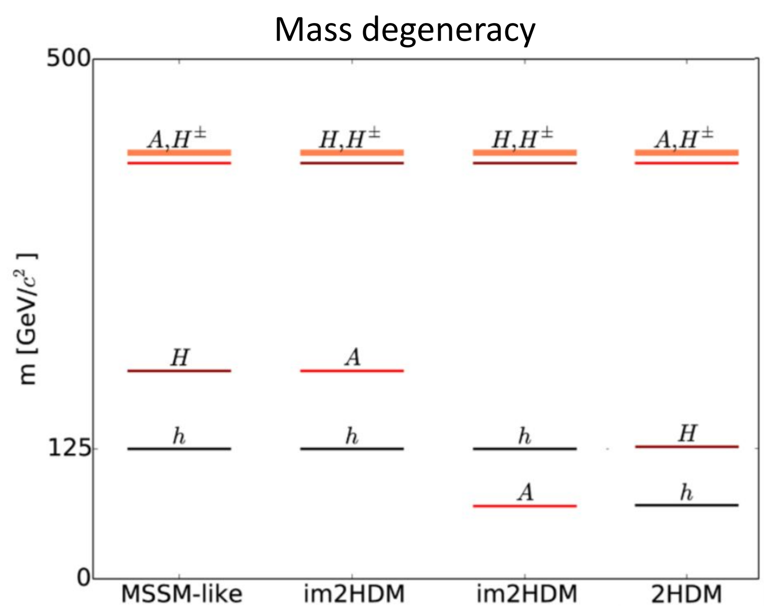
- H $\longrightarrow$ hh, $H^{\pm} \longrightarrow W^{\pm}Z$, H $\longrightarrow$ AZ, A$\longrightarrow$ Zh, H$\longrightarrow$tt …

Mid-high mass:

- A/H $\longrightarrow$ ττ/bb/μμ/WW/ZZ

Low mass:

- A $\longrightarrow$ ττ/bb/μμ
- Overlap with NMSSM (see later)



A/H → ττ

[Phys. Rev. Lett. 125 (2020) 051801]

Search in the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ in range [0.2,2.5] TeV

→ Single lepton triggers ~ 25 GeV, single τ around 150 GeV

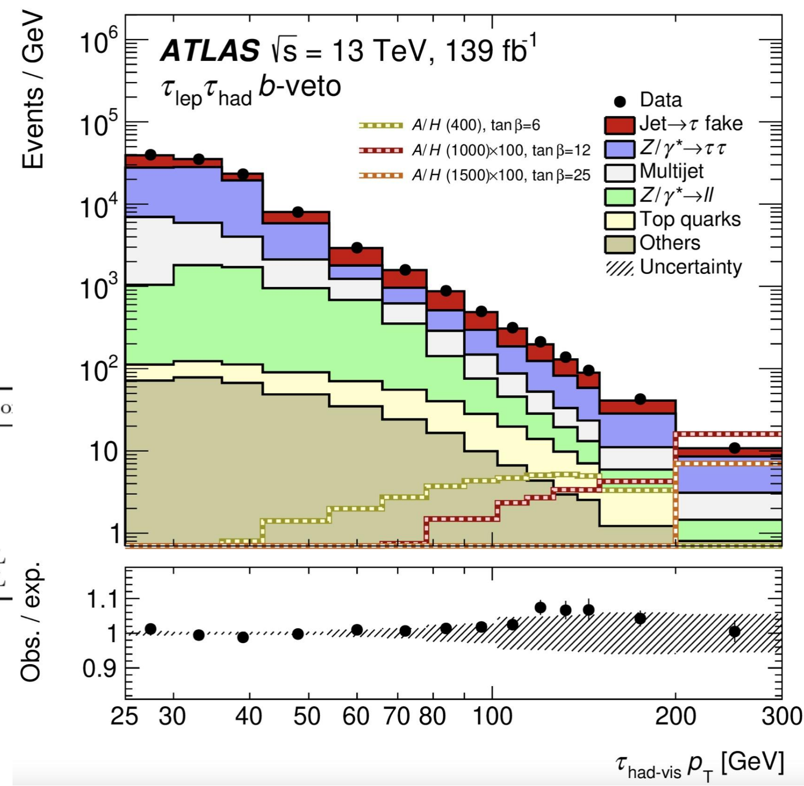
"Bump" hunting over the transverse mass spectrum defined with missing energy

$$m_T^{\mathrm{tot}} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\mathrm{miss}})^2 - (\boldsymbol{p}_T^{\tau_1} + \boldsymbol{p}_T^{\tau_2} + \boldsymbol{E}_T^{\mathrm{miss}})^2}$$

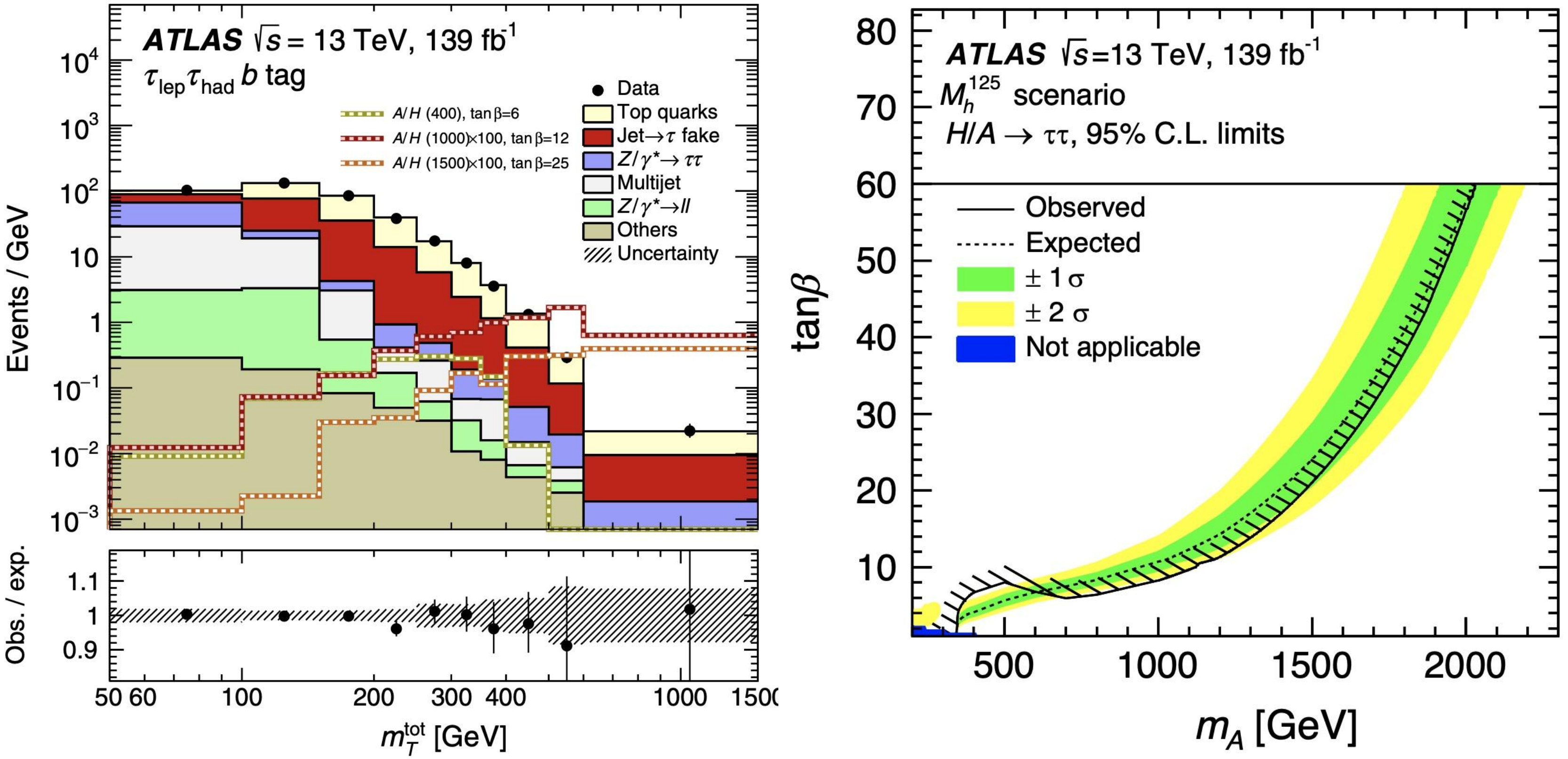
N_{bjet} categorization to exploit different production mechanisms

→ Dependence on tanβ for both b and τ

Process	Generator	PDF	UEPS	Cross-section o
ggF	Powheg-Box v2 [61,62,63,64,65]	CT10 [66]	Pythia 8.1 [67]	See text
bbH	MG5_aMC@NLO 2.1.2 [68,69]	CT10	Pythia 8.2 [70]	See text
W+jets	Sherpa 2.2.1 [71]	NNPDF 3.0 NNLO [72]	Sherpa 2.2.1 [73]	NNLO [74]
Z+jets	Powheg-Box v1 [61,62,63,75]	CT10	Pythia 8.1	NNLO [74]
$VV/V\gamma^*$	Sherpa 2.2	NNPDF 3.0 NNLO	Sherpa 2.2	NLO
$t\bar{t}$	Powheg-Box v2 [76,61,62,63]	NNPDF 3.0 NLO	Pythia 8.2	NNLO+NNLL
Single t	Powheg-Box v2 [84,85,86,61,62,63]	NNPDF 3.0 NLO	Pythia 8.2	NNLO+NNLL



A/H → ττ



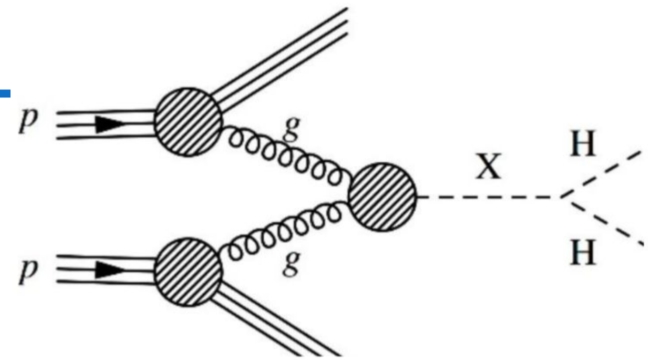
Source	ggF (400 GeV)	ggF (1 TeV)	bbH (400 GeV)	bbH (1 TeV)
Tau id. efficiency	0.14	0.16	0.12	0.08
Tau energy scale	0.33	0.09	0.22	0.03
Z+jets bkg. modeling	0.27	0.19	0.08	0.04
Mis-id. $\tau_{\text{had-vis}}$ bkg.	0.22	0.01	0.14	0.03
Others	0.09	0.04	0.11	0.02
Total	0.54	0.28	0.45	0.13

hh production

Can be done non-resonant (self coupling) or resonant

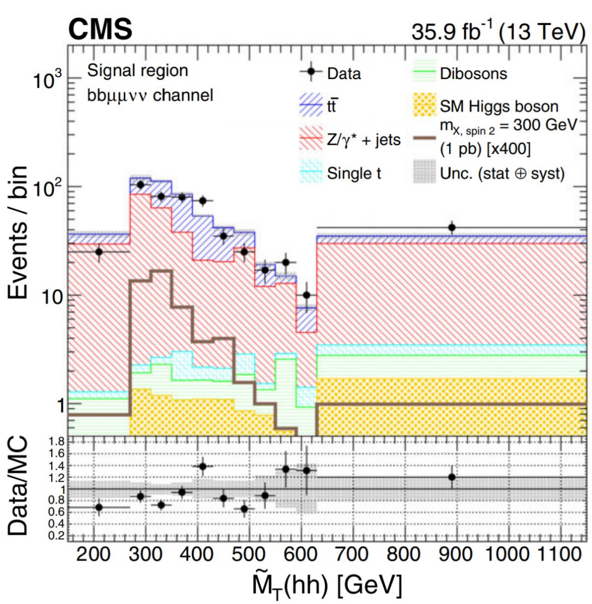
- The latter more relevant in these models

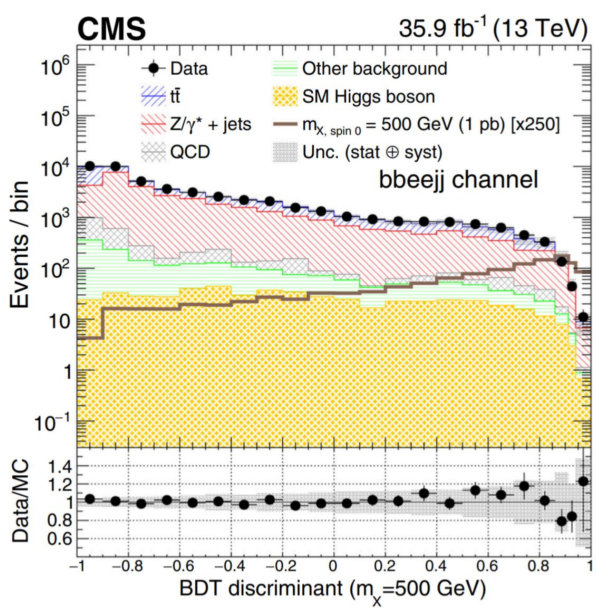
Strong compromise between statistics and purity

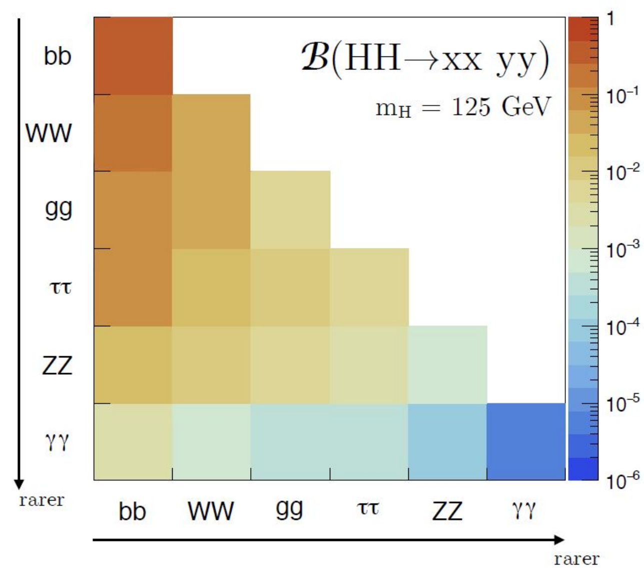


A case study: **hh → bbZZ** at CMS

- Z(ll) + Z($\nu\nu$/jj)
- Fit (pseudo)transverse mass in neutrino channel and BDT output in hadronic channel

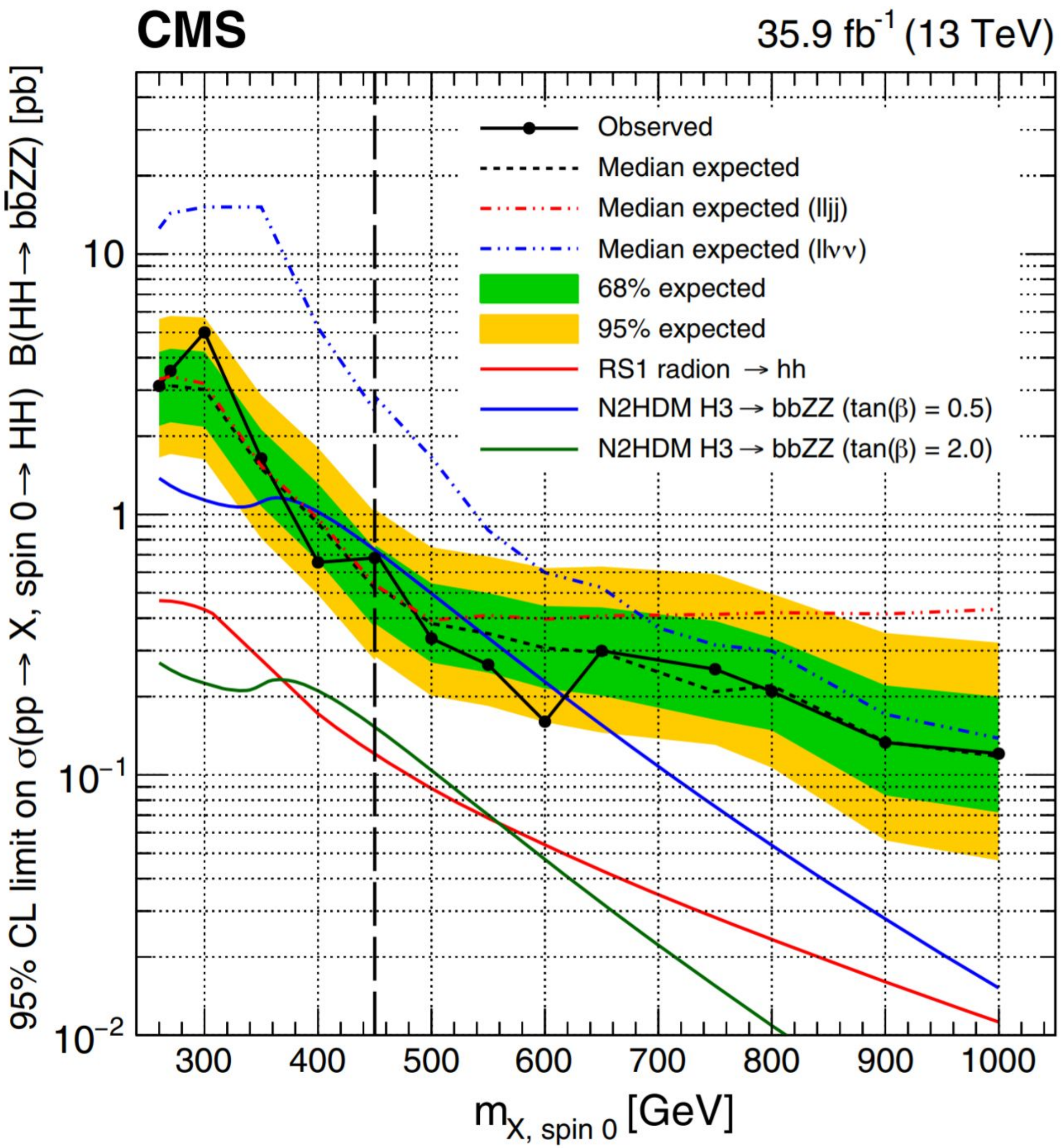






Phys. Rev. D 102 (2020) 032003

hh → bbZZ results

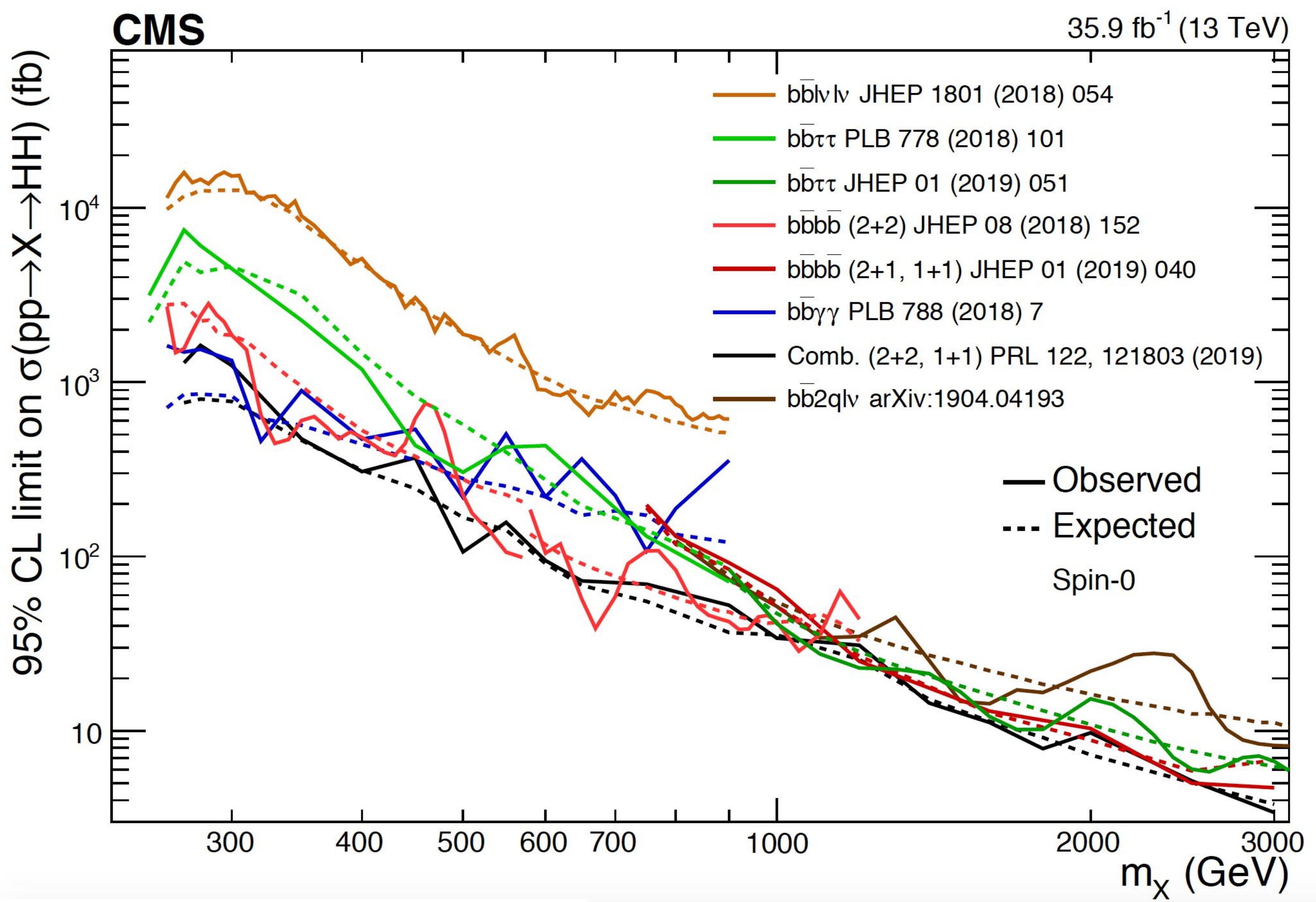


For tan□ = 0.5 exclude H → hh in 360-620 GeV range

Discontinuity at 450 because of different BDT setup for “high” mass

Also reinterpreted for spin-2 resonance for graviton searches

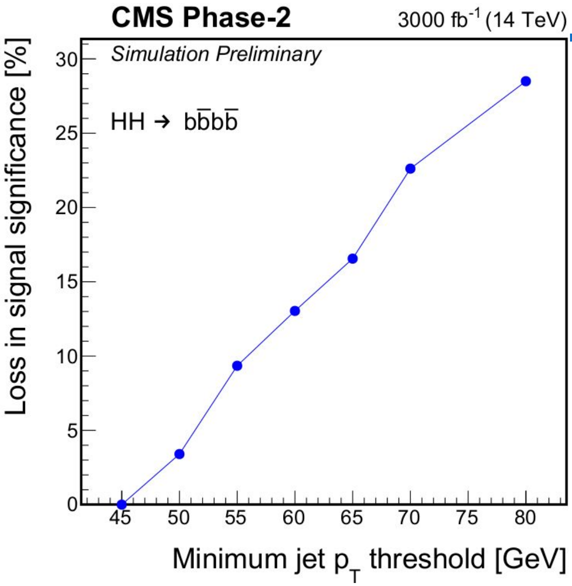
Intermezzo: hh combinations

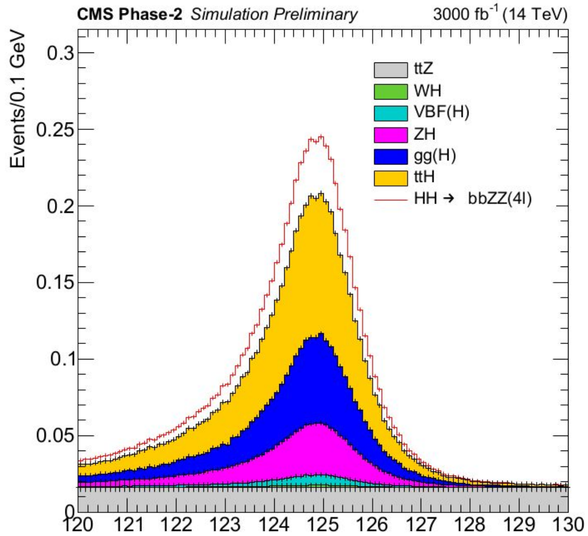


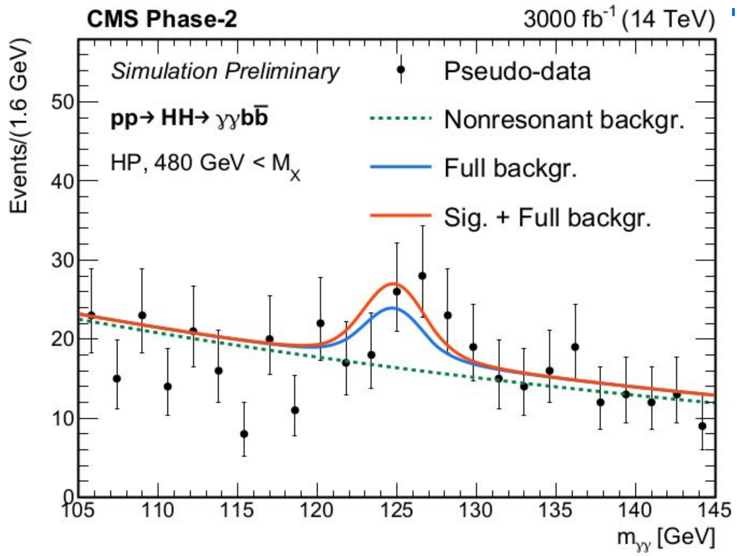
Phys. Rev. Lett. 122 (2019) 121803

hh at HL-LHC

CMS-FTR-18-019



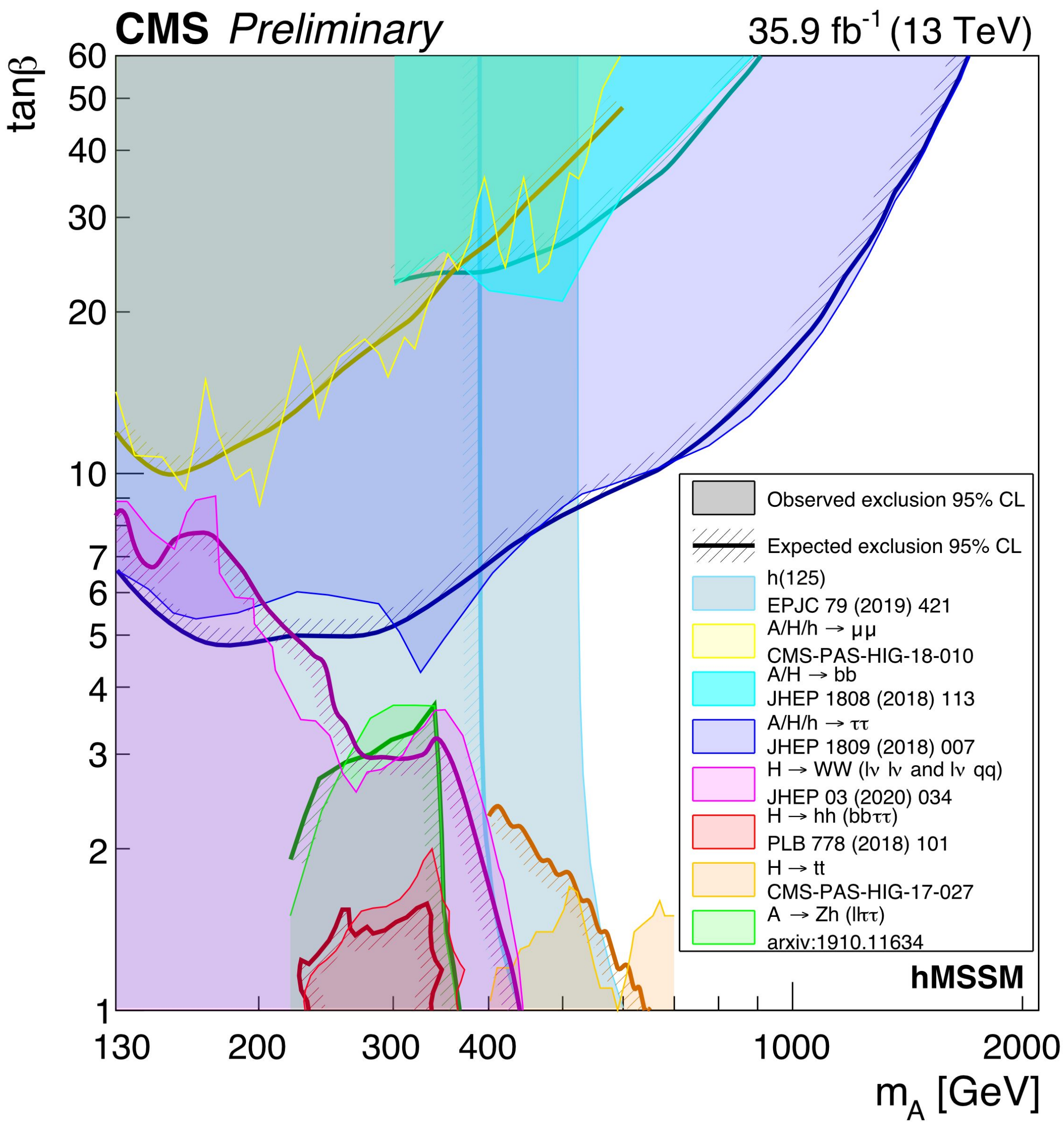




Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Combination shows LHC won't provide a complete picture on di-Higgs physics

Combining into hMSSM

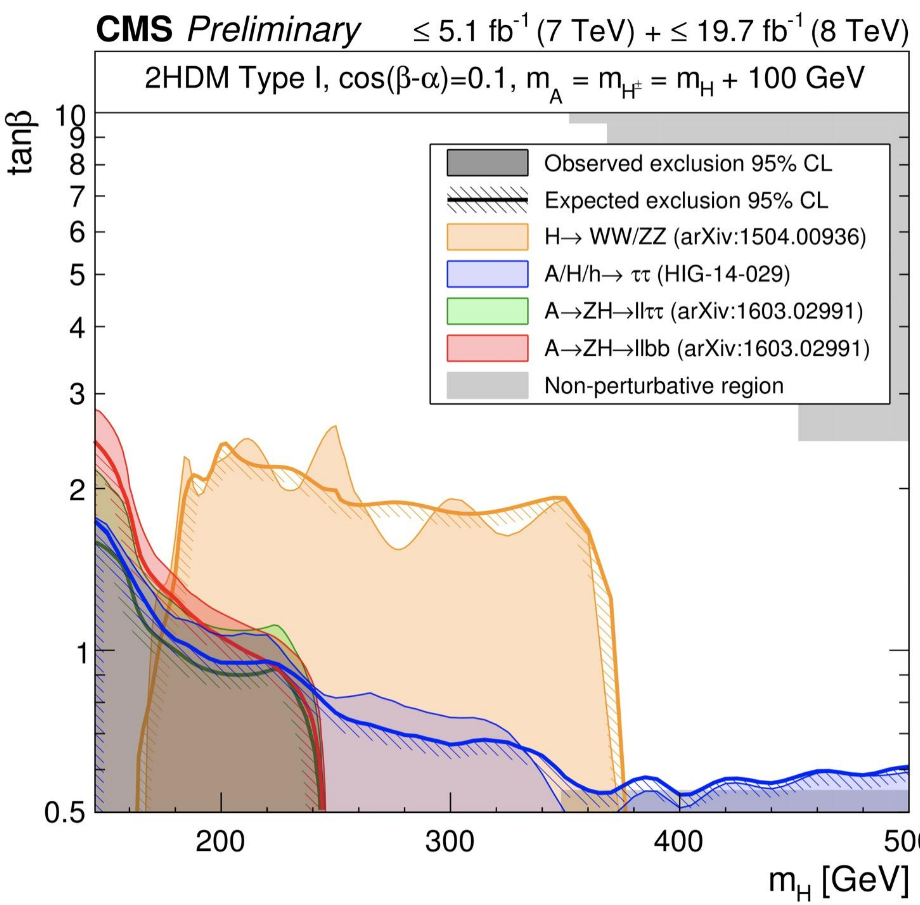


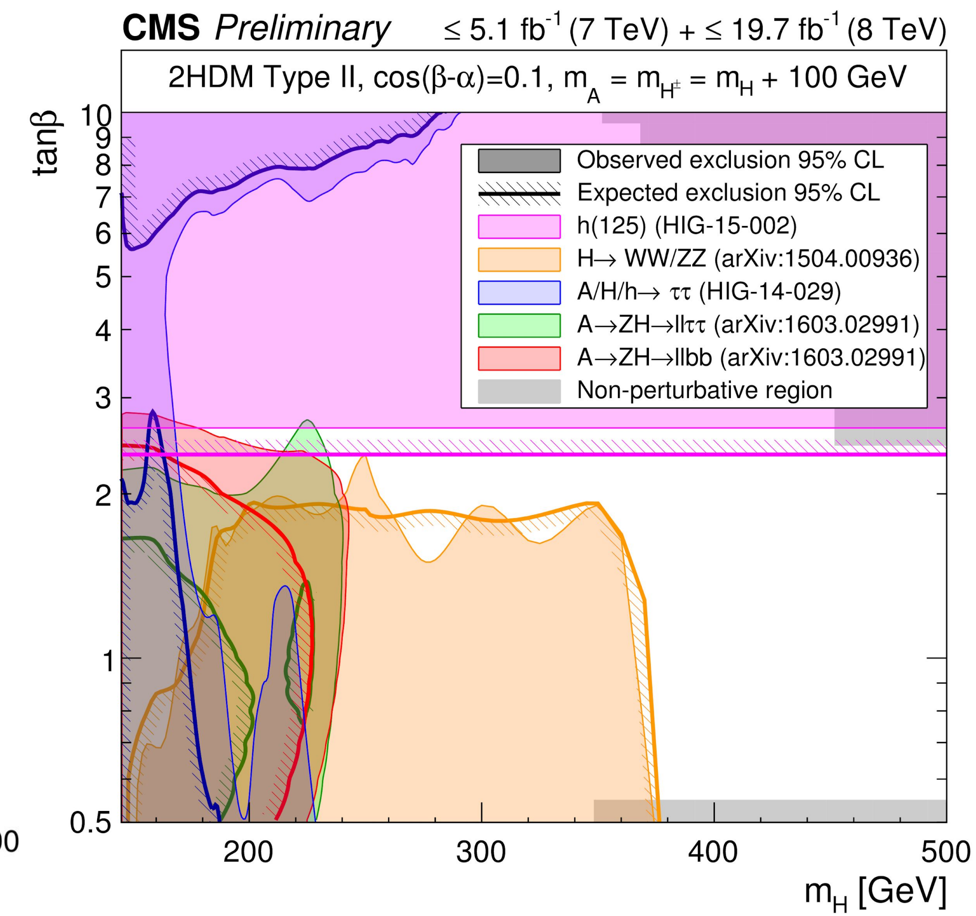
hMSSM:

- h_{125} interpreted as lower mass Higgs boson
- CP conserving Higgs sector
- Superpartners too heavy to contribute to production and decay

Strong limit provided by constraints from h_{125}

General 2HDM combination





Sensitivity strongly dependent on the choice parameters (and solution to ambiguities)

Still missing a full update to RunII of a generic 2HDM interpretation

2HDM + S

Common extension (see for example NMSSM)

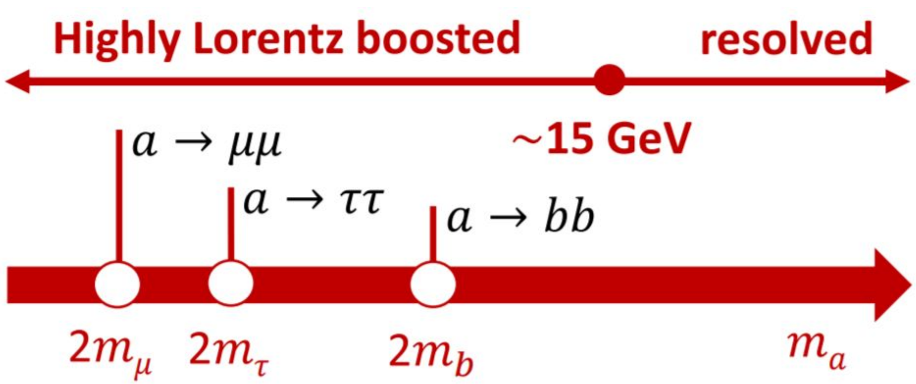
Helps solving the “μ-problem”

Add one singlet (2 d.o.f.)

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} \quad \phi' = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_5 + i\phi_6 \\ \phi_7 + i\phi_8\end{pmatrix} \quad +\phi_S$$

Typically searched in a “lower” mass boson in μμ/ττ/bb

- Of particular interest in **h → aa** decays



h/H → aa → μμττ

Search for collimated dilepton pairs

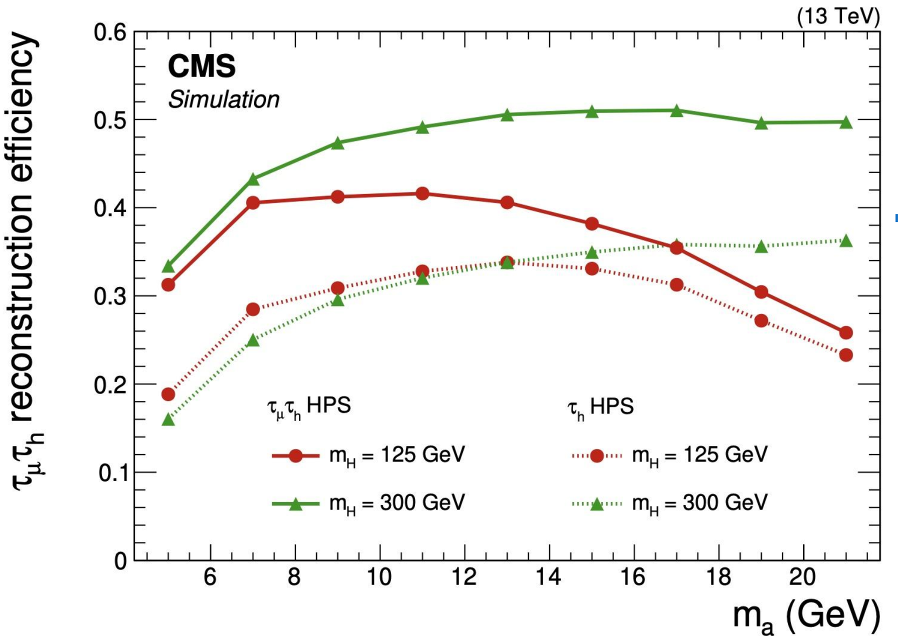
$3.6 < m_a < 21$ GeV

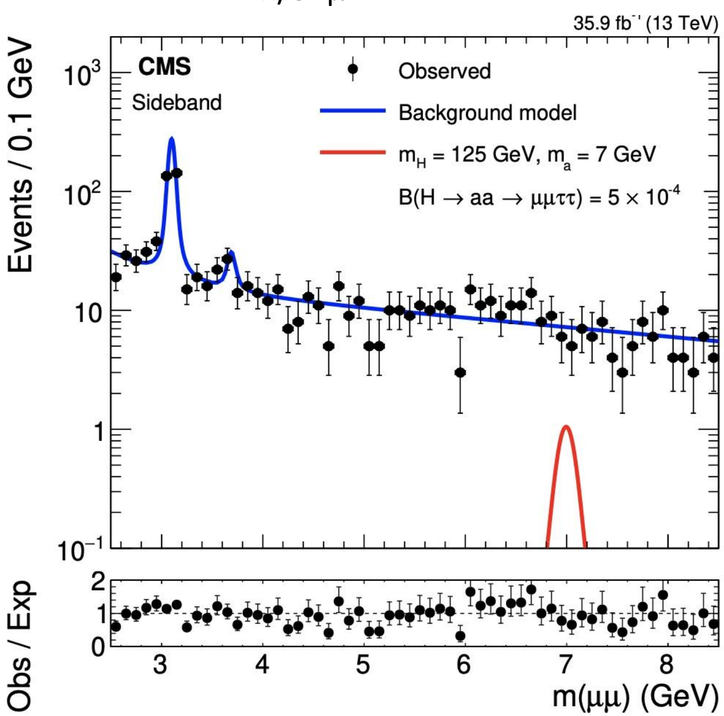
Require isolated μ trigger with $p_T > 24$ GeV

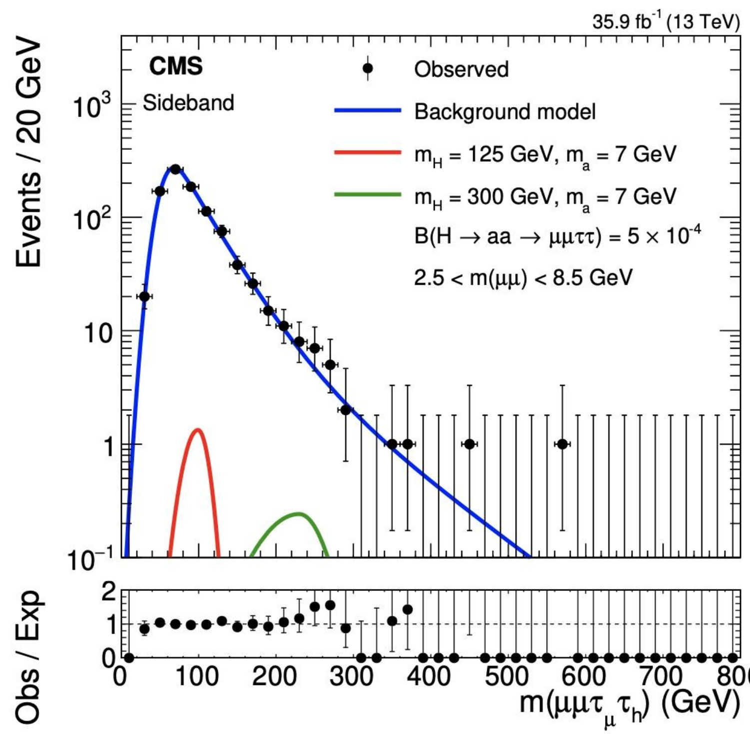
Custom τ-pair algo for collimated objects

→ allow for a non-isolated μ in one τ decay

Final state is $\mu\mu\tau_{h/e}\tau_\mu$







h/H → aa → μμττ

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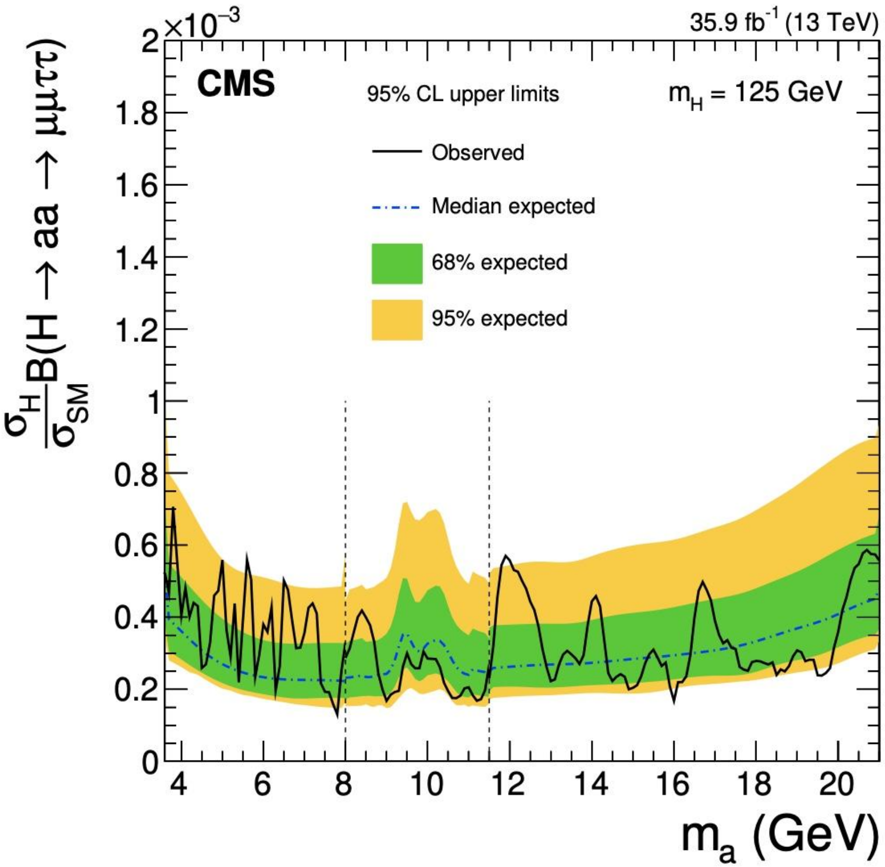
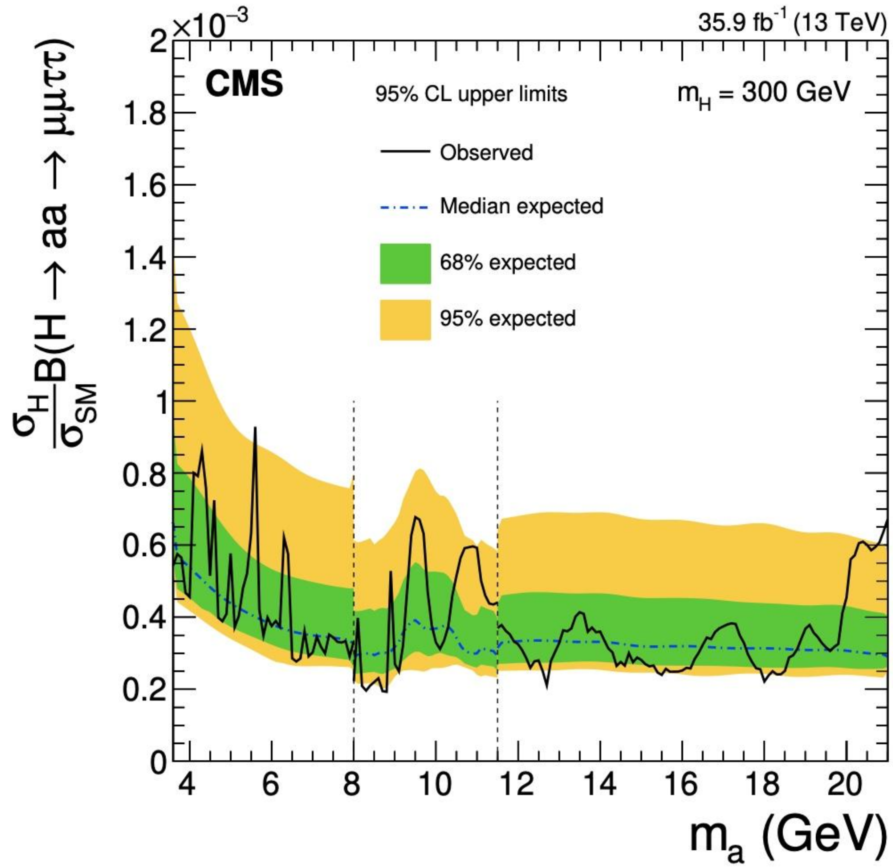
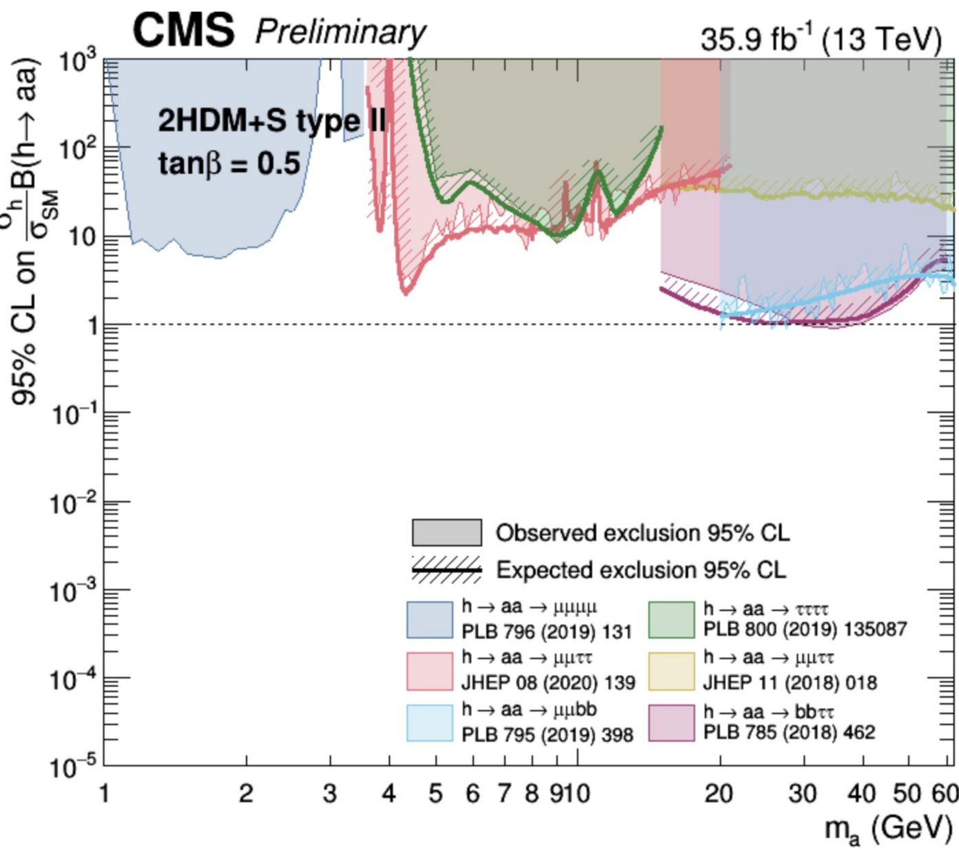
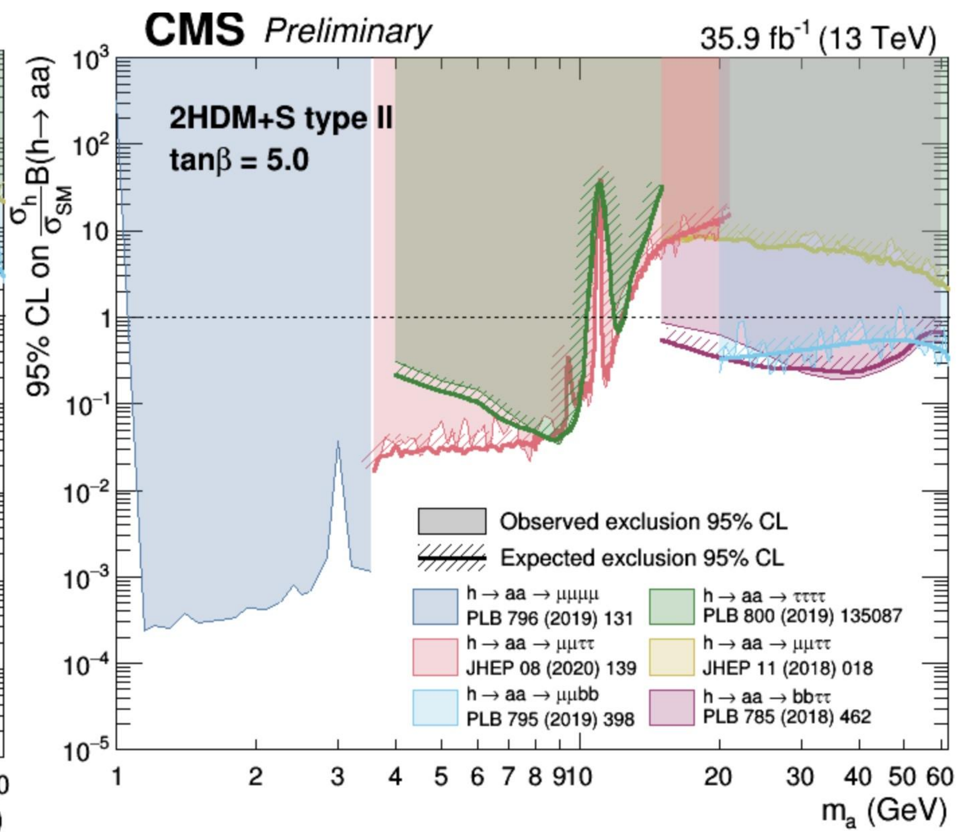




2HDM+S h⟶ aa combination





Strong dependence on tan□ and sign choice for couplings
All topologies necessary to fully investigate the spectrum
Most are statistically limited

LFV in Higgs decays

LFV strongly suppressed in SM

In Higgs decays, mediated by Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$

Scenarios include

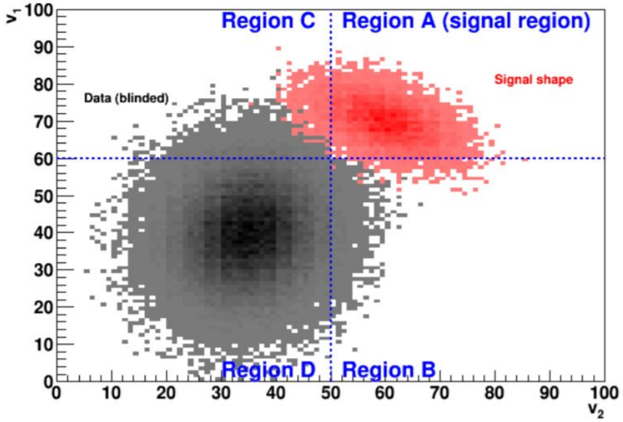
- Higgs multiplets
- SUSY
- composite Higgs
- RS extra dimensions
- ...

