De open deur, Léon Spilliaert

Neutral bosons as a portal to dark matter at the LHC

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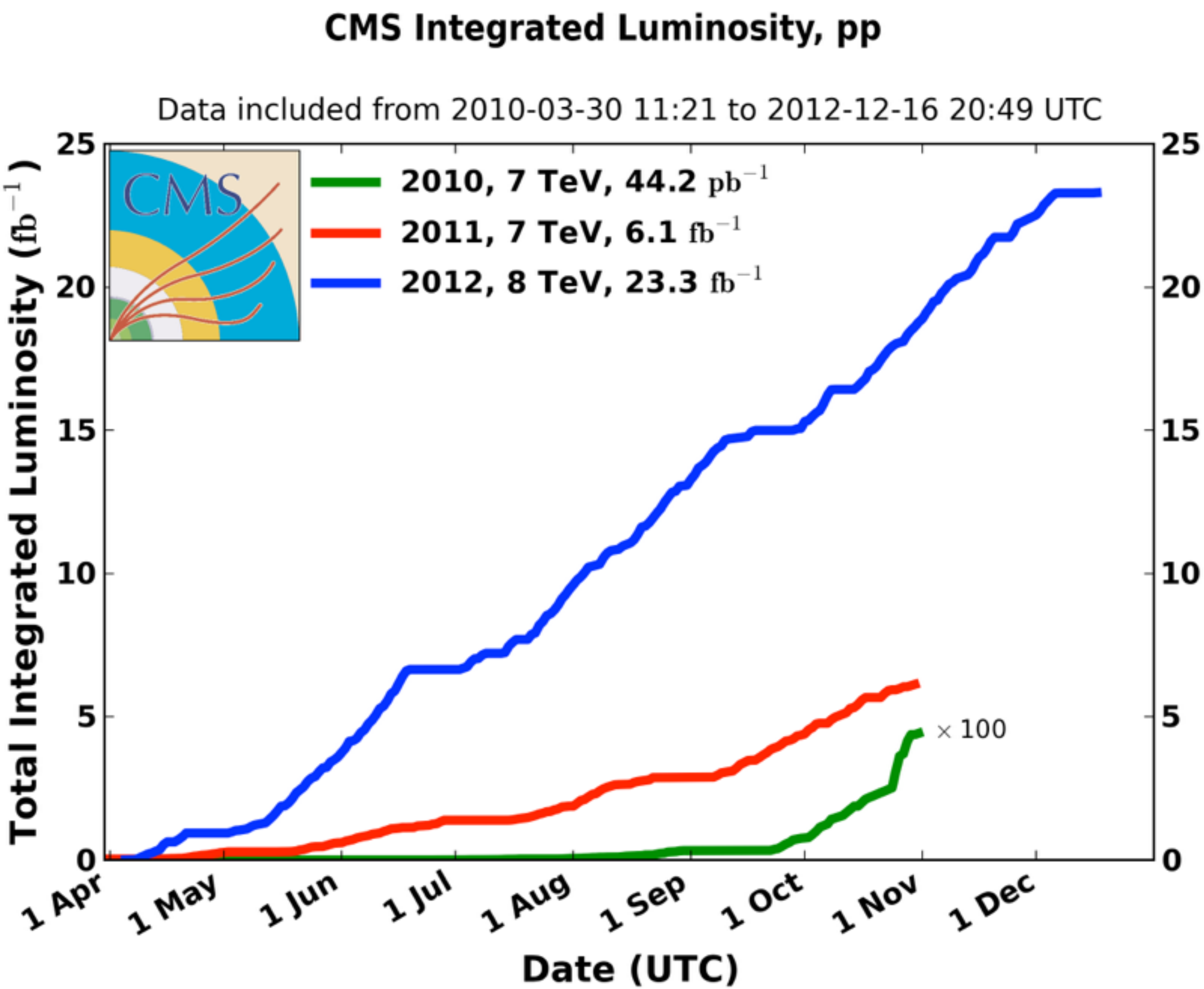
Université Catholique de Louvain

Cosmology, Particle Physics and Phenomenology - CP3

The potential of the LHC Run I…



3×10^8 W bosons

3×10^7 Z bosons

7×10^6 top pairs

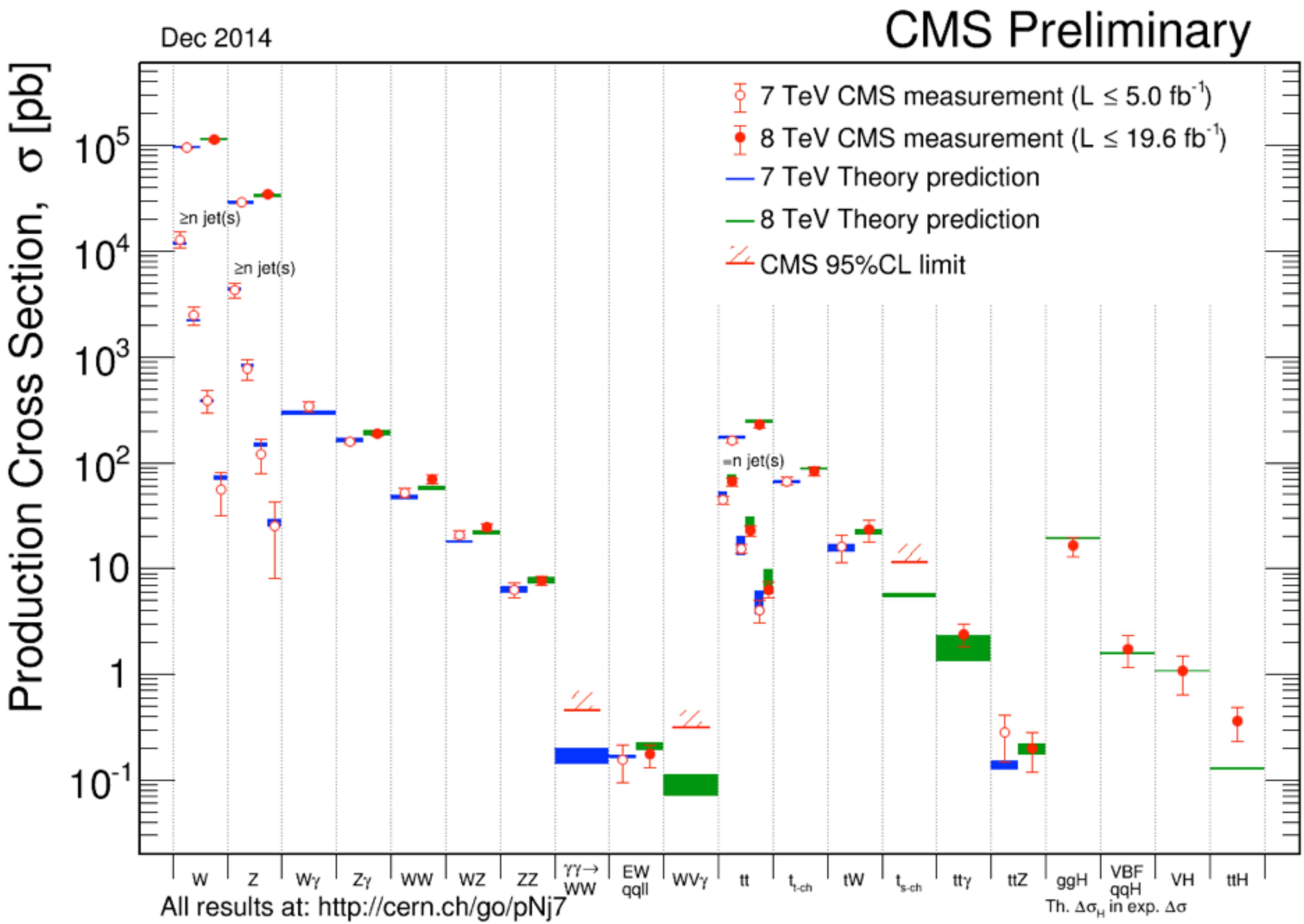
2×10^6 single tops

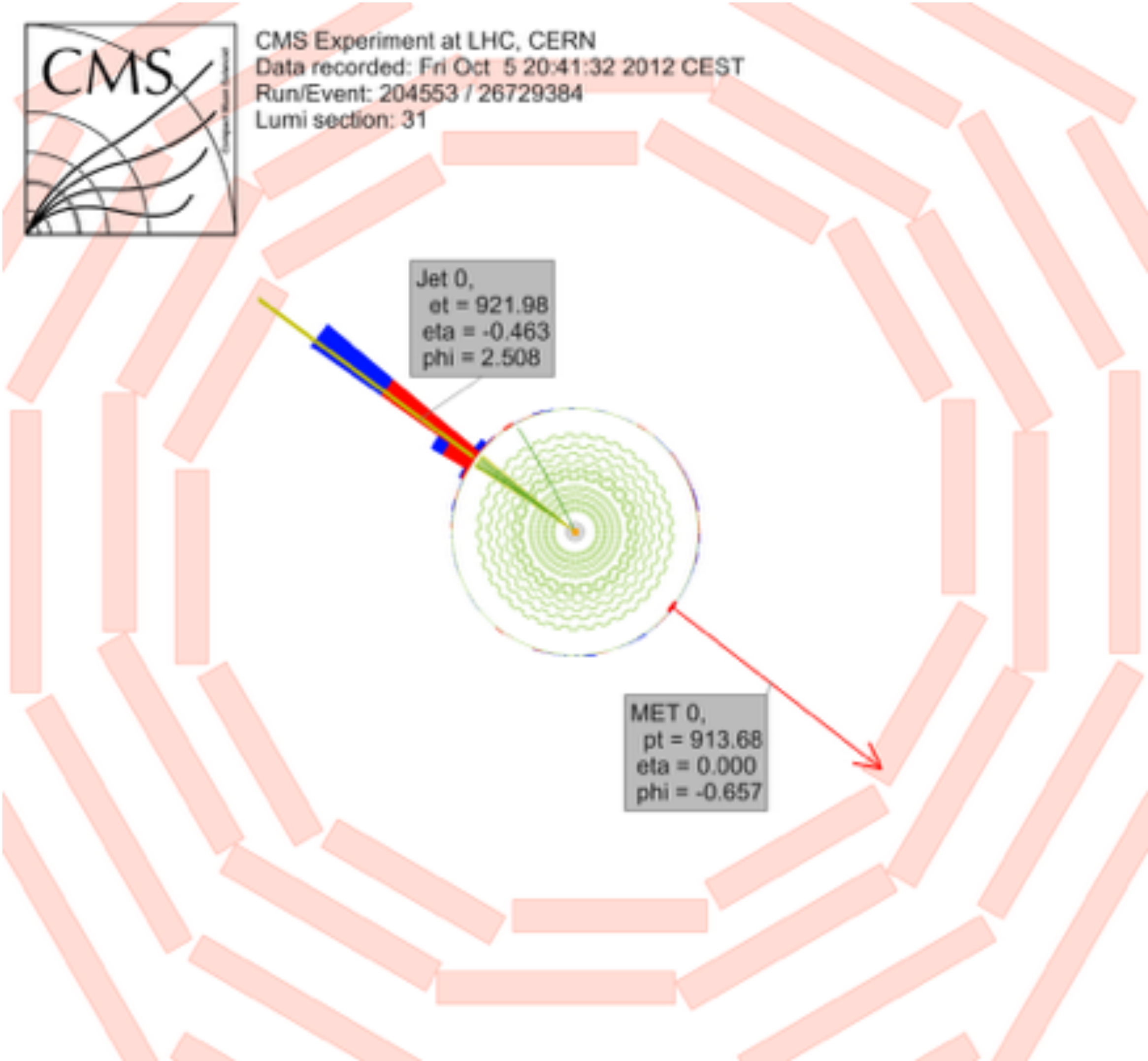
5×10^5 H

4×10^3 tt+H

22 four tops

…has been largely explored, and confirmed the SM

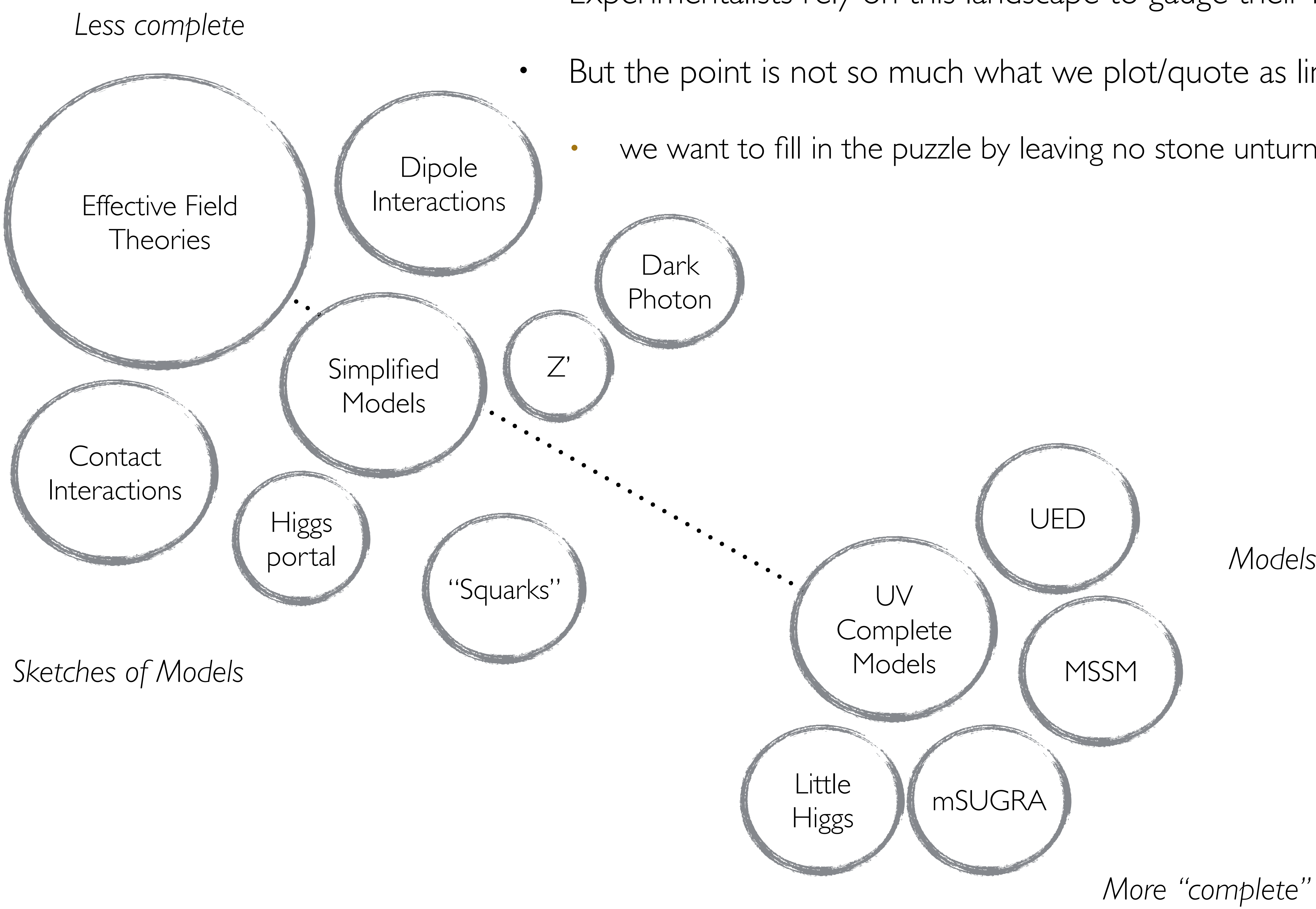




Seeking for signs of dark matter at the LHC

Landscape of theory/phenomenology space

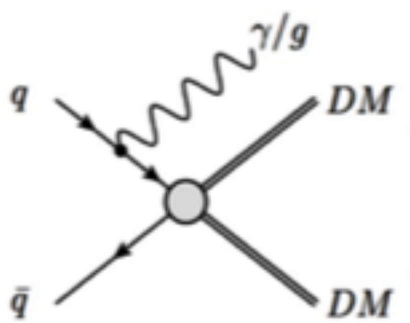
- Experimentalists rely on this landscape to gauge their findings
- But the point is not so much what we plot/quote as limit
  - we want to fill in the puzzle by leaving no stone unturned



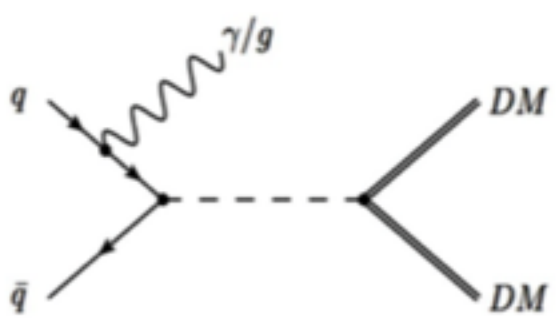
adapted from T.Tait @ LP2013

Direct production

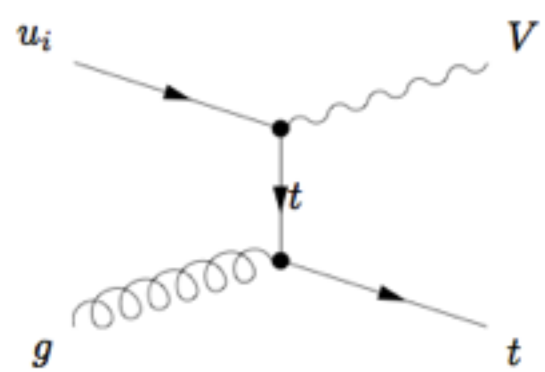
- Search for direct DM production
  - pair production recoiling against a SM particle: gluon, photon, vector boson,…
  - mediator, may couple preferentially to top quarks
  - interaction modelled by an effective field theory or simplified models (more parameters)

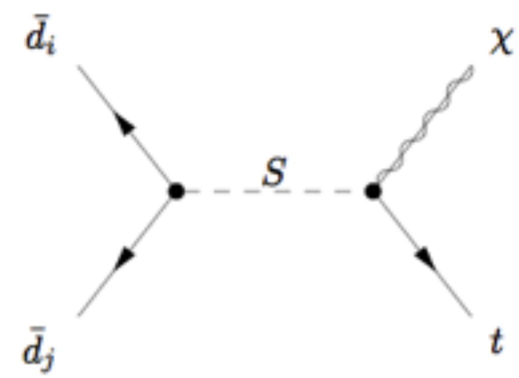


Point-like interaction
depends typically on cut-off scale and M_{DM}
can translate to a nucleon-DM cross section

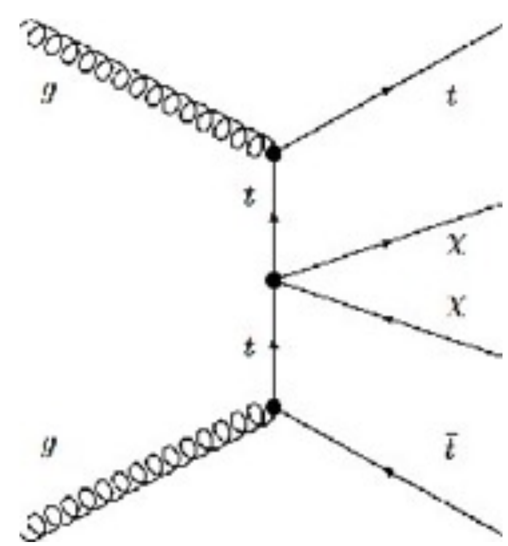


Specify mediator between SM and DM
introduces more parameters to scan





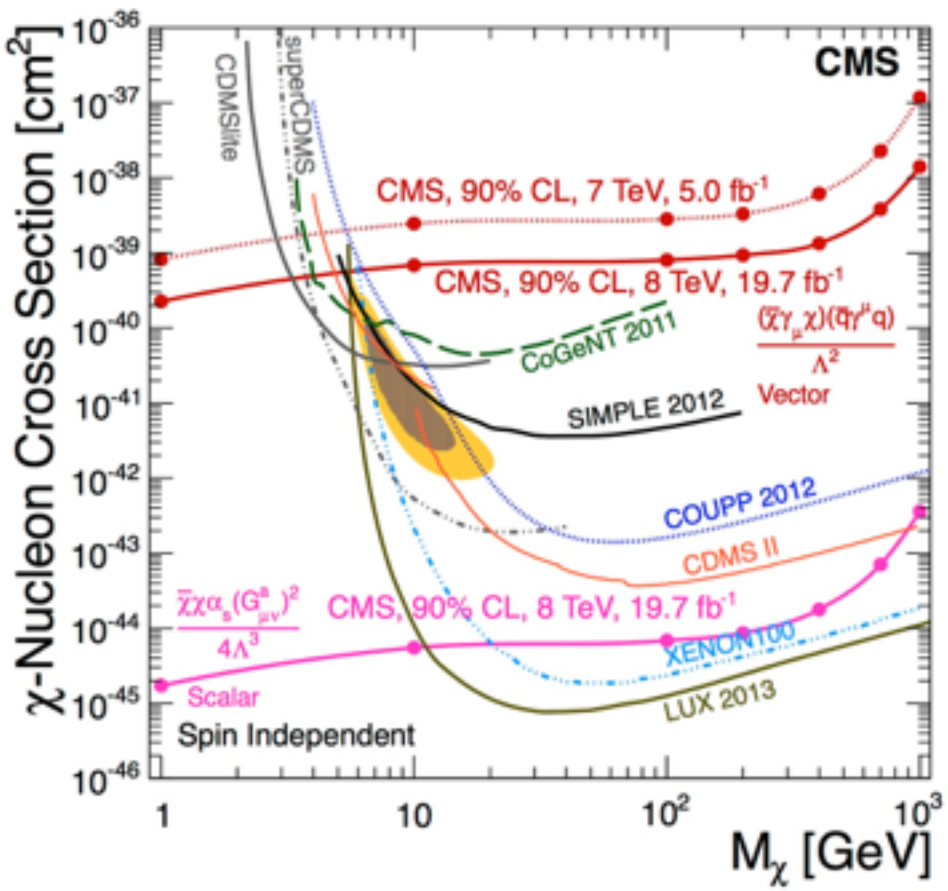
Mono-top production
coupling through FCNC diagrams
or resonant through
SM-DM mediator production

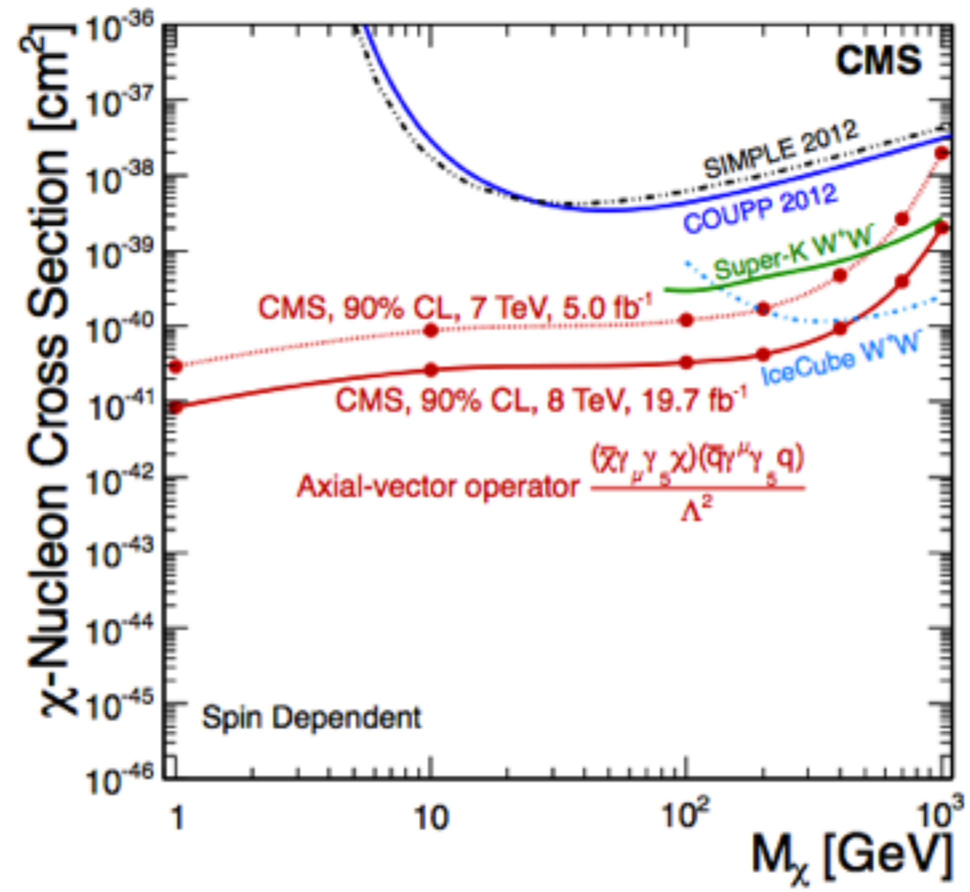


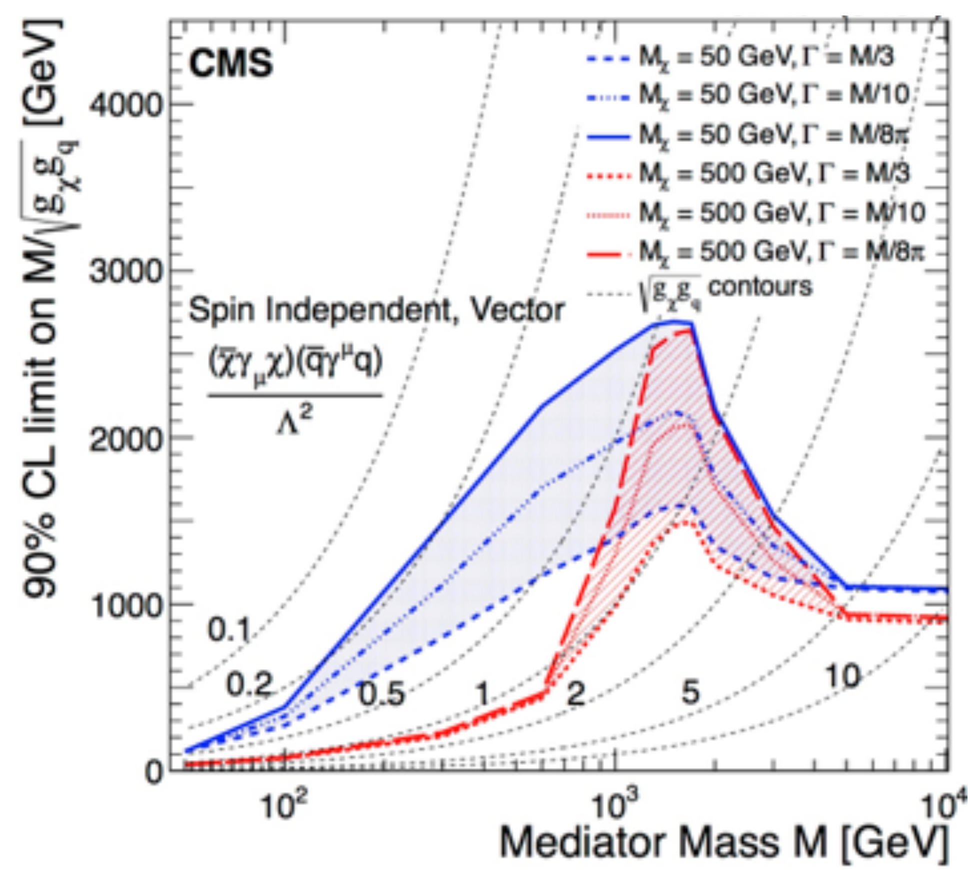
$$L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$

top-pair production + E_T^{miss}
generic signature
overlap with SUSY, Higgs, …

Limits from direct production



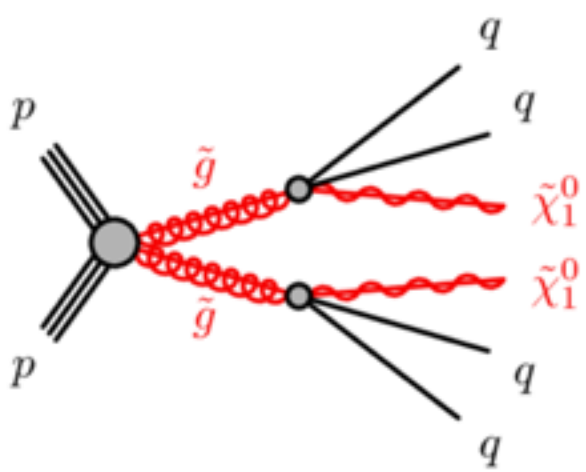




- From **mono-jet searches** - arXiv:1408.3583
  - complemented by mono-photon (arXiv:1408.3583)
  - and lepton+E_T^{miss} (arXiv:1408.2745)
  - scanned models (EFT or simplified model) rather competitive with direct searches
  - will benefit from higher integrated luminosity in Run II

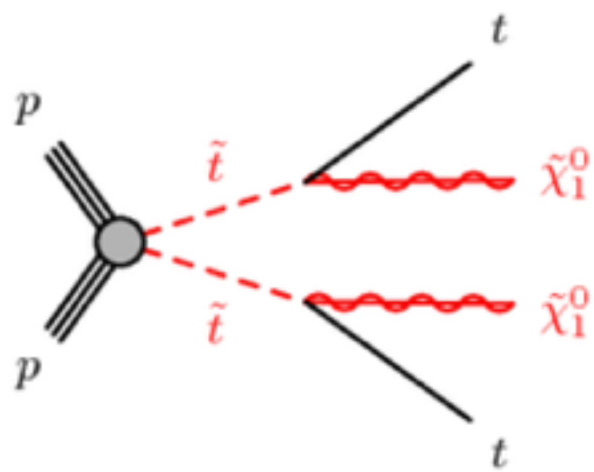
Signatures from supersymmetry

- **SUSY** models predict a stable lightest supersymmetric particle if R-parity conserved
  - produce DM in cascade decays from heavier new states
  - distinctive signature of missing transverse energy an an event



