Physics at run 2: prospects and opportunities

FRONTIER DETECTORS FOR FRONTIER PHYSICS

13th Pisa Meeting on Advanced Detectors

24-30 May 2015 - La Biodola, Isola d'Elba (Italy)

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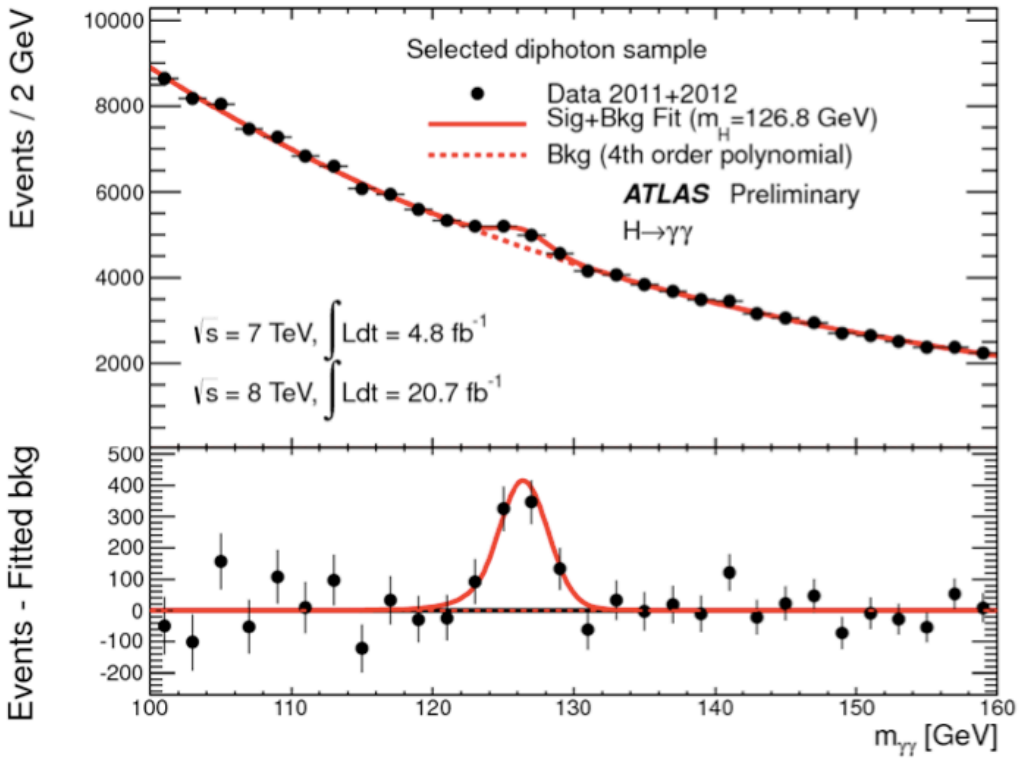
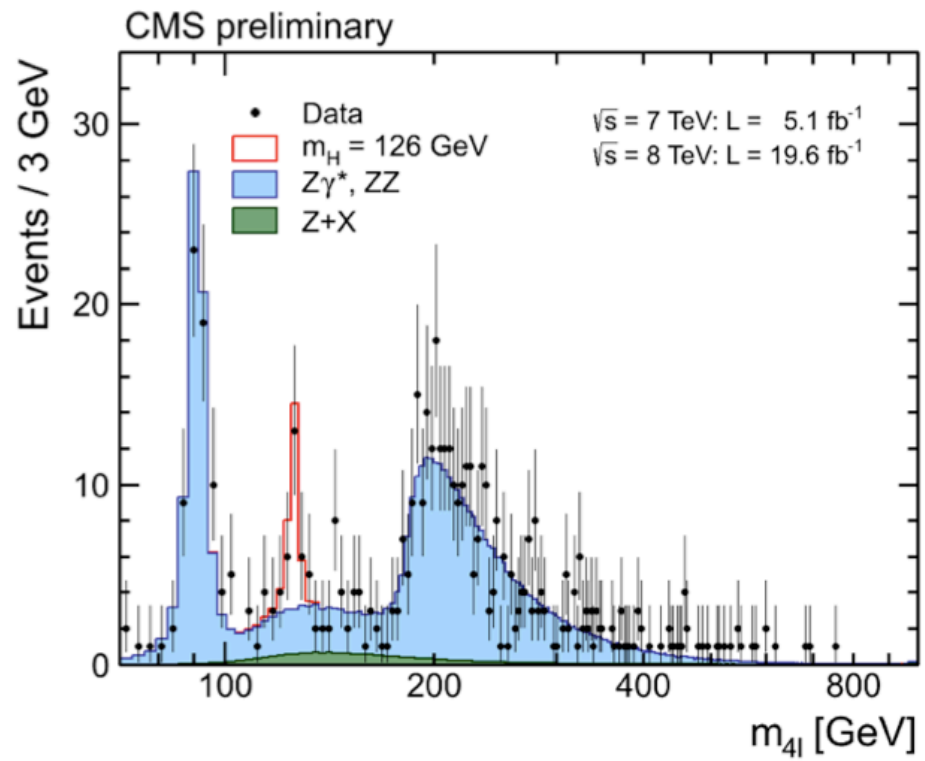
Key outcomes of 3 yrs at the LHC: # one

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the +/– 20% level .....





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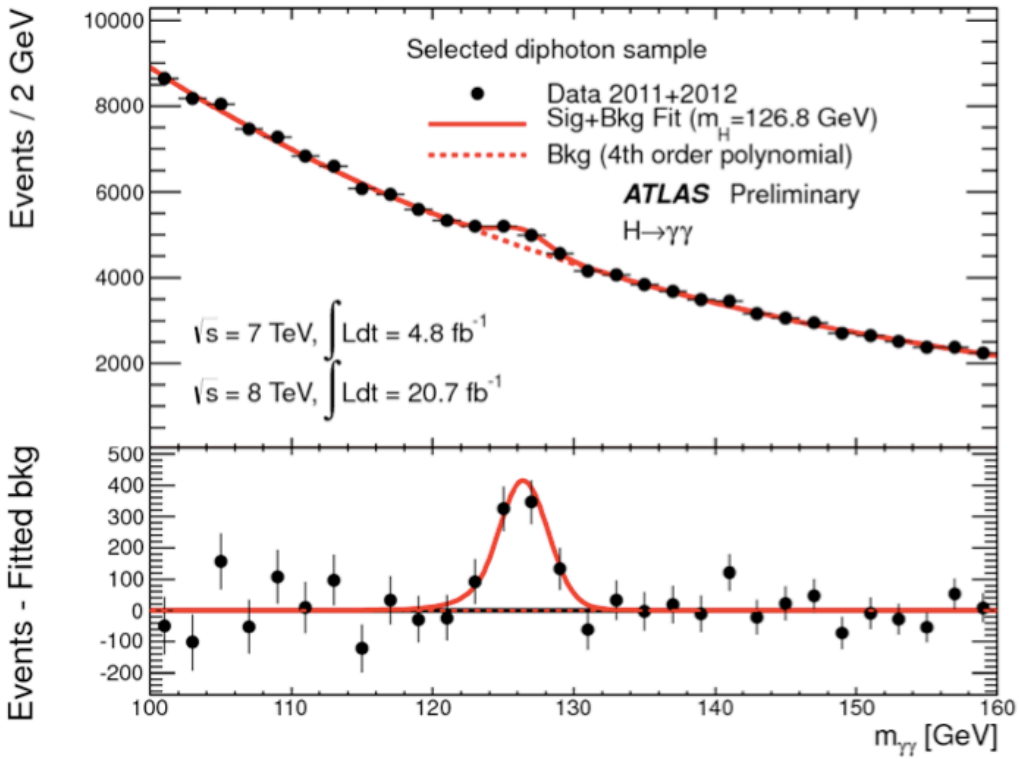

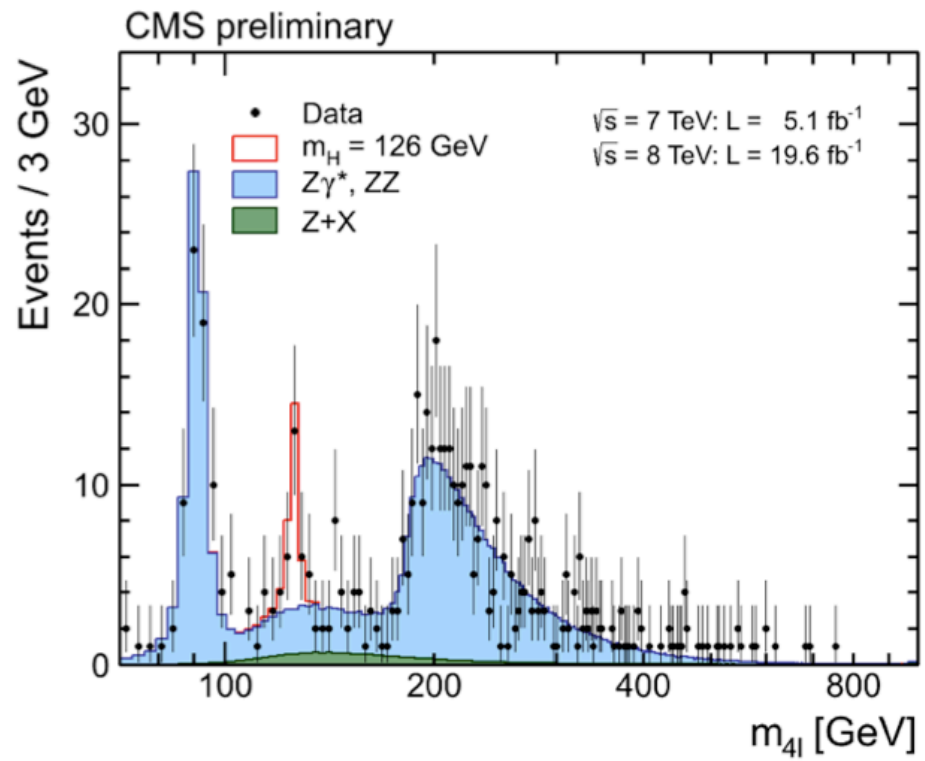

.... How far can we push the accuracy of these tests, and probe the mechanism of EWSB ?

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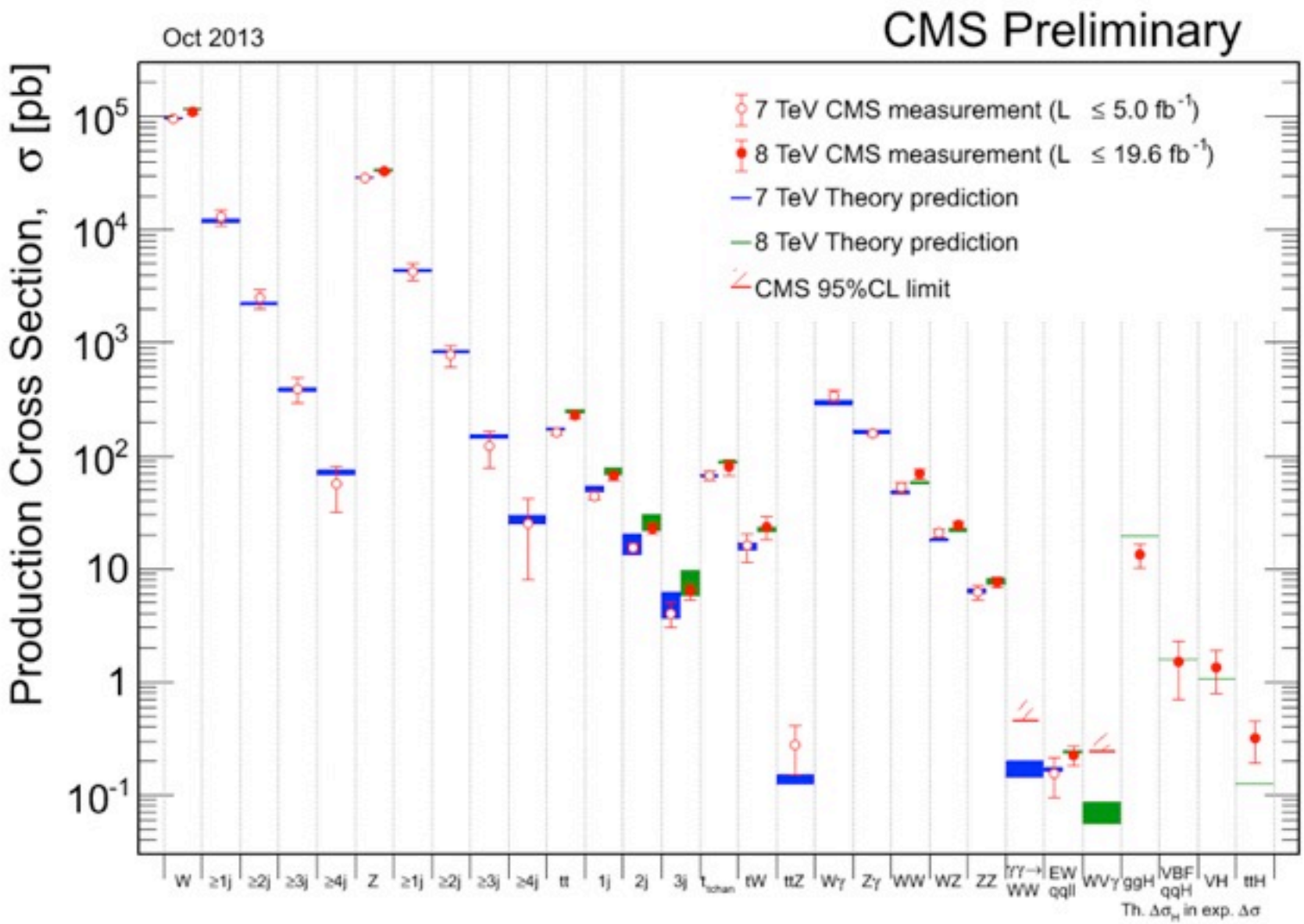
The theoretical description of high-Q^2 processes at the LHC is very good ....



