The LHC and Beyond: Future Paths in High Energy Physics

University of Lund
13 October 2016

Michelangelo L. Mangano
michelangelo.mangano@cern.ch
Theoretical Physics Department
CERN

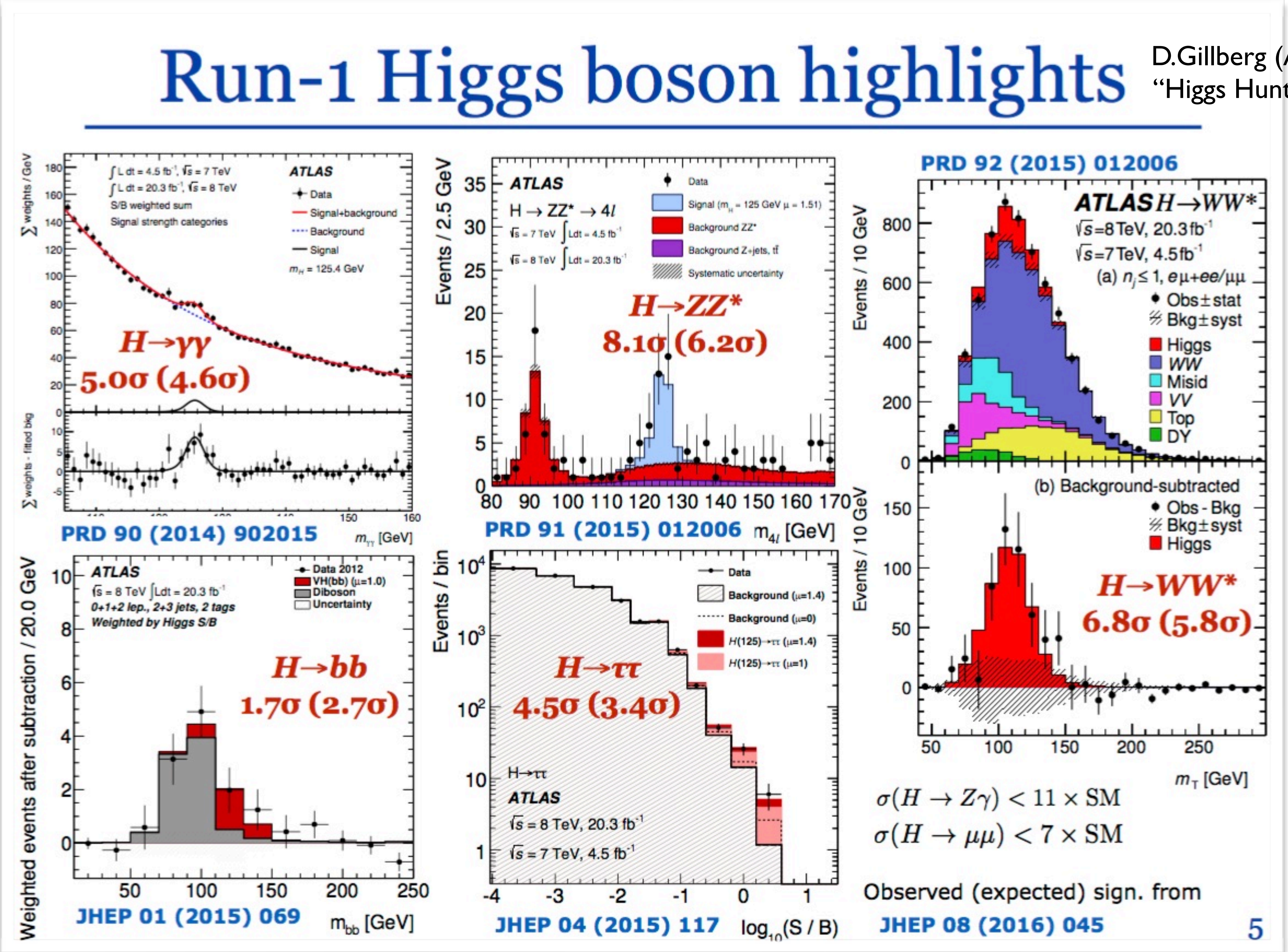
Outline

- The three key messages from the LHC:
  - on the Higgs
  - on BSM
  - on the SM

- What's next for the LHC?

- The road ahead: opportunities at a Future Circular Collider

Message 1: the Higgs is there



Run-1 Higgs boson highlights

$H \to \gamma\gamma$ 5.0σ (4.6σ)

PRD 90 (2014) 902015

$H \to ZZ^*$ 8.1σ (6.2σ)

PRD 91 (2015) 012006

PRD 92 (2015) 012006

$H \to WW^*$ 6.8σ (5.8σ)

$H \to bb$ 1.7σ (2.7σ)

JHEP 01 (2015) 069

$H \to \tau\tau$ 4.5σ (3.4σ)

JHEP 04 (2015) 117

$$\sigma(H \to Z\gamma) < 11 \times \mathrm{SM}$$
$$\sigma(H \to \mu\mu) < 7 \times \mathrm{SM}$$

Observed (expected) sign. from JHEP 08 (2016) 045

D.Gillberg (ATLAS) at
“Higgs Hunting” 2016

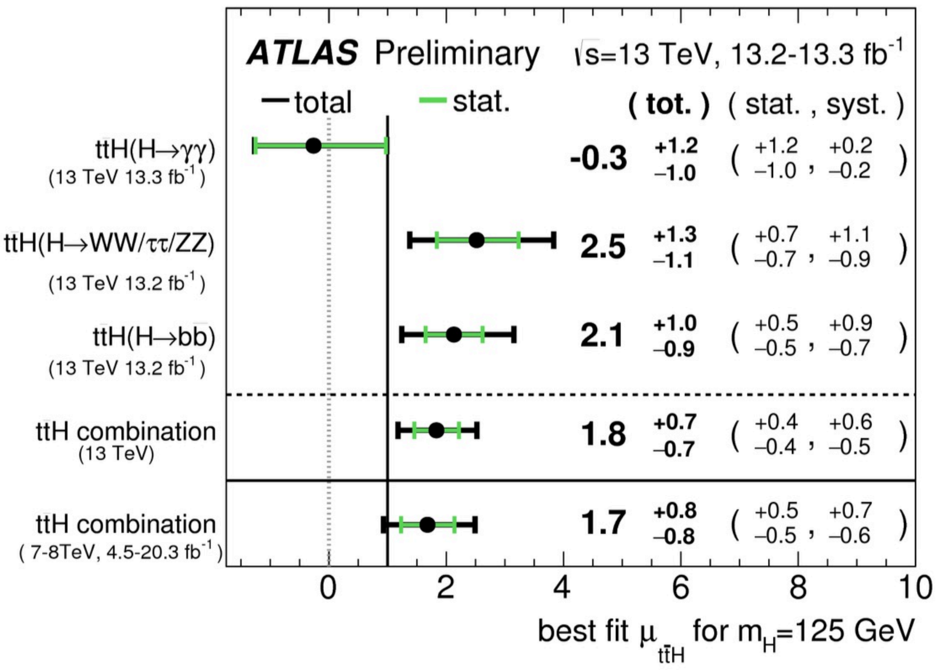
Run 1, global μ = 1.09 ± 0.11

ATLAS+CMS, JHEP 1608 (2016) 045

Highlights of 2015-16 Higgs measurements

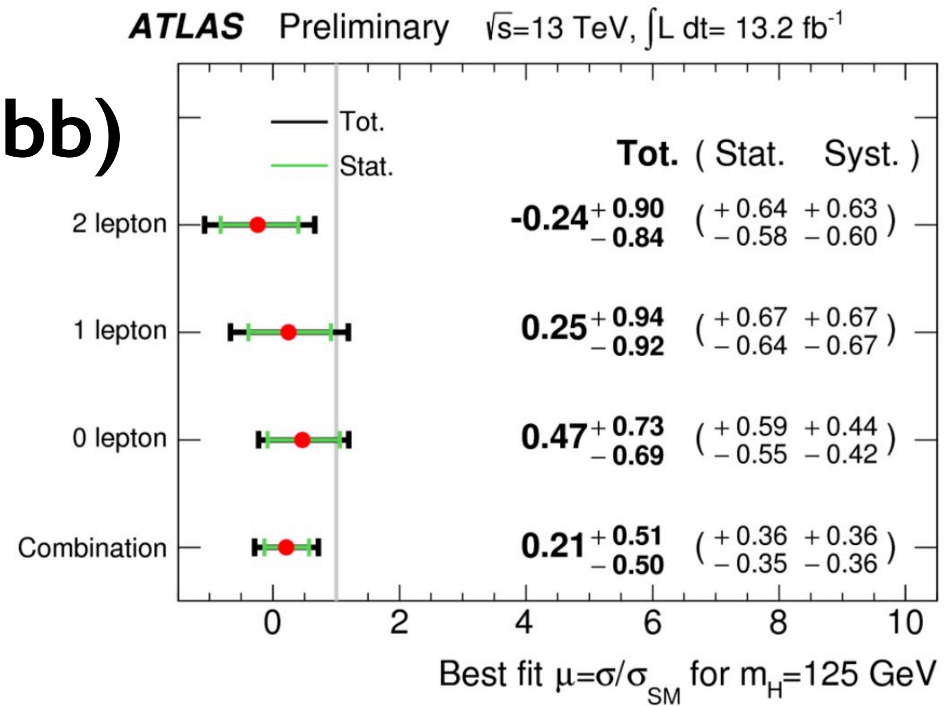
ATLAS summary: B. Mansoulié, CERN seminar Oct 11, http://indico.cern.ch/event/555813/

ttH

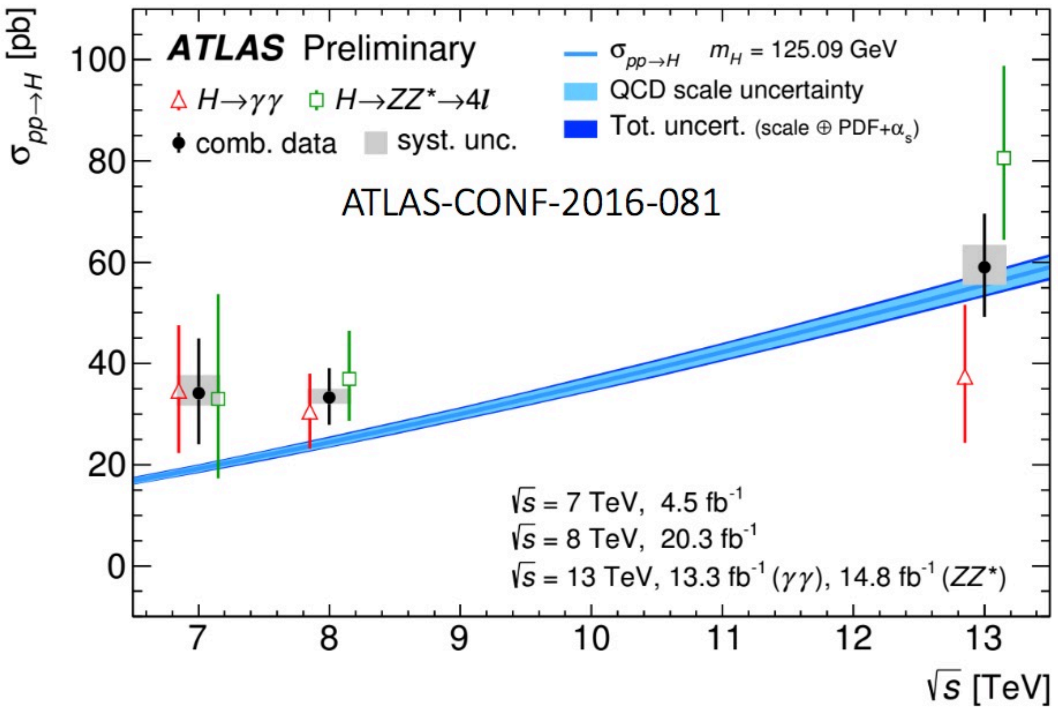


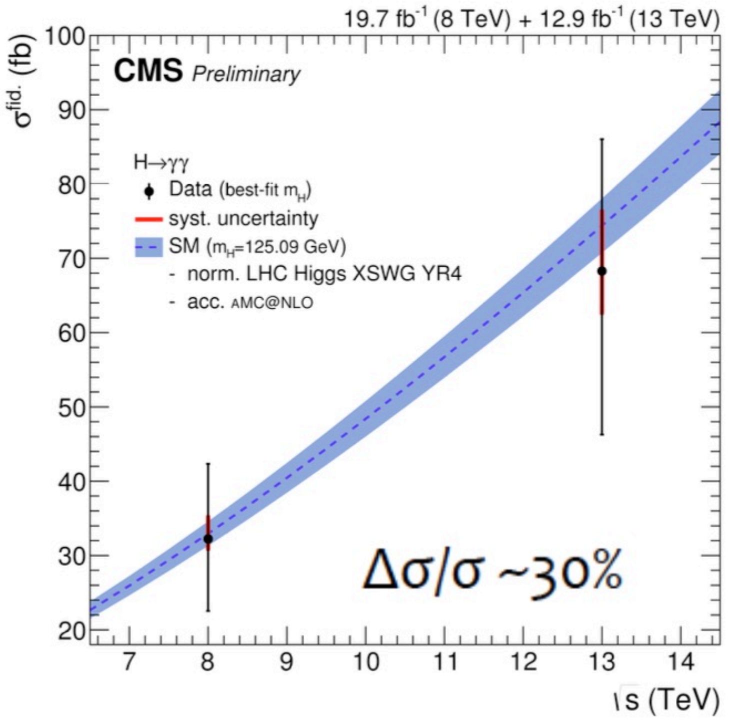
too much ….

VH(bb)

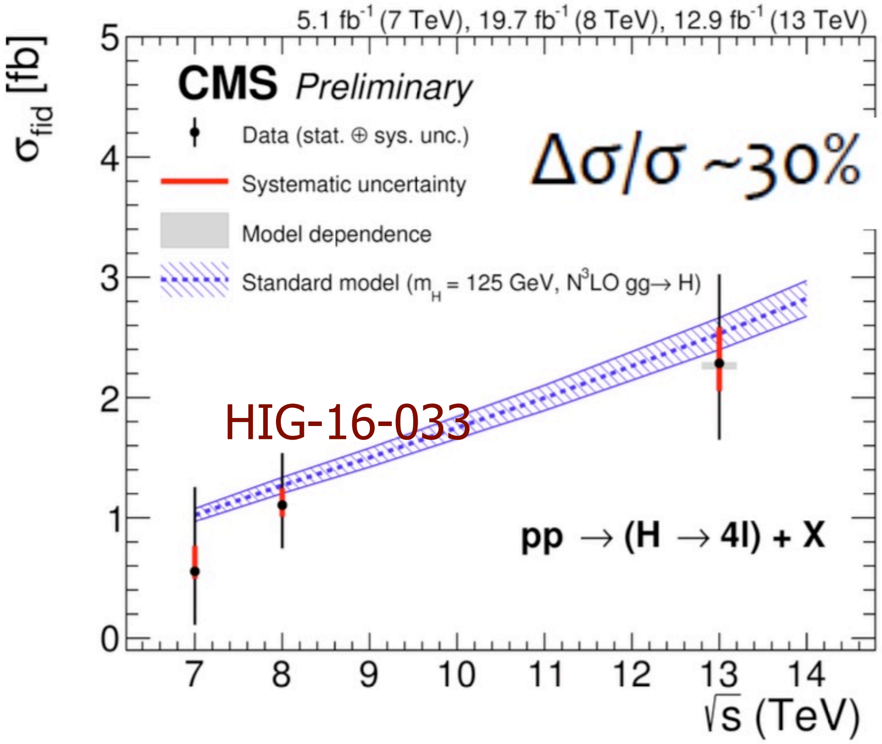


too little ….





Δσ/σ ~30%



Δσ/σ ~30%

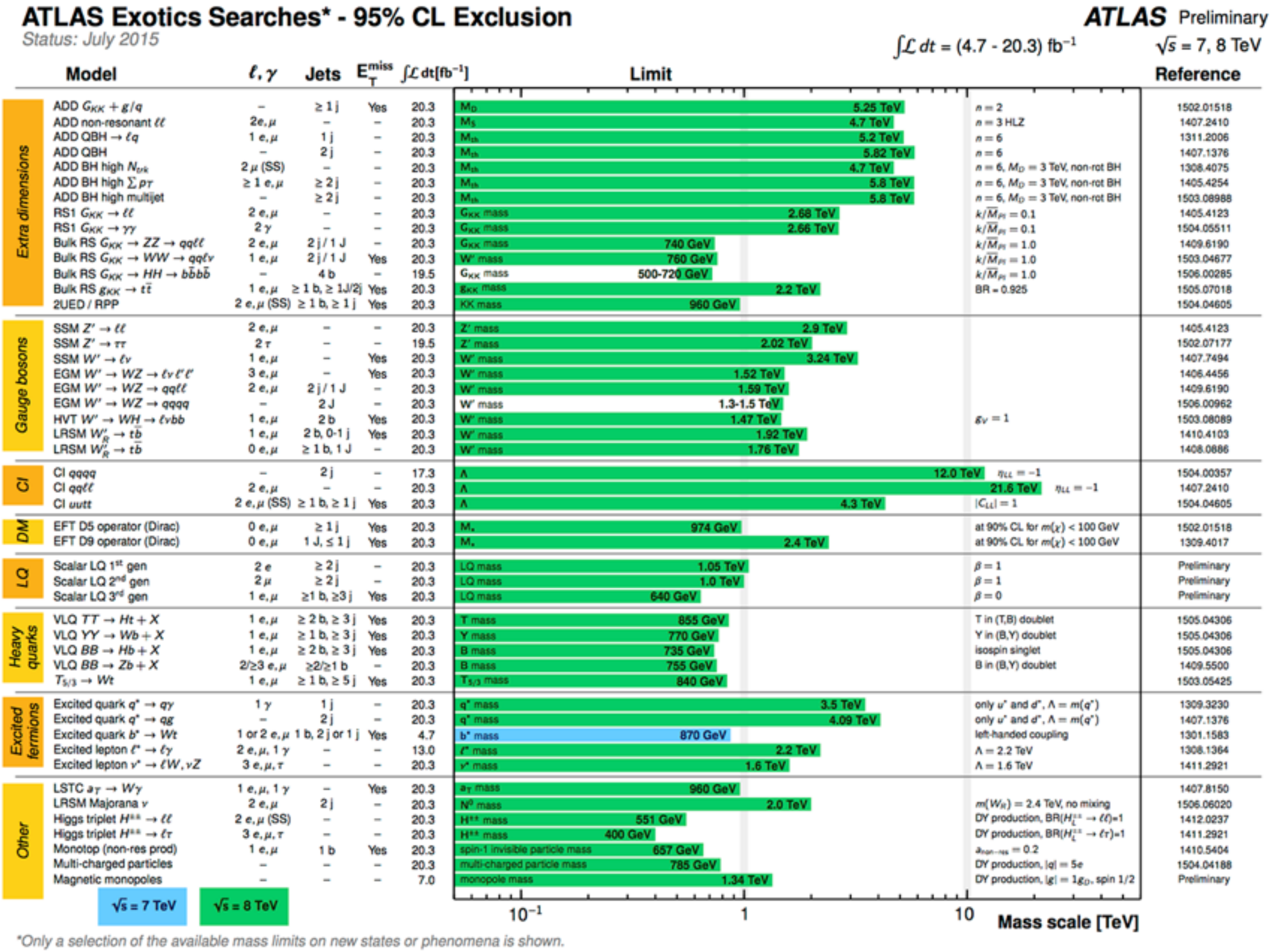
HIG-16-033

just about right …

Challenges for the Higgs programme

- How far can we push the precision on Higgs properties?
- How do we best exploit the Higgs as a probe of BSM phenomena?

Message 2: no *conclusive* signal of physics beyond the SM



ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

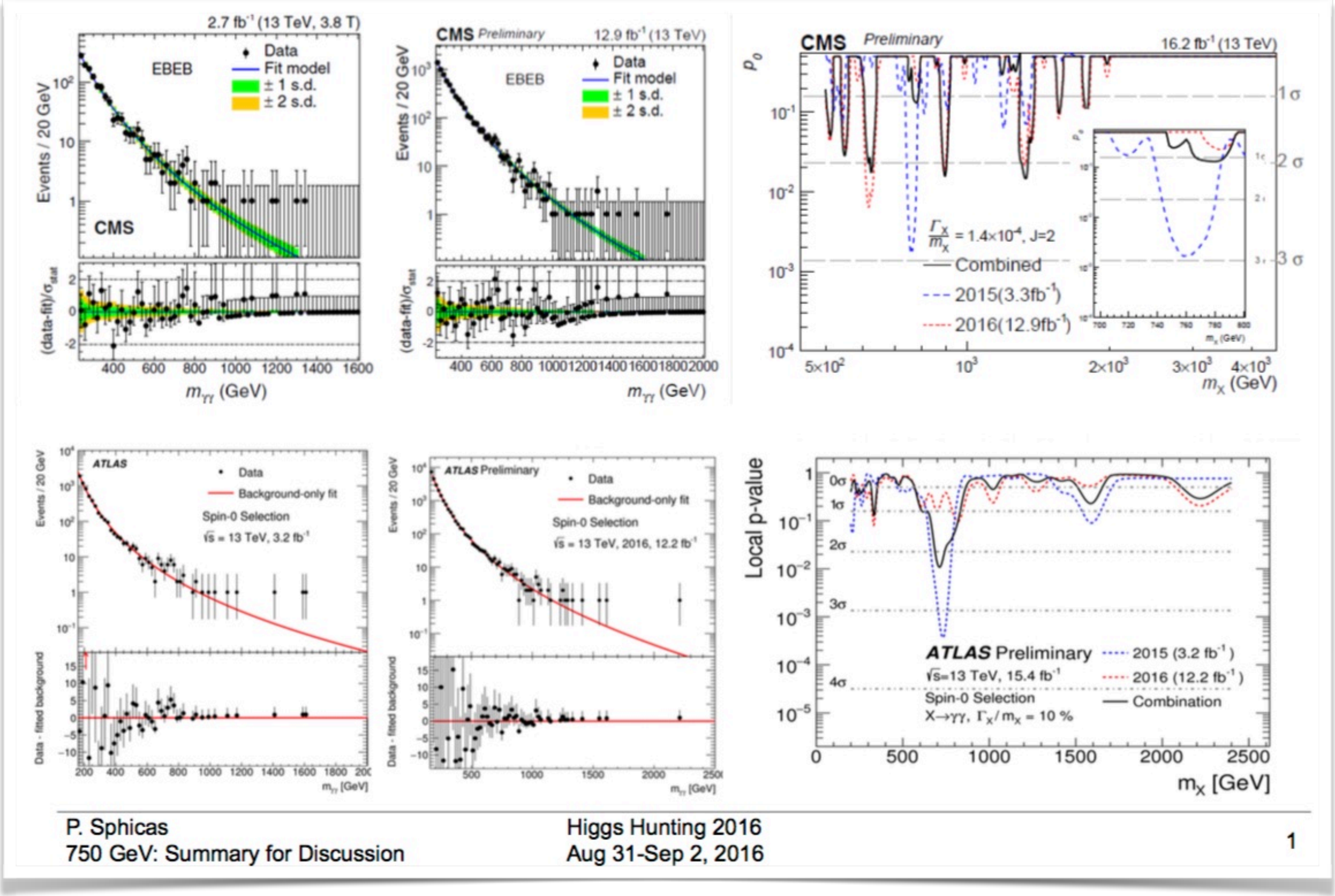
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2 e, \mu$	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	$1 e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	$2 e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	2 j / 1 J	Yes	20.3	W' mass 760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	$2 e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3 e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	$2 e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	EGM $W' \rightarrow WZ \rightarrow qqqq$	–	2 J	–	20.3	W' mass 1.3-1.5 TeV		1506.00962
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	$1 e, \mu$	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \rightarrow t\bar{b}$	$1 e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow t\bar{b}$	$0 e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	$2 e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	$2 e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL} \rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	$0 e, \mu$	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	$0 e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2 e$	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	$1 e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1 e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	$1 e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \rightarrow Wt$	$1 e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	1 j	–	20.3	q* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2 e, \mu, 1 \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3 e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	$2 e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2 e, \mu$ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	$1 e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	Preliminary

*Only a selection of the available mass limits on new states or phenomena is shown.

remarks

- Which BSM?
  - *known BSM*: dark matter, new sources of CPV and origin of BAU, neutrino masses
    - *we know something must be there, the search must continue*
  - *theoretically justified BSM*: origin of EWSB, solutions to the hierarchy problem
    - *the fact nothing has been found as yet doesn't eliminate the issues, if anything it makes them more puzzling and worthy of attention*
  - *possible surprises …*
- BSM probes:
  - direct search of new particles
  - indirect sensitivity through the measurement of Higgs properties, gauge boson couplings, the flavour sector (hvy flavour decays), etc.etc.
- Sensitivity to new physics from **precision** (small departures from SM behaviour, e.g. in the Higgs couplings), from large **statistics** (rare or forbidden decays), from **reach** in energy (explore large-Q^2). *Precision, large statistics and energy reach are the key ingredients of the LHC programme*

750 GeV, Summer 2016



P. Sphicas
750 GeV: Summary for Discussion

Higgs Hunting 2016
Aug 31-Sep 2, 2016

1

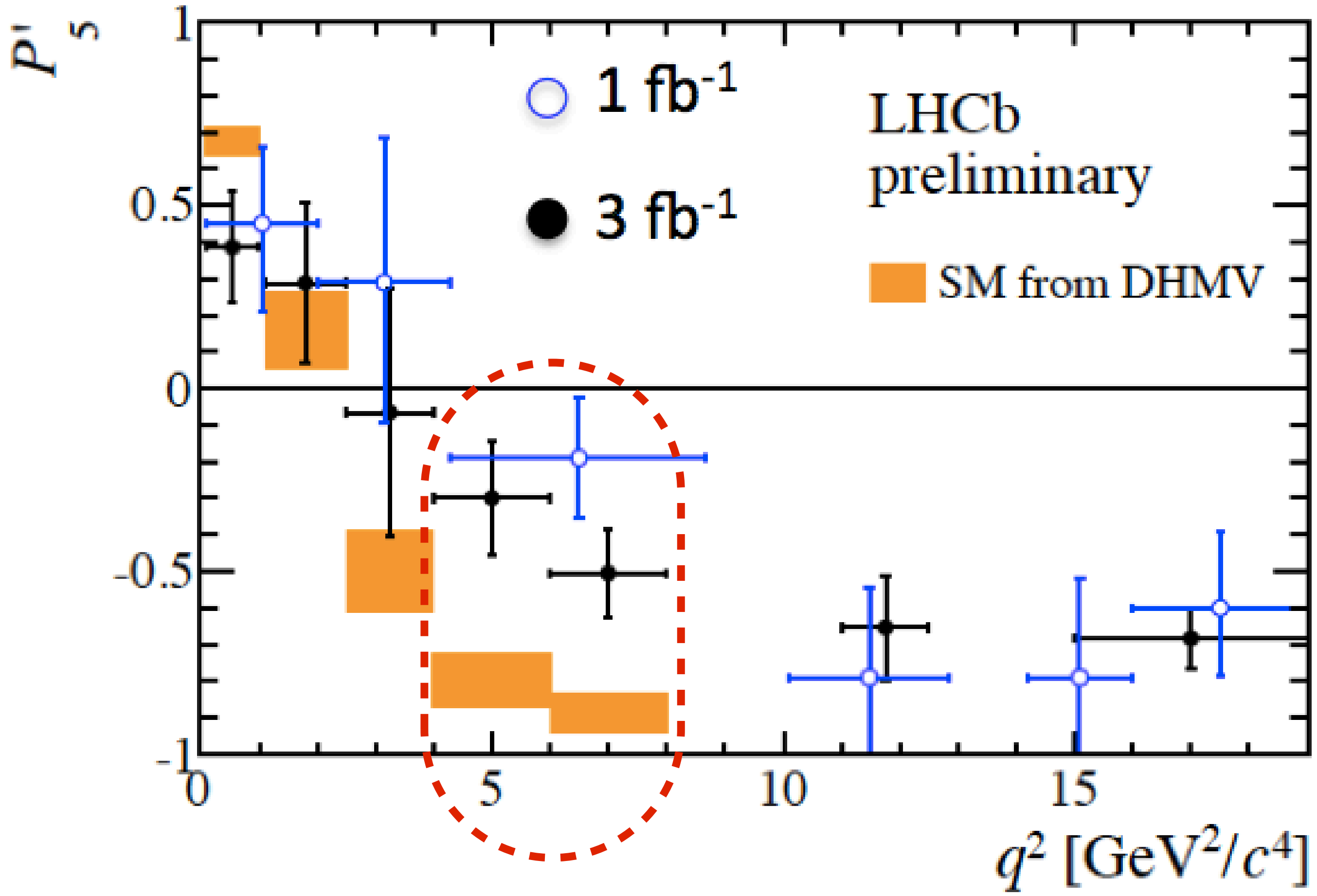
=> the resonant signal is not confirmed. But …

… little we know about the TeV scale!!

remarks

- Which BSM?
  - *known BSM*: dark matter, new sources of CPV and origin of BAU, neutrino masses
    - *we know something must be there, the search must continue*
  - *theoretically justified BSM*: origin of EWSB, solutions to the hierarchy problem
    - *the fact nothing has been found as yet doesn't eliminate the issues, if anything it makes them more puzzling and worthy of attention*
  - *possible surprises …*
- BSM probes:
  - direct search of new particles
  - indirect sensitivity through the measurement of Higgs properties, gauge boson couplings, the flavour sector (hvy flavour decays), etc.etc.

