Physics Potential of The LHC Upgrades

HL-LHC/HE-LHC Workshop

Wine & Cheese Seminar, FNAL, April 6, 2018

Tao Han

University of Pittsburgh

My 1st W&C seminar in 1999:

Physics Letters B

Volume 478, Issues 1–3, 6 April 2000, P

Physics potential of a Tevatron tripler

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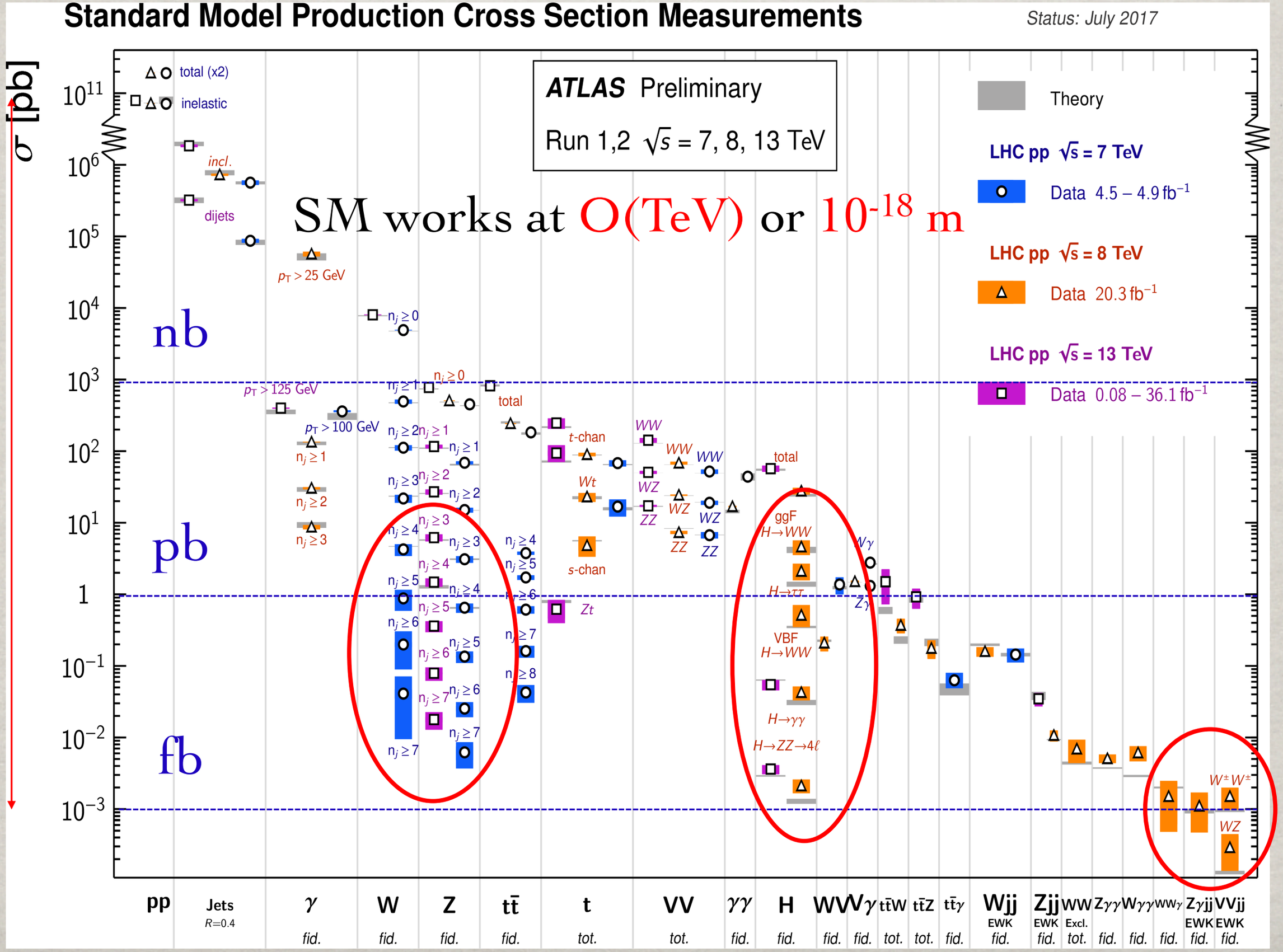
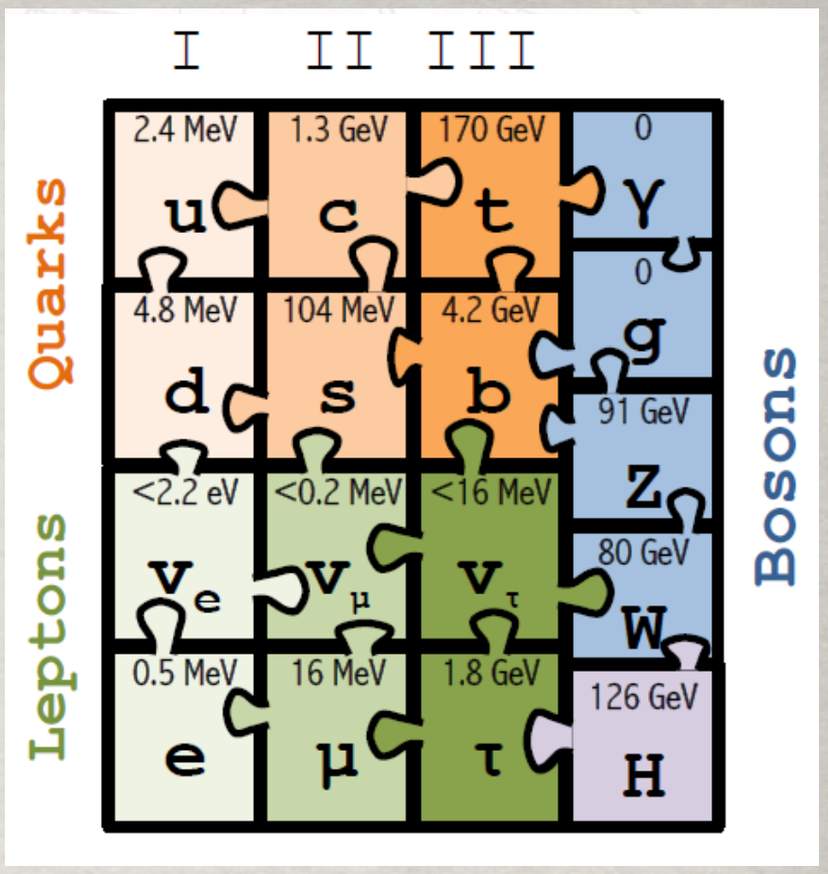
Abstract

We explore the capabilities for new physics discovery in proton-antiproton collisions at 5.4 TeV center-of-mass energy with luminosity $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at a Tripler upgrade of the Tevatron collider. The prospects are robust for the usual Higgs boson and supersymmetry benchmarks. With an integrated luminosity of 40 fb^{-1}, discoveries at 5σ could be made for a standard Higgs boson of mass $\lesssim$680 GeV (600 GeV for 10 fb^{-1}), a lighter chargino of mass $\lesssim$380 GeV, and an extra Z boson of mass $\lesssim$2.6 TeV; four-fermion contact interactions from new physics with scale $\lesssim$74 TeV could be excluded at the 95% confidence level.

LHC Rocks!


Standard Model Production Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 36.1 fb⁻¹
σ [pb]
O(14)
SM works at O(TeV) or 10-18 m
nb
pb
fb
total (x2)
inelastic
incl.
dijets
pT > 25 GeV
pT > 125 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
Zt
WW
WZ
ZZ
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
W±W±
WZ
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
WV fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Wjj EWK fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
WWγ fid.
Zγjj EWK fid.
VVjj EWK fid.



Completion of the SM:

First time ever, we have a quantum mechanical, relativistic, self-consistent theory: Weakly coupled, unitary, renormalizable, vacuum-(quasi?)stable.

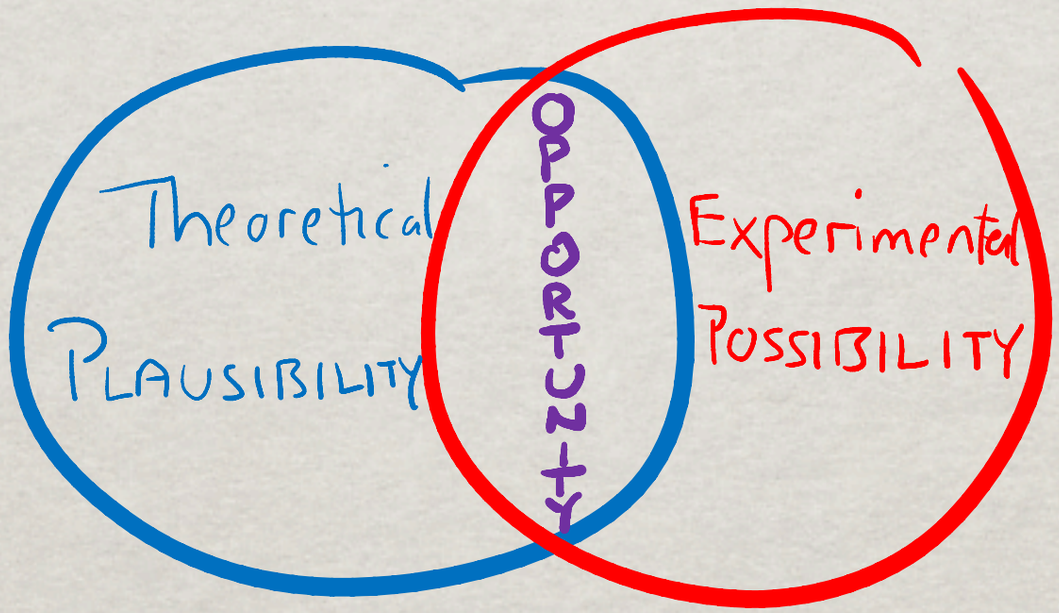
Valid up to an exponentially high scale!

Where is the next scale?

TeV or M_{Pl} ?

Raman Sundrum's "inspirational talk":

BUT OUR JOB IS CLEAR



Experimental Exploration with tentative theoretical guidance, reconnaisance, motivations, case studies.

SM as an Effective Field Theory

"The present educated view of the standard model, and of general relativity, is again that these are the leading terms in effective field theories." S. Weinberg, hep-th/9702027

"We are all Wilsonians now."

- J. Preskill, Quantum Frontier (2013)

In terms of a physical scale Λ ,
below which the theory is valid:

(relevant operators)

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \underline{c_0 \Lambda^4 + c_2 \Lambda^2 \mathcal{O}_{\text{dim } 2} + c_3 \Lambda \mathcal{O}_{\text{dim } 3}}$$

$$+ \underline{c_4 \mathcal{O}_{\text{dim } 4}} + \underline{\frac{c_6}{\Lambda^2} \mathcal{O}_{\text{dim } 6} + \ldots}$$

(marginal operators) (irrelevant operators)

SM as an Effective Field Theory

From observations: "Relevant operators (1)"

$$c_0\Lambda^4 \sim c.c.: \ (10^{-3}\ \mathrm{eV})^4 \sim (10^{-11}\Lambda_{\mathrm{QCD}})^4 \sim (10^{-14}v)^4 \sim (10^{-30}M_{\mathrm{Planck}})^4.$$

"Dark energy" / Cosmological constant.

A symmetry $c_0 \rightarrow 0$; or new principles?
(Gravity is far beyond the SM…)

$$c_2\Lambda^2 \sim m_h^2: \ \lambda v^2 \sim \mu^2 \sim (100\ \mathrm{GeV})^2 \sim (10^{-16}M_{\mathrm{Planck}})^2$$

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." Ken Wilson, 1970

→ "Hierarchy problem" between m_h & M_{Planck}

$\Lambda \sim 4\pi v$ near O(TeV)?
or new principles?

From observations: "Relevant operators (2)"

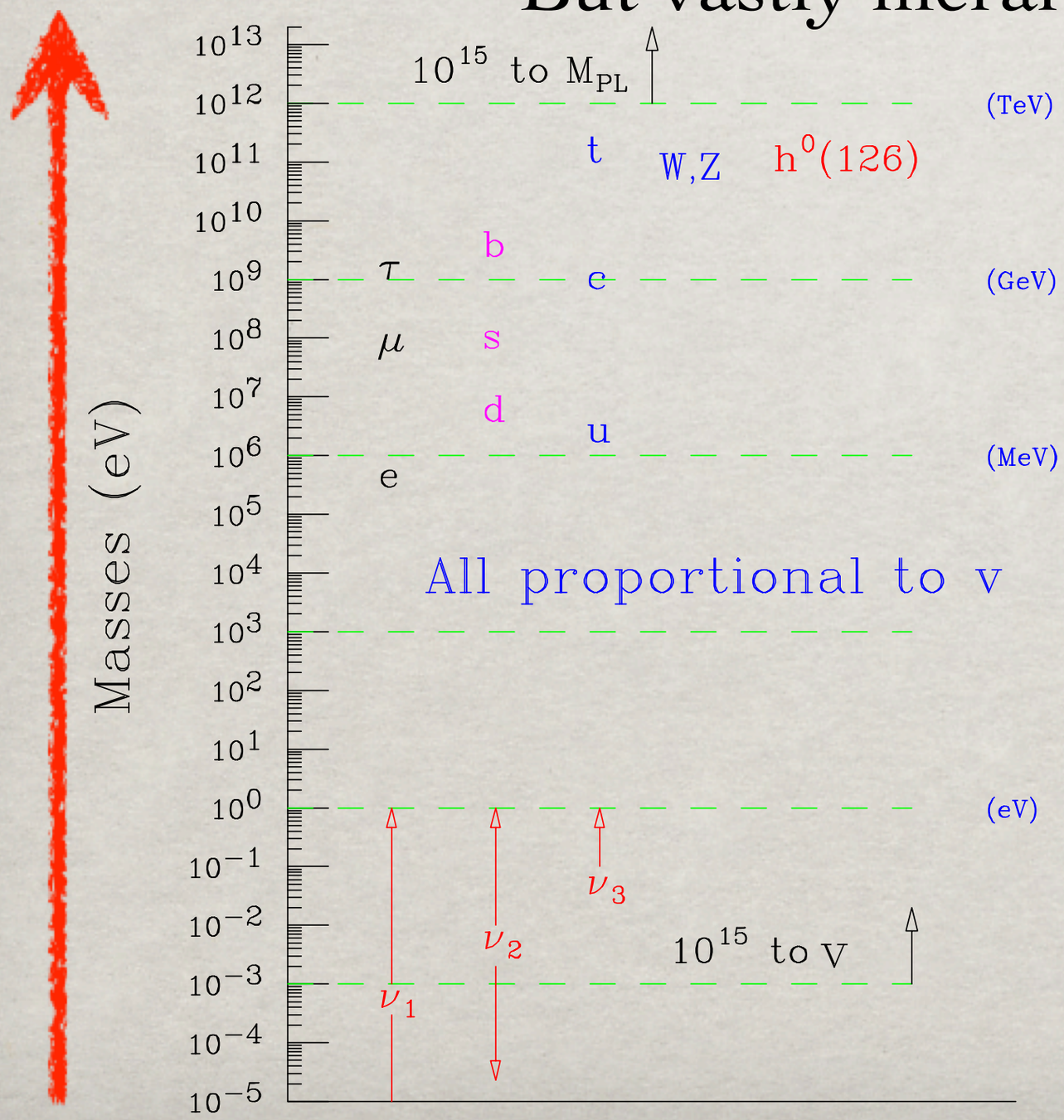
$c_2\Lambda^2 \sim m_w^2 : \; g^2v^2, \quad \delta m_w^2 \sim m_w^2 \ln(\Lambda/m_w)$ (gauge symm)

$c_3\Lambda \sim m_f : \; y_f v, \quad \delta m_f \sim m_f \ln(\Lambda/m_w)$ (chiral symm)

They are (technically) natural.

G. 't Hooft, 1997.

But vastly hierarchical...



Other mass terms:

- Dark Matter wanted!
- Neutrino masses:
  Dirac? Majorana?
- Any other states?
  new gauge bosons,
  vector-like fermions,
  lepto-quarks,
  more Higgs scalars
  SM partners, KK states?

From observations: "Marginal operators"

$c_4 \mathcal{O}_{\text{dim } 4} : \mathcal{L}_{SM}(\text{kinetic terms, interactions})$

All SM couplings and mixings well measured!

- Baryon-Antibaryon asymmetry!
- New CP-violation sources needed!
- Why hierarchical quark mixings?
- "bi-Maximal" neutrino mixings?
- Gauge unification (couplings & spectrum)?

Hierarchical questions / problems.

From observations: "Irrelevant operators"

$$\frac{c_6}{\Lambda^2}\mathcal{O}_{\text{dim 6}} : \frac{c_{ij}}{\Lambda^2}\overline{\psi}_i O\psi_j \; \overline{\psi}O\psi + \ldots$$

- Highly constrained by the non-existence of excessive FCNC, CPv … $\frac{c_{ij}}{\Lambda^2} < \frac{1}{(100\ \text{TeV})^2}.$

- "Minimal Flavor Violation" ? (SM Higgs structure)

A symmetry $c_{ij} \rightarrow 0$? or $\boldsymbol{\Lambda} >> 4\boldsymbol{\pi}$ v ?

or new principles?

The SM seems to be highly "unnatural"!

(in the Wilsonian sense)

"…whether naturalness is really a reliable criterion for evaluating success in physical theories. Could Wilson have steered us wrong?" J. Preskill, Quantum Frontier (2013)

The High Luminosity LHC Project: (HL-LHC)

CERN: HL-LHC is the top priority of the European Strategy for Particle Physics in its 2013 update, and is part of the 2016 roadmap of the European Strategy Forum on Research Infrastructures. It is formally approved by CERN Council in June 2016.

U.S. DOE: HL-LHC Accelerator and ATLAS and CMS Detector upgrades are called out in the P5 strategy and are high-priority at DOE.

CD-1 (Critical Decision): HL-LHC Accelerator Upgrade Project was approved in October 2017; HL-LHC ATLAS and CMS Detector Upgrade Projects are being reviewed.

"No doubt that future high energy colliders are extremely challenging projects.