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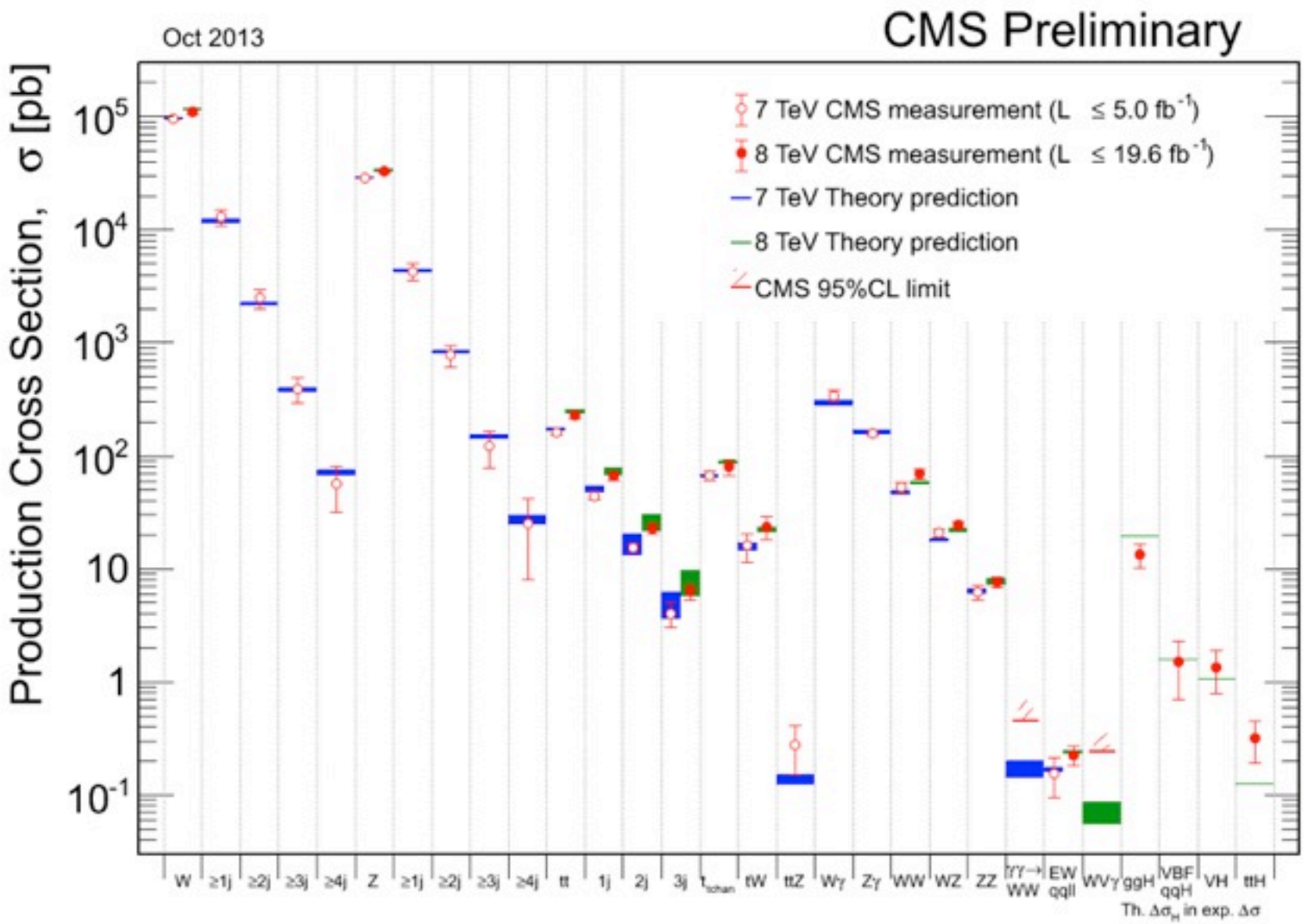
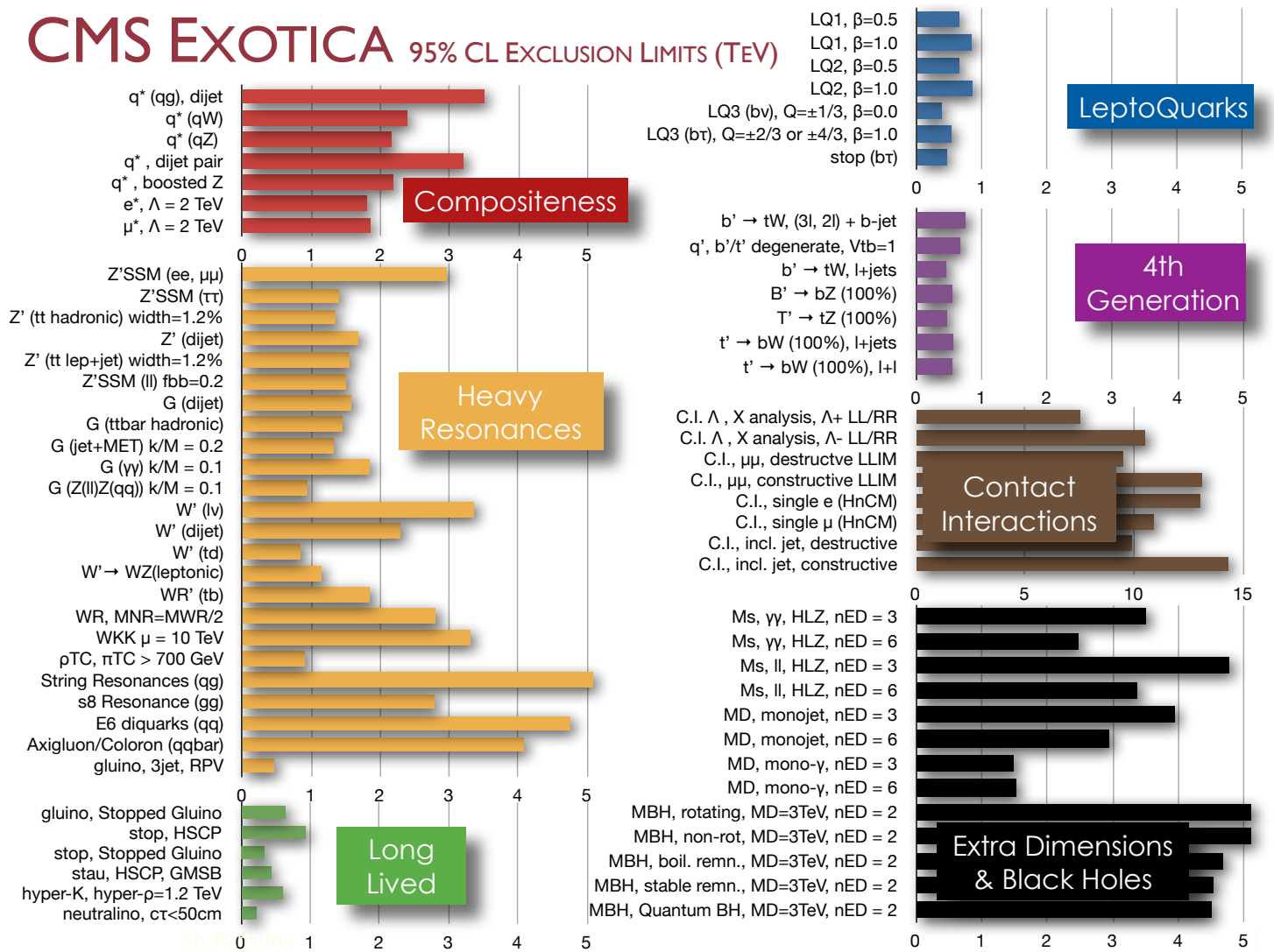


.... Can "precision" become a discovery tool ?

Key outcomes of 3 yrs at the LHC: # three

No sign of BSM, in any of the places the experiments have searched .....



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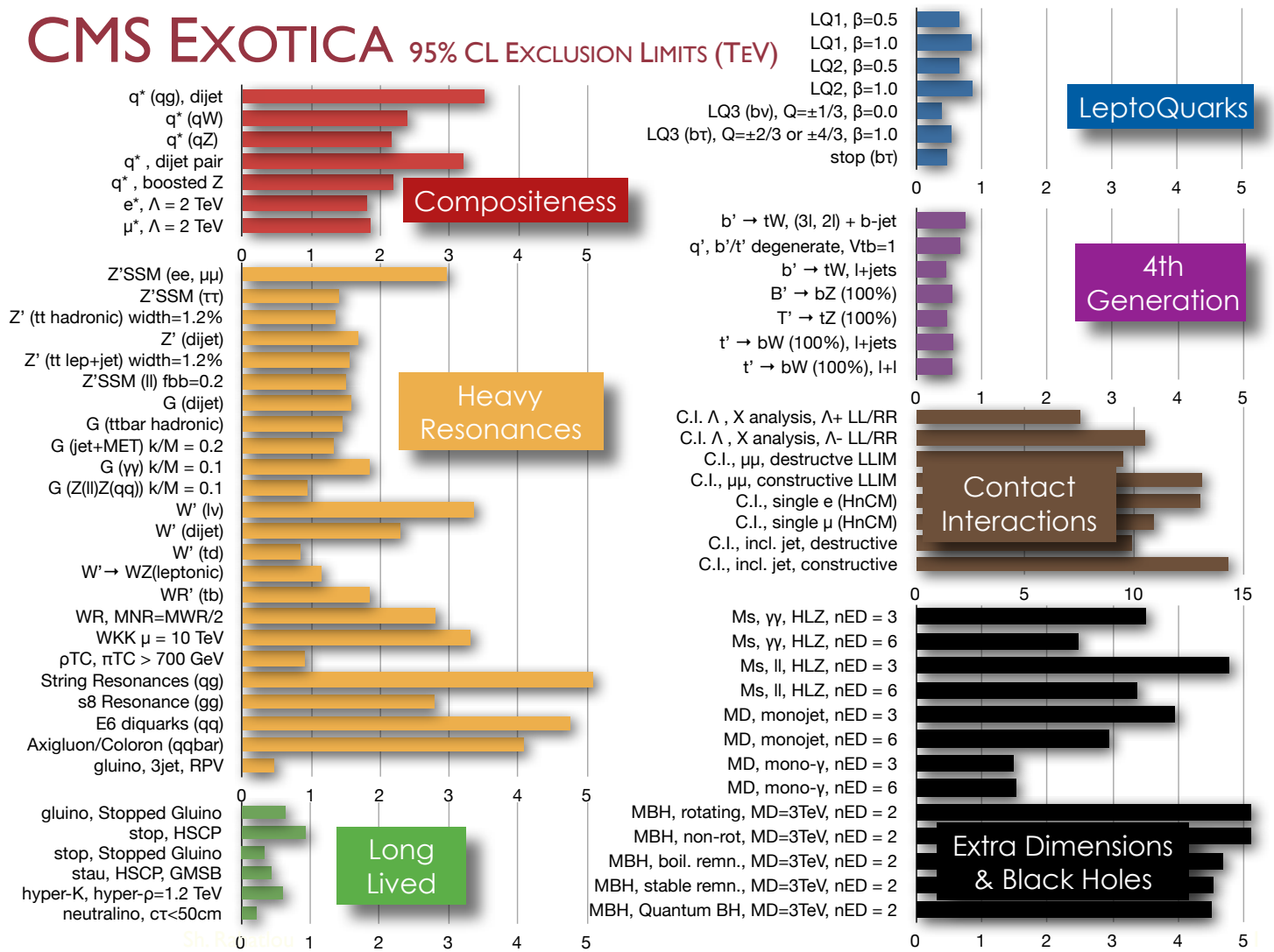

.... Where is everybody (DM, solution to the naturalness problem, sources of CPV, ...) ???