$H \rightarrow \mu e$ strongly constrained by indirect measurements

❖ concentrate on $H \rightarrow \mu\tau$ and $e\tau$

$H \to e\tau, \mu\tau$

CMS-PAS-HIG-20-009



Four final states: $\ell\tau_h$, $\ell\tau_{\ell'}$

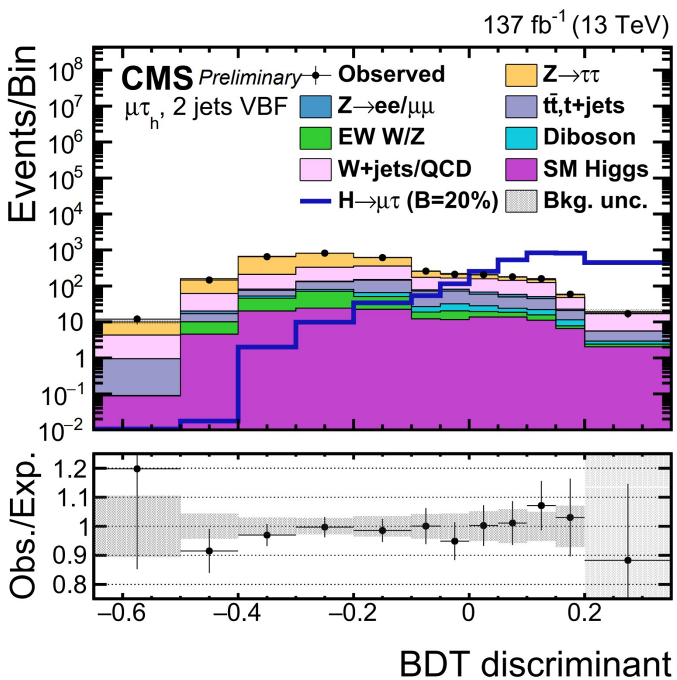
- Limit DY Z->$\ell\ell$ contributions

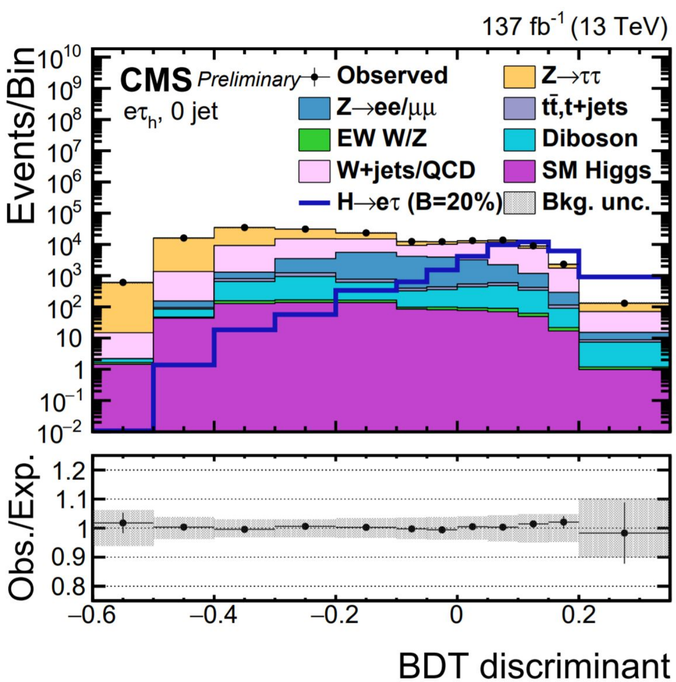
Samples characterized with BDT that is fitted to extract BR

- Binned in number of jets

Backgrounds: Z/H→ττ , Z→$\ell\ell$, H→ WW, mis-ID background

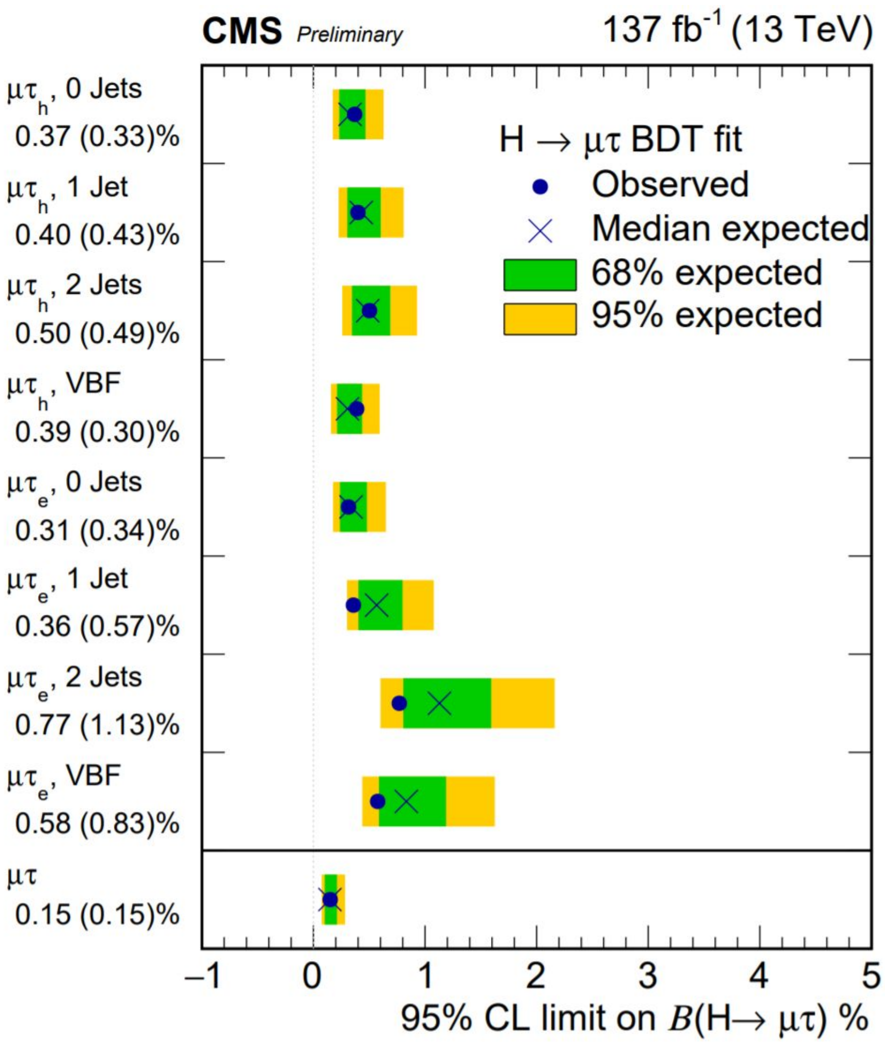
Use of embedded and ABCD methods for background estimate

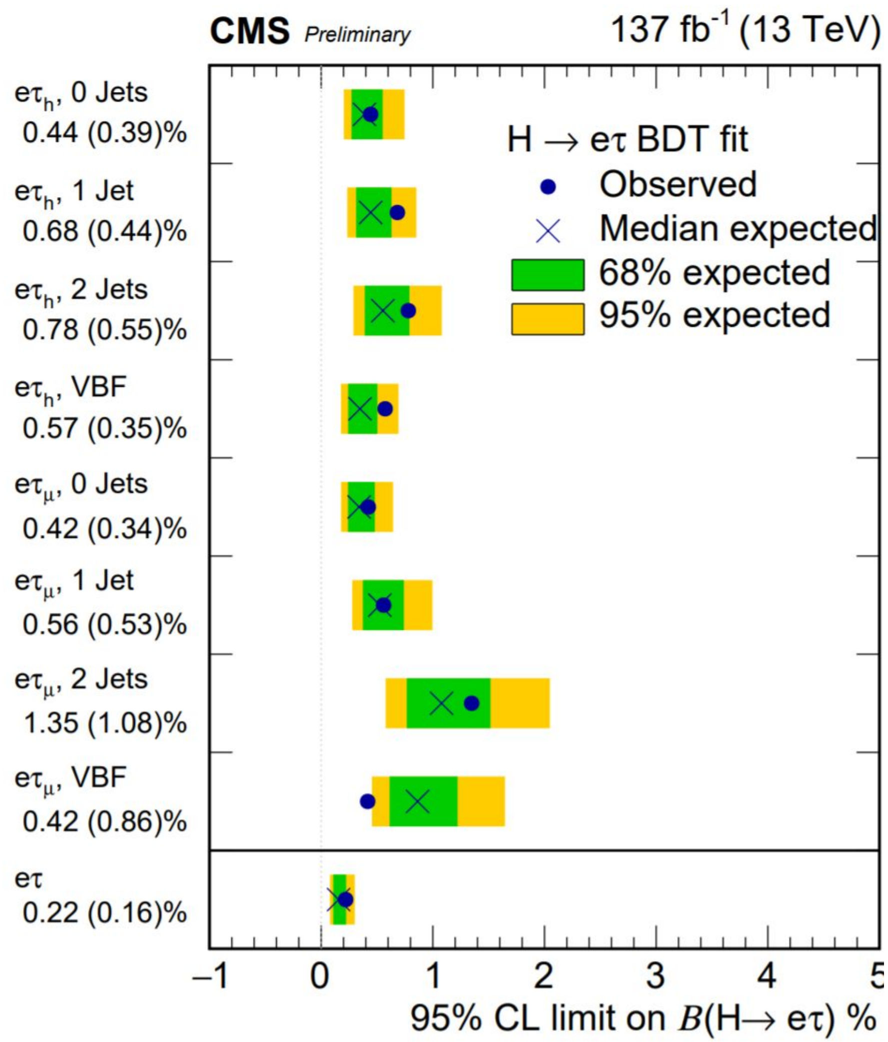




$H \to e\tau, \mu\tau$

CMS-PAS-HIG-20-009





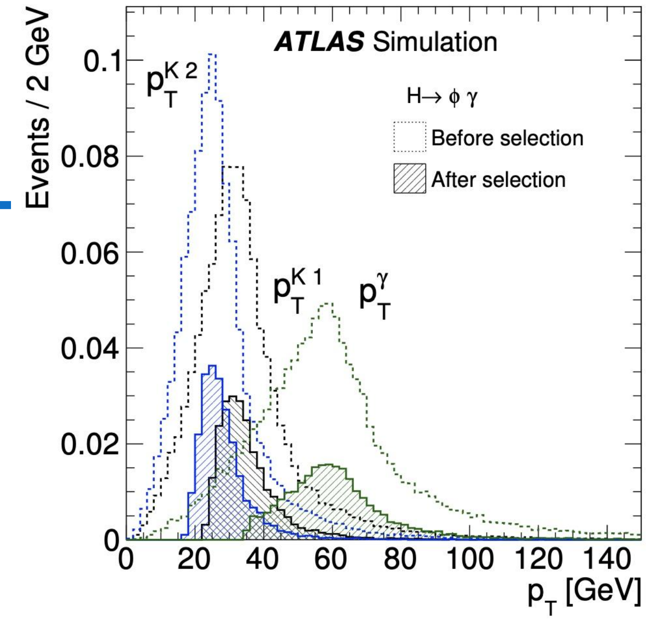
H → ϕ/ρ + γ

Coupling to first and second generations (and up-type quarks) for Higgs multiplets test

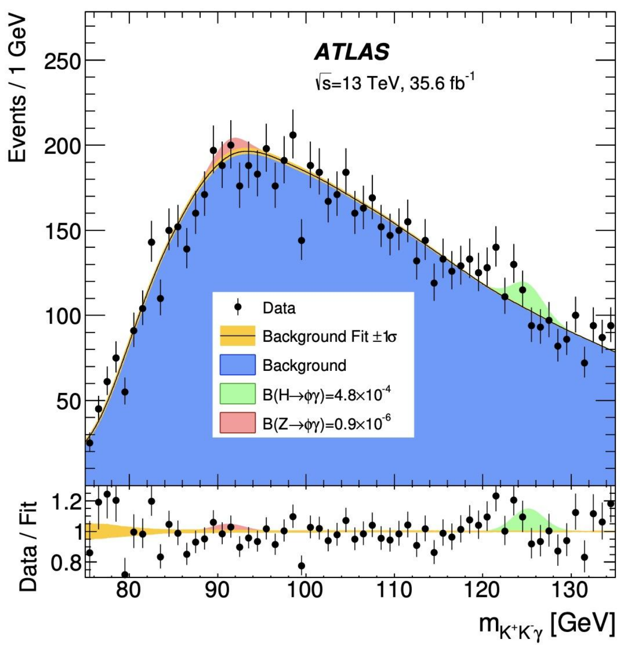
- Greatly suppressed in SM

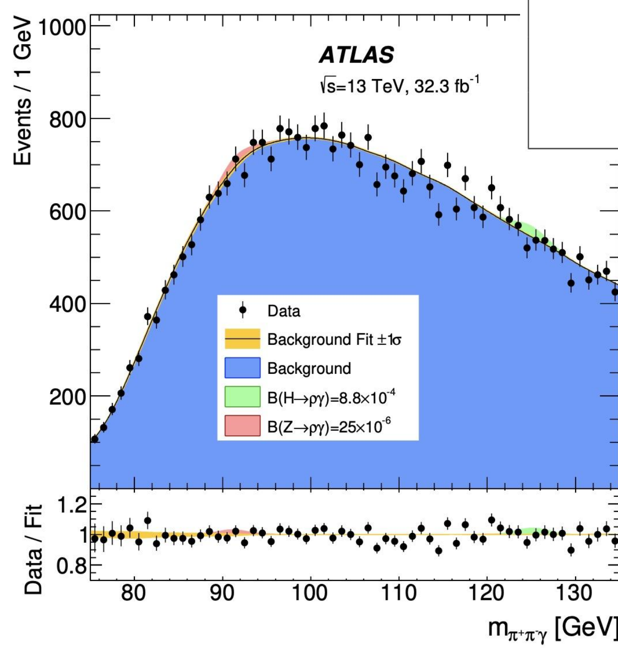
Experimental difficulty in trigger at LHC

- ATLAS: use photon + modified τ trigger



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25





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Considerations on future colliders

- Studies emerging to provide more complete view on Higgs perspectives in future colliders
- Fundamental step into decision making process for next generation accelerators
- Many scenarios, difficult to summarize all considerations, but...

Expected relative precision

kappa-0	HL-LHC	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$	FCC-ee/eh/hh
κ_W (%)	1.9	0.75	1.0	1.8	0.29	0.86	0.17	0.11	1.3	1.3	0.43	0.15
κ_Z (%)	1.6	1.2	0.95	0.29	0.23	0.5	0.26	0.23	0.13	0.2	0.17	0.12
κ_g (%)	2.4	3.6	1.5	2.3	0.97	2.5	1.3	0.9	1.5	1.7	1.0	0.52
κ_γ (%)	1.9	7.5	1.2	6.7	3.4	98⋆	5.0	2.2	3.7	4.7	3.9	0.35
$\kappa_{Z\gamma}$ (%)	10.6	–	4.0	99⋆	86⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.7
κ_c (%)	–	4.0	–	2.5	1.3	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t (%)	2.8	–	2.1	–	6.9	–	–	2.6	–	–	–	1.0
κ_b (%)	3.5	2.1	2.3	1.8	0.58	1.9	0.48	0.38	1.2	1.3	0.67	0.45
κ_μ (%)	4.6	–	1.9	15	9.4	320⋆	13	5.8	8.9	10	8.9	0.42
κ_τ (%)	1.8	3.3	1.3	1.9	0.7	3.0	1.3	0.89	1.3	1.4	0.73	0.49

Di-Higgs: cubic self-coupling

collider	(1) di-H excl.
HL-LHC	$^{+60}_{-50}$% (50%)
HE-LHC	10-20% (n.a.)
ILC_{250}	–
ILC_{350}	–
ILC_{500}	27% (27%)
$CLIC_{380}$	–
$CLIC_{1500}$	36% (36%)
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)
$FCC\text{-}ee_{240}$	–
$FCC\text{-}ee_{365}$	–
FCC-ee/eh/hh	5% (5%)
CEPC	–

Upper bounds from rarer decays

	HL-LHC	+LHeC	+HE-LHC	$+ILC_{500}$	$+CLIC_{3000}$	+CEPC	$+FCC\text{-}ee_{240}$	+FCC-ee/eh/hh
κ_u	570.	320.	420.	330.	430.	290.	310.	280.
κ_d	270.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.4	7.5	9.9	6.6	7.	6.4
κ_c	1.2		0.87	measured directly				

from arXiv:1905.03764

Wrap-up

- Since the discovery, the Higgs boson has been observed in several final states
- Precision on its observables ~ 10-20% in many cases
  - This will go down to a few % at the end of LHC
- Not many tensions, in general pretty much compatible with SM expectations

- Search for new physics can be done with precision measurements or exotic final states
- A large phenomenology available for searches at LHC
- Sometimes provide interest push on our experimental techniques
- Need of common benchmarks

Testing the SM: top, W, Z physics

SM: what we measure

Can generally be divided into two categories:

Processes

- Single boson
- Multiboson
- Vector boson scattering
- Multijet
- Double parton scattering

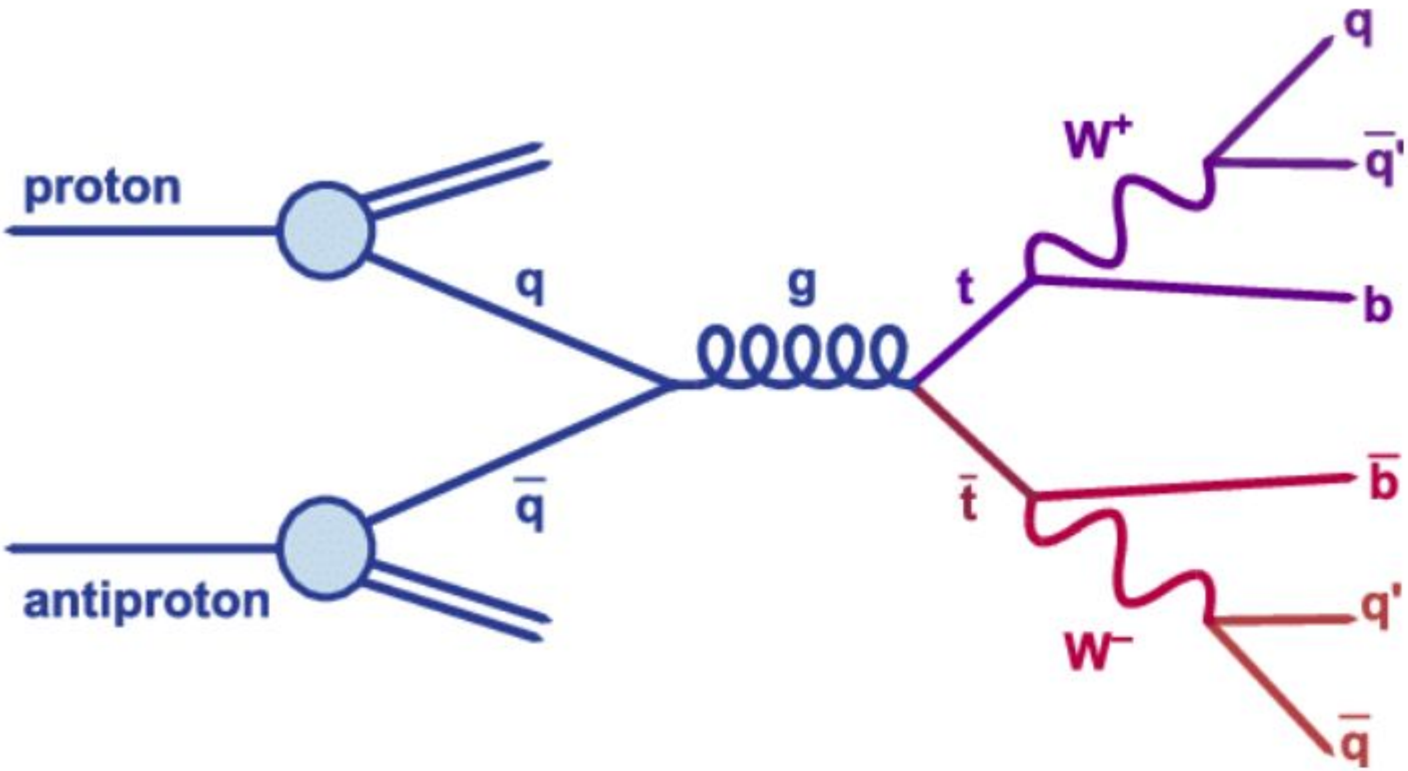
Observables

- Inclusive cross sections
- Differential cross sections
- Rare decays
- Parameters (mass, widths, etc.)
- Anomalous couplings

Many of these are limited by theoretical knowledge (generators!)

Top

top at LHC 101



Reminder: top decays before the typical hadronization phase
Decay modes: leptonic, semileptonic, hadronic

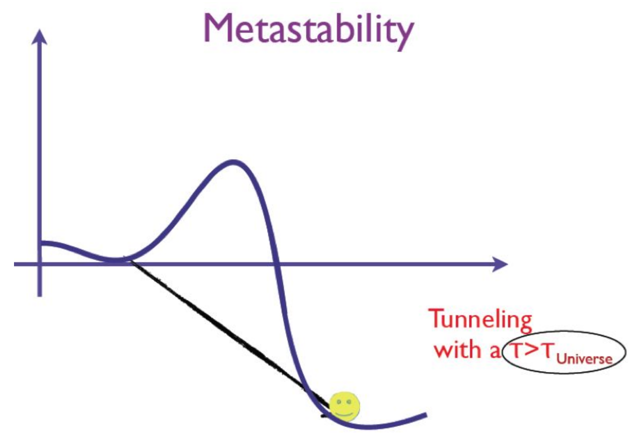
Importance of masses: an example

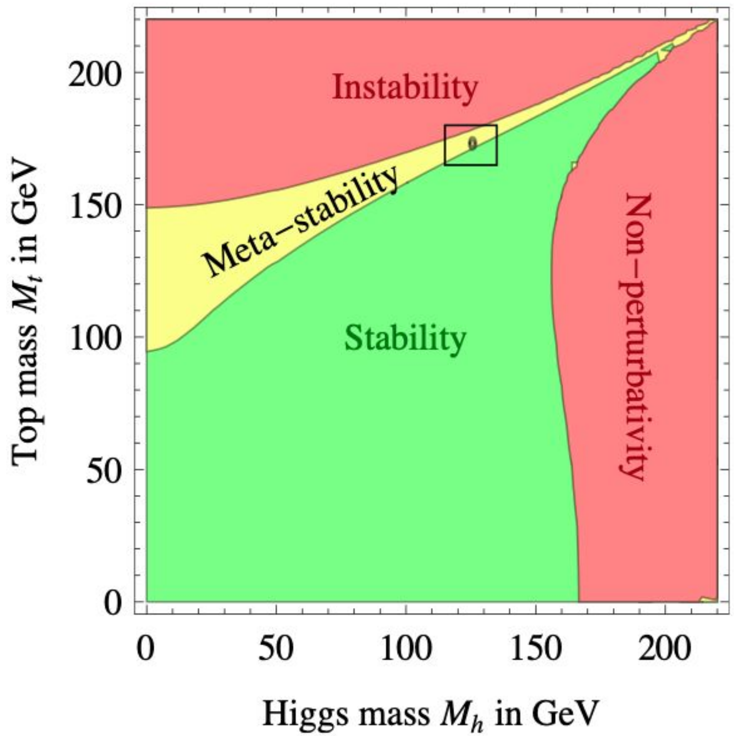
Higgs potential might be in a local minimum

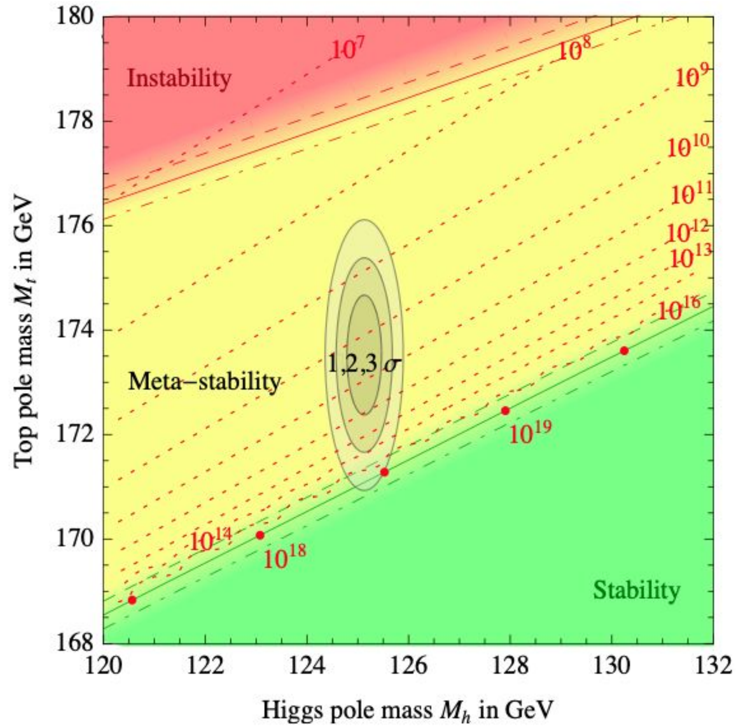
Three hypotheses for vacuum stability:

- Unstable, metastable, stable
- Lifetime very long (at least order of life of universe)

Strongly determined by SM parameters: m_t and m_H







Top cross section and mass

At LHC, main production of top is in tt pairs

Importance of cross section:

- Directly compare inclusive cross section to theory predictions (up to NNLO+NNLO QCD, with 5% precision)
- Differential cross sections for predictions and MC generators tuning
- Can extract other parameters (mass, α_s, etc)

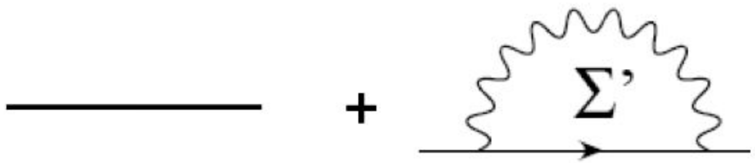
Mass measurements:

- Direct, from decay products (very dependent on MC)
- Indirect, from other observables (mainly cross section)

Top quark is quite unique: heaviest fundamental particle with color charge!

m_t: problems with definition

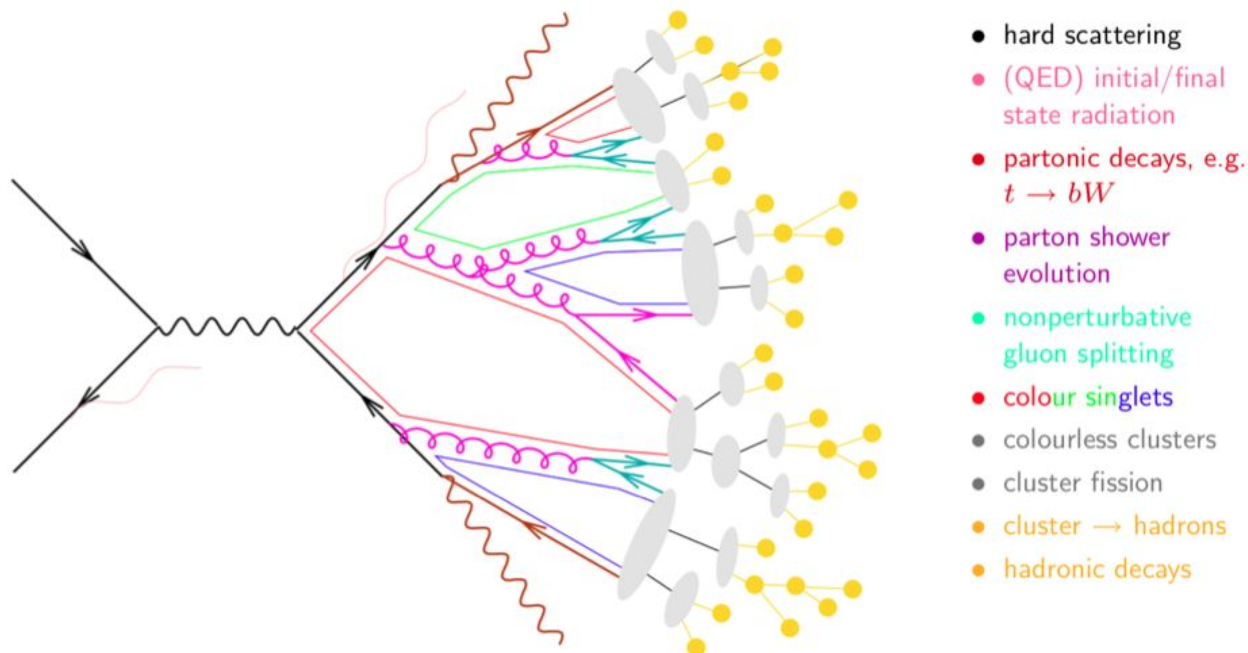
m_t relation to observables difficult to define



Two main approaches:

- $\overline{\text{MS}}$ scheme $m^0 = \overline{m}(\mu)\left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots\right]$
  - Running mass
  - Applies better for μ > m
  - Very different from kinematic mass
- Pole scheme $m^0 = m^{\mathrm{pole}}\left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots\right] - \Sigma^{\mathrm{fin}}(m^{\mathrm{pole}}, m^{\mathrm{pole}}, \mu)$
  - Mass at the pole of the renormalized propagator
  - Closer to a kinematic mass definition
  - Limited precision O(GeV)

MC generators



Challenges:

- Matrix elements
- Parton shower
- Hadronization

General considerations:

- QCD modelization partly first principles partly effective models
- Data often have better accuracy
- Different treatment of m_t in matrix elements and parton showers

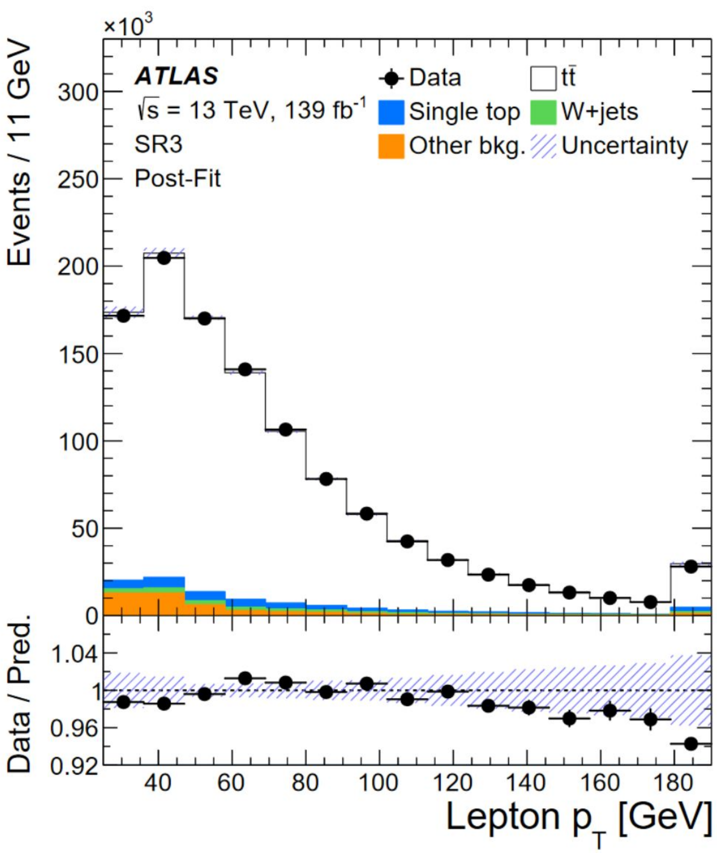
Inclusive σ_{tt} at 13 TeV

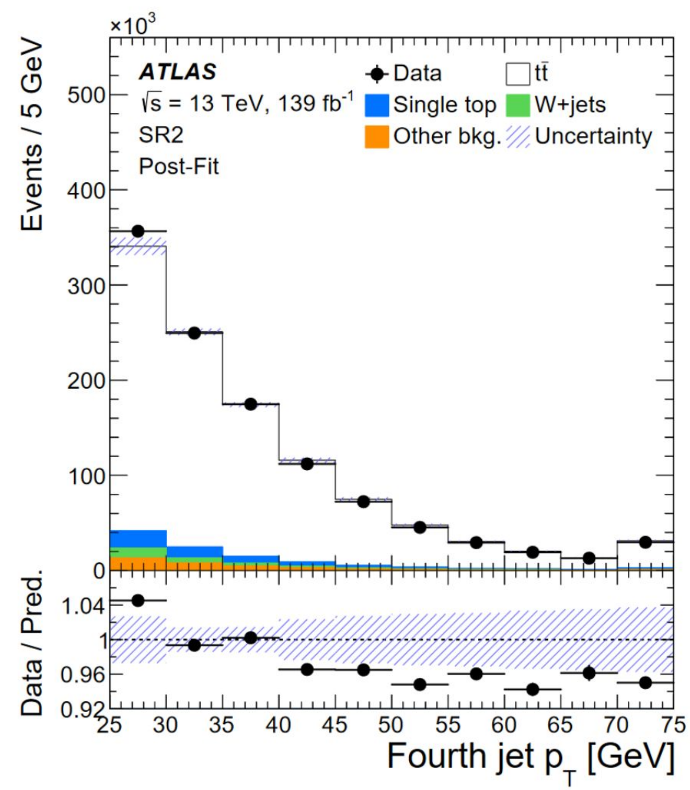
PLB 810 (2020) 135797

lepton+jet channel

- e/μ with p_T > 25/27/28 GeV for 2016/17/18
- 4 jets, one or two b-tagged
- $E_{T,miss}$ > 30 GeV and $m_T(W)$ > 30 GeV
- Split in different signal regions in number of (b-)jets

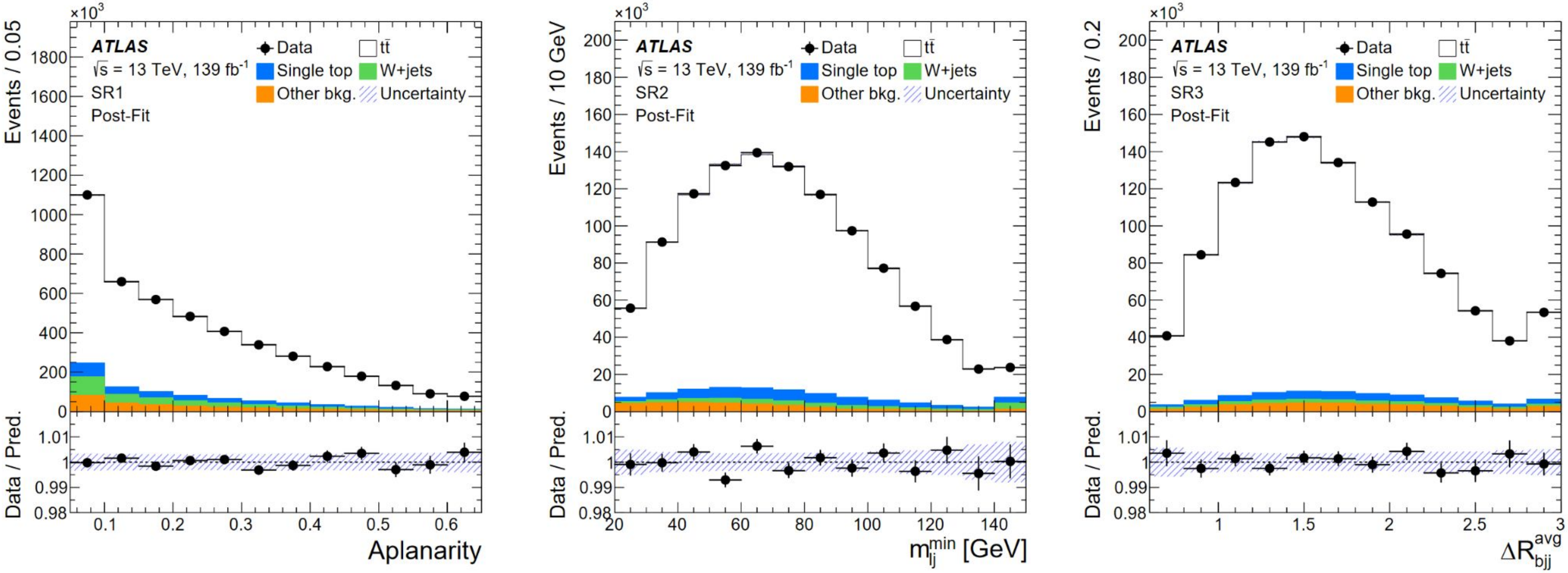
	>3j 1 b	=4j 2 b	>4j 2 b
	SR1	SR2	SR3
$t\bar{t}$	3 630 000 ± 210 000	990 000 ± 90 000	980 000 ± 100 000
W+jets	350 000 ± 160 000	24 000 ± 10 000	17 000 ± 9000
Single top	255 000 ± 31 000	52 000 ± 7000	37 000 ± 8000
Z+jets & diboson	80 000 ± 40 000	8000 ± 4000	5800 ± 3000
$t\bar{t}X$	15 600 ± 2100	2110 ± 290	7200 ± 1000
Multijet	210 000 ± 80 000	28 000 ± 10 000	22 000 ± 8000
Total prediction	4 540 000 ± 310 000	1 110 000 ± 100 000	1 070 000 ± 100 000
Data	4 540 886	1 100 558	1 103 317





Inclusive σ_{tt} at 13 TeV

PLB 810 (2020) 135797

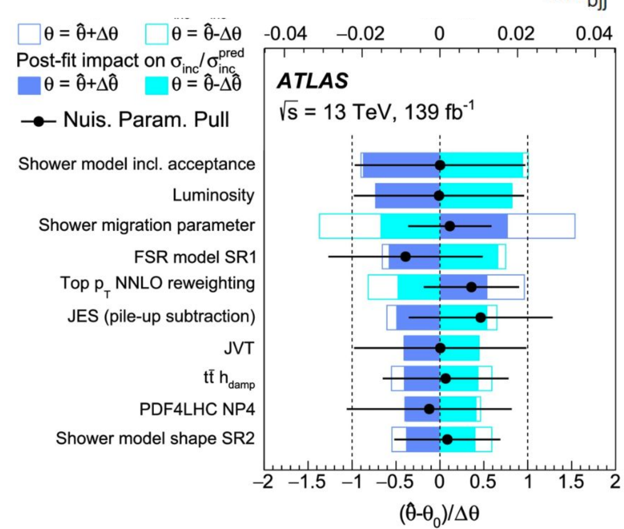


Total uncertainty below 5%, in good agreement with

NNLO and NNLL calculations

3D fit of angular and kinematic distributions

$$\sigma_{\text{inc}} = 830 \pm 0.4\,(\text{stat.}) \pm 36\,(\text{syst.}) \pm 14\,(\text{lumi.})\text{ pb}$$



σ_{tt} in lepton channel and m_t

Use leptonic W decays and count b-tagged jets

Only e-μ final state to reduce Z backgrounds

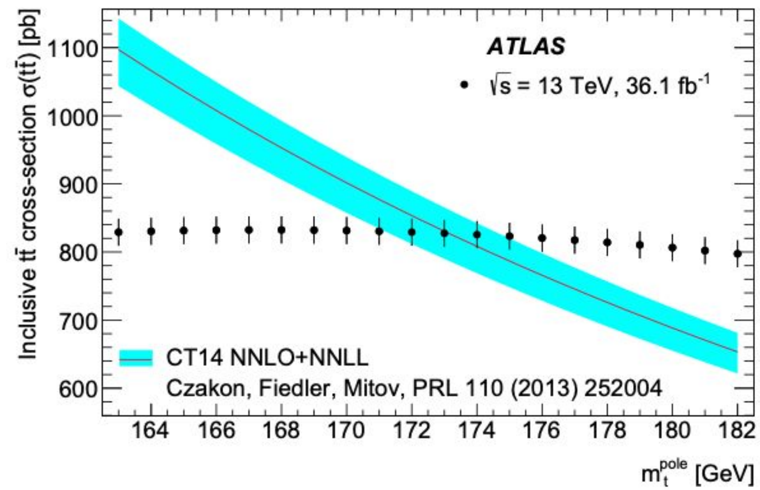
Inclusive:

- Most precise measurement of σ_{tt}

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\mathrm{stat}) \ \pm 11.5\,(\mathrm{syst}) \ \pm 15.7\,(\mathrm{lumi}) \ \pm 1.9\,(\mathrm{beam})\,\mathrm{pb}$$

- $m_{t,pole}$ limited by theory

EPJC 80 (2020) 528

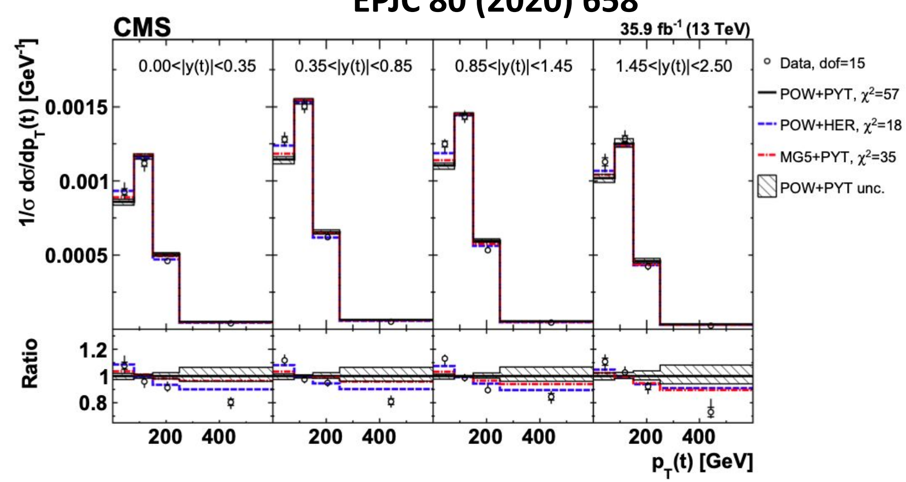


Differential (triple in M_{tt}, y and N_{jet})

- M_{tt} from kinematic fit with mass constraints on Ws and ts
- Simultaneous measurement of m_t and α_s
- Most precise determination $m_{t,pole}$

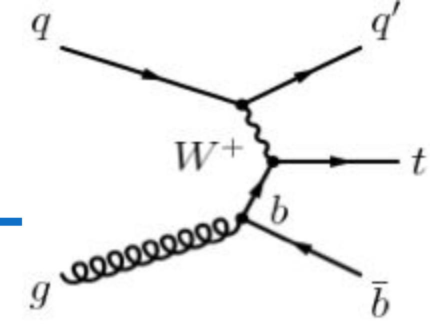
$$m_t^{\mathrm{pole}} = 170.5 \pm 0.7\,(\mathrm{fit}) \pm 0.1\,(\mathrm{model})^{+0.0}_{-0.1}\,(\mathrm{param}) \pm 0.3\,(\mathrm{scale})\,\mathrm{GeV}$$

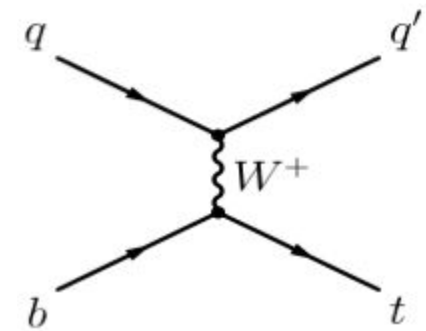
EPJC 80 (2020) 658



Single top production

CMS-PAS-TOP-19-009





Different sample from tt measurements → combination

Search for a charged lepton, missing energy, a b-jet and a light jet

Additional b-jet from gluon splitting undetected

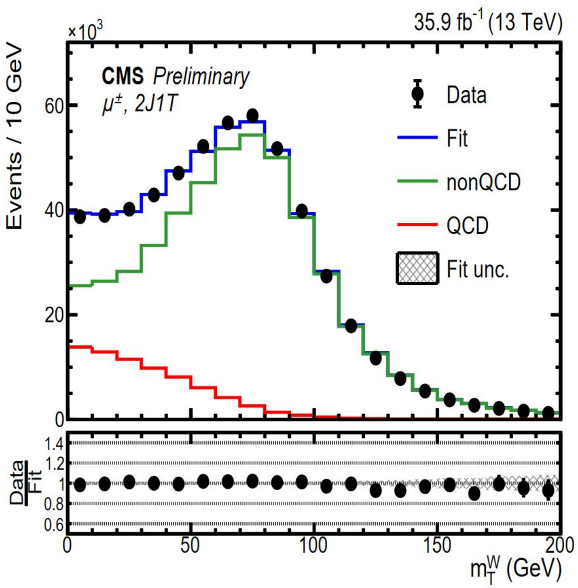
Use of W transverse mass for background rejection

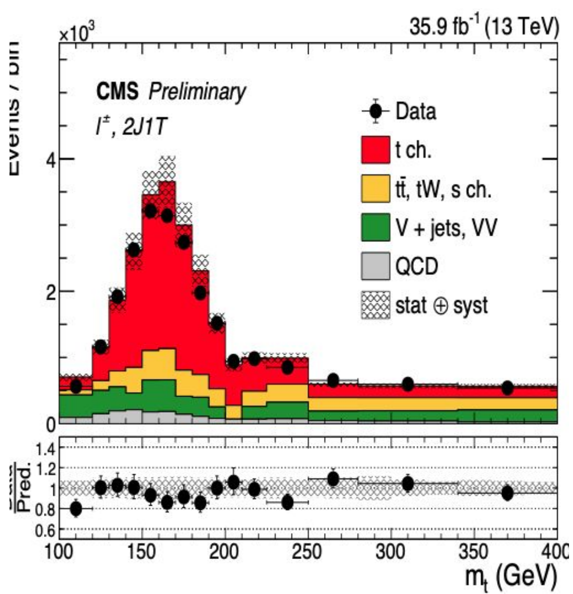
$$m_{\mathrm{T}}^{\mathrm{W}} = \sqrt{(p_{\mathrm{T},\ell} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_{\mathrm{x},\ell} + p_{\mathrm{x}}^{\mathrm{miss}})^2 - (p_{\mathrm{y},\ell} + p_{\mathrm{y}}^{\mathrm{miss}})^2}$$

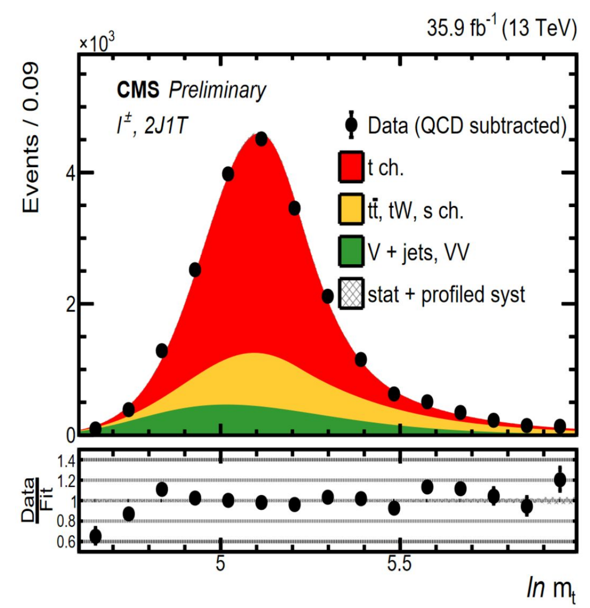
Mass determined from fit to spectrum

$$m_{\mathrm{t}} = 172.13 \pm 0.32\,(\mathrm{stat+prof})\,{}^{+0.69}_{-0.70}\,(\mathrm{syst})\ \mathrm{GeV} = 172.13^{+0.76}_{-0.77}\ \mathrm{GeV}$$

Fit on $\ln(m_t)$



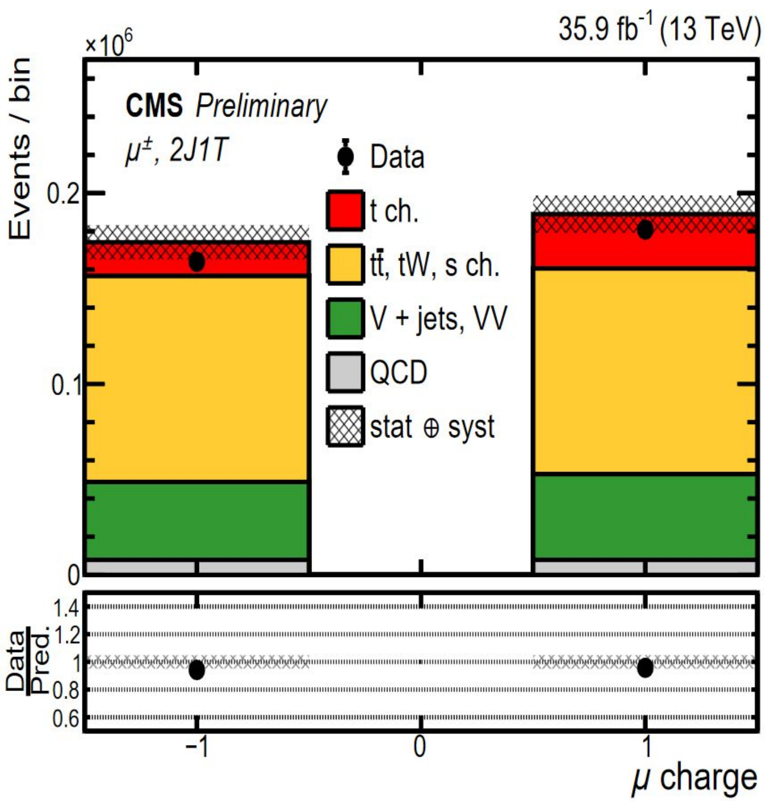


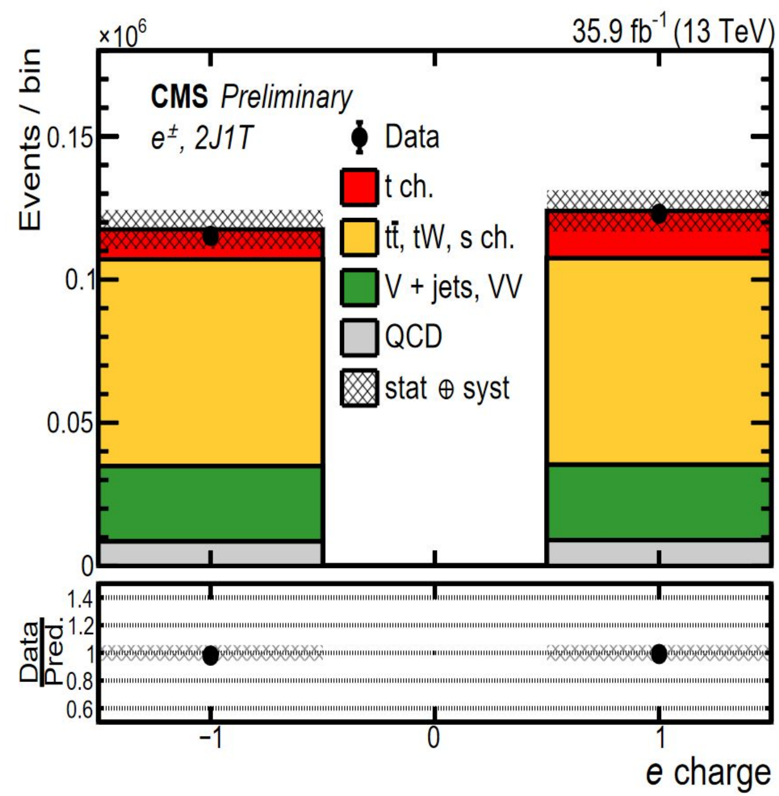


Single top production

CMS-PAS-TOP-19-009

Use lepton charge to separate t and tbar contributions to test CPT symmetry





$$\mathrm{R}_{m_\mathrm{t}} = \frac{m_{\bar{\mathrm{t}}}}{m_\mathrm{t}} = 0.995 \pm 0.004\,(\mathrm{stat}+\mathrm{prof})\,^{+0.002}_{-0.004}\,(\mathrm{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_\mathrm{t} = m_\mathrm{t} - m_{\bar{\mathrm{t}}} = 0.83 \pm 0.69\,(\mathrm{stat}+\mathrm{prof})\,^{+0.35}_{-0.74}\,(\mathrm{syst})\ \mathrm{GeV} = 0.83^{+0.77}_{-1.01}\ \mathrm{GeV}.$$

Running m_t

MS scheme approach: mass depends on the scale μ_m

Measure differential tt cross section in dilepton channel

as a function of M_{tt}

Running determined using NLO predictions

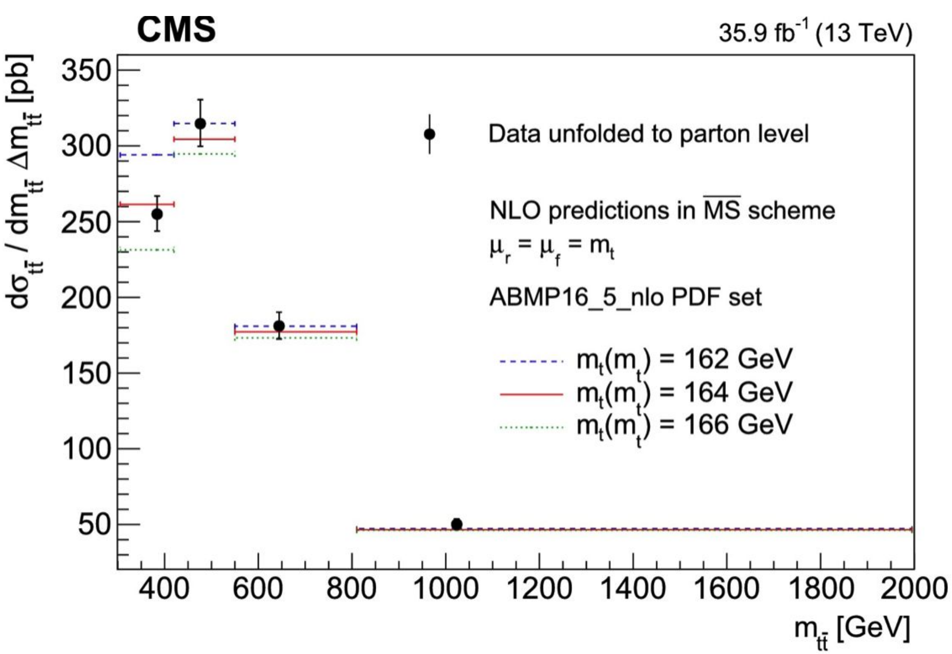
Exclude no-running scenario at 95% CL

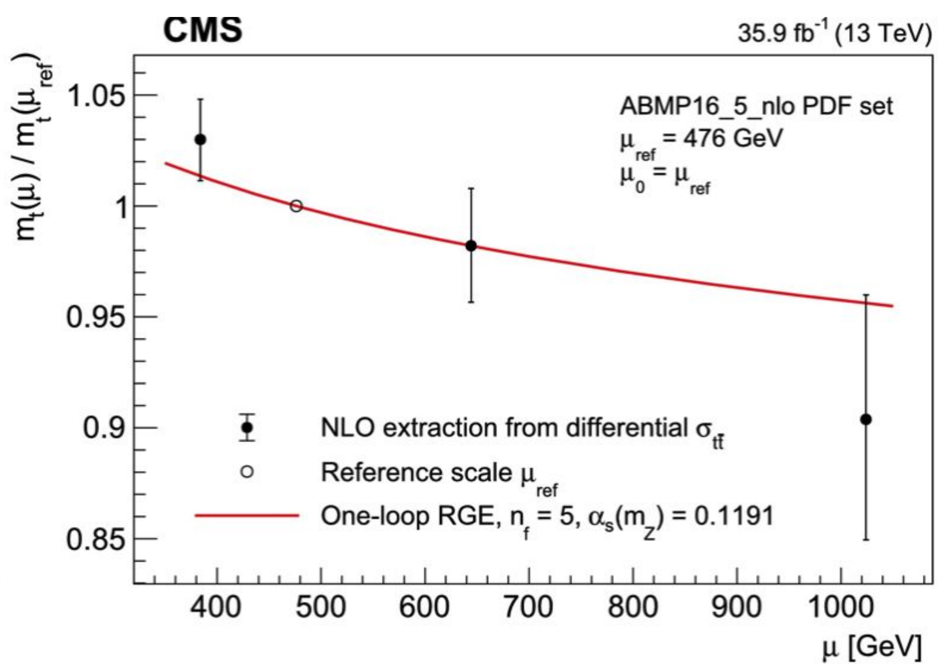
Solve the Renormalization Group Equation

$$\mu^2 \frac{\mathrm{d}m(\mu)}{\mathrm{d}\mu^2} = -\gamma(\alpha_S(\mu))\, m(\mu)$$