Flavour anomalies left over from run 1, some examples



- B → K∗μ+μ− anomaly

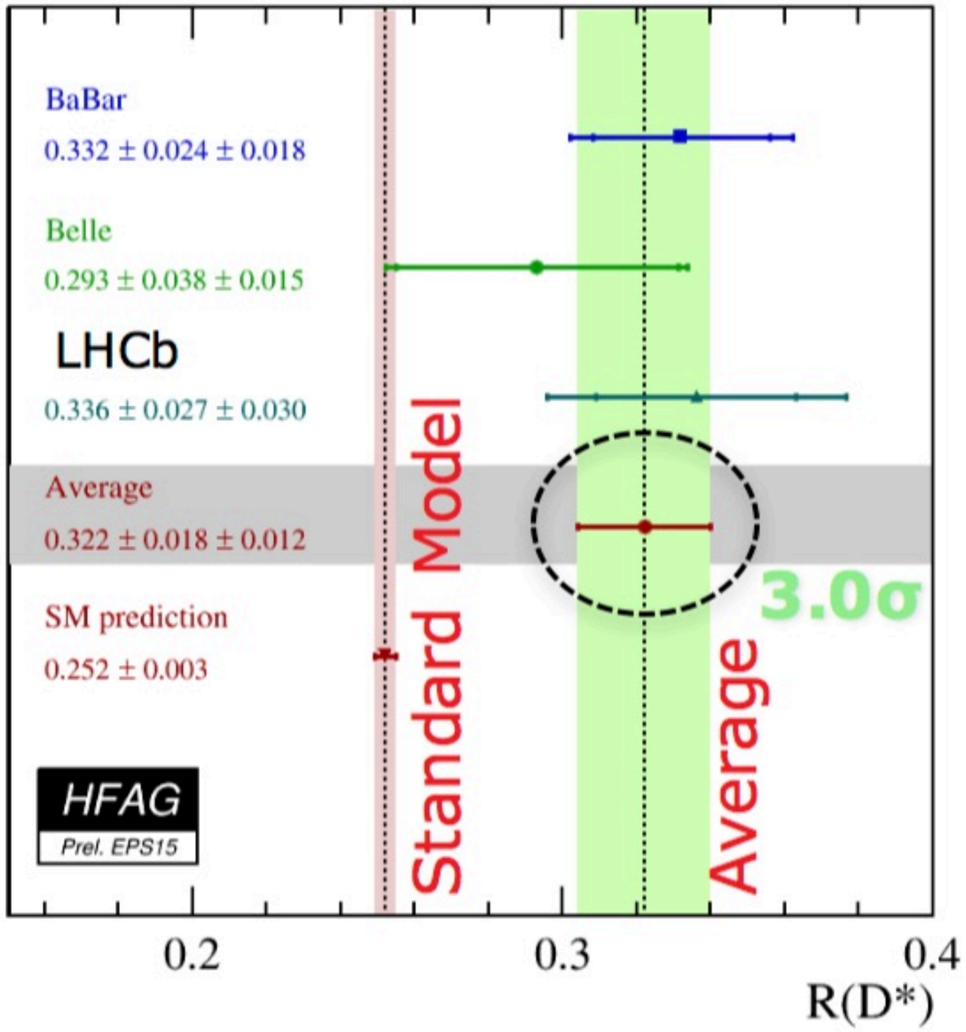
LHCb, arXiv:1308.1707
and
3fb^{-1} update LHCb−CONF−2015−002

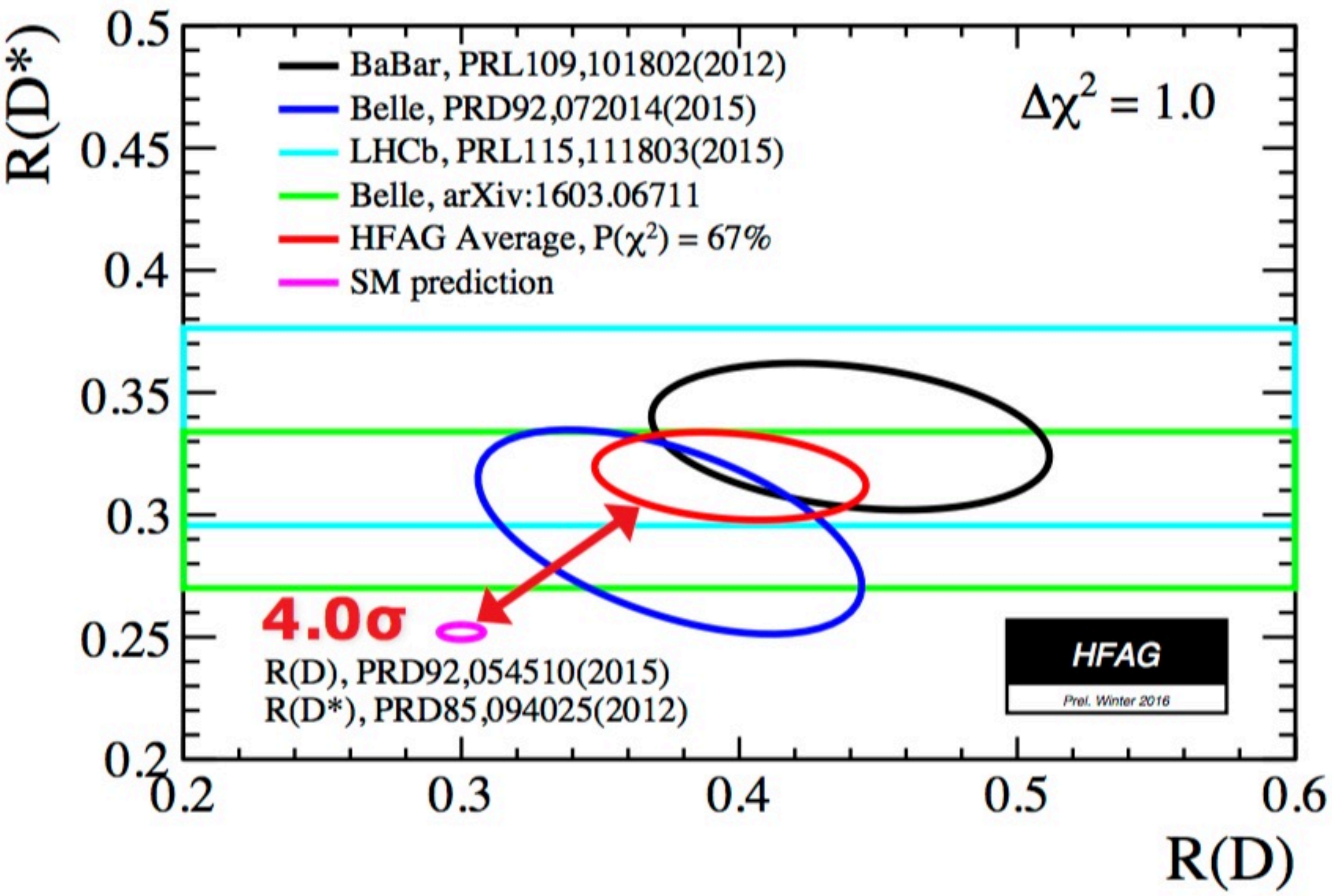
$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074}\underset{\text{stat}}{} \pm 0.036\underset{\text{syst}}{}$$

LHCb, arXiv:1406.6482

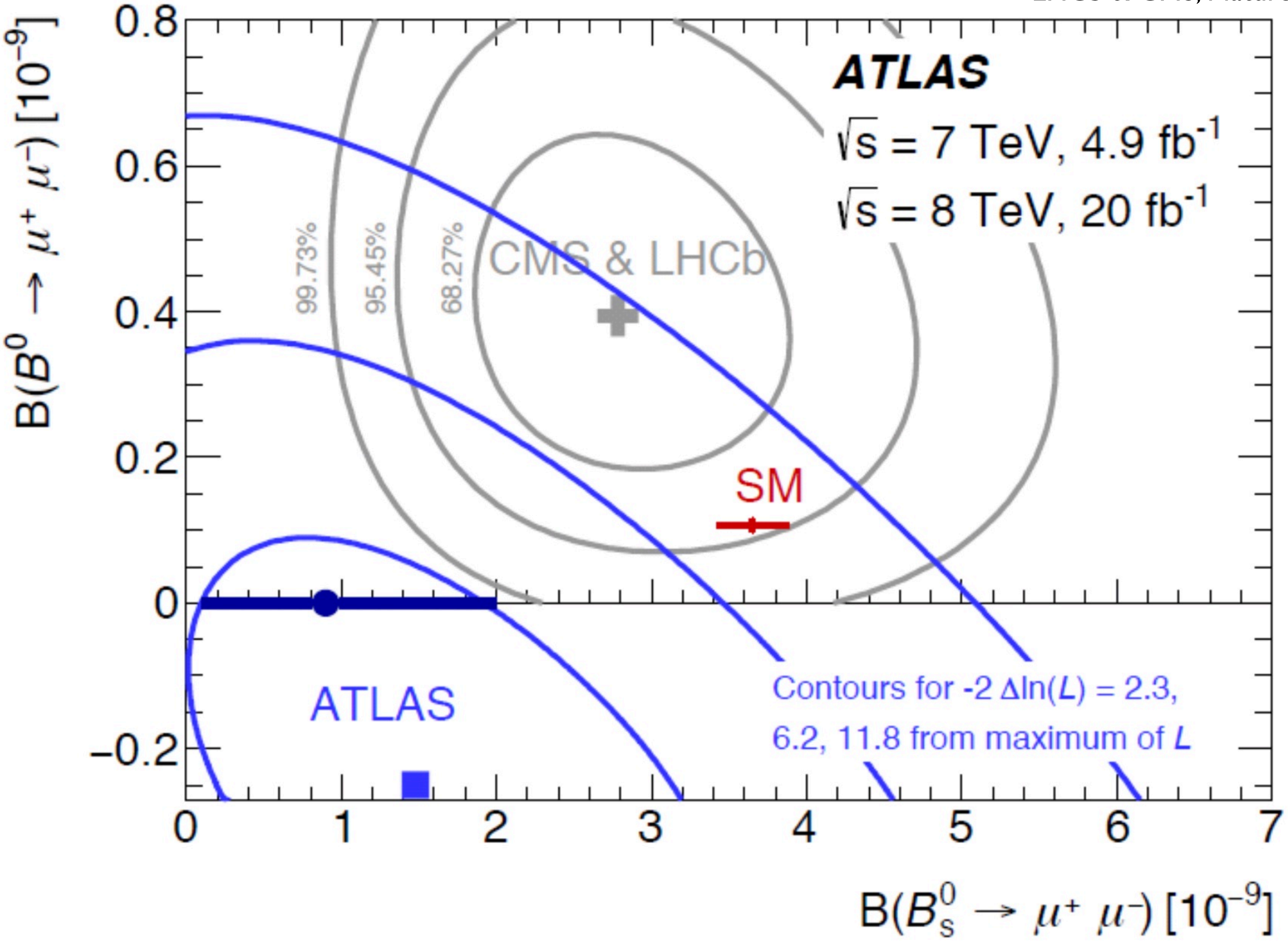
Flavour anomalies left over from run 1, some examples

$$R(D^{(*)}) = BR(B^0 \rightarrow D^{(*)}\tau\nu) \ / \ BR(B^0 \rightarrow D^{(*)}\mu\nu)$$





ATLAS, EPJ C76 (2016) 513
LHCb & CMS, Nature 522, 68–72 (2015)



$$R = \frac{BR(B^0 \rightarrow \mu\mu)}{BR(B_s{}^0 \rightarrow \mu\mu)} =$$

$0.14^{+0.08}_{-0.06}$ CMS+LHCb

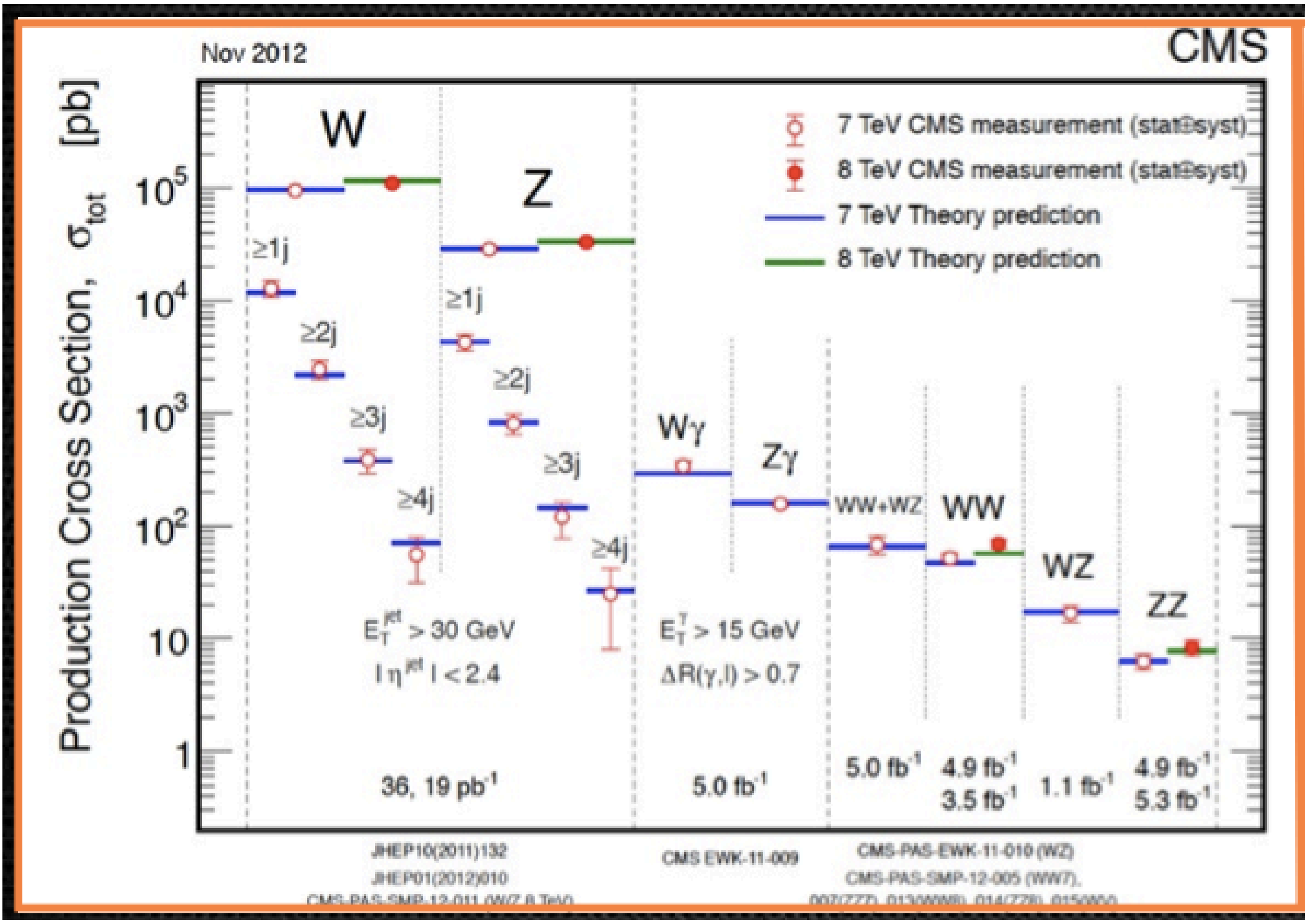
0.030 ± 0.003 SM

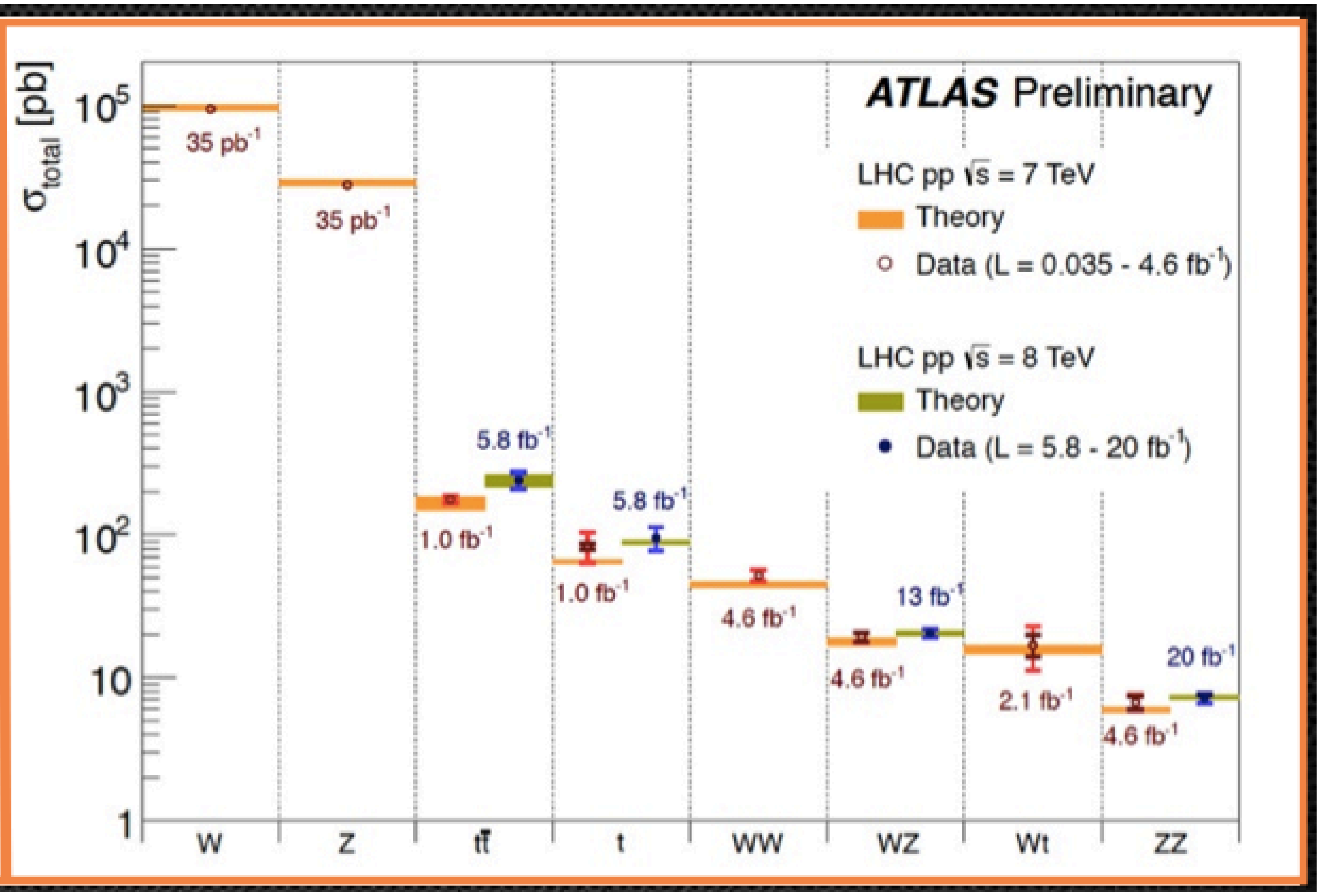
Challenges for the BSM programme

- Why don't we see new physics??
  - Is the mass scale beyond the LHC reach ?
  - Is the mass scale within LHC's reach, but final states are elusive to the direct search ?

- => Maximally exploit sensitivity to new physics from precision (small departures from SM behaviour, e.g. in the Higgs couplings), from large statistics (rare or forbidden decays), from reach in energy (explore large-Q2). *Precision, large statistics and energy reach are the key ingredients of the LHC programme*

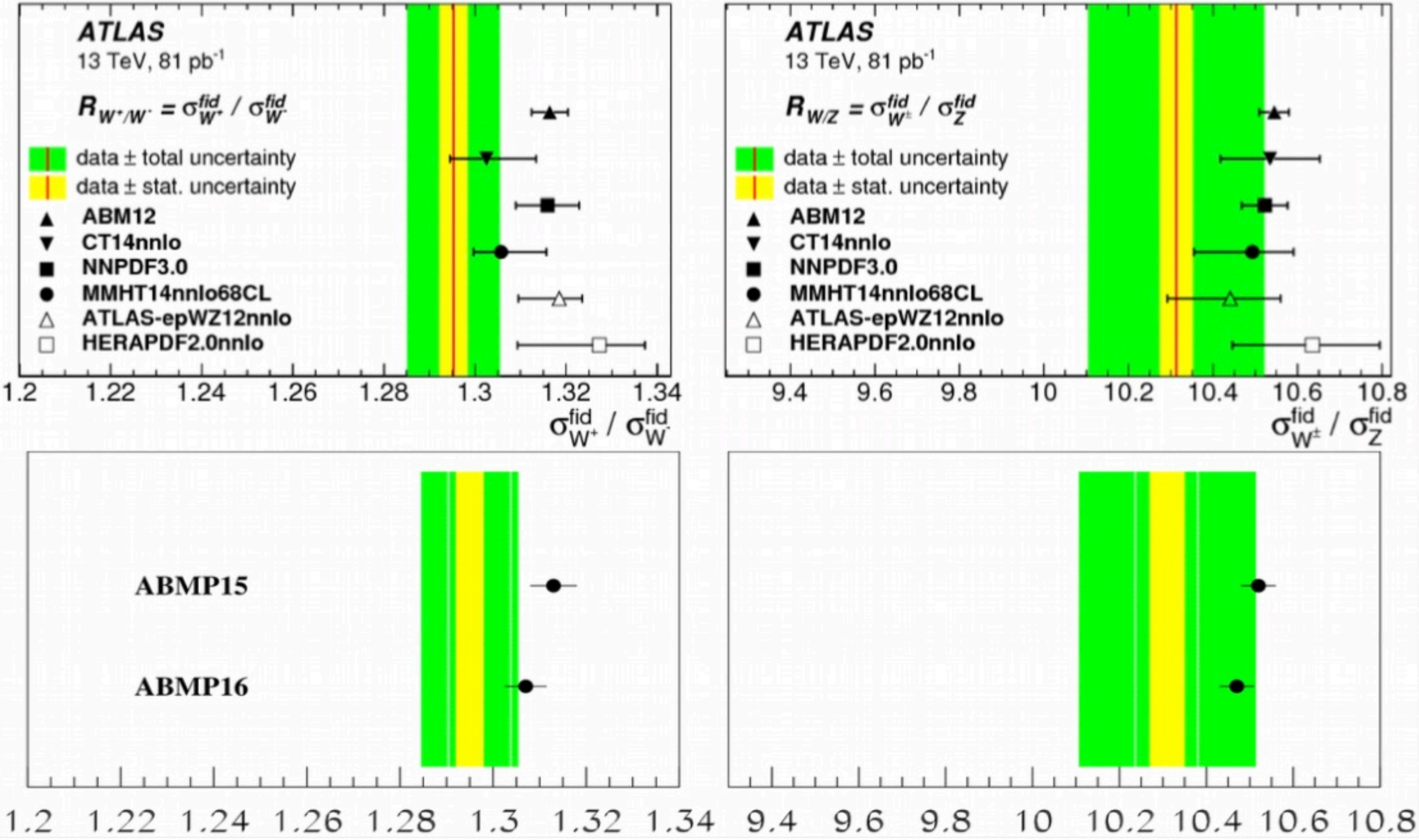
Message 3: The theoretical description of SM high-Q^2 processes at the LHC is very good ....