How do we access regions of parameters of BSM models where the search sensitivity is low?

Status of BSM

- Until few yrs ago, we had a benchmark model, MSSM, expected to deliver the following:
  - low-mass Higgs h^0, no heavier than ~130 GeV
  - ~TeV scale squarks and gluinos, to be seen rapidly at the LHC
    - ⇒ solution to the naturalness problem
  - extra Higgses (A^0 /H^0 /$H^{\pm}$) observed at the LHC
  - candidate for DM, confirmed by direct detection
  - interesting flavour phenomenology
    - explanation of $(g-2)_\mu$
    - sizable deviations from SM in $B(B_S \to \mu^+ \mu^-)$
    - $\mu \to e\gamma$ observed at MEG, consistent with SUSY neutrino masses induced at the GUT scale
    - CPV in the Higgs or squark/gluino sector, to explain BAU
    - electric dipole moments (e, n) measured, consistent with previous point

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- The above scenario may still happen, with a few-year delay, perhaps stretching a bit the "naturalness".
- This expectation is still high, and well justified

Naturalness

Naturalness is not a recent “fashion”: it’s an original sin of the SM itself ... See e.g.

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NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

Utrecht, The Netherlands

Aug 1979. 23 pp.

NATO Adv.Study Inst.Ser.B Phys. 59 (1980) 135

As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Pursuing naturalness beyond 1000 GeV will require theories that are immensely complex compared with some of the grand unified schemes.

A remarkable attempt towards a natural theory was made by Dimopoulos and Susskind [2]. These authors employ various kinds of confining gauge forces to obtain scalar bound states which may substitute the Higgs fields in the conventional schemes. In their model the observed fermions are still considered to be elementary.

Most likely a complete model of this kind has to be constructed step by step. One starts with the experimentally accessible aspects of the Glashow-Weinberg-Salam-Ward model. This model is natural if one restricts oneself to mass-energy scales below 1000 GeV. Beyond 1000 GeV one has to assume, as Dimopoulos and Susskind do, that the Higgs field is actually a fermion-antifermion composite field. Coupling this field to quarks and leptons in order to produce their mass, requires new scalar fields that cause naturalness to break down at 30 TeV or so.

We're finally there, at 1 TeV, facing the fears about a light SM Higgs anticipated long ago

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- Naturalness remains a guiding principle to drive the search of new phenomena at the LHC

Possible reasons for the lack of signals ...

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  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
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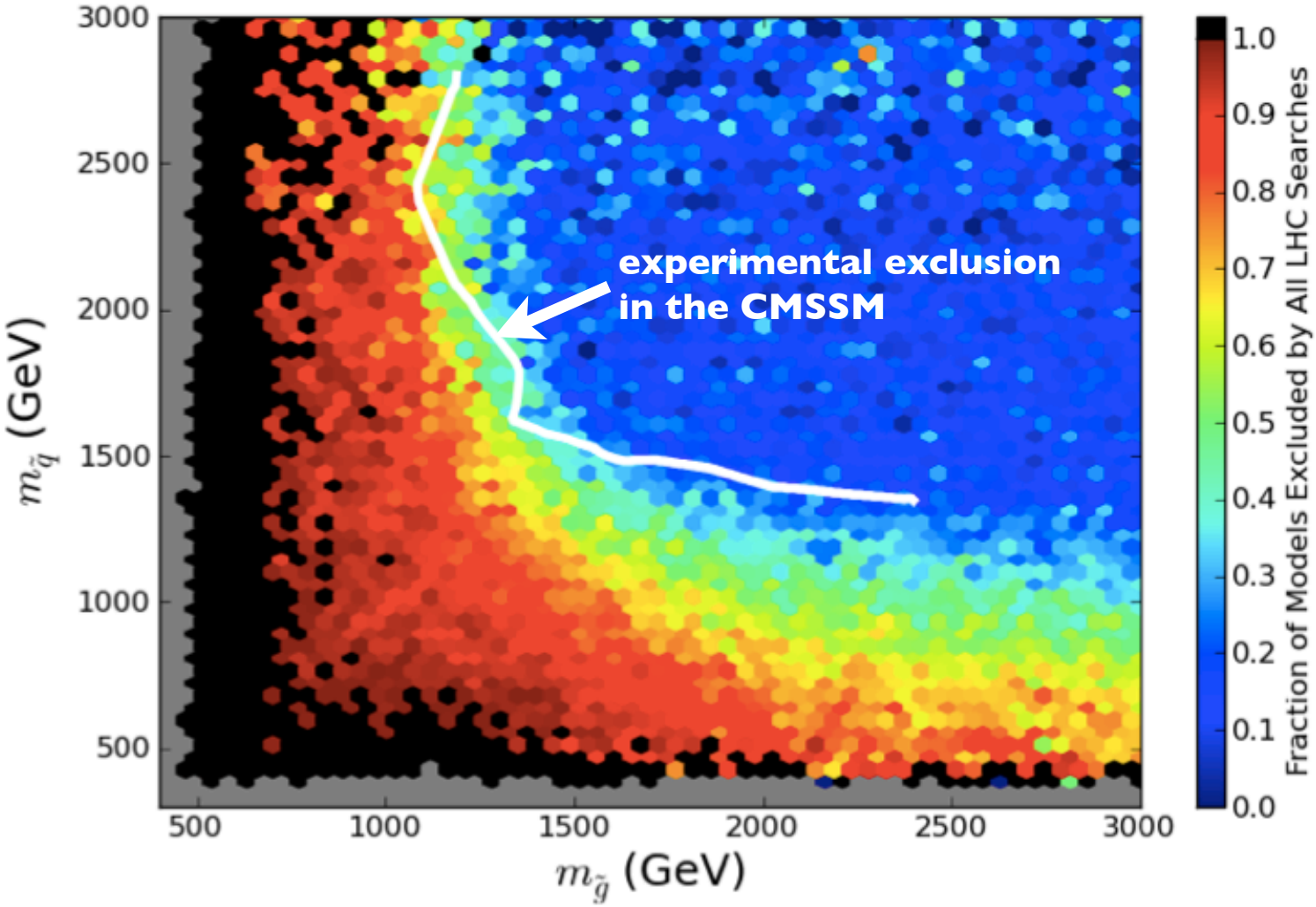
- Naturalness is an ill guided principle $\Rightarrow$ Anthropic principle

Example of ways out: explore less constrained SUSY models

Fraction of excluded models in the pMSSM (19 parameters MSSM)

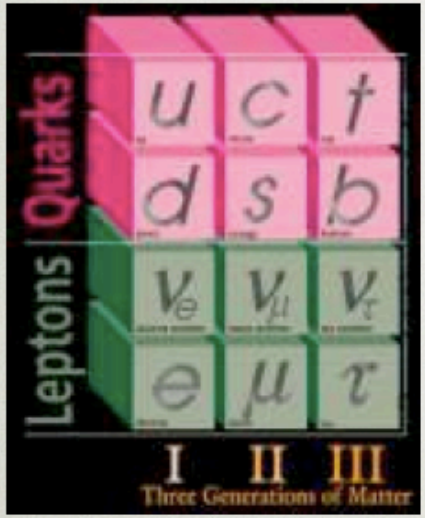


Rizzo et al, arXiv:1211.1981

Dark Matter

Our thinking has shifted

K. Zurek, Aspen 2014

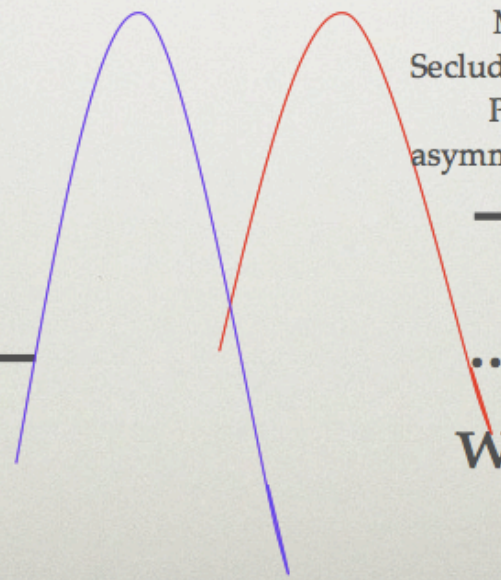


From a single, stable weakly interacting particle ..... (WIMP, axion)

Models: Supersymmetric light DM sectors, Secluded WIMPs, WIMPless DM, Asymmetric DM ..
Production: freeze-in, freeze-out and decay, asymmetric abundance, non-thermal mechanicsms ..

$M_p \sim 1$ GeV

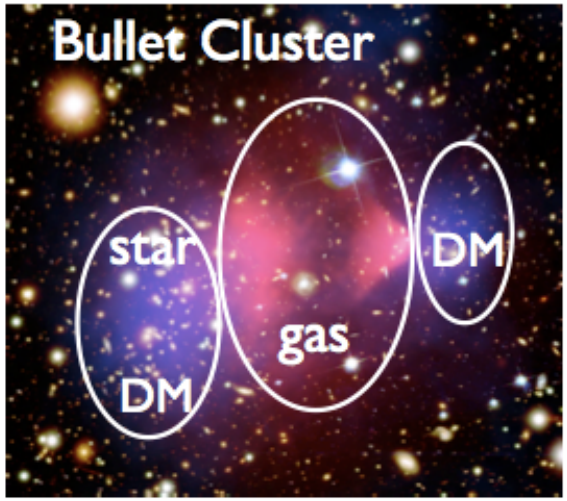
Standard Model

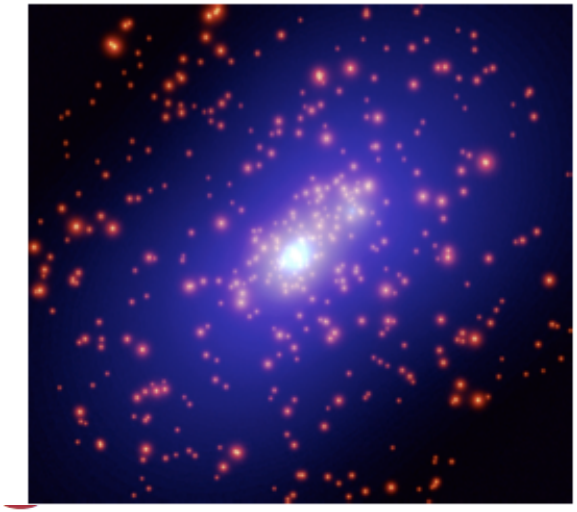


...to a hidden world with multiple states, new interactions

ASPEN 2014: https://indico.cern.ch/event/276476/

Evidence building up for self-interacting DM





- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/g) \sim 2\times10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

For a WIMP: $\sigma \sim 10^{-38}\,\mathrm{cm}^2\,(m_X/100\,\mathrm{GeV})$

SIDM indicates a new mass scale

Hai-BoYu, ASPEN 2014:
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via <u>weakly interacting</u> "portals"

Anomalies left over from run 1, some examples

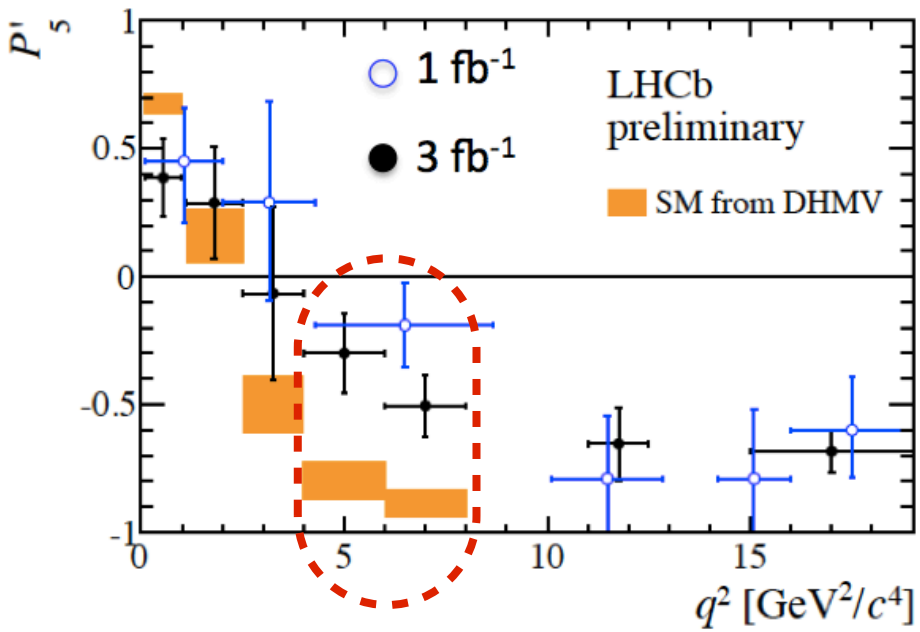
$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\%$$