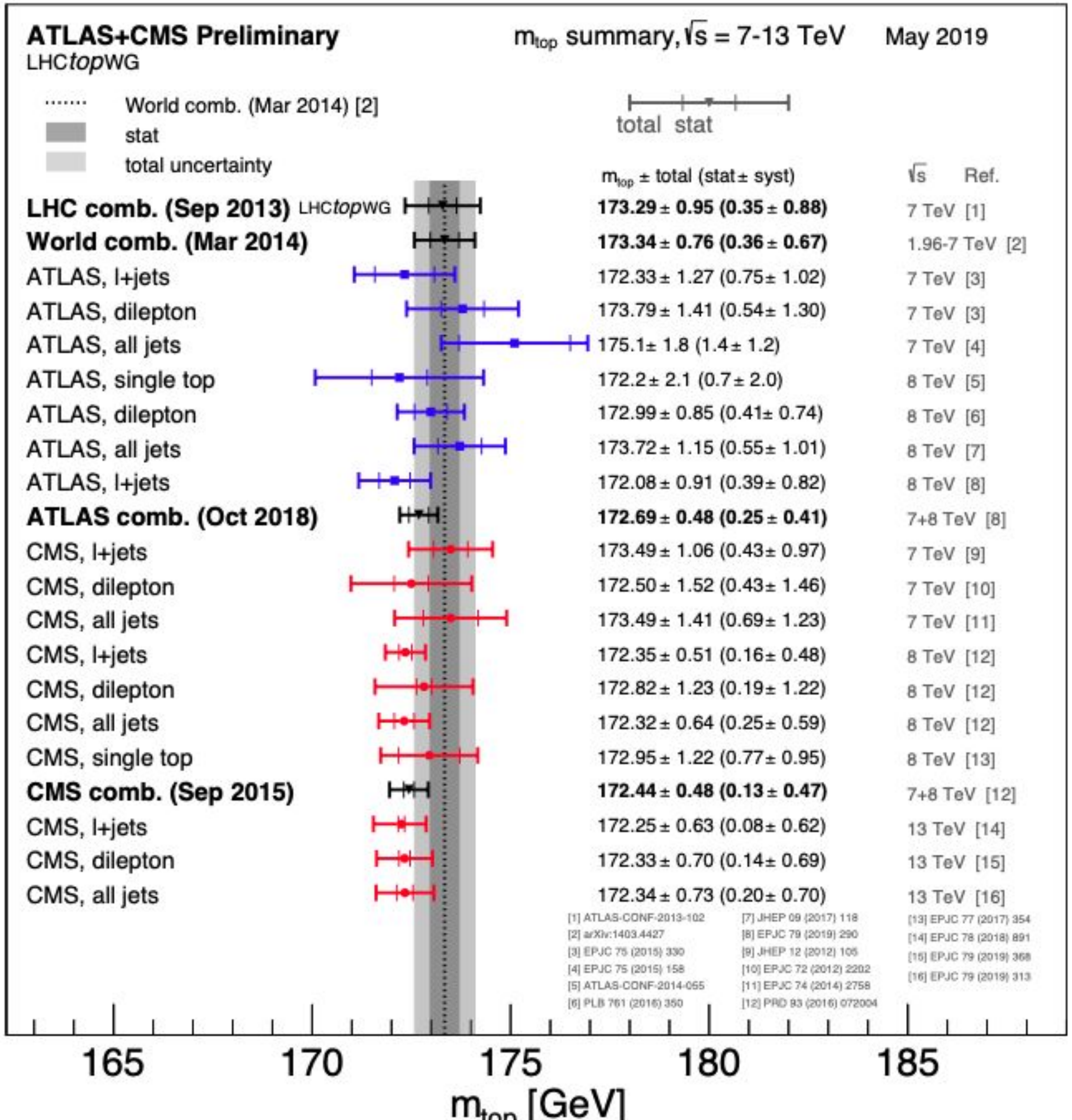
with γ known to 5-loop QCD

PLB 803 (2020) 135263





Mass combination



Heavily limited by systematics

- New ideas/technique more important than collecting statistics
- Constrained by theoretical uncertainties

Full combination long due

- Extremely complicated because of correlated systematics

Top charge asymmetry

ATLAS-CONF-2019-026

Expected effect due to proton PDFs

Null at LO, emerges in interference between qq and qg production in higher orders

- Valence quarks carry more momentum than sea antiquarks

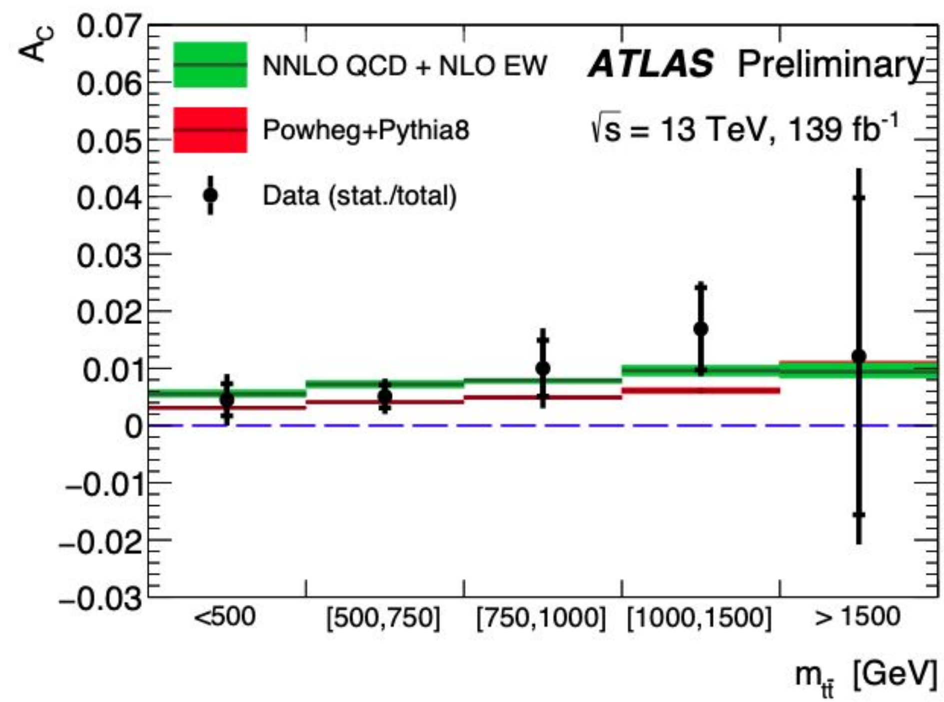
Use the single lepton final state

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

Use bayesian unfolding to extract rapidity with acceptance and detector resolution

$$A_C = 0.0060 \pm 0.0015$$

$$A_C^{NNLO} = 0.0064 \pm 0.0006$$



Result consistent with theory prediction

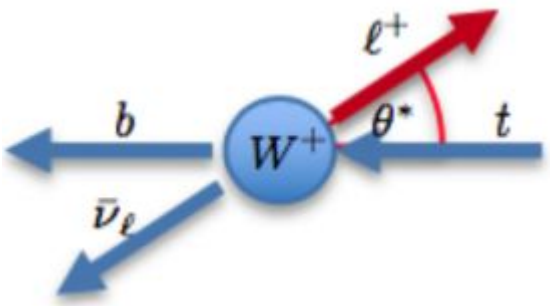
4σ significance for non-zero A_C

W polarization in top decays

In top decays, W polarization determined by V-A structure of vertex

In SM unitary imposes $F_0 + F_L + F_R = 1$

Anomalous contributions



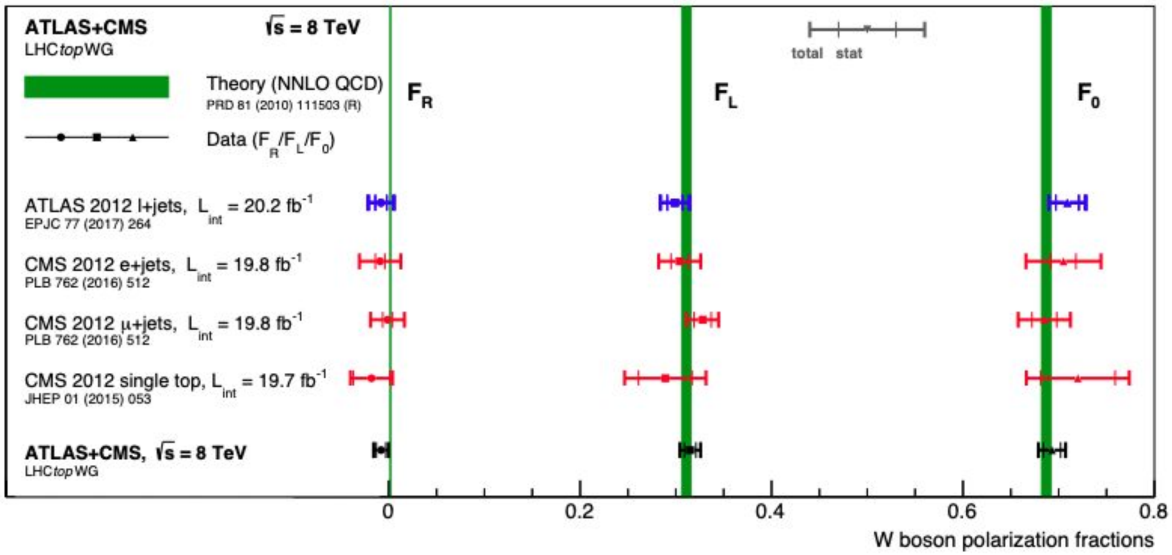
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\,F_0 + \frac{3}{8}(1-\cos\theta^*)^2\,F_L + \frac{3}{8}(1+\cos\theta^*)^2\,F_R$$

In SM: ~70% ~30% ~0%

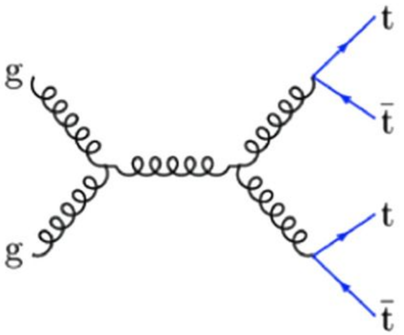
Combined ATLAS+CMS result (l+jets, single top) arXiv:2005.03799

$$F_0 = \quad 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst})$$
$$F_L = \quad 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst})$$
$$F_R = -0.008 \pm 0.005\,(\text{stat+bkg}) \pm 0.006\,(\text{syst})$$

Good agreement with theory predictions @ NNLO



tttt production



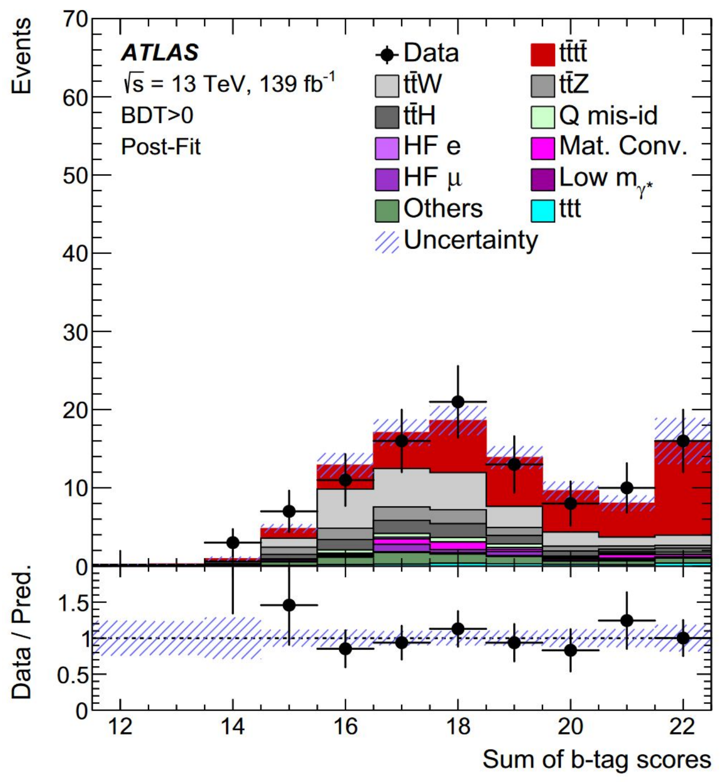
Massive state with ~ 700 GeV

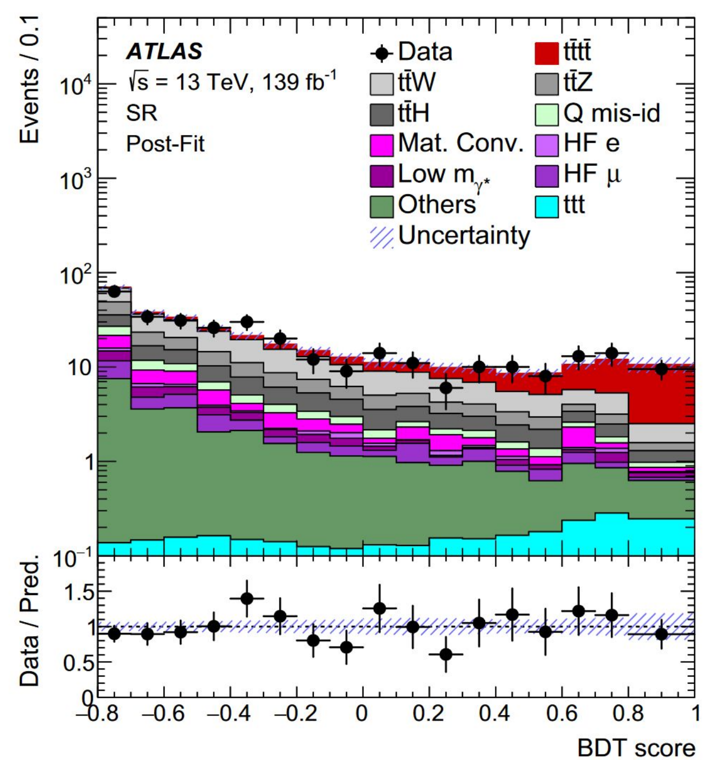
Sensitive to 2HDM scenarios

Combination in multiple decay channels

Most sensitive are 2LSS/3L

Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$	BDT
CR Conv.	$e^{\pm}e^{\pm} \| e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1\text{ GeV}]$ $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \| ee\mu$	–	$= 1$	$100 < H_T < 250$ GeV	Counting
CR HF μ	$e\mu\mu \| \mu\mu\mu$	–	$= 1$	$100 < H_T < 250$ GeV	Counting
CR ttW	$e^{\pm}\mu^{\pm} \| \mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1\text{ GeV}]$, $\lvert\eta(e)\rvert < 1.5$ For $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$ For $N_b \geq 3$, $H_T < 500$ GeV	Σp_T^{ℓ}

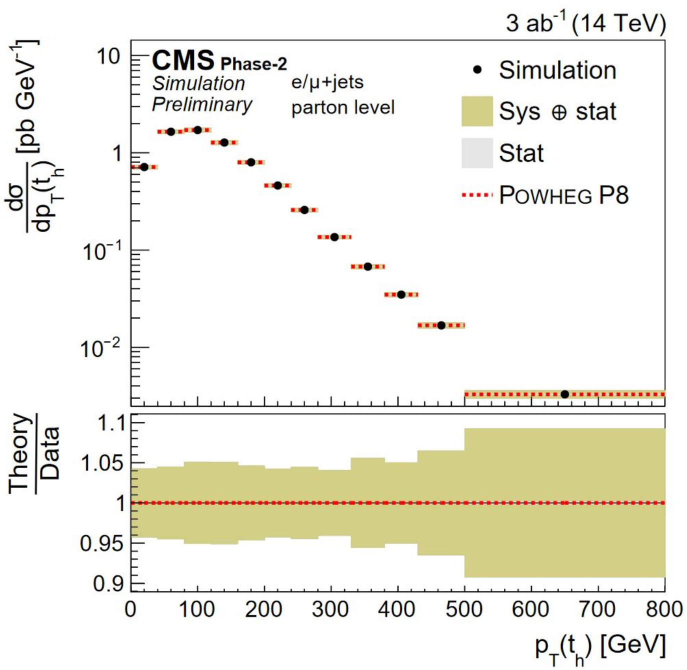


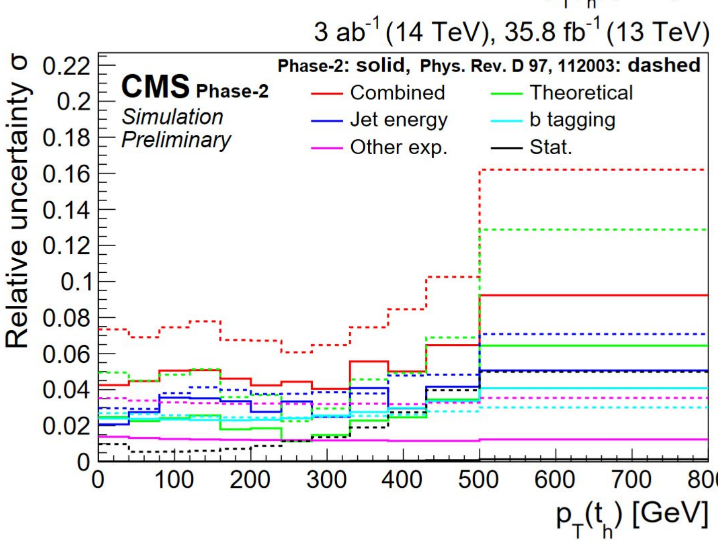


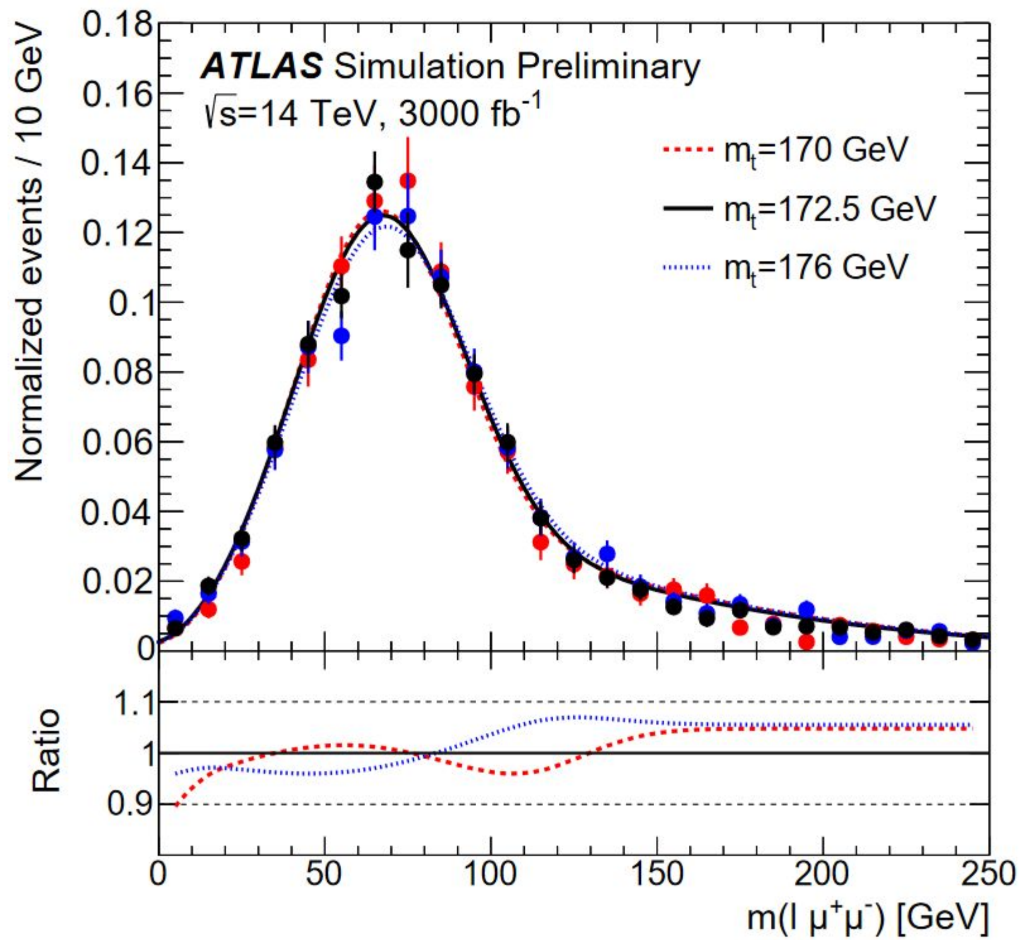
Significance of 4.3 (2.4)σ

EPJC 80 (2020) 1085

Top at HL-LHC



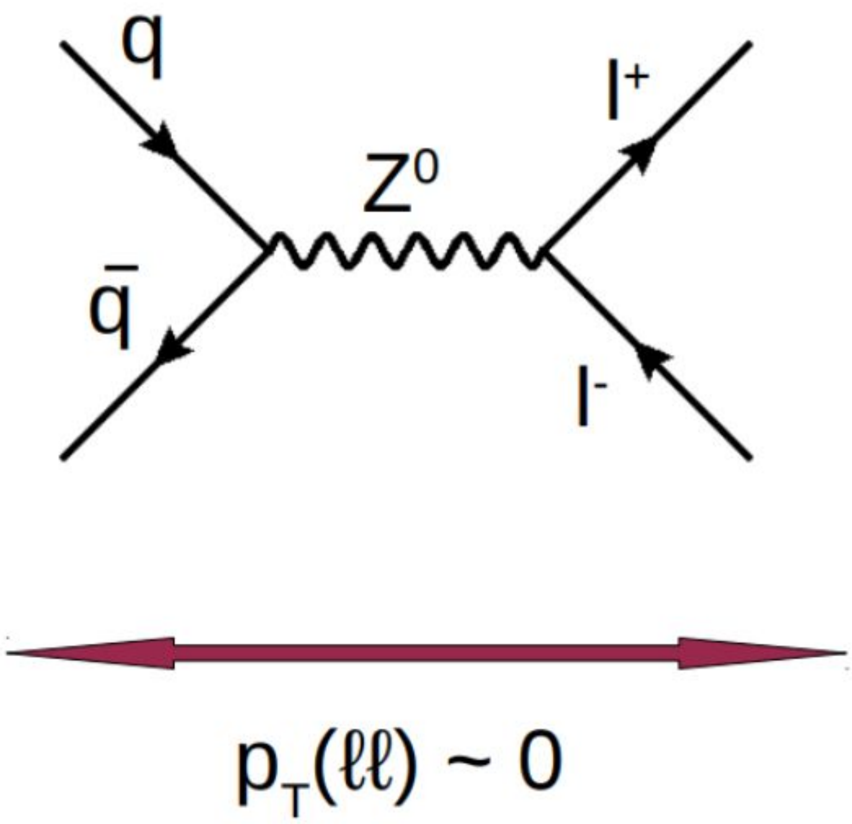


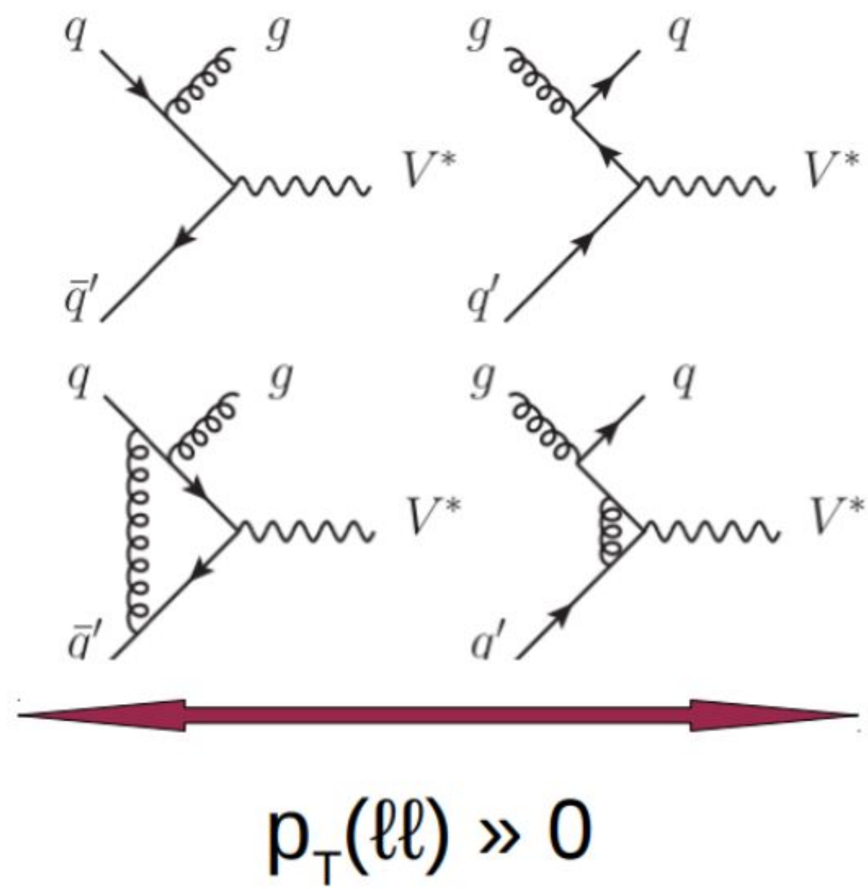


Resolution ~ 0.5 GeV on m_{top} using exclusive b decays

Vector bosons

Drell-Yan production 101





Theoretically very well known in SM up to NNLO

Experimentally very clean → the bread and butter of LHC experiments

Typical DY selection at LHC

JHEP 12 (2019) 061

Single lepton triggers with p_T > 24 GeV

Threshold higher in 2017/18

Isolation already at trigger

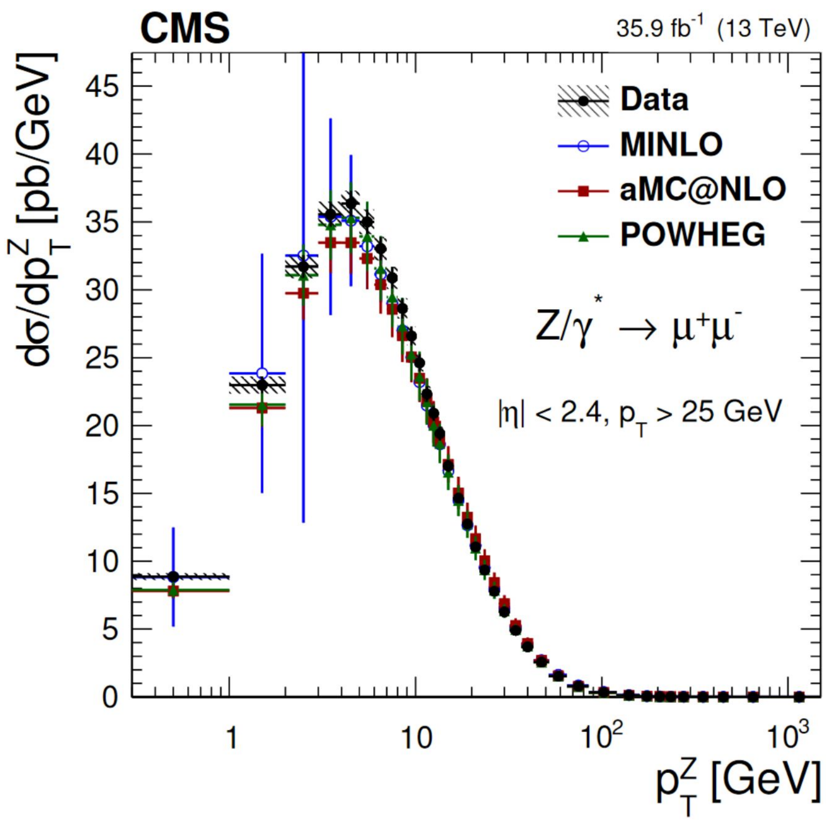
Tighter offline selection (usually O(GeV))

Select opposite charge same-flavor leptons within

the tracking acceptance

Reject events with additional leptons with p_T > 10 GeV

Main backgrounds are tt (leptonic), WW, tW



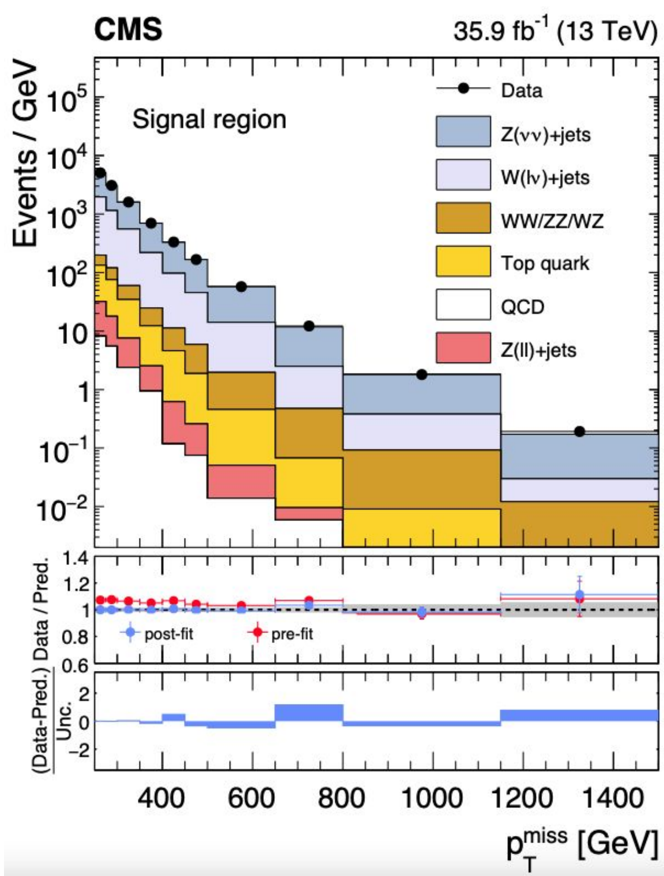
Final state	Data	$Z \to \ell\ell$	Resonant background	Nonresonant background
$\mu\mu$	20.4×10^6	20.7×10^6	30×10^3	41×10^3
ee	12.1×10^6	12.0×10^6	19×10^3	26×10^3

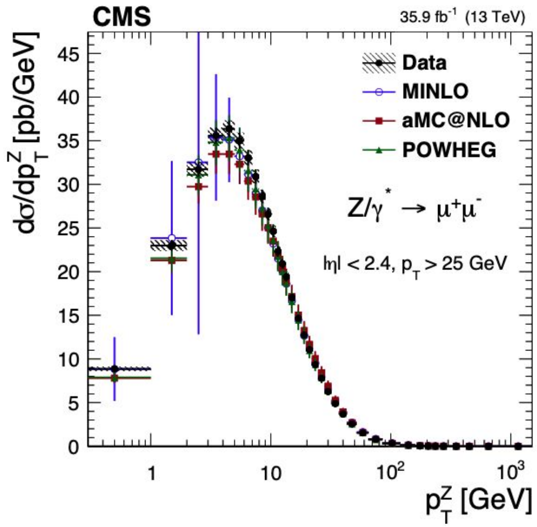
Z differential cross section

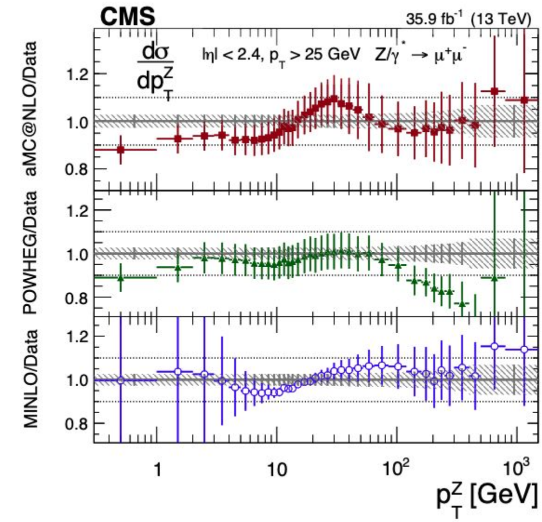
Important test of SM predictions

Use di-lepton + $\nu\nu$ for high p_T

- Lower stat. above 300 GeV + more precise $p_{T,miss}$







Normalized cross section measurement

p_T^Z (GeV)	$Z \to \ell\ell$	$Z \to \nu\nu$	$Z \to \ell\ell + \nu\nu$
200–300	$1.012^{+0.006}_{-0.007}$	$1.019^{+0.009}_{-0.009}$	$1.011^{+0.004}_{-0.004}$
300–400	$0.943^{+0.025}_{-0.025}$	$0.979^{+0.015}_{-0.015}$	$0.963^{+0.015}_{-0.014}$
400–500	$1.006^{+0.031}_{-0.030}$	$0.963^{+0.019}_{-0.019}$	$0.971^{+0.017}_{-0.016}$
500–800	$0.993^{+0.036}_{-0.036}$	$0.942^{+0.024}_{-0.024}$	$0.949^{+0.021}_{-0.020}$
800–1500	$1.036^{+0.099}_{-0.095}$	$0.869^{+0.059}_{-0.057}$	$0.914^{+0.052}_{-0.051}$

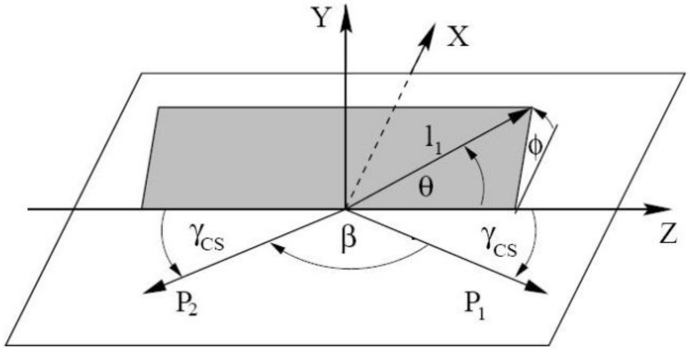
CMS-SMP-18-003

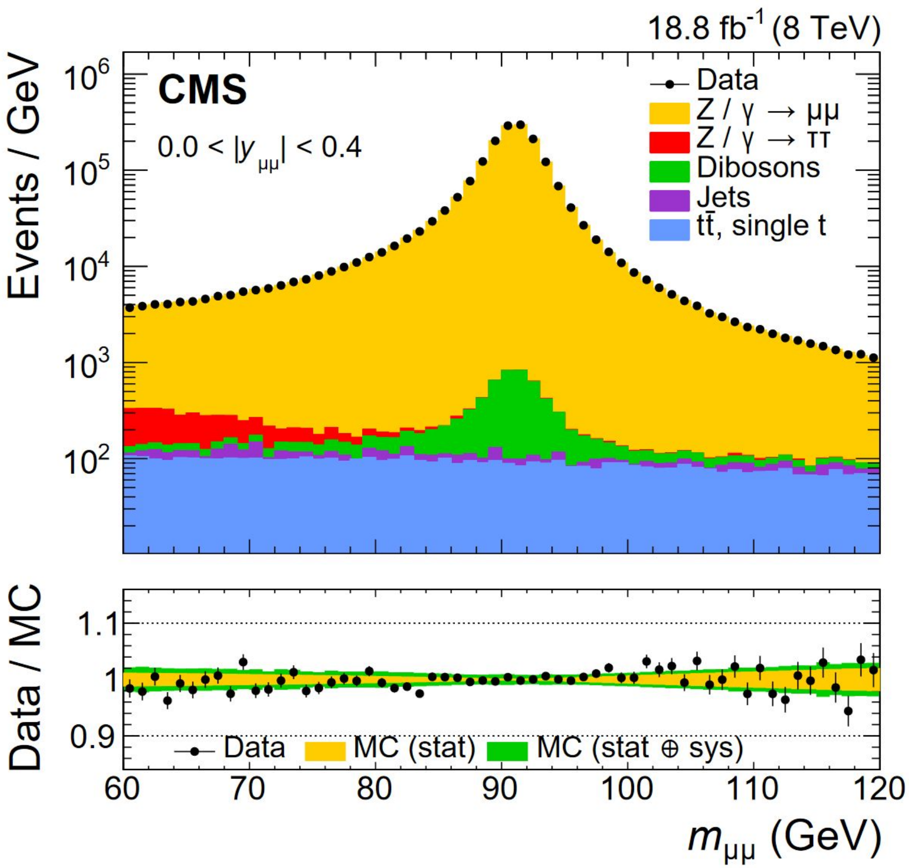
Weak mixing angle from A_{FB}

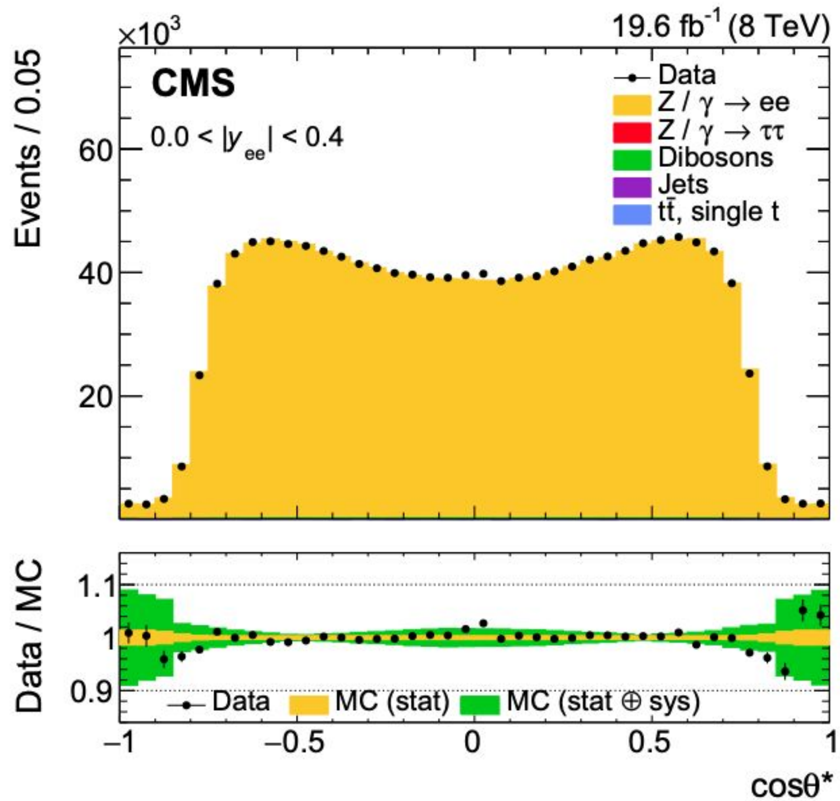
Eur. Phys. J C 78 (2018) 701

A_{FB} in DY events proportional to vector coupling (so $\sin^2\theta^l_{eff}$)

$$\cos\theta^* = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2)}} \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|} \quad A_{\mathrm{FB}} = \frac{3}{8}A_4 = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

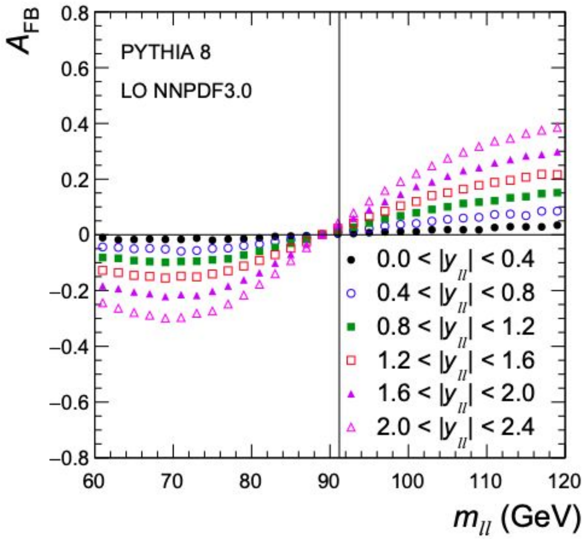




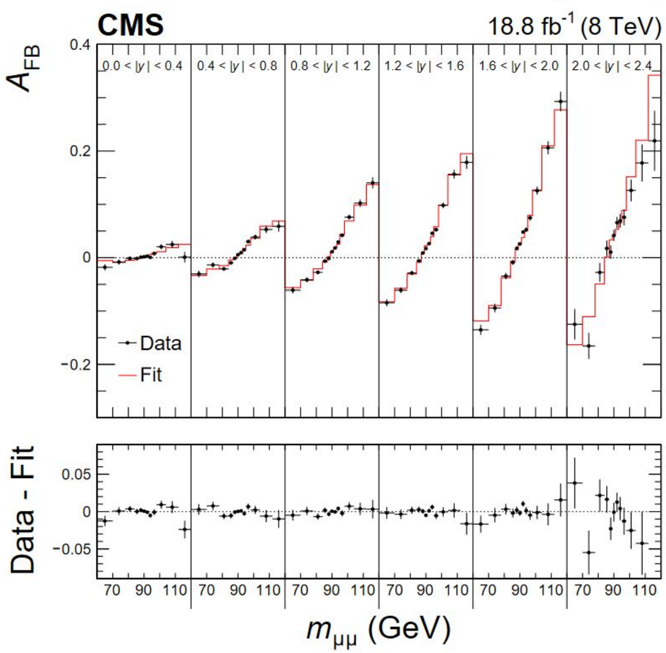


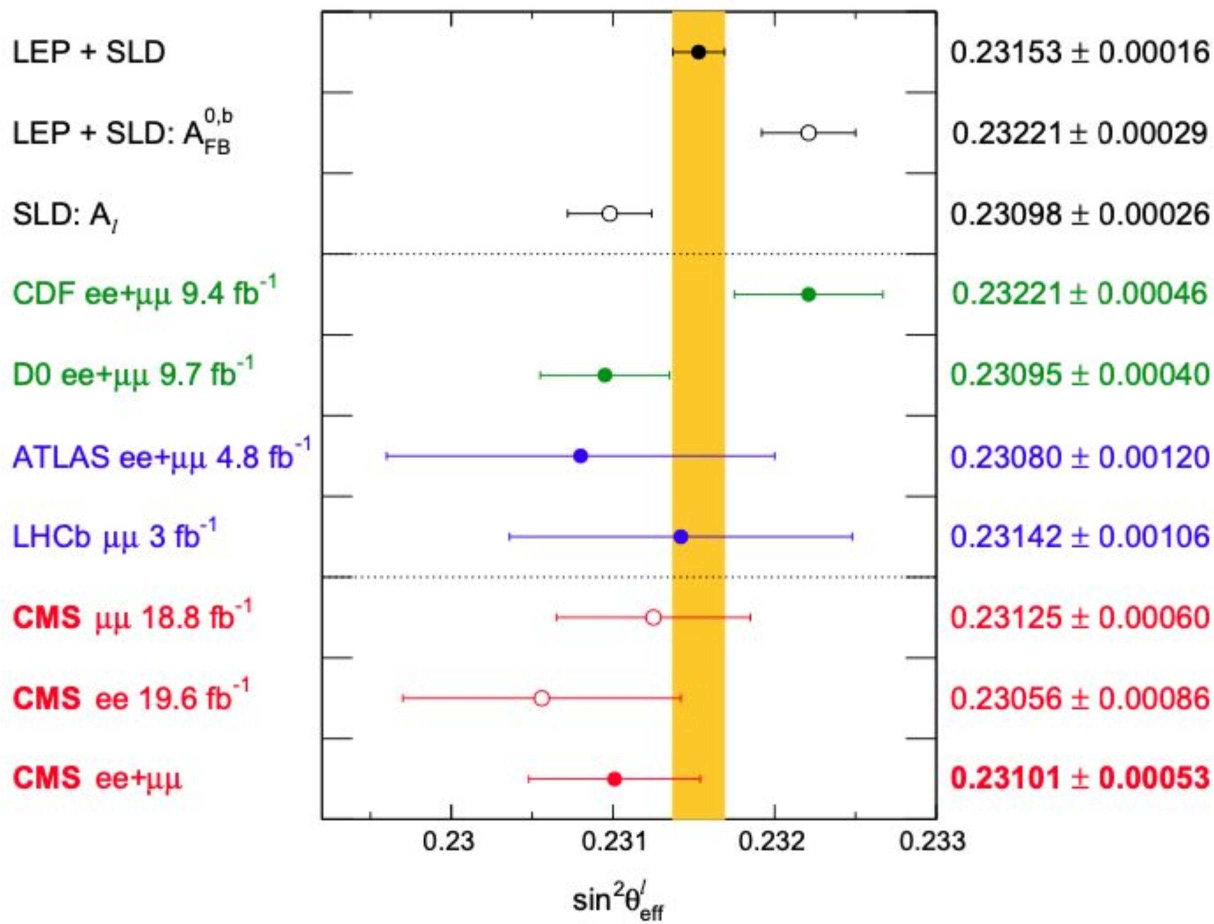
Weak mixing angle from A_{FB}

Eur. Phys. J C 78 (2018) 701



Go from A_{FB} to $\sin^2(\theta^l_{eff})$ using generator level distributions





W branching fractions

Important test of LFU in leptonic decays

Tension in LEP combination

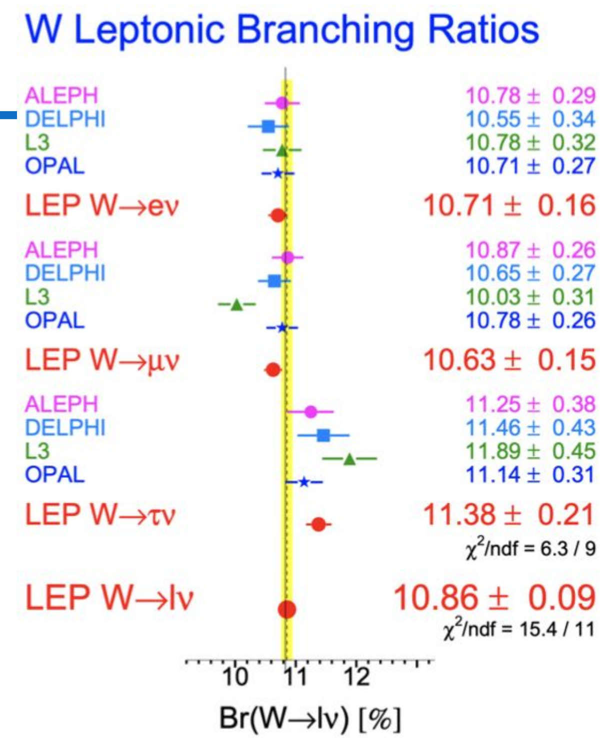
Measure inclusive hadronic BR

Use tt, tW, WW, W+jets production in N_{jet} categories

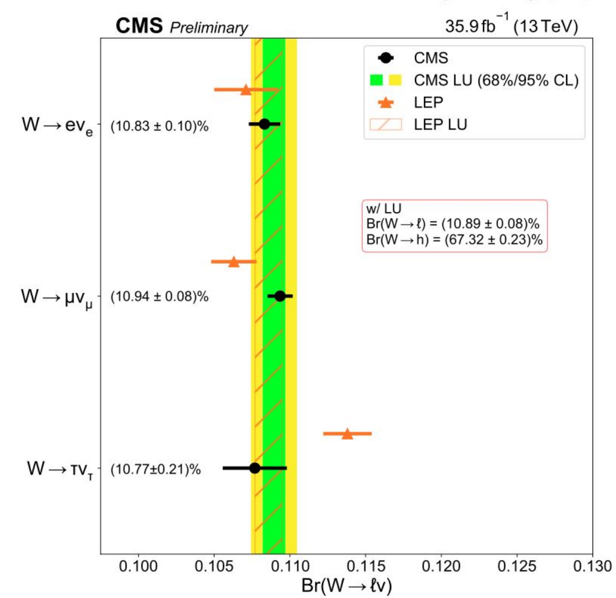
	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$; $ee, \mu\mu, e\mu$		
$N_b = 1$		$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					eh, μh
$N_b \geq 2$			$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					eh, μh

	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)$ %
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)$ %
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)$ %
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

PR 532, 119-244 (2013)



CMS PAS SMP-18-011



$W^{\pm} \rightarrow \pi^{\pm} \gamma$

CMS-SMP-20-008

Exclusive hadronic decay of W never observed

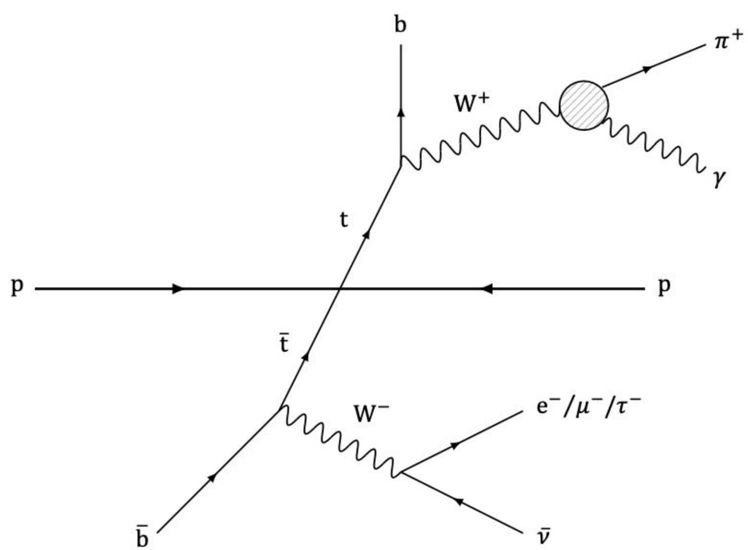
Interesting to tune hadronization description of vector bosons

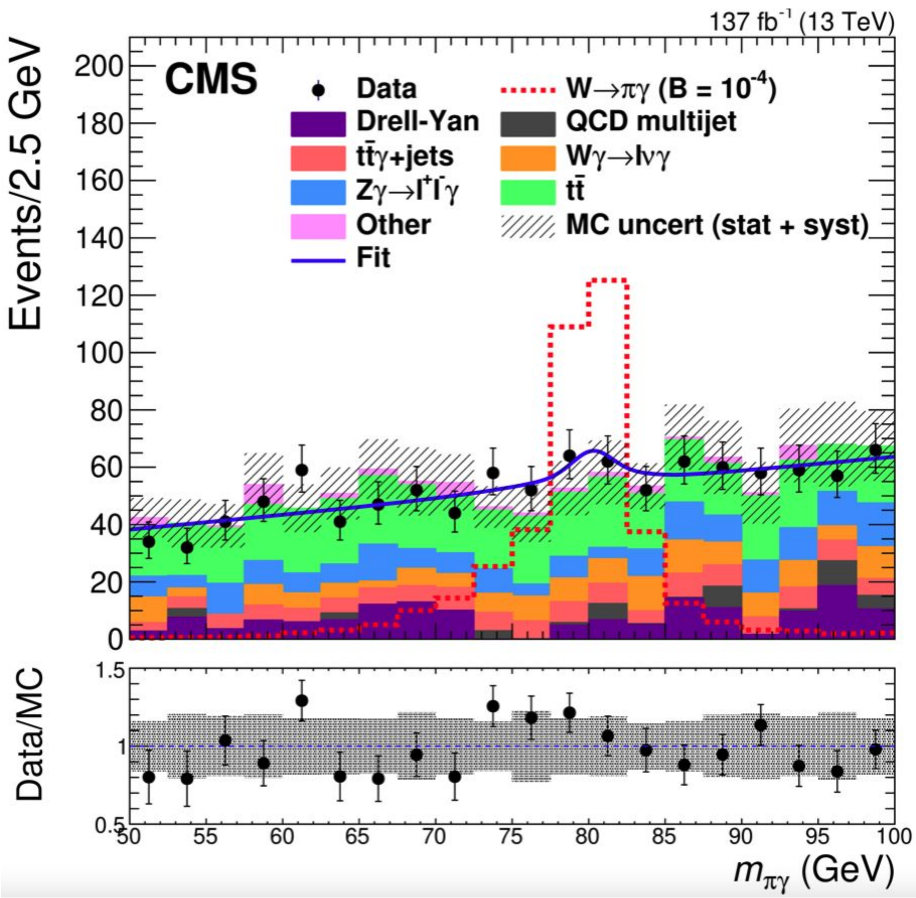
Direct search at LHC impossible (trigger!)