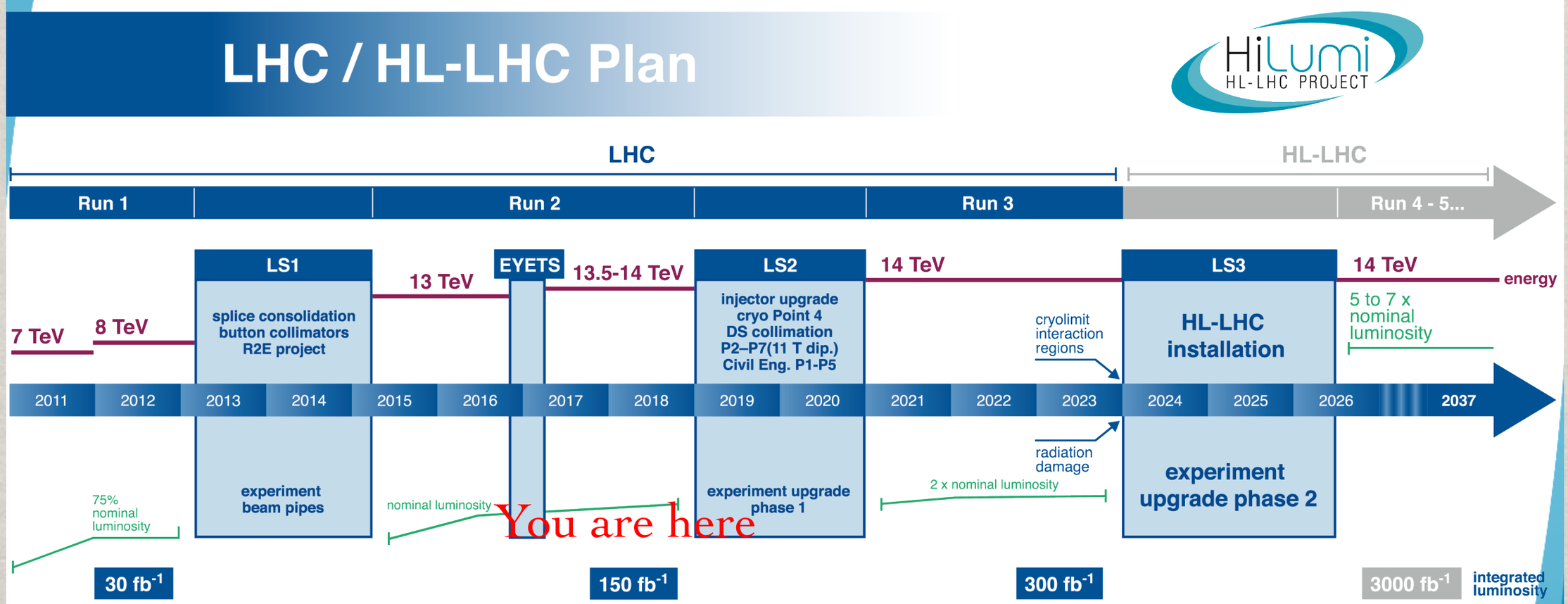
However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

Fabiola Gianotti, DG CERN

HL-LHC:
The Energy & Precision Frontier

Sasha Valishev

Timeline & Goal:
Commissioning 2026; 3 ab^{-1} by 2037 (250 fb^{-1}/y)

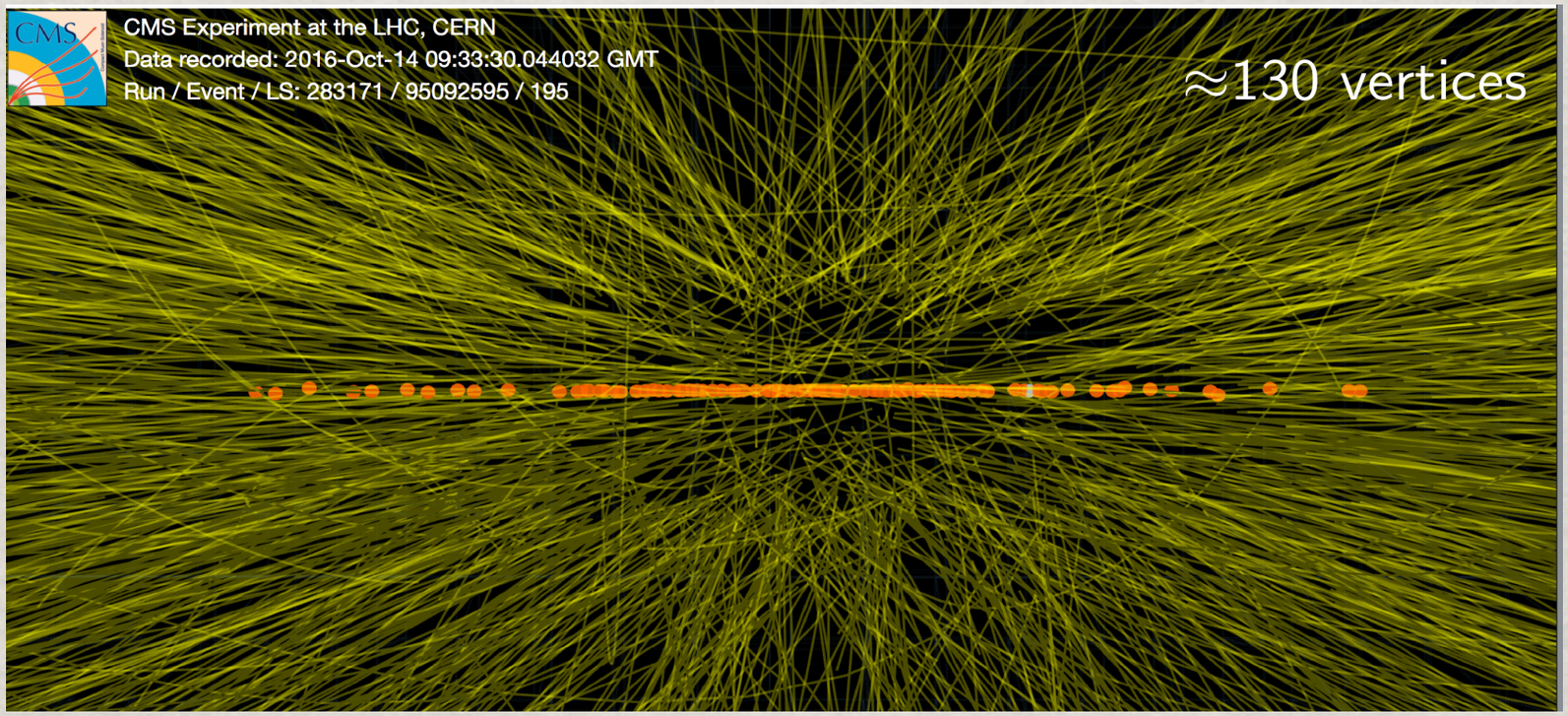


Levelled Luminosity $L = 5\times10^{34} cm^{-2} s^{-1}$

HL-LHC Experimentation Challenges

- Radiation hardness
- 150 – 200 pileups / bunch crossing!

A real-live event (CMS)



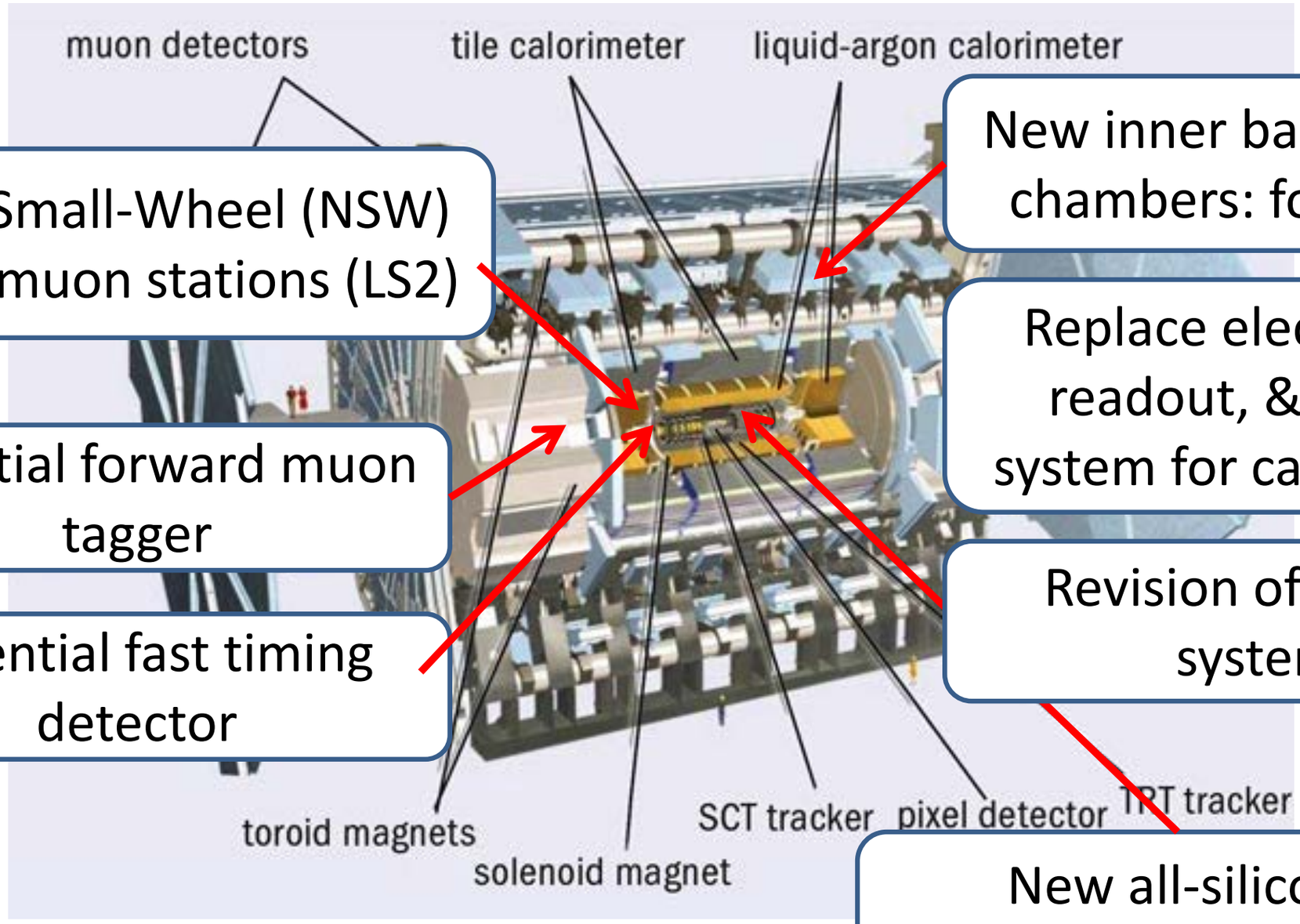
- Trigger
- isolation
- E_T^{miss}
- Vertexing

HL-LHC: The Detector Upgrades

ATLAS

Lydia I.-Fayard (2017)
Yangyang Cheng, this workshop

HL-LHC Upgrade: ATLAS Overview



New Small-Wheel (NSW) inner muon stations (LS2)

New inner barrel muon chambers: for trigger

Replace electronics, readout, & power system for calorimetry

Potential forward muon tagger

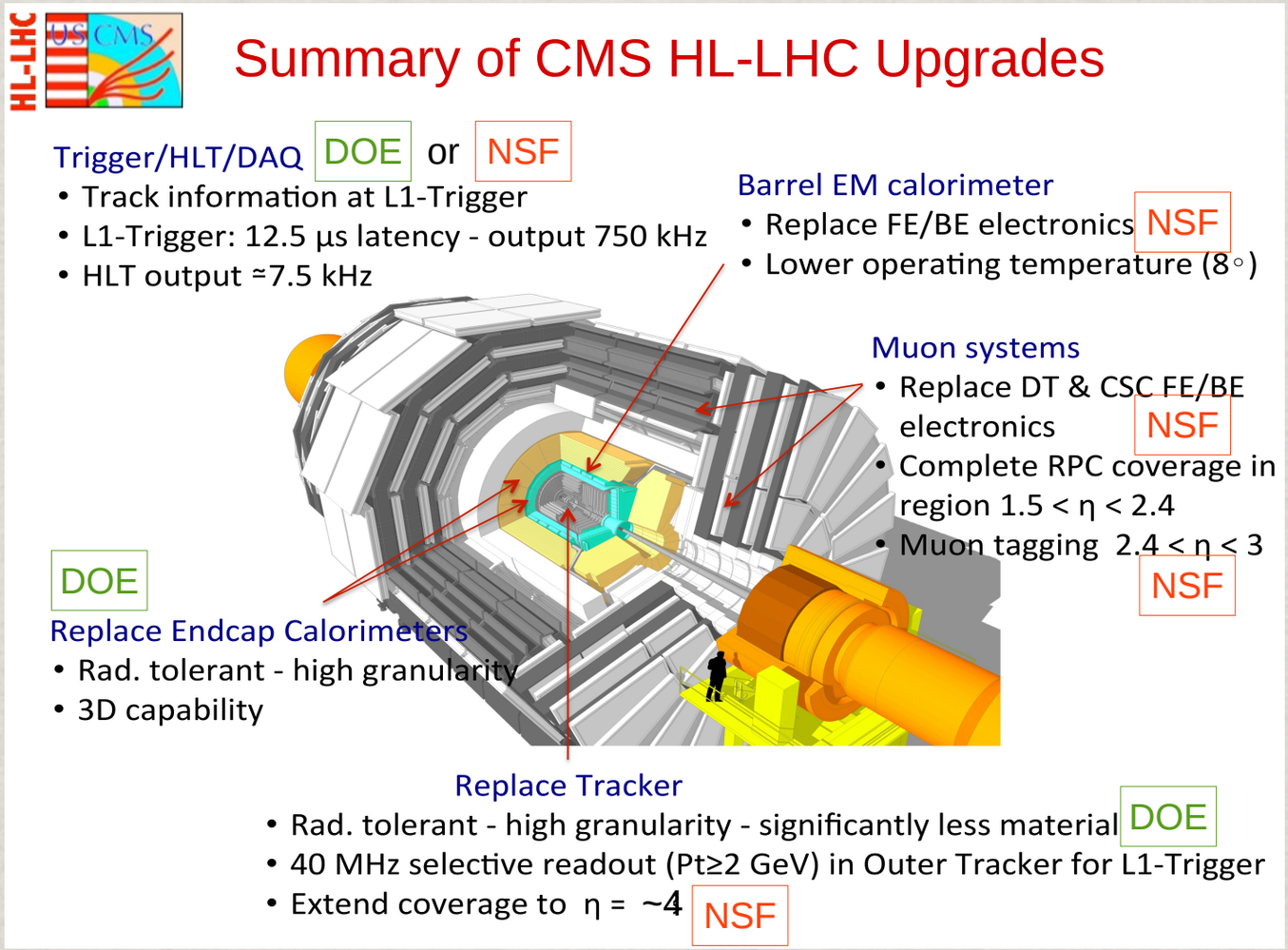
Revision of trigger system

Potential fast timing detector

New all-silicon inner tracker (ITK)

HL-LHC: The Detector Upgrades

CMS



Highlights:

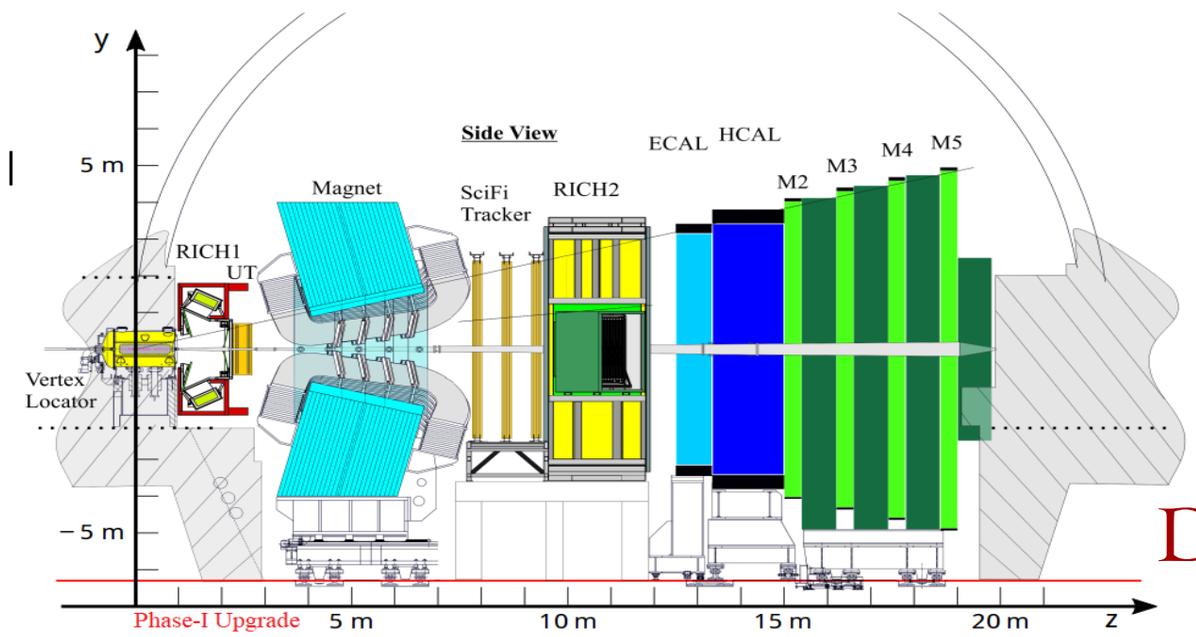
- New tracker, extended ~ 4 (2.5)
- Muon coverage ~ 3 (2.4)
- L1 trigger rate 750 kHz (100 kHz)
- Photon E resolution ~ few%
- Timing detector …

HL-LHCb Detector Upgrades

General aspects for a HL/HE LHCb

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		Run III						Run IV					Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE Phase I		$L = 2 \times 10^{33}$			LHCb Consolidation			$L = 2 \times 10^{33}$ $50\ fb^{-1}$			LHCb Ph II UPGRADE *		$L = 2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			ATLAS Phase II UPGRADE			HL-LHC $L = 5 \times 10^{34}$			ATLAS		HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr		$300\ fb^{-1}$			CMS Phase II UPGRADE						CMS		$3000\ fb^{-1}$	
Belle II		$5\ ab^{-1}$	$L = 8 \times 10^{35}$		$50\ ab^{-1}$									