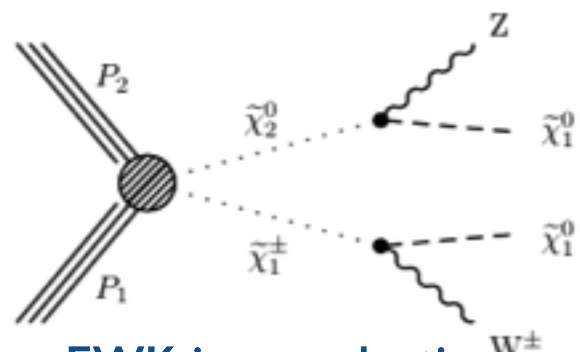
if gluinos are in reach of the LHC

4t / 2t2b / 4b + E_T^{miss}



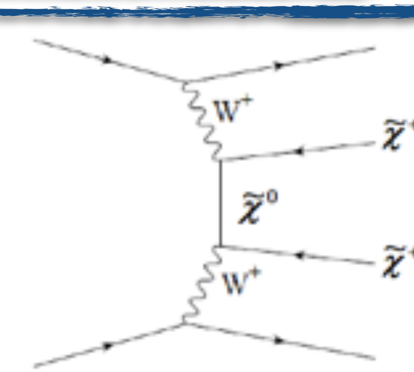
direct stop production

2t + E_T^{miss}



EWK-ino production

multileptons+E_T^{miss}



Chargino production

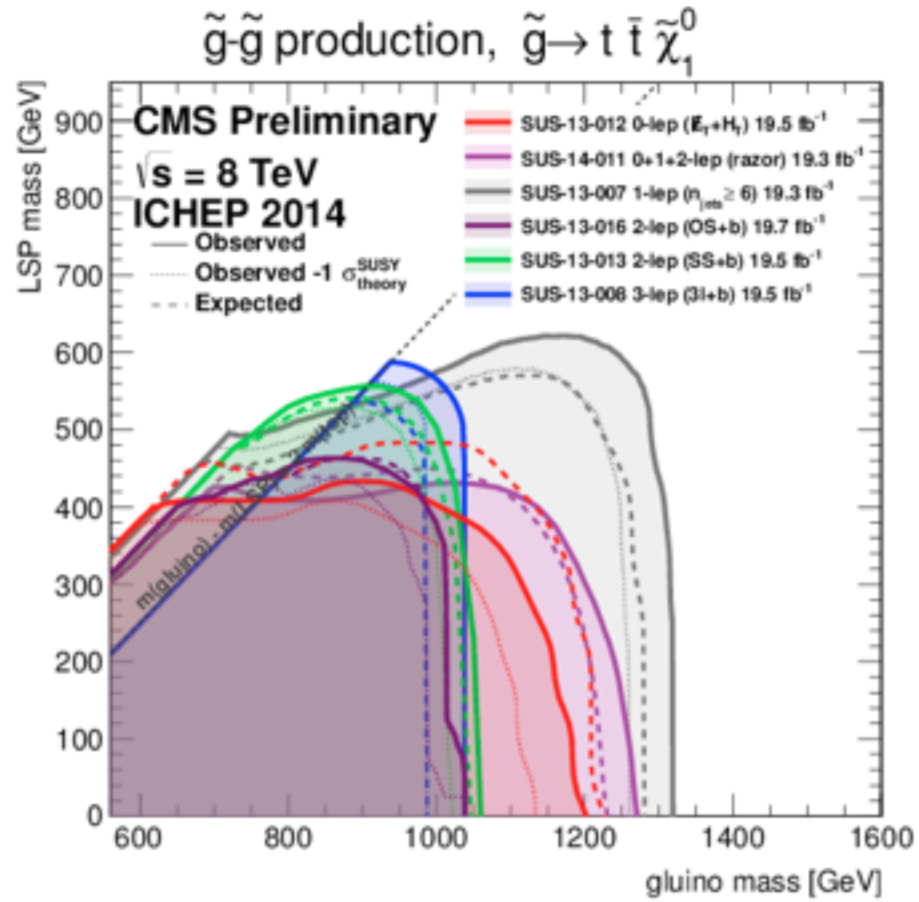
E_T^{miss} (+τ's)+ VBF jets

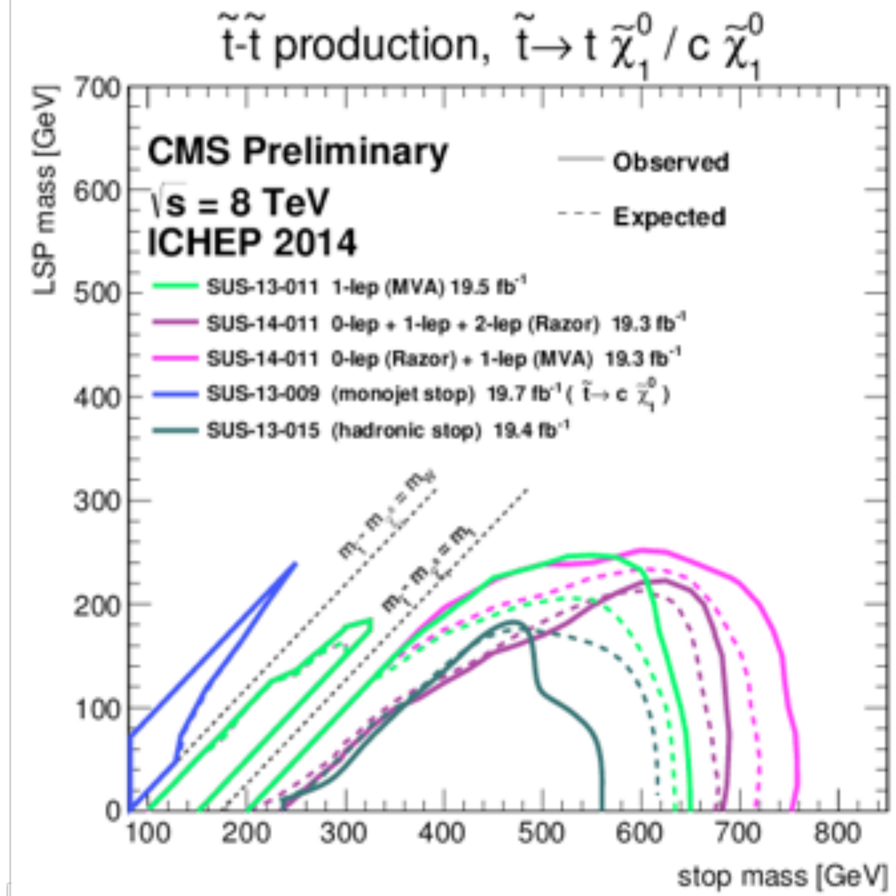
- Strong production channels will benefit from increase in $s^{1/2}$
- Sensitivity is driven by largest BR channels: full hadronic and l+jets
- Benefit from high luminosity sample to test compressed spectra

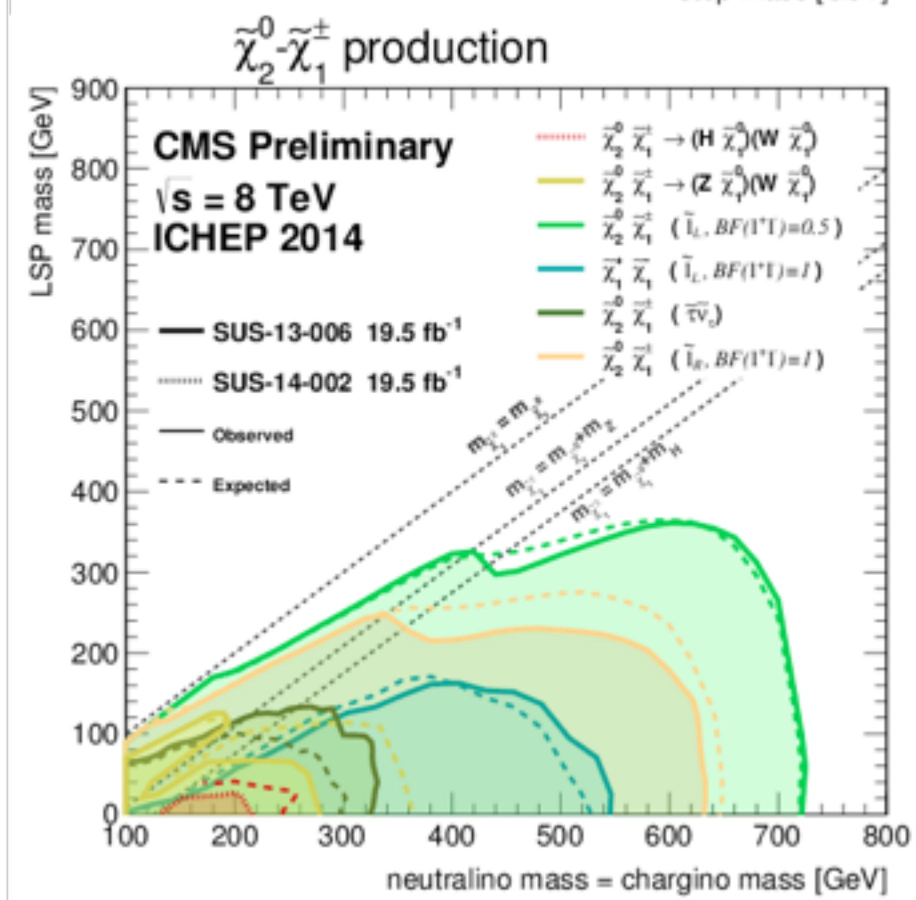
- Lower cross section wrt to strong production
- Benefit from clean signature
- Increasingly interesting with more data acquired

Limits from supersymmetry

CMS results on SUSY searches, available at *PhysicsResultsSUS*







- **Interpret search regions with simplified models**
  - exclusive contribution from production/decay mode
  - quantifies consistency between expectation and observation
  - can't be directly interpreted as limits on DM candidate
  - analyses can be recast in terms of other models
  - e.g. M<800 GeV disfavored in pMSSM context (SUS-13-020)

The (visible) Higgs

- The **Higgs discovery is a window of opportunity**
- Its properties are, so far, consistent with that of the SM Higgs
  - mass in the range expected by a global fit of the SM, $J^{PC}=0^{++}$ - consistent
  - couples to bosons and fermions as expected, but uncertainties are still large
  - data still allows for a large BR to BSM particles

Mass

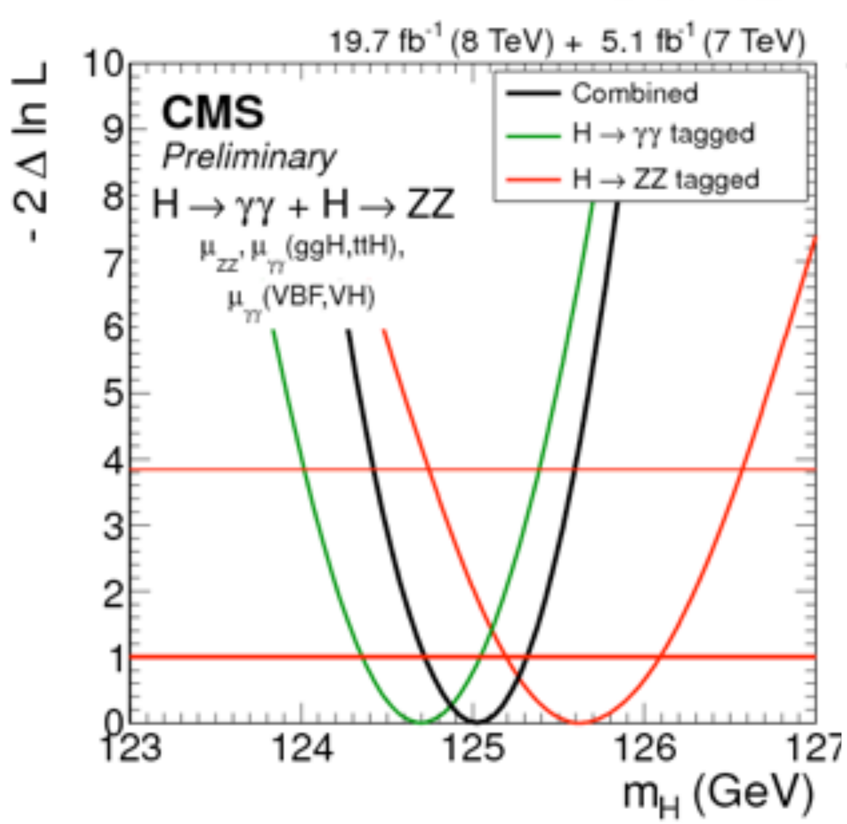
$125.03\ ^{+0.26}_{-0.27}\ \text{(stat.)}\ ^{+0.13}_{-0.15}\ \text{(syst.) GeV}$

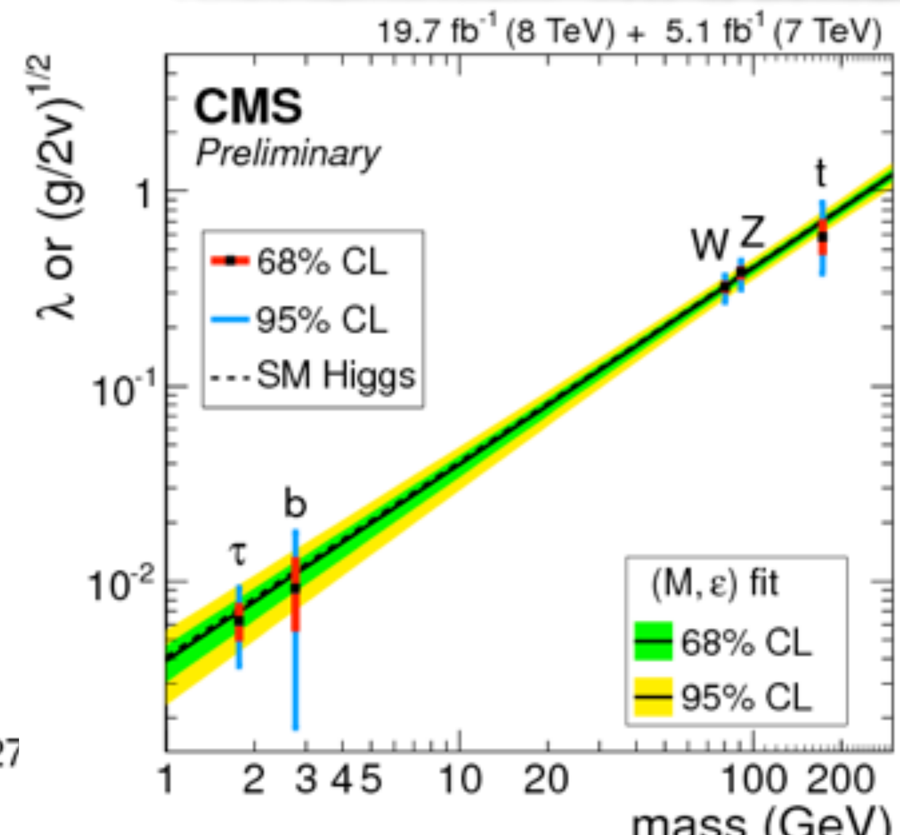
Signal strength

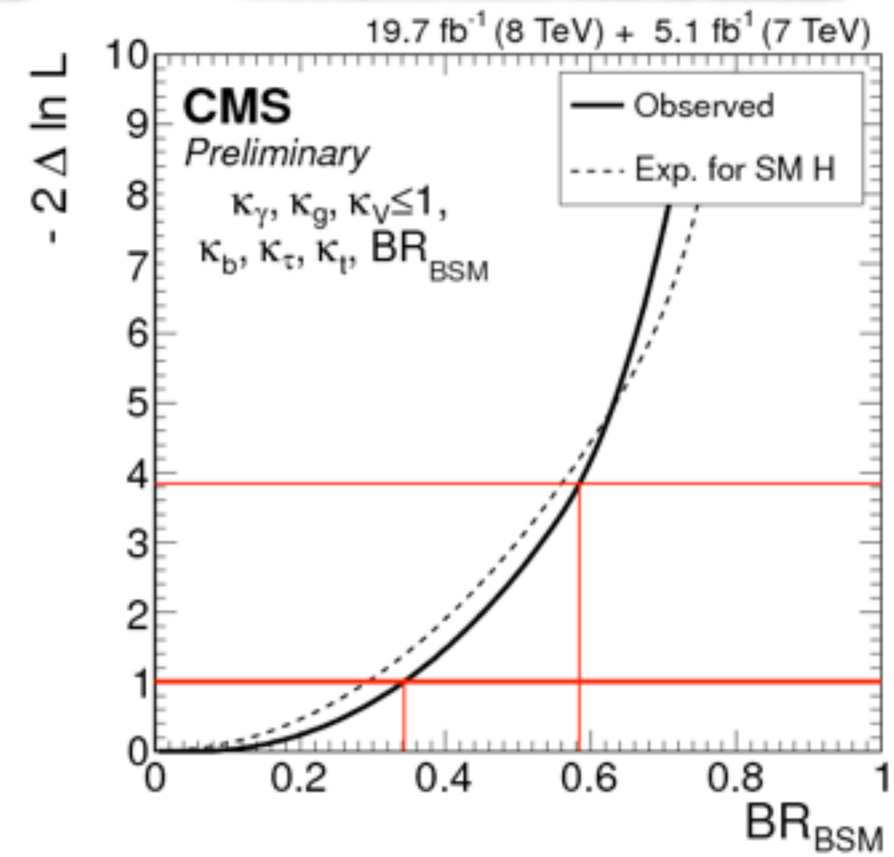
$1.00\ \pm 0.09\ \text{(stat.)}\ ^{+0.08}_{-0.07}\ \text{(theo.)}\ \pm 0.07\ \text{(syst.)}$

Decays to BSM

$BR_{BSM} \in [0,0.58]$ @ 95%CL





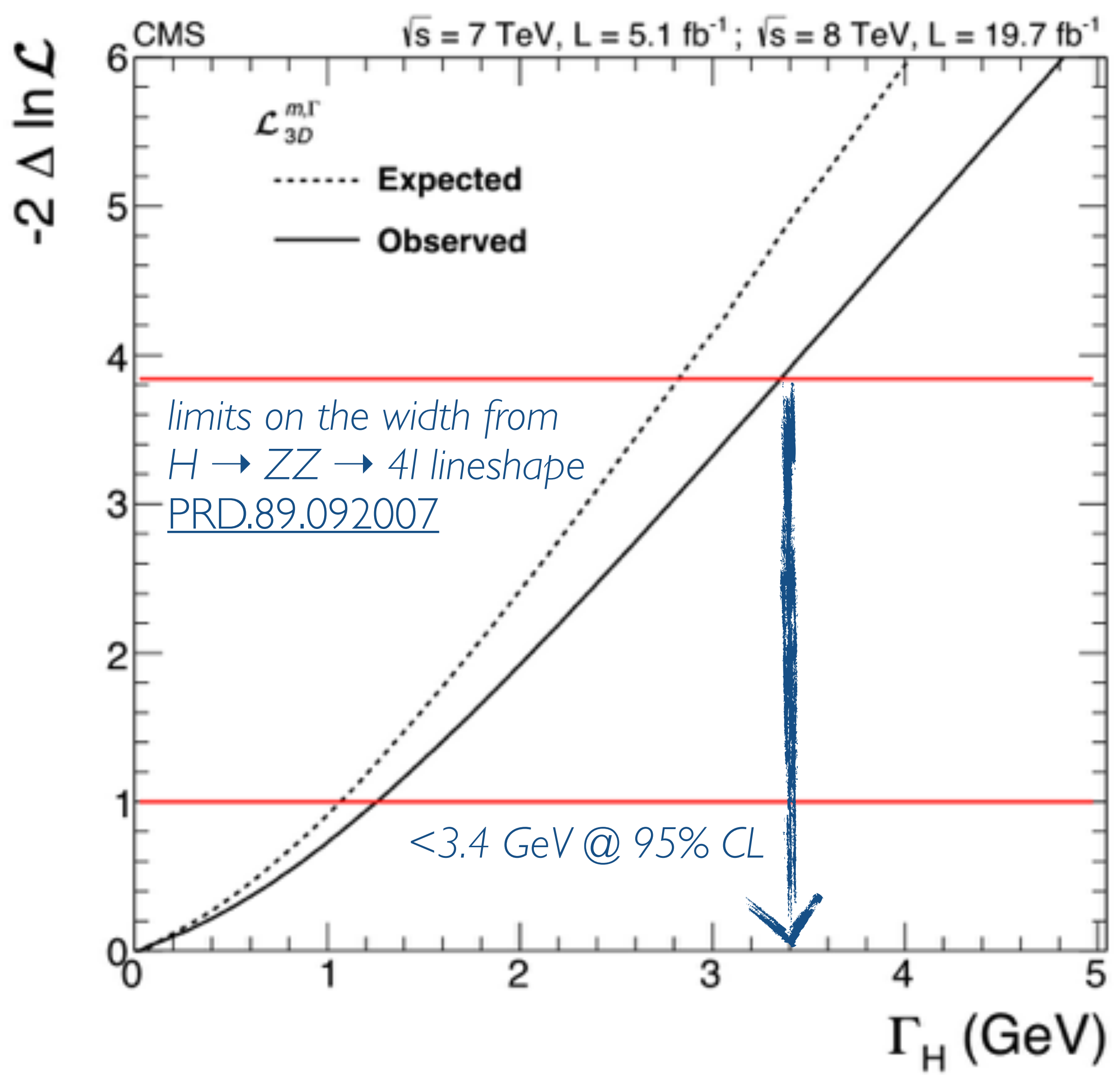


The Higgs portal

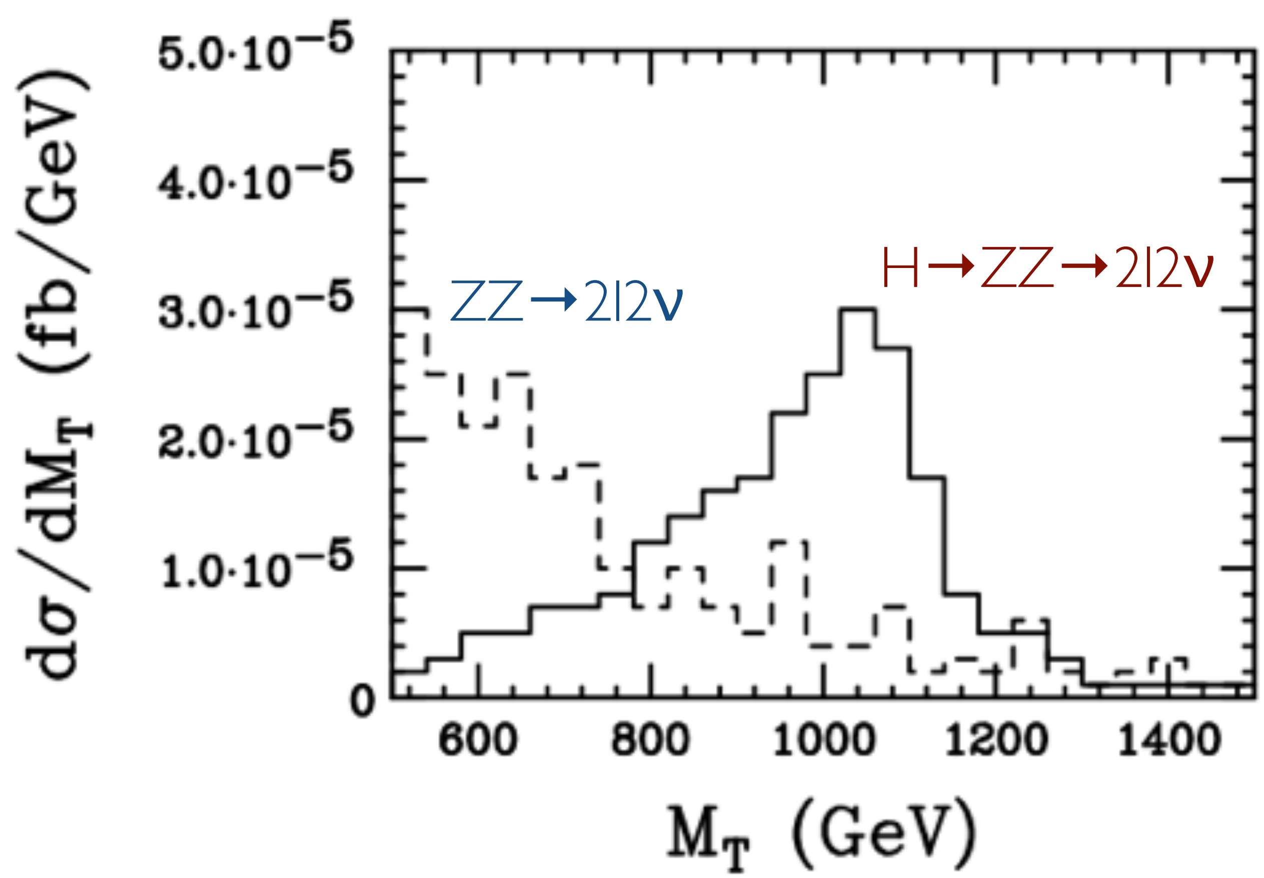
- If the SM scalar couples to dark matter

  ⇒ invisible Higgs decays

  ⇒ deviations in Higgs width (Γ_{SM}≃4.1 MeV)



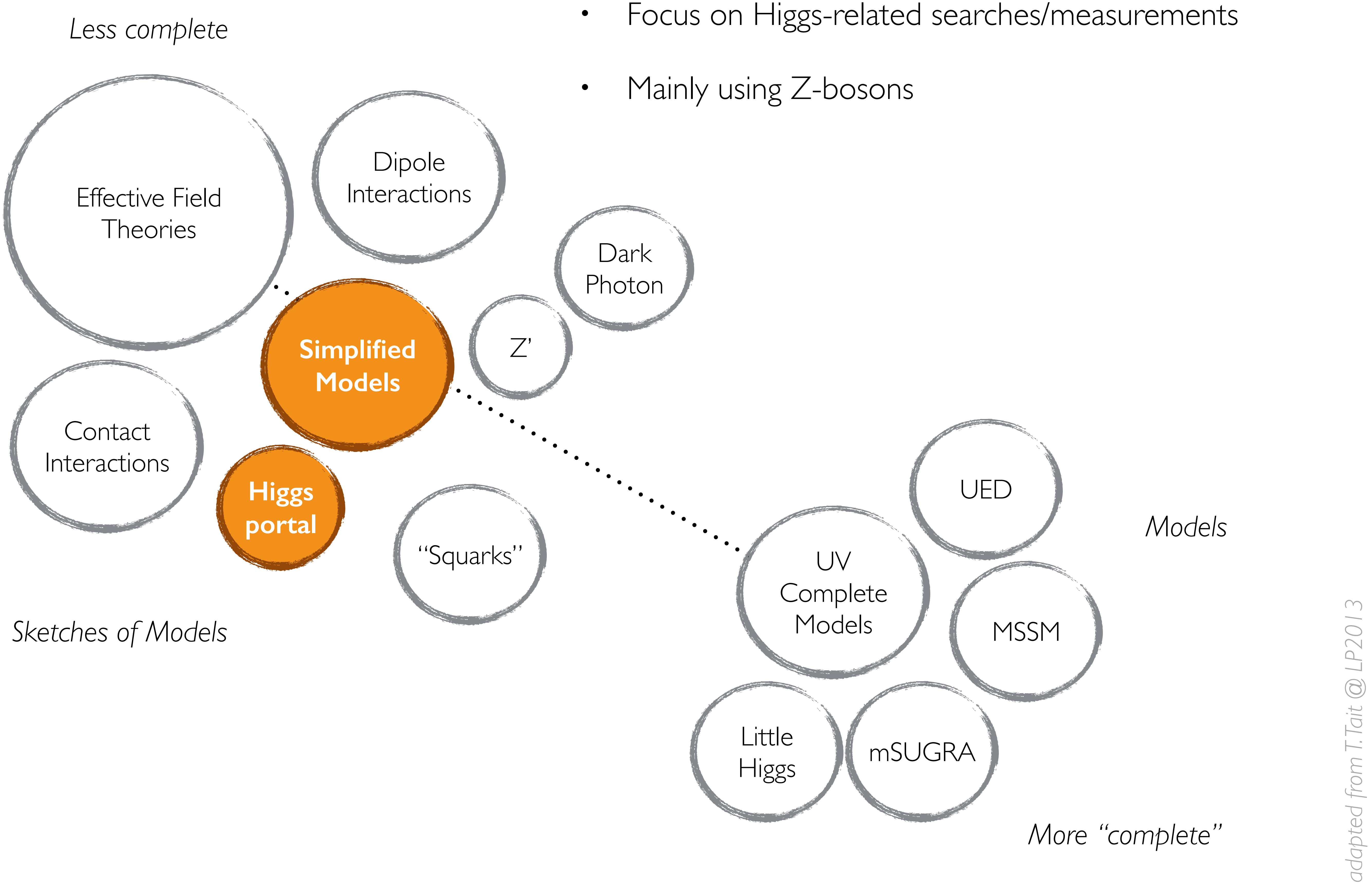
- More complex Higgs sector
  - a Higgs partner holds the key to the BSM world
  - resonant associated production, hh production, (possibly very narrow) high-mass diboson resonances, …