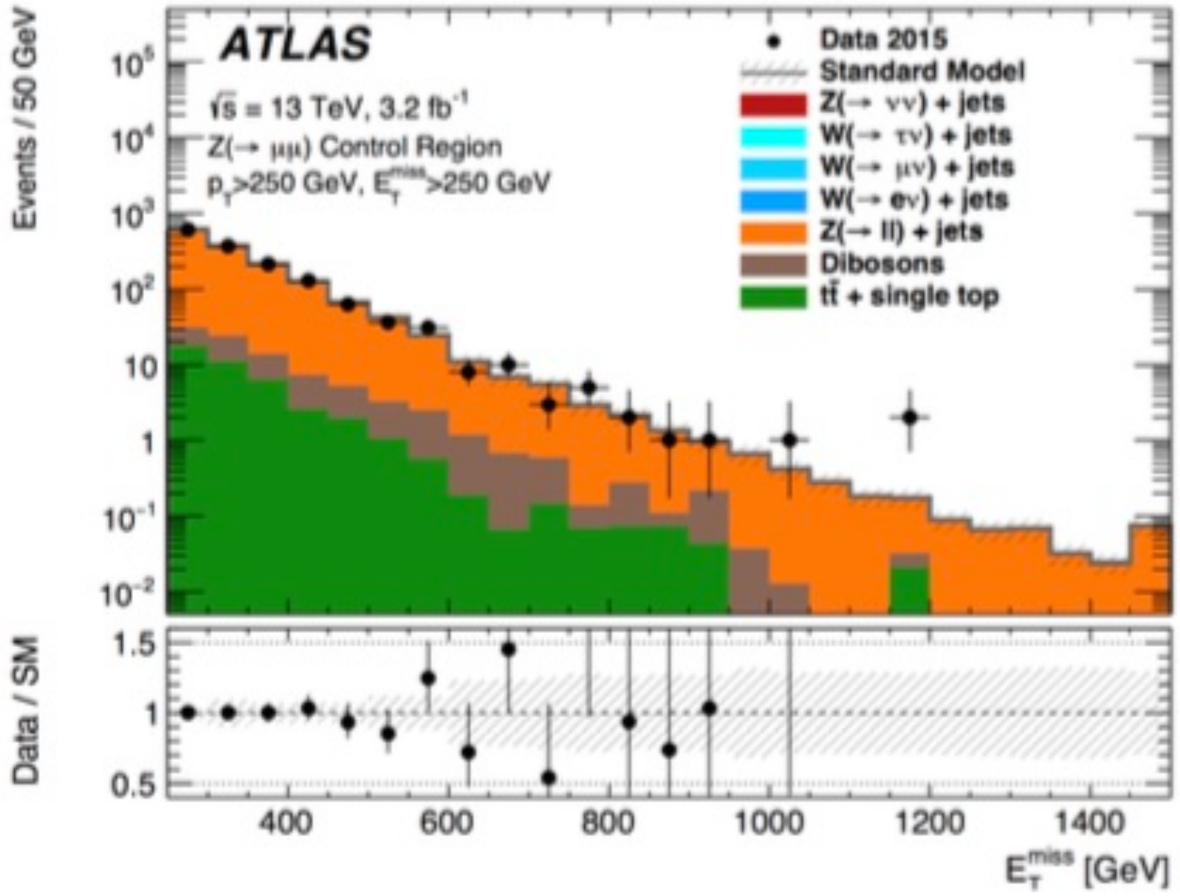


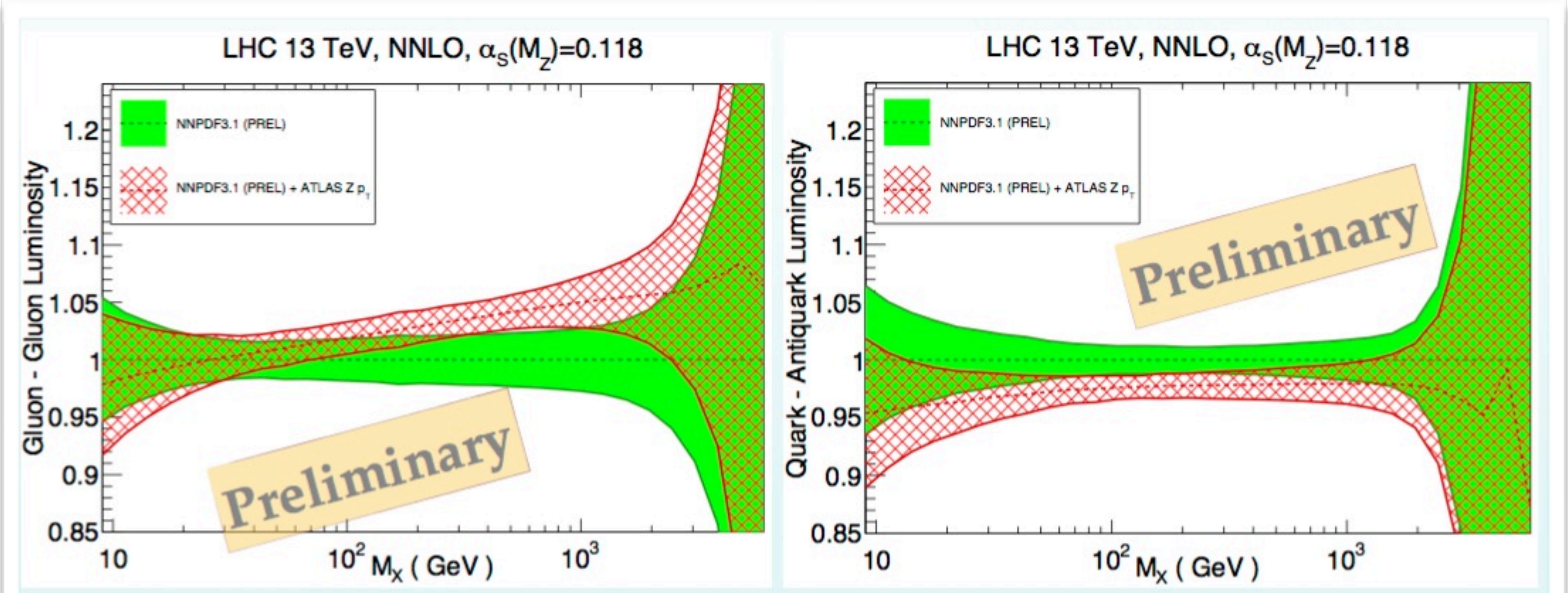
ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222



Impact of Z p_T spectrum on PDF fits





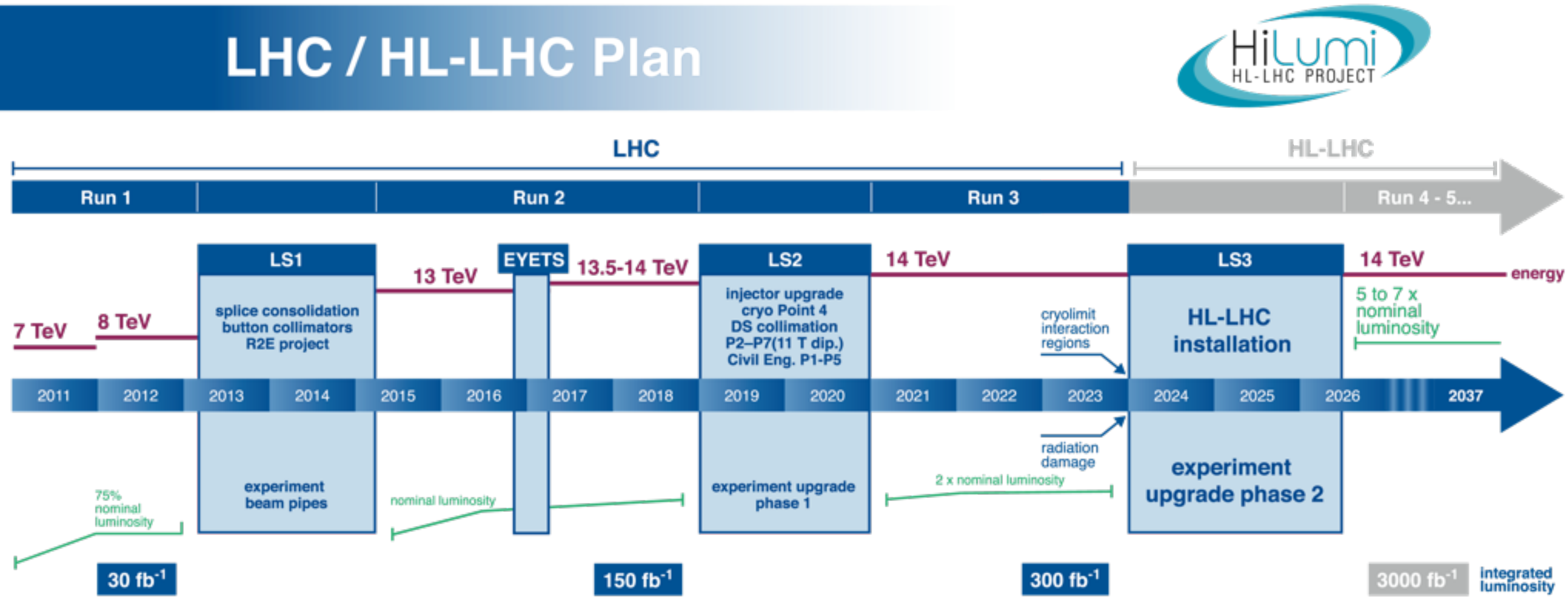
Preliminary NNPDF3.1 NNLO fits suggest a **sizeable impact** of the **LHC Z p_T data** on the PDFs

Challenges for the SM programme

Challenges:

- how much can the precision of SM predictions be improved?
- how far can we go in relying on TH modeling to improve the sensitivity to new physics?

Long-term LHC plan

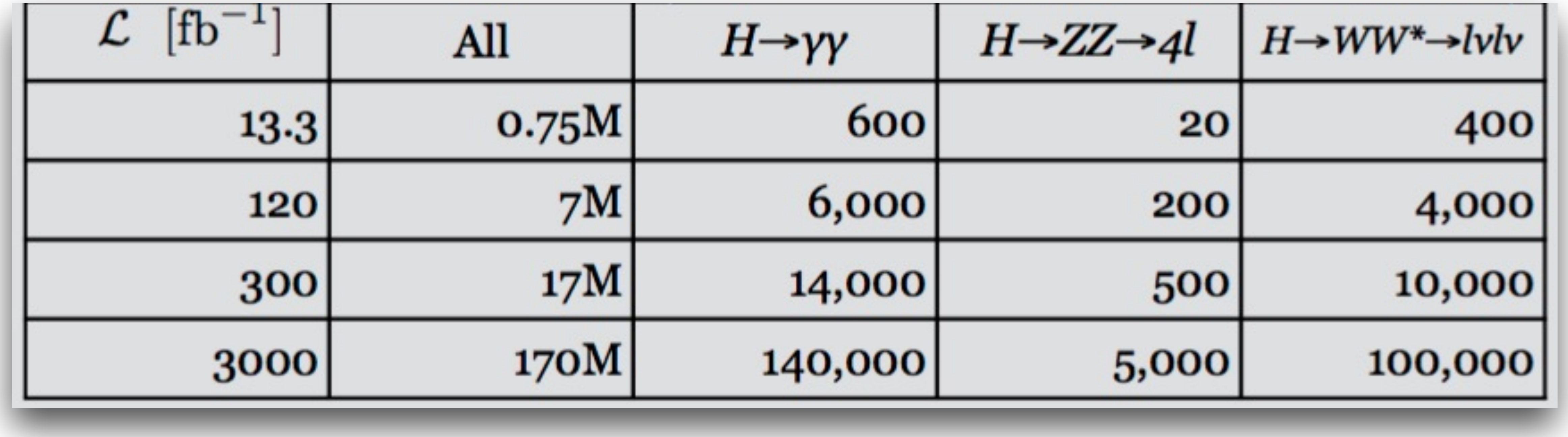


The 30fb^{-1} so far are just 1% of the final statistics

==>> the LHC physics programme has barely started! <<==

Precision Higgs physics at HL-LHC

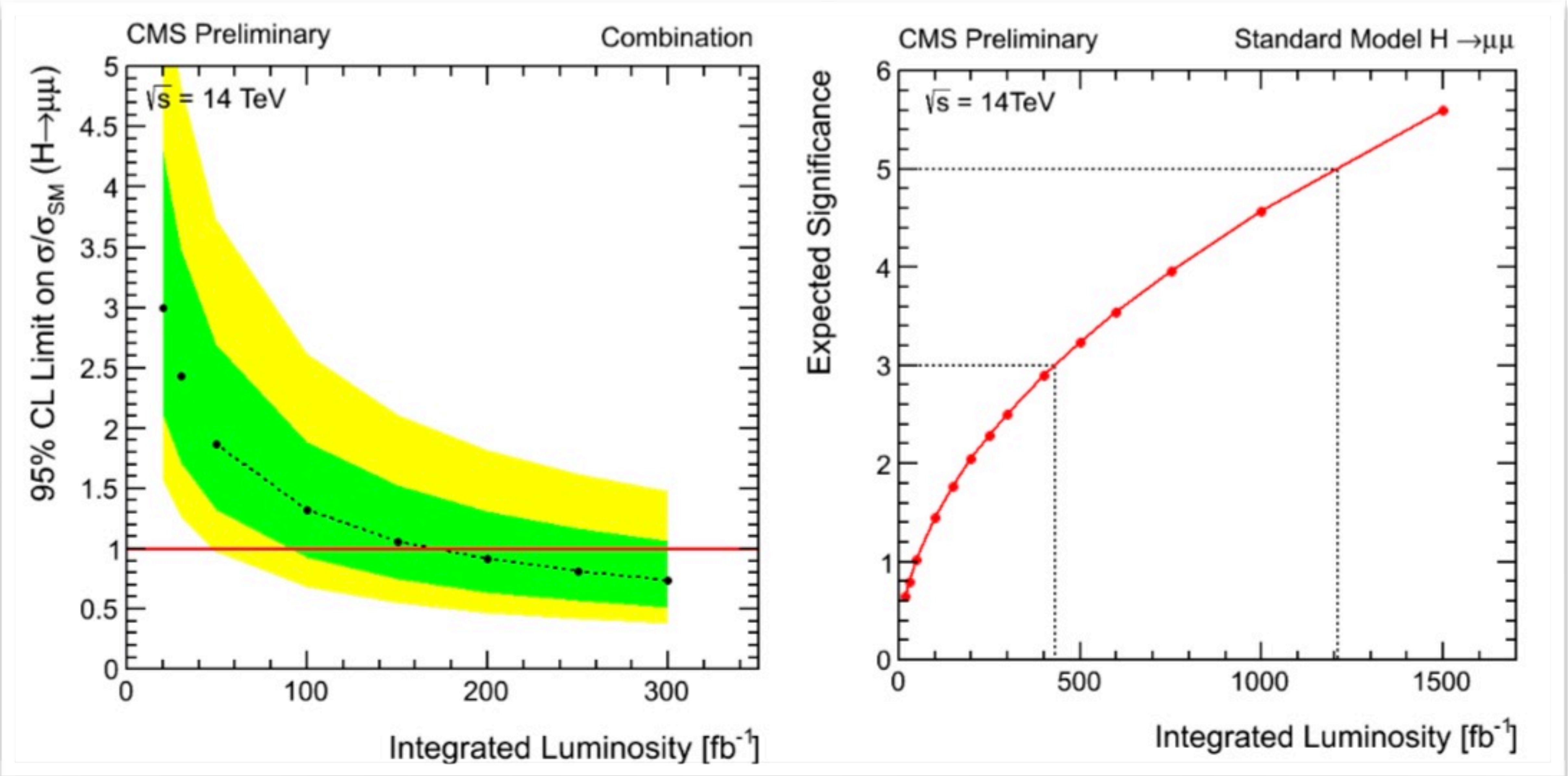
Future evolution of Higgs statistics



	$\mathcal{L}$ [fb^{-1}]	All	$H \to \gamma\gamma$	$H \to ZZ \to 4l$	$H \to WW^* \to l\nu l\nu$
July ‘16	13.3	0.75M	600	20	400
End ‘18	120	7M	6,000	200	4,000
End ‘23	300	17M	14,000	500	10,000
~ 2035	3000	170M	140,000	5,000	100,000

include estimates of analysis cuts and efficiencies

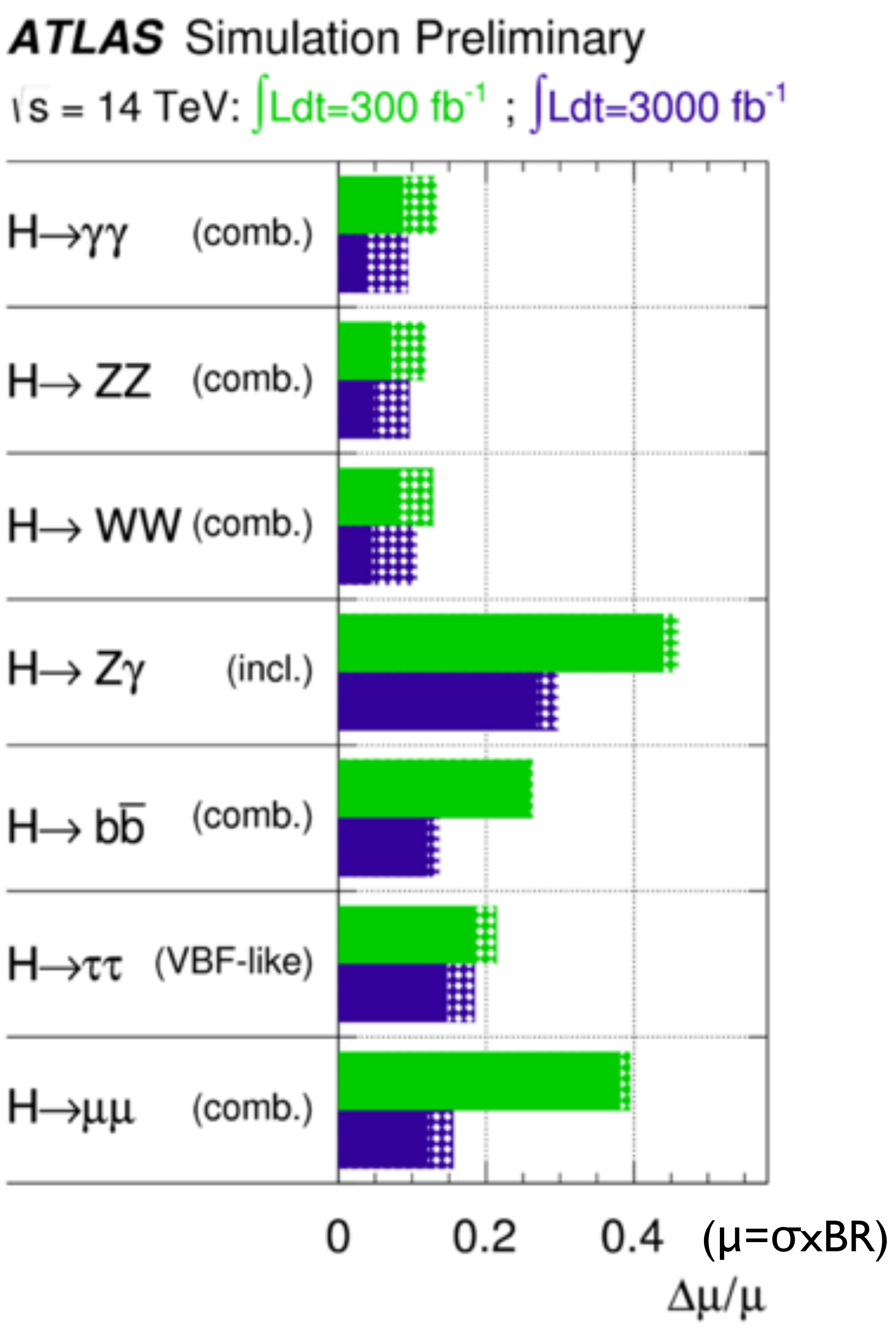
Projections for H couplings to 2nd generation

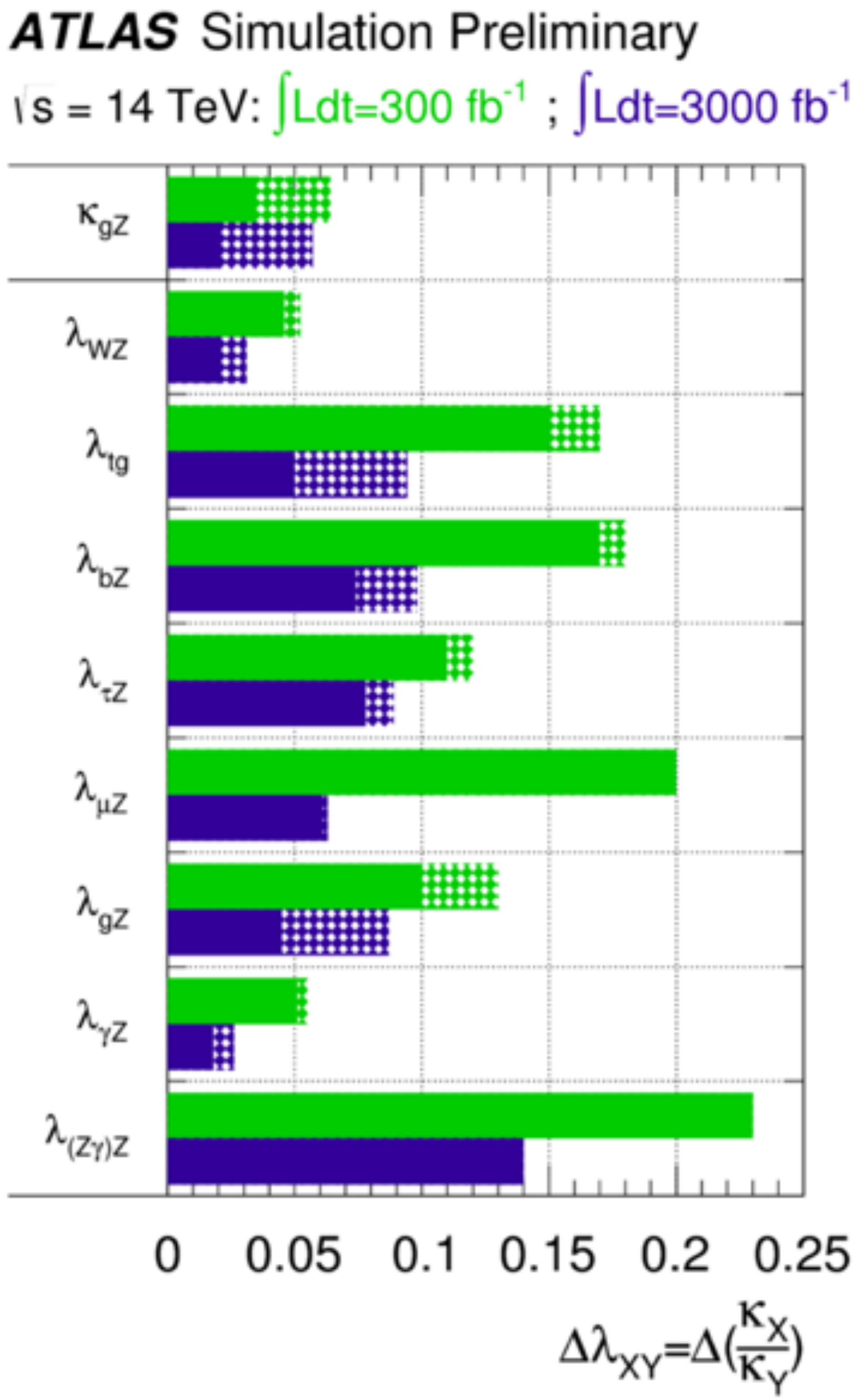


Projections from CMS-HIG-13-007

Projected precision on H couplings

ATL-PHYS-PUB-2014-016





solid areas: no TH systematics

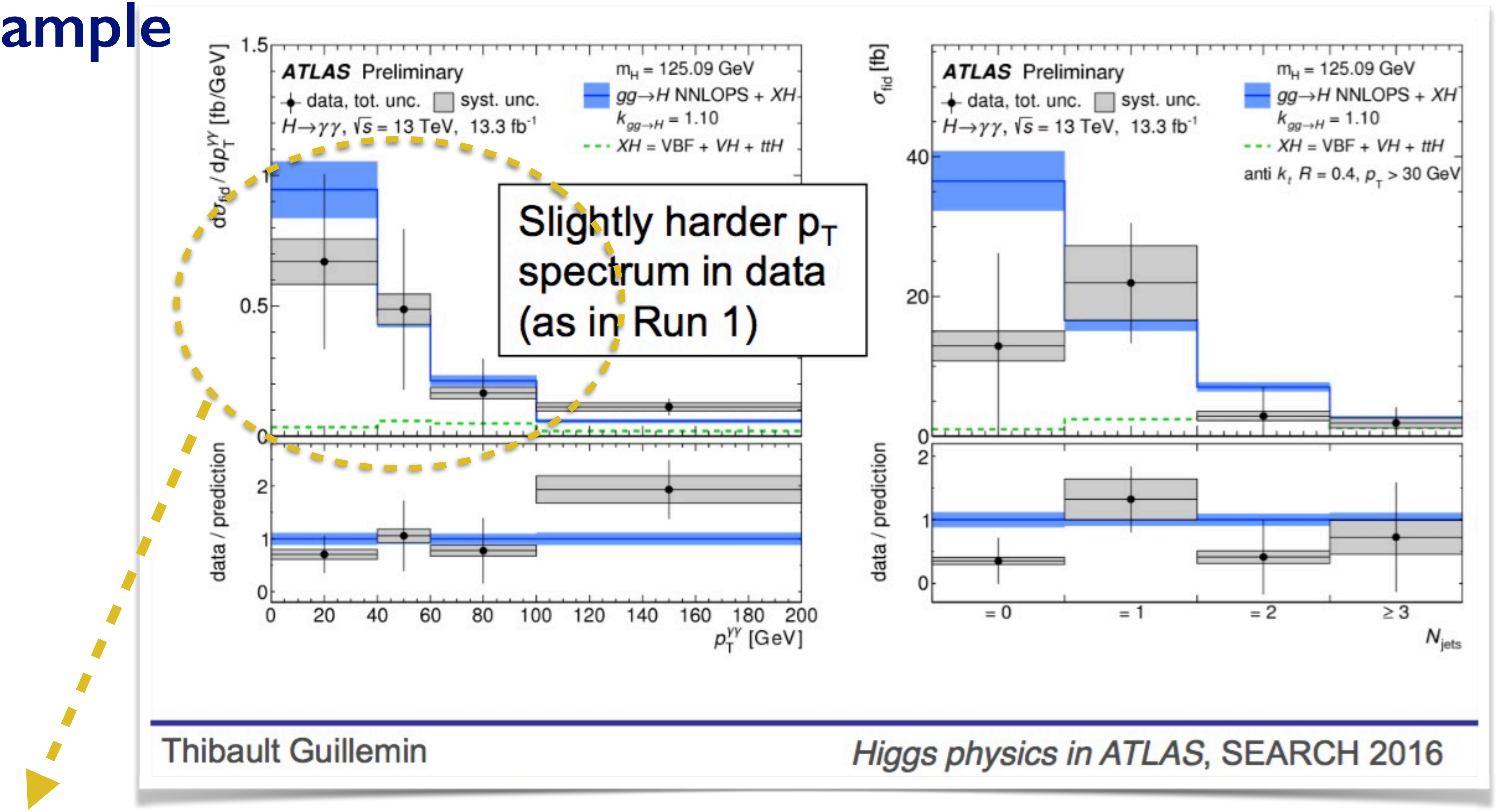
shaded areas: with TH systematics

Updates on the Higgs precision reach at HL-LHC were presented at the 2016 HL-LHC Workshop, Aix les Bains, Oct 4-7 2016:
(see V.Martin and M.Marono talks at
https://indico.cern.ch/event/524795/timetable/)

Current projections of future results are mostly extrapolations of today's analyses. Focus so far has been on exploring impact of higher luminosity and aging of detectors, to plan relevant upgrades and maintain or improve detector performance over the full LHC lifetime.

There is still plenty of room to design new analyses, exploiting in new ways the future huge statistics. Current projections should thus be seen as being likely rather conservative….

Example


Slightly harder p_T spectrum in data (as in Run 1)

Thibault Guillemin

Higgs physics in ATLAS, SEARCH 2016

- δstat ~ 5 δexp => ~25xL ~300fb^{-1} to equalize exp&stat uncert'y
- O(ab^{-1}) will provide an accurate, purely exptl determination of p$_T$(H) in the theoretically delicate region 0-50 GeV, and strongly reduce/suppress th'l modeling systematics affecting other measurements (e.g. WW*)
- More in general, a global programme of higher-order calculations, data validation, MC improvements, PDF determinations, etc, will push further the TH precision….

furthermore ….

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.

- We often talk about "**precise**" Higgs measurements. What we actually aim at, is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.