CMS-PAS-HIG-14-005

stat syst

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb, arXiv:1406.6482



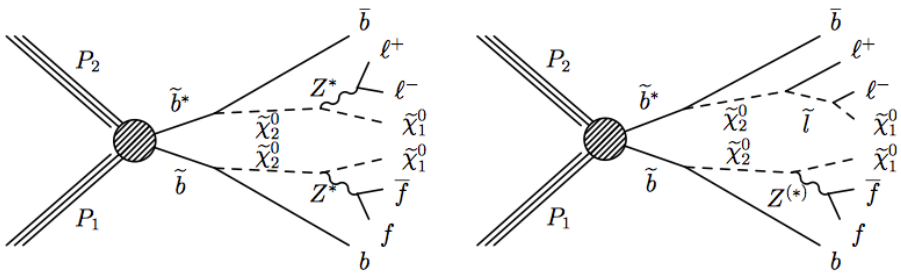
- $B \to K_* \mu^+\mu^-$ anomaly

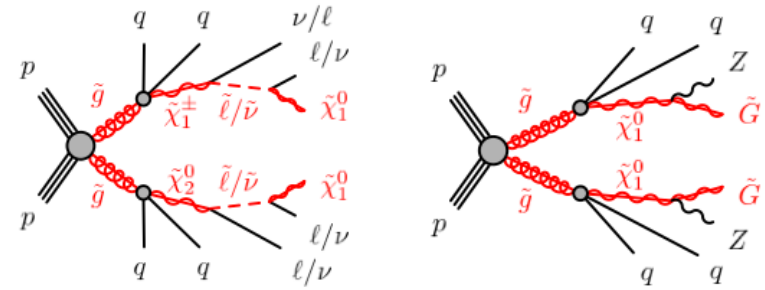
LHCb, arXiv:1308.1707 and
3fb^{-1} update LHCb−CONF−2015−002

For possible interpretation within a single BSM model
see e.g. Crivellin, D'Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged $L_\mu - L_\tau$)

Anomalies left over from run 1, some examples

Dileptons + jets + MET (SUSY searches)





CMS, http://arxiv.org/abs/1502.06031

ATLAS, http://arxiv.org/abs/1503.03290

$N_{jets\ (p_T>40\ GeV)} \geq 2$, $E_T^{miss} > 150$ GeV
or
$N_{jets\ (p_T>40\ GeV)} \geq 3$, $E_T^{miss} > 100$ GeV

low mass: m_{ll} = (20–70) GeV
On-Z: m_{ll} = (81–101) GeV

$N_{jets\ (p_T>35\ GeV)} \geq 2$, $E_T^{miss} > 225$ GeV
$H_T > 600$ GeV

On-Z: m_{ll} = (81–101) GeV

Anomalies left over from run 1, some examples

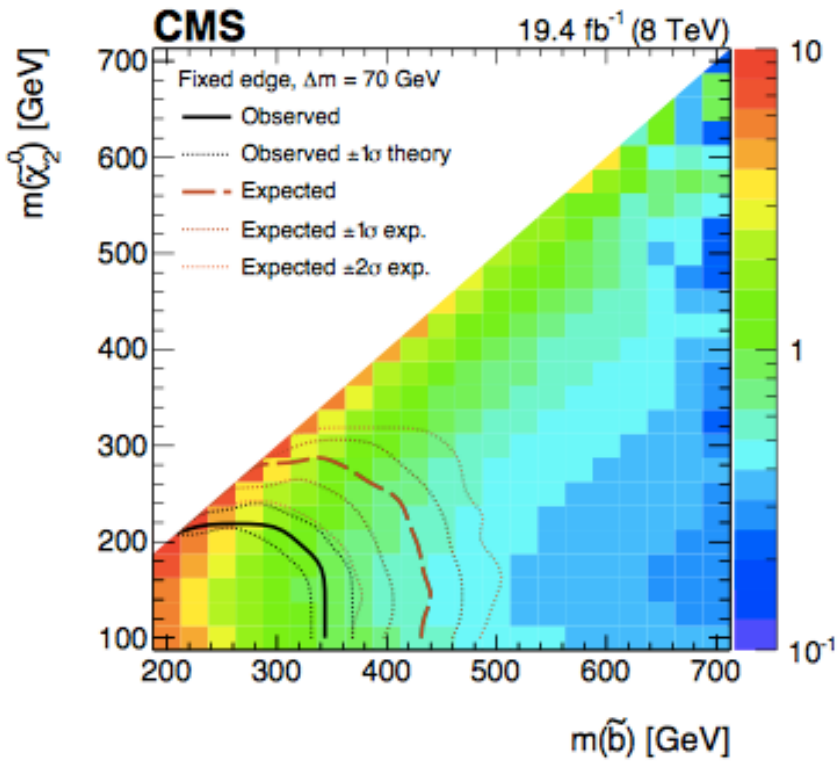
CMS, http://arxiv.org/abs/1502.06031

	Low-mass		On-Z	
	Central	Forward	Central	Forward
Observed	860	163	487	170
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$
Drell–Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17
Observed−estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}
Significance	$2.6\,\sigma$	$0.3\,\sigma$	$0.4\,\sigma$	$<0.1\,\sigma$

⇒2.6 σ

... no signal on-peak

σ(350 GeV) ratio 13TeV/8TeV ~ 4.5



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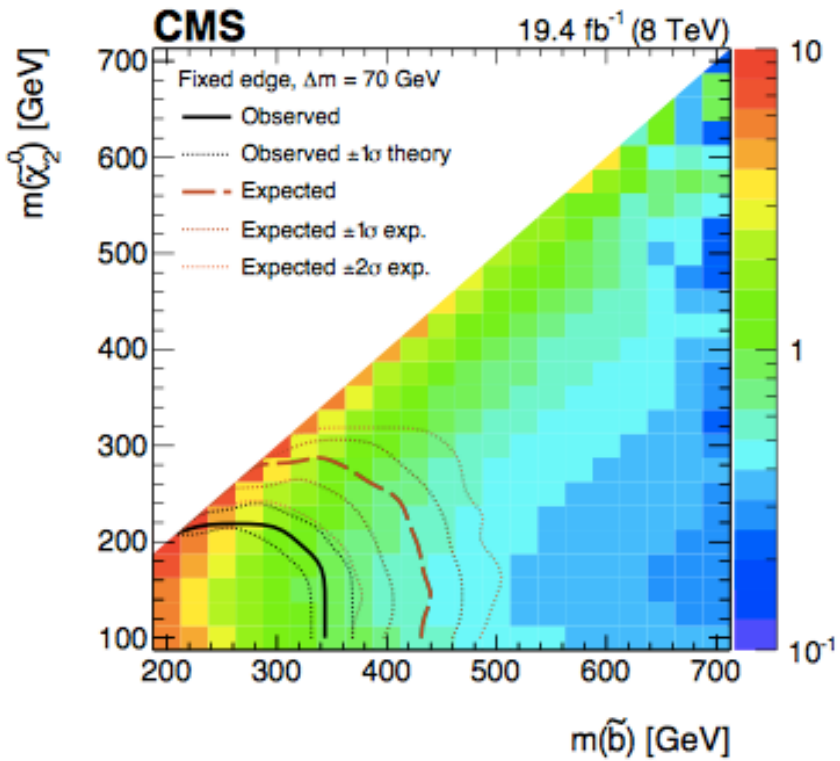
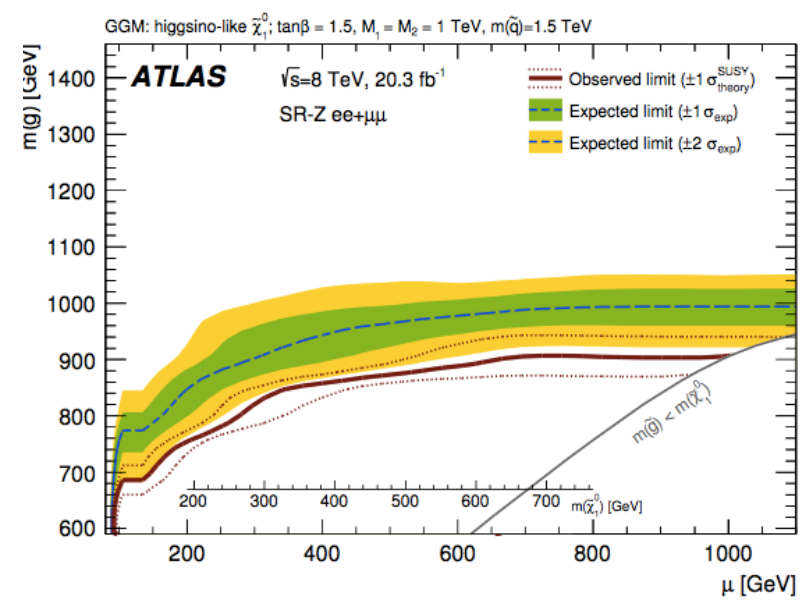


ATLAS, http://arxiv.org/abs/1503.03290

Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16 ⇒**3.0 σ**	13 ⇒**1.6 σ**	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
$Z/\gamma^* +$ jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

... but no signal off-peak

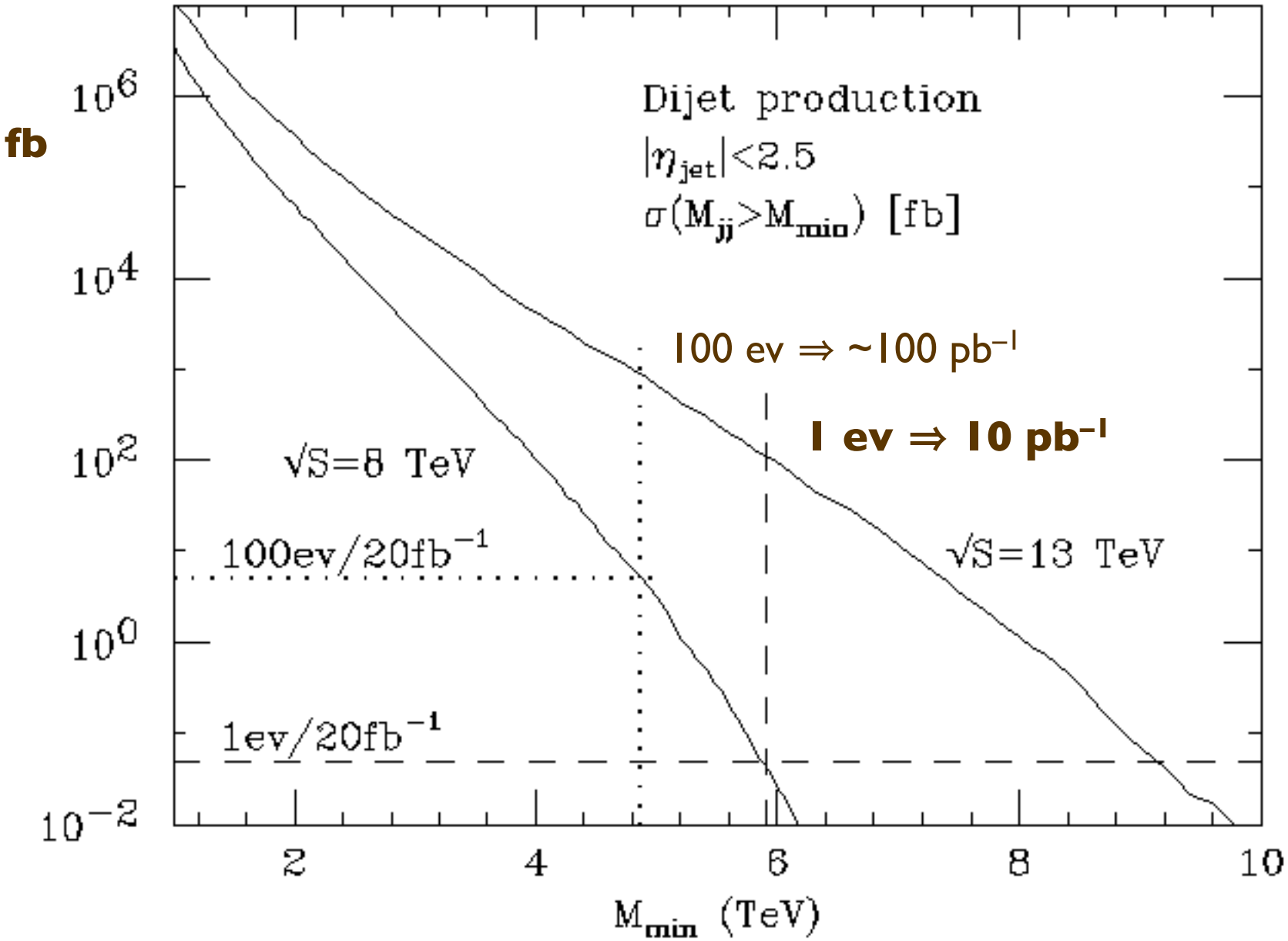
σ(800 GeV) ratio 13TeV/8TeV ~ 8.5



Already more than 10 TH interpretation papers on arXiv ....

