Theory Perspectives on the HL-LHC

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Gavin P. Salam (CERN)

ECFA High Luminosity LHC Experiments Workshop
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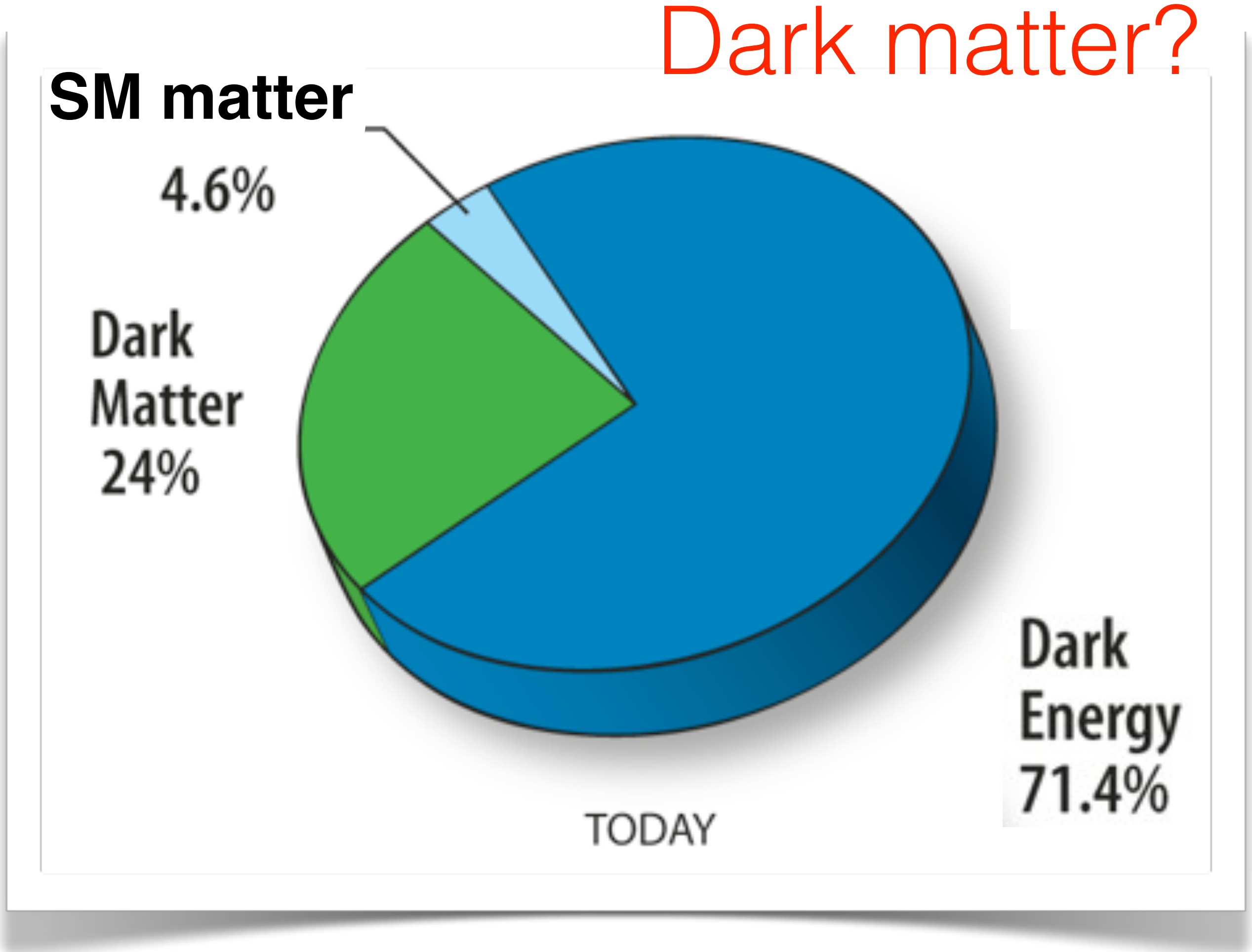
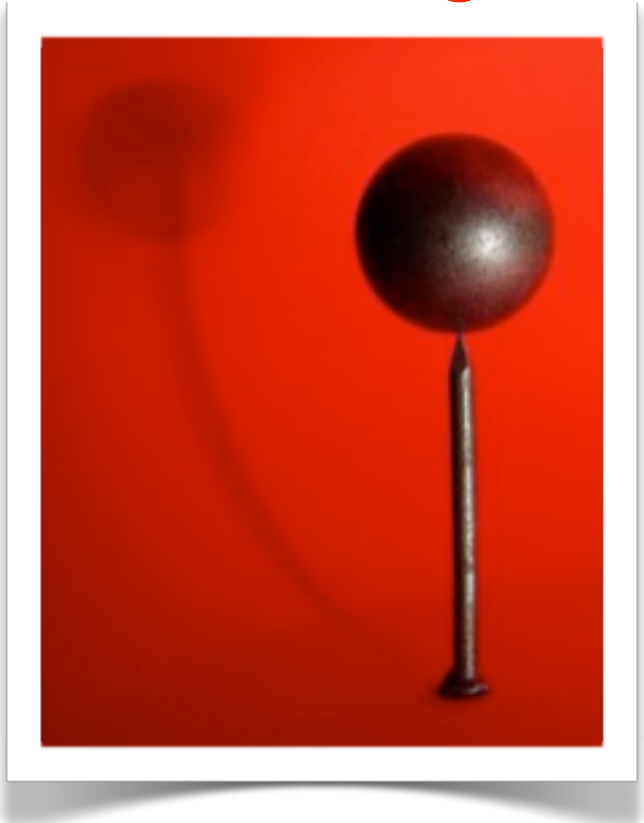
The SM is incomplete: big questions

Dark matter?

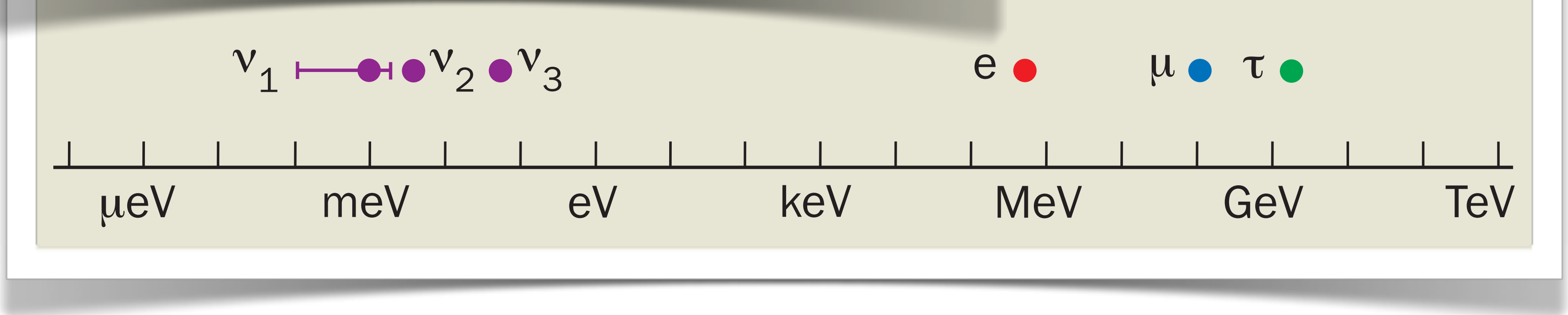


Fine-tuning?

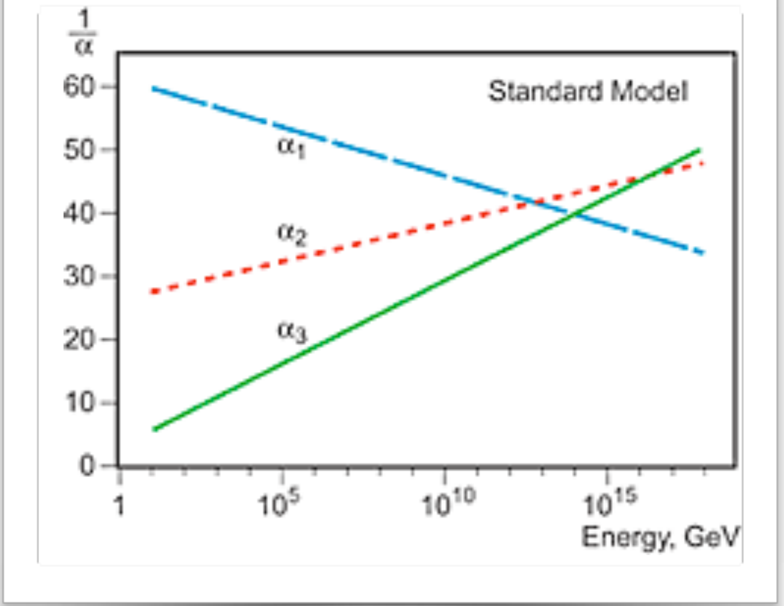


Origin of SM matter and flavor?

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007+0.004i \\ 10^{-6} & 0.007 & -0.04+0.0008i \\ 10^{-8}+10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



Unity of forces?



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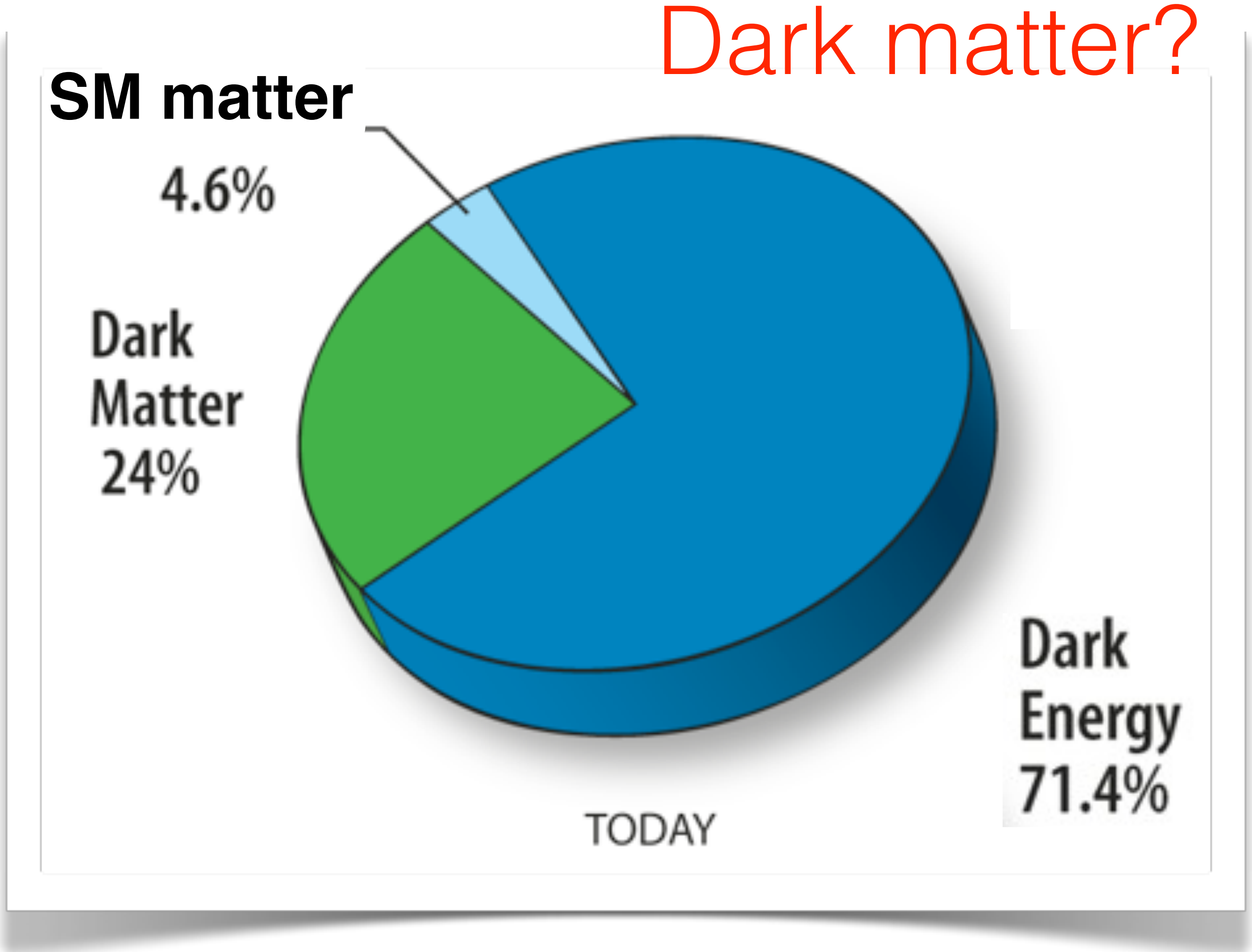

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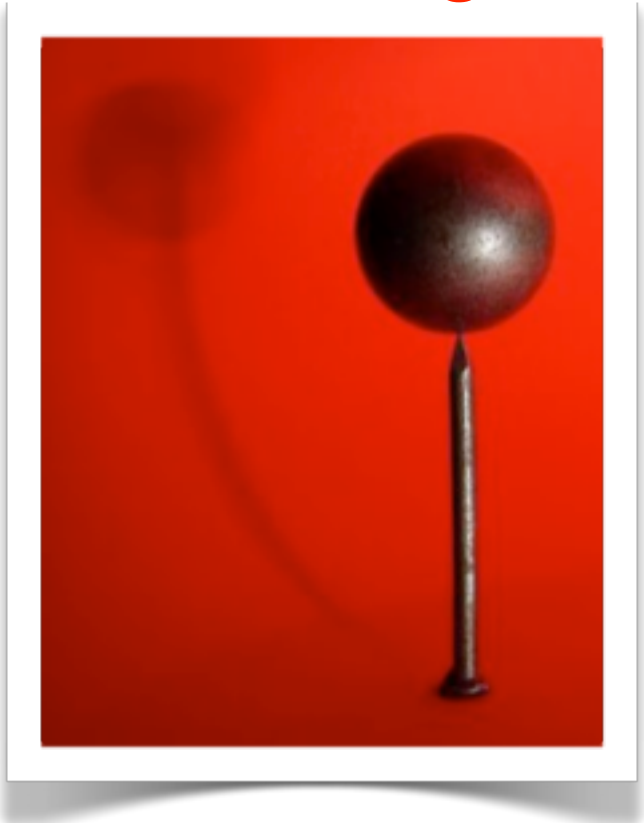

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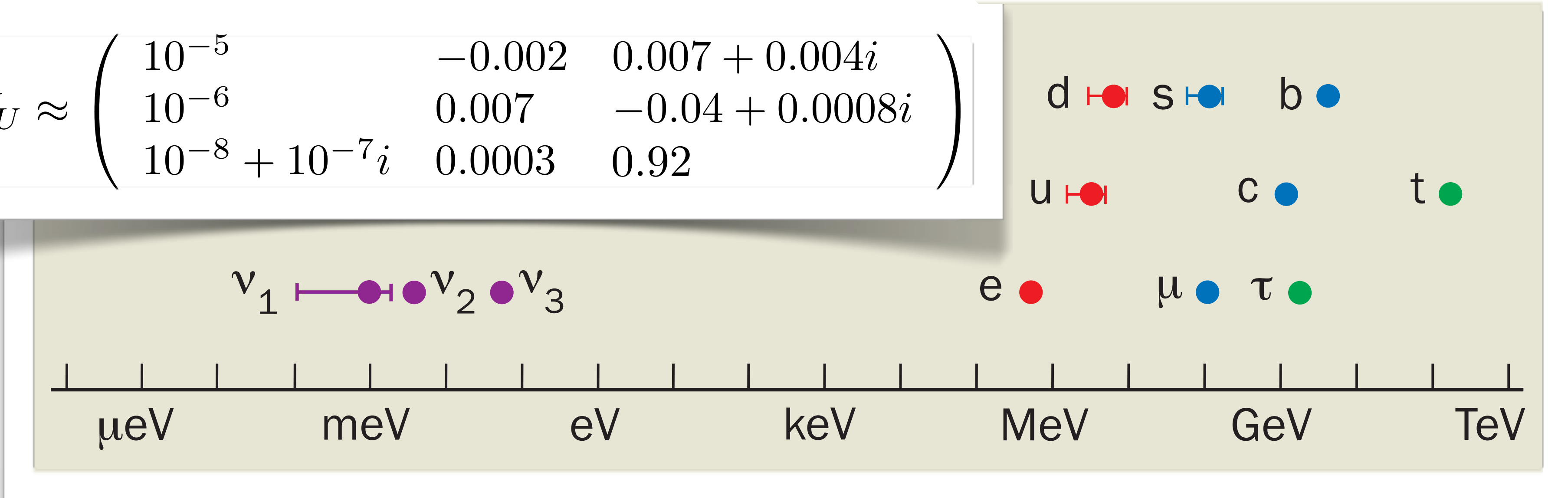

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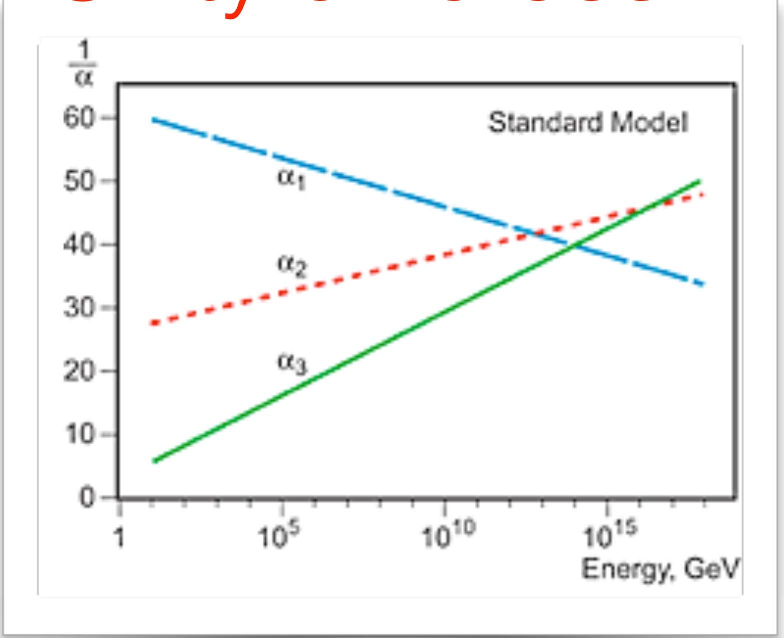
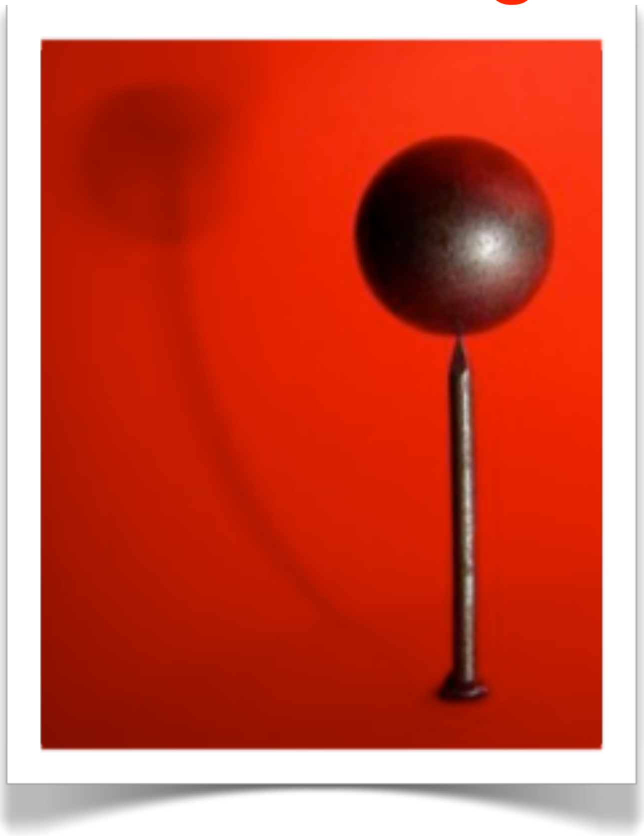


Motivation for new physics at the TeV scale

The SM alone suffers from destabilizing quantum fluctuations sensitive to the highest scales in nature (e.g. GUT, Planck scale).