- *Sensitivity* may not require extreme precision
    - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$\boxed{L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots}$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

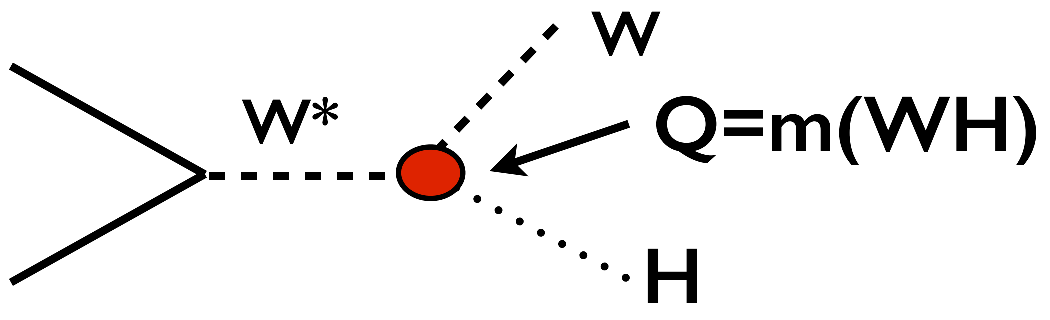
$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

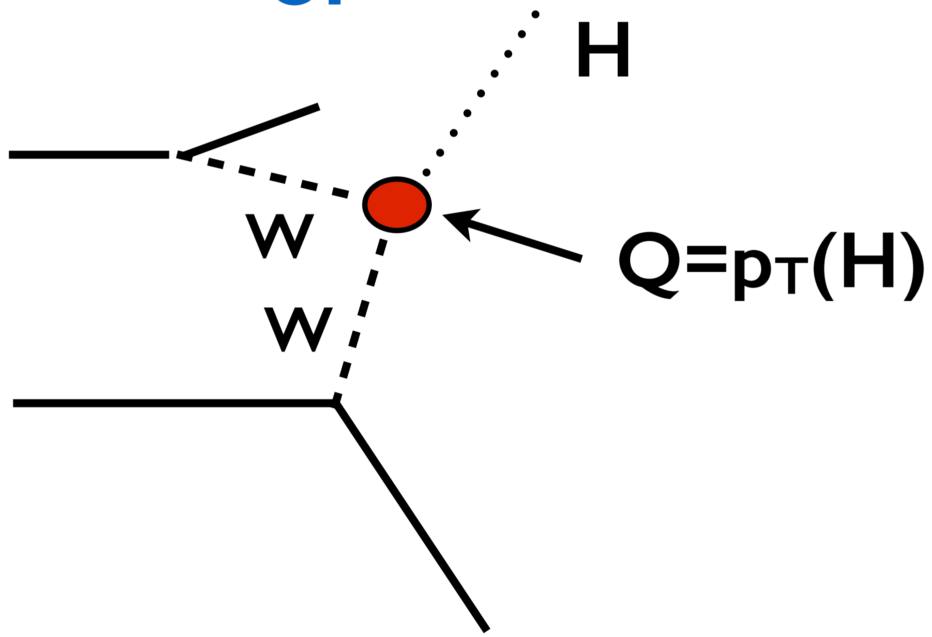
e.g. $\delta O_Q = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

Examples

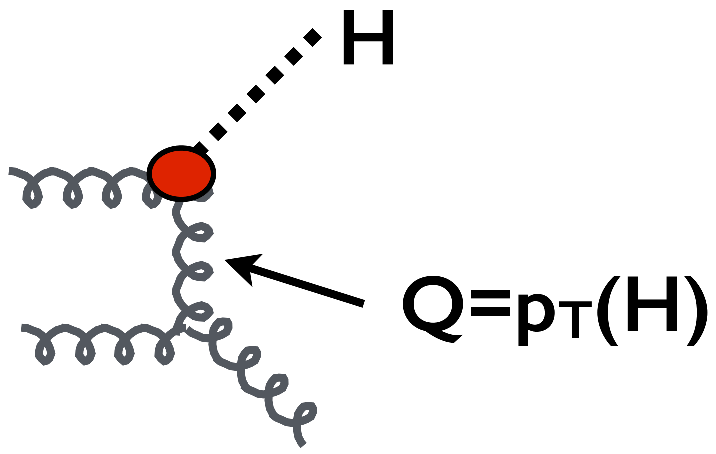
$\delta BR(H\to WW^*)$



or



$\delta BR(H\to gg)$



$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2 \quad \textbf{vs} \quad \delta O \sim \left(\frac{v}{\Lambda}\right)^2$$

For a high-Q observable ***O*$_Q$** to achieve the same Λ sensitivity of a "precision" observable ***O***, it is sufficient, for a given Q, to reach an accuracy

$$\delta O_Q \sim \delta O \left(\frac{Q}{v}\right)^2$$

Or, for a given accuracy **δ*O*$_Q$**, it's enough to have statistics on ***O*$_Q$** at a scale

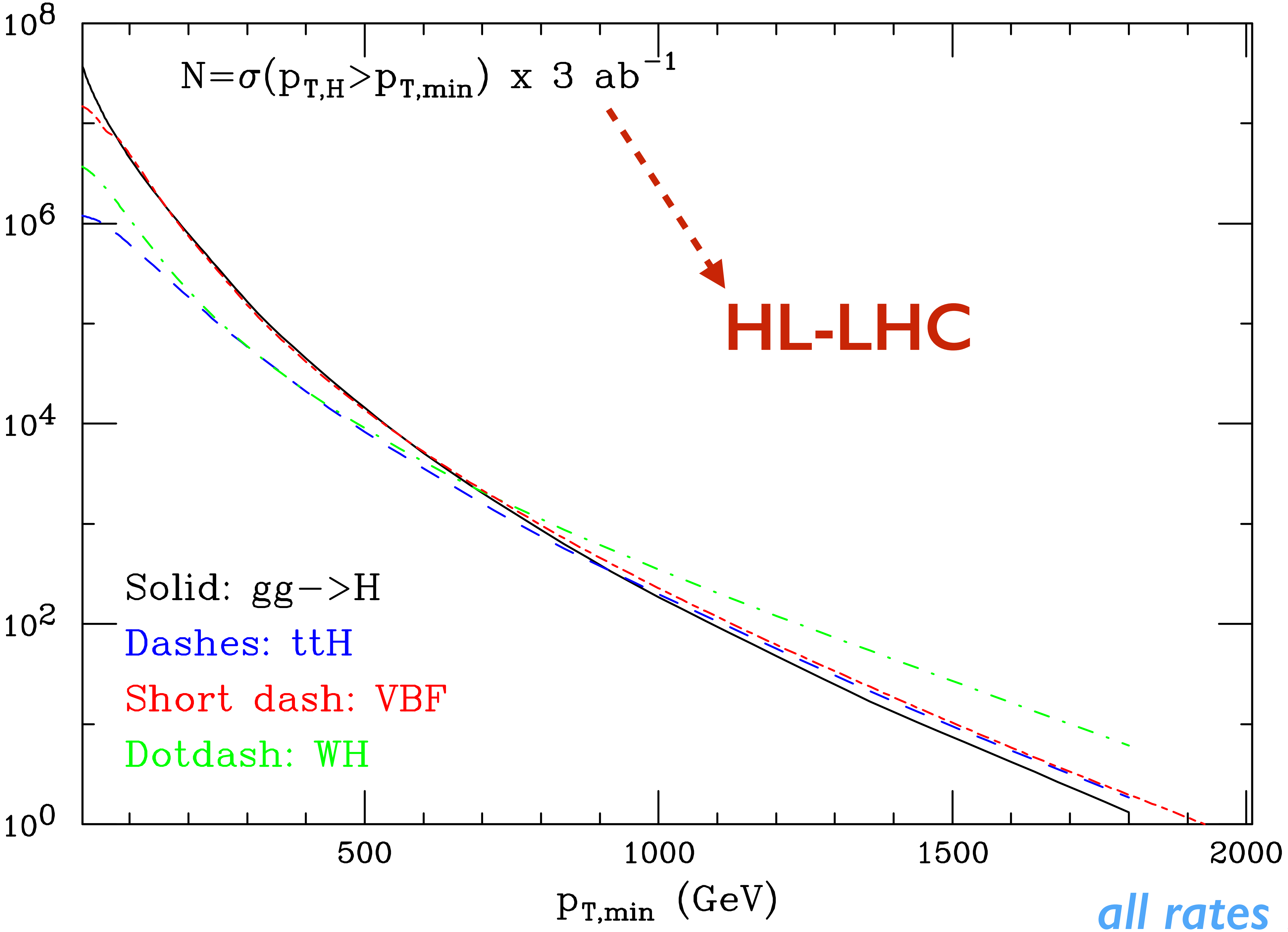
$$Q \sim v \left(\frac{\delta O_Q}{\delta O}\right)^{1/2}$$

E.g. for **δ*O***~10^{-2} (goal of precision BR measurements at HL-LHC):

– **δ*O*$_Q$**~10^{-1} ⇒ Q ~ 3 v ~ 750 GeV

– **δ*O*$_Q$**~10^{-2} ⇒ Q ~ v ~ 250 GeV

Probing large Q: Higgs production at large p_T



all rates LO

Examples: gg-> H at large p_T

(See also
Azatov and Paul arXiv:1309.5273v3)

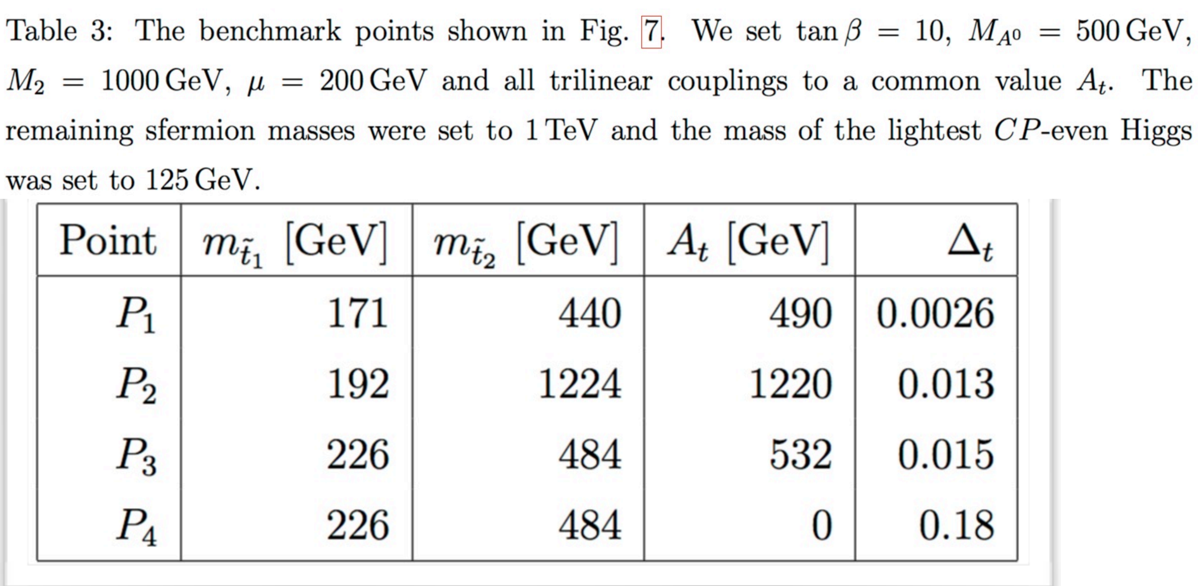
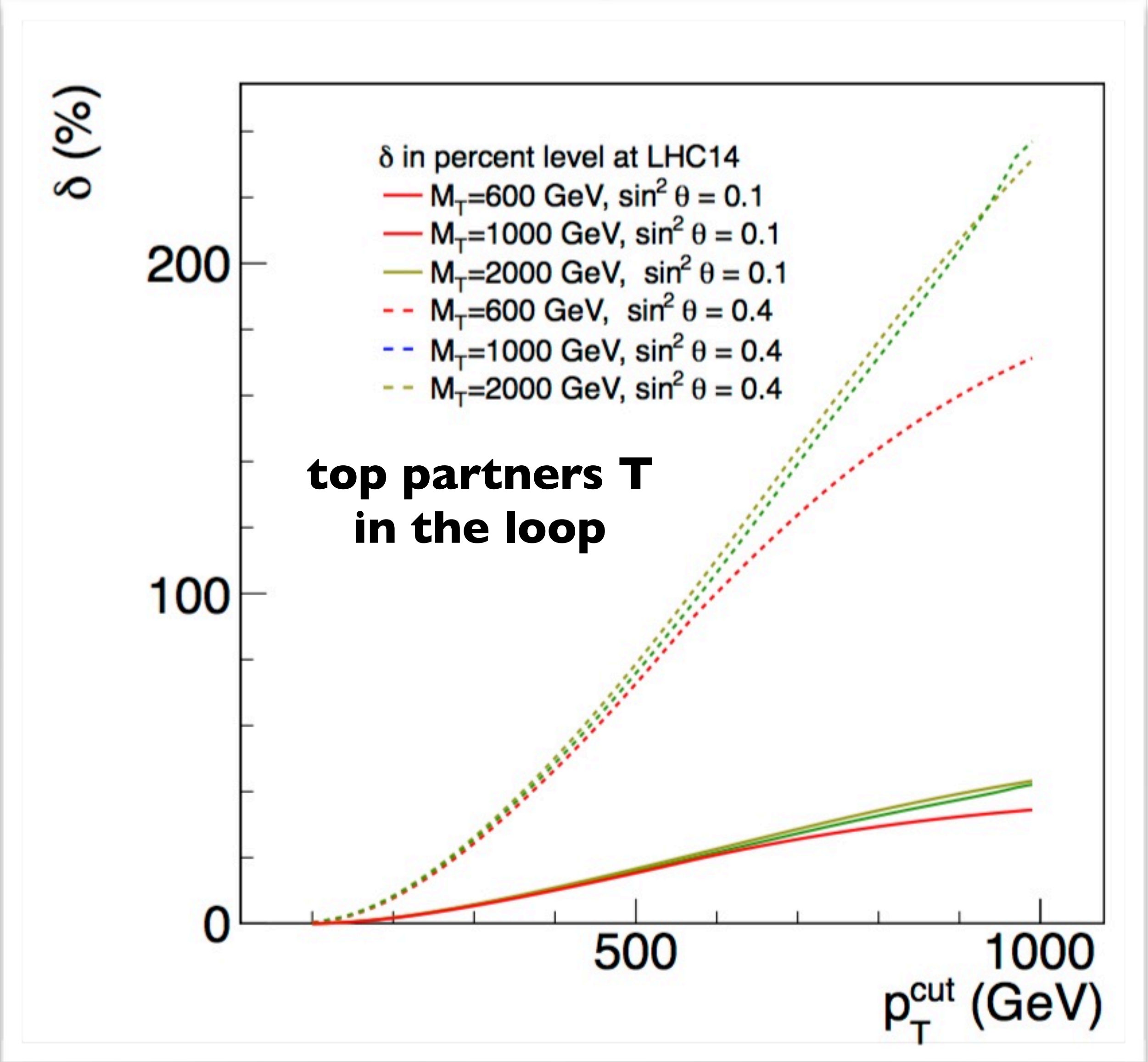


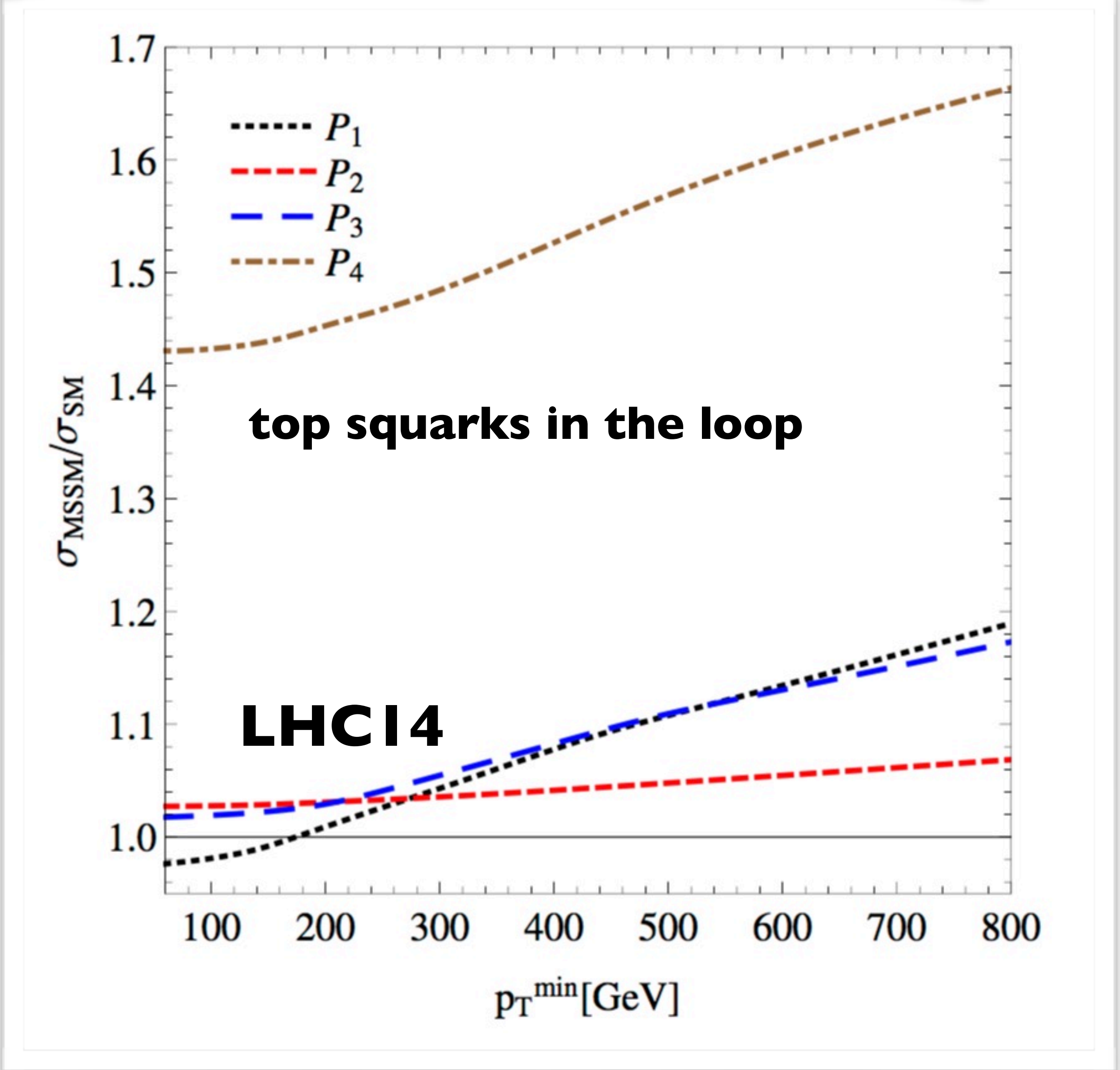
Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\mathrm{GeV}$, $M_2 = 1000\,\mathrm{GeV}$, $\mu = 200\,\mathrm{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was set to 125 GeV.

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18



top partners T in the loop

Banfi Martin Sanz, arXiv:1308.4771



top squarks in the loop

LHC14

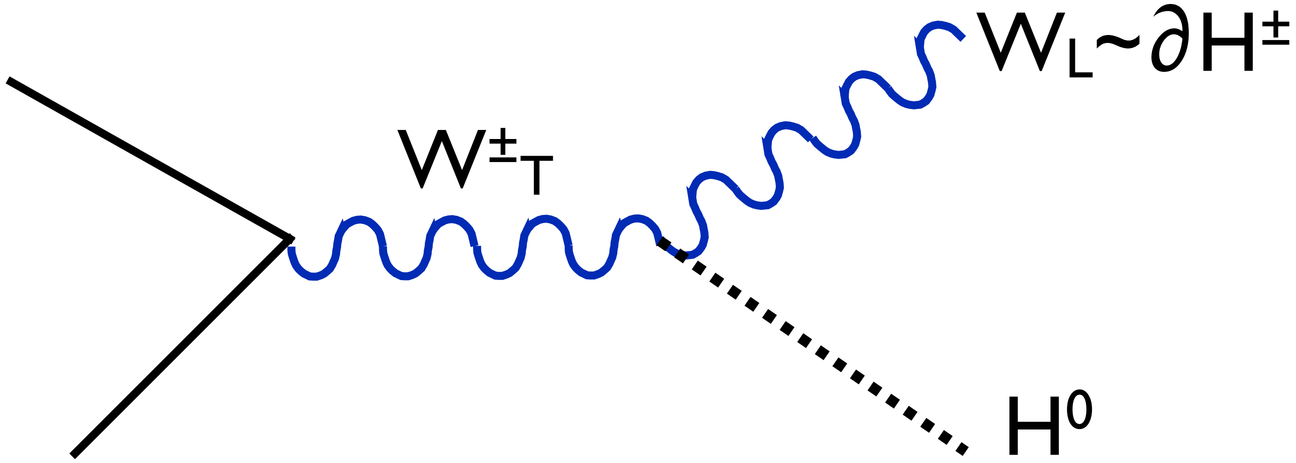
Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

10% sensitivity at p_T(H)~1TeV is compatible with 3ab^{-1} rates in previous page

- For high-Q observables, e.g. differential distributions vs Q, anomalies amount to changes, w.r.t. SM, in the shape of the distributions.
- Shapes are free from ultimate and possibly unbeatable experimental systematics, such as the luminosity determination
- Shapes are also independent of the impact of BSM on BR’s, which could compensate the impact on rates for inclusive production
- Shapes are typically less susceptible to theoretical systematics: one can often rely on a direct experimental determination of the SM reference behaviour, and can benefit from validation of the theoretical SM modeling through data/MC comparisons in control samples.

VH prodution at large m(VH)

See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320

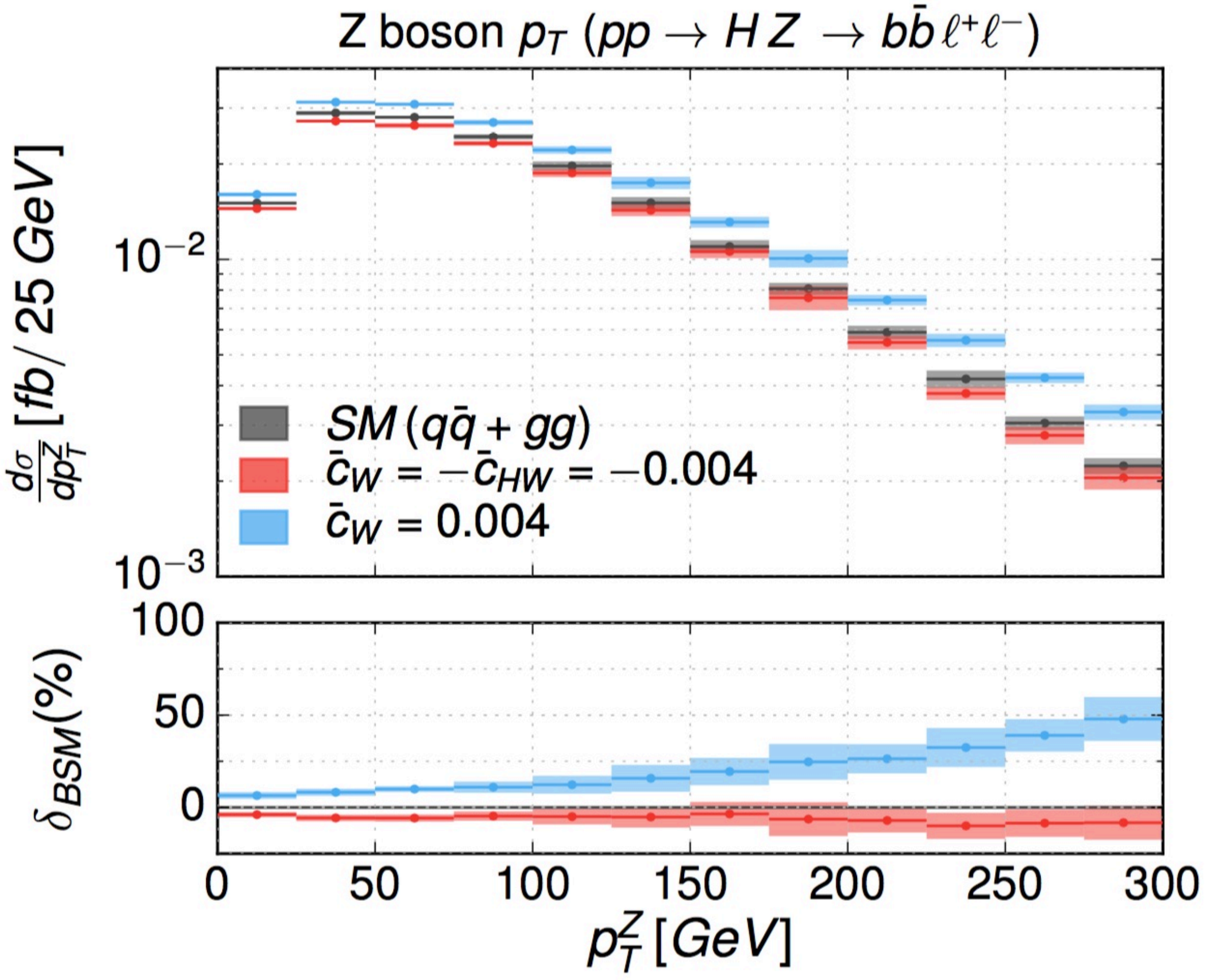


In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger\sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

➡

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W\frac{\hat{s}}{\Lambda^2}\right)^2$$