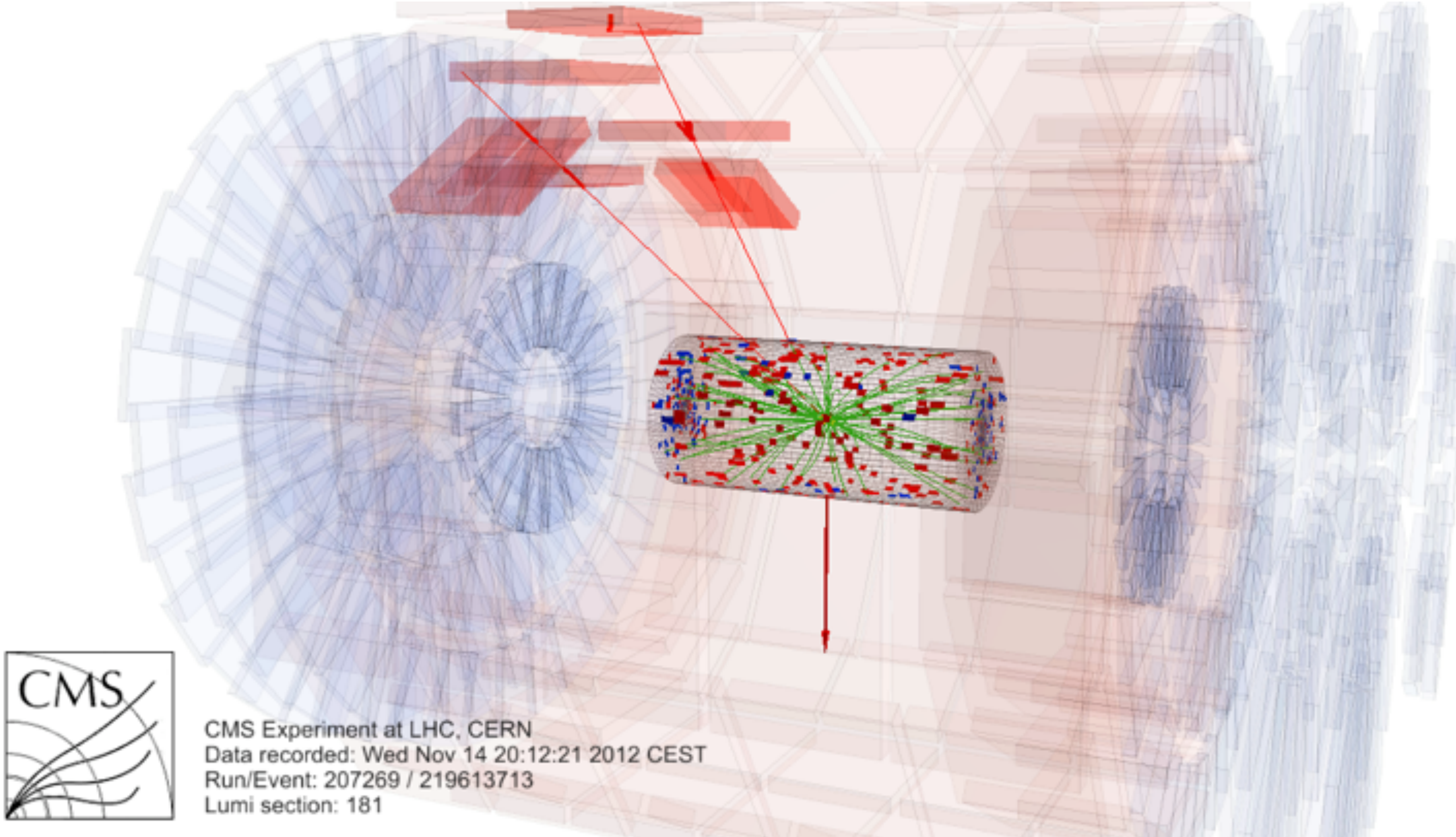


JHEP 0703:036,2007
arXiv:0803.1243

Landscape of theory/phenomenology space

- Focus on Higgs-related searches/measurements
- Mainly using Z-bosons

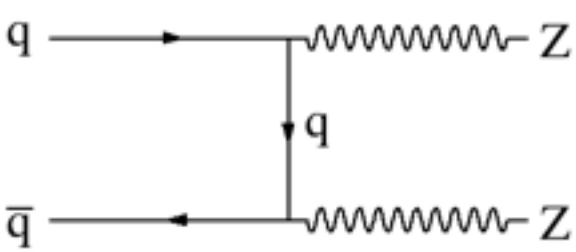


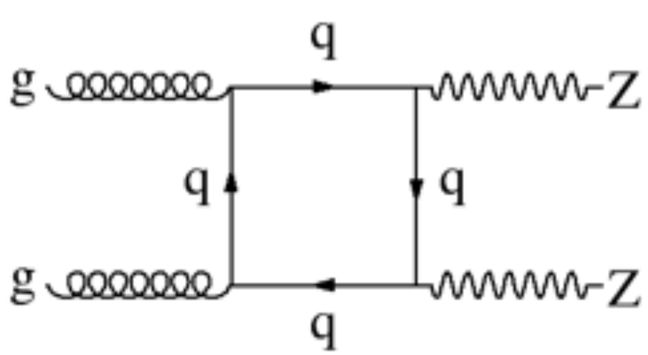


Using neutral bosons as probes for New Physics

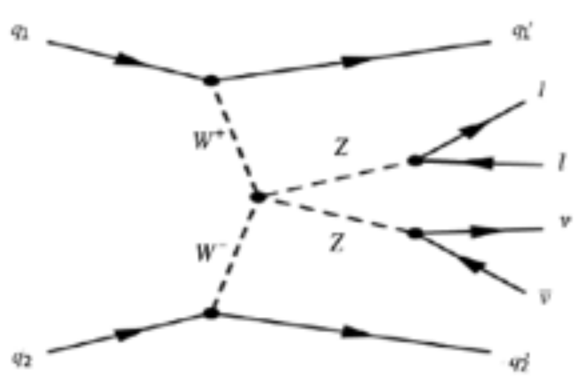
ZZ production at the LHC

- It has the smallest of the diboson cross sections O(10 pb)
  - t-channel production dominates, s-channel is suppressed by O(10^{-4})
    (unlike WZ and WW which benefit from triple gauge coupling)
  - dominated by quark-anti-quark annihilation with ~10% contribution from gluon-box diagram
  - vector boson fusion production of ZZ has very small cross section O(10 fb)

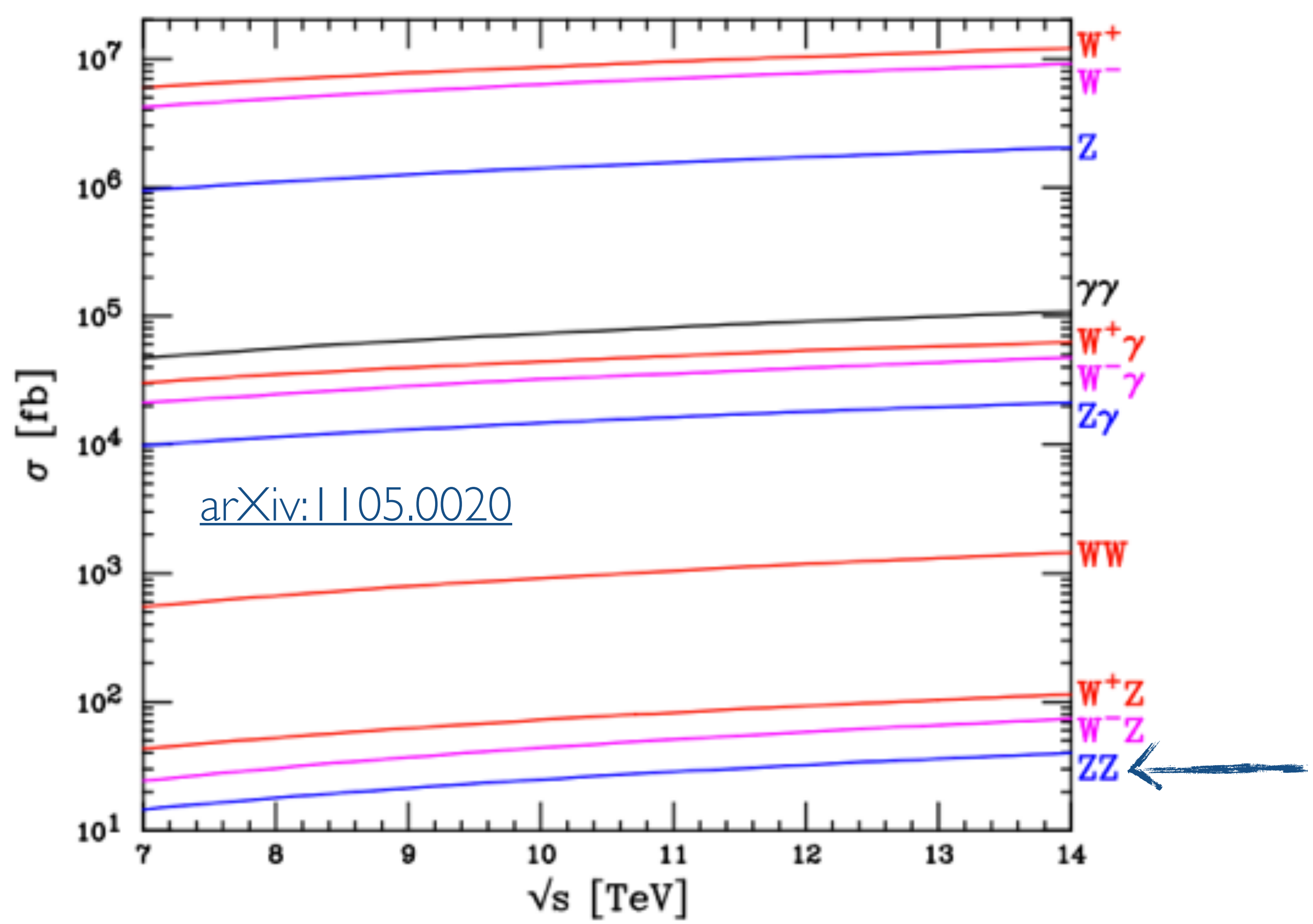




~7.9 pb



~2.8 fb



ZZ → $2\ell 2\nu$: a signature with large reach

- The ZZ → $2\ell 2\nu$ (ℓ=e,μ) offers a unique window to explore several physics cases
  - high branching ratio BR(Z→2ν)/B(Z→ 2ℓ)=3 → stat. gain with respect to golden 4ℓ channel
  - distinct signature with respect to main backgrounds: dilepton pair M~M_Z with recoil E_T^{miss}
  - Z→ 2ℓ used as a trigger (low thresholds allowed)
  - drawback: poor mass reconstruction

$X^{(*)}$ → ZZ → $2\ell 2\nu$

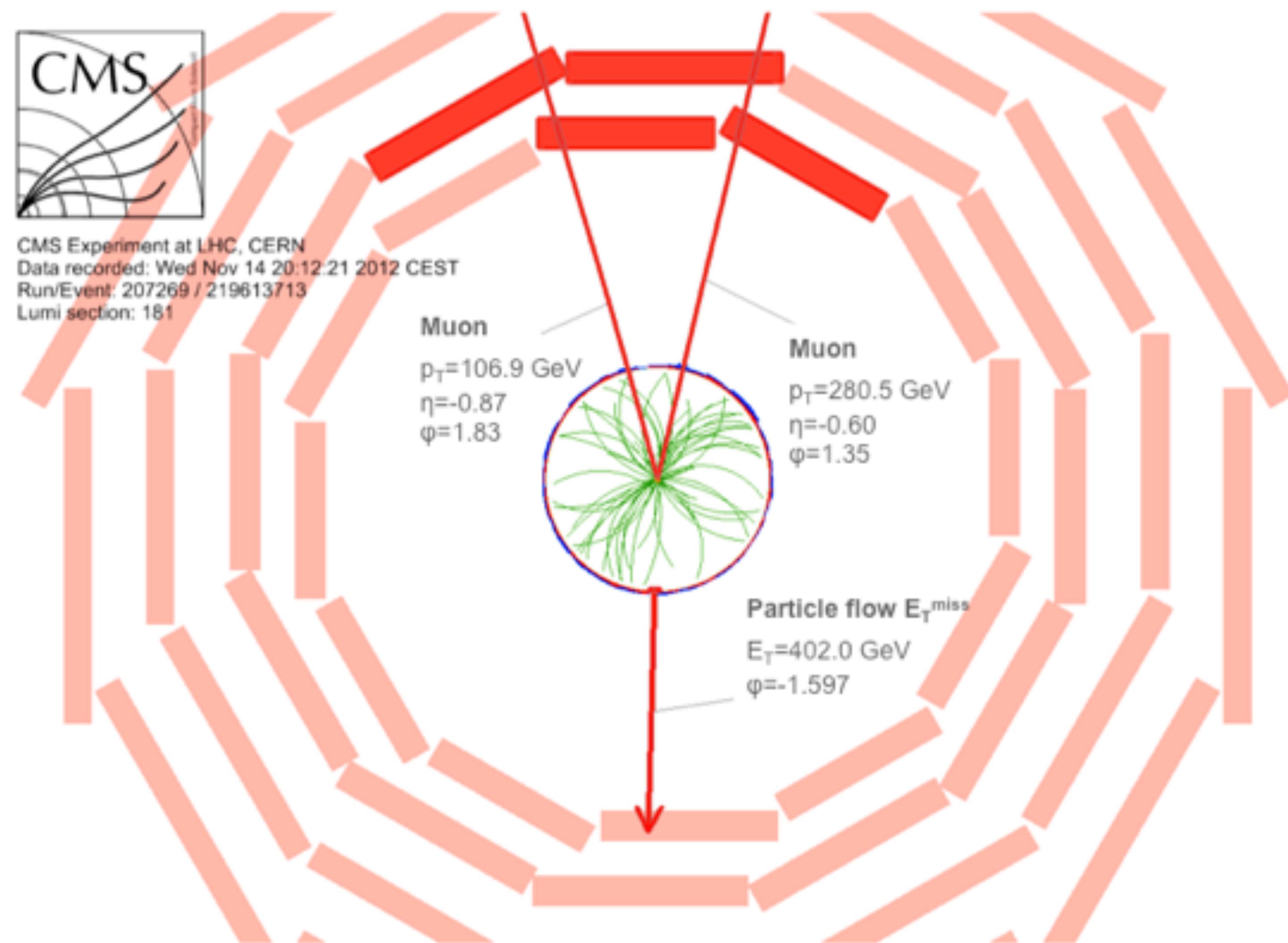
ZH → 2ℓ+H_{inv}

anomalous ZZ couplings

Z+DM

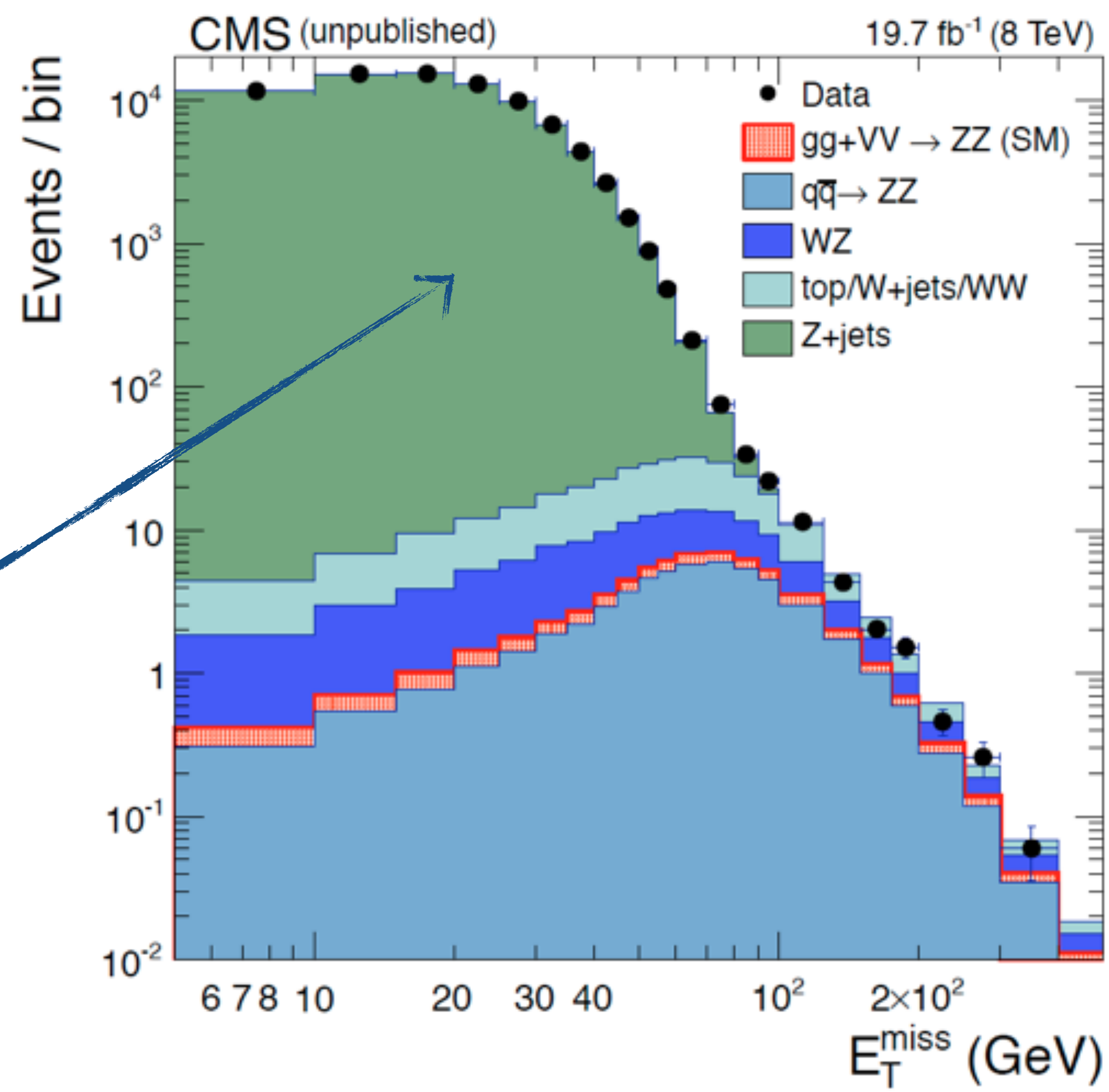
. . .

missing ET



Main backgrounds in the $2\ell 2\nu$ channel I

- **Z+jets (DY)** dominates after dilepton selection
  - no real E_T^{miss} (modulo small contributions from $Z \rightarrow \tau\tau$ /semi-leptonic heavy flavour decays)
  - jet energy/scale resolution, acceptance, pileup dominates resolution of the Z recoil
  - hard to model even with full simulation
- Use photon events to **model DY from data**
  - γ+jets has similar diagrams as Z+jets
  - mitigate mass effect by reweighing in p_T
  - reweigh in each exclusive jet multiplicity bin
  - tails have to be corrected by subtracting expectations for residual $\gamma + E_T^{miss}$ events (e.g. $Z\gamma \rightarrow \gamma\nu\nu$) - 50% unc. assigned on this correction



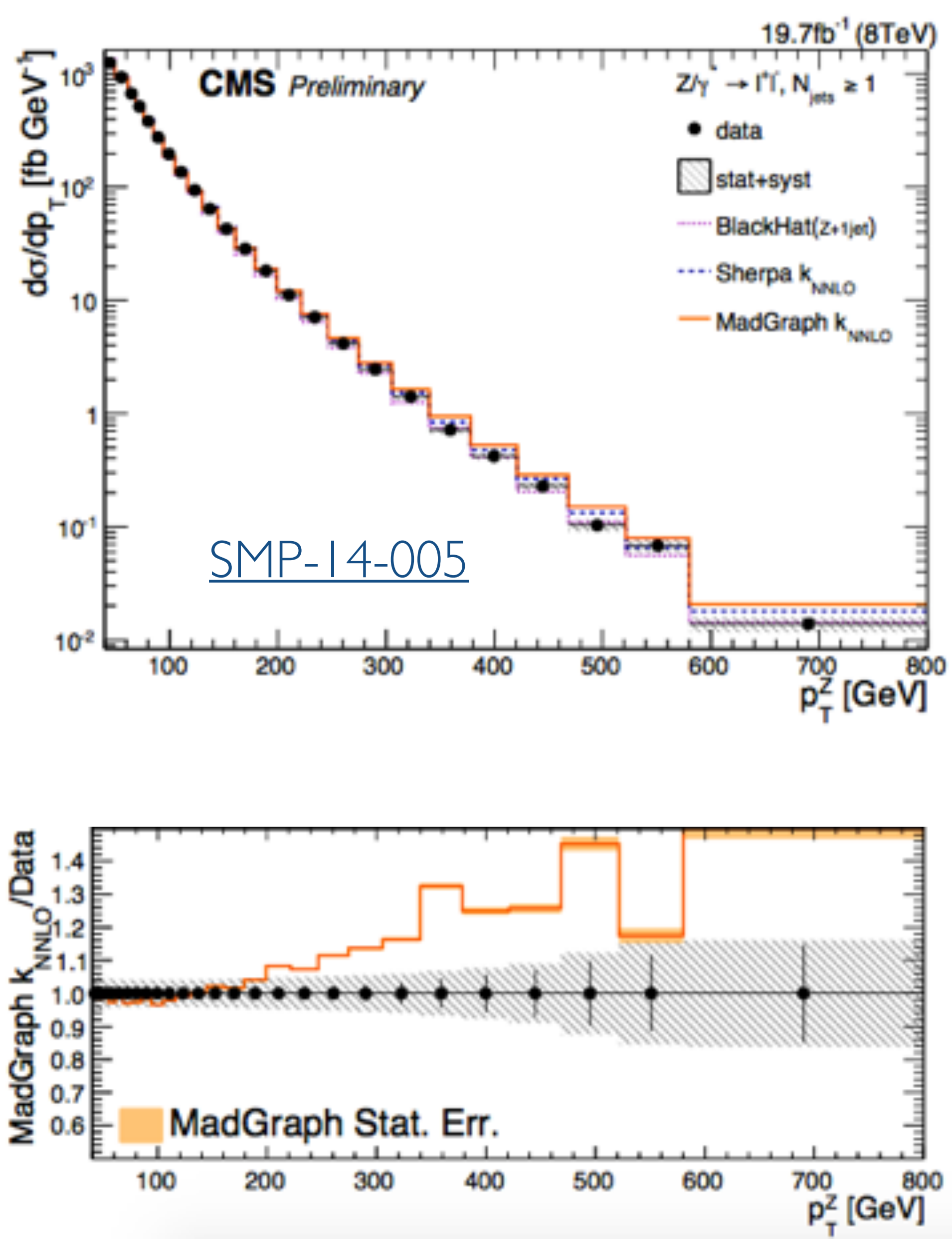
=2 leptons: p_T>20 GeV |η|<2.5

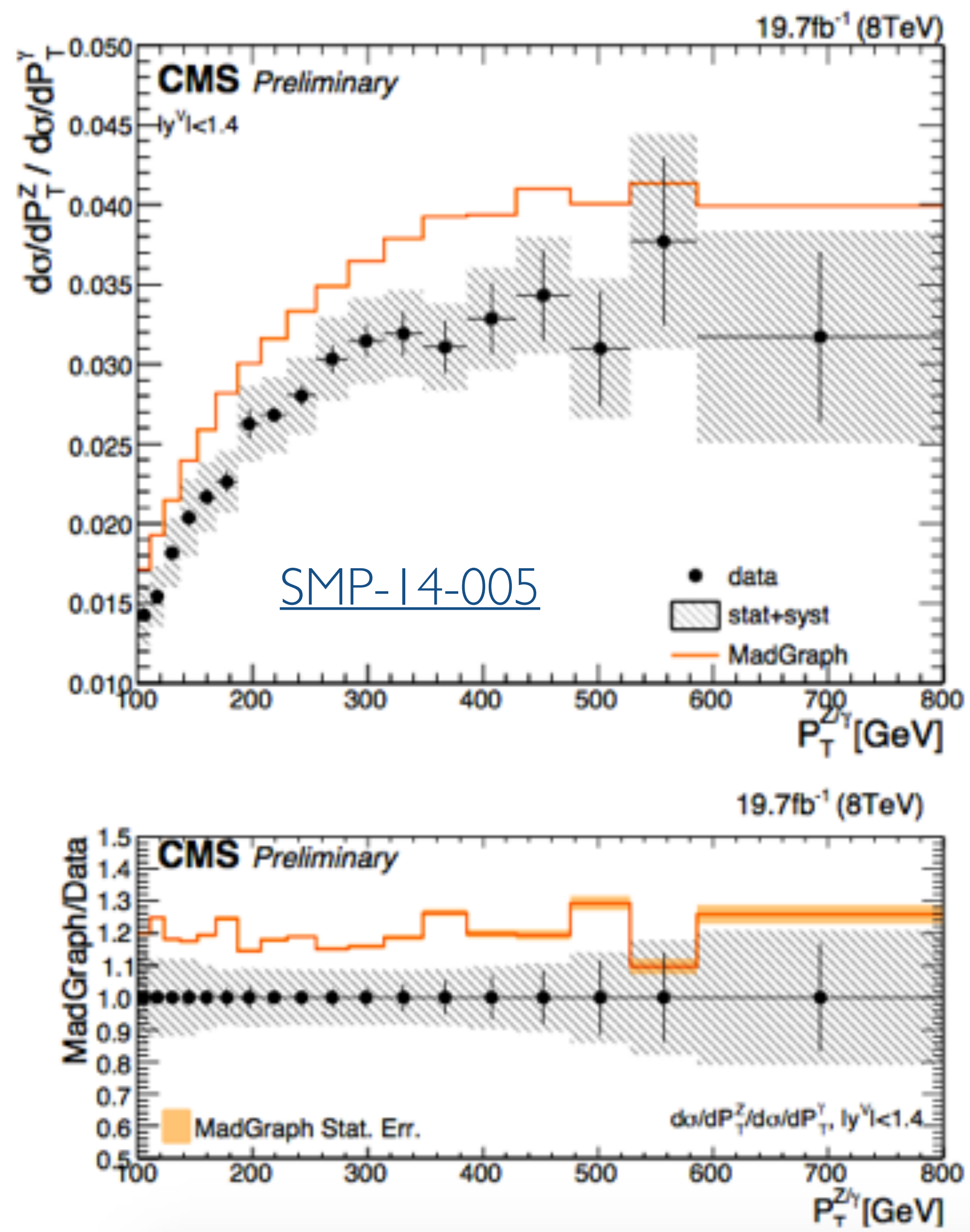
$|M_{ll}-M_Z|$ < 15 GeV $p_T(Z)$>50 GeV

Note on Z/ɣ kinematics

- Compatibility tests on simulation are used to assess validity of the method: closure within 15%
  - LO simulation (Madgraph-based) describes poorly high-p_T distribution but captures p_T ratio correctly
  - underlying source of disagreement in p_T description seems to have same source in Z and ɣ events

Z p_T

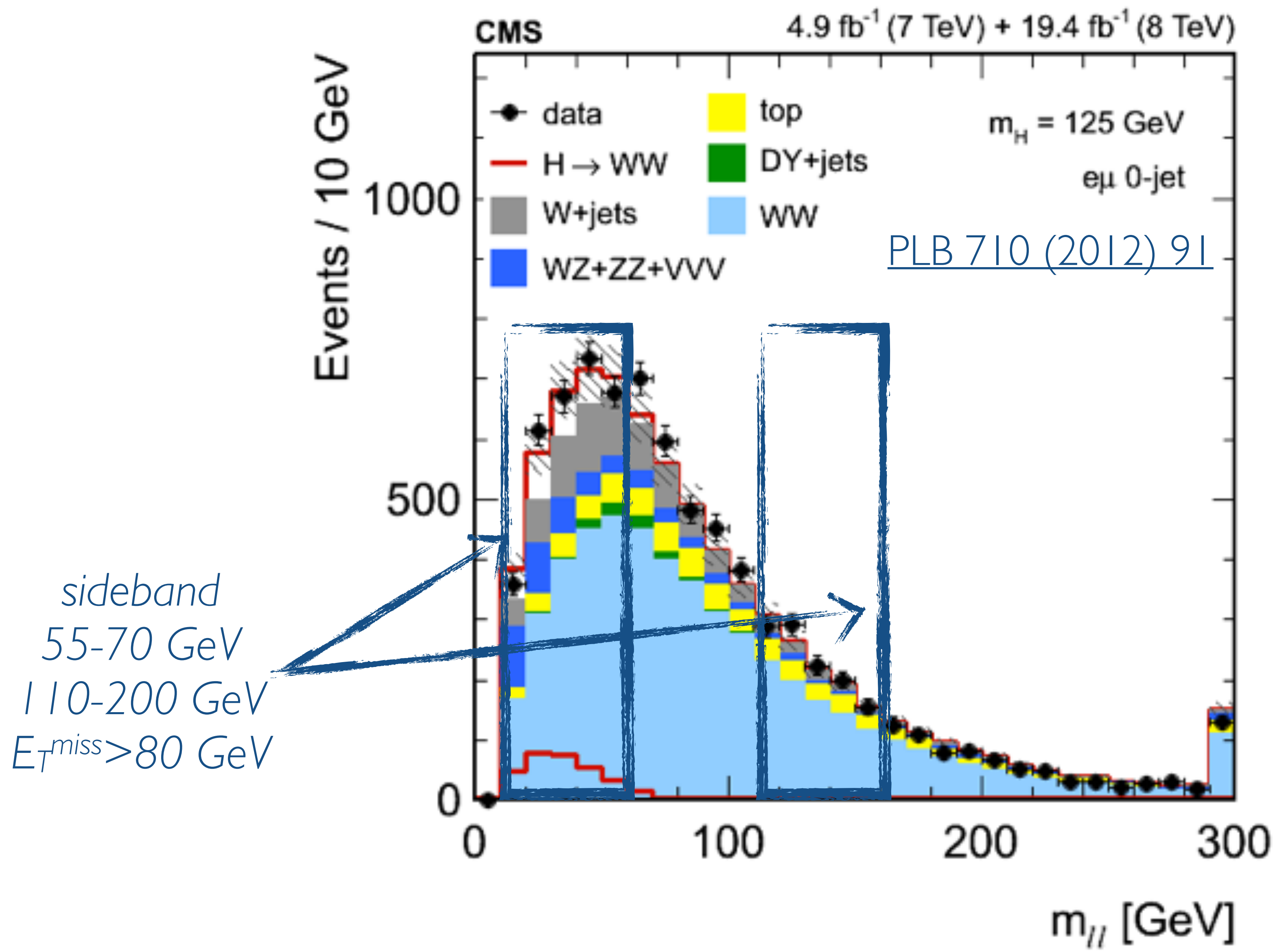




Z p_T / ɣ p_T

Main backgrounds in the $2\ell2\nu$ channel II

- **Non-resonant backgrounds**: WW, top-pair + single-top-production
  - normalised under Z mass window from selected e**μ** events (lepton flavour symmetry)
  - use "Z-sideband" to scale and correct for trigger/selection efficiency $N_{\ell\ell} = \left(\frac{N_{\ell\ell}}{N_{e\mu}}\right)_{\text{sideband}} N_{e\mu}$
  - caveat (or benefit?) of this method: if signal contributes with WW final state it gets subtracted