Fine-tuning?



Given a fundamental theory at a high scale Λ, a light Higgs requires fine-tuning in the fundamental theory of order $(m_H/\Lambda)^2$.

Naturalness: absence of special conspiracies between phenomena occurring at very different length scales.

A strong motivation for new physics at TeV colliders. Most interesting theories offer solutions to open problems of the SM.

What are the theory motivations for HL-LHC?
I.e. what is 300 → 3000 fb^{-1} good for?

This is not a report from a working group (so far there is no TH WG), but rather our survey of some of the main points, including consultations with colleagues.

Outline

1. Higgs sector in SM & beyond

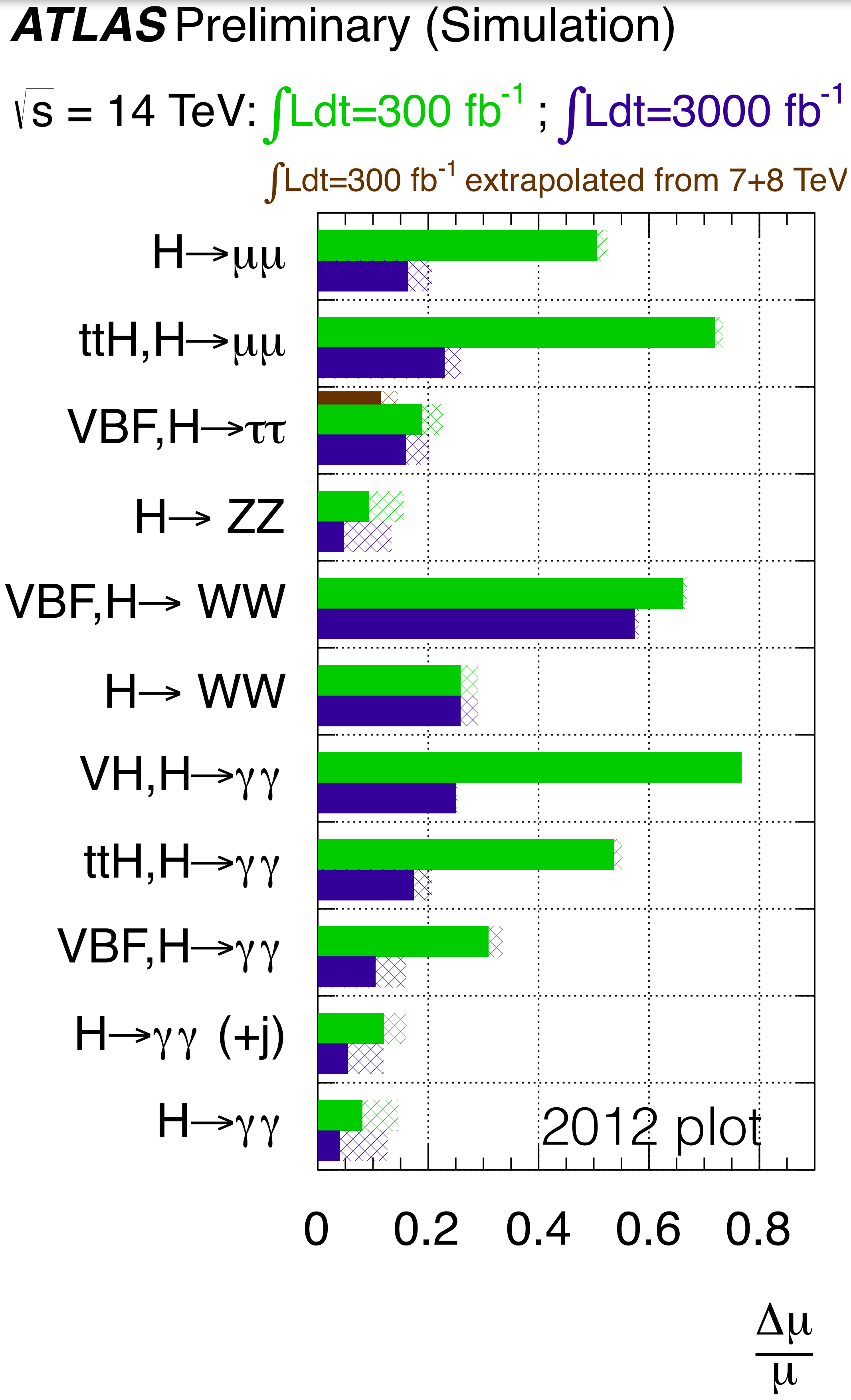
2. Direct searches for New Physics

3. SM sector, including theory prospects (e.g. for use in Higgs physics)

NB: given breadth of topics, references will be illustrative, not exhaustive

1. Higgs sector in SM & beyond

What does 14 TeV @3000fb^{-1} bring?



arXiv:1307.7135

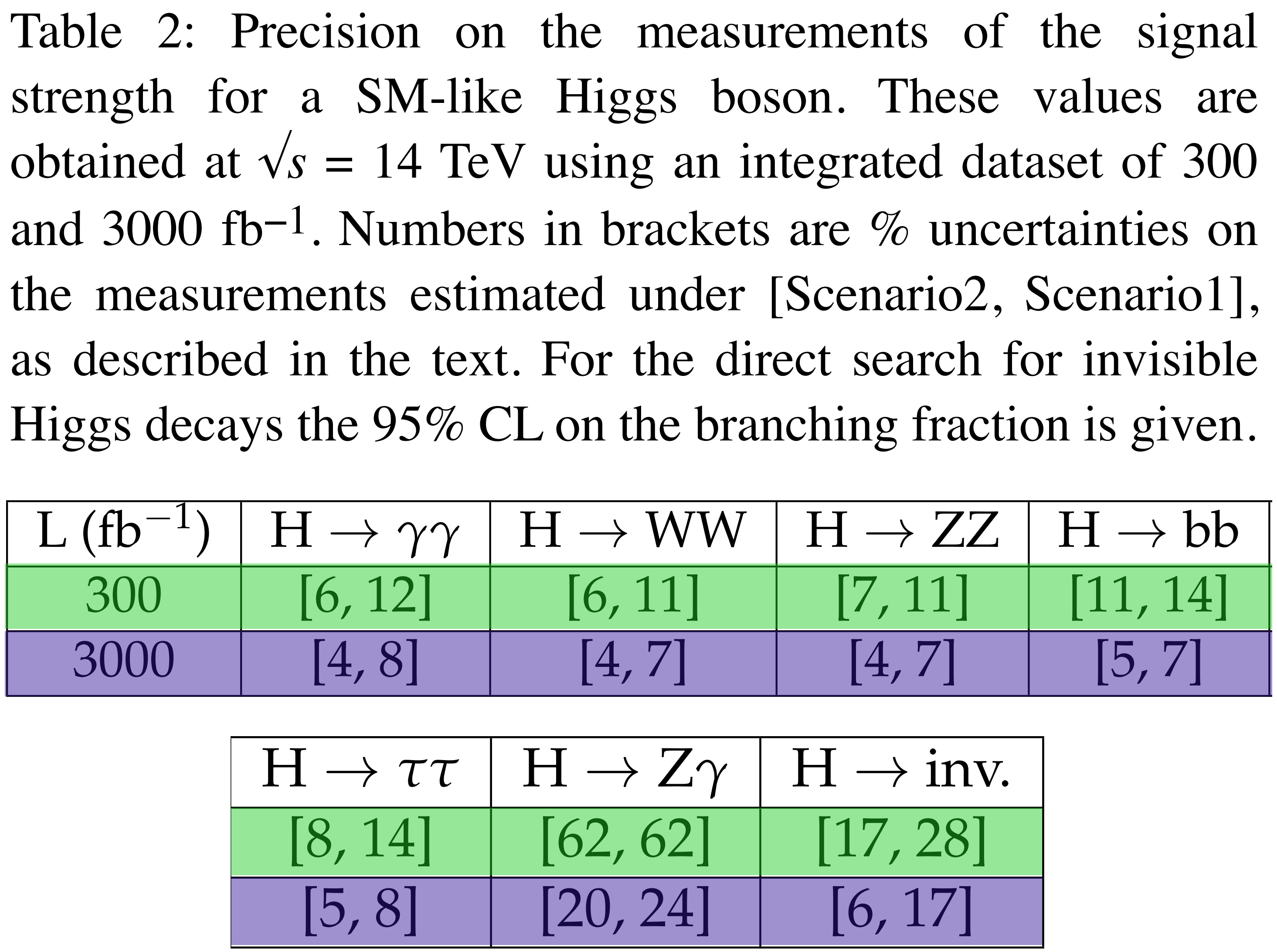


Table 2: Precision on the measurements of the signal strength for a SM-like Higgs boson. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 and 3000 fb^{-1}. Numbers in brackets are % uncertainties on the measurements estimated under [Scenario2, Scenario1], as described in the text. For the direct search for invisible Higgs decays the 95% CL on the branching fraction is given.

L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]

$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.
[8, 14]	[62, 62]	[17, 28]
[5, 8]	[20, 24]	[6, 17]

What does 14 TeV @3000fb^{-1} bring?

- Increased precision on existing channels
- Observation of rare decays $Z\gamma$, $\mu^+\mu^-$, cc
- Double Higgs production
- Longitudinal Vector-Boson Scattering

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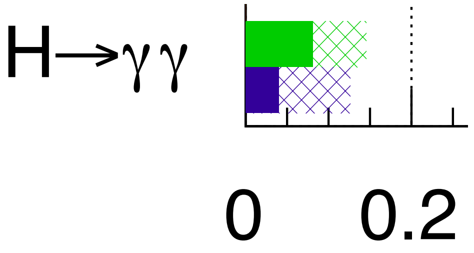

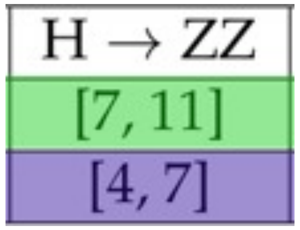

$H \to ZZ$
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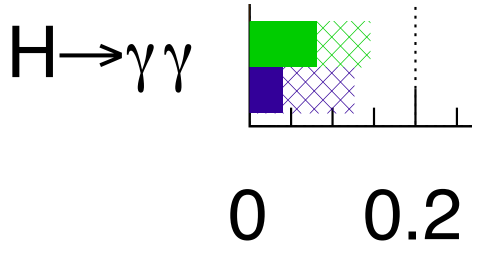

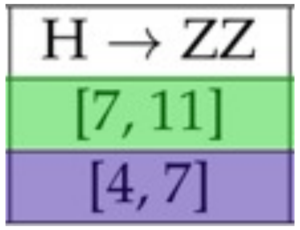

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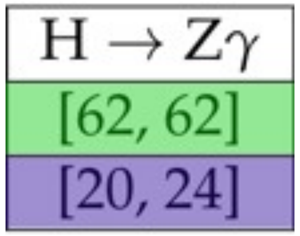

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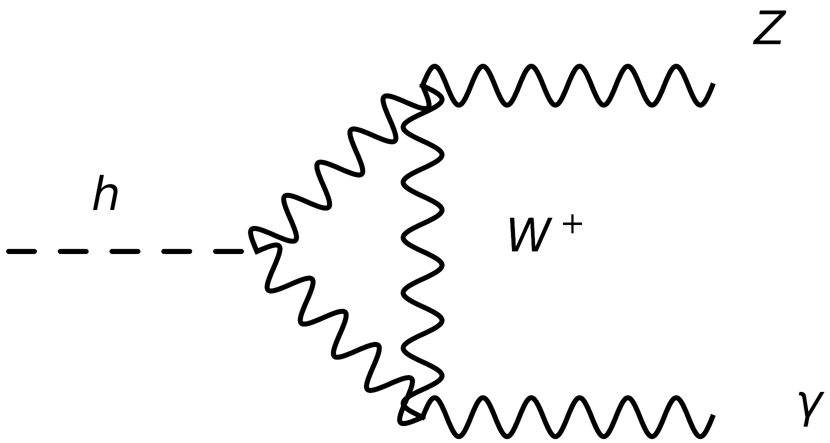
Why γZ is important

- γZ like γγ and gg loop induced, but sensitive to effects invisible in γγ and gg (because of chiral couplings)
- In composite Higgs: Not protected by Goldstone symmetry, large γZ while γγ and gg small

SM



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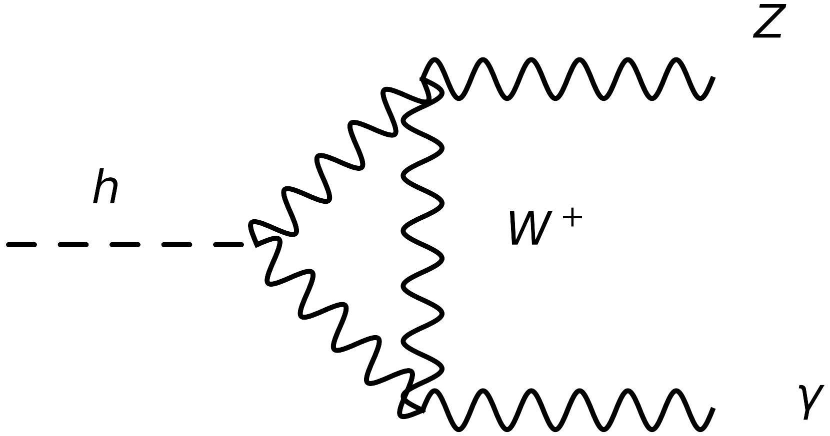
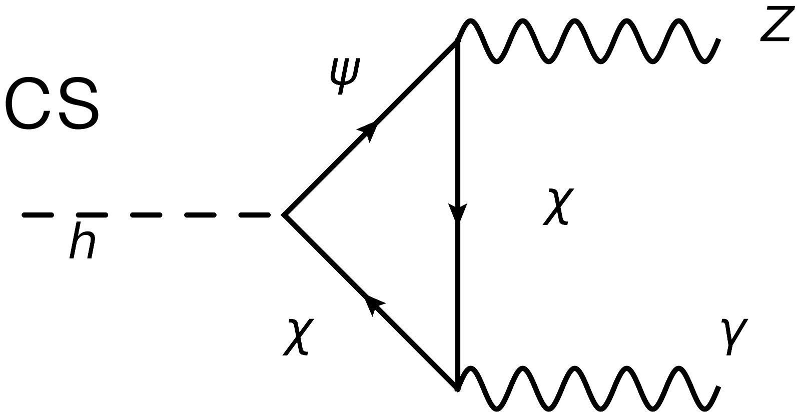


New physics



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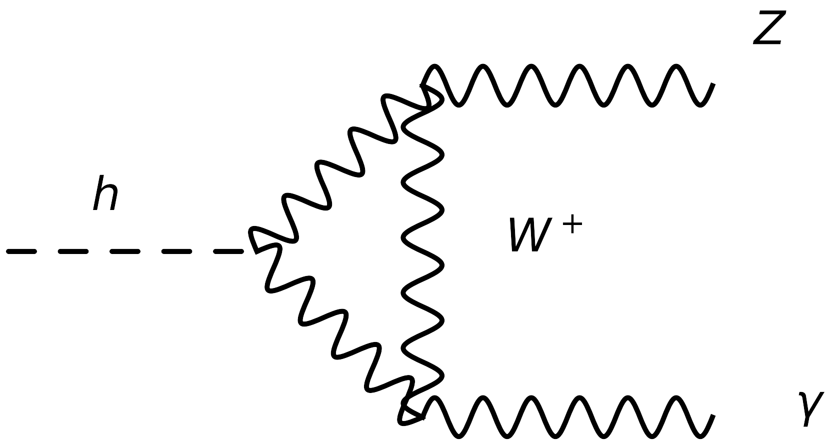

