Physics at run 2: prospects and opportunities

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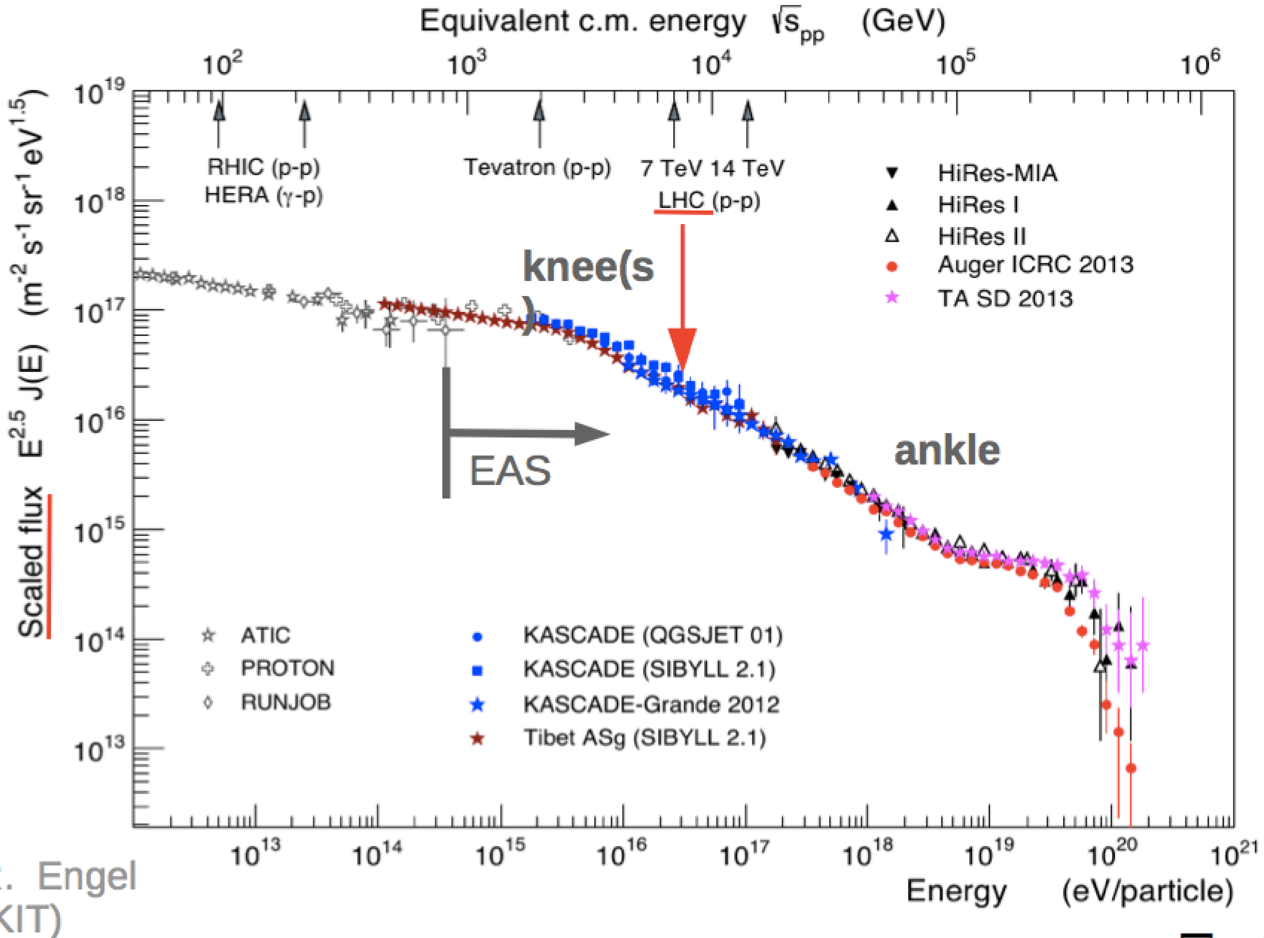
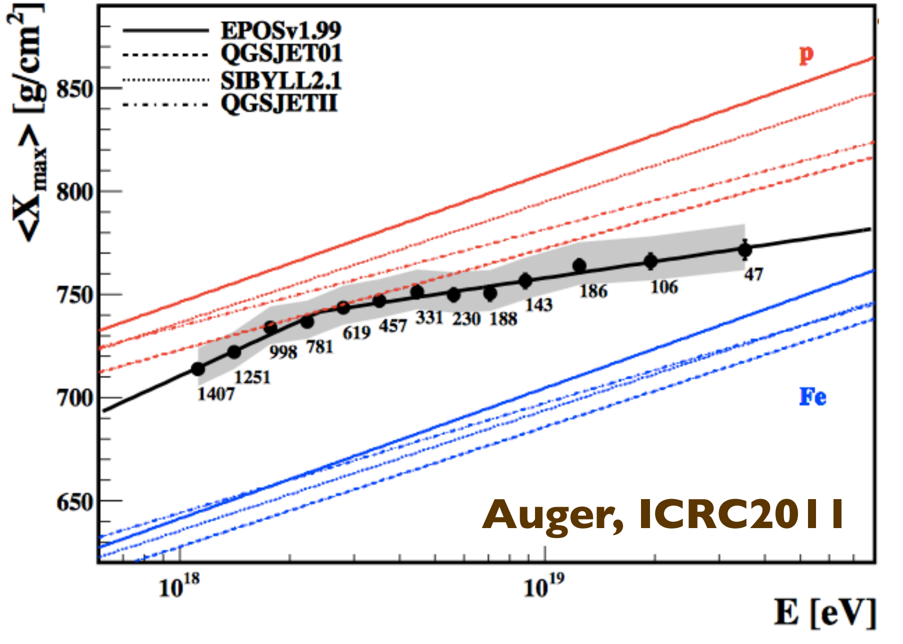
  ➡ *how much richer and broader can the physics programme become? which new surprises?*

some examples, off the beaten path of higgs, susy etc

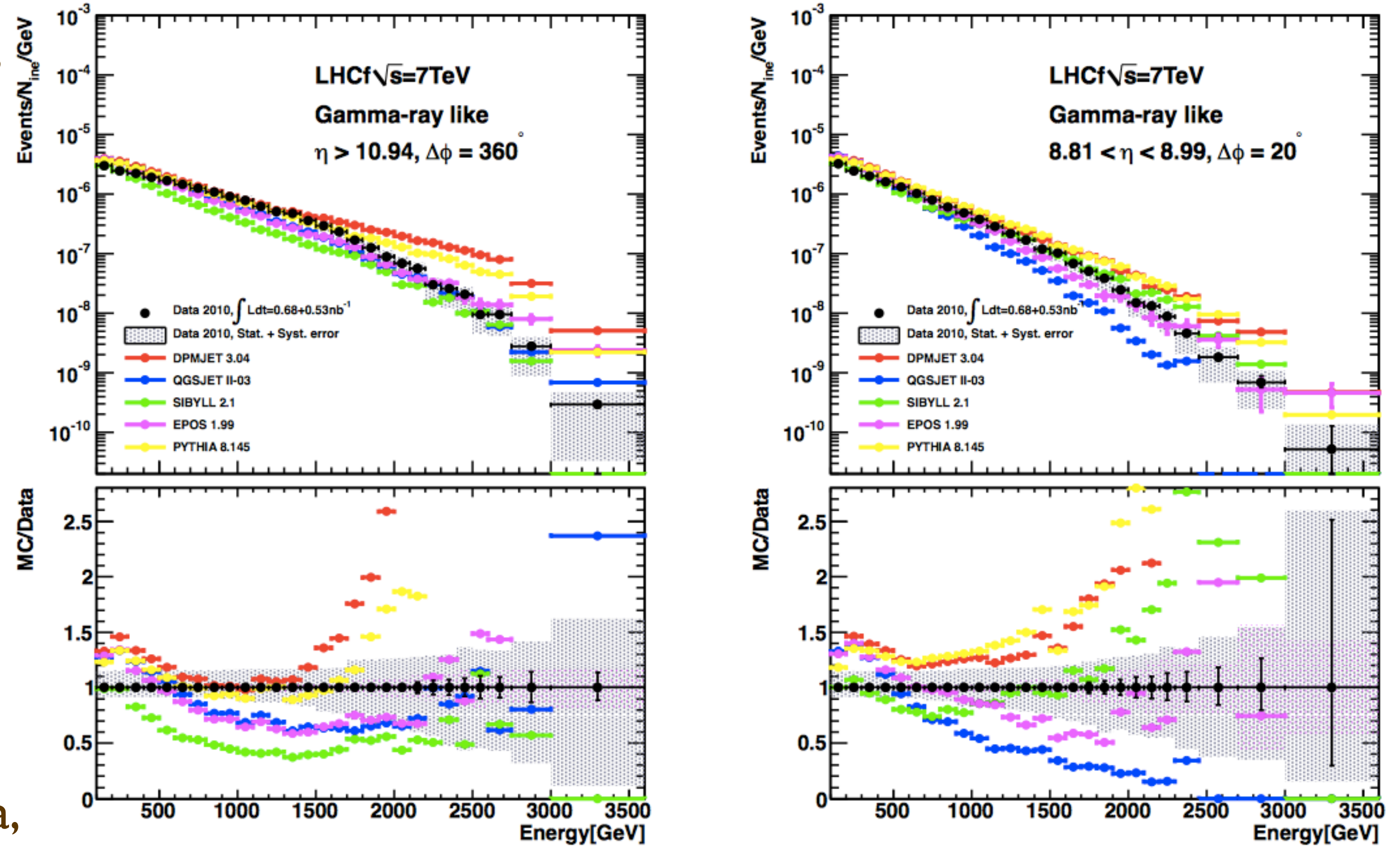
LHC & CRs



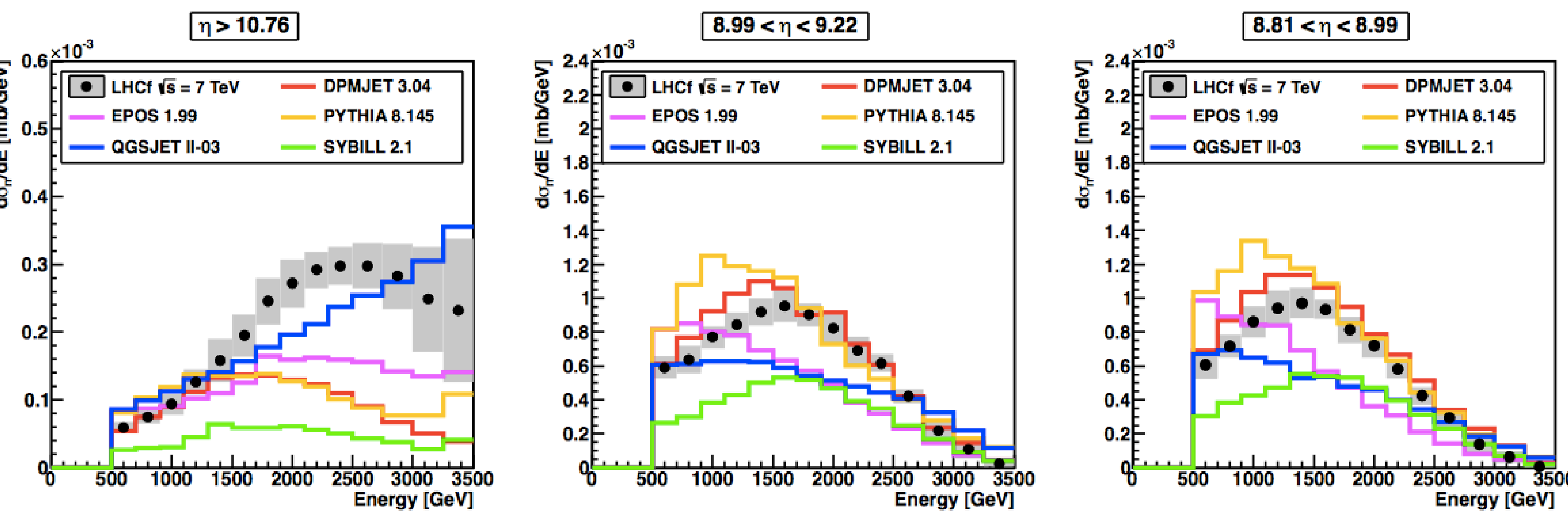
R. Engel (KIT)



LHCf, fwd photon energy spectra, arXiv:1104.5294

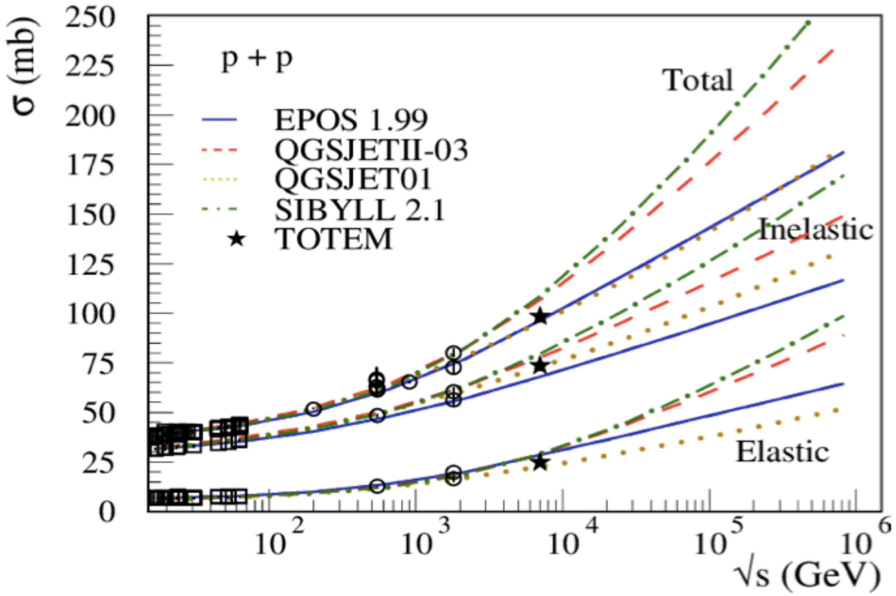


LHCf, fwd neutron energy spectra, arXiv:1503.03505

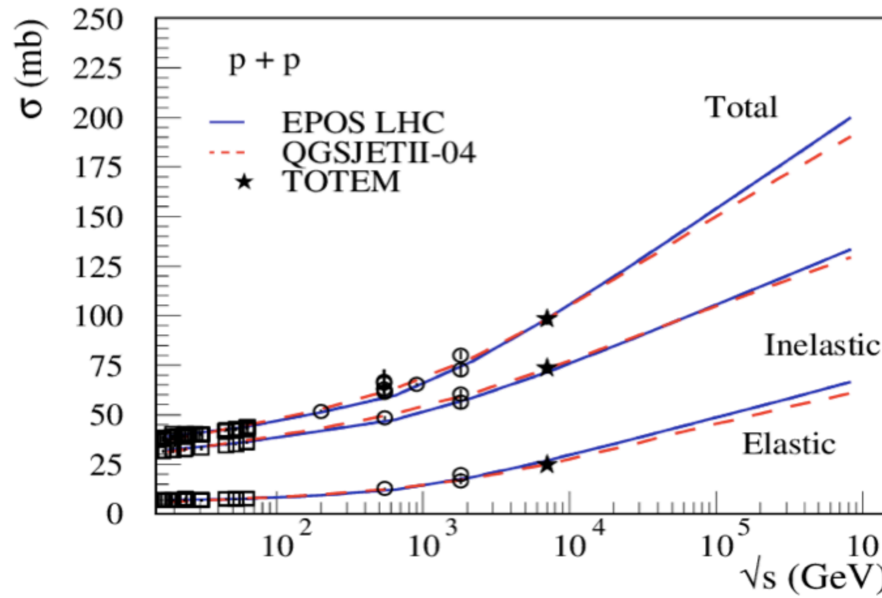


Tuning CR MCs with LHC data (mostly from the first few pb^{-1} ....)