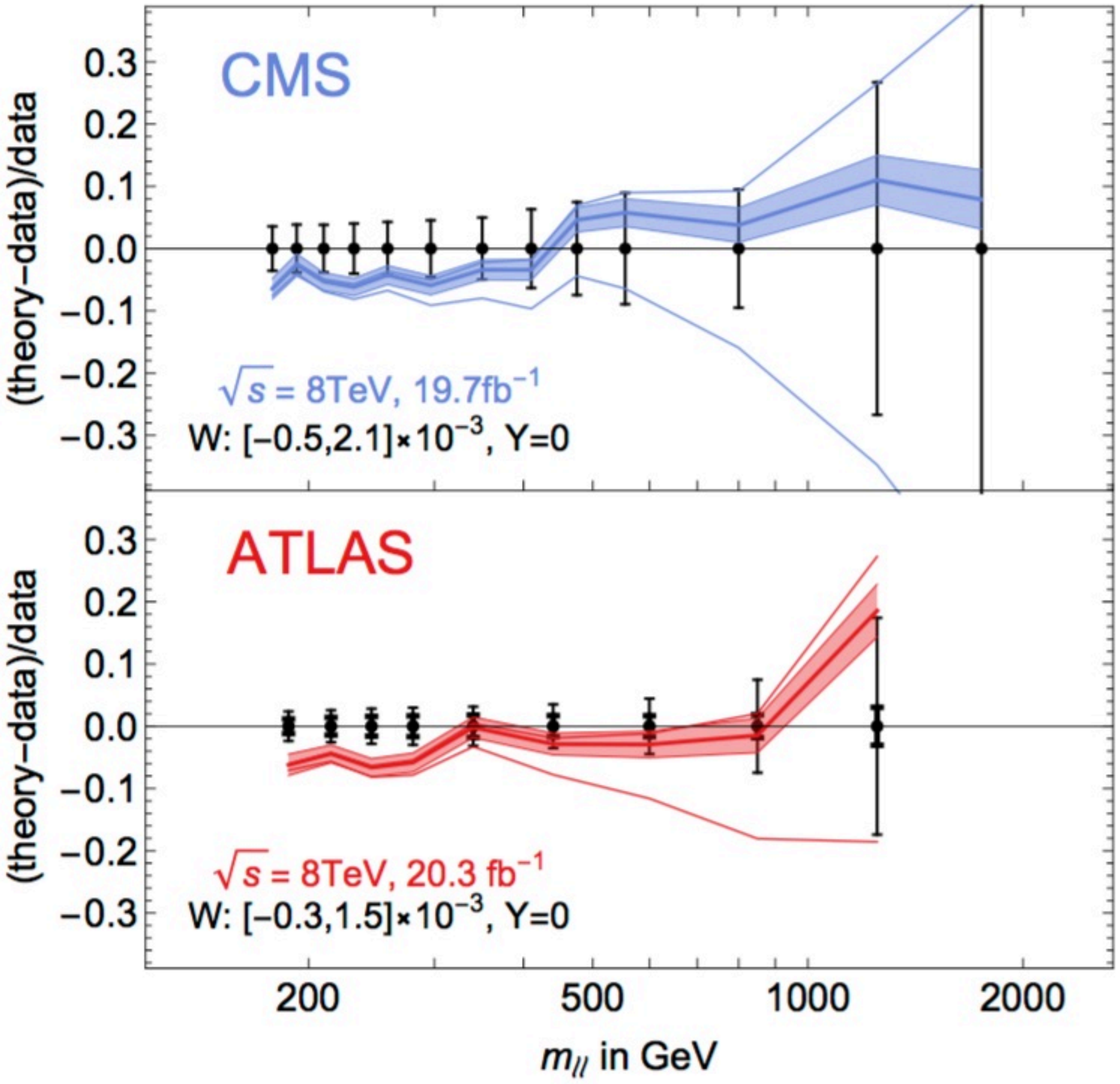


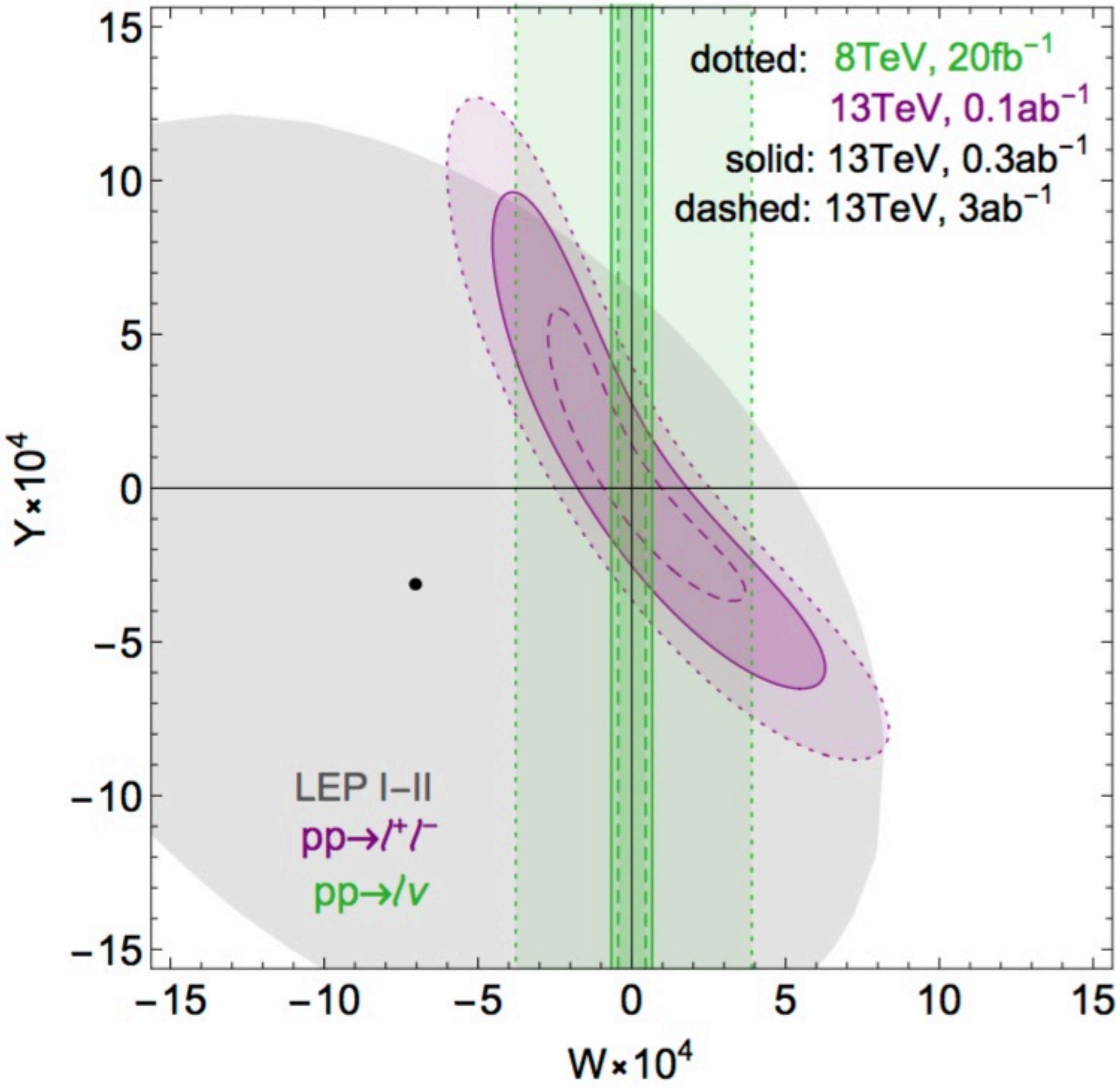
Mimasu, Sanz, Williams, arXiv:1512.02572v

Ex: Probes of dim-6 op's with high-mass DY

M.Farina et al, arXiv:1609.08157

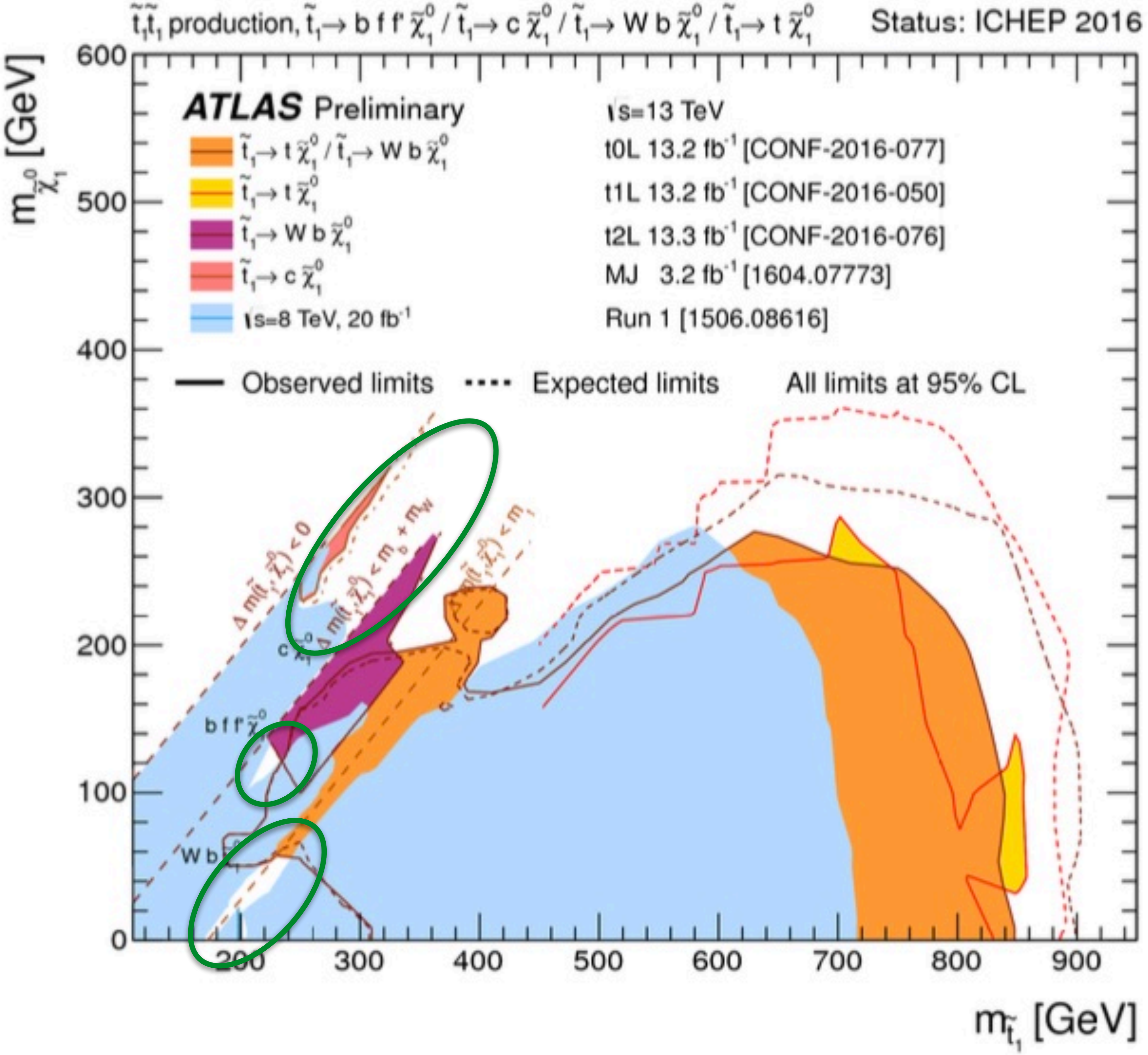
	universal form factor ($\mathcal{L}$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$





The need for, and the power, of novel ingenuity

Example: stop searches

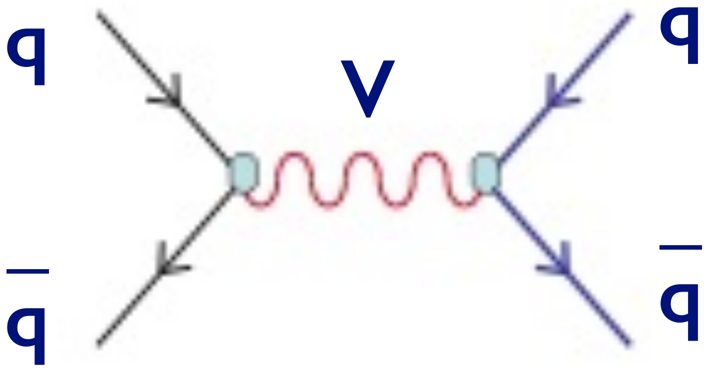


The challenge: gain sensitivity to all small gaps of parameter space, achieve a complete a conclusive coverage of the accessible phase space.

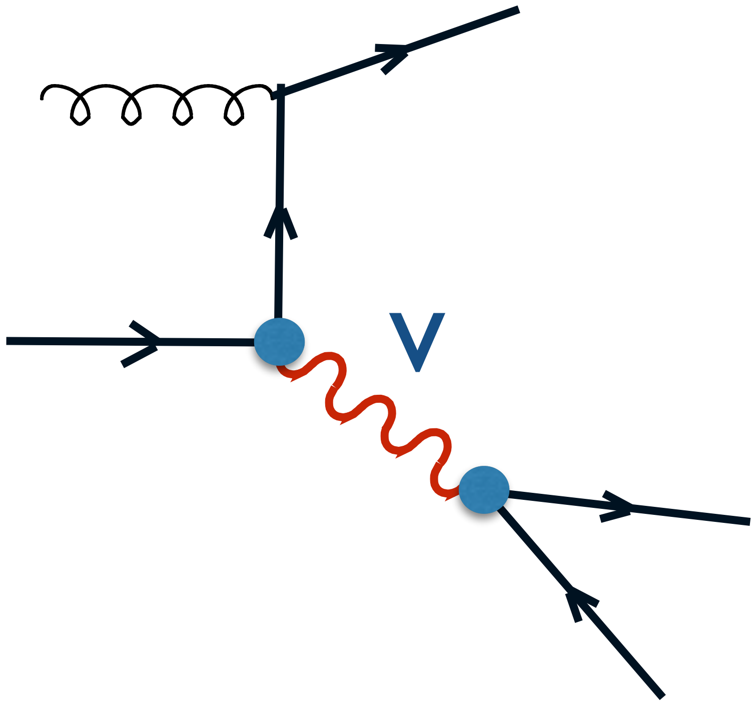
Probing each corner of this phase space is almost like a small-experiment in itself!!

Larger statistics, giving access to more secluded kinematical regions, allow to exploit new powerful analysis tools, and gain sensitivity to otherwise elusive signatures

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



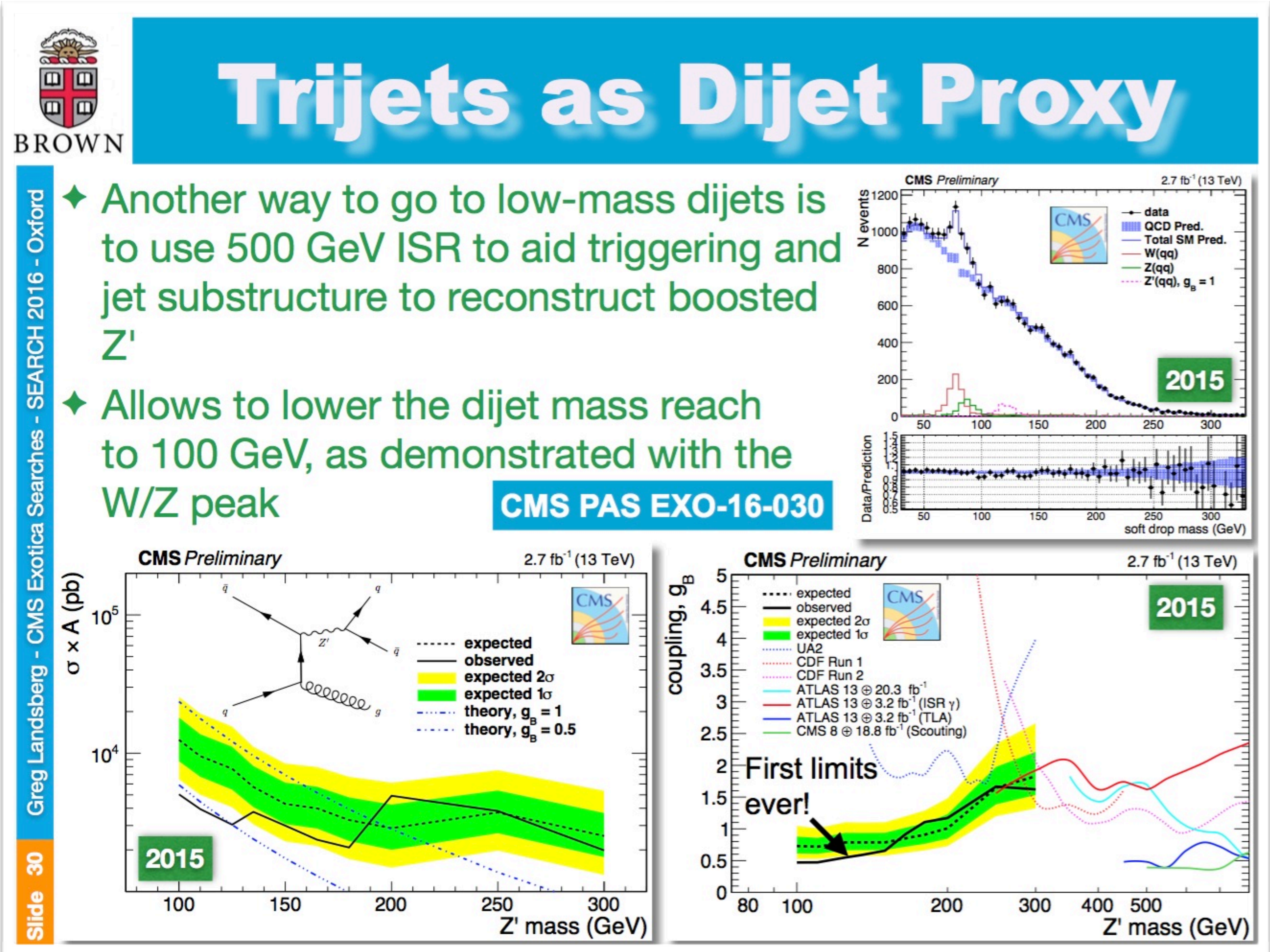
search impossible at masses below few hundred GeV, due to large gg→gg bg's and trigger thresholds



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%

Example: search for low-mass dijet resonances



BROWN

Trijets as Dijet Proxy

- ✦ Another way to go to low-mass dijets is to use 500 GeV ISR to aid triggering and jet substructure to reconstruct boosted Z'
- ✦ Allows to lower the dijet mass reach to 100 GeV, as demonstrated with the W/Z peak

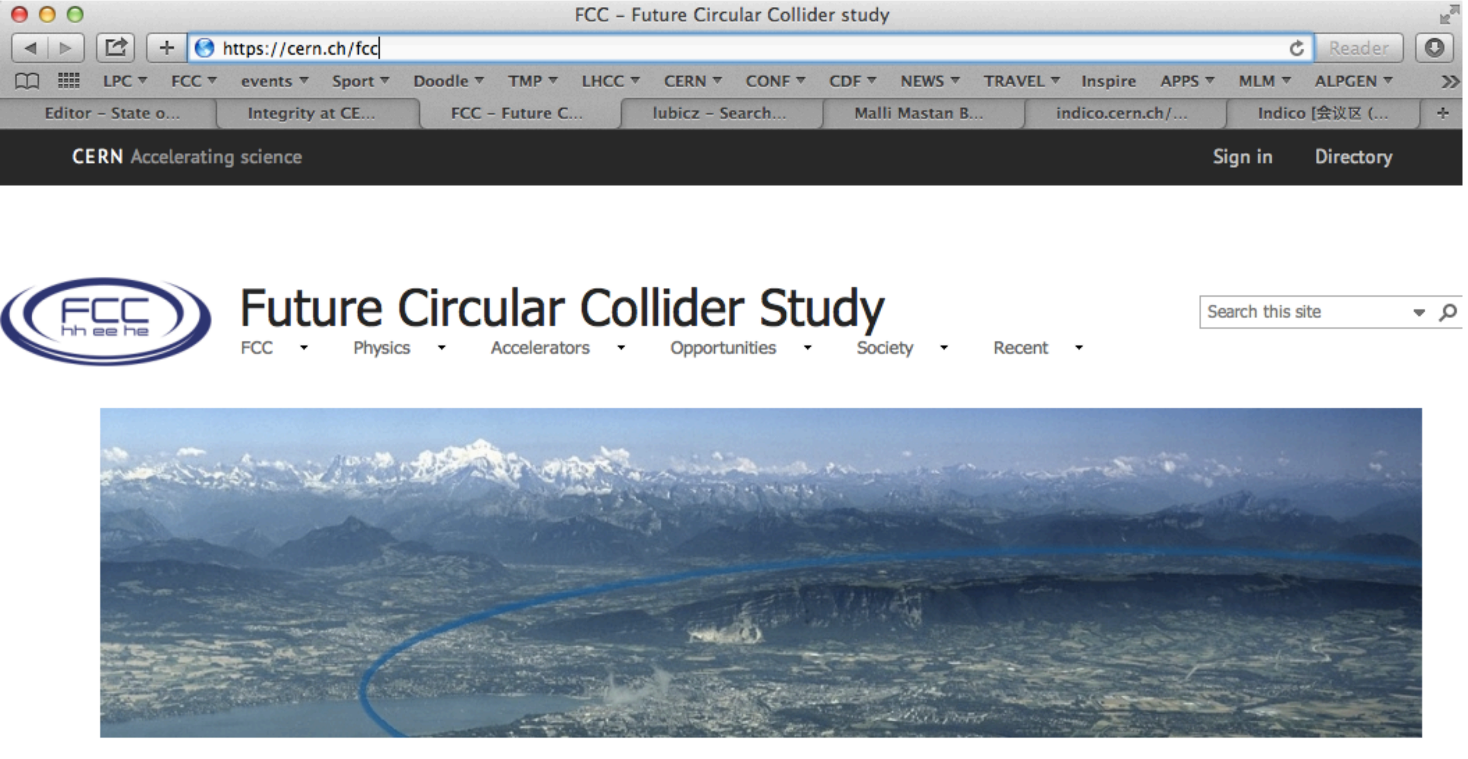
CMS PAS EXO-16-030

First limits ever!

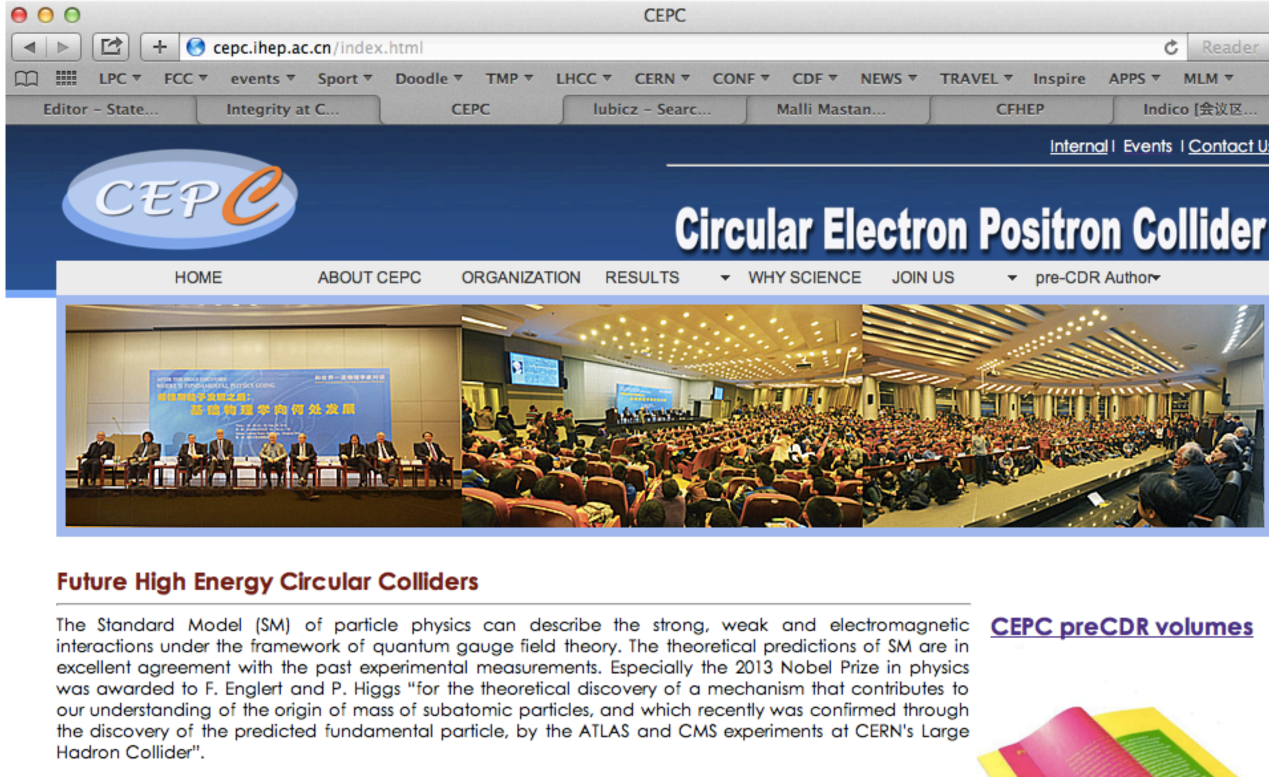
Greg Landsberg - CMS Exotica Searches - SEARCH 2016 - Oxford

Beyond the LHC

http://cern.ch/fcc



http://cepc.ihep.ac.cn



Future High Energy Circular Colliders

The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially the 2013 Nobel Prize in physics was awarded to F. Englert and P. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

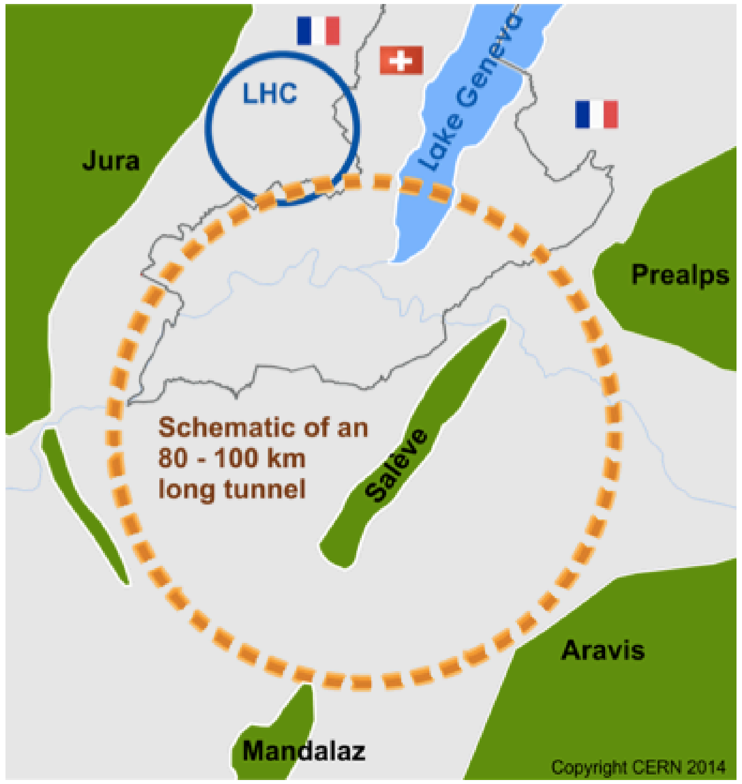
CEPC preCDR volumes

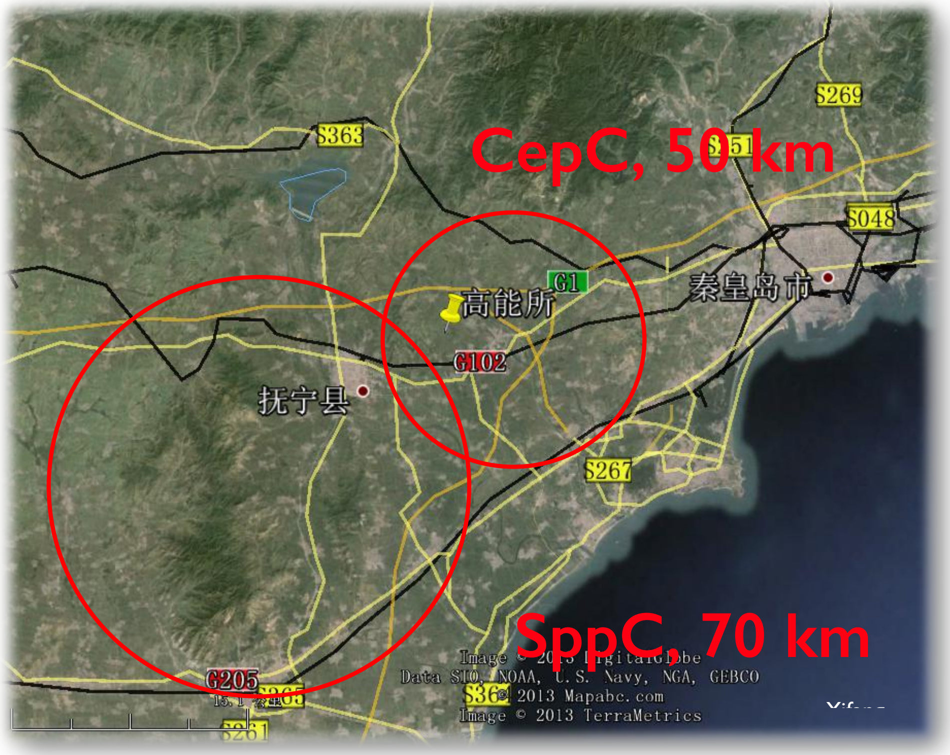
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area





Key issue

Why don't we see the new physics ?