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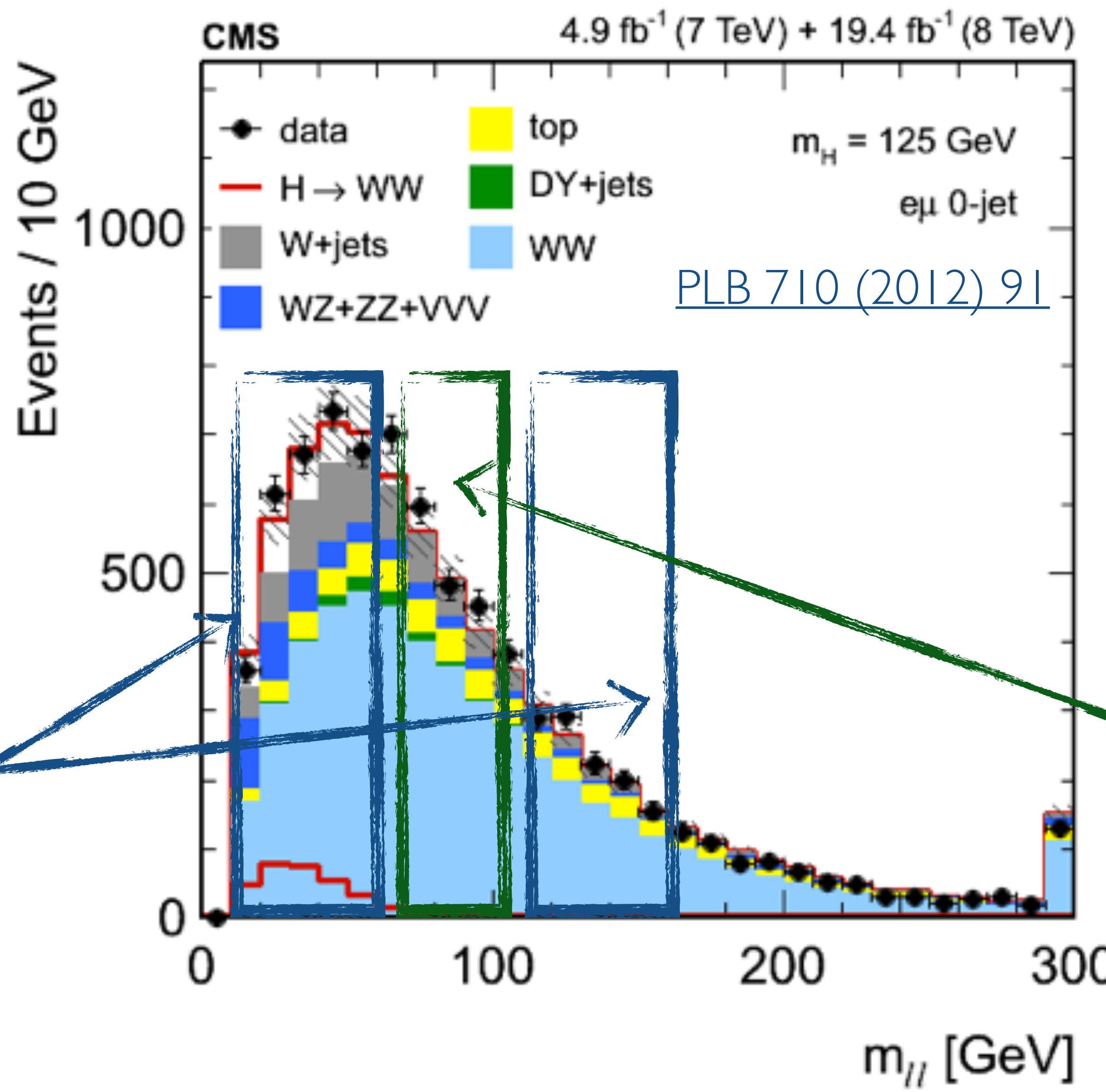


sideband
55-70 GeV
110-200 GeV
E_T^{miss}>80 GeV

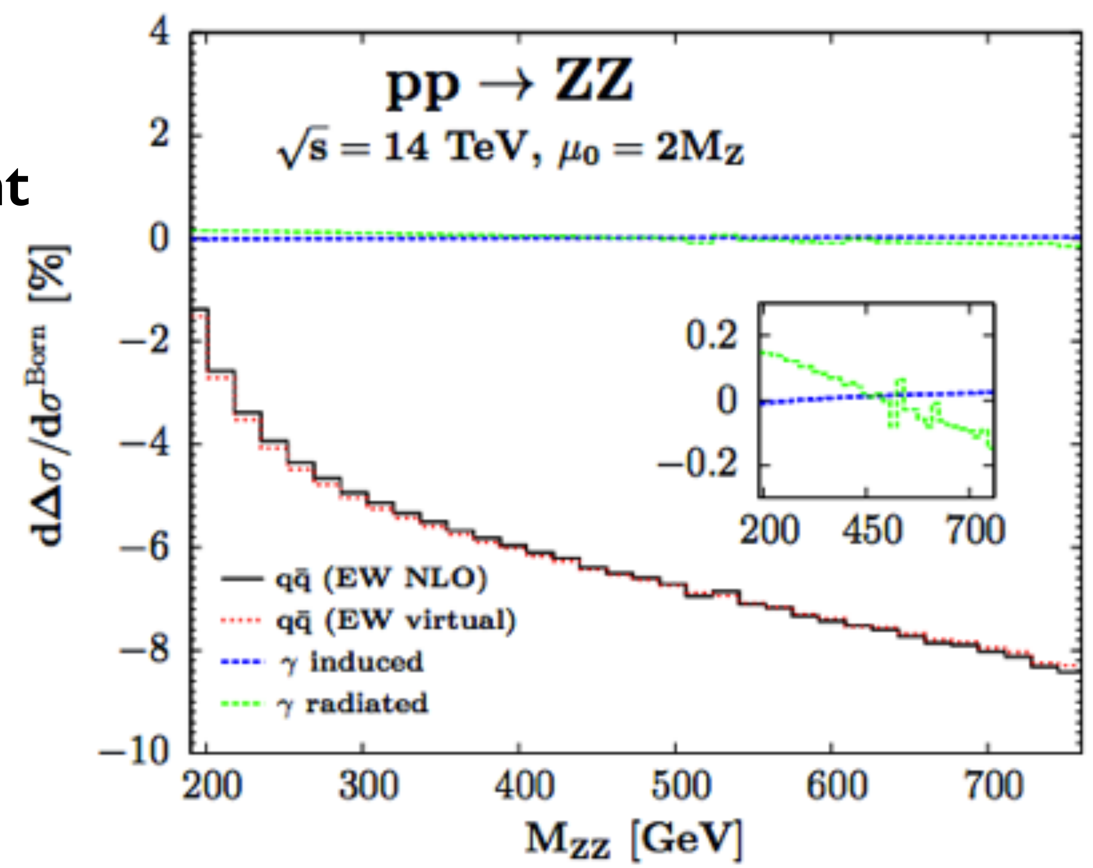
use to re-scale
to signal region
0.47 for ee / 0.61 for $\mu\mu$
with 15% intrinsic syst unc.

Main backgrounds in the $2\ell 2\nu$ channel III

- **After pre-selection** (E_T^{miss}>80 GeV) **main backgrounds are WZ and ZZ productions**
  - modelled using Madgraph, gg ➞ ZZ from gg2VV
  - normalisation uncertainties from QCD scales and PDF estimated with MCFM/gg2VV (~10%)
  - variation of QCD scales in Madgraph used to assign uncertainty on shapes for qq ➞ WZ/ZZ (2-10%)
  - uncertainty on NNLO k-factor for gg ➞ ZZ + conservative 10% from missing orders

- However **NLO EWK corrections are also important**
  - virtual corrections + photon radiation
  - use available computations from

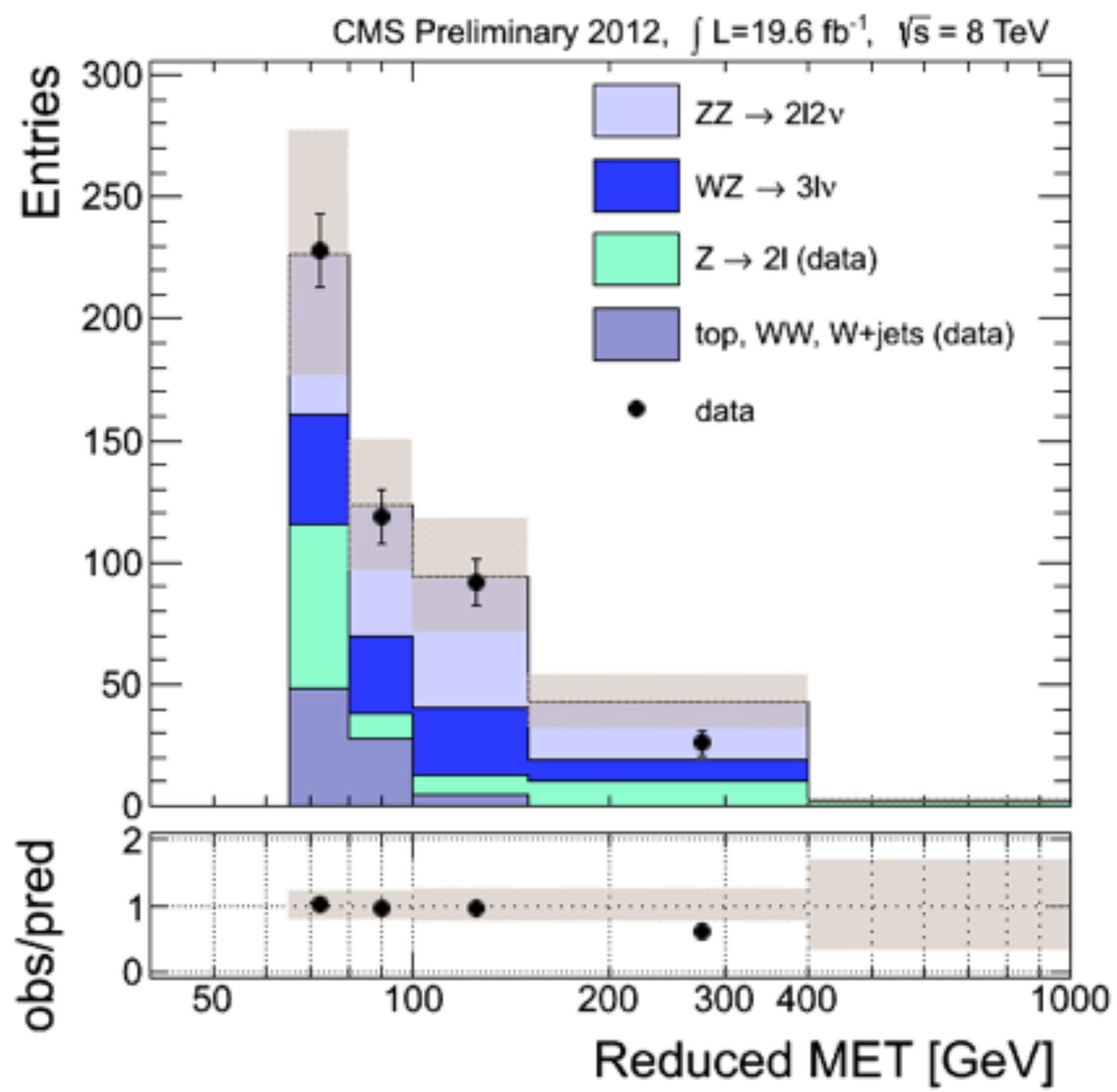
    Kasprik et al JHEP 1312 (2013) 071,arXiv:1305.5402, PRD 88, 113005 (2013)
  - re-weight base simulation as function of partonic- -s, -t and depending on parton flavours



  - NLO EWK x NLO QCD correction assigned as uncertainty due to missing mixed EWxQCD contrib.

ZZ cross section from $2\ell 2\nu$

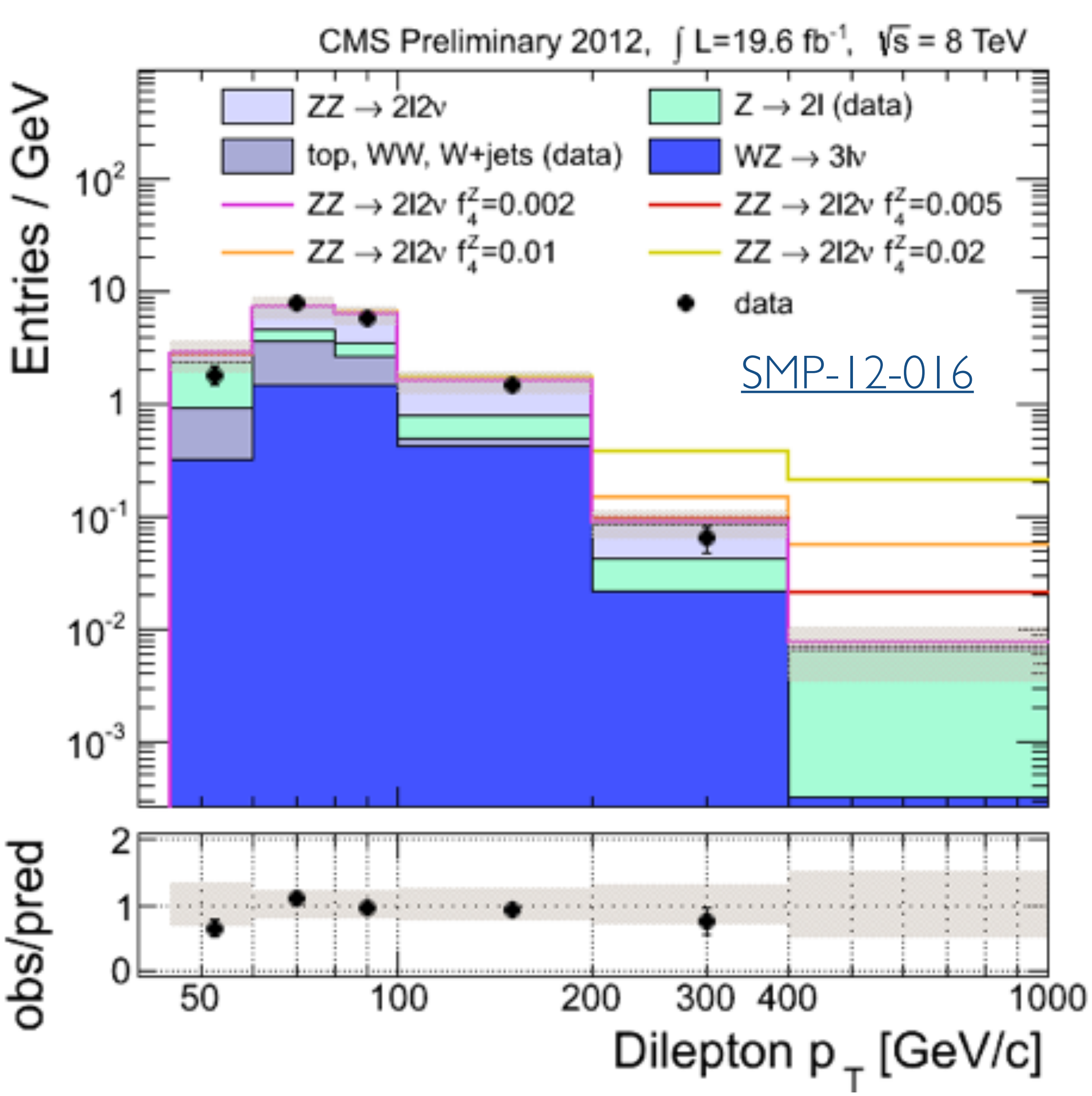
- Put all together to measure ZZ cross section
- Fit distribution for E_T^{miss} and extract σ/σ_{SM}
- **Result in agreement with SM prediction**
- Uncertainty dominated by
  - WZ/ZZ modelling (~17%)
  - DY estimate / non-resonant background (~12%)
  - Jet energy scale (~12%)
- Precision-wise: less performing than 4ℓ
  - however: powerful channel to set limits on anomalies



$$\boxed{\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 6.8^{+0.8}_{-0.8}\,(\mathrm{stat})\,^{+1.8}_{-1.4}\,(\mathrm{syst})\ \pm 0.3\,(\mathrm{lumi})\ \mathrm{pb}}$$ $2\ell 2\nu$

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 7.7 \pm 0.5\,(\mathrm{stat.})\,^{+0.5}_{-0.4}\,(\mathrm{syst.}) \pm 0.4\,(\mathrm{th.}) \pm 0.2\,(\mathrm{lum.})\,\mathrm{pb}$$ 4ℓ

Limits on anomalous triple gauge couplings



SMP-12-016

- Anomalous contributions expected to **change**
  - overall **rate** of the ZZ production
  - distort **kinematics**, e.g. the Z p_T

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left\{\left[f_4^\gamma(\partial_\mu F^{\mu\alpha}) + f_4^Z(\partial_\mu Z^{\mu\alpha})\right] Z_\beta\left(\partial^\beta Z_\alpha\right) - \left[f_5^\gamma(\partial^\mu F_{\mu\alpha}) + f_5^Z(\partial^\mu Z_{\mu\alpha})\right]\tilde{Z}^{\alpha\beta} Z_\beta\right\}$$

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- Use this information to set limits on aTGC
  - shape **analysis of the observed Z p_T**
  - compare to alternative predictions (Sherpa-based)
  - no form-factor applied to preserve unitarity

Most stringent limits on neutral aTGCs from $2\ell2\nu$ analysis

Dataset	f_4^Z	f_4^γ	f_5^Z	f_5^γ
7 TeV	[-0.0088; 0.0085]	[-0.0098; 0.011]	[-0.0096; 0.0096]	[-0.011 ; 0.010]
8 TeV	[-0.0038; 0.0040]	[-0.0049; 0.0039]	[-0.0041; 0.0038]	[-0.0049; 0.0046]
Combined	[-0.0030; 0.0034]	[-0.0039; 0.0031]	[-0.0036; 0.0032]	[-0.0038; 0.0038]

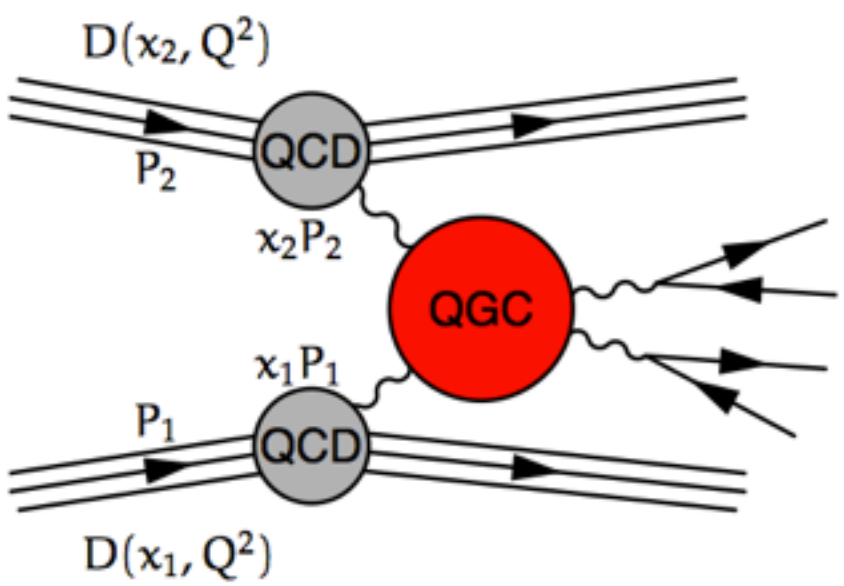
CP-violating *CP-conserving*

Towards Vector Boson Fusion production measurements

FSQ-12-035 sub. to EPJC

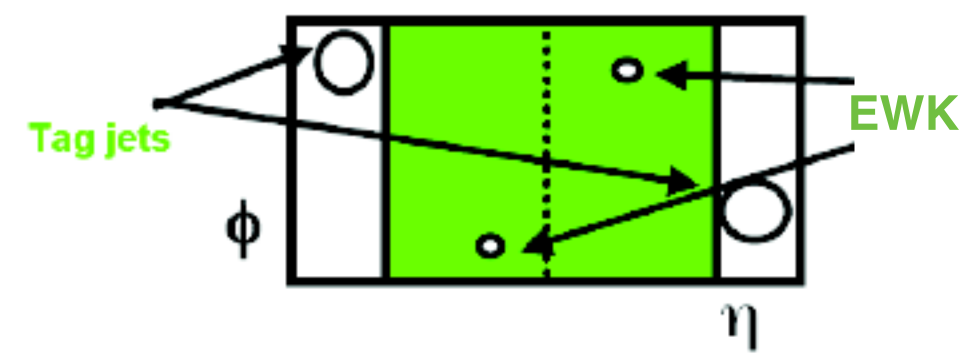
Towards vector-boson fusion measurements

- **Run I (almost) did not provide enough statistics to study VBS/VBF**
  - observed EWK Zjj processes, got close to observe EWK $\ell^{\pm}\ell^{\pm}$jj



- **Of obvious interest for Run II :**
  - improve on the study of Higgs production through VBF
  - test unitarity of $V_L V_L$ scattering near the TeV scale
  - BSM production through VBF processes (e.g. charginos as in slide 7)

- **VBF channels provide a unique way to test the SM**
  - essential for the Higgs-searches/measurements
  - how well do we expect simulation to model these processes?
  - do we understand extra QCD radiation in the VBF phase space?

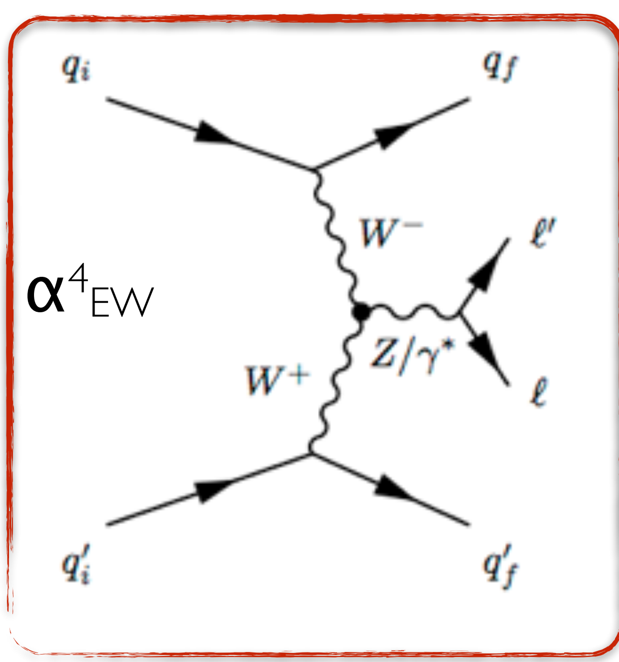


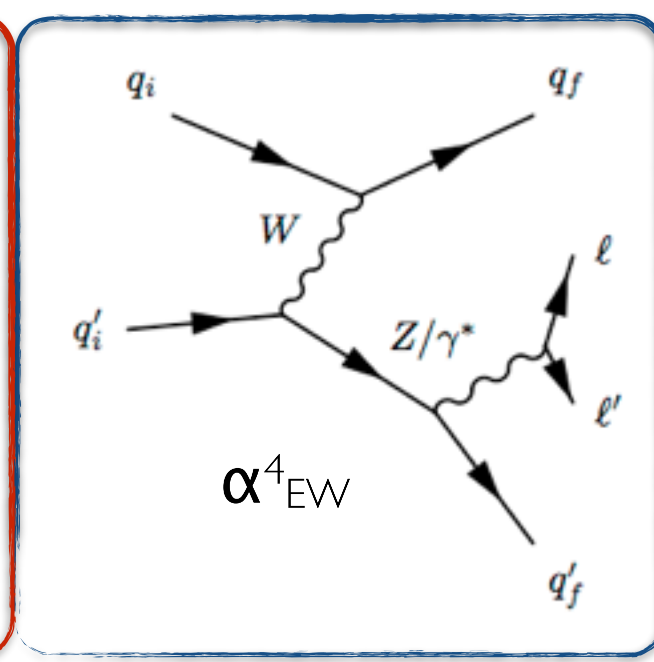
Forward jets, high energy
Suppressed color flow=rapidity gap

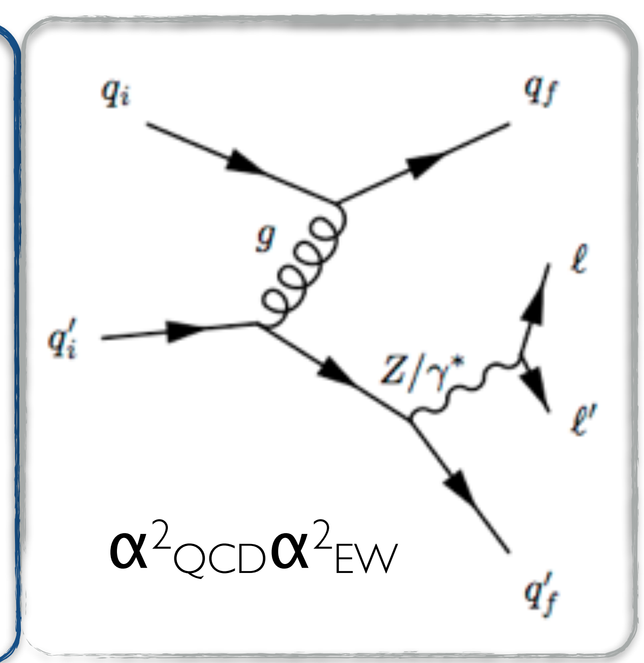
Use observation-level EWK Zjj to test pQCD

EWK Zjj production at the LHC

- **Jets have distinct properties when produced at O(α^2_{EW})**
  - two extra jets are produced color singlet exchanges
  - W, Z or γ exchange via t-channel: $Q^2 = E_q^2 \cdot (1-x) \cdot \theta \sim M_W^2 \rightarrow \theta \sim 0$
  - production of additional mini-jets is suppressed
- **Production includes triple gauge coupling vertex** amongst the diagrams
  - Negative interference terms suppress σ(VBF Z) by a factor of ≈2.5
  - σ(EWK Zll+2j)/σ(VBF H126)=0.14 → high statistics sample to probe color singlet exchange
- **Residual interference with background -** O($\alpha^2_{QCD}\alpha^2_{EW}$) - diluted at very M_{jj} (>2 TeV)

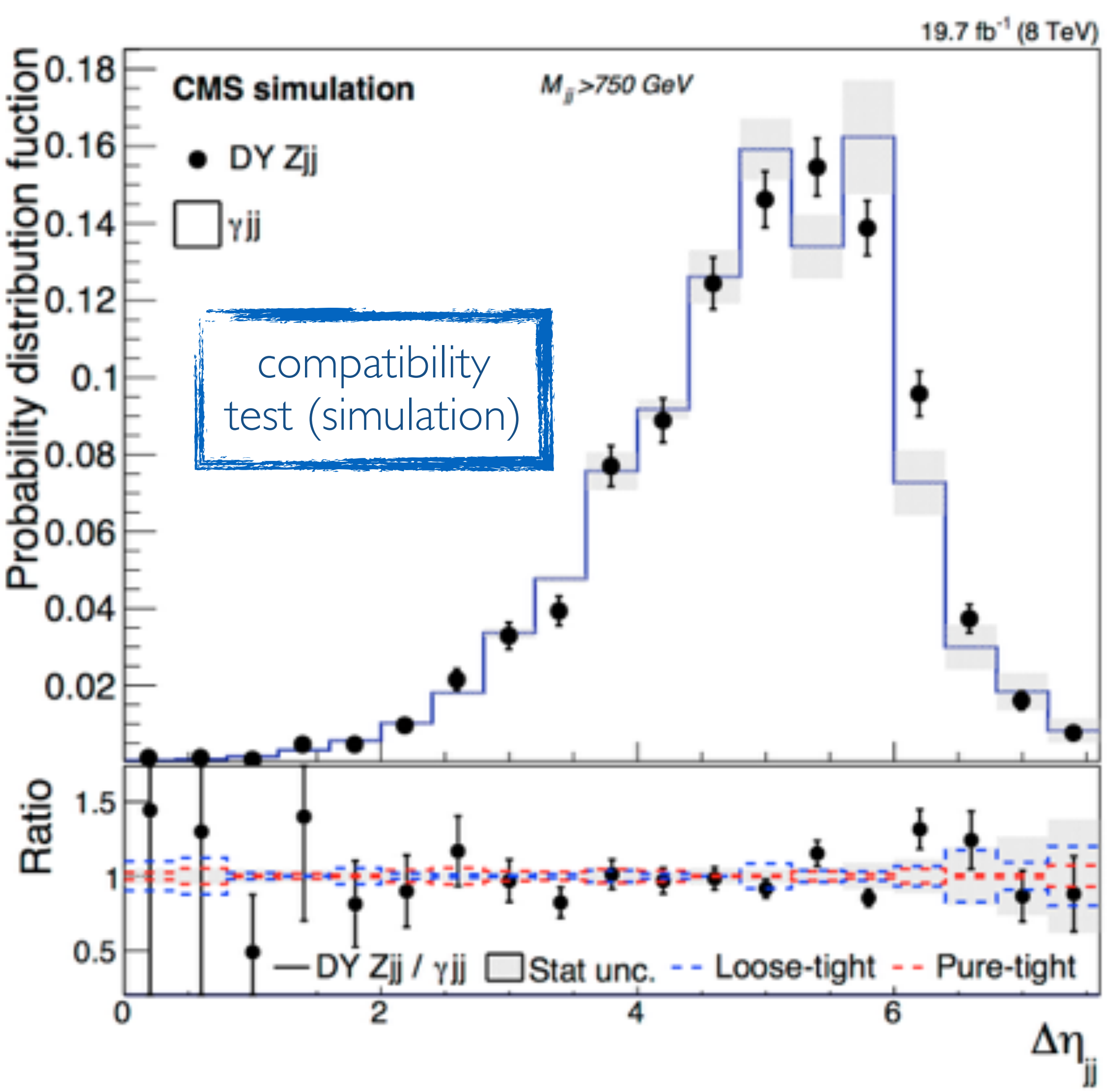


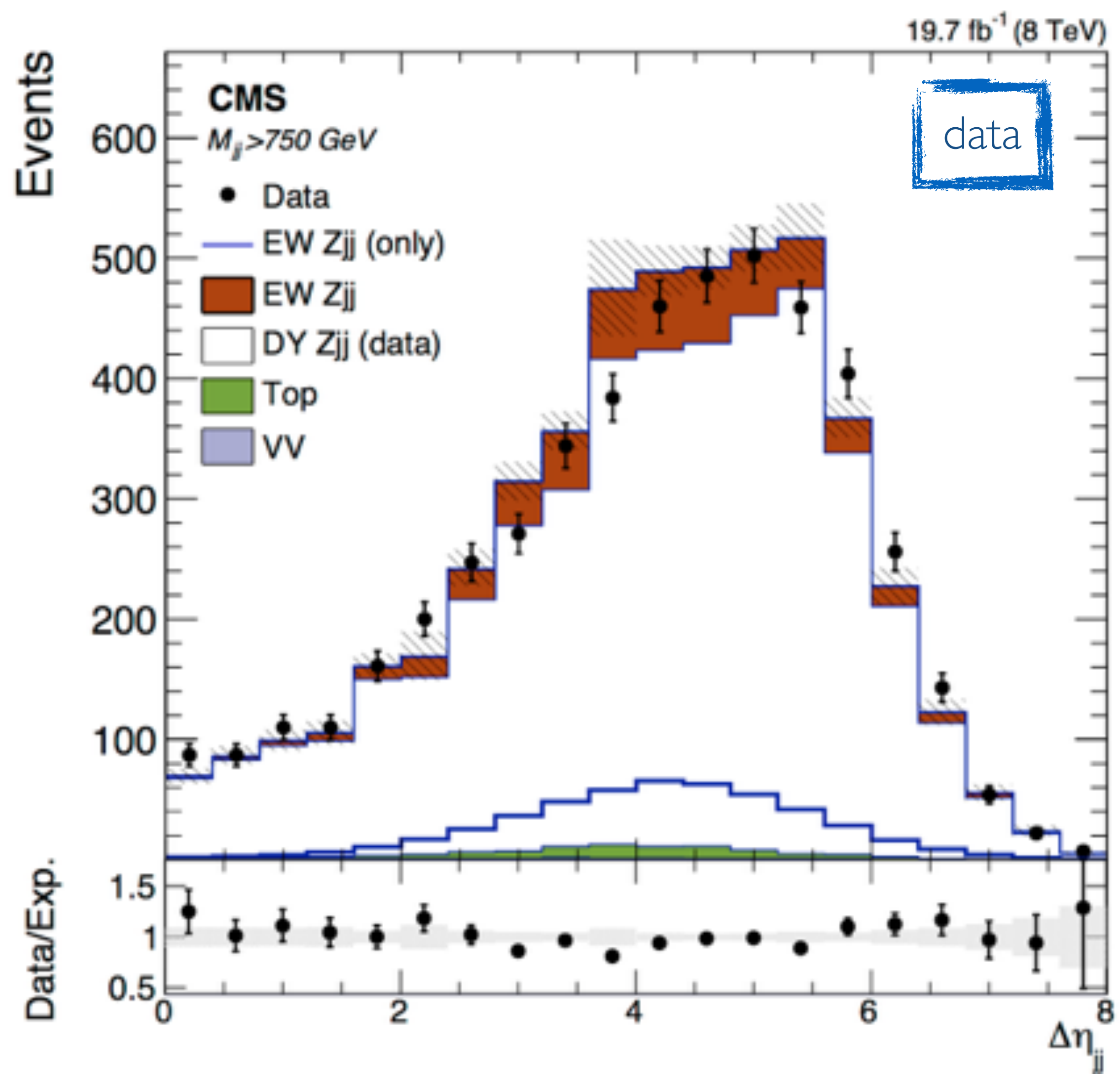




Exploring the Z⟷ɣ similarities to tame QCD Zjj

- To gain confidence in the identification of EW Zjj production use data-driven model for QCD Zjj
  - cross-validate main prediction based on simulation (Madgraph+Pythia6)
  - use photon + 2 jet events (EW ɣjj / QCD ɣjj is suppressed relatively to Zjj case)
  - re-weight photon p_T to match Z p_T after matching kinematics selection (p_T>50 GeV and |y|<1.4442)