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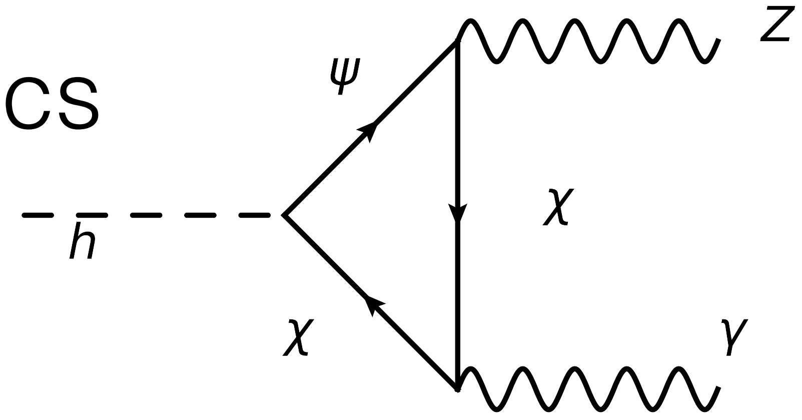
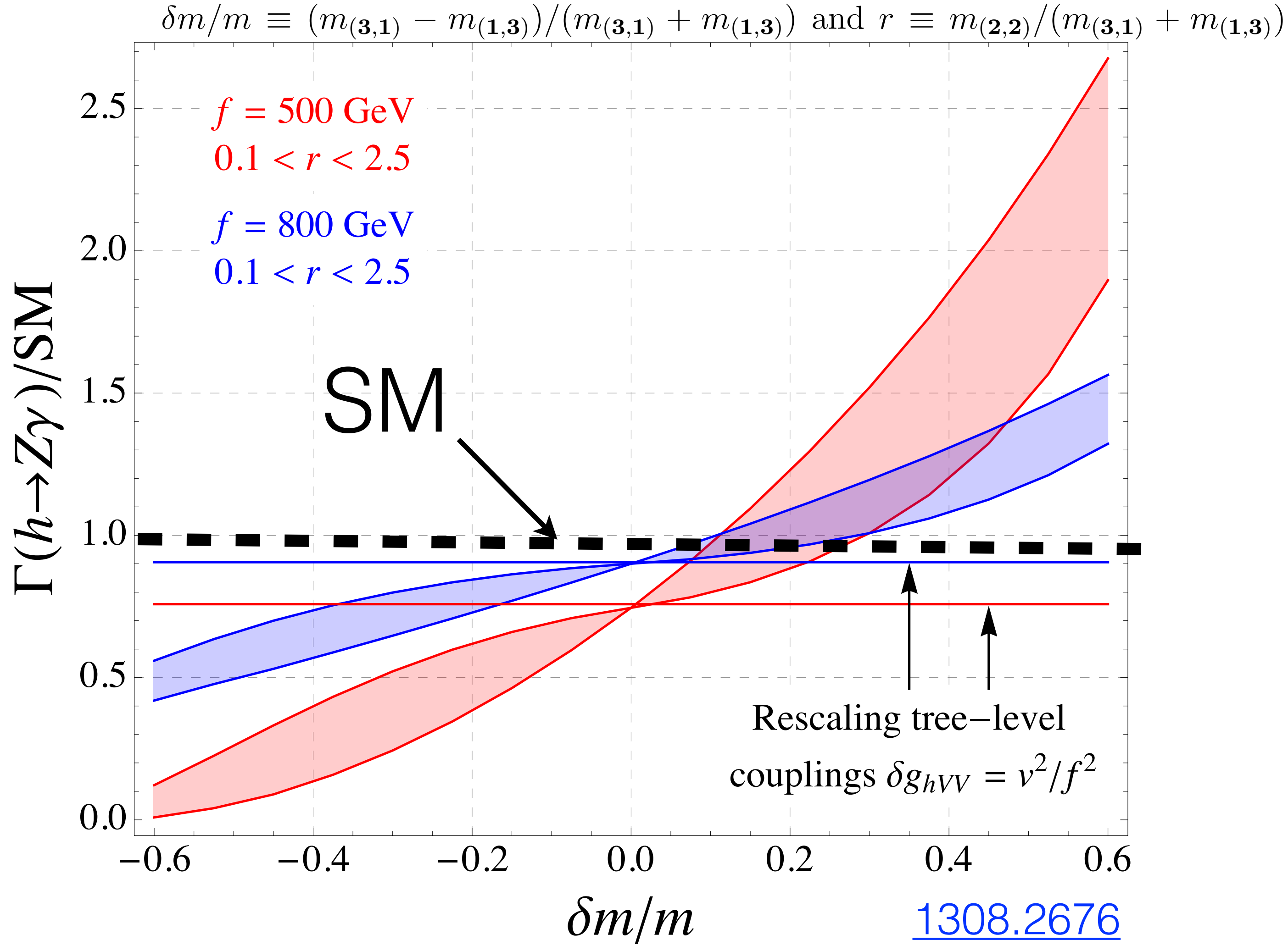




1308.2676

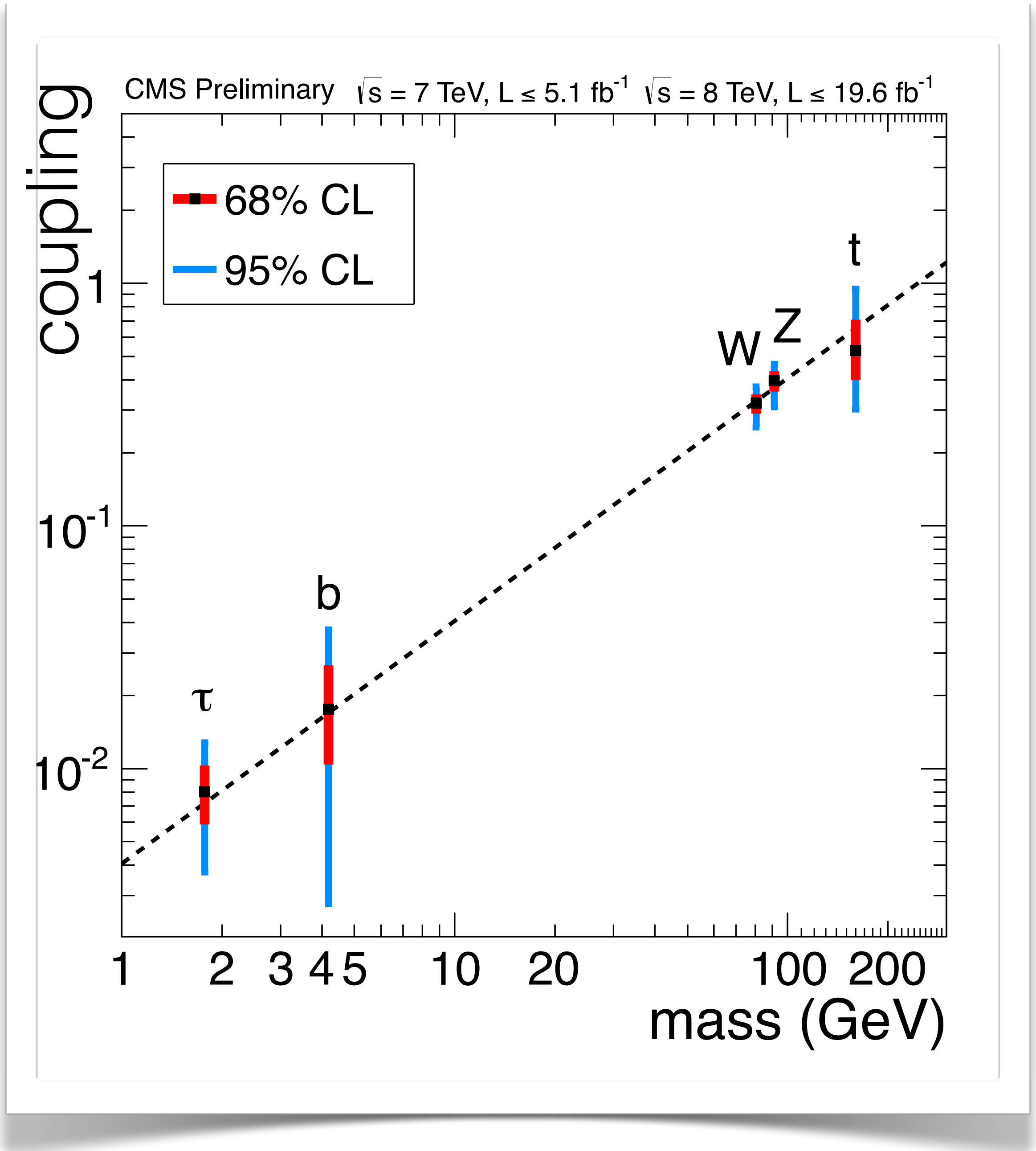
H → $\mu^+\mu^-$

- By LHC14@300, we'll have probed all 3rd generation fermion couplings to O(10–20%)

- H → $\mu^+\mu^-$ gives us access to 2nd lepton generation, i.e. is the mass-generation mechanism same for all generations, for quarks and leptons?

mass ∝ coupling to Higgs ?

$$Br(H \to \mu^+\mu^-)_{\rm SM} = 2.2 \cdot 10^{-4}$$



$H \to cc$

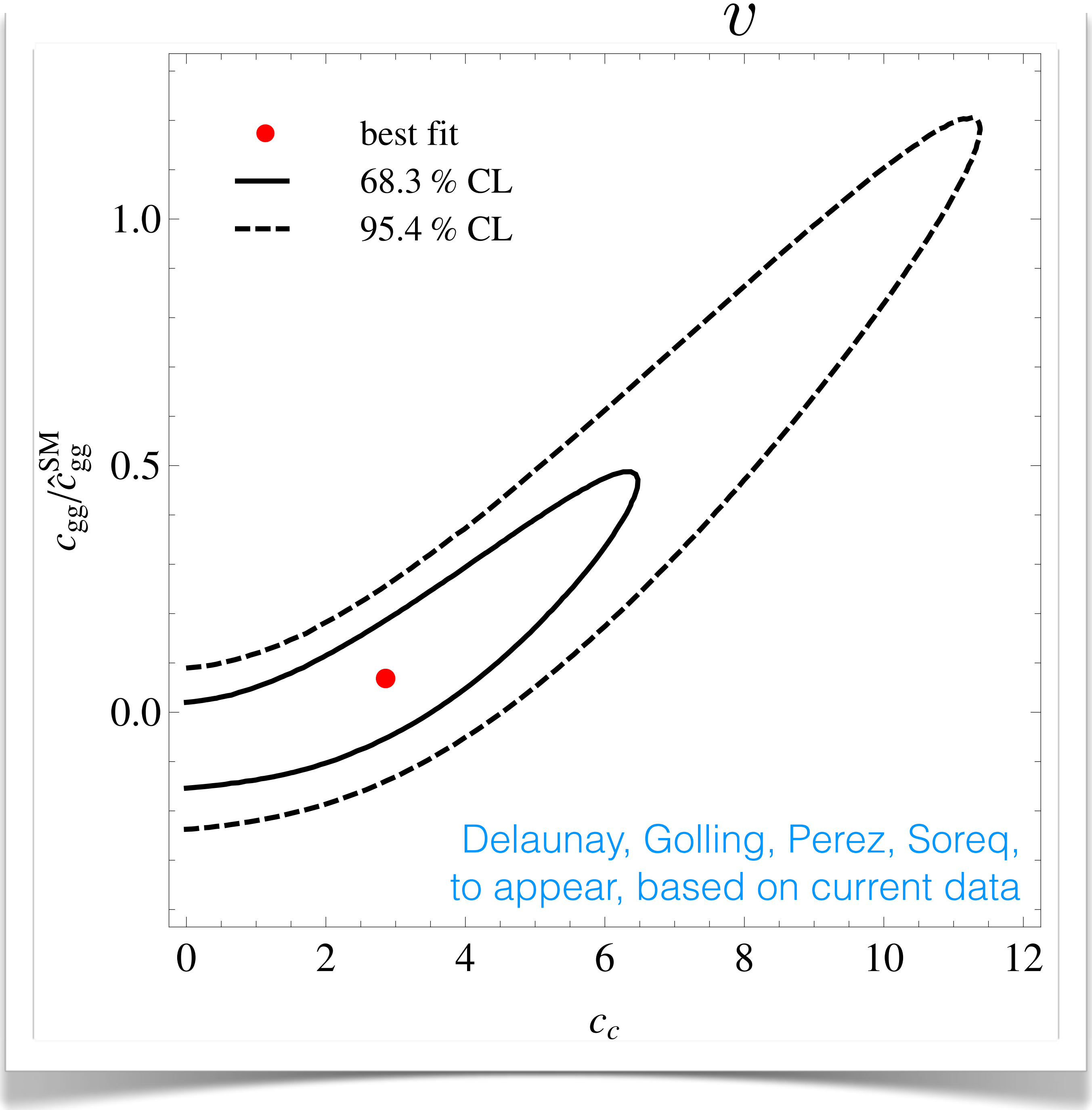
- Hcc coupling can still be 4-8 x SM

$$\mathcal{L} = c_c\, h\, \frac{m_c}{v} \bar{c}c + \ldots$$

- In composite Higgs

$$c_c \simeq 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\epsilon_c^2 \frac{g_\psi^2 v^2}{m_\psi^2}\right)$$

large for composite charm and light charm partners



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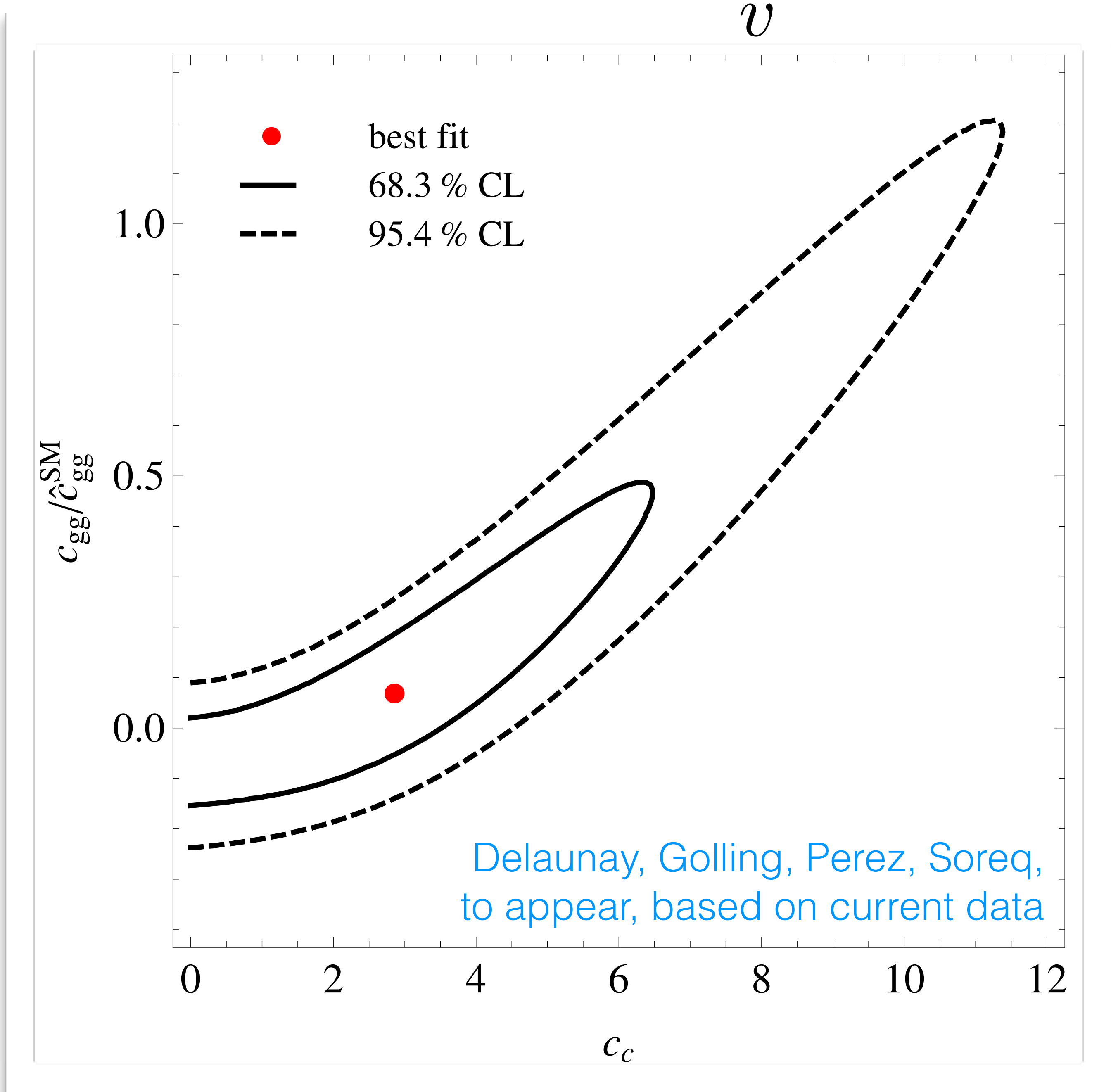

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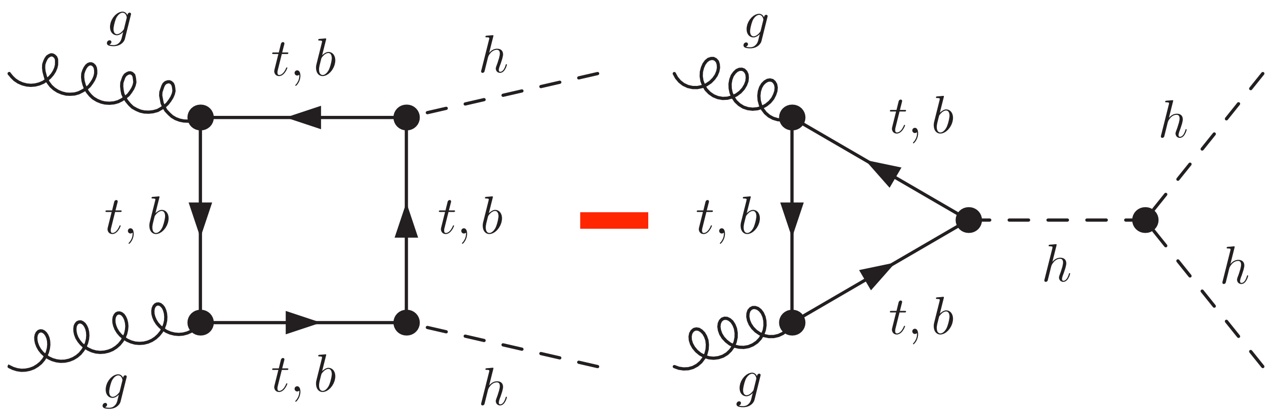
Measuring it?

Like H→bb, but with charm tagging?