Pre - LHC



Post - LHC



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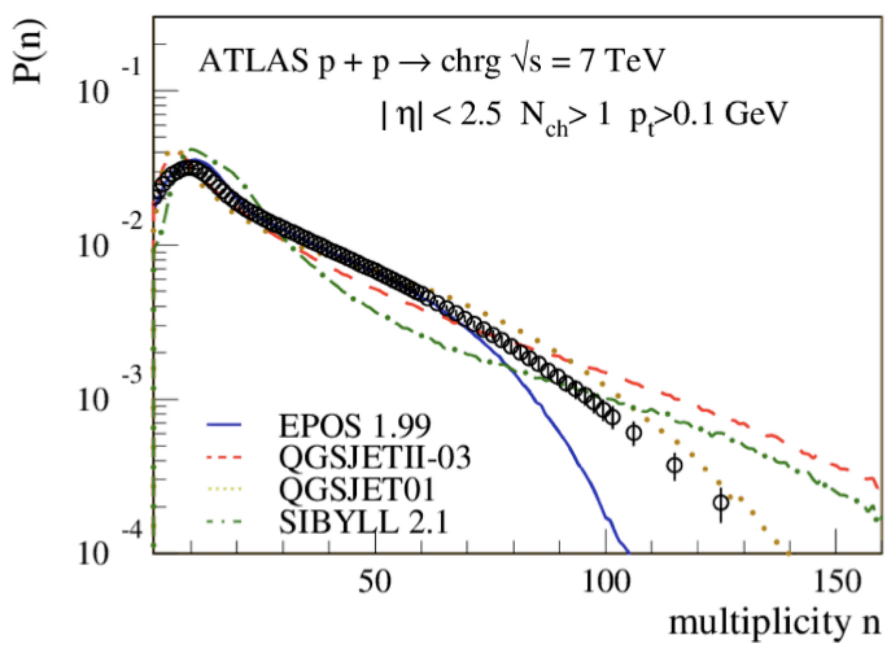
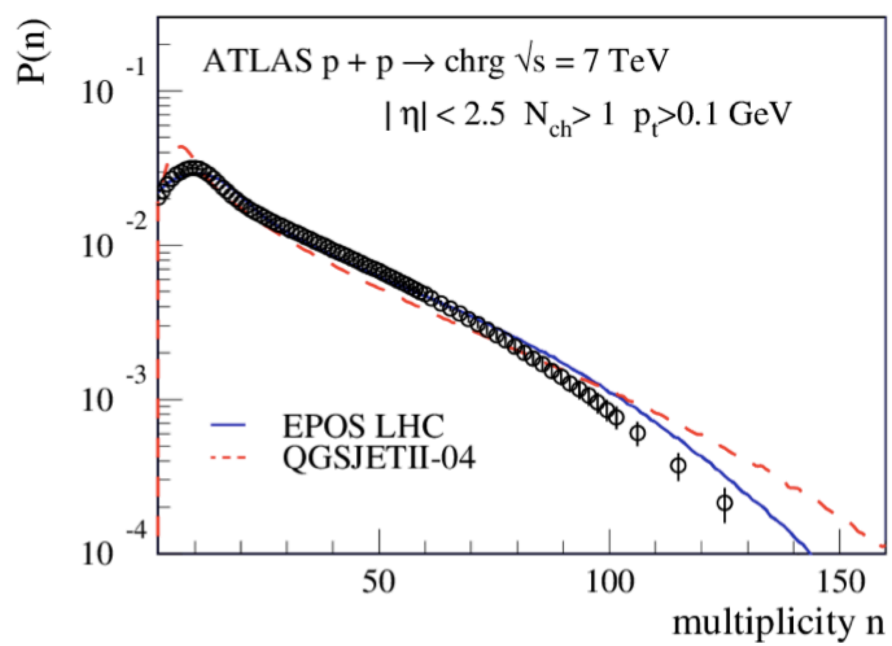
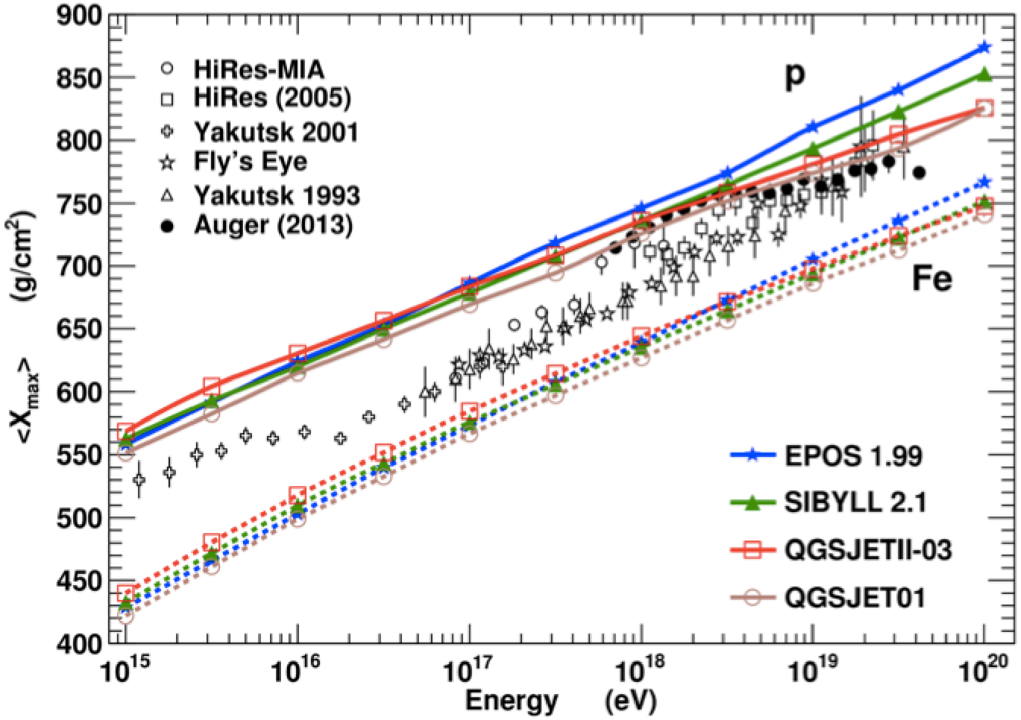
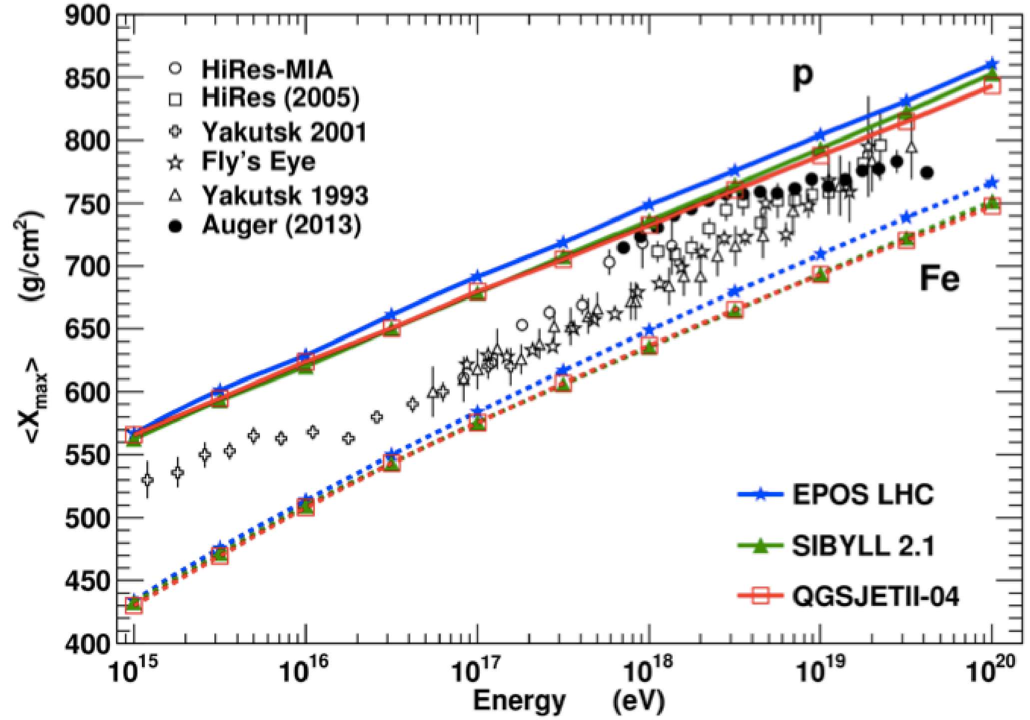


Post - LHC

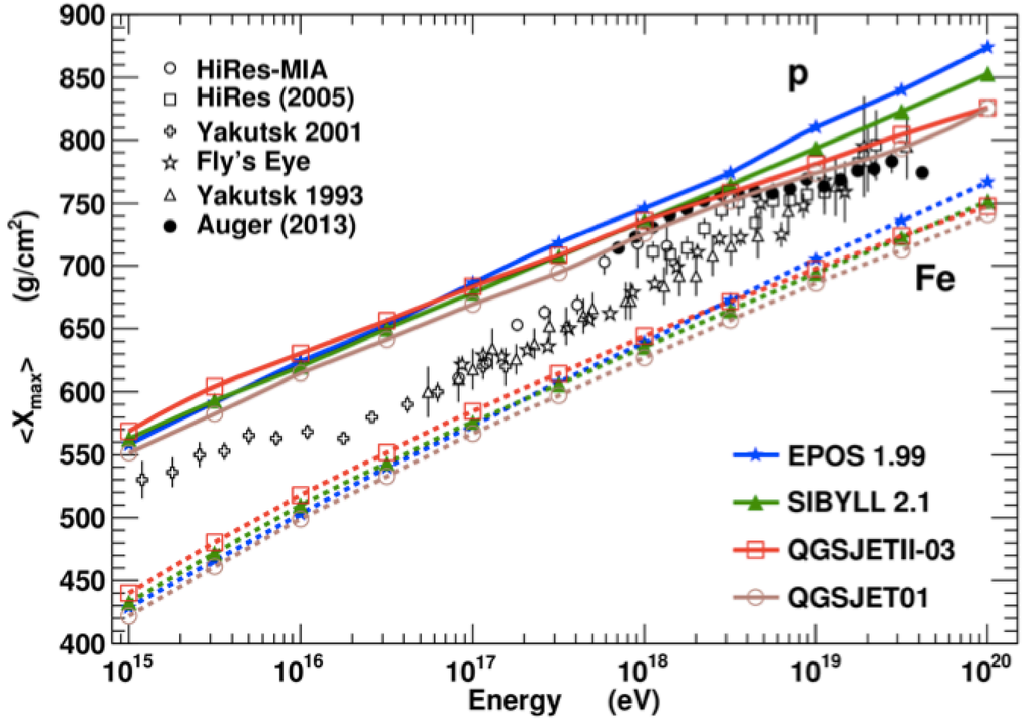


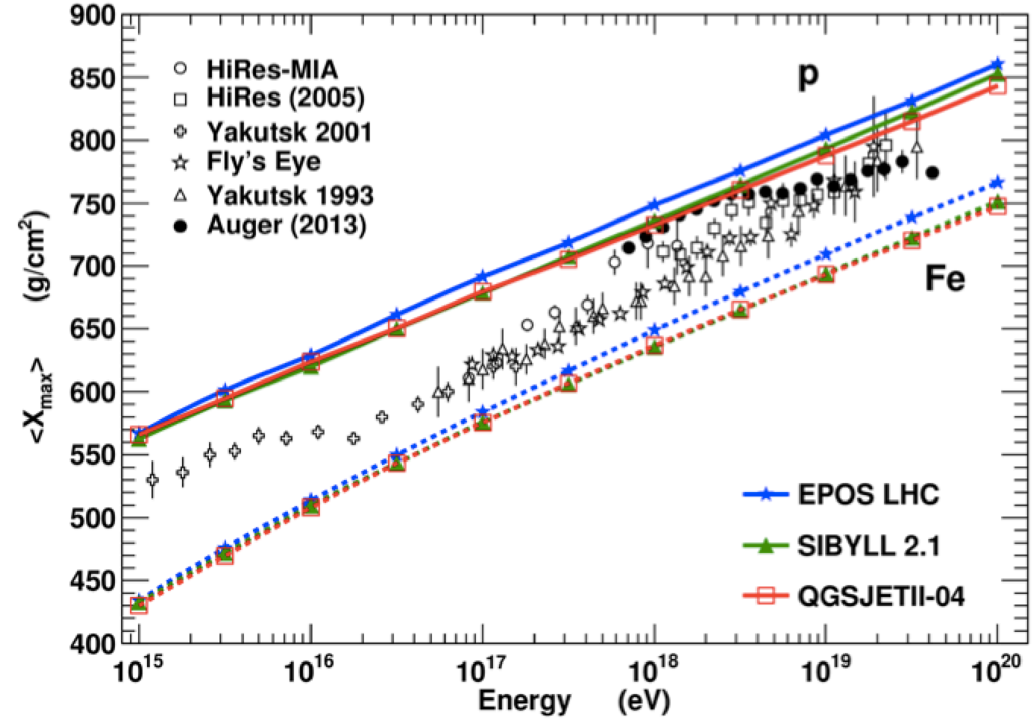
T.Pierog, at ISVHECRI 2014, CERN, August 18-22 2014





Uncertainty on 〈X_{max}〉 reduced from ~50 g/cm^2 to ~20 g/cm^2 ([proton – iron]~100 g/cm^2)





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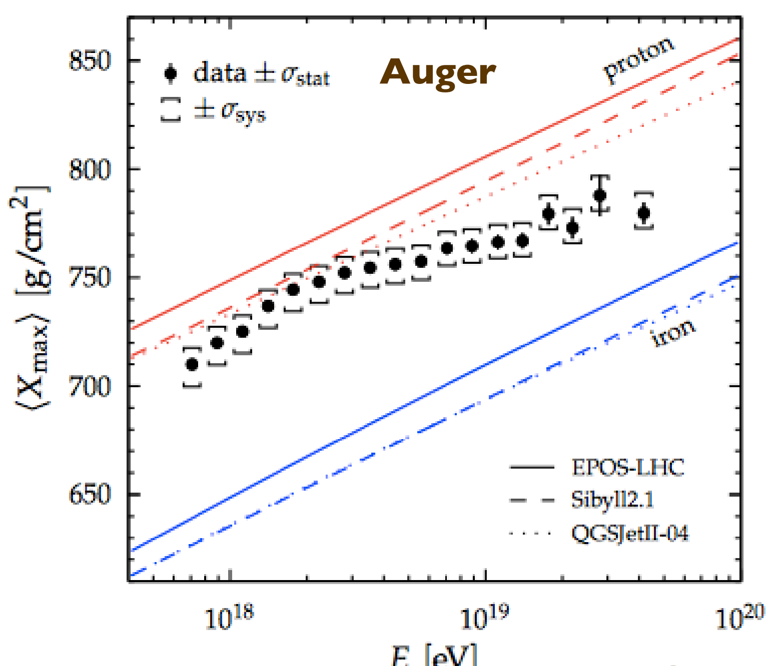
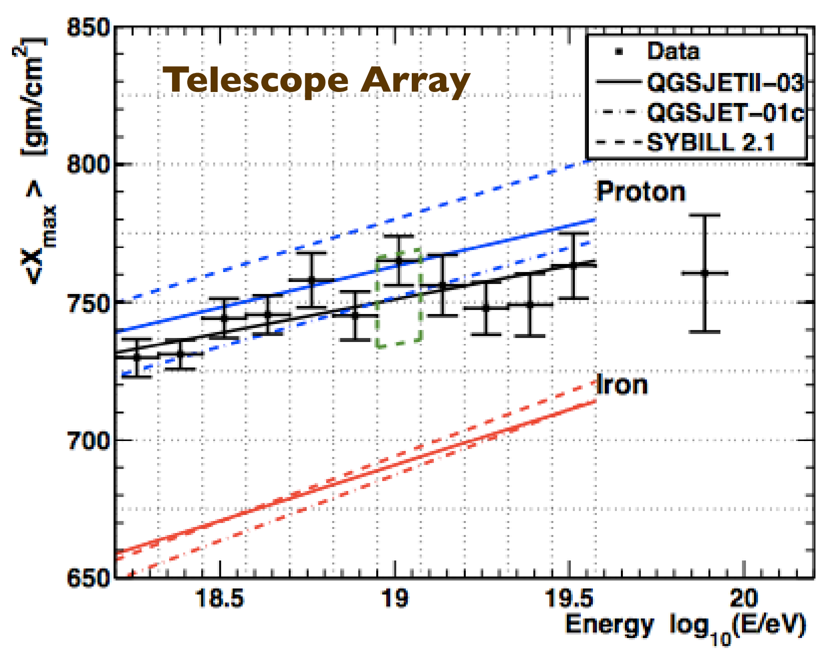




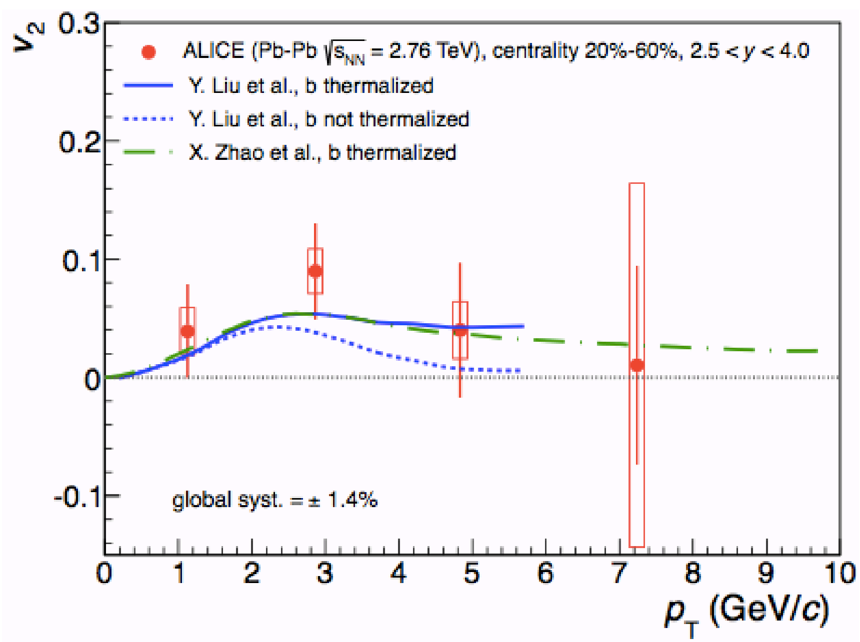
〈Xmax〉 as measured by the Pierre Auger (left) and Telescope Array (right) Collaboration [2, 3]. The colored lines denote predictions of air shower simulation (note that different models are shown in the left and right panel, only Sibyll2.1 is the same). The black line on the right panel is a straight-line fit to the TA data.