BUT, one can use tt production

Pion is produced from EWK process, so

isolation applies



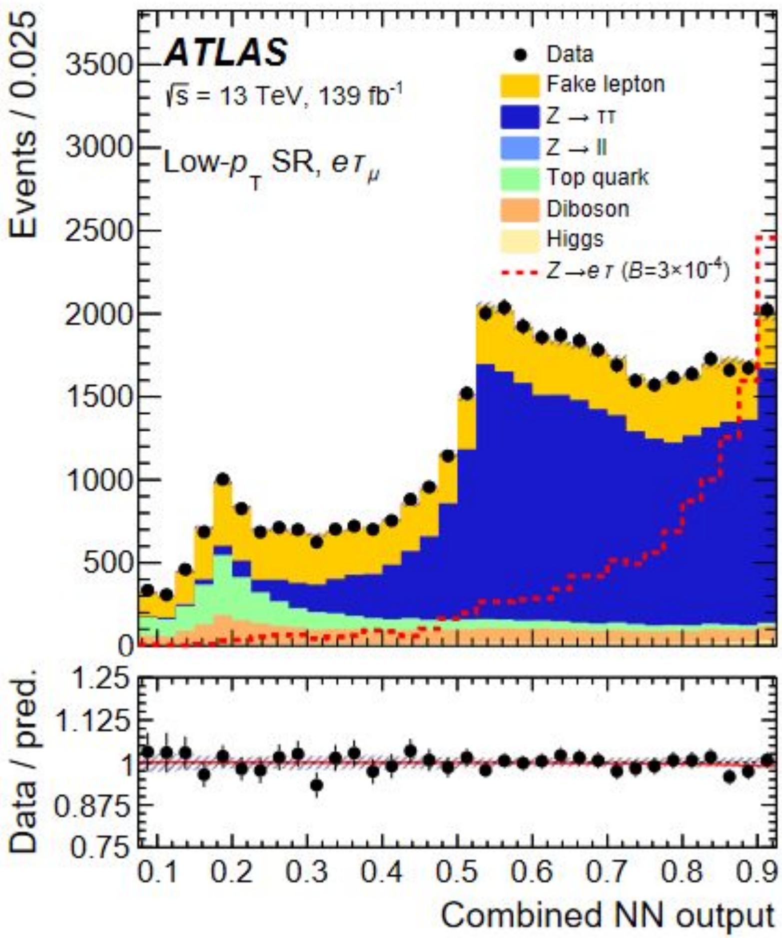


$BR(W^{\pm} \rightarrow \pi^{\pm}\gamma) < 1.50 * 10^{-5}$ @ 95%CL

LFV in Z decays

Search for Z $\rightarrow \ell\tau$, with both leptonic and hadronic τ decays

Use NN for S/B discrimination through fit



Source of uncertainty	Uncertainty in $\mathcal{B}(Z \rightarrow \ell\tau)$ [$\times10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
E_T^{miss}, jets and flavor tagging	±2.1	±2.4
E_T^{miss}	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \rightarrow \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

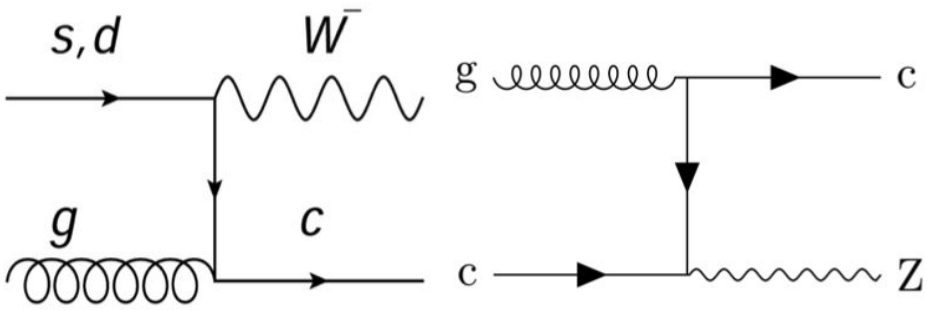
Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \rightarrow \ell\tau)$ [$\times10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{had}$ Run 1 + Run 2, unpolarized τ [9]	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{had}$ Run 2, left-handed τ [9]	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{had}$ Run 2, right-handed τ [9]	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

V+heavy flavor

Important for MC tuning

Major background in many BSM searches

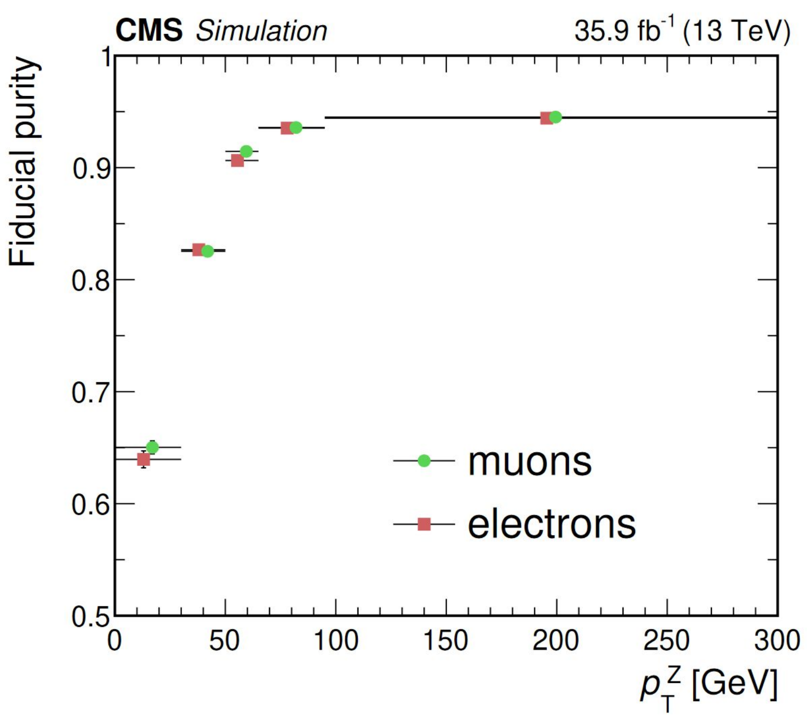
Probe of heavy quark PDF

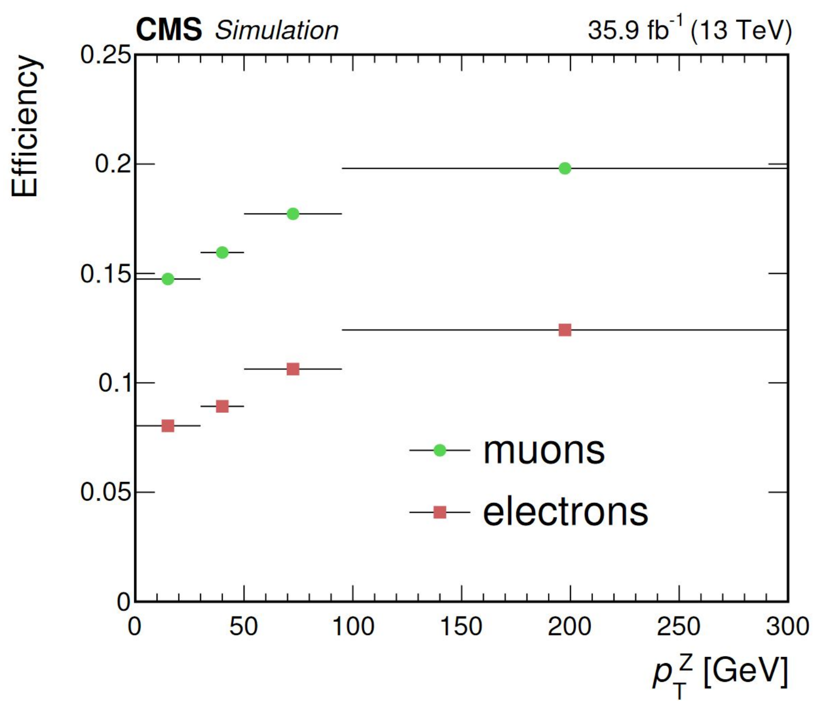


Case study: Z+charm

Measure using m_{SV} and c-tagger

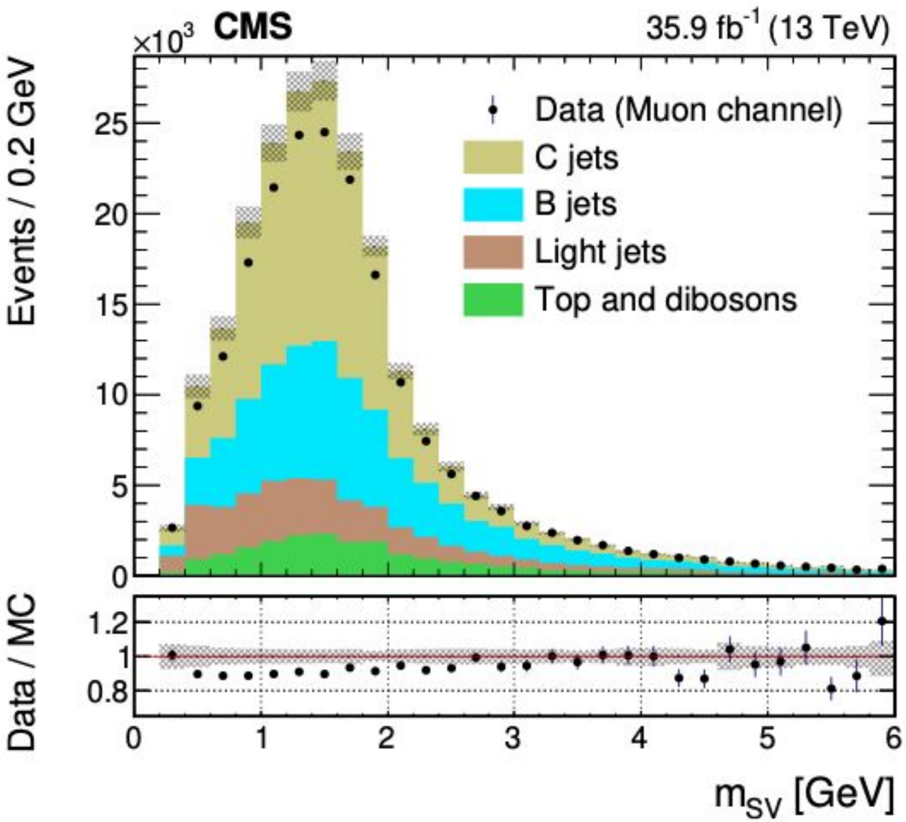
JHEP 04 (2021) 109

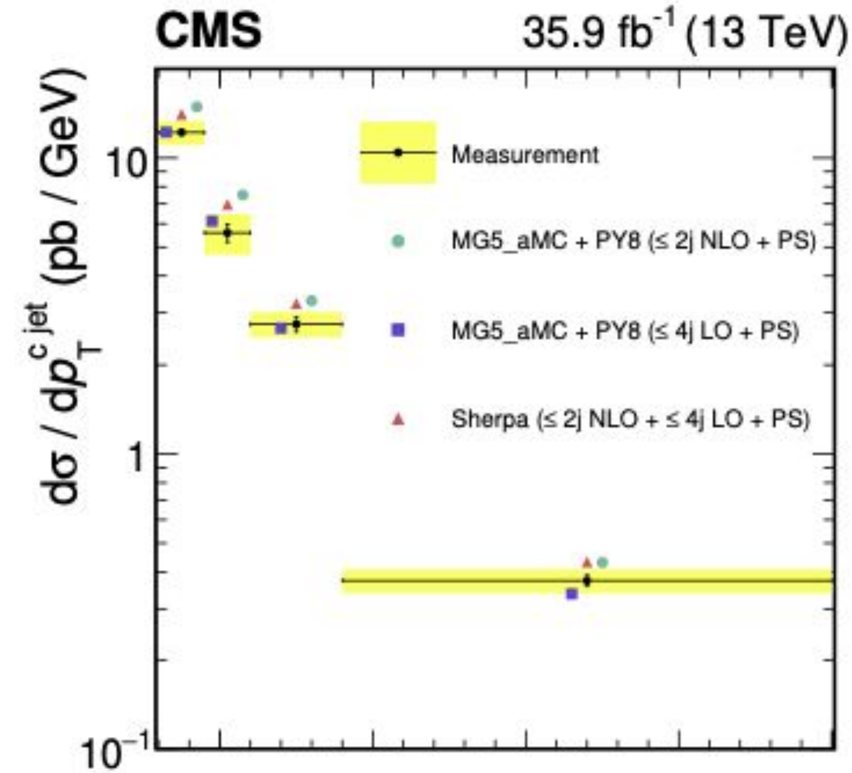




V+heavy flavor

JHEP 04 (2021) 109





$$\sigma_{fid.meas} = 405.4 \pm 5.6(\text{stat}) \pm 24.3(\text{exp}) \pm 3.7(\text{theo})\ \text{pb}$$

$$\sigma_{theo} = 524.9 \pm 11.7(\text{theo})\ \text{pb}$$

Channel	QCD (%)	PDF (%)	c tag/mistag (%)	JER (%)	JES (%)	Pileup (%)	Top Pair (%)	ID\Iso (%)	$\mathcal{L}$ (%)	MC stat. (%)
$\mu\mu, p_T^{c\ jet}$	5.5	0.5	4.2	3.9	4.8	1.5	0.6	1.0	2.5	4.2
$\mu\mu, p_T^{Z}$	1.9	0.5	4.2	1.1	3.9	1.6	0.8	1.0	2.5	3.1
$ee, p_T^{c\ jet}$	6.4	0.6	4.2	3.1	6.4	3.0	0.7	2.6	2.5	6.3
ee, p_T^{Z}	2.6	0.5	4.1	1.1	4.8	1.8	0.6	2.6	2.5	3.8

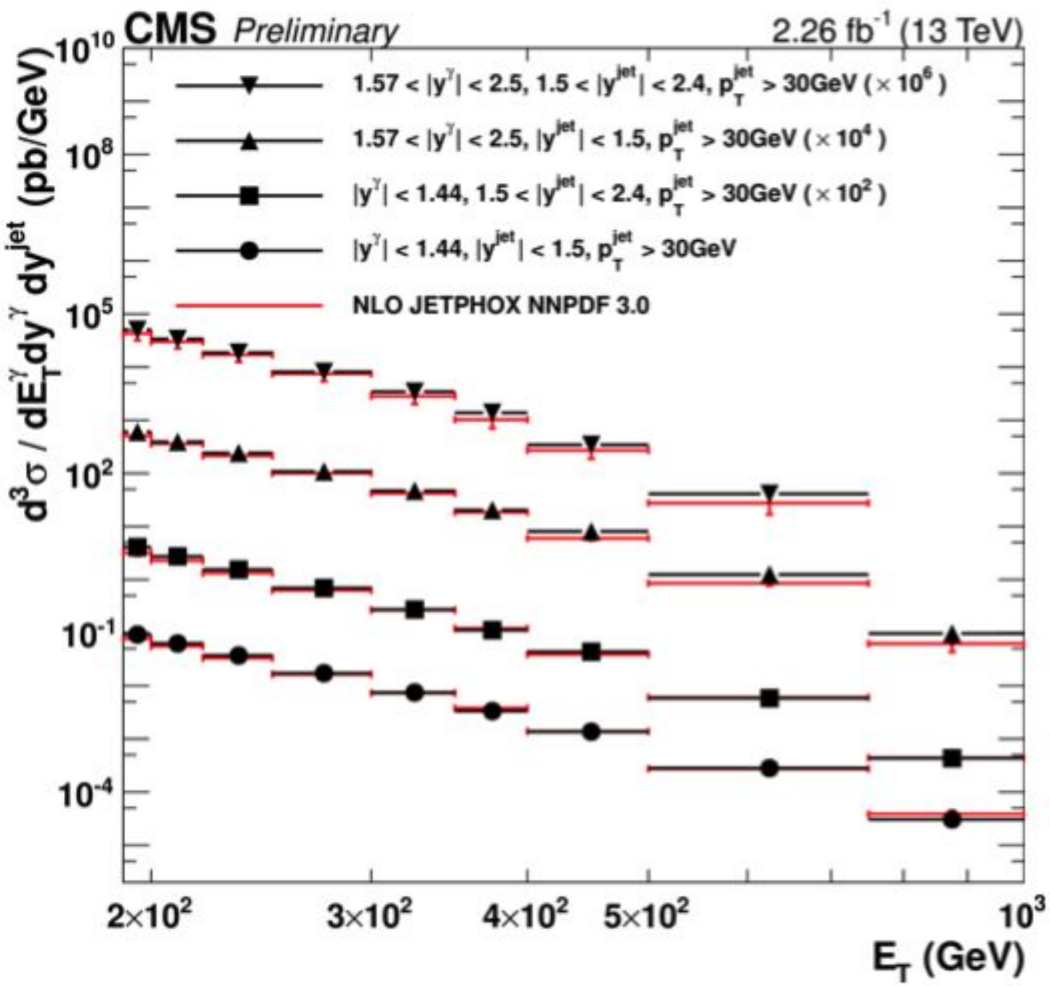
Charm content of proton overestimated?

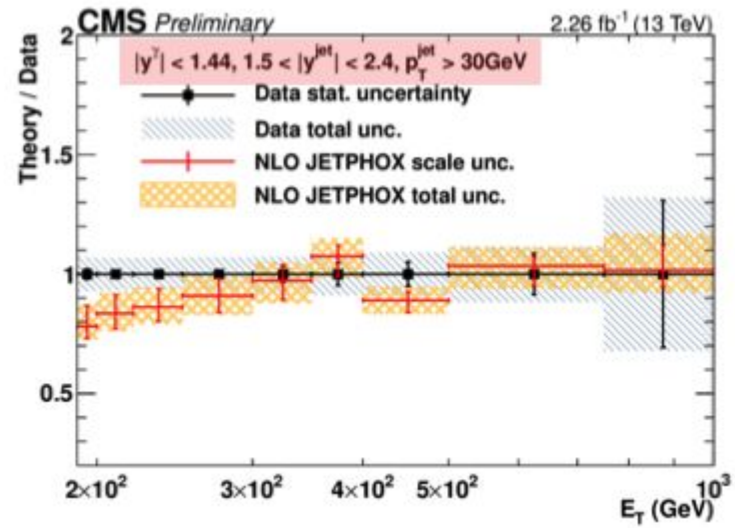
Triple differential γ+jets

Eur. Phys. J. C 79 (2019) 20

Main processes are quark-gluon Compton scattering and qq annihilation

Test of QCD and probe of gluon PDF





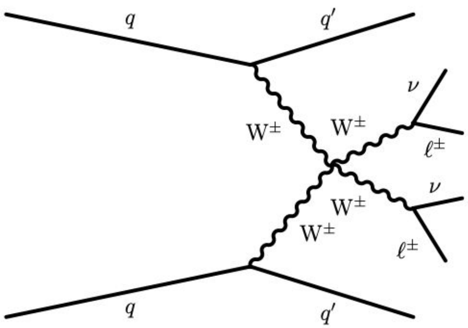
NLO calculations available for comparison

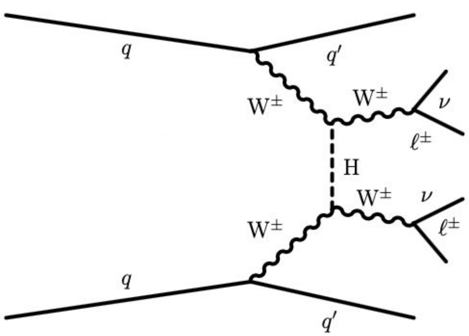
Data with low uncertainties in lower E_T regions, can allow to constrain/select PDF sets

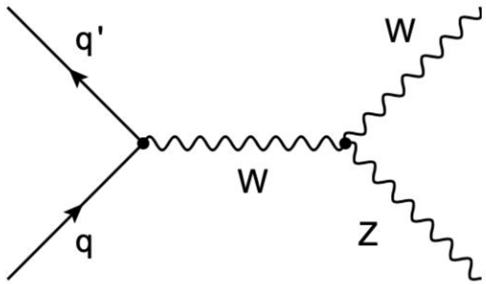
Self coupling

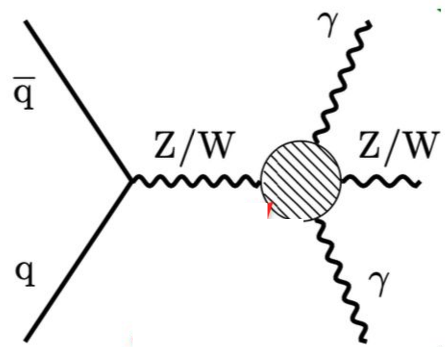
W/Z(/ɣ) self couplings predicted by non-abelian structure of electroweak theory

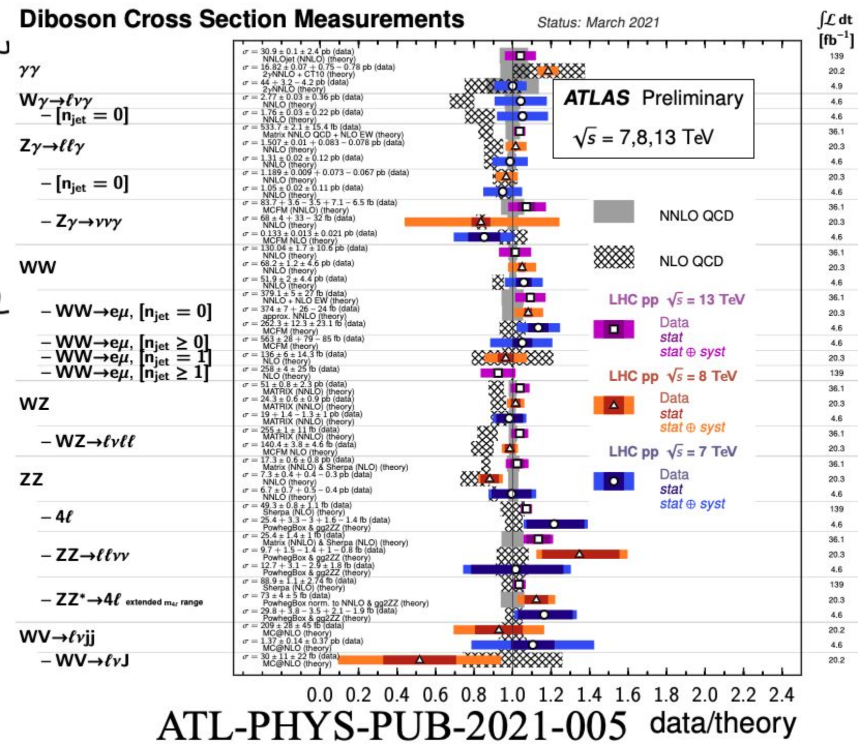
Large zoo of topologies to be explored











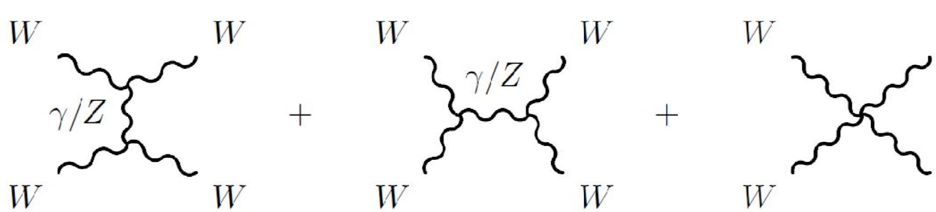
→ Inclusive di-(multi-) boson production, w/o jets

→ Constrain anomalous couplings $L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \ldots$

Higgs and V-V scattering

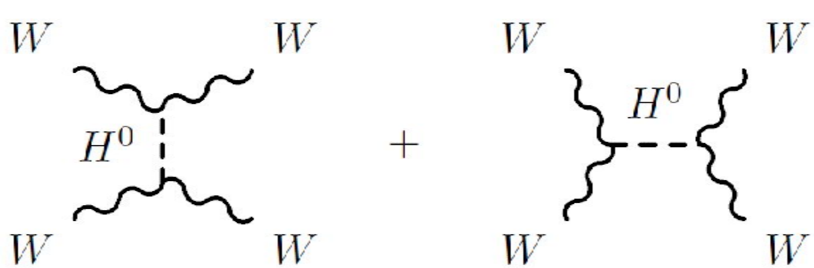
Scattering of W-W bosons

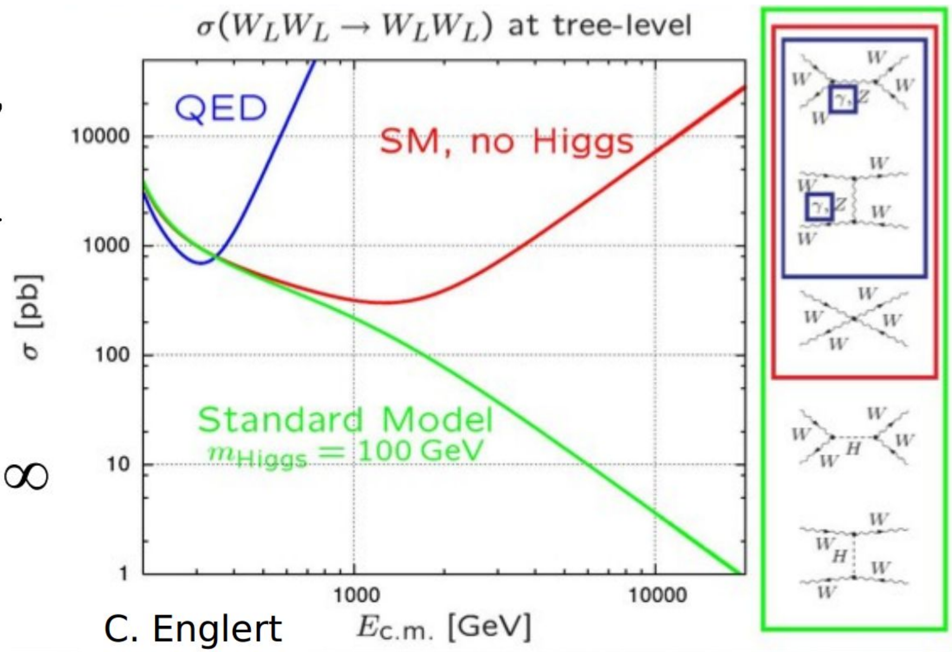
$$M\left(W^{+}W^{-} \rightarrow W^{+}W^{-}\right) \propto \frac{s}{m_w^2} \; for\, s \rightarrow \infty$$



Higgs boson restores unitarity (if m_H < 1 TeV)

$$M\left(W^{+}W^{-} \rightarrow W^{+}W^{-}\right) \propto m_H^2 \; for\, s \rightarrow \infty$$



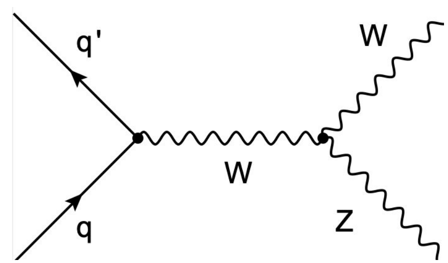


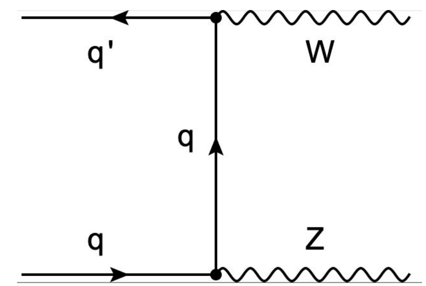
WZ production

Study of WZ production at 13 TeV in leptonic final states

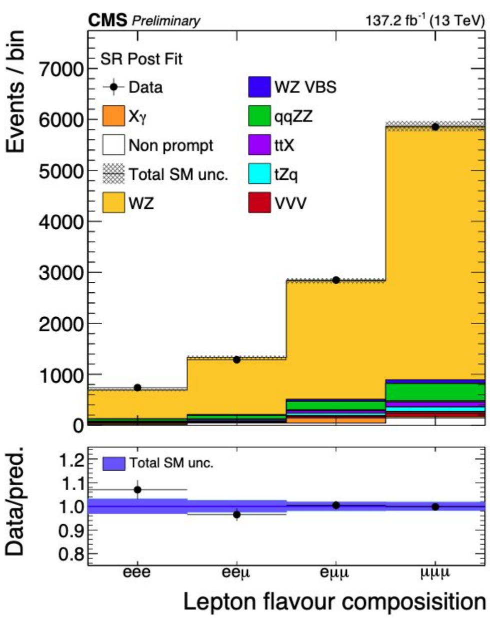
- Inclusive total and differential cross sections
- Charge asymmetry and polarization
- Triple gauge couplings

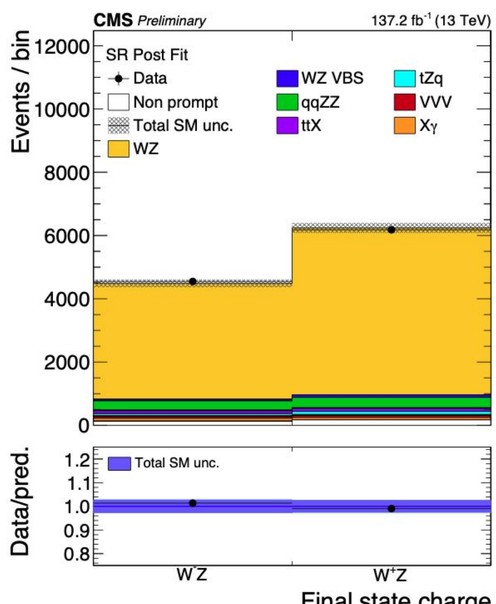
CMS-PAS-SMP-20-014

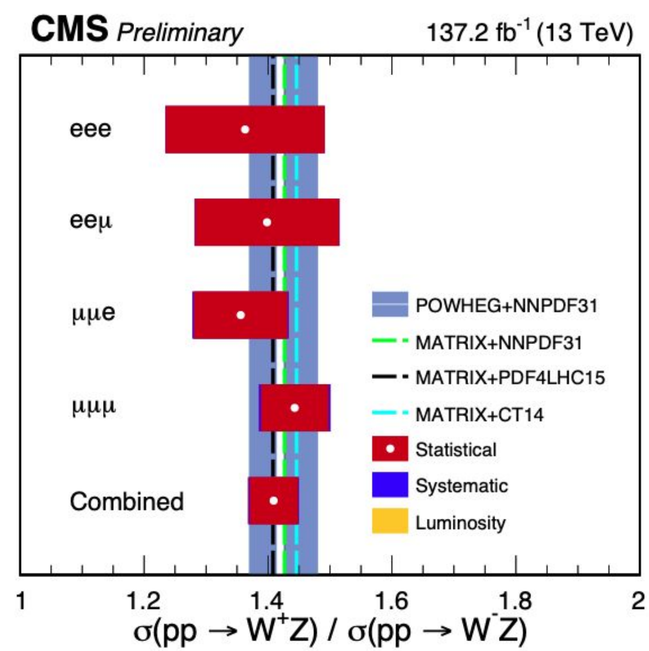




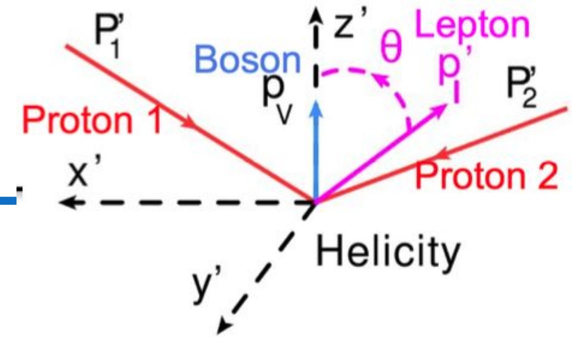
Charge asymmetry: good test of proton PDF description







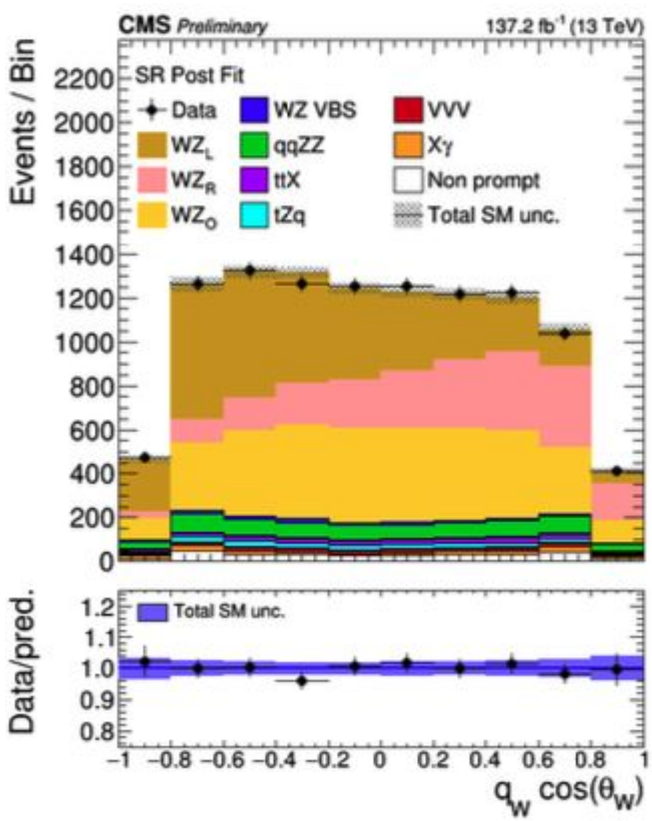
WZ - polarization

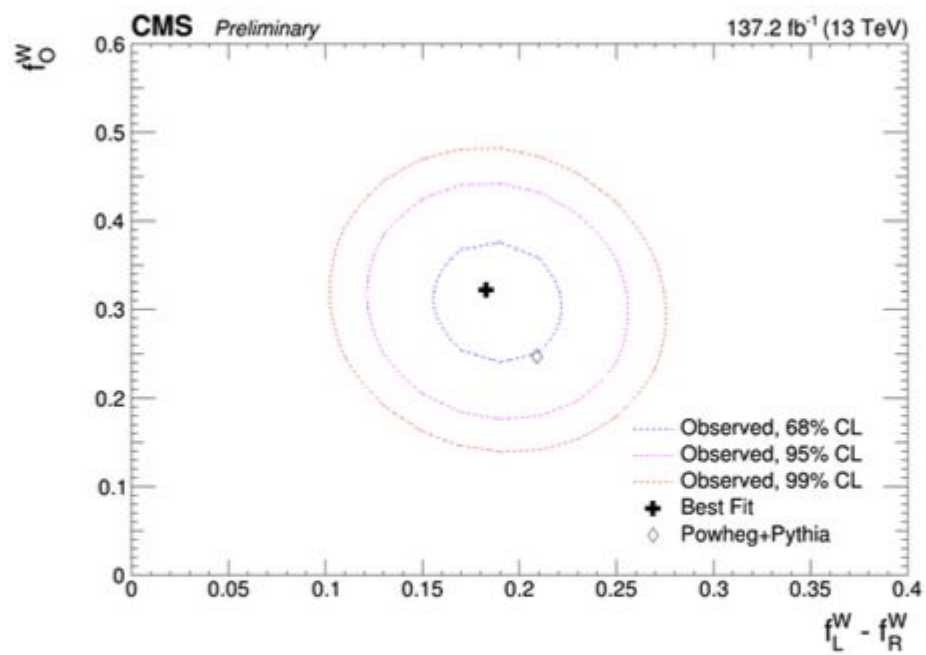


Intermediate scalars → increased longitudinal component

Non-resonant → increased transversal polarization

$$\frac{d\sigma}{\sigma d\cos\theta^{W\pm}} = \frac{3}{8}\left[(1\mp\cos(\theta^{W\pm}))^2 f_L^W + (1\pm\cos(\theta^{W\pm}))^2 f_R^W + 2\sin^2(\theta^{W\pm}) f_0^W\right]$$





Evidence of longitudinal polarization at 5.6σ (4.3σ expected)

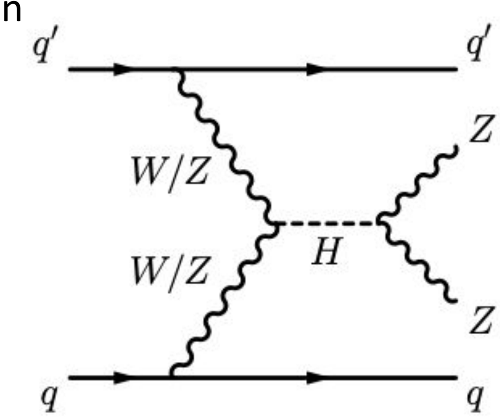
VVjj production

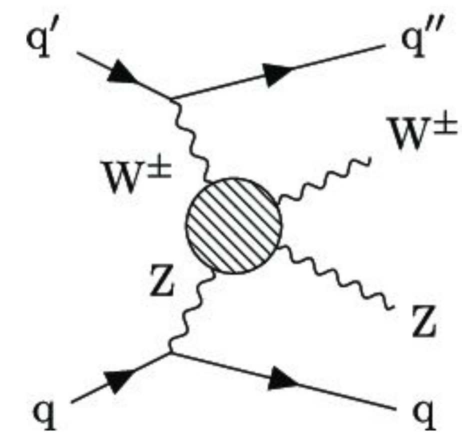
An “electroweak signature”(-ish) of VV production

Currently well established, several

measurements strive for precision

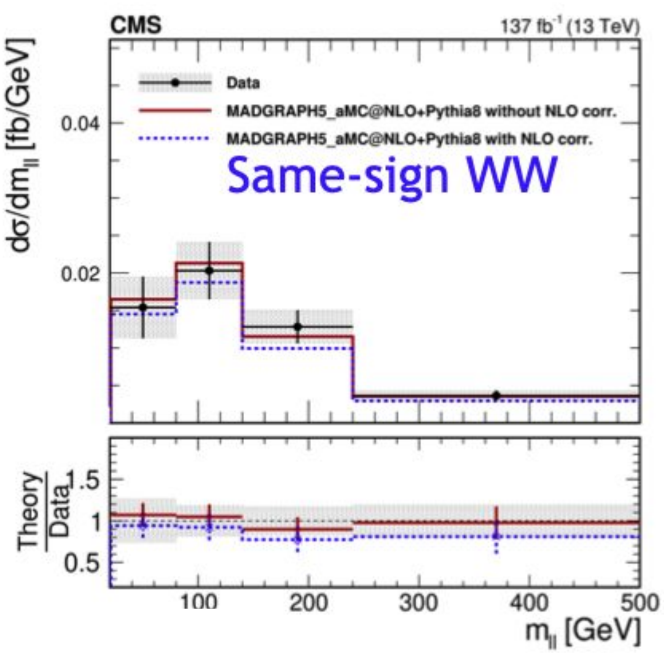
NLO predictions available

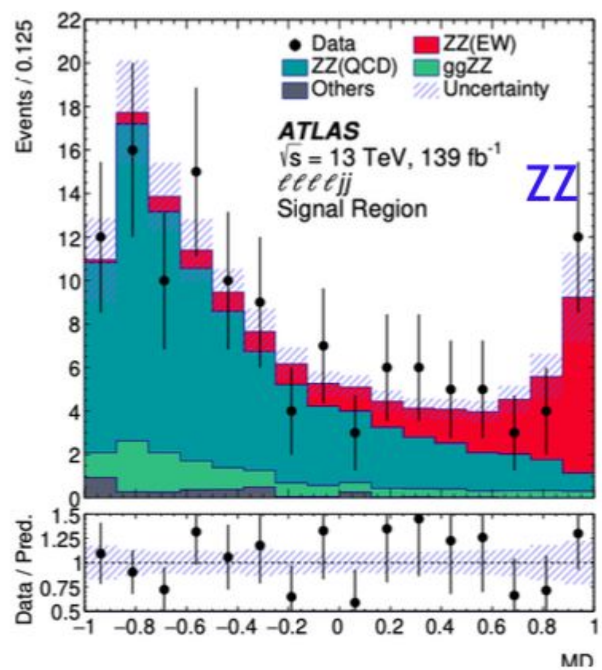


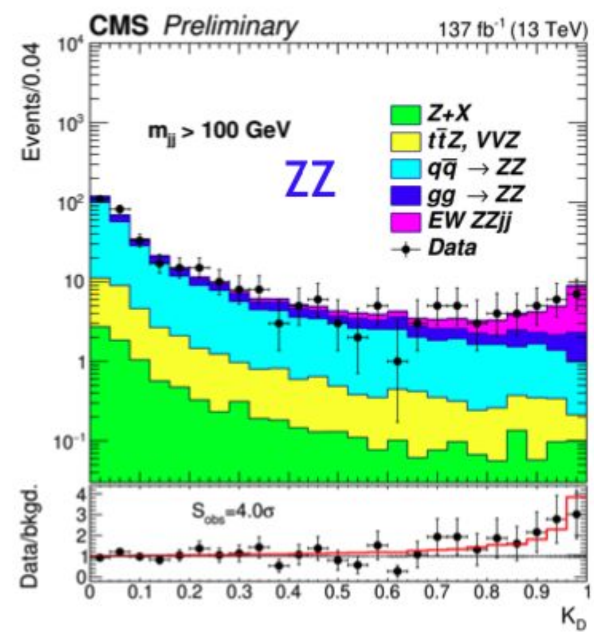


ATLAS: ZZ production

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	$1.5 \quad \pm 0.4$	0.95 ± 0.22	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	$0.7 \quad \pm 0.7$	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ







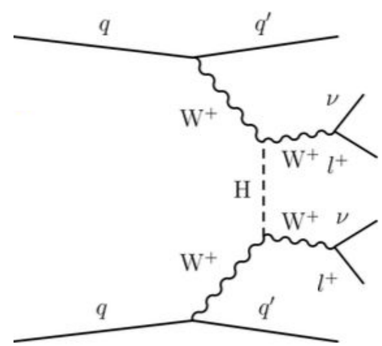
WWjj polarization

PLB 812 (2021) 136018

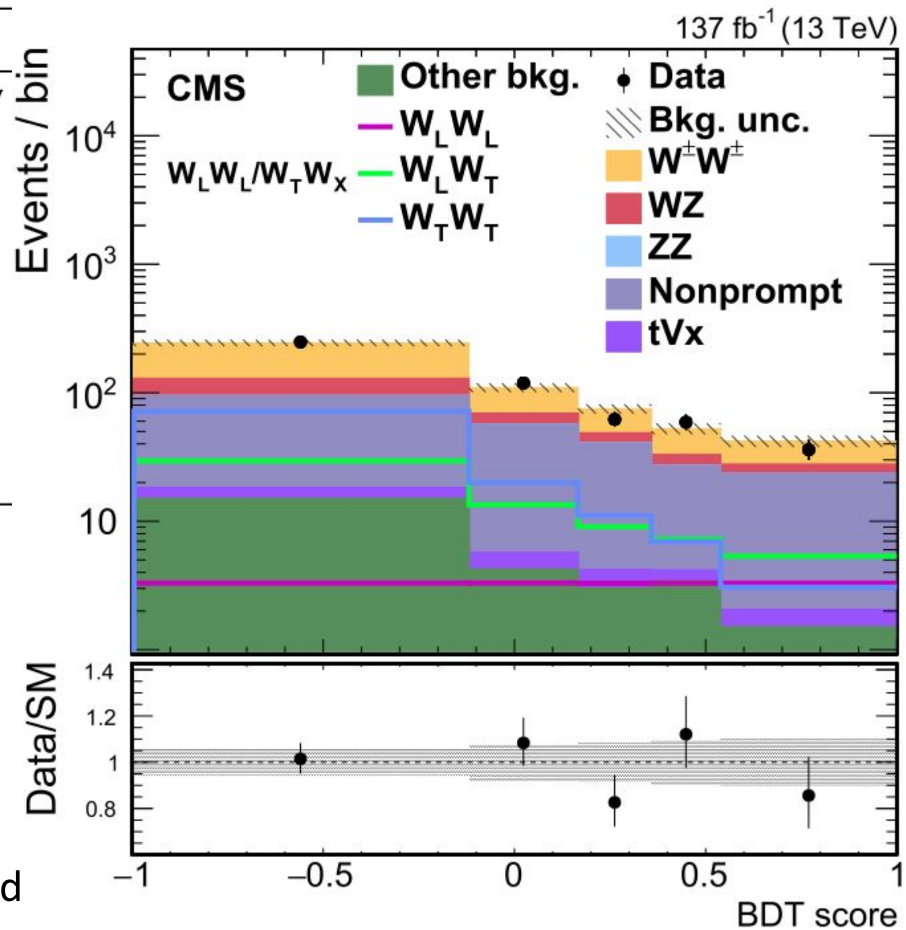
Longitudinal component sensitive to Higgs boson restoring unitarity

Limited combinations of longitudinal/transverse polarization of same-sign WW

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
p_T^{miss}	>30 GeV
b quark veto	Required
Max(z_ℓ^*)	<0.75
m_{jj}	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5



Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21



Production of at least one L-polarized W with observed significance of 2.3σ (3.1σ expected)

Photon induced WW production

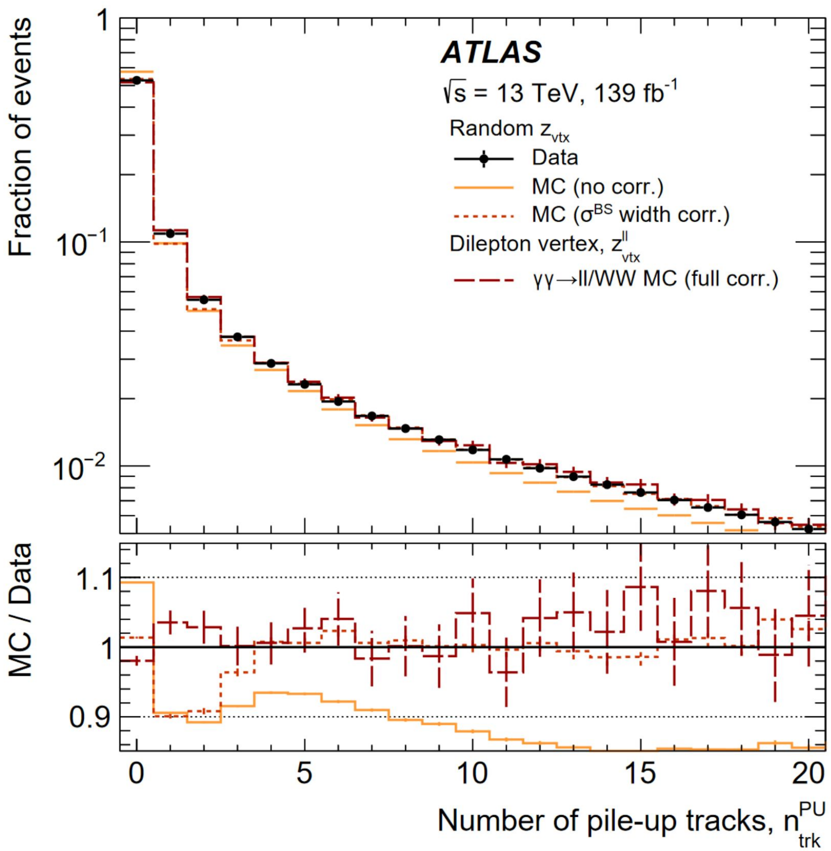
Observation of W pairs produced by di-photons

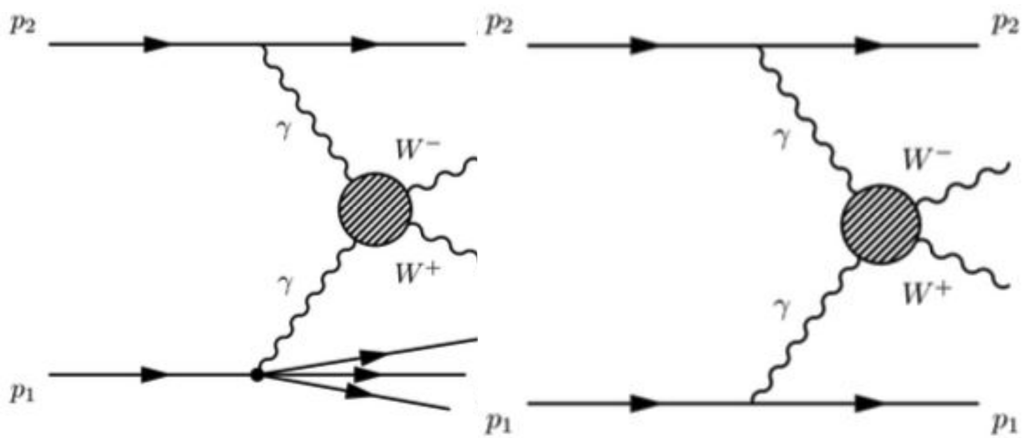
Search for di-lepton final state (different flavor)

To reject DY

Require zero additional charged particles (after PU)

based on lepton vertex

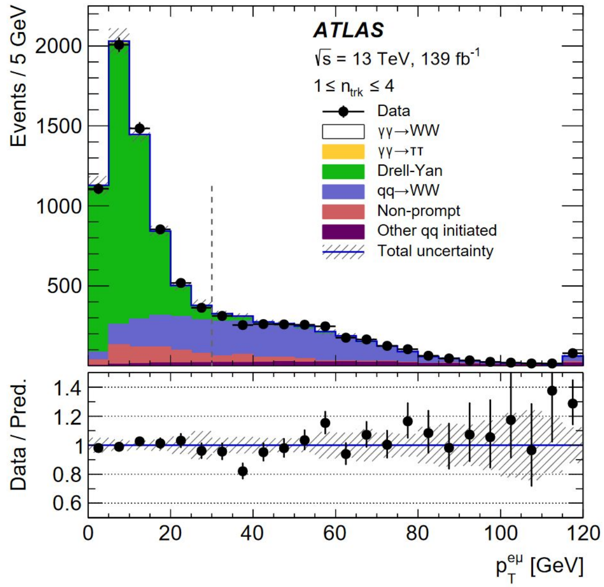


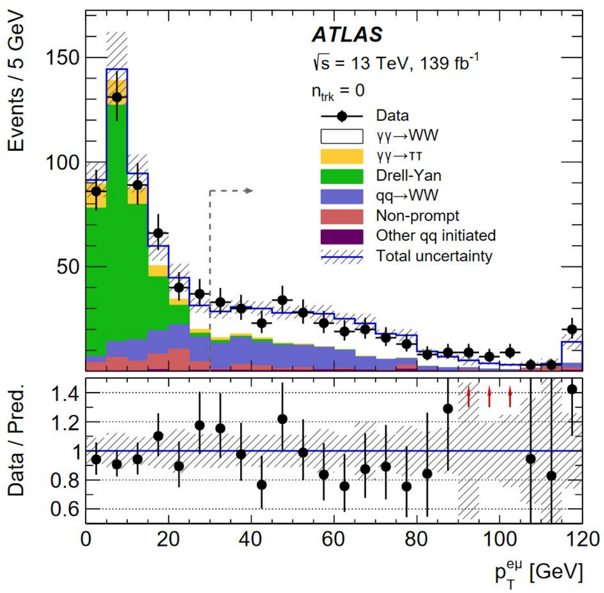


Arxiv:2010.04019

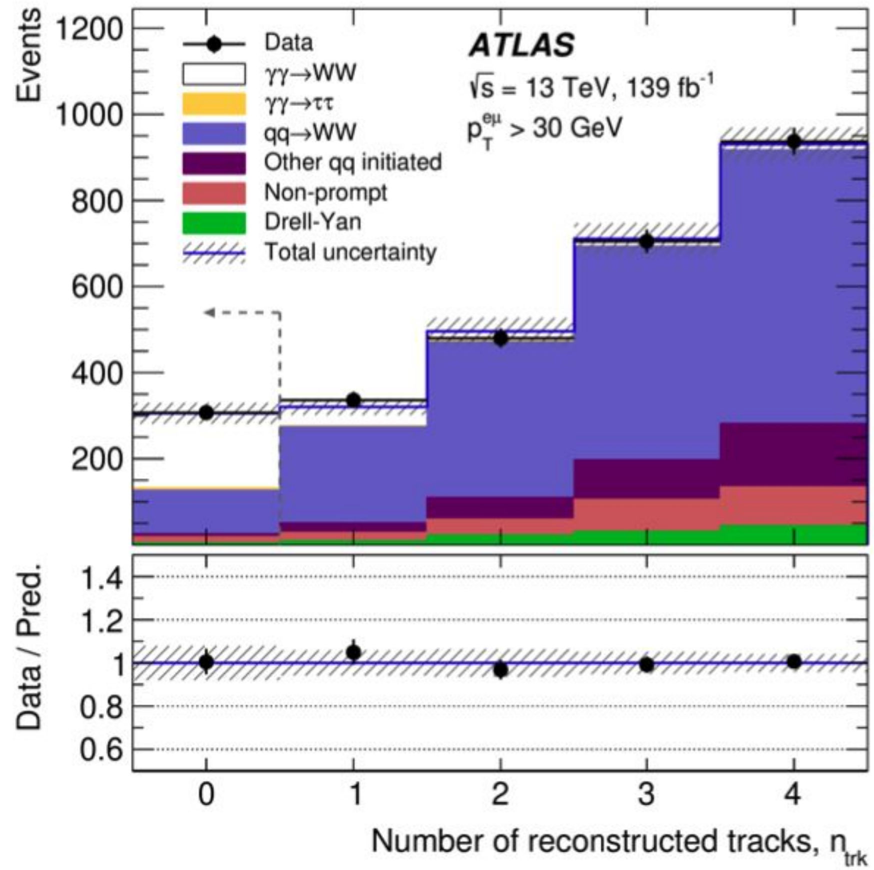
	Signal region		Control regions	
n_{trk}	$n_{trk} = 0$		$1 \leq n_{trk} \leq 4$	
$p_T^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

Photon induced WW production





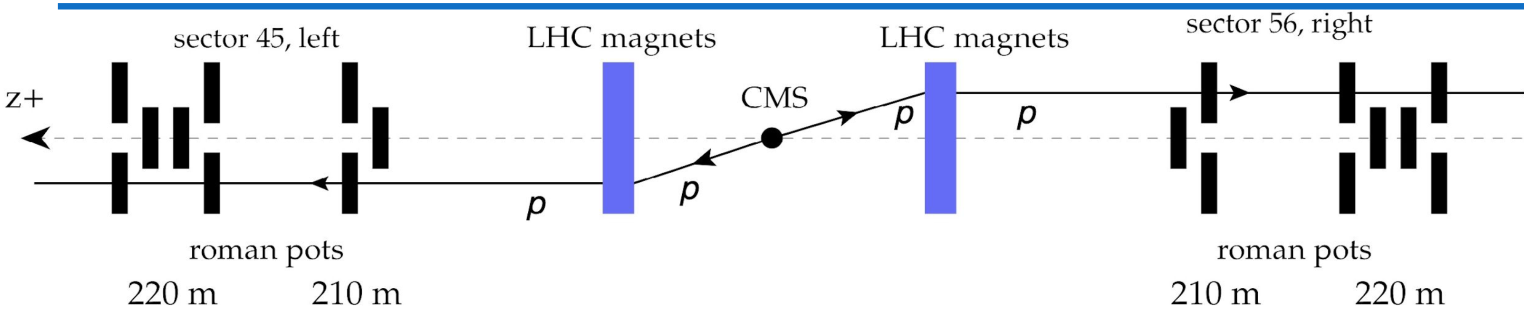
Event counting in kinematic categories



$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

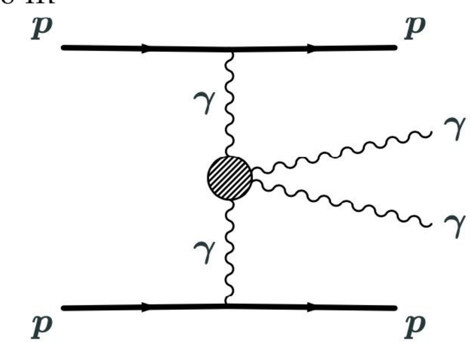
Arxiv:2010.04019

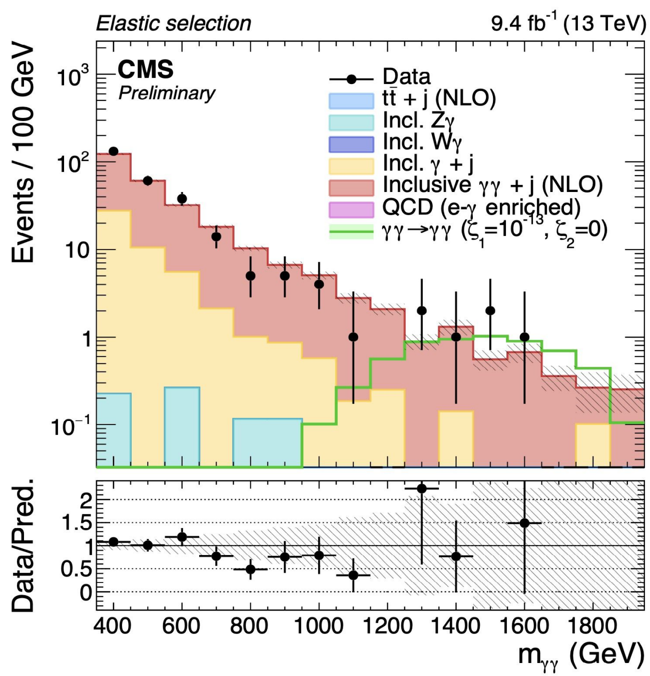
Exclusive γγ with intact protons



CMS PAS EXO-18-014

- Composite measurement with CT-PPS for proton tag
- 2016: 9.6 fb^{-1}, extendable to full Run2 (110 fb^{-1})
- Performed for $m_{\gamma\gamma}$ > 350 GeV
- Closed kinematics!