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

Today, the study of the physics potential of a future facility can at best document its performance, e.g. according to criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions. E.g.

- *is DM a thermal WIMP?*
- *did baryogenesis take place during the EW phase transition?*
- *is there a TeV-scale solution to the hierarchy problem?*
- ...

Focus on high-E pp colliders

- Guaranteed deliverables:
  - precision study of Higgs and top quark properties, and exploration of EWSB phenomena
  - *NB: outcome will be enhanced by synergy with results of an e^+e^- collider*

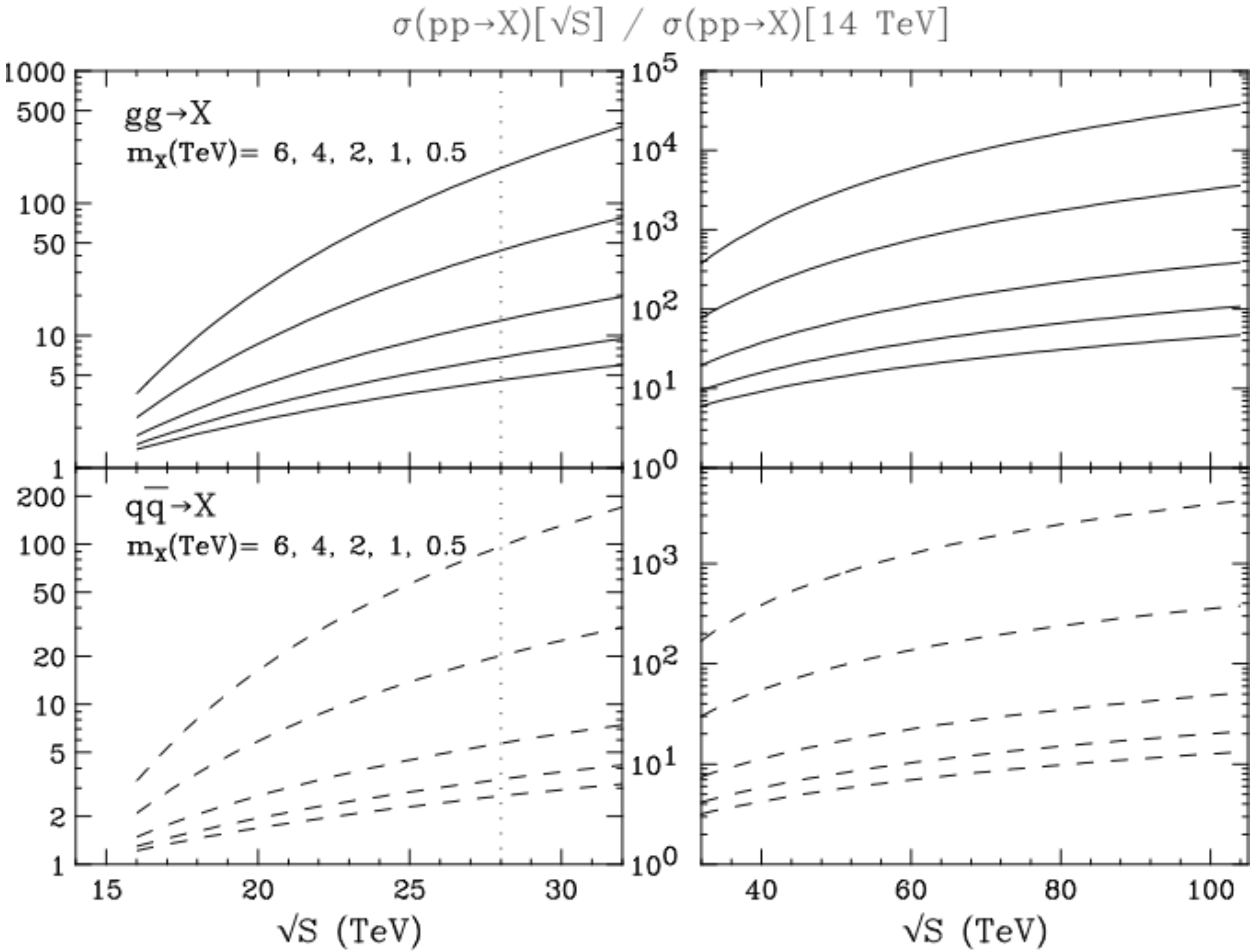
- Exploration potential:
  - mass reach enhanced by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
  - statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC

- Possible Yes/No answers:
  - ~100 TeV needed to fully address questions tied to the TeV scale (e.g. WIMPs, EW Baryogenesis, TeV-scale naturalness)

- The weight of each item in the previous list depends on
  - the evolution of theoretical thinking, model building
  - the outcome of the LHC
  - the outcome of the full experimental landscape
    - flavour physics: at LHC, K & B factories, leptonic sector, g–2, EDMs, neutrinos
    - DM: direct and indirect searches, cosmological studies (*eg. is DM strongly selfinteracting?*)
    - Searches for axions, ALPs, dark photons, ...
    - ....

- Future developments in any of the points above will allow to sharpen and focus the assessment of the role of future pp colliders

Example: possible E evolution of scenarios with the discovery of a new particle at the LHC



Possible questions/options

- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *28 TeV would be insufficient ....*)

- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?

- etc.etc.

Our studies today focus on exploring possible scenarios, assessing the physics potential, defining benchmarks for the accelerator and detector design and performance, in order to better inform the discussions that will take place when the time for decisions comes...

FCC-hh parameters and lum goals

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} cm^{-2}s^{-1} (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} cm^{-2}s^{-1} (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

Reference literature

- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - "High-precision αs measurements from LHC to FCC-ee", arXiv:1512.05194
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: ***"Physics at 100 TeV"***, Report, 5 chapters:
  - SM processes, arXiv:1607.01831
  - Higgs and EWSB studies, arXiv:1606.09408
  - BSM phenomena, arXiv:1606.00947
  - Heavy Ions at the FCC, arXiv:1605.01389
  - Physics opportunities with the FCC injectors, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

~700 pages

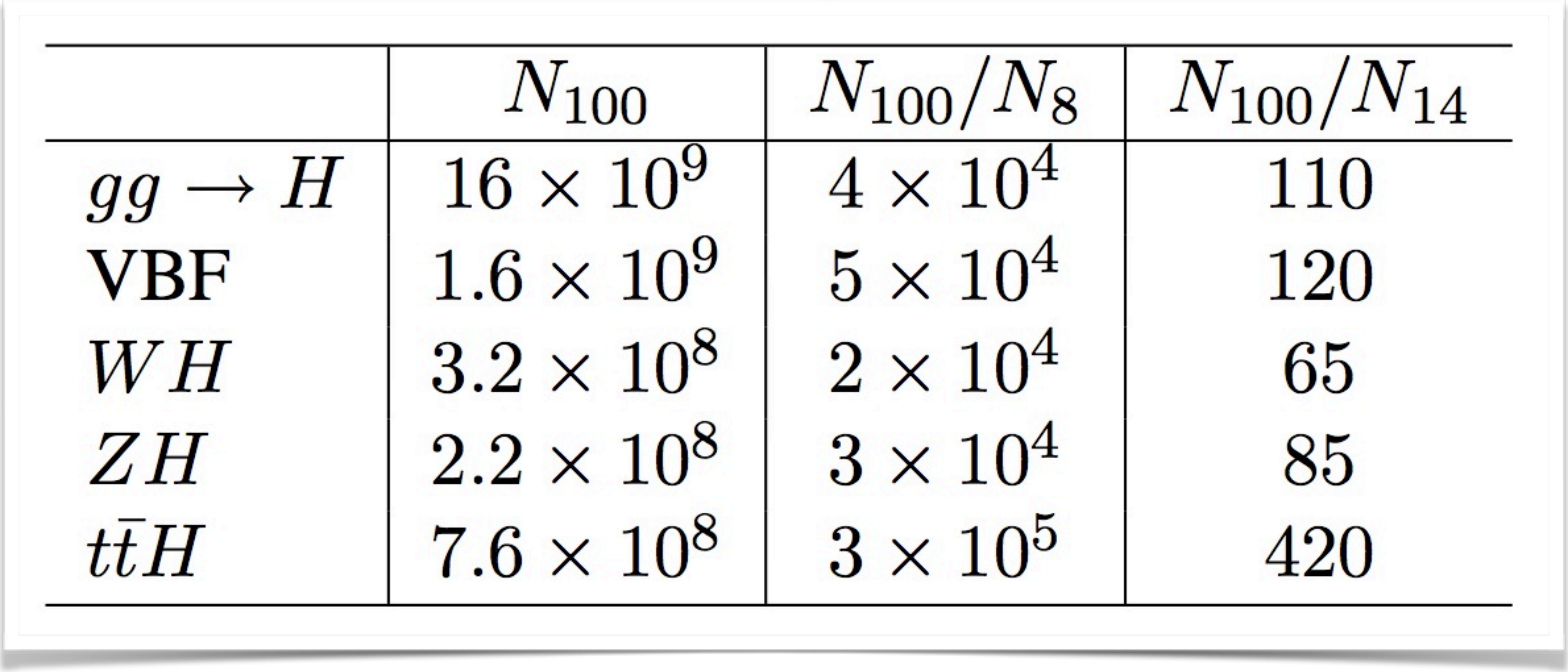
- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, see:
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081
- N. Arkani-Hamed, T. Han, M. Mangano, and L.-T. Wang, Physics Opportunities of a 100 TeV pp Collider, arXiv:1511.06495

Examples of the physics potential of the 100 TeV collider

SM Higgs at 100 TeV



	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

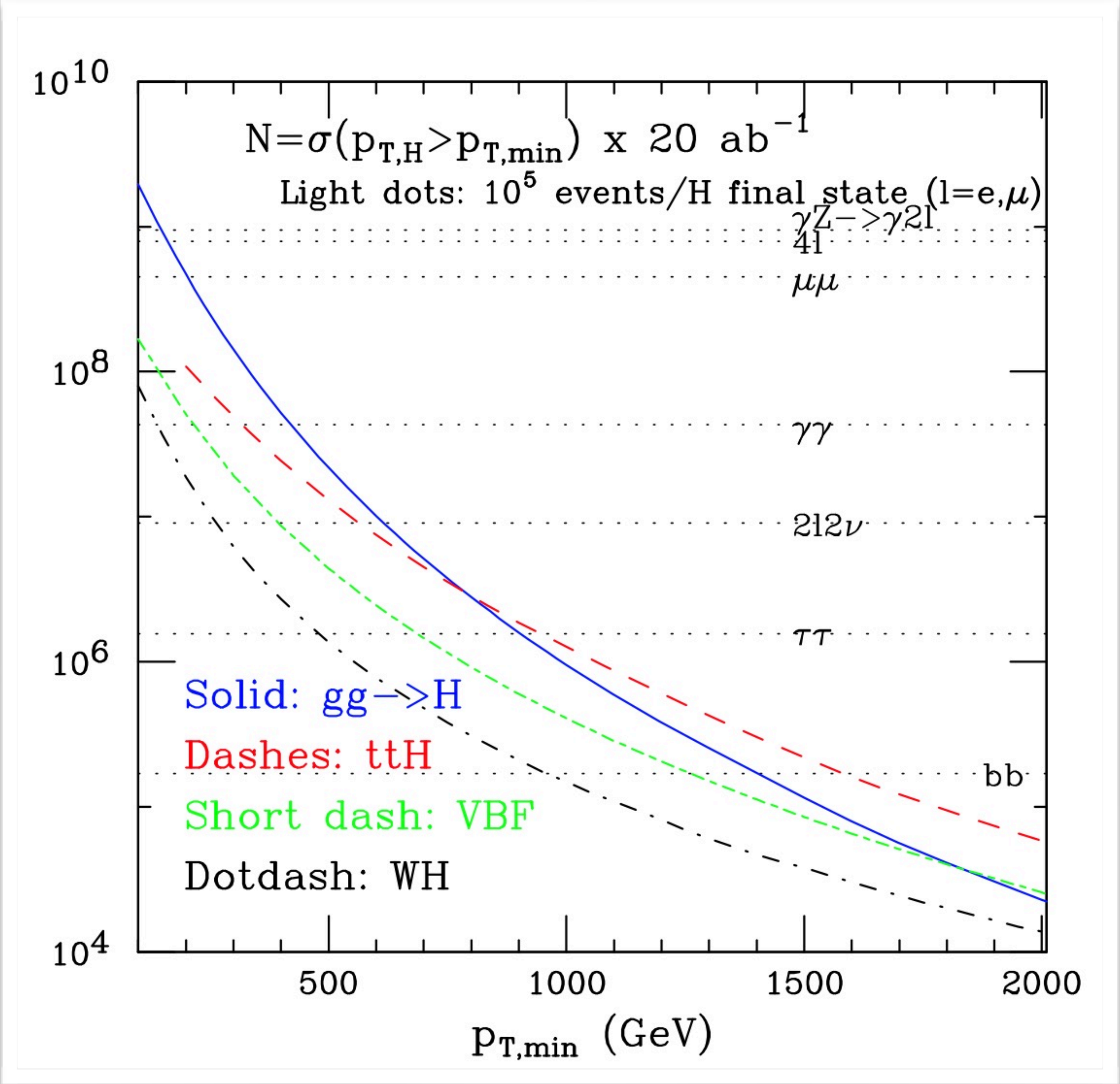
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

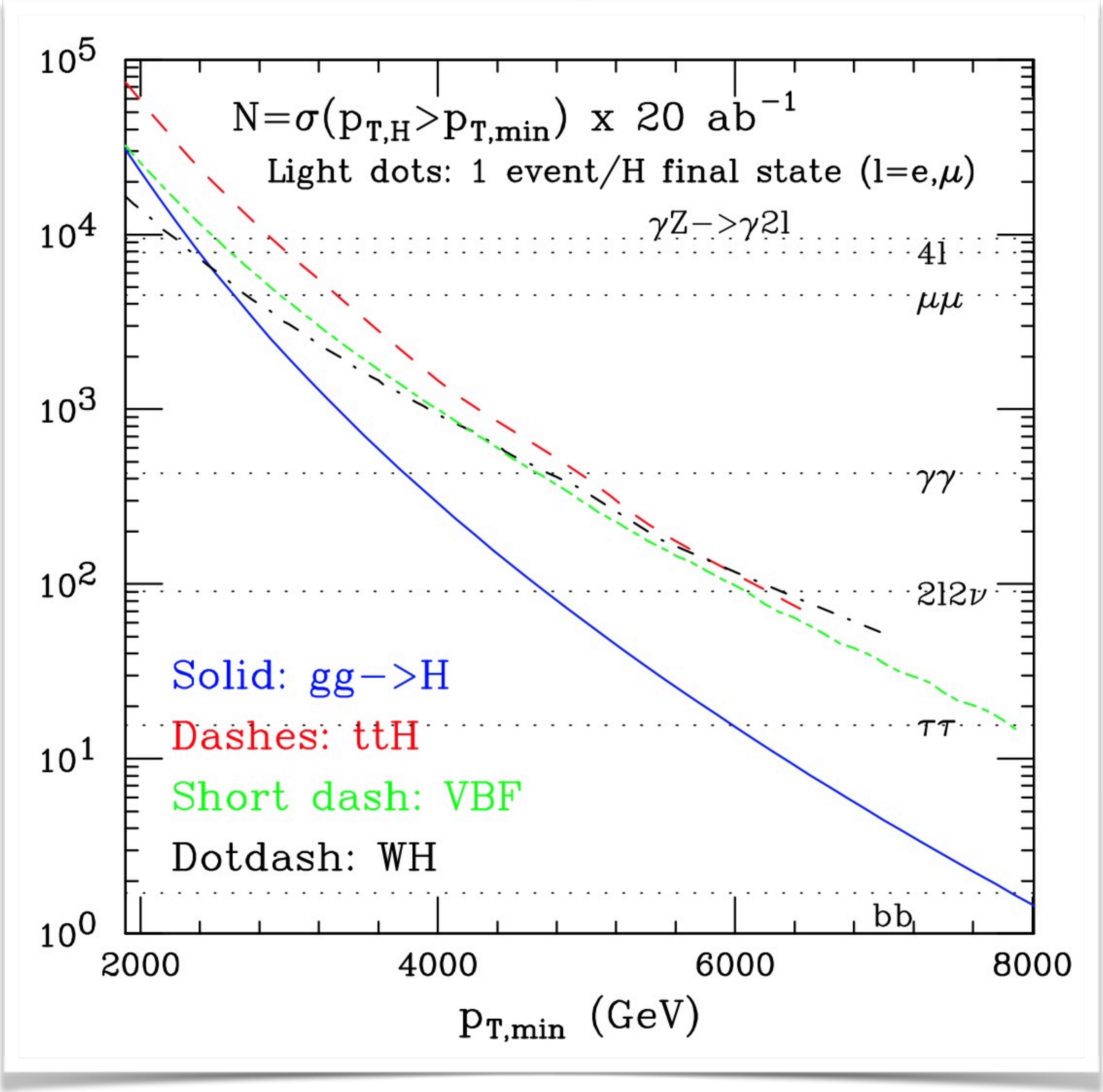
- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

H at large p_T



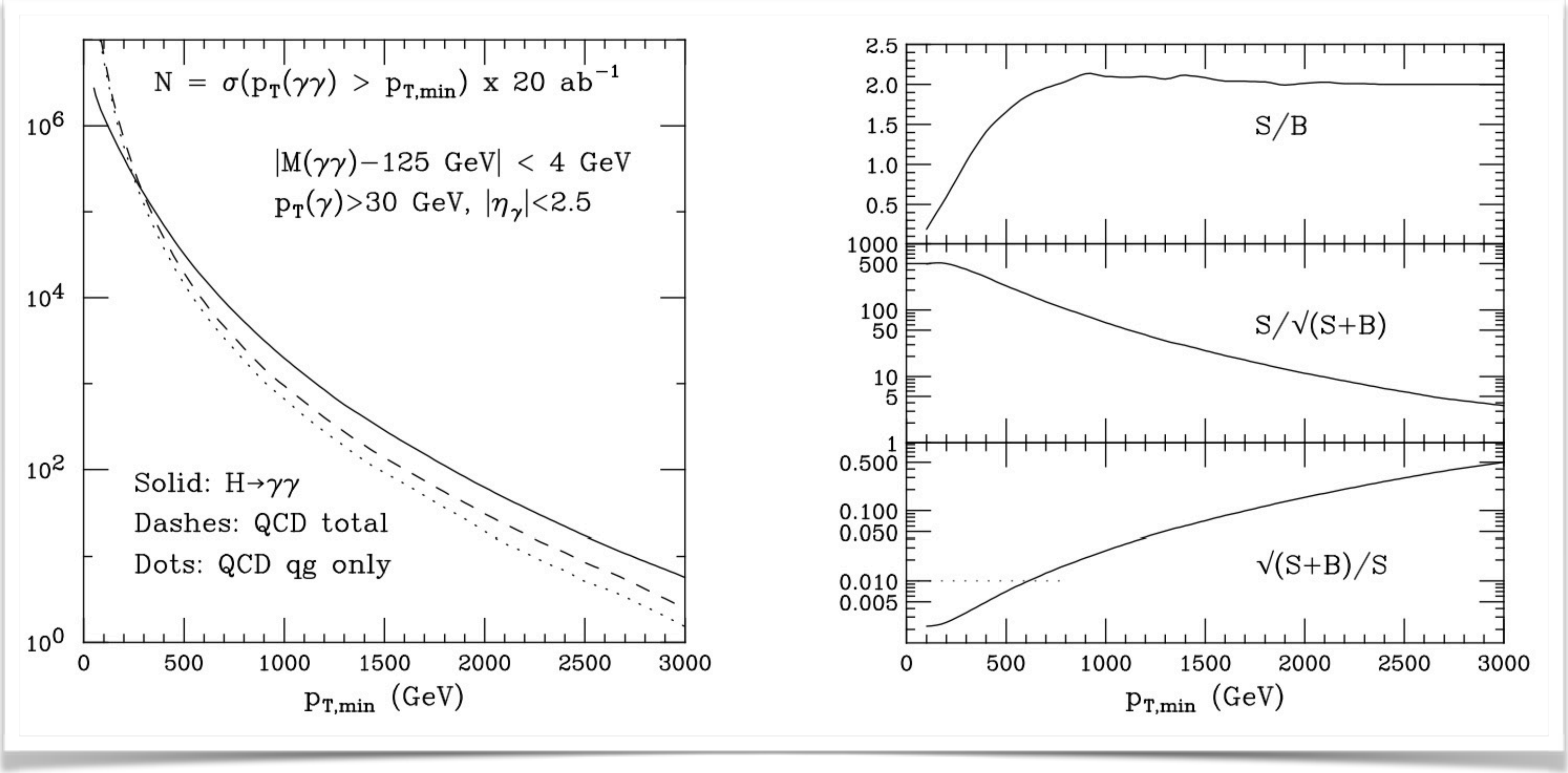
- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

H at large p_T



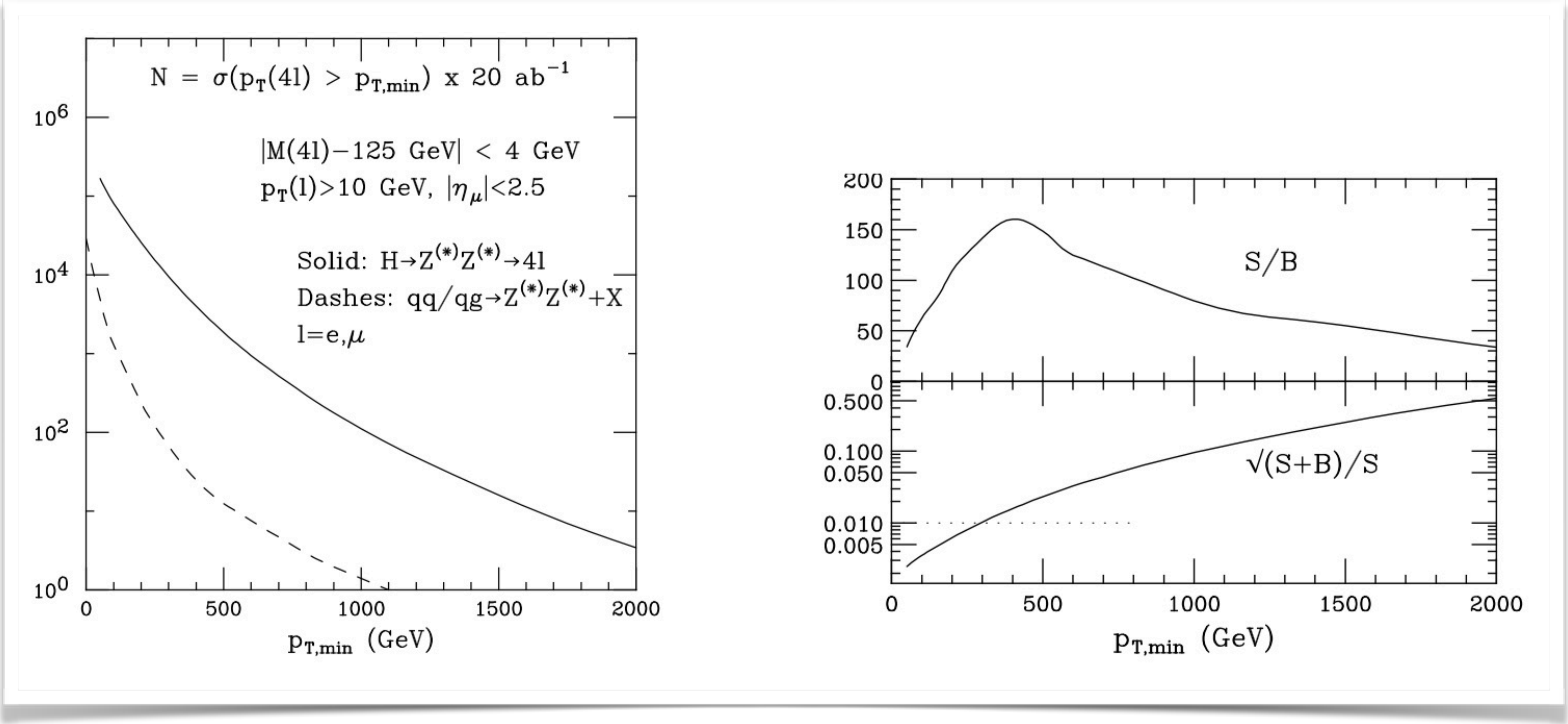
- Statistics in potentially visible final states out to several TeV

gg→H→γγ at large p_T



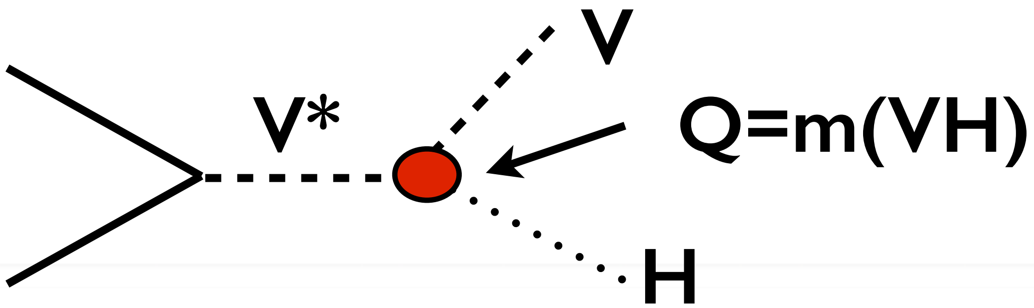
- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Very clean probe of Higgs production up to large $p_T(H)$.
  - What's the sensitivity required to probe relevant BSM deviations from SM spectrum?
  - Exptl mass resolution at large pt(H)?