Auger and Telescope Array WG, arXiv:1503.07540

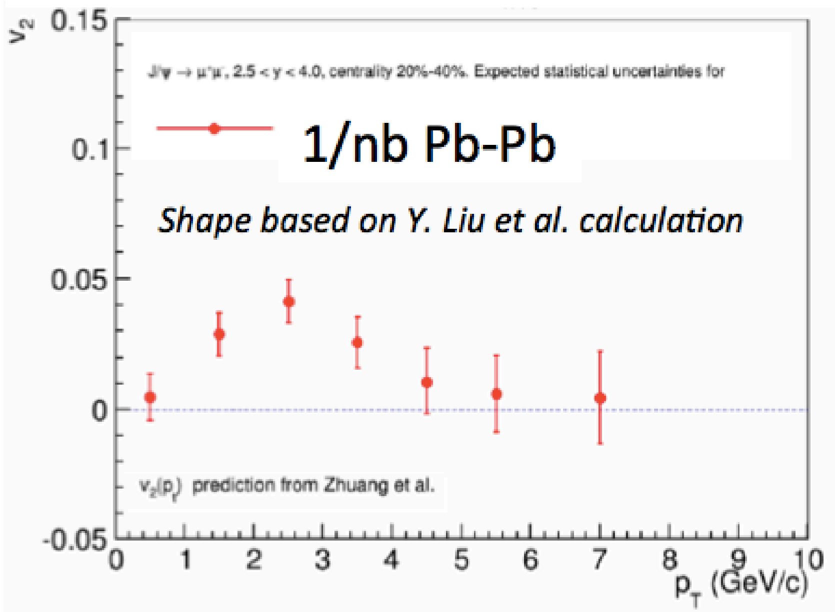
J/ψ – azimuthal anisotropy in AA (v_2)

- Heavy-quark and quarkonium in-medium thermalization and medium (transport) properties: flow of J/ψ, D-mesons, HF-leptons
- In-medium parton energy loss: open-charm, HF-lepton suppression
  - R_{AA}: new reach **at low-p_T (down to p_T < 1 GeV/c)** and high-p_T
- Multiple-parton interactions in pp and pA (via high-multiplicity events)

Present measurement: Indication of J/ψ flow



Projection for Run-2: >5σ measurement

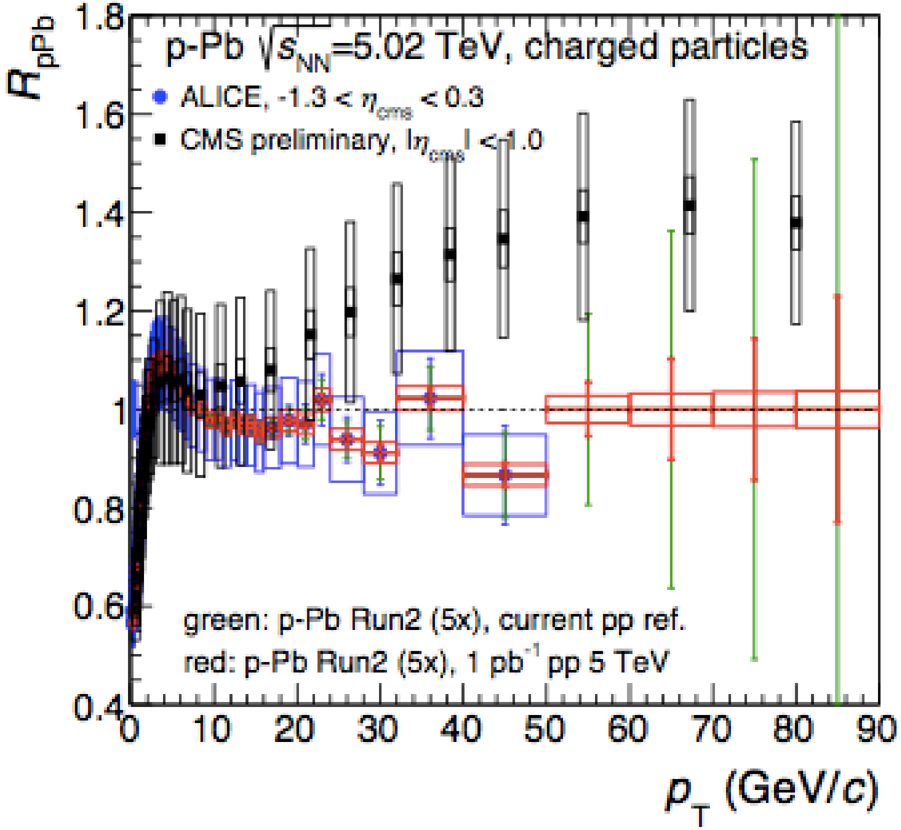


Charged hadron R_{pPb}

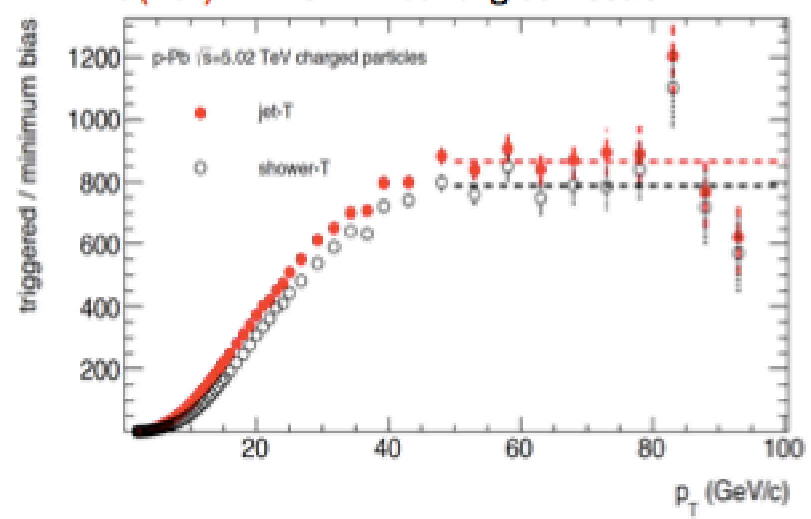
- Two pronged approach min. bias and high-p_T triggers:
  - Higher statistics in pPb (up to x 5)
  - Reference pp measurement at 5 TeV (few 10^6 events; 1/pb)

discrepancy between ALICE and CMS (+ATLAS)

need O(1/pb) for conclusive measurement



+ O(10^9) MB for EMCal trig correction



Glueballs

Run 1, evidence of sensitivity to $f_0(1710) \to \rho^0 \rho^0$ from 3nb^{-1} joint CMS/TOTEM

- $f_0(1710)$, 0^{++} glueball candidate
- No info on production rate in gg channel
- Conflicting knowledge (B factories, Zeus) on:
  - mass
  - decay BRs to u/d vs strange mesons (crucial to assess consistency with glueball interpretation): ππ, ρρ, KK

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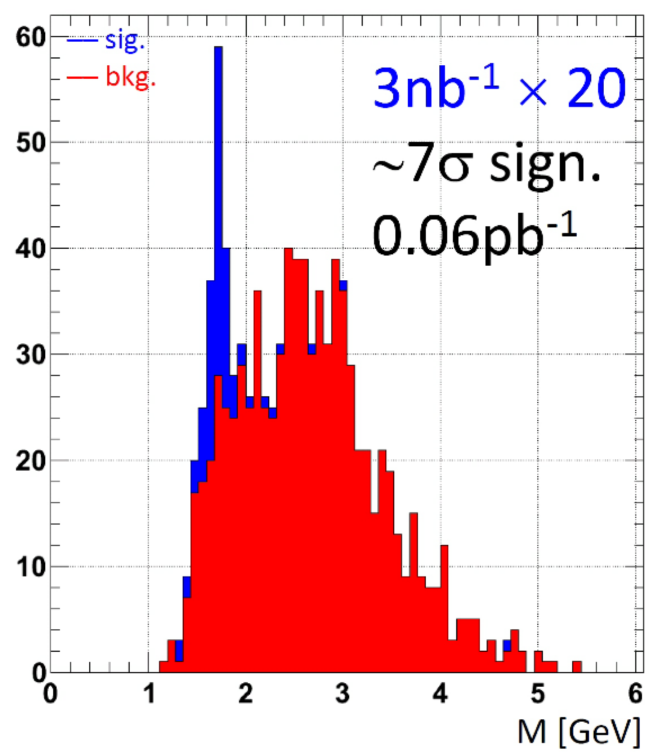
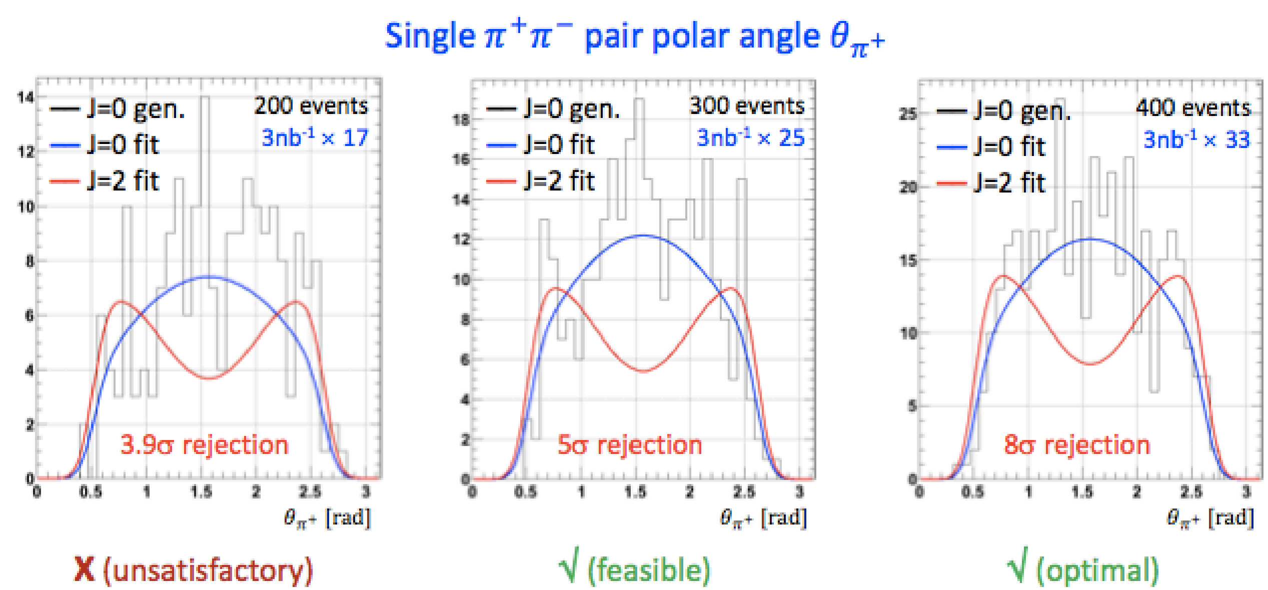
Run2 projections:
$0.05pb^{-1}$ for discovery, $O(1pb^{-1})$ for BR measurements and first angular analysis, $O(5pb^{-1})$ for partial wave analysis in full mass range (40 MeV bins)



- f→ρρ→2π+2π, acceptance modelled
- $J = 0$ generated, $J = 0$ and $J = 2$ fitted



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
    - $\Rightarrow$ 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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- This expectation is still high, and well justified

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- Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of ***naturalness will ultimately require an understanding***.
- Naturalness remains a guiding principle to drive the search of new phenomena at the LHC

Anomalies / pending items from run 1, some examples

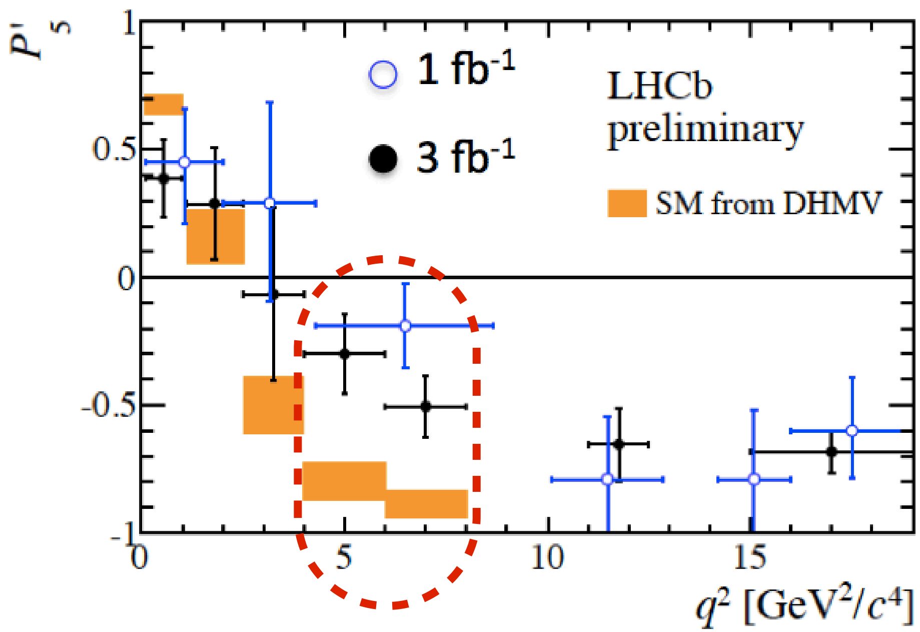
$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\,\%$$

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

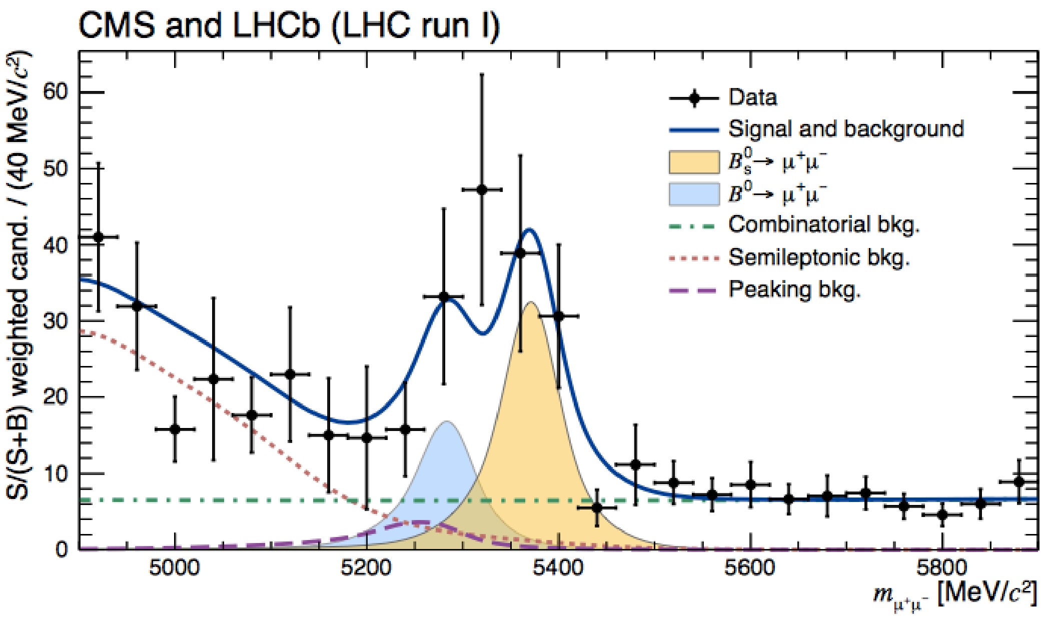


•$B \to K_* \mu^+\mu^-$ anomaly

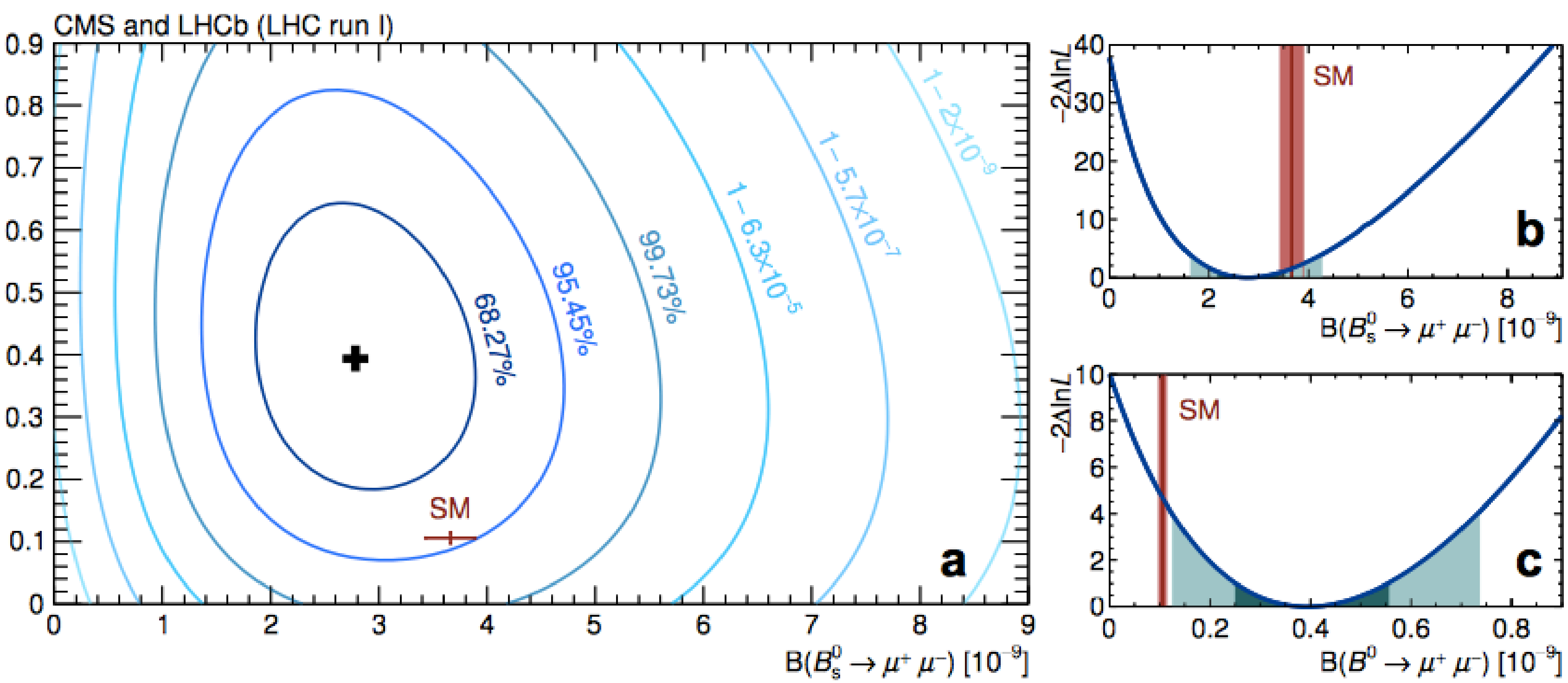
LHCb, arXiv:1308.1707 and
3fb^{-1} update LHCb−CONF−2015−002