No event survives matching of protons and photons

First limit on quartic couplings:

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

$$|\zeta_1| < 3.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_2 = 0)$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_1 = 0)$$

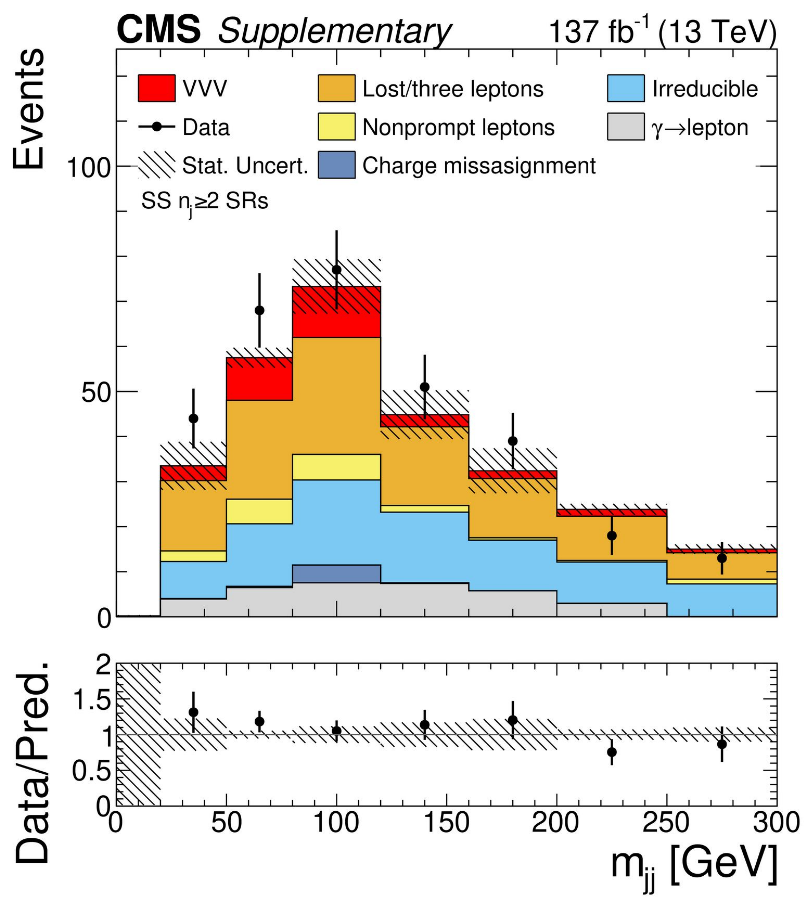
VVV: first observation

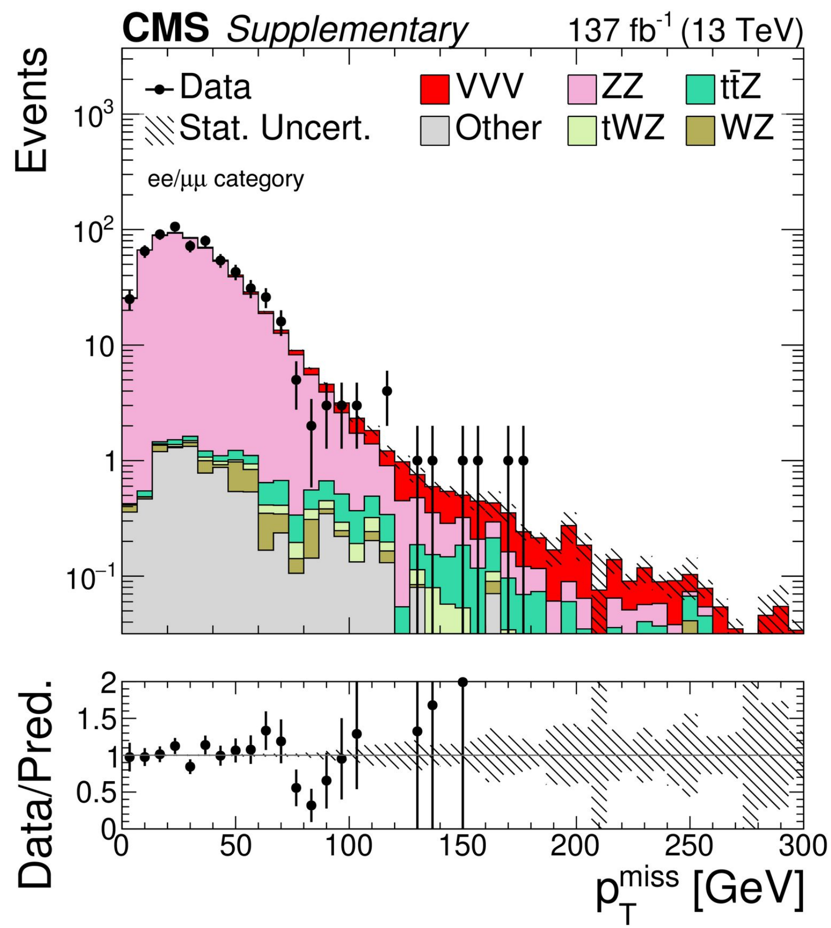
Phys. Rev. Lett. 125 (2020) 151802

Fundamental test of non-abelian structure of EWK

- Triple and quartic couplings

	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Targeted signal	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$





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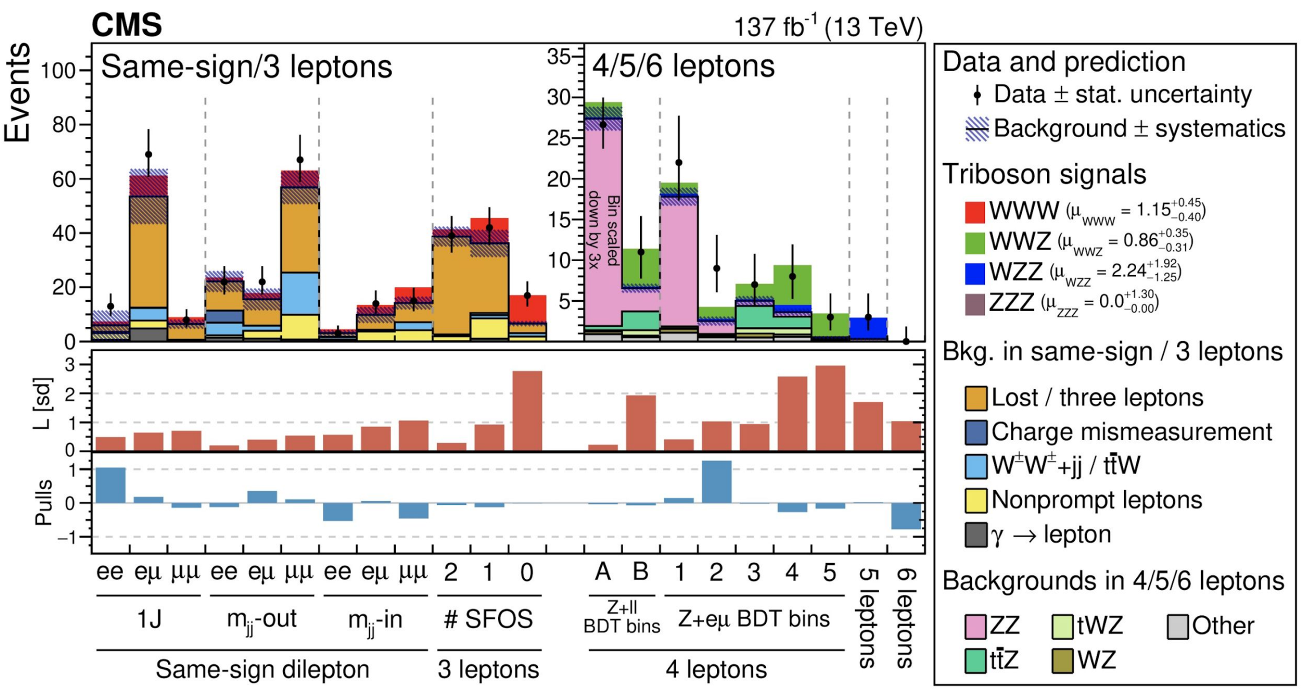
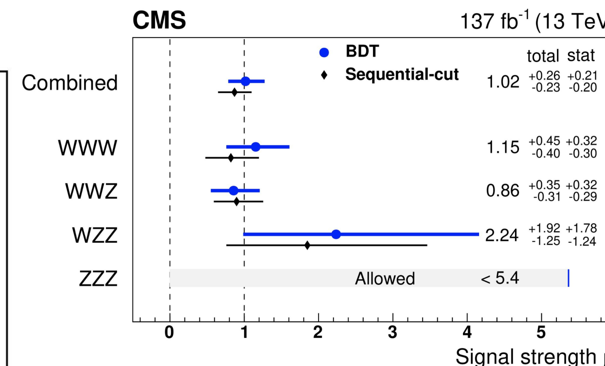




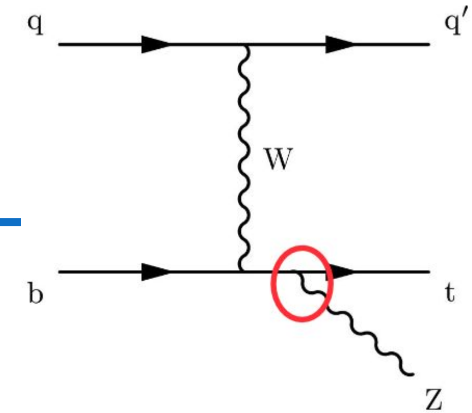
Final state	Significance [σ]
WWW	3.3 (3.1)
WWZ	3.4 (4.1)
WZZ	1.7 (0.7)
ZZZ	0 (0.9)
Combined	5.7 (5.9)

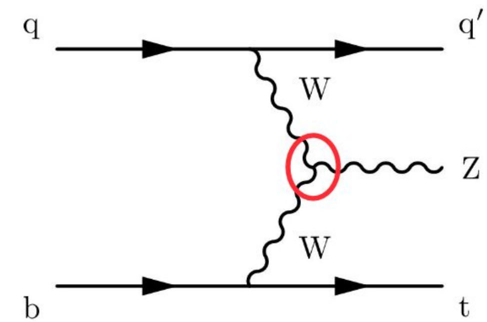
Evidence for WWW and WWZ and VVV observation
Fully statistically dominated

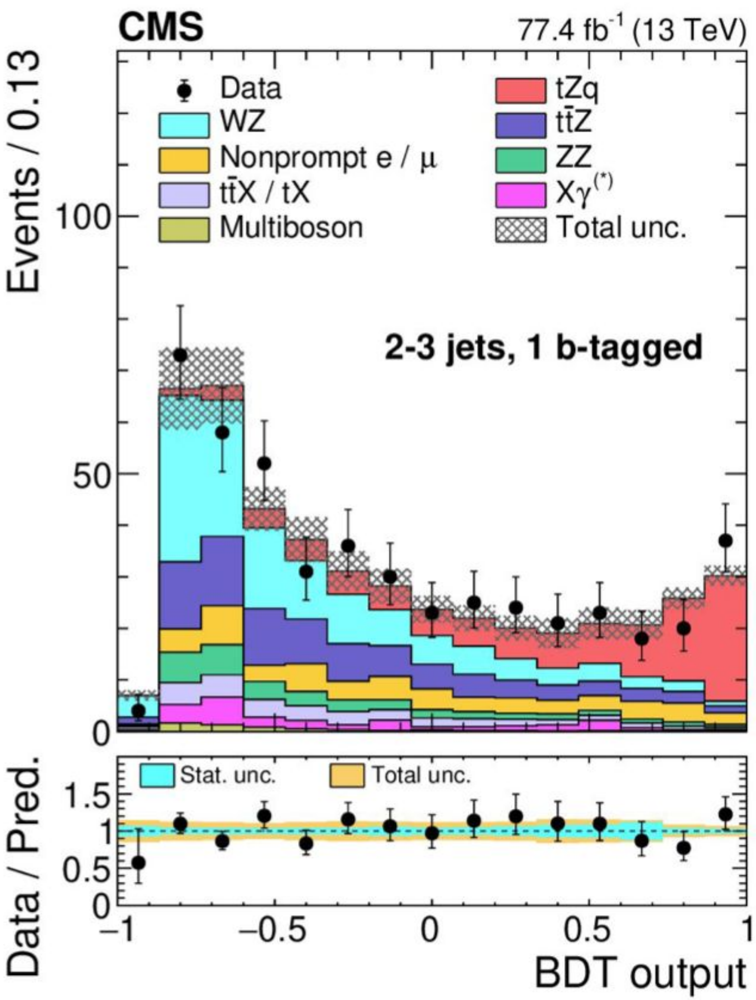
Observation of tZq

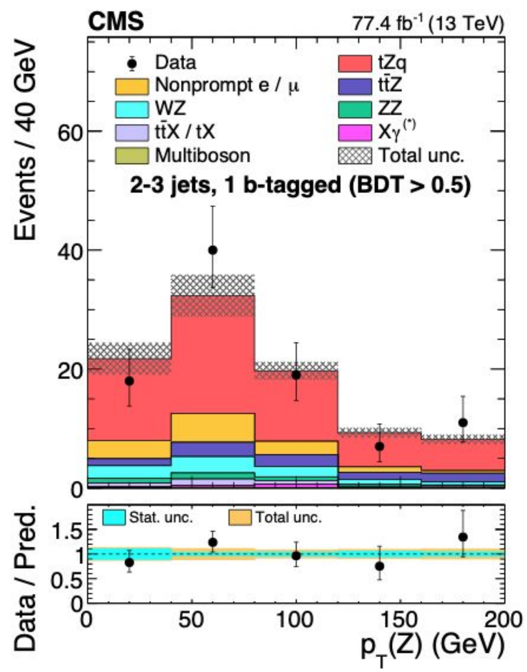
Rare process, sensitive to WWZ coupling

Searched in fully leptonic final state, with two jets (one b-tagged)









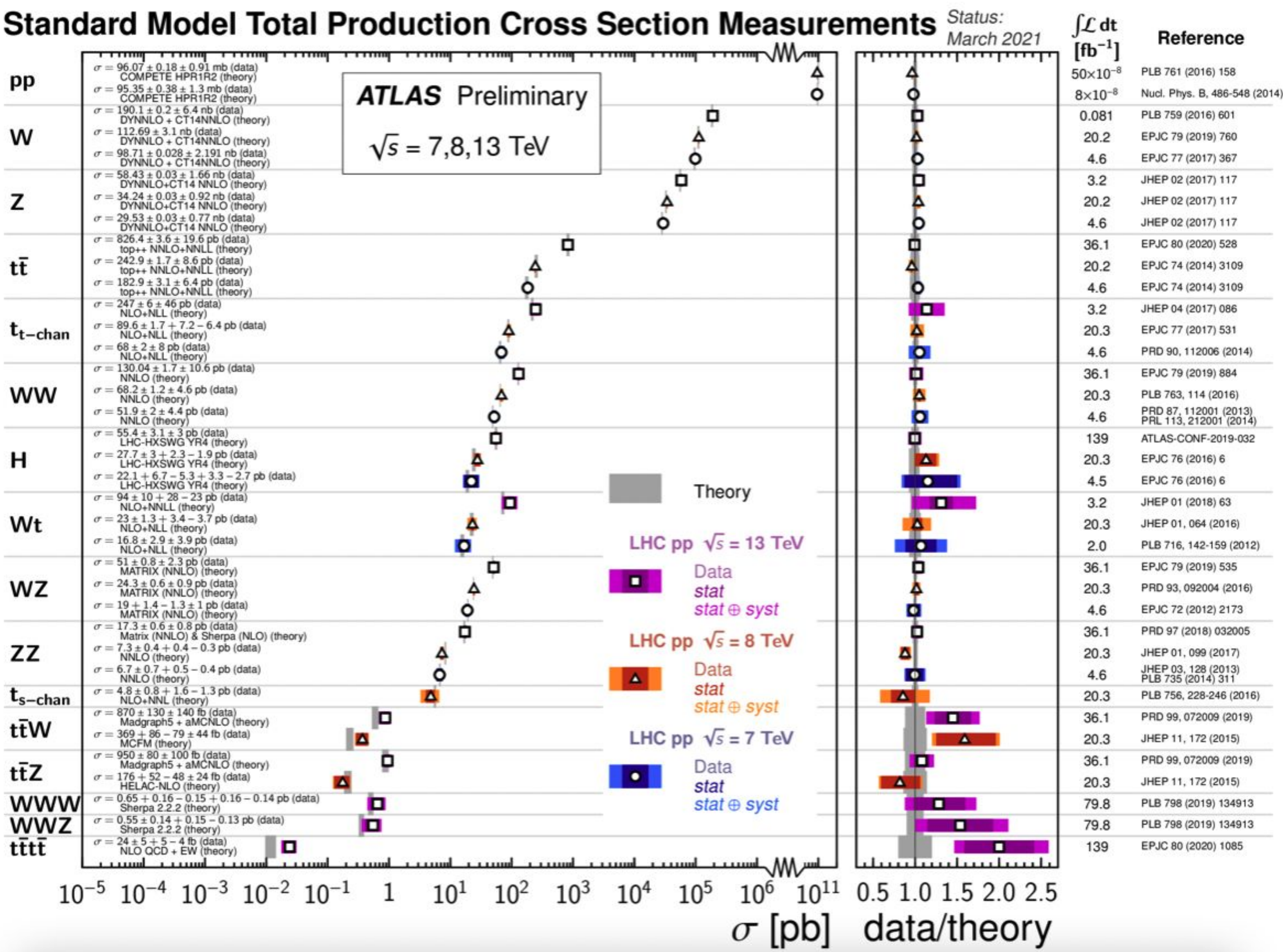
PRL 122 (2019) 132003

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

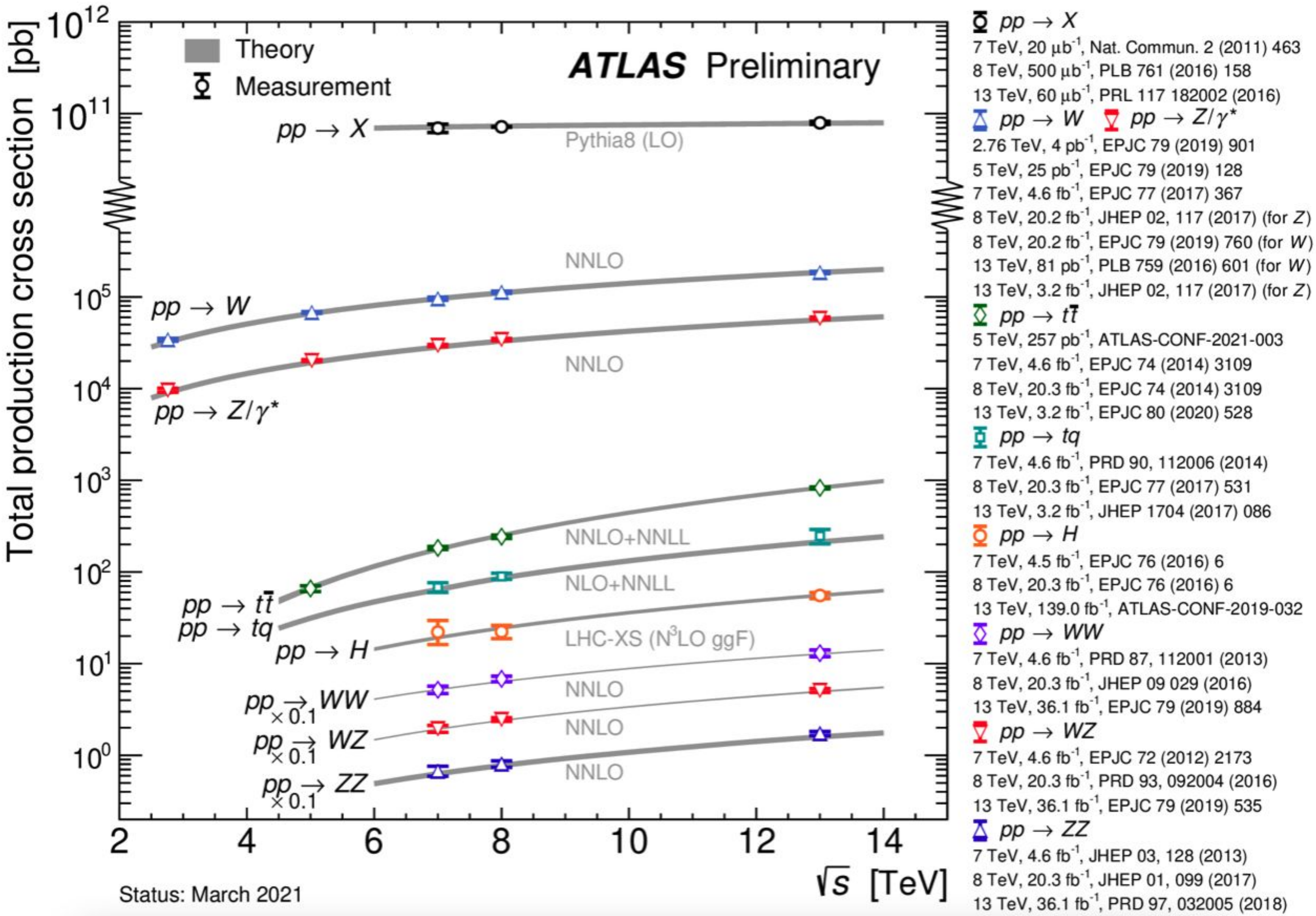
good agreement with theoretical NLO prediction

$$\sigma_{SM}(pp \rightarrow tZq \rightarrow tl^+l^-q) = 94.2 \pm 3.1 \text{ fb}$$

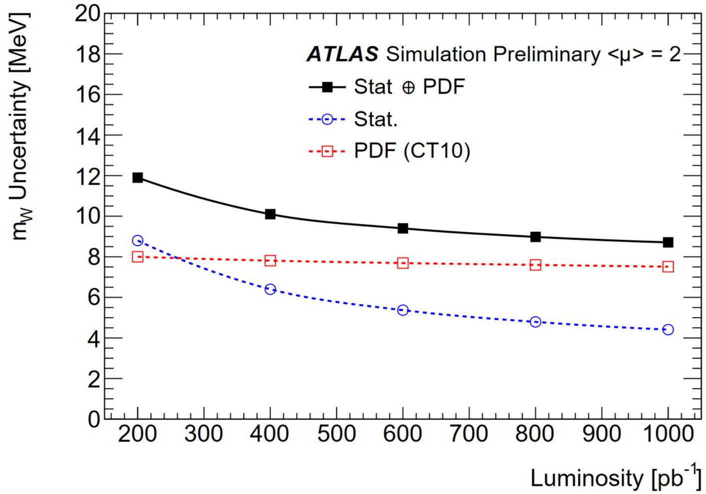
Complete picture

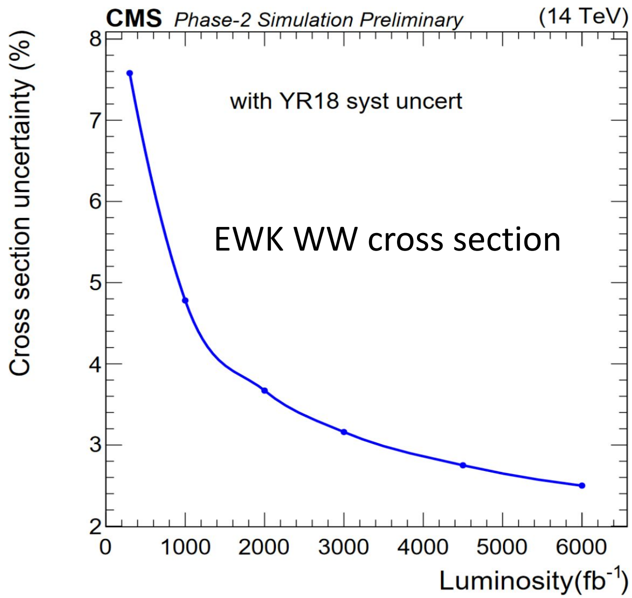


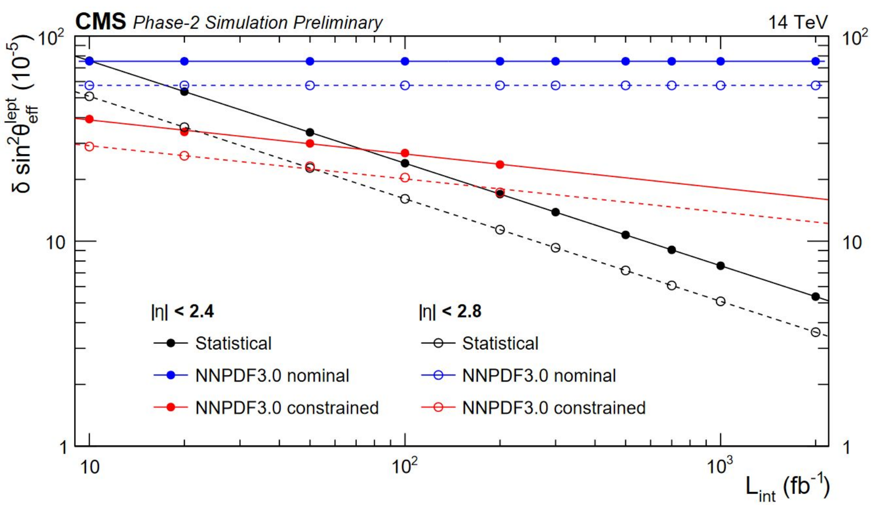
Complete picture (II)

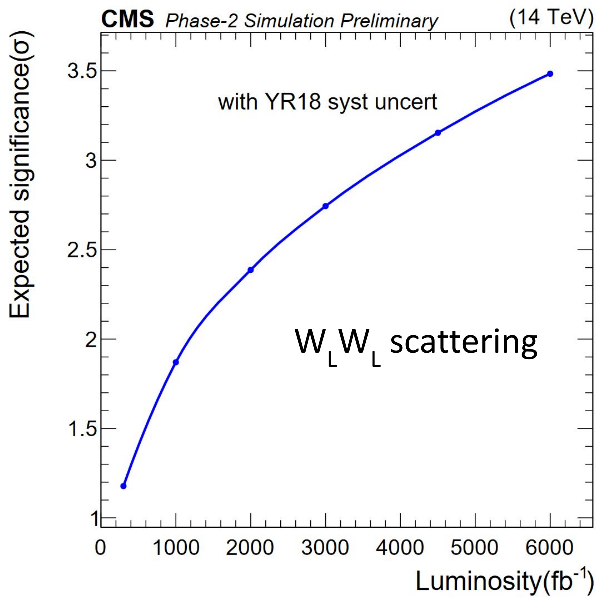


Vector bosons at HL-LHC









Wrap-up

LHC is a top/vector boson factory

- Huge amount of final states and possible analyses to be performed
- Physics program of experiments far from being completed

Direct access to many fundamental parameters of SM

- Incentive to work with(in) theory community

Serve both search for new physics and improve understanding of SM (often via MC tuning)

- Many final states relevant for BSM searches (see next)

Many analyses start to be systematically limited

- Push on experimental techniques

Flavor physics

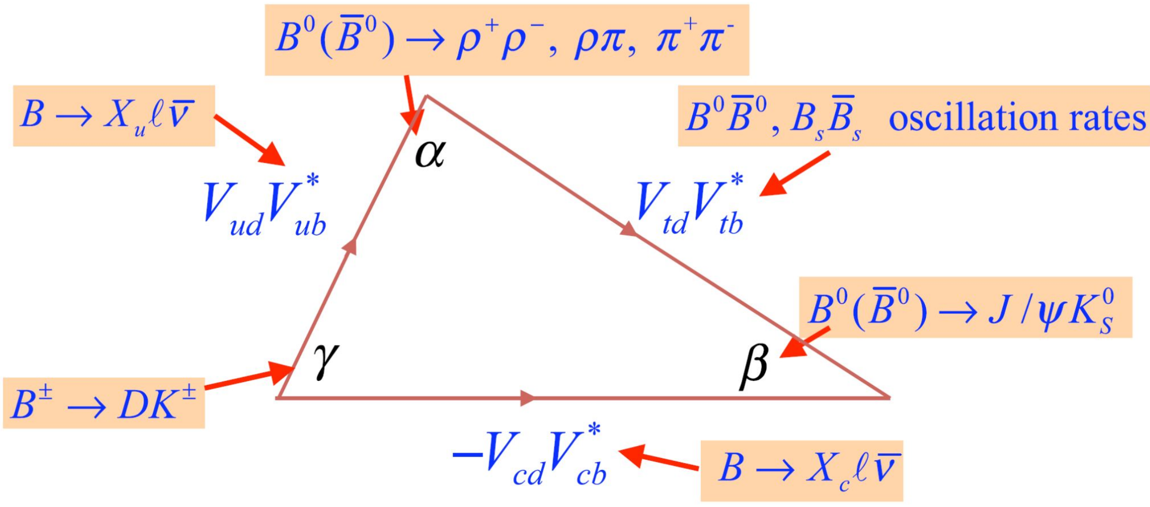
CKM 101

CKM matrix is a rotation matrix between quark mass eigenstates and weak interaction eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

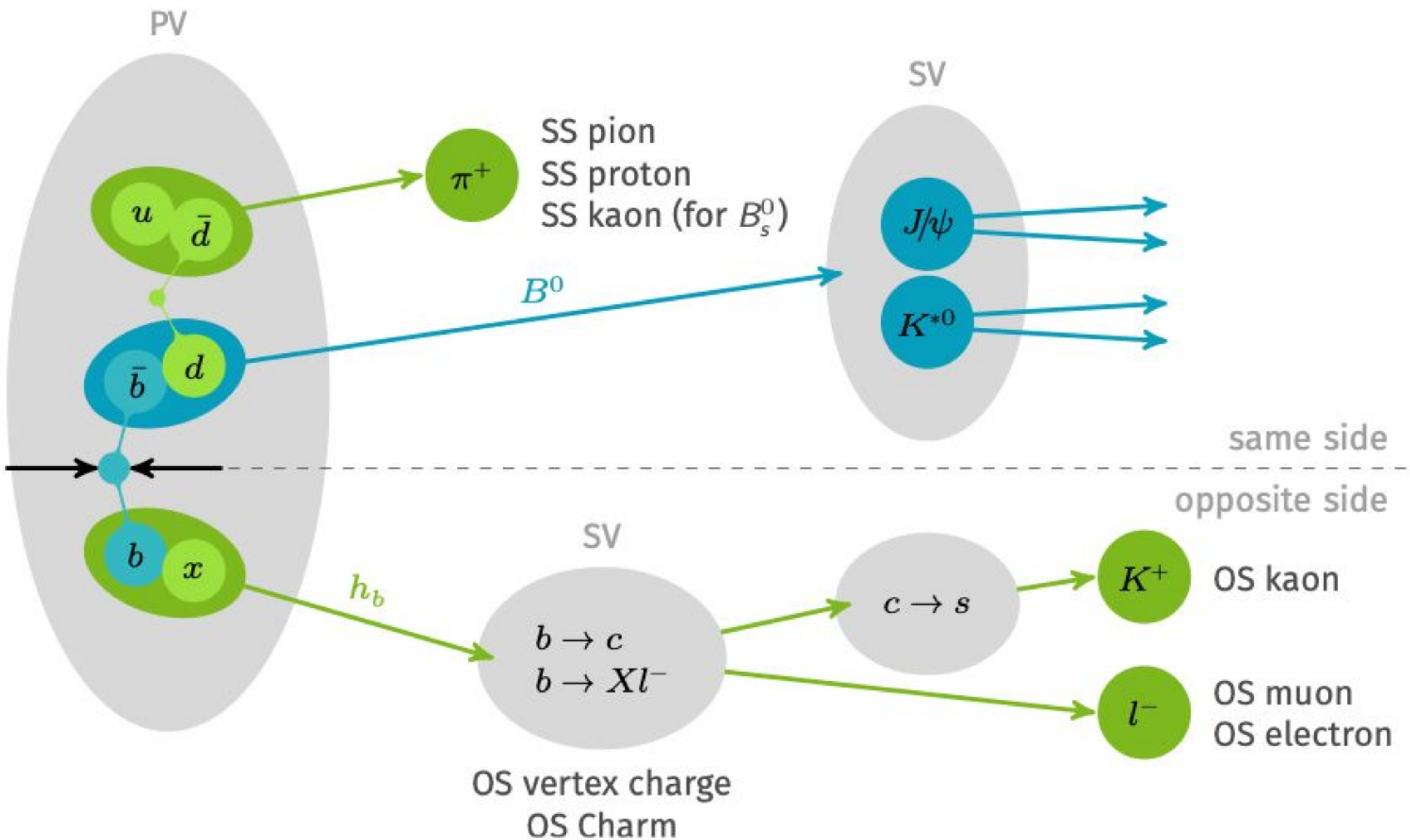
Unitarity conditions and three generations
$\rightarrow$ 3 degrees for rotation + 1 irreducible phase

Additional phases if more generations



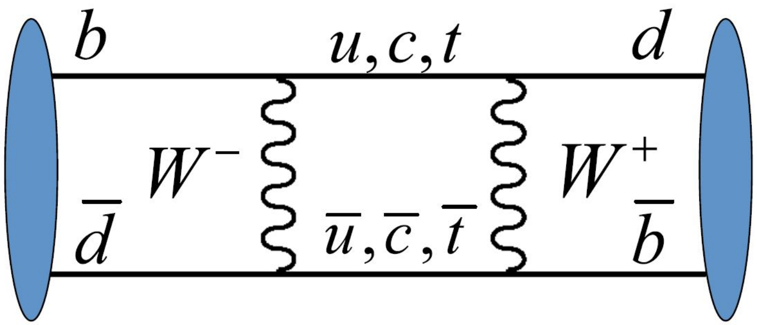
It's all about the phases! Remember: CPV only emerges in interference between diagrams

Flavor tagging at LHC



Mistag rate introduces dilution factor to measured CP violation

B oscillations

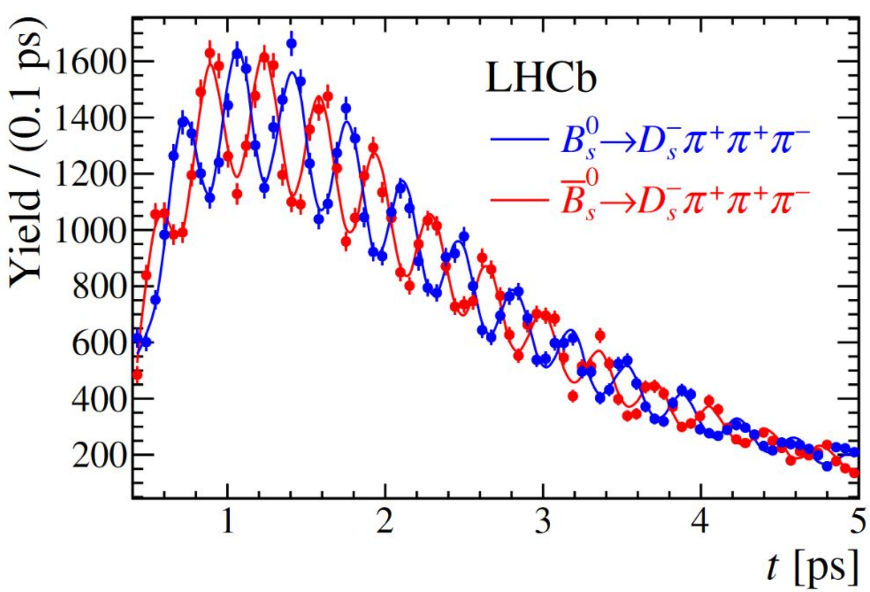


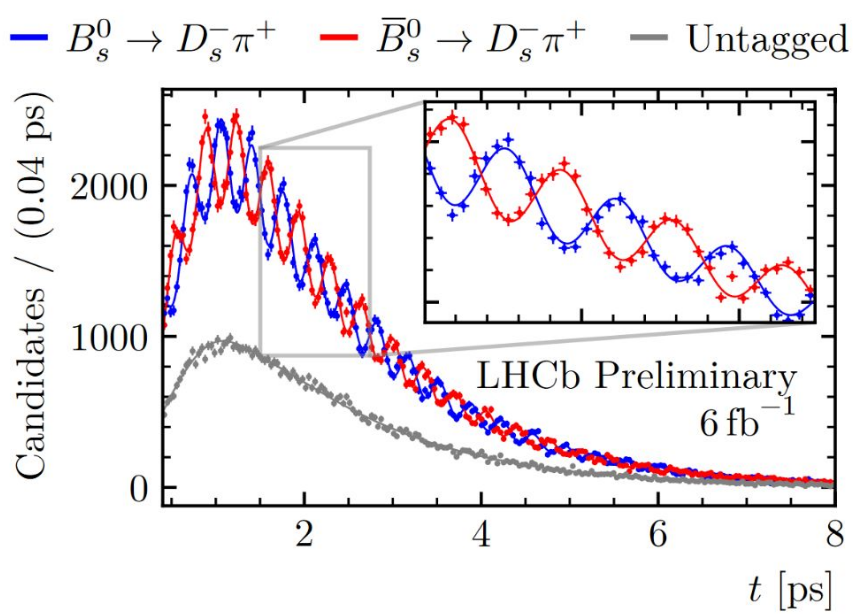
Oscillation frequency with $\Delta m = m_H - m_L$

Need optimal time resolution to be sensitive

LHCb reaches ~15% in B_s period resolution

$\Delta m_s = (17.7666 \pm 0.0057)\ ps^{-1}$





arXiv:2011.12041

CPV

Three types of measurable CP violation:

1) in decay (direct): amplitude of decay and CP conjugate are different. Can occur in charged B mesons

$$\mathcal{P}(B^0 \to f) \neq \mathcal{P}(\bar{B}^0 \to \bar{f})$$

2) in mixing

$$\mathcal{P}(B^0 \to \bar{B}^0) \neq \mathcal{P}(\bar{B}^0 \to B^0)$$

3) in interference of decay and mixing

Quantities to measure

$$A_{CP} = \frac{\left|\overline{A}_{\overline{f}}\right|^2 - \left|A_f\right|^2}{\left|\overline{A}_{\overline{f}}\right|^2 + \left|A_f\right|^2}$$

Time integrated

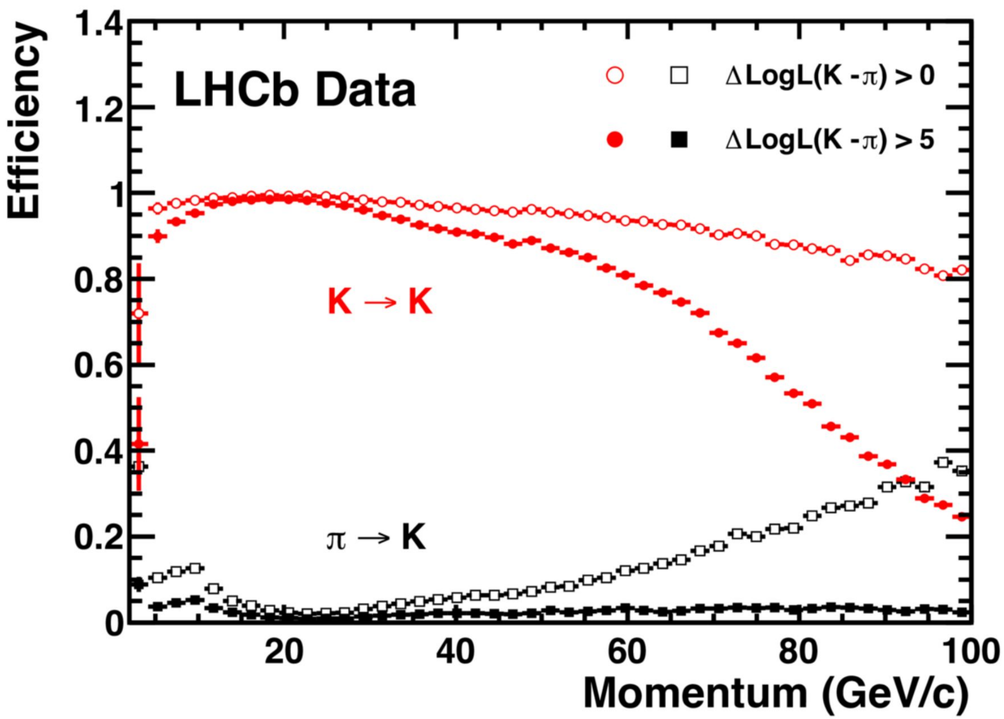
$$A_{CP}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

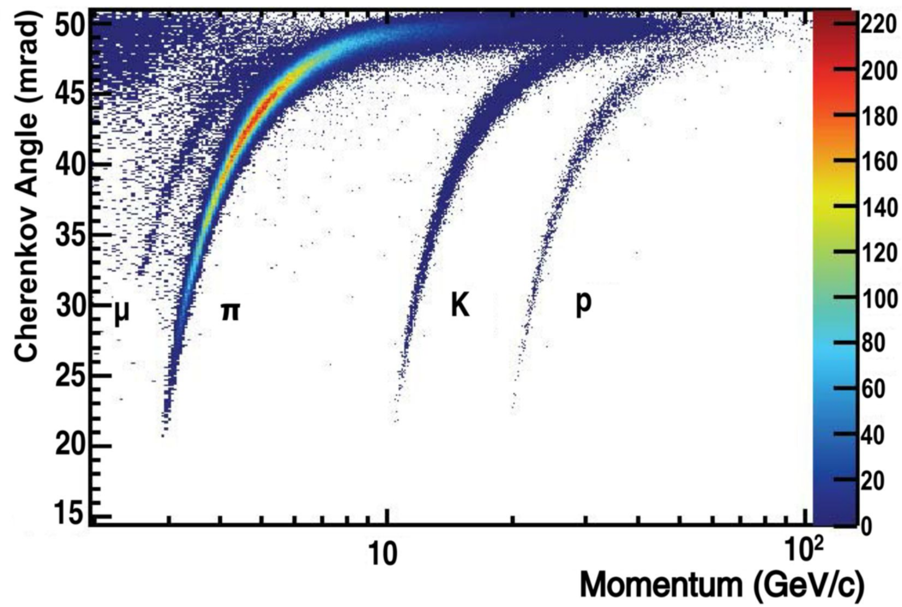
Time dependent

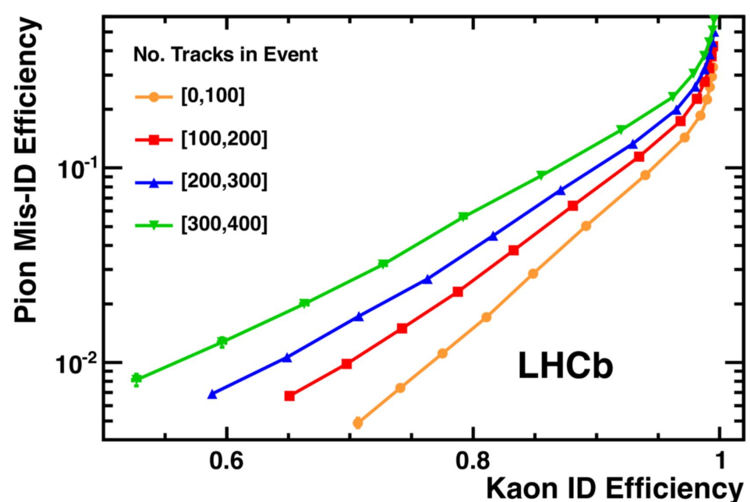
The key is PID (and vertexing…)

K/π discrimination fundamental for LHCb physics program

along with vertex determination



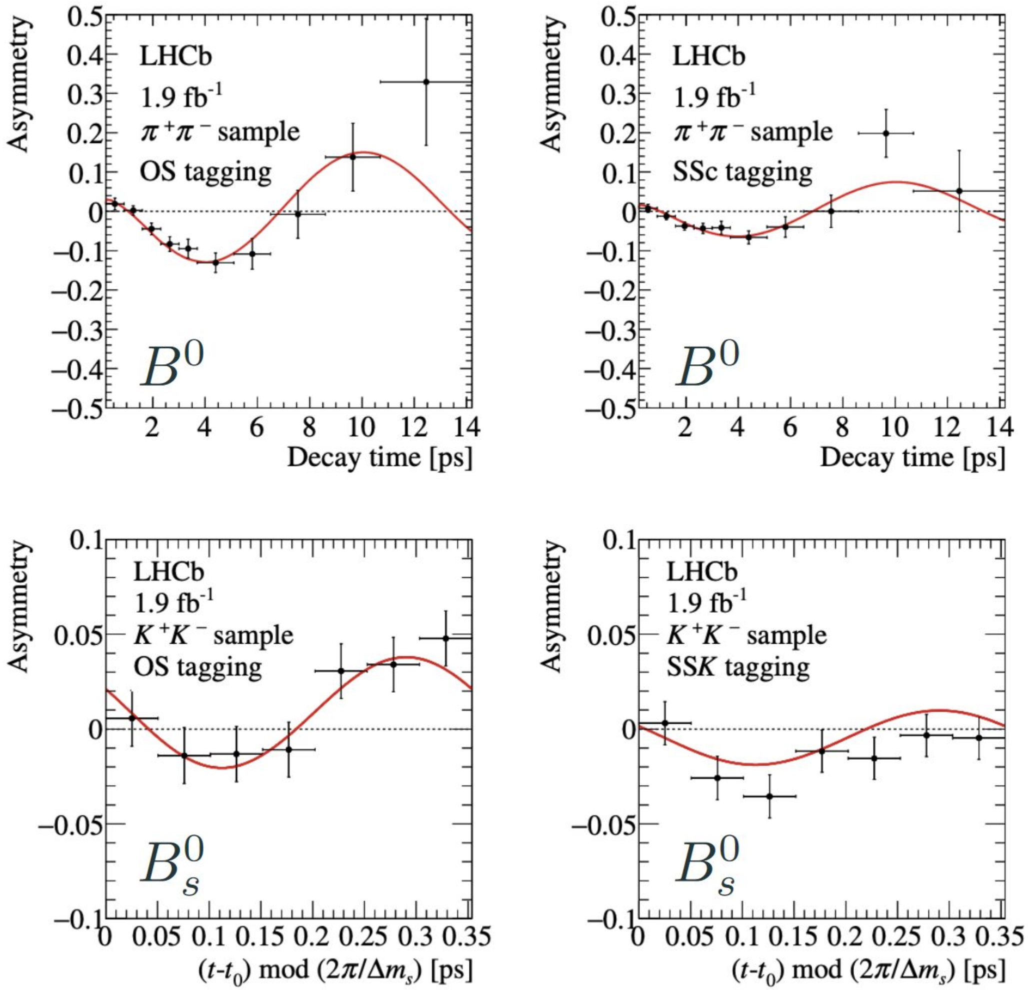




$B^0_{(s)} \rightarrow h^+h^-$

$$B^0 \to \pi^+\pi^-, B_s^0 \to K^+K^-$$
$$B^0 \to K^+\pi^-, B_s^0 \to K^-\pi^+$$

arXiv:2012.05319



First observation of time-dependent CPV in the B_s system

$$\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015 \\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013 \\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014 \\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015 \\
\mathcal{A}^{\Delta\Gamma}_{KK} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}$$

$$\begin{aligned}
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \pm 0.0033 \\
A_{CP}^{B_s^0} &= 0.236 \pm 0.013 \pm 0.011.
\end{aligned}$$

The K-π puzzle

Isospin invariance should hold(-ish) for A_{CP}

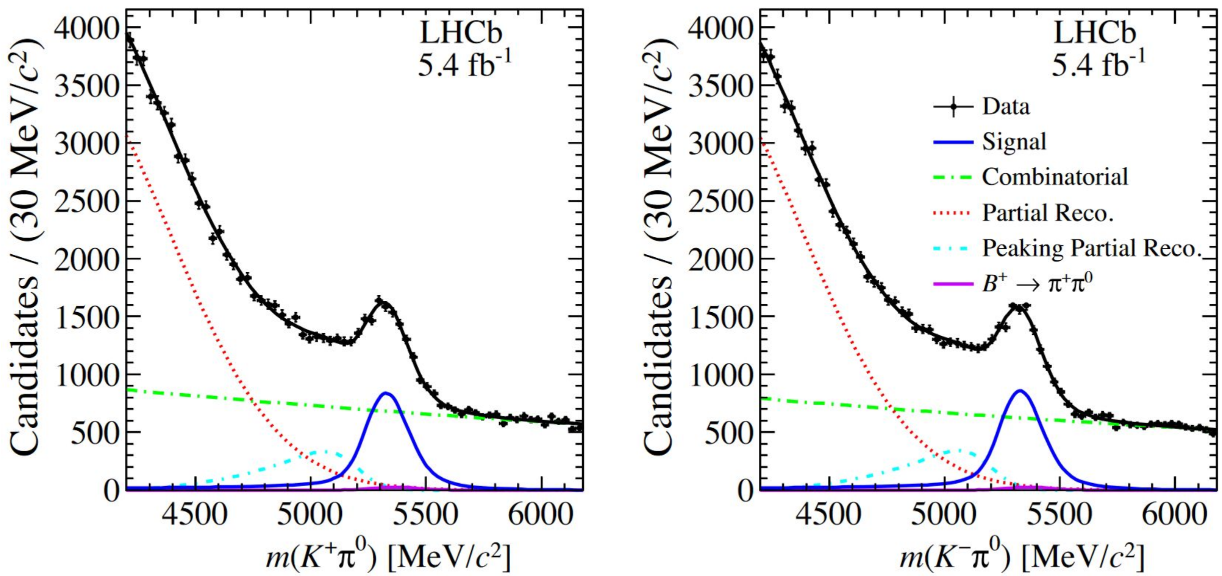
PRL 126, 091802

but $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.122 \pm 0.022$

This is known as the K-π puzzle

LHCb also measured $B^+ \longrightarrow K^+\pi^0$

Very challenging in hadronic environment



$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003,$$

$$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$$

now 8σ from zero

γ from B→Dh

Main way to access $\gamma = \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right]$

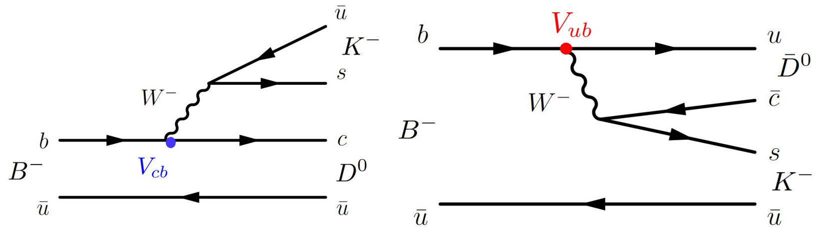
Workhorse of LHCb physics program

Interference between favoured and suppressed diagrams

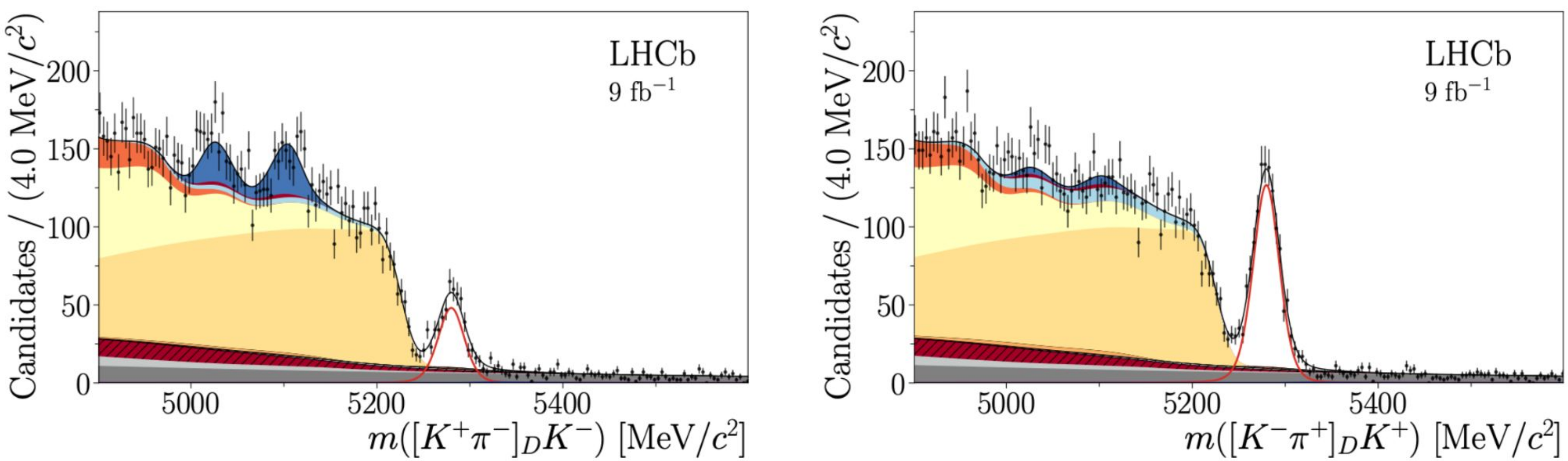
Final state common to D^0 and anti-D^0

Relative weak phase + strong phase

2-body → constant   multibody → function of Dalitz plot position



$$A_B \propto A_D + r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}$$



$$A_K^{\pi K} = -0.451 \quad \pm 0.026$$

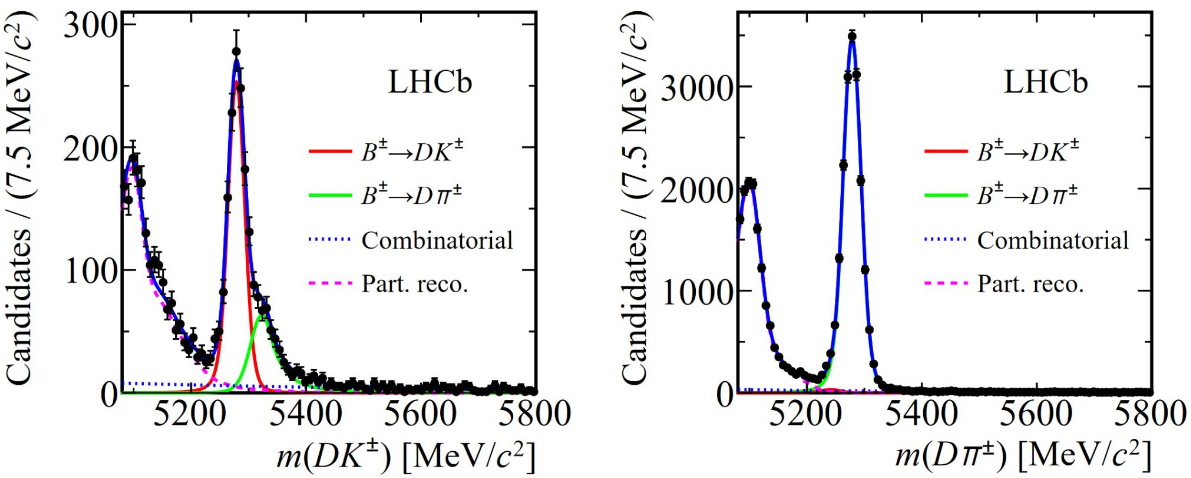
arXiv:2012.09903

γ from B⟶Dh

Multibody charm decays: Dalitz plot!