$\times 10$ particle multiplicity
$\times 10$ vertex multiplicity

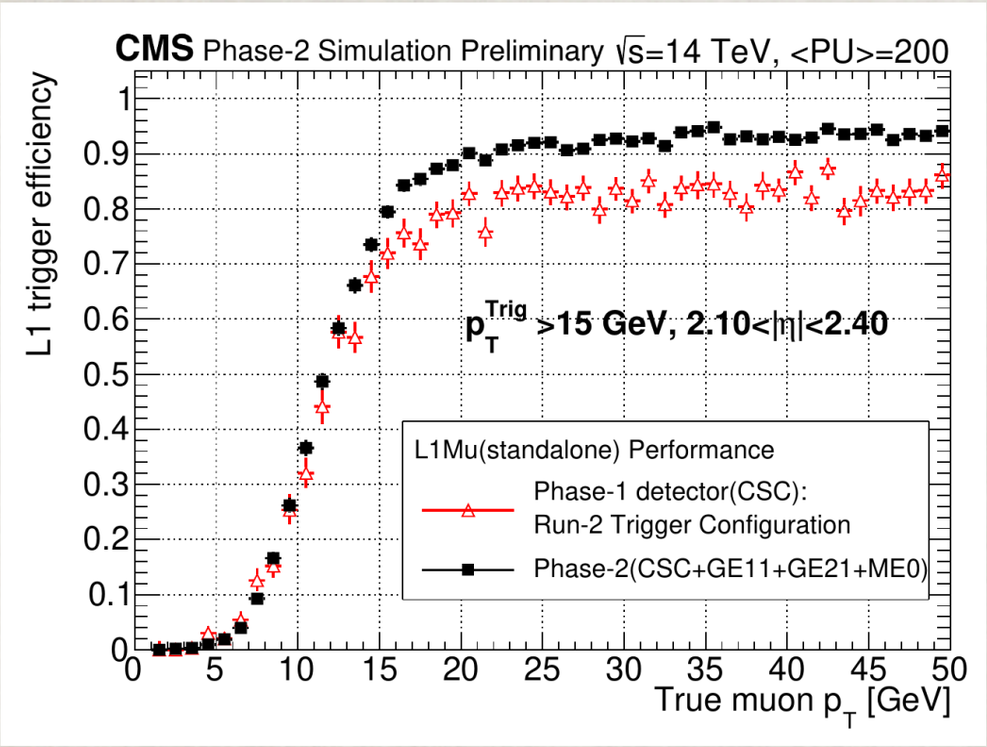


- Triggerless readout at 40 MHz
- New vertex locator
- New tracking (UT, SciFi)

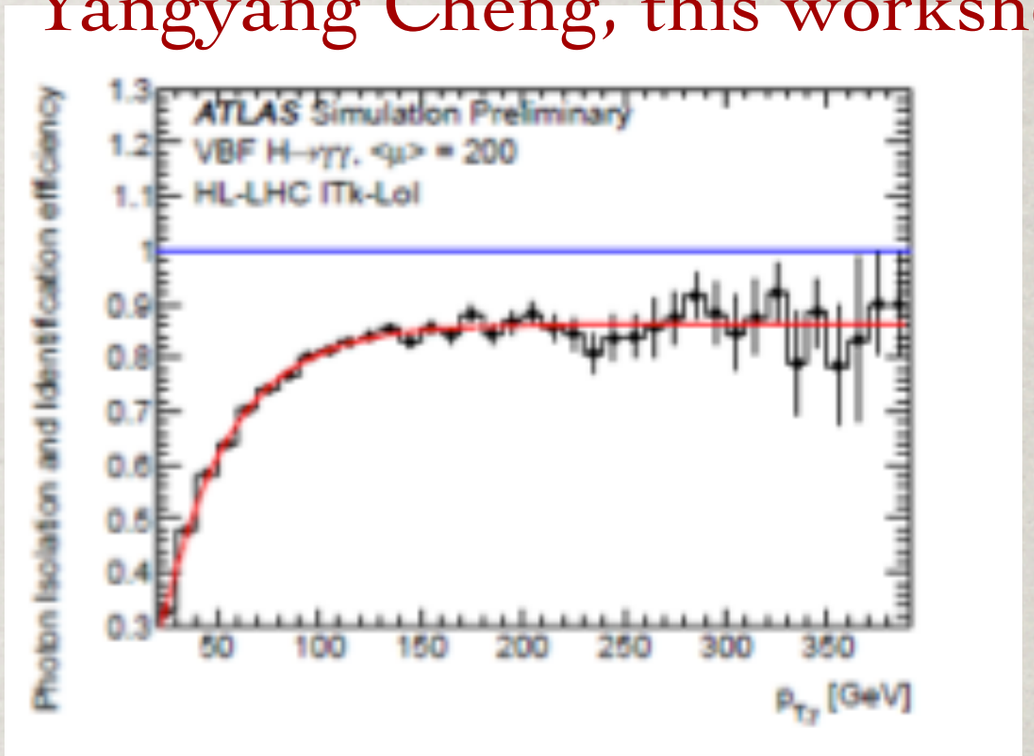
Dan Craik, this workshop

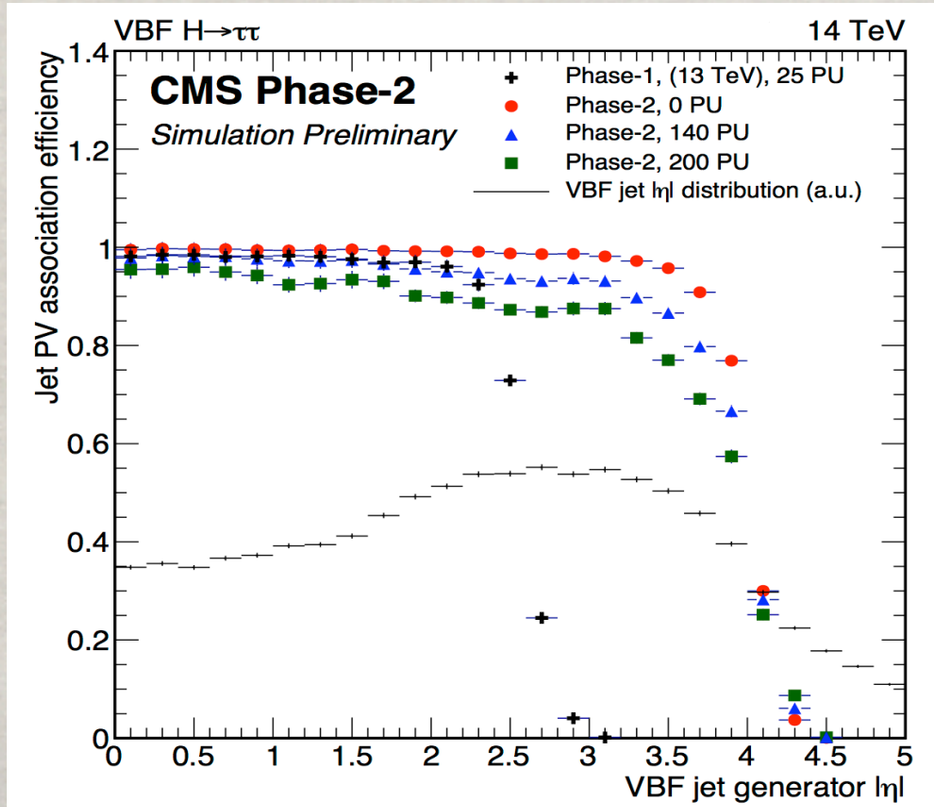
Great Detectors!

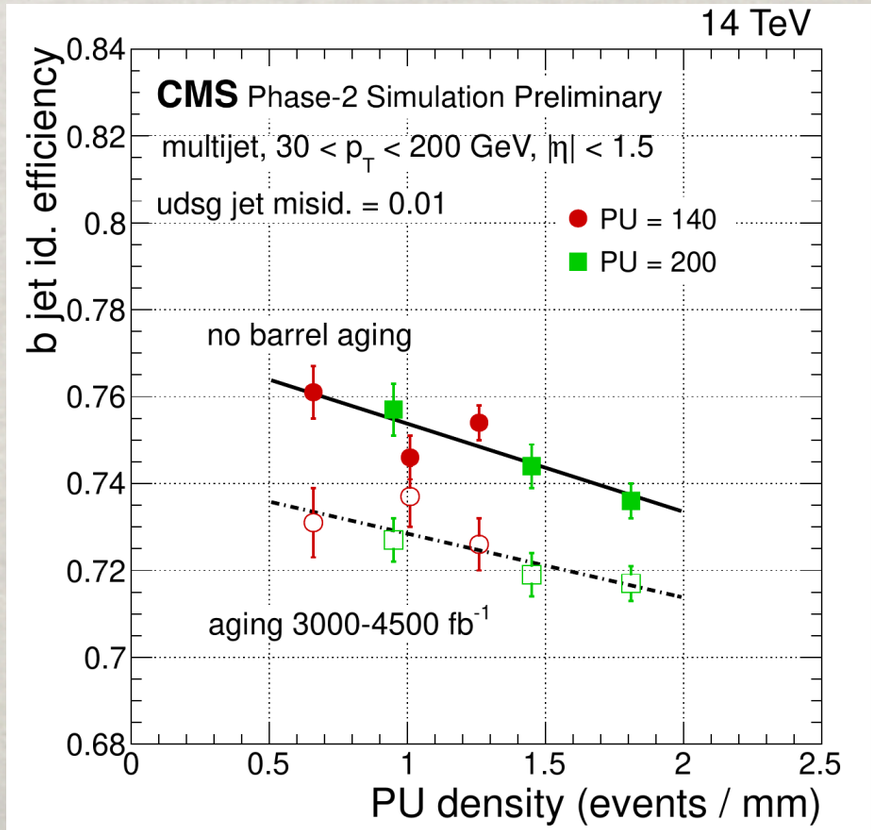
Josh Bendavid (CMS, 2017)



Lydia I.-Fayard (2017);
Yangyang Cheng, this workshop







Well-motivated Targets:

1. "Naturalness": top squark and T' partner, with the "fine-tune" to a level

$$v^2/\Lambda^2 \sim 6\% \ (1 \text{ TeV}/\Lambda)^2$$

2. Precision Higgs measurements:

Complementary to the BSM direct searches

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \text{a few \% for } M \approx 1 \text{ TeV}$$

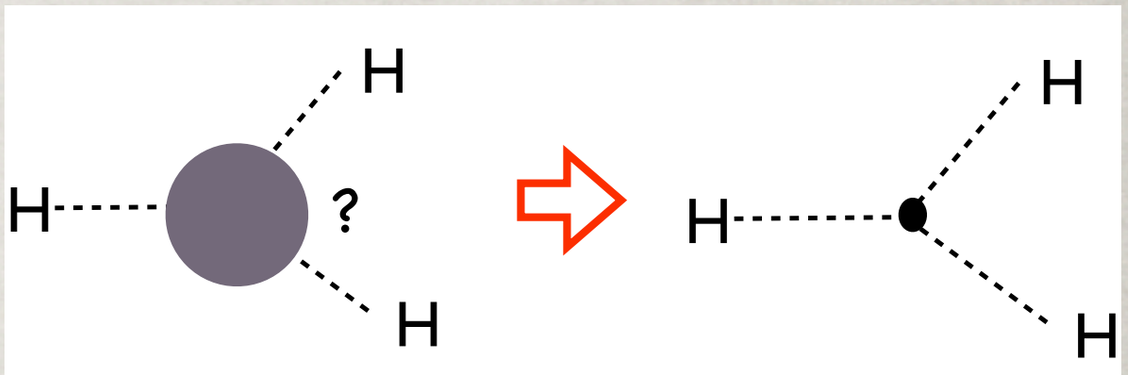
Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(v/f)^2$	(tree-level)	50%
H^0, A^0	6%	$(500 \text{ GeV}/M_A)^2$		
T'			$-10\% \ (1 \text{ TeV}/M_T)^2$ (loop)	
HL-LHC, 3 ab^{-1}:	5%	10%	5%	50%

3. Higgs Self-couplings:

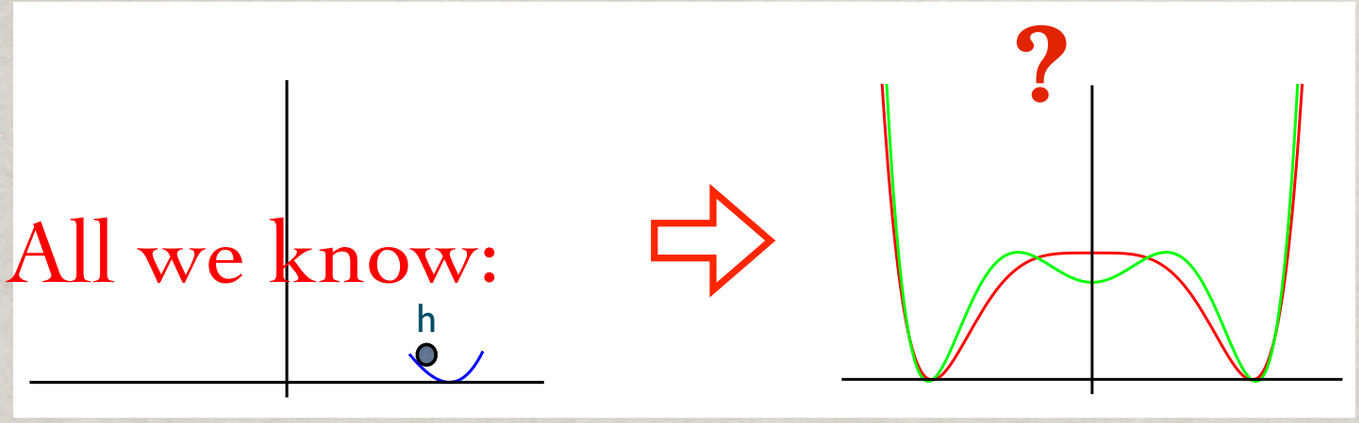
$$\mathcal{L} = -\frac{1}{2}m_H^2 H^2 - \frac{g_{HHH}}{3!}H^3 - \frac{g_{HHHH}}{4!}H^4$$

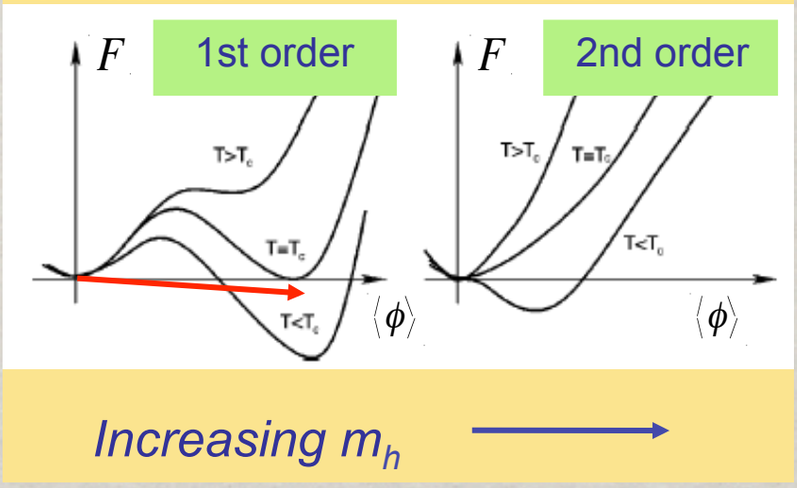
$$g_{HHH} = 6 \quad v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \quad = \frac{3m_H^2}{v^2}.$$



Triple Higgs boson coupling λ_{hhh} :

Test the shape of the Higgs potential,
probe the fate of the EW-phase transition (EWPT):
O(100%) deviation needed for 1st order EWPT;
O(10%) accuracy needed for a conclusive test.

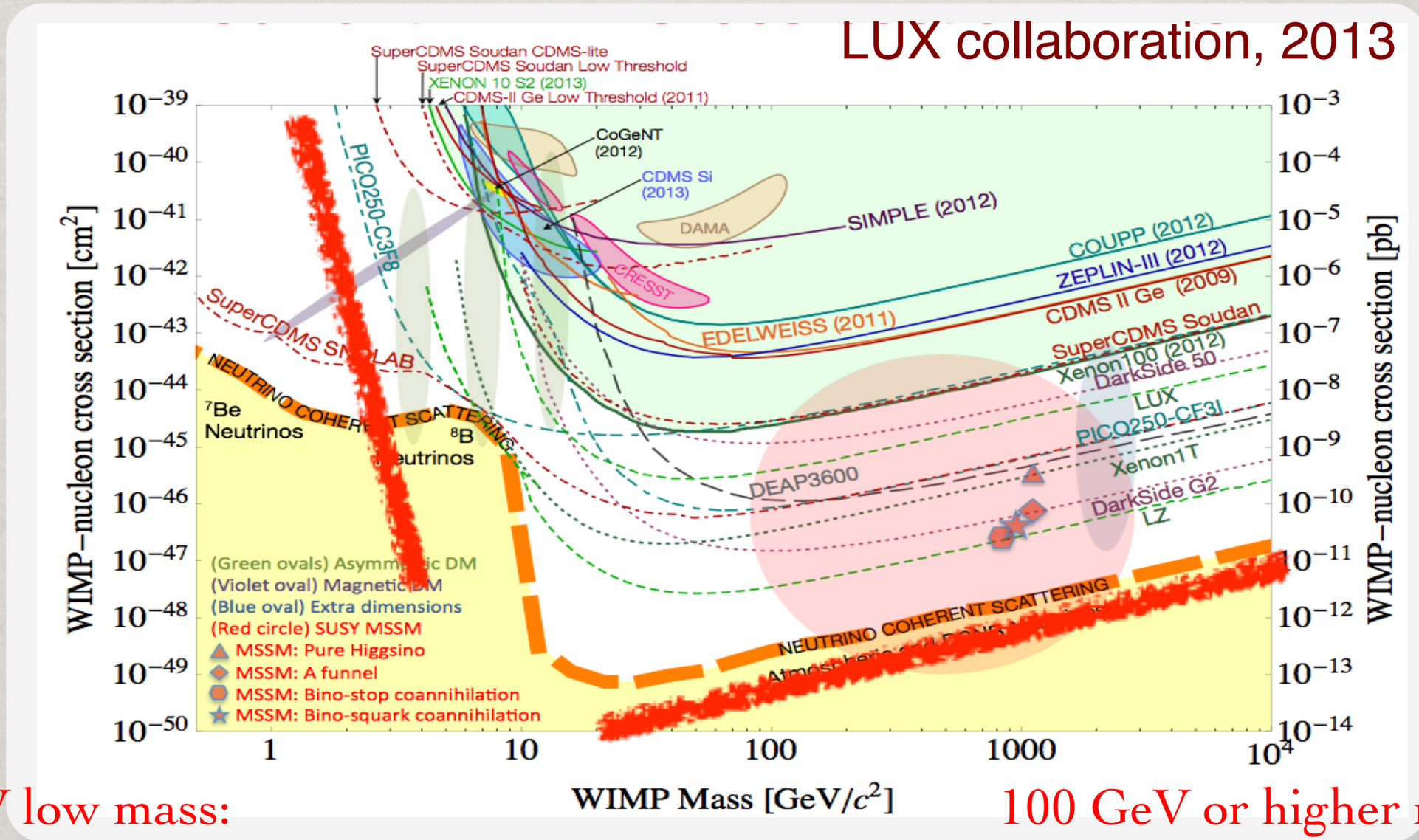




M. Ramsey-Musolf, this workshop

4. Thermal WIMP DM:

$$\Omega h^2 = 0.11 \times \left(\frac{\langle \sigma v \rangle_{\rm freeze}}{2.2 \times 10^{-26}\ {\rm cm}^3/{\rm s}} \right)^{-1}, \quad \sigma \propto g_{\rm eff}^4 / M_{\rm DM}^2. \rightarrow M_{\rm DM} < 1.8\ {\rm TeV} \left(\frac{g_{\rm eff}^2}{0.3} \right)$$