For possible interpretation within a single BSM model
see e.g. Crivellin, D'Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged L_μ–L_τ)

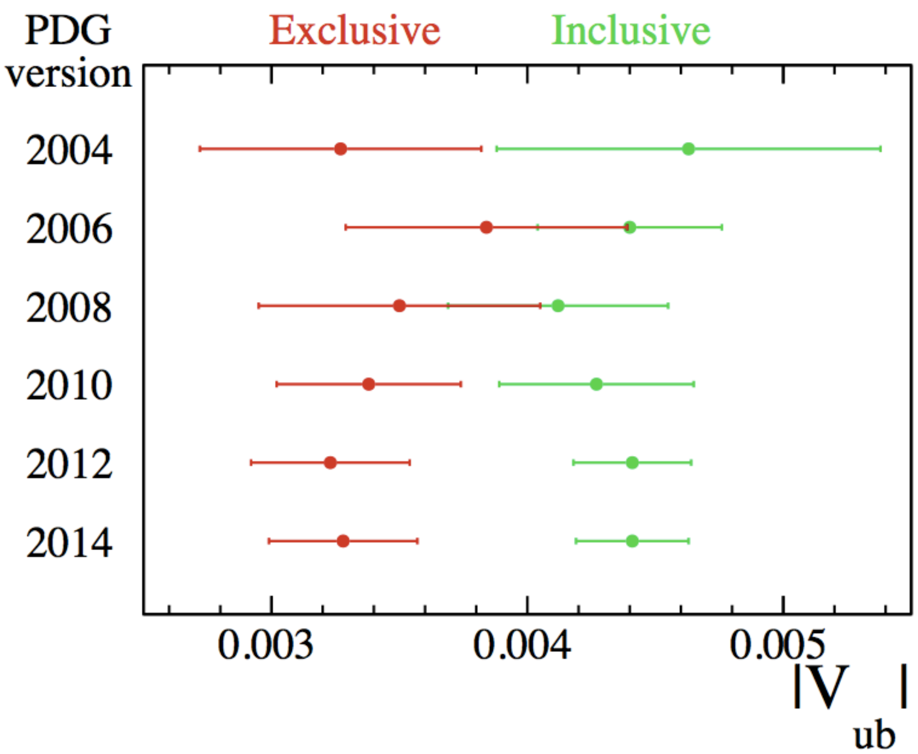
CMS/LHCb $B_{(S)} \to \mu^+\mu^-$



$$\frac{BR(B \to \mu^+\mu^-)}{BR(B_S \to \mu^+\mu^-)}$$ 2.3σ high w.r.t. SM

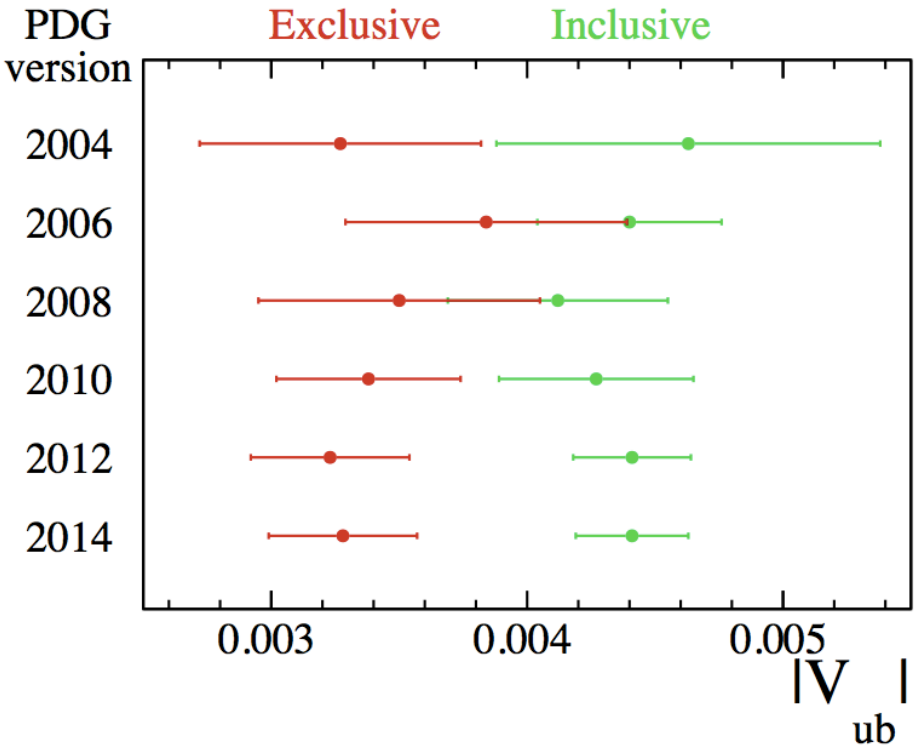


V_{ub} puzzle



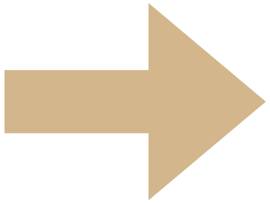
PDG version
Exclusive
Inclusive
2004
2006
2008
2010
2012
2014
0.003
0.004
0.005
|V ub|

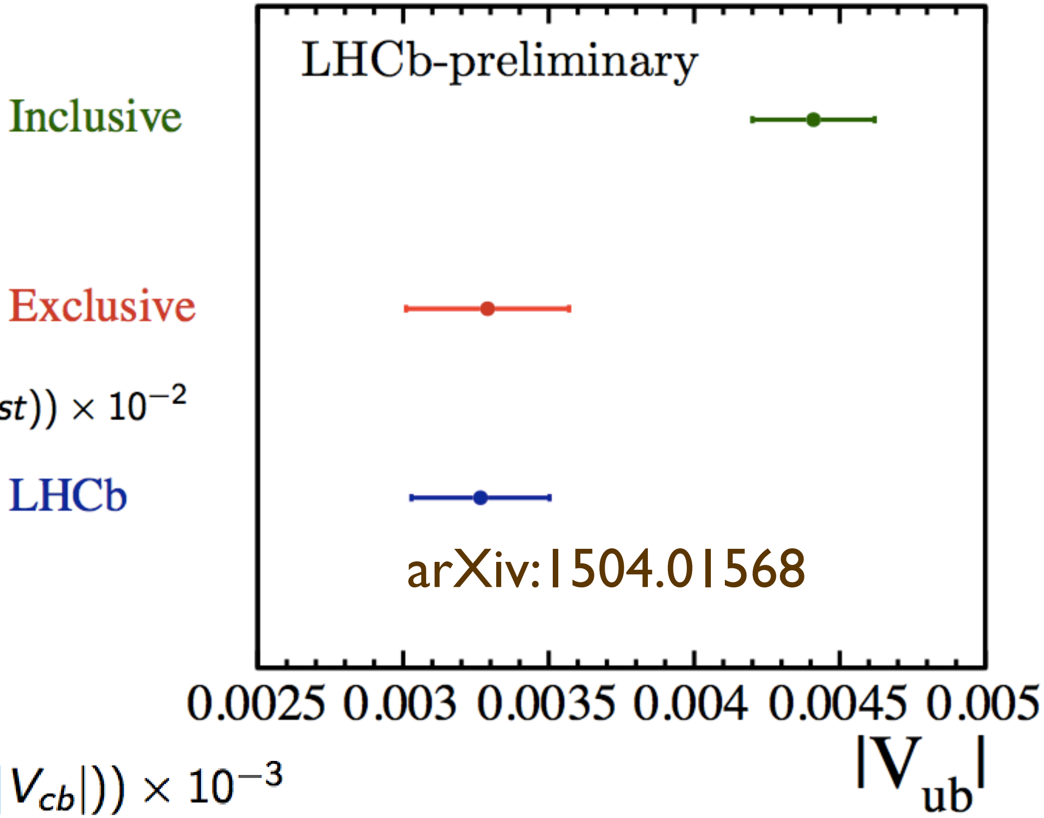
V_{ub} puzzle



$\Lambda_b \to p\mu\nu$ at LHCb

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

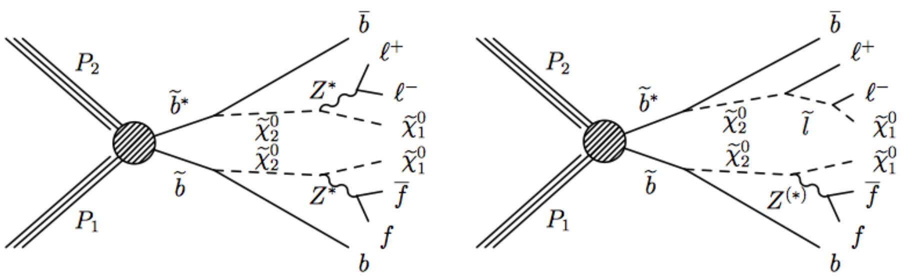




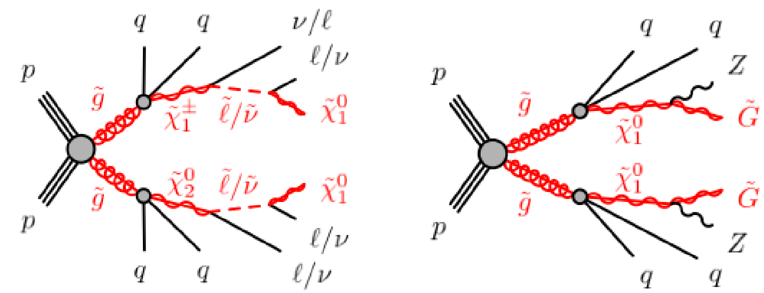
$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$

Anomalies left over from run 1, examples at large Q

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) ≥2, E_T^{miss} > 150 GeV
or
N_{jets} (p_T>40 GeV) ≥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) ≥2, E_T^{miss} > 225 GeV
H_T > 600 GeV

On-Z: m_{ll} = (81–101) GeV

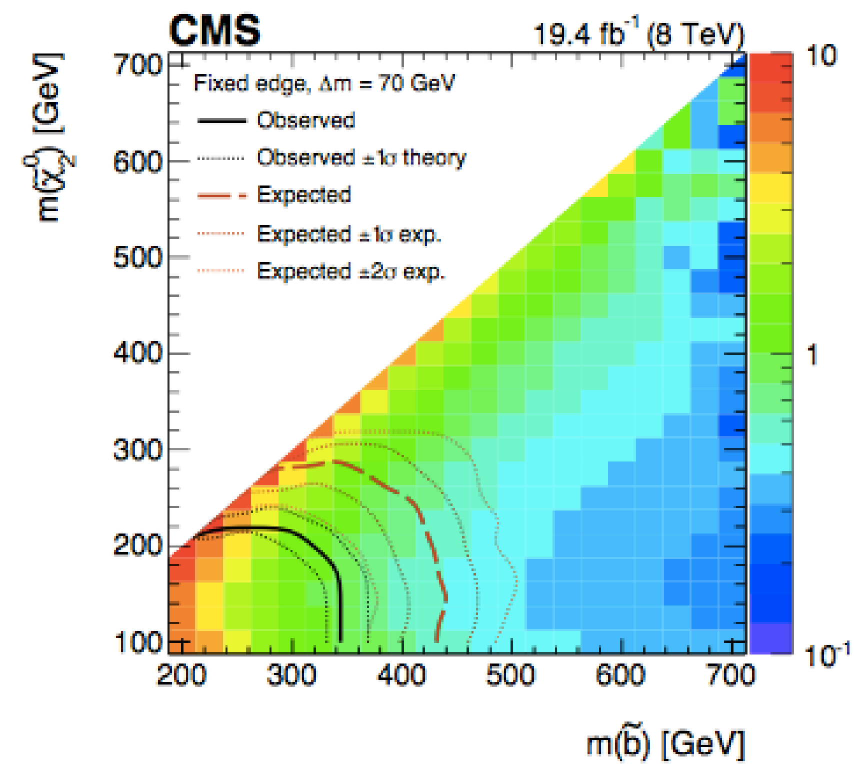
CMS, http://arxiv.org/abs/1502.06031

	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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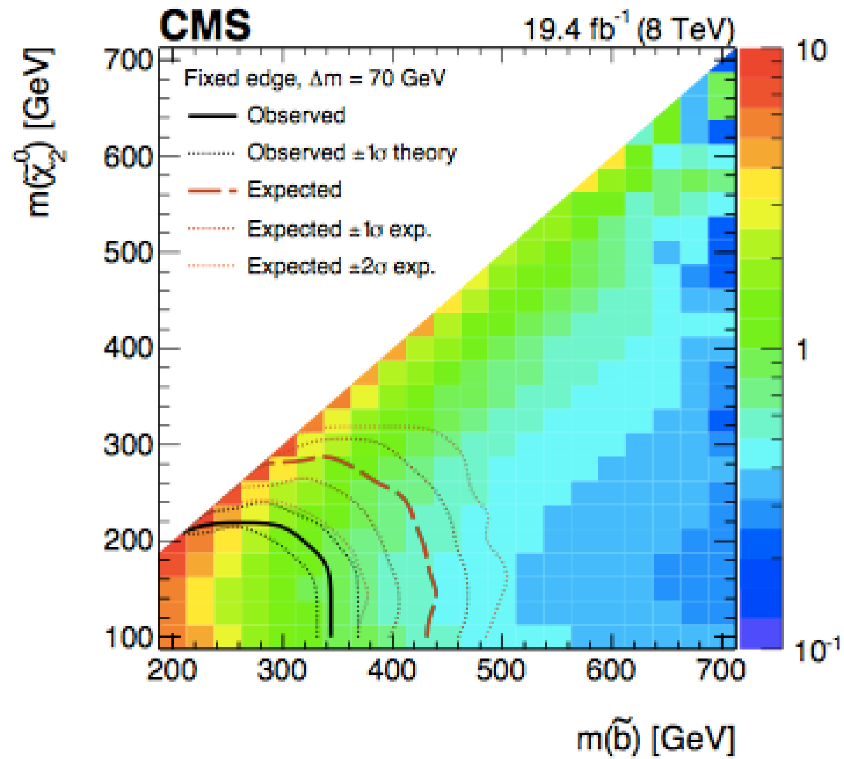
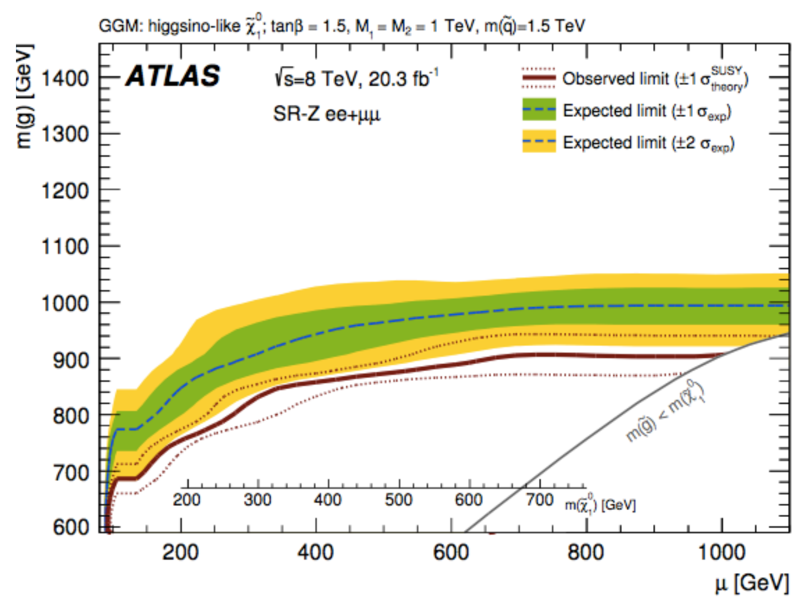


ATLAS, http://arxiv.org/abs/1503.03290

Channel	SR-Z *ee*	SR-Z *μμ*	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/γ^* + 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	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

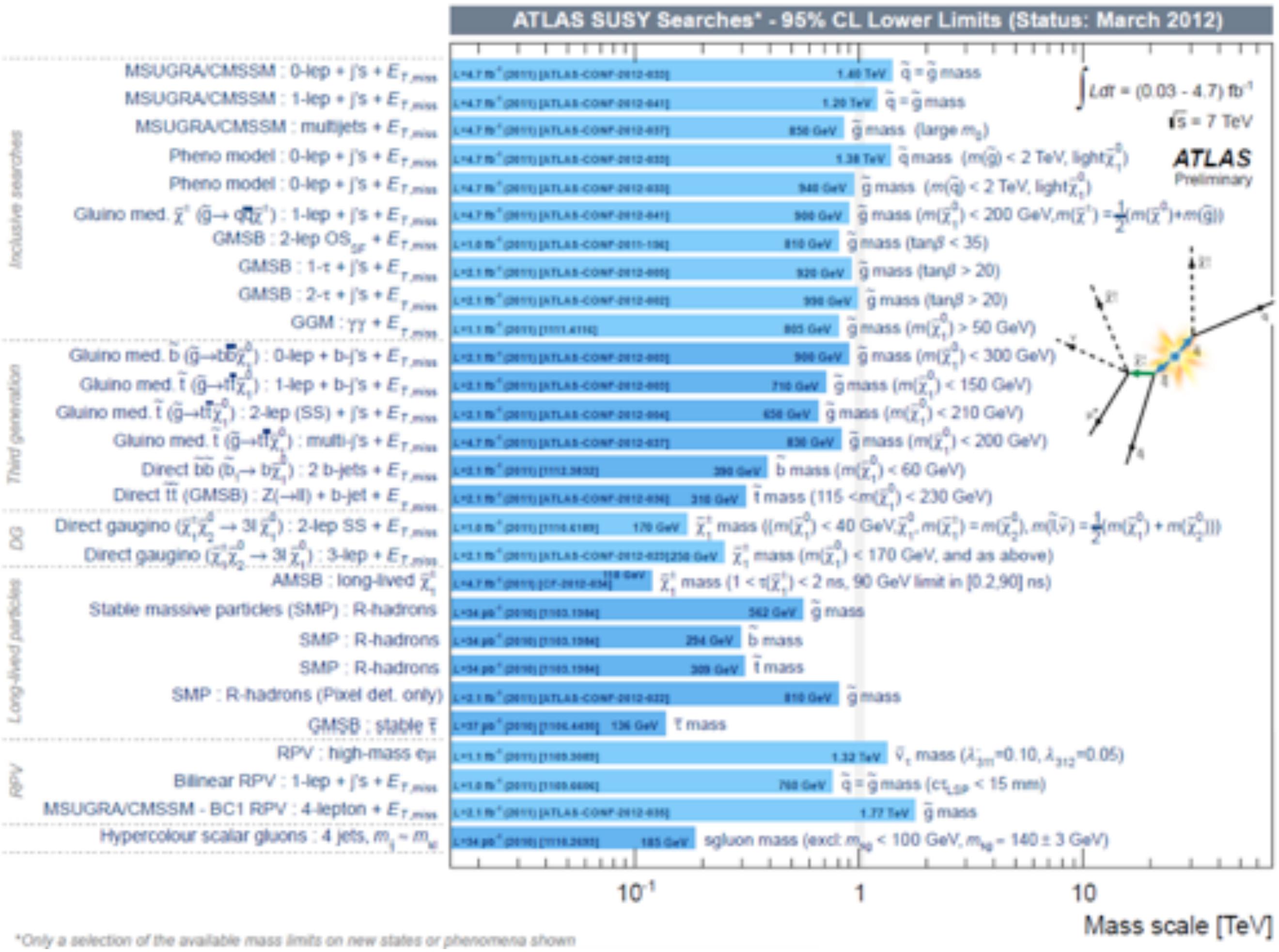
... but no signal off-peak

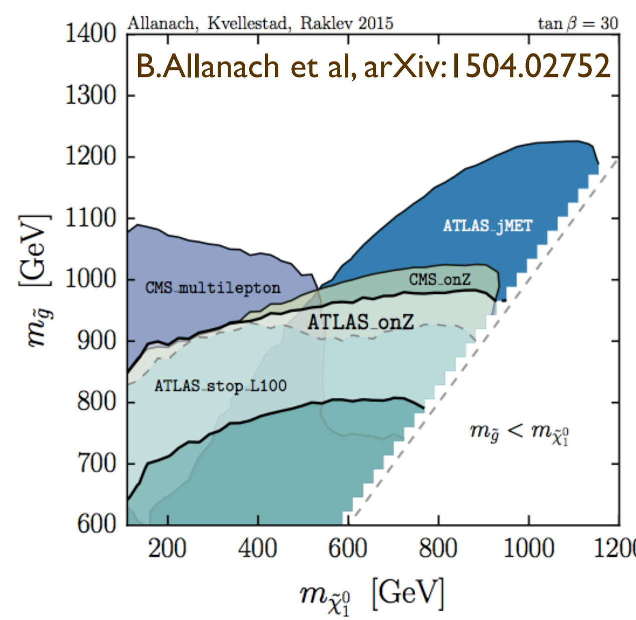
σ(800 GeV) ratio 13TeV/8TeV ~ 8.5



Already more than 10 TH interpretation papers on arXiv ….

a remark ....





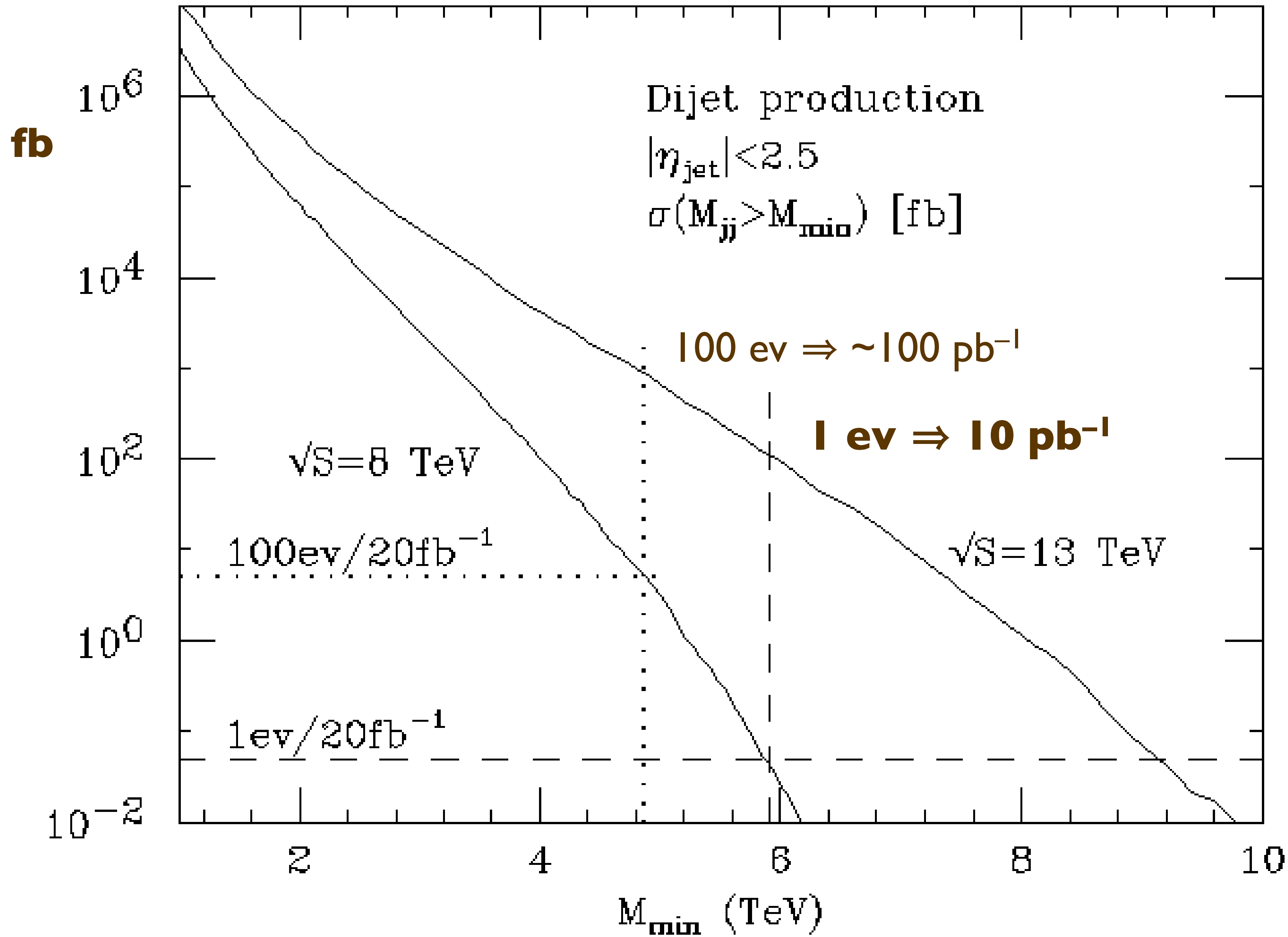
Assessing the consistency/significance of such anomalies in view of the multitude and diversity of existing constraints, is becoming more and more difficult!

⇒ relevance of "recasting" frameworks and tools,

"simplified models" approaches, proper documentation and archival of exptl results, ...

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

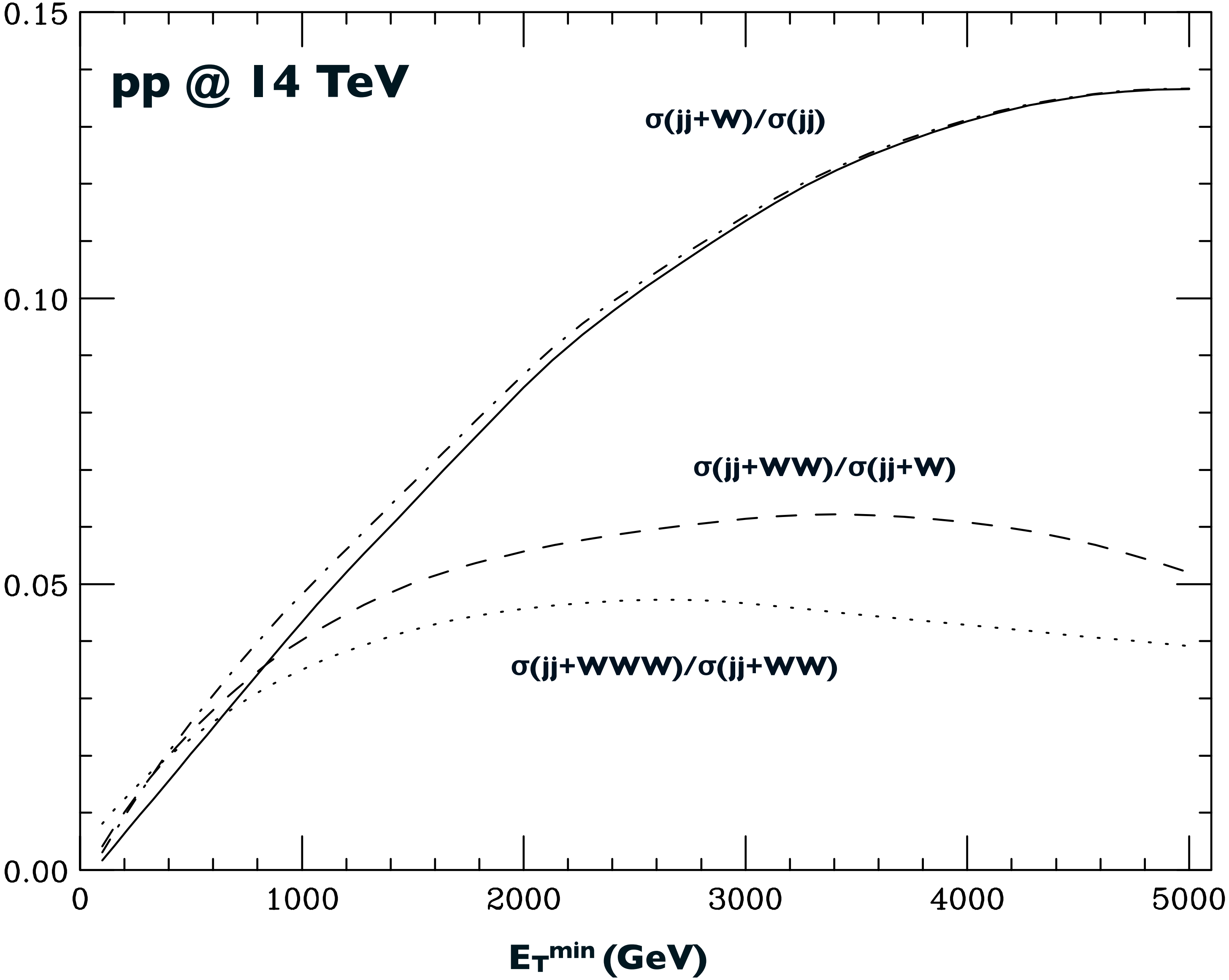
Rate comparison 8 vs 13 TeV: dijet production



Remarks

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

W production in dijet events



$\sigma(jj+W)/\sigma(jj)$

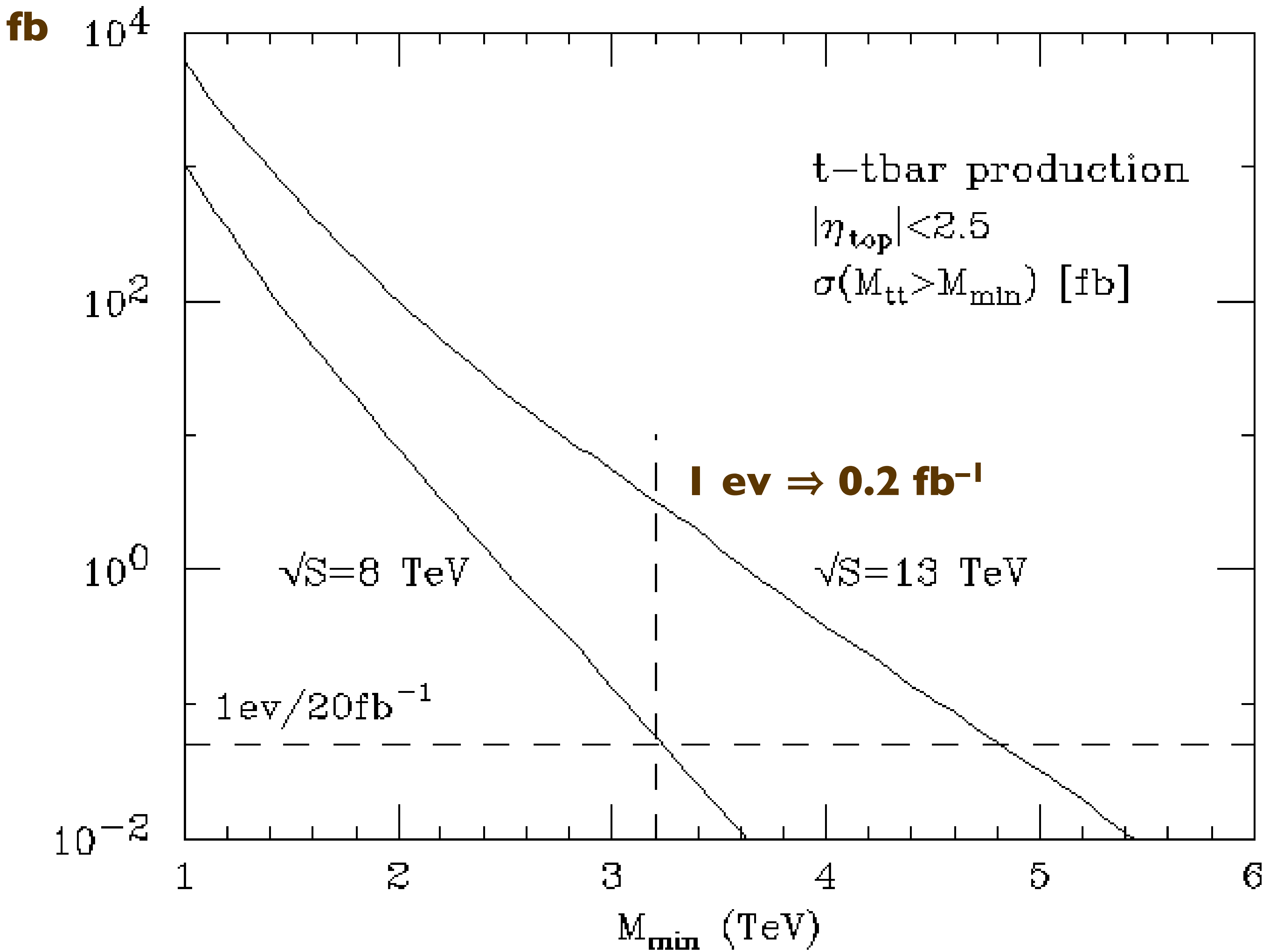
with

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

Dotdashes: $\sigma(jj)$ in the denominator replaced by $\sigma(jj, \text{no } gg \rightarrow gg)$

- **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**

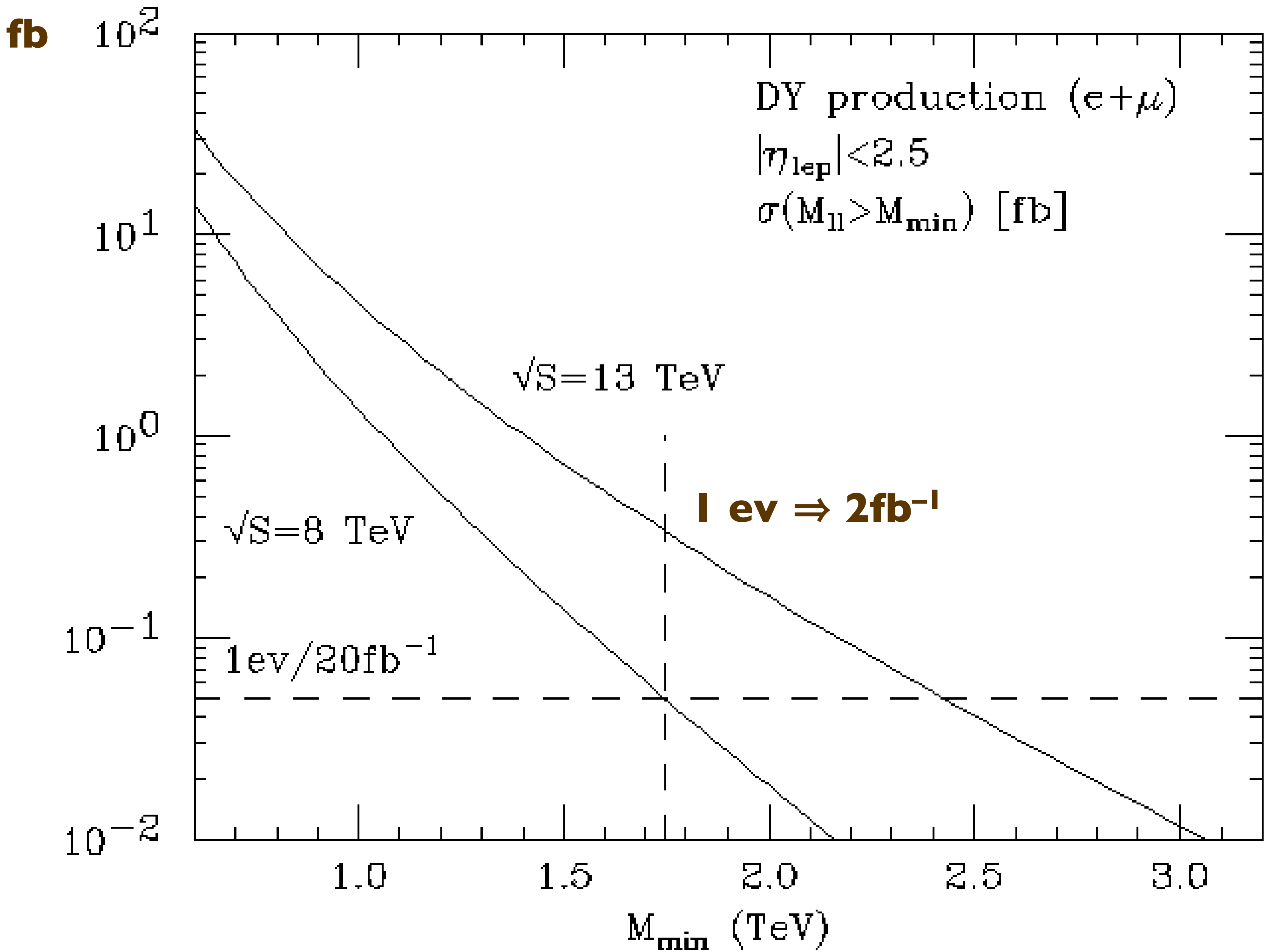
Rate comparison 8 vs 13 TeV: t tbar production



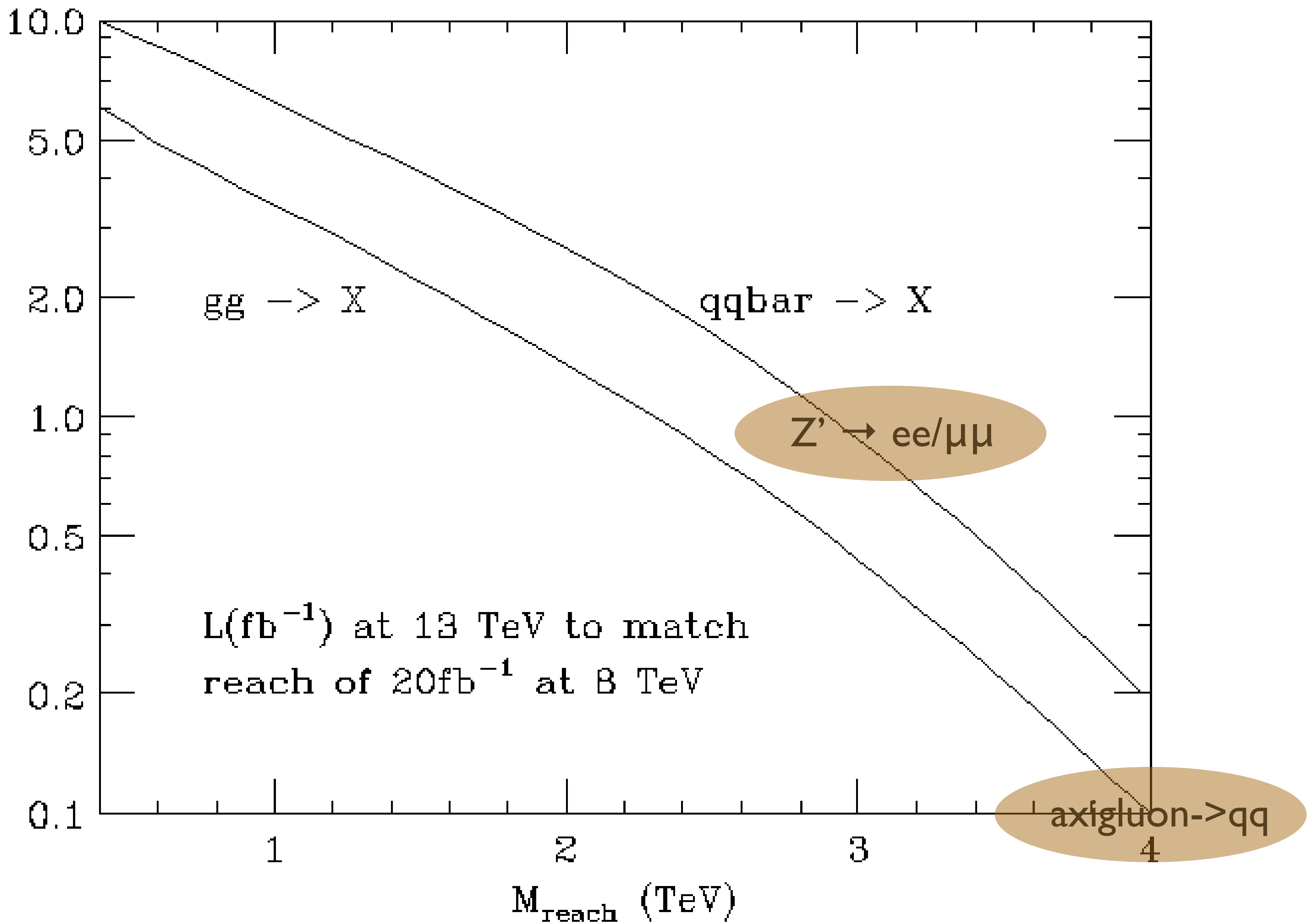
Remarks

- 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



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

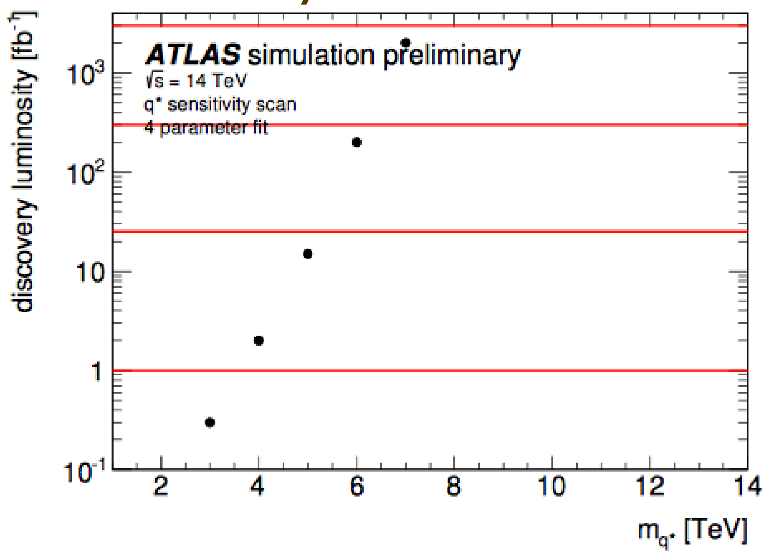


See also http://collider-reach.web.cern.ch, by Salam and Weiler

ATLAS/CMS projections for early discovery in run 2: dijet resonances

ATL-PHYS-PUB-2015-004

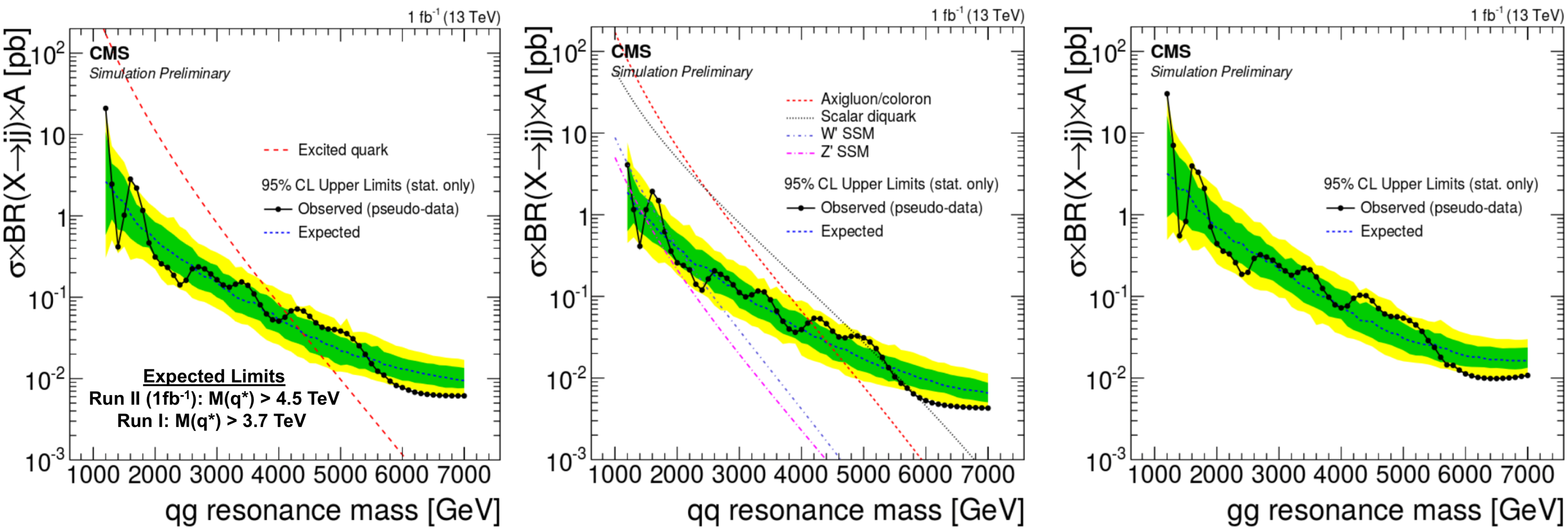
Discovery reach vs ∫L



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

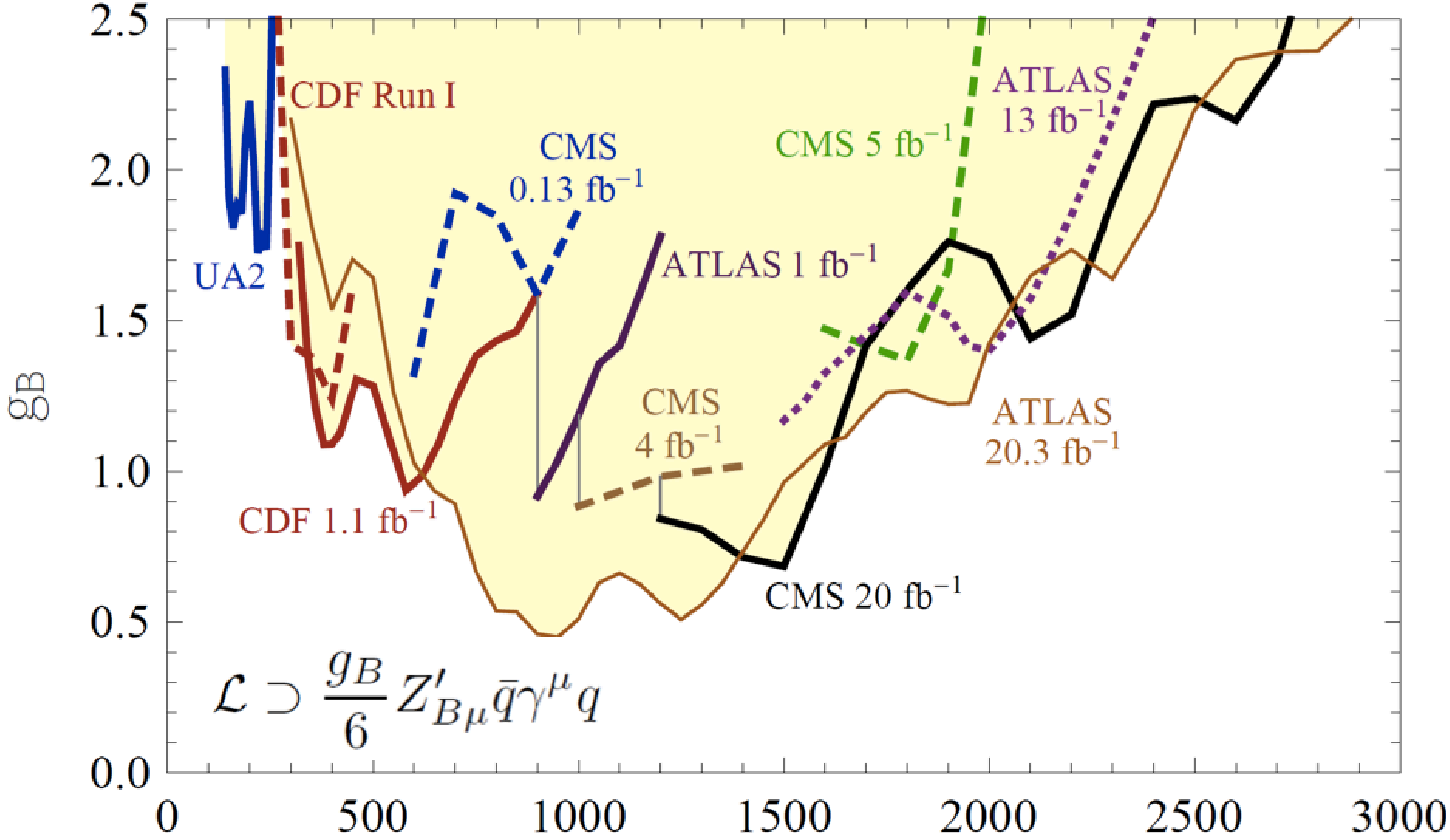
CMS, PHYS14 exercise



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

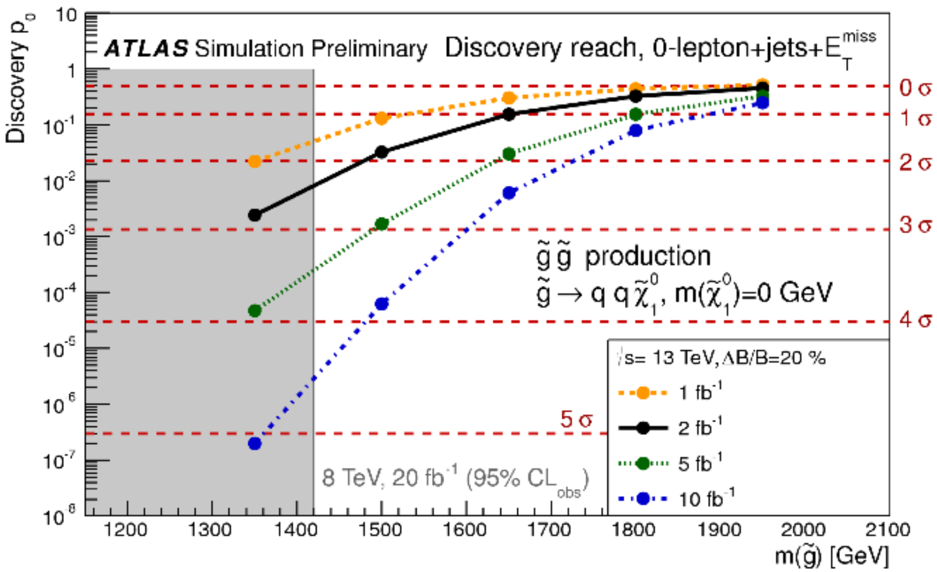
Current g_B vs. $M_{Z'}$ limits: Z'_B dijet resonance

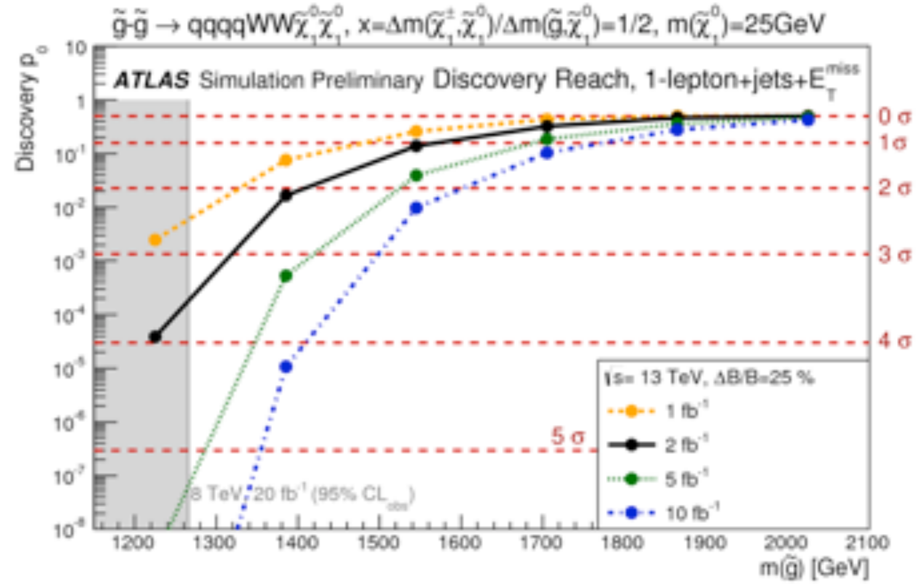


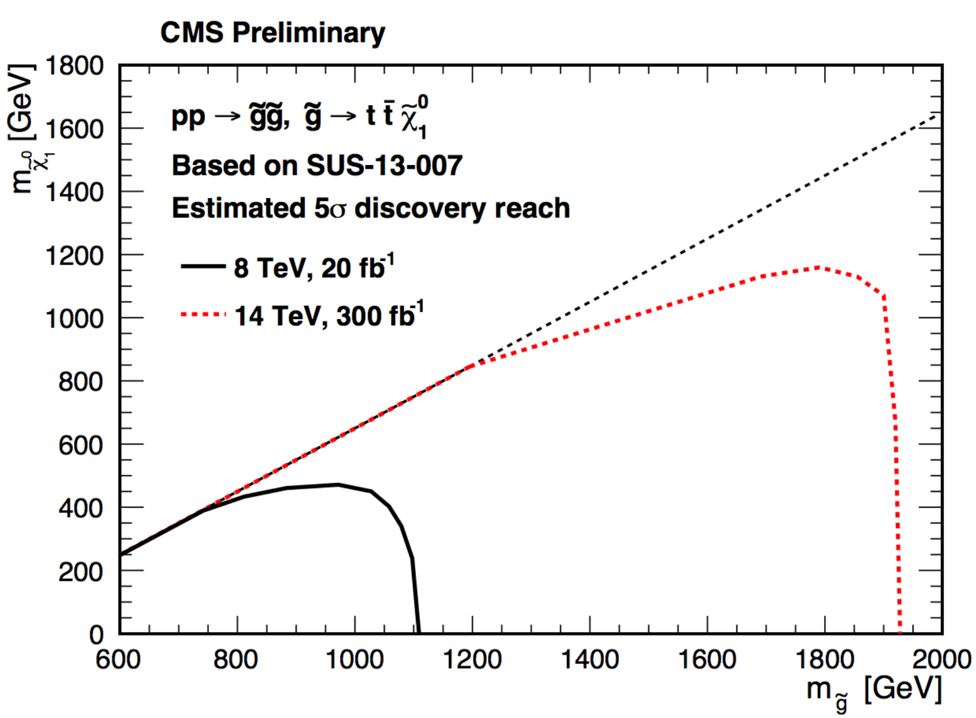
B. Dobrescu, F. Yu arXiv:1306.2629, updated (F.Yu) with new ATLAS arXiv:1407.1376 results