For example using D->$K_s\pi\pi$

$$A_B(m_-^2, m_+^2) \propto A_D(m_-^2, m_+^2) + r_B e^{i(\delta_B-\gamma)} A_{\bar{D}}(m_-^2, m_+^2)$$



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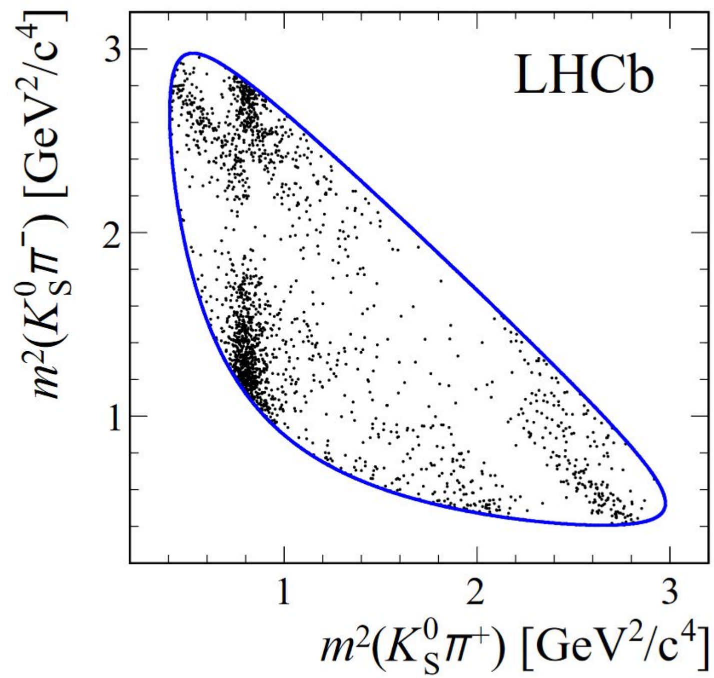
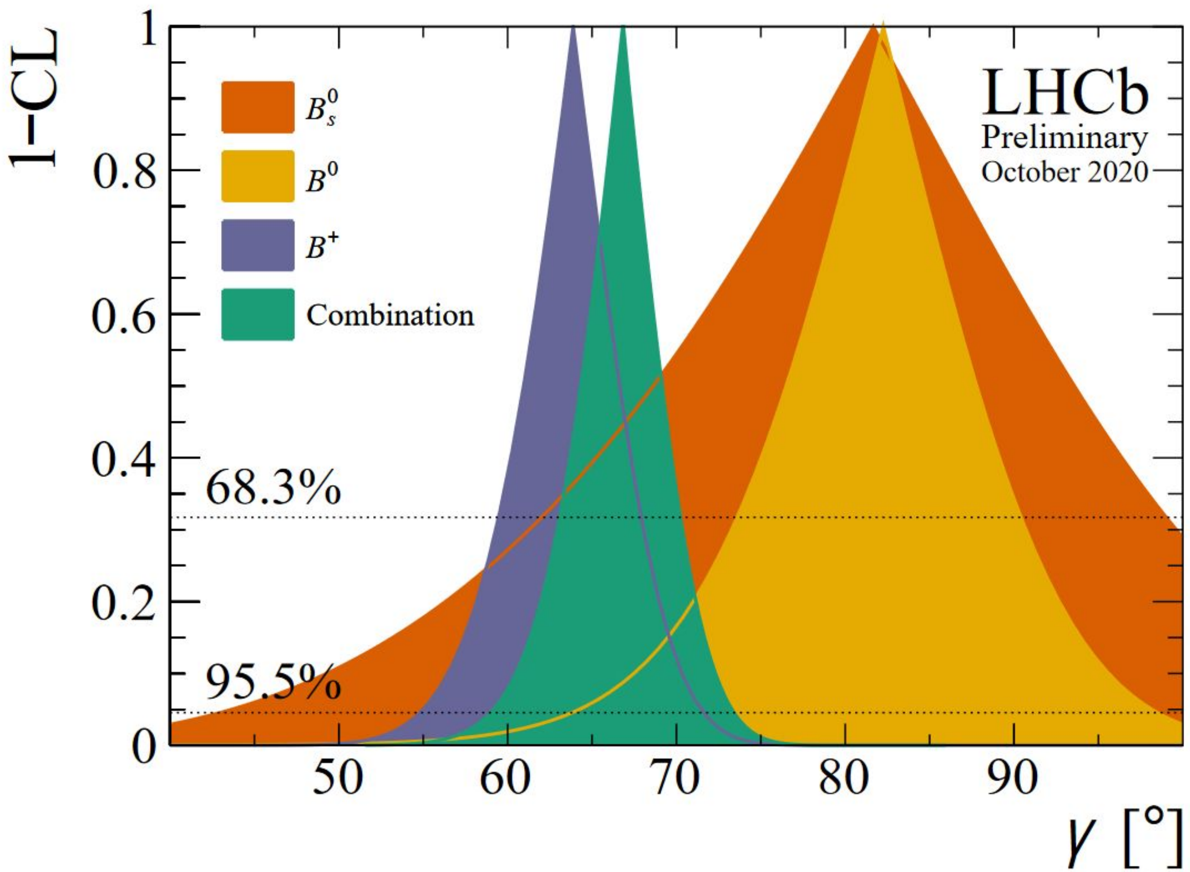


$$\gamma = 87^\circ \,{}^{+11^\circ}_{-12^\circ} \left({}^{+22^\circ}_{-23^\circ}\right),$$
$$r_B = 0.086 \,{}^{+0.013}_{-0.014} \left({}^{+0.025}_{-0.027}\right)$$
$$\delta_B = 101^\circ \,{}^{+11^\circ}_{-11^\circ} \left({}^{+22^\circ}_{-23^\circ}\right).$$

γ combination

B decay	D decay
$B^+ \to Dh^+$	$D \to h^+h^-$
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$
$B^+ \to Dh^+$	$D \to K^0_S h^+h^-$
$B^+ \to Dh^+$	$D \to K^0_S K^\pm\pi^\mp$
$B^+ \to D^*h^+$	$D \to h^+h^-$
$B^+ \to DK^{*+}$	$D \to h^+h^-$
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$
$B^0 \to D^\mp\pi^\pm$	$D^\pm \to K^\mp\pi^\pm\pi^\pm$
$B^0_s \to D_s^\mp K^\pm$	$D_s^\pm \to h^\pm h^\mp\pi^\pm$
$B^0_s \to D_s^\mp K^\pm\pi^\pm\pi^\mp$	$D_s^\pm \to h^\pm h^\mp\pi^\pm$



Experimental combination

$$\gamma = (67 \pm 4)^\circ$$

Theoretical prediction

$$\gamma = \left(65.7^{+0.9}_{-2.7}\right)^\circ$$

LHCb-CONF-2020-003

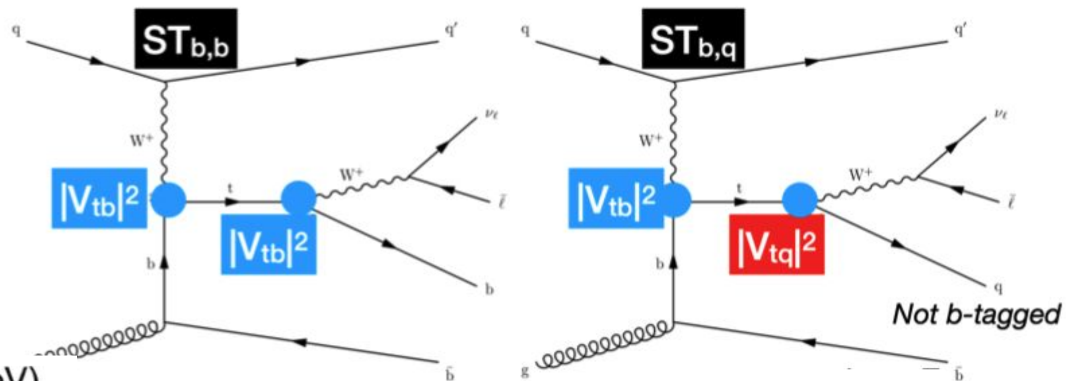
Top row

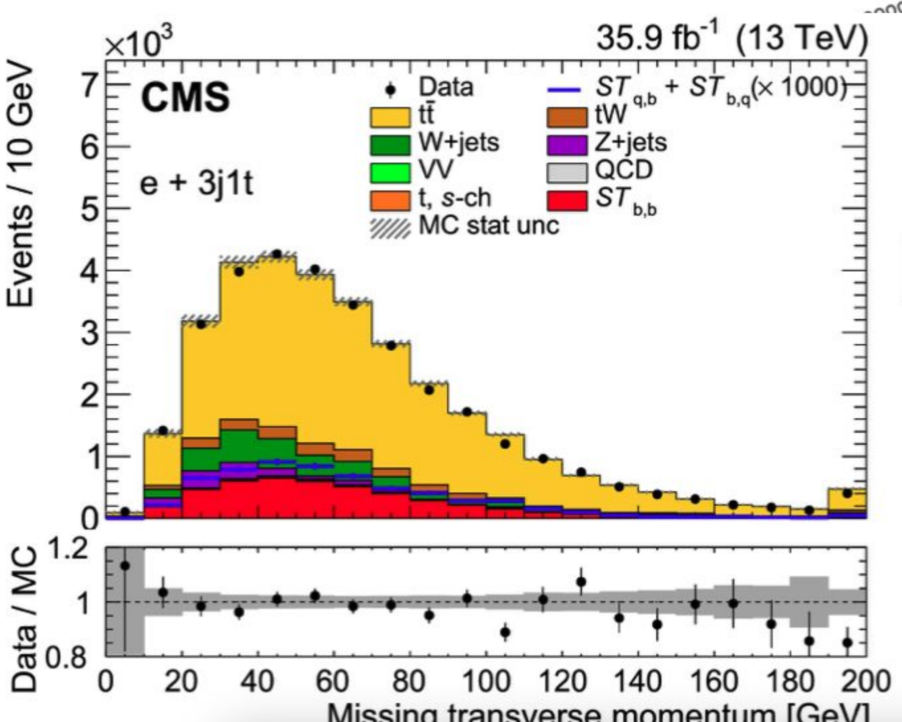
PLB 808 (2020) 135609

User top t-channel to measure its CKM elements

Leptonic W decay

Simultaneous fit in categories of $N_{(b)jet}$





Assume unitarity

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057, \ |V_{tb}| > 0.97$$

Unconstrained total width

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06, \ |V_{tb}| = 0.988 \pm 0.024$$

First direct measurement of third generation elements in a model independent way

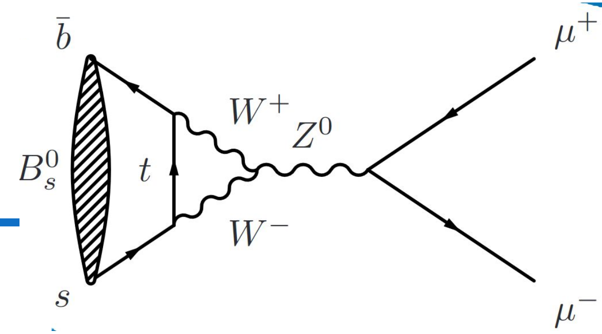
Leptonic B decays

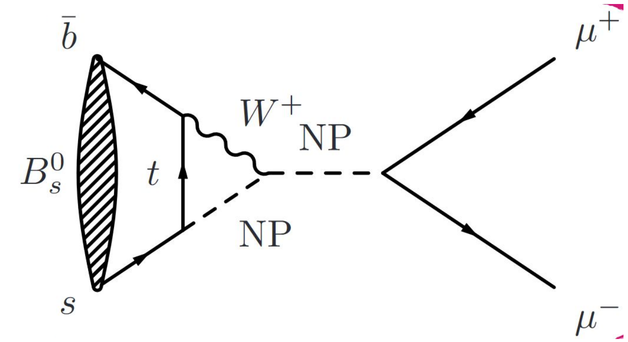
Highly suppressed in SM (FCNC + helicity)

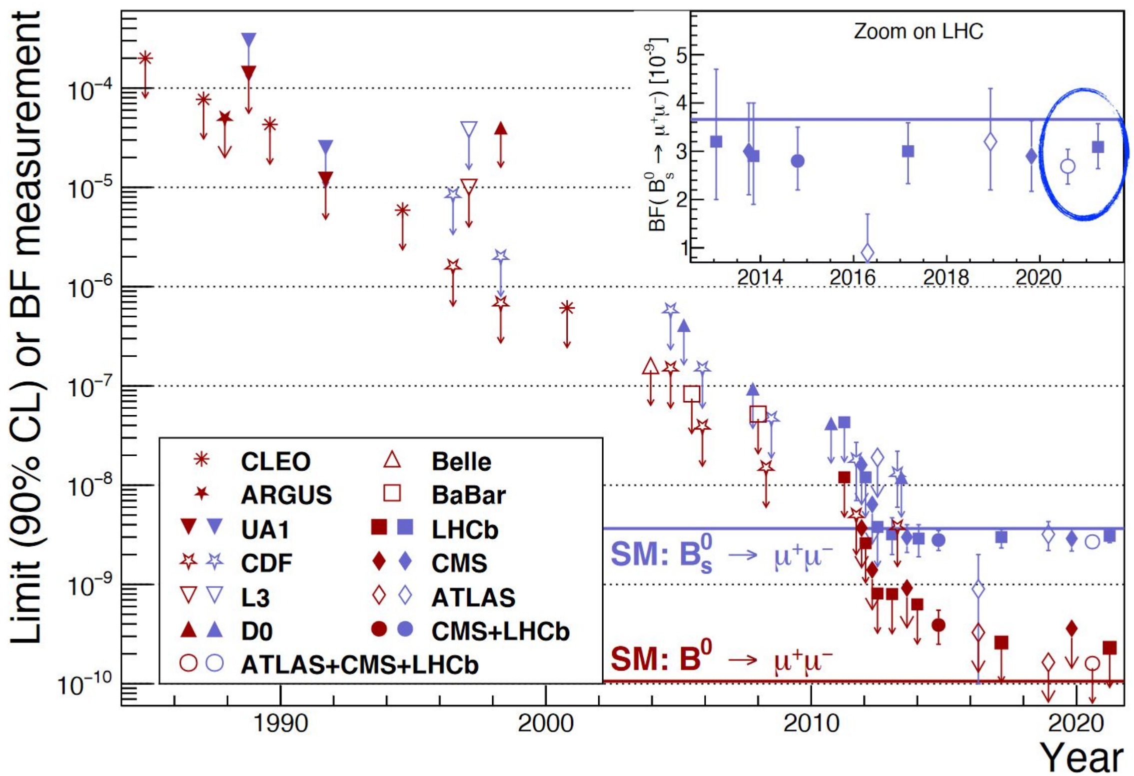
Very little uncertainty for hadronic part

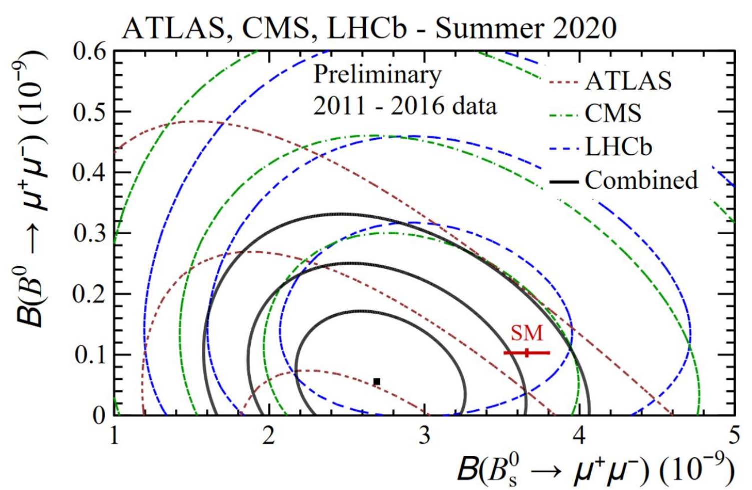
Analysis can be performed by all three experiments

$$\begin{aligned}\mathcal{B}(B_s^0 \to \mu^+\mu^-) &= (3.66 \pm 0.14) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &= (1.03 \pm 0.05) \times 10^{-10}\end{aligned}$$









LHCb-CONF-2020-002

B(s)-> $\mu\mu$ at LHCb

Bump hunting in the $m_{\mu\mu}$ spectrum in [4.9,6] GeV

Use of BDT trained on two-body B decays to improve sensitivity

Main background is dimuon combinatorics

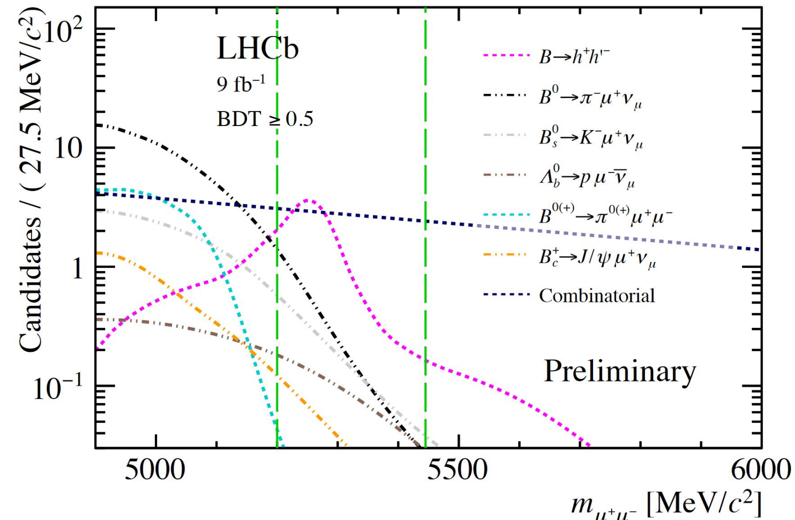
Need to normalize to another process (hadron collider!)

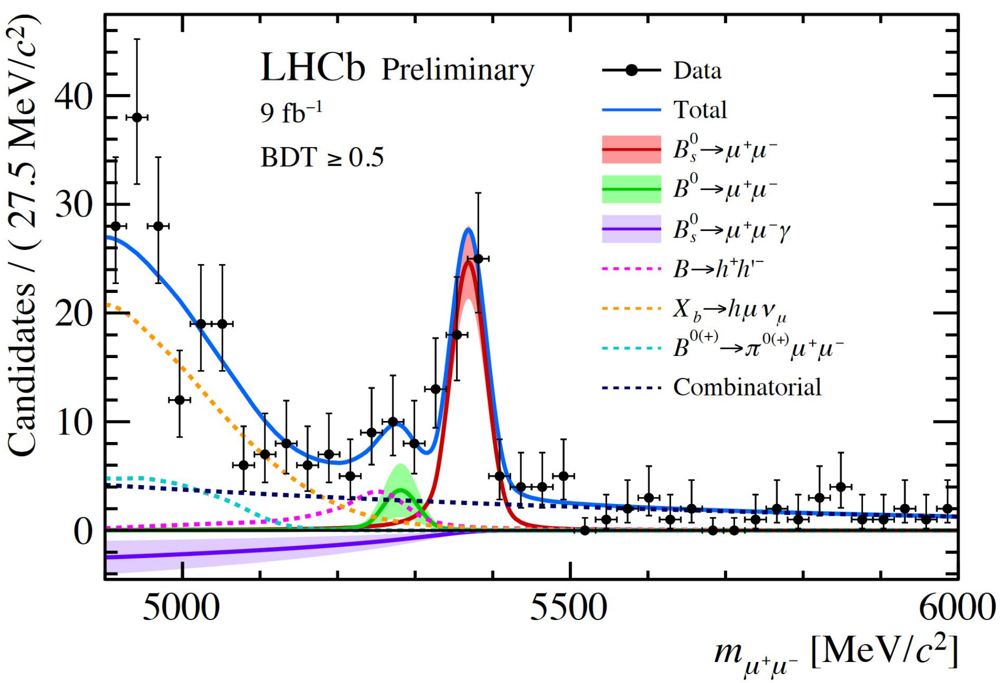
$$\mathscr{B}(B^0_{(s)} \to \mu^+\mu^-(\gamma)) = \frac{f_{\rm sig}}{f_d}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}\frac{N_{\rm sig}}{N_{\rm norm}}\mathscr{B}({\rm norm})$$

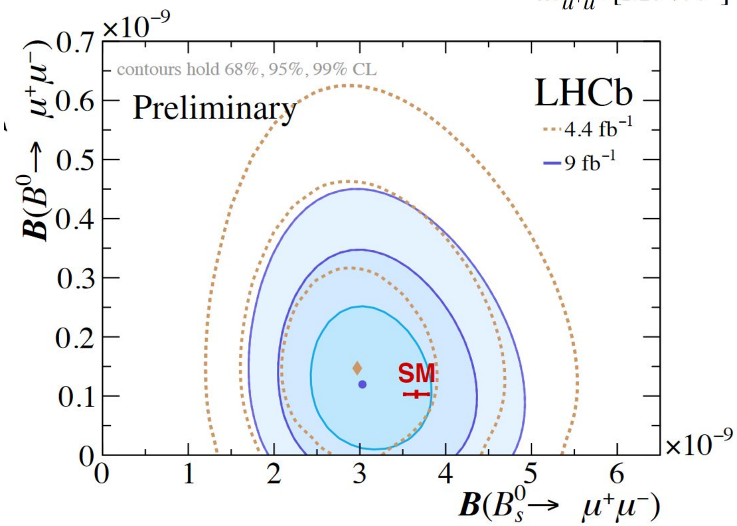
typically $B^+ \to J/\psi\, K^+$

f_s/f_d measured by LHCb

One of the most important uncertainties







$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09\,{}^{+\,0.46}_{-\,0.43}\,{}^{+\,0.15}_{-\,0.11}\right)\times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times10^{-10}$$ 95% CL

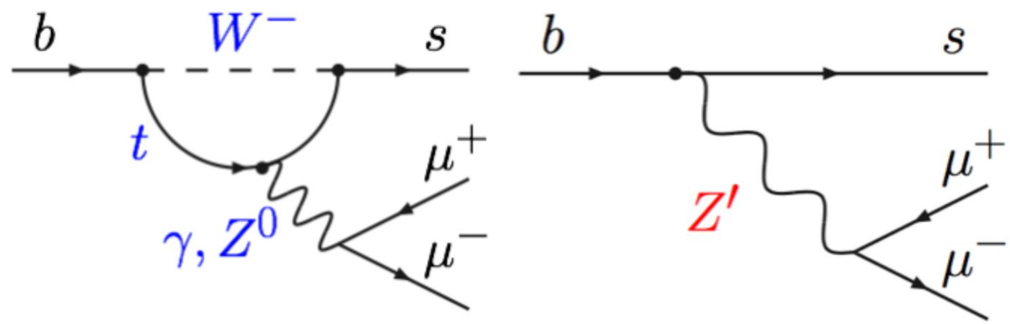
LFU and b⟶sll

In SM couplings of leptons to vector bosons are flavor independent

This doesn't hold in NP

b⟶ sll: a good lab of FCNC

rare in SM (loop), can enter at tree level in NP



$B \longrightarrow K^{(*)}l^+l^-$ has an extensive physics program at LHCb (and with tensions wrt SM)

Typical selection (from the BR measurement):

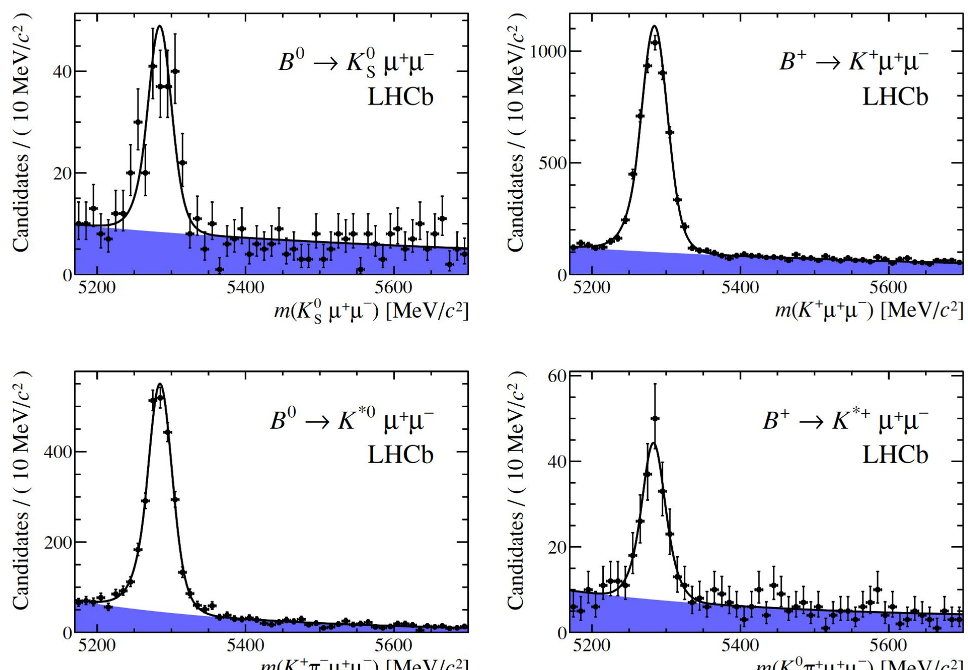
Muon trigger + secondary b-vertex

K_S and K^* selection with mass cuts

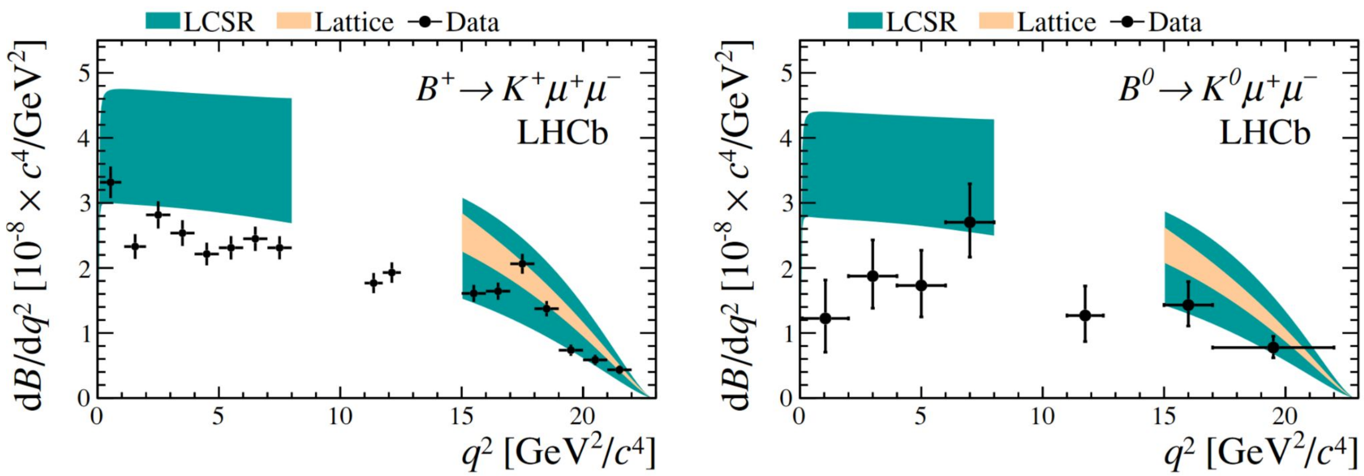
$5170 < m_{K\mu\mu} < 5700$ GeV

BDT selection based on kinematics

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



B⟶ $K^{(*)}$ll: many puzzles



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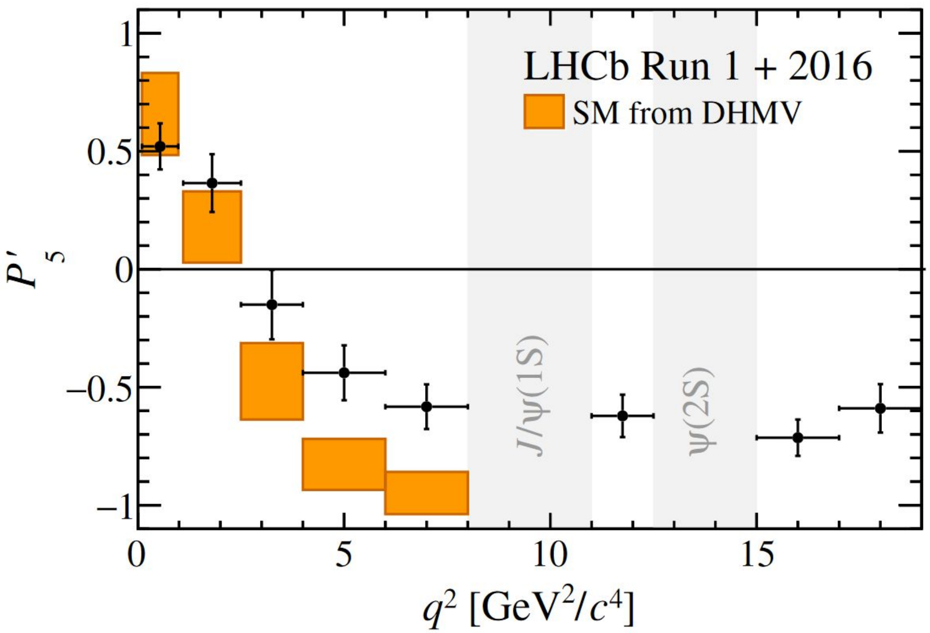


PhysRevLett 125 (2020) 011802

Measurement of R_K

Well defined LFU variable

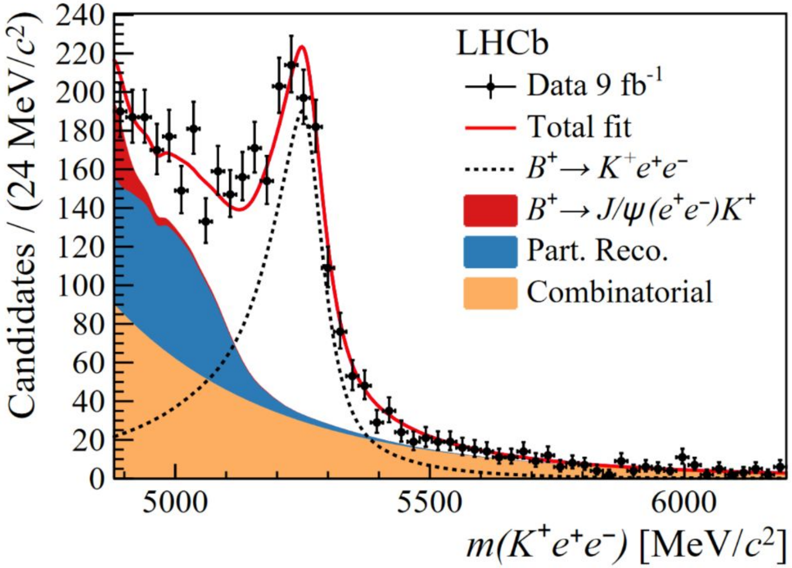
R_K ~ O(1) in SM

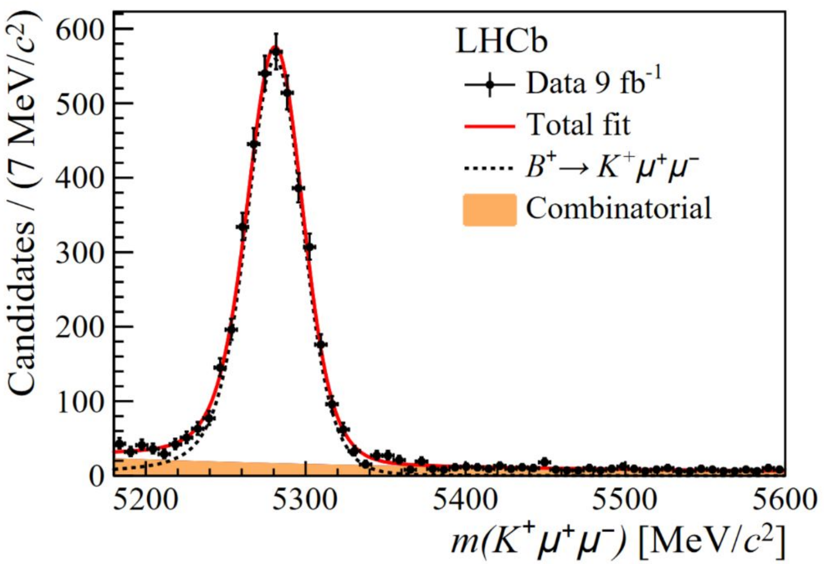
+ O(%) EM corrections

Use double ratio wrt $J/\psi\mu$ to control e-μ contamination

$$R_K = \frac{\int_{1.1}^{6.0} \frac{d\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1}^{6.0} \frac{d\mathcal{B}(B^+\to K^+e^+e^-)}{dq^2} dq^2}$$

$$R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to J/\psi(\to\mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+\to K^+e^+e^-)}{\mathcal{B}(B^+\to J/\psi(\to e^+e^-)K^+)}$$



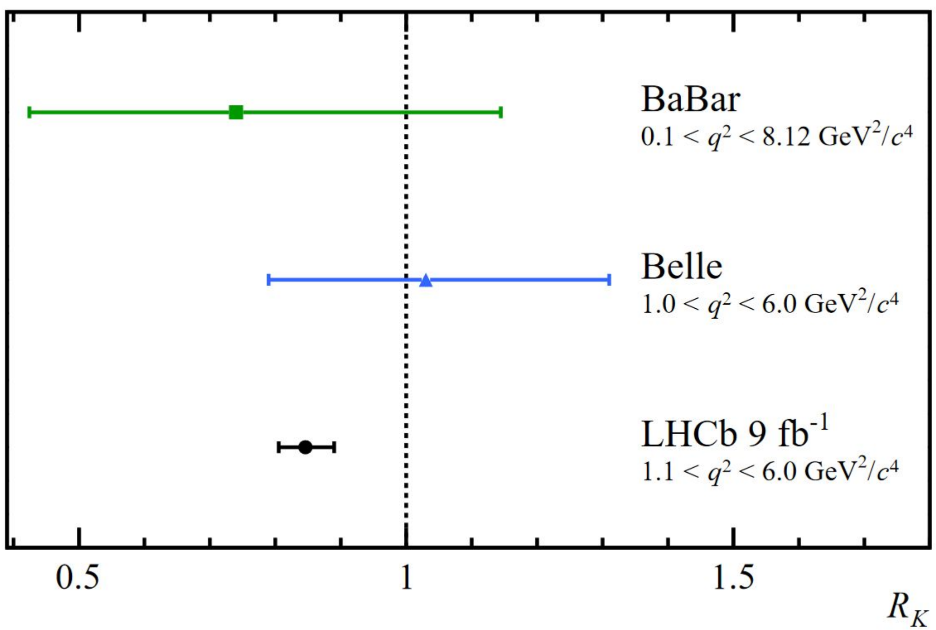


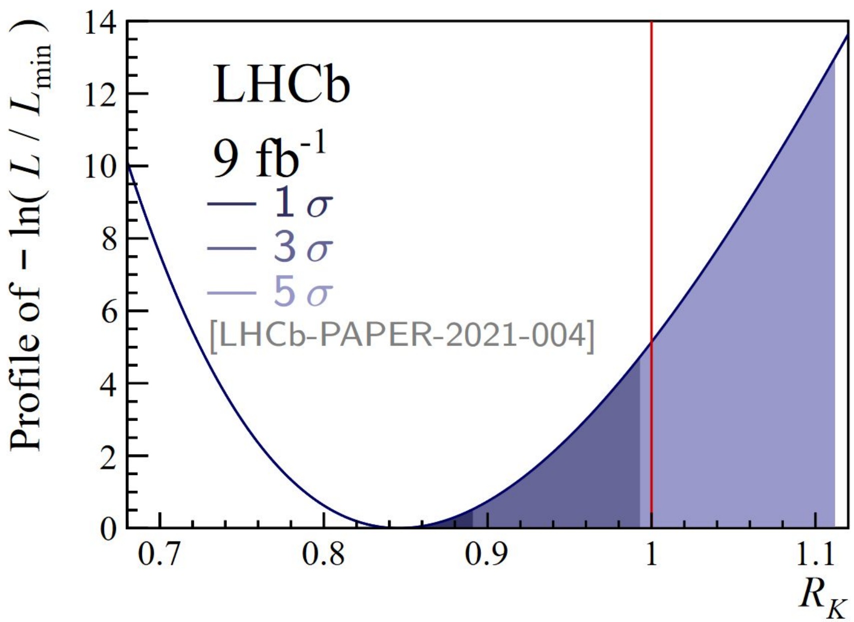
Measurement of R_K

Decay mode	Yield
$B^+ \to K^+e^+e^-$	$1\,640 \pm 70$
$B^+ \to K^+\mu^+\mu^-$	$3\,850 \pm 70$
$B^+ \to J/\psi(\to e^+e^-)K^+$	$743\,300 \pm 900$
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	$2\,288\,500 \pm 1\,500$

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

3.1σ from SM expectation





CPV in charm decays

CPV in up sector largely suppressed in SM

Asymmetries expected of $O(10^{-4}\text{-}10^{-3})$

but very large hadronic uncertainties

LHCb: measure the difference between the asymmetries in KK and $\pi\pi$ final states

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\mathrm{dir}} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma,\end{aligned}$$

need to determine the initial flavor of the D meson, so in reality measure

$$A_{\mathrm{raw}}^{\pi-\mathrm{tagged}}(f) \equiv \frac{N(D^{*+}\to D^0(f)\pi^+) - N(D^{*-}\to \bar{D}^0(f)\pi^-)}{N(D^{*+}\to D^0(f)\pi^+) + N(D^{*-}\to \bar{D}^0(f)\pi^-)}$$

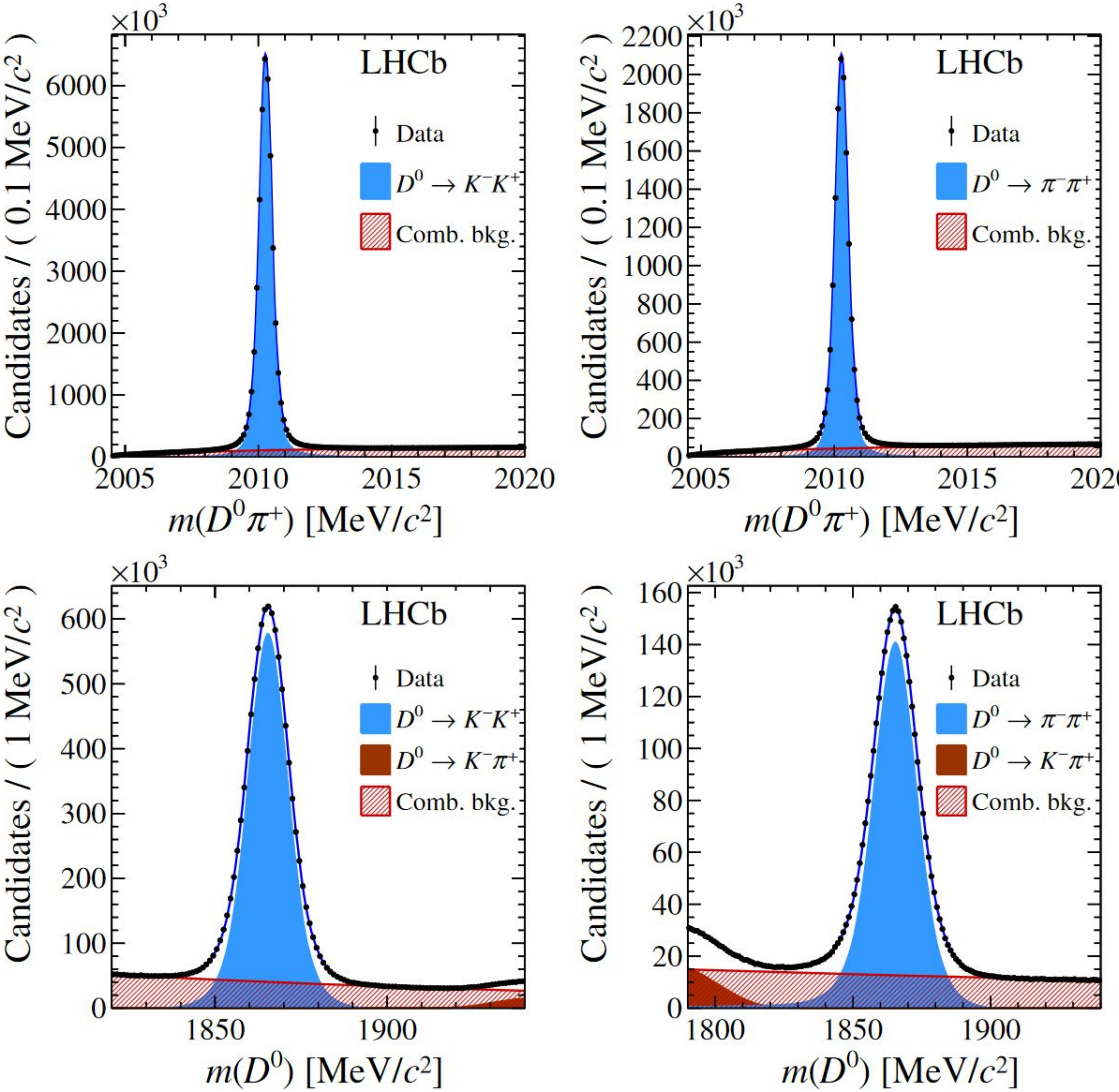
which relates to what we are interested by

$$A_{\mathrm{raw}}^{\pi-\mathrm{tagged}}(f) \approx A_{CP}(f) + A_{\mathrm{D}}(\pi) + A_{\mathrm{P}}(D^*)$$

can also use b->clν decays

$D^0 \to h^+h^-$

PhysRevLett 122 (2019) 211803

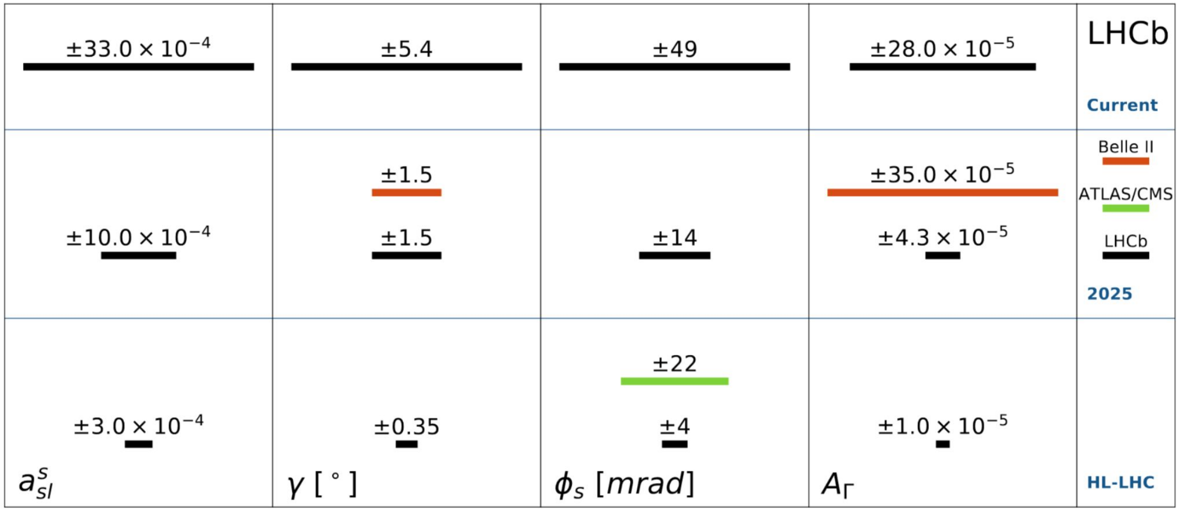


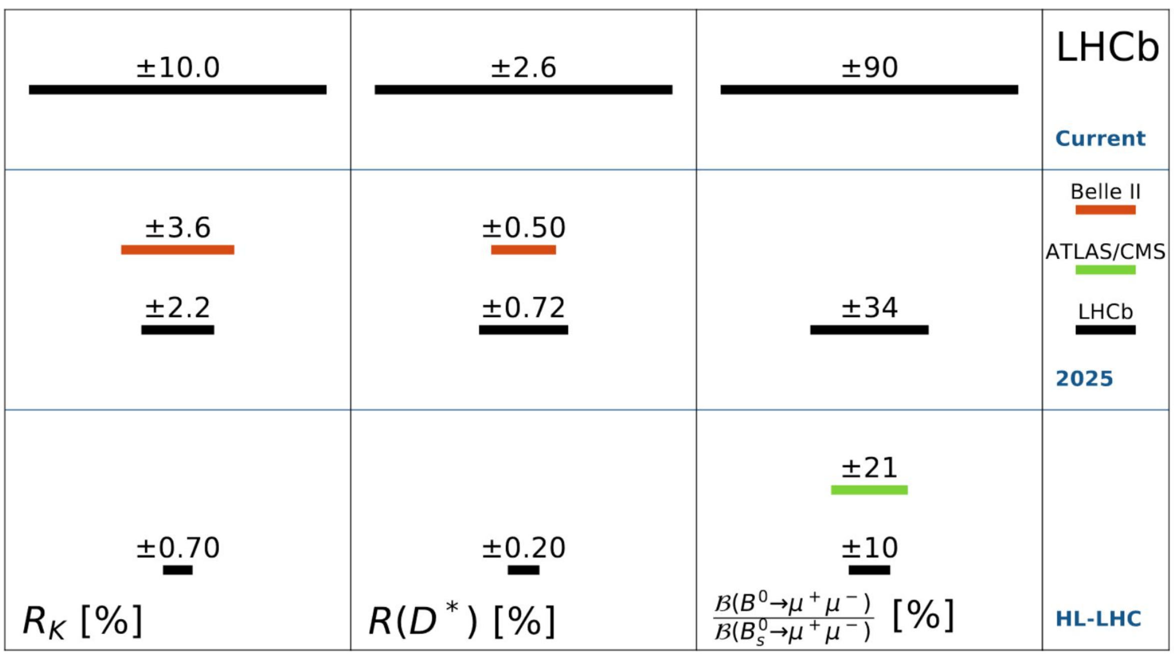
$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}.$$

Combined

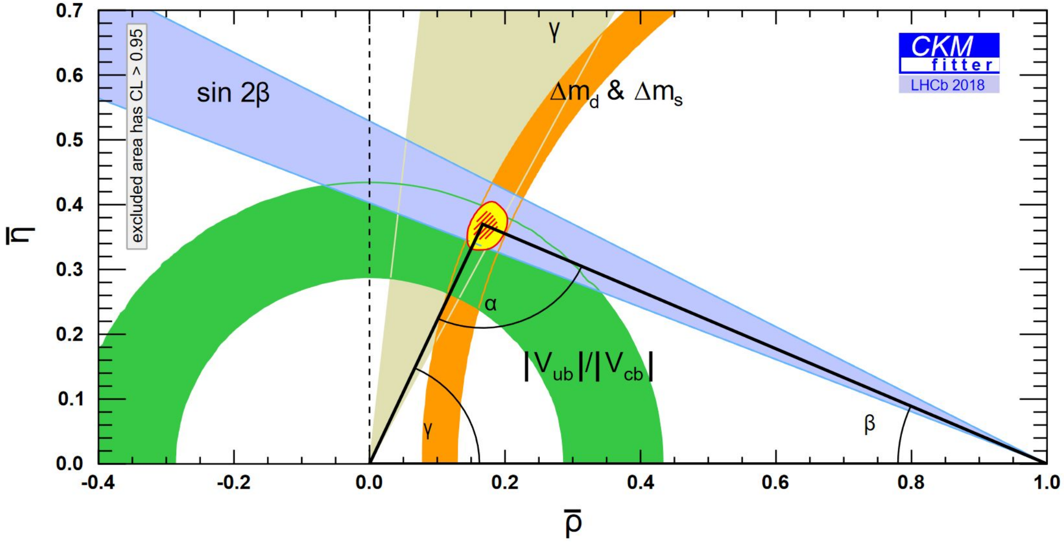
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

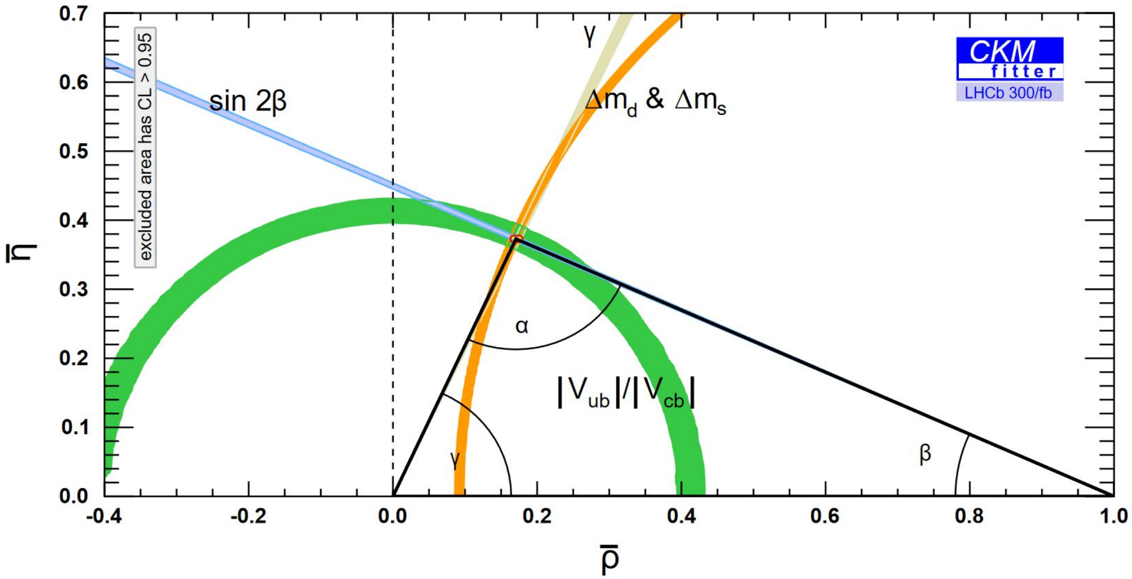
Flavor physics at HL-LHC





Flavor physics at HL-LHC

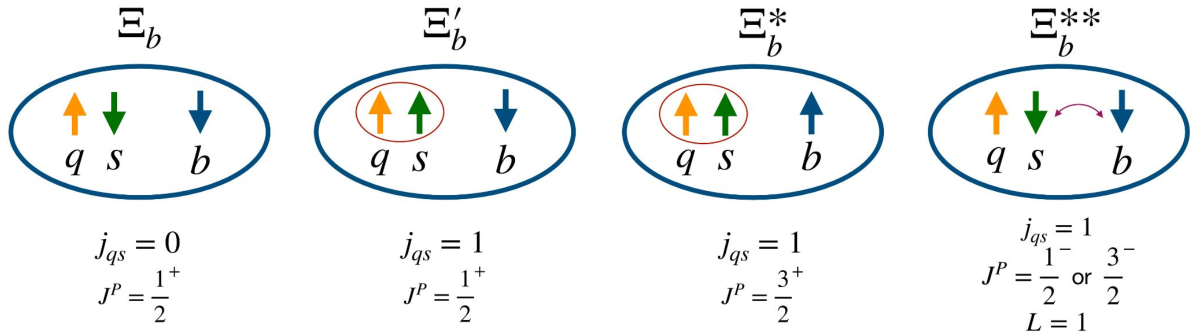




Spectroscopy: a case study

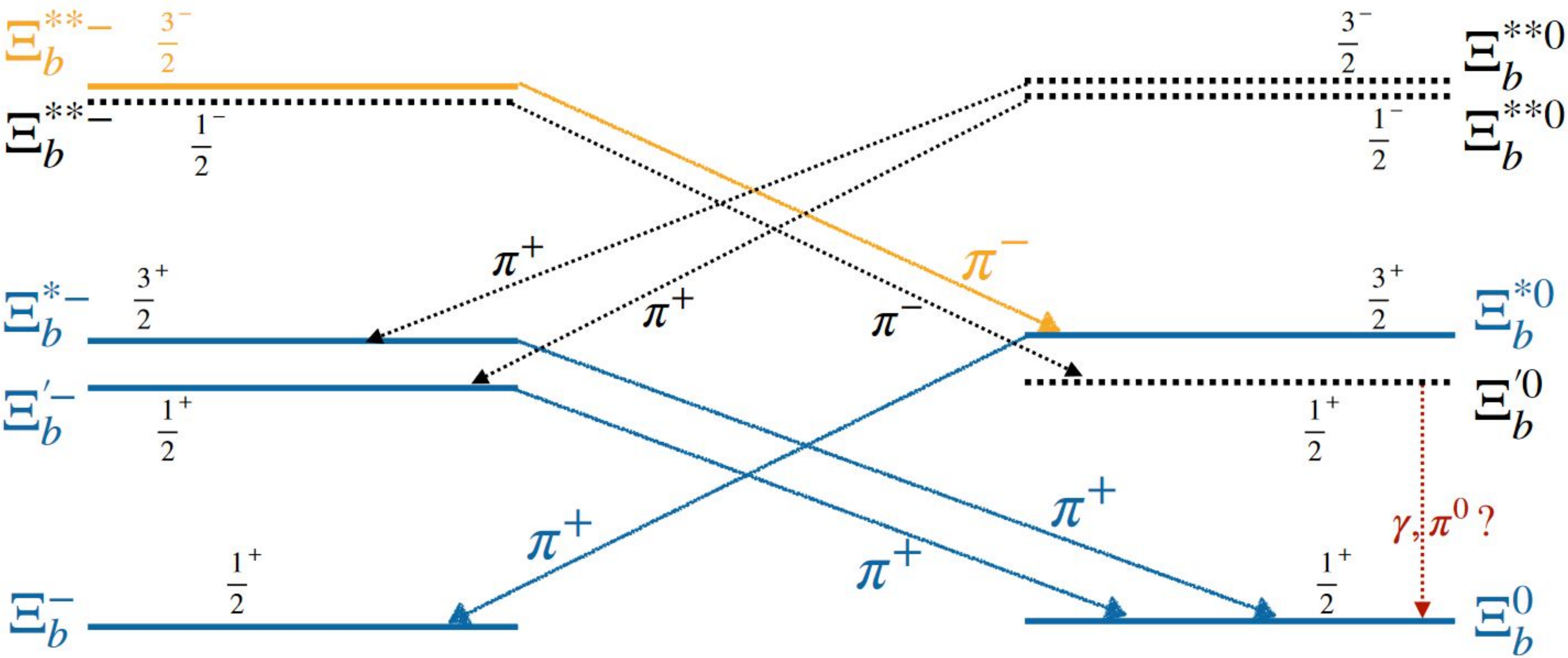
Ξ_b baryons: a rich zoo

q=u,d



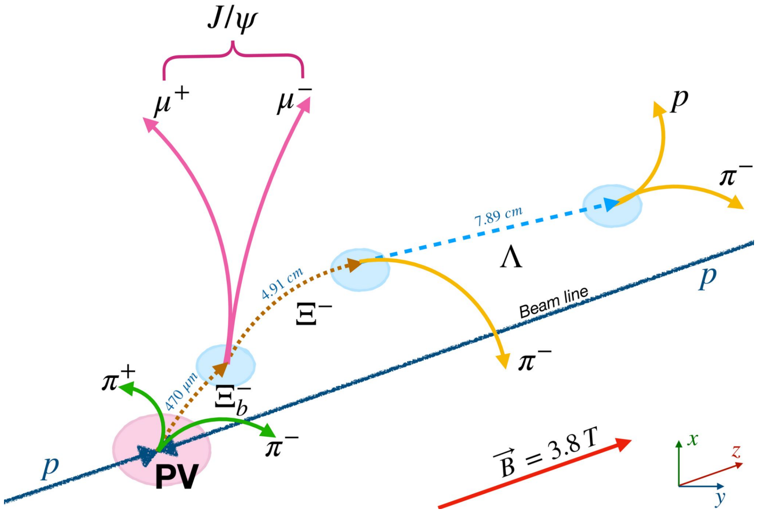
Doubly excited states expected

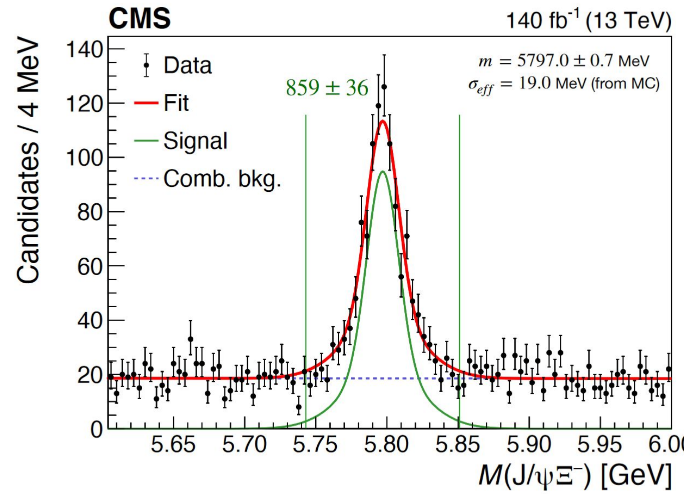
in analogy with Ξ_c

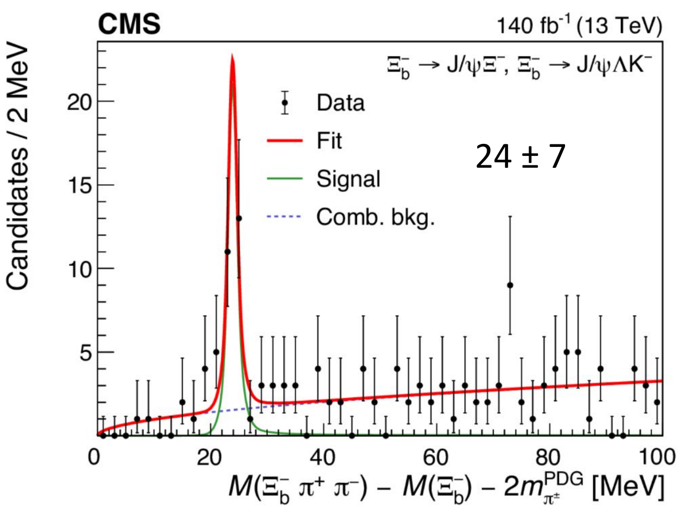


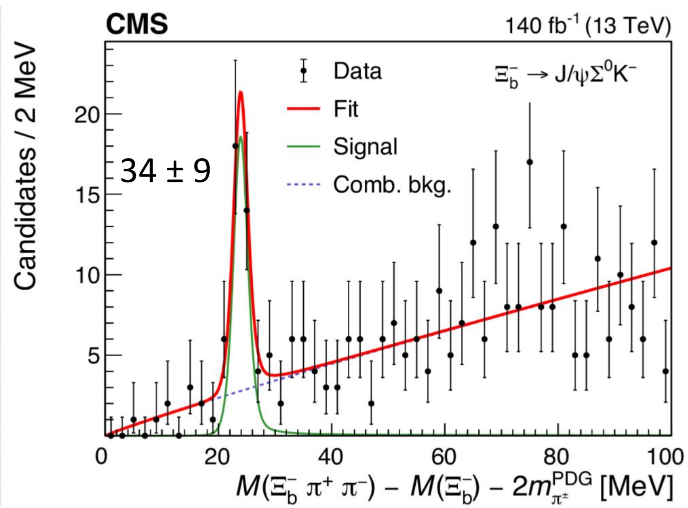
Ξ_b^{**} cascade

CMS-BPH-20-004









Simultaneous fit with common mass and natural width

Eccess with > 6σ

$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ \mathrm{MeV}$$
$$\Gamma(\Xi_b(6100)^-) < 1.9\ \mathrm{MeV}$$

Exotic searches

Definition

Exotic-ness is in the eye of the beholder

Two approaches to BSM:

- "SM" topologies, like di-particle searches

- "BSM" topologies, like (LF)V, high missing energy, etc

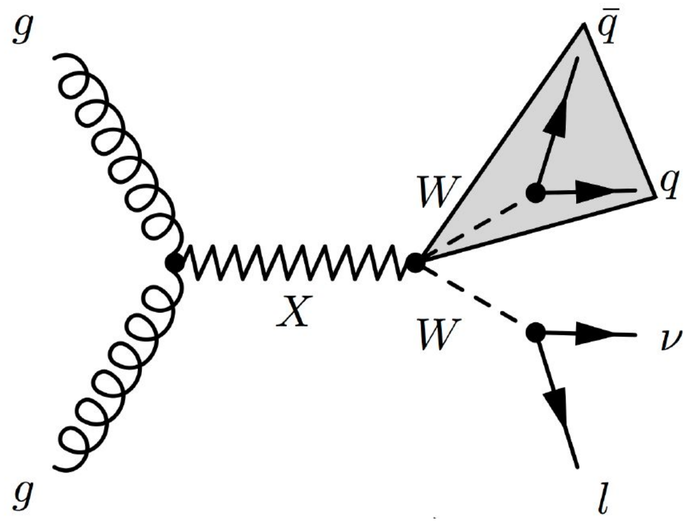
Boosted topologies

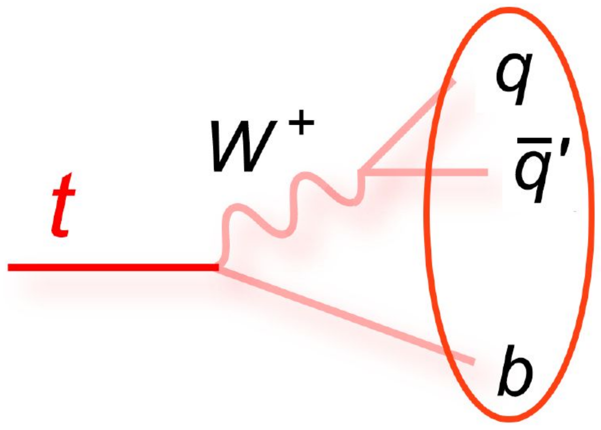
Searches for massive particles into bosons and top

$\longrightarrow$ decay products highly collimated

Rethinking of reconstruction/ID techniques:

- merged jets
- isolated leptons
- b-tagging





High mass di-lepton

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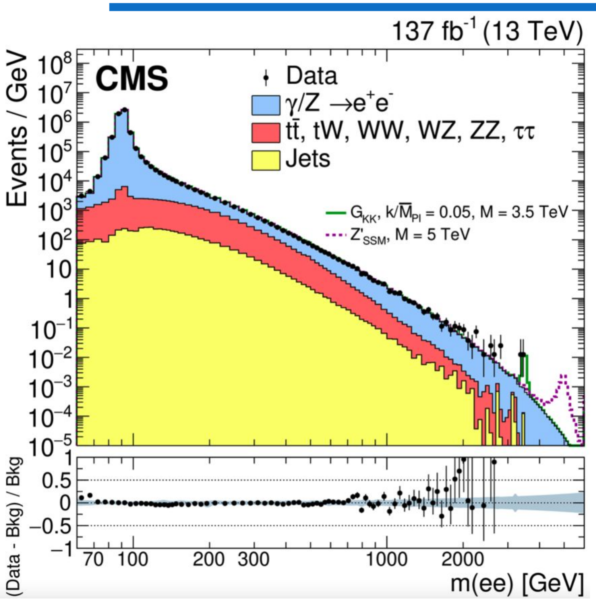
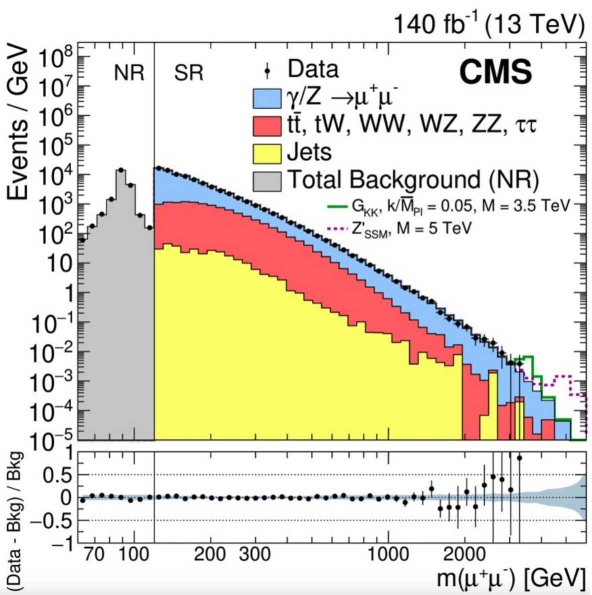


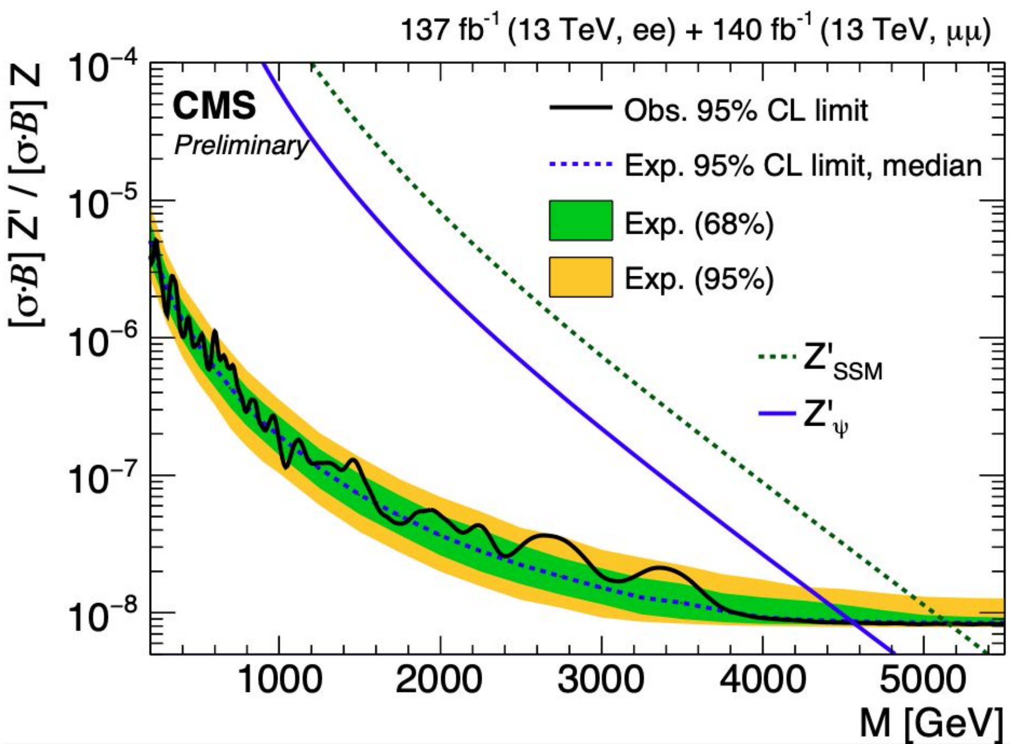


Use di-lepton spectrum for (non-)resonant search and LFU test

Interpretation in the context of resonant Z' in GUT models

Search wrt DY to improve sensitivity

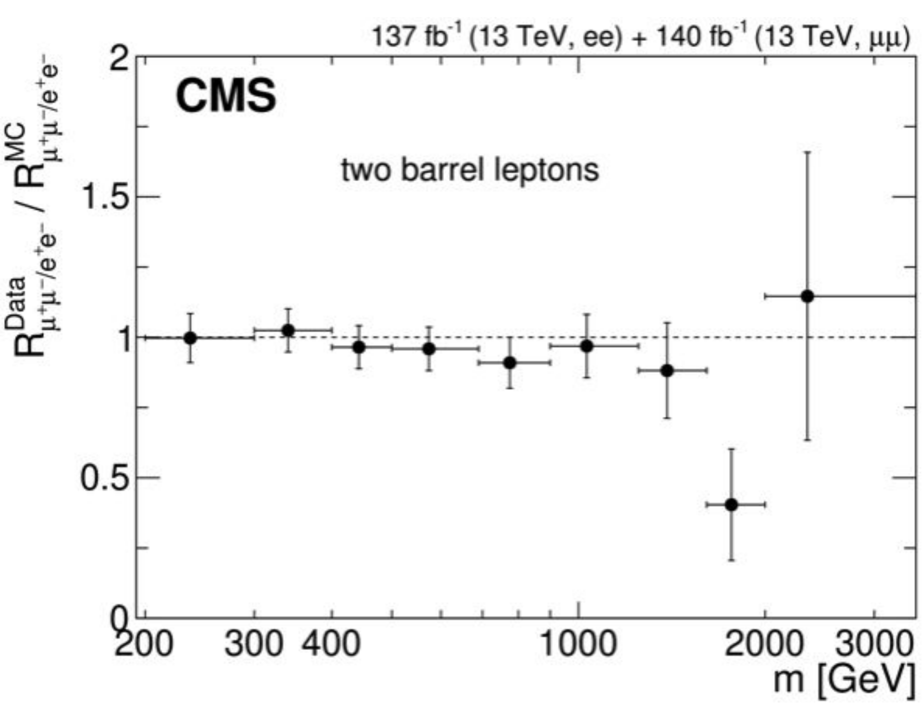
$$R_\sigma = \frac{\sigma(\mathrm{pp} \to \mathrm{Z}' + X \to \ell\ell + X)}{\sigma(\mathrm{pp} \to \mathrm{Z} + X \to \ell\ell + X)}$$



More interpretations

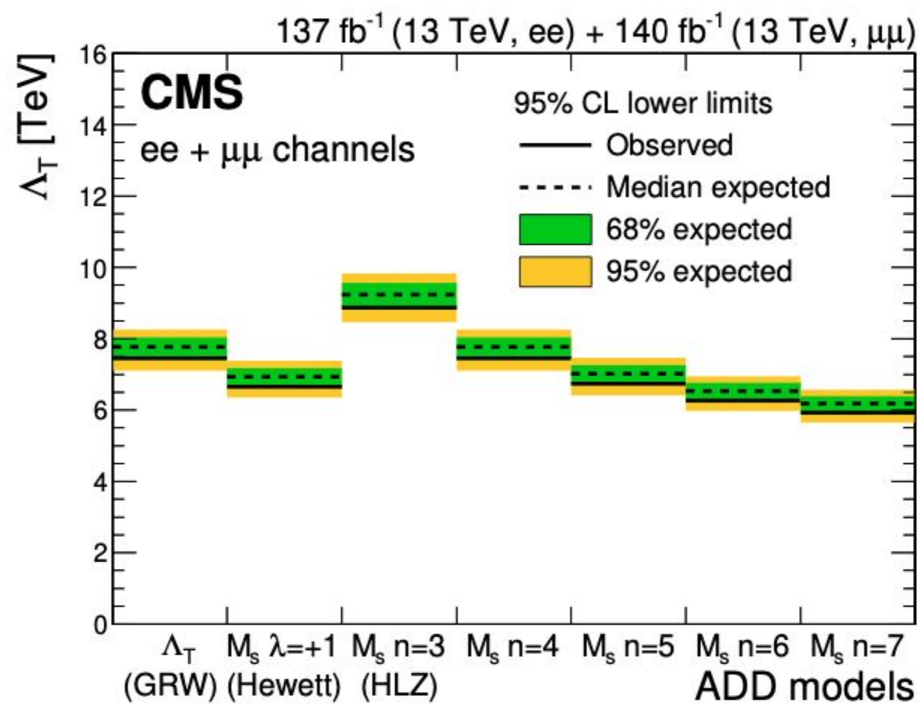
Use the di-muon and di-lepton mass spectra to test LF universality in high energy regime

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



Limit on ultraviolet cutoff in ADD models

- Quasi-continuum KK graviton modes
- Non-resonant cross section increase at high mass for virtual graviton contributions



X → tt

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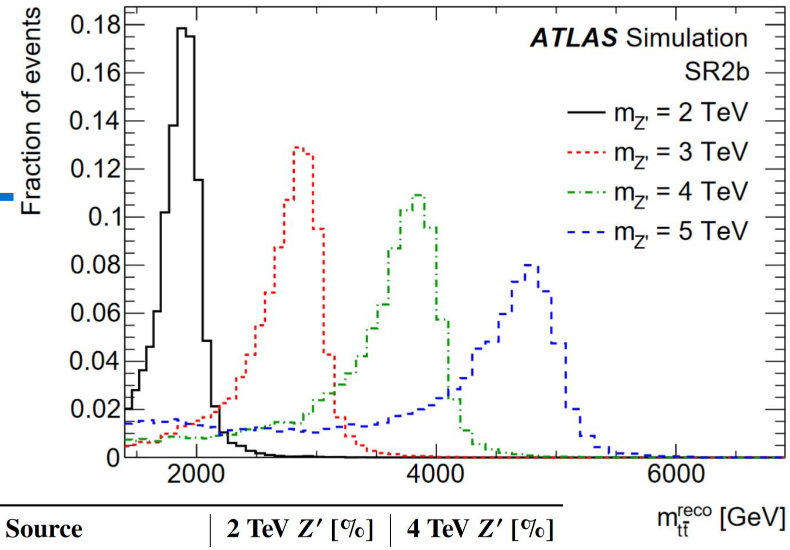
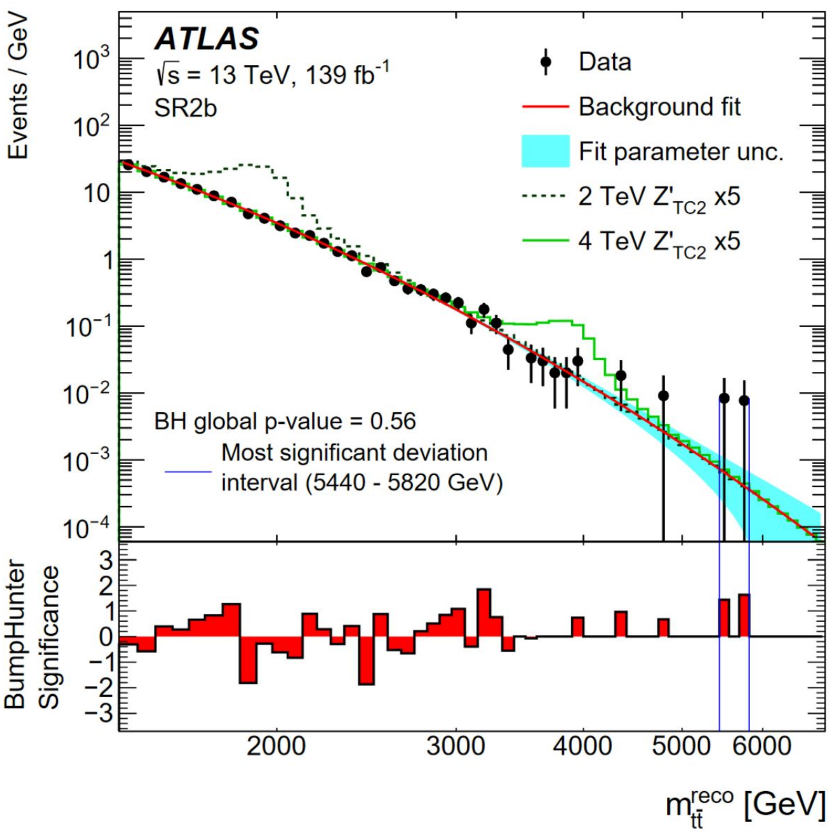
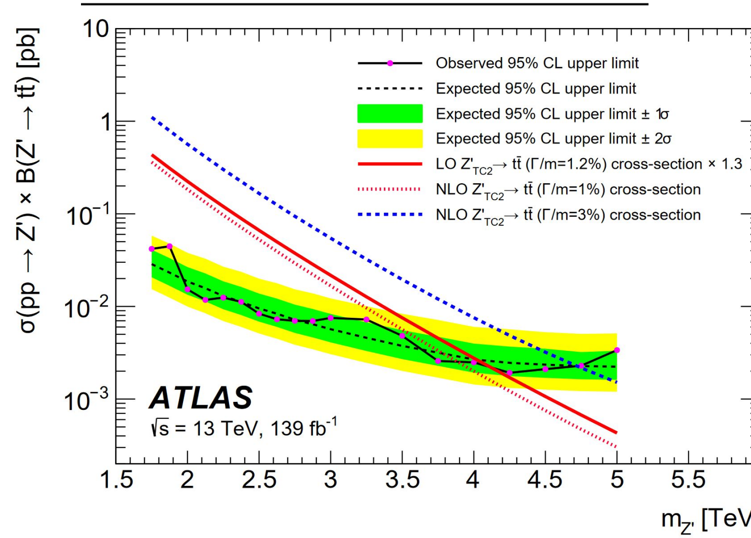
Bump hunting over the tt spectrum

- Search in fully hadronic decay
  - Top decay as a single jet with substructure
  - Use DeepNN to discriminate internal structure



Source	2 TeV Z' [%]		4 TeV Z' [%]	
	SR1b	SR2b	SR1b	SR2b
JES	35	34	47	44
JMS	5.0	4.3	9.5	7.9
JER	0.1	0.1	0.1	< 0.1
JMR	3.9	4.0	8.0	8.0
b-tagging	14	5.0	23	5.3
Top-tagging	9.0	9.3	10	10
Luminosity	1.7	1.7	1.7	1.7
Pile-up modelling	0.2	0.2	0.2	0.2





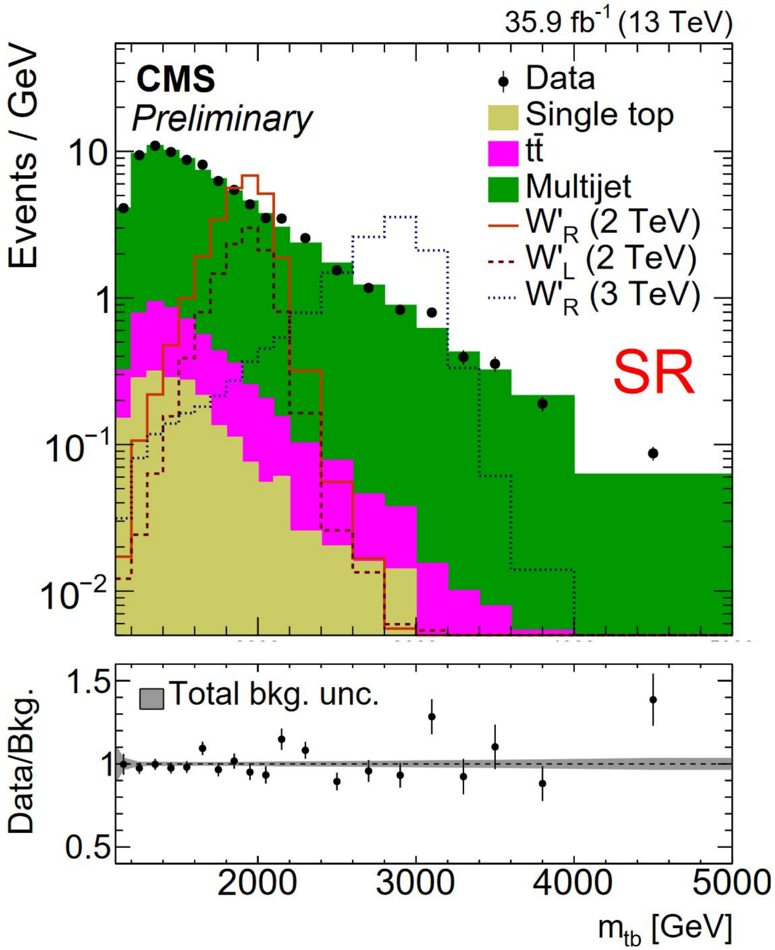
W’ → tb

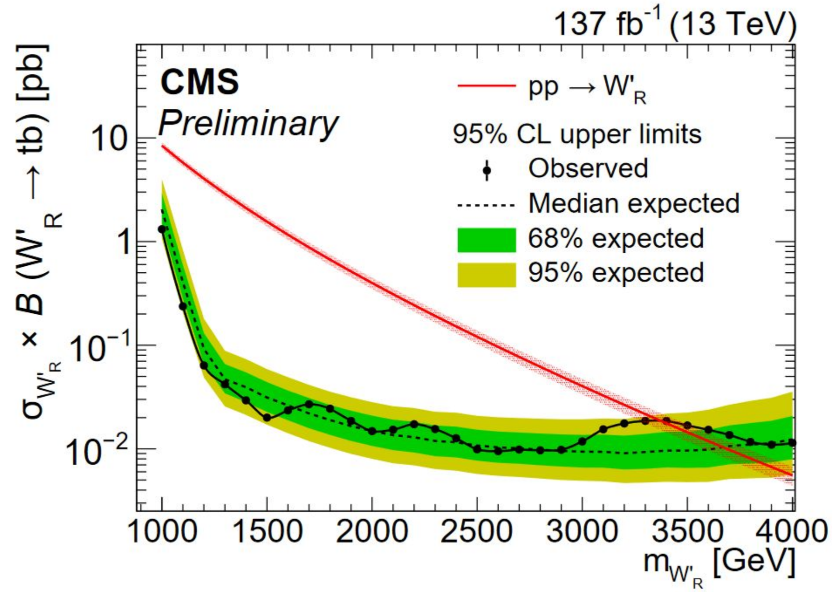
CMS-PAS-B2G-20-005

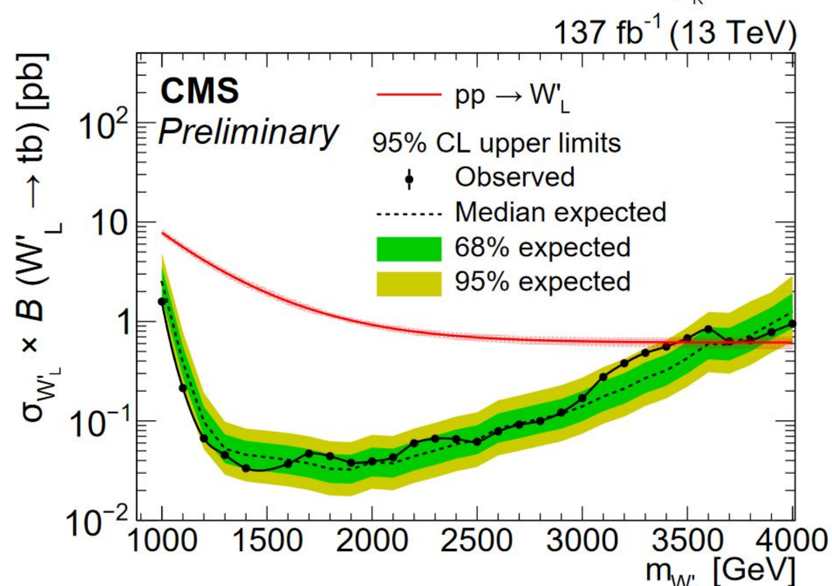
Search over m_{tb} spectrum

Top tagging of highly boosted jet

Account for acceptance difference due to chirality







Search for X→Z V→$\nu\nu$qq

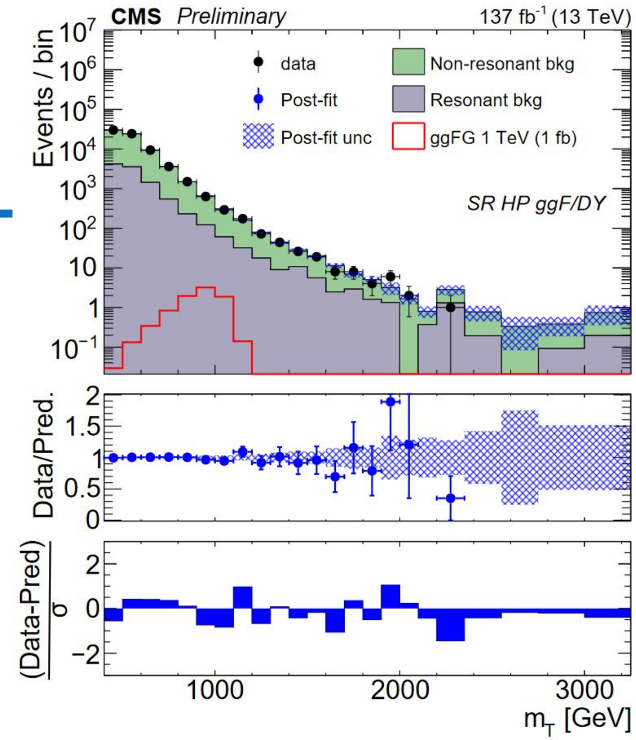
Search for resonance in diboson spectrum

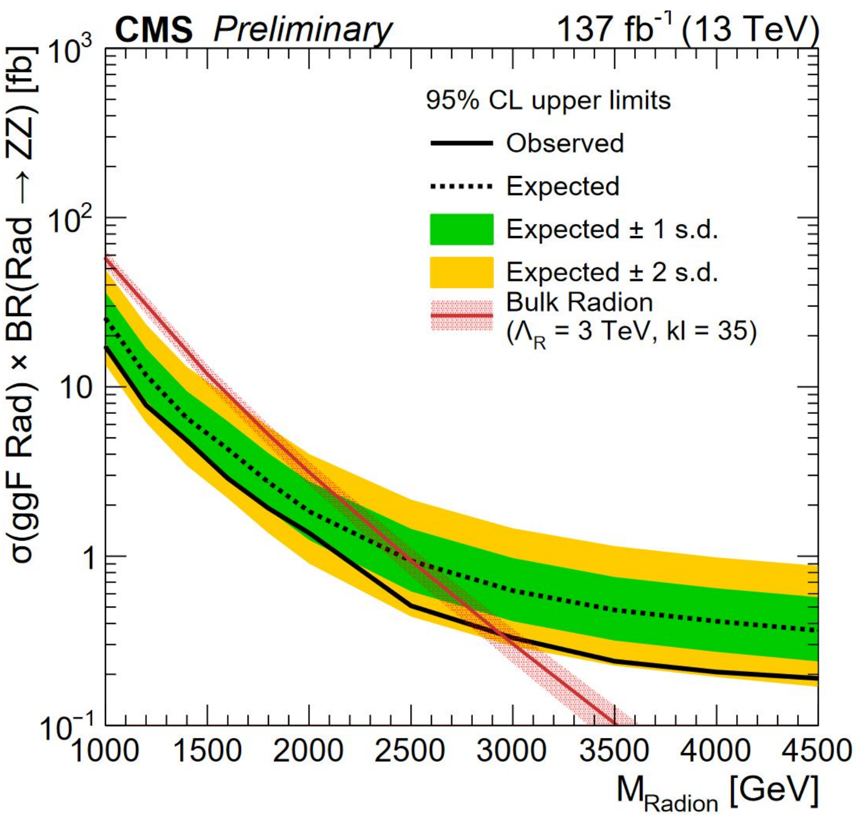
Compatible with radions, gravitons, Z’, W’, ...

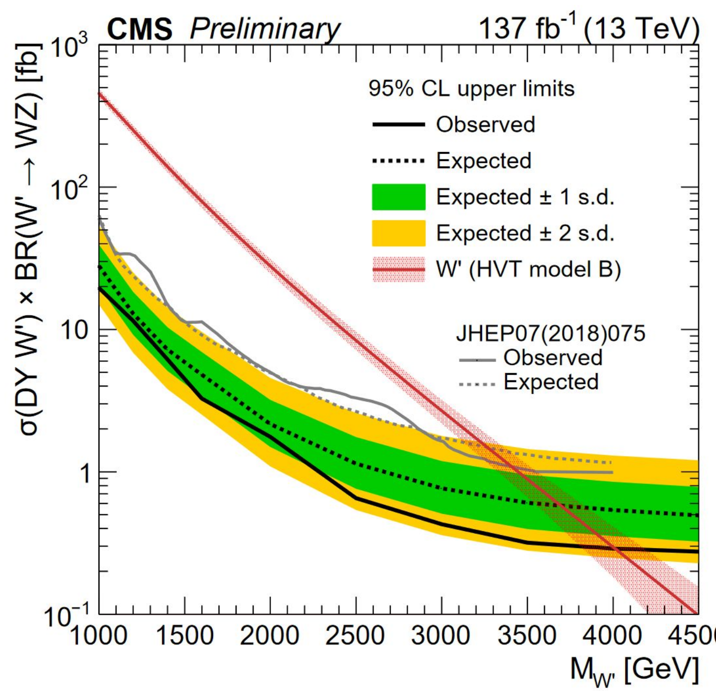
Discriminating observable is the transverse mass

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{J}} p_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos\Delta\phi]}$$

CMS-PAS-B2G-20-008







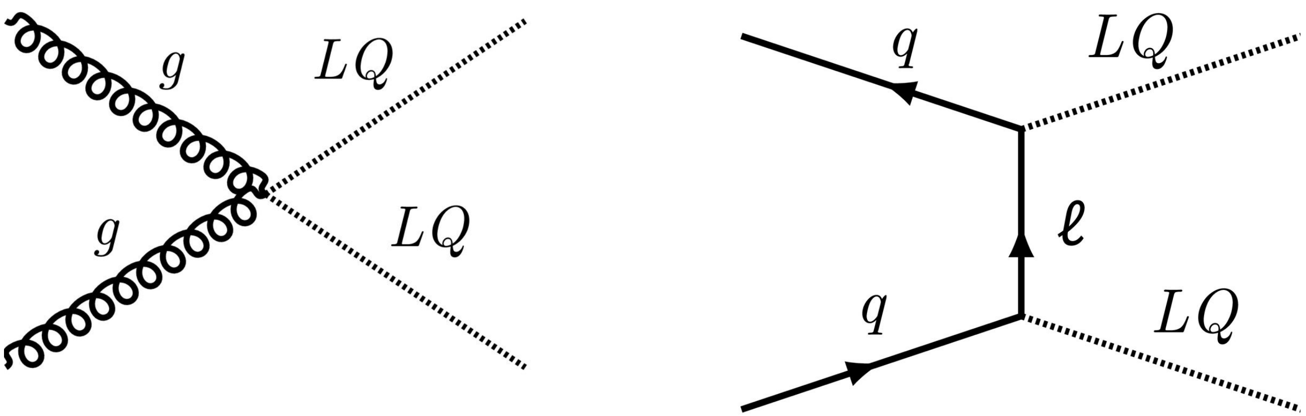
Leptoquarks

Bosons carrying lepton and baryon numbers

RPV SUSY, GUT

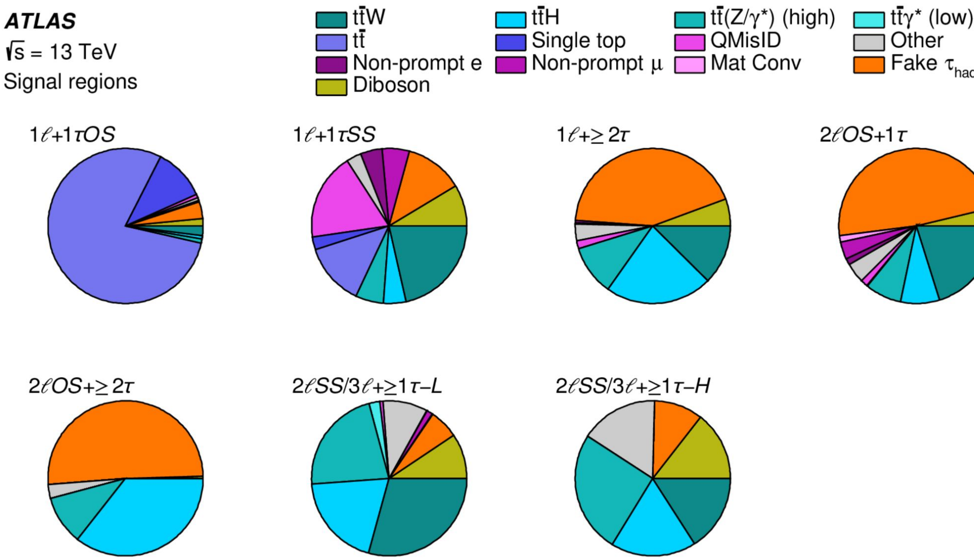
Compatible with recent LFU violation hints in B physics

- scalar or vector
- carry fractional charge
- color triplet



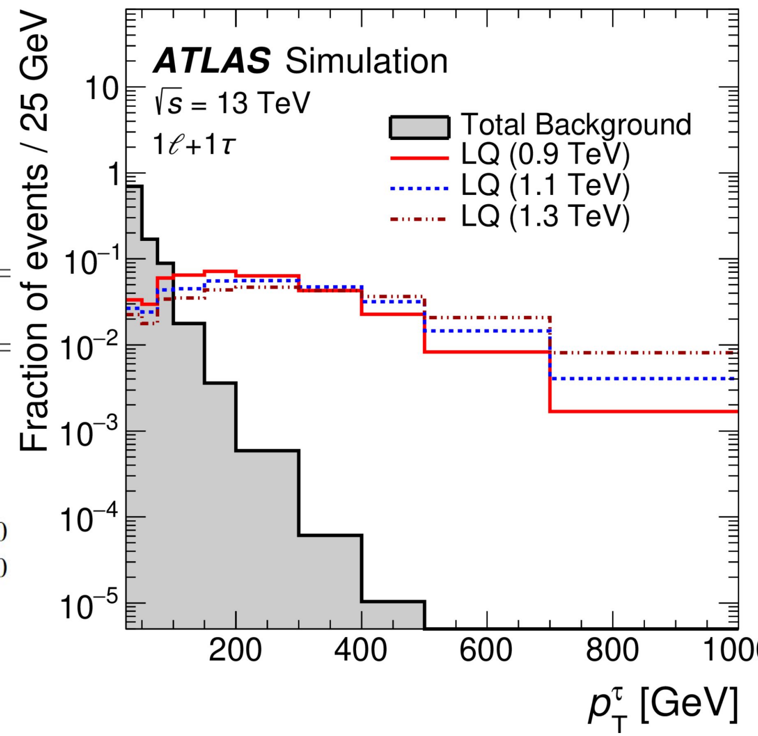
LQ → $t\tau$

arXiv:2101.11582



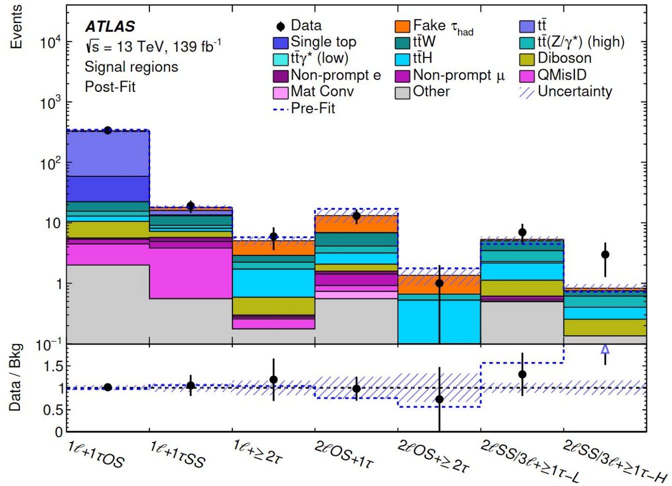
Pair production in 2t2τ

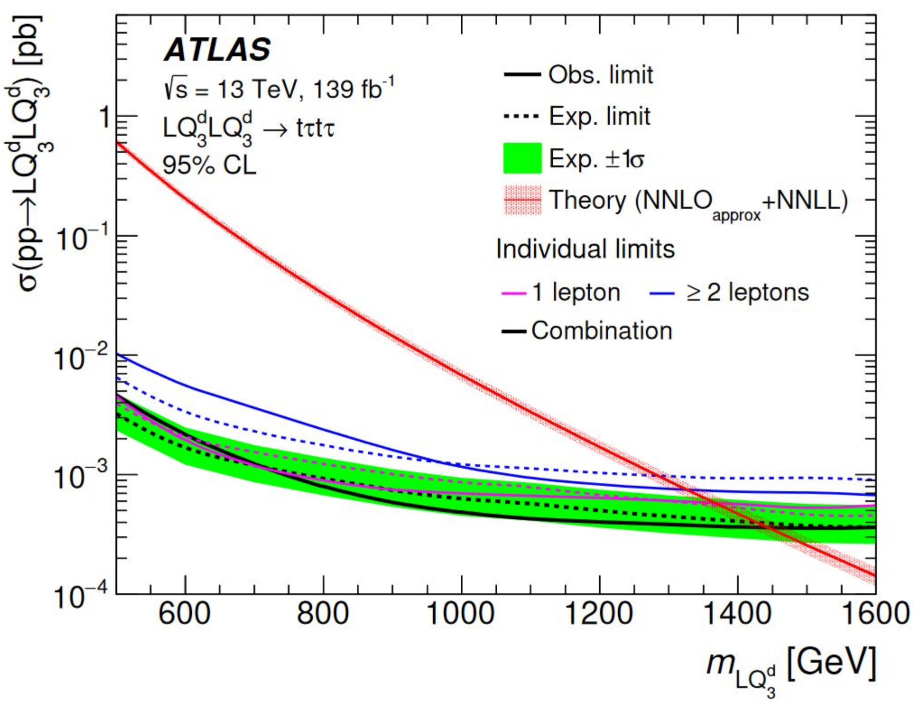
Division in categories of leptonic decays of W and τ

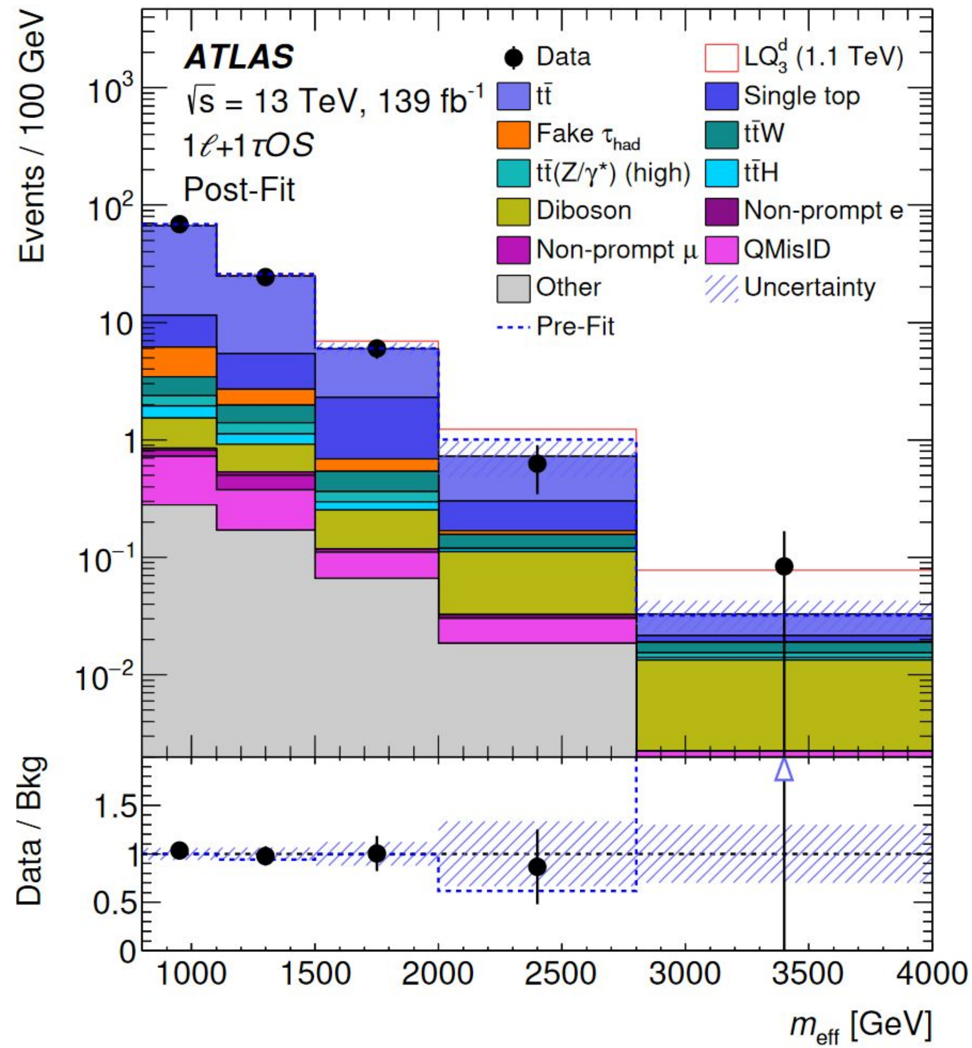


	1ℓ+1τOS			1ℓ+1τSS			1ℓ+$\geq 2\tau$		
	CR	VR	SR	CR	VR	SR	CR	VR	SR
e/μ selection		T			T			T	
$N_{\tau_{\rm had}}$		1			1			≥ 2	
$N_{\rm jets}$		≥ 4			≥ 3			≥ 2	
$\tau_{\rm had}$ ID		Medium			Medium			Loose	
$\ell\tau_{\rm had}$ charge		OS			SS			—	
$p_{\rm T,1}^{\tau}$ [GeV]	≥ 50	50–150	≥ 150	≥ 50	50–150	≥ 150	≥ 50	50–100	≥ 100
$p_{\rm T,2}^{\tau}$ [GeV]		—			—		≥ 25	25–50	≥ 50
$N_{b\text{-jets}}$	≥ 2	≥ 1		≥ 2	≥ 1		≥ 2	≥ 1	
$m_{\ell\tau}$ [GeV]	—	≥ 200		—	—	≥ 200		—	
$m_{\rm T}(\ell, E_{\rm T}^{\rm miss})$ [GeV]		—		—	—	≥ 100		—	
$m_{\tau\tau}$ [GeV]		—			—		—	≥ 100	
$E_{\rm T}^{\rm miss}$ [GeV]	—	≥ 80		—	—	≥ 50		—	
$m_{\rm eff}$ [GeV]	< 800	≥ 800		< 800	≥ 800		< 800	≥ 800	

LQ → $t\tau$


ATLAS
√s = 13 TeV, 139 fb⁻¹
Signal regions
Post-Fit
Data
Single top
tt̄γ* (low)
Non-prompt e
Mat Conv
Pre-Fit
Fake τhad
tt̄W
tt̄H
Non-prompt μ
Other
tt̄
tt̄(Z/γ*) (high)
Diboson
QMisID
Uncertainty
Events
Data / Bkg
1ℓ+1τOS
1ℓ+1τSS
1ℓ+≥2τ
2ℓOS+1τ
2ℓOS+≥2τ
2ℓSS/3ℓ+≥1τ-L
2ℓSS/3ℓ+≥1τ-H


ATLAS
√s = 13 TeV, 139 fb⁻¹
LQ₃ᵈLQ₃ᵈ → tτtτ
95% CL
Obs. limit
Exp. limit
Exp. ±1σ
Theory (NNLOapprox+NNLL)
Individual limits
1 lepton
≥ 2 leptons
Combination
σ(pp→LQ₃ᵈLQ₃ᵈ) [pb]
m_LQ₃ᵈ [GeV]


ATLAS
√s = 13 TeV, 139 fb⁻¹
1ℓ+1τOS
Post-Fit
Data
tt̄
Fake τhad
tt̄(Z/γ*) (high)
Diboson
Non-prompt μ
Other
Pre-Fit
LQ₃ᵈ (1.1 TeV)
Single top
tt̄W
tt̄H
Non-prompt e
QMisID
Uncertainty
Events / 100 GeV
Data / Bkg
m_eff [GeV]

Vector-like quarks

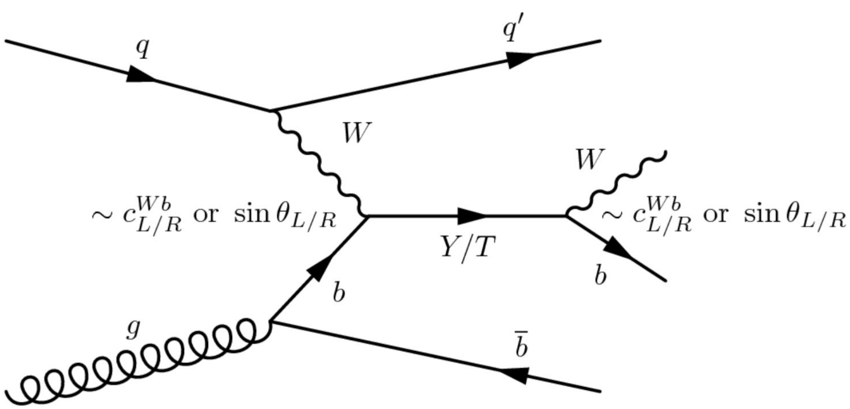
Vector-like quarks in composite/little Higgs, SUSY

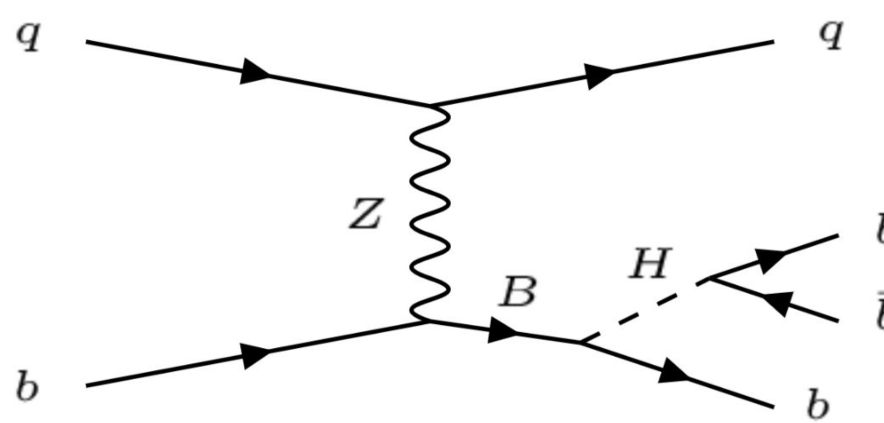
Spin ½ color triplets

L and R transform in same way under gauge → mass not generated by Yukawa Higgs interaction

Interact with SM with Yukawa couplings → third generation

Decay via neutral or charged current



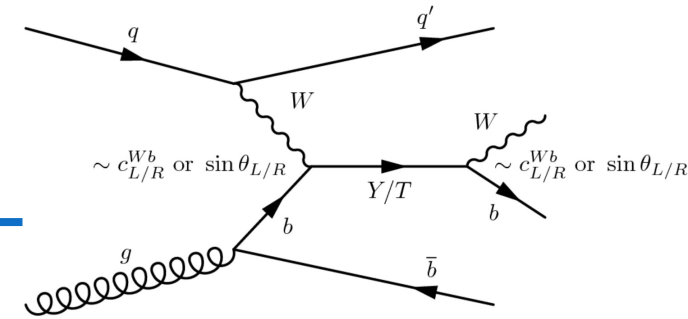


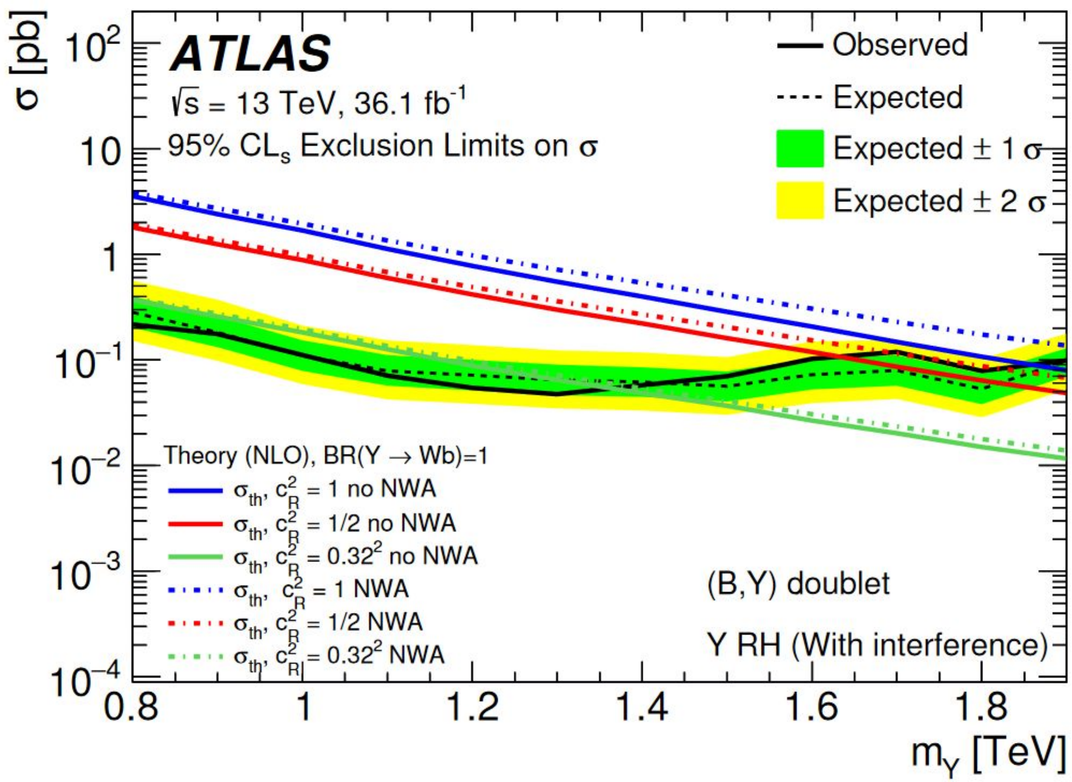
T → Wb

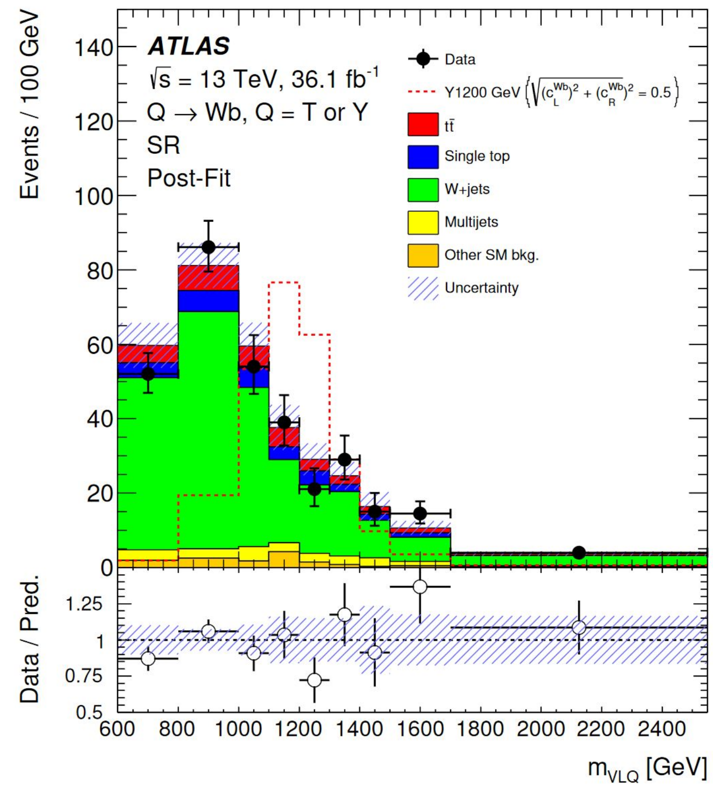
Search in leptonic W decay

- Three jets, one b-tagged
- Exactly 1 lepton

Include interference with SM single top production







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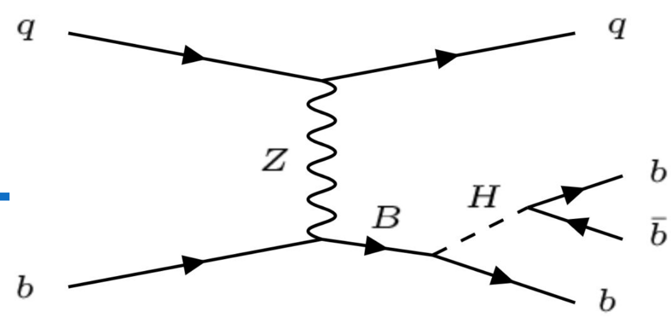
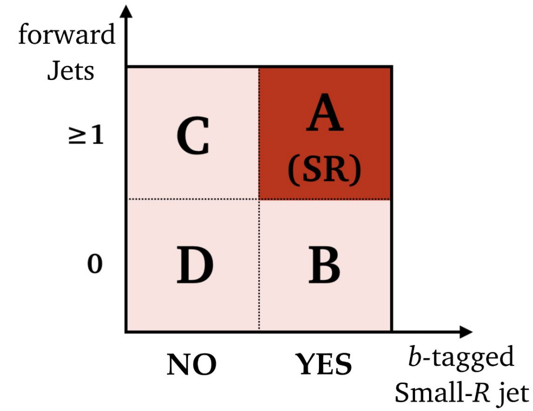
$B \rightarrow bH(bb)$

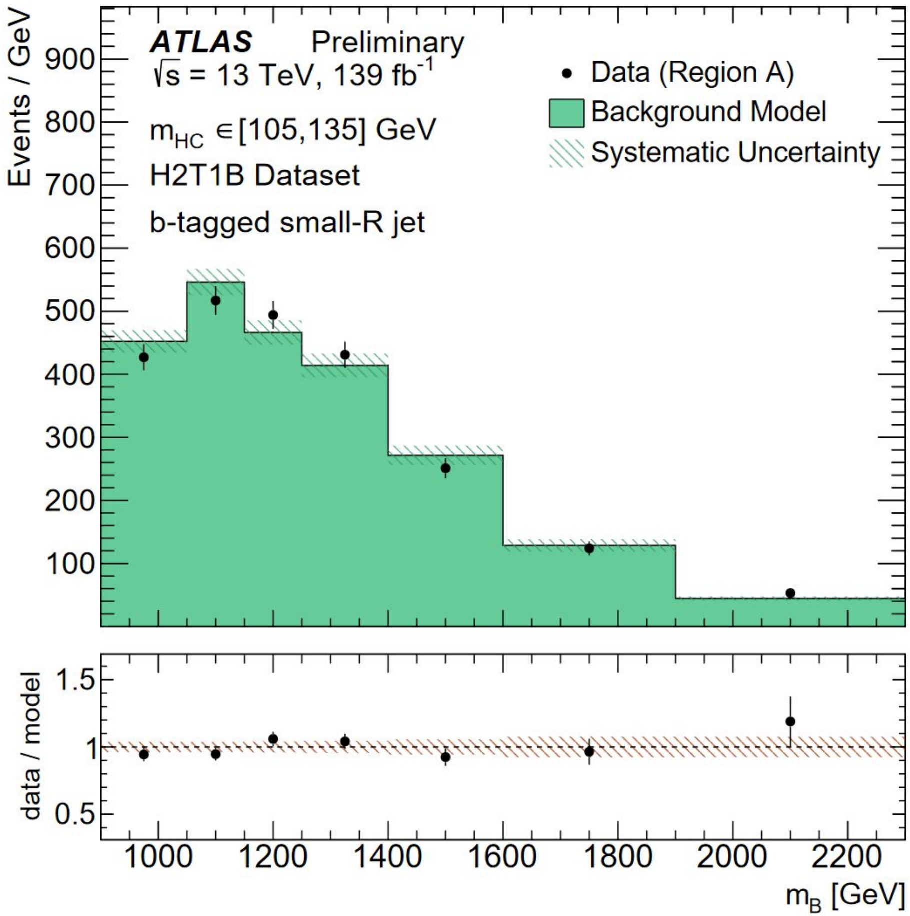
ATLAS-CONF-2021-018

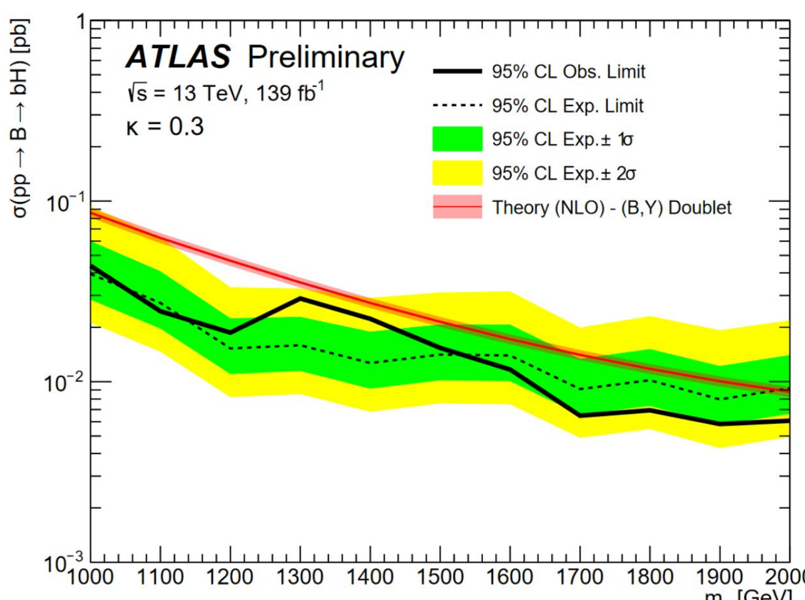


Veto isolated leptons

Boosted Higgs → reconstructed as a single large jet







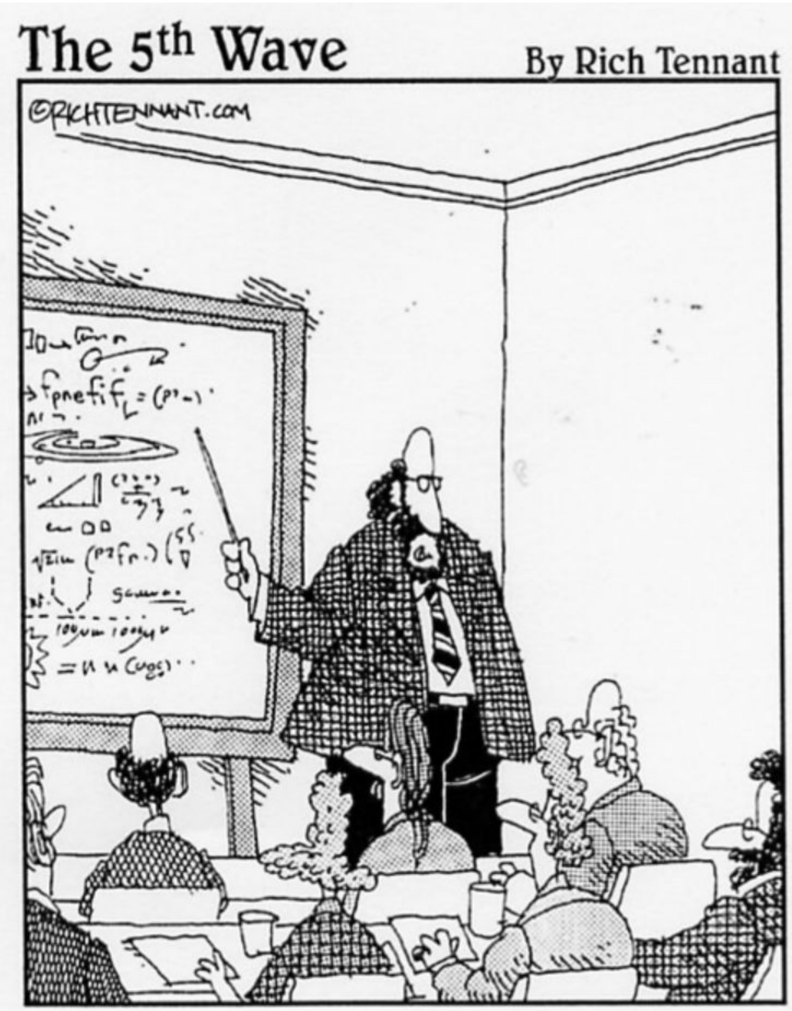
Dark matter

Search for DM in a much more controlled environment

Main limitation is missing energy resolution

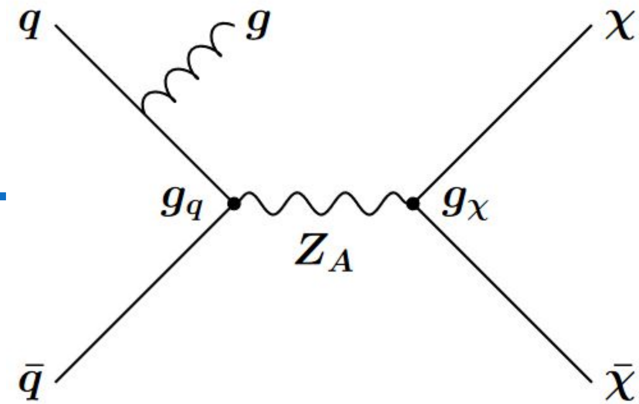
Vast array of models and topologies to test