How long before run 2 extends the discovery reach of run 1?

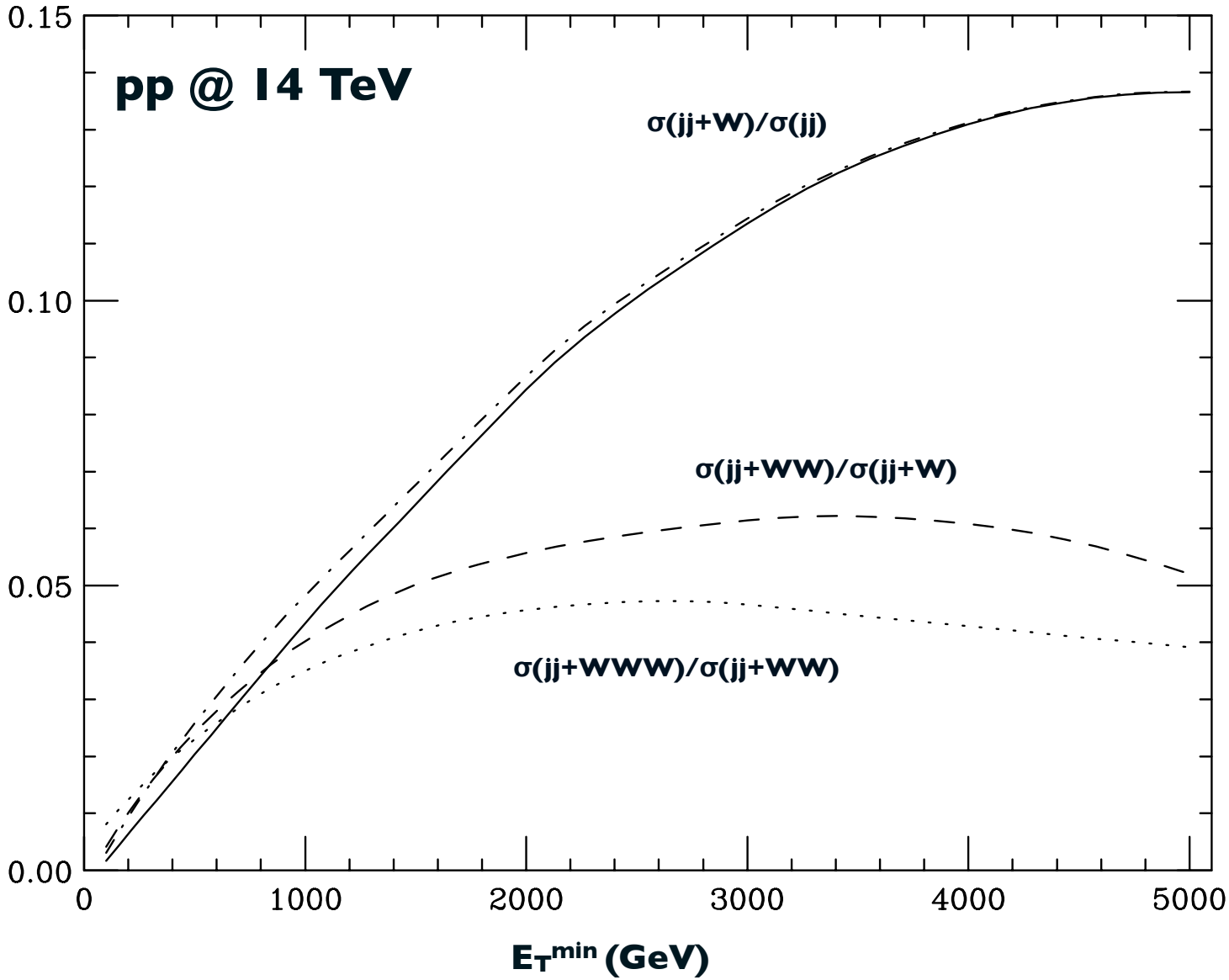
Rate comparison 8 vs 13 TeV: dijet production



Remarks

- Large statistics of jets with E_T in the multi-TeV range =>
  - start measurements of large EW effects

W production in dijet events



σ(jj+W)/σ(jj)

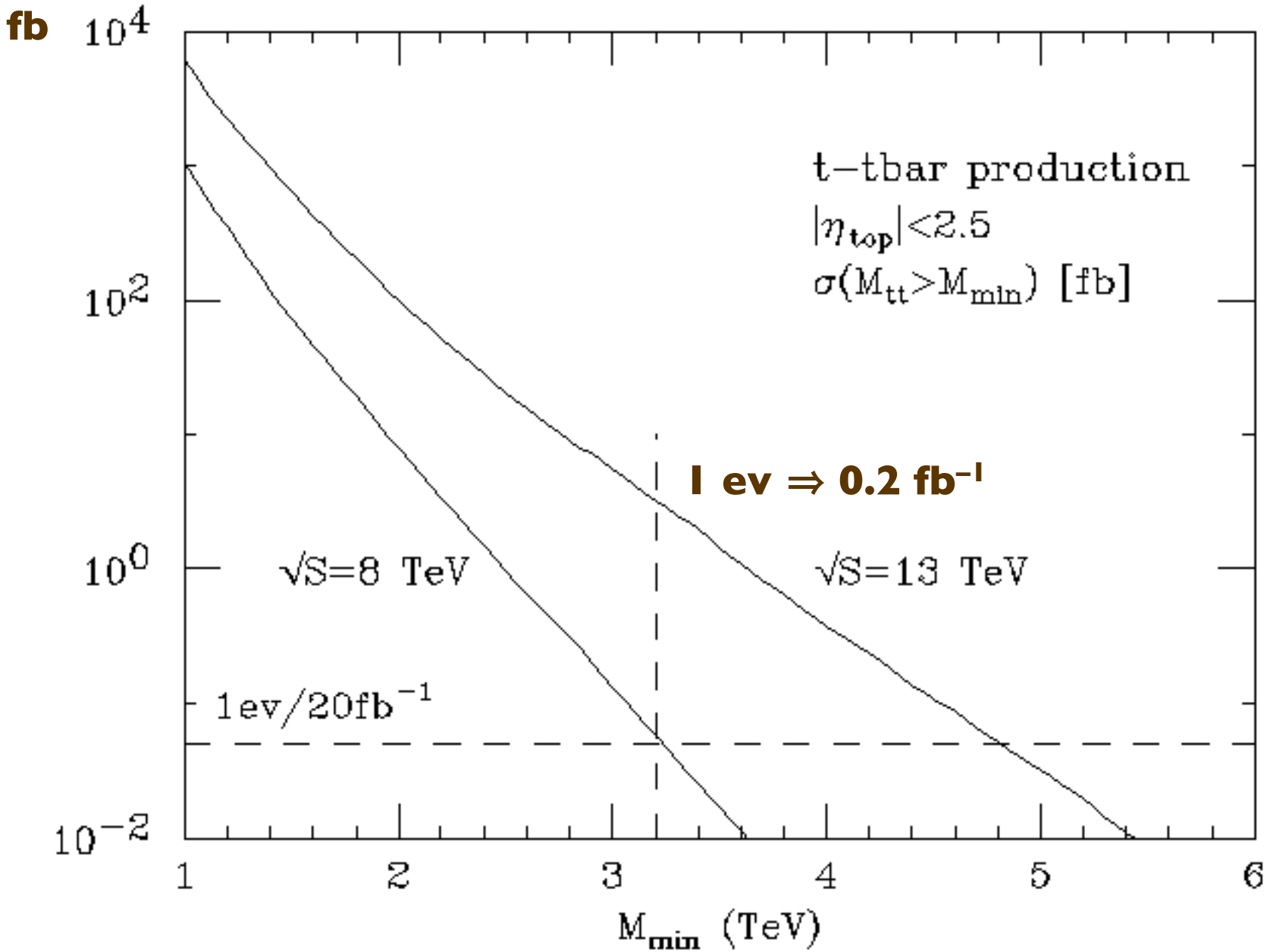
with

$E_{T,leading\ jet} > E_T^{min}$

Dotdashes: σ(jj) in the denominator replaced by σ(jj, no gg→gg)

- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **It would be interesting to go after these W and Zs, and verify their emission properties**

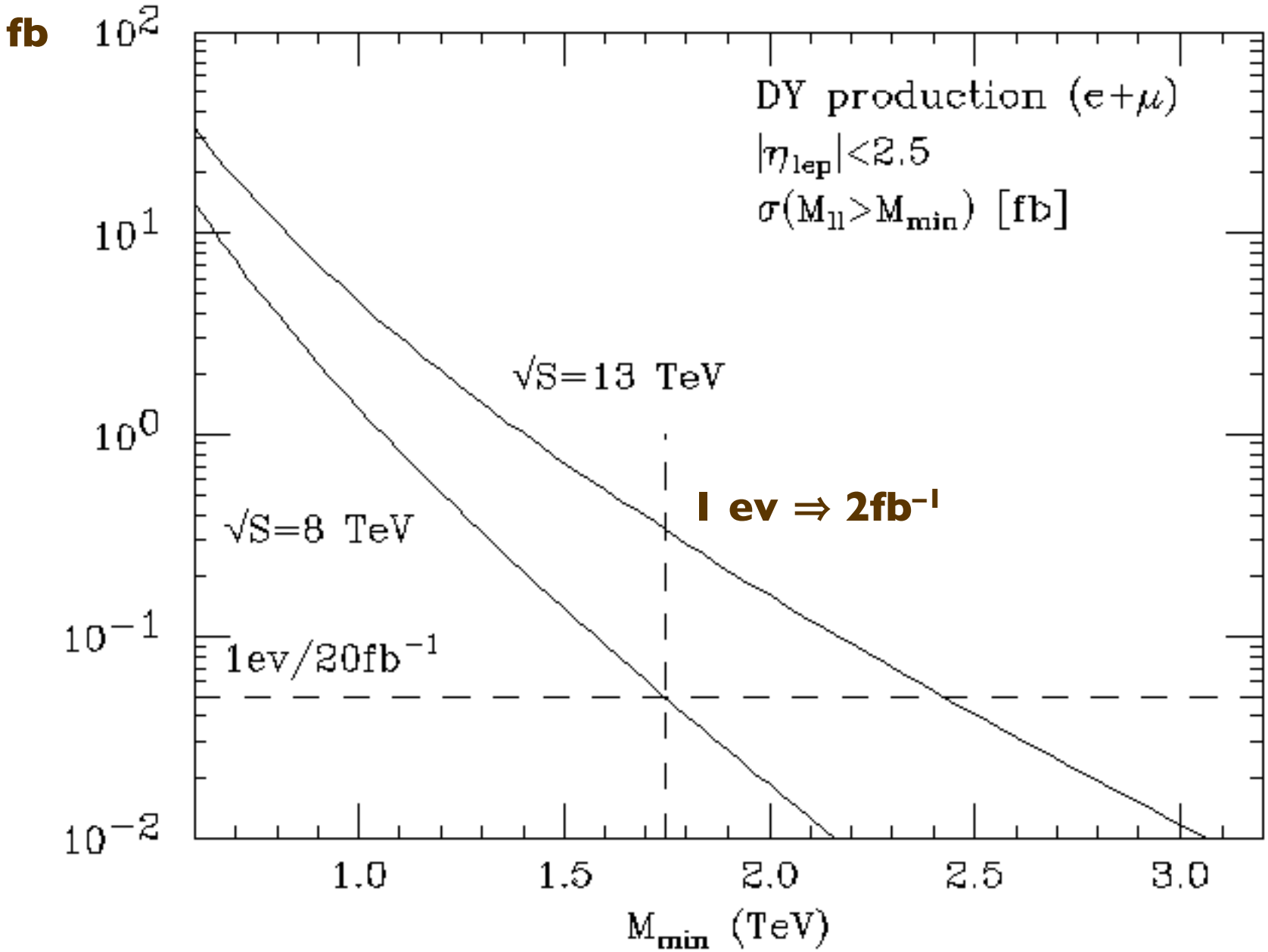
Rate comparison 8 vs 13 TeV: t tbar production