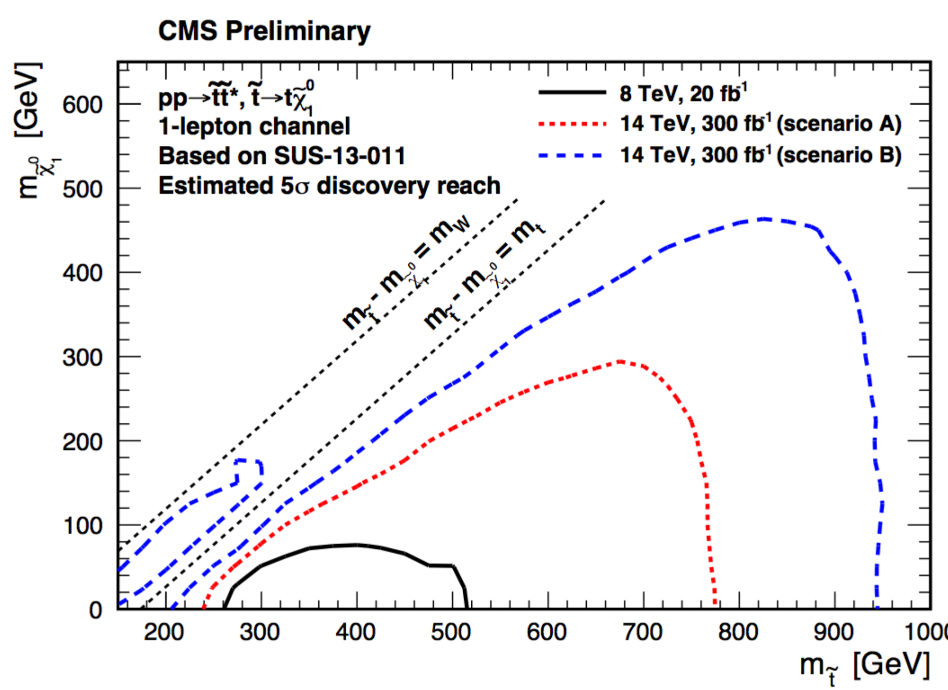
ATLAS/CMS projections for discovery in run 2: SUSY

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









Observation

- For what concerns the extension of the discovery reach at high mass, 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

	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 1 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/

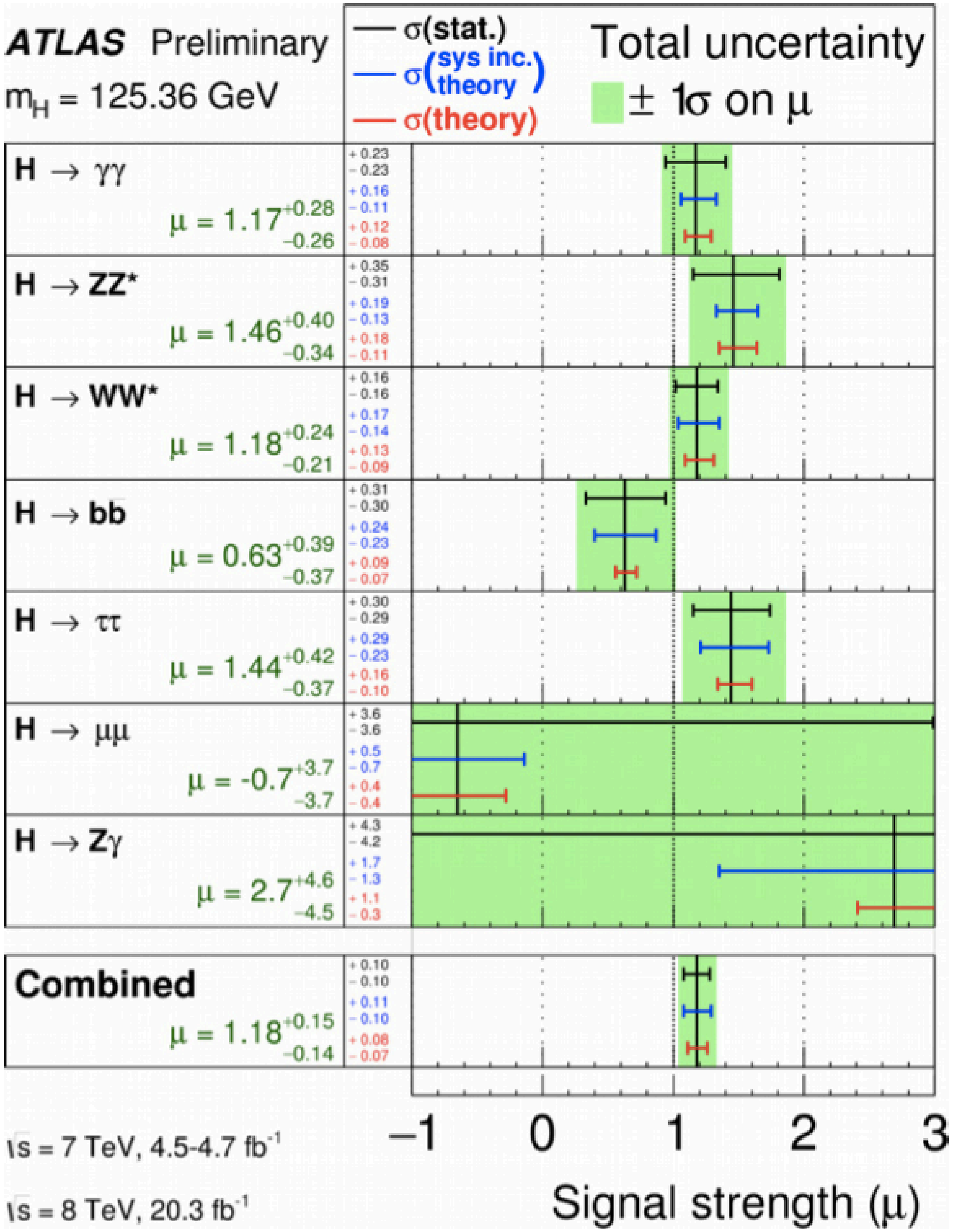
Mass:

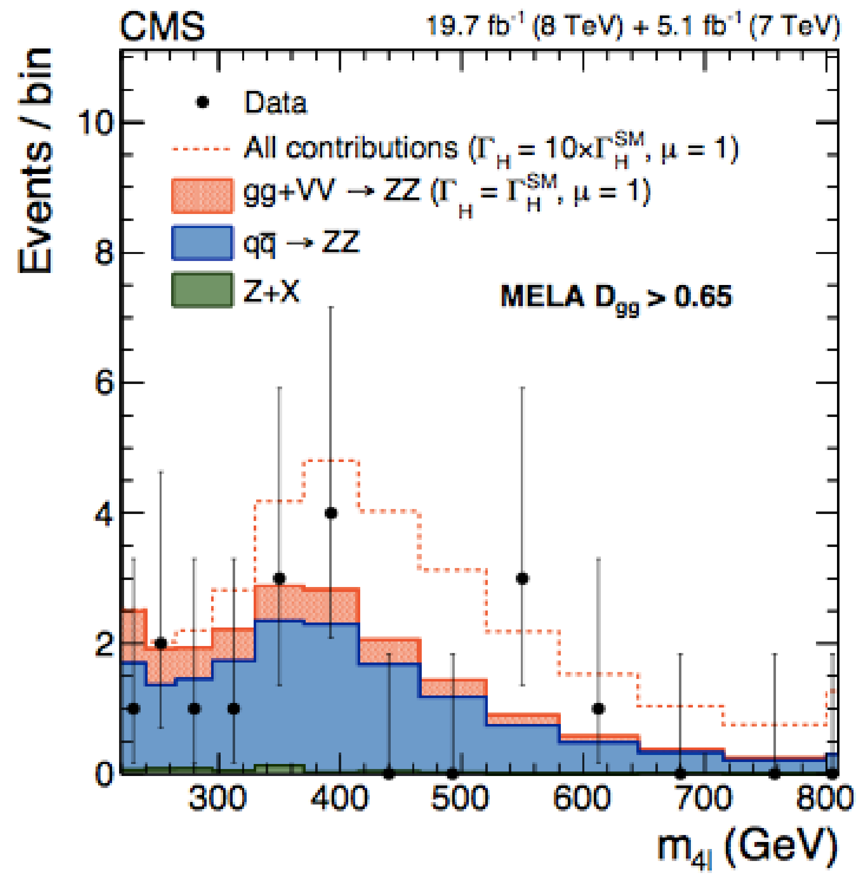
$$m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})\ \text{GeV}$$

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

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

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


ATLAS Preliminary
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.17 +0.28 −0.26
H → ZZ*
μ = 1.46 +0.40 −0.34
H → WW*
μ = 1.18 +0.24 −0.21
H → bb
μ = 0.63 +0.39 −0.37
H → ττ
μ = 1.44 +0.42 −0.37
H → μμ
μ = -0.7 +3.7 −3.7
H → Zγ
μ = 2.7 +4.6 −4.5
Combined
μ = 1.18 +0.15 −0.14
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Signal strength (μ)


CMS
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Events / bin
Data
All contributions (Γ_H = 10×Γ_H^SM, μ = 1)
gg+VV → ZZ (Γ_H = Γ_H^SM, μ = 1)
qq̄ → ZZ
Z+X
MELA D_gg > 0.65
m_4l (GeV)

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**
  - *of course not in all channels ..... for* ttH production and H→bb decays the goal is still confirmation of the signal

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- Higher stat will allow
  - more thorough studies of systematics, particularly theoretical modeling of signals and backgrounds in fiducial regions
  - to fragment studies into more signal regions, with complementary systematics and sensitivity to signal properties

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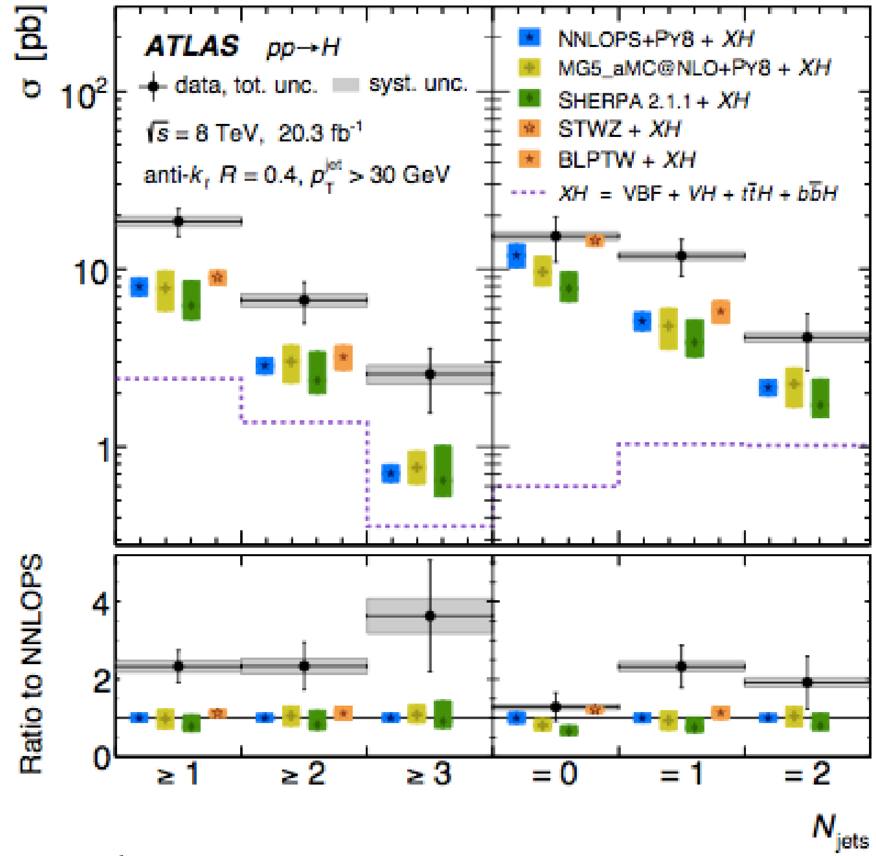
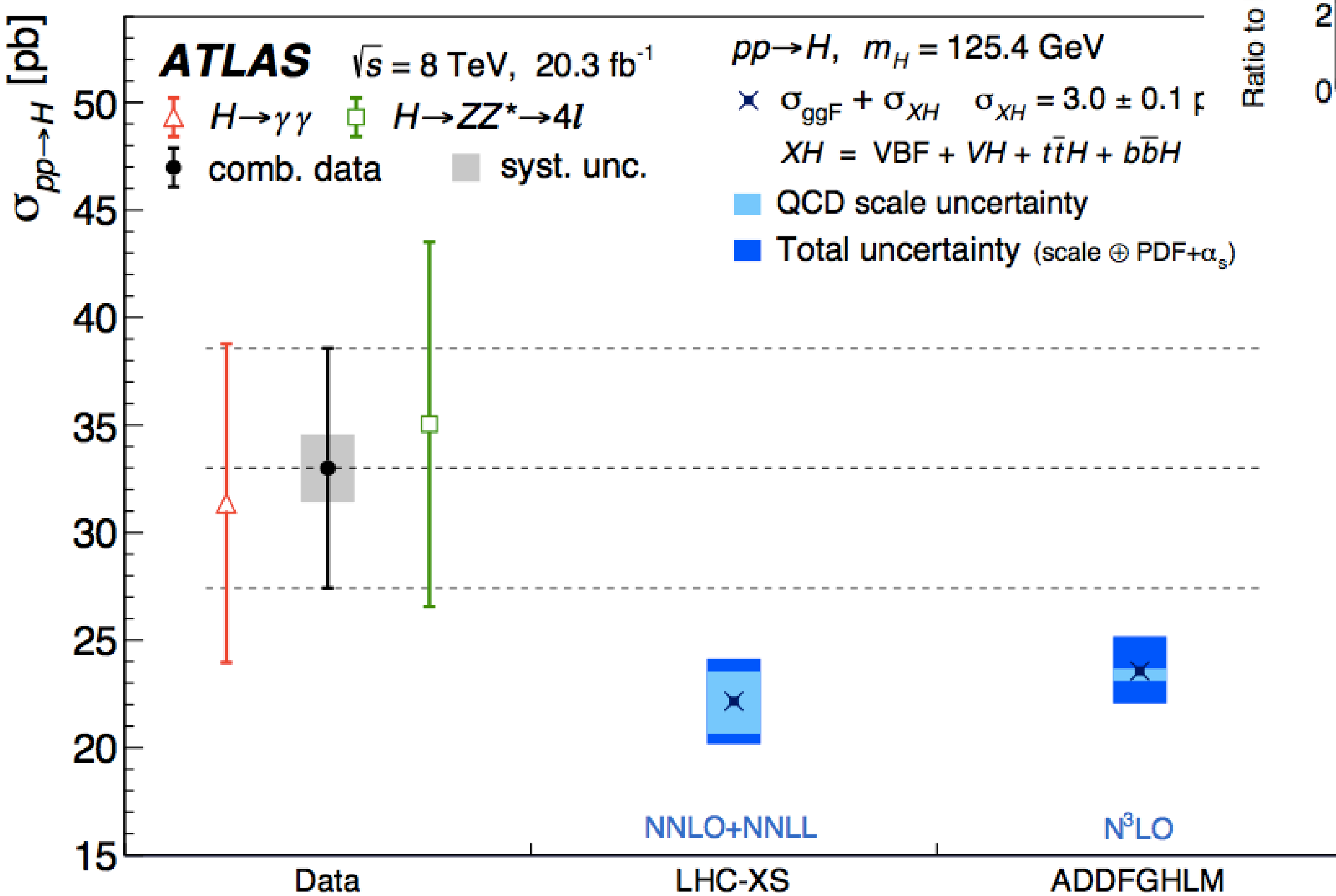
  - to fragment studies into more signal regions, with complementary systematics and sensitivity to signal properties
- Run 2 will prepare the ground for the work needed to fully exploit the ultimate HL-LHC luminosity in terms of Higgs physics, and will give us a much more clear picture of what the ultimate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

Example: ATLAS, arXiv:1504.05833

Total and Differential Higgs Cross Sections from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

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





NB Most of the TH vs data discrepancy comes from final states with ≥ 1 jet, which in other analyses (WW^*) are left out ....

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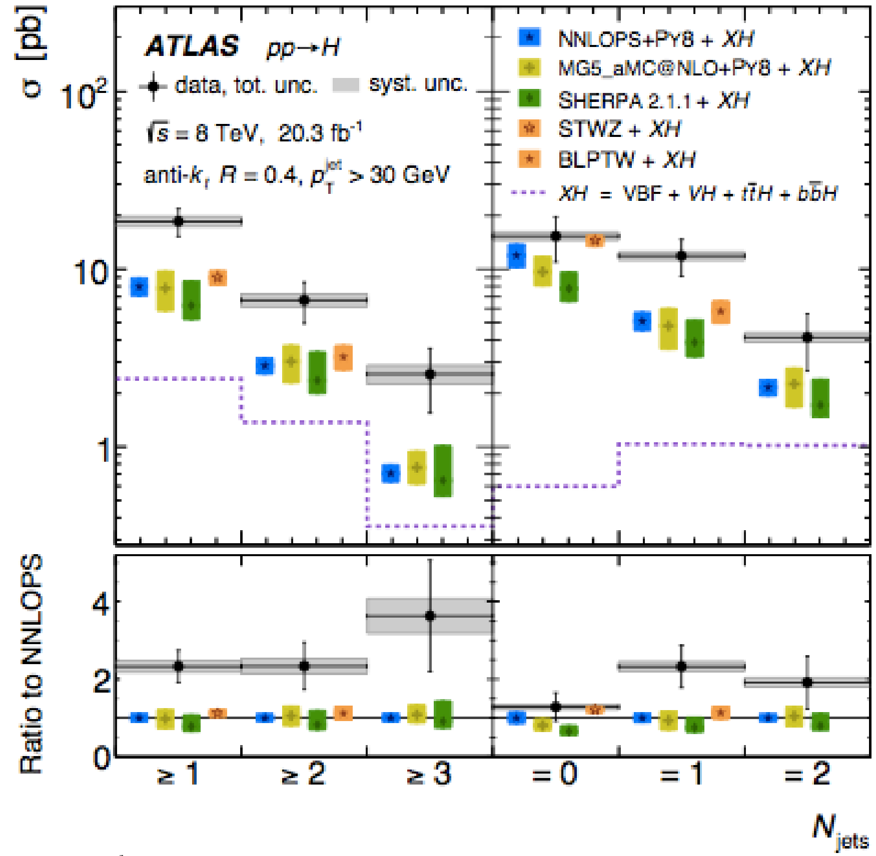
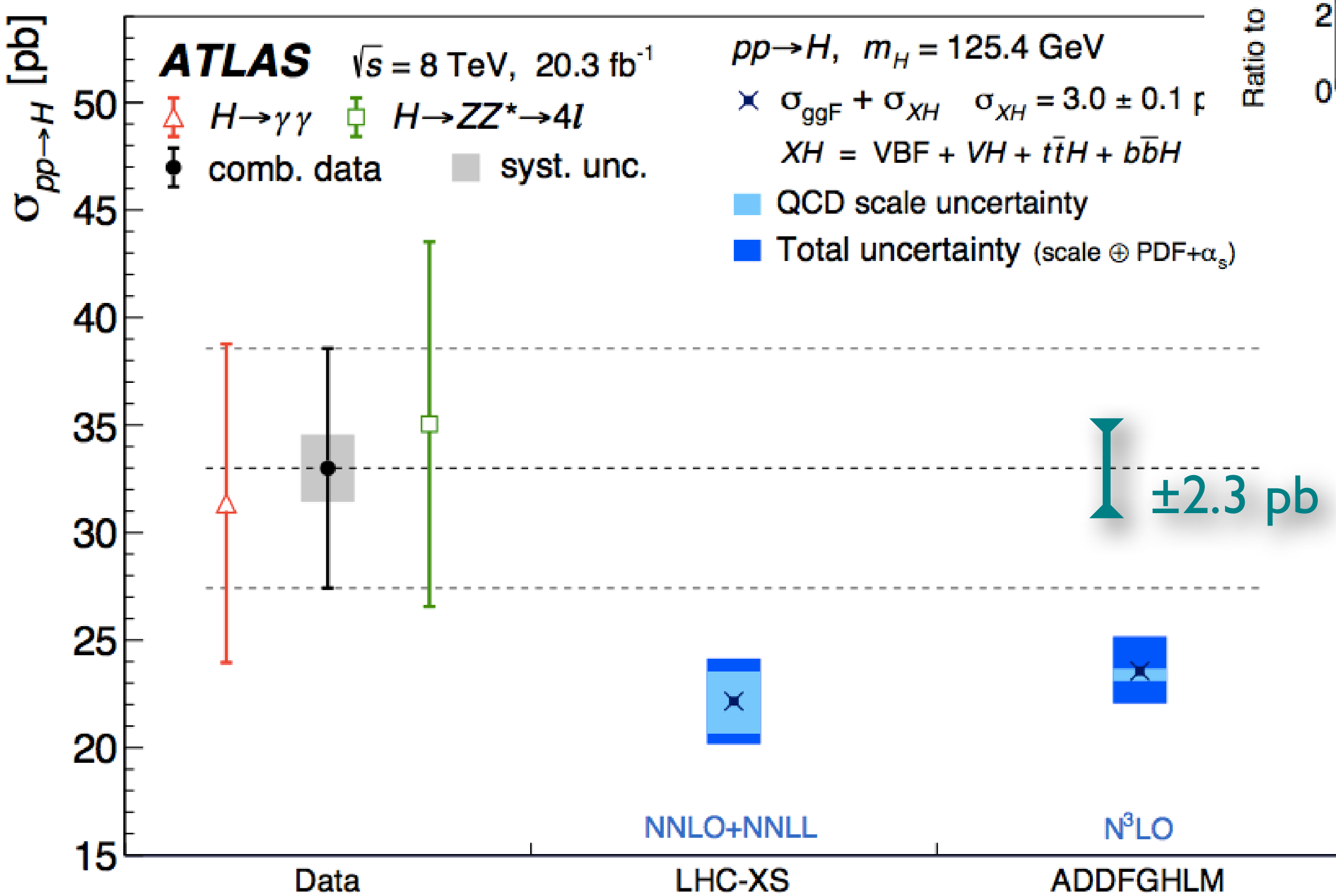
x 10 statistics ⇒

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





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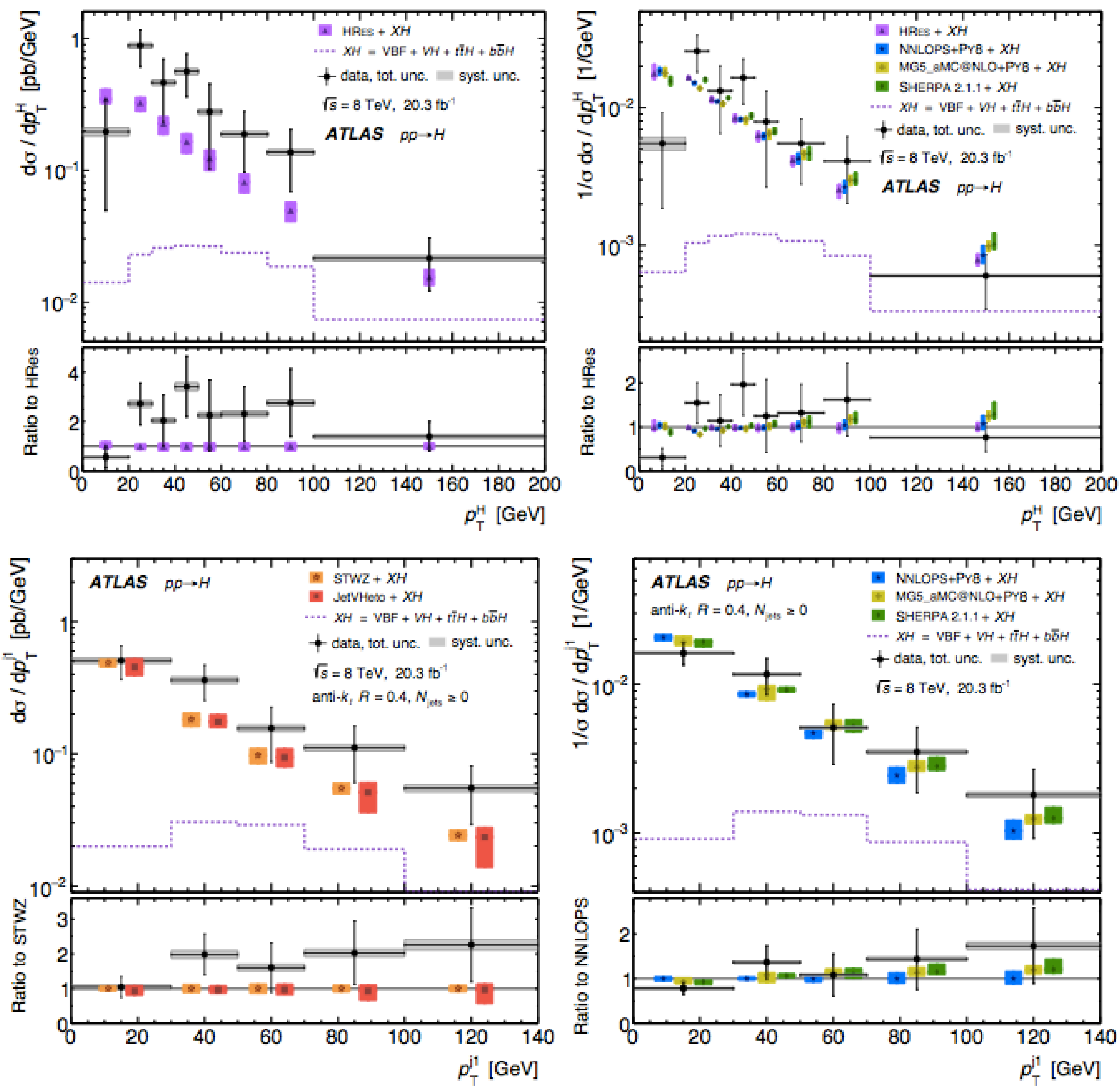
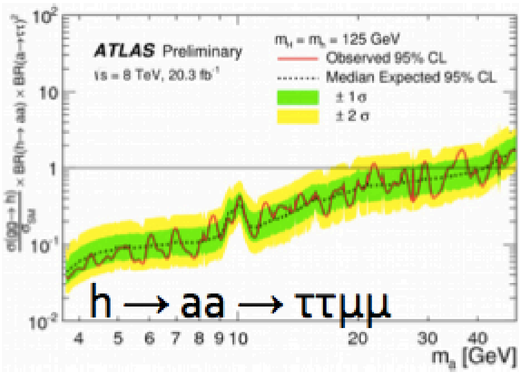
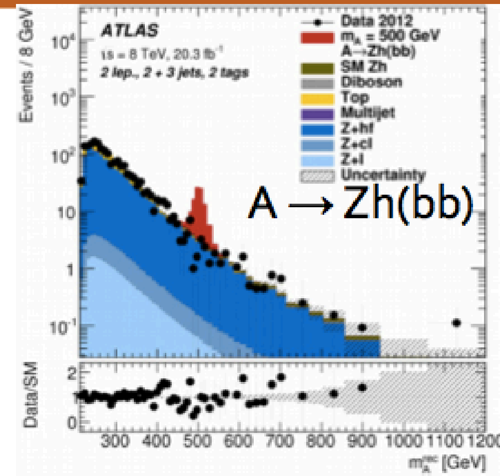
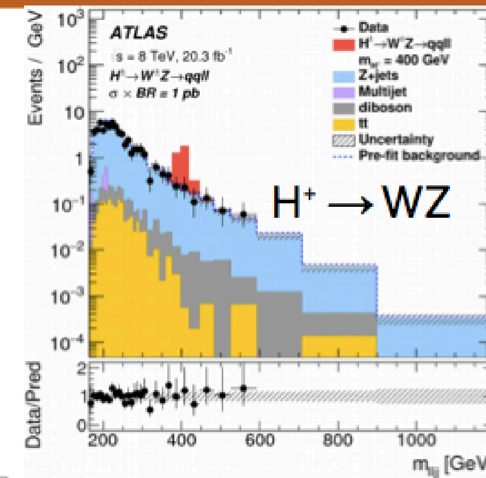
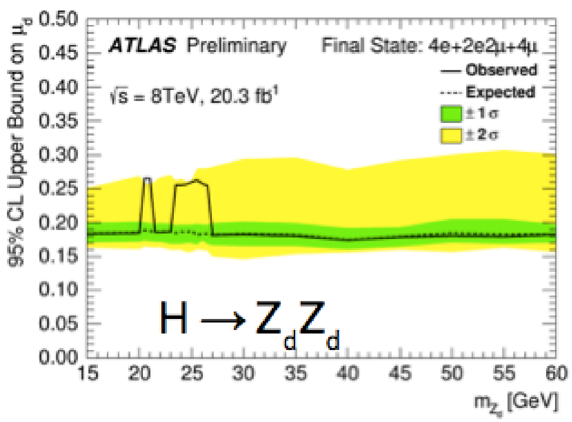

ATLAS pp→H
HRes + XH
NNLOPS+PY8 + XH
MG5_aMC@NLO+PY8 + XH
SHERPA 2.1.1 + XH
STWZ + XH
JetVHeto + XH
XH = VBF + VH + ttH + bbH
data, tot. unc.
syst. unc.
√s = 8 TeV, 20.3 fb⁻¹
anti-kt R = 0.4, Njets ≥ 0
dσ / dp_T^H [pb/GeV]
1/σ dσ / dp_T^H [1/GeV]
dσ / dp_T^j1 [pb/GeV]
1/σ dσ / dp_T^j1 [1/GeV]
Ratio to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

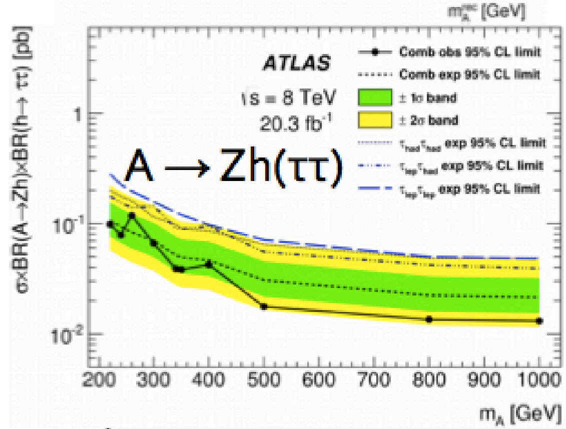
BSM Higgs searches

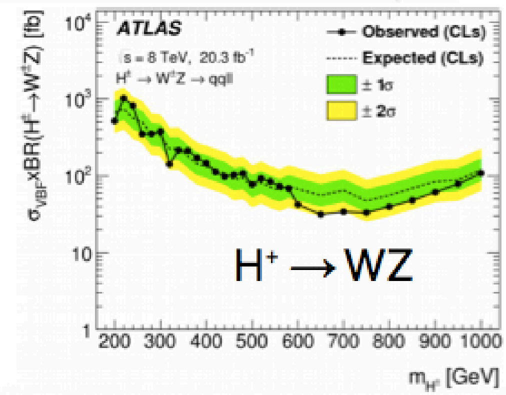








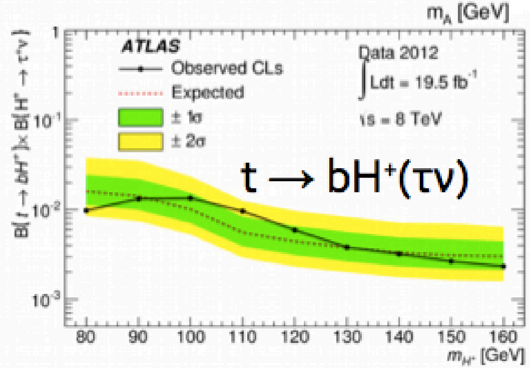


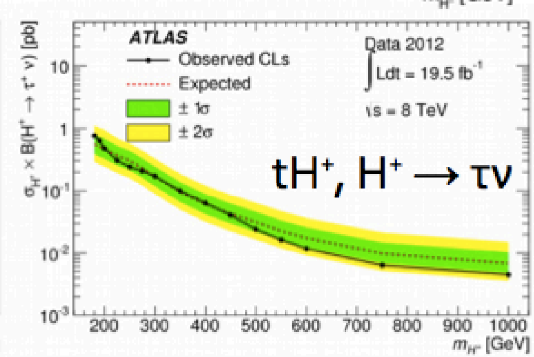


Many channels
Nothing found yet …

NEW!

- $h \to aa \to \tau\tau\mu\mu$: *HIGG-2014-02*
- $A \to Zh$: *arxiv:1502.04478, sub. to PLB*
- $H^+ \to WZ$: *HIGG-2014-13, sub. to PRL*
- $H^+ \to \tau\nu$: *arxiv:1412.6663, acc. by JHEP*
- $h \to (Z/Z_d)\, Z_d \to 4\ell$: *ATLAS-CONF-2015-003*





PH-LHC seminar, ATLAS H studies: P. Onyisi, http://indico.cern.ch/event/360241/

Final remarks

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- In run 2 Higgs physics will step into the precision era. The success of this programme will benefit from through campaigns of bread and butter measurements of SM dynamics, needed to develop, improve and validate the theoretical tools required to push the precision and reliability of the interpretation of experimental data.
- Regardless of the emergence of direct BSM discoveries, LHC measurements will address the fundamental questions of our field, and the answers obtained from data will greatly extend our understanding of nature