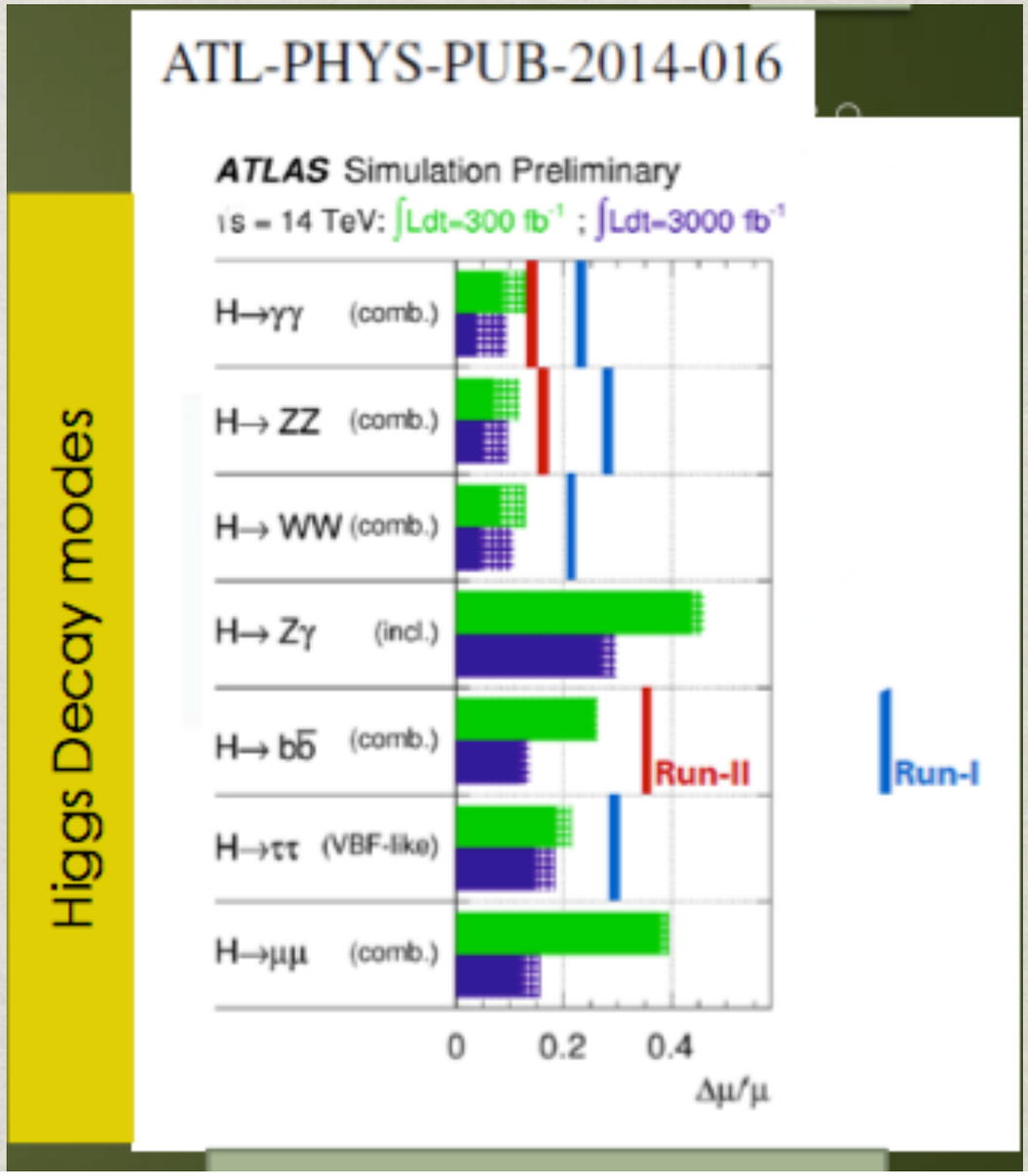
GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD difficult;
HE Collider for O(1) TeV

HL-LHC: Physics Highlights (a few)

Higgs couplings:

Lydia I.-Fayard (ATLAS, 2017);
S. Jezequel, this workshop



CMS: arXiv:1307.7135v2

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

(%)

HL: Good for rare decays:
e.g. Higgs coupling to the second family:

T. Plehn et al., hep-ph/0107180; TH, B. McElrath, hep-ph/0201023
Lydia I.-Fayard (ATLAS, 2017)

Higgs coupling to light leptons: H->μμ

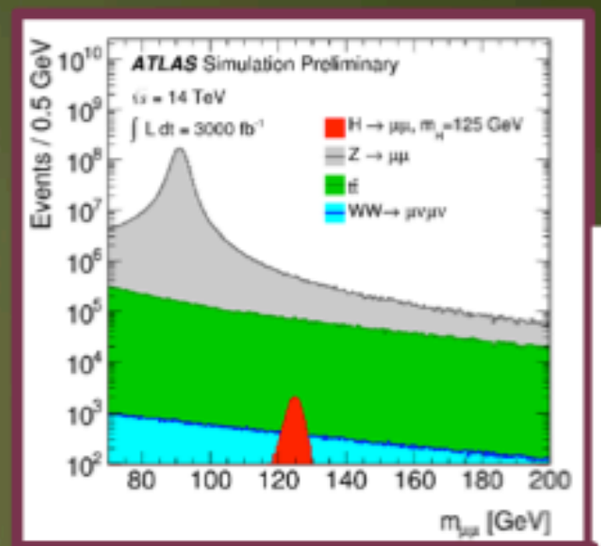
60

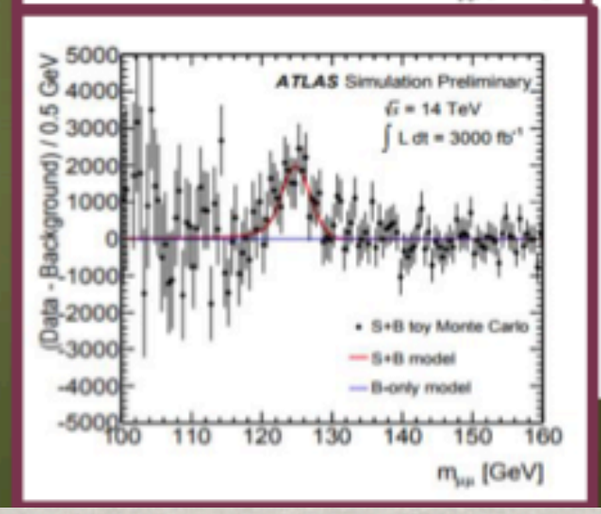
Coupling to second generation
Candle for HL-LHC
Small BR ~ 2x10-4
ATLAS Run2 (36 fb-1) 13 TeV : μ=-0.1+-1.5

Projections for HL-LHC
→With Run 1-like cuts, cut based analysis
→Main background from Z/γ*, ttbar and WW

With 3000 fb-1 → 7.0 σ
Δμ/μ → +- 20%

→Optimized analysis ready, coming soon public in the Muon –TDR.





ATL-PHYS-PUB-2013-014

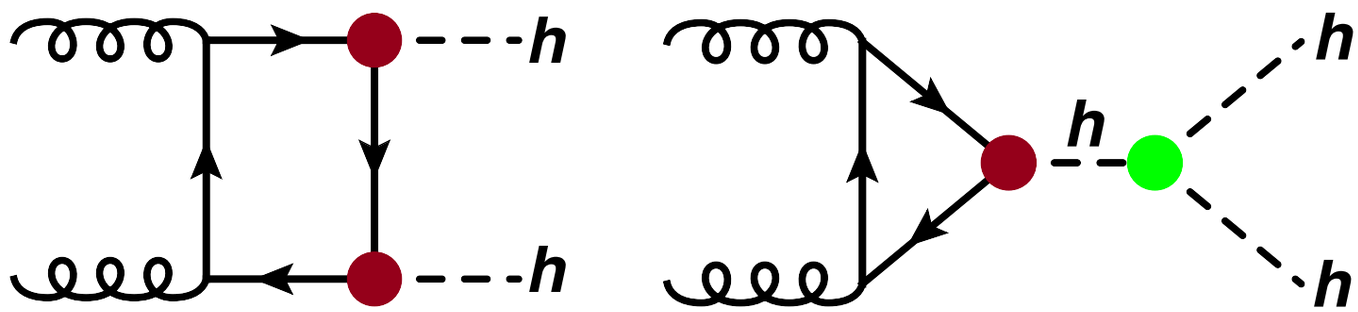
CORFU September 2017
04/09/2017

Higgs pair production & triple coupling:

Lydia I.-Fayard (ATLAS, 2017);
C. Vernieri, this workshop;
Peter Bokan, this workshop

SM Higgs boson pair production at the LHC

SM Higgs boson pair production (gluon-gluon fusion - ggF):



Higgs-fermion Yukawa coupling Higgs boson self-coupling

Channel	CMS	ATLAS
HH → bbbb	$Z(\sigma_{HH}(SM))=0.39\ \sigma$	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L.
HH → bbττ	1.6 xSM	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L.
HH → bbγγ	1.43 σ Very weak signal.	1.5 σ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only)

S. Jezequel, this workshop

Expected coverage by LHC experiments

	CMS	ATLAS	LHCb
Couplings Studies	✔✔★	✔✔★	
Differential CrossSections	✔★	✔★	Courtesy M. Cepeda
Width		✔	
CPV	✔★	✔	
Rare Decays	μμ,cc	Zγ,J/ψγ,FCNC μμ,ργ,cc	Hcc/Hbb
Exotic Decays	LFV; Invisible, DarkSusy; 4jets		
DiHiggs	✔✔★	✔✔★	
Additional Scalars	A->Zh, high mass ττ, low mass γγ	μμ, ZZ, A->Zh, ττ, WW	Higgs at LHeC : U. Klein

Legend: Past Studies, 2017 TDRs, Wishlist for 2018

Stay tuned : CMS public page , ATLAS public page

S. Jezequel; E. Stamou;
Dan Craik, this workshop

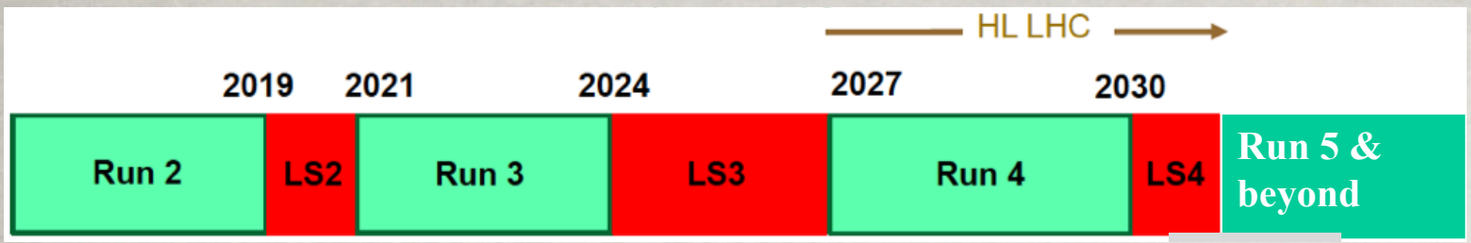
$H^0 \to c\bar{c}$ @ LHCb: future

Prospects for upgrade phase 2

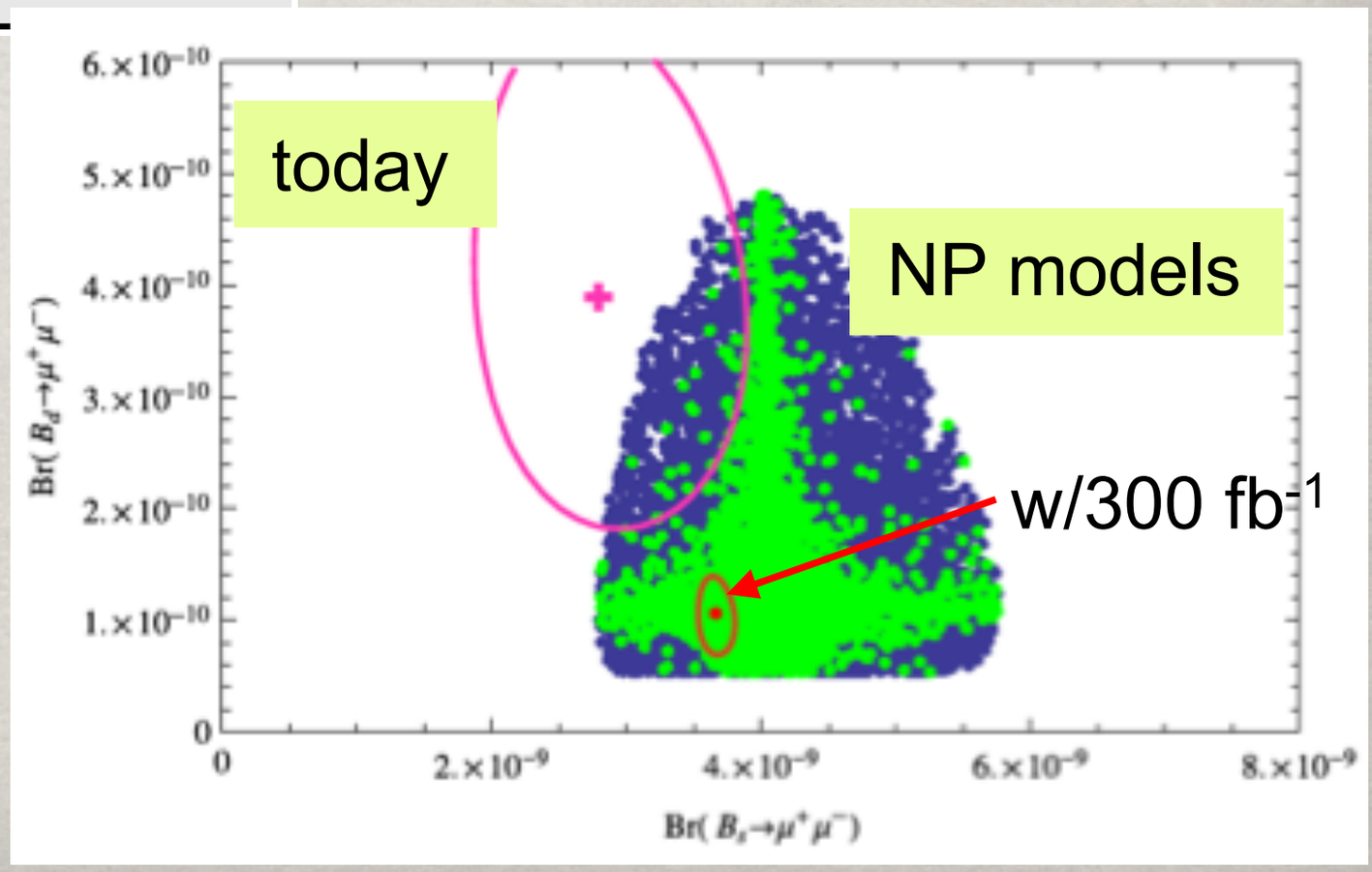
- *VH* cross-section in LHCb acceptance increases by a factor of ~ 7 from 8 TeV to 14 TeV
- After 300 fb^{-1}, expect to set limit on Yukawa coupling of $\sim 7 y^c_{\mathrm{SM}}$
- With improvements to detector performance and $b - c$ separation, and looser tagging requirements, this could be brought to $\sim 2 y^c_{\mathrm{SM}}$
- If VBF production can also be utilised, this could yield similar statistics

HL-LHC: Flavor Physics

Hassan Jawahery, this workshop

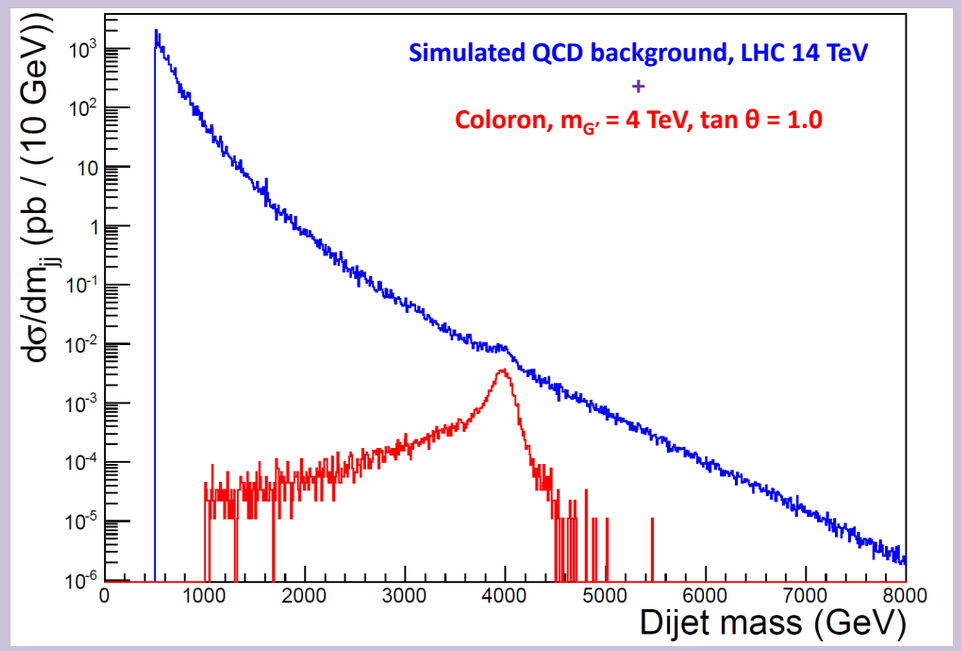


	Now	LHCb upgrade I	Belle-II	LHCb-Upgrade II
Data size		50 fb^{-1}	50 ab^{-1}	300 fb^{-1}
γ	5°	1°	1°	0.4^o
ϕ_s	0.025	0.008	--	0.003
$B \to \mu\mu / B_s \to \mu\mu$	90%	~40%	--	~20%
$B \to K^{(*)}\nu\nu$	--	~12%	--	



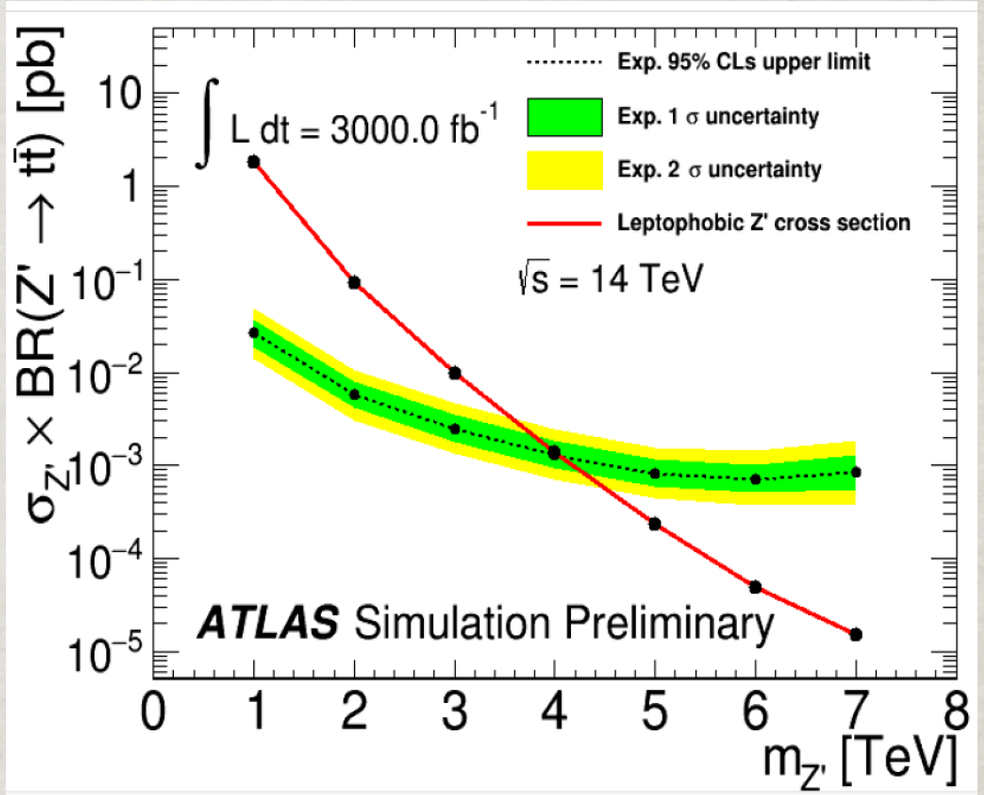
HL-LHC: Bump-hunting benefits from high lumi

Z′ bump hunting



FY [1308.1077]

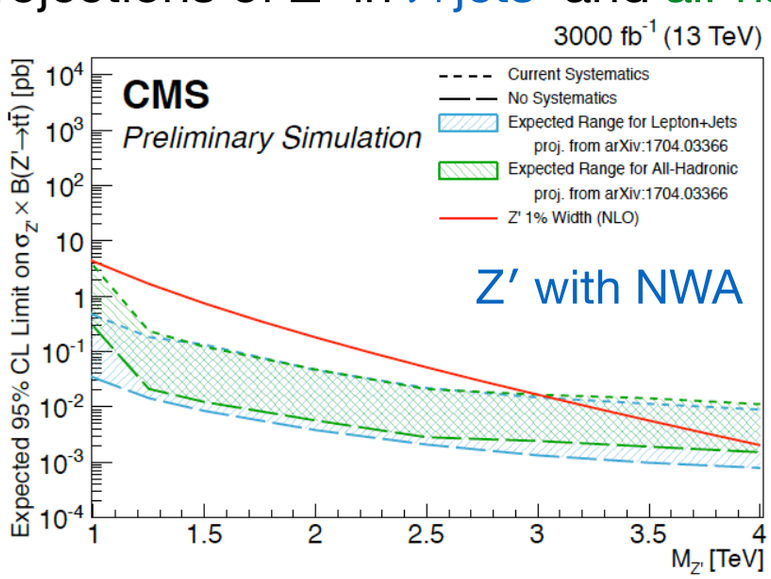
Felix Yu – Z′ Physics

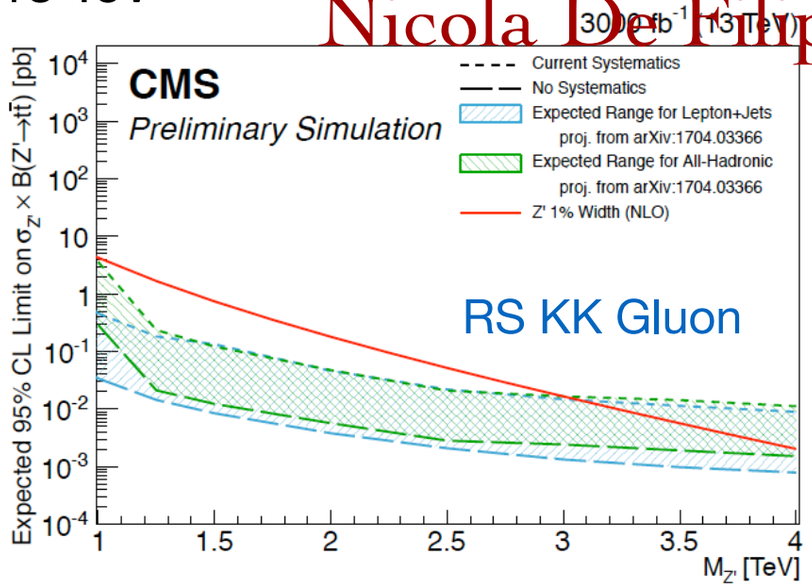


Z' → tt

Sadia Khailil, this workshop, CMS-PAS-FTR-16-005;
Nicola De Filippis, this workshop

Projections of Z′ in *l*+jets and all-had @ 13 TeV



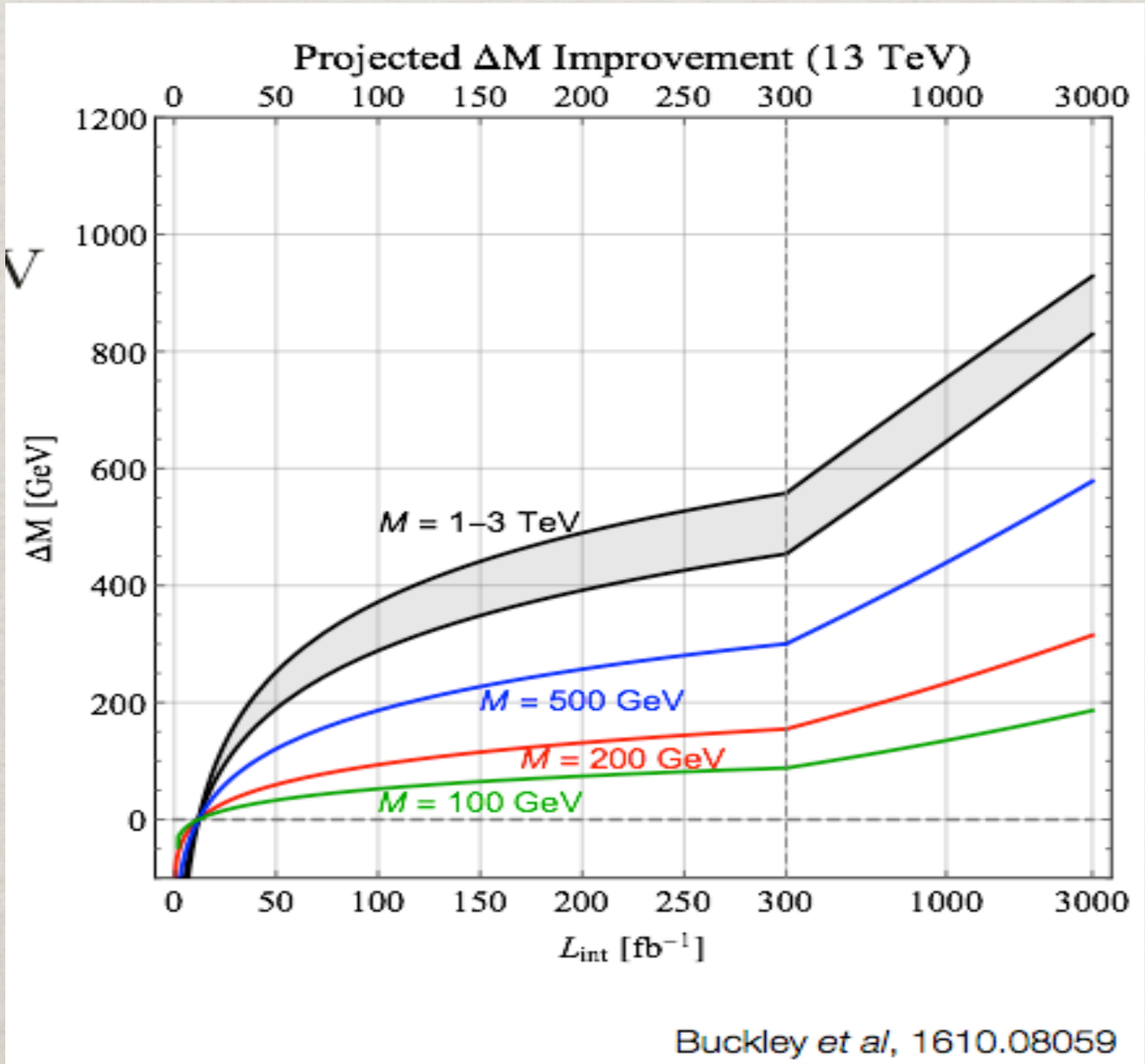


Mass scale reach for higher lumi:

Hinchliffe, Kotwal, Mangano, Quigg, L.-T. Wang, arXiv:1504.06108.

$$\hat{\sigma} \propto \frac{1}{M^2}$$

$\Delta M/M \sim 50\% \log(L_2/L_1)$



Buckley *et al*, 1610.08059

HE-LHC: The New Energy Frontier

Vladimir Shiltsev, this workshop

HE-LHC design goals and basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)

key technologies:

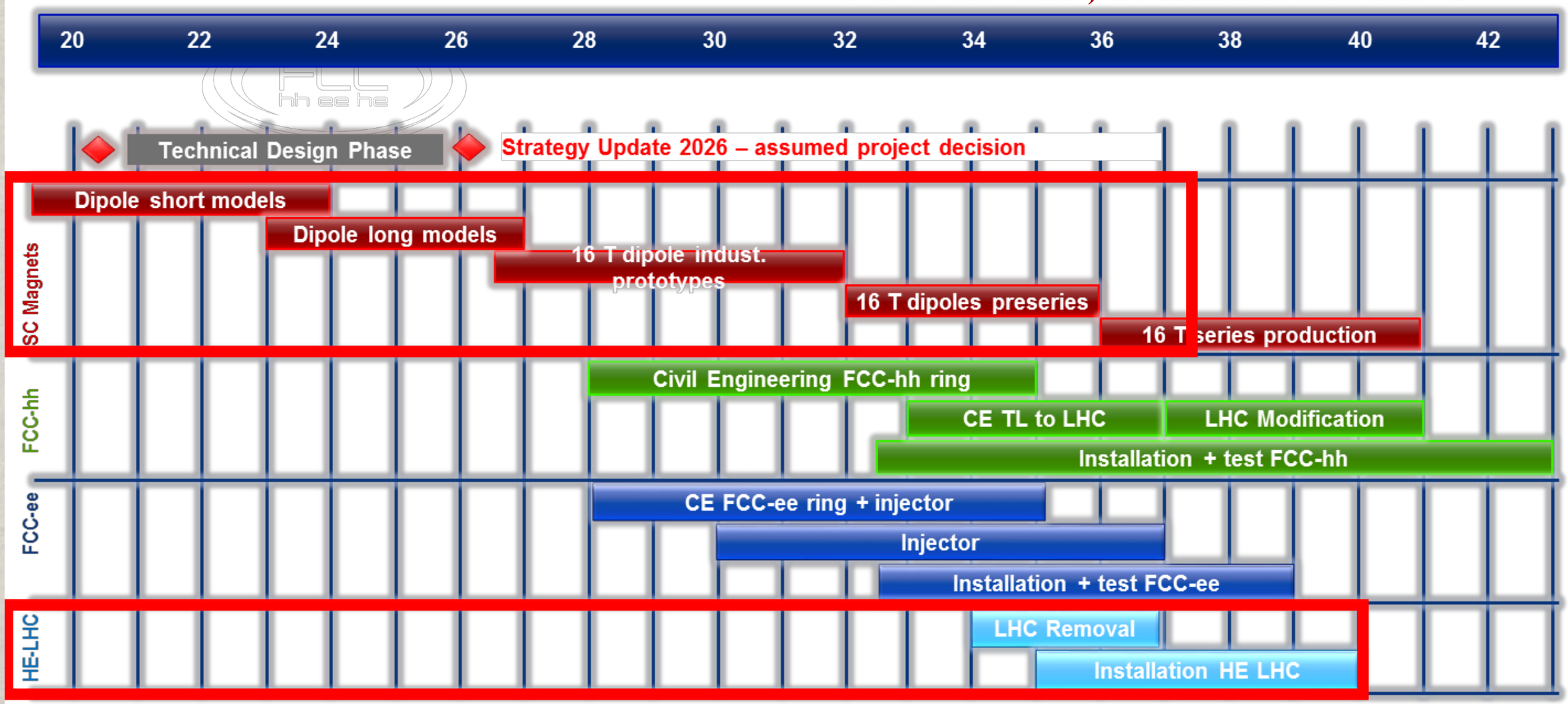
- FCC-hh magnets (curved!) & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

Fastest Possible Technical Schedules

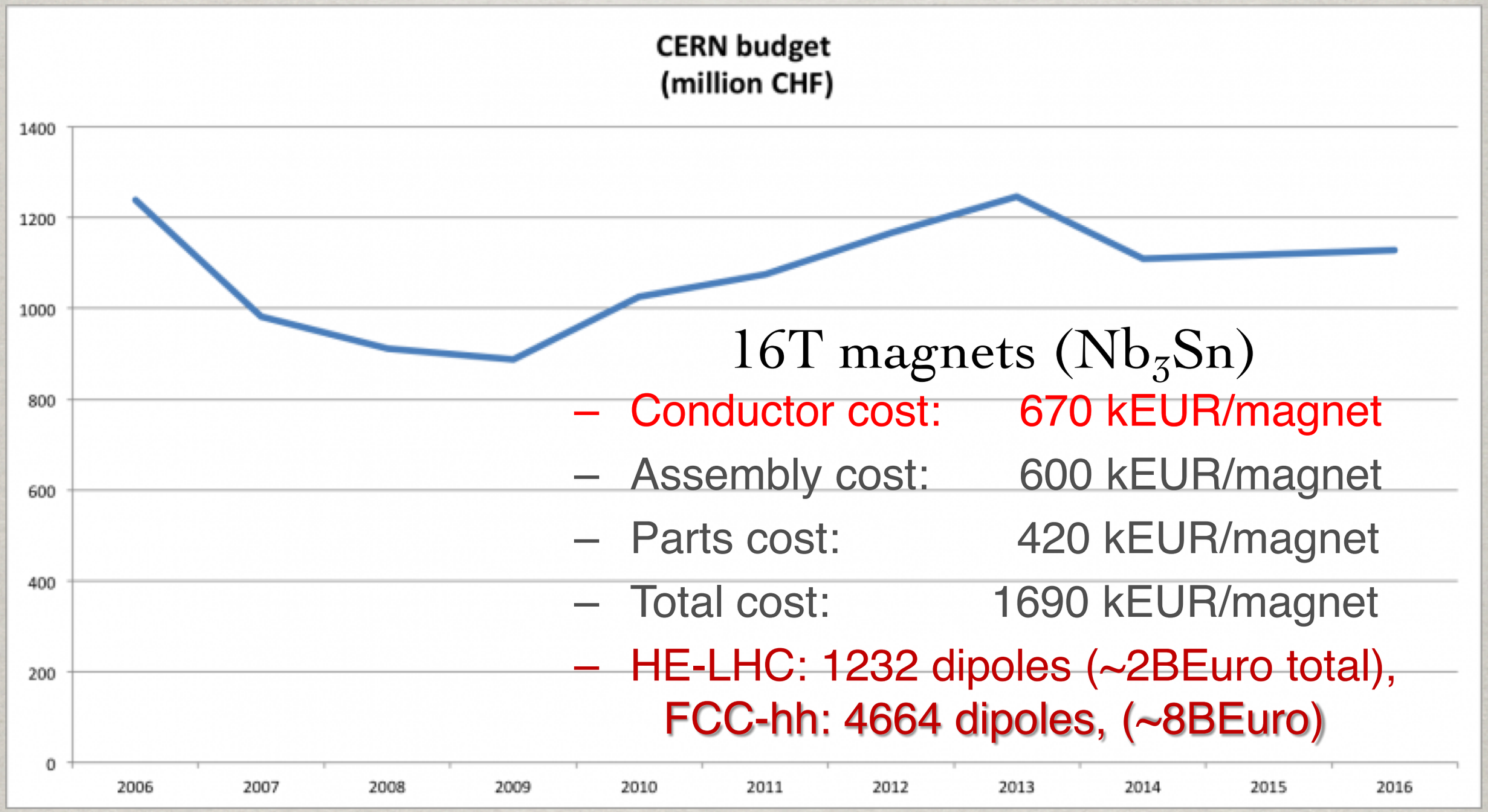
M. Benedikt, F. Zimmermann '17



HE-LHC design & construction

technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)
- Options: FCC-ee @ 2039; FCC-hh @ 2043.

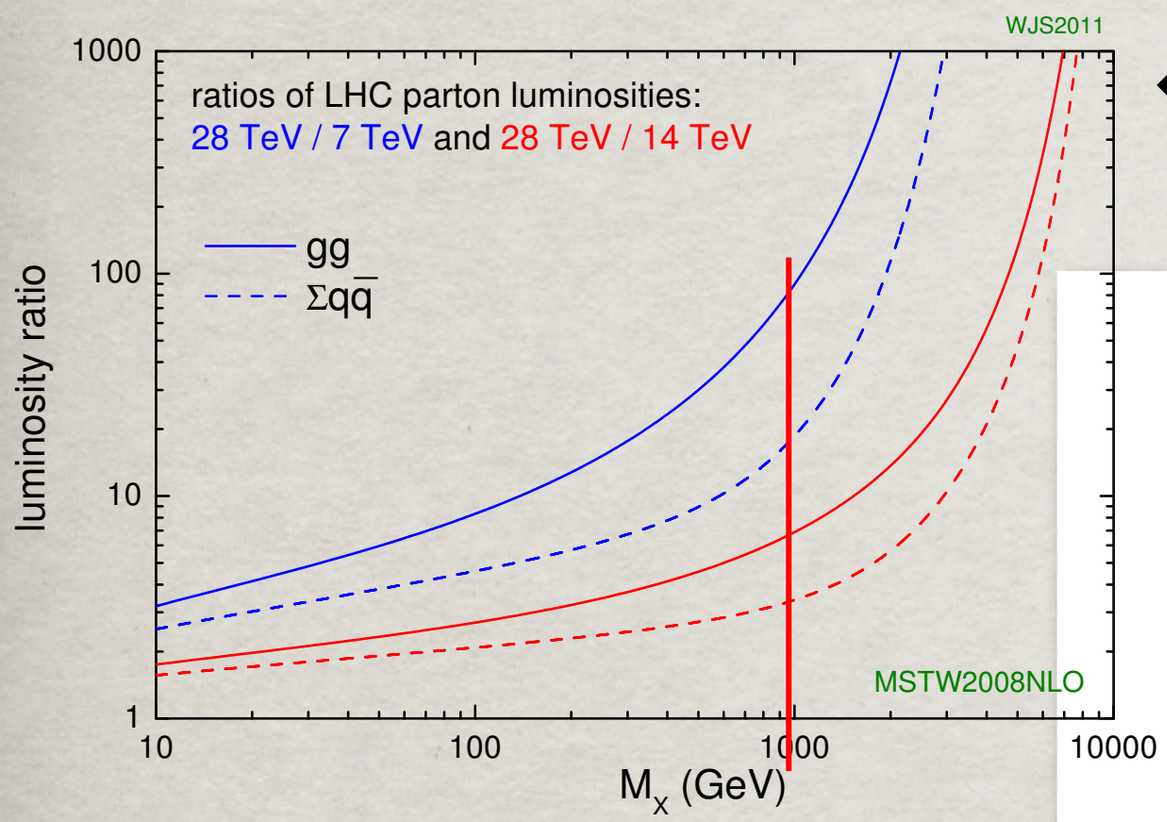


16T magnets (Nb_3Sn)

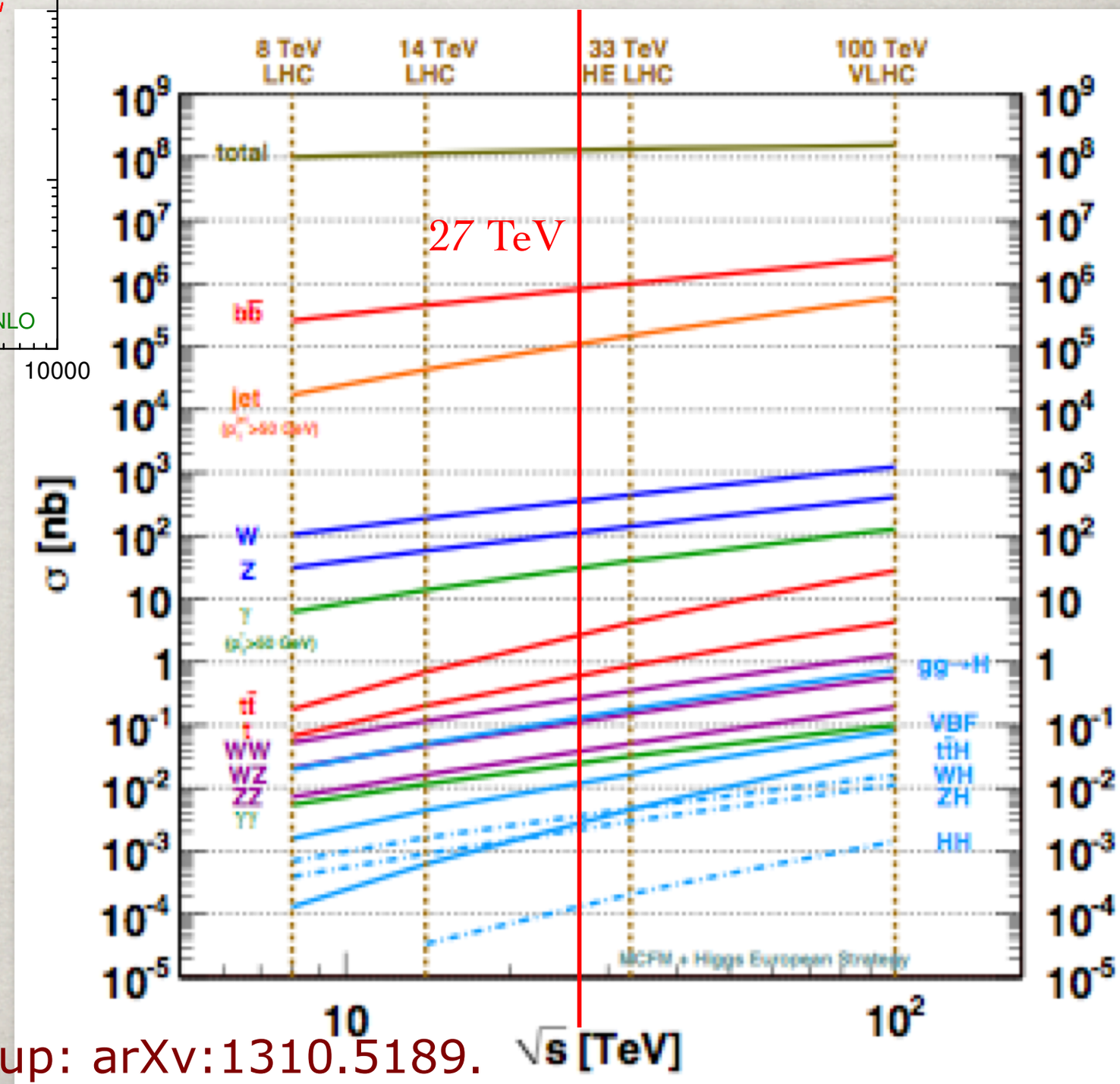
- Conductor cost: 670 kEUR/magnet
- Assembly cost: 600 kEUR/magnet
- Parts cost: 420 kEUR/magnet
- Total cost: 1690 kEUR/magnet
- HE-LHC: 1232 dipoles (~2BEuro total), FCC-hh: 4664 dipoles, (~8BEuro)

Vladimir Shiltsev, this workshop

HE-LHC: New Energy Frontier



← Parton lumi increased by
6x @ 1 TeV; 10^3x @ 8 TeV!

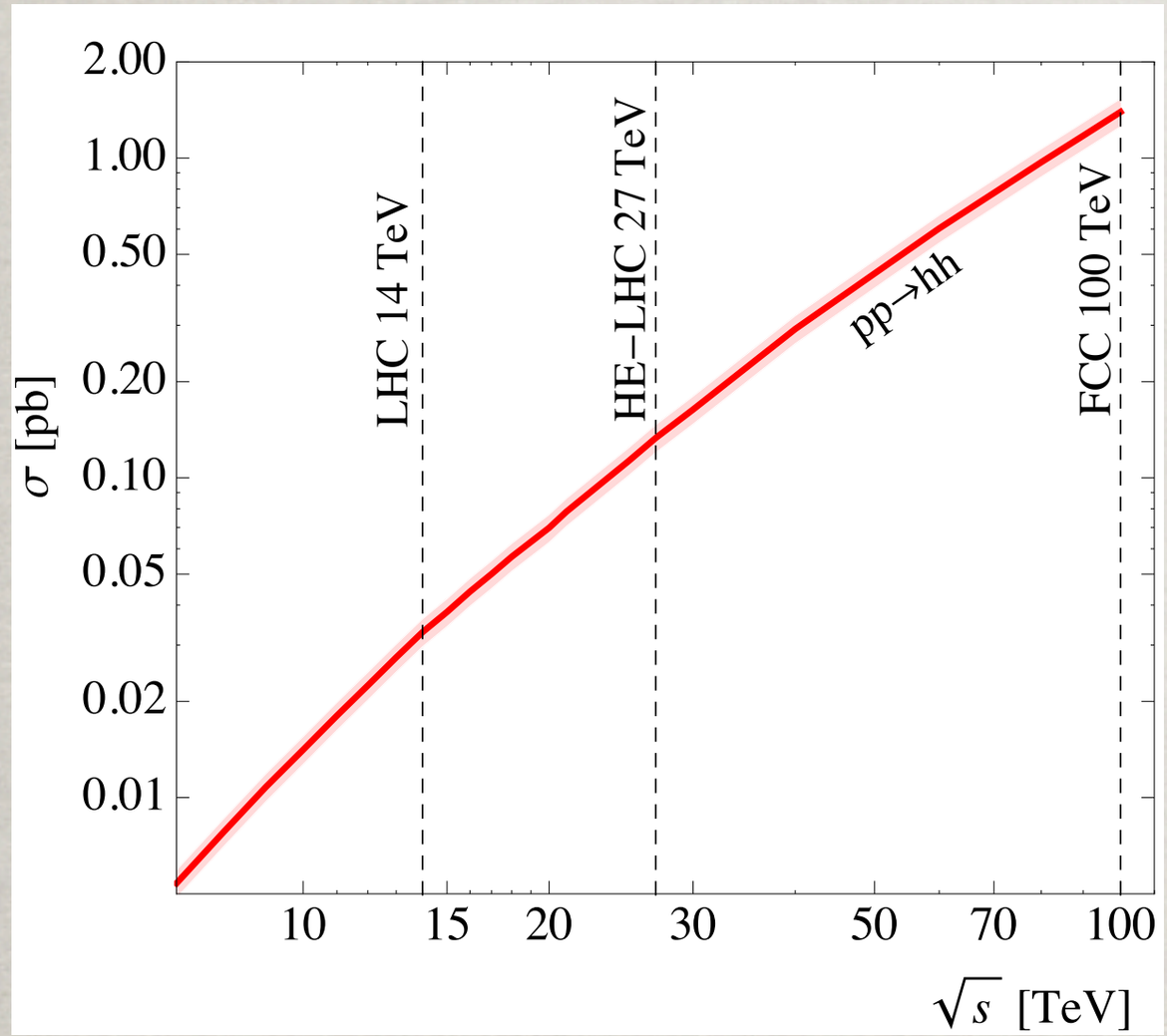


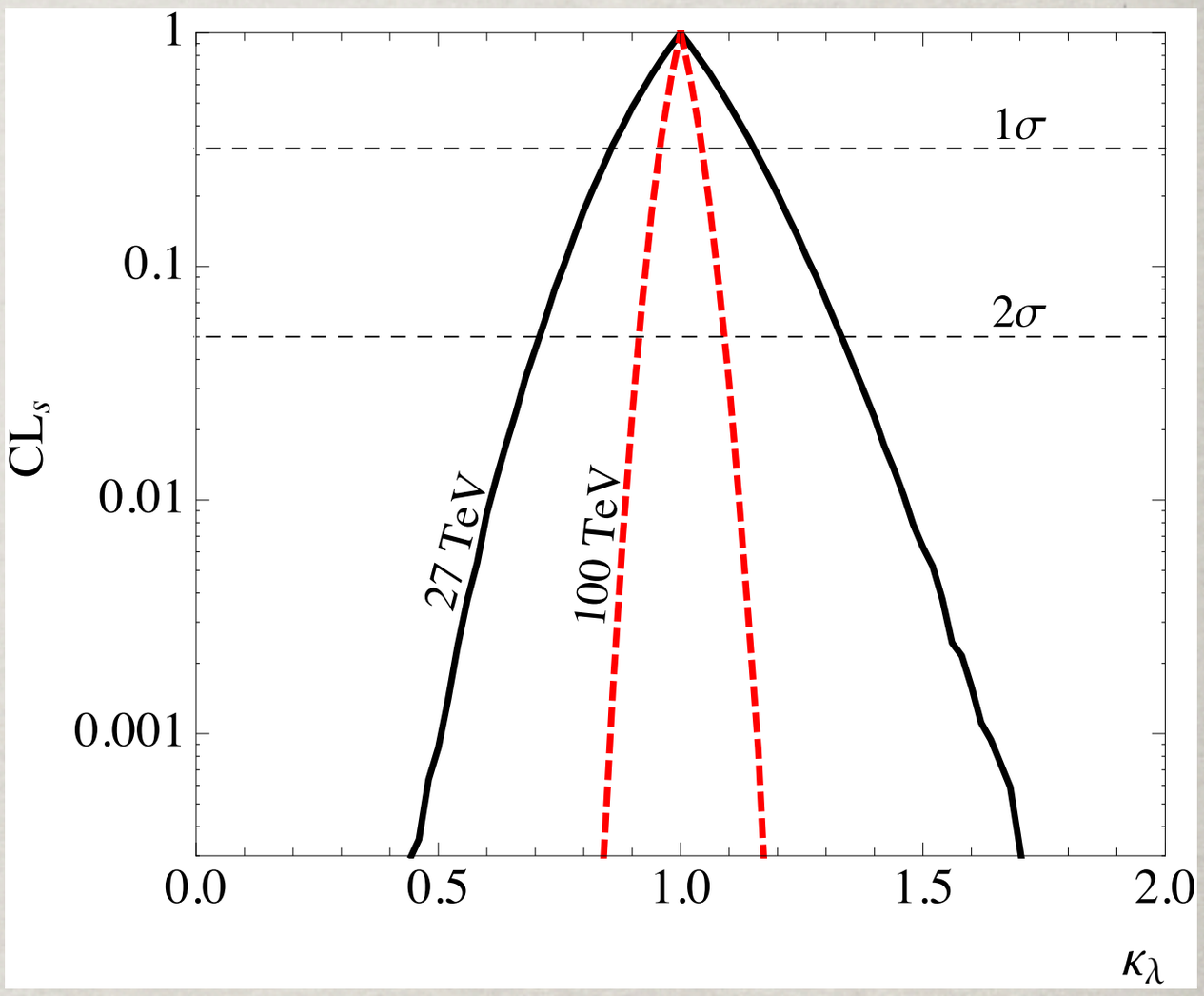
σ(h) → 2.5x
σ(hh) → 3x
σ(tth) → 4x
Lumi up by 5x →
events up 15-20x

Snowmass QCD Working Group: arXv:1310.5189.

HE-LHC: Higgs self-coupling

D. Goncalves, TH, F. Kling, T. Plehen, M. Takeuchi, arXiv:1802.04319.





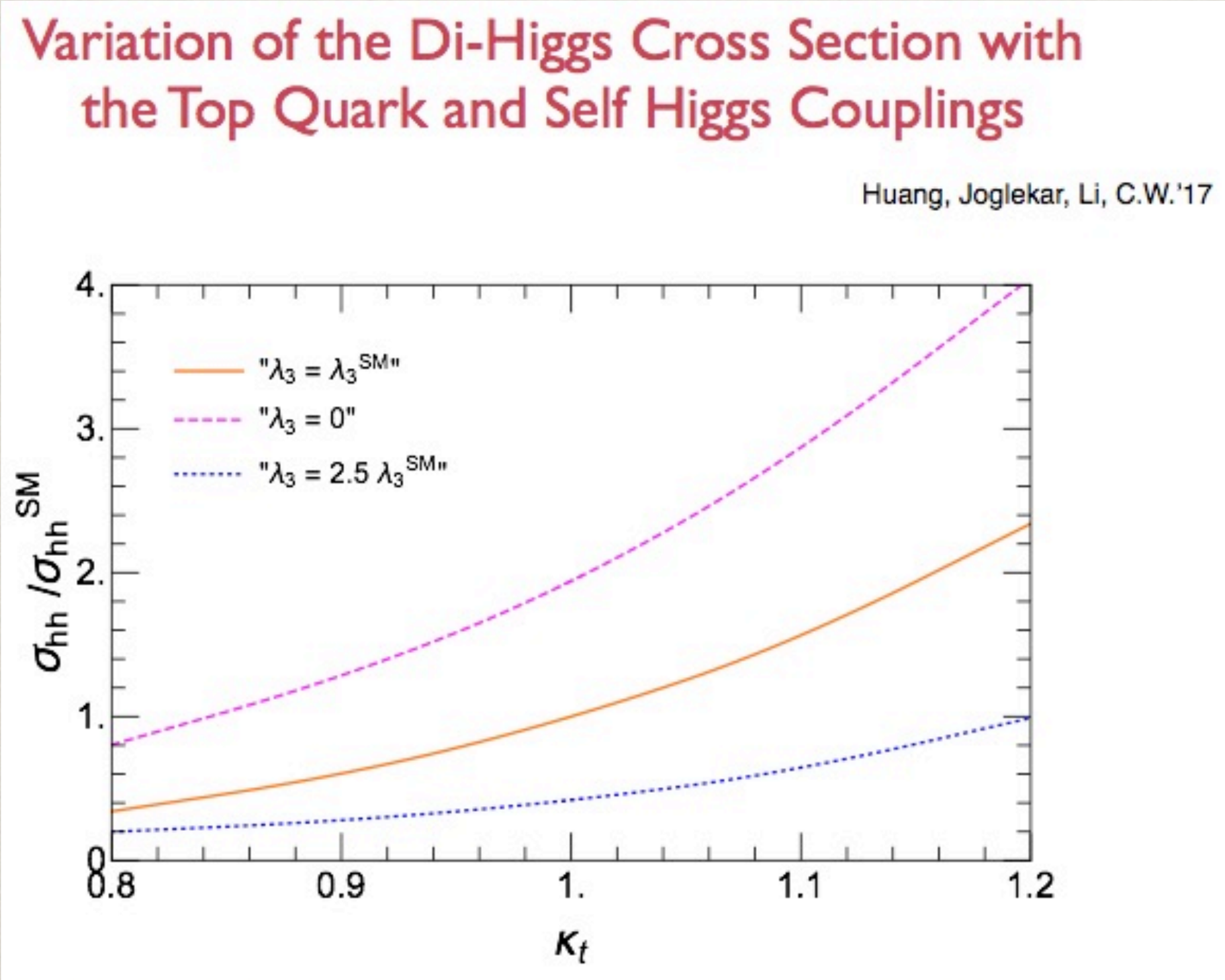
Cross section increases ~3x.