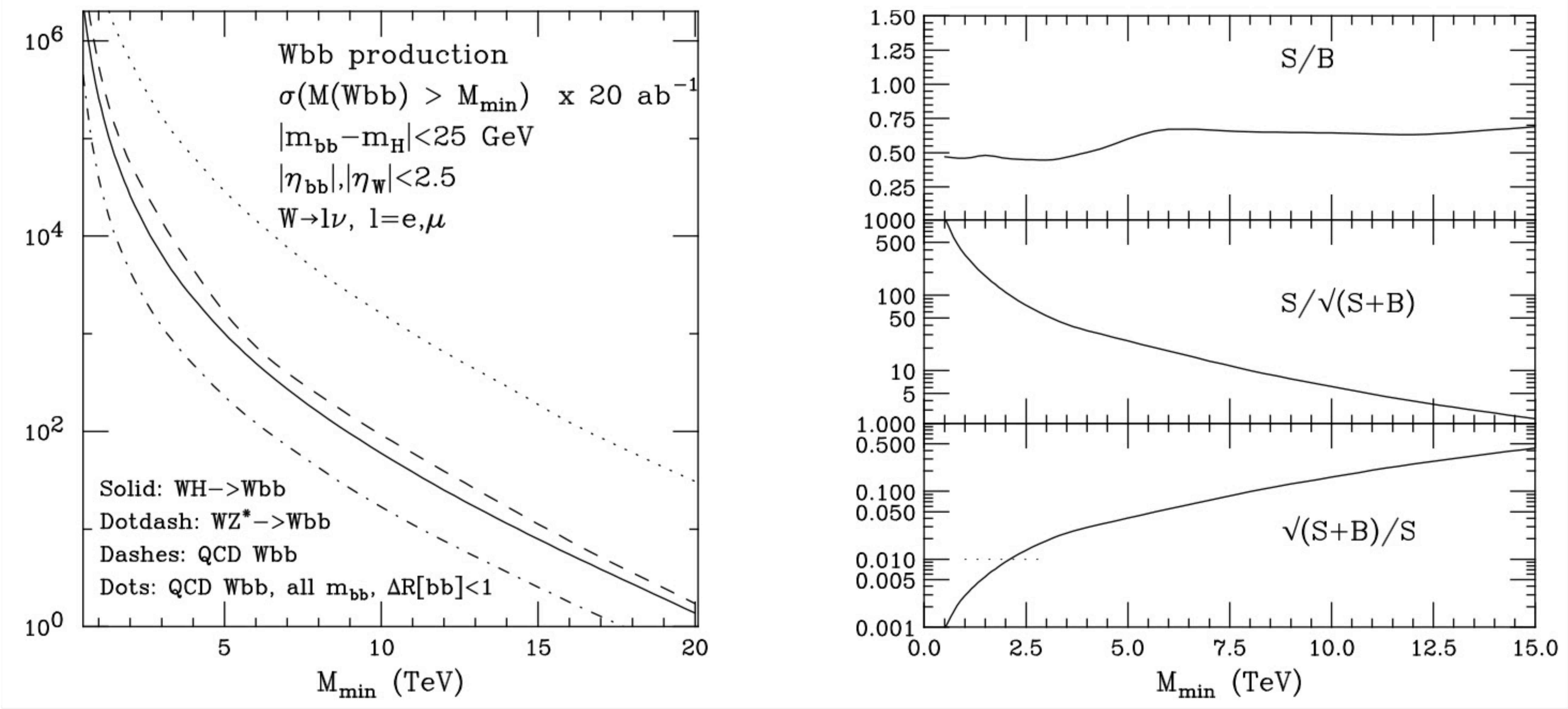
gg→H→4 *lept's* at large p_T



- Statistics sufficient for a per-mille level measurement of B(H→γγ)/B(H→4ℓ)
  - exptl systematics??
- Use precise B(H→4ℓ) from FCC-ee to achieve per-mille precision on B(H→γγ)

WH→Wbb at large M_{WH}



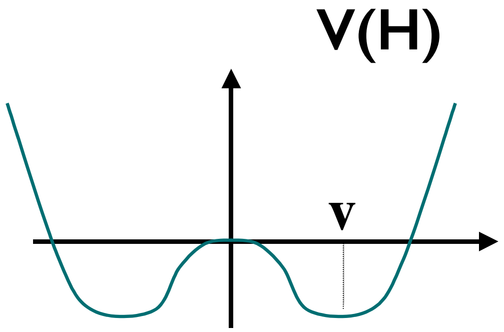


- Bg level greatly sensitive to bb mass resolution. Can be improved using jet substructure studies? => more work required
- Sensitivity to higher-dim ops in the VVH coupling ⇔ B(H→VV*)?
- Systematics on slope of M_{HV} ? (For EFT constraints don't need absolute rate)

Higgs selfcouplings

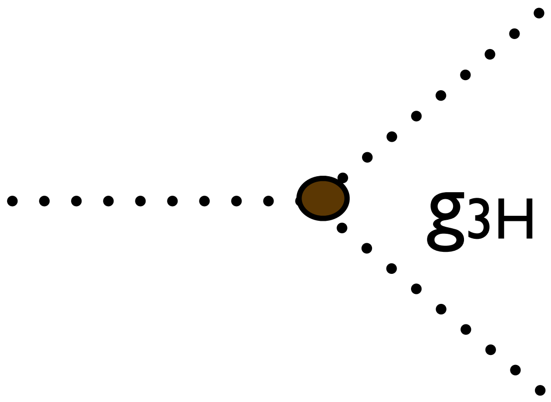
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

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

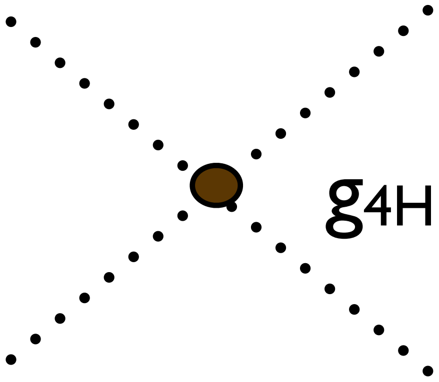


$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \frac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



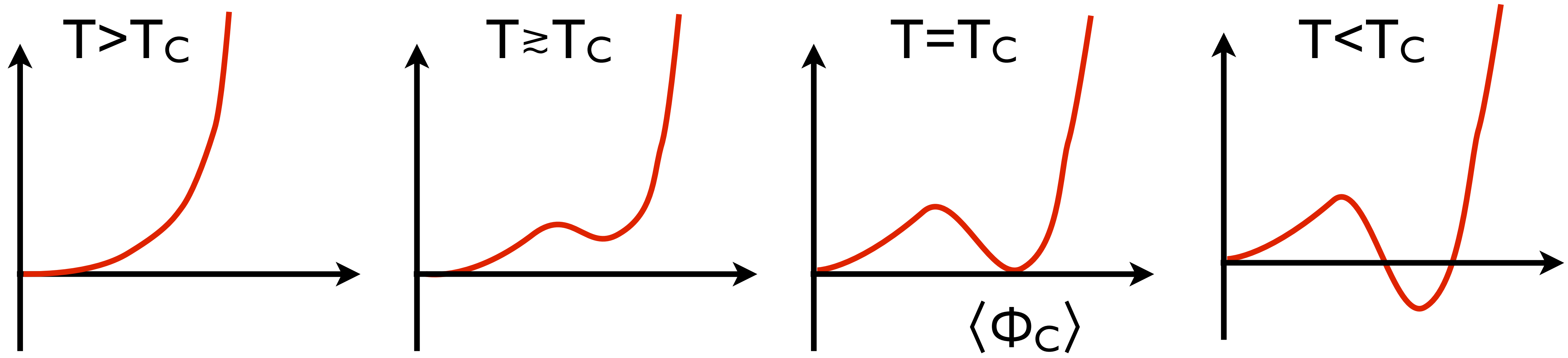
$g_{3H} \Rightarrow 6\lambda\,v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

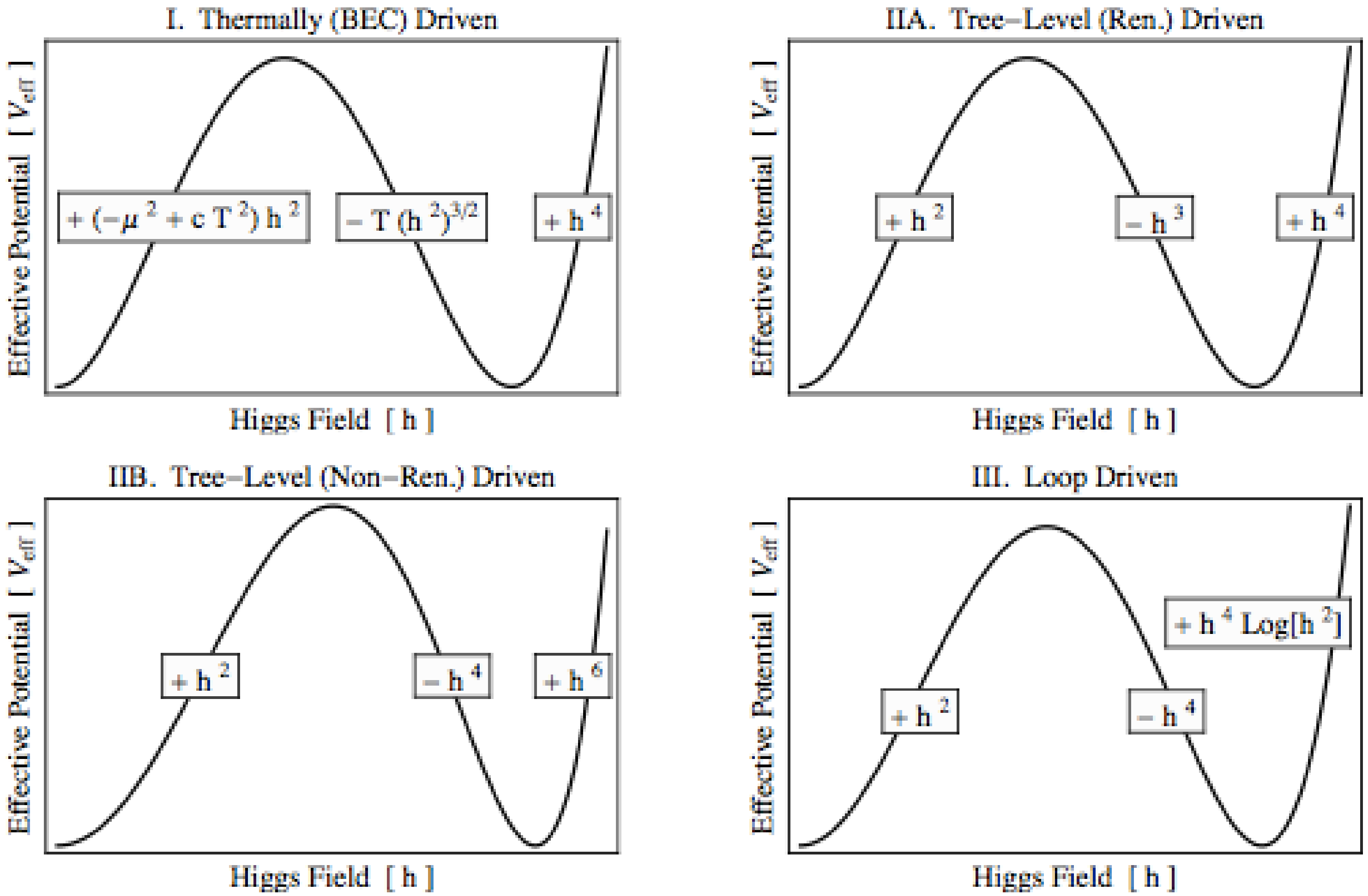
Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

The nature of the EW phase transition

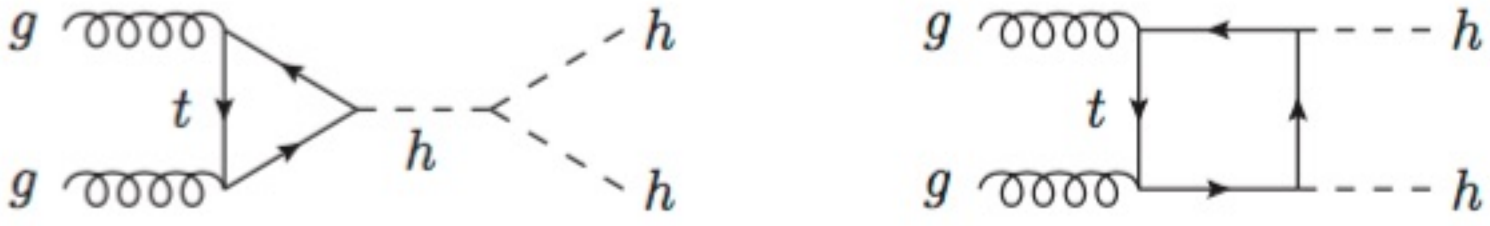


Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

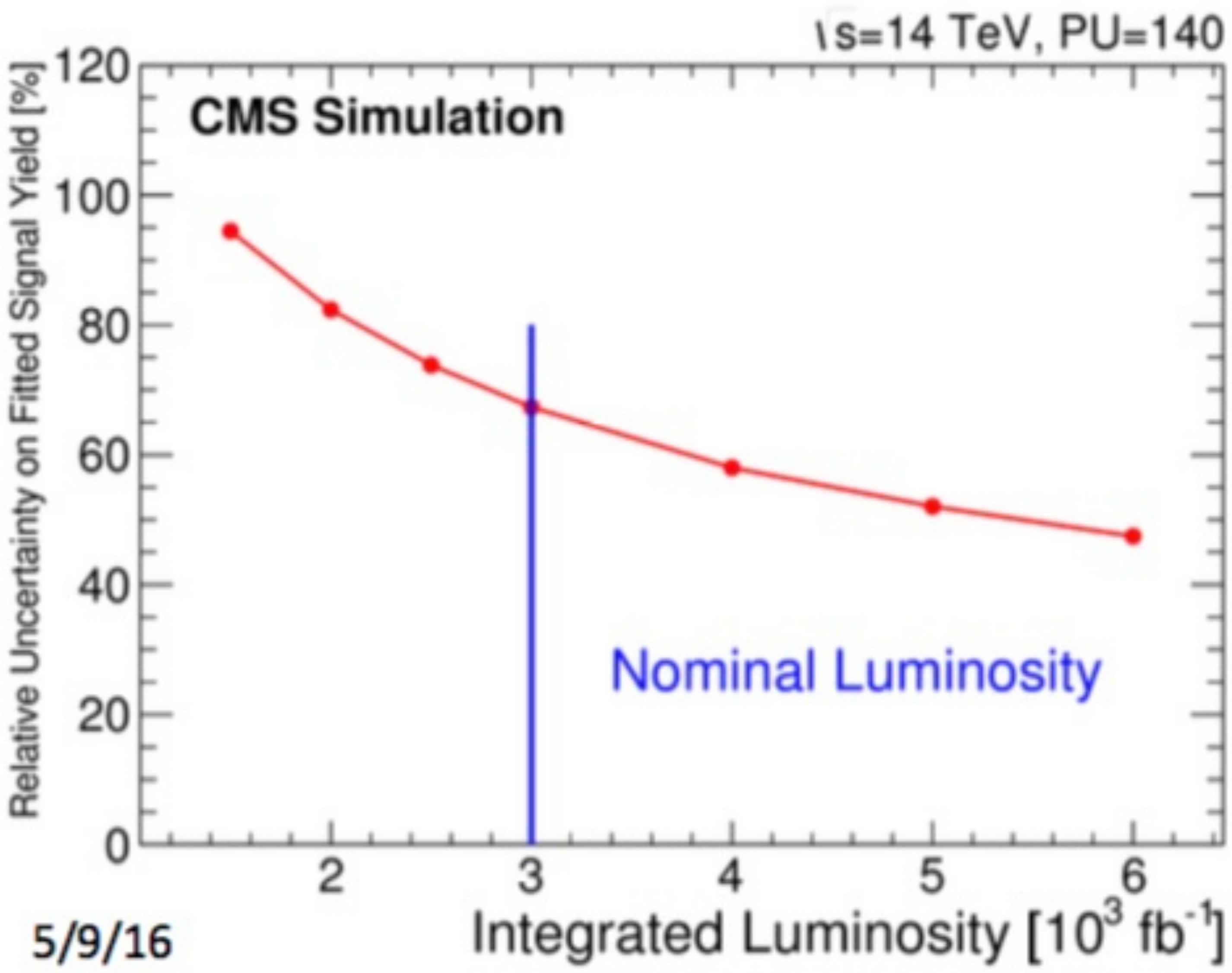
In the SM this requires $m_H \lesssim 80$ GeV ⇒ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible



Higgs pair production, H self-coupling



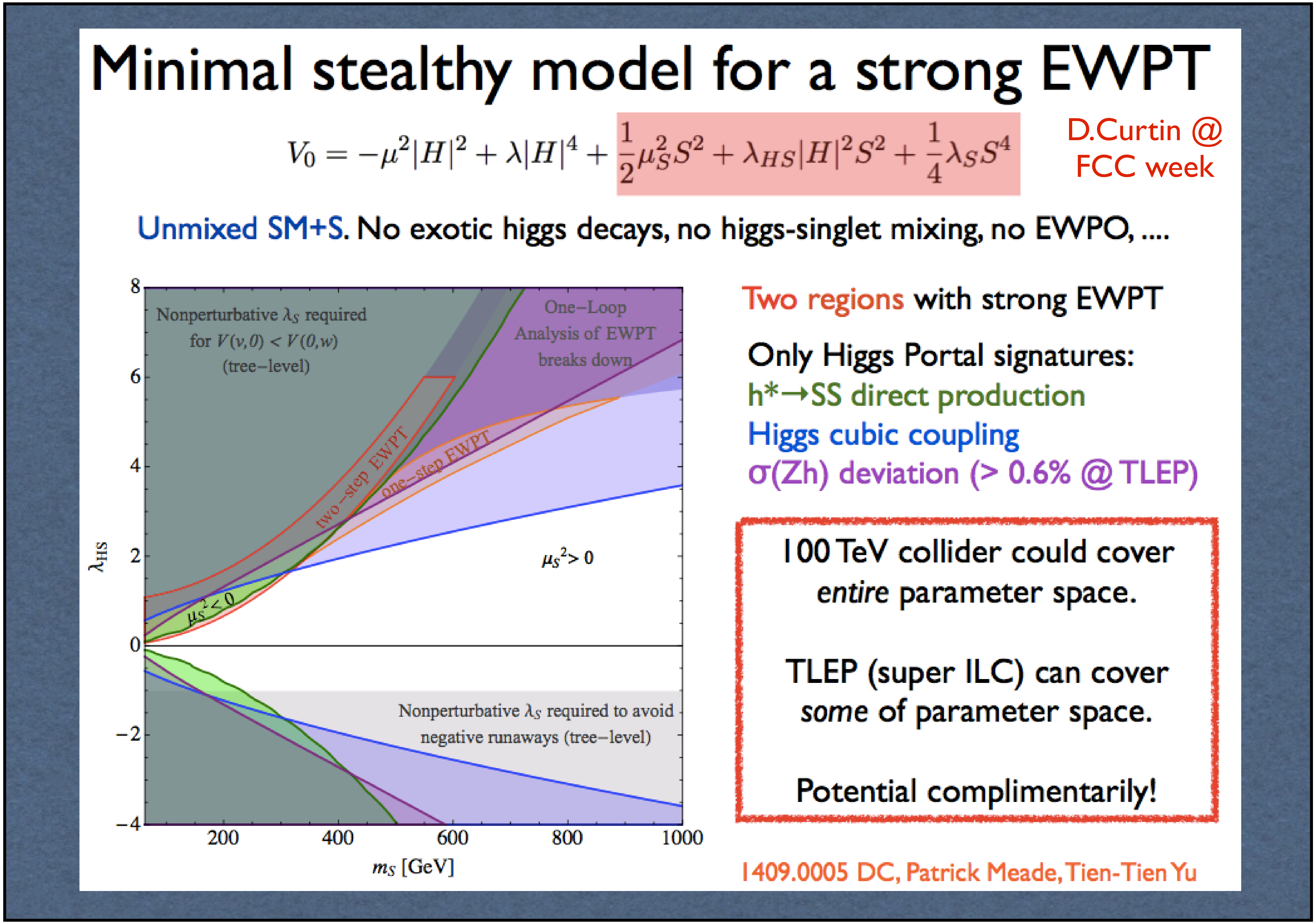
HL-LHC



5/9/16

Only HH→bbγγ
More channels being studied
Possible reach for [$3ab^{-1}$ x 2expts] ~ 30% ?

==> <5% @ FCC-hh
(details in the Report)



Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

D.Curtin @ FCC week

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...

Two regions with strong EWPT

Only Higgs Portal signatures:
h*→SS direct production
Higgs cubic coupling
σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

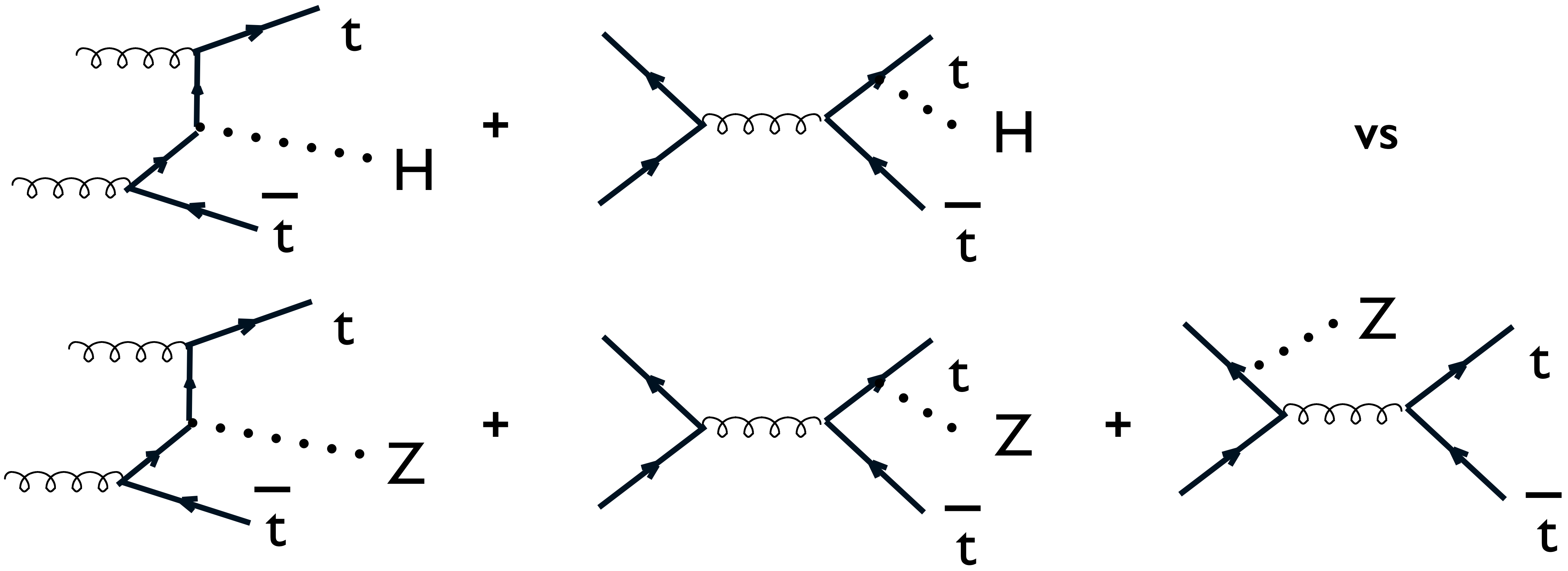
Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

⇒ Appearance of first "**no-lose**" arguments for classes of compelling scenarios of new physics

Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:

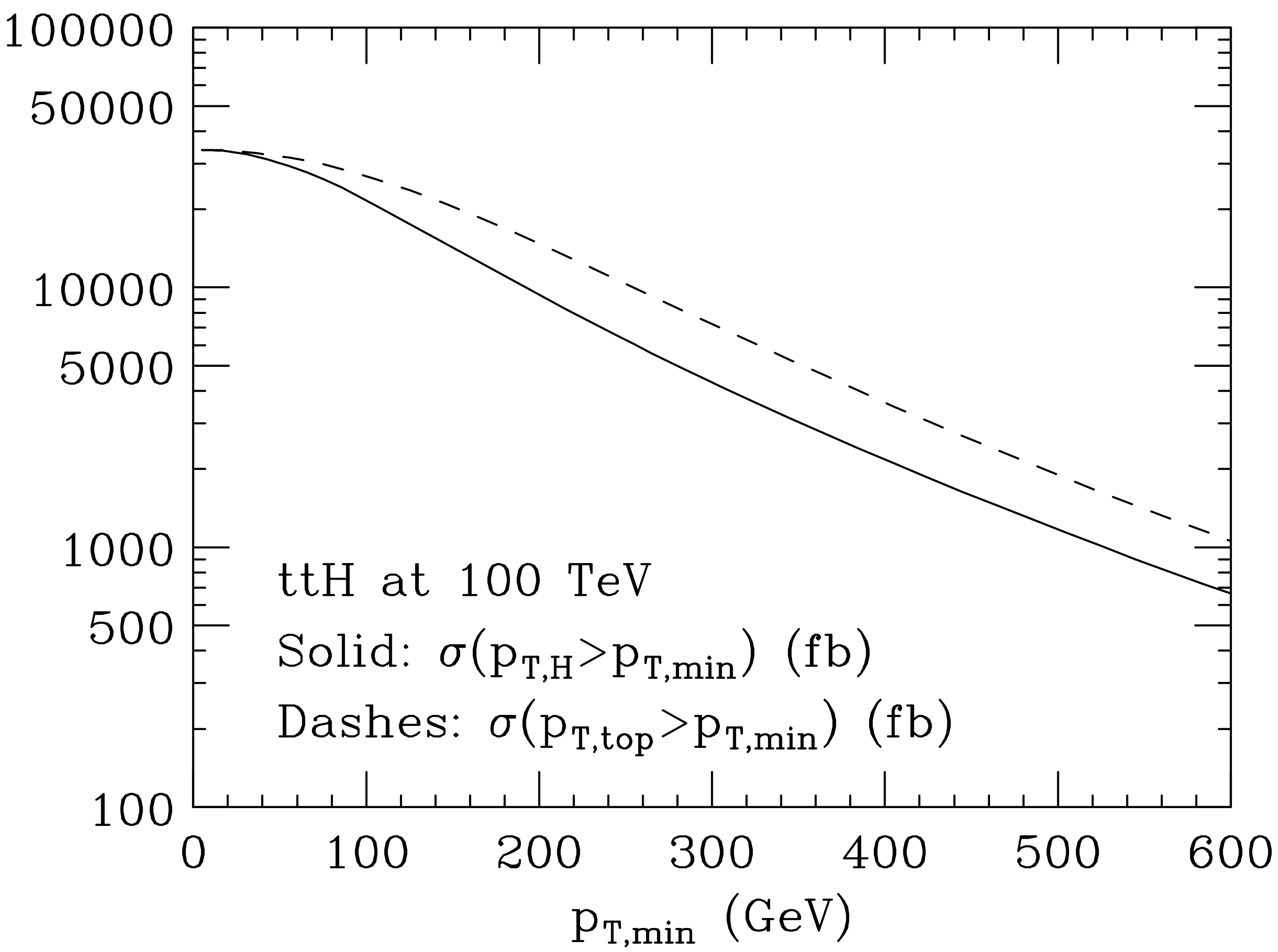
  - o correlated QCD corrections, correlated scale dependence
  - o correlated α_S systematics

- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:

