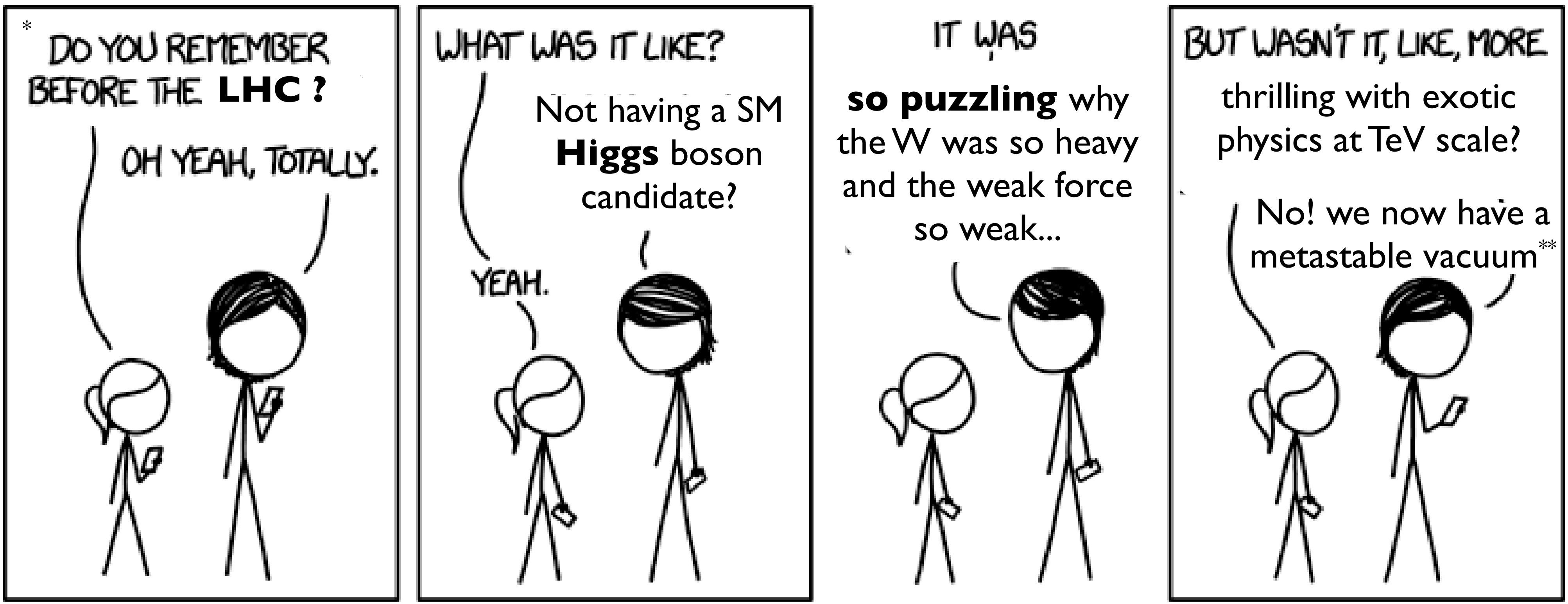
Measuring the width of the heaviest elementary particles at the LHC

P. Silva (CERN/LIP)

Tuesday, 6th May 2014

LIP Seminar

Introduction



* adapted from xkcd#1348 ** Degrassi, G. et al arXiv:1205.6497

Introduction

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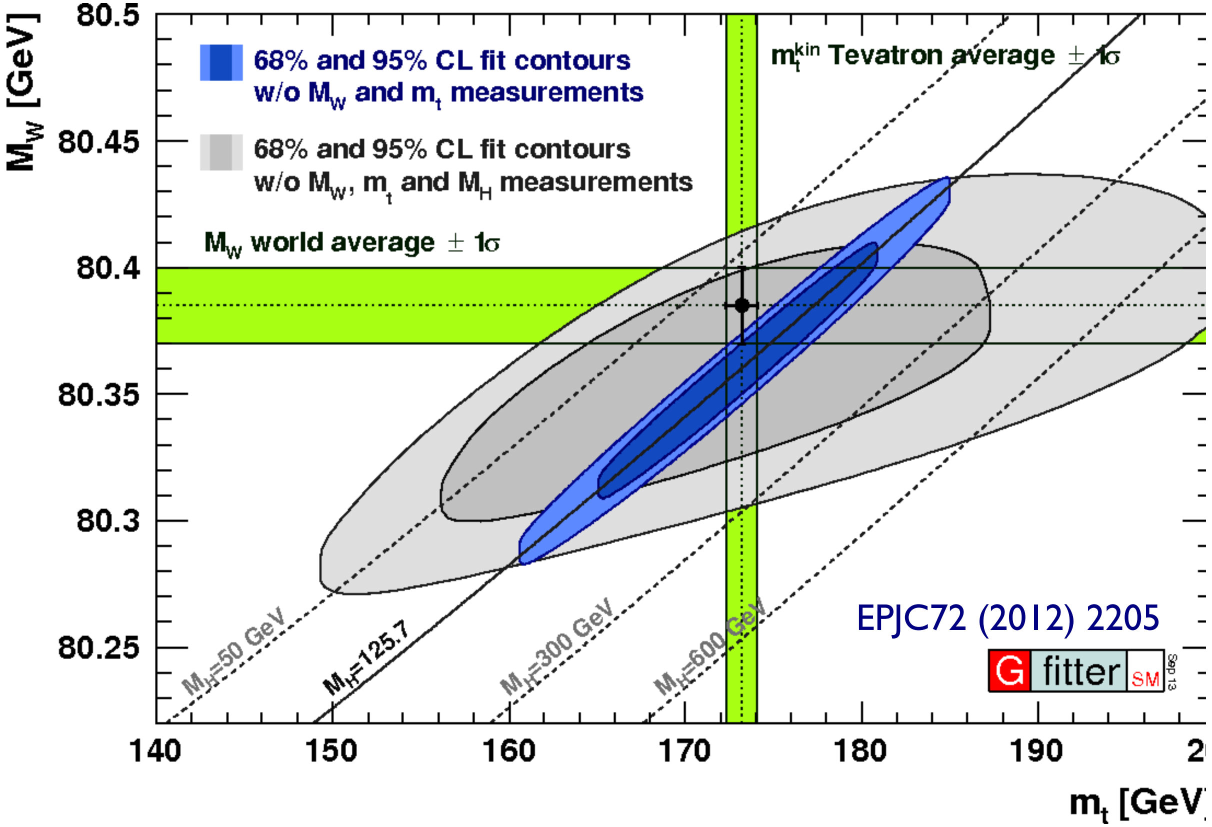
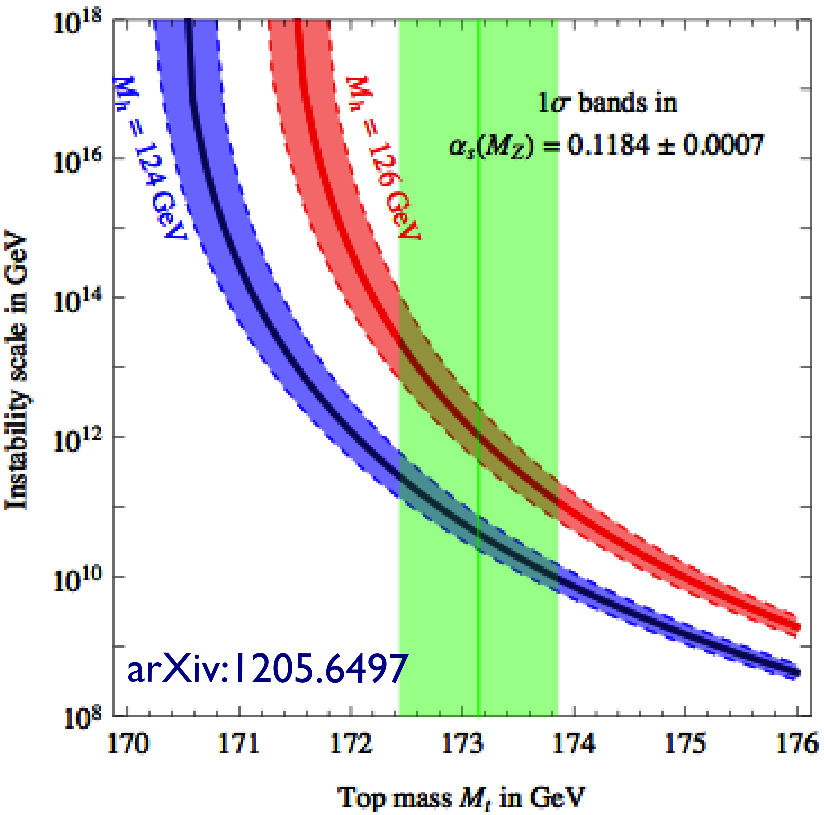
  - maybe there is something around the 13 TeV corner which did not appear at 8 TeV...
  - **precision electroweak measurements are needed** to understand what's going on





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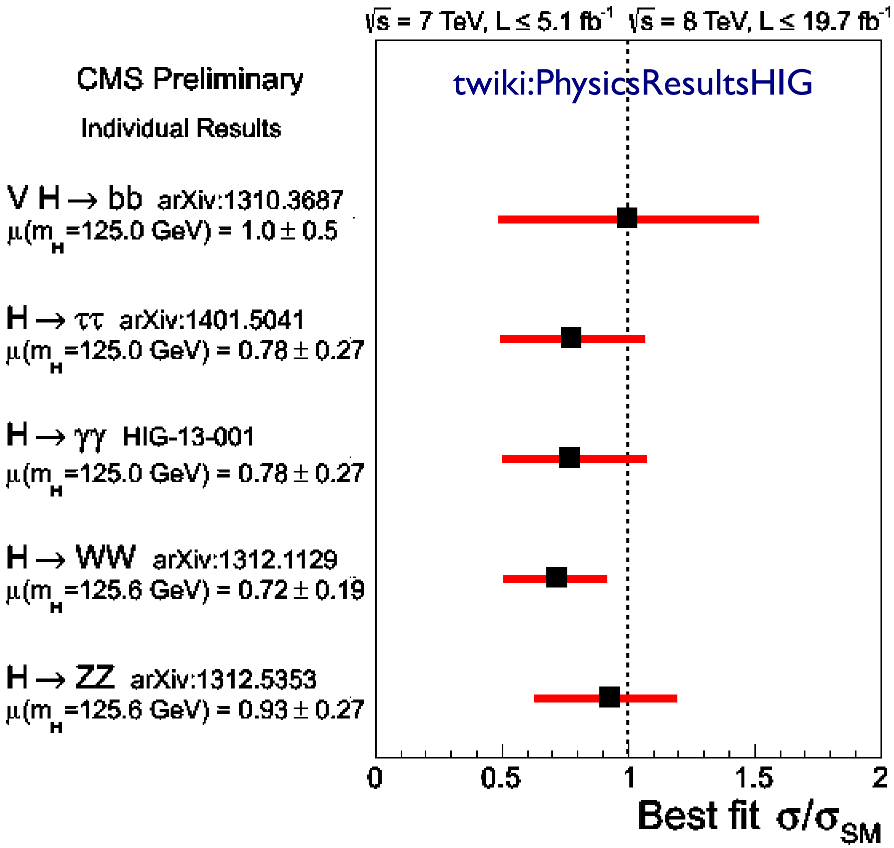
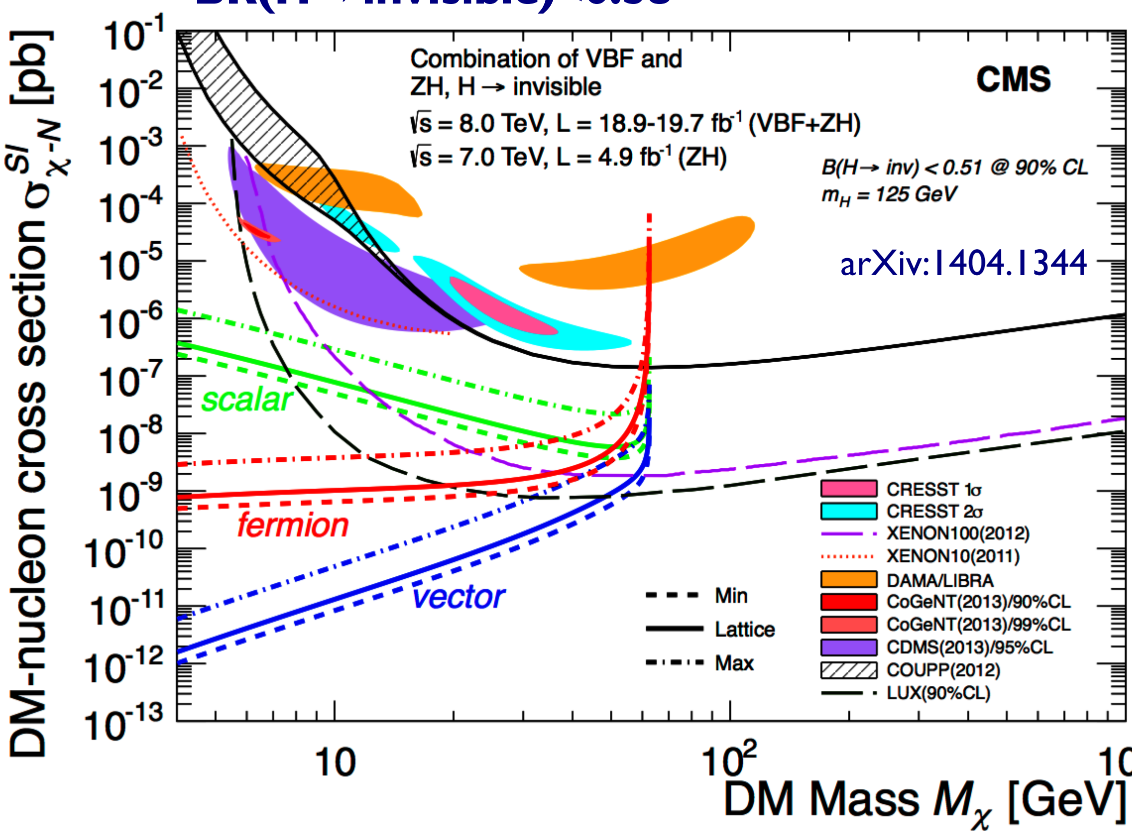


BR(H → invisible)<0.58



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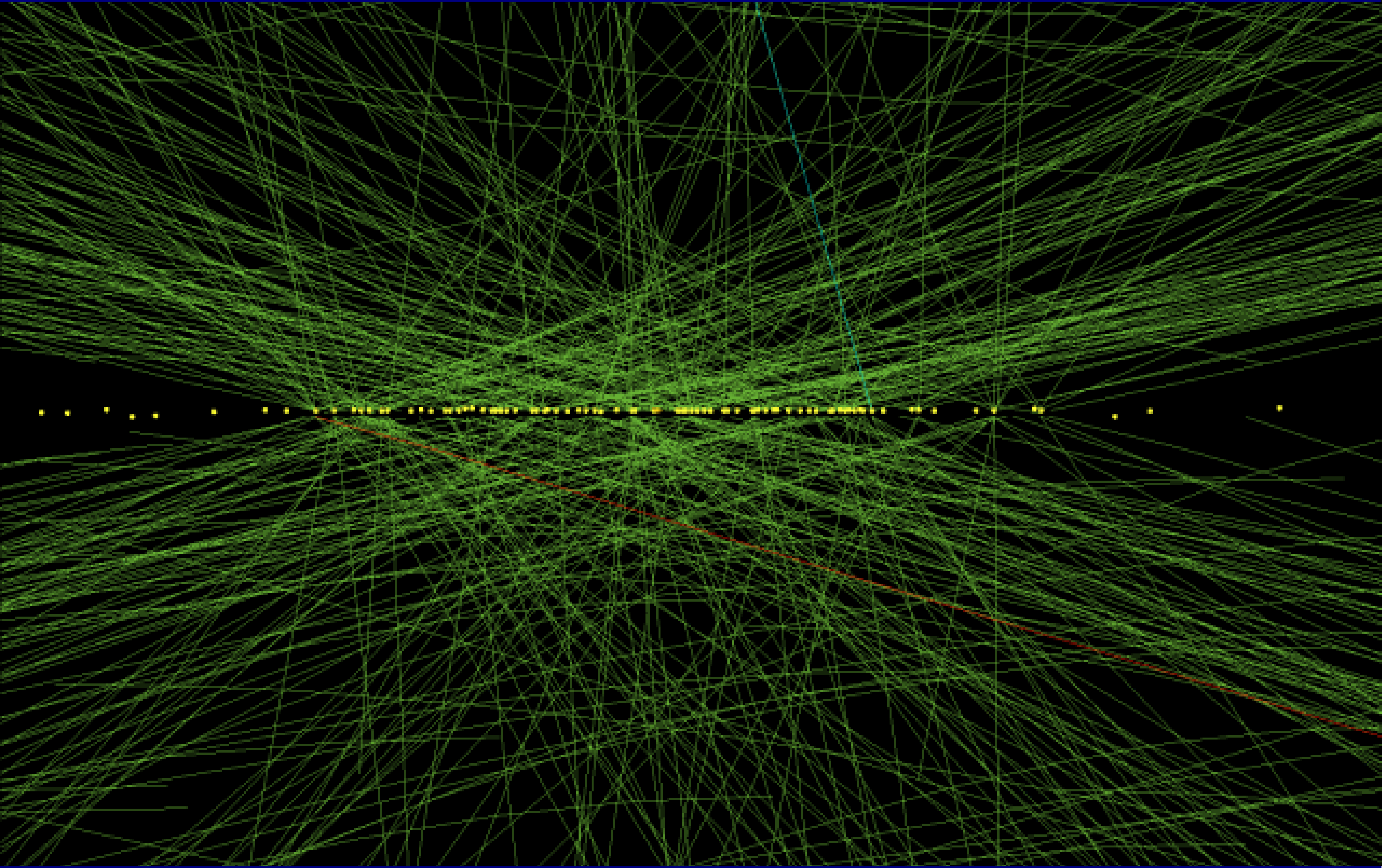

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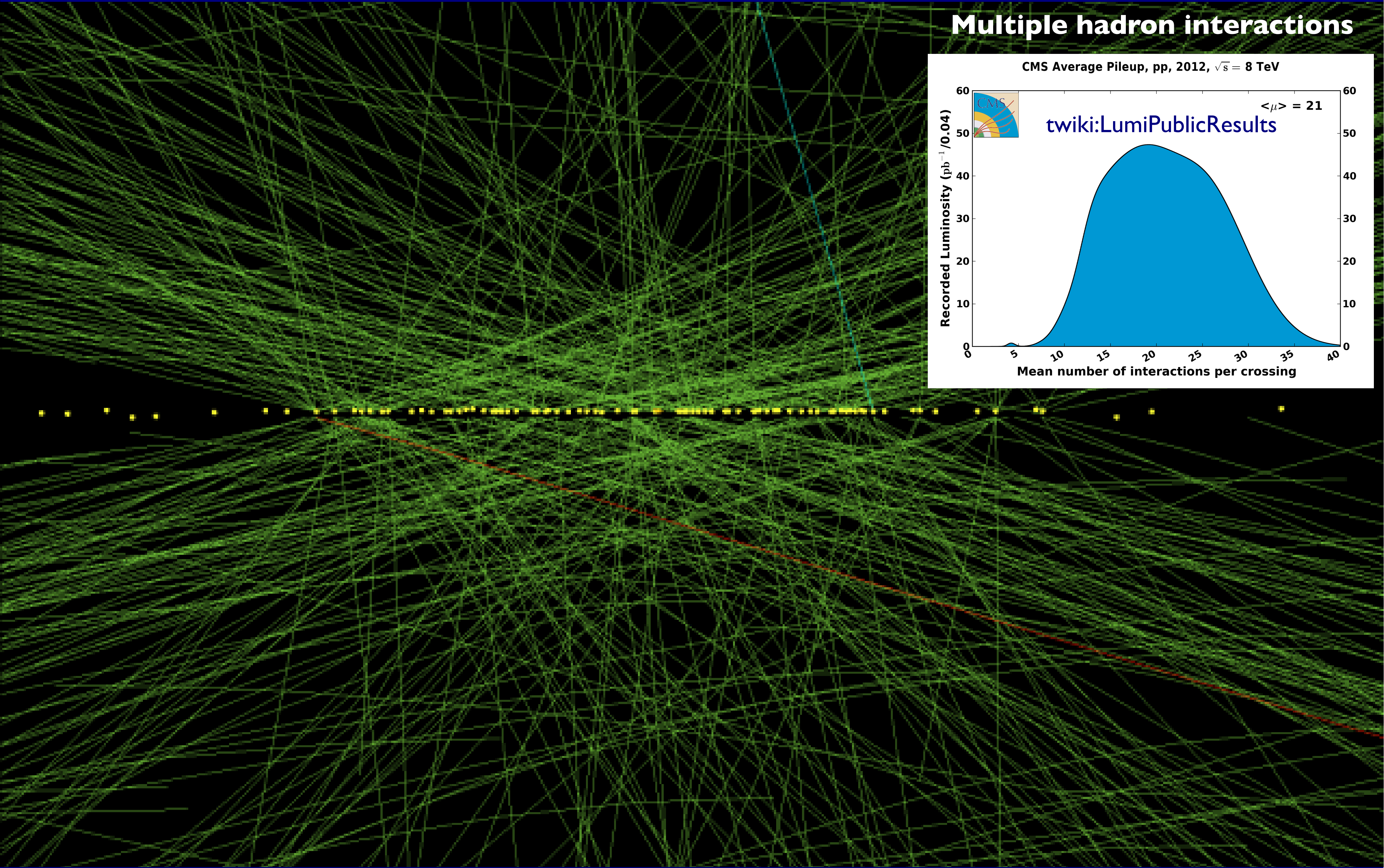
Multiple hadron interactions



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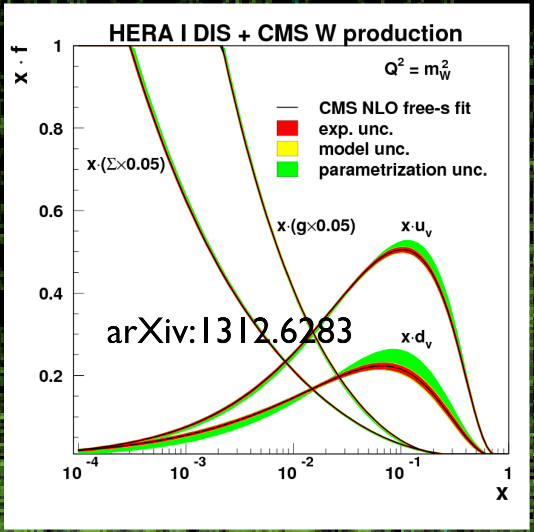
PDFs



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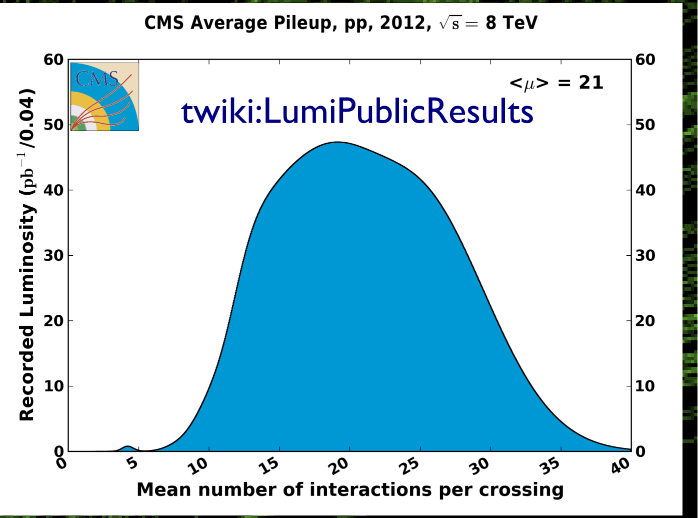

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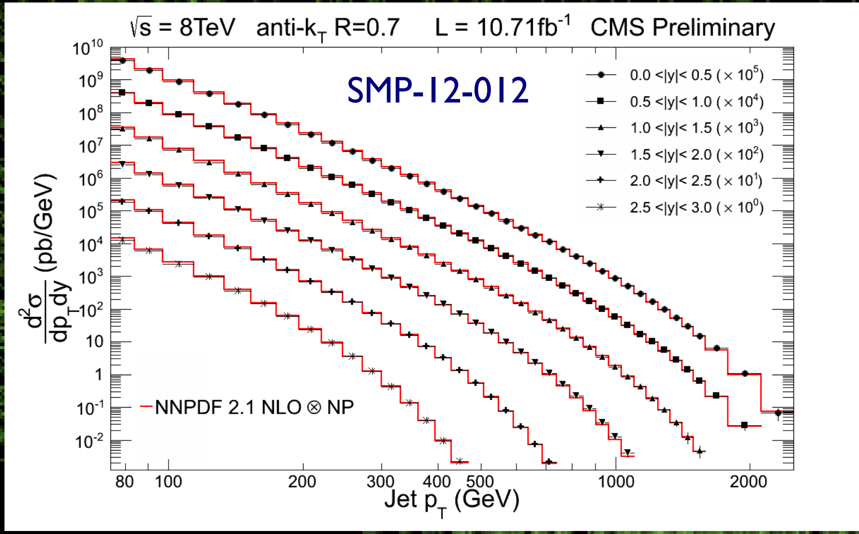
α_s-induced processes dominate



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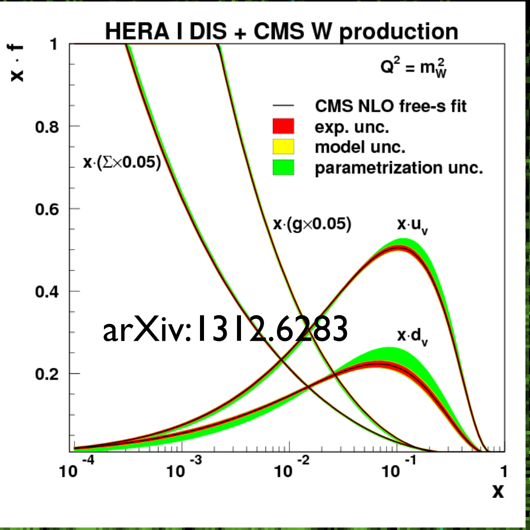

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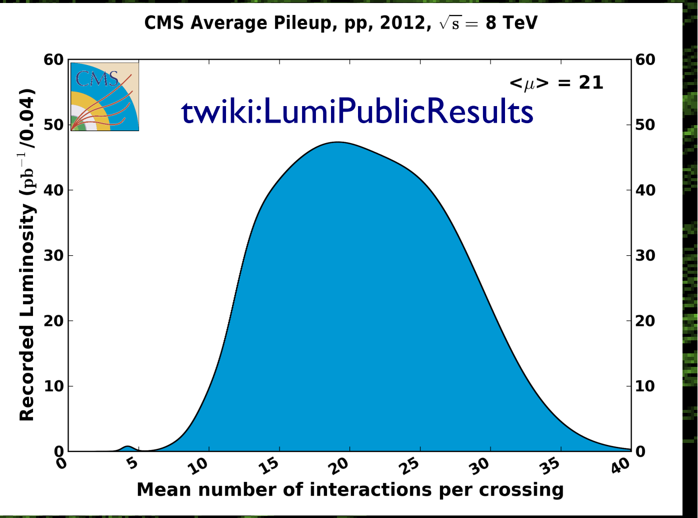

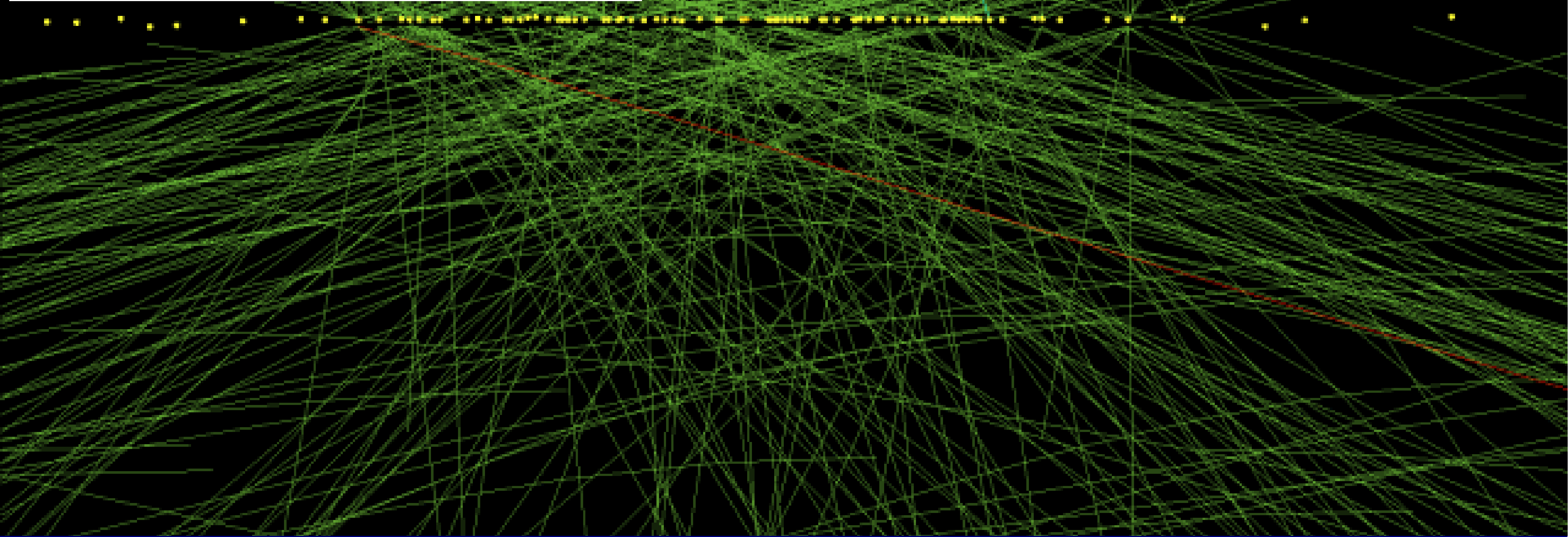

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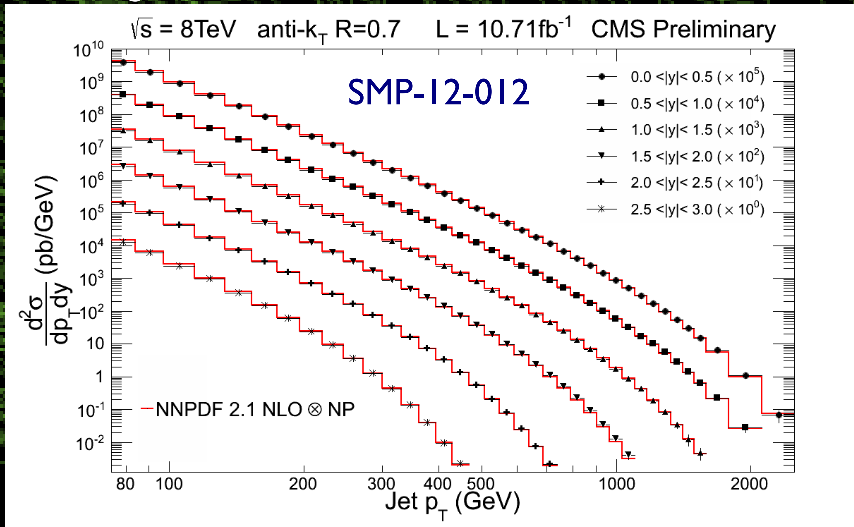

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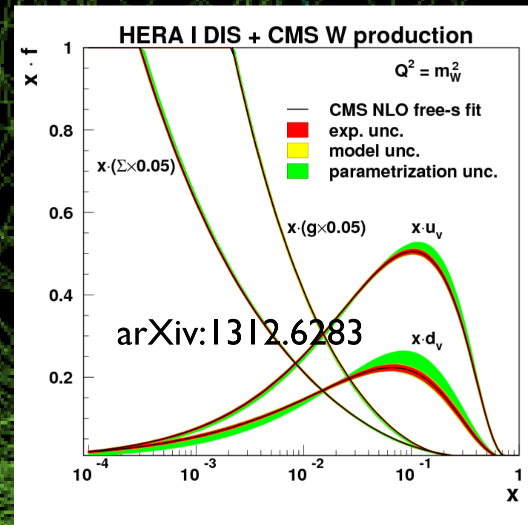

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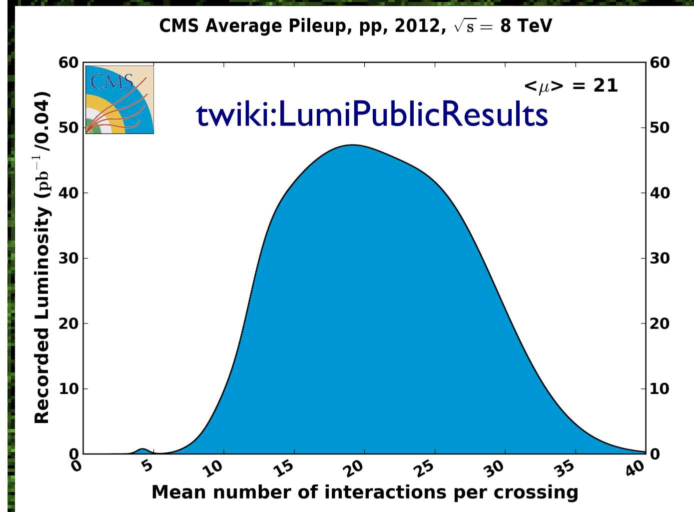
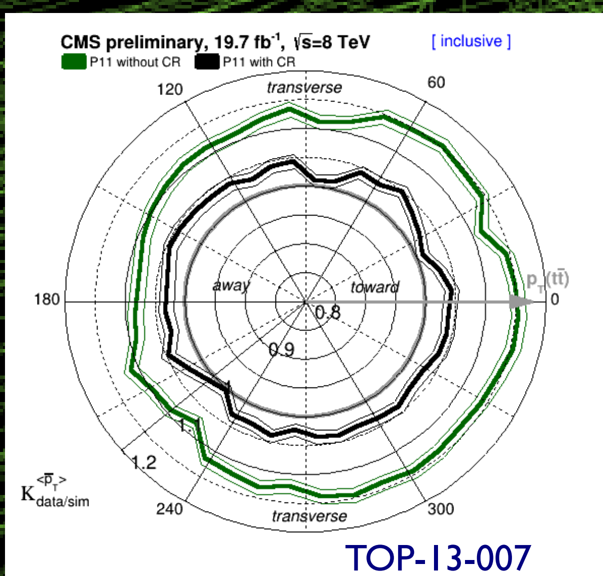


Interplay with underlying event, e.g. colour reconnection



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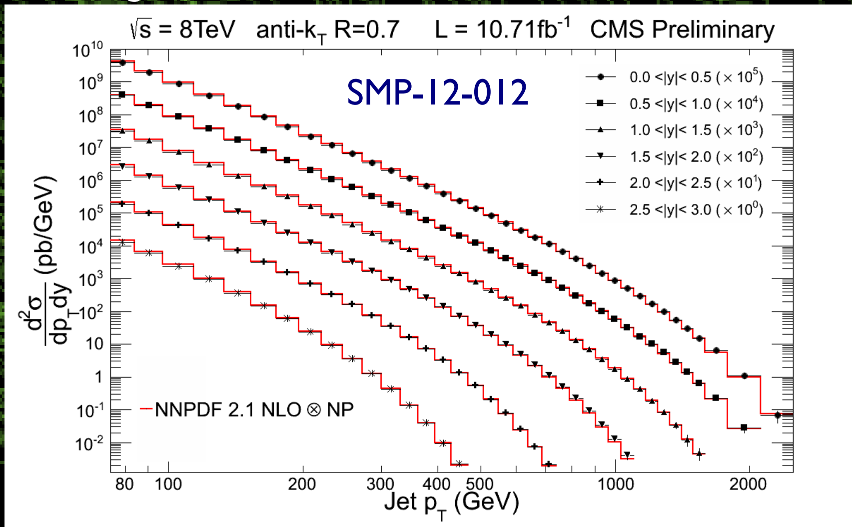

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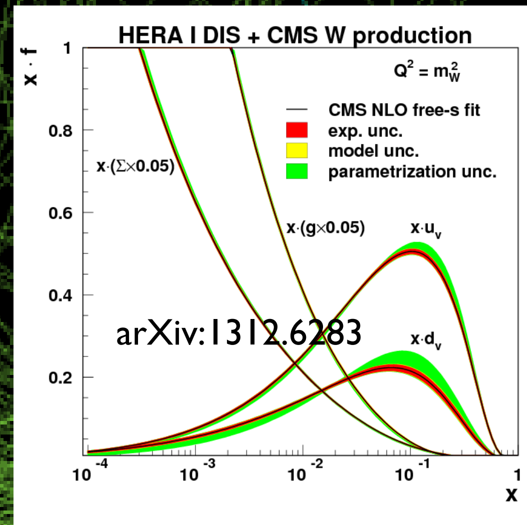

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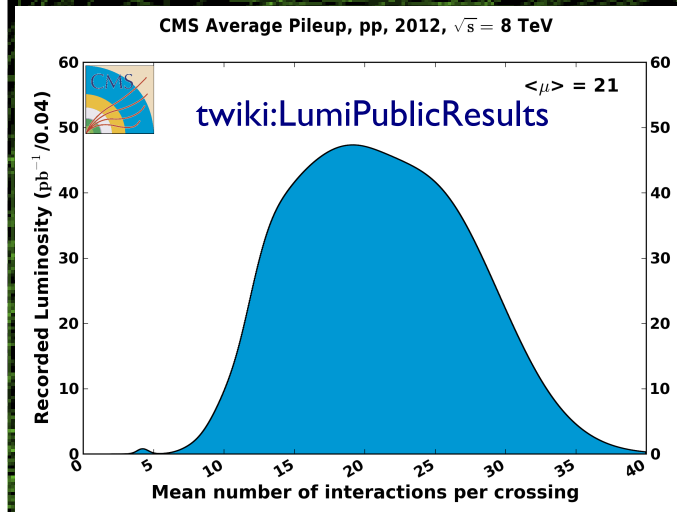
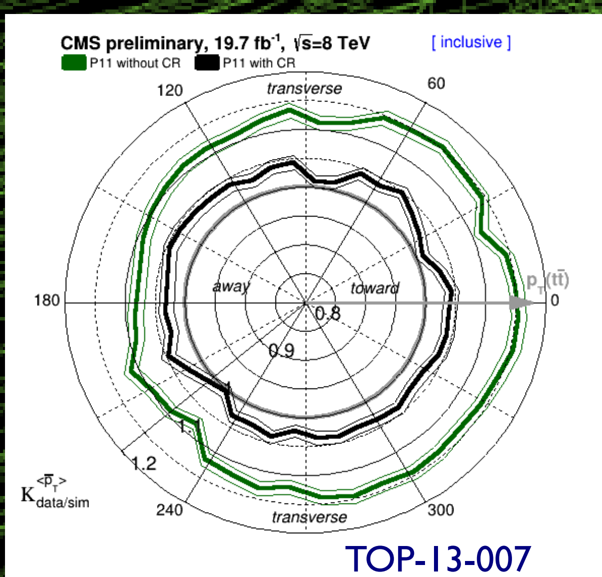
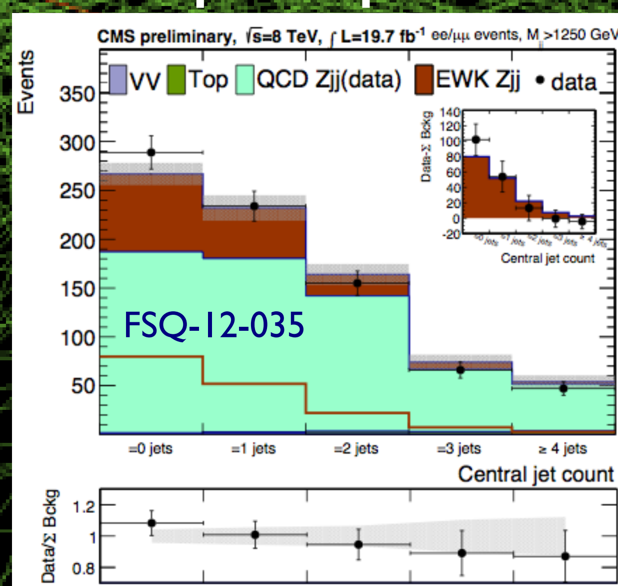


Interplay with underlying event, e.g. colour reconstruction



Large backgrounds hard to model in phase-space corners



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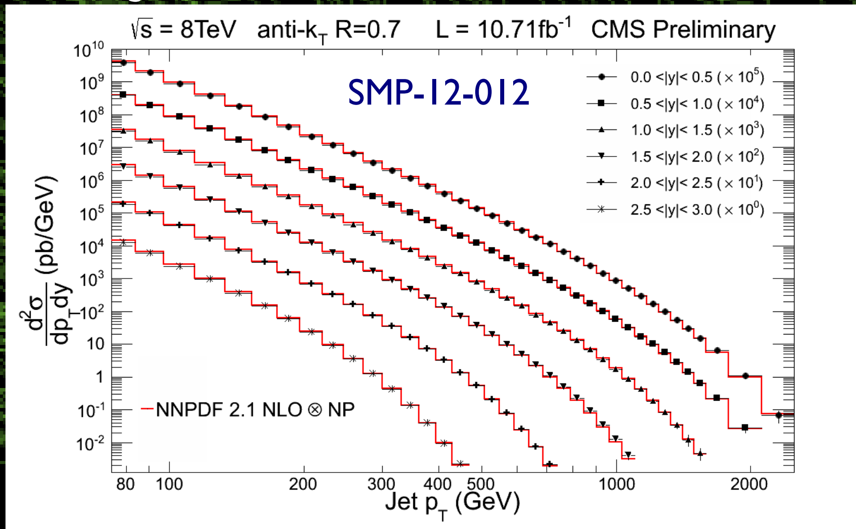

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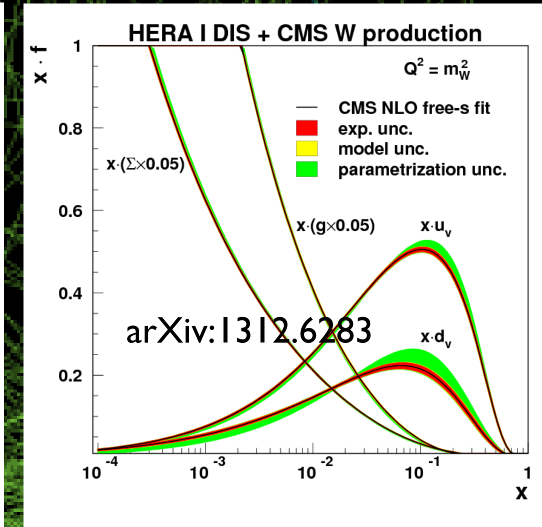

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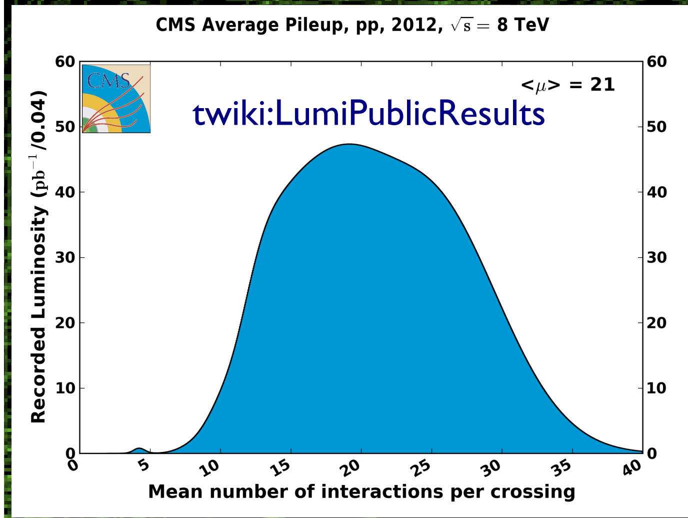

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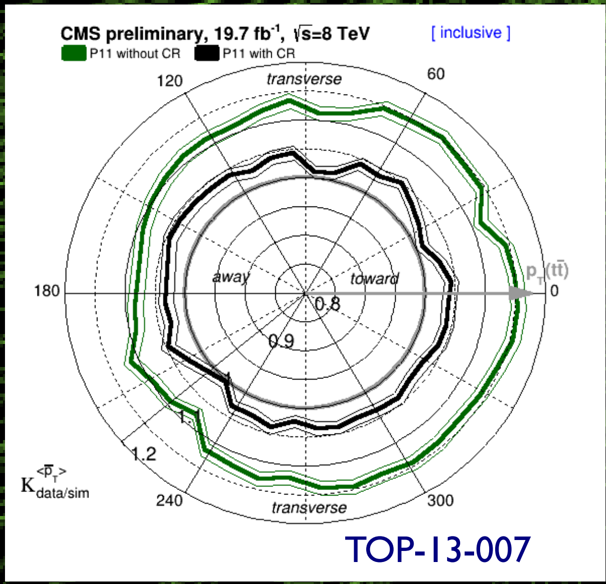

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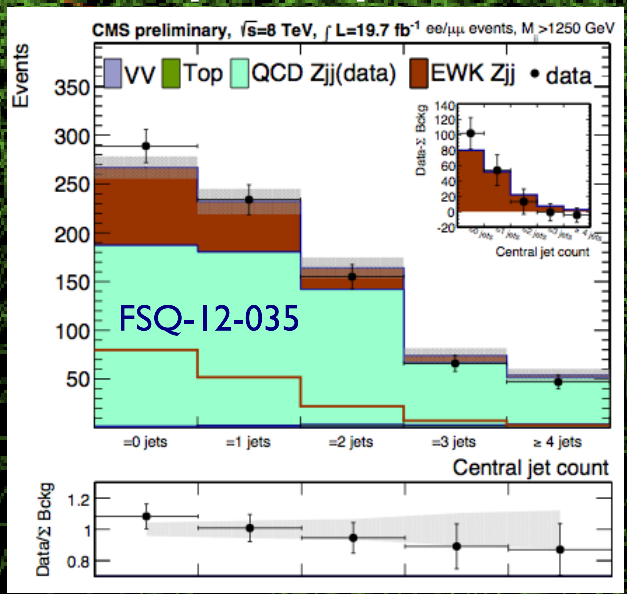
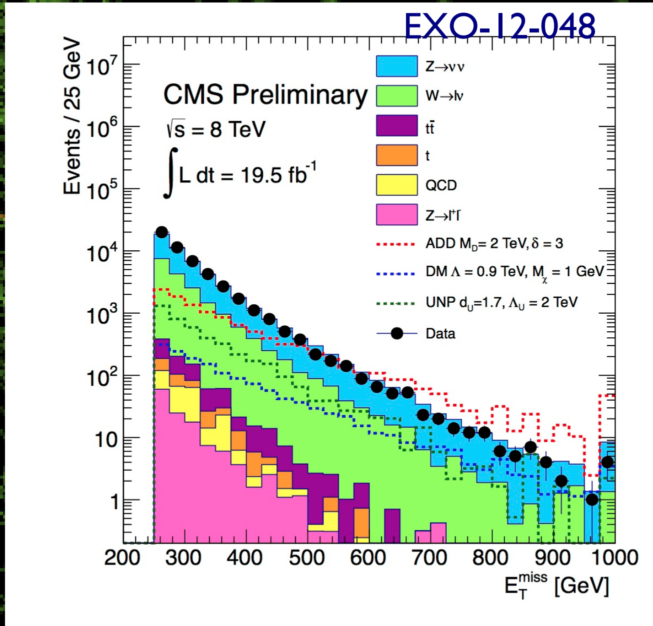
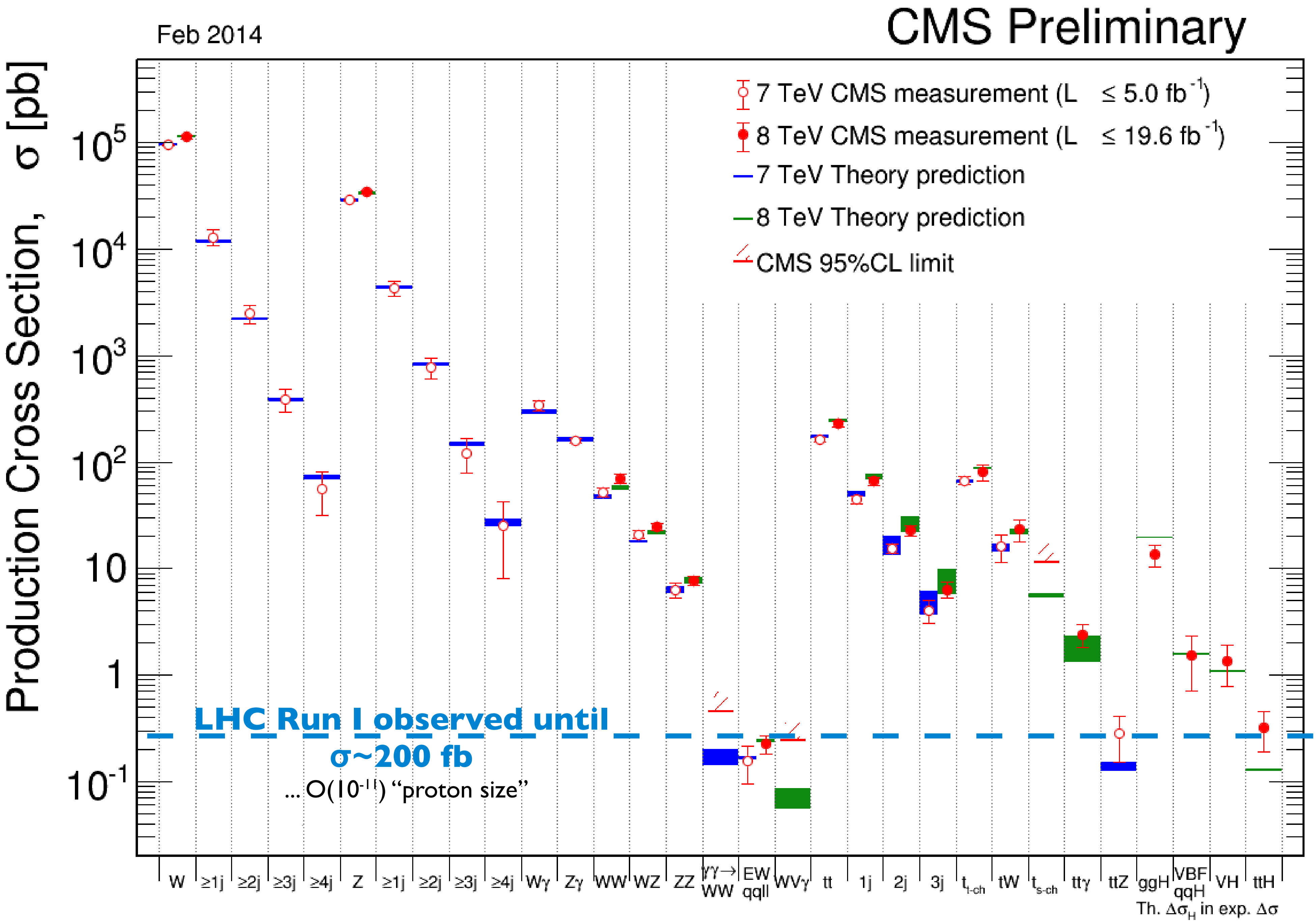


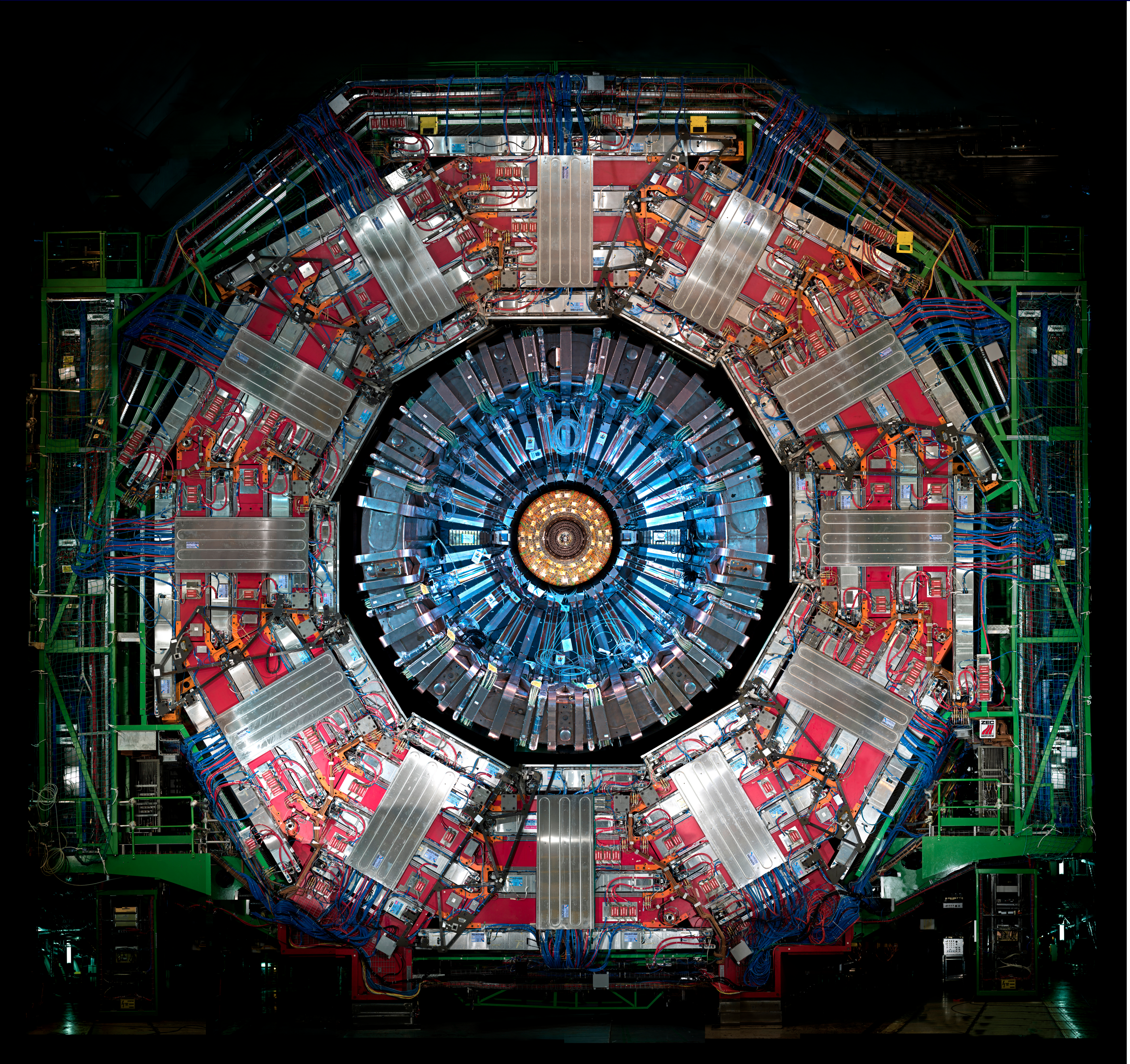
Missing transverse energy



… the theoretical description of high-Q^2 processes is very good …



… and the detectors have outstanding performance



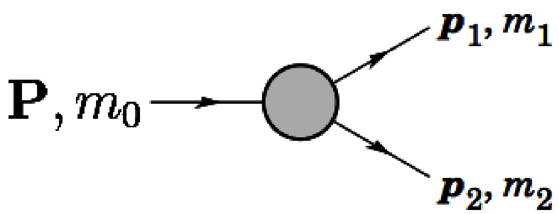
CMS detector, 2008 JINST 3 S08004

CMS detector

- **Matching the excellent performance of the LHC**
- Sub-detector efficiencies from 97.1%-99.9% at/or with better than design performance
- Coping successfully with the pileup challenge in all fronts: trigger, DAQ, computing, reconstruction

The case for the width of a resonance

- **Mass of unstable particles is observed with a spread**
  - direct consequence of **Heisenberg's principle**



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

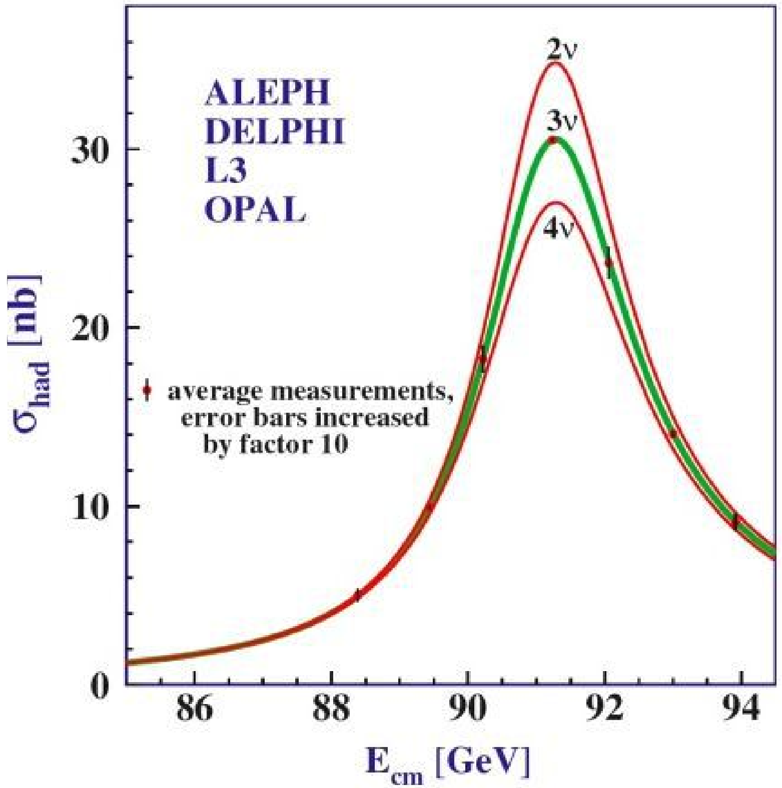
  - **width (Γ)** quantifies intrinsic mass resolution : distance at half-maximum = 1 / lifetime

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

- Knowing the **interactions** involved we predict Γ

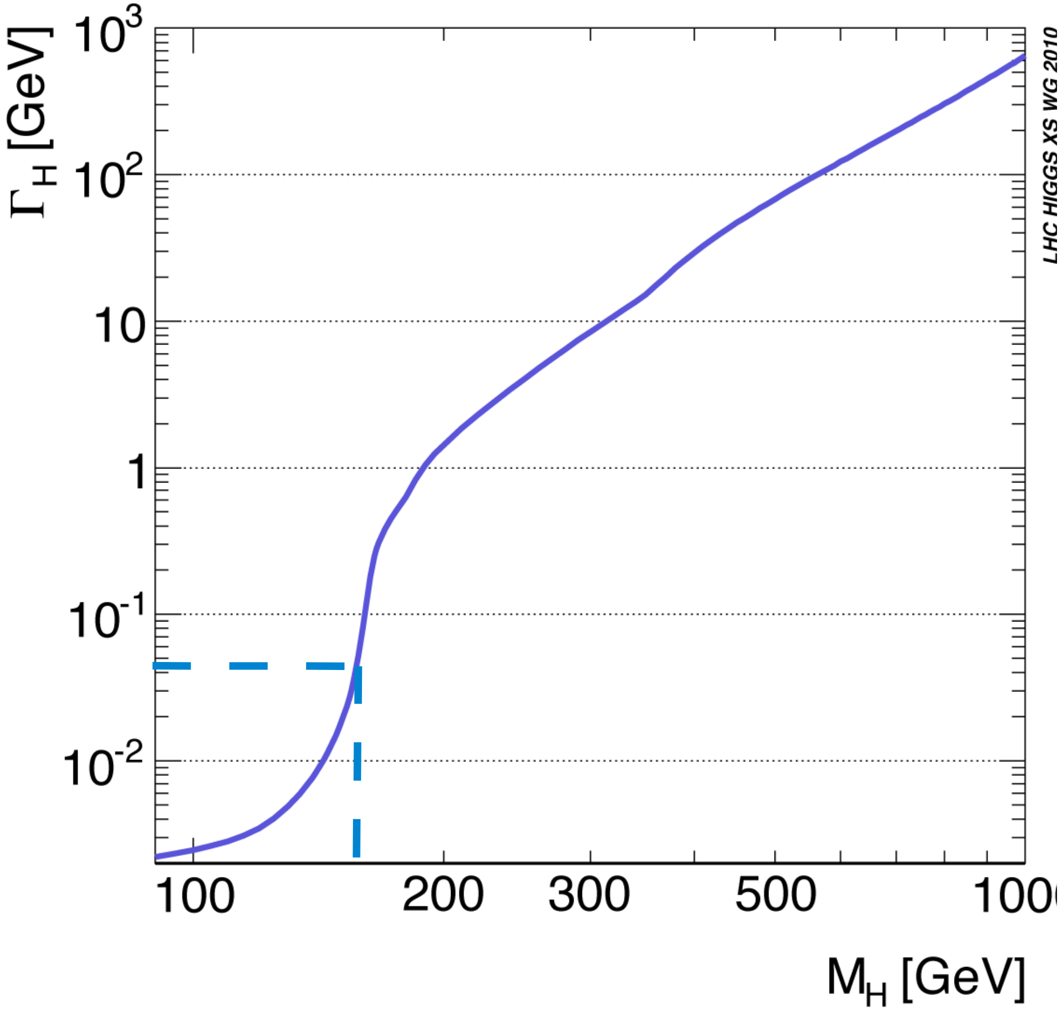
$$d\Gamma = \frac{(2\pi)^4}{2m_0}|\mathcal{M}|^2 d\Phi_n(P \to \sum_{i=1}^{n} p_i)$$

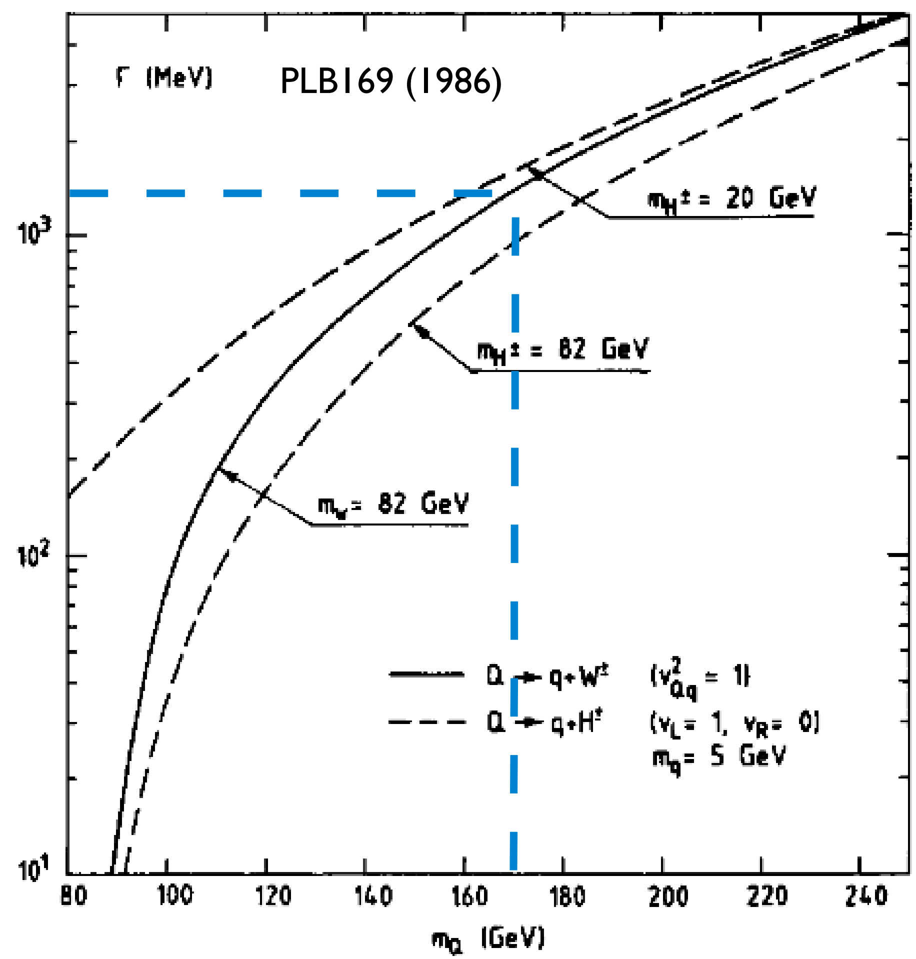
Measuring Γ directly tests the (in)completion of a theory ▸



Lineshape-based width measurements

- **Hard to measure from mass lineshape: limited by detector resolution**
  - **Higgs boson** Γ_{SM}(m=125 GeV)=4.15 MeV
  - **Top quark** Γ_{SM}(m=173.3 GeV)=1.35 GeV





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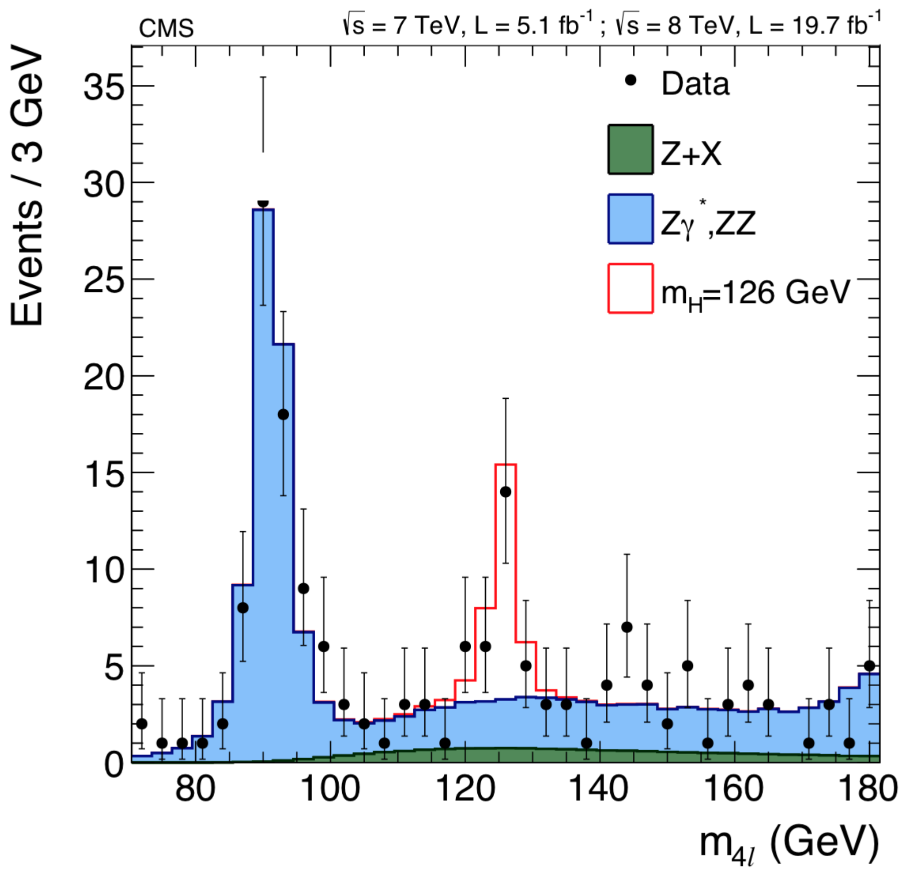

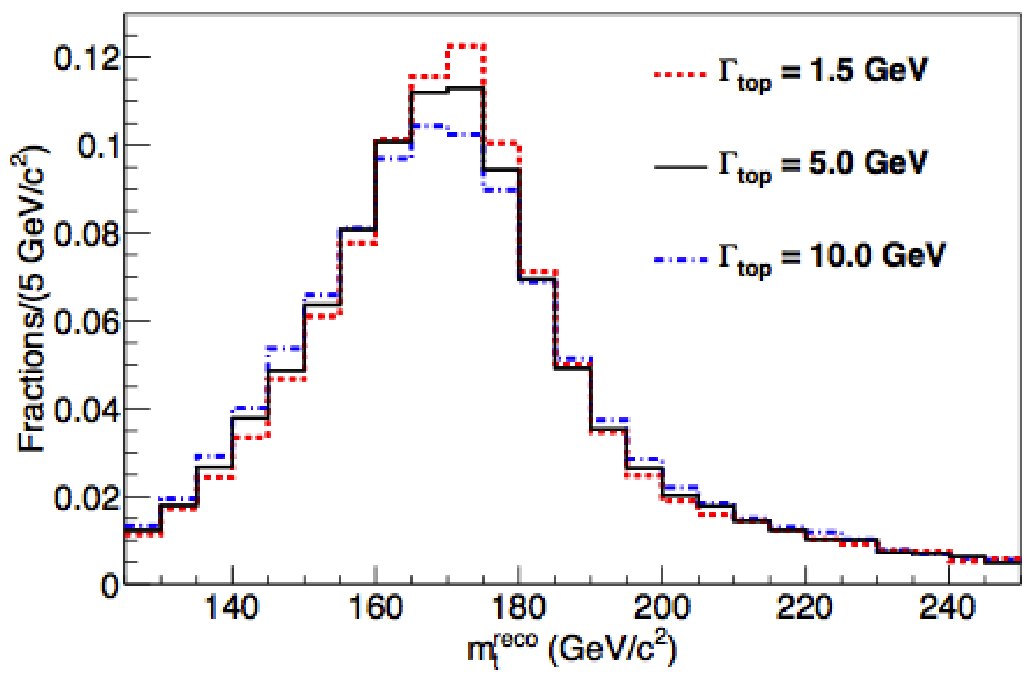

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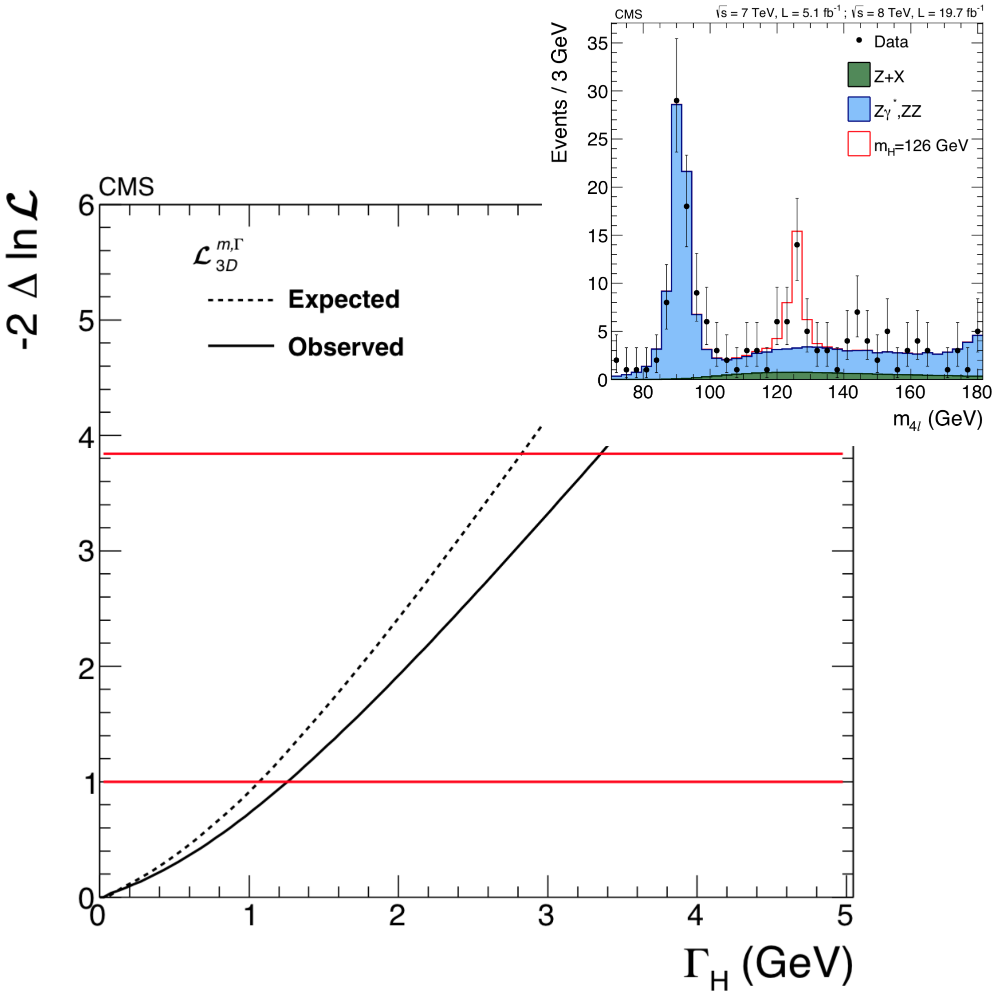
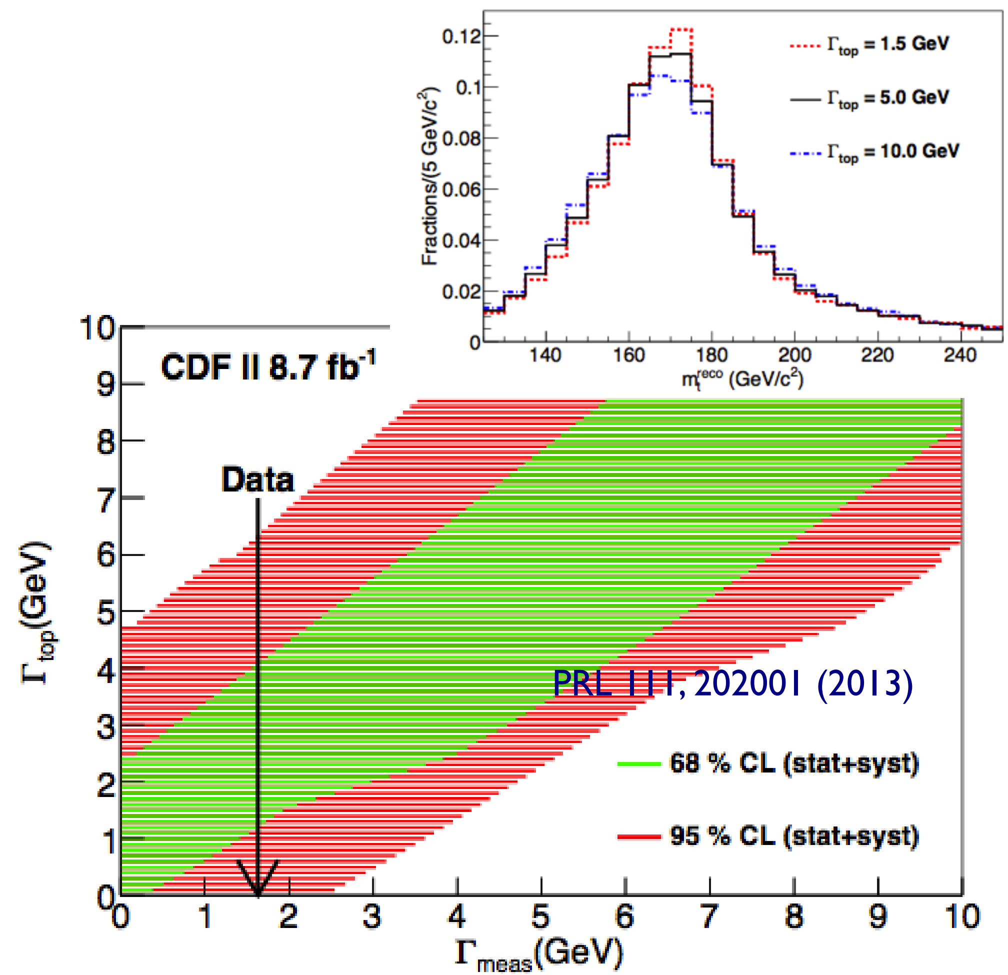
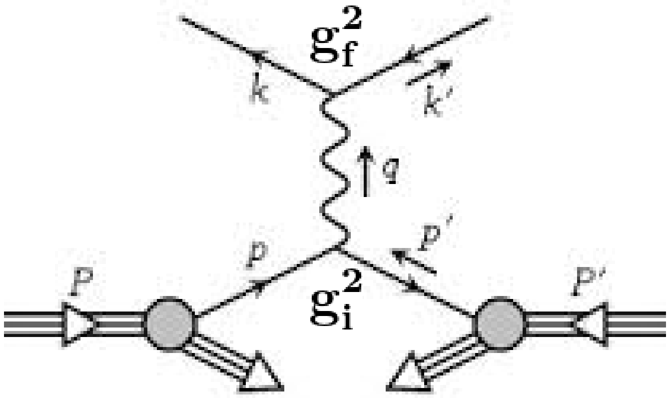
  - From 4l (γγ) mass: Γ<3.4 (7) GeV @ 95% CL
  - **Top quark** Γ_{SM}(m=173.3 GeV)=1.35 GeV
  - From fit to (bqq'): Γ<6.38 GeV @ 95% CL





Rate-based width measurements

- **There is no such thing as a promptly produced Higgs, top,** Z,W, …
  - what happens between the initial and final state is protected by the Heisenberg principle
- **Cross section depends on the propagator and** on the **couplings** of a particle



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

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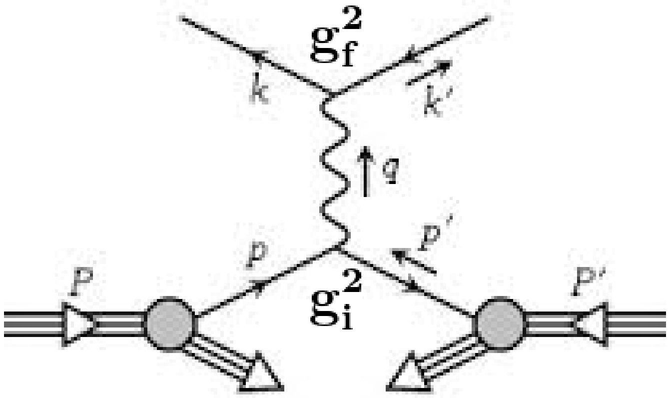
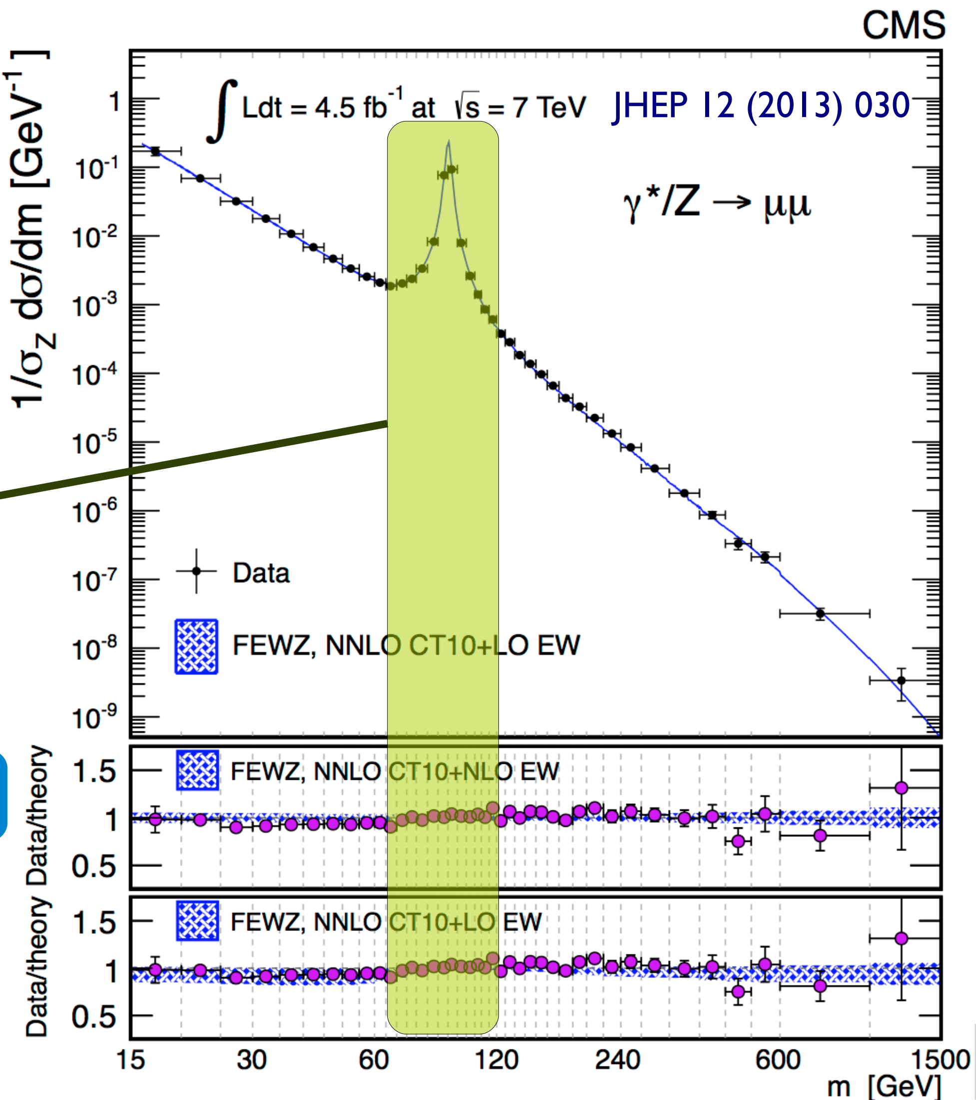


$$\sigma_{\mathrm{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$



- **Measure independently couplings and σ**
  - e.g. C.P. Yuan, Phys. Rev. D 41, 42 (1990)
  - Note: in practice measure BR's, not couplings

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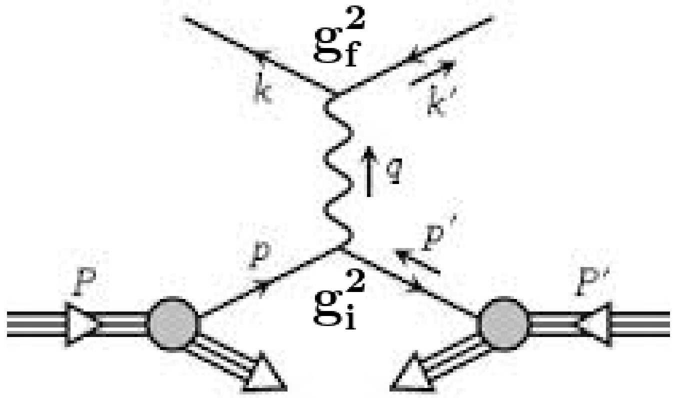
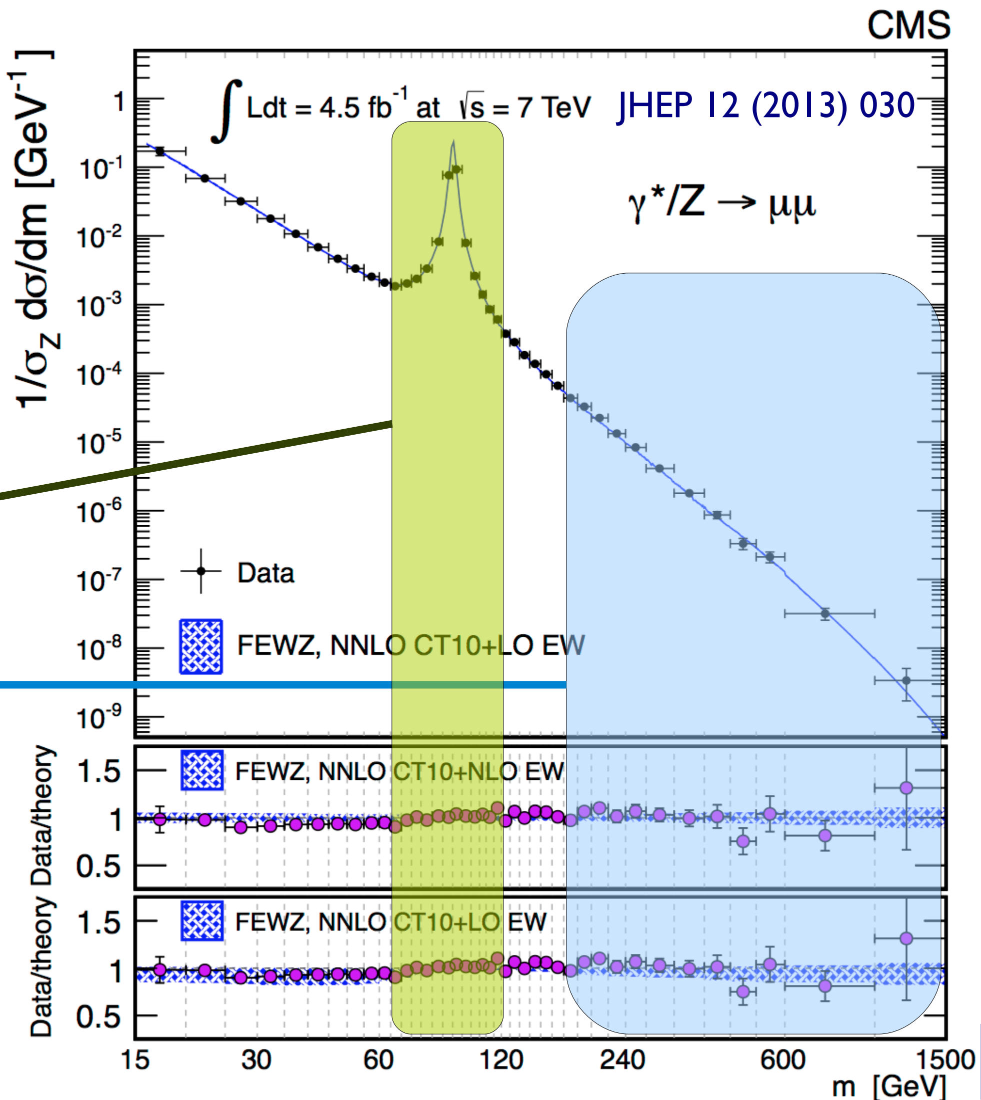


$$\sigma_{\mathrm{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$

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



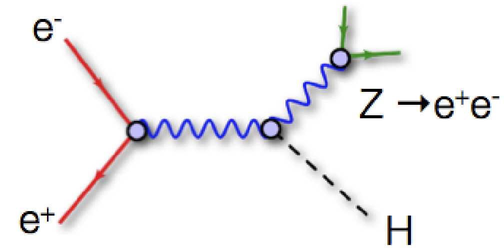
- **Measure** $\frac{\sigma_{\mathrm{off-shell}}}{\sigma_{\mathrm{on-shell}}} \propto \Gamma$

e.g. Caola, Melnikov PRD 88 (2013) 054

Prospects for Γ_H at lepton colliders

- **e^+e^- colliders:** ZH events can be tagged from the recoil mass ►
  - measure $\sigma(ZH)$ and combine with $BR(H \to ZZ)$ to determine width

    (similar to method described in slide 12)
  - potentially reach 1% uncertainty at FCC-ee/TLEP

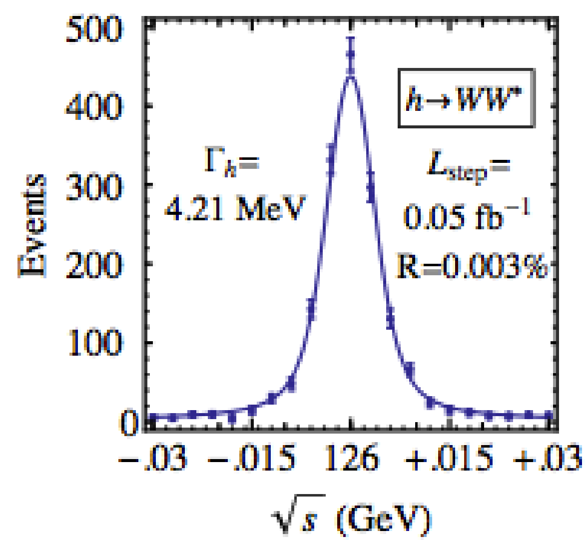


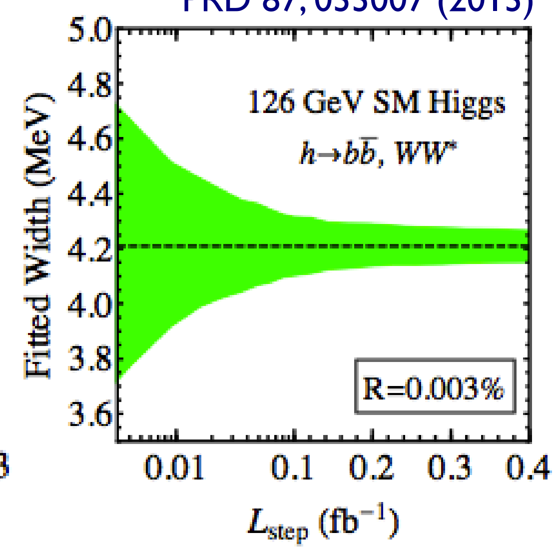
arXiv:1310.8361

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	(−0.8, +0.3)	(−0.8, +0.3)	(−0.8, +0.2)	(same)	(0, 0)	(0, 0)	(0, 0)	(−0.8, 0)	(−0.8, 0)
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%

- **$\mu^+\mu^-$ colliders:** H threshold scan ►
  - High resolution in c.o.m energy
  - Large s-channel production of H (m_μ/m_e>>1)
  - ~3% uncertainty on the width

PRD 87, 033007 (2013)

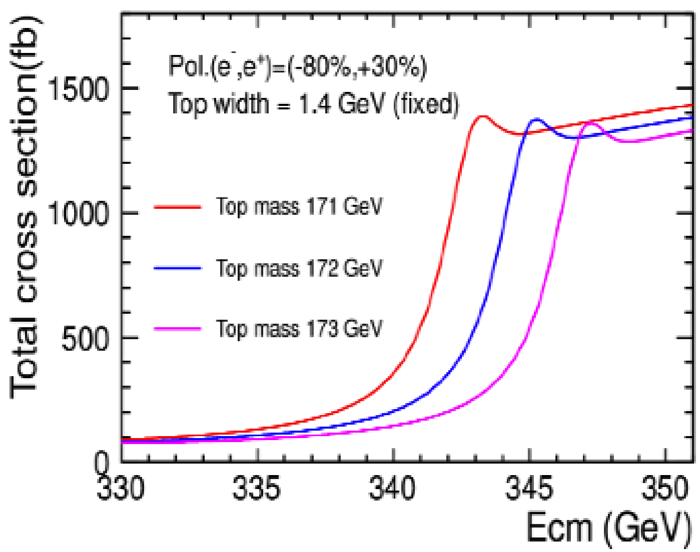


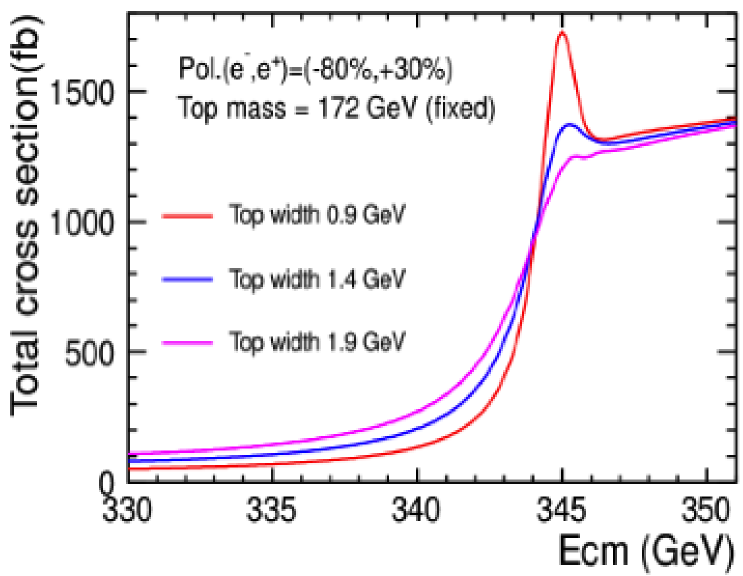


Prospects for Γ_t at the ILC e^+e^- collider

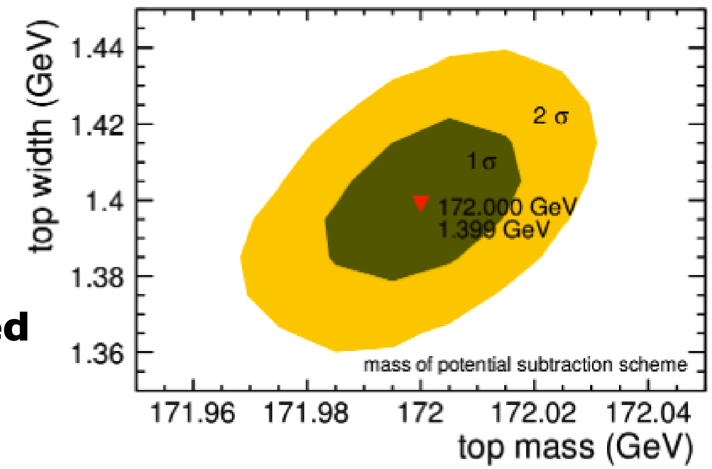
- **Threshold scan** can be performed and used to **extract different parameters**

$$\sigma_{t\bar{t}} = f(\sqrt{s}, m_t, \Gamma_t, \alpha_S, m_H)$$





- From arXiv:1310.0563
  - 16 MeV stat. uncertainty on mass
  - **21 MeV stat. uncertainty on width**
  - **~100 MeV syst. uncertainty expected**



Measuring the top quark width at the LHC

Using a sample of tt dilepton events **we measure $R=B(t\rightarrow Wb)/\Sigma B(t \rightarrow Wq)$**.

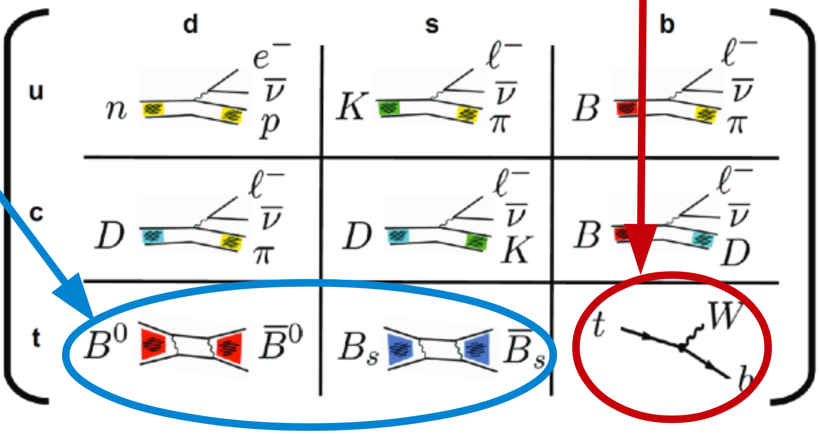
The result is **combined with a single-top-quark cross section** to **derive Γ_t**.

A lower limit on the CKM matrix element $|V_{tb}|>0.975$ is also derived, at 95%CL.

The **results** presented are **detailed in arXiv:1404.2292** *(sub. to PLB)*

Top decays

- The **top is the only quark decaying directly through an EWK interaction**
  - charged currents involving the top are dominated by $|V_{tb}| = 0.999152^{+0.000030}_{-0.000045}$
  - $|V_{td}|/|V_{ts}| = 0.211 \pm 0.006$ precisely known



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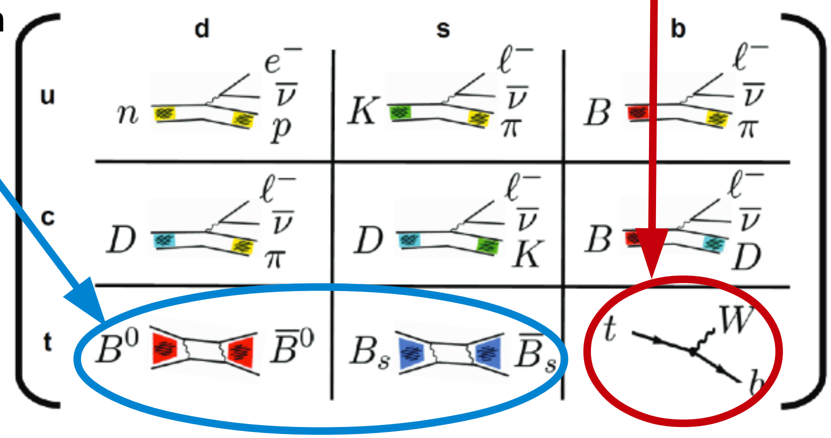
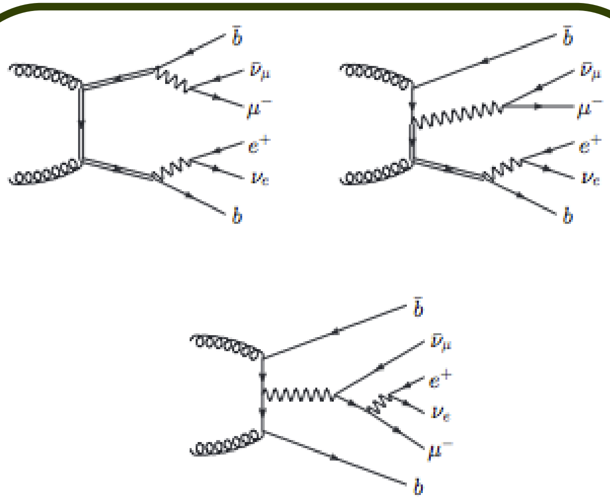
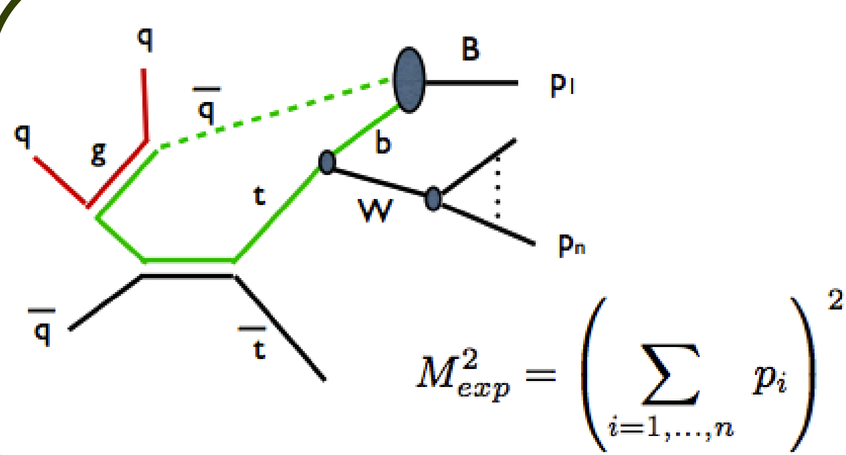


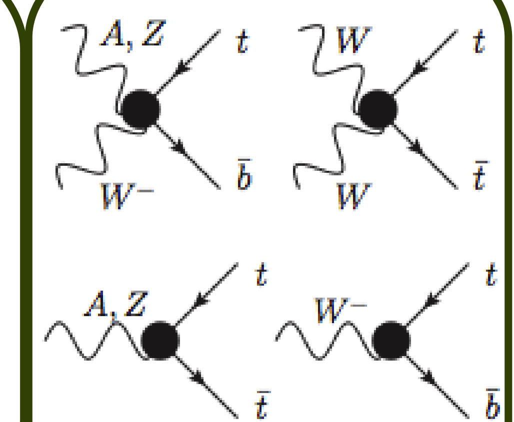
- But...is this all there is to know on **how does the top disintegrate?**
  - **what's the total width of this particle?**
  - how does it relate with its mass?
  - how is its production dynamics related with its decay products?
  - can we unambiguously reconstruct a top quark from its decay products?



arXiv:1311.4893 arXiv:1305.7088



M. Mangano @ TOPLHCWG



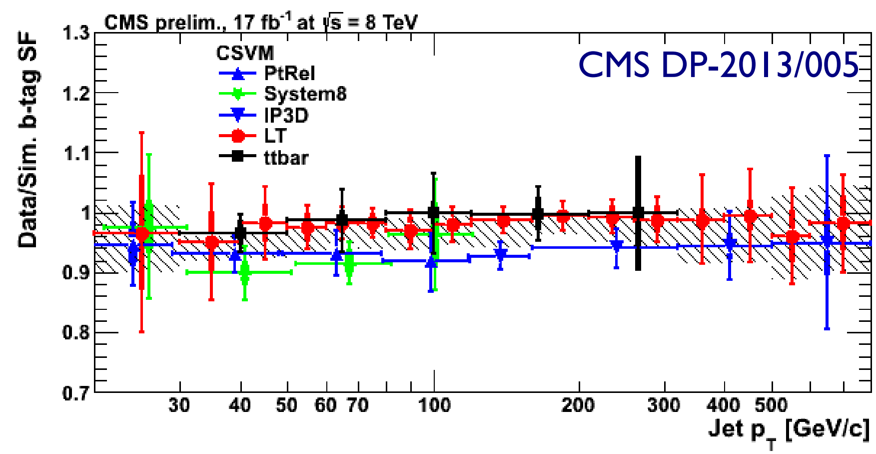
arXiv:1302.1101

Measuring the tWb coupling strength

- **Counting single top quarks: the signal strength is measures V_{tb} directly**
  - t-channel is easily accessible at the LHC σ(8 TeV)=87.1 pb
  - given $\sigma(pp \to tj) \propto |V_{\rm tb}|^2 \sigma_{\rm b}^{\rm t-ch} \to \frac{\Delta V_{\rm tb}}{V_{\rm tb}} = \frac{1}{2}\left(\frac{\Delta\sigma^{\rm meas}}{\sigma^{\rm meas}} \oplus \frac{\Delta\sigma^{\rm th}}{\sigma^{\rm th}}\right)$
  - for an experimental uncertainty ~9% and theory uncertainty ~3% (approx. NNLO) → **ΔV_{tb}~4-5%**

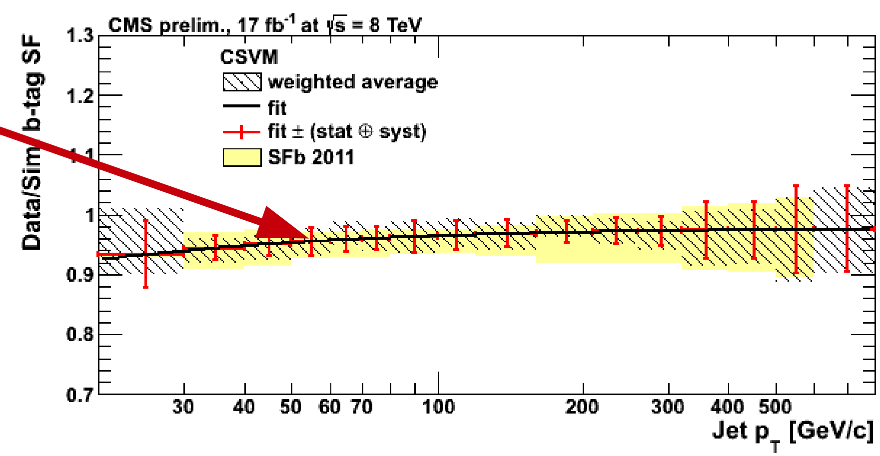
Measuring the tWb coupling strength

- **Counting single top quarks: the signal strength is measures V_{tb} directly**
  - t-channel is easily accessible at the LHC σ(8 TeV)=87.1 pb
  - given $\sigma(pp \rightarrow tj) \propto |V_{\mathrm{tb}}|^2 \sigma_{\mathrm{b}}^{\mathrm{t-ch}} \rightarrow \frac{\Delta V_{\mathrm{tb}}}{V_{\mathrm{tb}}} = \frac{1}{2}\left(\frac{\Delta\sigma^{\mathrm{meas}}}{\sigma^{\mathrm{meas}}} \oplus \frac{\Delta\sigma^{\mathrm{th}}}{\sigma^{\mathrm{th}}}\right)$
  - for an experimental uncertainty ~9% and theory uncertainty ~3% (approx. NNLO) → **ΔV_{tb}~4-5%**



- **Counting how often the top decays to a bottom quark**
  - measure R=B(t → Wb) / B(t → Wq)=$|V_{tb}|^2$

    under the assumption of the 3x3 CKM matrix unitarity
  - given $R \propto \varepsilon_{\mathrm{b}} \rightarrow \frac{\Delta V_{\mathrm{tb}}}{V_{\mathrm{tb}}} \propto \frac{1}{2}\frac{\Delta\varepsilon_{\mathrm{b}}}{\varepsilon_{\mathrm{b}}}$
  - for an experimental uncertainty ~2% on b-tagging → **ΔV_{tb}~1%**

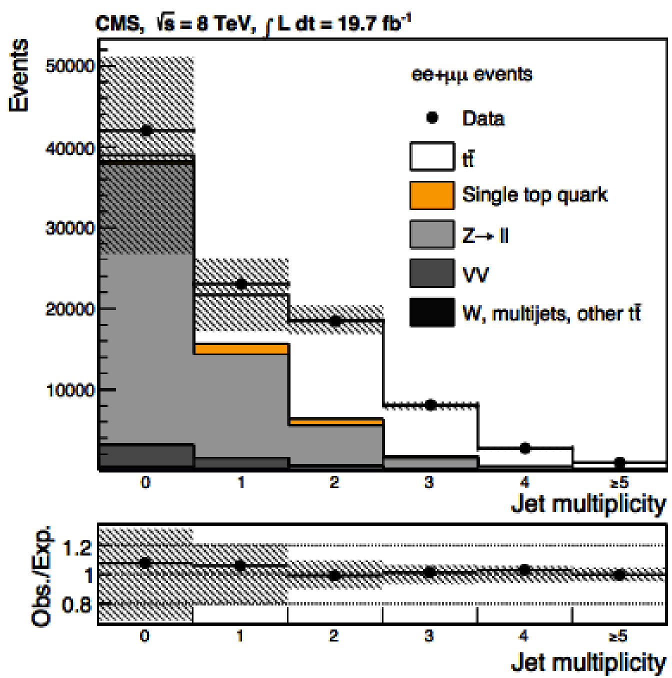


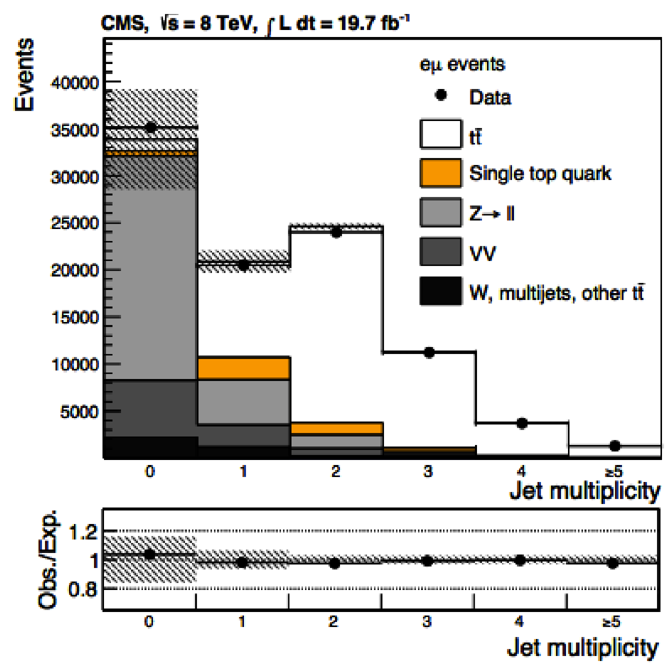
Both cases are complementary and open different windows for NP contributions

Sample used for the analysis

- **We select dilepton events in data**
  - Lower branching ratio (≈0.065) but cleaner signature (S/S+B≈70-87%)
  - ≥ 2 isolated prompt leptons with op. sign + ≥ 2 jets + E_T^{miss}>40 GeV and Z veto for ee/μμ channels

Source	ee	$\mu\mu$	eμ
$W \to \ell\nu$, multijets, other $t\bar{t}$	134 ± 91	43 ± 10	$(38 \pm 20) \times 10$
VV	292 ± 15	333 ± 16	995 ± 39
$Z/\gamma^* \to \ell\ell$	$(297 \pm 63) \times 10$	$(374 \pm 79) \times 10$	$(184 \pm 39) \times 10$
Single top quark	526 ± 26	583 ± 26	1834 ± 64
$t\bar{t}$ dileptons (signal)	$(1003 \pm 50) \times 10$	$(1104 \pm 54) \times 10$	$(349 \pm 17) \times 10^2$
Total	$(1395 \pm 81) \times 10$	$(1574 \pm 96) \times 10$	$(400 \pm 17) \times 10^2$
Data	13723	15596	38892





Cross section measurement

- Compare the number of events selected in each jet multiplicity bin with expectations
  - let the **signal strength $\mu=\sigma/\sigma_{th}$** to **float freely**
  - include systematic uncertainties (θ_i) as correction factors (distributed as log-normal – $\rho(\theta_i)$)

$$\mathcal{L}(\mu,\theta) = \prod_k \mathcal{P}\left[N_k, \hat{N}_k(\mu,\theta_i)\right] \cdot \prod_i \rho(\theta_i) \xrightarrow{\text{profile unc.}} \lambda(\mu) = \frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})}$$

- Result is in **agreement with NNLO+NNLL**

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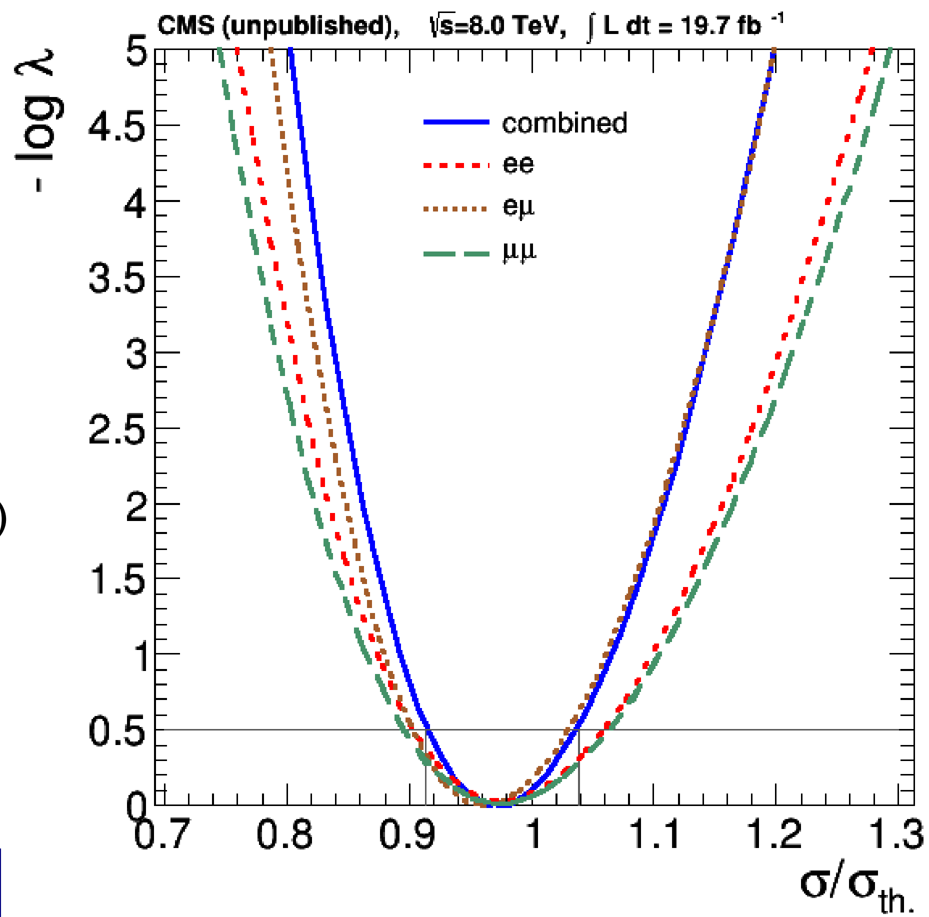
$$\boxed{\sigma(t\bar{t}) = 238 \pm 1\,(\text{stat.}) \pm 15\,(\text{syst.})\,\text{pb}}$$

6% unc

- Main uncertainties:
  - *experimental*: luminosity, selection efficiency
  - *theory*: QCD scales, ISR/FSR model (ME-PS matching)

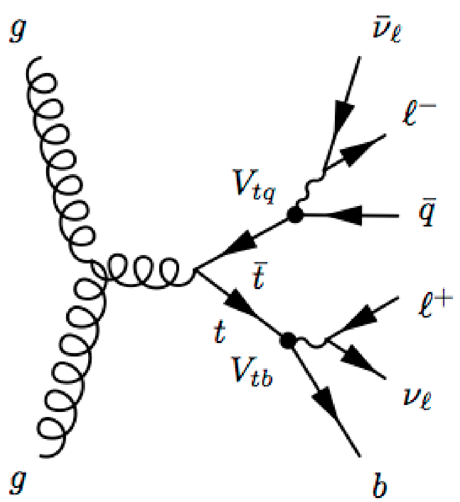


Technique is used to derive the purity of the sample in each event category

The jet misassignment problem

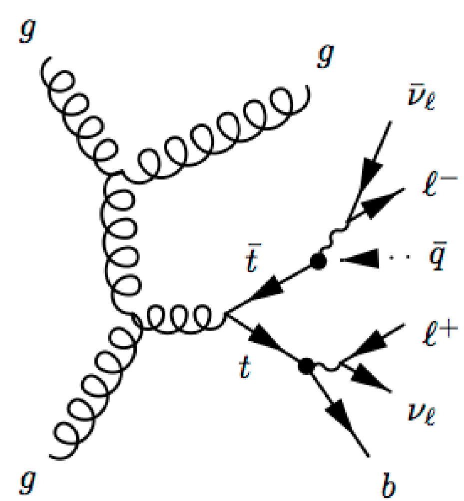
- Although we select a high purity sample, **not all jets come from t → Wq**
    - **ISR/FSR contamination** is non-negligible
    - signal jets are often soft in p_T or fail tracker acceptance
- All the events selected can be **interpreted as a sum of three categories**

Signal-like



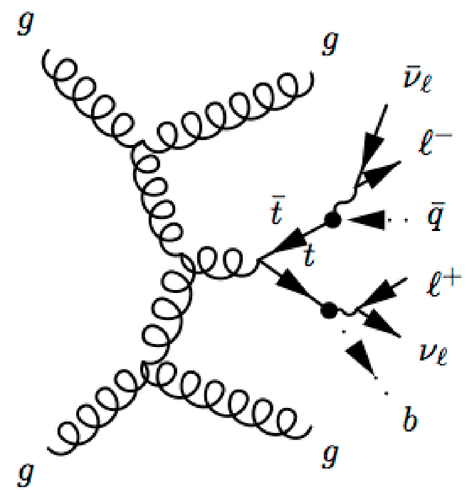
Two t→Wq decays selected

Single-top quark like



One t→Wq decays selected

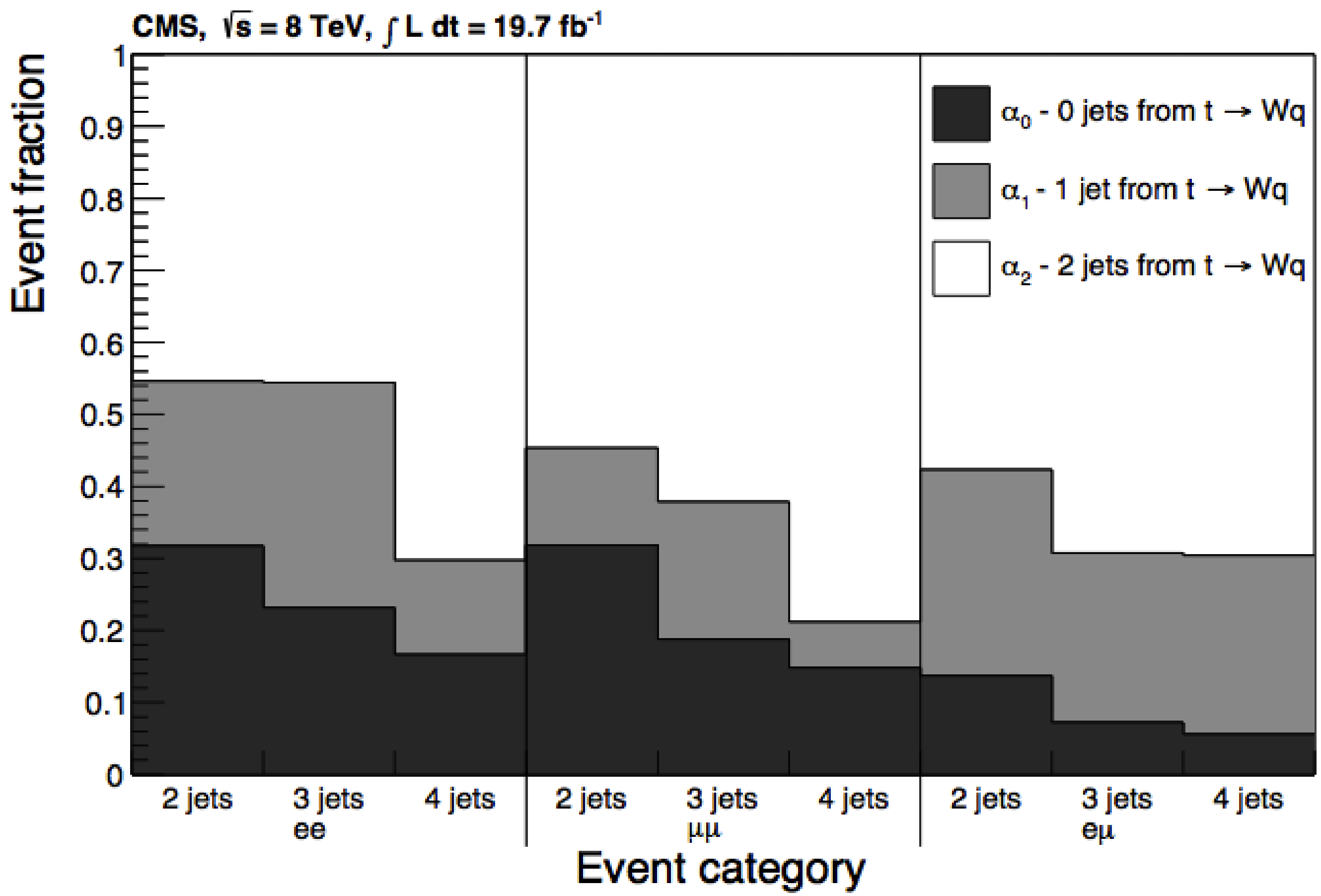
Background-like



No t→Wq decays selected

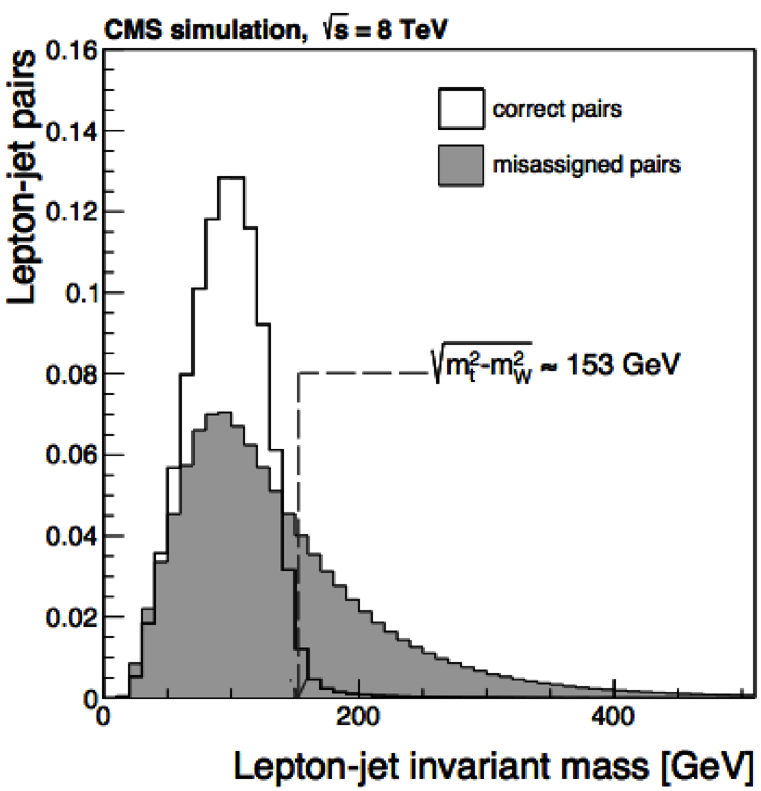
The jet misassignment problem

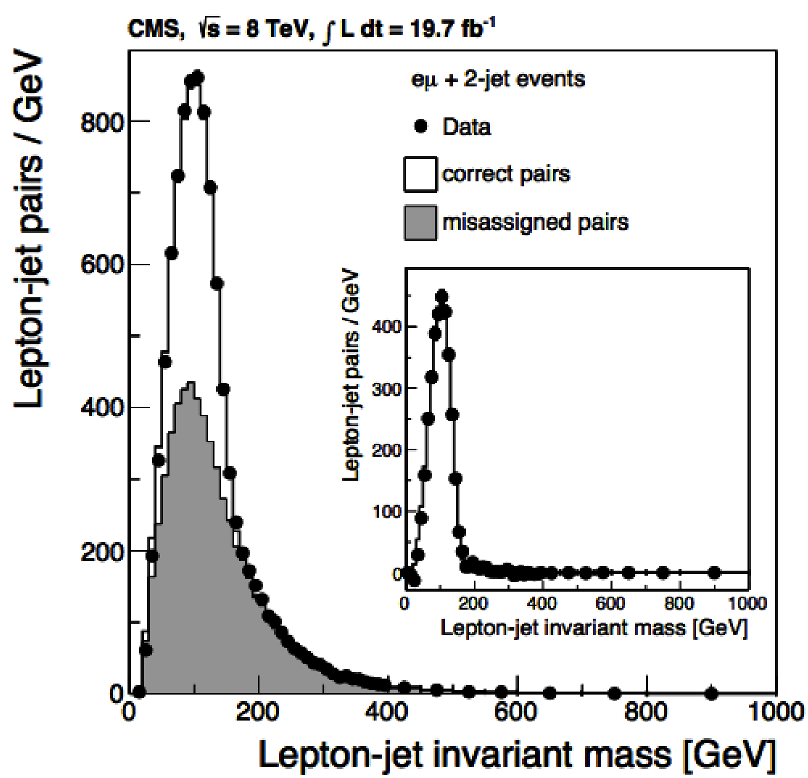
- Although we select a high purity sample, **not all jets come from $t \rightarrow Wq$**
  - **ISR/FSR contamination** is non-negligible
  - signal jets are often soft in p_T or fail tracker acceptance
- All the events selected can be **interpreted as a sum of three categories**



Jet misassignment measurement

- We **consider the lepton-jet invariant mass spectrum**
  - pairs with signal jets have an end-point defined by the top quark mass
  - misassignments can be modeled from data: randomly rotate lepton direction before pairing with jet
- **Fit spectrum** with two components **to extract the fraction of jets from t → Wq**

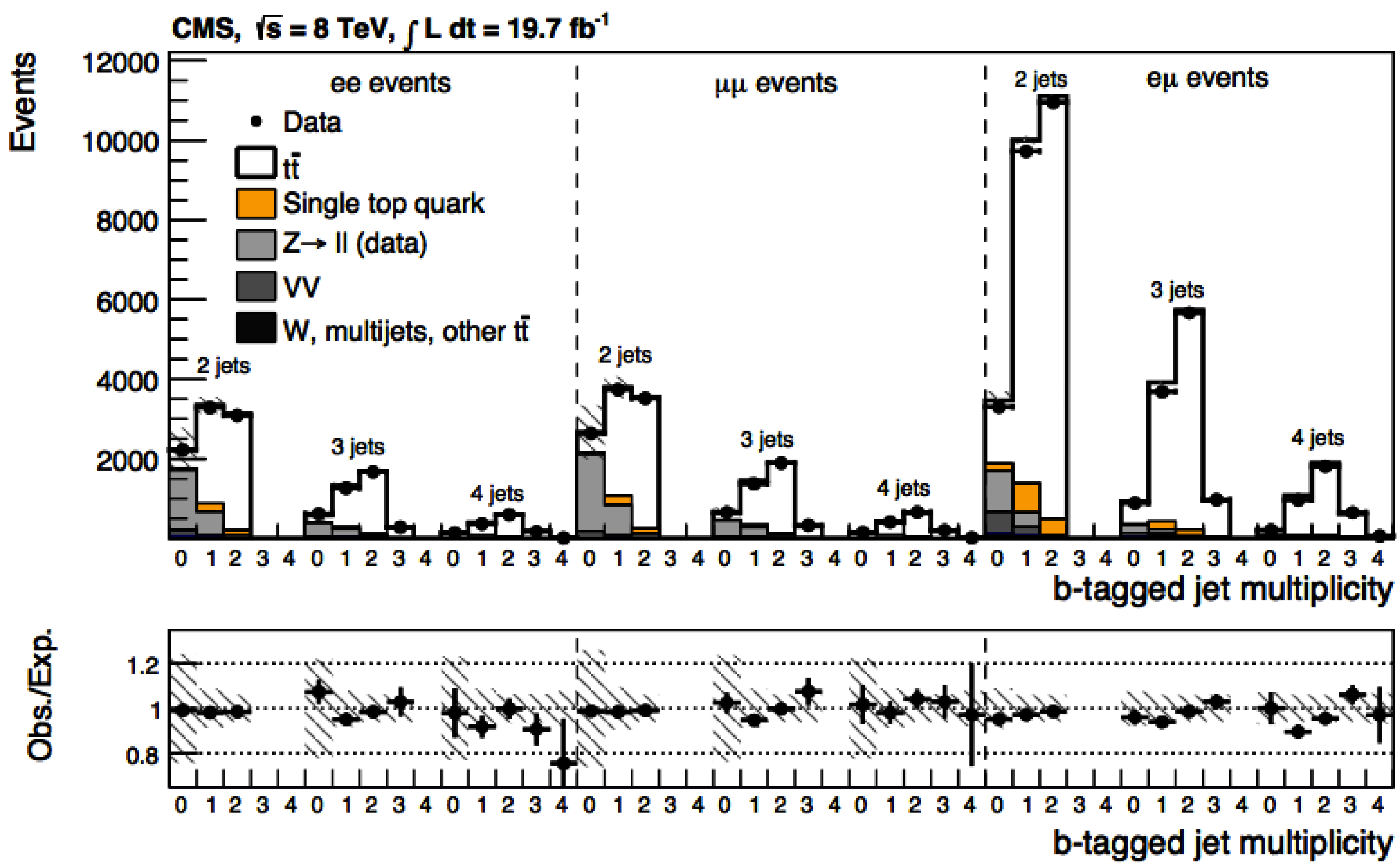




Although measured in data, **expectations from simulation match observations** → good description of ISR/FSR with Madgraph+Pythia6

How many signal jets are from b's?

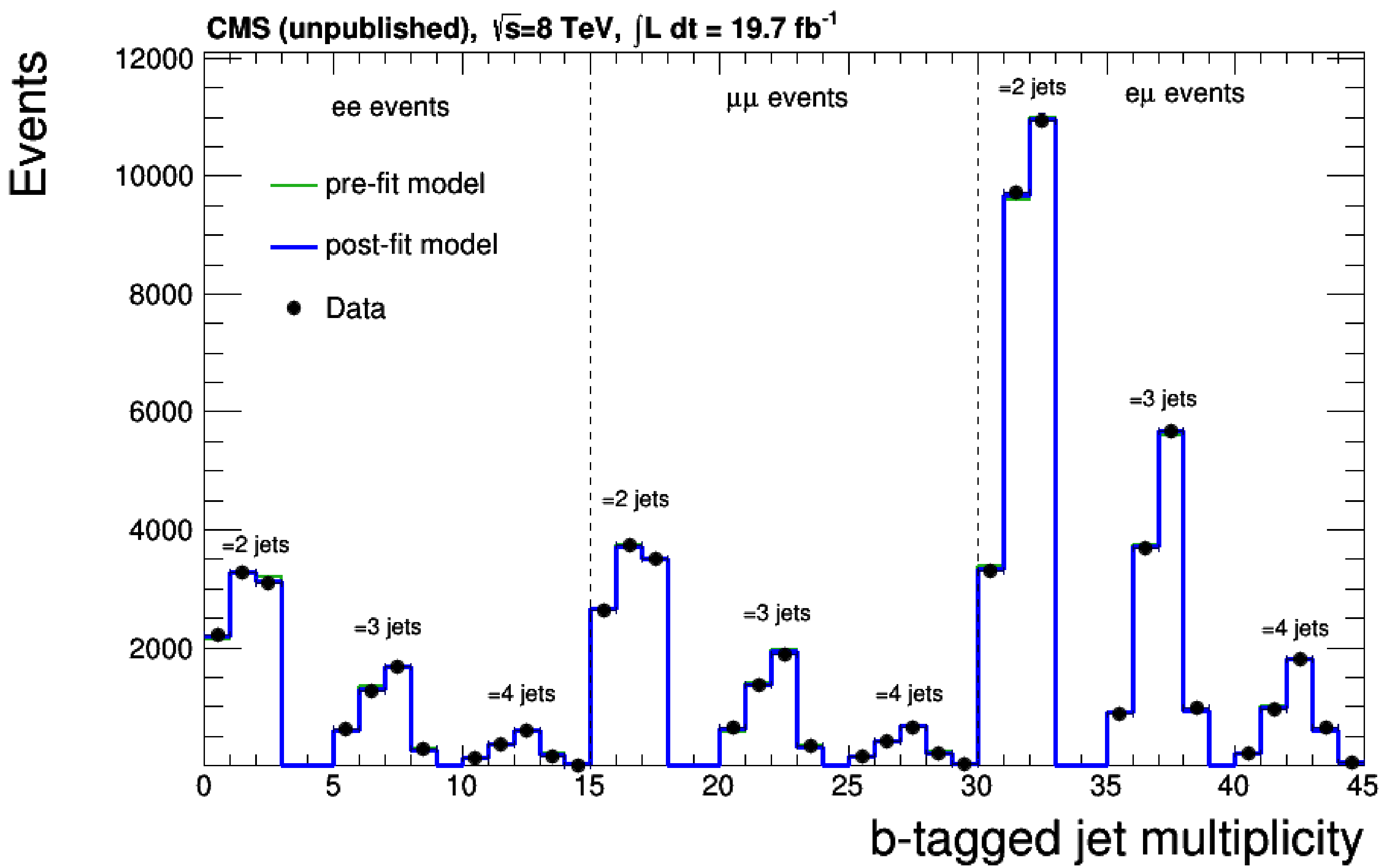
- **Count the number of b-tagged jets** and compare with expectations
- **Data in agreement with simulation+data-based backgrounds expectations**
  - could use simulation based templates for different top decay possibilities
  - but would be limited by SM-like interpretation and by theory related uncertainties



How many signal jets are from b's?

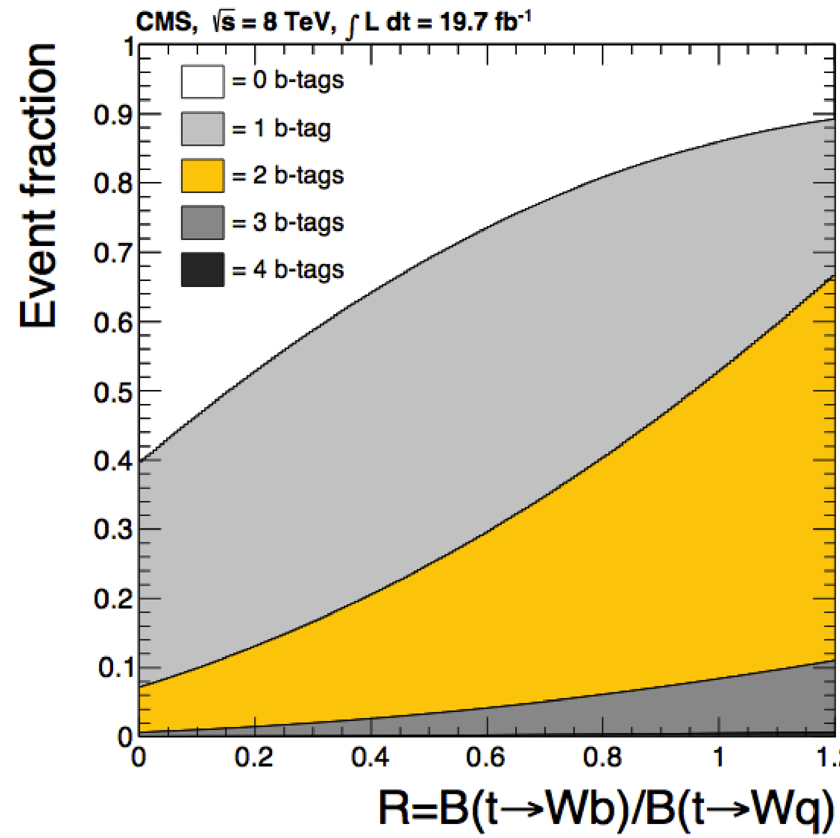
- **Count the number of b-tagged jets** and compare with expectations
- **Parametric model** based on: tt purity, fraction of t → Wq and b-tag/mistag efficiencies
  - e.g. in an event with 2 jets, both from top probability two observe 2 b-tags

$$P_{2j,2t,2d} = \mathcal{R}^2\varepsilon_b^2 + 2\mathcal{R}(1-\mathcal{R})\varepsilon_b\varepsilon_q + (1-\mathcal{R})^2\varepsilon_q^2$$



Measuring R=B(t→Wb)/B(t→Wq)

- The observed b-tagged jet multiplicity is compared with the probability model ▶
- Profile the likelihood containing all the uncertainties on the input parameters:



$$\mathcal{L}(\mathcal{R},\boxed{f_{t\bar{t}},k_{st}},\boxed{f_{\rm correct}},\boxed{\varepsilon_b,\varepsilon_q,\varepsilon_{q}},\theta_i) = \prod_{\ell\ell}\prod_{N_{\rm jets}\geq 2}\prod_{k=0}^{N_{\rm jets}}\mathcal{P}[N_{\rm ev}^{\ell\ell,N_{\rm jets}}(k),\hat{N}_{\rm ev}^{\ell\ell,N_{\rm jets}}(k)]\prod_i \mathcal{G}(\theta_i^0,\theta_i,1).$$

quantity to measure

Purity of the sample

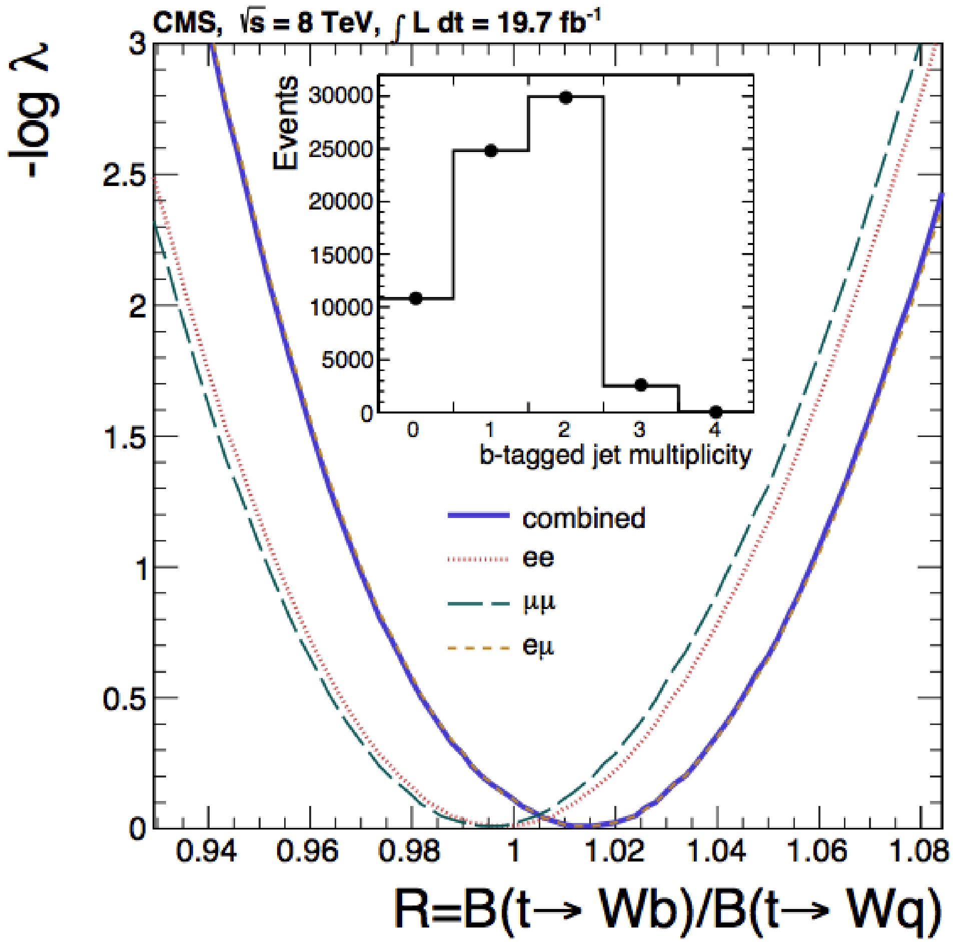
N(t → Wq) reconstructed

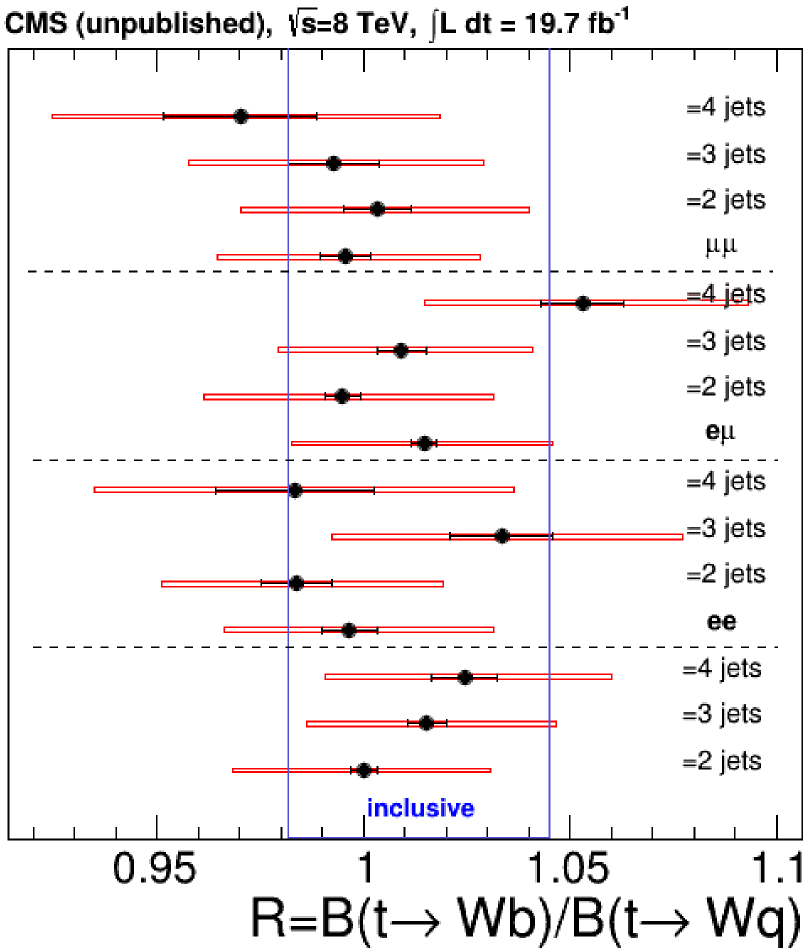
Tagging efficiencies based on dijet measurements

Uncertainties

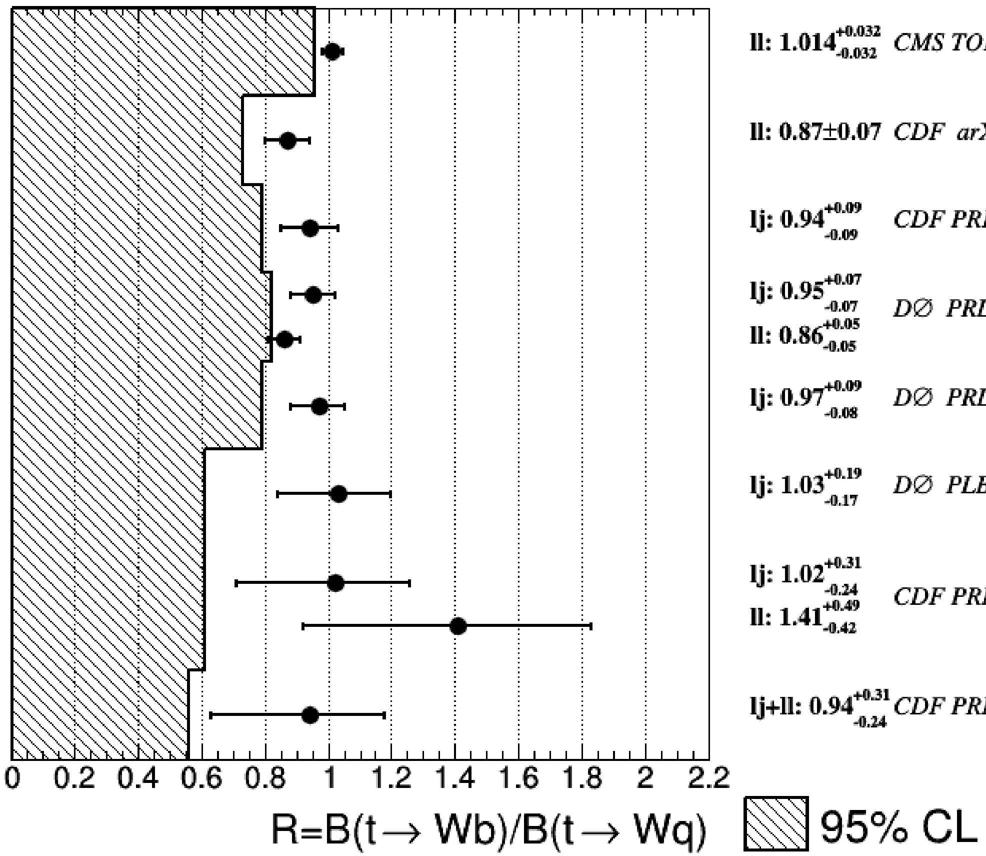
Result

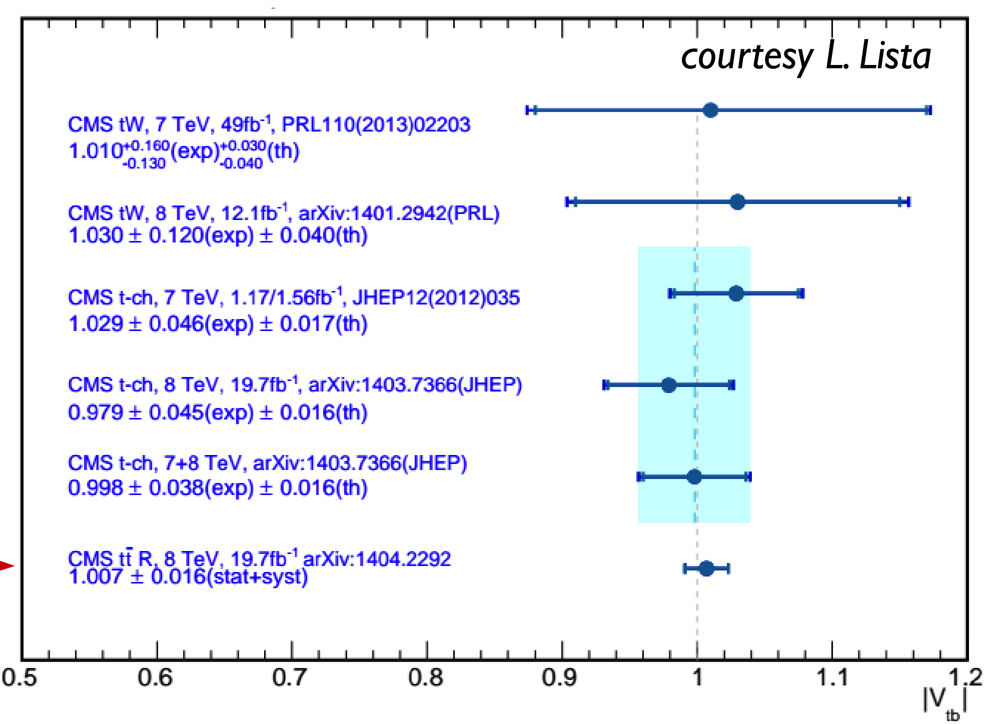
- After the fit **we measure** $\boxed{\mathcal{R} = 1.014 \pm 0.003\,(\text{stat.}) \pm 0.032\,(\text{syst.})}$
  - uncertainty is dominated by the b-tagging efficiency
  - good agreement observed between the exclusive and inclusive categories, all agree with the SM
  - after imposing the 3x3 CKM unitarity we measure $\boxed{|V_{tb}| = 1.007 \pm 0.016\,(\text{stat.+syst.})}$





Result in the current experimental context



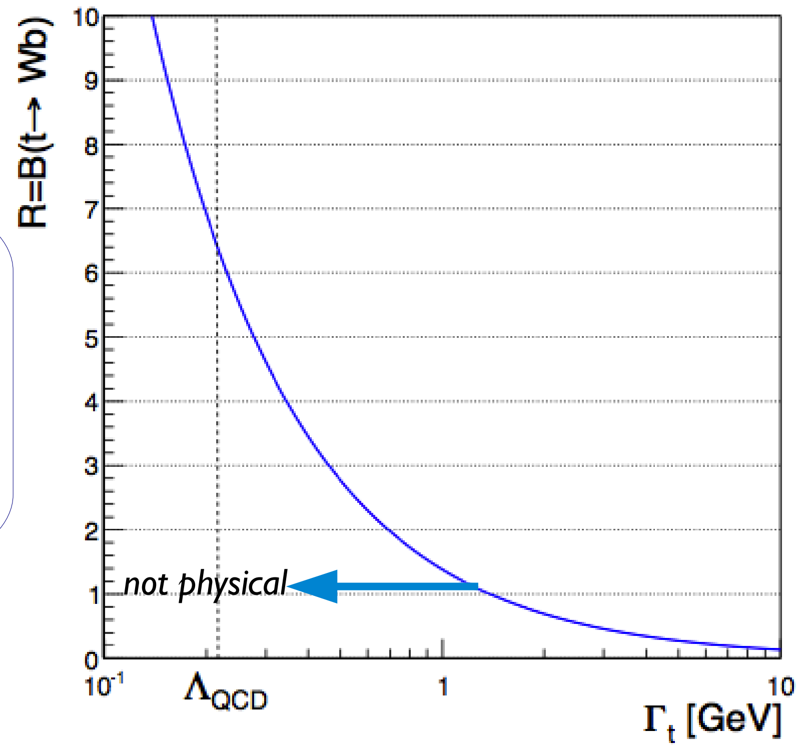


From R to the total width

- **The partial width to Wb is well known at NLO**

$$\boxed{\Gamma(t \to Wb)_{\text{th}} = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_S}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]}$$

  - Using the PDG values and m_t=172.5 GeV $\boxed{\rightarrow \Gamma_b\text{=1.329 GeV}}$
  - Assuming only CC EWK top decays $\boxed{\rightarrow \Gamma_t=\Gamma_b/|V_{tb}|^2=\text{1.331 GeV}}$



- **How to extract Γ_t from R?** Combine:

t → Wb decay

(this measurement)

$$B(t \to Wb) = \frac{\Gamma(t \to Wb)}{\Gamma_t}$$

single top EWK production

(t-channel measurement)

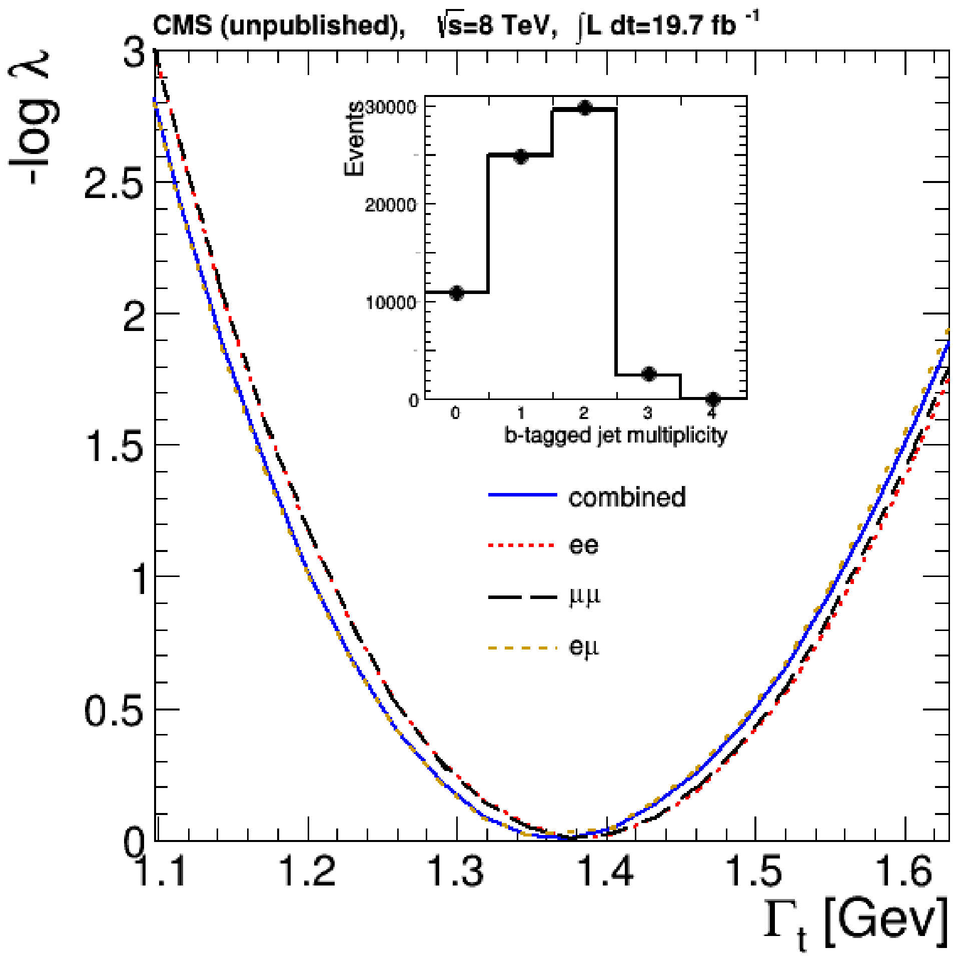
$$\Gamma(t \to Wb) = \sigma(t-\text{ch.})\frac{\Gamma(t \to Wb)_{\text{th}}}{\sigma(t-\text{ch.})_{\text{th}}}$$

  - Re-parametrize R as function of Γ_t and repeat fit

Result

$$\boxed{\Gamma_t = 1.36 \pm 0.02\,(\text{stat.})^{+0.14}_{-0.11}\,(\text{syst.})\,\text{GeV}}$$

11% total uncertainty @ the expected ILC-level, supersedes 24% attained by D0



Source	Uncertainty (%)
Experimental uncertainties:	
ε_b	4.3
ε_q	0.3
$f_{t\bar{t}}$	0.3
DY	0.2
misidentified lepton	0.1
JER	0.4
JES	0.7
unclustered E_T^{miss}	<0.1
integrated luminosity	0.5
pileup	0.8
simulation statistics	0.4
f_{correct}	0.5
selection efficiency	0.1
Single-top quark *t*-channel cross section	9.2
Theoretical uncertainties:	
top-quark mass	0.6
top-quark p_T	0.4
ME-PS	0.8
μ_R/μ_F	0.8
signal generator	0.4
underlying event	0.1
colour reconnection	0.1
hadronisation	0.4
PDF	<0.1
$t \to Wq$ flavour	0.3
$\lvert V_{td}\rvert/\lvert V_{ts}\rvert$	0.1
relative single-top-quark fraction (tW)	0.10
VV (theoretical cross section)	0.09
extra sources of heavy flavour	0.3
Total uncertainty (%)	10.5

Unpublished

Looking ahead for signs of NP - I

- **Given we measure Γ_t to be close to Γ_b there is little room for NP**
- Interpretation must however be made carefully given the SM-like hypothesis made
  - follow EFT-like approach (e.g. Degrande et al. arXiv:1302.1101, DIS 2014)

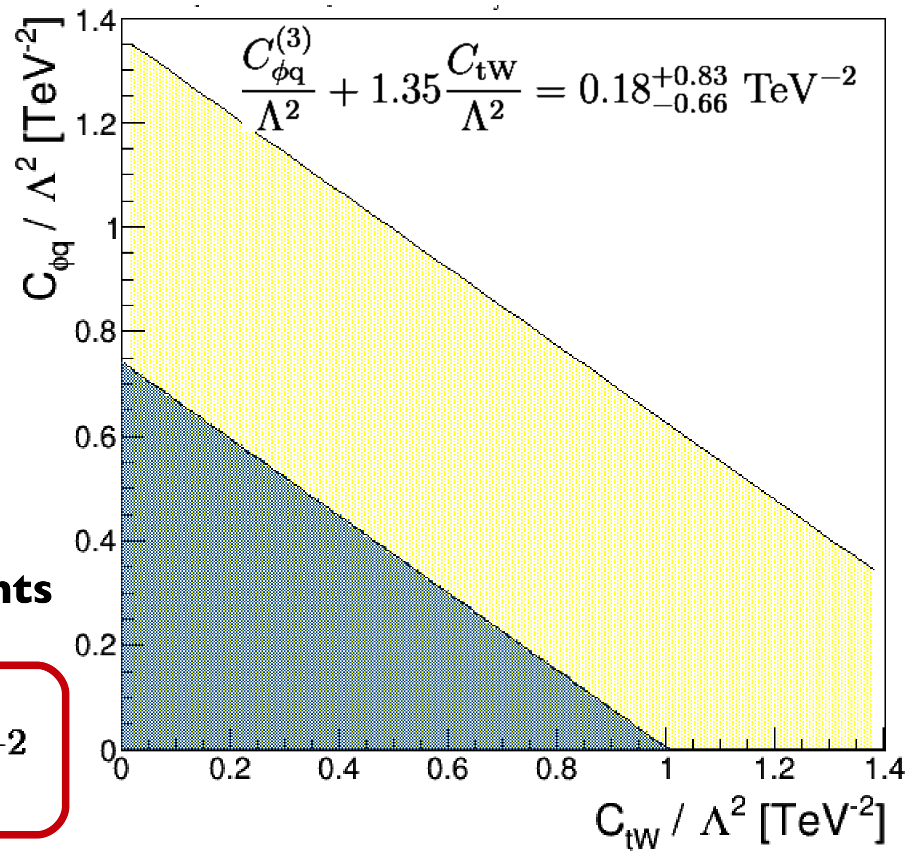
Looking ahead for signs of NP - I

- **Given we measure Γ_t to be close to Γ_b there is little room for NP**
- Interpretation must however be made carefully given the SM-like hypothesis made
  - follow EFT-like approach (e.g. Degrande et al. arXiv:1302.1101, DIS 2014)
- Most relevant **EFT operators affecting Γ_t**

$$\frac{\Delta\Gamma_t}{\text{GeV}} = \left[0.17\frac{C_{\phi q}^{(3)}}{\Lambda^2} + 0.23\frac{C_{tW}}{\Lambda^2}\right]\text{TeV}^2$$

  - C_{tW} – responsible for anomalous tWb couplings
  - $C_{\varphi q}$ – responsible for FCNH
- **Can combine with CMS W helicity measurements**

$$\frac{C_{\rm tW}}{\Lambda^2} = 0.088^{+0.44}_{-0.45}\ \text{TeV}^{-2} \qquad \boxed{\frac{C_{\phi\rm q}^{(3)}}{\Lambda^2} = 0.3^{+1.4}_{-1.2}\ \text{TeV}^{-2}}$$



Bounding the Higgs boson width

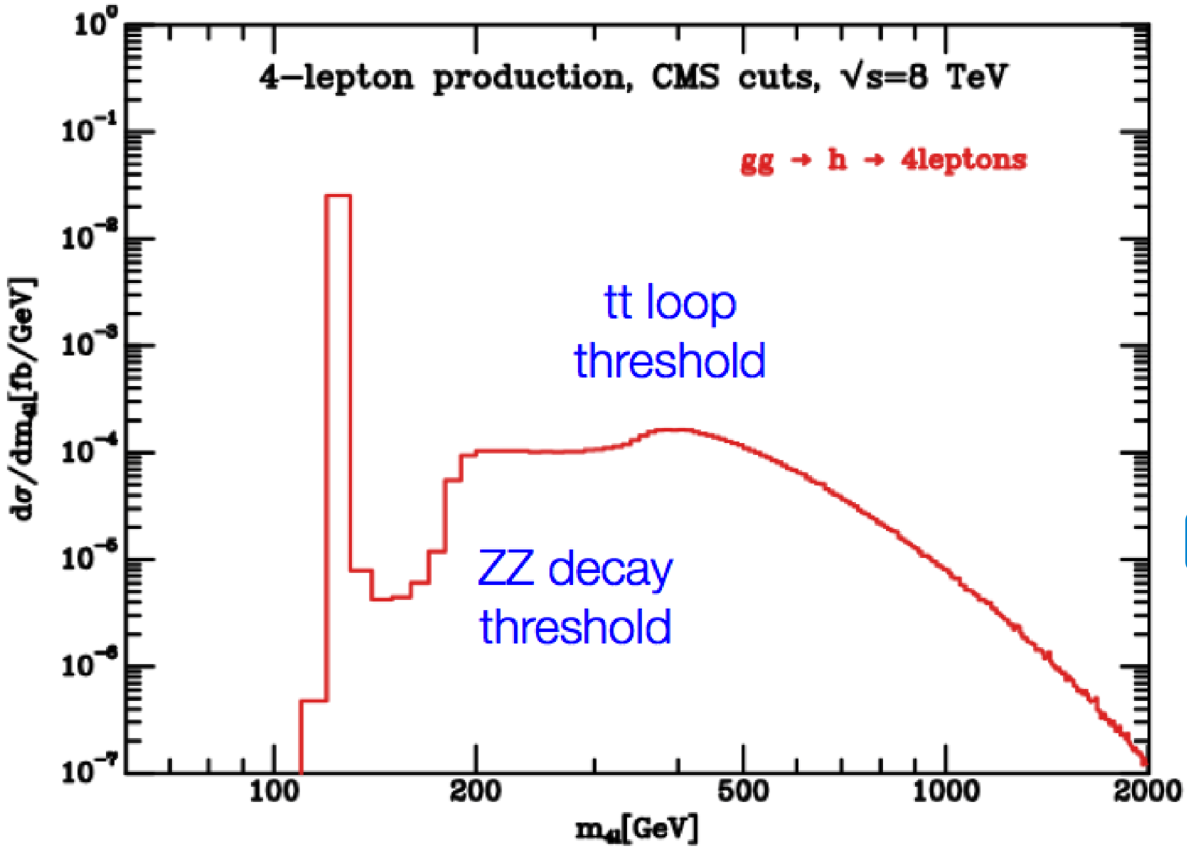
We constrain the total Higgs boson width, Γ_H, using off-shell production and decay to 4l or 2l2ν.

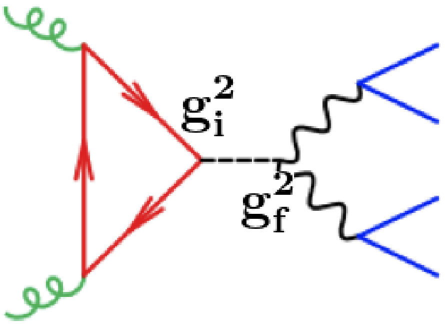
A fit of the 4l mass or 2l+MET transverse mass, combined with the on-shell measurement of the Higgs boson cross section, leads to an upper limit of $\Gamma_H < 4.2\Gamma^{SM}_H$ @ 95% CL.

The results presented are detailed in CMS-PAS-HIG-14-002 *(paper in preparation)*

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

Higgs off-shell production and decay

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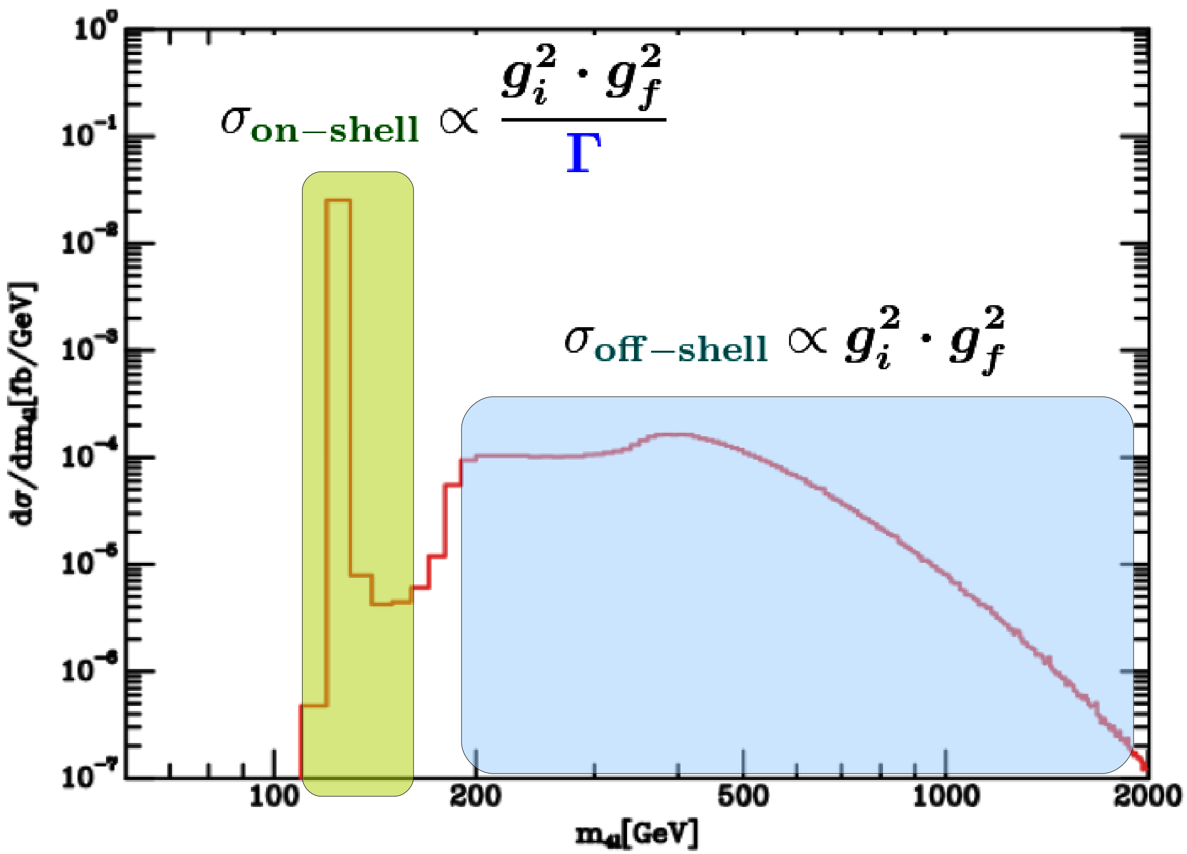

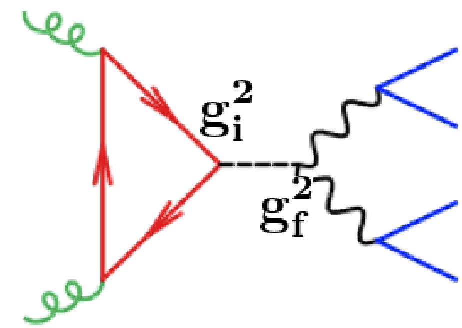

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
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Extract width from: $\frac{\sigma_{\mathrm{off-shell}}}{\sigma_{\mathrm{on-shell}}} \propto \Gamma$

assuming couplings are independent of m_{VV}

Analysis strategy

- **Search for anomalous ZZ production through gluon-gluon fusion at high mass**

$$\frac{d\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2 \cdot \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

re-scale SM couplings

measured on-shell

$\mu(\mathrm{obs}) = 0.93^{+0.26}_{-0.24}$

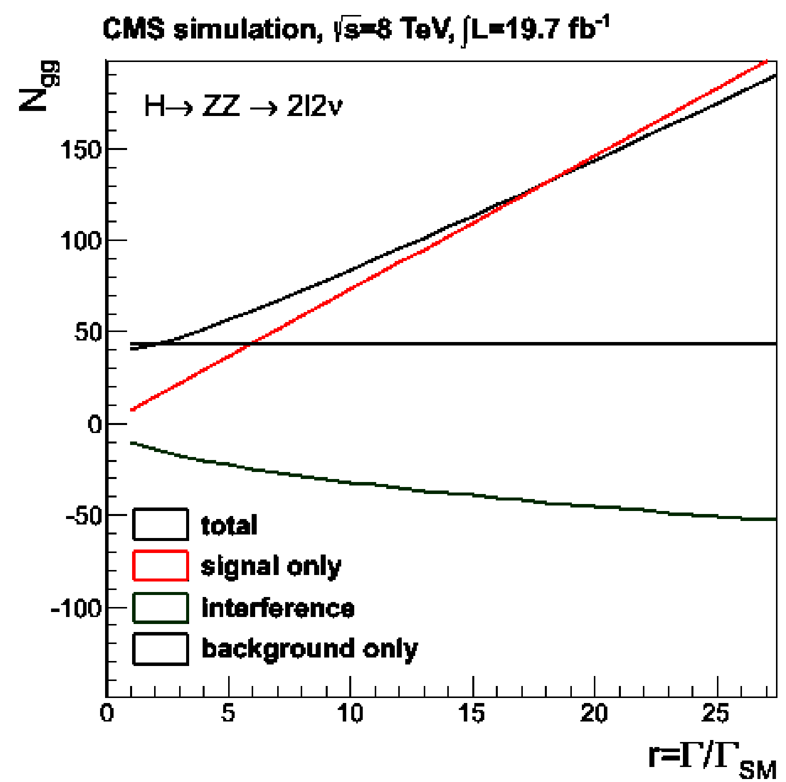
$\mu(\mathrm{exp}) = 1.00^{+0.27}_{-0.24}$

Γ/Γ_H, to be fit

SM expectations

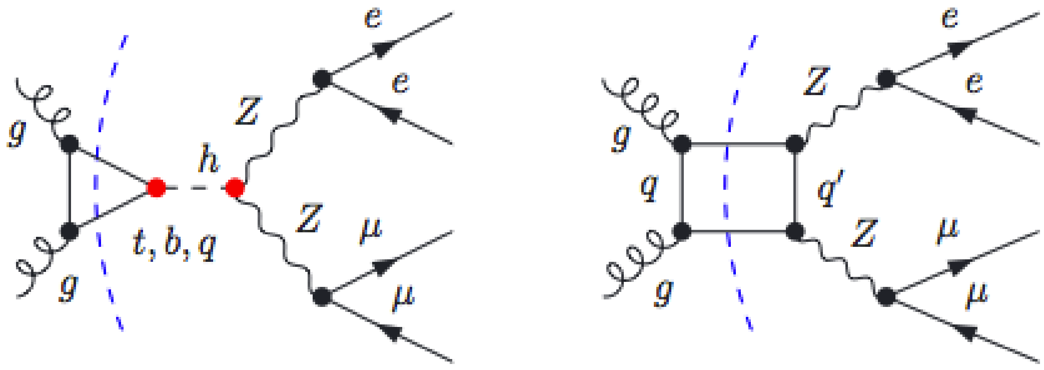
- Inclusive final states, include in parameterization
  - **signal, continuum and interference**
  - assume inclusive signal strength μ

$$N_{gg\to ZZ}\left[\mu r \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{\mu r} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}\right]$$
$$+ N_{\mathrm{VBF}}\left[\mu r \times \mathcal{P}^{VBF}_{\mathrm{sig}} + \sqrt{\mu r} \times \mathcal{P}^{VBF}_{\mathrm{int}} + \mathcal{P}^{VBF}_{\mathrm{bkg}}\right]$$

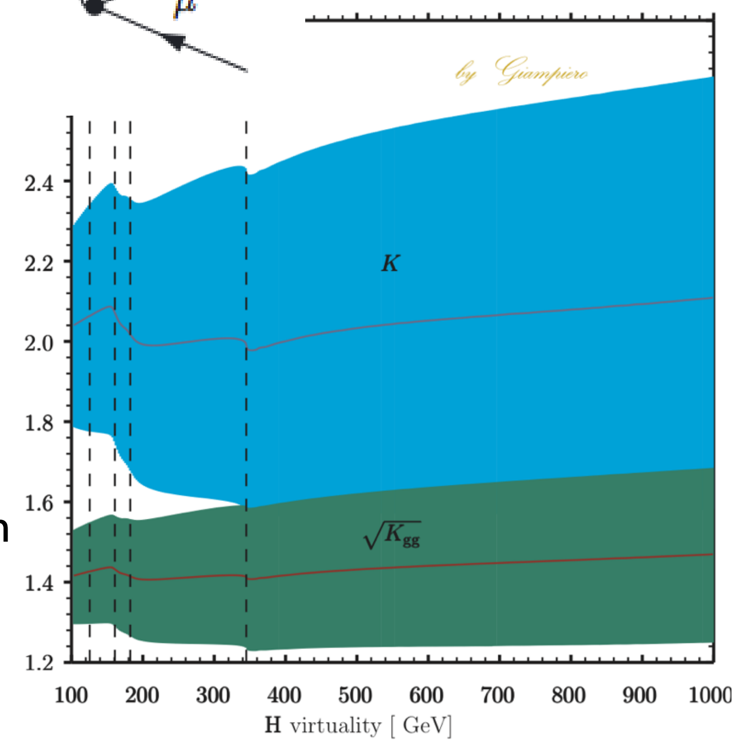


Signal simulation

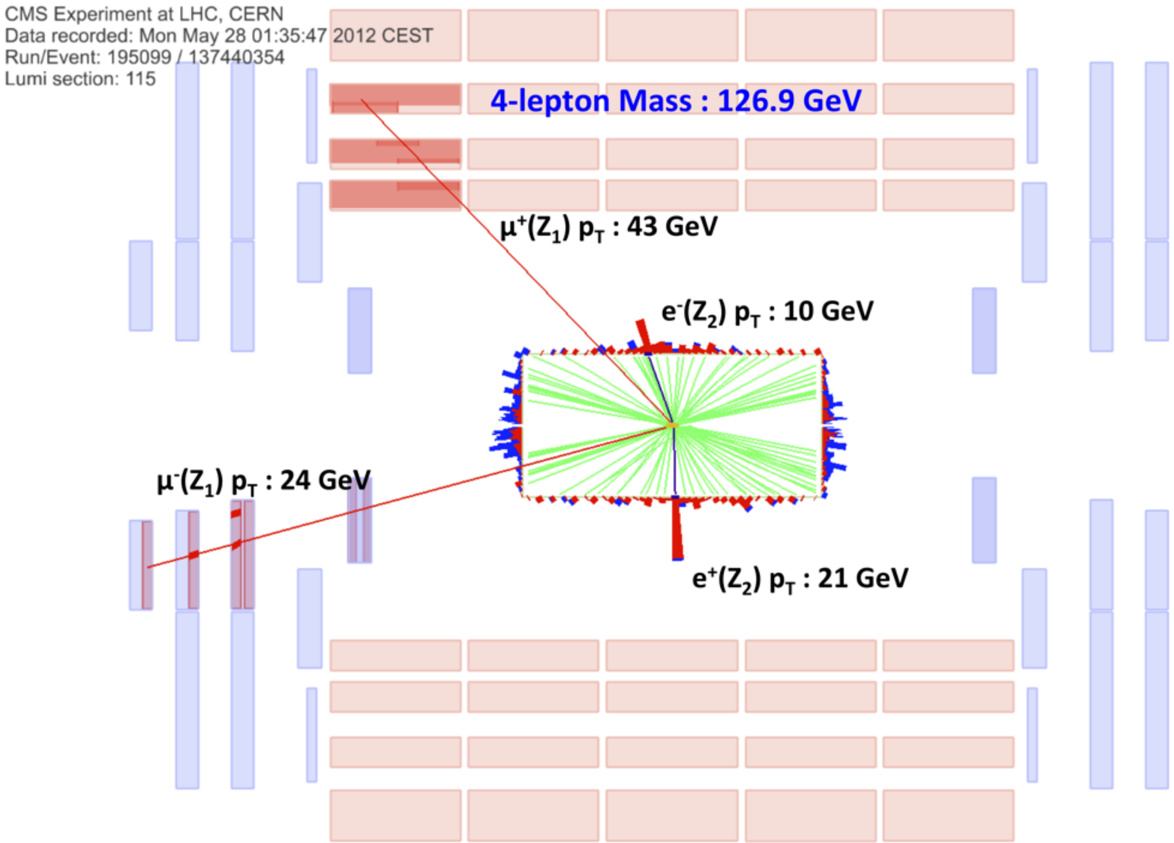
- **Gluon fusion production** generated @ LO with gg2VV or MCFM (m_H=125.6 GeV)
  - Inclusive generation: Higgs, continuum background and interference

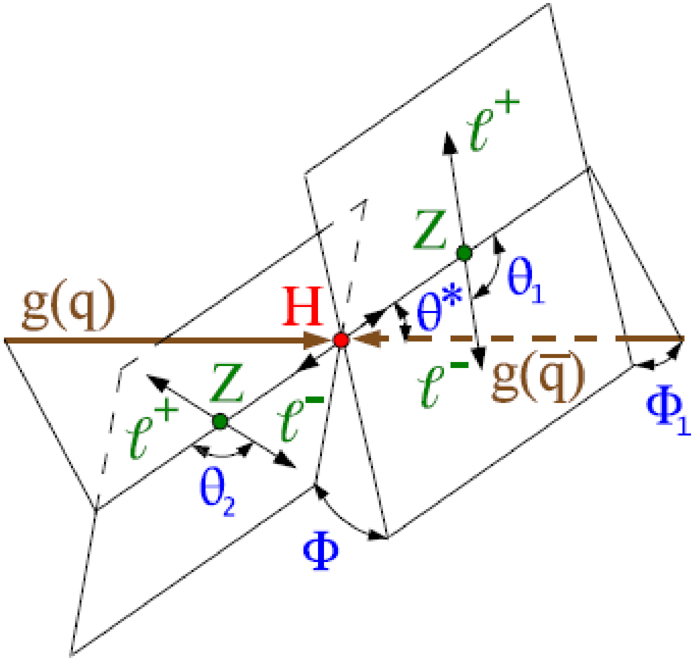


  - Running renormalization and factorization scales := mZZ/2
- **NNLO k-factors for gg → VV**
  - Bonvini et al. PRD88 (2013) 034032, Passarino arXiv:1312.2397
  - applied as a function of m_{ZZ} to signal and background
- **VBF production** is generated with Phantom or Madgraph
  - Expect to yield ~10% in the high mass regime
  - inclusive generation, as in gg case



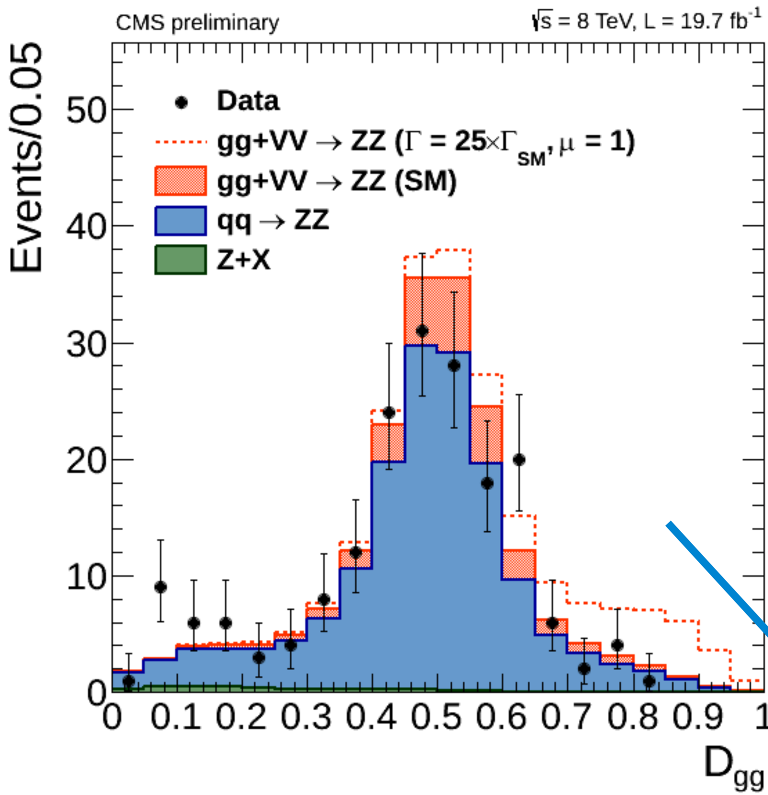
Golden channel: H → ZZ → 4l

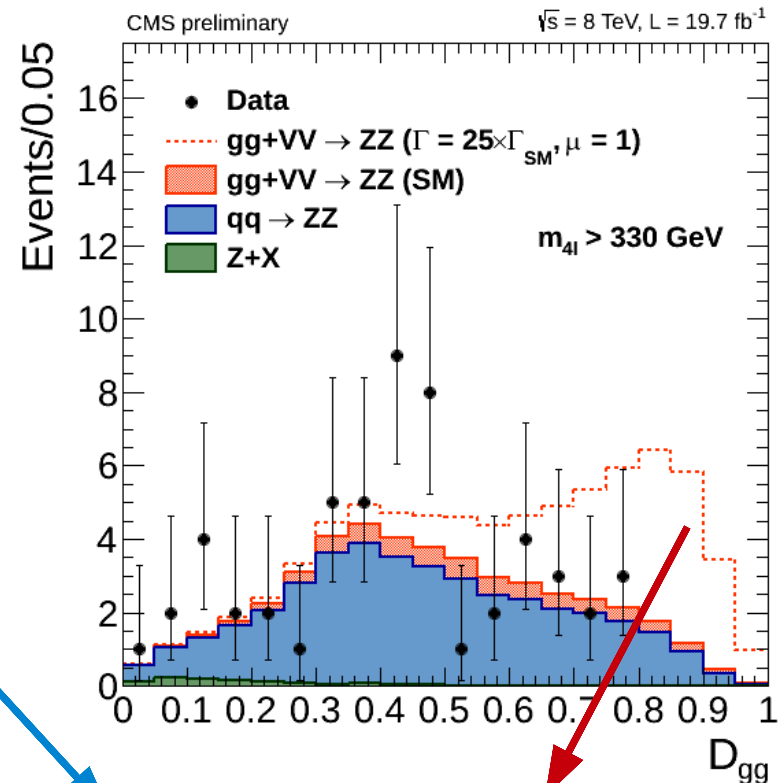




- Golden-channel for Higgs discovery and properties measurement (arXiv:1312.5353)
- Main background is irreducible from qq → ZZ; residual Z+X extrapolated from data
- Access to on-shell and off-shell production
- Analyze m_{4l} or kinematic discriminant based on matrix-element probabilities

Discriminators and event yields for 4l

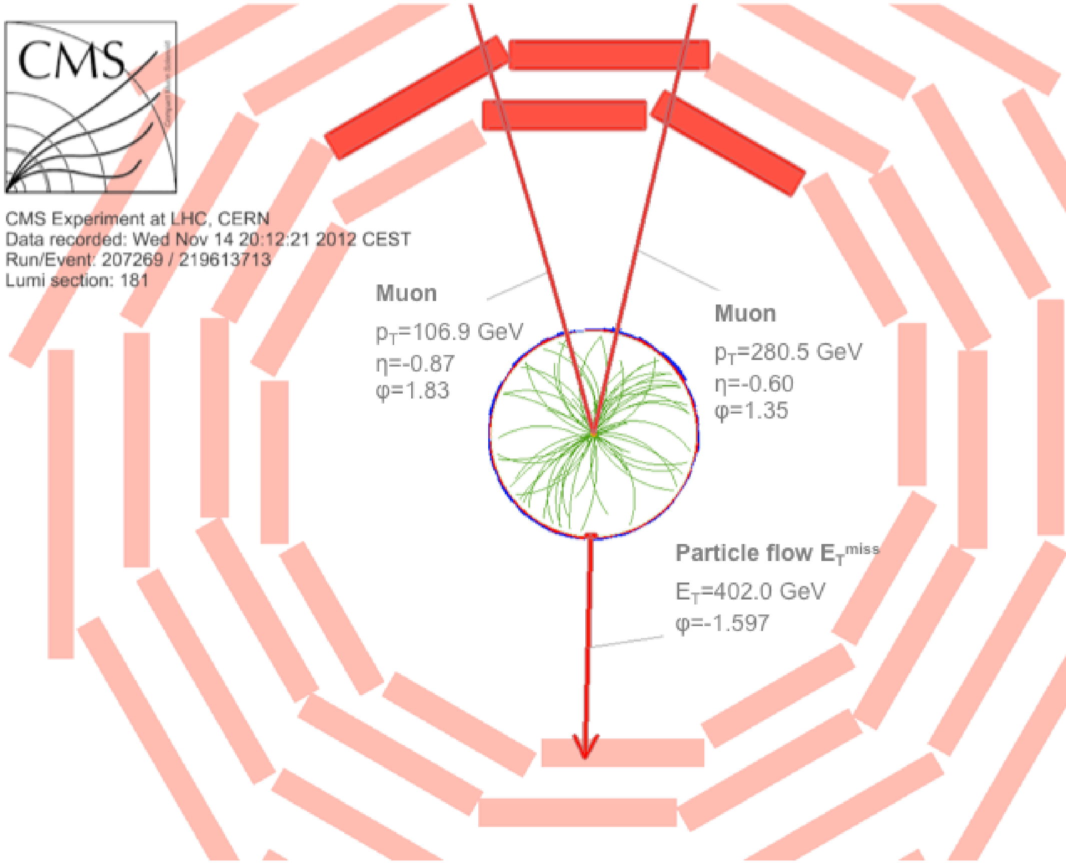




+D_{gg}>0.65

		Full region	Signal-enriched region
	$gg + \mathrm{VBF} \to 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	$2.22^{+0.15}_{-0.17}$	$1.20^{+0.08}_{-0.09}$
	$gg + \mathrm{VBF} \to 4\ell$ (background)	$31.1^{+3.0}_{-3.1}$	2.12 ± 0.21
(a)	$gg + \mathrm{VBF} \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	$29.6^{+2.8}_{-2.9}$	$1.73^{+0.16}_{-0.17}$
	$gg + \mathrm{VBF} \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 15$)	$51.8^{+4.9}_{-5.0}$	13.1 ± 1.1
(b)	$q\bar{q} \to 4\ell$	154.7 ± 7.4	8.6 ± 0.4
(c)	Reducible background	3.7 ± 0.6	0.44 ± 0.08
(a+b+c)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	188.0 ± 7.9	10.8 ± 0.4
	Observed	183	8

High-mass specialist: H → ZZ → 2l2v



- BR(2l2v) ~ 6x BR(4l) → crucial when σ is low
- Main backgrounds:
  - Instrumental: Z+jets (from photon+jets)
  - Non-resonant: WW, top (from eμ control)
  - Irreducible: ZZ, WZ
- Tight cuts: can't access Higgs on-shell

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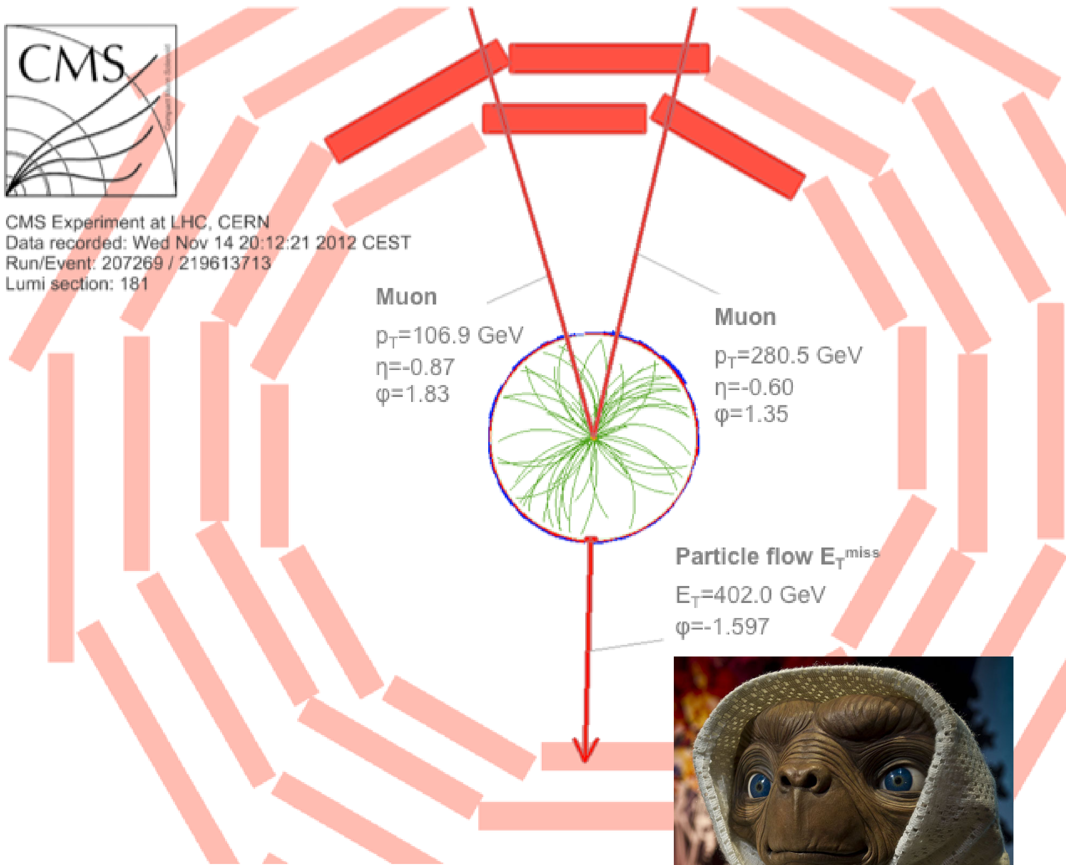

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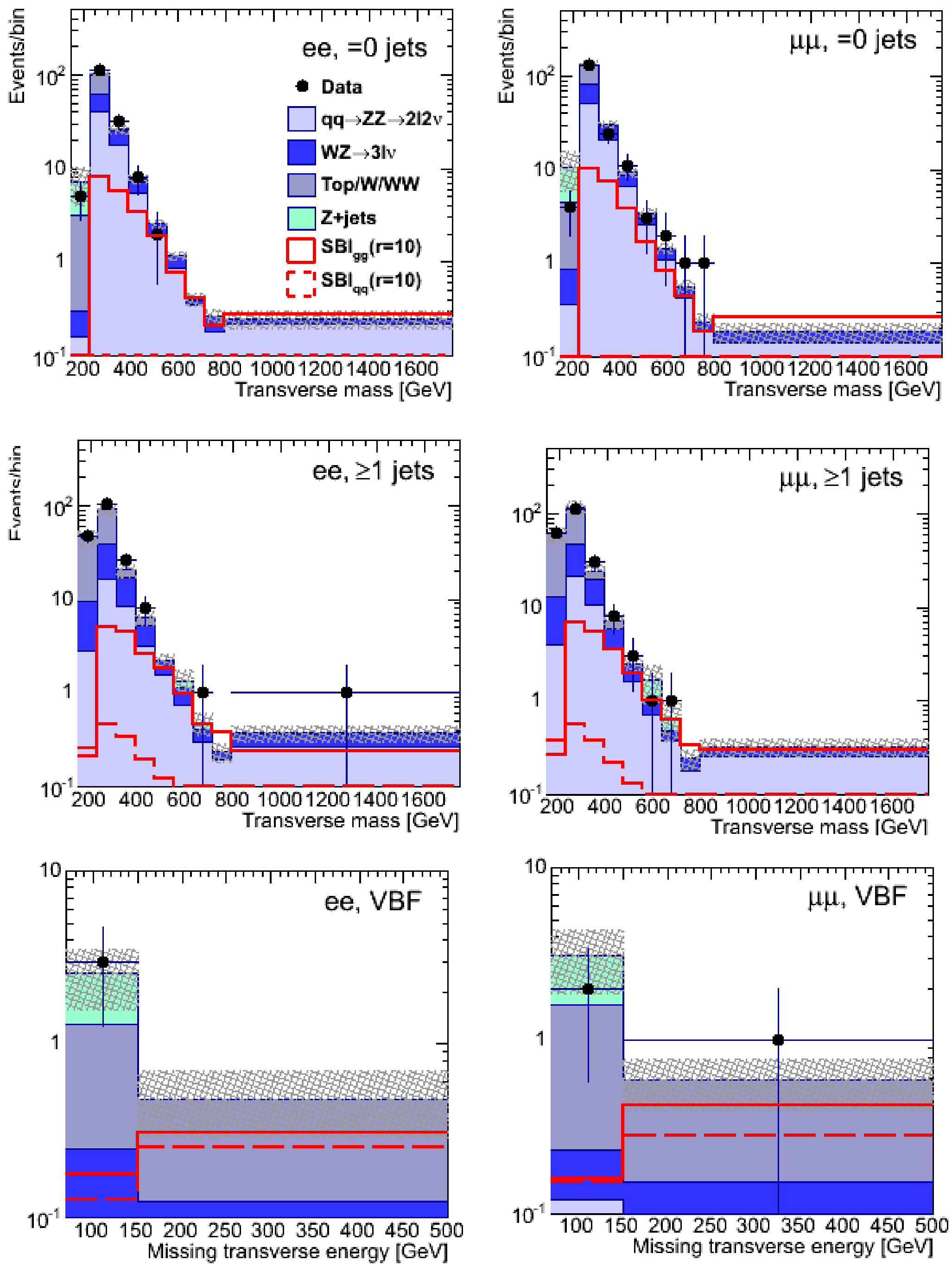
- Main backgrounds:
  - Instrumental: Z+jets (from photon+jets)
  - Non-resonant: WW, top (from eμ control)
  - Irreducible: ZZ, WZ
- Tight cuts: can't access Higgs on-shell
- Missing transverse energy (E_t^{miss})

$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_T^{miss\,2} + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{miss}\right]^2$$

Discriminators and event yields for 2l2ν



- Categorize events according to jets
  - VBF category has priority

    M_{jj}>500 GeV, |Δη|>4, central jet veto
  - If not VBF count jets with p_T>30 GeV

- Event yields in a signal-enriched region
  - E_t^{miss} > 100 GeV and m_T > 350 GeV

		ee	$\mu\mu$
	gg + VBF (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	2.3±0.5	2.7±0.6
	gg + VBF (background)	5.4±1.2	6.5±1.4
(a)	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	4.8±1.1	5.7±1.3
	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 10$)	19.2±5.5	22.6±6.7
	$q\bar{q} \to ZZ$	25.0±2.1	29.4±2.5
(b)	WZ	11.6±1.2	13.5±1.4
	$t\bar{t}$/tW/WW	3.3±1.1	4.2±1.4
	Z + jets	1.5±0.9	2.4±1.4
(a+b)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	46.2±3.0	55.3±3.7
	Observed	39	52

Systematic uncertainties

- **Theory uncertainties**
  - gg → ZZ

    QCD scales varied by 2 and ½ with corresponding NNLO k-factor variations

    PDF variations by using CT10, MSTW2008 and NNPDF2.1 (PDF4LHC prescription)

    Additional 10% on continuum gg→ZZ background (limited knowledge at higher orders)

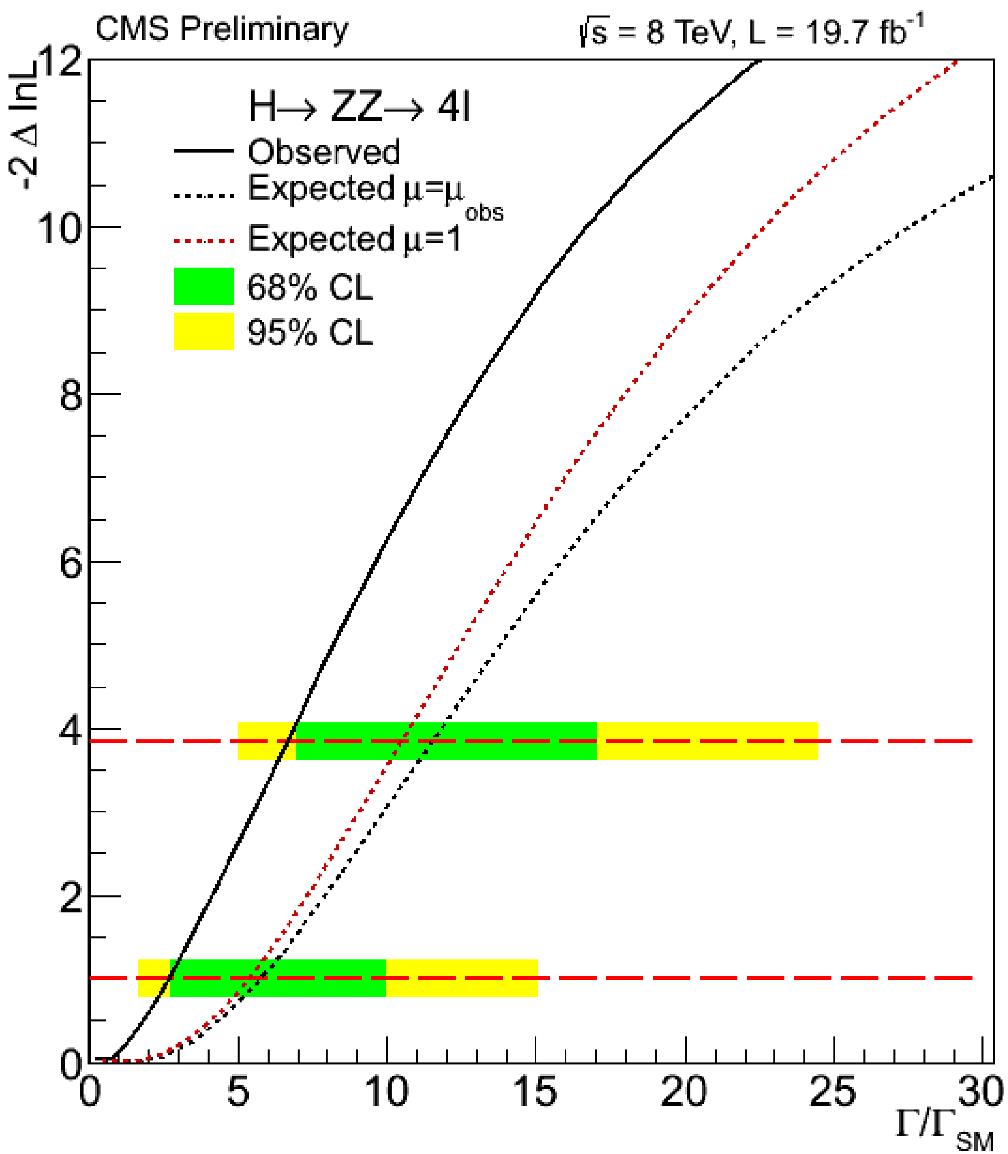
    Jet binning uncertainties computed with MCFM: typically uncorrelate gg → ZZ in different bins

    Approximate simulation of VBF shapes (4l - specific)
  - qq → ZZ/WZ

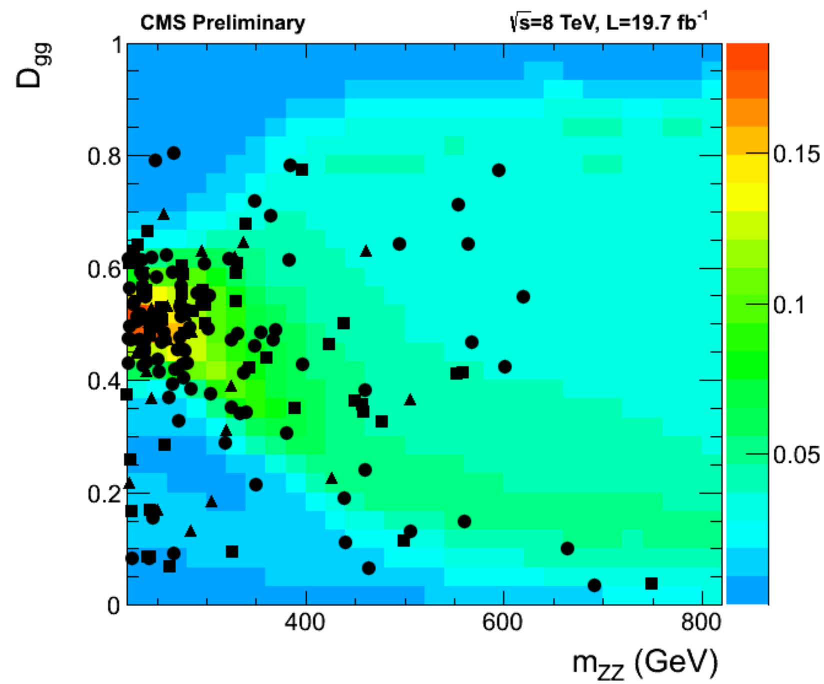
    QCD scales and PDF uncertainties following similar prescription as above
- **Experimental uncertainties**
  - Lepton trigger, id, isolation efficiencies
  - Jet energy scale/resolution, unclustered E_T^{tmiss}, b-tagging efficiency (2l2ν – specific)
  - Integrated luminosity
  - Data-based background estimations

Uncertainty effects are taken into account to both rate and shape.

Results: 4l analysis



- A 2D fit to m_{4l} and D_{gg}



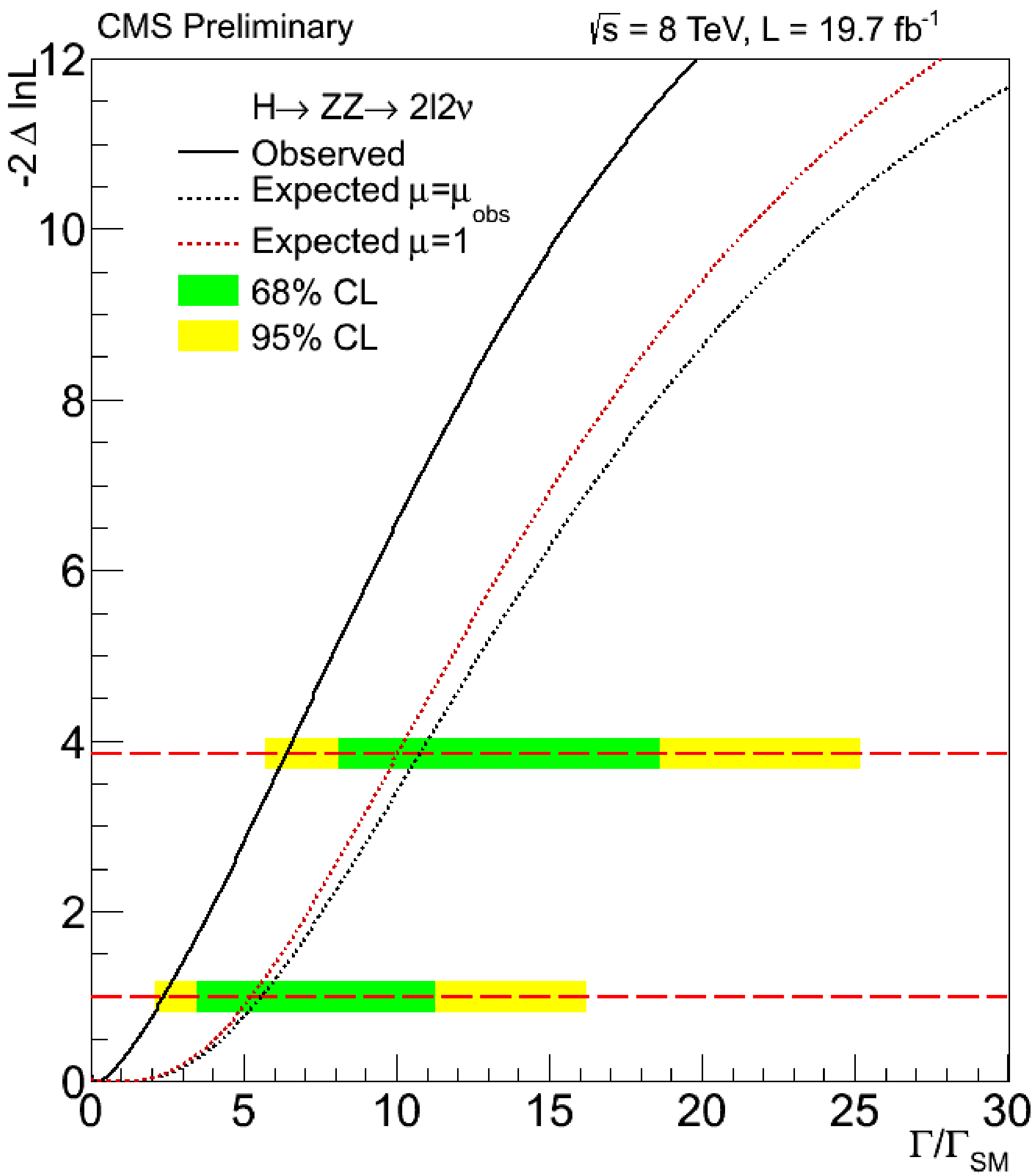
- Observed (expected) limit: r < 6.6 (11.5)

  equivalent to **Γ < 27.4 MeV at 95% CL**

- Best fit value: $r = 0.5^{+2.3}_{-0.5}$

  equivalent to $\Gamma = 2.0^{+9.6}_{-2.0}$ MeV

Results: 2l2ν analysis

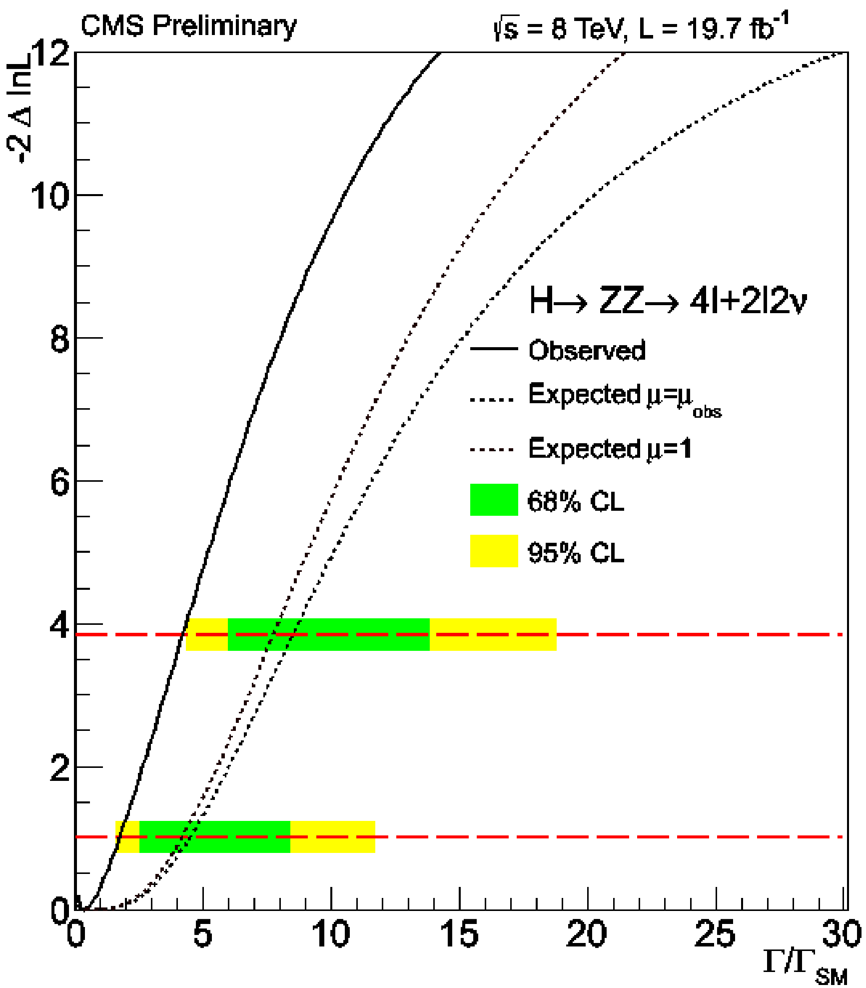


- A 1D fit to m_T (0,≥1 jets) and E_T^{miss} (VBF)
- Cross-check in different categories
  - Fit dominated by non-VBF categories
  - ee : r < 6.9 (14.3 expected)
  - μμ : r < 14.0 (13.7 expected)
  - Counting analysis: r < 12.4 (16.4 expected)
- Observed (expected) limit: r < 6.4 (10.7)

  equivalent to **Γ < 26.6 MeV at 95% CL**
- Best fit value: $r = 0.2^{+2.2}_{-0.2}$

  equivalent to $\Gamma = 0.8^{+9.1}_{-0.8}$ MeV

Results: combined



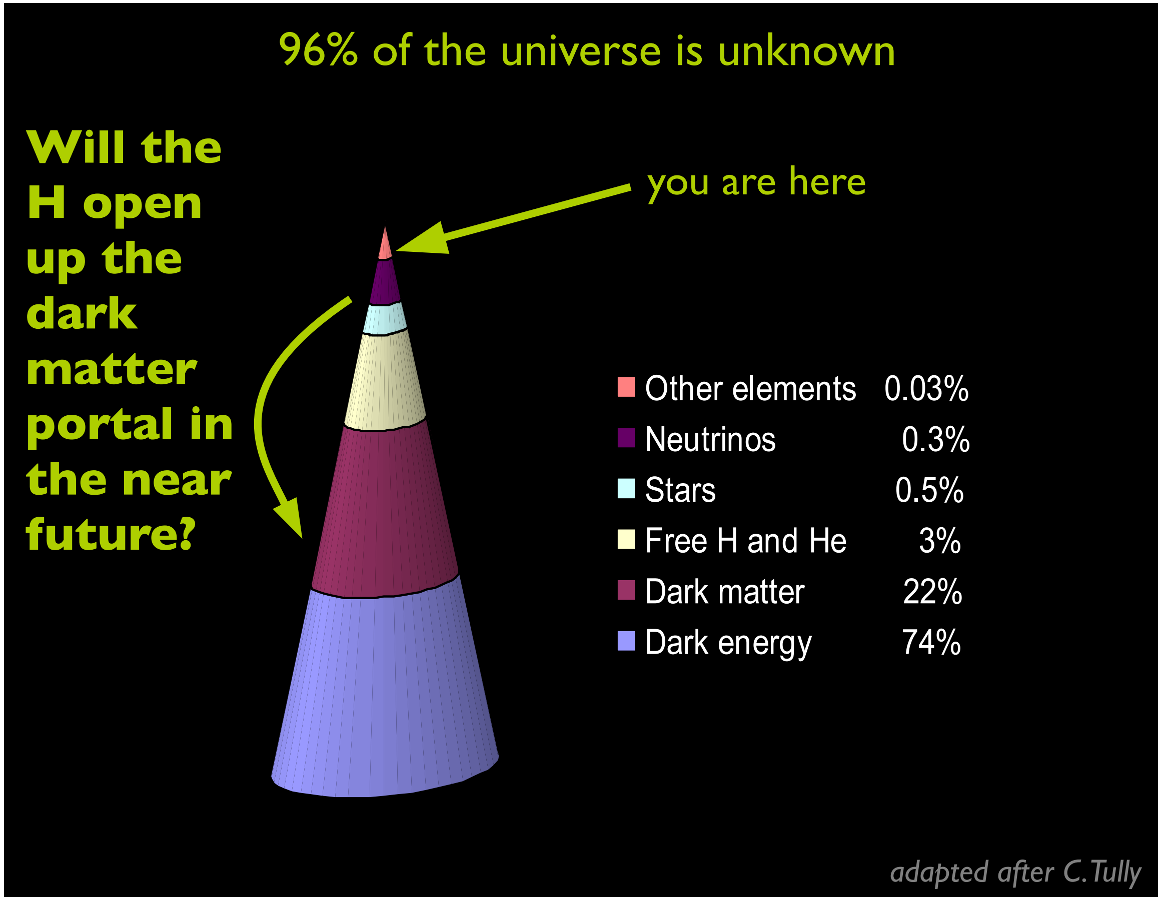
- Supersedes direct measurements from 4l and γγ
- Observed limit << Expected limit
  - p-value~0.02 ...
  - Consistent between independent analysis/final states
  - Feldman-Cousins-based results consistent
  - hitting theoretical prediction accuracy already?

	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

The LHC can effectively grasp Γ_H !

Looking ahead for signs of NP - II

- Although the result is outstanding we are **still far away from testing NP from Γ_H**
  - will be useful in view of a global fit to Higgs properties
  - direct limits on BR(H → invisible) are ~30-40% better at this stage
- Run II will provide enough statistics to improve considerably → needs theory follow-up



Summary

Summary

- **LHC: finding the Higgs is great, but not enough**
  - maybe there is something around the 13 TeV corner which did not appear at 8 TeV...
  - **precision electroweak measurements are needed** to understand what's going on

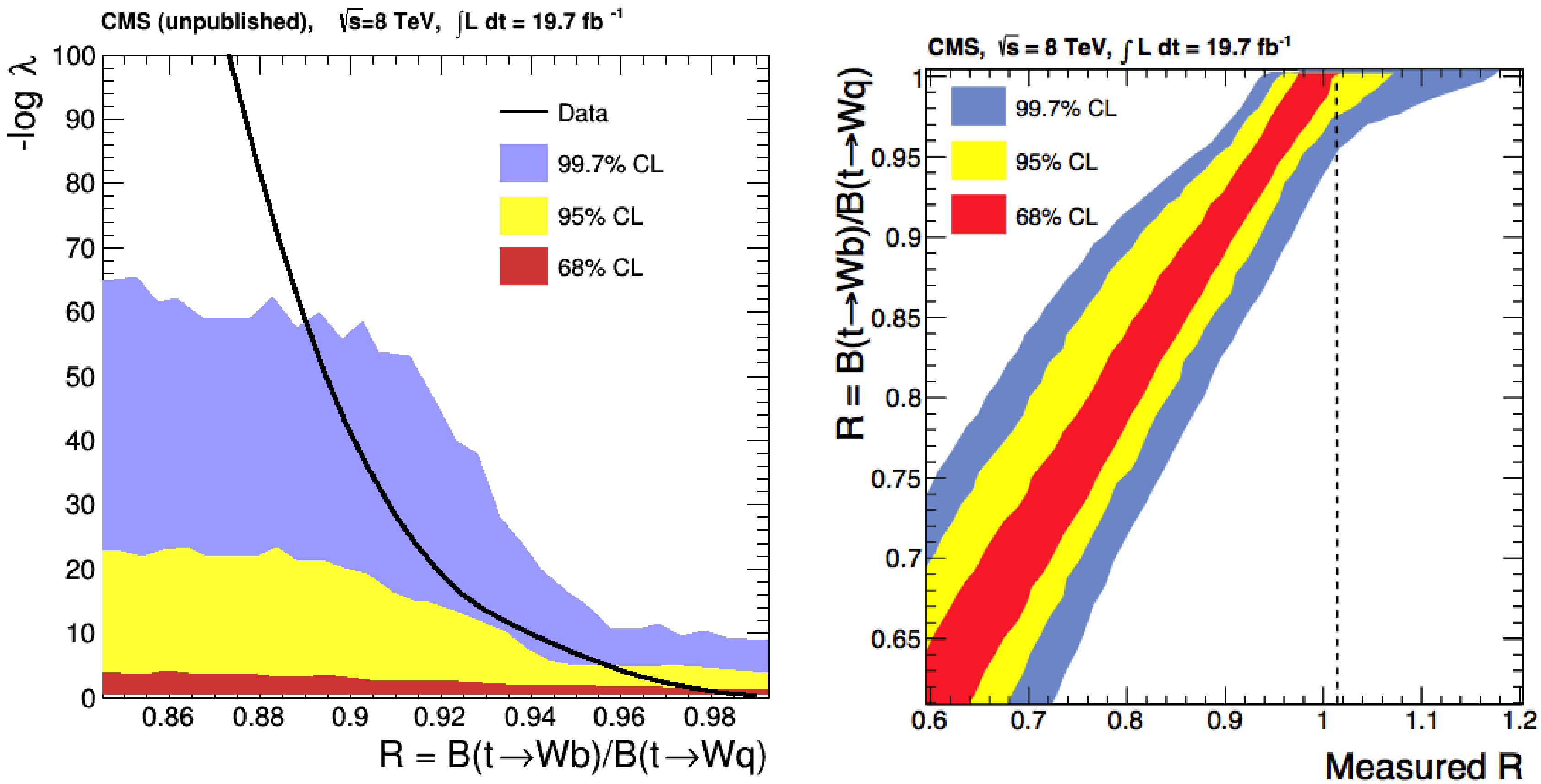
- **Case for width measurements**
  - bound NP effects or test SM completeness from total width
  - very hard to measure directly from the mass lineshape : use rate-based techniques

- **Two different approaches for Γ_t and Γ_H presented today**
  - top quark: uncertainty at the 11% level → little room left for NP, but possibility to improve
  - higgs boson: getting close to the SM → still a lot of room for NP, how near will we get with 13 TeV?
  - in both cases: **these are new results and world's best**

Backup

Imposing the R ≤ 1 physical boundary

- The fits for R, $|V_{tb}|$ or Γ_t are unconstrained
  - Physical boundary imposed a posteriori using a Feldman-Cousins procedure PRD57:3873-3889,1998
  - Throw pseudo-experiments including systematic uncertainties and imposing physical boundary
  - Obtain acceptance regions for the test statistics at different confidence levels
  - Compare with data to derive the lower endpoint of the interval



Indirect Γ_t measurement from D0

- **D0** has performed an indirect measurement of Γ_t (PRL 106 (2011) 022001/PRD85 (2012) 091104)
- The total width can be indirectly inferred combining

single top t-channel cross section

yields access to the Wb partial width

$$\Gamma(t \to Wb) = \sigma(\mathrm{t-ch.}) \frac{\Gamma(t \to Wb)_{\mathrm{th}}}{\sigma(\mathrm{t-ch.})_{\mathrm{th}}}$$

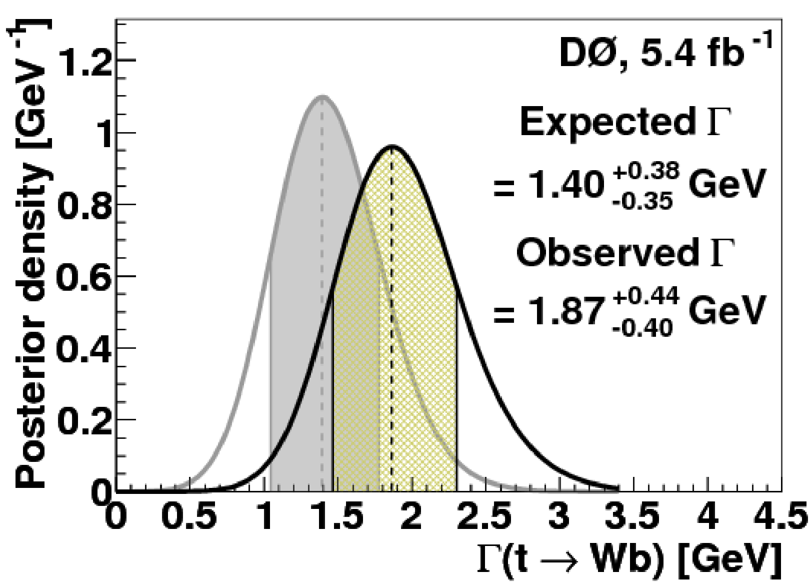
measurement of R=B(t→Wb)/B(t→Wq)

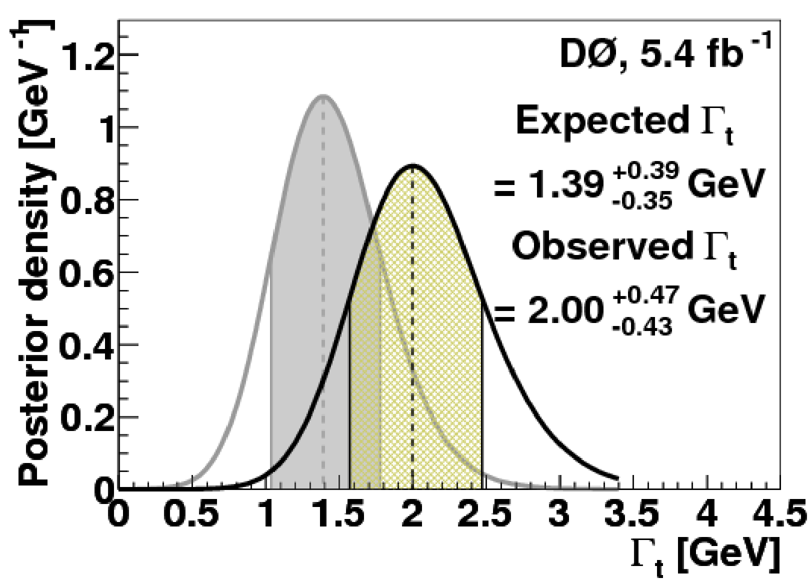
yields access to the Wb branching ratio

$$B(t \to Wb) = \frac{\Gamma(t \to Wb)}{\Gamma_t}$$

$$\boxed{\Gamma_t = \frac{\sigma(\mathrm{t-ch.})}{B(t \to Wb)} \frac{\Gamma(t \to Wb)_{\mathrm{th}}}{\sigma(\mathrm{t-ch.})_{\mathrm{th}}}}$$

- Combine the two measurements to extract Γ_t
  - Derive posterior probabilities from σ(t-channel) and R
  - Γ_t**>1.37 GeV at 95% CL** (JES/JER, luminosity, W+jets, signal generator and ε_b dominate unc.)





Projections: pre-HIG-14-002

LHC run I

Method	Measured quantity	Γ_H [MeV]	Γ_H/Γ_H^{SM}
CMS-PAS-HIG-13-016	Width $\times$ resolution	< 6900	< 1600
1305.3854 (Dixon-Li)	Mass shift in $\gamma\gamma$, $\Delta m_H \sim 1$ GeV	< 800	< 200
1312.1628 (CEW)	Ratio WW, $m_T > 130$, 300 GeV	$< 500, 180$	$< 125, 45$
1311.3589 (CEW)	Ratio ZZ, $m_{4\ell} > 130$, 300 GeV, MEM	$< 170, 100, 60$	$< 43, 25, 15$

LHC 3ab^{-1}

Method	Measured quantity	Γ_H [MeV]	Γ_H/Γ_H^{SM}
Snowmass estimate 3 ab^{-1}	Width $\times$ resolution	< 200	< 50
1305.3854 (Dixon-Li) 3 ab^{-1}	Mass shift in $\gamma\gamma$, $\Delta m_H \sim 100$ MeV	< 60	< 15
1307.4935 (CM) 3 ab^{-1}	Ratio ZZ, $m_{4\ell} > 130$, 300 GeV	$< 40, 20$	$< 10, 5$