Or via H→ J/ψ γ ? 1306.5770

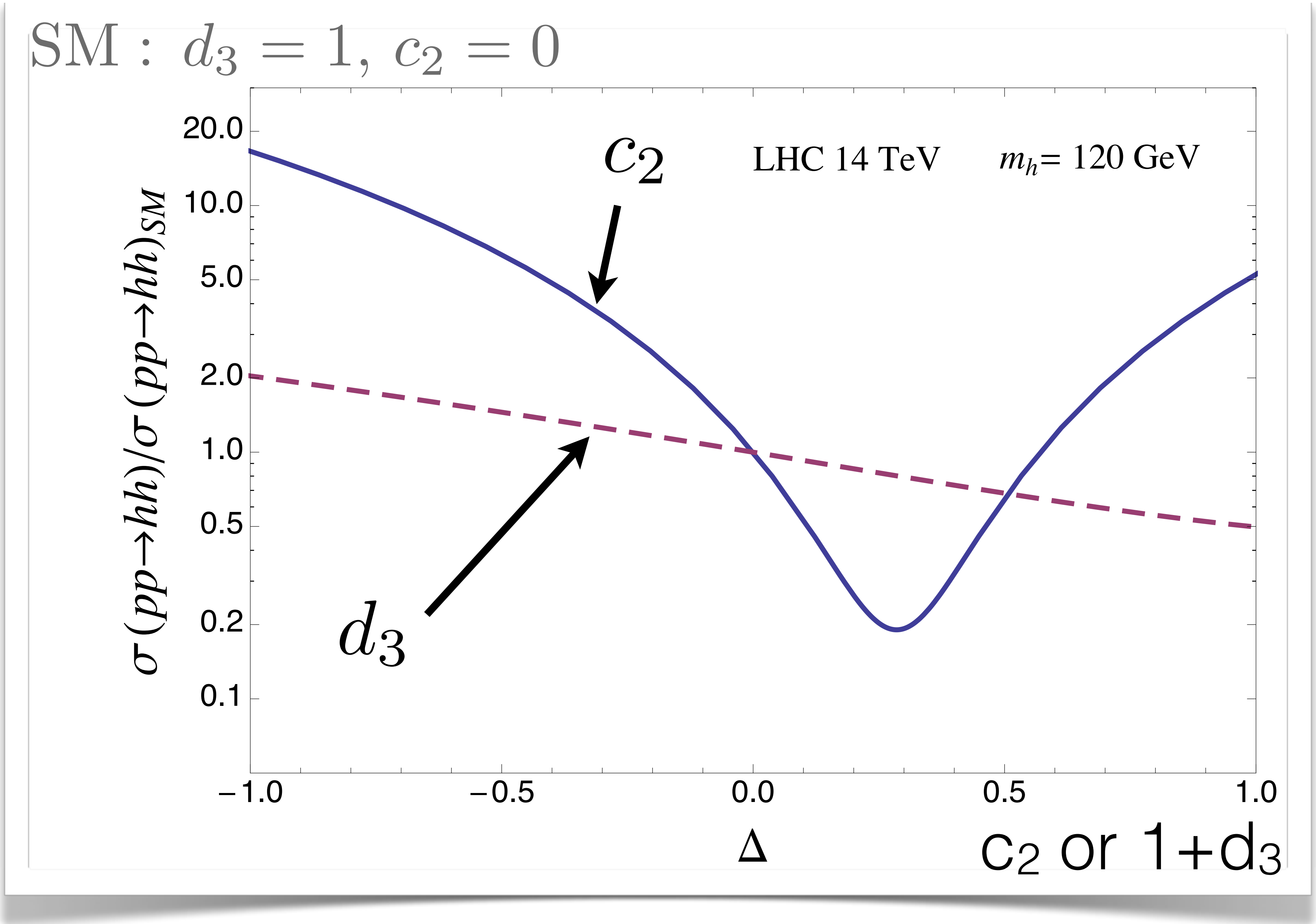
Double Higgs production beyond the SM

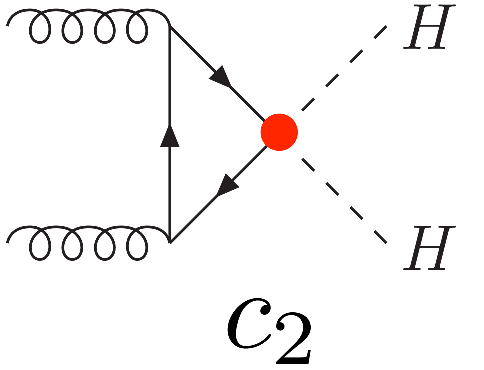
- In SM, access to self-coupling — test of structure of Higgs potential
- Composite Higgs, MSSM at low tanß, dilaton drastically affect HH rate
- Not an easy measurement, because of box–vertex destructive interference:
  cross section of 40±3 fb [de Florian & Mazzitelli 1309.6594]

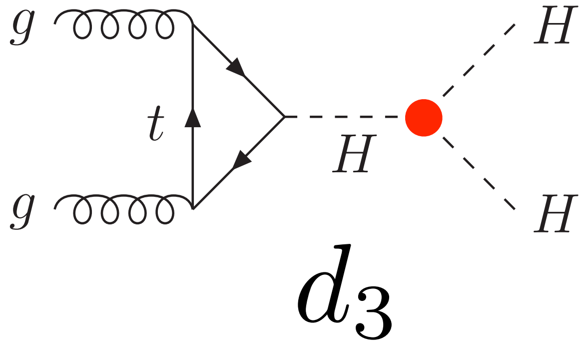


Double Higgs production beyond the SM

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - d_3 \frac{1}{6} \left(\frac{3m_h^2}{v} \right) h^3 - m_t \bar{q}_L t_R \left(1 + c_t \frac{h}{v} + c_2 \frac{h^2}{v^2} \right)$$







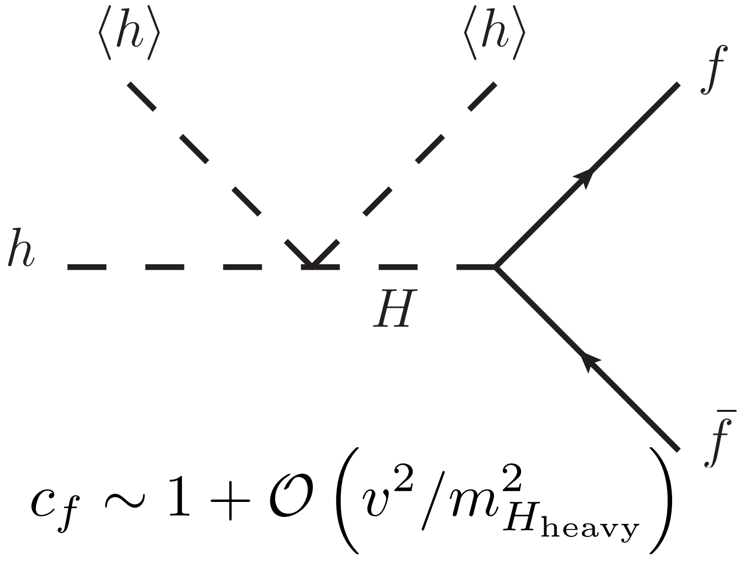
1205.5444

Why higher precision is important

Supersymmetry example:
MSSM tree-level Higgs mass ≤ M_Z, lift via

1) large quantum fluctuation from the stop
2) new interactions, e.g add singlet: NMSSM

Unravel with precise ffH coupling measurement



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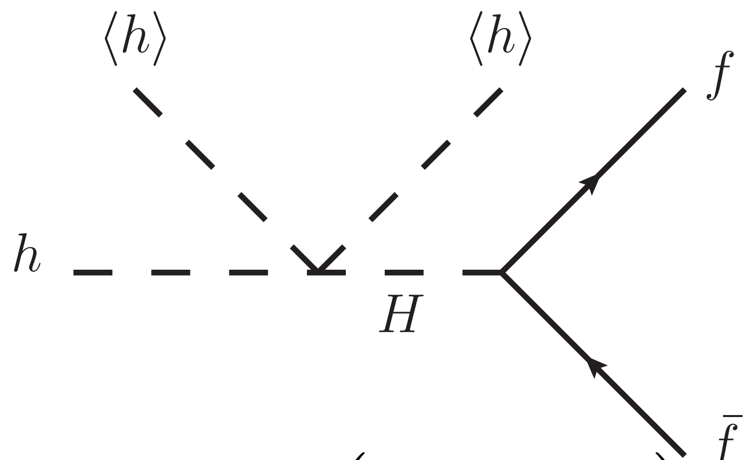

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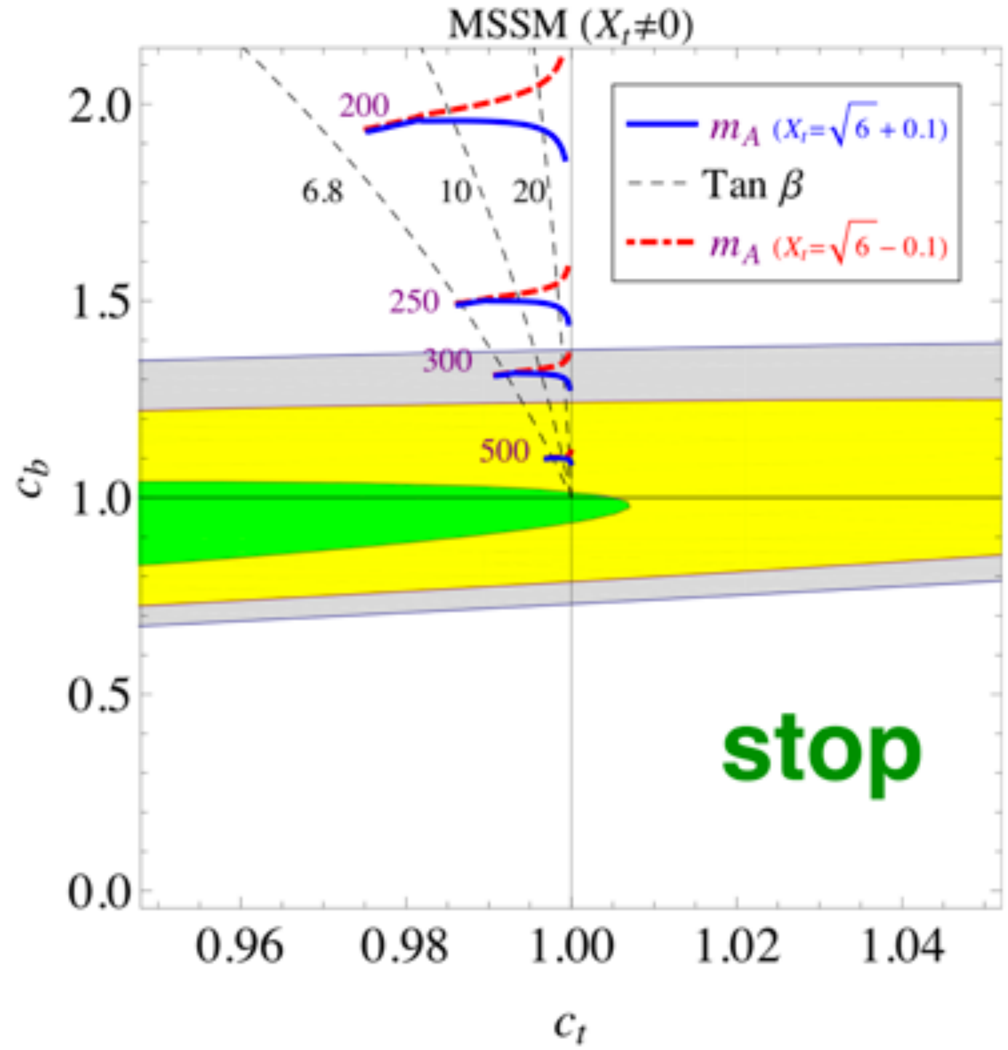

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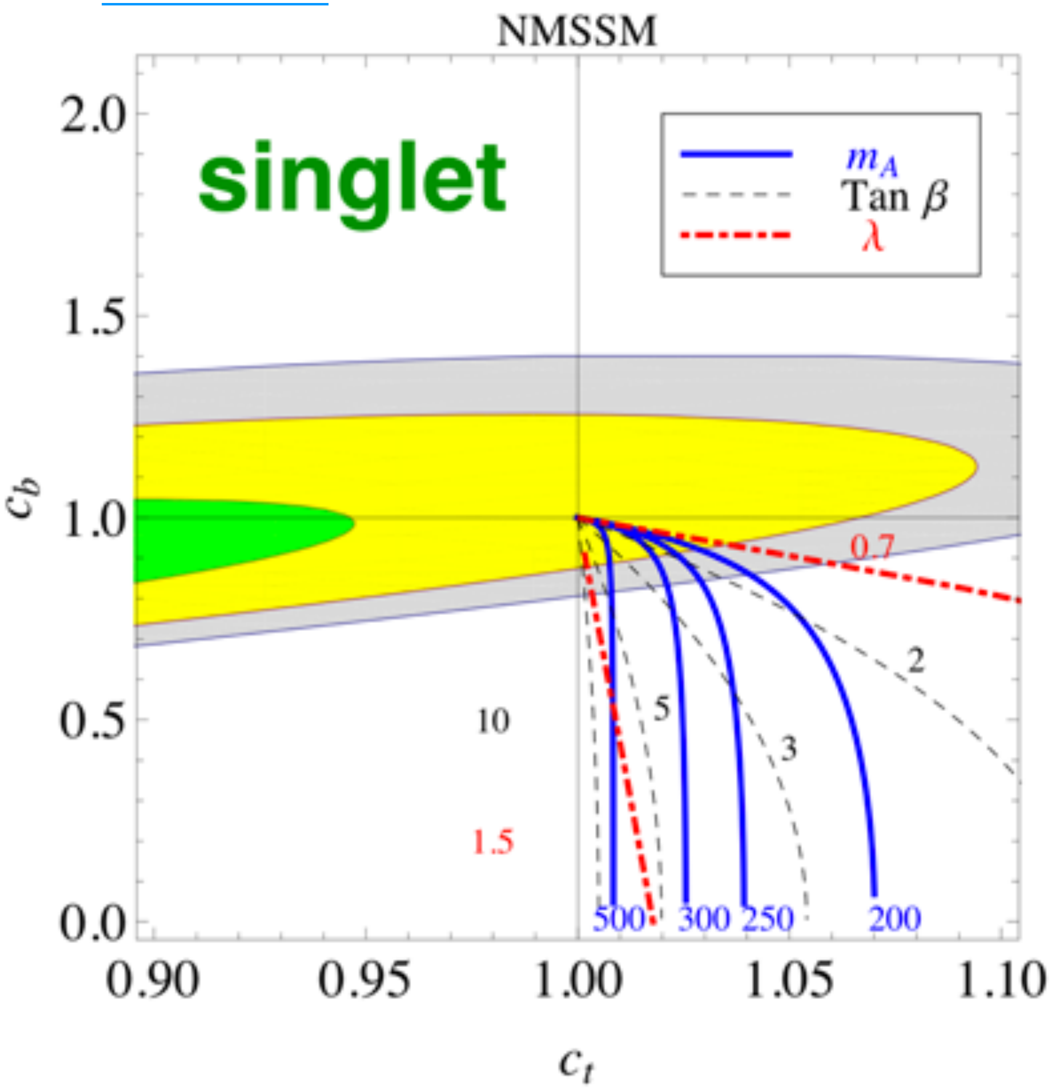
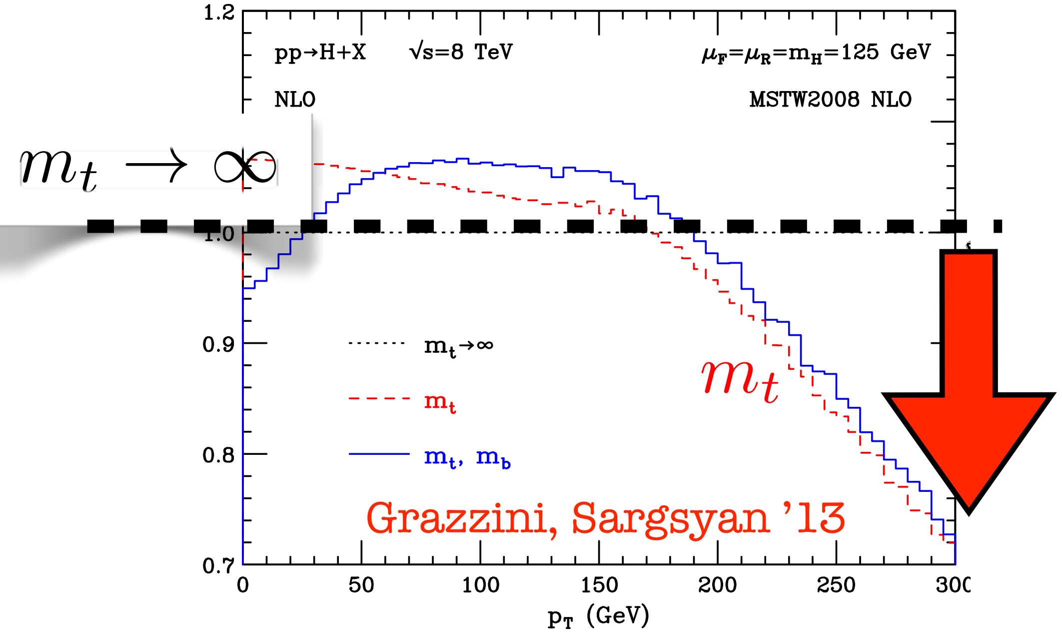


Why high p_T Higgs is important

SM + $$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\text{SM}} = (1+(c_g - c_t)v^2)^2$$

Degeneracy ‘short-distance’ vs ‘long-distance’



Grazzini, Sargsyan ’13

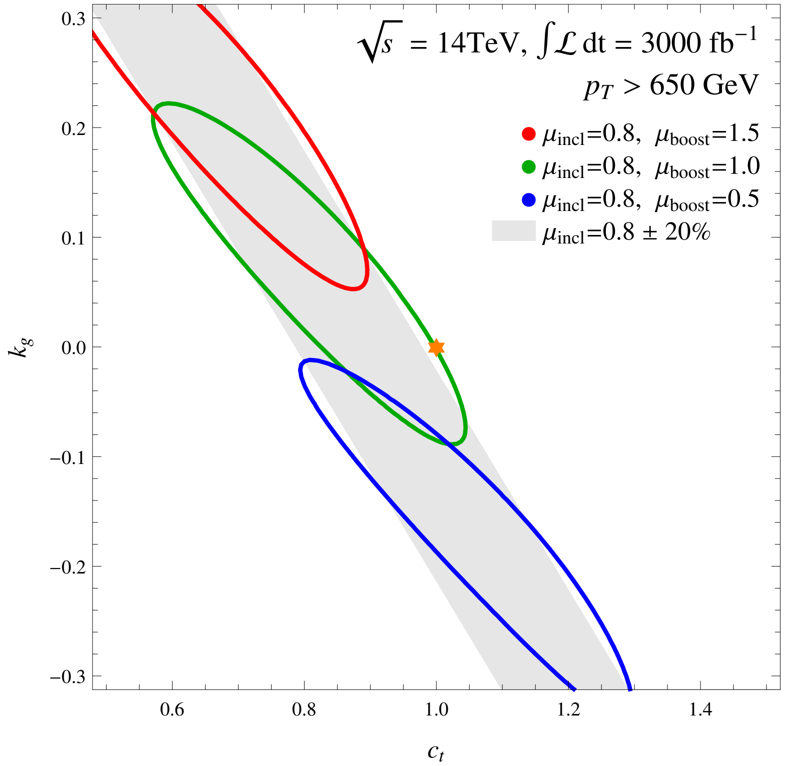
Baur, Glover ’90,
Langenegger et. al ’06,

$\text{higgs} - p_T$

high p_T tail resolves
loop dynamics,
breaks degeneracy

c_g

Grojean, Salvioni, Schlaffer, Weiler

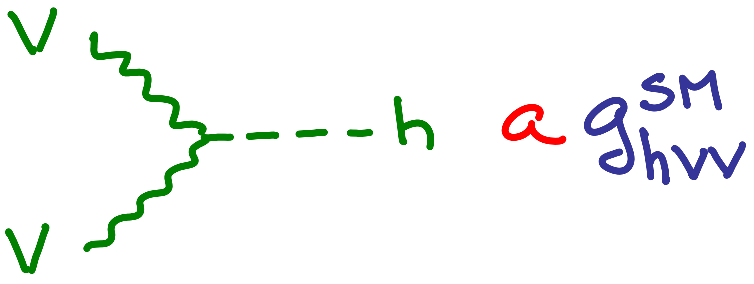


c_t

WW scattering

- Any deviation in WWH coupling necessarily implies problems with tree-level unitarity in WW scattering (H alone doesn't completely unitarize it).
- A given deviation in the couplings → upper bound at which strong interaction effects must appear. Signatures: growth of WW scattering amplitude or resonances
- E.g. for 20% deviations, scale is ~ 5 TeV

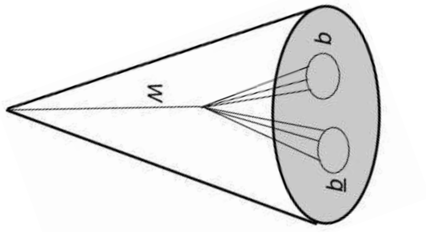
see e.g. [1005.4269](1005.4269)



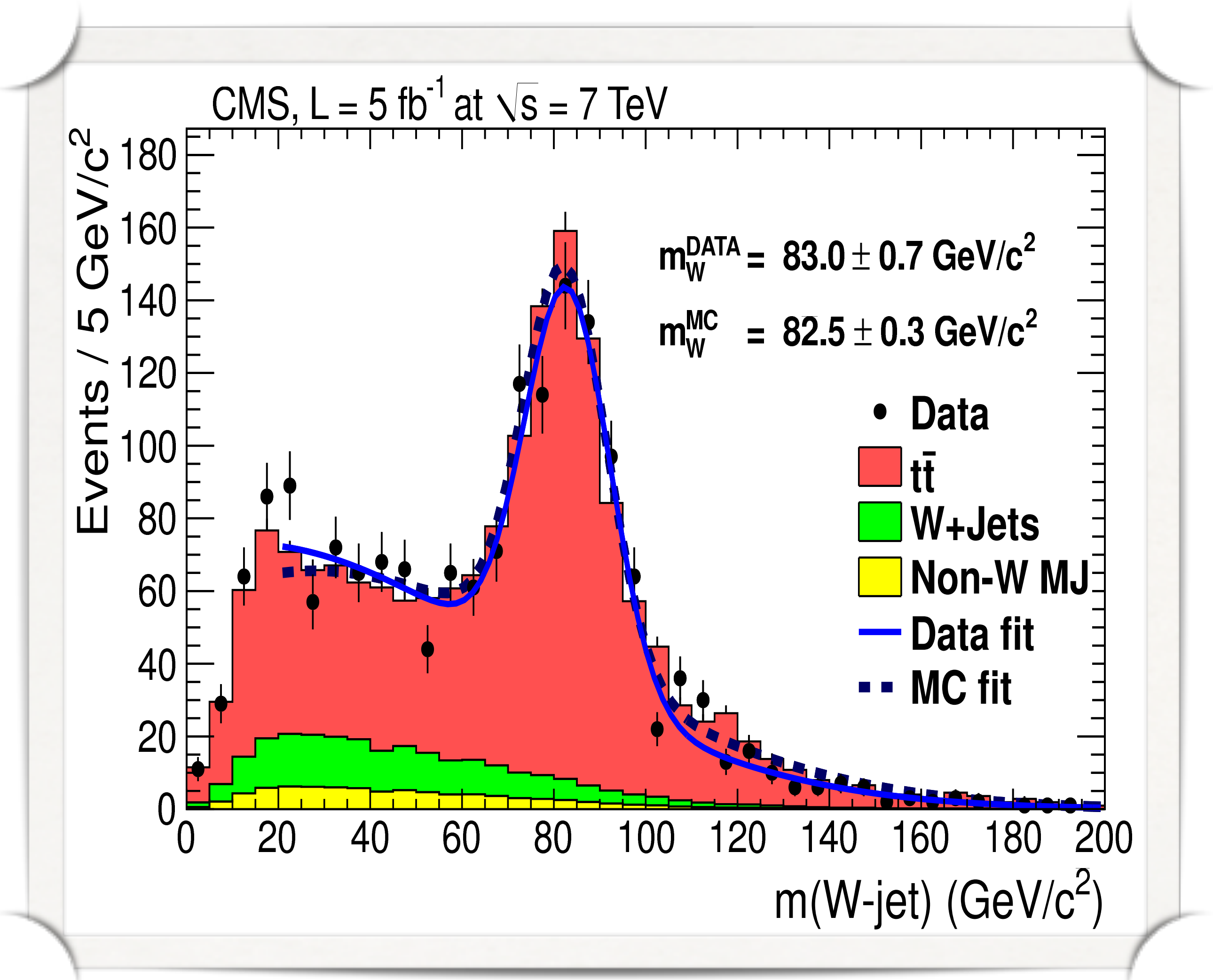
$$\Lambda \approx \frac{4\pi v}{\sqrt{1-a^2}}$$

Vector Boson Scattering and jet substructure

W's in a single jet



At high p_t, W decays are collimated: for hadronic decays, both "jets" clustered into a single jet. Such "W"-jets can be **tagged**.



- Jet substructure can play an important role in VBS studies [larger hadronic BR, full M_{VV} reco]
- Crucial in many BSM studies, with W's, Z's, H's, tops coming from high-mass new-physics objects
- Important to **keep substructure in mind in performance studies**

2. Direct searches for New Physics

What reach does 3ab^{-1}@14 TeV bring?

Consider a given search today (e.g. 19fb^{-1}@8TeV), sensitive to a mass scale $\boldsymbol{M}_{\textbf{low}}$, e.g. $M_{Z'}$ or $2m_{\text{squark}}$.

How can we estimate the corresponding "reach", M_{new}, of a search at 14 TeV, with 300 or 3000 fb^{-1}?

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Very basic estimate: solve following equation for $\boldsymbol{M_{\mathbf{high}}}$

$$\boxed{\frac{N_{\text{signal-events}}(M^2_{\text{high}}, 14\,\mathrm{TeV}, \mathrm{Lumi})}{N_{\text{signal-events}}(M^2_{\text{low}},\ 8\,\mathrm{TeV},\ 19\mathrm{fb}^{-1})} = 1}$$

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Even simpler: instead of ratio of # of events, **use ratio of "partonic luminosities"** (e.g. $q\bar{q}$ lumi, gg lumi)

[including correct dimensional factors]
NB valid if bkgd & signal driven by same partonic channel

Luminosity method: check 2

1208.1447
ATLAS-CONF-2013-024

gg

stop limits	[expected]	(lsp = 0gev)
7tev, 4.7 ifb	500 gev	
8tev, 20.5 ifb	650 gev	---> 675 GeV

qqbar

ATLAS EXOT-2011-06
ATLAS-CONF-2012-129
ATLAS-CONF-2013-017

sequential z-prime	[expected]	
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EXOT-2011-07
ATLAS-CONF-2012-088
ATLAS-CONF-2012-148

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excited quark q*	[expected]	(NB,sig ≠ bgd scaling)
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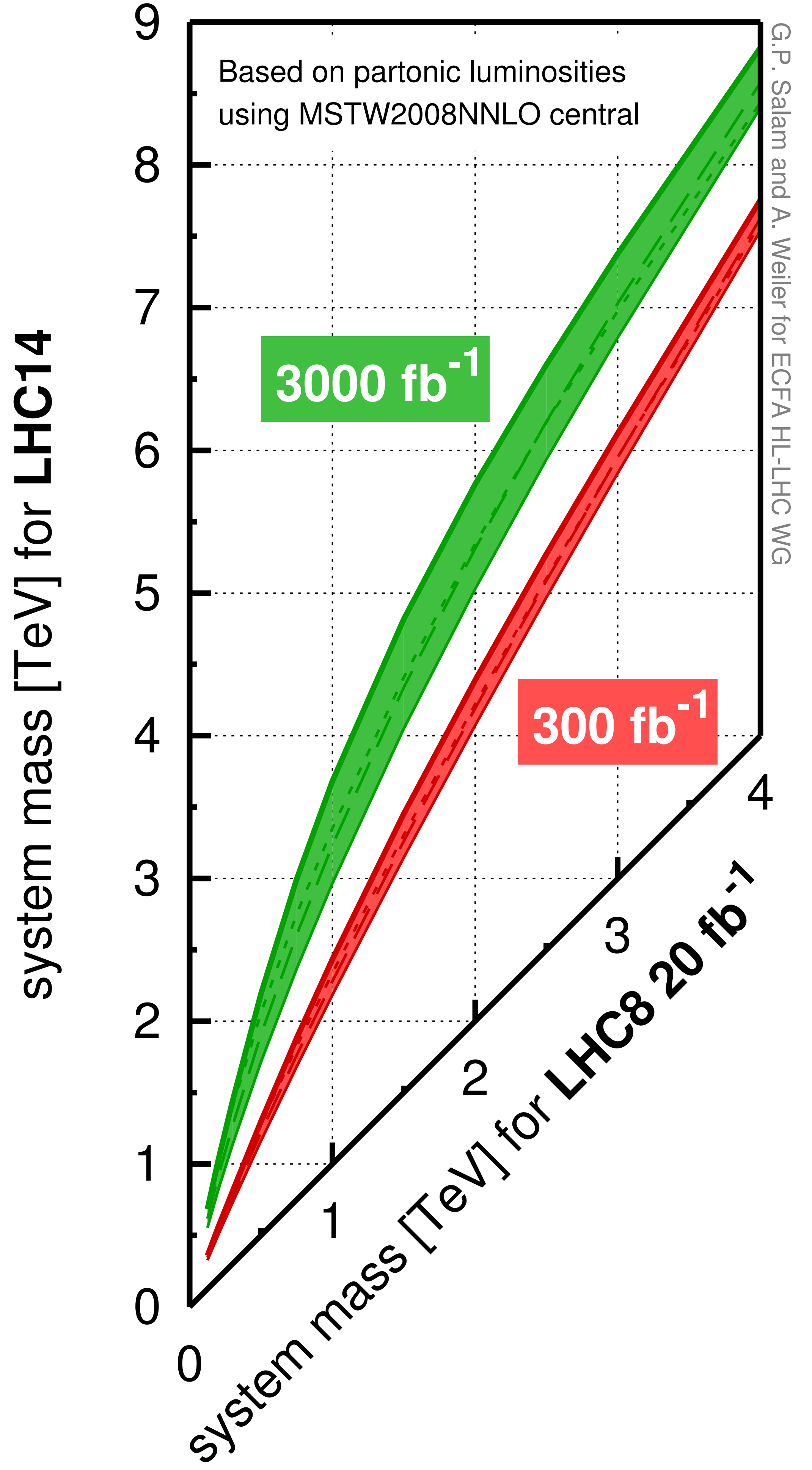
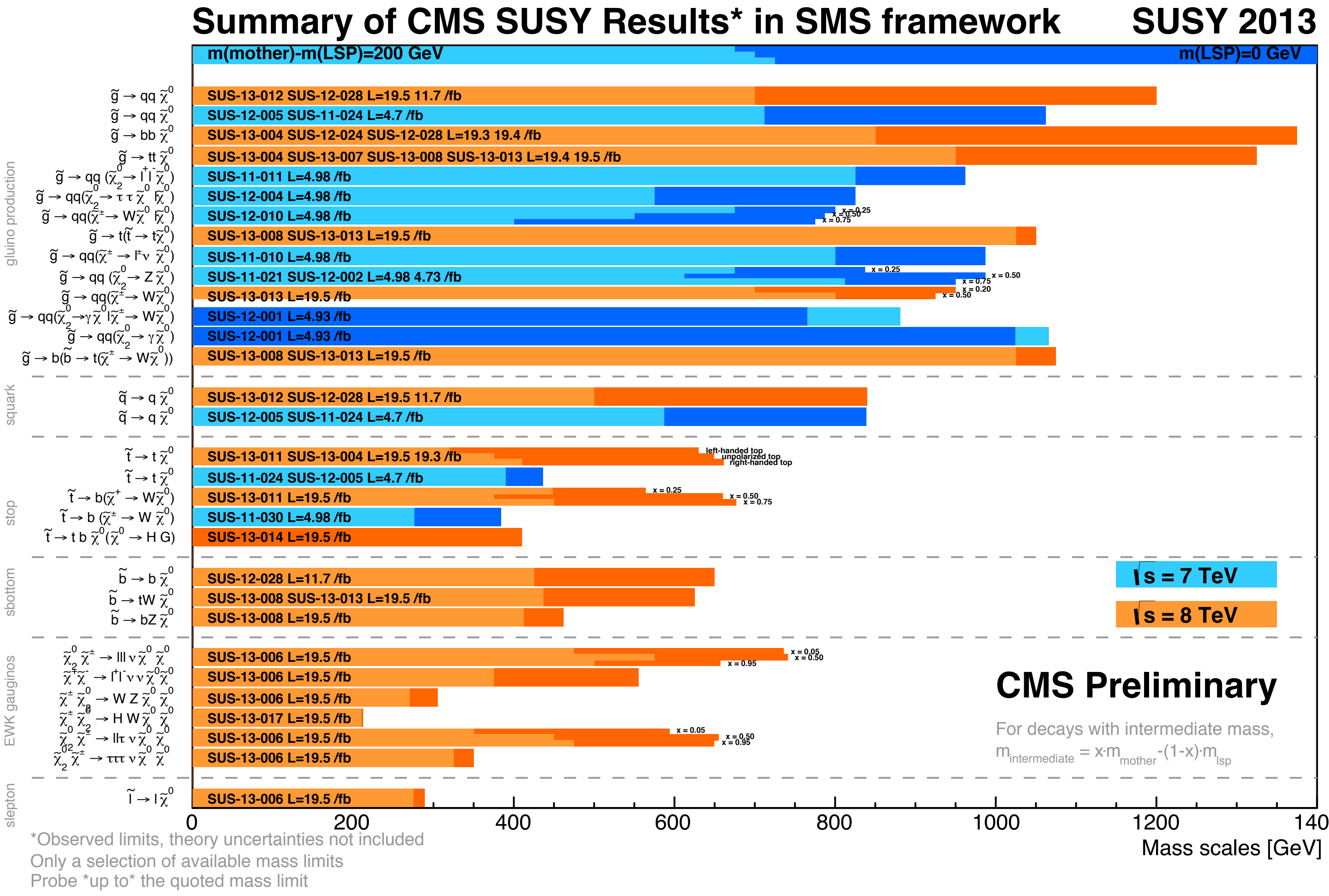
Lumi
method

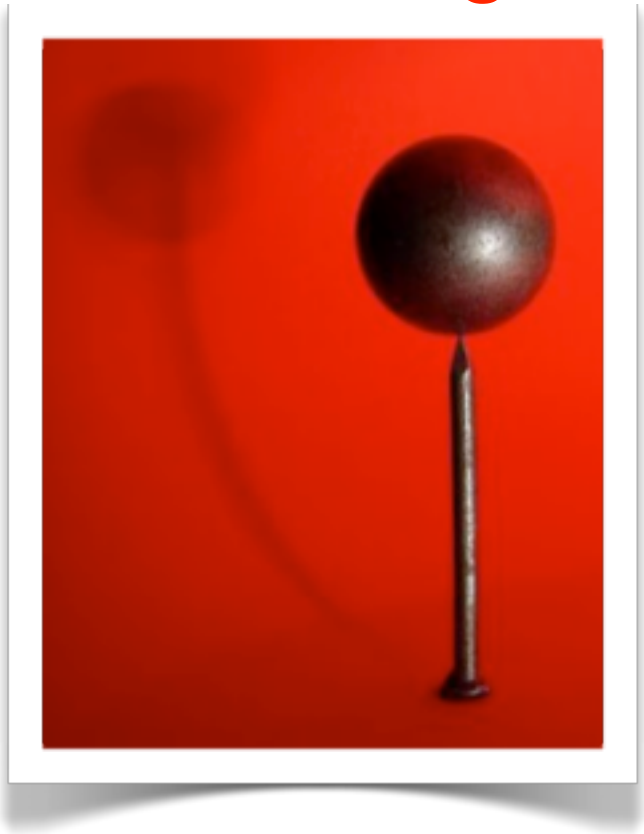


Take existing searches and figure out reach at 14 TeV, for different lumis



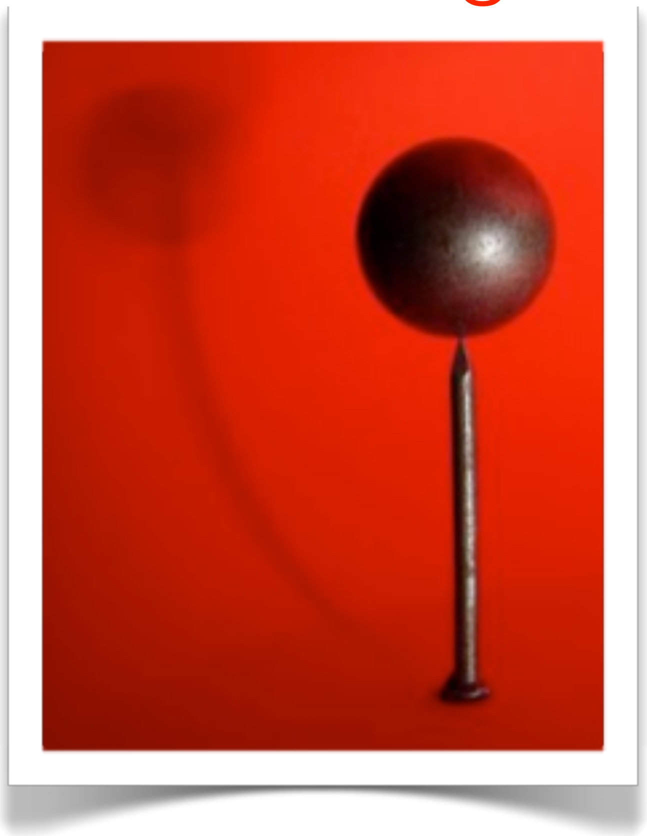
Probing naturalness

Fine-tuning in the Higgs sector



Probing naturalness

Fine-tuning in the Higgs sector



Light Higgs

stabilizing quantum corrections

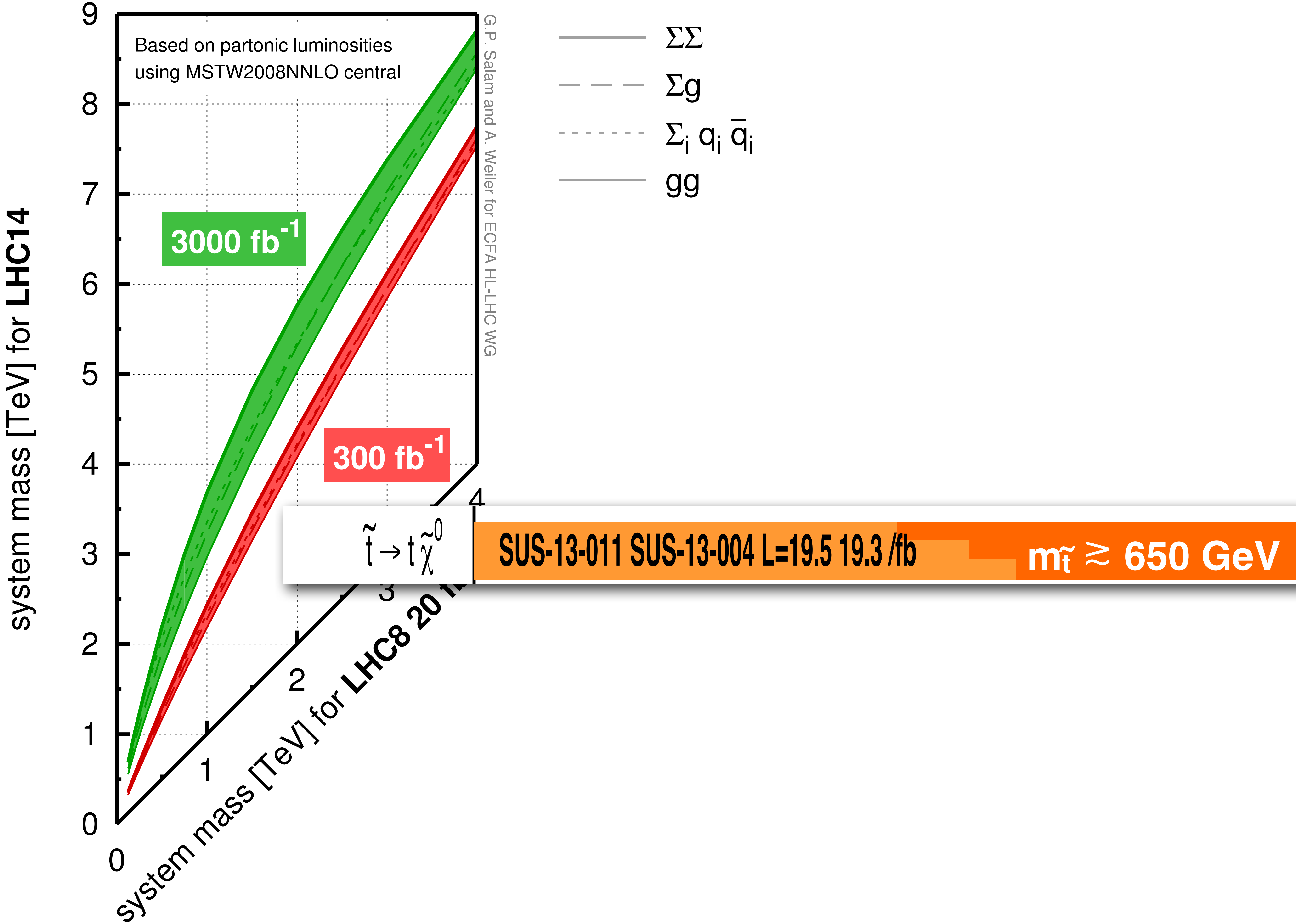
?

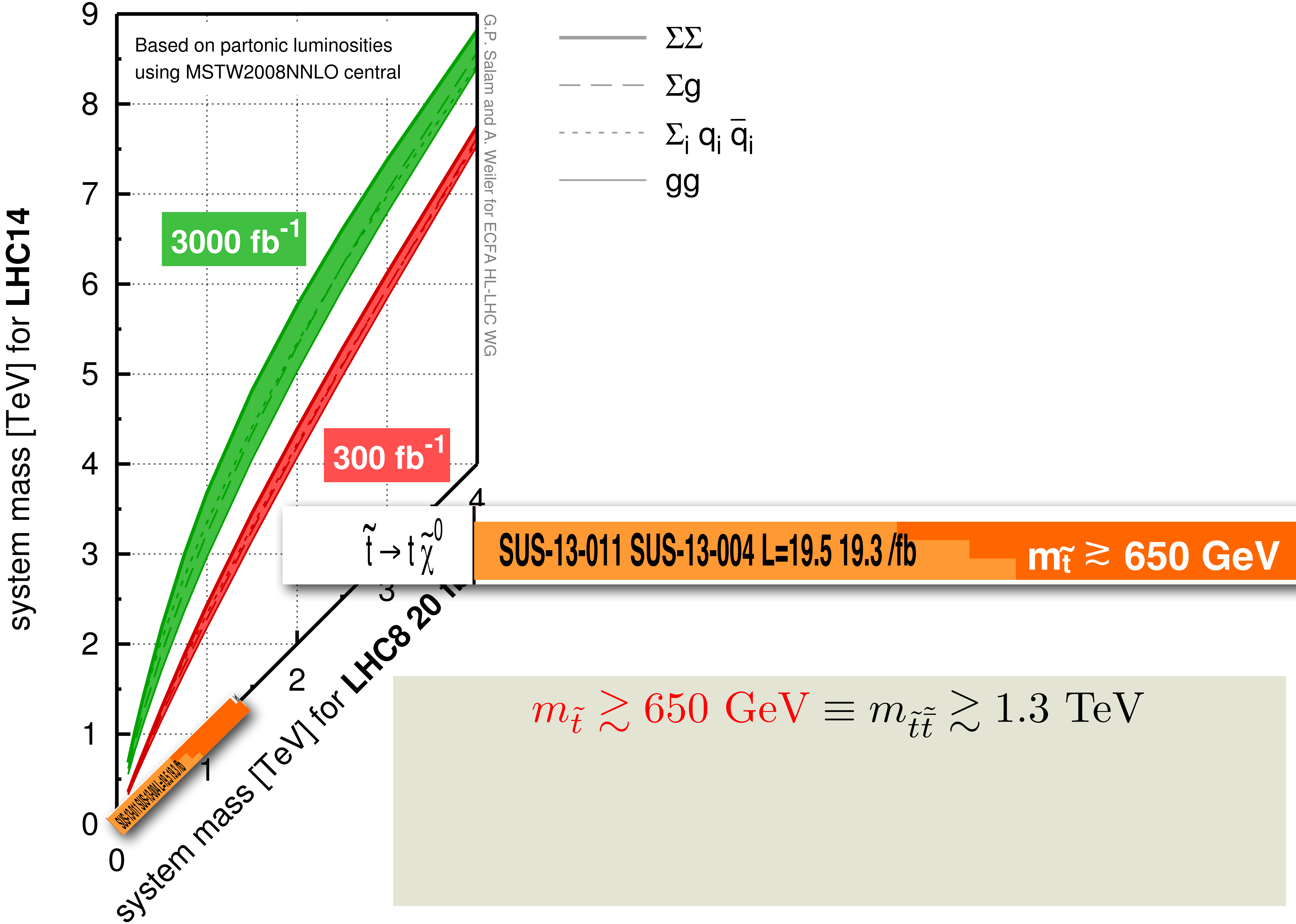
light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, …

supersymmetry

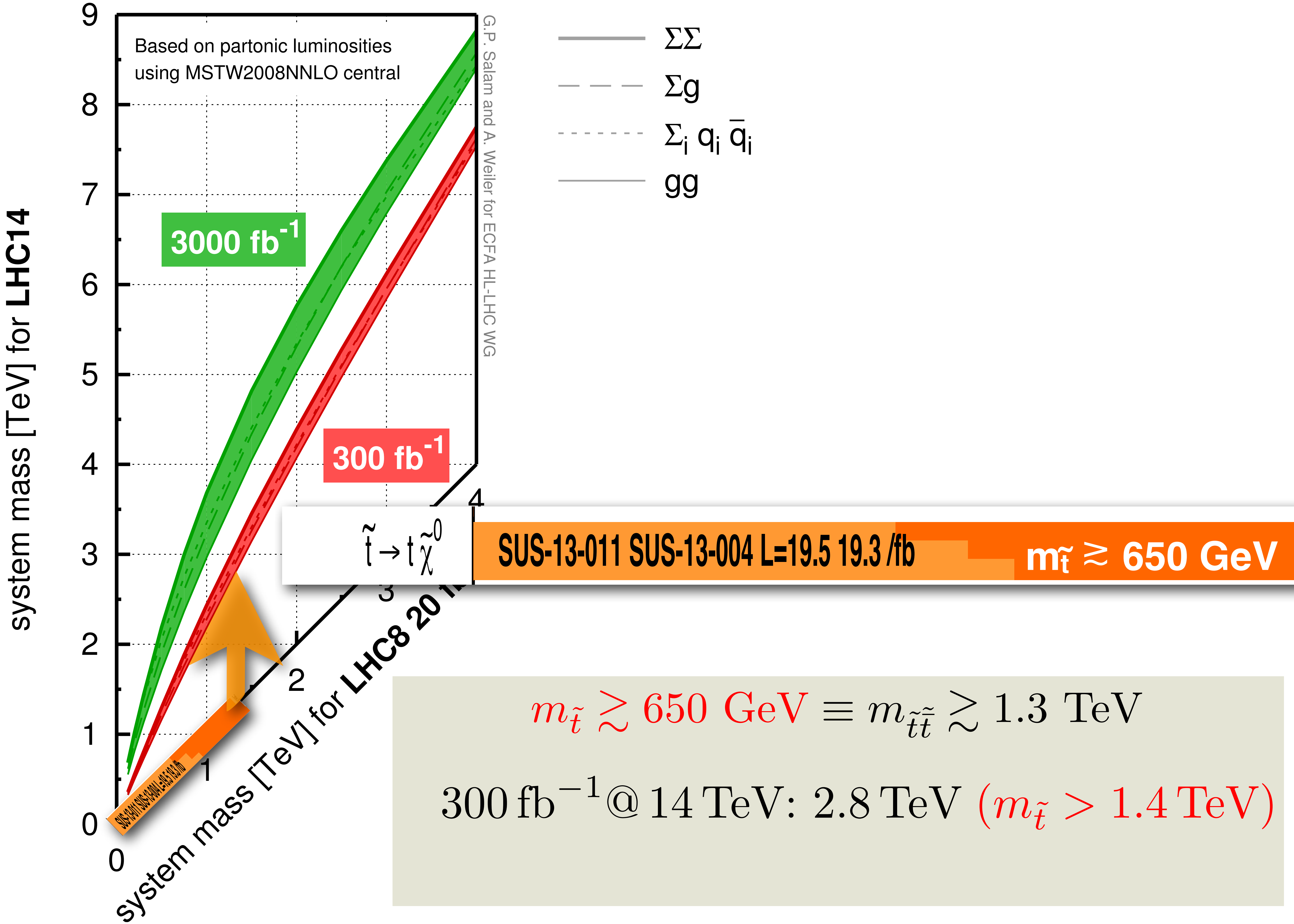
light top partners (Q=5/3,2/3,1/3)

composite Higgs


Based on partonic luminosities
using MSTW2008NNLO central
3000 fb^{-1}
300 fb^{-1}
G.P. Salam and A. Weiler for ECFA HL-LHC WG
ΣΣ
Σg
$\Sigma_i q_i \bar{q}_i$
gg
system mass [TeV] for LHC14
system mass [TeV] for LHC8 20
0
1
2
3
4
5
6
7
8
9
$\tilde{t} \rightarrow t \tilde{\chi}^0$
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
$m_{\tilde{t}} \gtrsim$ 650 GeV

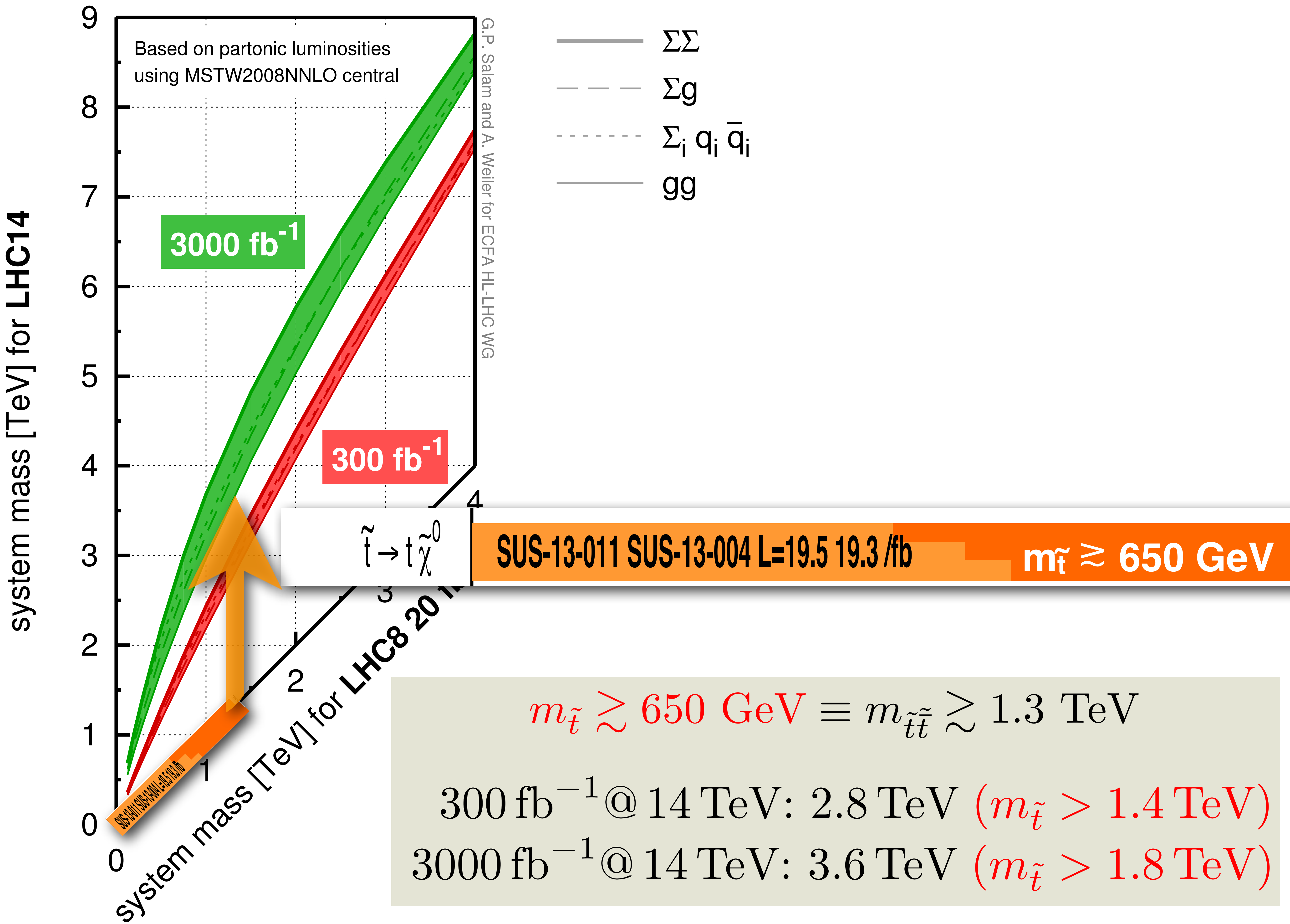


$$m_{\tilde{t}} \gtrsim 650\ \text{GeV} \equiv m_{\tilde{t}\tilde{t}} \gtrsim 1.3\ \text{TeV}$$



$$m_{\tilde t} \gtrsim 650~\text{GeV} \equiv m_{\tilde t \tilde t} \gtrsim 1.3~\text{TeV}$$

$$300\,\text{fb}^{-1} @\, 14\,\text{TeV}:\ 2.8\,\text{TeV}\ \left(m_{\tilde t} > 1.4\,\text{TeV}\right)$$



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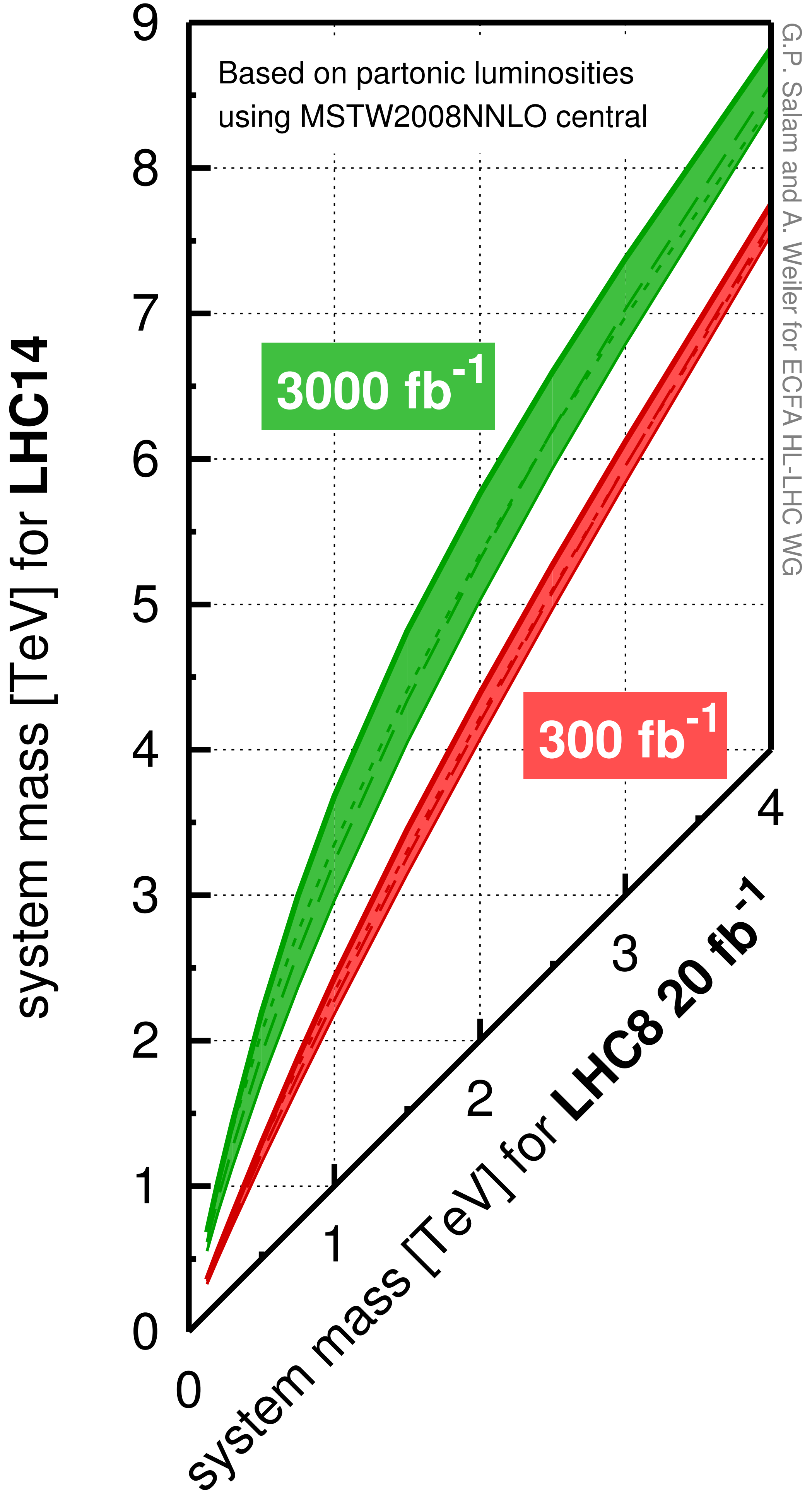
$$3000\,\text{fb}^{-1} @\, 14\,\text{TeV}:\ 3.6\,\text{TeV}\ \ (m_{\tilde t} > 1.8\,\text{TeV})$$



G.P. Salam and A. Weiler for ECFA HL-LHC WG

Increase in c.o.m. energy to 14 TeV brings substantial extra reach

x10 in lumi also brings extra TeV in reach

That can be quite significant (e.g. 35-50%) at the lower end of the range, e.g. when today's limits are ~ 1 TeV.

These numbers are to be taken as **indicative of what might be posible**

—

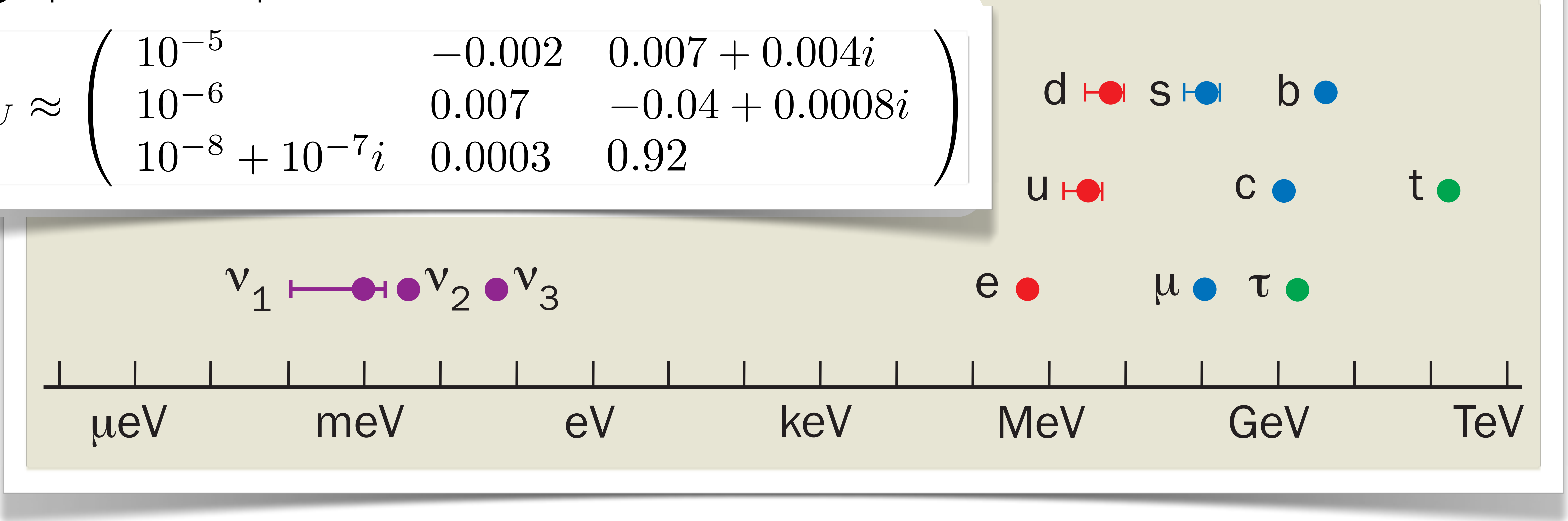
real life may be tougher,
future analyses may be cleverer

Open Problem of the SM

Origin of SM matter and flavour?

e.g.up/charm/top mass matrix:

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007+0.004i \\ 10^{-6} & 0.007 & -0.04+0.0008i \\ 10^{-8}+10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



Compare to other couplings of the SM:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\text{Higgs}} \sim 1/8$

FCNCs are sensitive SM flavour structure

- The SM flavour sector has passed all tests at B-factories and recently at LHCb, ATLAS and CMS
- Less likely to find O(1) deviations from the SM, need theoretically clean observables.
- High potential flavour measurements,some examples

$$R = \frac{\mathcal{B}(B^0 \to \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \to \mu^+ \mu^-)}$$

$$q_0^2 \; A_{\mathrm{FB}}(K^{*0} \mu^+ \mu^-)$$

CKM γ

$$\phi_s(B_s^0 \to J/\psi \phi)$$

- Top FCNC rate sensitivity can be improved by ~ 4x

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R = $\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$

Clean prediction 1208.0934

$\delta R/R = \pm 0.06 \pm 2\sigma^r_{f_{s/d}}$

$q_0^2 \; A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$

clean theory, BSM sensitivity

$\phi_s(B_s^0 \to J/\psi\phi)$

CKM γ

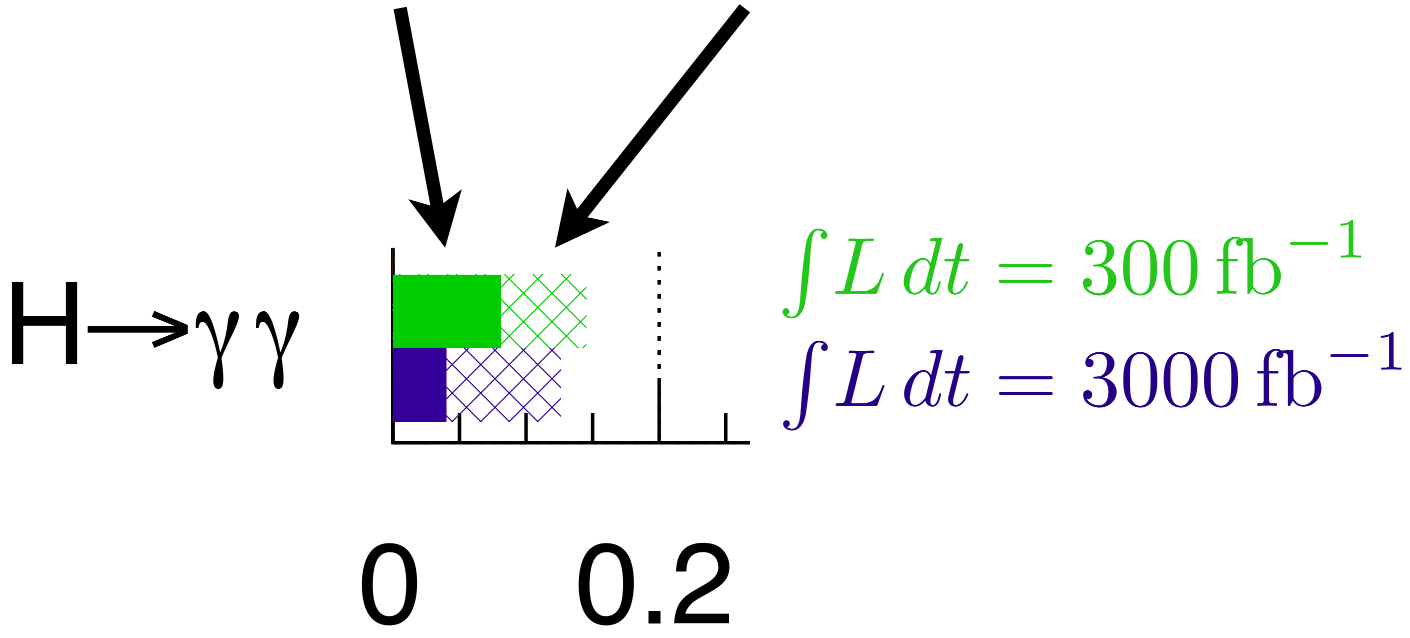
up to
1° precision
measurement

- Top FCNC rate sensitivity can be improved by ~ 4x

3. SM sector, including theory prospects (e.g. for use in Higgs physics)

Assuming
no theory
uncertainty

Assuming
today's theory
(and PDF) uncertainty



Many uncertainties cancel in ratios, e.g. γγ /ZZ.

But what are prospects for doing better directly on cross sections?

Sources of uncertainty?

- **Missing higher orders** (“scale”) in QCD and EW. **~ 10%**

- Extra QCD uncertainties in the presence of **cuts** (e.g. jet vetoes). **~ 10%**

- **PDF uncertainties** (within/between groups), **~ 7%**

- **Fundamental constants** (α_s, m_b, etc.) ~ few %

m_H (GeV)	Cross Section (pb)	+error %	- error %	+scale %	-scale %	+(PDF+α_s) %	-(PDF+α_s) %
125	49.85	19.6	-14.6	12.2	-8.4	7.4	-6.2

HXSWG gg→ H

Sources of uncertainty?

- **Missing higher orders** (“scale”) in QCD and EW. **~ 10%**

  [Need higher-order inclusive X-sections]

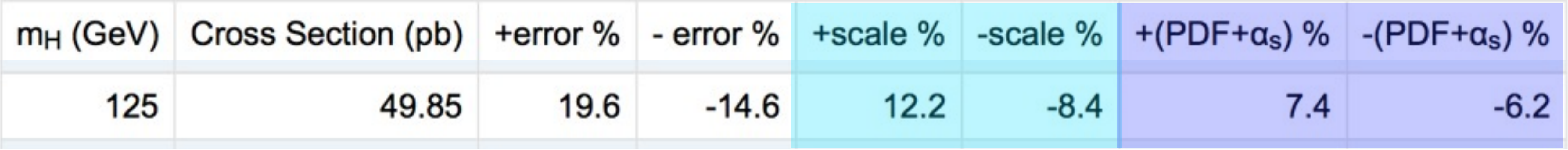
- Extra QCD uncertainties in the presence of **cuts** (e.g. jet vetoes). **~ 10%**

  [Need higher-order differential X-sections, fixed-order, resummed & MC]

- **PDF uncertainties** (within/between groups), **~ 7%**

  [Need better data & better theory to interpret it]

- **Fundamental constants** (α_s, m_b, etc.) ~ few %



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HXSWG gg→ H

A small selection of Theory progress

gg → H

Since 11 years: NNLO (+ threshold)
In 1-2 years? NNNLO (+ threshold)

1208.3130, 1211.6559
1302.4379, 1306.2223

Since 10 years: NLO + parton shower
Past month: NNLO + parton shower

1309.0017

A small selection of

Theory progress

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pp → H+jet (matters for searches with jet vetoes, jet selections, etc.)

Since 10–14 years: NLO, NNLL H p_t resummation
Past year: NNLL jet resummation
NNLO (gluonic part)

1206.4998, 1307.0025, 1307.1808
1302.6216

A small selection of

Theory progress

$gg \to H$

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$pp \to H$+jet (matters for searches with jet vetoes, jet selections, etc.)

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NNLO (gluonic part) 1302.6216

NNLO for other 2→2 is **here now (e.g. $\gamma\gamma$, $t\bar{t}$)** or soon

Projected uncertainties for gg→H

Buehler & Lazopoulos, arXiv:1306.2223

Expected N^{3}LO (scale) uncertainties depend on size of N^{3}LO corrections (parametrised by K)

Order	Cross section [pb]	$\sigma/\sigma_{\mathrm{NNLO}}$	$\sigma/\sigma_{\mathrm{LO}}$
LO	$10.31^{+26.9\%}_{-16.6\%}$	0.51	1.00
NLO	$17.41^{+20.8\%}_{-12.7\%}$	0.86	1.69
NNLO	$20.27^{+8.3\%}_{-7.1\%}$	1.00	1.97
N^{3}LO (K=0)	$18.53^{+1.2\%}_{-7.9\%}$	0.91	1.80
N^{3}LO (K=5)	$19.23^{+0.3\%}_{-5.1\%}$	0.95	1.87
N^{3}LO (K=10)	$19.92^{+0.0\%}_{-2.6\%}$	0.98	1.93
N^{3}LO (K=15)	$20.62^{+0.4\%}_{-2.2\%}$	1.02	2.00
N^{3}LO (K=20)	$21.31^{+2.0\%}_{-3.1\%}$	1.05	2.07
N^{3}LO (K=30)	$22.70^{+6.0\%}_{-4.9\%}$	1.12	2.20
N^{3}LO (K=40)	$24.09^{+9.6\%}_{-6.5\%}$	1.19	2.34

Today

Near future:
Depending on size of N^{3}LO correction (K), final uncertainty could be anywhere from 2% to 8%

Projected uncertainties for gg→H

Buehler & Lazopoulos, arXiv:1306.2223

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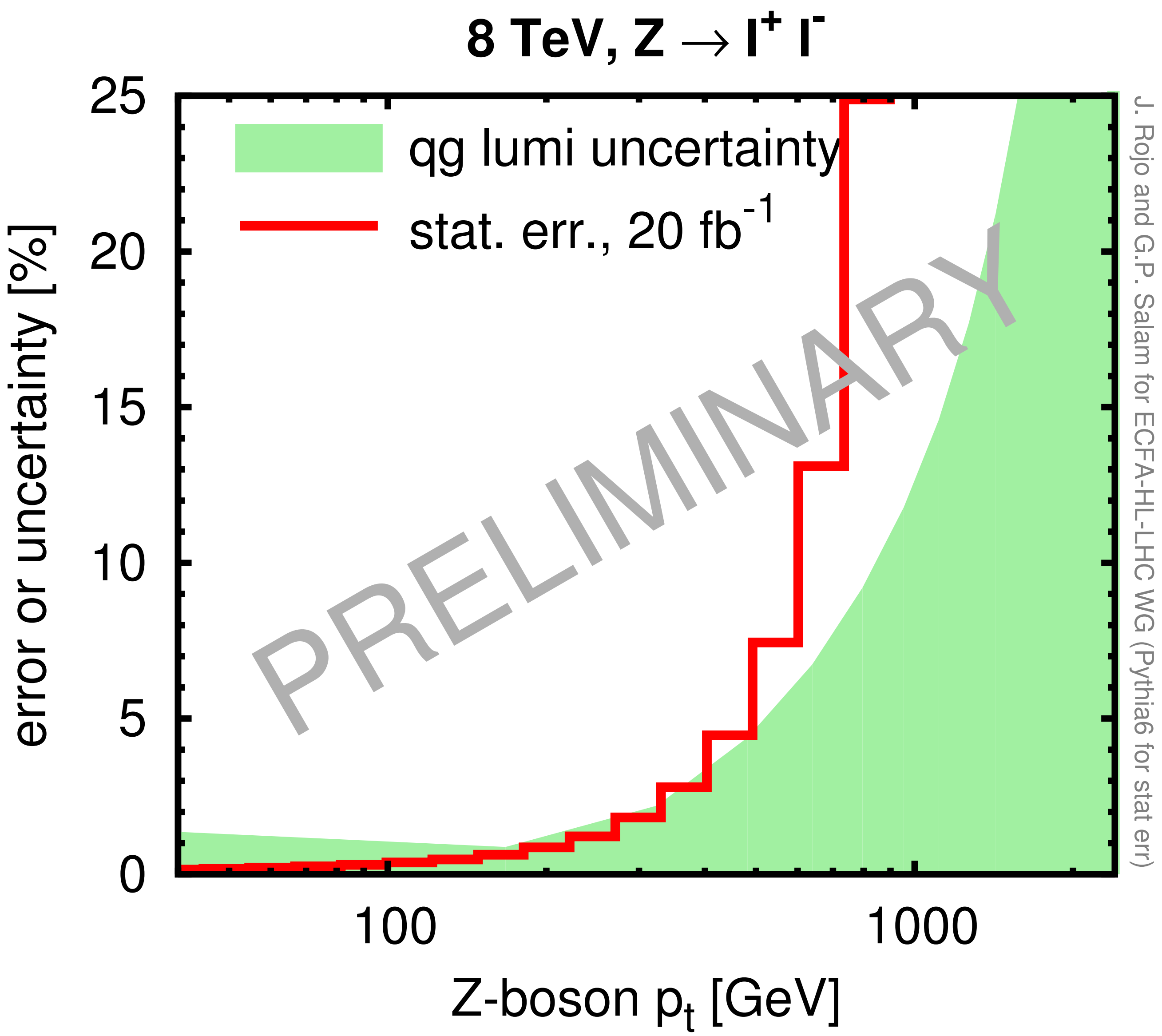
Today

Near future:

Roughly what comes out of N^{3}LO estimate from Ball et al, 1303.3590

e.g. of HL-LHC precision SM measurement: Z p_t spectrum



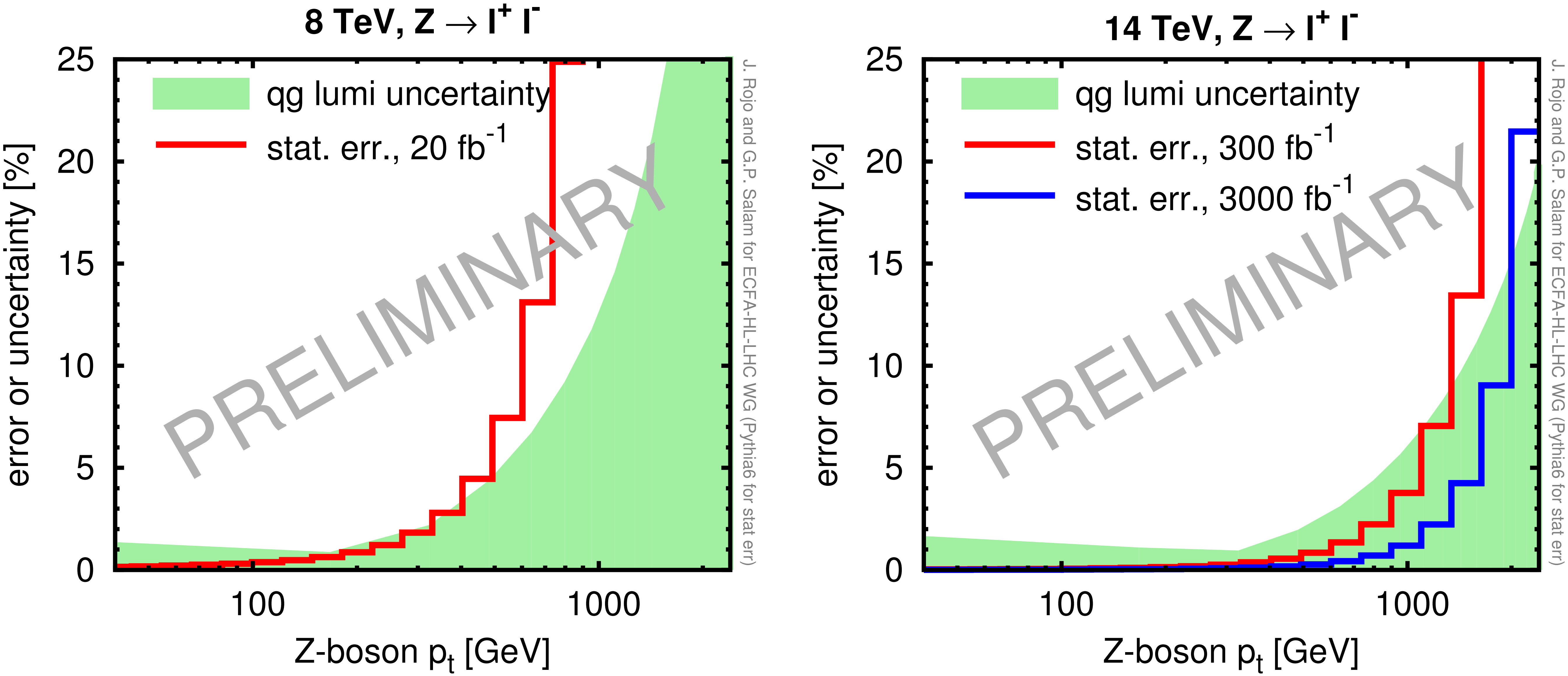
[Thanks to J. Rojo for partonic lumi uncertainties]

Emerging realisation that the Z p_t spectrum is a potentially very precise handle on PDFs [quark × glue × α_s]

Today, will mainly be a vital confirmation(?) of existing knowledge.

$t\bar{t}$ is also a powerful handle, cf. 1303.7215

e.g. of HL-LHC precision SM measurement: Z p_t spectrum



J. Rojo and G.P. Salam for ECFA-HL-LHC WG (Pythia6 for stat err)

J. Rojo and G.P. Salam for ECFA-HL-LHC WG (Pythia6 for stat err)

For p_t ~ 1 TeV, HL-LHC could bring **5x gain in precision**!

[but only if theory prediction is good enough — today only NLO]

Heavy Ion Collisions

The thermal dimension to the exploration of the standard model

HL-LHC brings x10–100 in data: 10nb^{-1} ~ 0.4 fb^{-1} pp equivalent

Same processes as pp , but different motivations & regimes

e.g. Z/γ+jet at high p_T, to study balance between jet and the Z.

Rare "probes": open heavy flavour (jets, elliptic flow)

Quarkonium dissociation: low-pt charmonium elliptic flow, multi-differential ϒ production.

Low-mass di-leptons: thermal radiation γ (→ e^+e^-) to map temperature during system evolution; modification of ρ spectral function to probe chiral symmetry restoration

See talk by A. Dainese for details

CONCLUSIONS

Conclusions

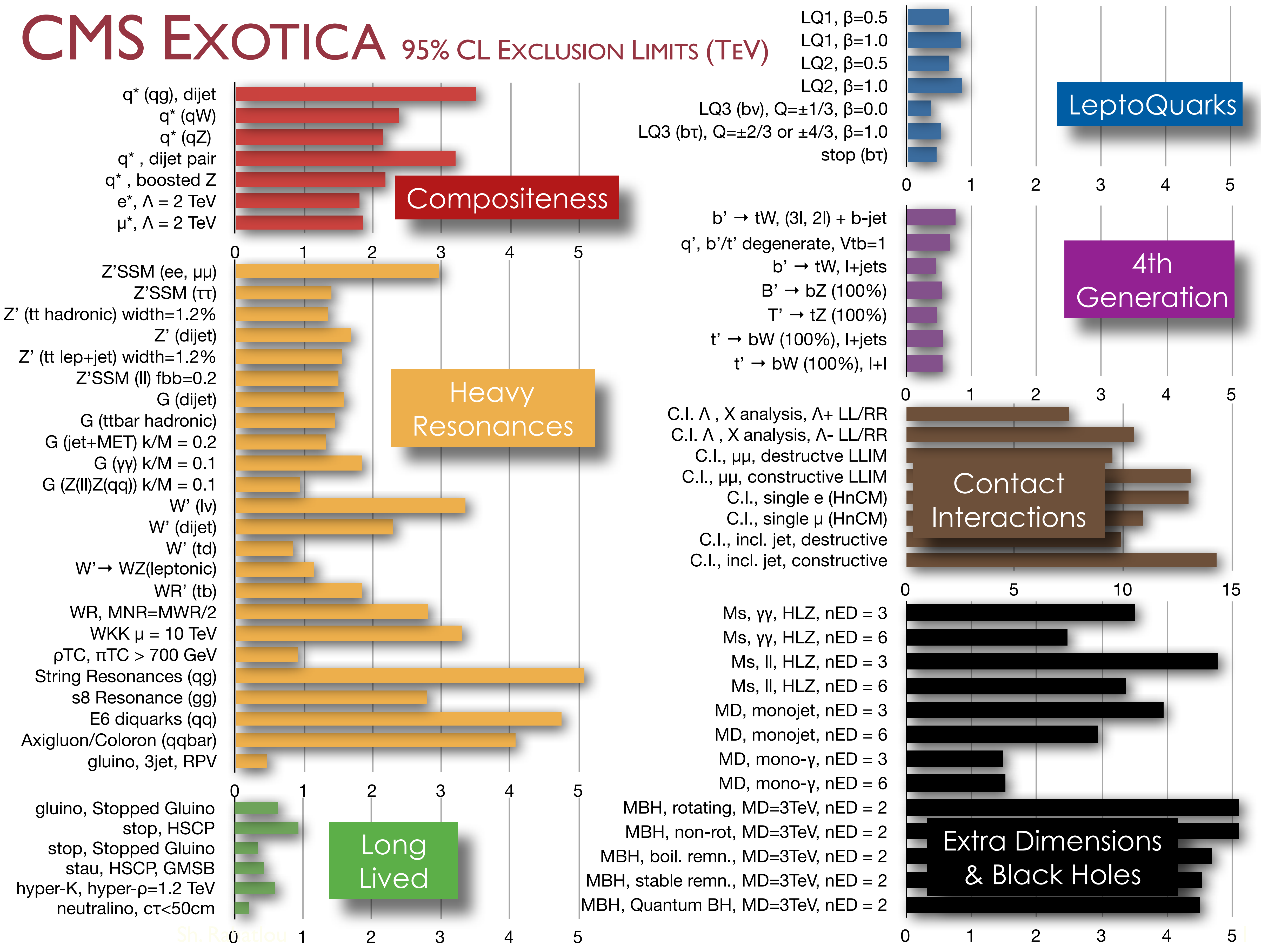
HL-LHC:

- Opens new channels for Higgs studies and significantly improved precision
- Gives substantial extra reach in some new-physics searches, especially for signals with small cross sections
- Will need theory improvements to get full benefits and will offer precision SM measurement opportunities

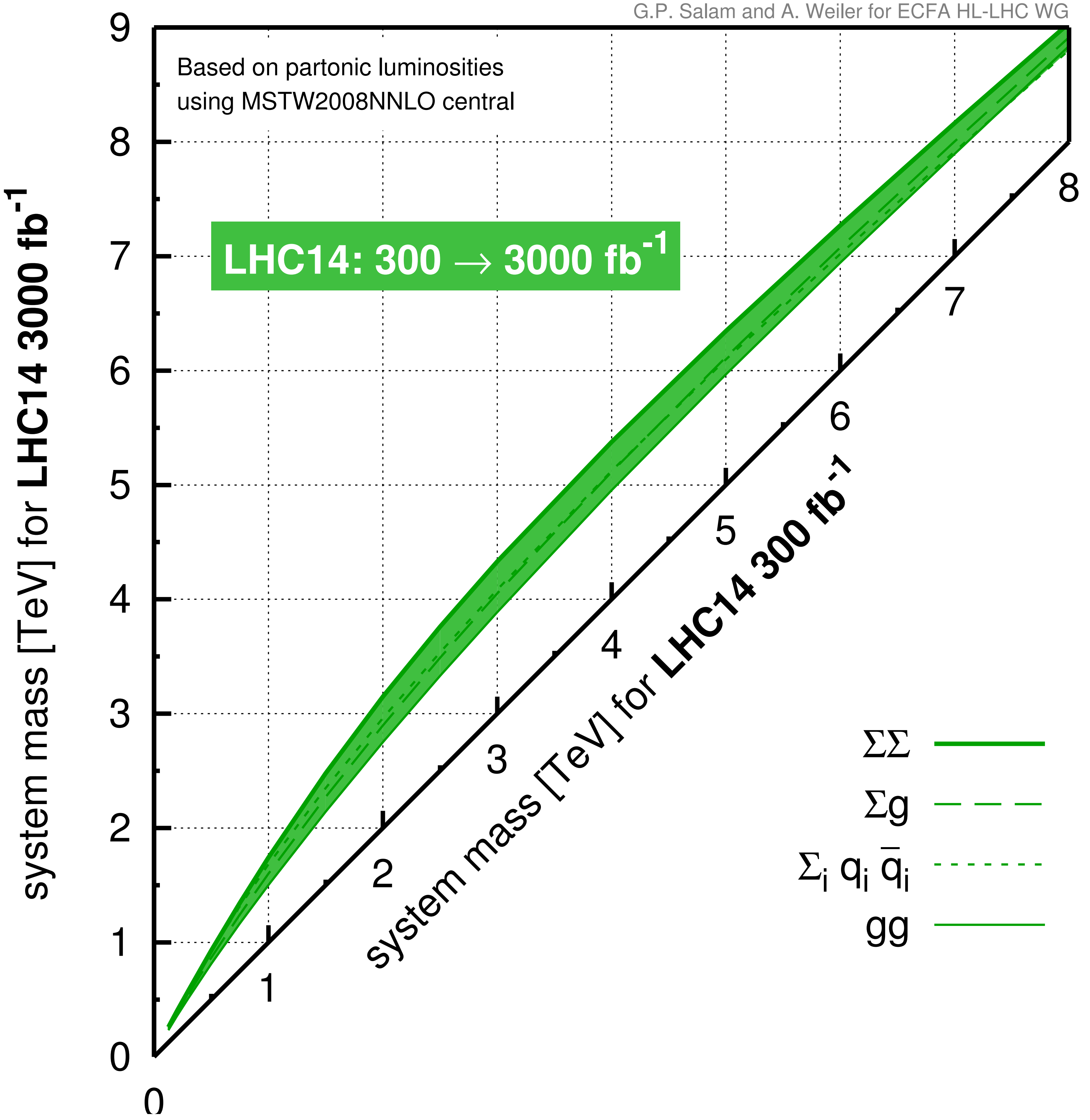
Many of the details in the coming talks!

BACKUP SLIDES

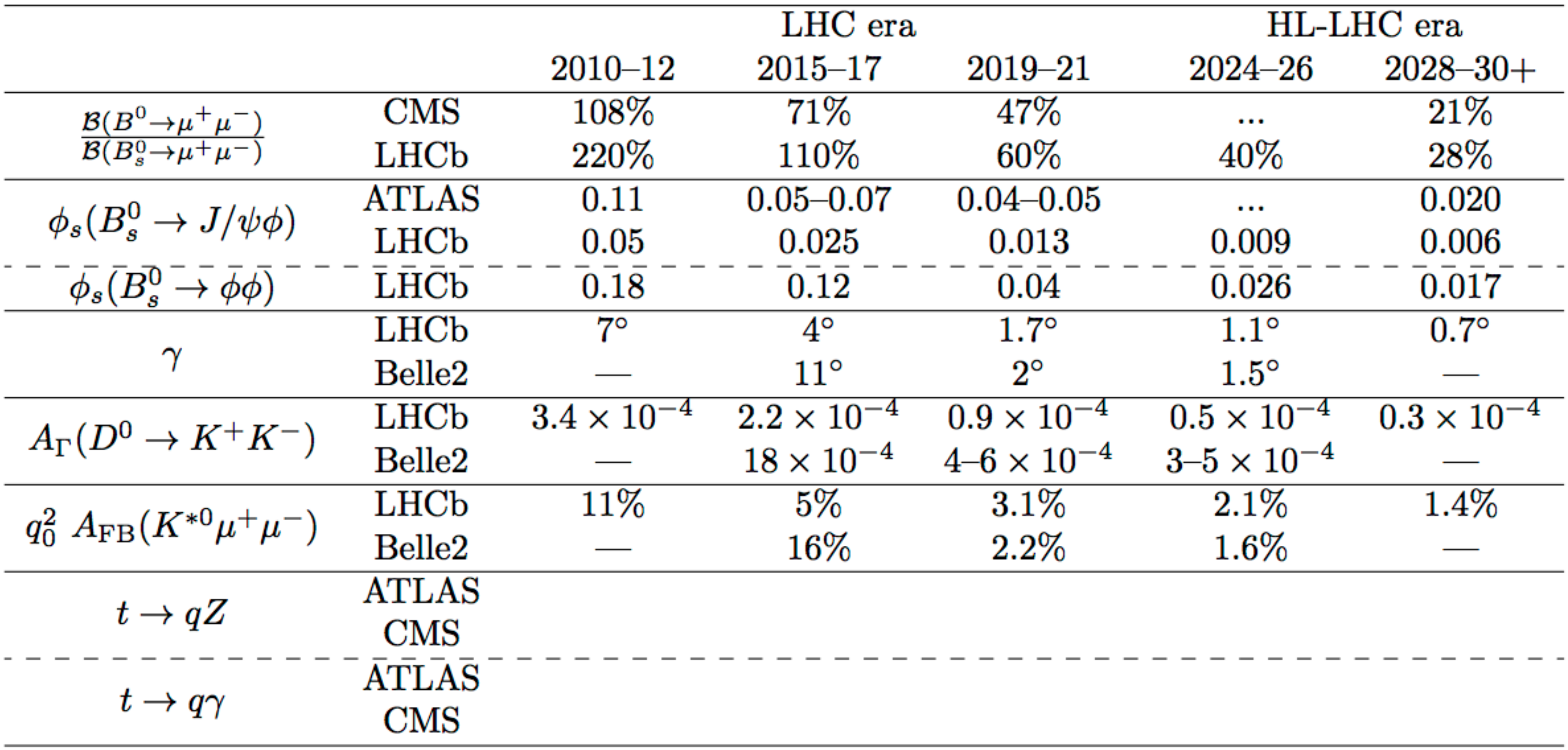
CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



Gain at 14 TeV from 300 → 3000 fb^{-1}



Expected sensitivities of key heavy-flavour observables



			LHC era		HL-LHC era	
		2010–12	2015–17	2019–21	2024–26	2028–30+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$	CMS	108%	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$\phi_s(B^0_s \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B^0_s \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle2	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle2	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	LHCb	11%	5%	3.1%	2.1%	1.4%
	Belle2	—	16%	2.2%	1.6%	—
$t \to qZ$	ATLAS					
	CMS					
$t \to q\gamma$	ATLAS					
	CMS					

See talk by M.-H. Schune for more numbers & details

Contrasting points of view on theory uncertainties

E.g. Ahrens et al (1008.3162), who say uncertainty can be made small, O(3%) in their framework even without N^3LO,

Baglio & Djouadi (1012.0530), David & Passarino (1307.1843), who argue it may be larger than widely accepted so far.

Bottom line?

We'll know more in a year or two, once N^3LO appears.

On 15 year timescale, TH community will learn yet more and hopefully move towards greater consensus on the uncertainties.

But ratios of observables (e.g. $ZZ^* / \gamma\gamma$) not affected.