Remarks

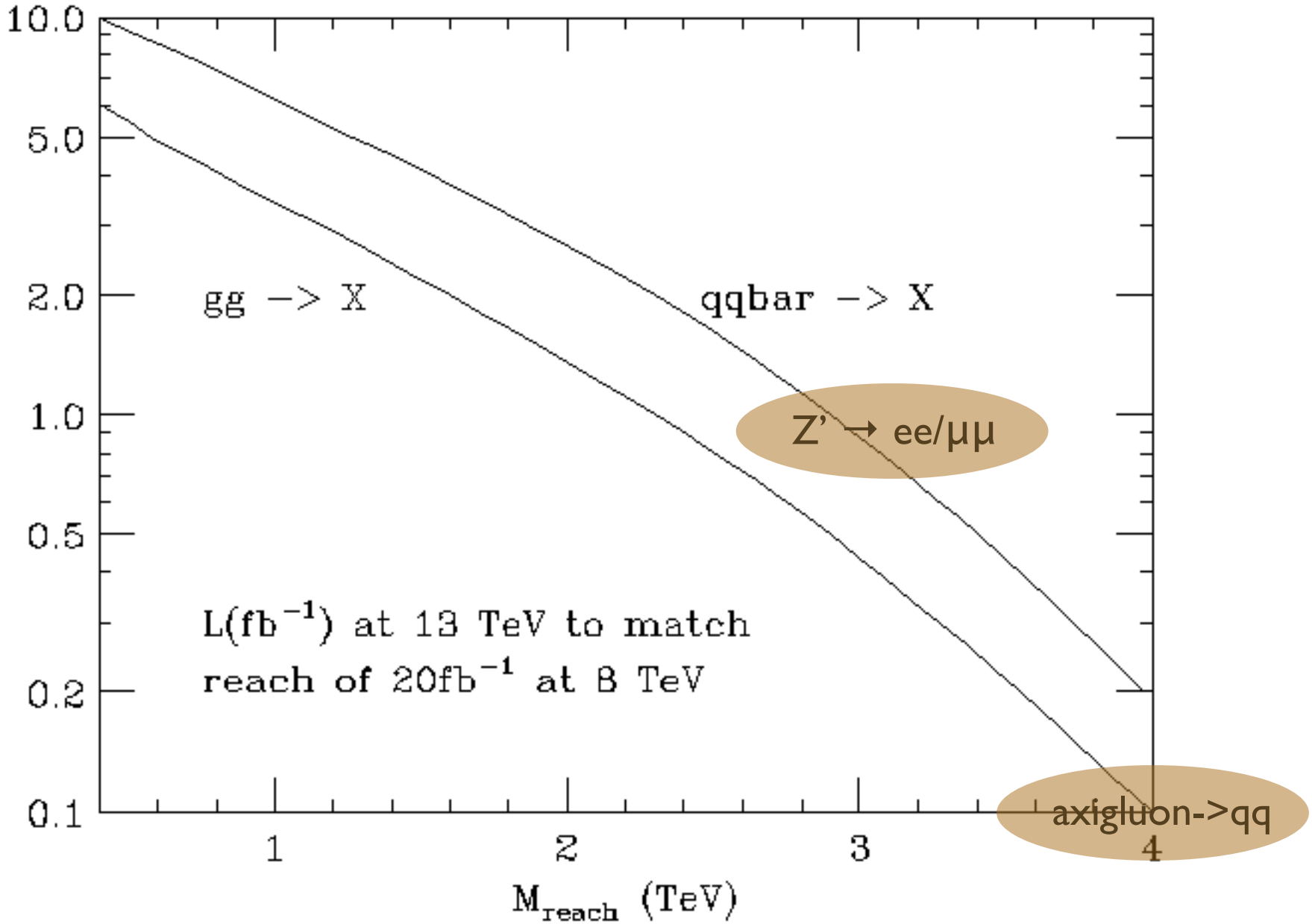
- After ~20 fb^{-1} top quark E_T probed above 2-3 TeV =>
  - Lorentz factor γ larger than 10:
    - top jet ~ b jet at LEP !
  - all top decay products within a cone with R<0.1
    - "hyper"-boosted regime for top tagging ...

Rate comparison 8 vs 13 TeV: Drell-Yan production



1 ev ⇒ 2fb^{-1}

13 TeV luminosity required to match BSM sensitivity reached so far ($20fb^{-1}$) at 8 TeV

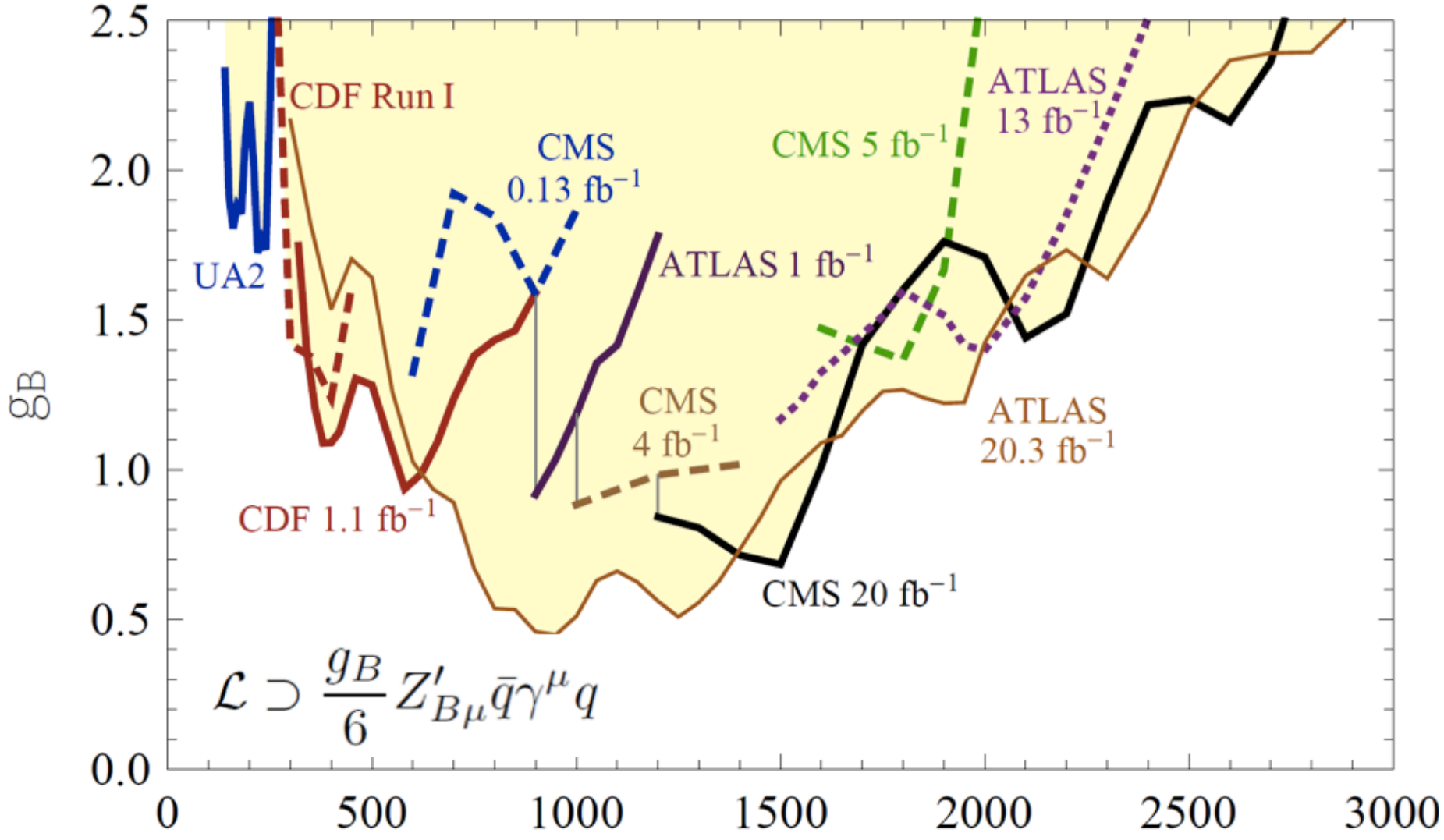


See also http://collider-reach.web.cern.ch, by Salam and Weiler

Remarks

- Large statistics of jets with E_T in the multi-TeV range =>
  - start measurements of large EW effects
- Further studies at high energy/luminosity should not just focus on pushing the high mass end, but also on exploring low-couplings at low mass

Current g_B vs. $M_{Z'}$ limits: Z'_B dijet resonance

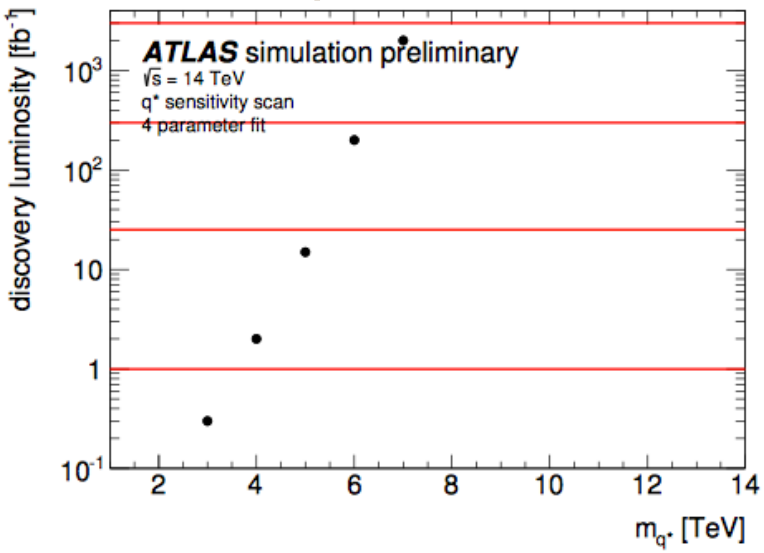


B. Dobrescu, F. Yu arXiv:1306.2629, updated (F.Yu) with new ATLAS arXiv:1407.1376 results

ATLAS projections for early discovery in run 2

Dijet *resonances: ATL-PHYS-PUB-2015-004*

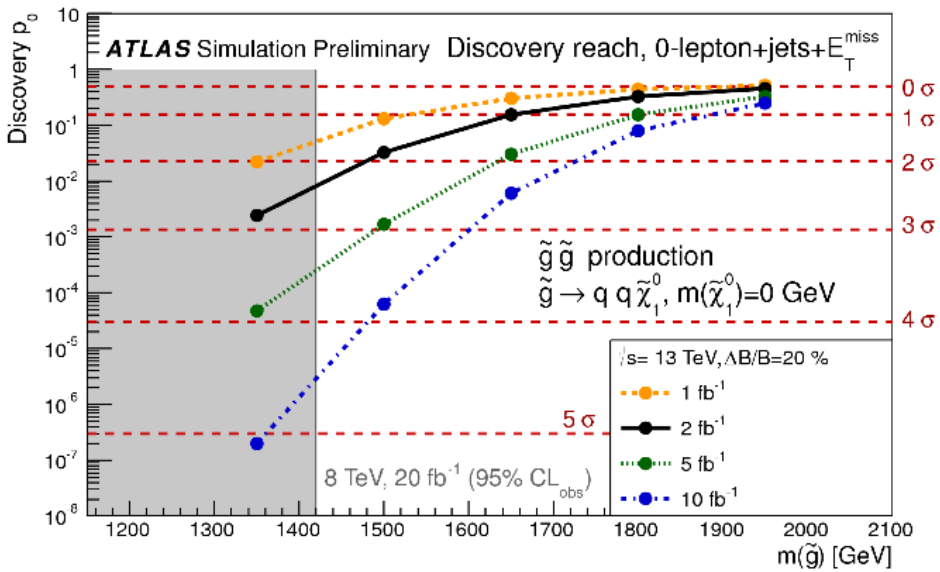
Discovery reach vs ∫L

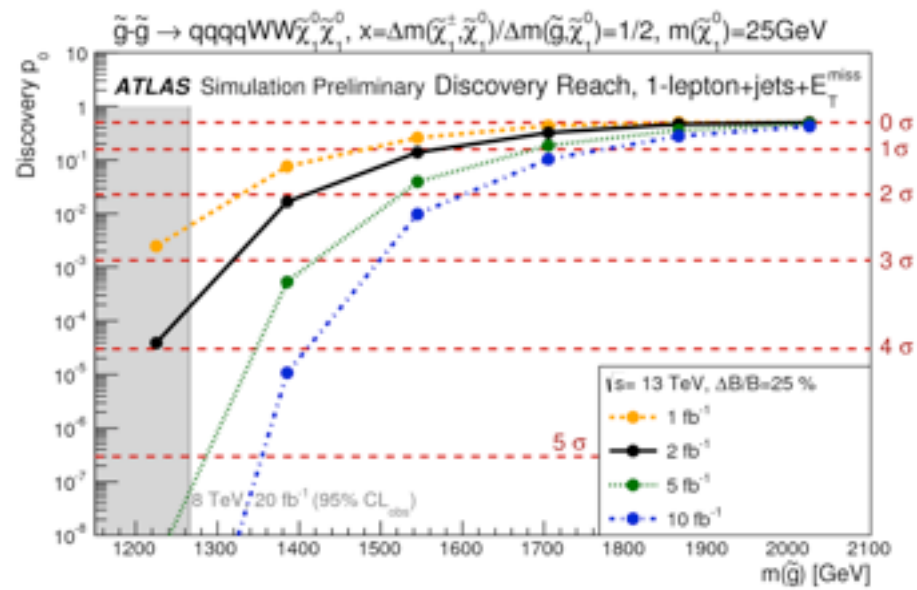


Exclusion reach vs ∫L

integrated luminosity [fb^{-1}]	m_{q^*} [TeV]
0.1	4.0
1	5.0
5	5.9
25	6.6
300	7.4
3000	8.0

SUSY: *ATL-PHYS-PUB-2015-005*





Remarks

- For what concerns the extension of the discovery reach, nothing in the future of the LHC programme will match the step forward from 20 fb^{-1} at 8 TeV to 100 fb^{-1} at 13 TeV

Higgs rates, 8 vs 13 TeV

(Discussion of Higgs physics status, issues and prospects in Toni Pich's talk)

	σ(8 TeV)	σ(13 TeV)	ratio
gg→H	19.3	43.9	**2.3**
VBF	1.58	3.75	**2.4**
WH	0.70	1.38	**2.0**
ZH	0.42	0.87	**2.1**
ttH	0.13	0.51	**3.9**

From Higgs Cross Section WG, @m_H = 125 GeV

⇒ run 2 statistics ~10-20 times larger than run 1

run I H statistics in perspective

Most recent updates of Higgs results at CERN PH LHC seminars:

ATLAS H studies: P. Onyisi, http://indico.cern.ch/event/360241/
CMS H studies: P. Musella, http://indico.cern.ch/event/360238/
ATLAS/CMS m_H : N.Wardle, http://indico.cern.ch/event/360243/

Mass:

$$m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})\ \text{GeV}$$

Rate (μ=data/SM for $\sigma \cdot$ BR) :

$$\mu_{ATLAS} = 1.18 \pm 0.10(\text{stat}) \pm 0.07(\text{expt}) \pm 0.08(\text{theory})$$

$$\mu_{CMS} = 1.00 \pm 0.09(\text{stat}) \pm 0.07(\text{expt}) \pm 0.08(\text{theory})$$

H @ run 2 in perspective

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- **Run 1 → Run 2 will mark the transition from statistics-limited to systematics-dominated Higgs physics**
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- Higher stat will allow
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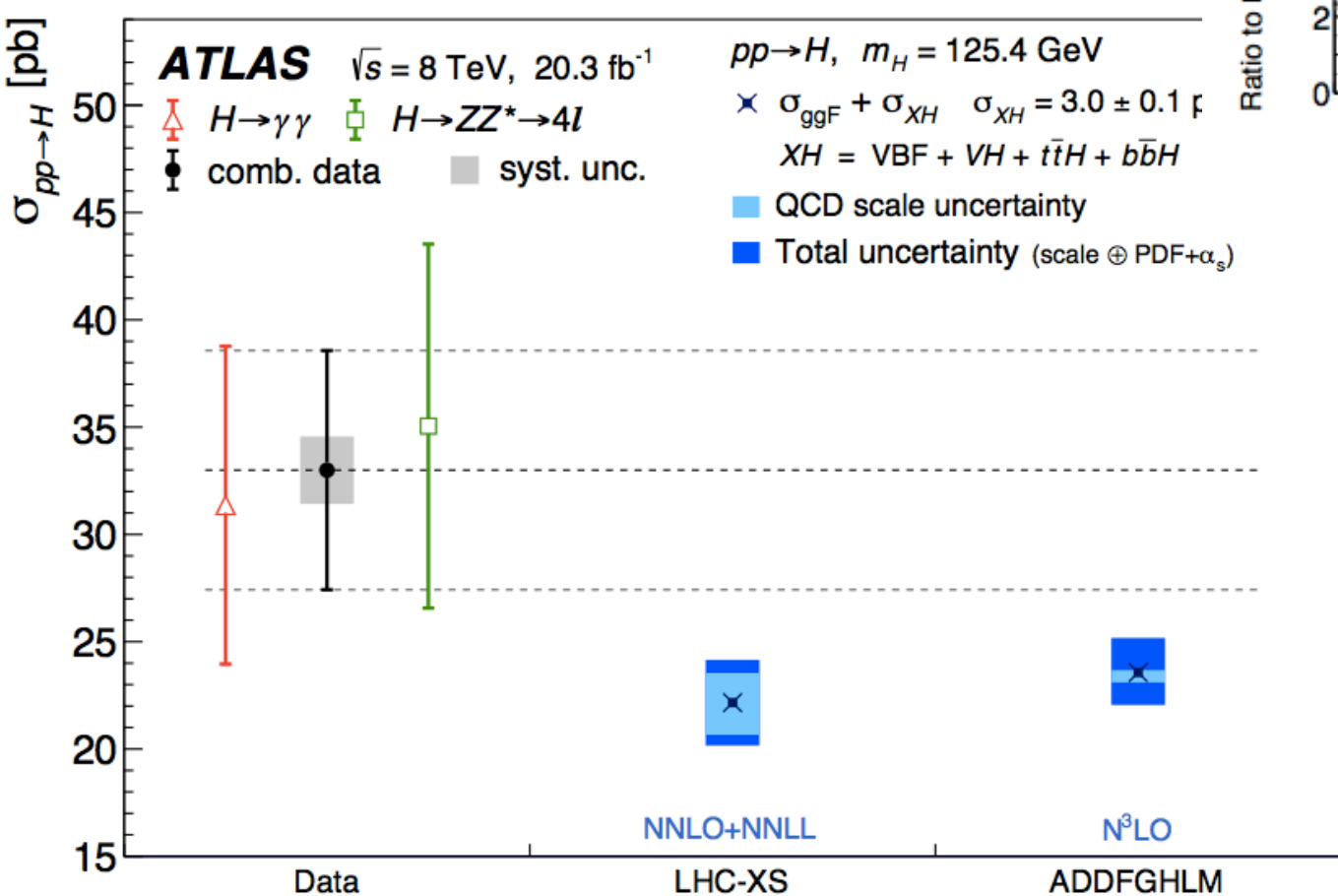
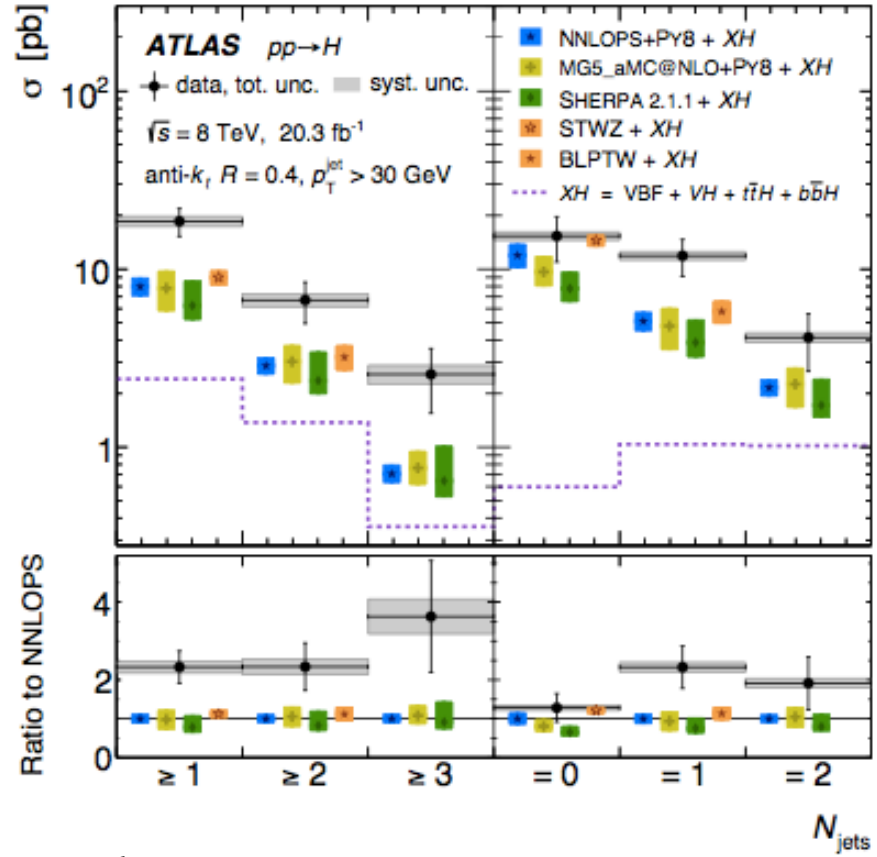
  - to fragment studies into more signal regions, with complementary systematics and sensitivity to signal properties
- Run 2 will prepare the ground for the work needed to fully exploit the ultimate HL-LHC luminosity in terms of Higgs physics, and will give us a much more clear picture of what the ultimate precision targets can be

Example: ATLAS, arXiv:1504.05833

Total and Differential Higgs Cross Sections from H → γγ and H →ZZ* →4l

$\sigma(pp \to H) = 33.0 \pm 5.3(\text{stat}) \pm 1.6(\text{syst})$ pb
$= 33.0 \pm 5.5(\text{tot run 1})$ pb





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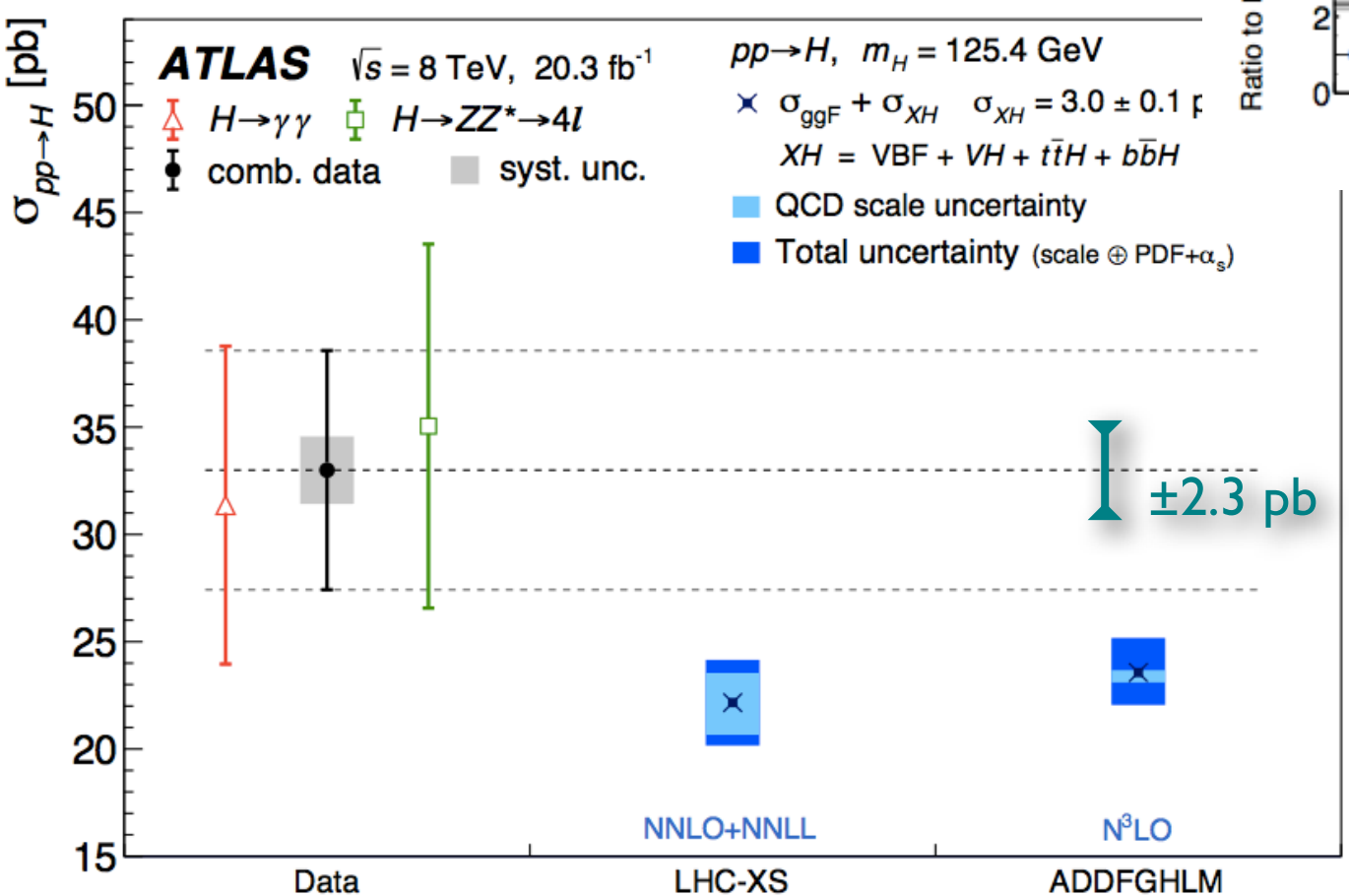
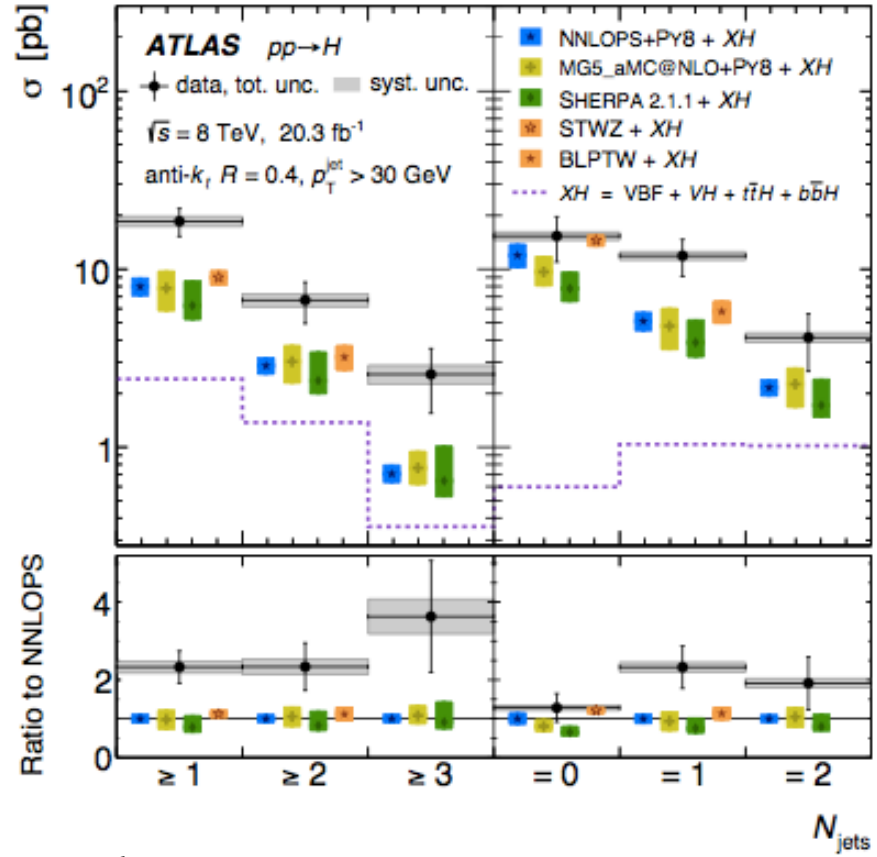
x 10 statistics ⇒

$\sigma(pp \to H) = XX \pm 2.3$ pb





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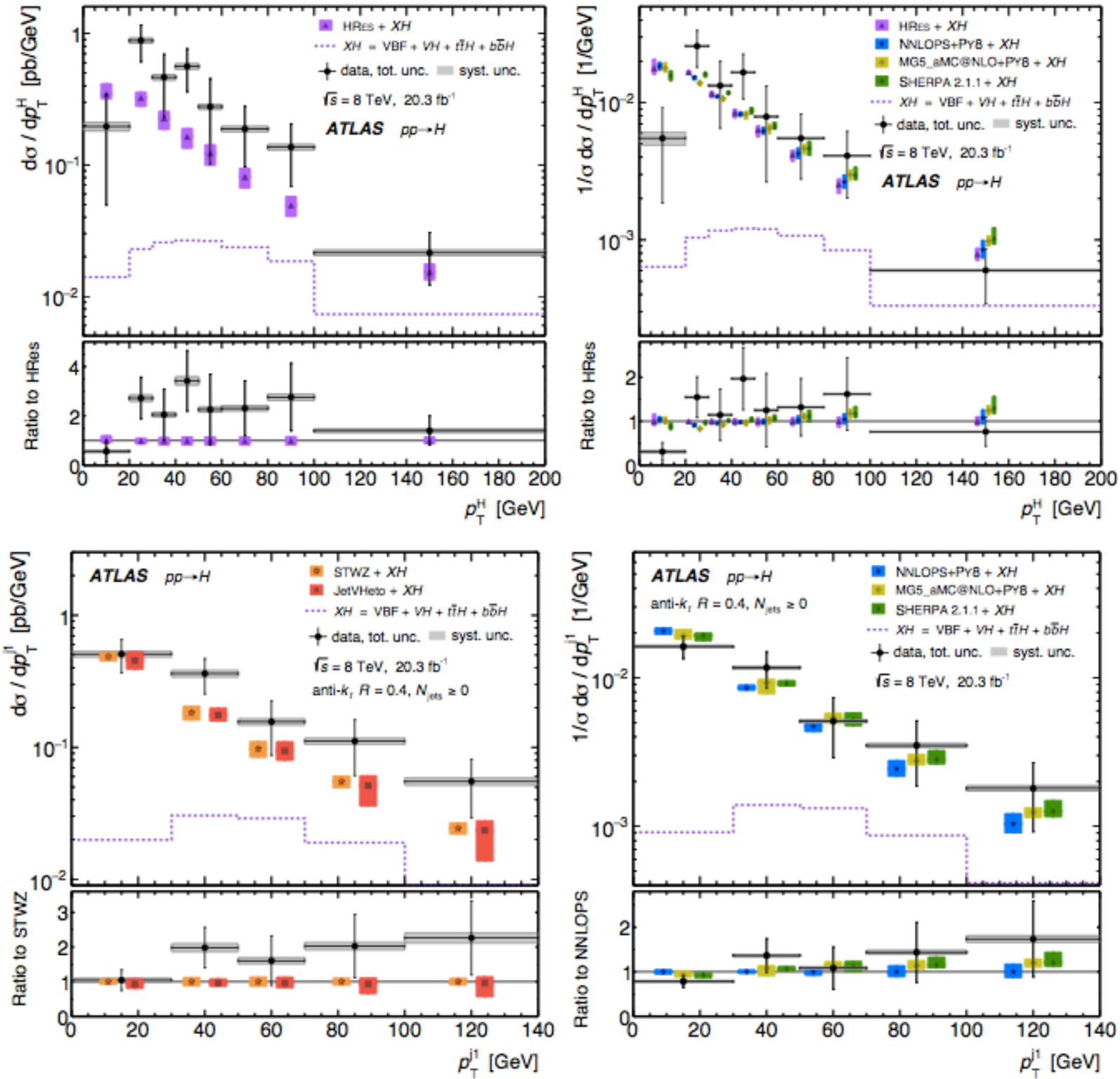
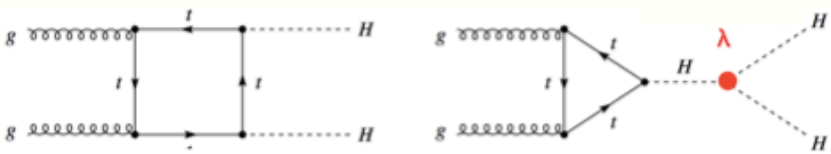
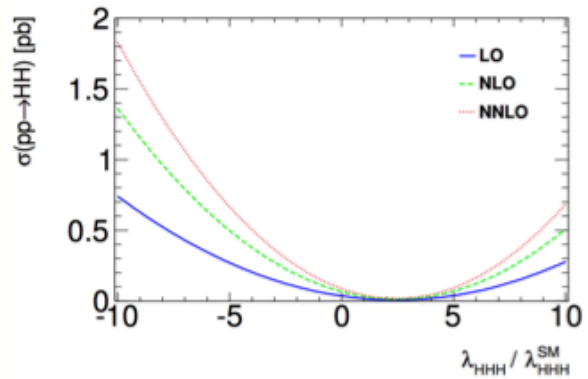
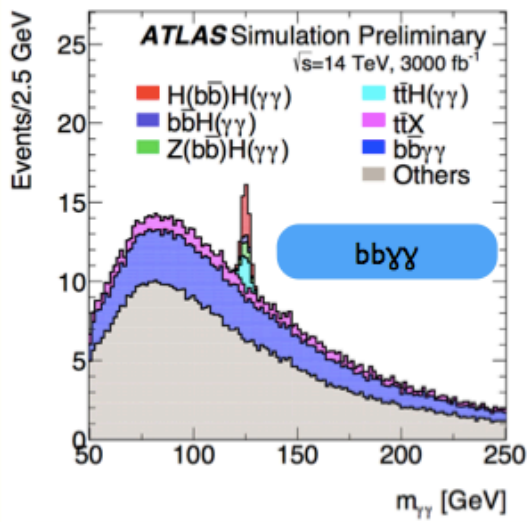

HRes + XH
XH = VBF + VH + tt̄H + bb̄H
data, tot. unc.
syst. unc.
√s = 8 TeV, 20.3 fb⁻¹
ATLAS pp→H
dσ / dp_T^H [pb/GeV]
Ratio to HRes
p_T^H [GeV]
NNLOPS+PY8 + XH
MG5_aMC@NLO+PY8 + XH
SHERPA 2.1.1 + XH
1/σ dσ / dp_T^H [1/GeV]
STWZ + XH
JetVHeto + XH
anti-k_t R = 0.4, N_jets ≥ 0
dσ / dp_T^j1 [pb/GeV]
Ratio to STWZ
1/σ dσ / dp_T^j1 [1/GeV]
Ratio to NNLOPS
p_T^j1 [GeV]

Not quite for run 2: Higgs selfcoupling: HH→bbγγ

- Measurement of the Higgs pair production to probe the trilinear coupling and thus the Higgs potential
- Negative interference between the box and s-channel leading to suppression of event yield



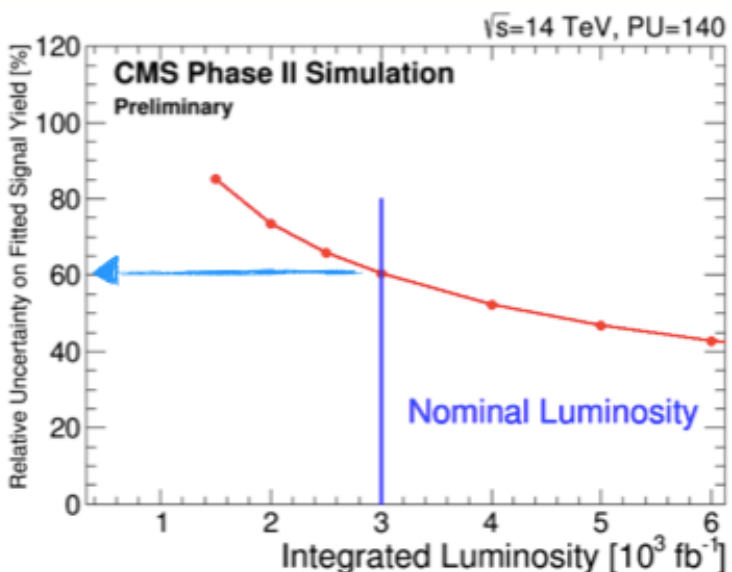




process	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2
S/√B (split barrel and endcap)	1.3

ATL-PHYS-PUB-2014-019

Physics Performance for 2nd ECFA workshop



3ab^{-1}: 60% precision on signal yield (SM coupling)

→ 40% with 2 expts

→ 30% including other channels?

→ 25% with experience?

→ ?? %

must be optimistic!

Not to be forgotten: continued improvement in the measurement of SM parameters and dynamics:

- m_{top} , m_W , $\sin^2\theta_W$, CKM and flavour
- PDFs
- spectroscopy:
  - heavy-flavoured hadrons (esp baryons)
  - meson spectroscopy in exclusive central production: $pp \rightarrow pp\ X$ (to explore e.g. nature of 0^{++} glueball candidates like $f_0(1710)$ (TOTEM/CMS, ATLAS/AFP))
- very forward physics of relevance to cosmic ray shower modeling (LHCf)
- elastic, diffractive, total cross sections (all expts)
- HI collisions, including pA
- .....

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