  - o correlated PDF systematics
  - o correlated m_{top} systematics

For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

arXiv:1507.08169



$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

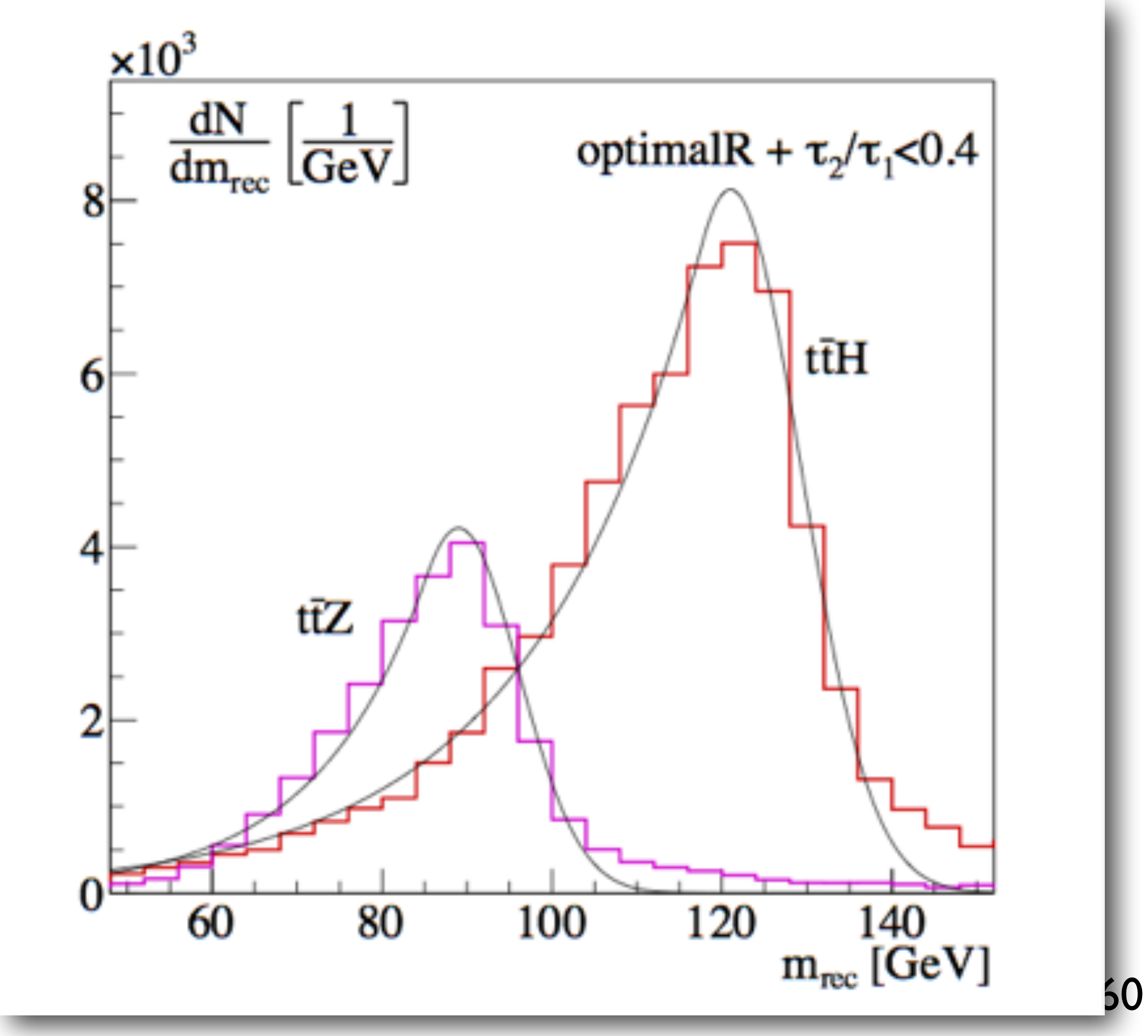
Events/20ab^{-1} , with tt→$\ell\nu$+jets

⇒ huge rates, exploit boosted topologies

Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

- δy_t (stat + syst $_{TH}$) ~ 1%

- great potential to reduce to similar levels $\delta_{\text{exp syst}}$
- consider other decay modes, e.g. 2l2nu



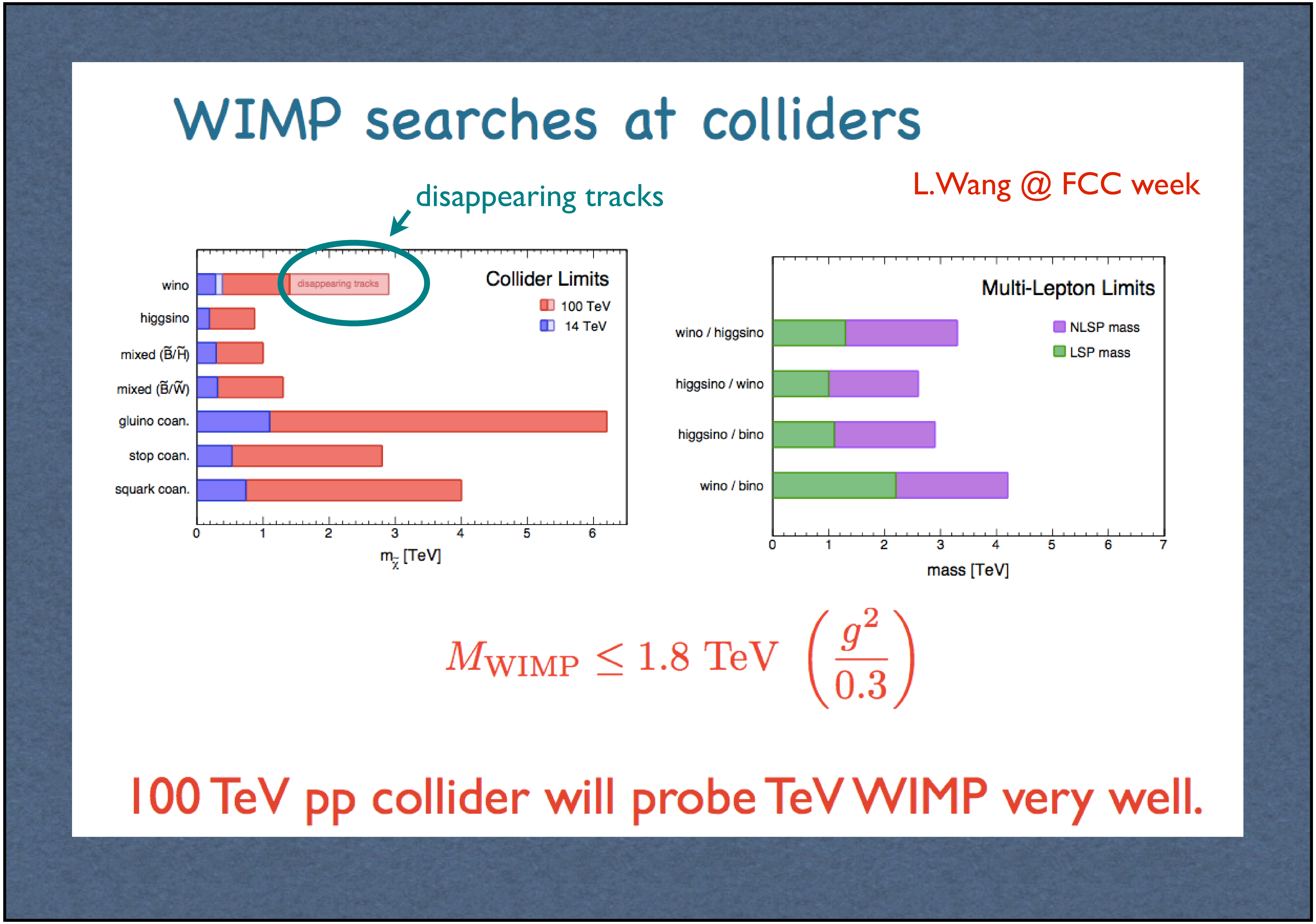
Summary of Higgs precision reach at FCC-hh

- (sub)-% precision in ratios of BRs to WW, ZZ, γγ, γZ
- ~% level for y_{top} from ttH and for H->μμ
- ≲5% precision for SM H selfcoupling λ

Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- We would like to understand whether a future collider can answer more specific questions, such as:
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

Towards no-lose arguments for some Dark Matter scenarios:



WIMP searches at colliders

L.Wang @ FCC week

disappearing tracks

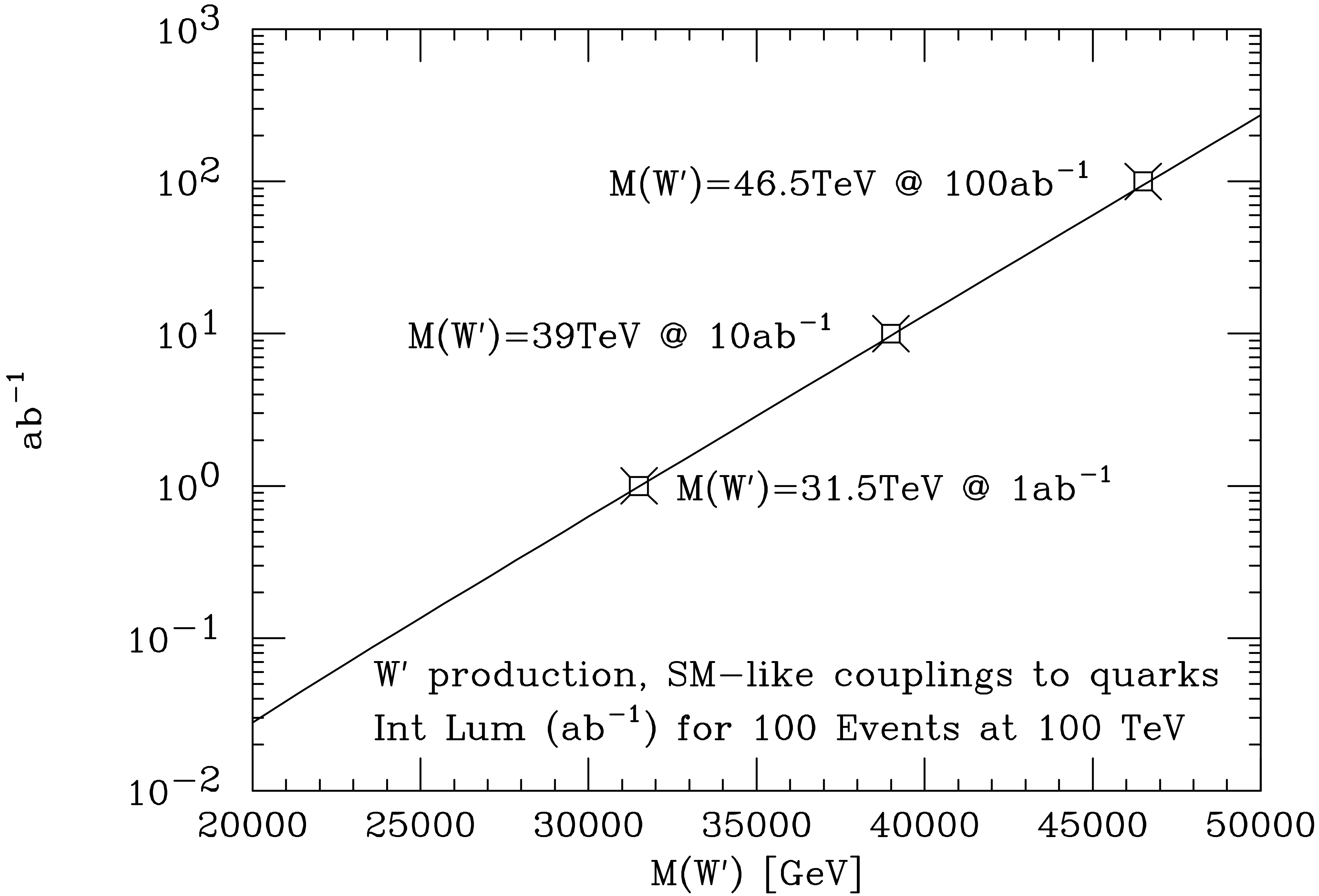
$$M_{\rm WIMP} \le 1.8\ {\rm TeV} \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

New gauge bosons discovery reach

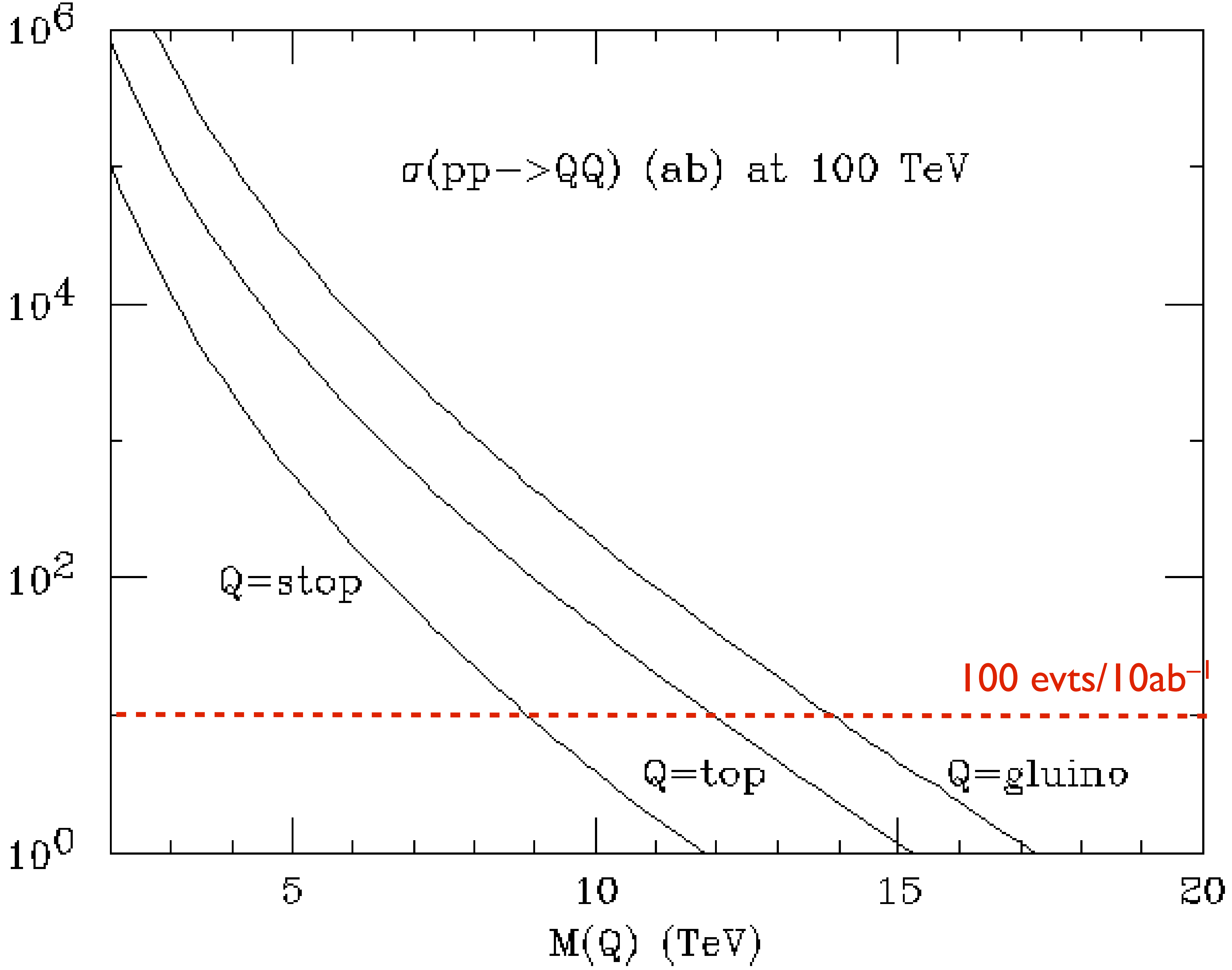
Example: **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}\, BR_{lept} \sim 0.1 \times \sigma_{W'}\, BR_{lept}$, ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

Discovery reach for pair production of strongly-interacting particles



Top quark production

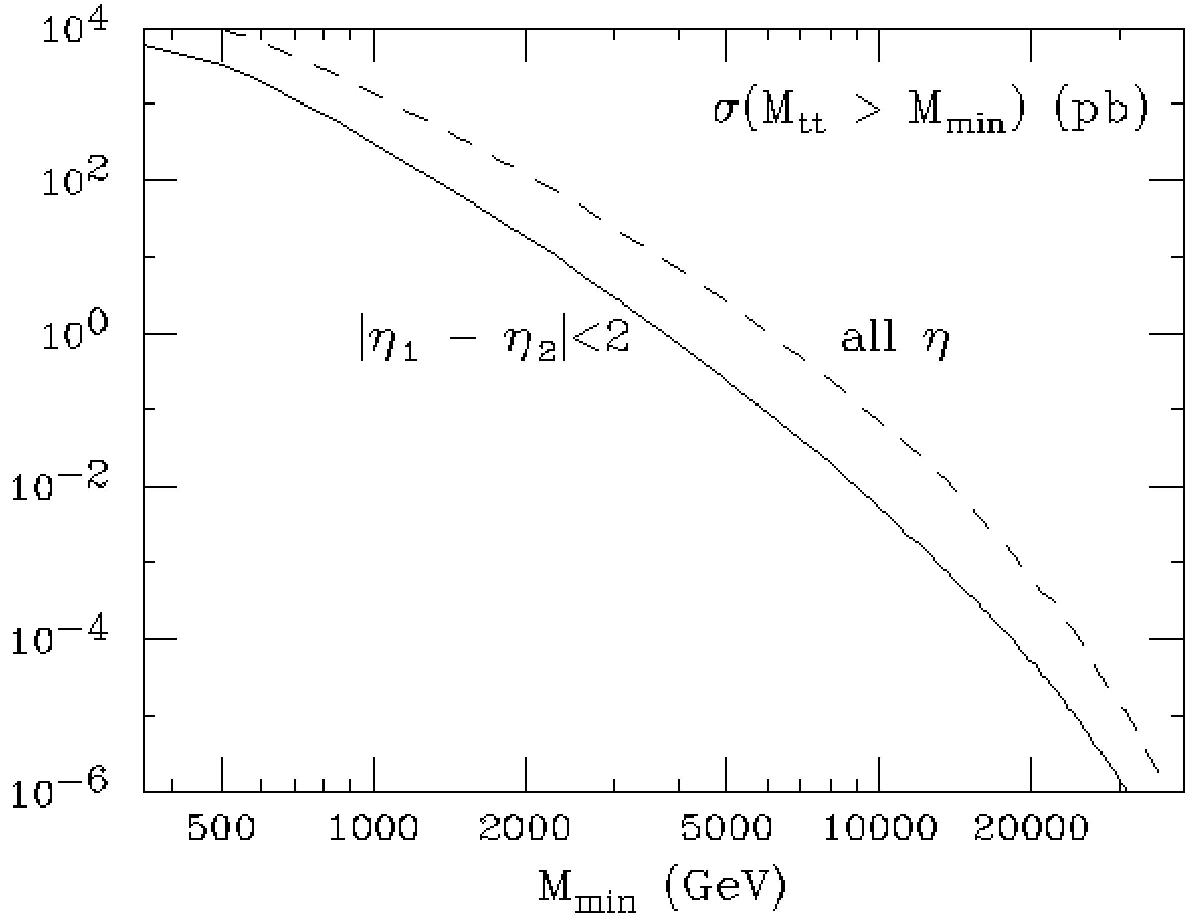
PDF	σ(nb)	δ_{scale}(nb)	(%)	δ_{PDF}(nb)	(%)
CT14	34.692	$+1.000$ -1.649	$(+2.9\%)$ (-4.7%)	$+0.660$ -0.650	$(+1.9\%)$ (-1.9%)
NNPDF3.0	34.810	$+1.002$ -1.653	$(+2.9\%)$ (-4.7%)	$+1.092$ -1.311	$(+3.1\%)$ (-3.8%)
PDF4LHC15	34.733	$+1.001$ -1.650	$(+2.9\%)$ (-4.7%)	± 0.590	$(\pm 1.7\%)$

$\sigma_{\text{tot}}(100\text{ TeV}) \sim 35 \times \sigma_{\text{tot}}(14\text{ TeV})$

- $\Rightarrow$ about 10^{12} top quarks produced in 20 ab^{-1}
  - rare and forbidden top decays
  - 10^{12} fully inclusive W decays, triggerable by "the other W"
    - rare and forbidden W decays
    - $3\ 10^{11}$ $W \to$ charm decays
    - 10^{11} $W \to$ tau decays (*)
  - 10^{12} fully charge-tagged b hadrons

(*) NB: From LEP2 $BR(W\to\tau) / BR(W\to e/\mu) \sim 1.066 \pm 0.025$ => ~ 2.5 σ off ….

Inclusive top quark production



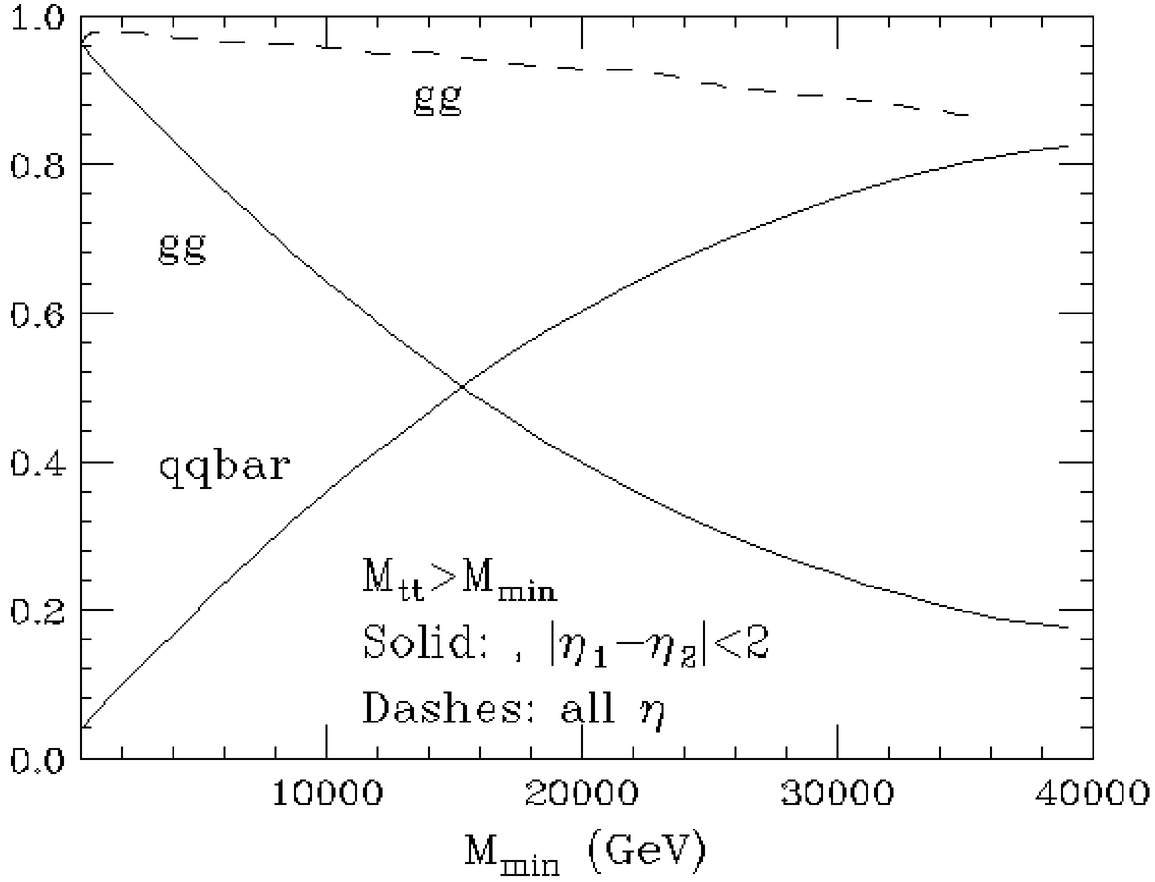
Ex: integrated rates as a function of t-tbar invariant mass for centrally (inclusive) produced tops

Statistics out to over 30 TeV with 10ab^{-1}
Inclusive rate ~ 10 times larger at highest mass

Ex: gg initial state content for central (vs inclusive) t-tbar pairs, vs M(tt)

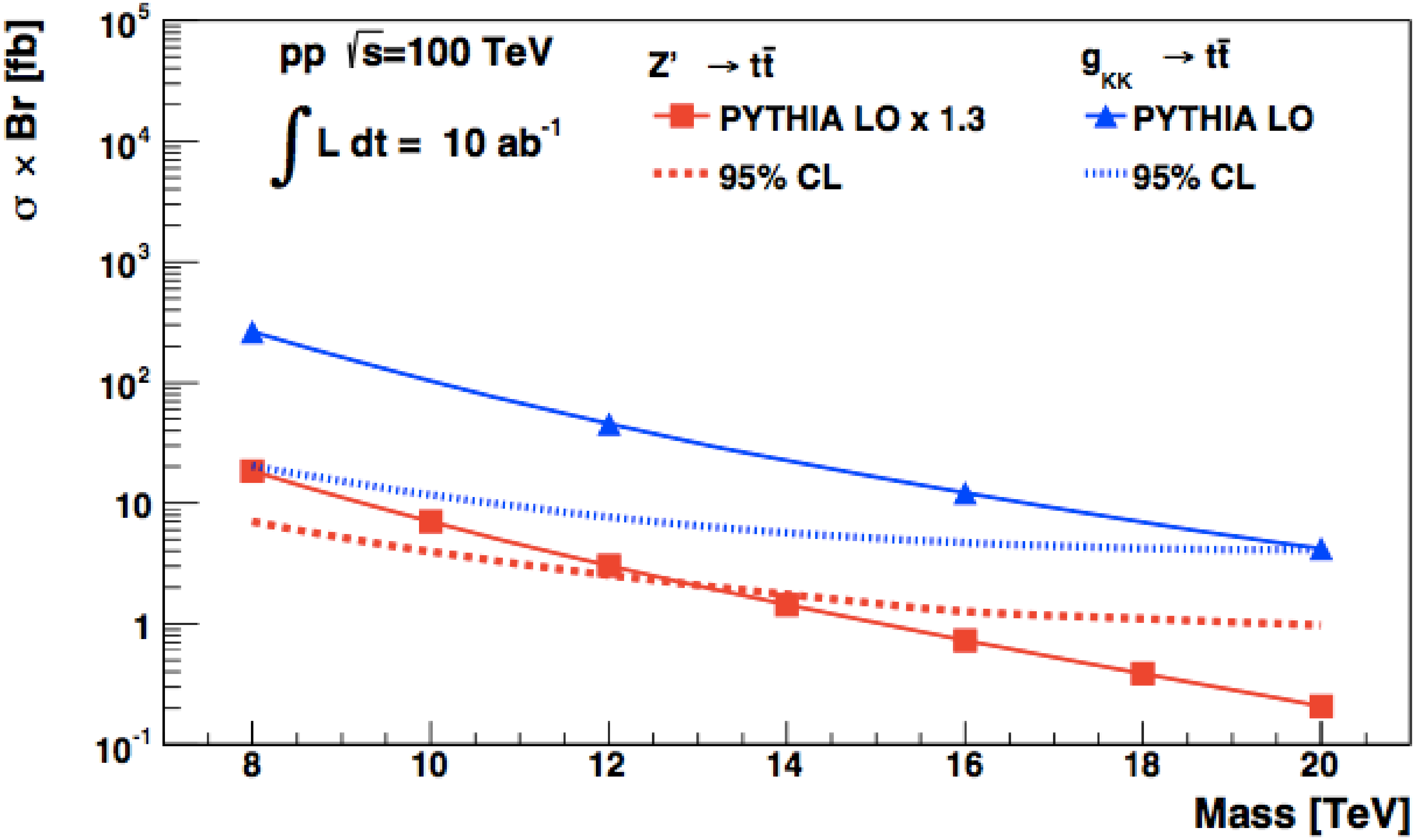
In central production, dominated by gg up to ~ 15 TeV. Still 20% gg at the kinematic edge of ~ 30 TeV

For inclusive prodution, >90% gg!



Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



Final remarks

- The study of the SM will not be complete until we exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open. The full LHC programme, and a following FCC-like facility, will be required to complete this exploration
- The BSM-search programme at the LHC is more than a 1-experiment/ 1-measurement deal. It features hundreds of stand-alone individual measurements of separate probes, it's the most complete and reaching enterprise available today and in the near future to explore in depth physics at the TeV scale with an immense discovery potential and still ample room for progress
- The BSM-search progamme relies on a complex and multidimensional programme of SM and QCD dynamics measurements, that will grow in parallel with the increase in luminosity and with the progress in the searches

Final remarks

- As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era
- Skepticism towards the ability to continue improving the theoretical precision and experimental systematics should not curtail the ambition to produce ever better Higgs measurements in the far future of hadron colliders, and probe its properties to (sub)percent precision at HL-LHC (FCC-hh): there are plenty of opportunities for new tackles that will emerge as we move along ….
- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches.