Best ways to test the Standard Model and best sensitivity to new physics

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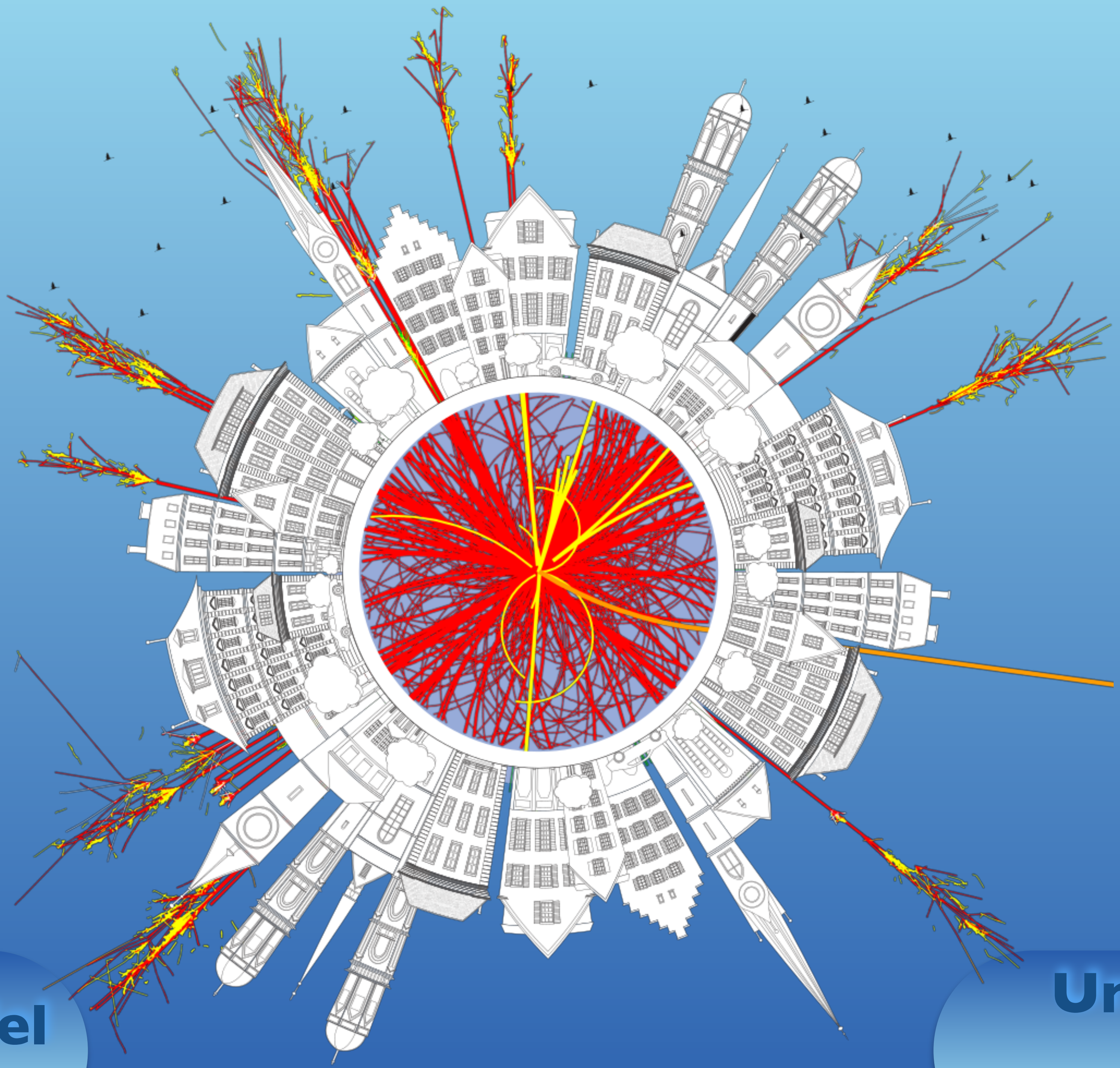

Standard Model @ LHC

**University of Zurich
23-26 April 2019**

Mandate from the programme committee:

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With this talk we would like to look at the physics program of the LHC and ***critically review the methods and ideas proposed so far in the investigation of new physics****, opening the discussion to new ideas, new approaches, new avenues.*

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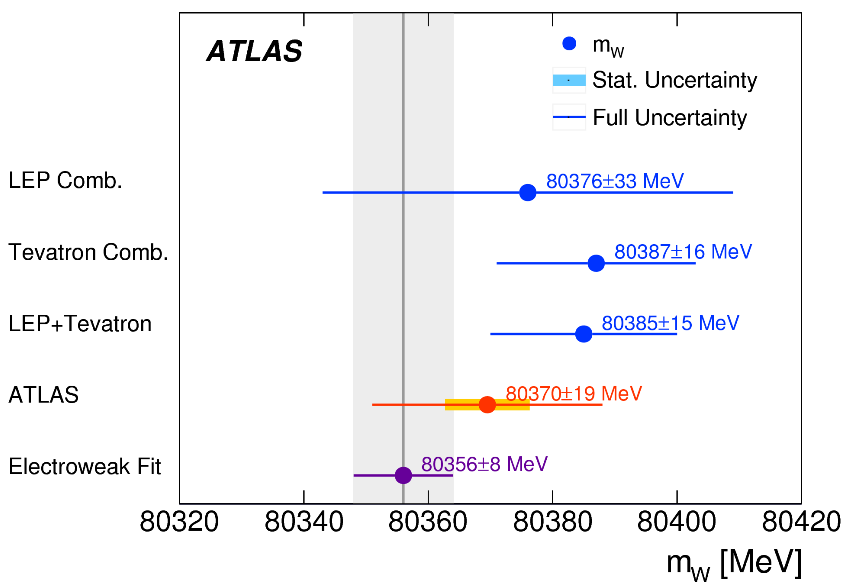
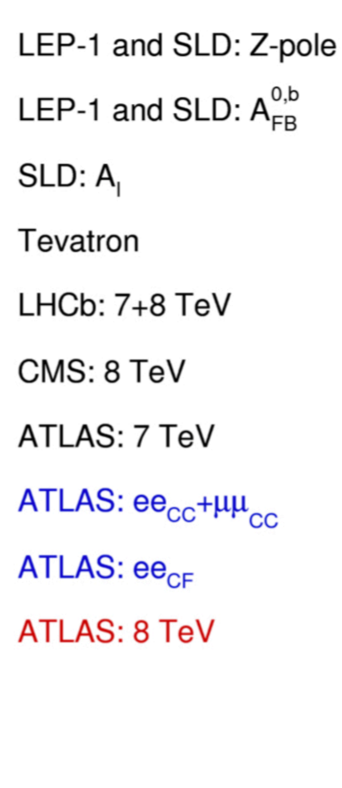
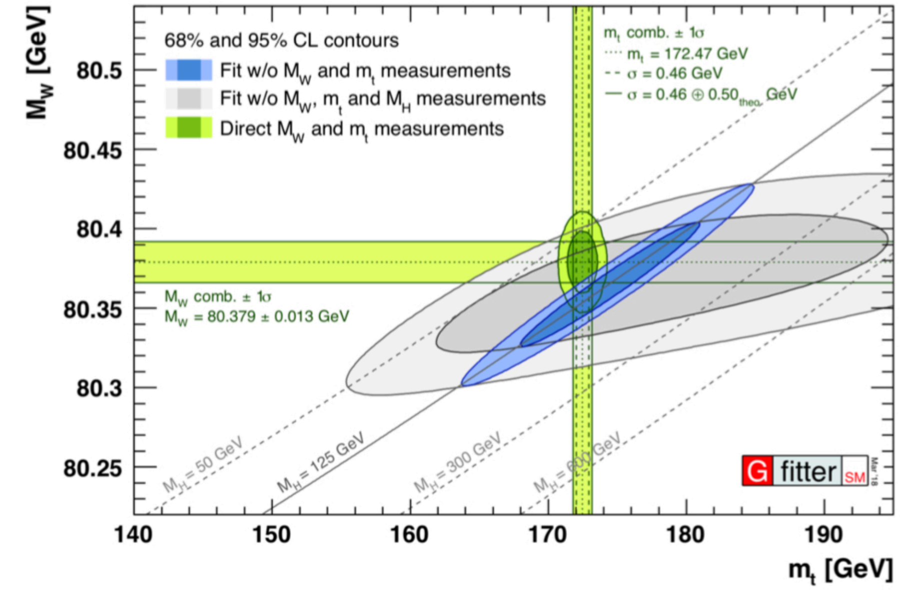
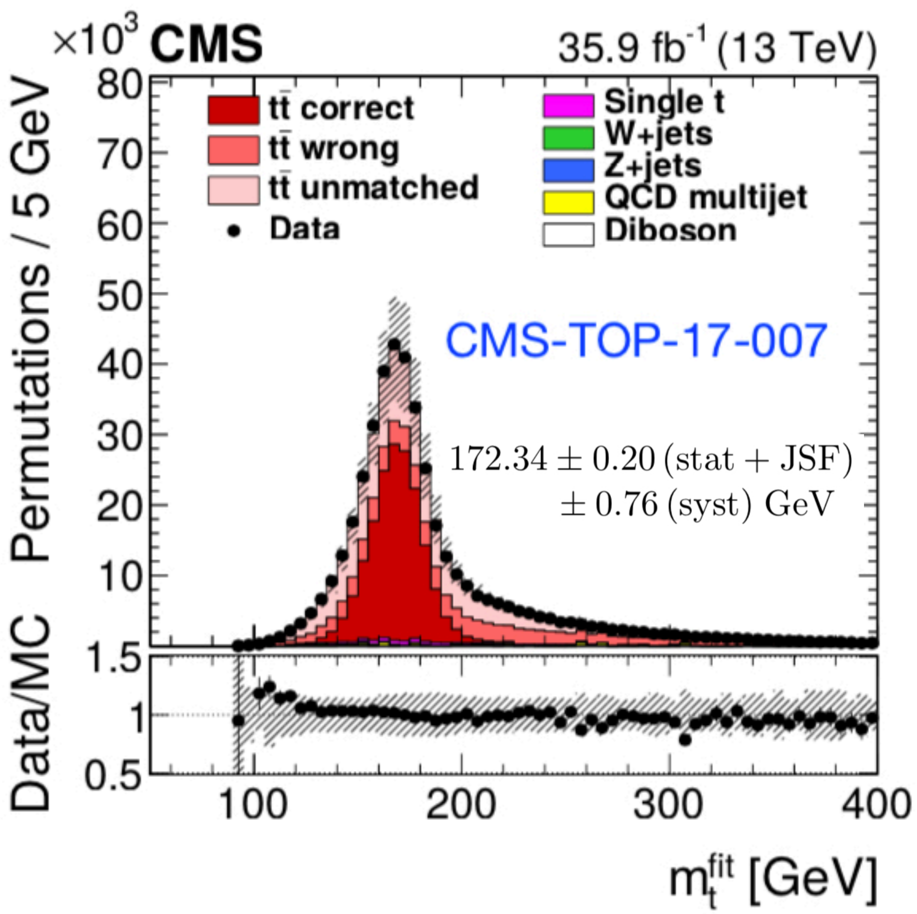
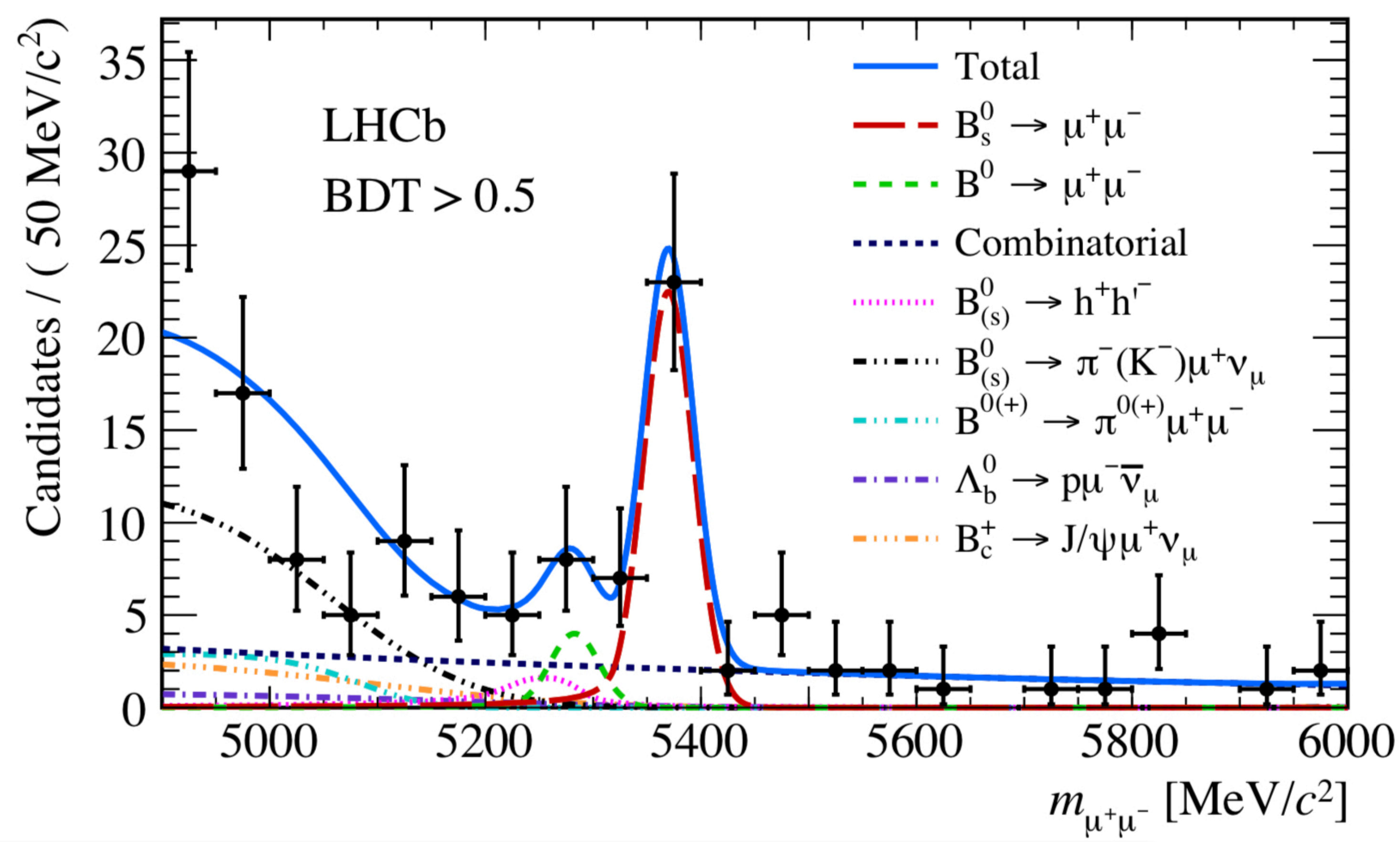
  - re-interpretation tools, simplified models, EFT, …



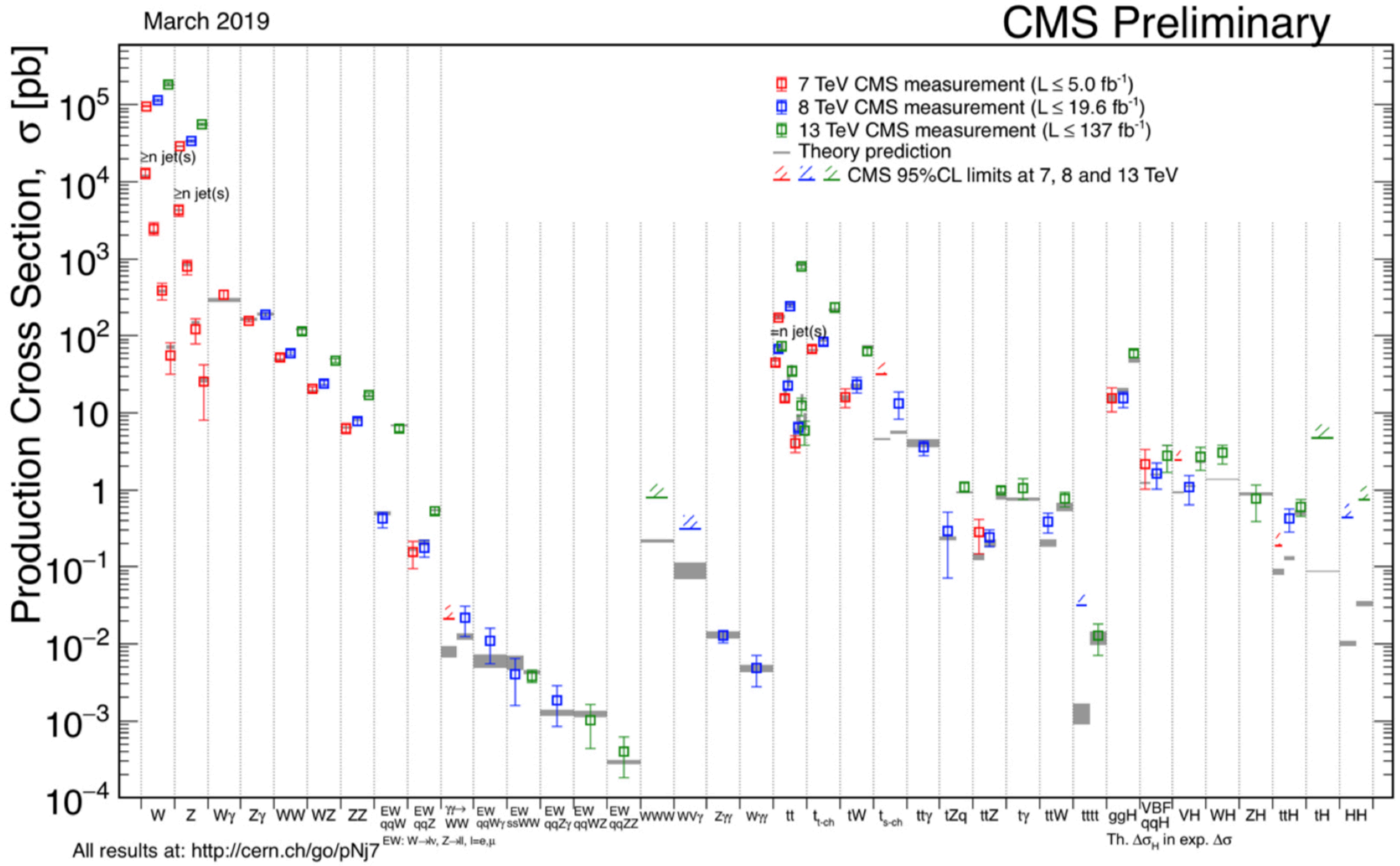


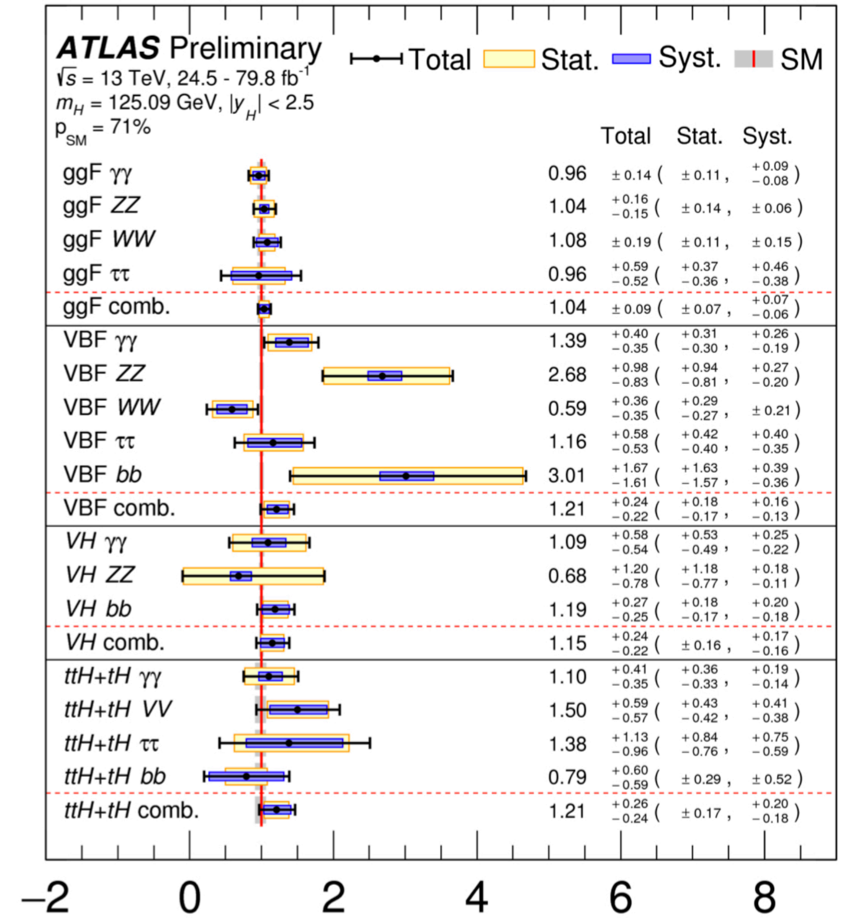


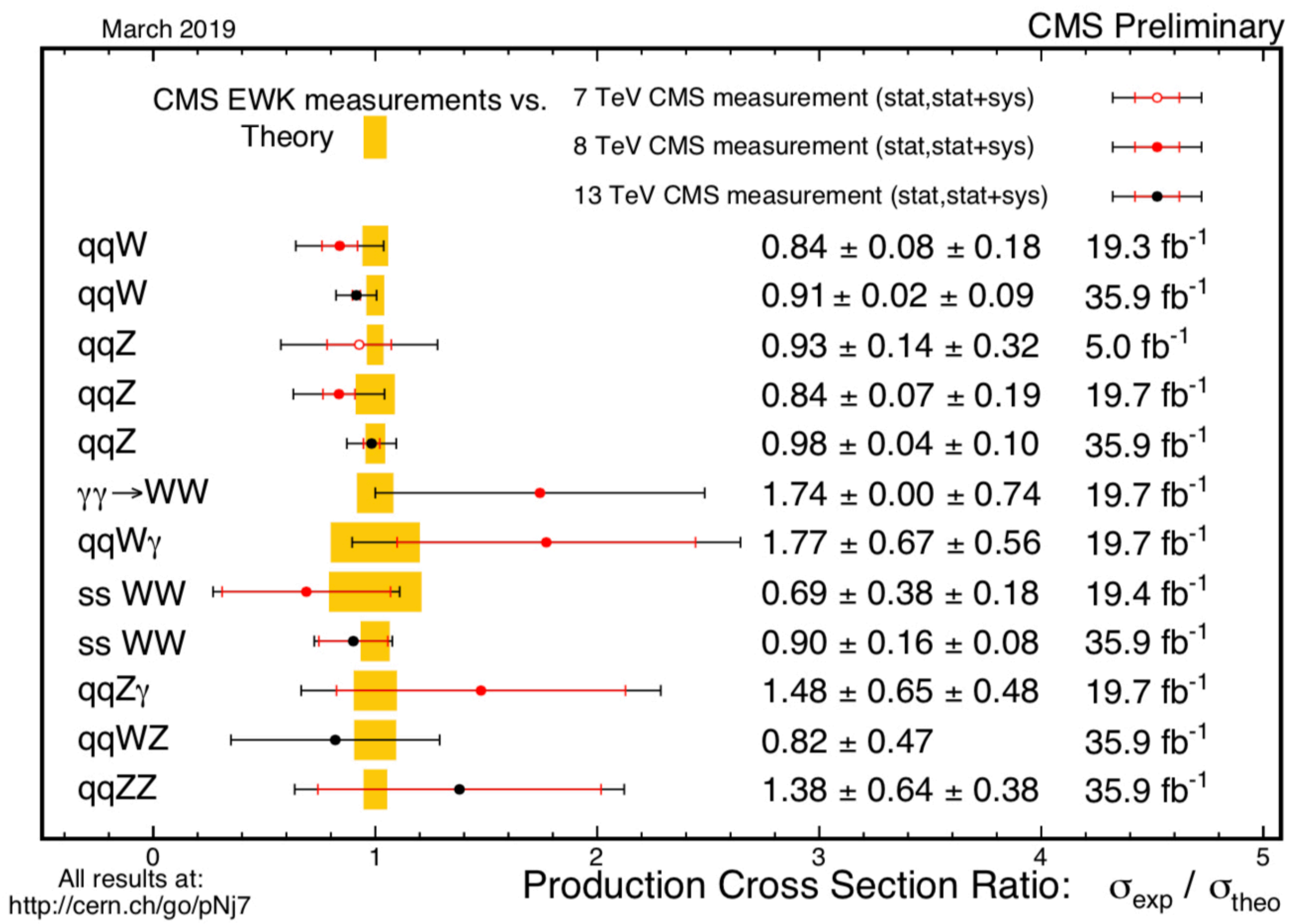


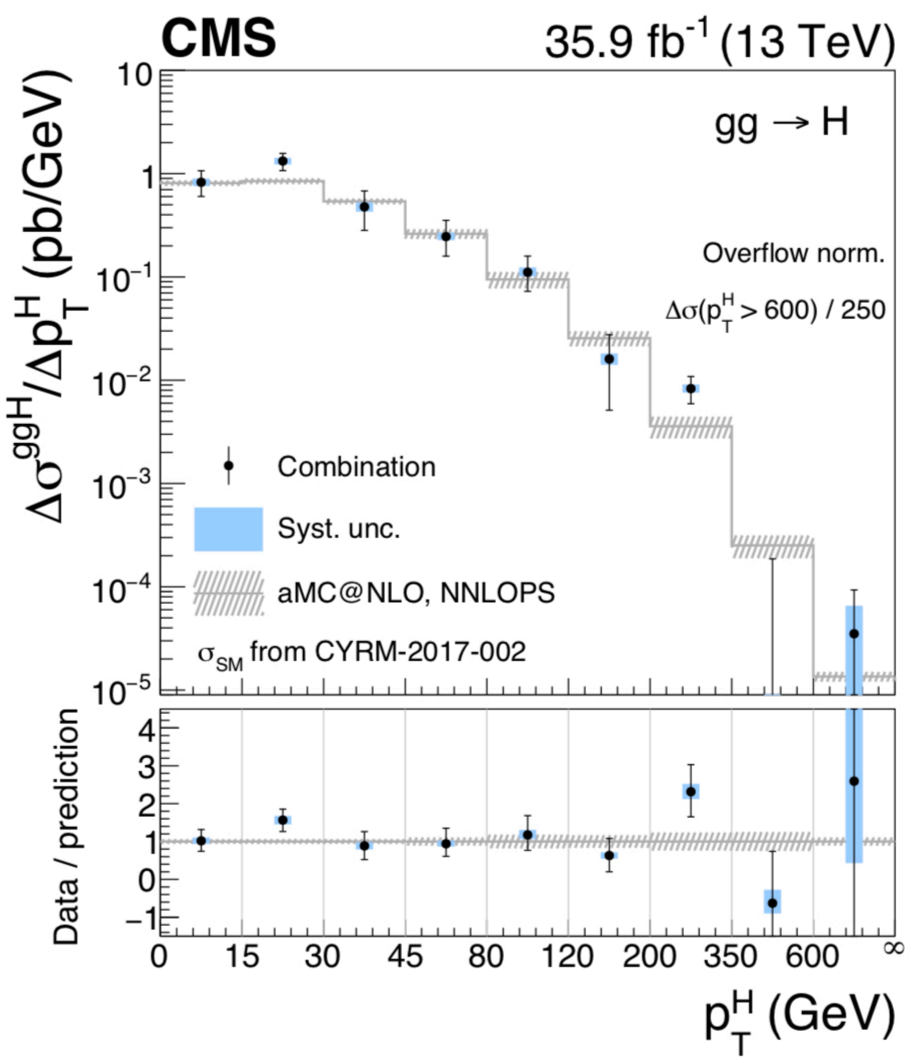


$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$


March 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
All results at: http://cern.ch/go/pNj7
Th. Δσ_H in exp. Δσ

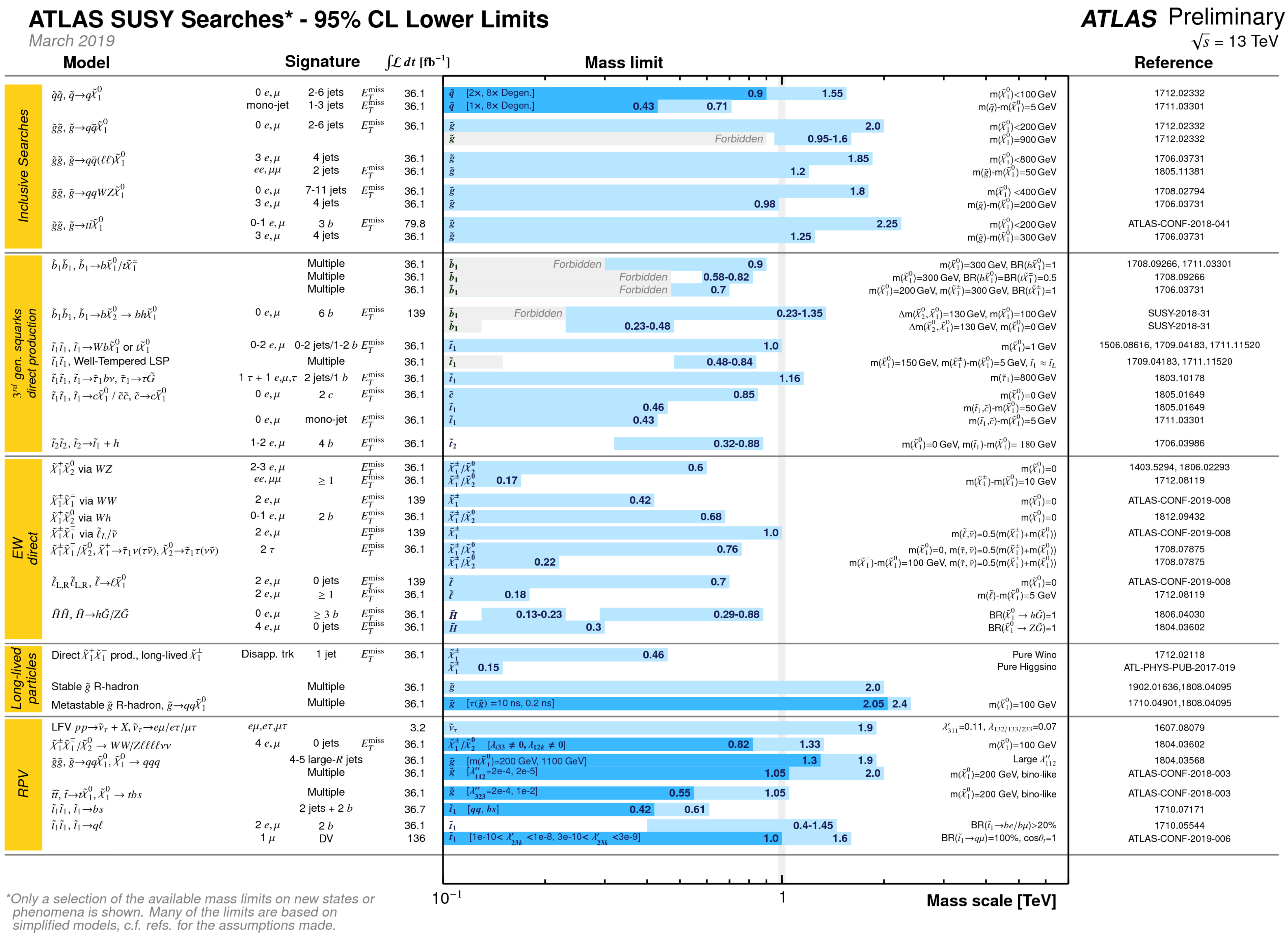

ATLAS Preliminary
Total
Stat.
Syst.
SM
√s = 13 TeV, 24.5 - 79.8 fb-1
m_H = 125.09 GeV, |y_H| < 2.5
p_SM = 71%
Total Stat. Syst.
ggF γγ 0.96
ggF ZZ 1.04
ggF WW 1.08
ggF ττ 0.96
ggF comb. 1.04
VBF γγ 1.39
VBF ZZ 2.68
VBF WW 0.59
VBF ττ 1.16
VBF bb 3.01
VBF comb. 1.21
VH γγ 1.09
VH ZZ 0.68
VH bb 1.19
VH comb. 1.15
ttH+tH γγ 1.10
ttH+tH VV 1.50
ttH+tH ττ 1.38
ttH+tH bb 0.79
ttH+tH comb. 1.21


March 2019
CMS Preliminary
CMS EWK measurements vs. Theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
qqW 0.84 ± 0.08 ± 0.18 19.3 fb-1
qqW 0.91 ± 0.02 ± 0.09 35.9 fb-1
qqZ 0.93 ± 0.14 ± 0.32 5.0 fb-1
qqZ 0.84 ± 0.07 ± 0.19 19.7 fb-1
qqZ 0.98 ± 0.04 ± 0.10 35.9 fb-1
γγ→WW 1.74 ± 0.00 ± 0.74 19.7 fb-1
qqWγ 1.77 ± 0.67 ± 0.56 19.7 fb-1
ss WW 0.69 ± 0.38 ± 0.18 19.4 fb-1
ss WW 0.90 ± 0.16 ± 0.08 35.9 fb-1
qqZγ 1.48 ± 0.65 ± 0.48 19.7 fb-1
qqWZ 0.82 ± 0.47 35.9 fb-1
qqZZ 1.38 ± 0.64 ± 0.38 35.9 fb-1
All results at: http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo


CMS
35.9 fb-1 (13 TeV)
gg → H
Overflow norm.
Δσ(pT H > 600) / 250
Combination
Syst. unc.
aMC@NLO, NNLOPS
σSM from CYRM-2017-002
Δσ^ggH/Δp_T^H (pb/GeV)
Data / prediction
p_T^H (GeV)

.. and much more!

- QCD dynamics under all conditions, leading to “discoveries” in many areas: spectroscopy, total/elastic/diffractive cross sections, thermodynamics, collective phenomena in small&large systems, …
- Flavour physics of top, bottom, charm: rare decays, CKM, CPV, …
- EW interactions in the TeV region
- searches, searches, searches ….



ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ | 0 e,μ 2-6 jets E_T^{miss} 36.1 | $\tilde{q}$ [2×, 8× Degen.] 0.9 1.55 | m($\tilde{\chi}^0_1$)<100 GeV | 1712.02332
mono-jet 1-3 jets E_T^{miss} 36.1 | $\tilde{q}$ [1×, 8× Degen.] 0.43 0.71 | m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301
$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$ | 0 e,μ 2-6 jets E_T^{miss} 36.1 | $\tilde{g}$ 2.0 | m($\tilde{\chi}^0_1$)<200 GeV | 1712.02332
$\tilde{g}$ Forbidden 0.95-1.6 | m($\tilde{\chi}^0_1$)=900 GeV | 1712.02332
$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$ | 3 e,μ 4 jets 36.1 | $\tilde{g}$ 1.85 | m($\tilde{\chi}^0_1$)<800 GeV | 1706.03731
$ee,\mu\mu$ 2 jets E_T^{miss} 36.1 | $\tilde{g}$ 1.2 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.11381
$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$ | 0 e,μ 7-11 jets E_T^{miss} 36.1 | $\tilde{g}$ 1.8 | m($\tilde{\chi}^0_1$) <400 GeV | 1708.02794
3 e,μ 4 jets 36.1 | $\tilde{g}$ 0.98 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV | 1706.03731
$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$ | 0-1 e,μ 3 b E_T^{miss} 79.8 | $\tilde{g}$ 2.25 | m($\tilde{\chi}^0_1$)<200 GeV | ATLAS-CONF-2018-041
3 e,μ 4 jets 36.1 | $\tilde{g}$ 1.25 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV | 1706.03731
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$ | Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.9 | m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1 | 1708.09266, 1711.03301
Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.58-0.82 | m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5 | 1708.09266
Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.7 | m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1 | 1706.03731
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$ | 0 e,μ 6 b E_T^{miss} 139 | $\tilde{b}_1$ Forbidden 0.23-1.35 | Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV | SUSY-2018-31
$\tilde{b}_1$ 0.23-0.48 | Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV | SUSY-2018-31
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$ | 0-2 e,μ 0-2 jets/1-2 b E_T^{miss} 36.1 | $\tilde{t}_1$ 1.0 | m($\tilde{\chi}^0_1$)=1 GeV | 1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP | Multiple 36.1 | $\tilde{t}_1$ 0.48-0.84 | m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$ | 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$ | 1 τ + 1 e,μ,τ 2 jets/1 b E_T^{miss} 36.1 | $\tilde{t}_1$ 1.16 | m($\tilde{\tau}_1$)=800 GeV | 1803.10178
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$ | 0 e,μ 2 c E_T^{miss} 36.1 | $\tilde{c}$ 0.85 | m($\tilde{\chi}^0_1$)=0 GeV | 1805.01649
$\tilde{t}_1$ 0.46 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.01649
0 e,μ mono-jet E_T^{miss} 36.1 | $\tilde{t}_1$ 0.43 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$ | 1-2 e,μ 4 b E_T^{miss} 36.1 | $\tilde{t}_2$ 0.32-0.88 | m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV | 1706.03986
EW direct
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ | 2-3 e,μ E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6 | m($\tilde{\chi}^0_1$)=0 | 1403.5294, 1806.02293
$ee,\mu\mu$ ≥ 1 E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17 | m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV | 1712.08119
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW | 2 e,μ E_T^{miss} 139 | $\tilde{\chi}^\pm_1$ 0.42 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-008
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh | 0-1 e,μ 2 b E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.68 | m($\tilde{\chi}^0_1$)=0 | 1812.09432
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 e,μ E_T^{miss} 139 | $\tilde{\chi}^\pm_1$ 1.0 | m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | ATLAS-CONF-2019-008
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$ | 2 τ E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76 | m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | 1708.07875
$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22 | m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | 1708.07875
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$ | 2 e,μ 0 jets E_T^{miss} 139 | $\tilde{\ell}$ 0.7 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-008
2 e,μ ≥ 1 E_T^{miss} 36.1 | $\tilde{\ell}$ 0.18 | m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1712.08119
$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 e,μ ≥ 3 b E_T^{miss} 36.1 | $\tilde{H}$ 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1 | 1806.04030
4 e,μ 0 jets E_T^{miss} 36.1 | $\tilde{H}$ 0.3 | BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1 | 1804.03602
Long-lived particles
Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$ | Disapp. trk 1 jet E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1$ 0.46 | Pure Wino | 1712.02118
$\tilde{\chi}^\pm_1$ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019
Stable $\tilde{g}$ R-hadron | Multiple 36.1 | $\tilde{g}$ 2.0 | 1902.01636,1808.04095
Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$ | Multiple 36.1 | $\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4 | m($\tilde{\chi}^0_1$)=100 GeV | 1710.04901,1808.04095
RPV
LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ 3.2 | $\tilde{\nu}_\tau$ 1.9 | λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 e,μ 0 jets E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33 | m($\tilde{\chi}^0_1$)=100 GeV | 1804.03602
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$ | 4-5 large-R jets 36.1 | $\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9 | Large λ''_{112} | 1804.03568
Multiple 36.1 | $\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$ | Multiple 36.1 | $\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | 2 jets + 2 b 36.7 | $\tilde{t}_1$ [qq, bs] 0.42 0.61 | 1710.07171
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$ | 2 e,μ 2 b 36.1 | $\tilde{t}_1$ 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544
1 μ DV 136 | $\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1 | ATLAS-CONF-2019-006
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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=> the talks at this mtg are a celebration of 10 yrs of success stories of both experimental and theoretical communities

=> the inability to "disentangle evidence of new physics…" is not a failure of the approaches… it's just that new physics isn't there yet!

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- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … and who knows how important a given measurement can become, to assess the validity of a future theory?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

*[…] **critically review the methods and ideas proposed so far in the investigation of new physics**, opening the discussion to new ideas, new approaches, new avenues.*

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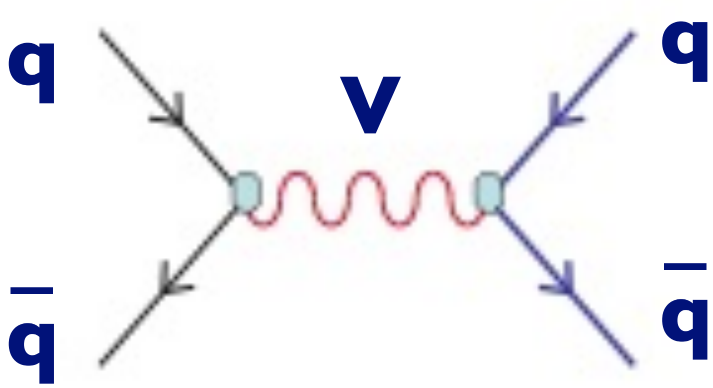
There are plenty of examples showing the multitude and ingenuity of new ideas that emerged from the cross talk of theoretical developments and experimental opportunities

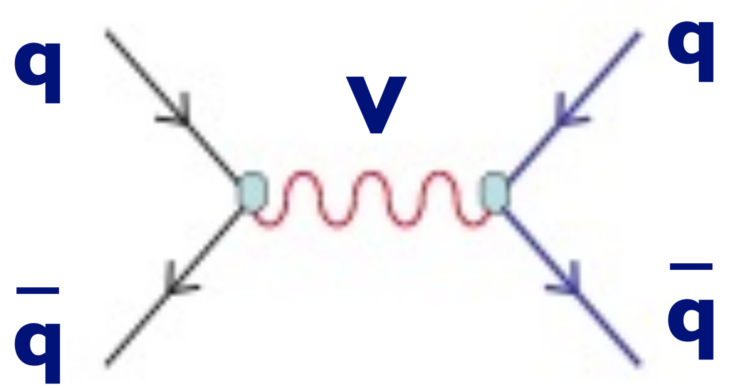
Example: DM searches in MET+X (X=jet, V, …)

Example: search for low-mass resonances V→2 jets



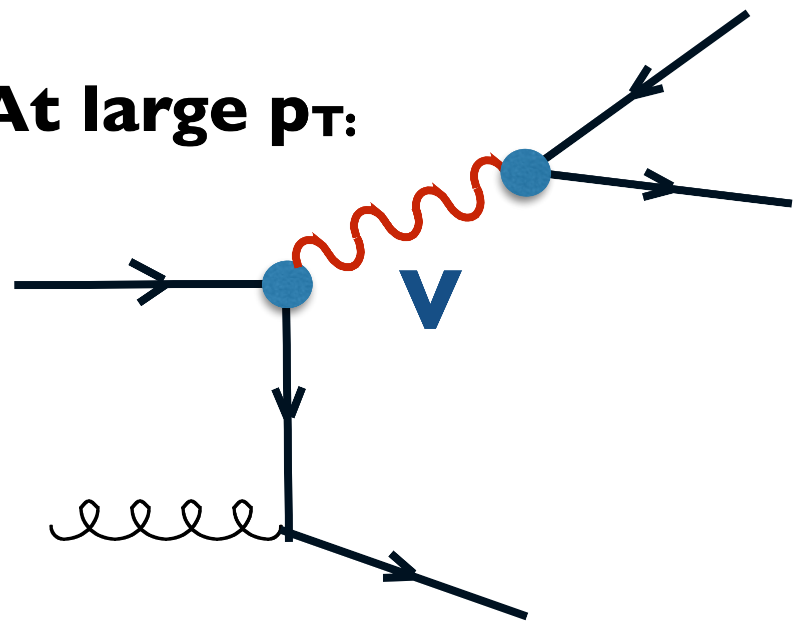
search impossible at masses below few hundred GeV,
due to large gg→gg bg's and trigger thresholds

Example: search for low-mass resonances V→2 jets



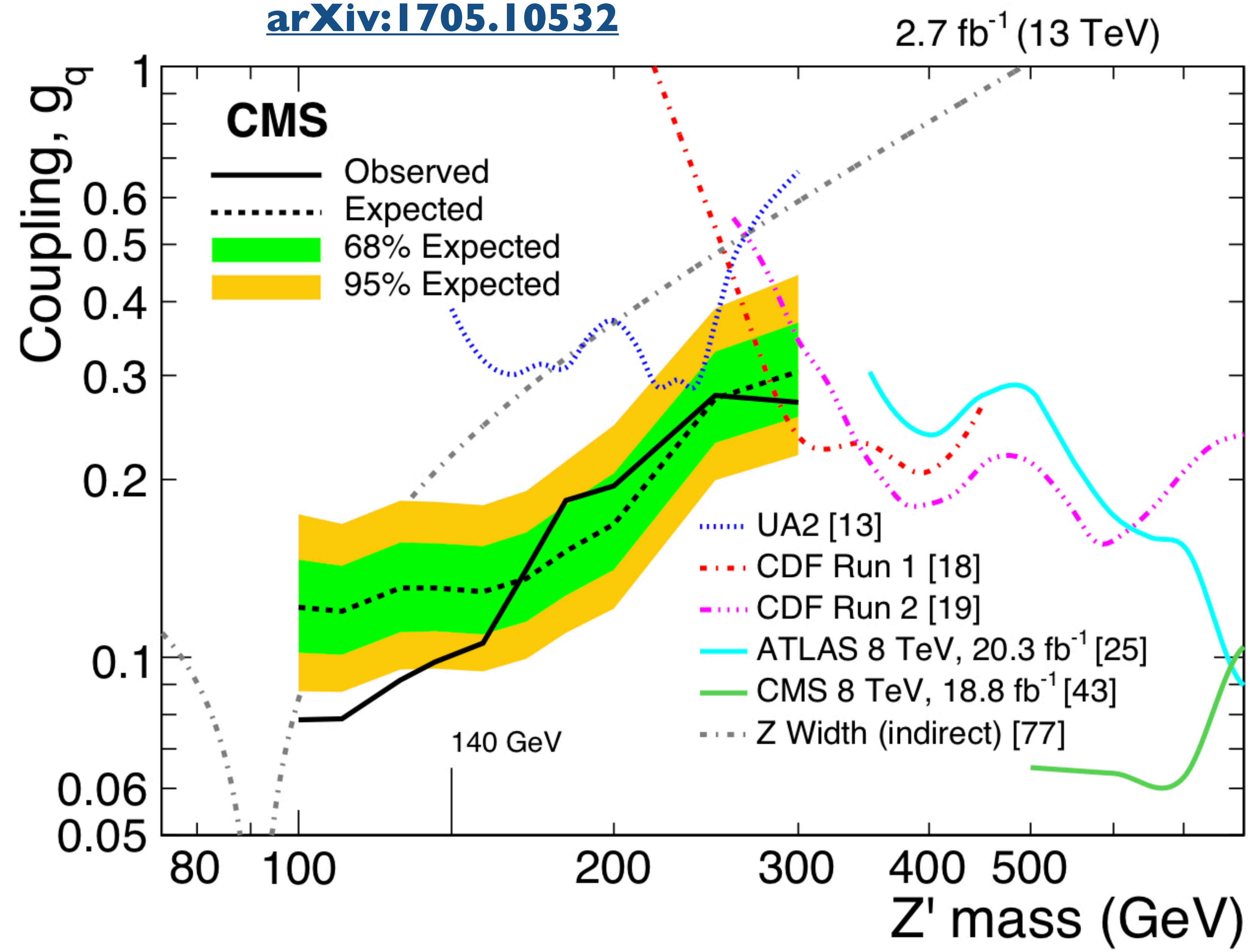
search impossible at masses below few hundred GeV, due to large gg→gg bg's and trigger thresholds

At large p_T:



- S/B improves (qg initial state dominates both S and B)
- use boosted techniques to differentiate V→qq vs QCD dijets
- ε_{trig} ~ 100%

arXiv:1705.10532



The realization that loopholes were being left in searches (eg LLPs) led to new dedicated strategies with the existing detectors:

… and to the planning of dedicated upgrades for HL-LHC (eg timing), or of dedicated new detectors (FASER, Mathusla, Codex-b, …)

Critical reviews of methods and many new ideas/ models for the search programme discussed during the

HL/HE-LHC Physics workshop

and documented in the WG reports:

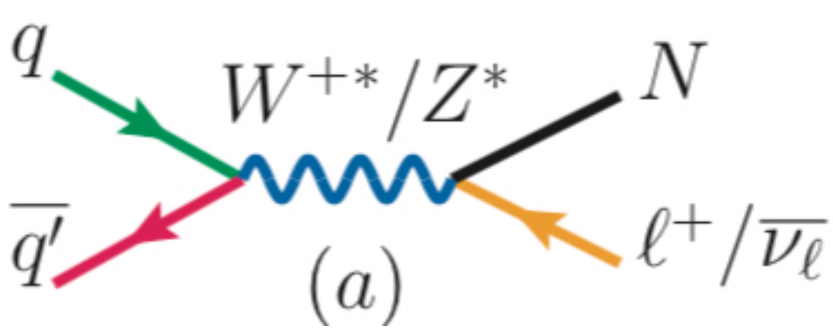
WG1 report
http://arxiv.org/abs/arXiv:1902.04070 (219 pages)
WG2 report
http://arxiv.org/abs/arXiv:1902.00134 (364 pages)
WG3 report
http://arxiv.org/abs/arXiv:1812.07831 (279 pages)
WG4 report
http://arxiv.org/abs/arXiv:1812.07638 (292 pages)
WG5 report
http://arxiv.org/abs/arXiv:1812.06772 (207 pages)
"Volume 2" (collection of ATLAS and CMS public notes):
https://arxiv.org/abs/1902.10229 **(1369 pages)**

I will not repeat any of the material shown there, but will raise a couple of additional points

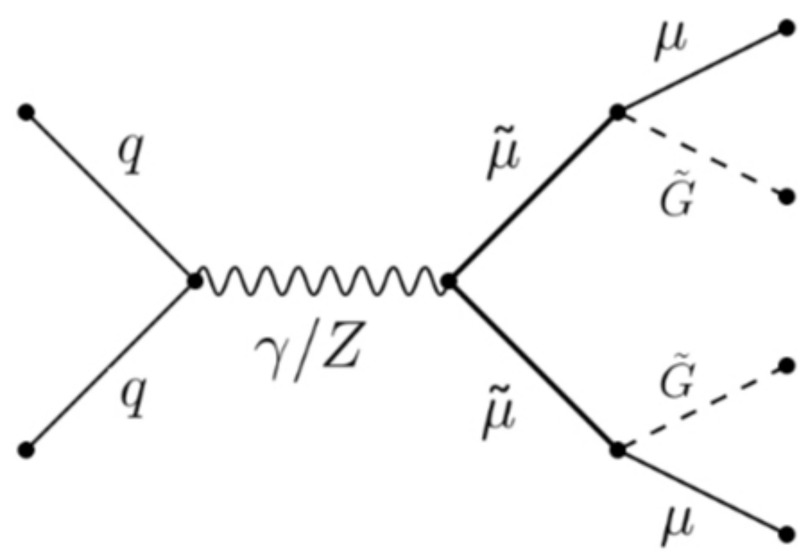
Explore and test more systematically lepton universality

Several BSM signatures can lead to differences in rates between electrons and muons. Tests of lepton universality should become a common feature of all SM measurements at high Q^2, since even tiny e/μ/τ asymmetries could hint at some otherwise elusive process

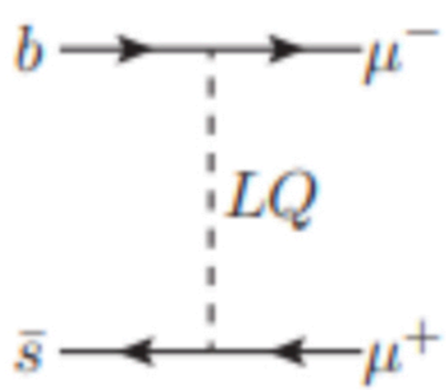
Heavy neutrino N production

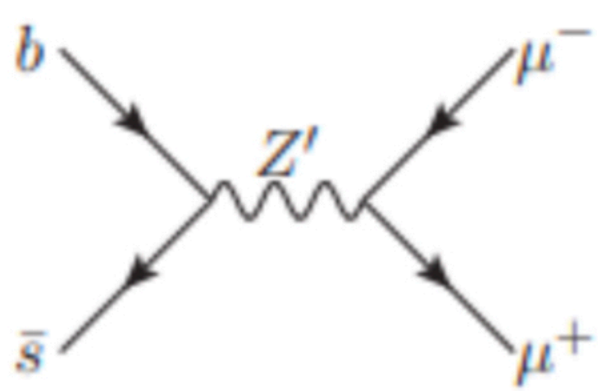


Sleptons



Leptoquarks or Z’ from flavour anomalies





Greljio, Marzocca, https://arxiv.org/pdf/1704.09015.pdf

Challenge Use data to minimize systematics of relative e/μ/τ efficiencies and acceptances, avoiding the risk of calibrating away new physics

Ex:

- correlate inclusive $Z \to ee$, μμ, ττ for low-pt leptons
- correlate high-pT $Z \to ee$, μμ, ττ for high-pt leptons
- avoid high-mass DY, or “W” (ℓ+MET) as they might hide NP

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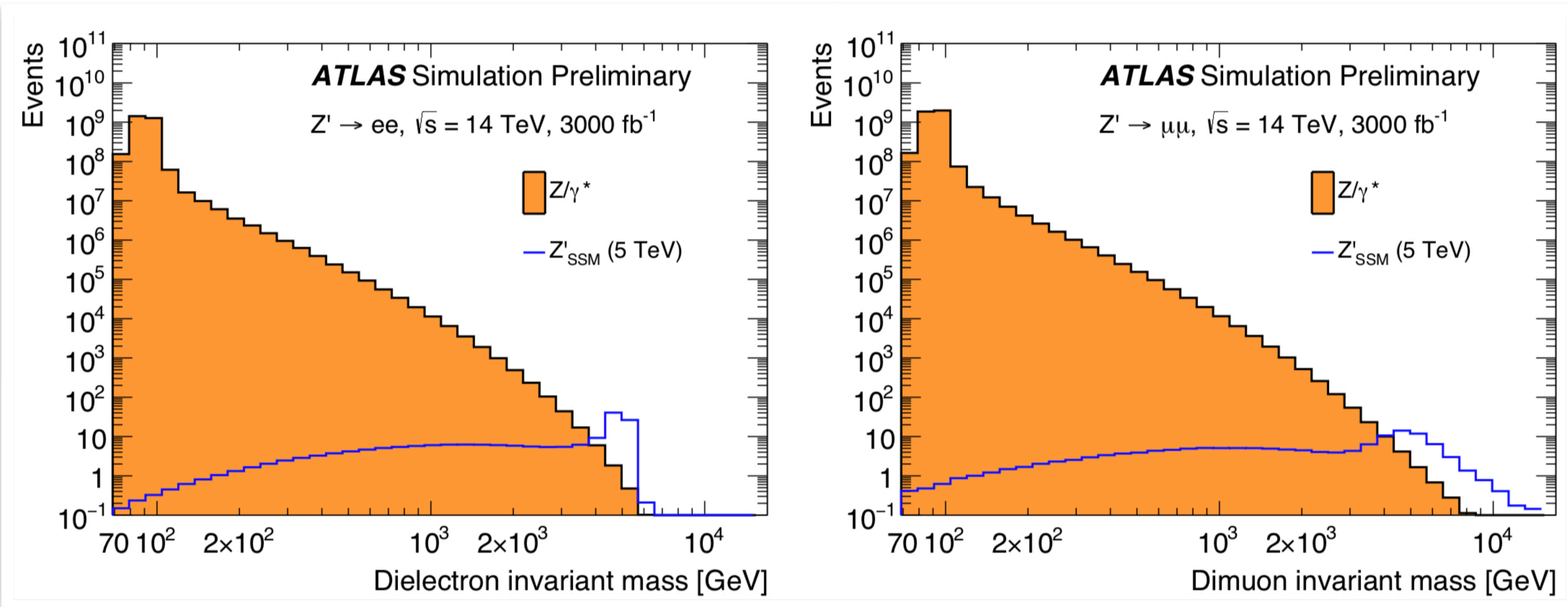
Challenge



How well can we establish the e/mu universality in the decays of such a Z', given the poor mass resolution in the dimuon channel?

Are there ways to at least partly improve the $m_{\mu\mu}$ resolution, eg exploiting the unphysical missET that arises from the independent mismeasurement of the two muons?

More systematic use of top quark events

σ_{tot}(14 TeV) ~ 1 nb

- 3×10^9 top pairs produced in 3 ab^{-1}
- $\Rightarrow$ $O(10^8)$ events triggered with one top fully reconstructed and charge-tagged, to allow the fully inclusive study of the second top decay.
- In addition to the search for non-($t \rightarrow Wb$) decays, study:
  - $O(10^8)$ fully inclusive $t \rightarrow Wb$ decays
    - 10^8 fully charge-tagged b hadrons
    - rare and forbidden W decays
    - 3 10^7 $W \rightarrow$ charm (exercise charm-tagging algos ?)
    - **10^7 $W \rightarrow$ tau decays**

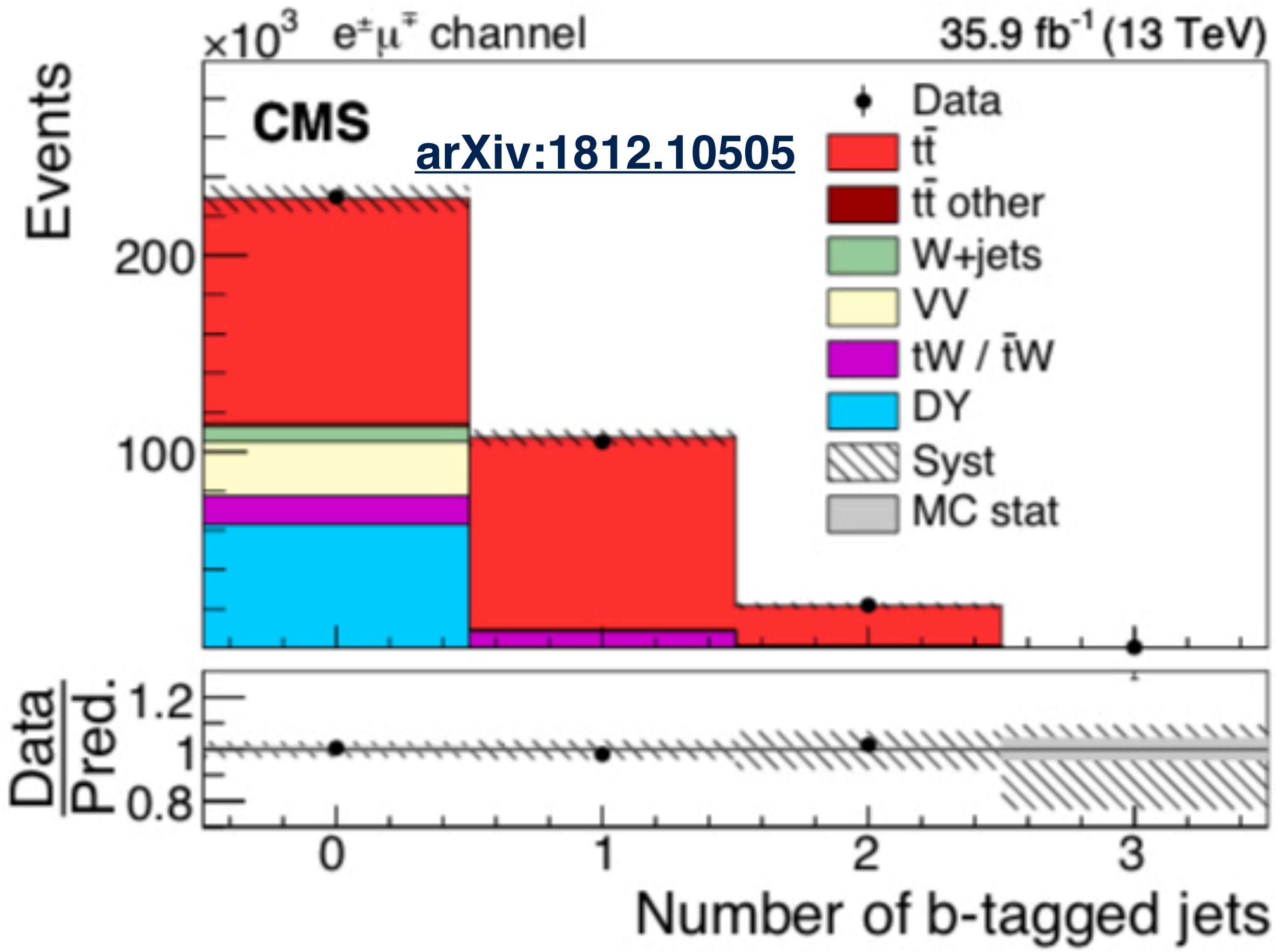
A concrete application: testing lepton universality in W decays

PDG entries dominated by LEP2 data

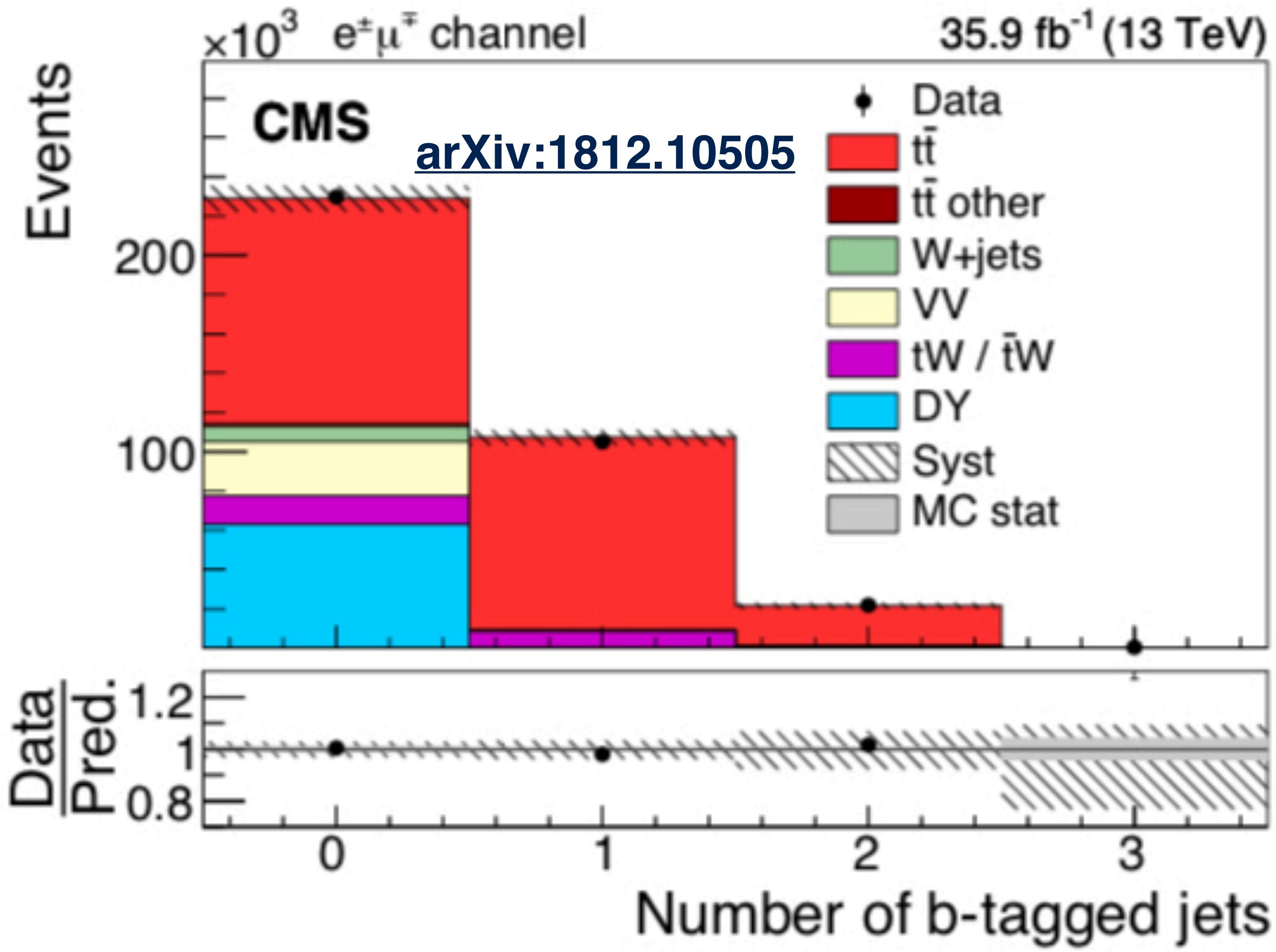
W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40192
$\mu^+\nu$		(10.63 ± 0.15) %		40192
$\tau^+\nu$		(11.38 ± 0.21) %		40173

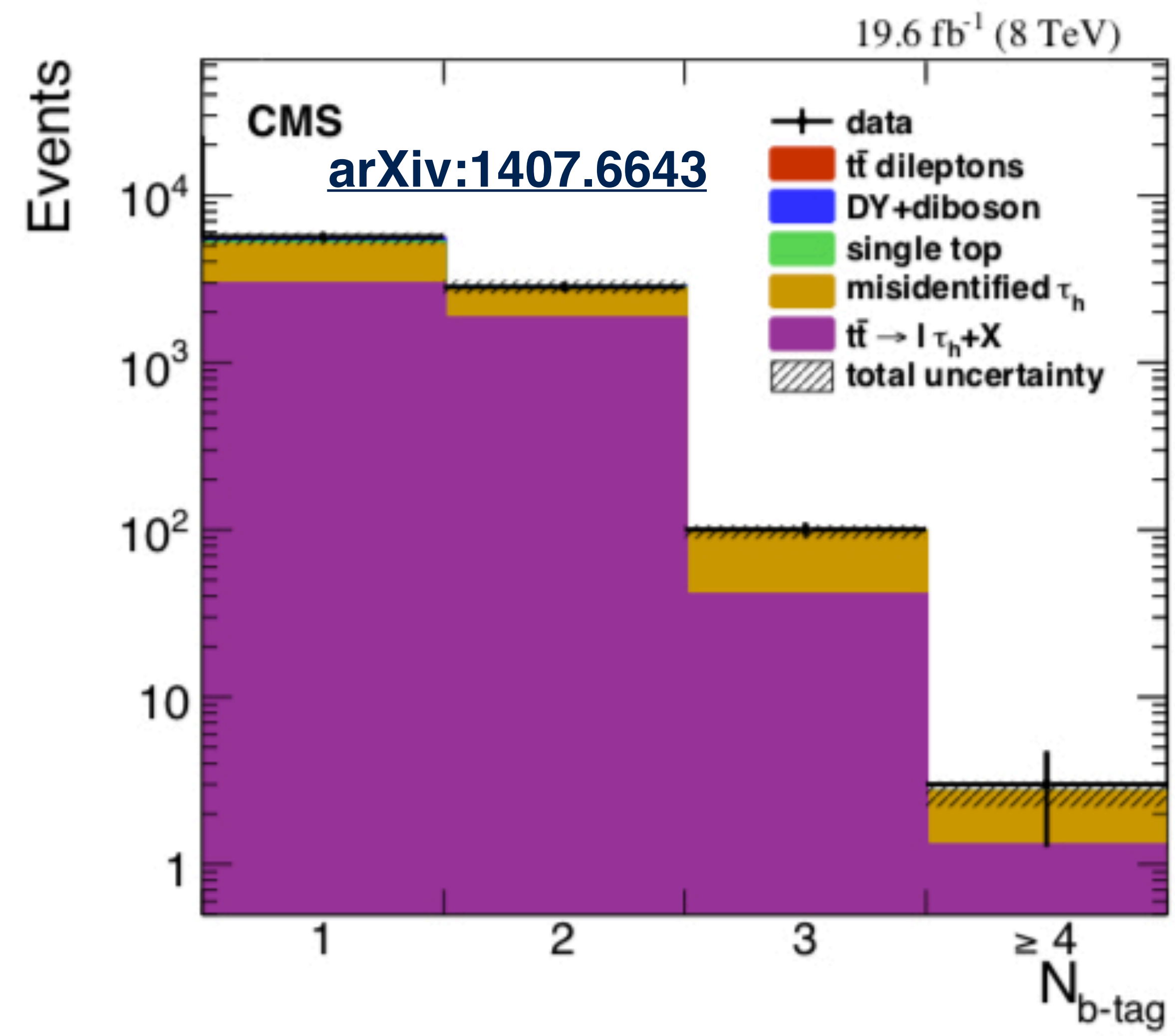
BR(τ) / BR(e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ

A 2-3% measurement would be very competitive: can the LHC clarify this issue with its tt→ℓτ events?



eμ: ~20K evts / 35.9fb^{-1} at 13 TeV => ~2M evts / 3ab^{-1} at 14 TeV





eμ: ~20K evts / 35.9fb^{-1} at 13 TeV => **~2M evts** / 3ab^{-1} at 14 TeV

lτ: ~2K evts / 19.6fb^{-1} at 8 TeV => **~1.2M evts** / 3ab^{-1} at 14 TeV

=> plenty of statistics to play with analysis, identify appropriate kinematical fiducial regions, and reduce potential systematics!

Use Z → ττ = Z → ℓℓ to reduce syst's?

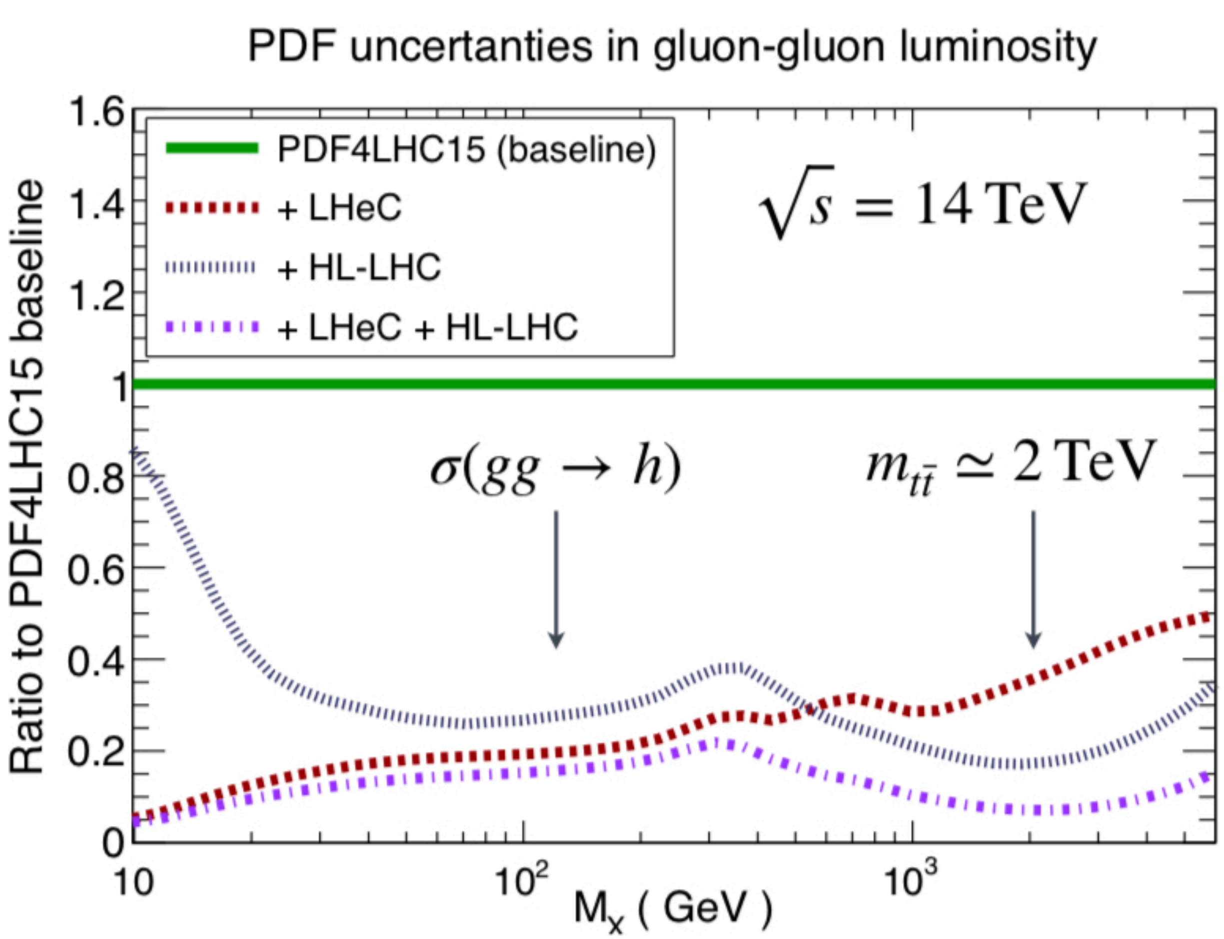
Ultimate PDFs

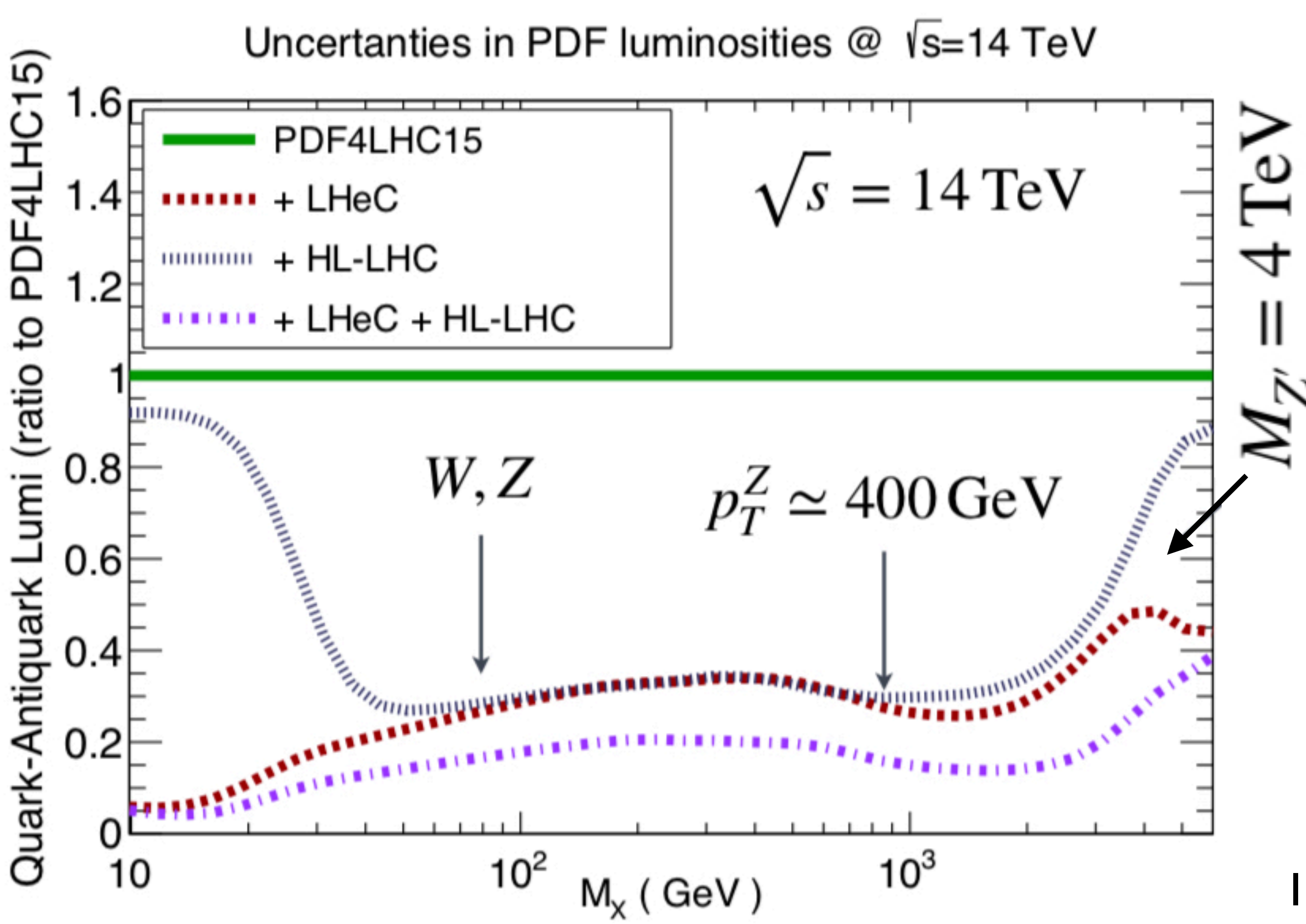
R. Abdul Khalek, S. Bailey, J. Gao, L. Harland-Lang and J. Rojo

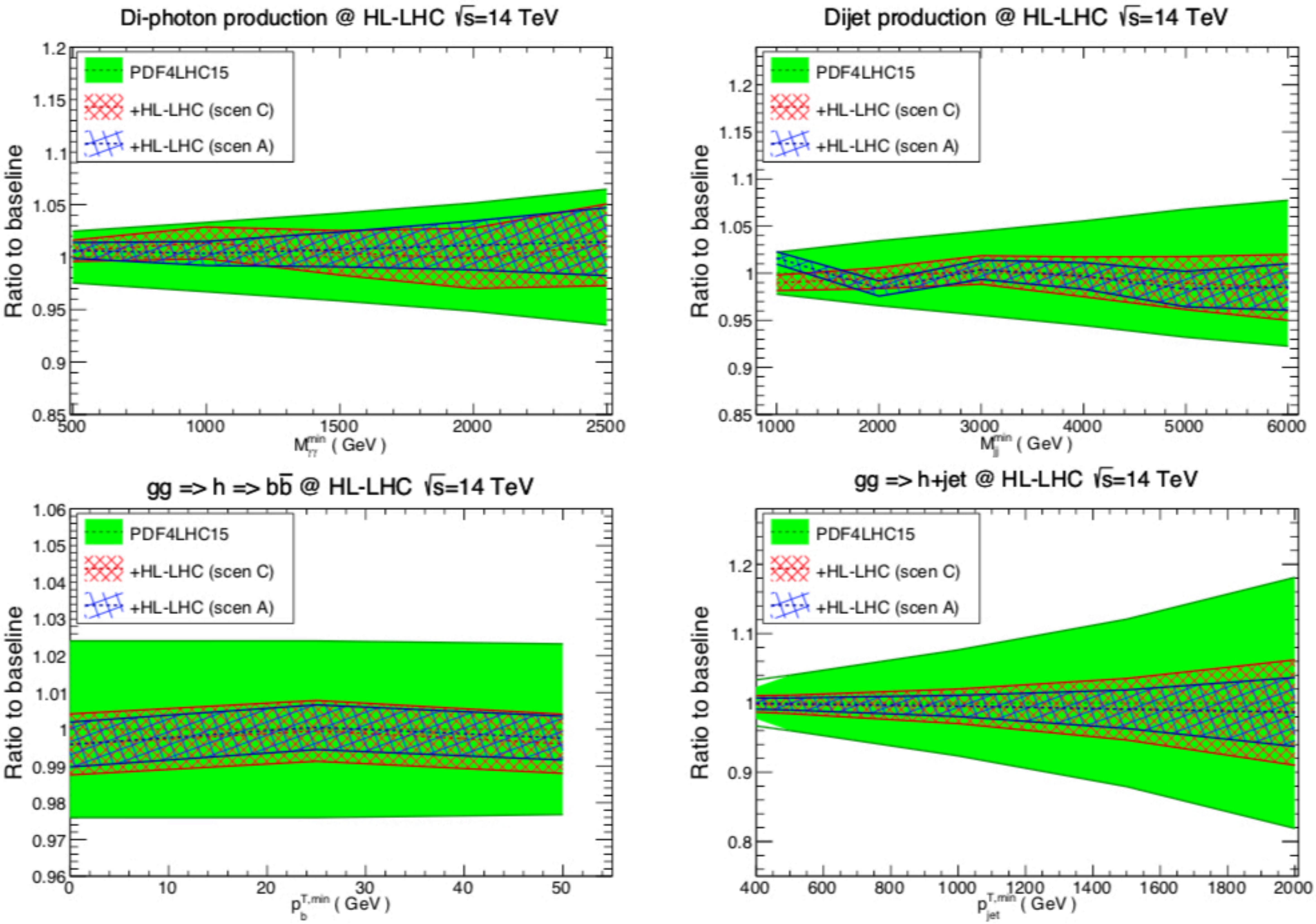
WG1 report

PDF uncertainties HLLHC / Current	10 GeV < Mx < 40 GeV	40 GeV < Mx < 1 TeV	1 TeV < Mx < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)
up-strange luminosity	0.73 (0.67)	0.38 (0.27)	0.42 (0.38)

From J.Rojo's talk yesterday



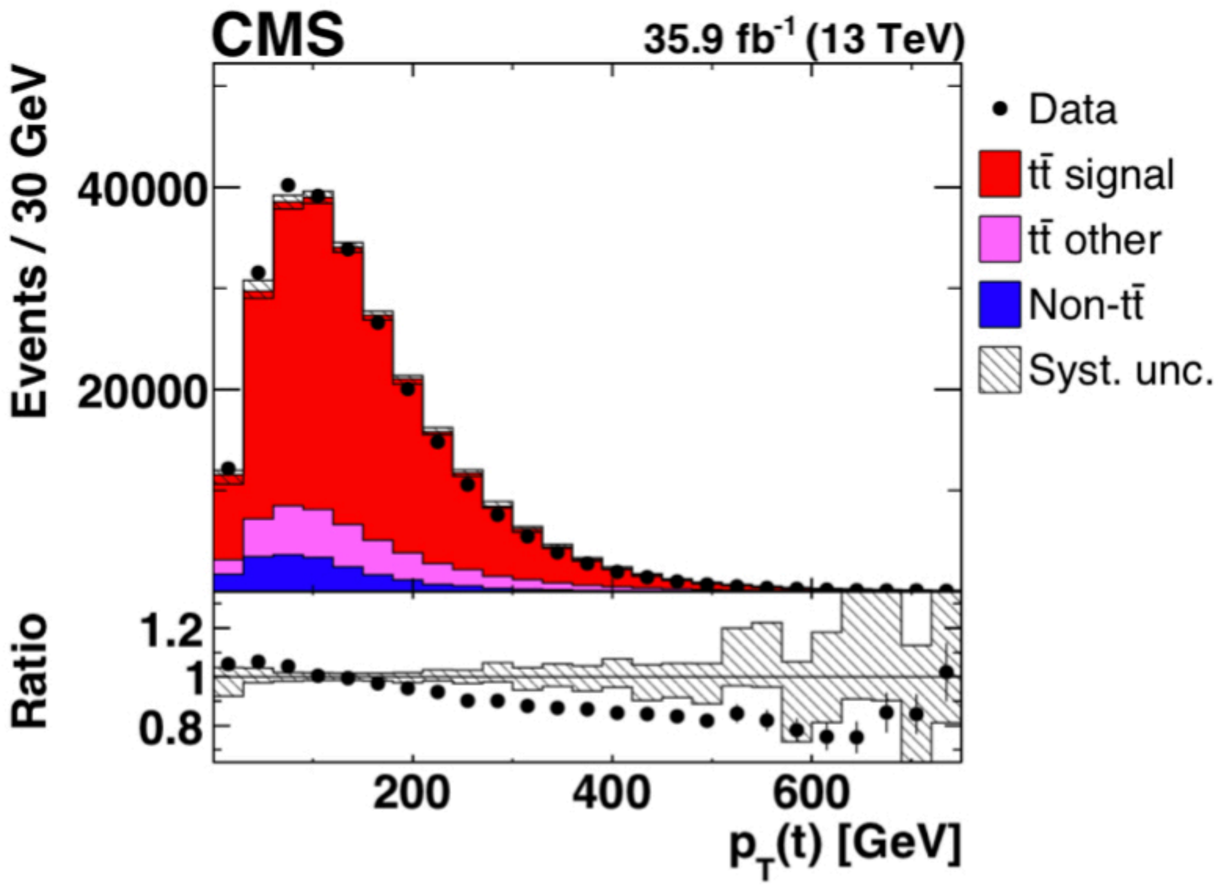


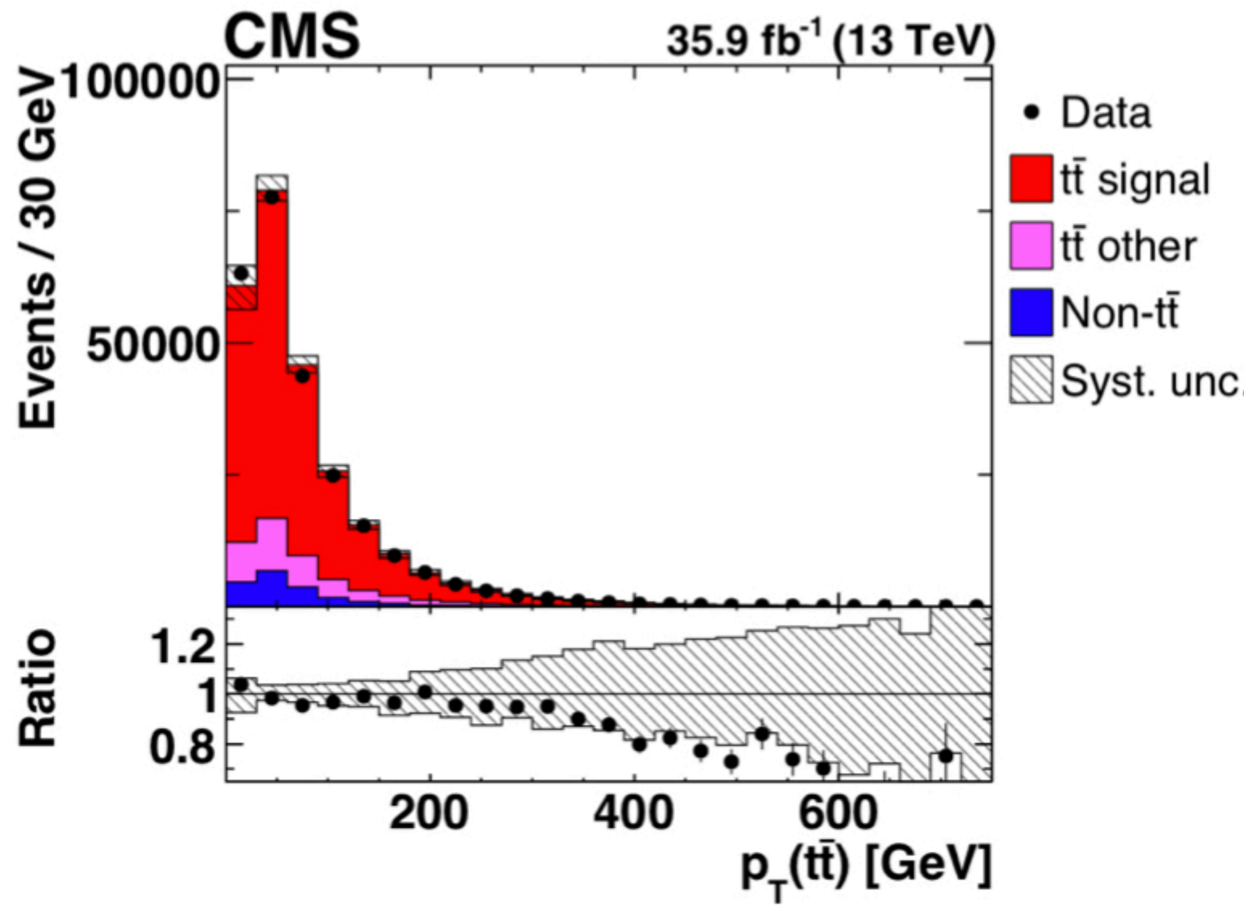


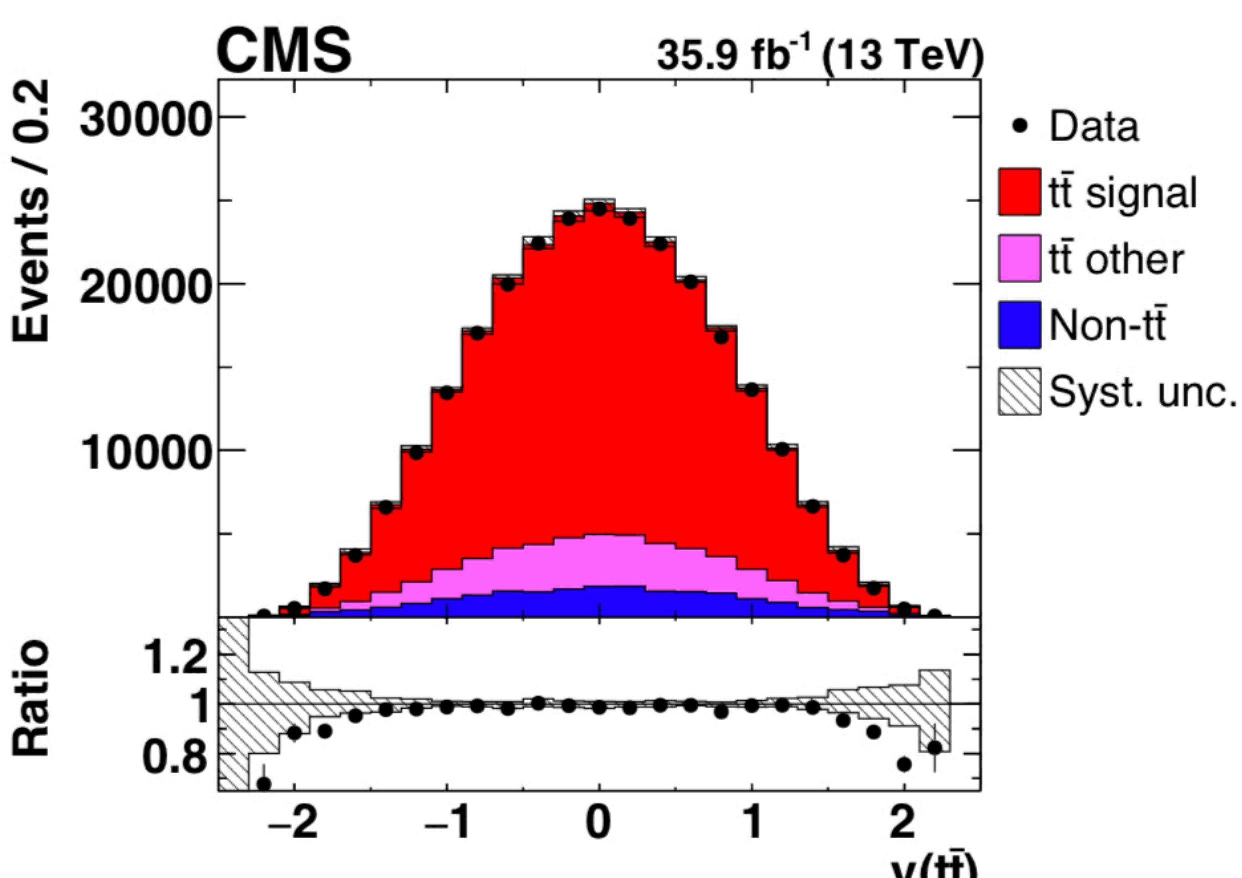
WG1 report (R. Abdul Khalek, S. Bailey, J. Gao, L. Harland-Lang and J. Rojo)

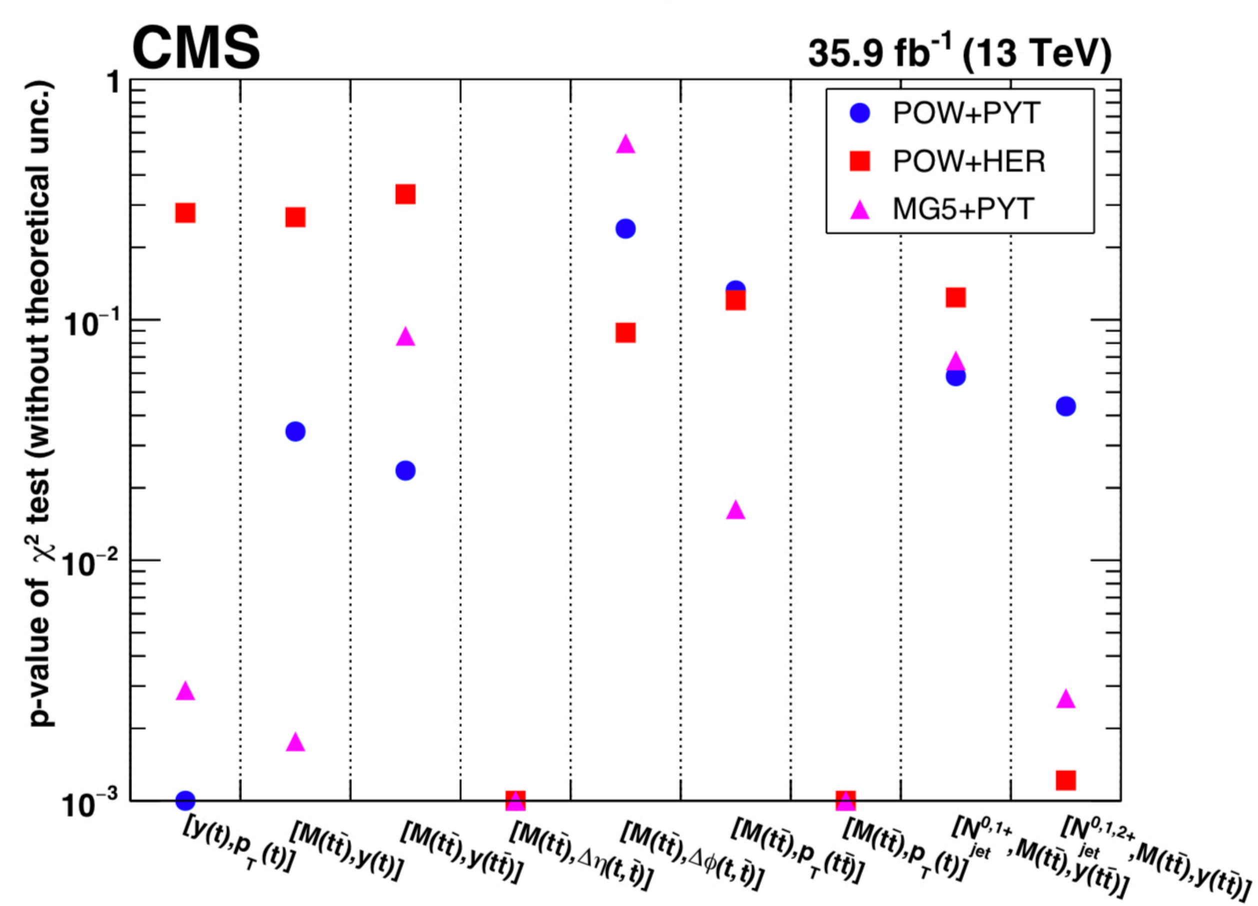
CMS: fitting m_t, α_S, PDF from ttbar production

http://arxiv.org/abs/arXiv:1904.05237









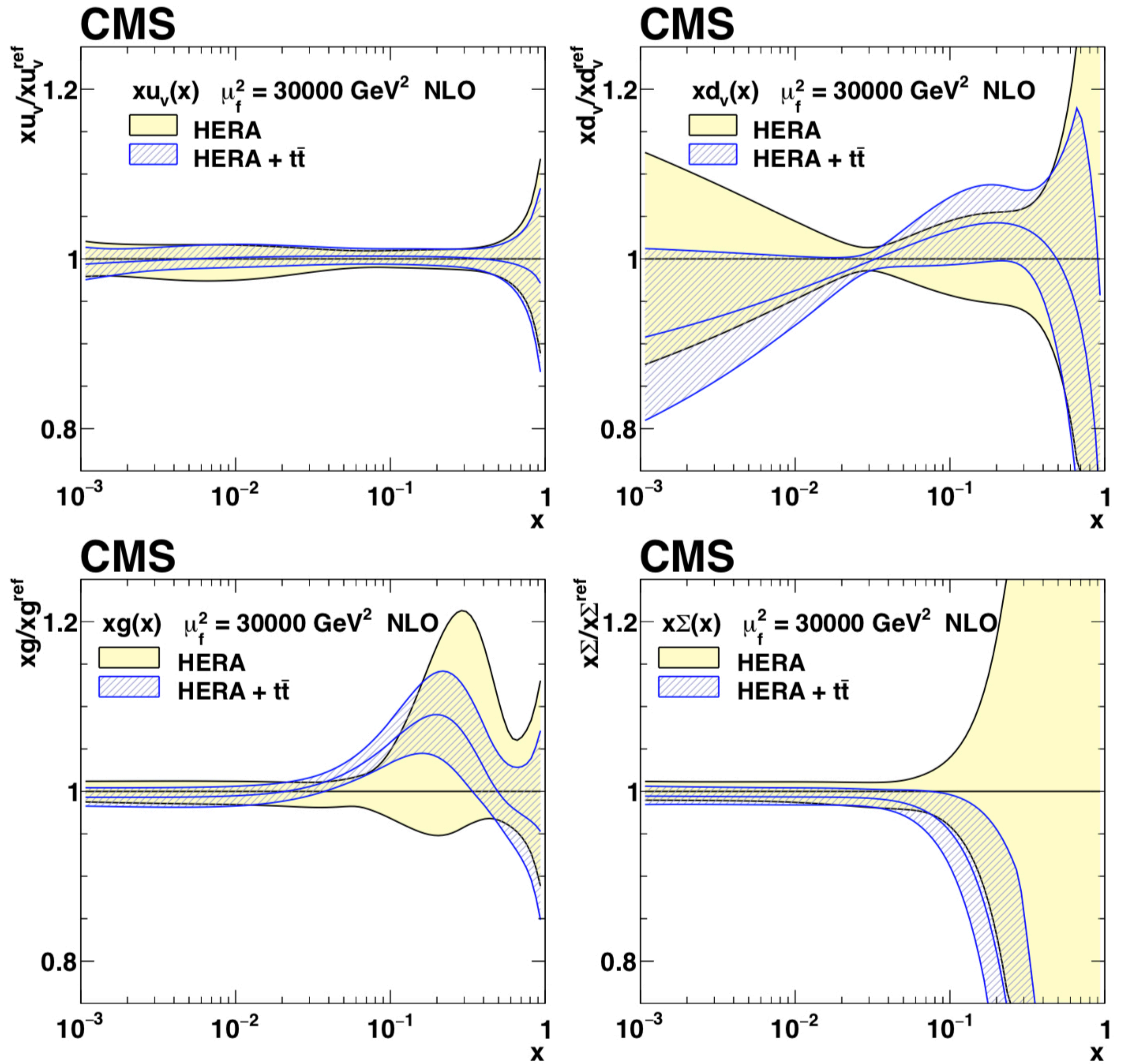
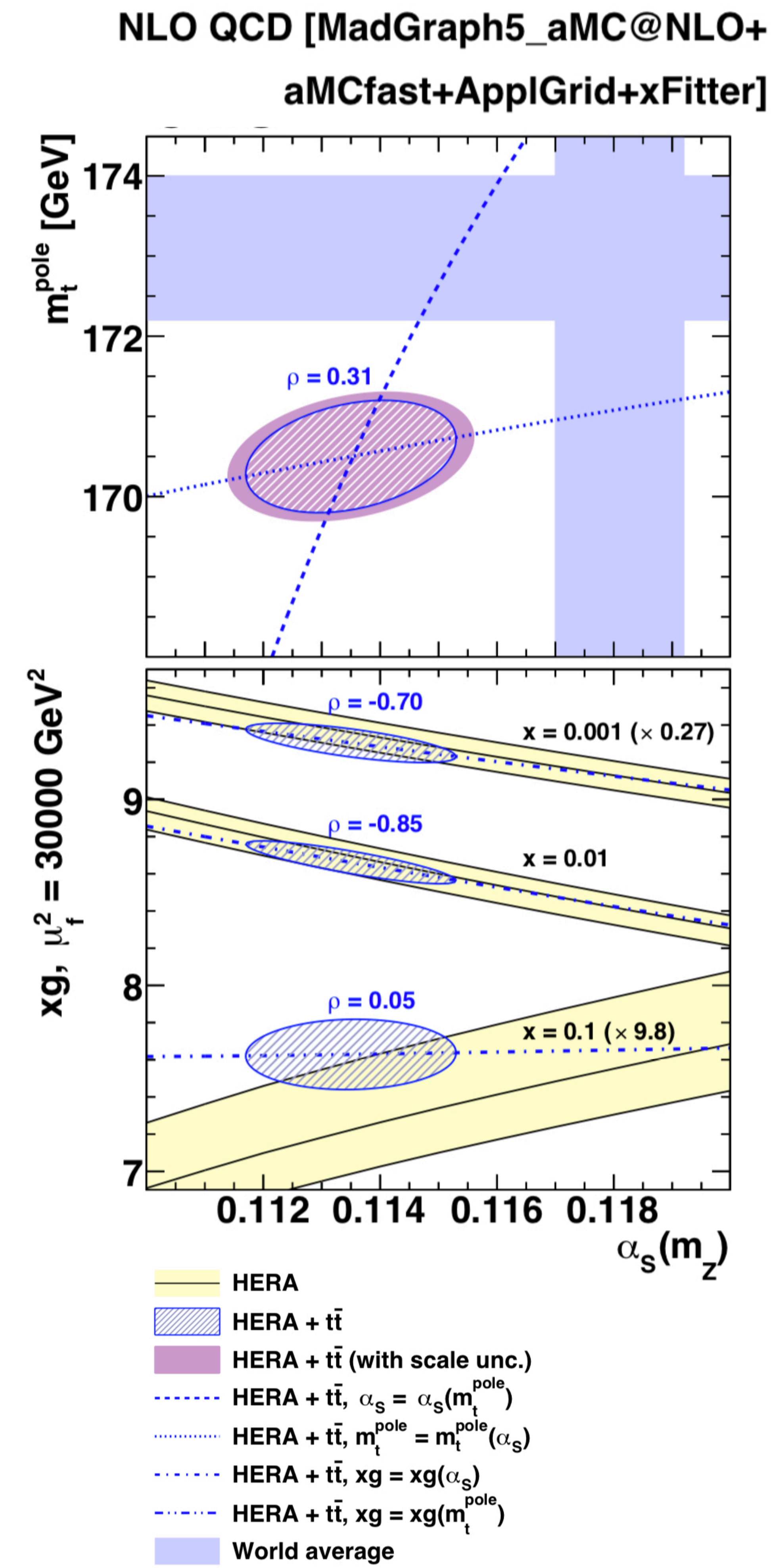
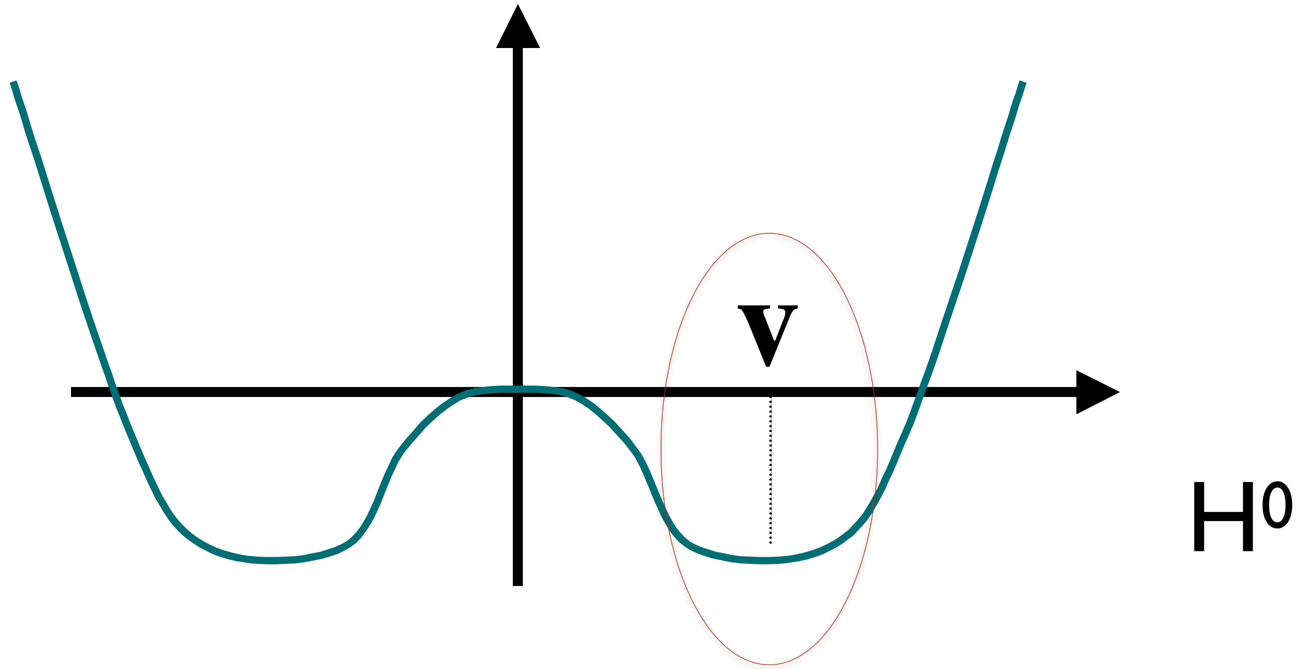


Figure 22: The PDFs with their total uncertainties in the fit using the HERA DIS data only, and the HERA DIS and $t\bar{t}$ data. The results are normalised to the PDFs obtained using the HERA DIS data only.



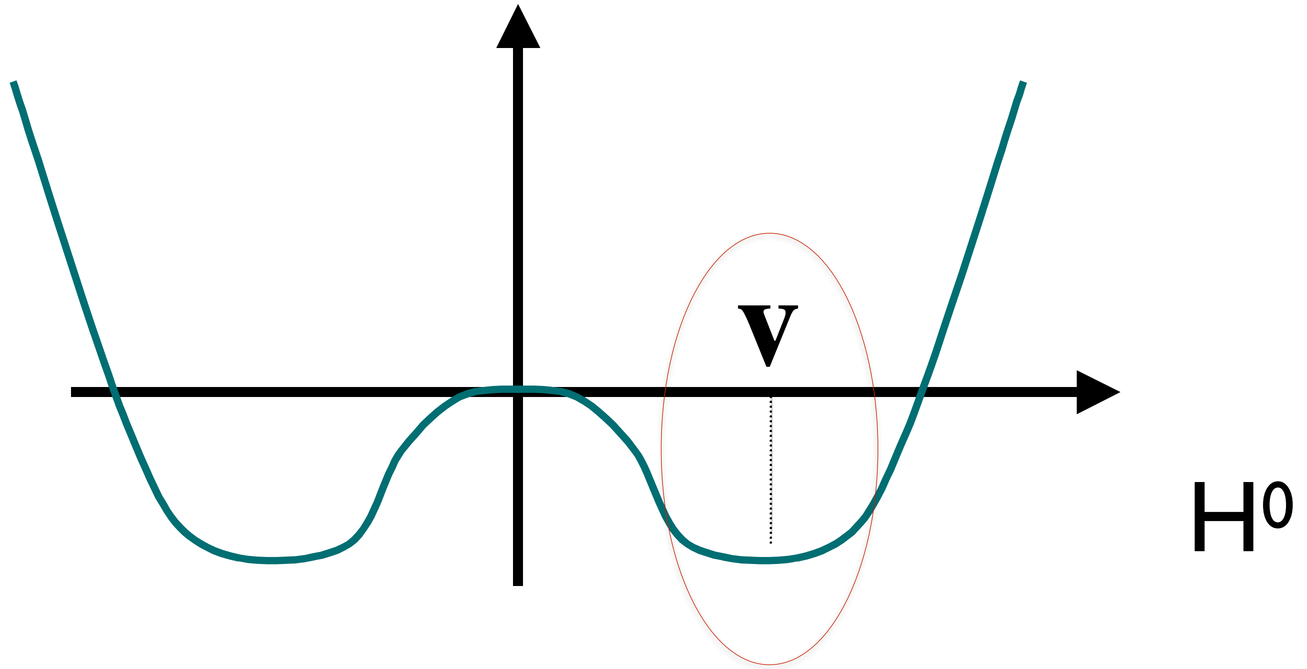
Challenge of these works: hard to assess that we're not fitting away in the PDF or m_t some inadequacy of the TH modeling….

A couple of final remarks related to the Higgs



$$V(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

Who ordered that ?

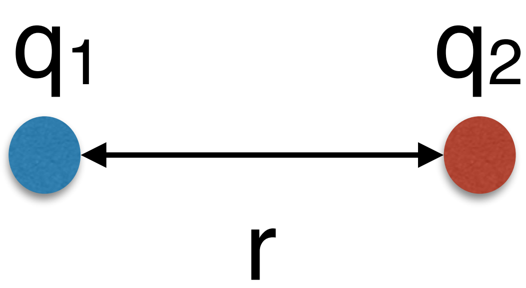


$$V(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

Who ordered that ?

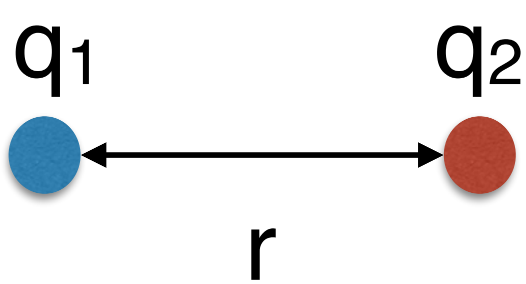
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics



$$V(r) = + \frac{q_1 \times q_2}{r^{1}}$$

Electromagnetic vs Higgs dynamics



quantized,
in units of
fixed charge

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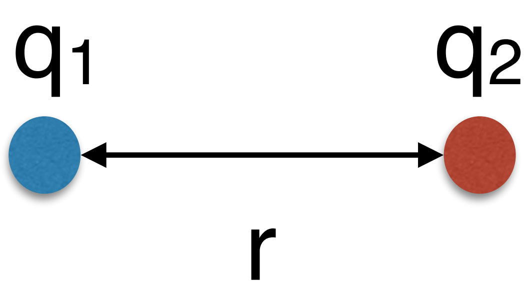

quantized,
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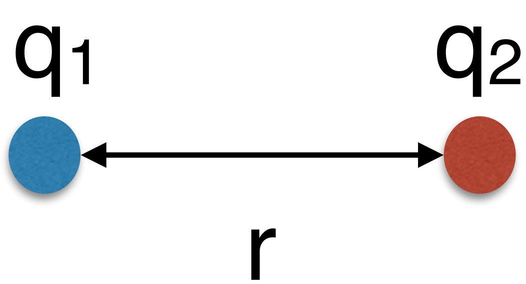
$$V(r) = + \frac{q_1 \times q_2}{r^{1}}$$

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem

Electromagnetic vs Higgs dynamics



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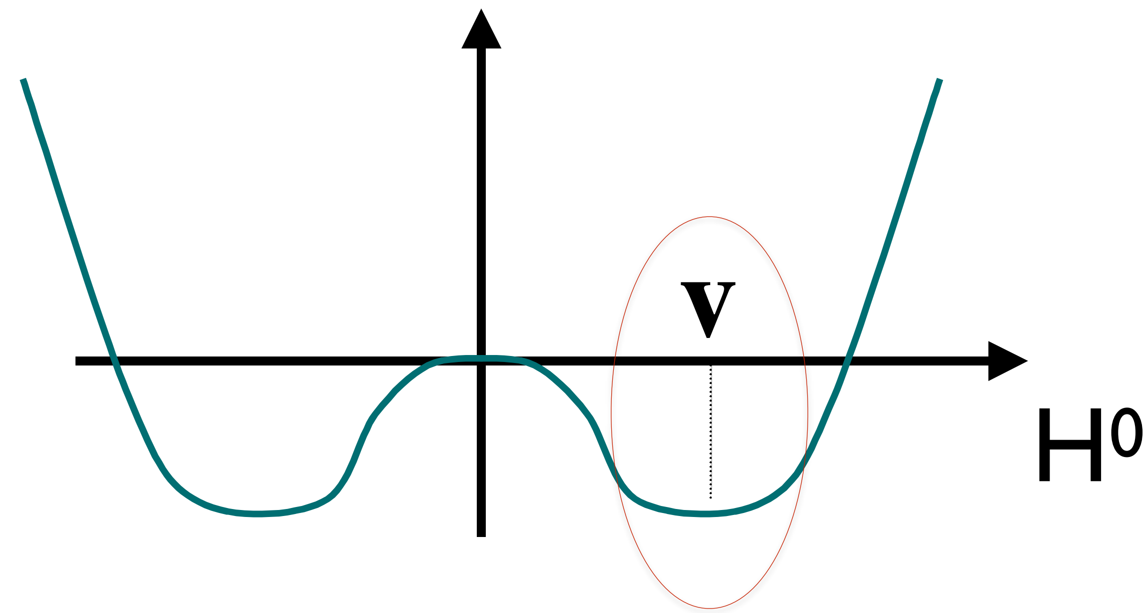
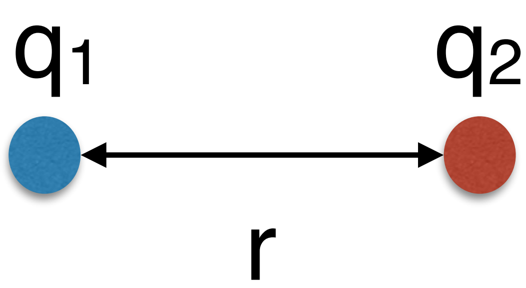


$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Electromagnetic vs Higgs dynamics



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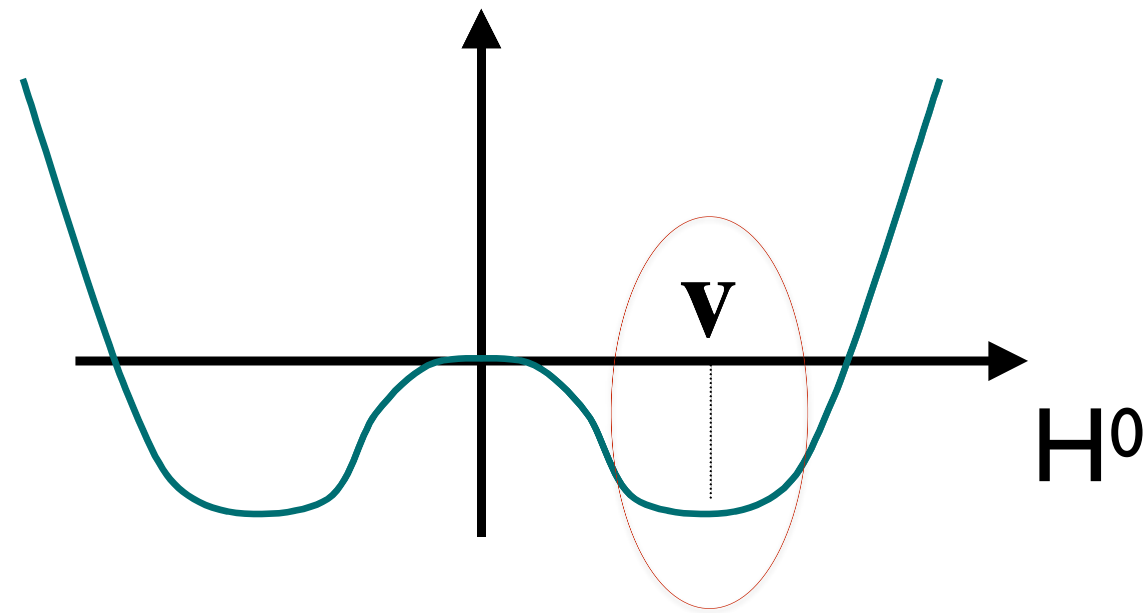
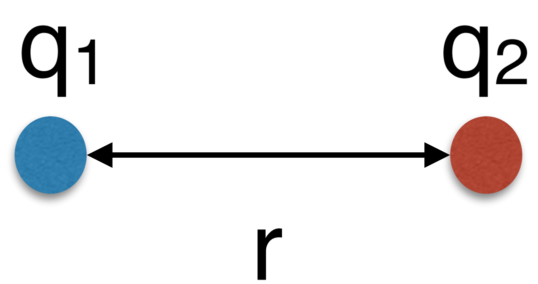


$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

Electromagnetic vs Higgs dynamics



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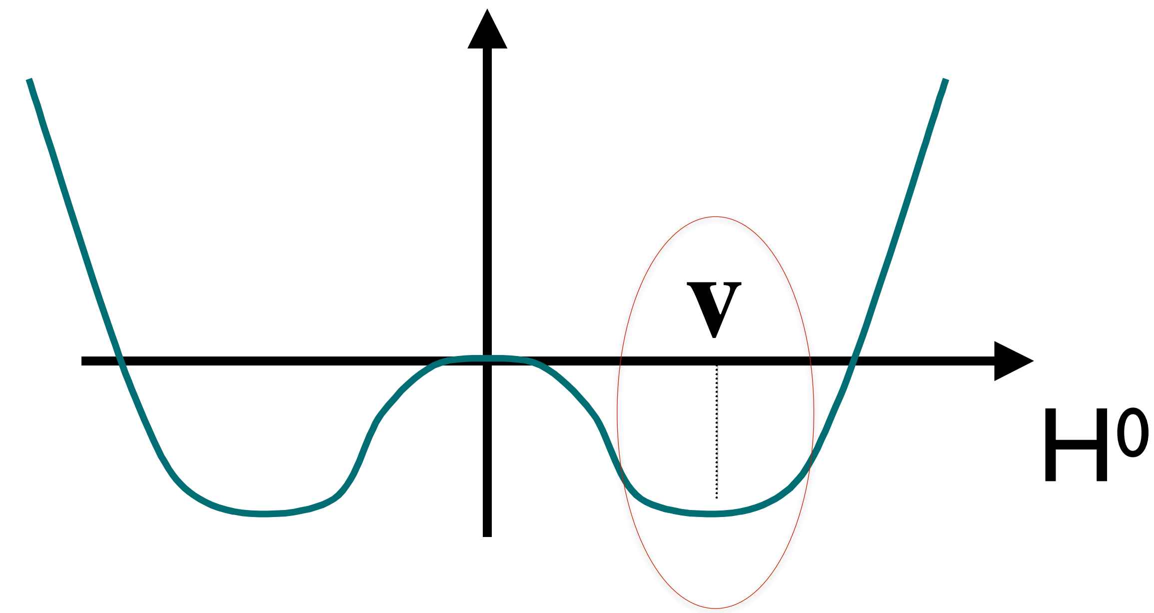

any function of $|H|^2$ would be ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

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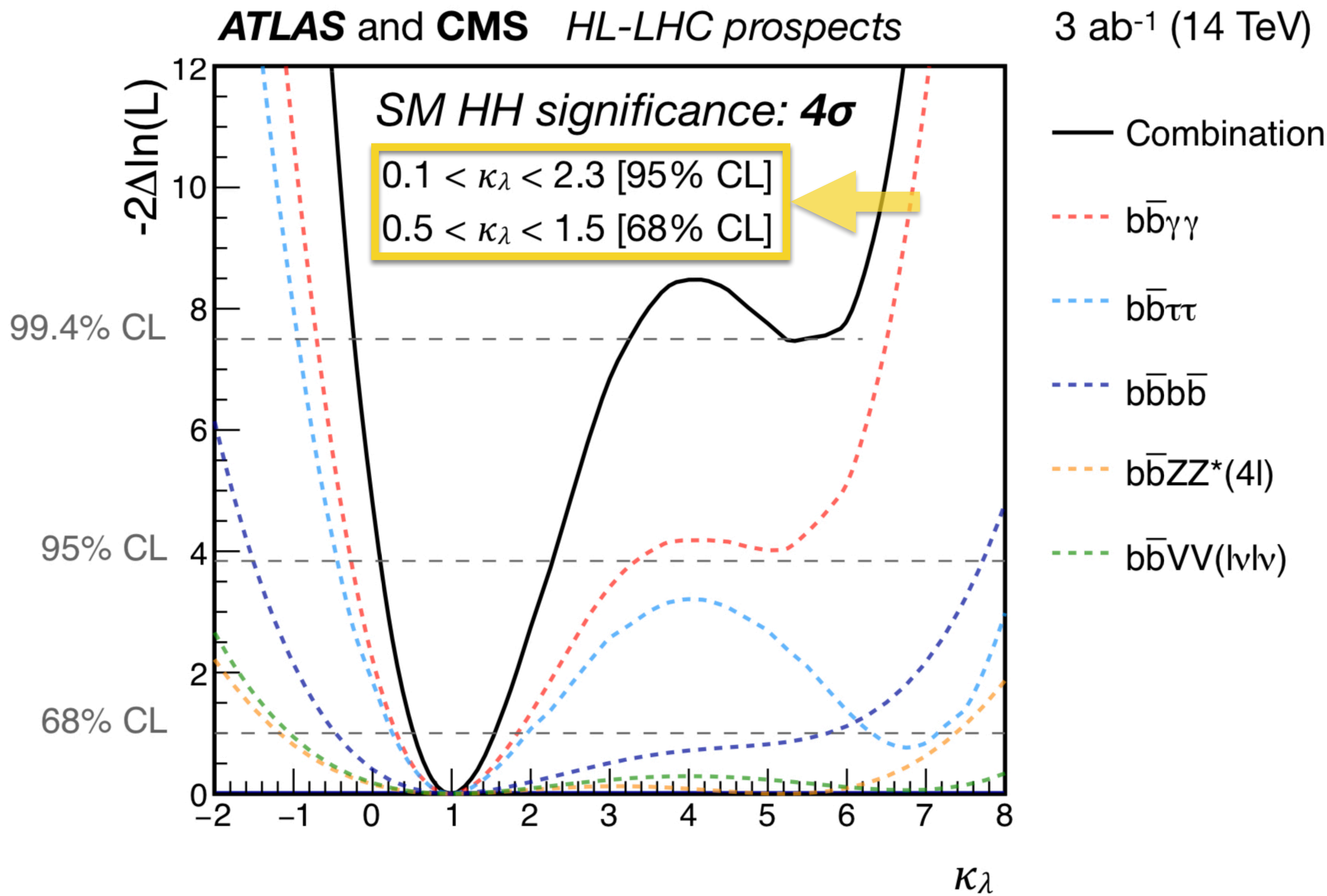
- For superconductivity, this came later, with the identification of $e^- e^-$ Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either case we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

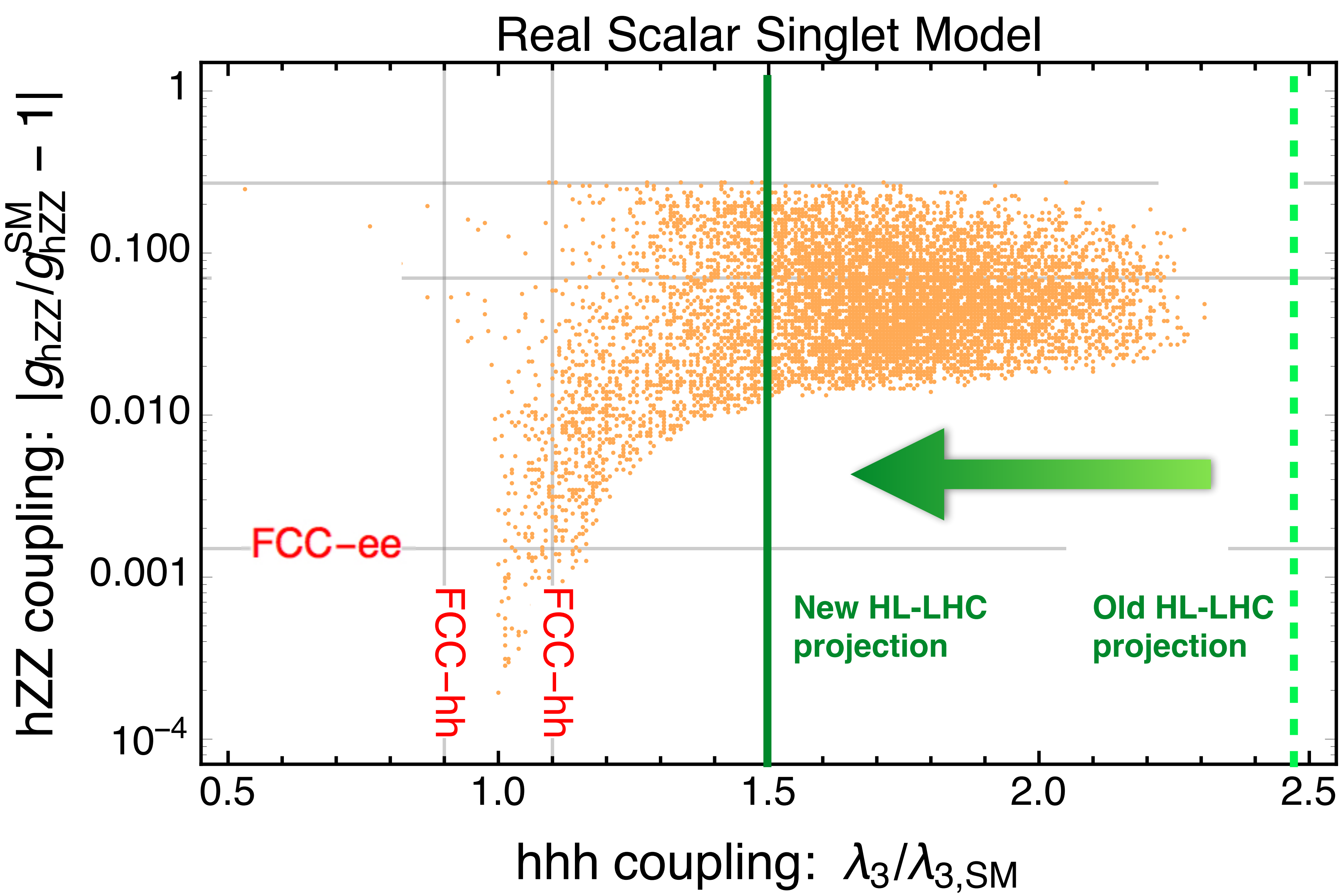
Higgs self-coupling projections @ HL-LHC *



* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

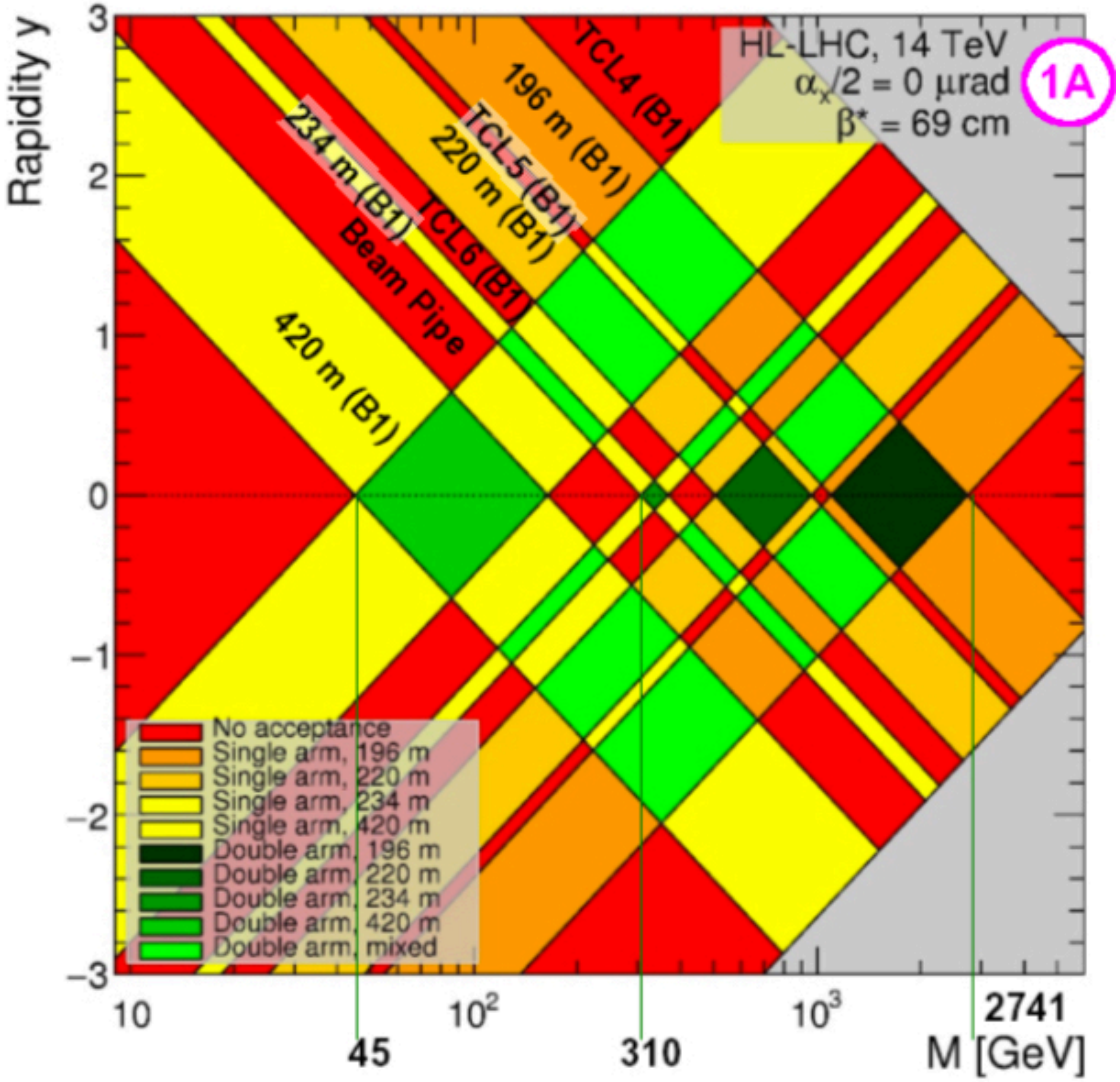
Constraints on models with 1st order phase transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$



Bringing the HL-LHC sensitivity to the ±50% level, makes a big dent in this class of BSM models!

Is there still a physics case to study exclusive pp→ppH production?
There is in principle a final opportunity to consider a new detector at +/– 420m from IP1/IP5 …



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- Time will improve the TH predictions even more, larger statistics and upgrade detectors will open new doors, with clear opportunities to reduce systematics and increase sensitivity, most of them documented in the HL-LHC reports

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- Immense amount of thought and work, both from the exptl and TH communities, went into today's state of the art
- Time will improve the TH predictions even more, larger statistics and upgrade detectors will open new doors, with clear opportunities to reduce systematics and increase sensitivity, most of them documented in the HL-LHC reports
- The main change I would advocate is a change in attitude towards the relation between measurements, deviations and discoveries