Good complementarity with astrophysics searches



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

Mono-X searches

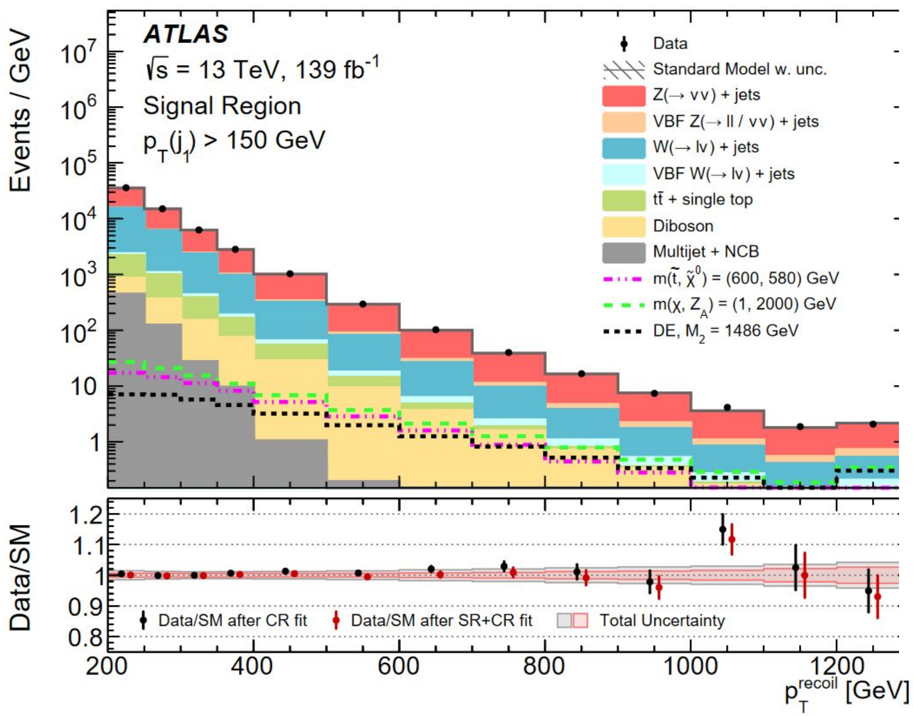


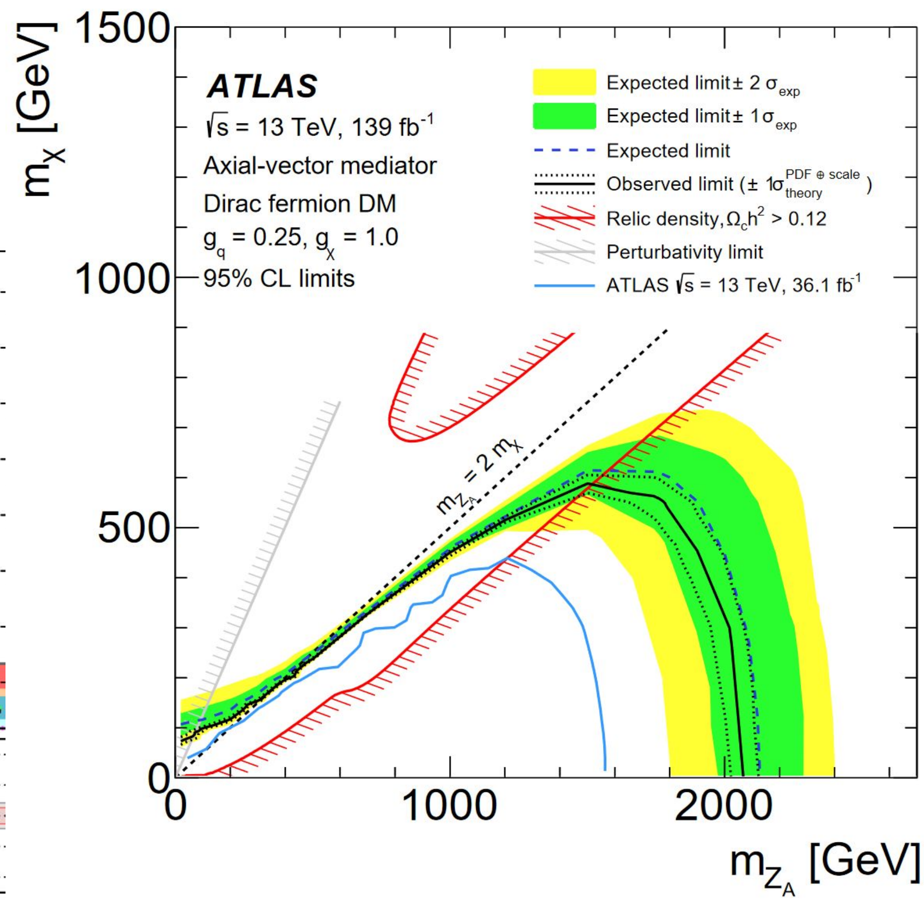
Search for large $E_{T,miss}$ in association with SM particle(s)

Especially powerful for pair production

Case study: mono-jet

- Trigger $E_{T,miss}$ > 200 GeV
- Jet with p_T > 150 GeV
- Veto on leptons and photons





arXiv:2102.10874

H⟶ invisible

ATLAS-CONF-2020-052

Search for missing energy associated with H production

- VBF, ZH, WH signatures

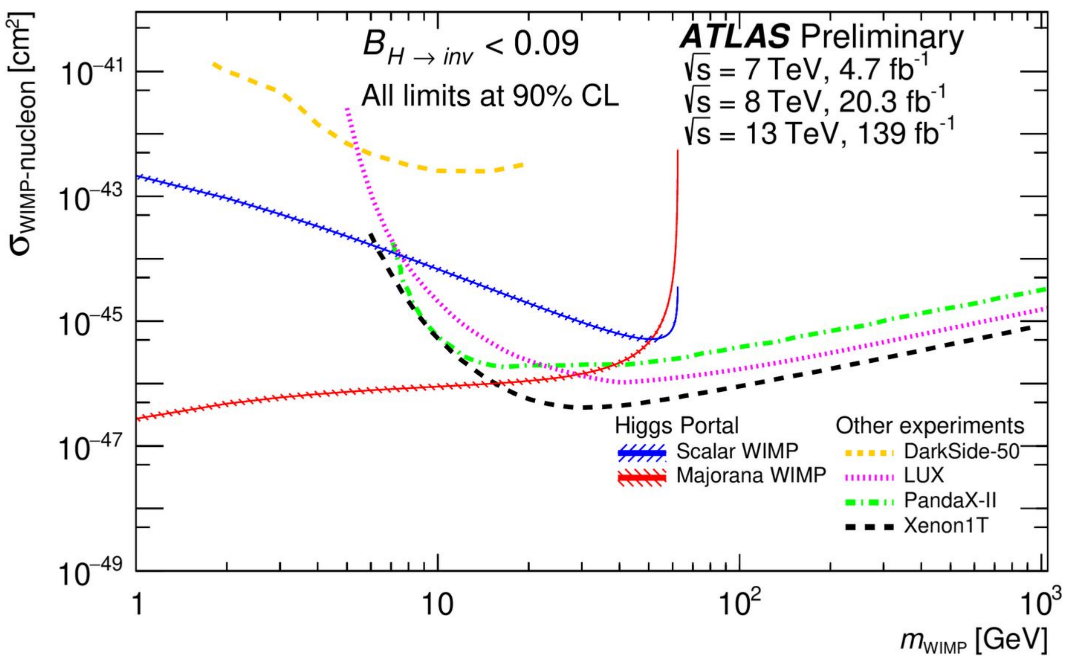
Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$

Interpret in the context of Higgs portal models

Translate limit into DM-N cross section in EFT

Very competitive and complementary search

…. but many assumptions on this plot!



Unfortunately, systematics will limit future prospects of these measurements

H → invisible at HL-LHC

CMS-FTR-18-016

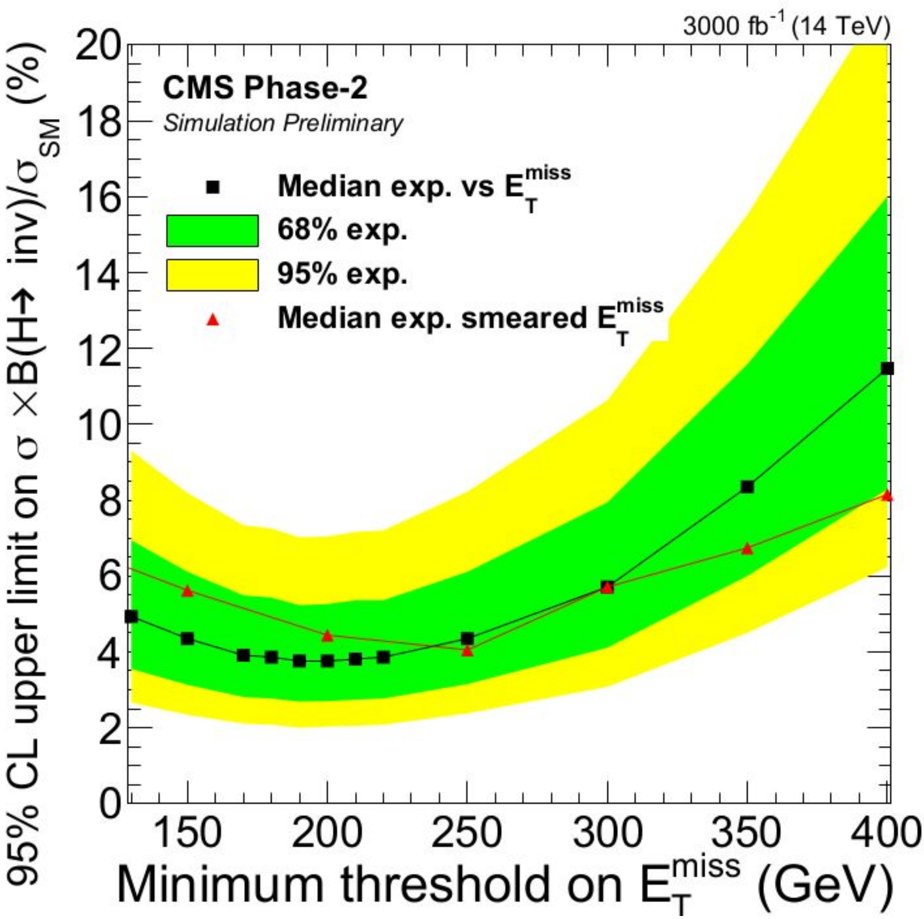
- Projections to 3 ab^{-1} show search limited by systematic uncertainties
- Not the biggest surprise: tough analysis in pp environment, with great experimental challenges

Interesting exercise:

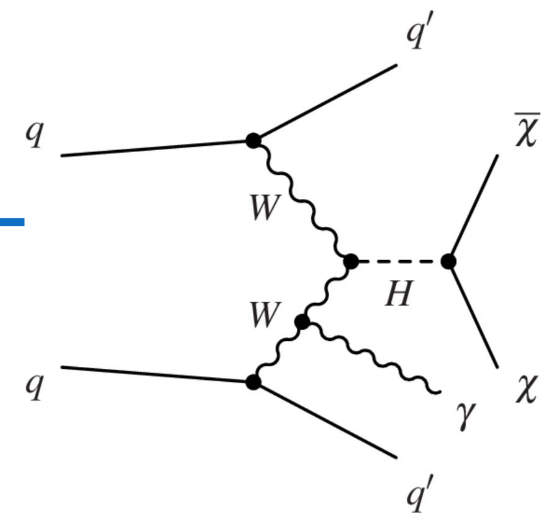
- Test scenario with missing mass resolution worse by factor 2
  - Case of *extreme* PU conditions

Conclusion:

- Analysis is flexible enough to yield similar limits with selection re-optimization

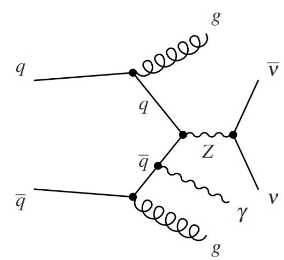


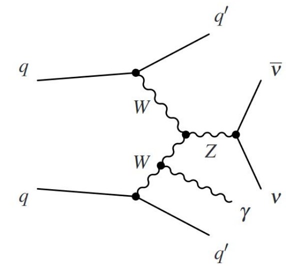
Alternative: VBF H(->inv)+γ



Search for VBF jets, isolated photon and $E_{T,miss}$

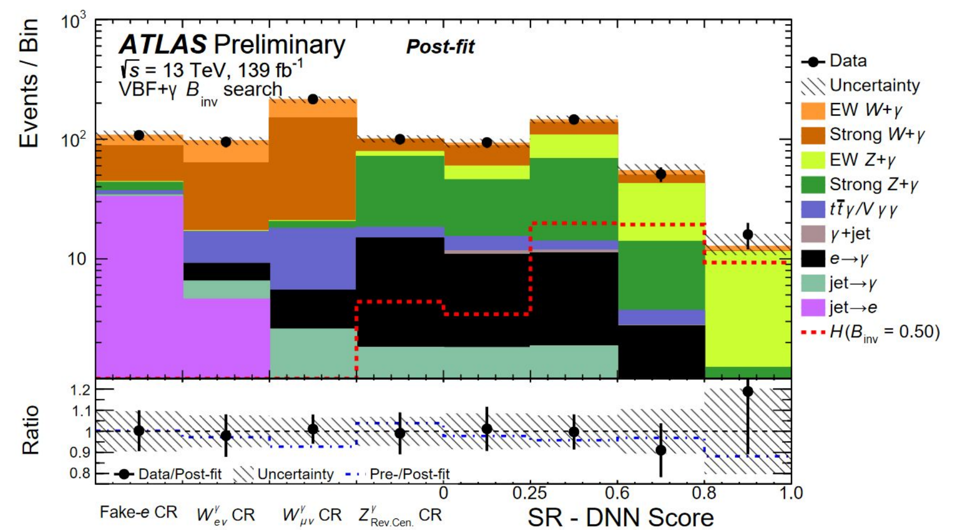
Dominant backgrounds:





ATLAS-CONF-2021-004

Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake−e CR
p_{T} (j_1) [GeV]			> 60		
p_{T} (j_2) [GeV]			> 50		
N_{jet}			2,3		
$N_{\text{b-jet}}$			< 2		
$\Delta\phi_{\text{jj}}$			< 2.5 [2.0]		
$\lvert\Delta\eta_{\text{jj}}\rvert$			> 3.0		
$\eta(j_1) \times \eta(j_2)$			< 0		
C_3			< 0.7		
m_{jj} [TeV]			> 0.25		
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150	–	> 80	> 150	< 80
$E_{\text{T}}^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150
$E_{\text{T}}^{\text{jets,no-jvt}}$ [GeV]			> 130		
$\Delta\phi(j_i, E_{\text{T}}^{\text{miss,lep-rm}})$			> 1.0		
N_{γ}			1		
p_{T} (γ) [GeV]			> 15, < 110 [> 15, <max(110,0.733 × m_{T})]		
C_{γ}	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4
$\Delta\phi(\gamma, E_{\text{T}}^{\text{miss,lep-rm}})$			> 1.8 [–]		
N_{ℓ}	0	1 μ	1 e	0	1 e
p_{T} (ℓ) [GeV]			> 30		



Observed BR < 0.37 @ 95% CL

Expected $0.34^{+0.15}_{-0.10}$

Statistically limited, very promising for HL-LHC

Displaced vertices

CMS-PAS-EXO-19-013

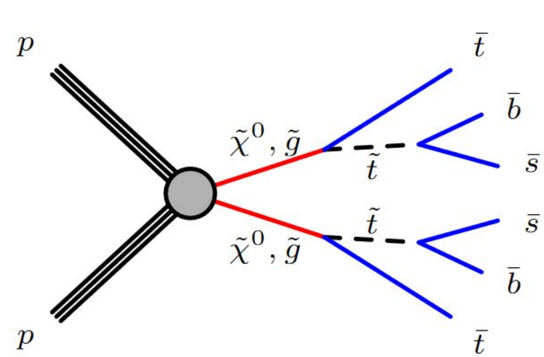
Both SUSY and some DM models (overlap) predict long living particles produced at LHC

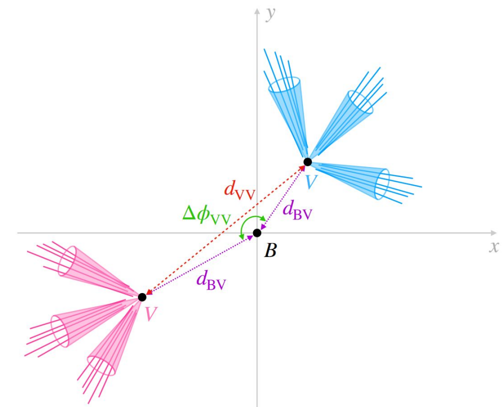
Secondary vertex can be up to 10 cm

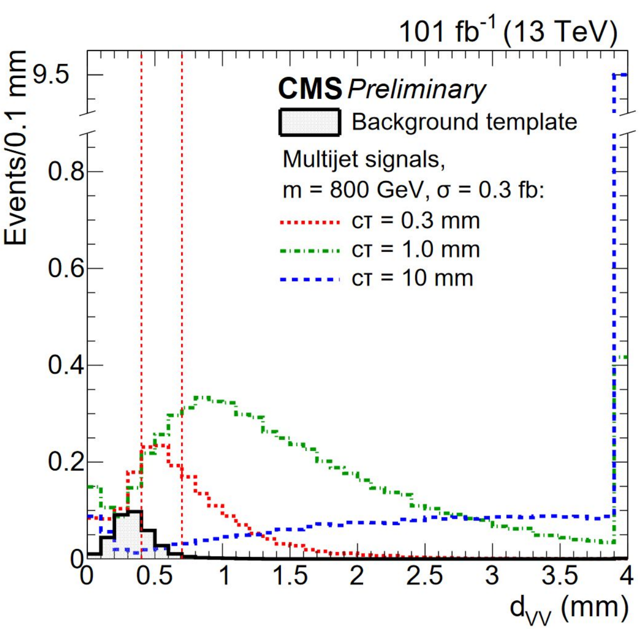
Dedicated tracking algorithms

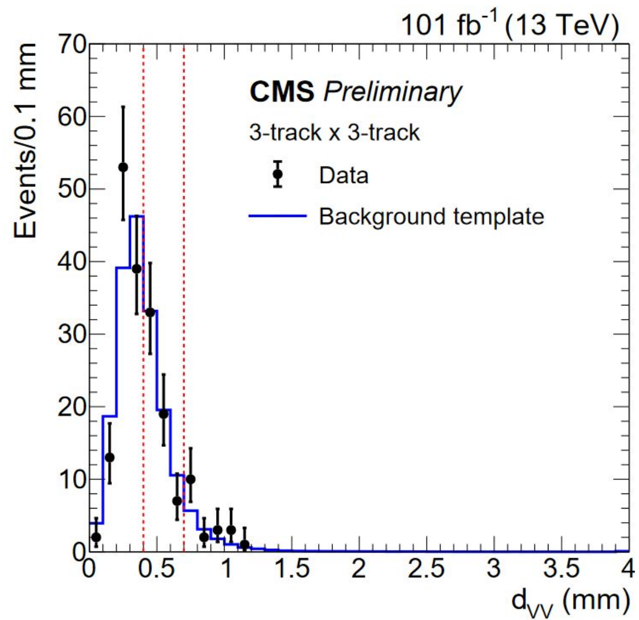
CMS search in multi-jet final state

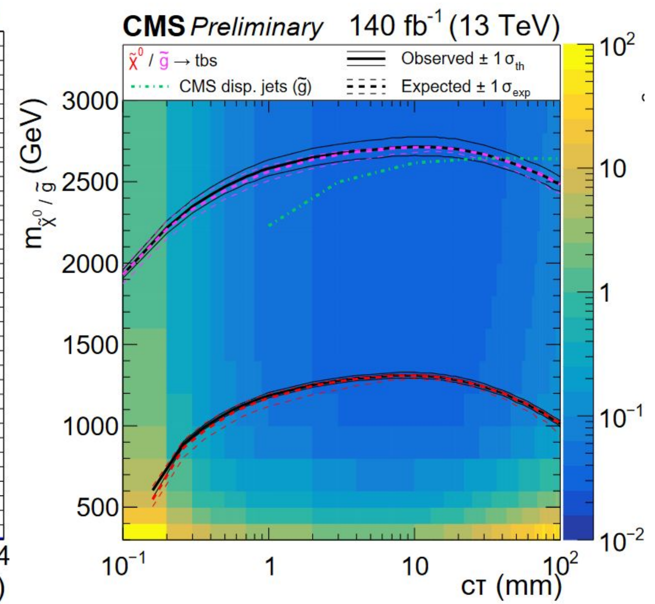
- Displaced vertices on transverse plane
- Masses of LLP > 600 GeV (trigger)







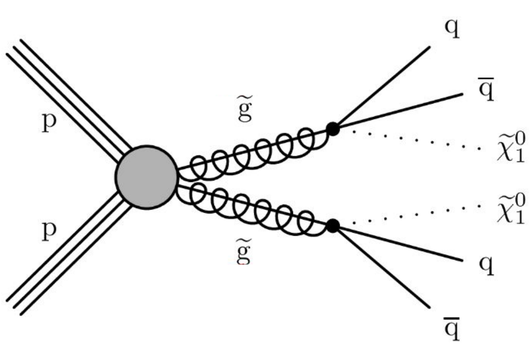


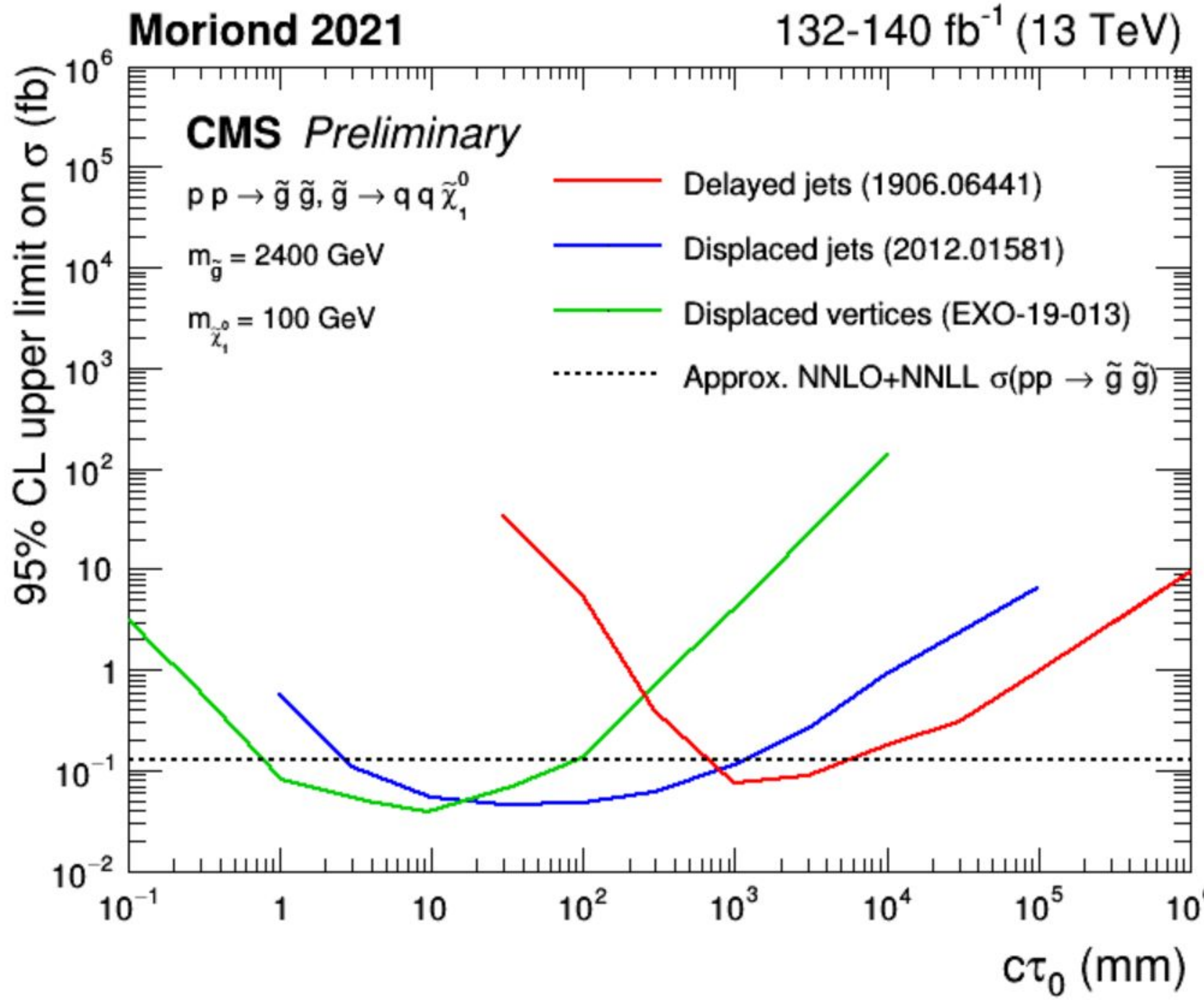


Combining displacements

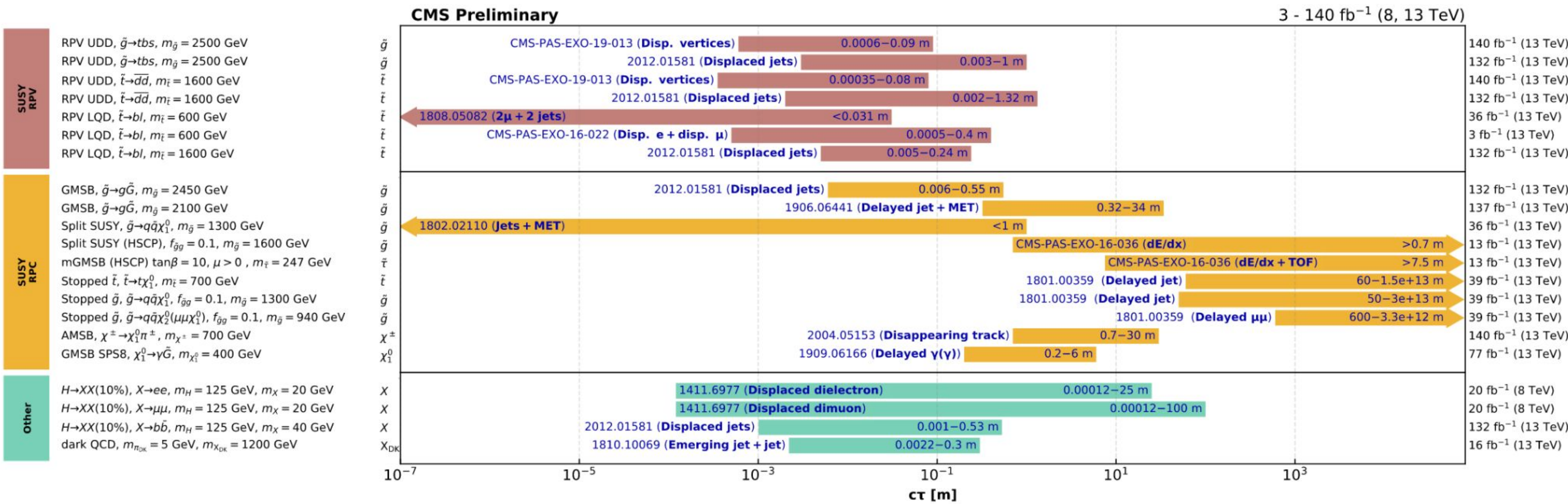
Depending on distance travelled, displaced objects appear in different detectors

Combine different techniques to cover larger parameter space





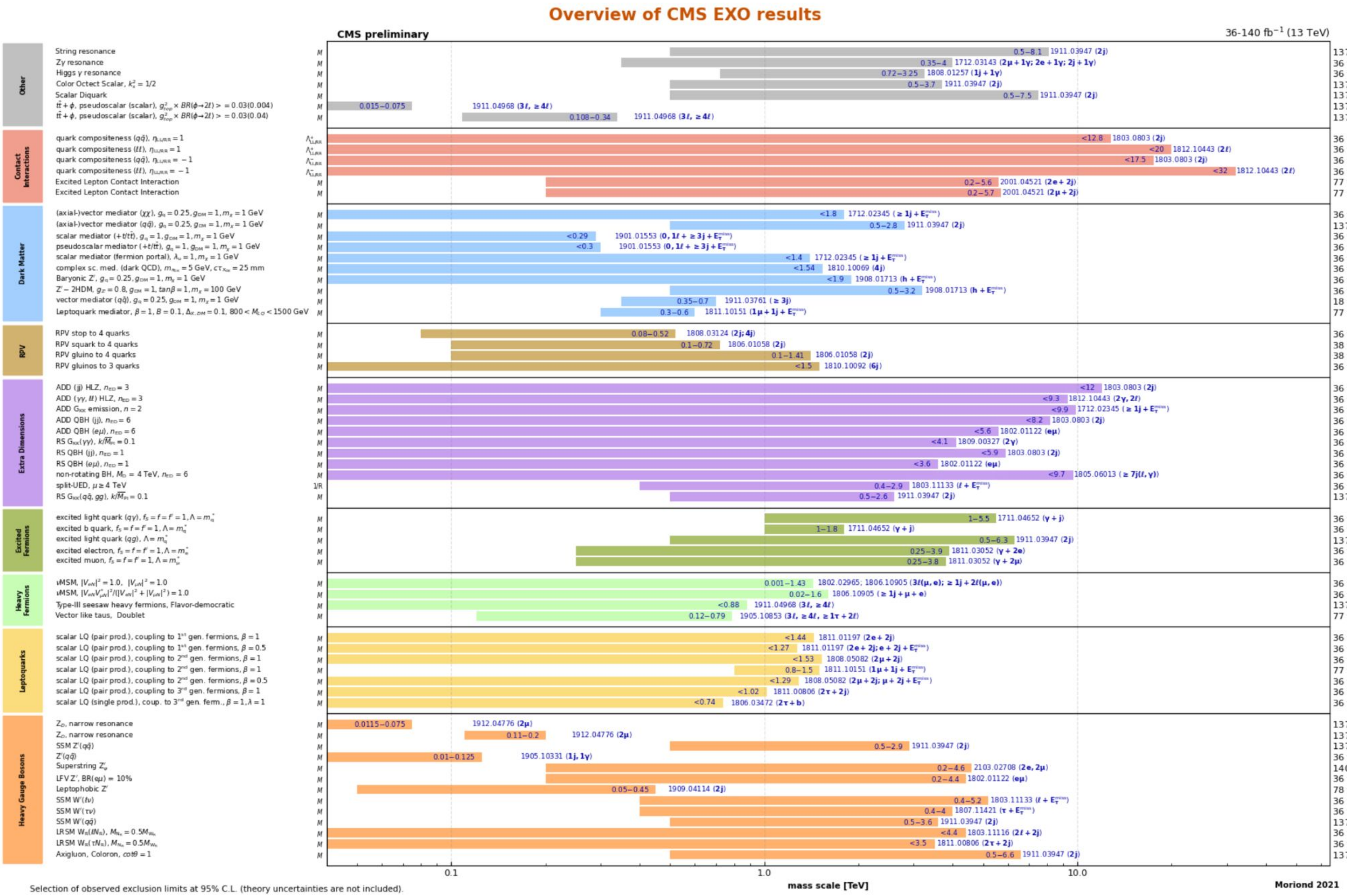
Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Moriond 2021

The (overwhelming) picture



Wrap up

LHC has a robust flavor physics program

- Complementarity among experiments
- Measurements competitive with B-factories

Exotica represents main searches of BSM physics at LHC

Versatility of experiments allows to search for a large set of topologies

Built on SM physics, but new techniques are needed

We do not know if/when LHC will see BSM signals

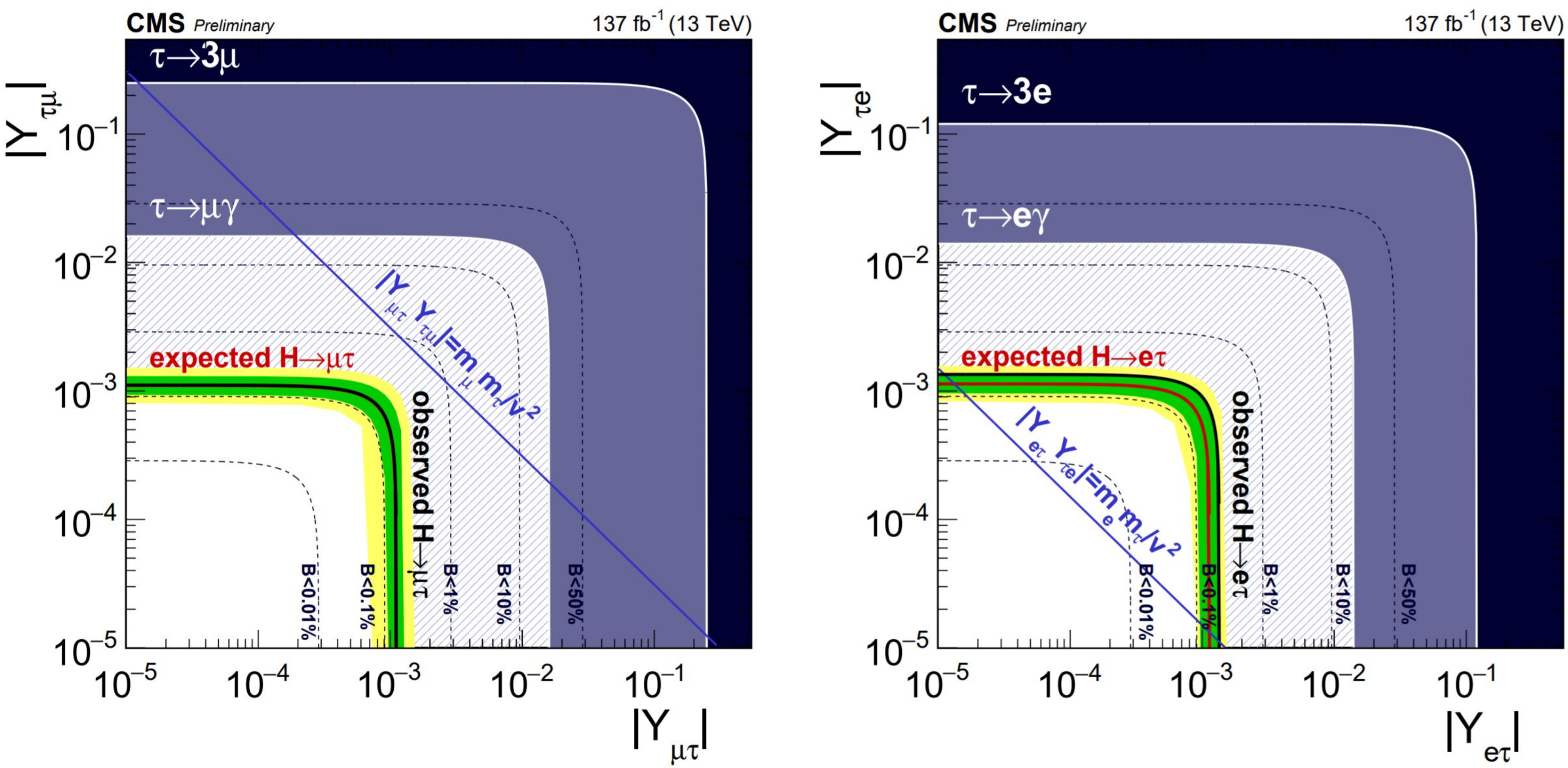
$\longrightarrow$ **leave no stone unturned!**

Backup

$H \to e\tau, \mu\tau$

CMS-PAS-HIG-20-009

Derived from $\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}(|Y_{\ell^\alpha \ell^\beta}|^2 + |Y_{\ell^\beta \ell^\alpha}|^2)$



Higgs triplets

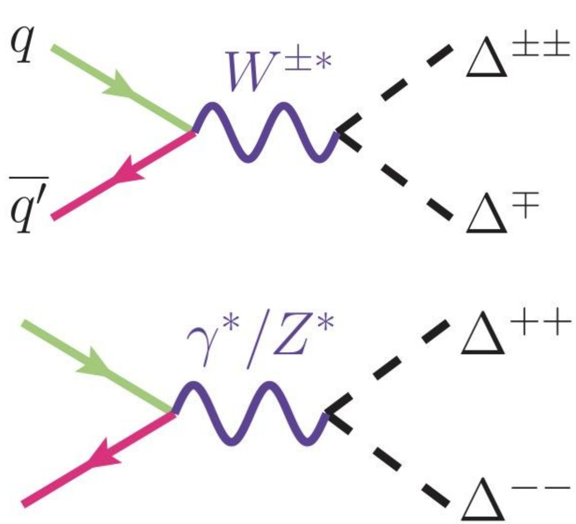
Higgs sector organized in triplets: a nice way to provide neutrino masses via type-II seesaw mechanism

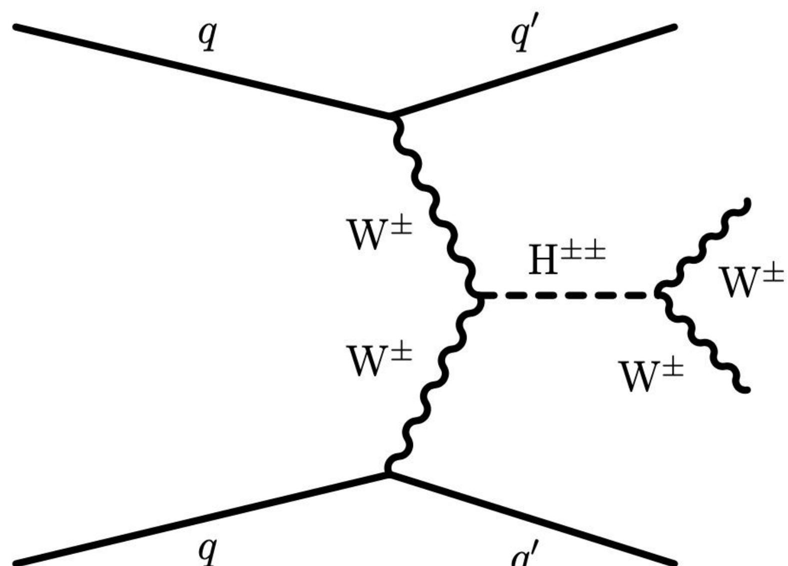
→ Generic forms suffer for large radiative corrections

Georgi-Machacec: two triplets, one real and one complex

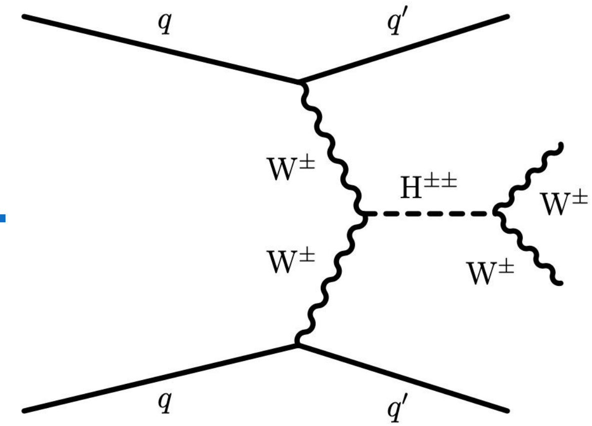
corrections preserved via custodial symmetry

Generates two scalars, $H_{1,2}^{+}$, H^{++}





$H^{+(+)} \rightarrow$ vector bosons



VBF $H^+ \rightarrow W^+Z$ and $H^{++} \rightarrow W^+W^+$ in leptonic decays

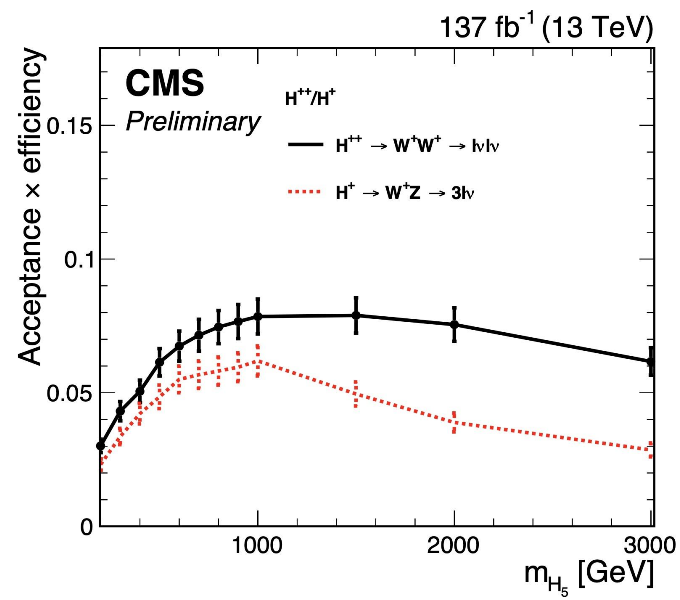
Mass degeneracy

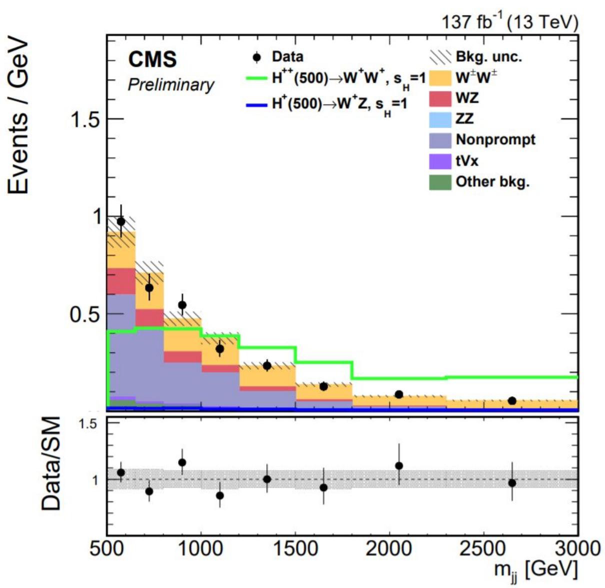
$\rightarrow$ simultaneous search in $200 < m_{H5} < 2000$ GeV range

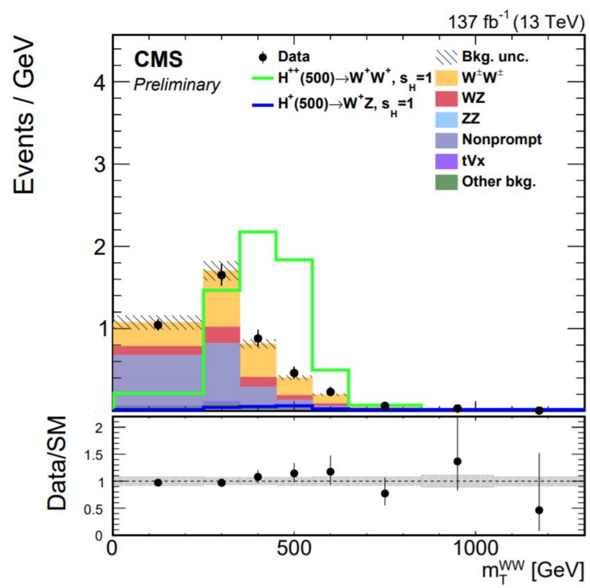
tt, tZq and ZZ backgrounds estimated from data

inverting b-tag and same-sign selections

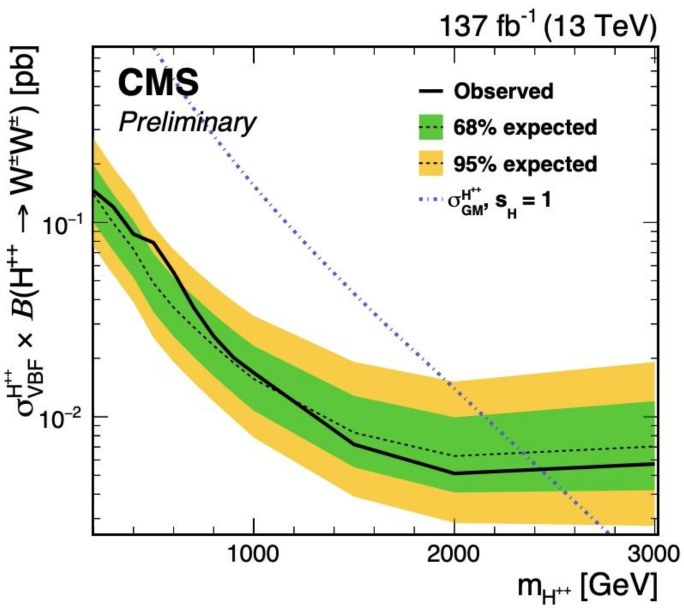
Fit m_{jj}, m_T^{VV} $$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$

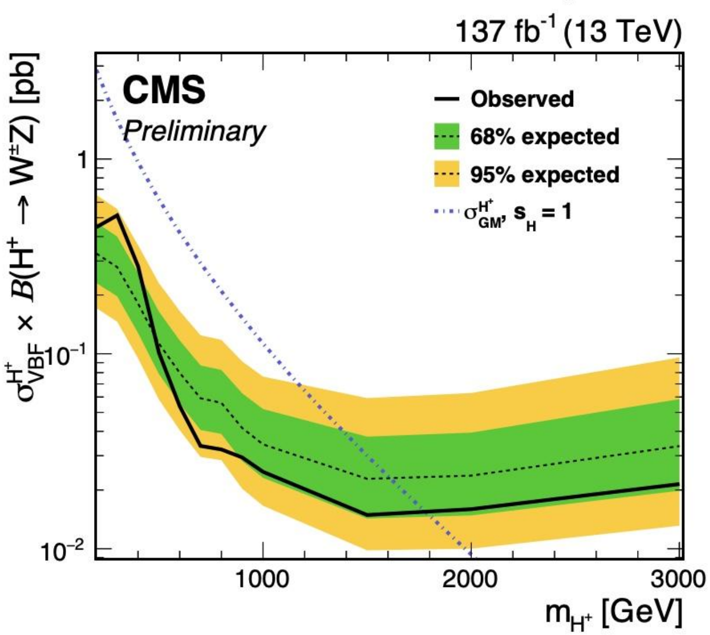


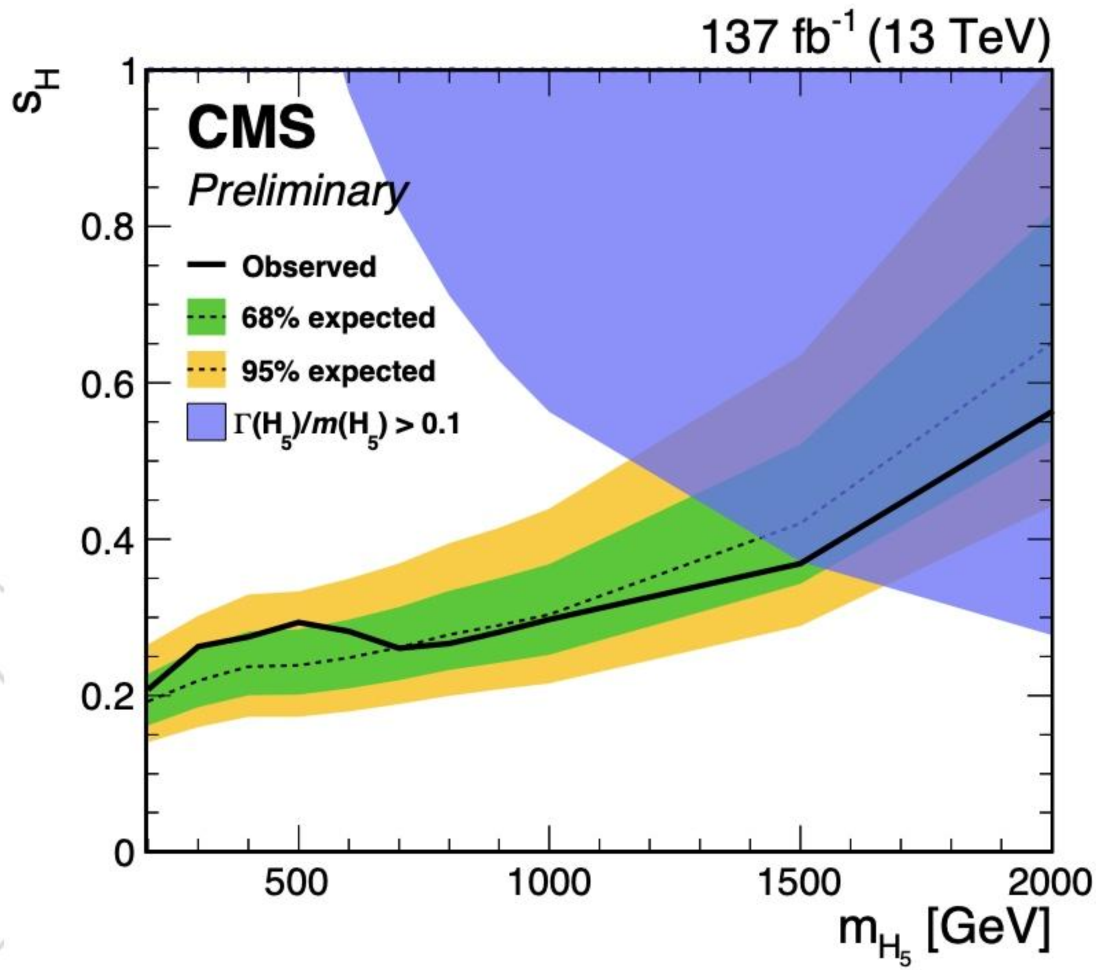




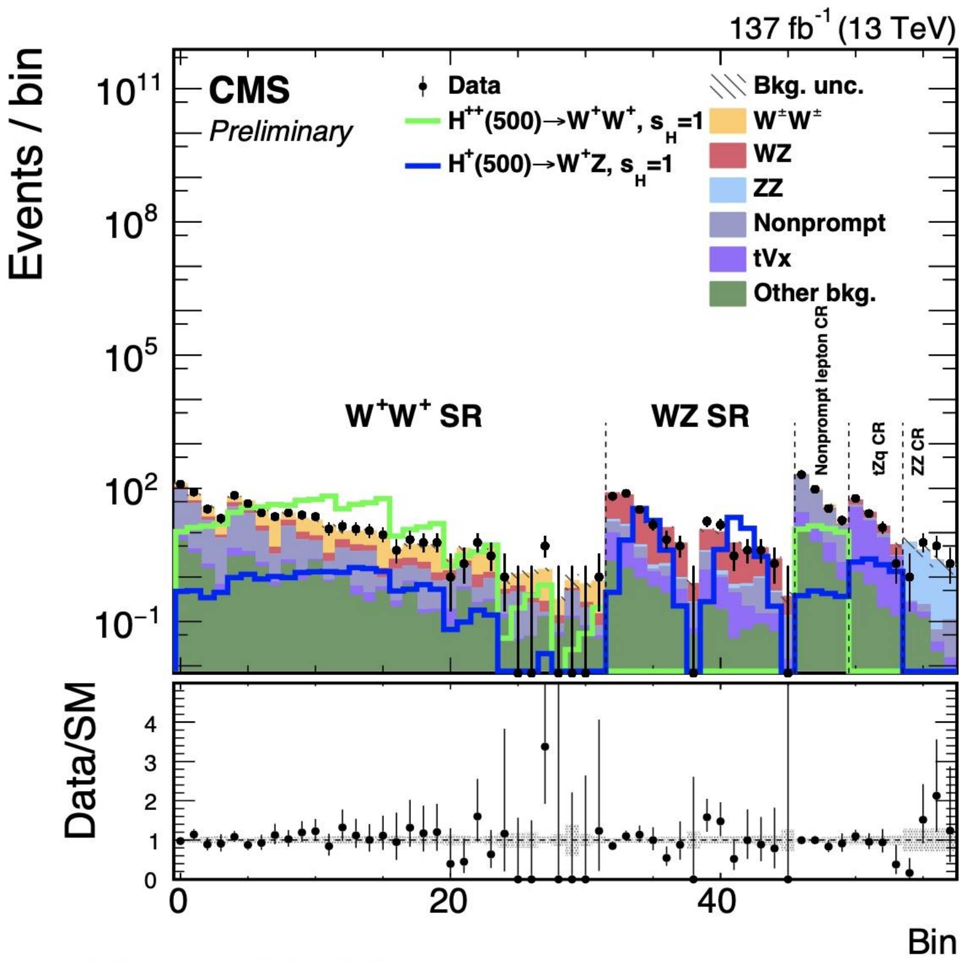
$H^{+(+)} \to$ vector bosons







$H^{+(+)} \longrightarrow$ vector bosons



Source of uncertainty	$\Delta\mu$ background-only
Integrated luminosity	0.002
Lepton measurement	0.003
JES and JER	0.003
Pileup	0.001
b tagging	0.001
Trigger	0.001
Limited sample size	0.005
Nonprompt rate	0.002
$W^{\pm}W^{\pm}$/WZ rate	0.014
Other prompt background rate	0.002
Signal rate	—
Total systematic uncertainty	0.016
Statistical uncertainty	0.021
Total uncertainty	0.027