Signal extraction strategy

- A single **cut-and-count approach is insufficient to extract the signal**

M_{jj} (GeV)	Channel	VV	Top quark	DY Zjj	Total backgrounds	EW Zjj	Data
450–550	ee	20±2	68±4	5438±731	**5526±731**	94±6	**5809**
	$\mu\mu$	27±2	96±4	7325±983	**7448±983**	128±8	**8391**
550–750	ee	16±1	56±3	3802±496	**3874±664**	112±7	**4139**
	$\mu\mu$	30±2	69±4	5234±683	**5333±896**	155±10	**5652**
750–1000	ee	5.4±0.5	20±2	1300±188	**1325±236**	73±5	**1384**
	$\mu\mu$	7.5±0.6	26±2	1846±262	**1880±313**	98±6	**1927**
>1000	ee	2.7±0.4	10.2±0.8	600±84	**613±90**	84±6	**684**
	$\mu\mu$	4.2±0.4	13±1	913±127	**930±122**	114±8	**923**

S/B~0.12

- **Combine** several **jet-related variables in a multivariate analysis**
  - avoid information on extra jet emission
  - cross-check independently 3 analyses making or not use of Z kinematics, different jet reconstruction algorithms, different background predictions (MC or data-based)
  - fit the discriminator shape correlating signal (EW Zjj), background (QCD Zjj) and interference

$$\hat{N}^{\ell\ell jj}(\mu, \upsilon) = \mu N_{\mathrm{EW\ Zjj}} + \sqrt{\mu\upsilon} N_{\mathrm{I}} + \upsilon N_{\mathrm{DY\ Zjj}},$$

EW Zjj strength

QCD Zjj strength

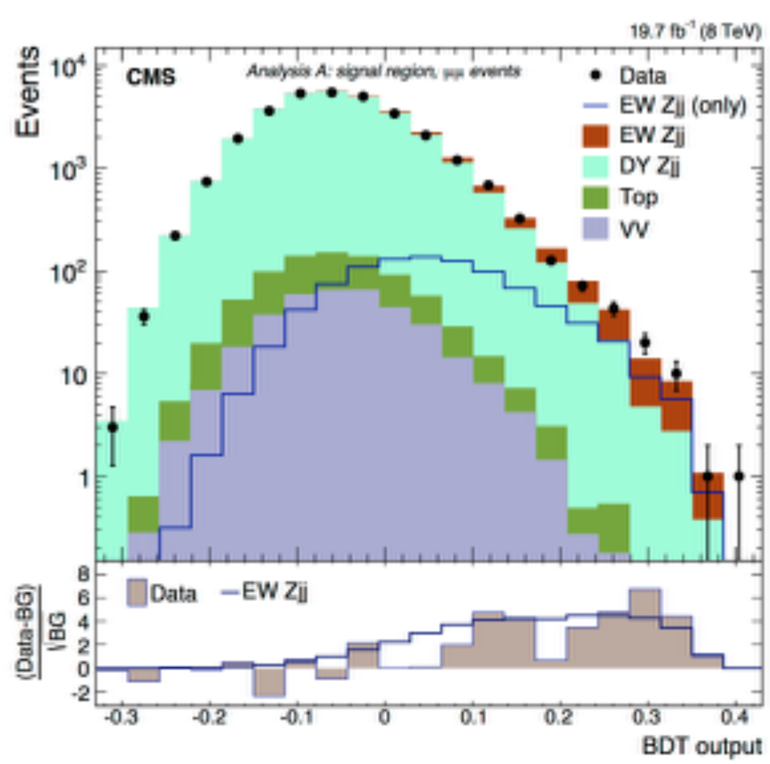
Result: $\sigma(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 174 \pm 15\,(\mathrm{stat}) \pm 40\,(\mathrm{syst})\ \mathrm{fb}$

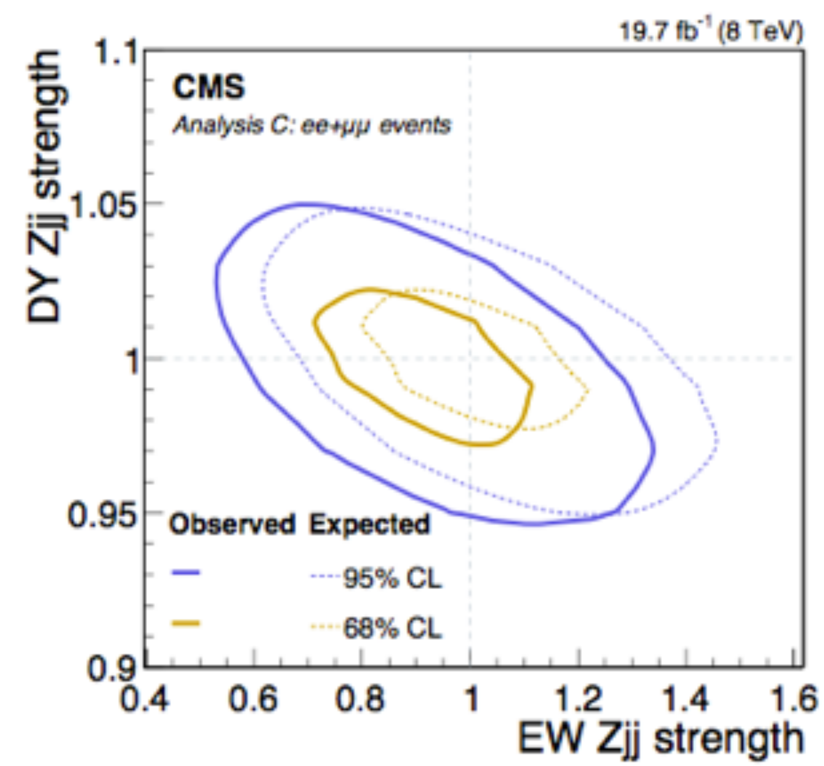
- All analyses are in agreement with each other and with the SM: $\sigma_{\mathrm{LO}}(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 208 \pm 18\ \mathrm{fb}$.
  - analysis C allows the data-driven QCD Zjj background to float freely

largest systematics from interference and DY Zjj modelling
(in analysis C is stat dominated)

	Analysis A			Analysis B	Analysis C		
	ee	$\mu\mu$	$\mathrm{ee}+\mu\mu$	$\mu\mu$	ee	$\mu\mu$	$\mathrm{ee}+\mu\mu$
Luminosity	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Trigger/lepton selection	0.04	0.04	0.04	0.04	0.04	0.04	0.04
JES+residual response	0.06	0.05	0.05	0.04	0.06	0.05	0.05
JER	0.02	0.02	0.02	0.02	0.04	0.04	0.03
Pileup	0.01	0.02	0.02	0.01	0.01	0.01	0.01
DY Zjj	0.07	0.05	0.07	0.08	0.14	0.12	0.13
q/g discriminator	<0.01	<0.01	<0.01	—	<0.01	<0.01	<0.01
Top, dibosons	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01
Signal acceptance	0.03	0.04	0.04	0.04	0.06	0.06	0.06
DY/EW Zjj interference	0.14	0.14	0.14	0.13	0.06	0.08	0.08
Systematic uncertainty	0.19	0.18	0.19	0.17	0.17	0.17	0.18
Statistical uncertainty	0.11	0.10	0.07	0.09	0.24	0.21	0.16
$\mu = \sigma/\sigma_{\mathrm{th}}$	0.82	0.86	0.84	0.89	0.91	0.85	0.88

background rejection at >5σ level!

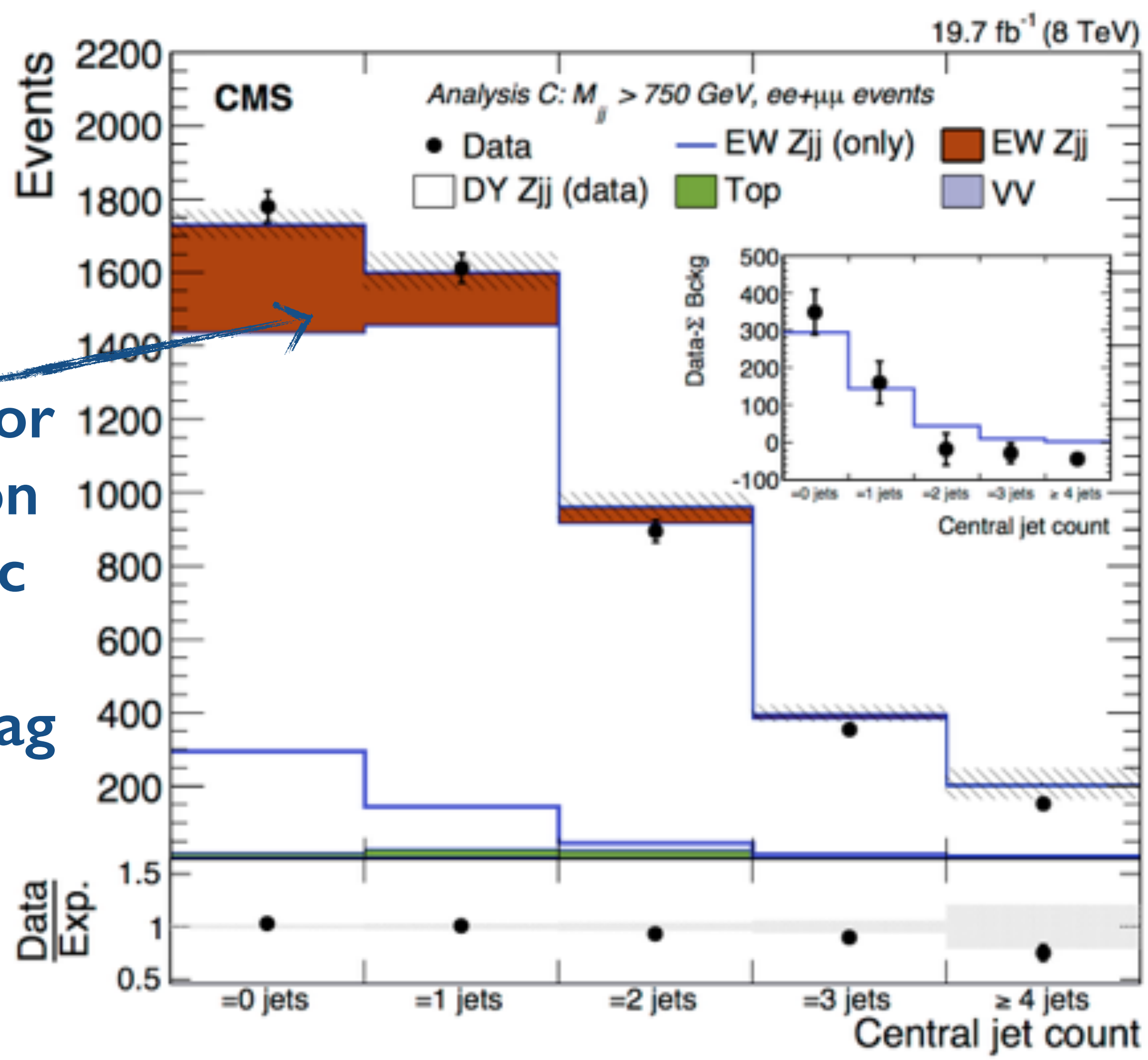


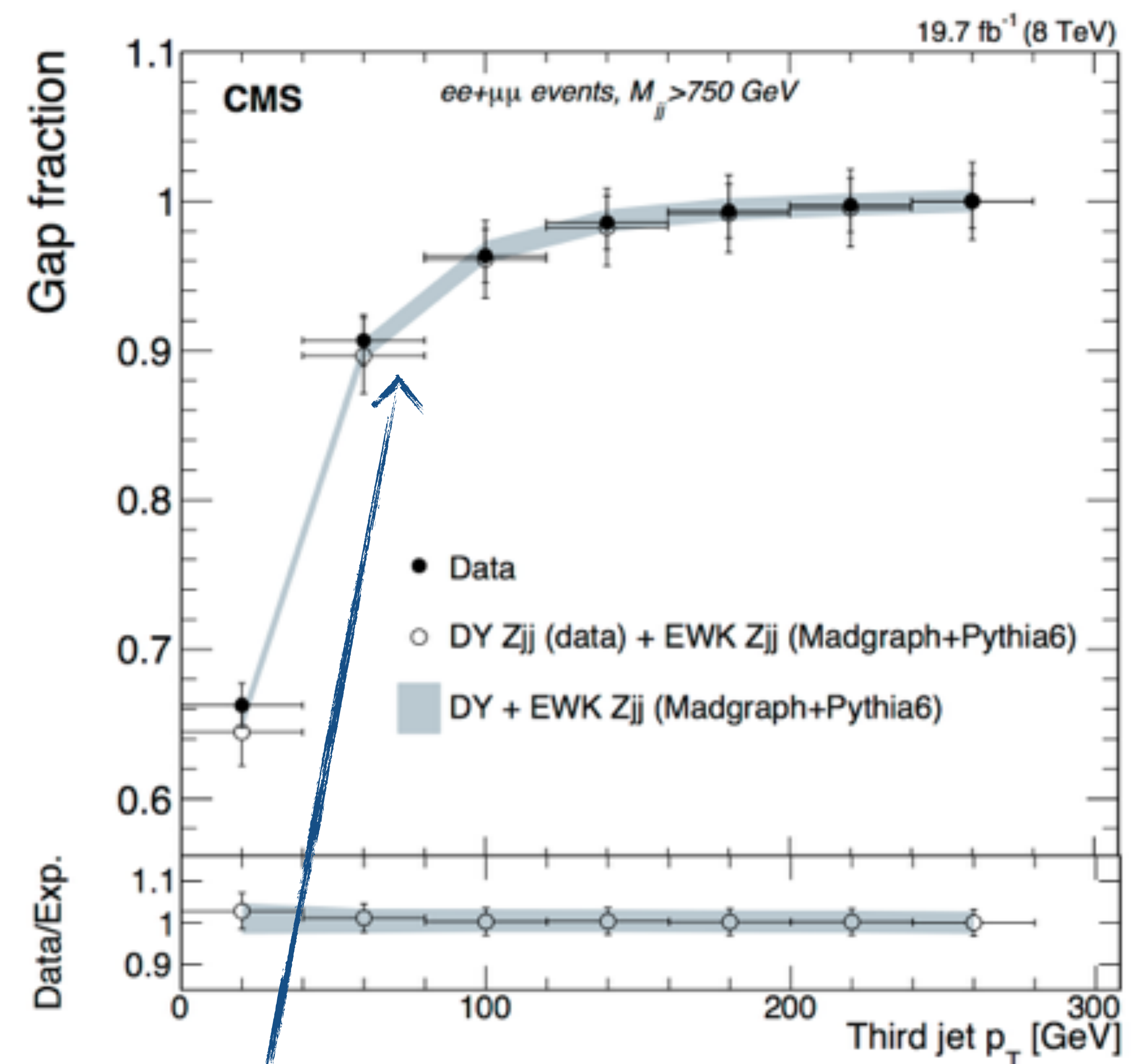


Hadronic activity in VBF phase space region

- Given no information on the emission of extra jets was used
  - study further the hadronic activity in the rapidity gap region
  - compare data-driven predictions using Madgraph simulation and data-driven prediction
  - note: no extra partons at matrix element level - parton shower emissions

evidence for suppression of hadronic activity in between tag jets





good agreement between data-based and MC-based expectations for extra jet veto

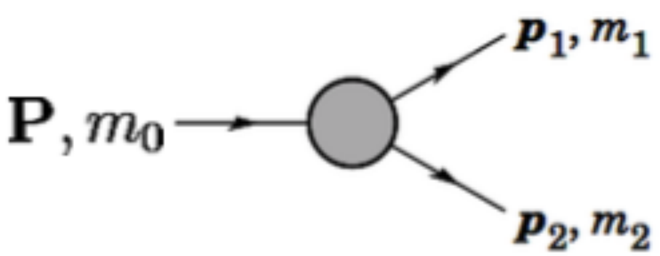
Bounds on the Higgs width from off-shell production

PLB 736 (2014) 64

The width of a resonance

- We observe the mass of unstable particles with a spread
  - direct consequence of the Heisenberg principle

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$



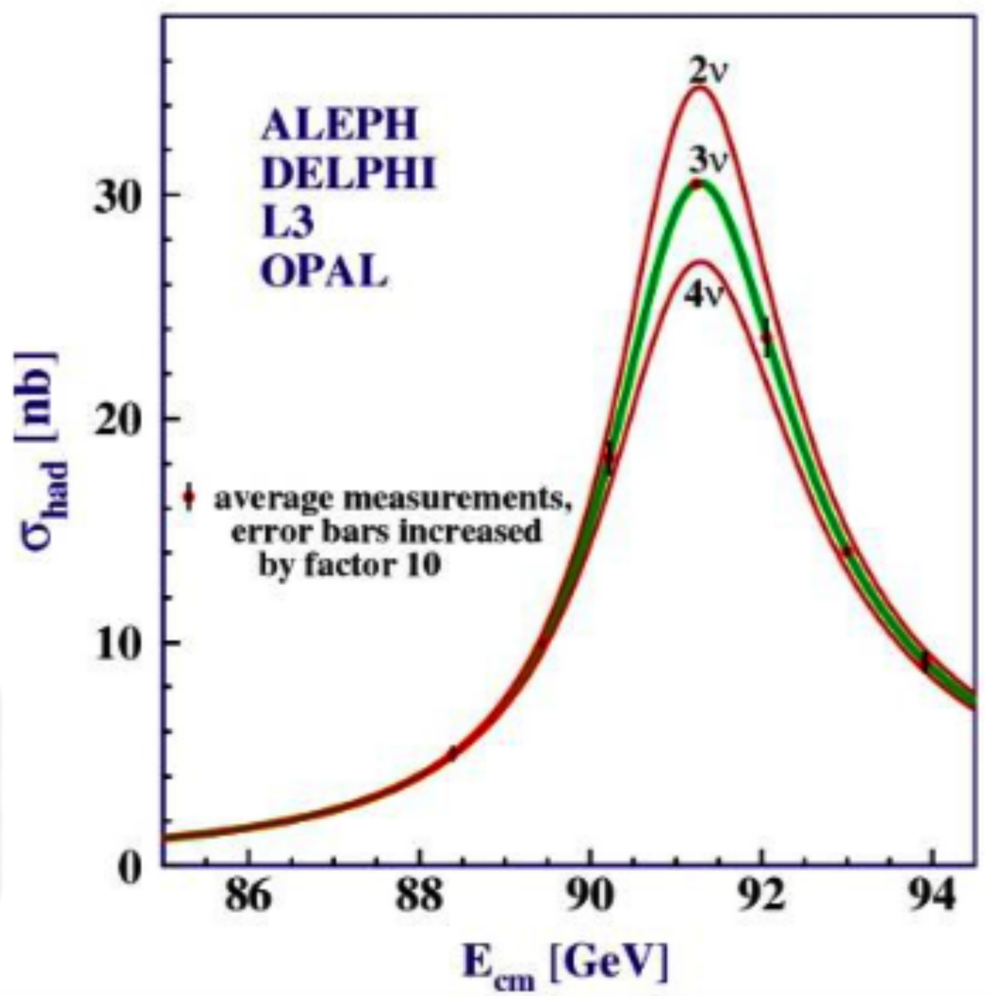
  - the width (Γ) quantifies the intrinsic mass resolution : distance at half-maximum = 1/lifetime

$$\Delta E = \frac{\Gamma}{2} = \frac{\hbar}{2\tau}$$

  - know the interactions involved we can predict Γ

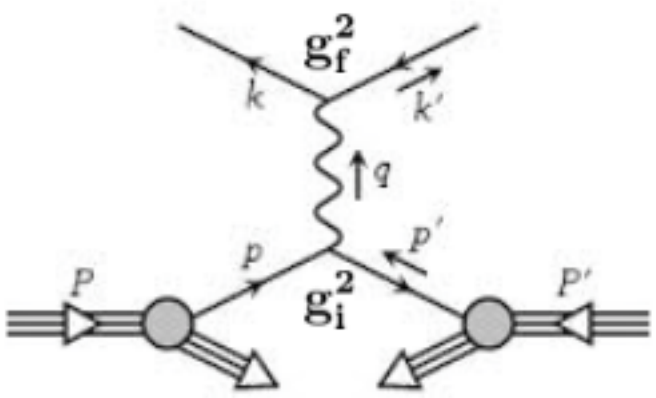
$$d\Gamma = \frac{(2\pi)^4}{2m_0} |\mathcal{M}|^2 d\Phi_n(P \to \sum_{i=1}^{n} p_i)$$

A measurement of the width tests directly the (in)completion of a theory.



Rate-based width measurements

- Detector resolution often an experimental limit in the measurement of the width
- However the observed production rate holds, as well, information on Γ
  - depends on the propagator and the couplings of a particle



$$\sigma \propto \int \frac{g_i^2 \cdot g_f^2}{(s - m_0^2)^2 + \Gamma^2 m^2} ds$$

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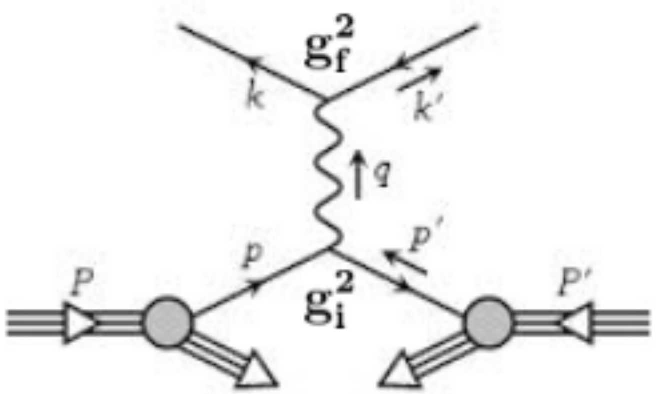
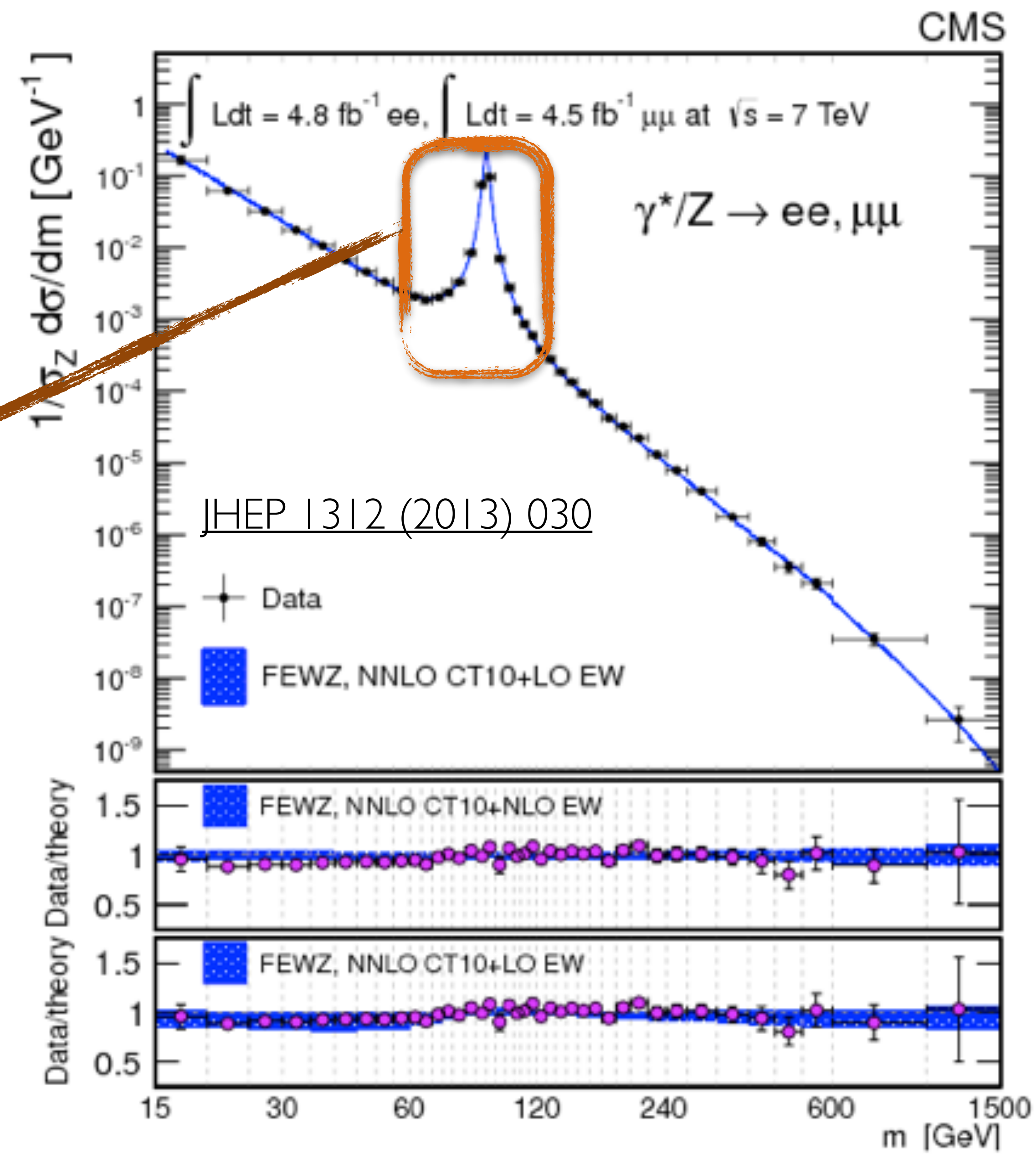


$$\sigma_{\text{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$



  - Measure independently BR and σ to determine Γ

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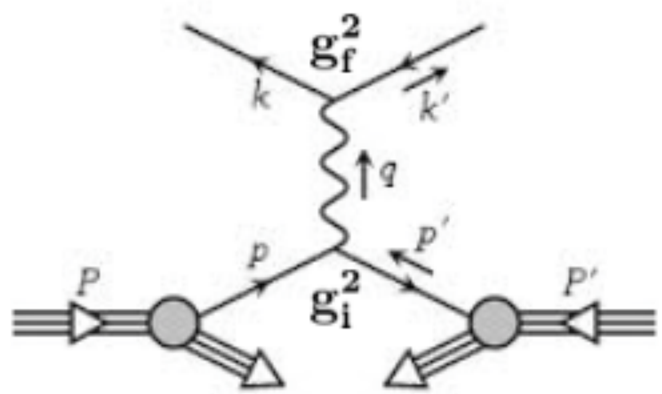

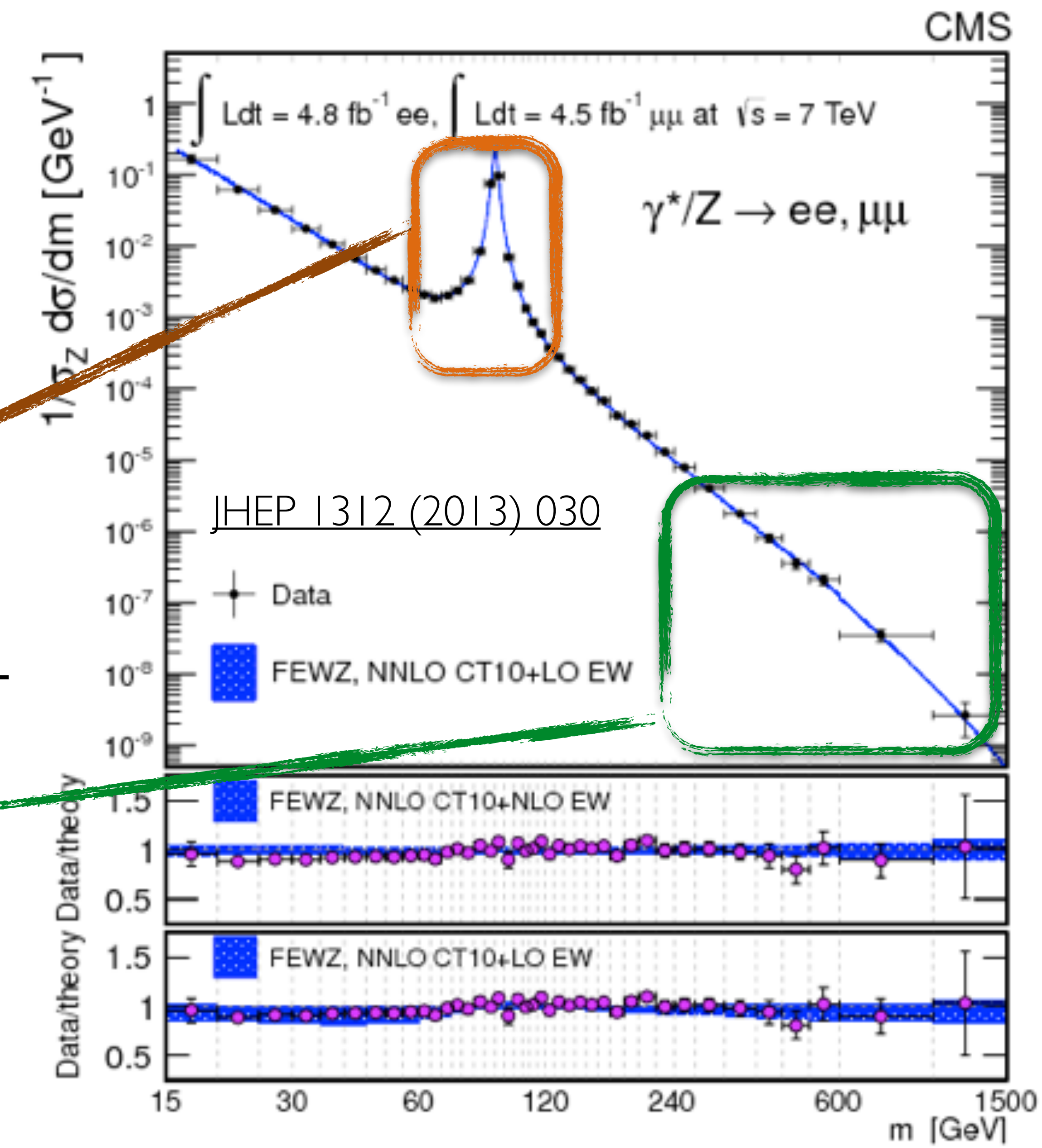

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- Measure independently BR and σ to determine Γ

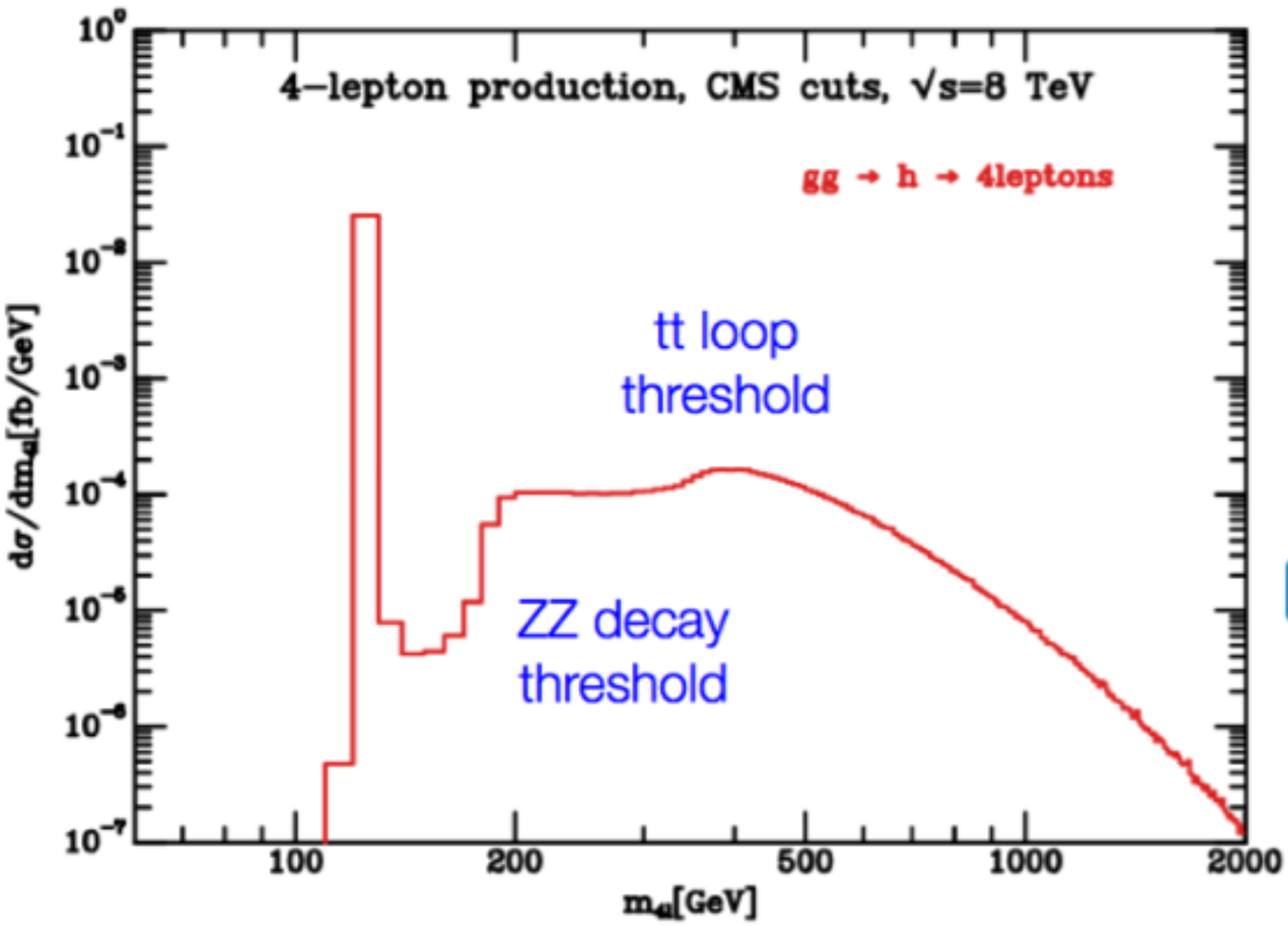
$$\sigma_{\text{off-shell}} \propto g_i^2 \cdot g_f^2$$

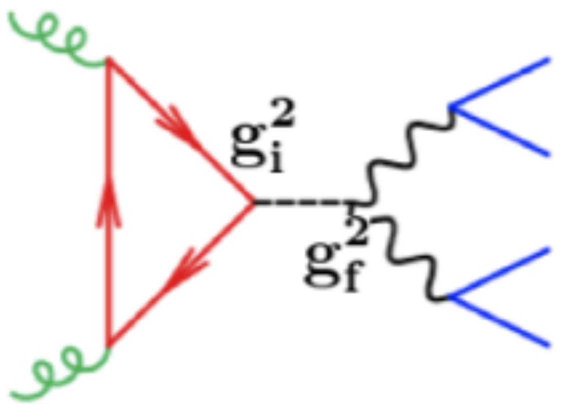
- The ratio off-shell / on-shell measures Γ

$$\boxed{\frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} \propto \Gamma}$$

Higgs off-shell production and decay

- Although the SM Higgs is expected to be very narrow ~8% production is off-shell
  - mixed effect of production and decay with enhancements at $2m_V$ and $2m_t$ thresholds
  - modelling initially implementation in gg2VV by Kauer and Passarino, JHEP 08 (2012) 16
  - follow-up Caola and Melnikov PRD88 (2013) 054025, Campbell et al arXiv:1311:3589





	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

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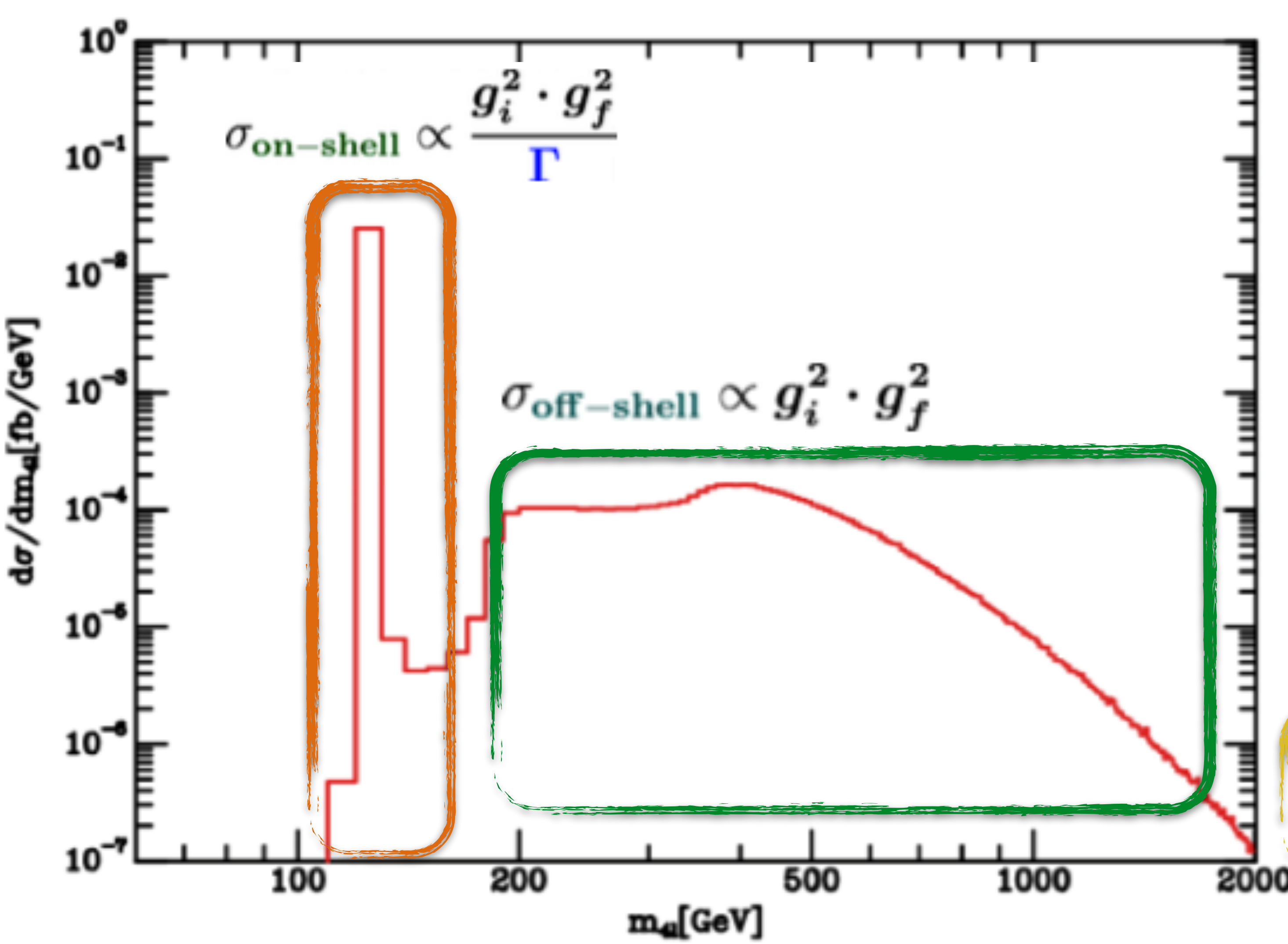

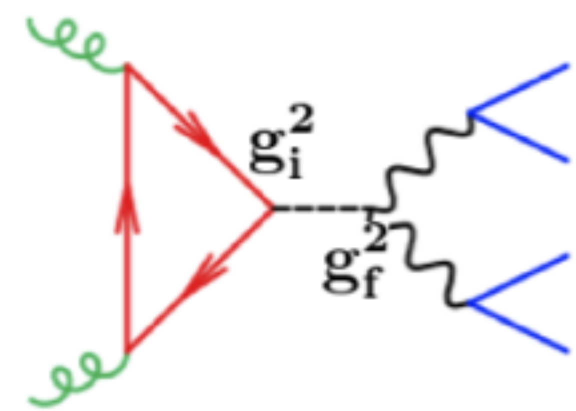

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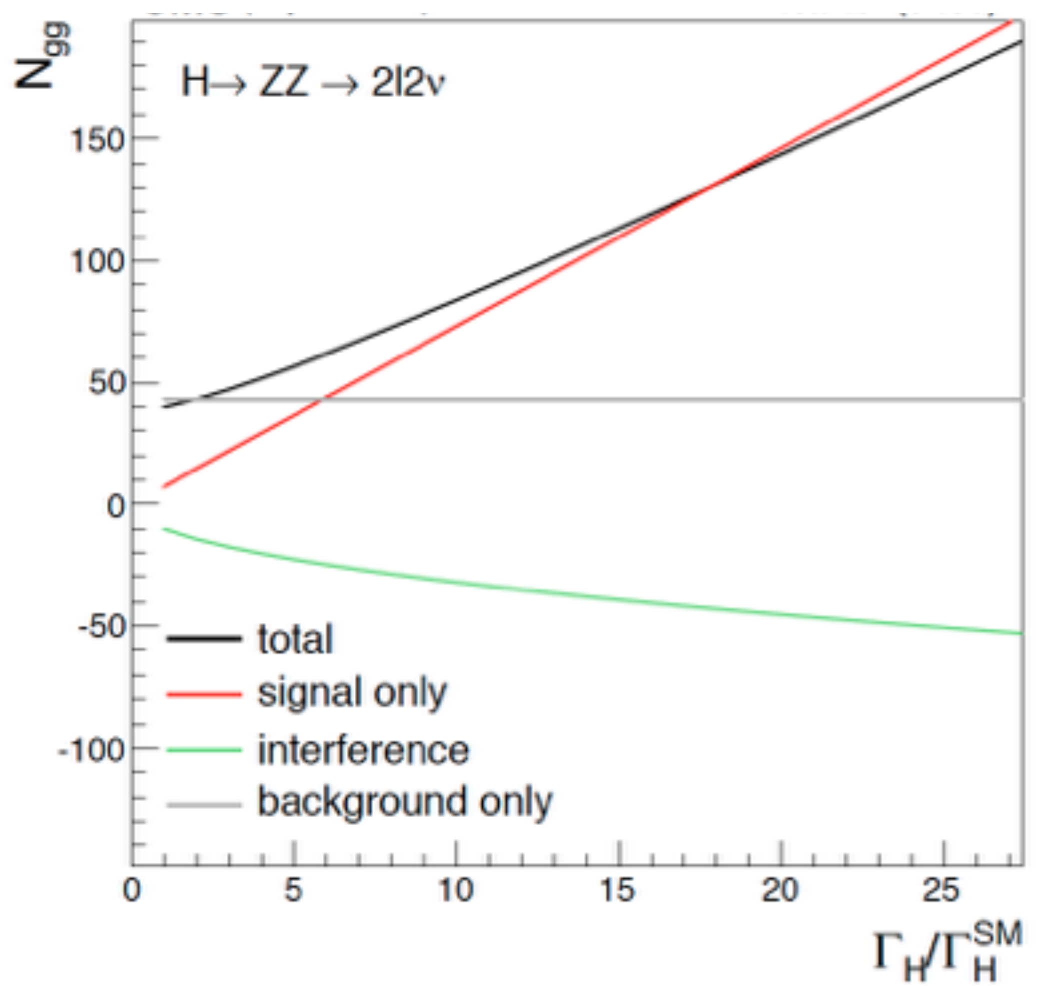
Extract Γ, from off-shell / on-shell ratio, assuming couplings independent of m_{VV}

Analysis strategy

- Search for anomalous ZZ production through gluon-gluon and vector boson fusion

- Inclusive final state observed (4ℓ or $2\ell2\nu$)

- Parametrisation for expected event yields contains
  - separate terms for signal, continuum and interference
  - separate gg and VBF components
  - profile likelihood fit is performed to different distributions

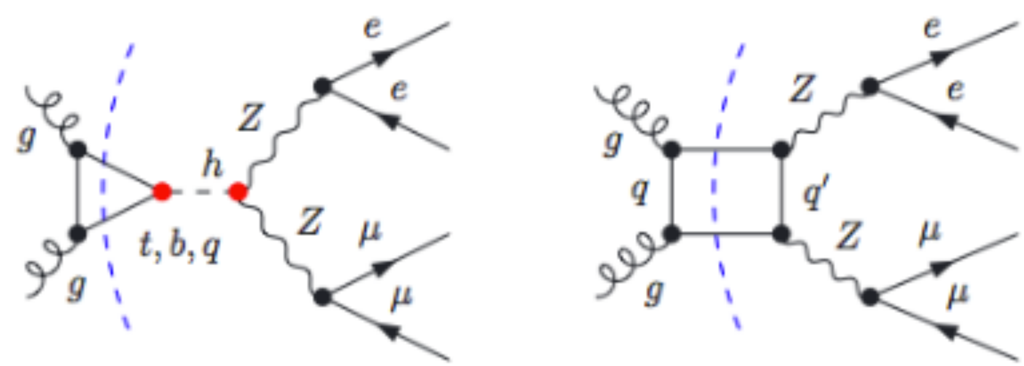


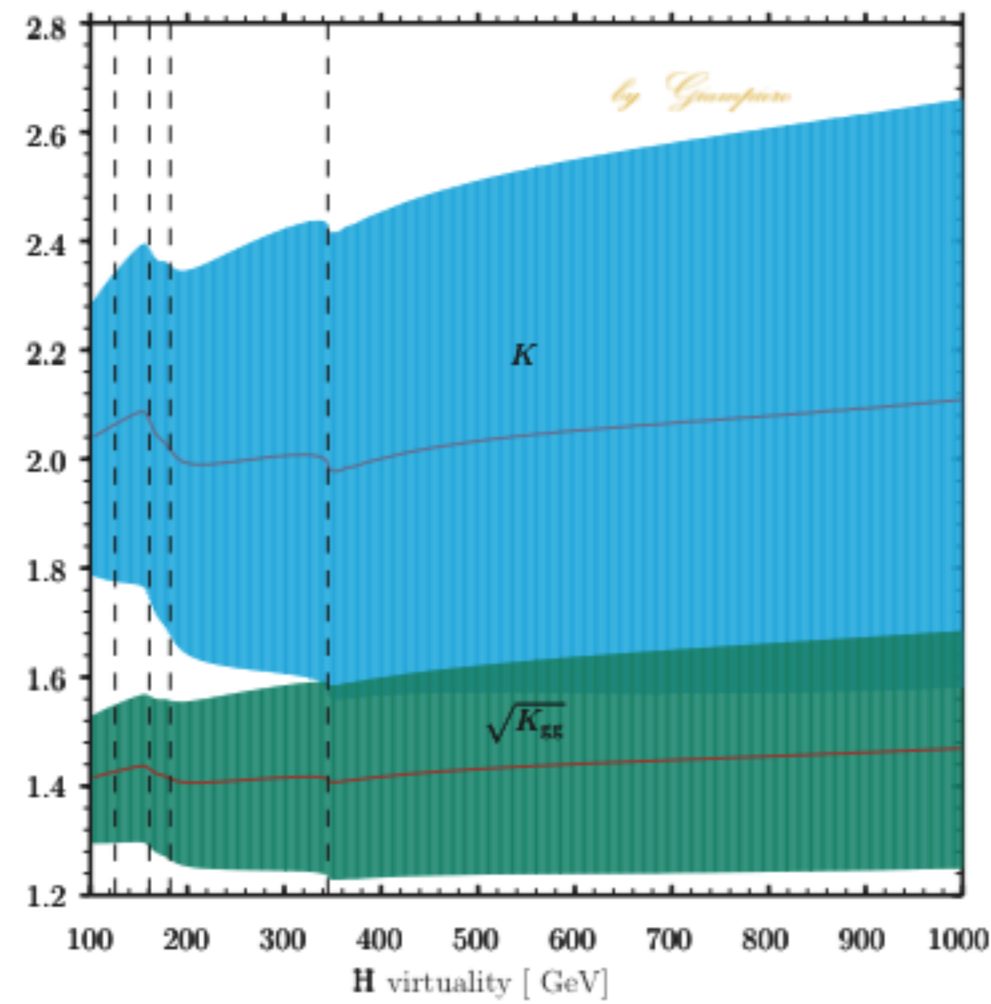
$$\mathcal{P}_{\rm tot}^{\rm off\text{-}shell}(\vec{x}) = \left[\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0) \times \mathcal{P}_{\rm sig}^{\rm gg}(\vec{x}) + \sqrt{\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0)} \times \mathcal{P}_{\rm int}^{\rm gg}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm gg}(\vec{x})\right]$$
$$+ \left[\mu_{\rm VBF} \times (\Gamma_{\rm H}/\Gamma_0) \times \mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \sqrt{\mu_{\rm VBF} \times (\Gamma_{\rm H}/\Gamma_0)} \times \mathcal{P}_{\rm int}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm VBF}(\vec{x})\right]$$
$$+ \mathcal{P}_{\rm bkg}^{\rm q\bar{q}}(\vec{x}) + \ldots$$

Signal models

- **ggH** modelled with gg2VV or MCFM (m_H=125.6 GeV)
  - inclusive generation: Higgs, continuum and interference
  - dynamic renormalisation and factorisation scales := $m_{ZZ}/2$
  - scaled with NNLO k-factors for gg → VV as function of m_{ZZ}

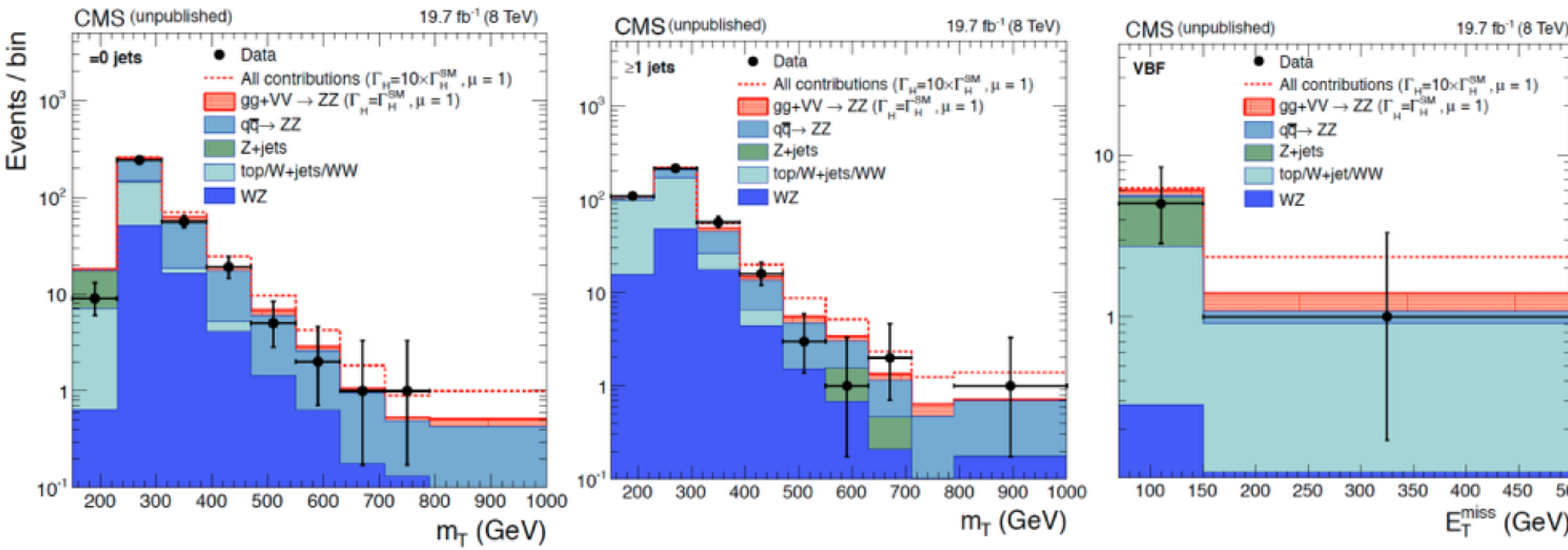
  Bonvini et al. PRD88 (2013) 034032, Passarino arXiv:1312.2397





- **VBF** production is generated with Phantom or Madgraph
  - expect to yield ~10% in the high mass regime
  - inclusive generation, as in gg case
  - no dynamical scaling is applied on VBF models

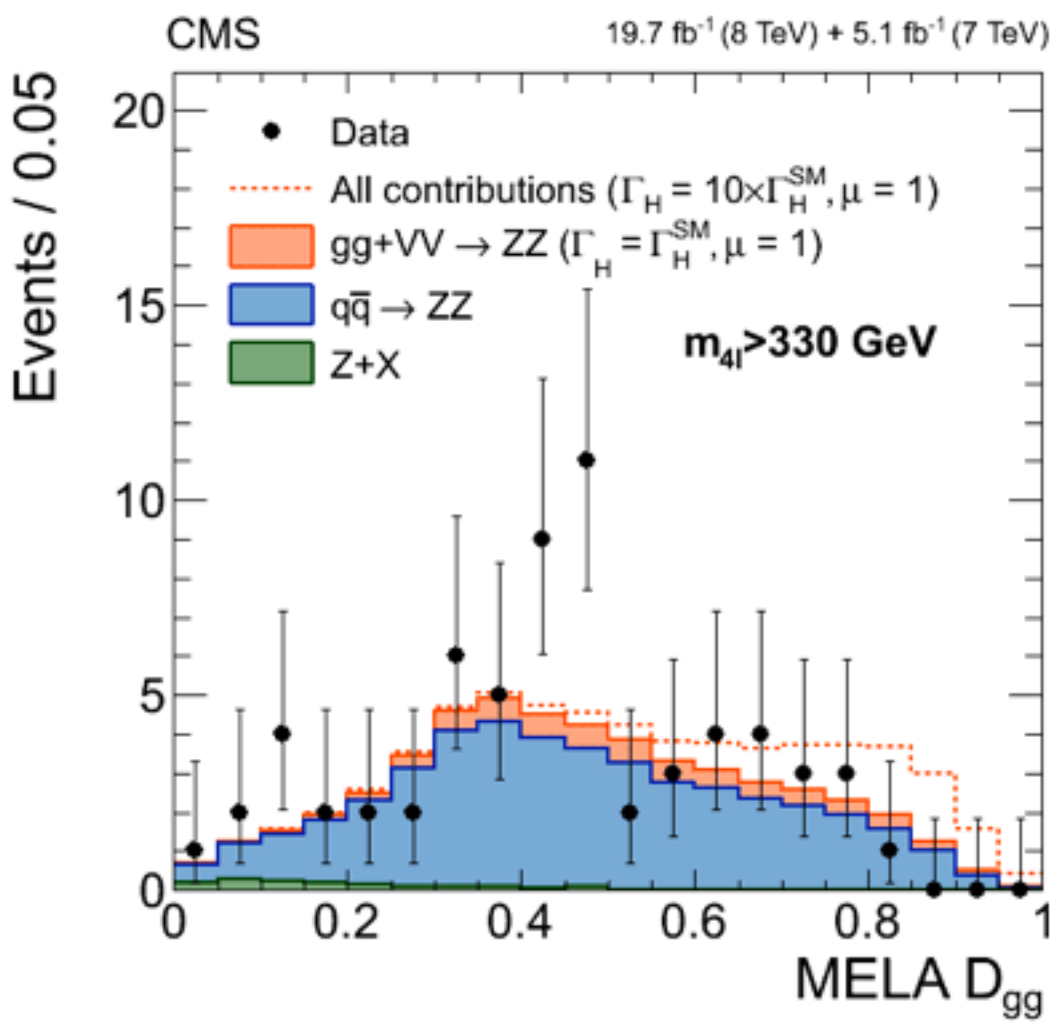
Discriminators used in the $2\ell 2\nu$ analysis

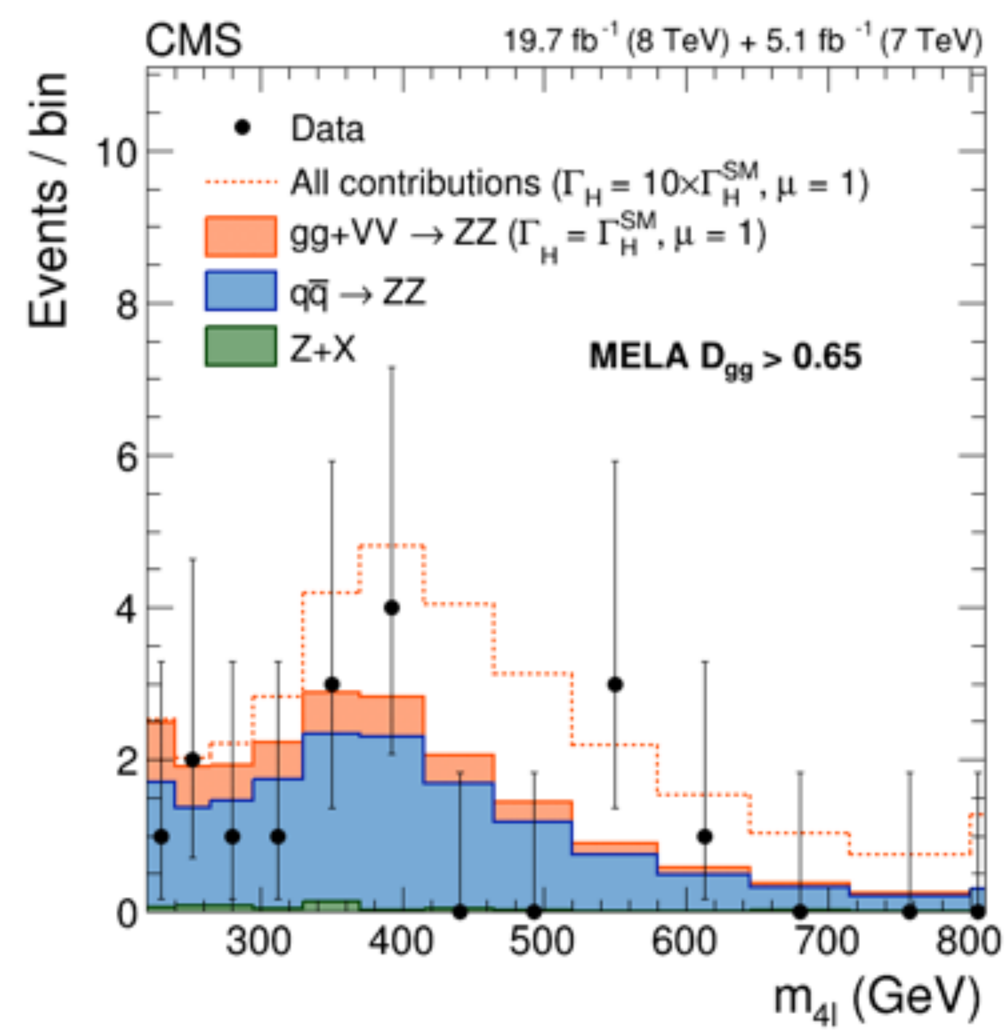


- Analysis has been checked inclusively and binned according to the jets
  - VBF category has priority, selected with M_{jj}>500 GeV, **Δη**>4 + central jet veto: use E_T^{miss}
  - if no VBF jet count jets with p_T>30 GeV : use transverse mass
- Data is in agreement with the expectations, in all the categories

Discriminators used in the 4ℓ analysis

- Use a matrix-element likelihood approach (MELA)
    - use information about Z masses and angles in the CM frame
    - optimize gg → ZZ separation according to expected sensitivity for Γ





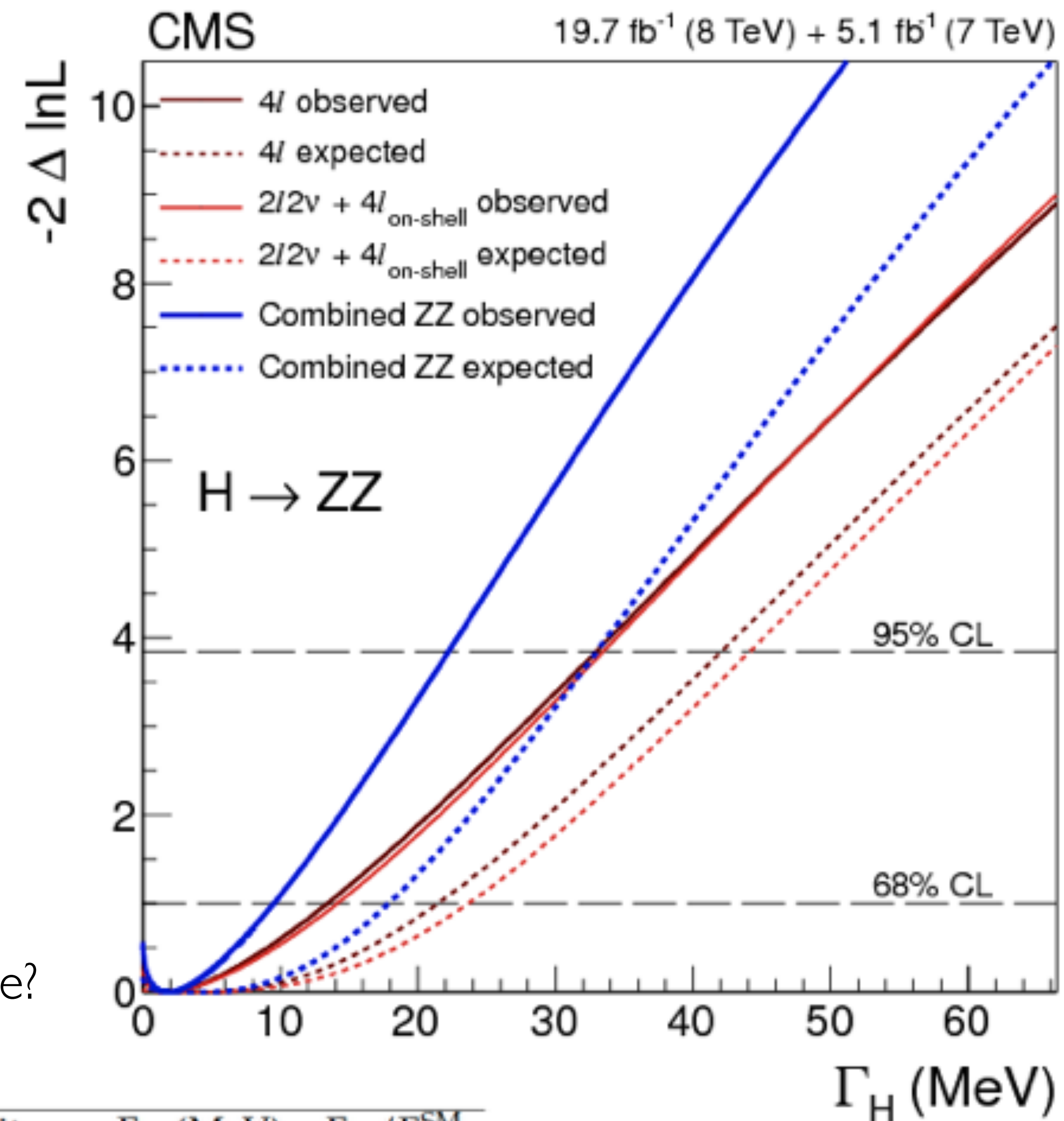
Results

- Both channels are combined to set limits

$\Gamma_H < 5.4\ \Gamma_H^{SM}$ @ 95% CL

still allowing large room for BSM contributions

- Observed limits are overall stringent then expected
  - improved agreement with NLO EWK corrections (WZ/ZZ production)
  - indicative that higher order corrections are non-negligible?



Analysis	Observed/ Expected	95% CL limit on Γ_H (MeV)	95% CL limit on Γ_H/Γ_H^{SM}	Γ_H (MeV)	Γ_H/Γ_H^{SM}
4ℓ	Expected	42	10.1	$4.2^{+17.3}_{-4.2}$	$1.0^{+4.2}_{-1.0}$
	Expected (no syst.)	41	10.0	$4.2^{+17.1}_{-4.2}$	$1.0^{+4.1}_{-1.0}$
	Observed	33	8.0	$1.9^{+11.7}_{-1.9}$	$0.5^{+2.8}_{-0.5}$
$4\ell_{\text{on-shell}} + 2\ell2\nu$	Expected	44	10.6	$4.2^{+19.3}_{-4.2}$	$1.0^{+4.7}_{-1.0}$
	Expected (no syst.)	34	8.3	$4.2^{+14.1}_{-4.2}$	$1.0^{+3.4}_{-1.0}$
	Observed	33	8.1	$1.8^{+12.4}_{-1.8}$	$0.4^{+3.0}_{-0.4}$
Combined	Expected	33	8.0	$4.2^{+13.5}_{-4.2}$	$1.0^{+3.2}_{-1.0}$
	Expected (no syst.)	28	6.8	$4.2^{+11.3}_{-4.2}$	$1.0^{+2.7}_{-1.0}$
	Observed	22	5.4	$1.8^{+7.7}_{-1.8}$	$0.4^{+1.8}_{-0.4}$

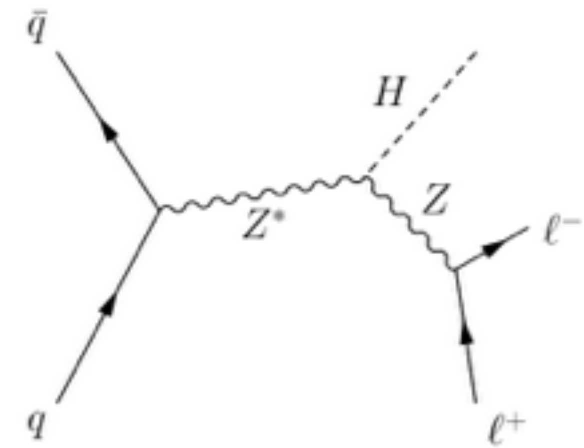
150x more stringent than from on-shell line-shape measurement

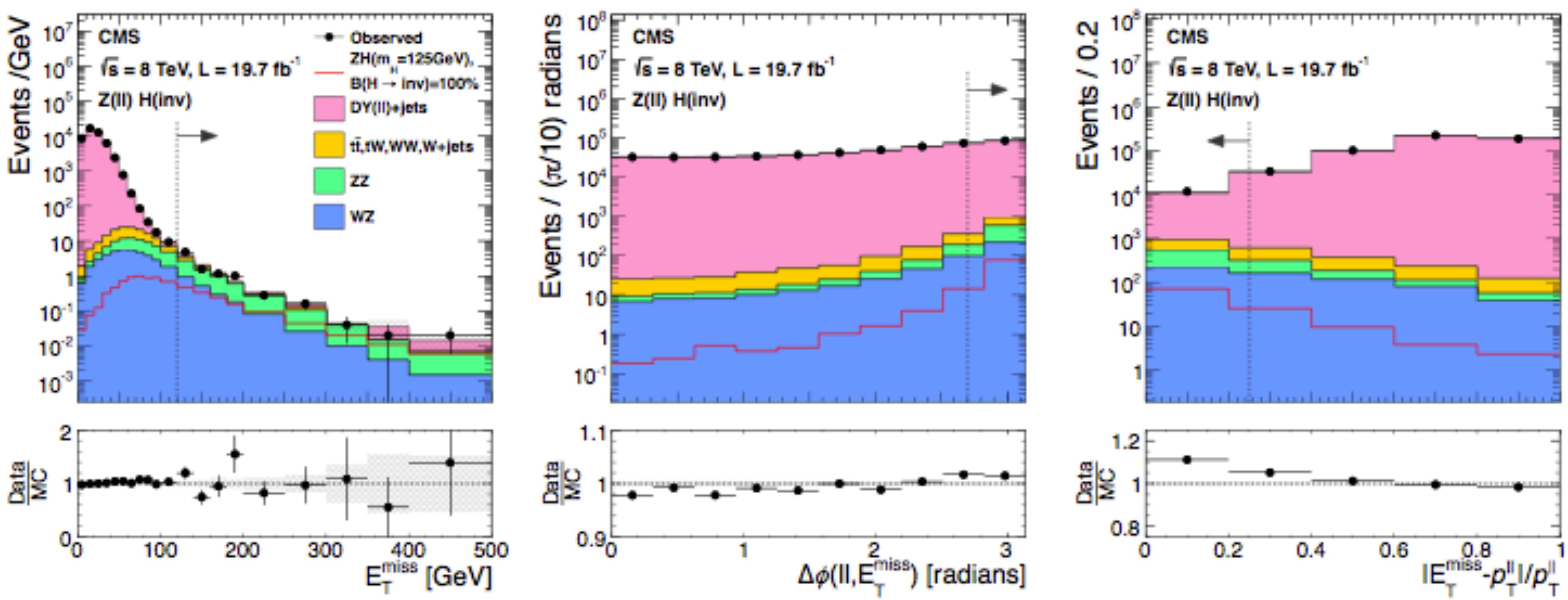
Directly searching for invisible Higgs decays

EPJC 74 (2014) 2980

Invisible Higgs decays in $Z_{\ell\ell}H$

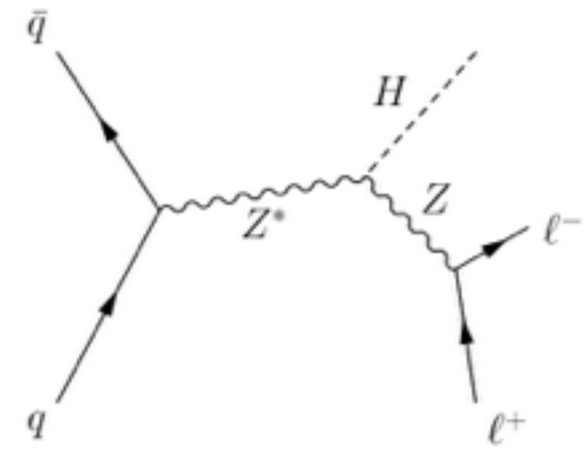
- Associated production with a Z can be used to search for H → invisible
  - re-cast $2\ell 2\nu$ analysis for non-resonant topology
  - adapt final selection for back-to-back configuration between 2ℓ and E_T^{miss}

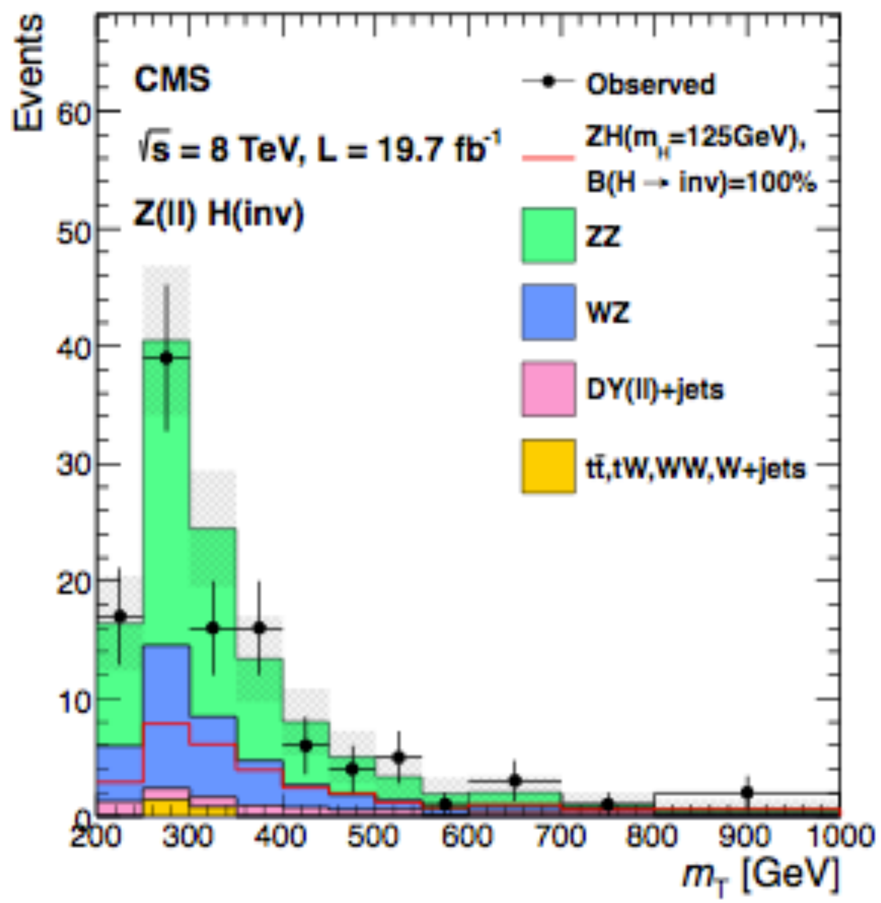


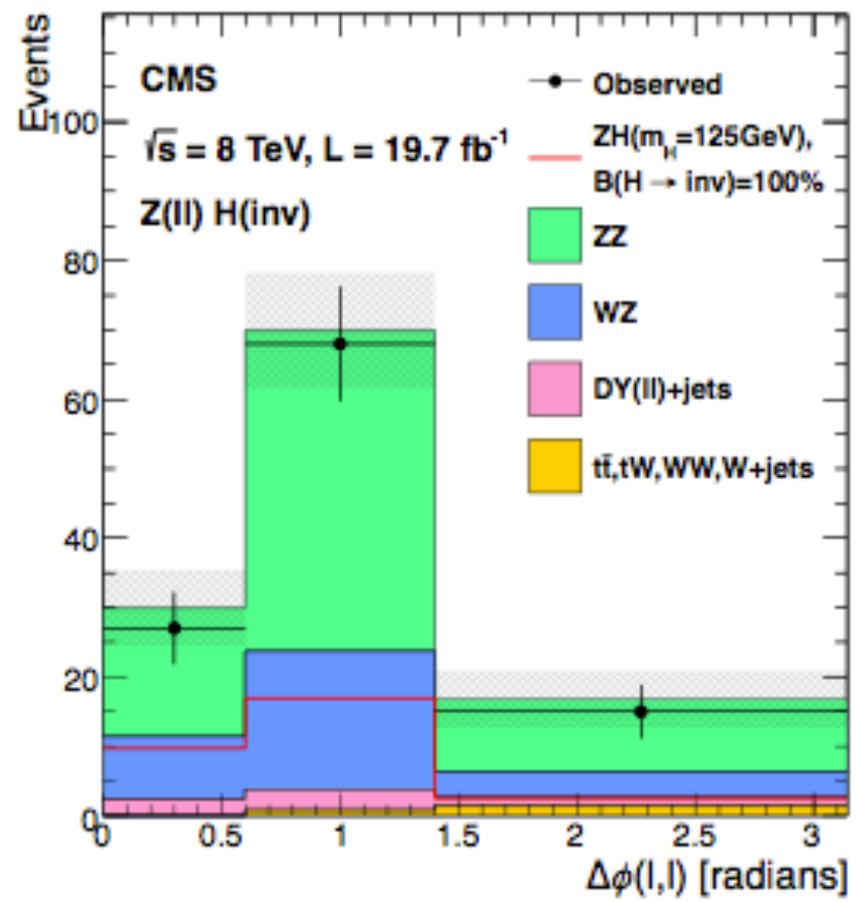


Invisible Higgs decays in $Z_{\ell\ell}H$

- Associated production with a Z can be used to search for H → invisible
  - re-cast $2\ell 2\nu$ analysis for non-resonant topology
  - adapt final selection for back-to-back configuration between 2ℓ and E_T^{miss}
  - categorize the search according to the observed jet multiplicity (0 jets or 1 jet)
  - use transverse mass shape and azimuthal angle between leptons to set upper limits

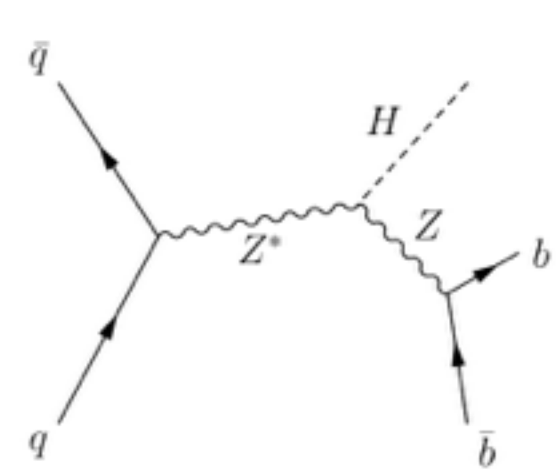




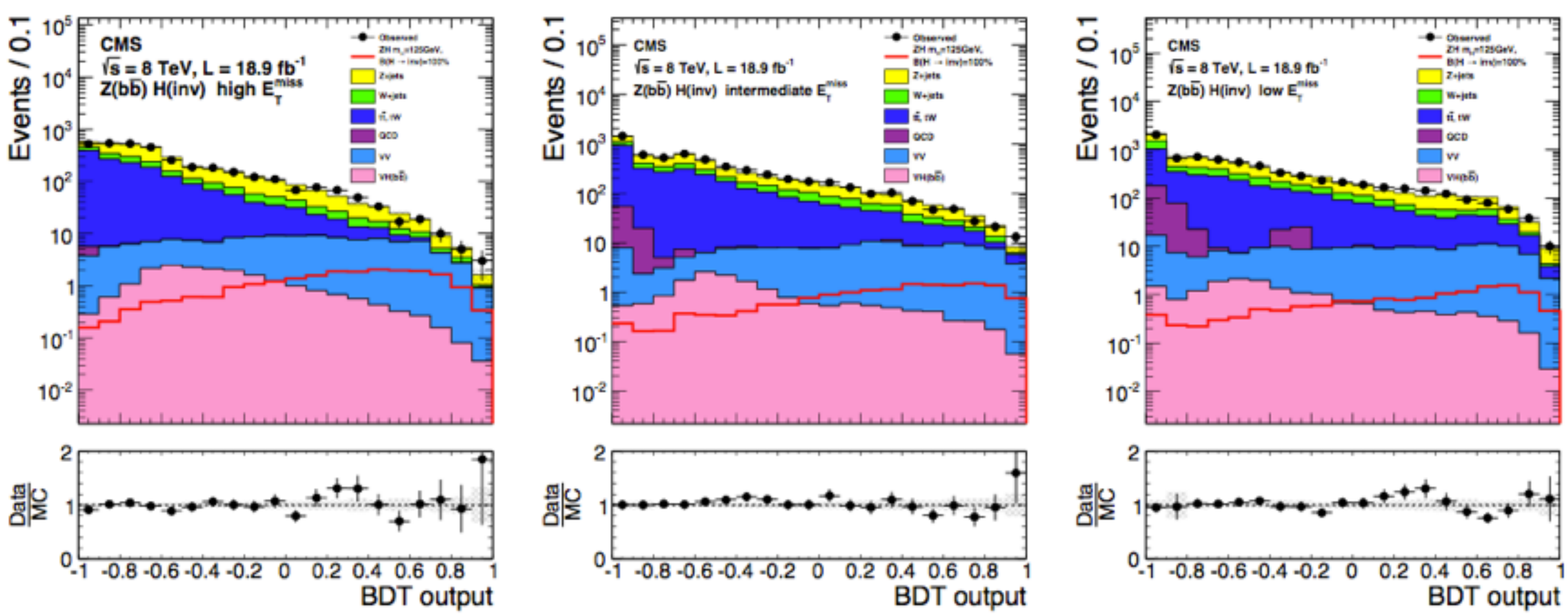


Invisible Higgs decays in $Z_{bb}H$

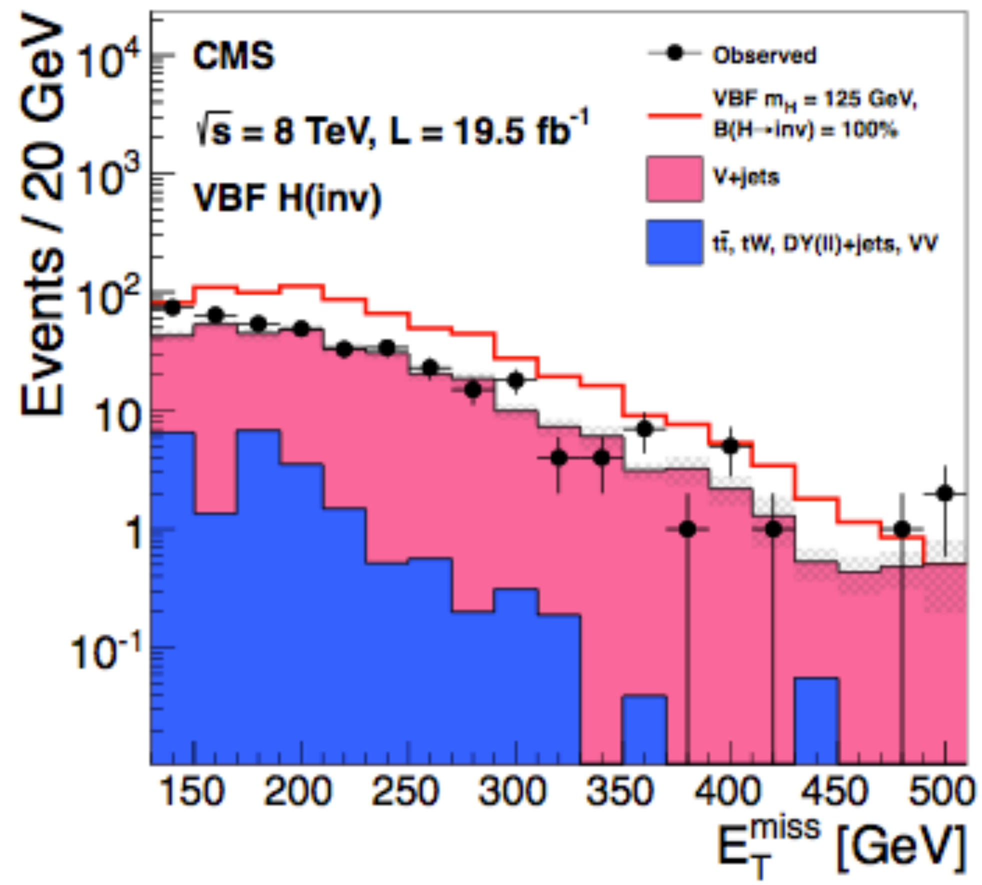
- Complement with a re-cast of the H→bb analysis in the ZH production mode
  - 2 b-tagged jets, no additional leptons in the event
  - require back-to-back configuration between Z and H (**ΔΦ**>2 rad)
  - categorize events in low/medium and high E_T^{miss} regions: 100-130 / 130-170 and >170 GeV
  - reduce instrumental bkg by requiring **ΔΦ**(jet, E_T^{miss})>0.5-0.7 rad, **ΔΦ**(tk-E_T^{miss}, E_T^{miss})<0.5 rad, $E_T^{miss}/H_T^{1/2}$>3
  - improve energy resolution with a b-jet energy regression



final limits set after fitting the shape of a multivariate discriminator making use of the kinematics and b-tagging information



Invisible Higgs decays in VBF

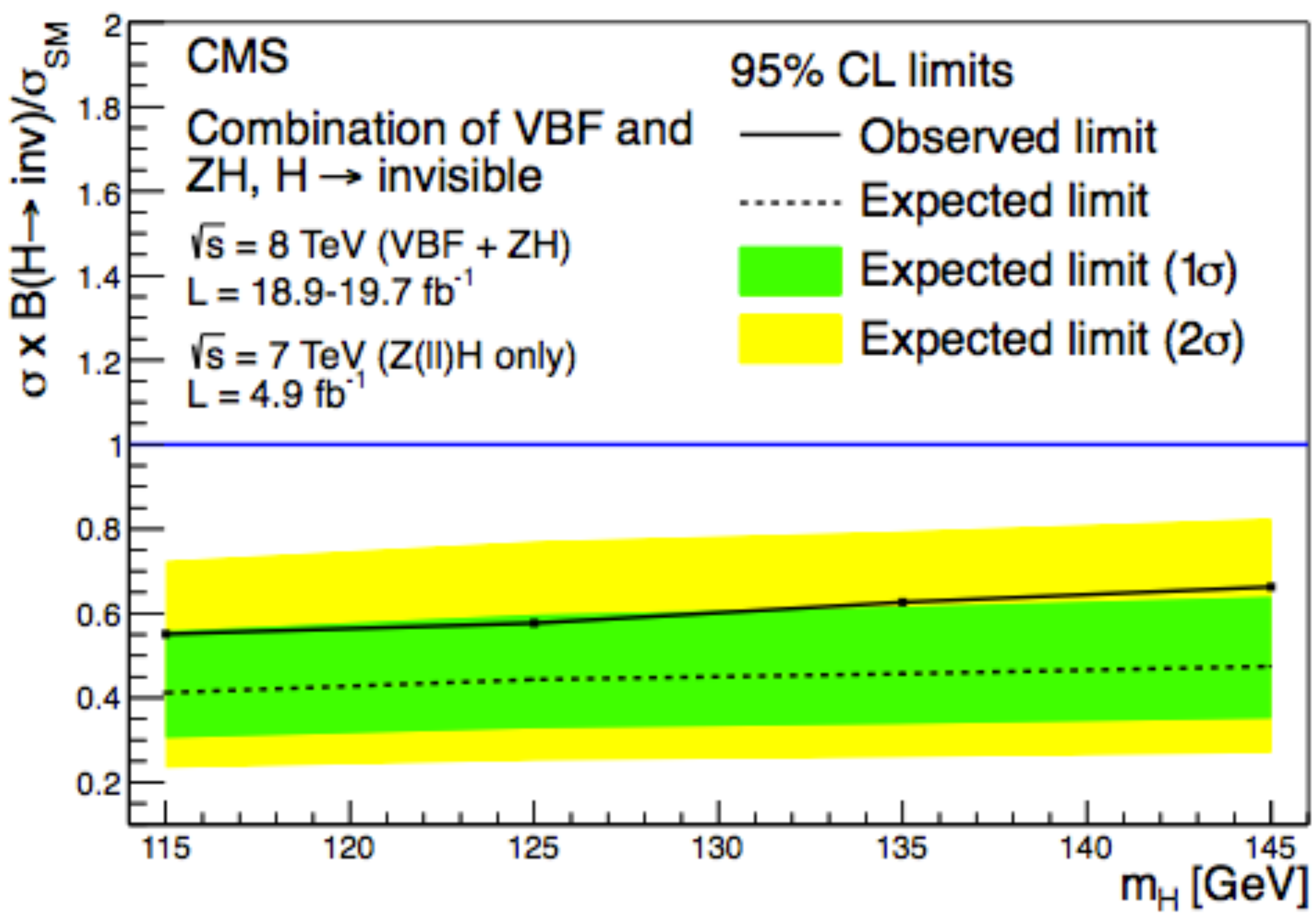


- Using VBF+E_T^{miss} triggers
  - muons not used for E_T^{miss} so that W/Z control samples are saved
  - p_T>40 GeV M_{jj}>800 GeV $\Delta\eta_{jj}$>3.5 E_T^{miss} >65 GeV
- Offline: reject extra leptons and tighten cuts
  - p_T>50 GeV M_{jj}>1100 GeV $\Delta\eta_{jj}$>4.2 E_T^{miss} >130 GeV
  - $\Delta\Phi_{jj}$<1.0 rad + central jet veto applied
  - expected efficiency of 0.6% for BR_{inv}=100%
- Main backgrounds are extrapolated from control regions
  - Z→νν from Z→μμ : $N^{s}_{\nu\nu} = (N^{c}_{\mu\mu\mathrm{obs}} - N^{c}_{\mathrm{bkg}}) \cdot \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)} \cdot \frac{\varepsilon^{s}_{\mathrm{ZMC}}}{\varepsilon^{c}_{\mathrm{ZMC}}}$
  - W→eν/μν from single lepton samples (ignore lepton veto) : $N^{s}_{\ell} = (N^{c}_{\ell\mathrm{obs}} - N^{c}_{\mathrm{bkg}}) \cdot \frac{N^{s}_{\mathrm{WMC}}}{N^{c}_{\mathrm{WMC}}}$
  - W→τν similar to the previous but ignoring central jet veto, to increase statistics
  - QCD apply rescale using control regions defined by E_T^{miss} and central jet veto requirements

Combination of the three channels

- VBF search yields the most stringent limits
  - improve by a factor of 11% after combination
  - **BR_{inv}<0.58% for m_H=125 GeV @ 95%CL**
  - improve over indirect limit from visible decays (BR_{inv}<0.89% @ 95%CL)

m_H (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(H \to inv)/\sigma_{SM}$ VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—



From BR$_{inv}$ to limits on dark matter interactions

- Possible in the context of **Higgs-portal model of DM interactions**
  - hidden sector provides viable stable DM particles
  - direct renormalisable couplings to the SM Higgs
- If $M_\chi < M_H/2$ then can translate Γ_{inv} width to spin-independent DM-nucleon cross section
  - details in arXiv:hep-ph/0605188, PLB 709 (2012) 65, EPJC 73 (2013) 2455

$$\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2},$$

$$\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12 M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}.$$

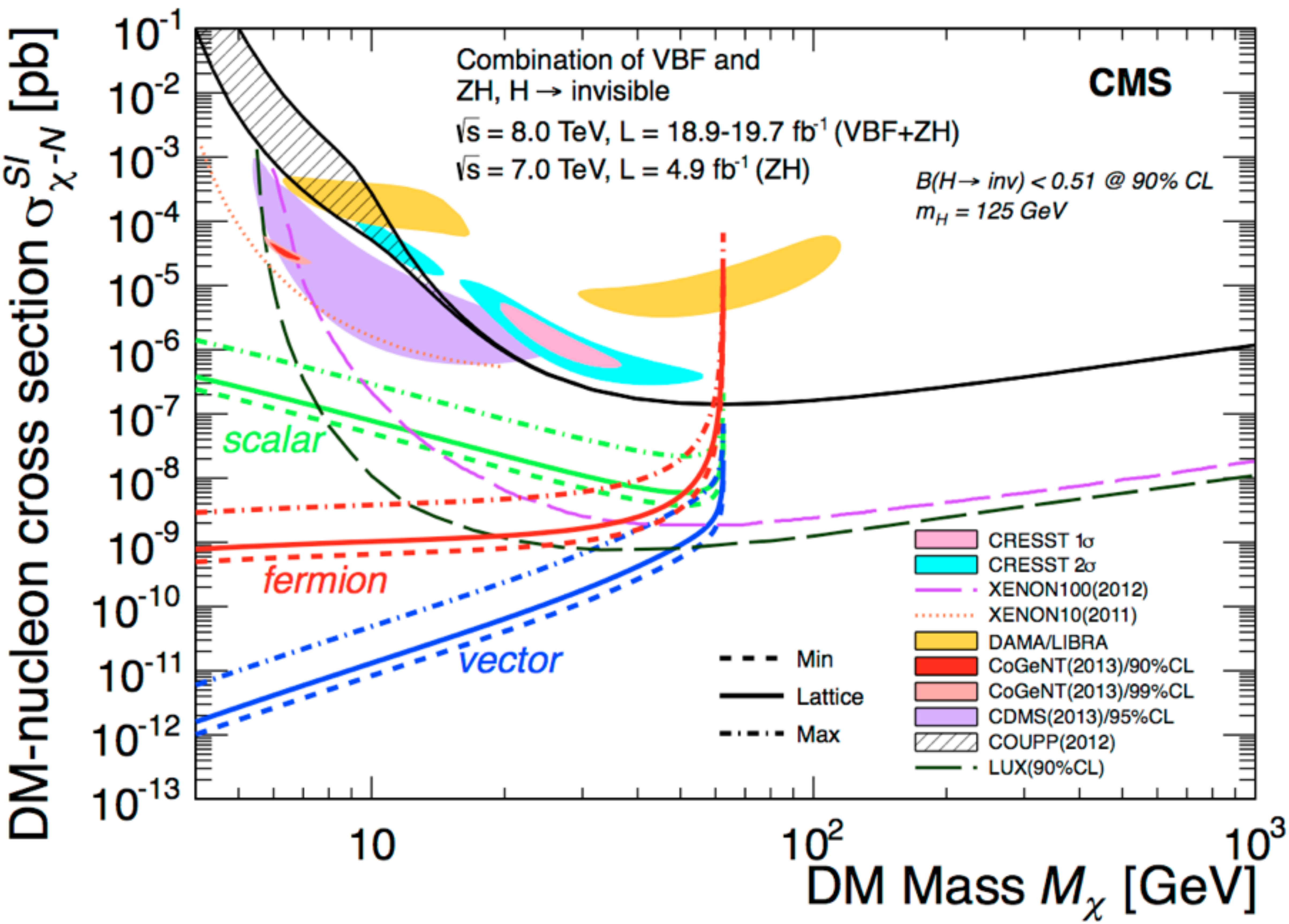
m_N - nucleon mass ~0.939 GeV
$v=246/\sqrt{2}$ GeV (vev)
f_N~0.326 central value for coupling (from lattice*)

$\beta = \sqrt{1 - 4M_\chi^2/m_H^2}.$

$\Gamma_{inv} = \Gamma_{SM} BR_{inv}/(1-BR_{inv})$

**PRD 81(2010) 014503, PRL 103(2009) 122002*

Upper limits on spin-independent DM-nucleon cross sections



Searching for a high-mass Higgs partner

HIG-13-014

EWK singlet model

- Assume there is a second EWK singlet scalar which shares the vev with H(125)
- Unitarity forces the couplings of the two scalars to be inter-related: $C^2+C'^2=1$
- The production cross section for the EWK singlet is then scaled by

$$\mu' = \boxed{C'^2}\,\boxed{(1 - BR_{\text{new}})}$$

bound by unitarity

allows it to couple to a hidden sector

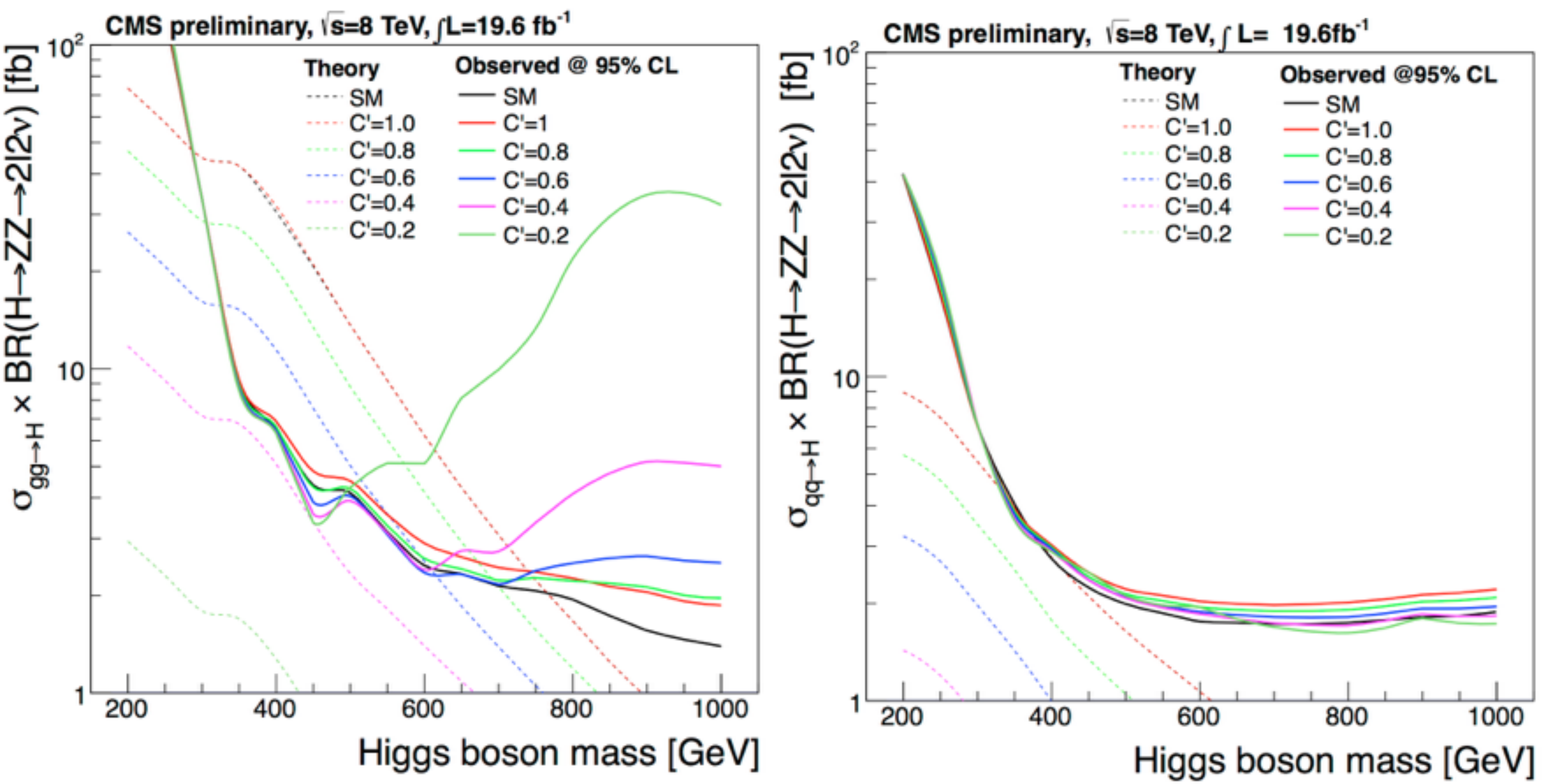
- Consequently, also the width of the new state is changed with respect to the SM case

$$\Gamma' = \Gamma_{\text{SM}} \cdot \frac{C'^2}{1 - BR_{\text{new}}}$$

- In general, if $C'^2<1-BR_{new}$ resonance will be narrower with respect to SM

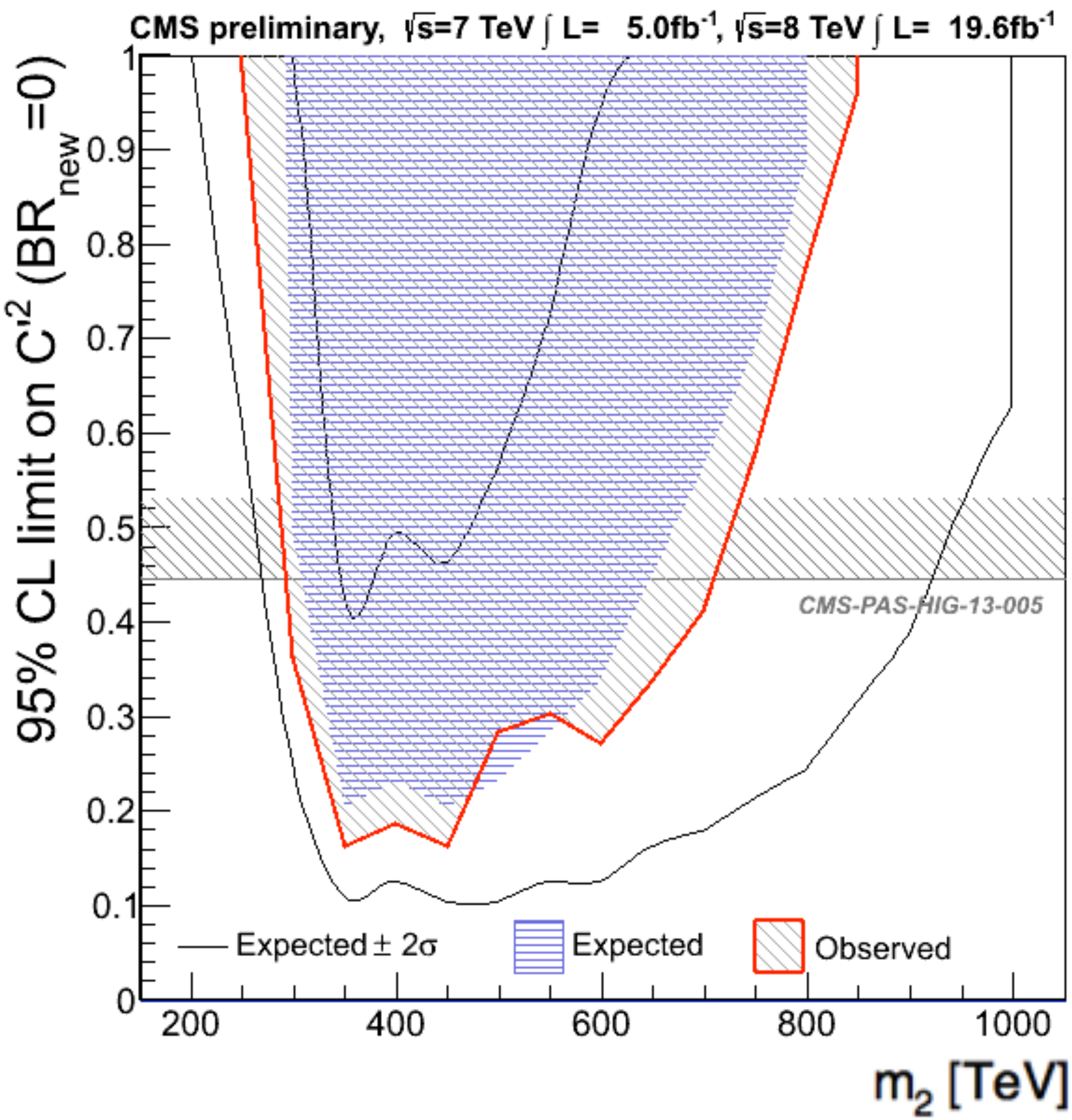
Search and results

- Strategy is similar to the one used to bound the Higgs width from off-shell production
- Signal is generated with gg2VV
  - scan different masses and C' values, include term for interference with the background
  - limits set on absolute cross section separately for gluon-gluon and VBF production modes



Reach of the results I

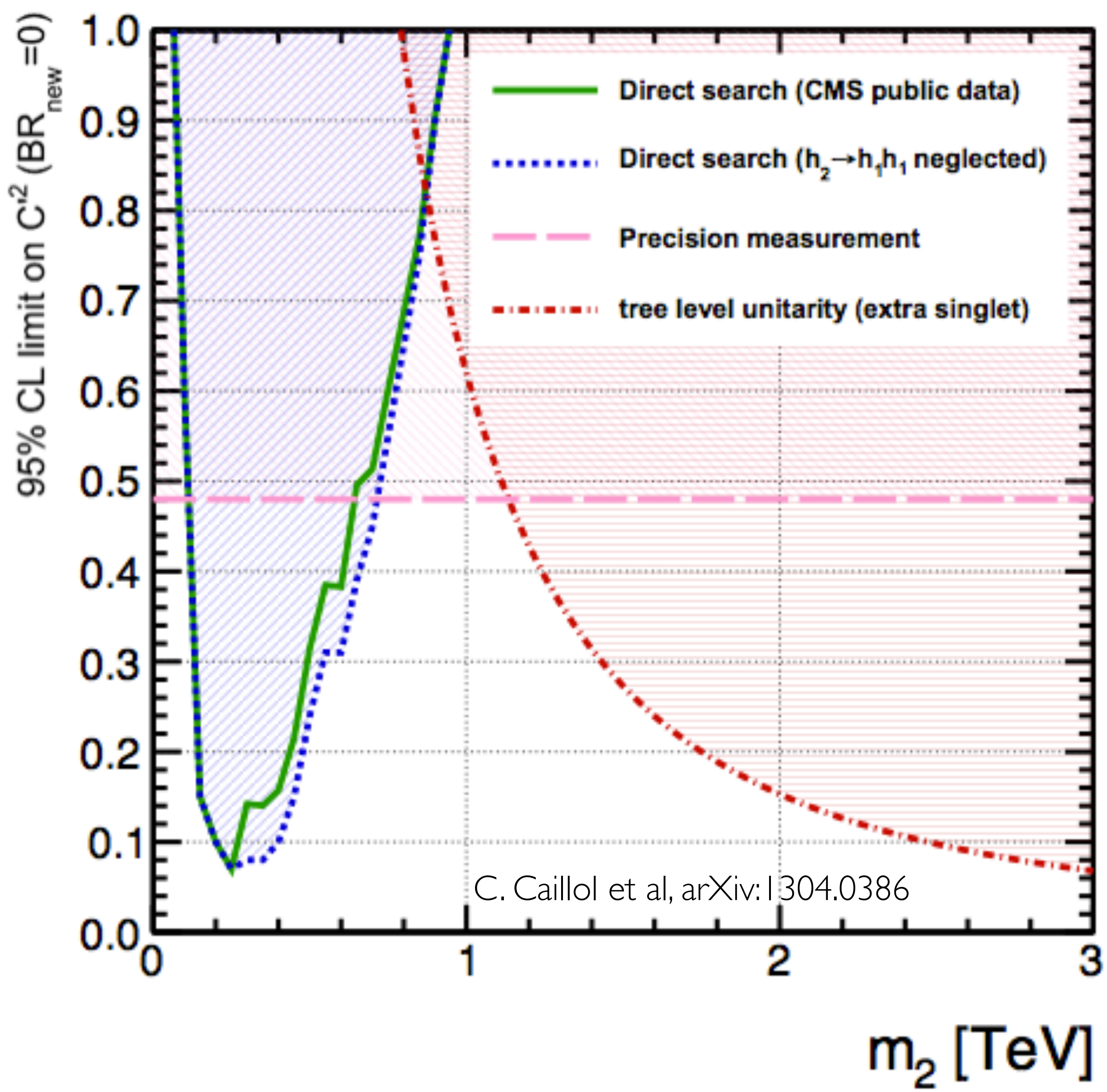
- Assuming gg and VBF have similar contributions as in the SM case
- Scan the exclusion limit on the signal strength for the production of the high mass Higgs partner as function of C'^2
- Significantly improve over indirect limits from H(125) signal strength : motivates to continue scanning the high mass region



Reach of the results II

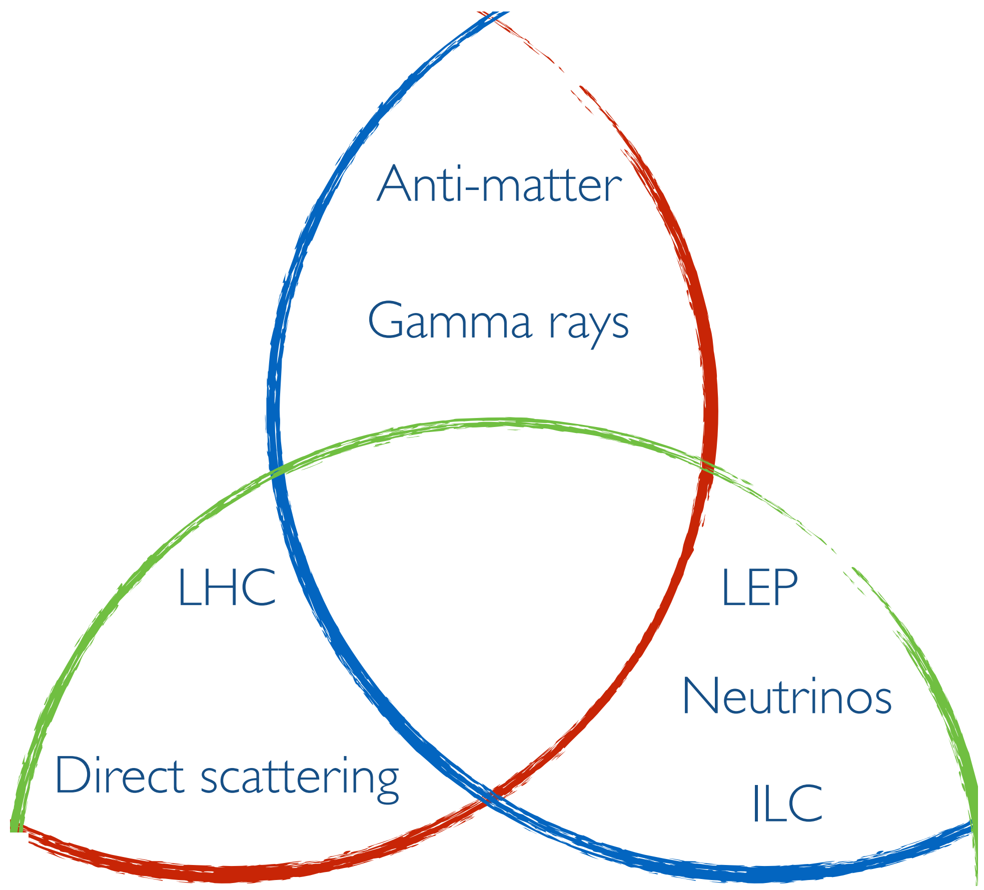
- Assuming gg and VBF have similar contributions as in the SM case
- Scan the exclusion limit on the signal strength for the production of the high mass Higgs partner as function of C'^2
- Significantly improve over indirect limits from H(125) signal strength : motivates to continue scanning the high mass region
- Moreover we are still faraway from crossing the TeV scale

Run II will bring the necessary data



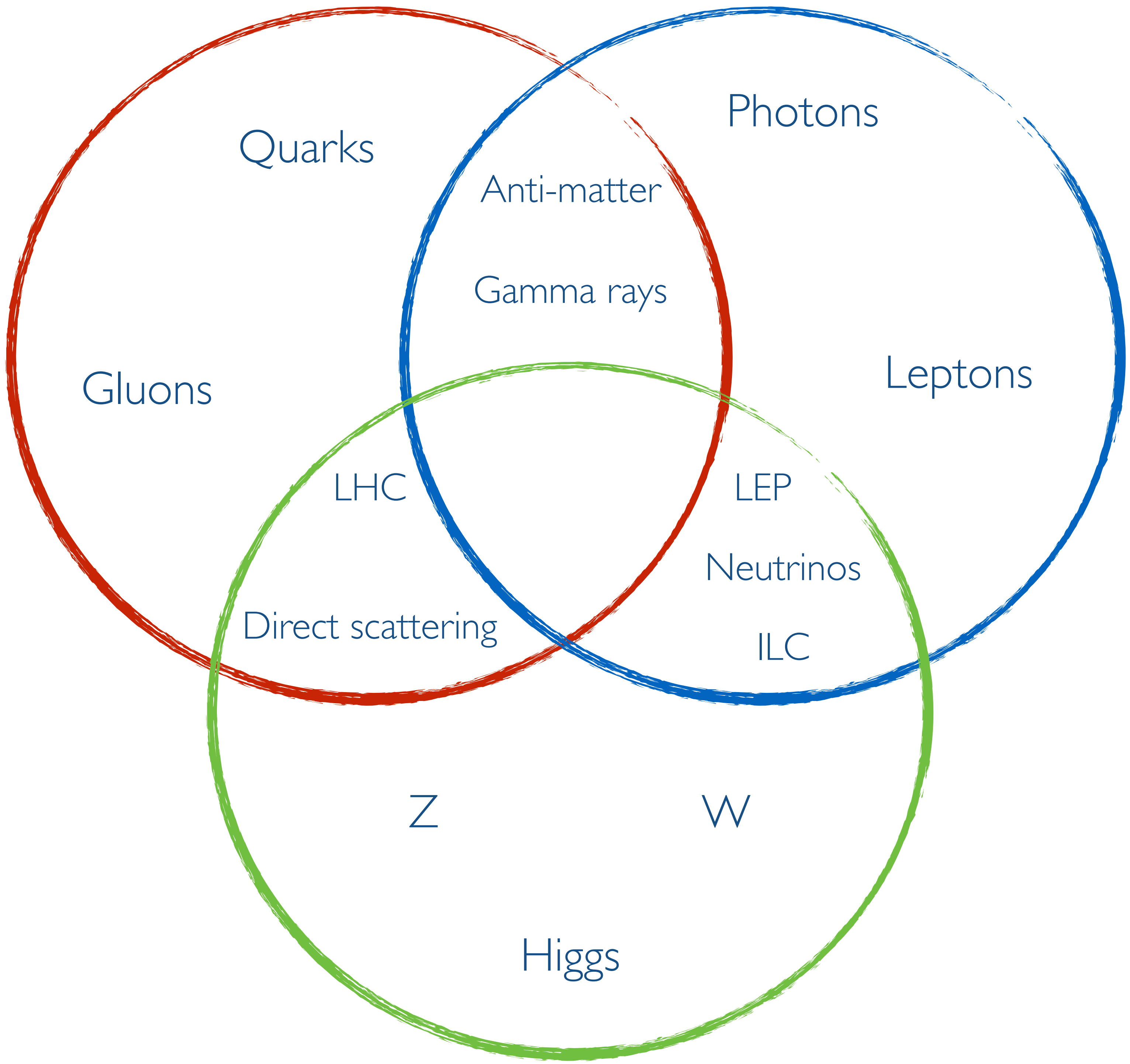
Conclusions

Whichever frontier you prefer to cross…



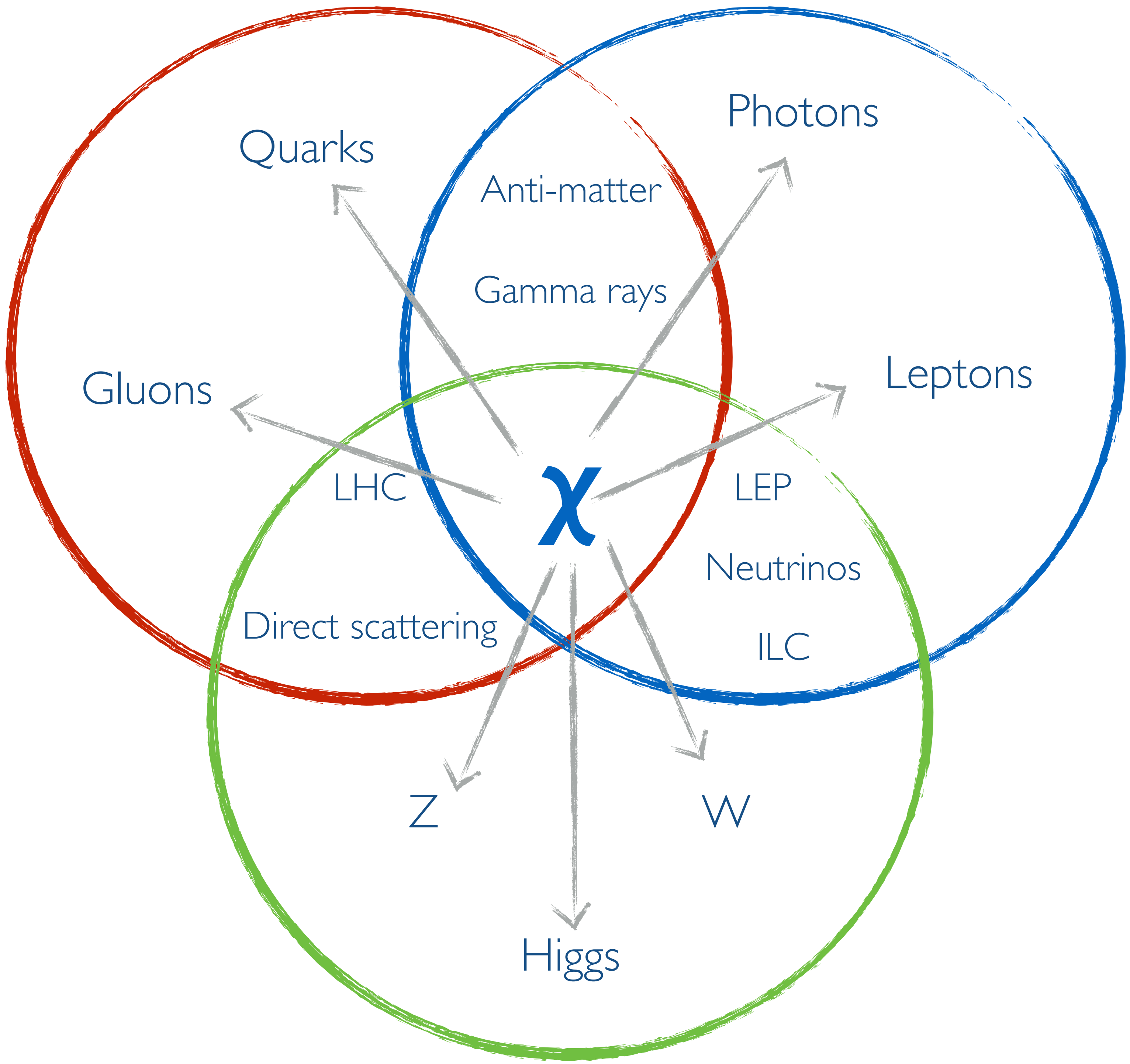
adapted from T. Tait @ LP2013

…the point is not about what one may exclude from the data…



adapted from T. Tait @ LP2013

…but about how it helps filling in the puzzle…



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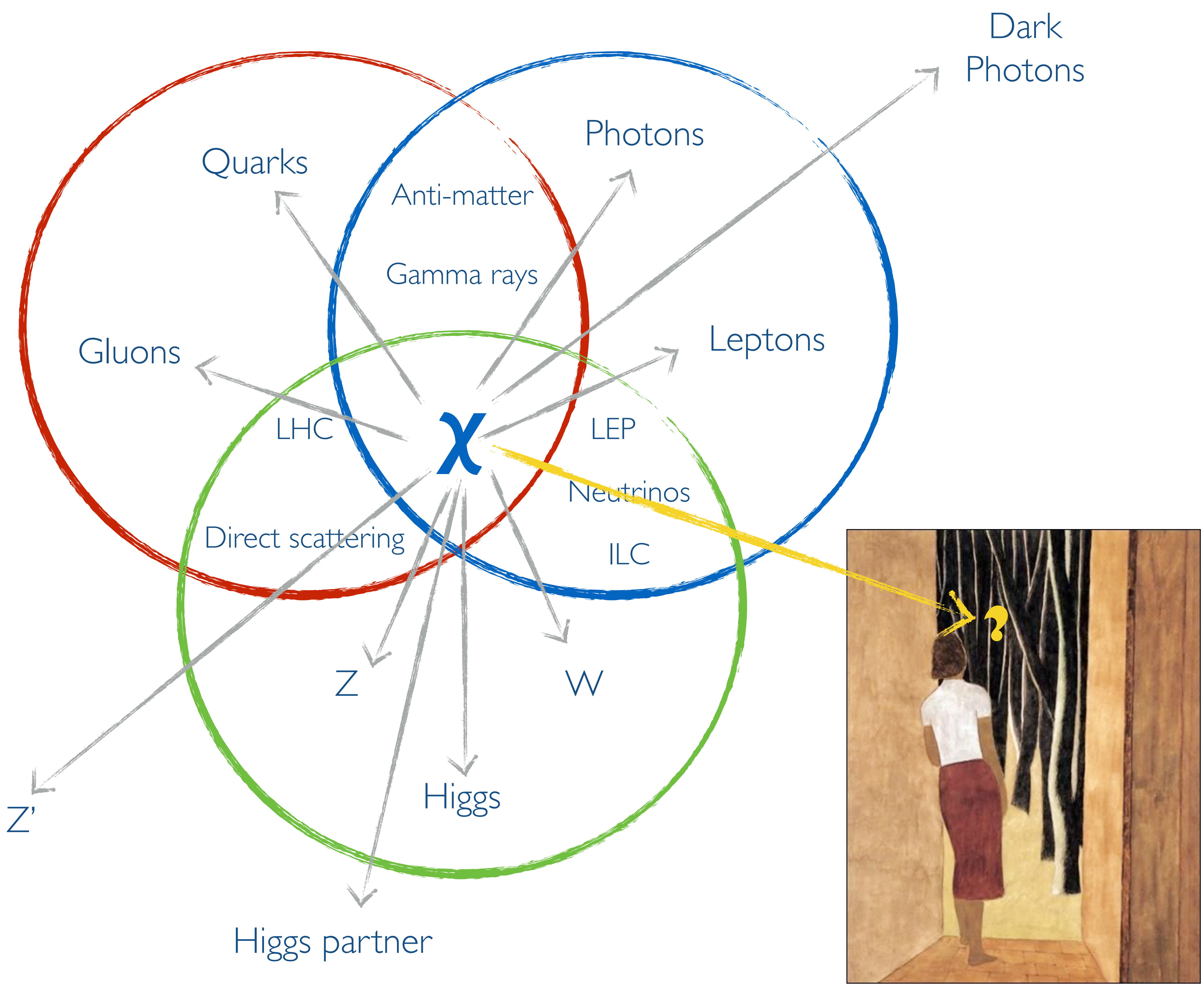
…or re-framing our paradigms



adapted from T.Tait @ LP2013

Conclusions

- The recently discovered Higgs boson may hold a key to the DM world
  - we have a unique opportunity to start probing it at the LHC
  - many alternative windows using final states containing Z bosons in the final state
- Combination of all searches of invisible Higgs yields competitive constraints
  - complemented by off-shell width measurements
  - complemented by direct searches for exotic Higgs partners or other models
- Run II with increased energy and expected 300fb^{-1} to be acquired may bring surprises!