hh → bb $\gamma\gamma$: $\delta\lambda$ ~ 30% @ 2σ

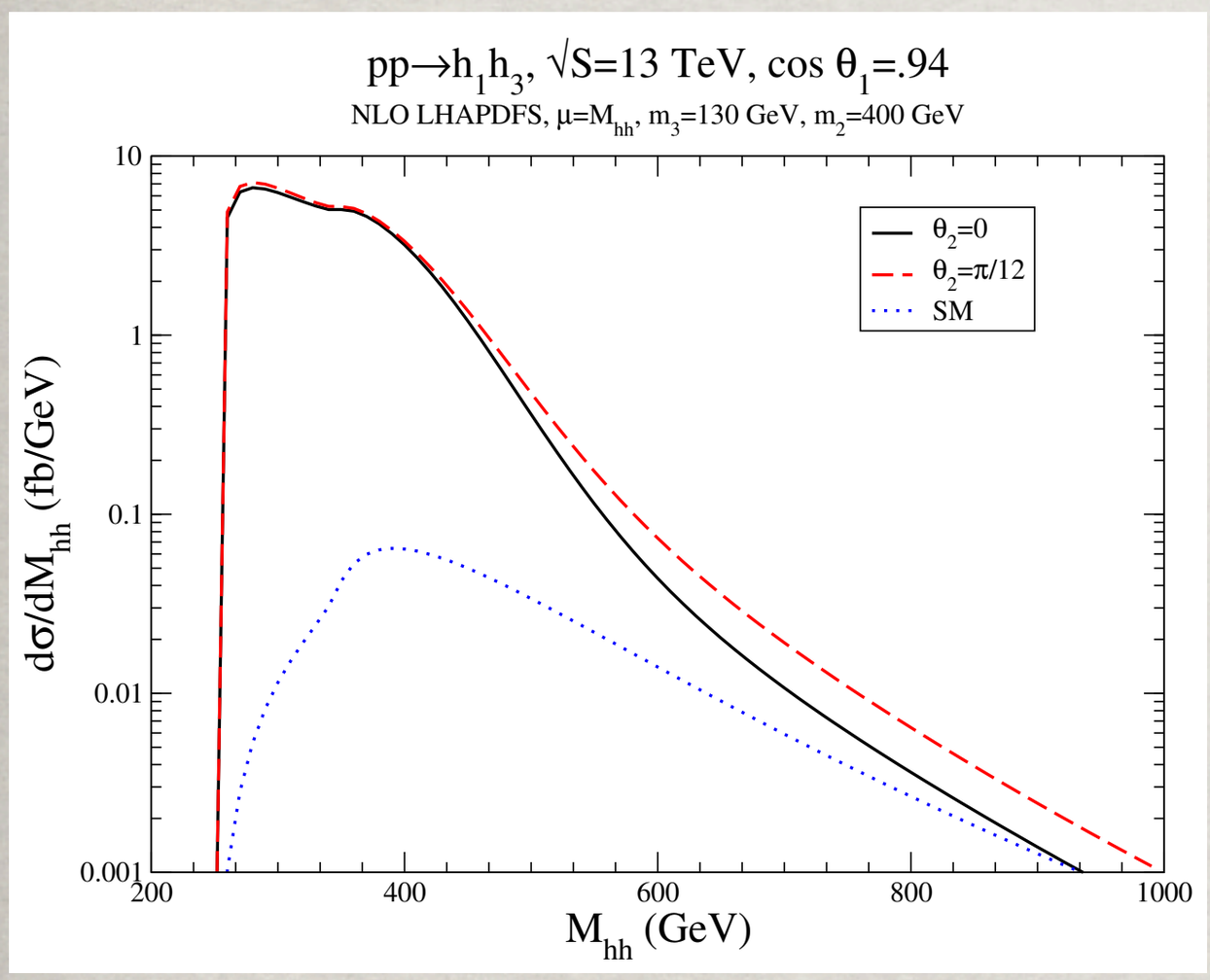
Also, S. Homiller, P. Meade, this workshop.

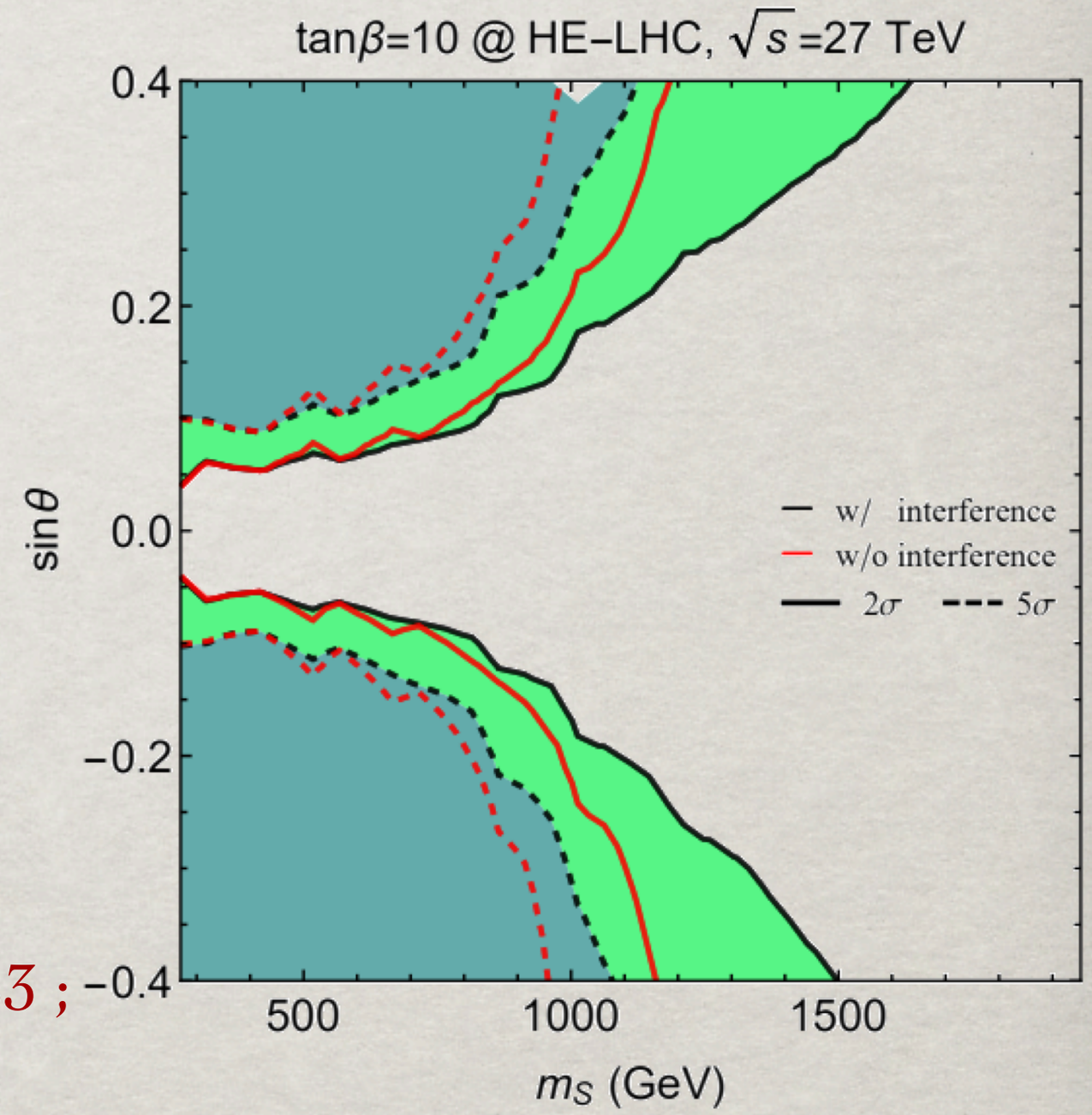
hh sensitive to new physics:

C. Wagner, this workshop.



hh sensitive to new physics:



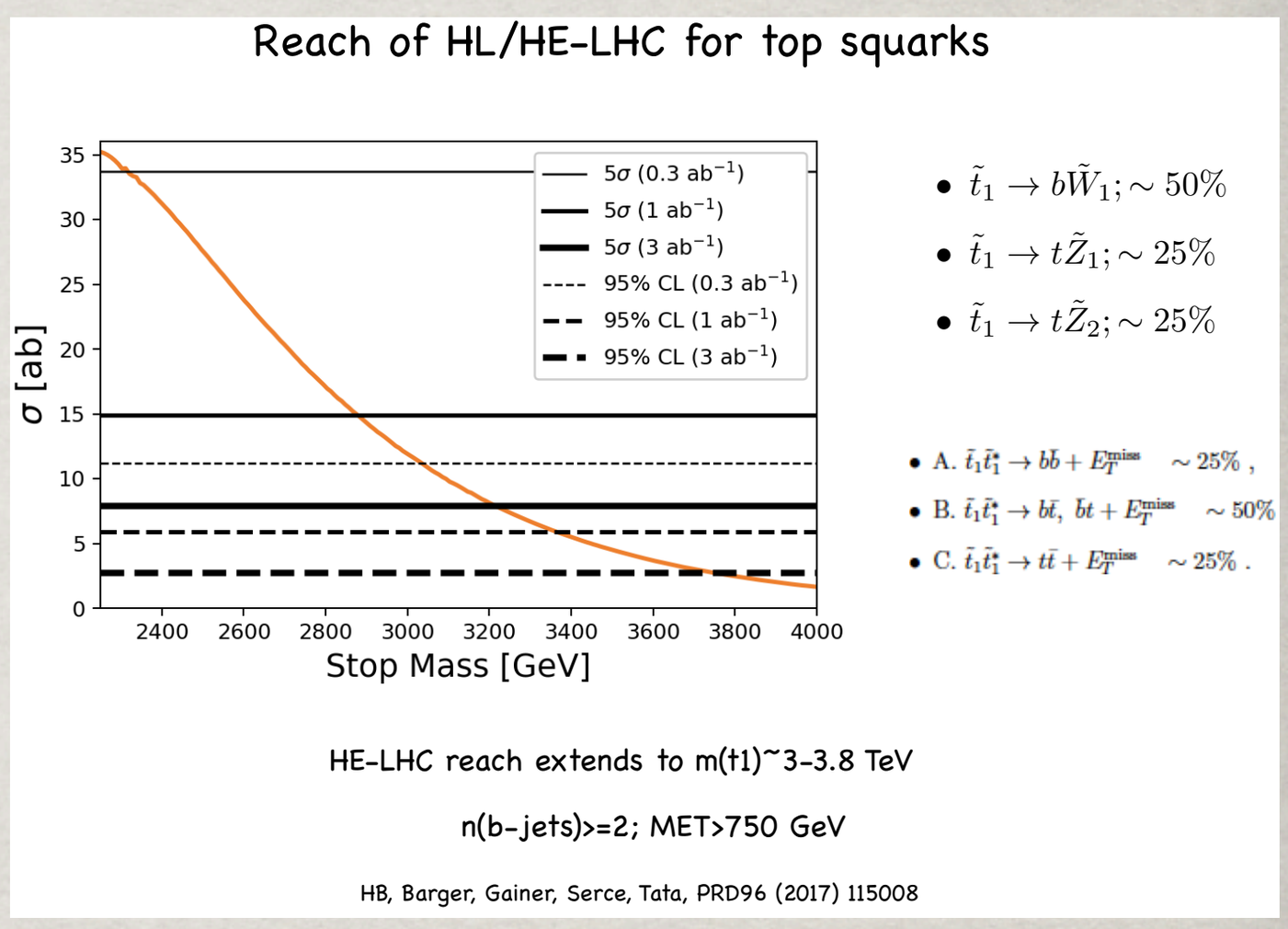


S. Dawson, M. Sullivan, 1711.06683 ;
I. Lewis, S. Dawson, 1605.04944.

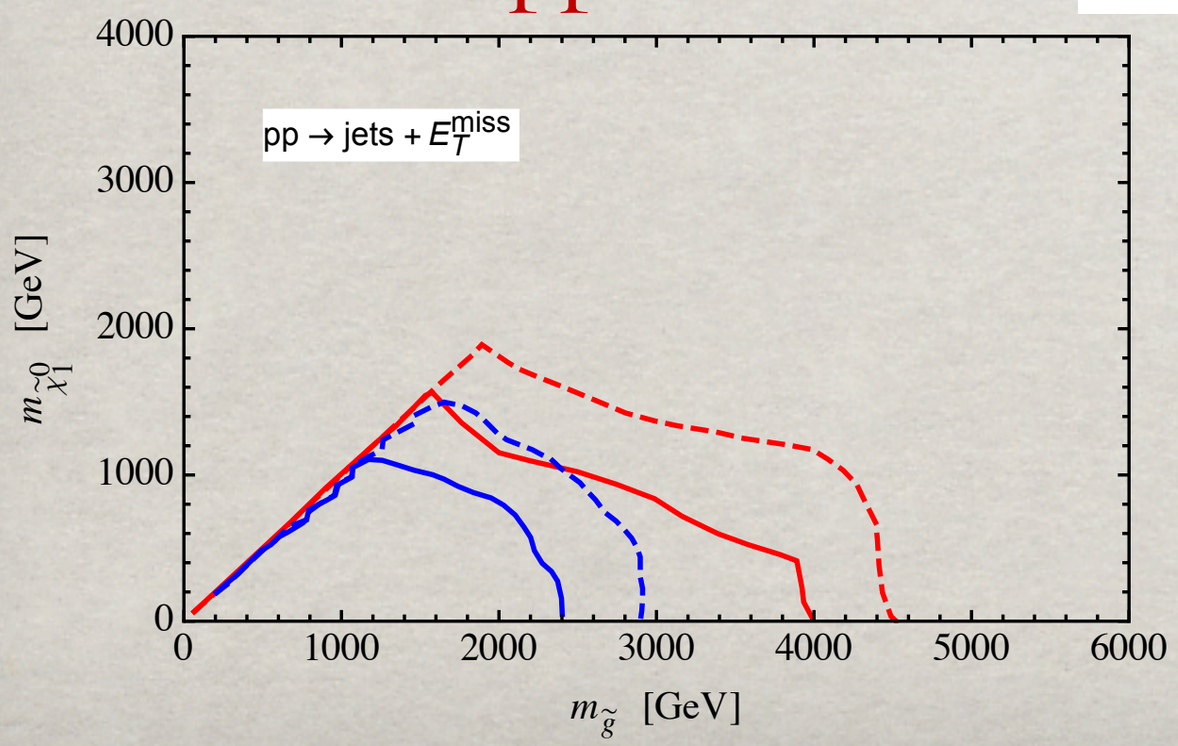
M. Carena, Z. Liu, M. Riembau, arXiv:180100794.

HE-LHC: Extended SUSY Reach:

H. Baer, this workshop.



A recent update:
TH, A. Ismail, B. Haghi,
to appear.

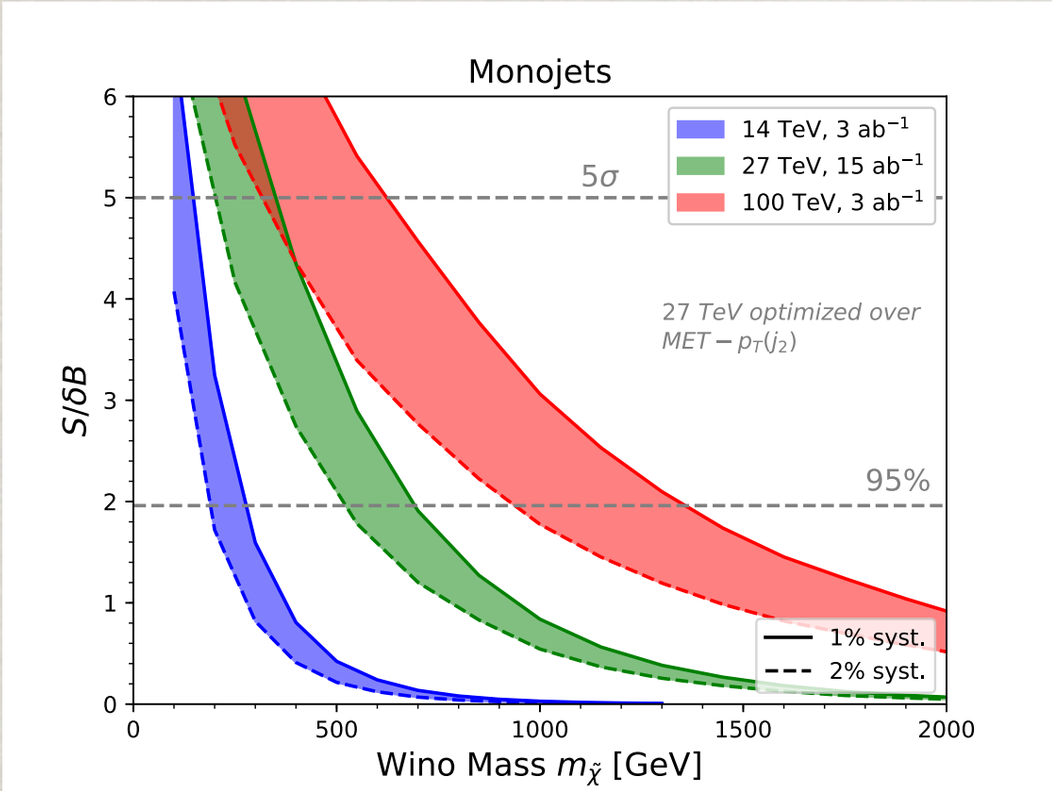


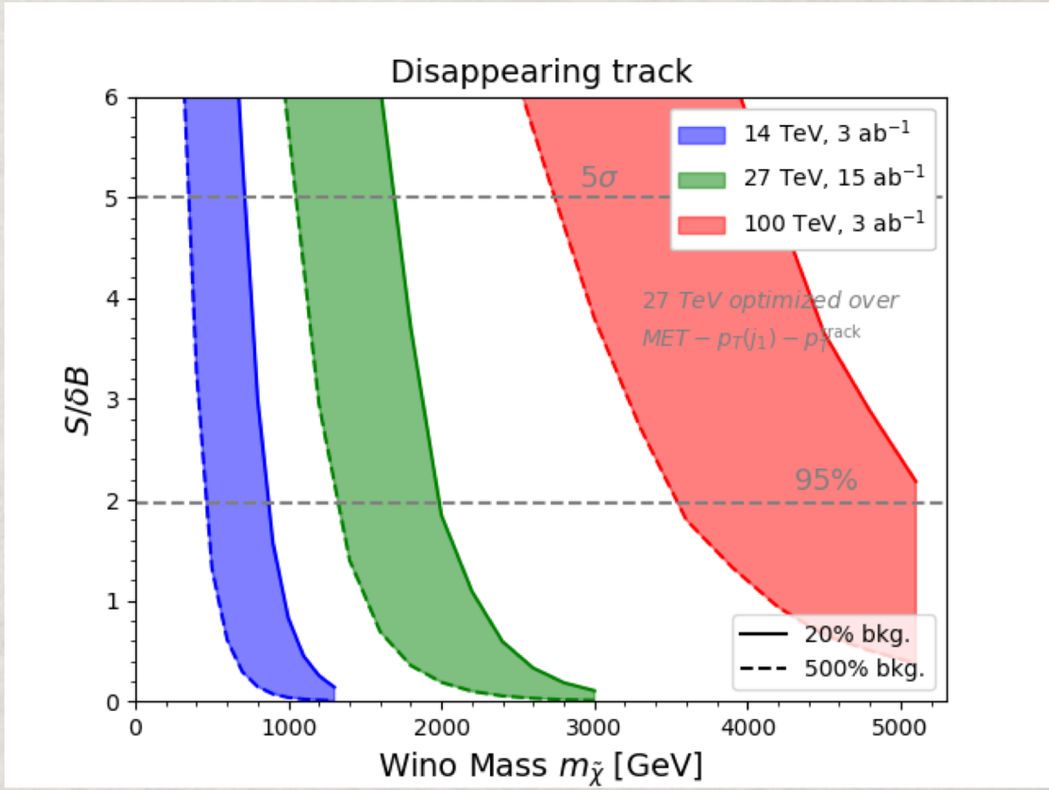
- 27 TeV, 15000 fb^{-1}, exclusion %95 CL
- 27 TeV,15000 fb^{-1}, 5σ discovery
- 14 TeV, 3000 fb^{-1}, exclusion %95 CL, ATLAS 2014
- 14 TeV,3000 fb^{-1}, 5σ discovery, ATLAS 2014

HE-LHC improves 50%-60%

HE-LHC: WIMP Dark Matter

TH, S. Mukhopadhyay, X. Wang, this workshop;
M. Low, D. Egana-Ugrinovic, J. Ruderman, L.-T. Wang, to appear.

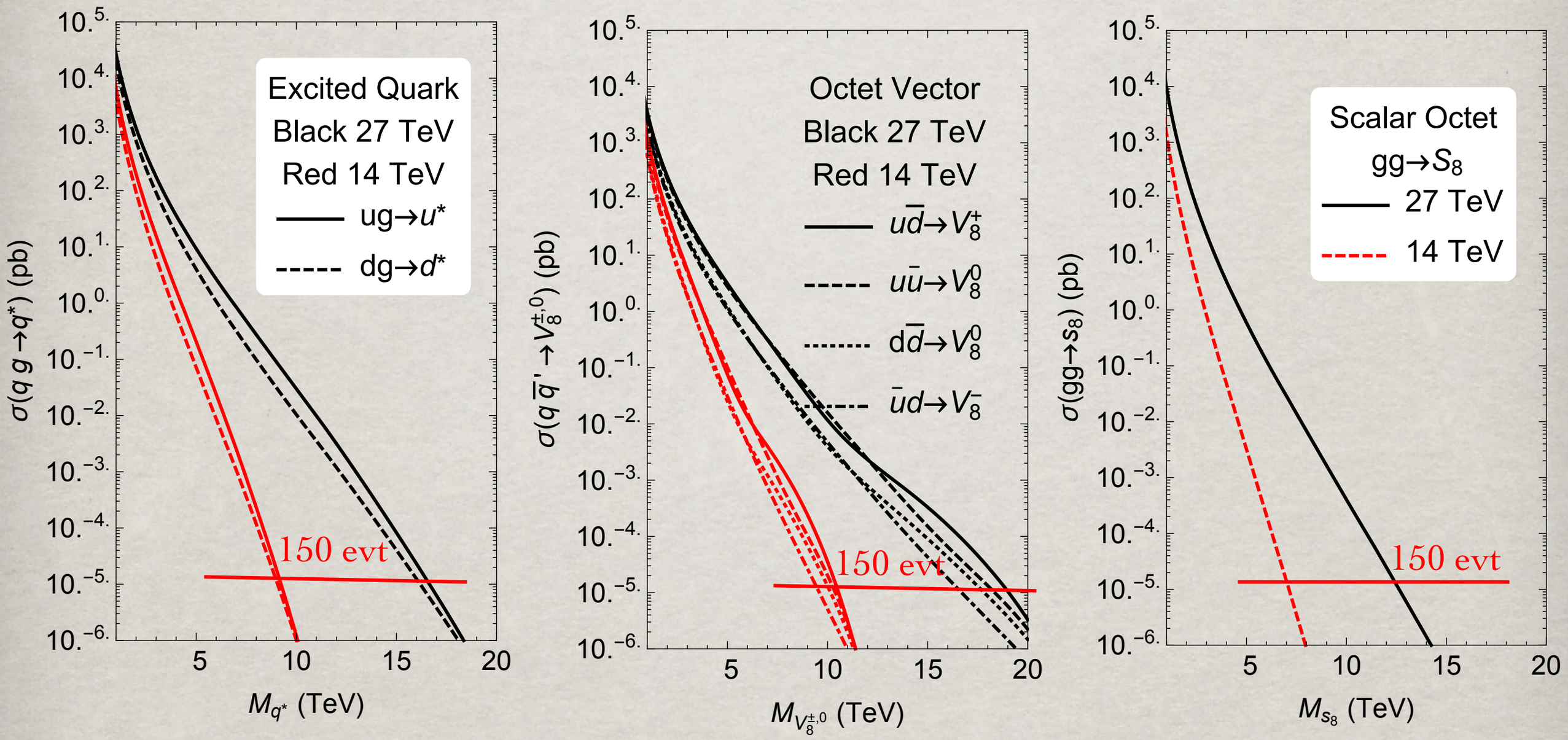




	2**σ**@HL-LHC →	HE-LHC →	FCC
Wino monojet:	300 GeV	700 GeV	1400 GeV
Wino disappearing track:	800 GeV	2000 GeV	5000 GeV
Higgsino monojet:	200 GeV	500 GeV	900 GeV
Higgsino disappearing track:	250 GeV	500 GeV	1100 GeV

HE-LHC: threshold for new Resonances

TH, I. Lewis, Z. Liu, to appear.



Color resonance → 2 jets:

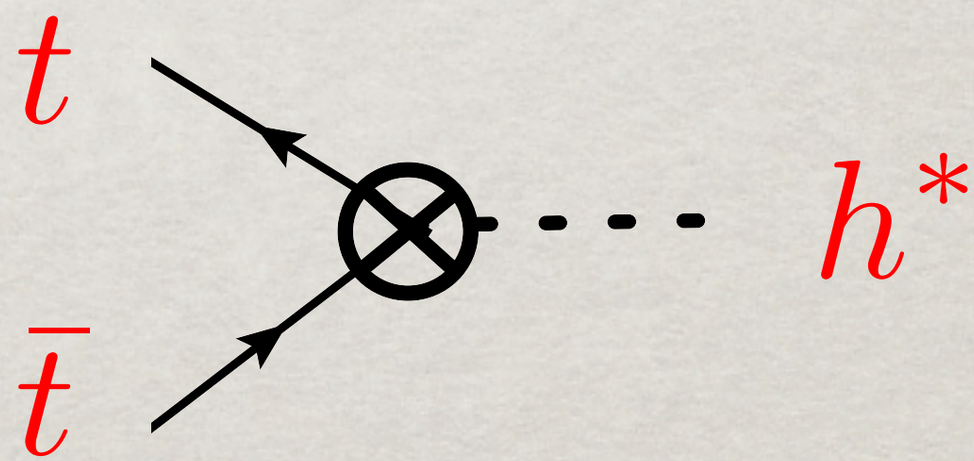
LHC	14 TeV	27 TeV
	7-8 TeV	13-18 TeV

HE-LHC: Higgs Coupling @ High Scales

In absence of new physics beyond the Standard Model from the current searches at the LHC,

We must study the SM Higgs at high scales:

- Sensitive to new physics
- "Naturalness" is a UV problem.
- "Higgs portal" to a subtle (hidden) sector.



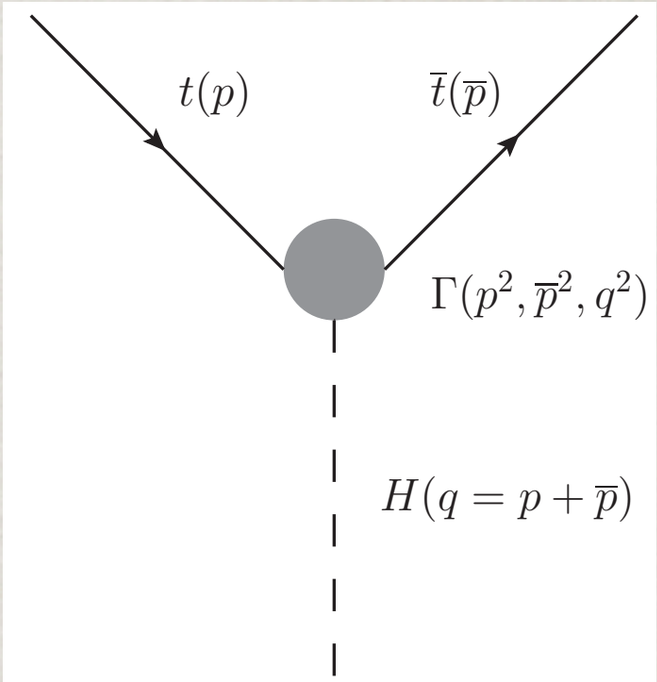
$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h} \text{ and } \sigma_{\rm off} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL,2017); arXiv:1803.09751.

e.g. Higgs is composite at Λ:

The Momentum-dependent Form Factor:

$$V_{ttH}(p^\mu, \bar{p}^\mu) = \frac{\sqrt{2}m_t}{v}\Gamma\left(p^2/\Lambda_c^2, \bar{p}^2/\Lambda_c^2, q^2/\Lambda_c^2\right)$$



Current 95%CL bound
from the LHC Higgs signal:

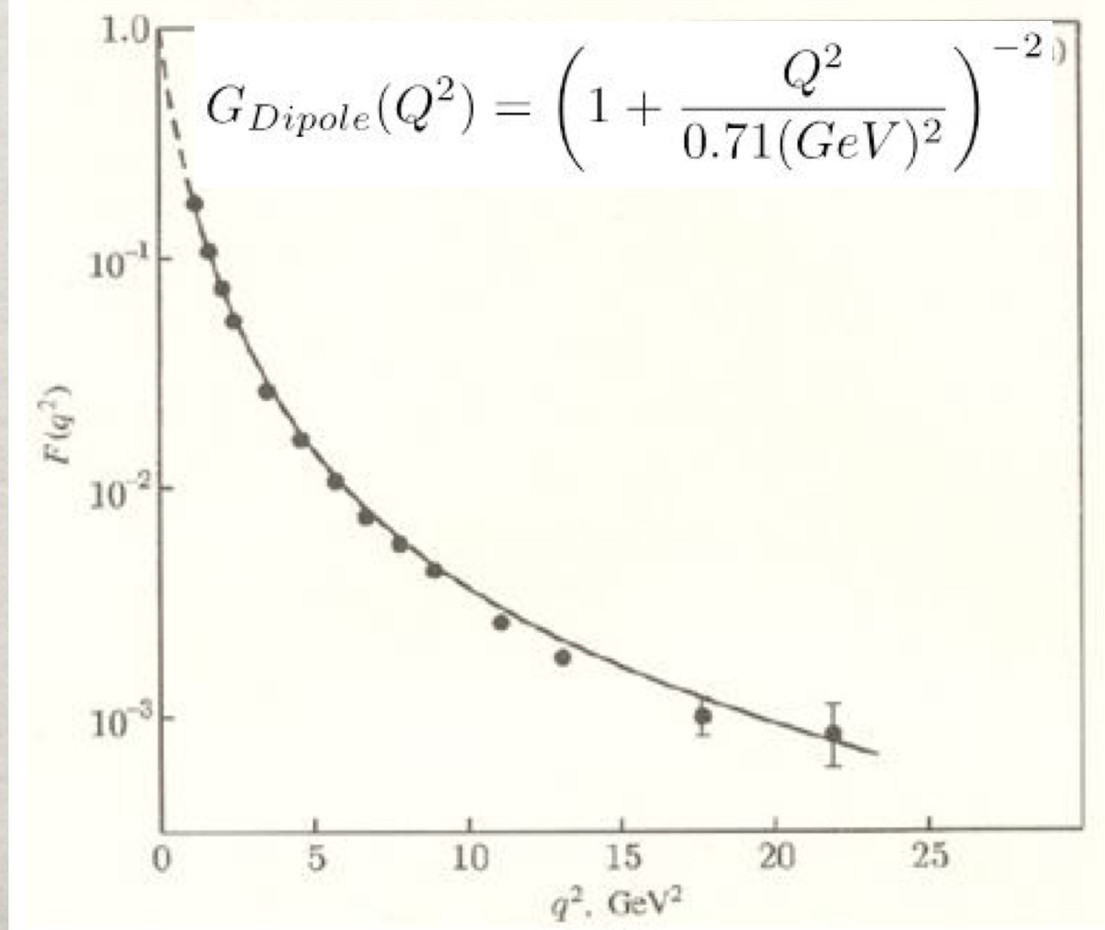
$$\left|\Gamma\left(m_h^2/\Lambda^2\right)^2 - 1\right| < 0.1$$

Analogous to nucleon form factor:

$$\Gamma\left(q^2/\Lambda_c^2\right) = \frac{1}{(1 + q^2/\Lambda_c^2\ )^n}$$

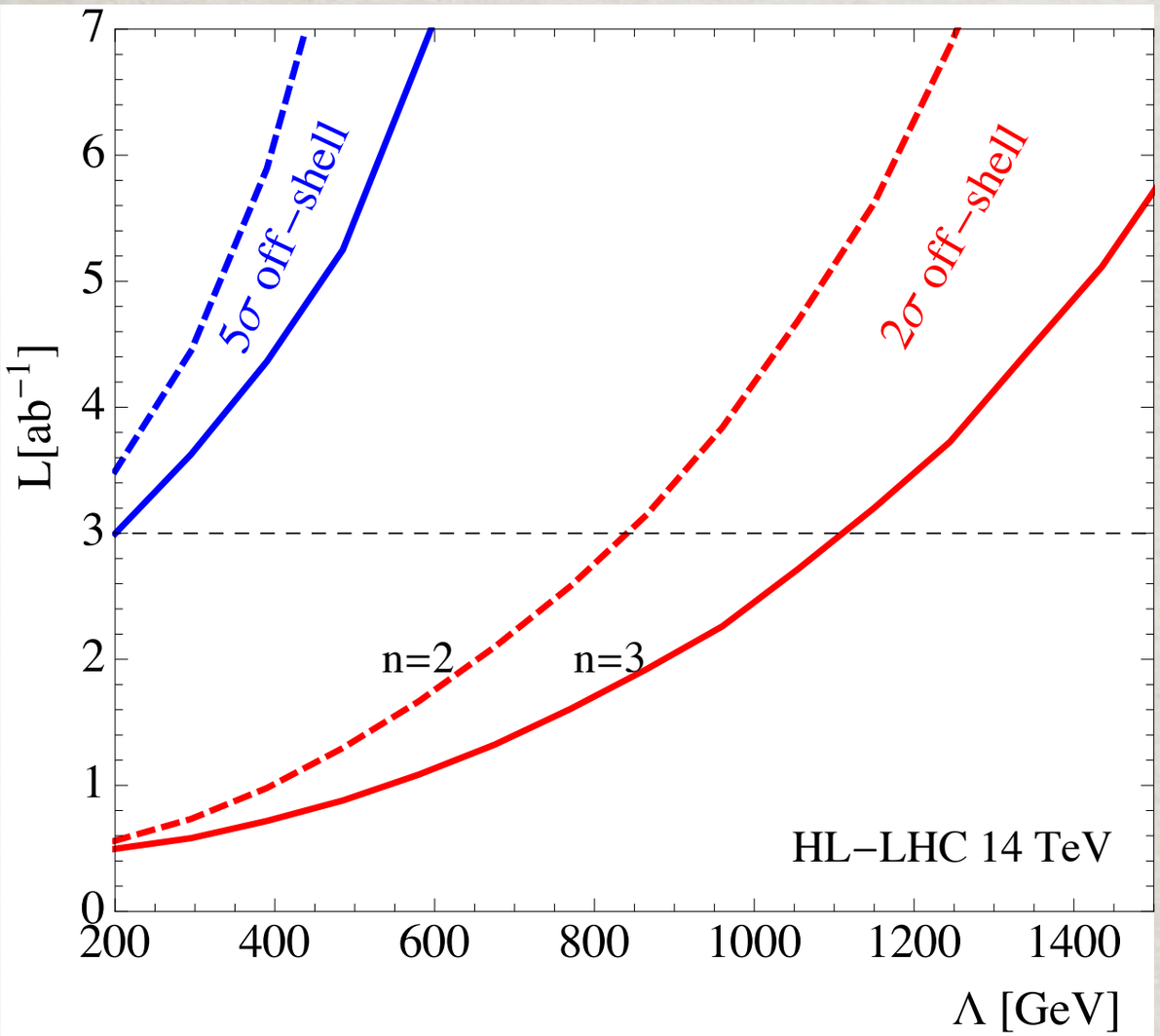
n=2 → "Dipole FF"

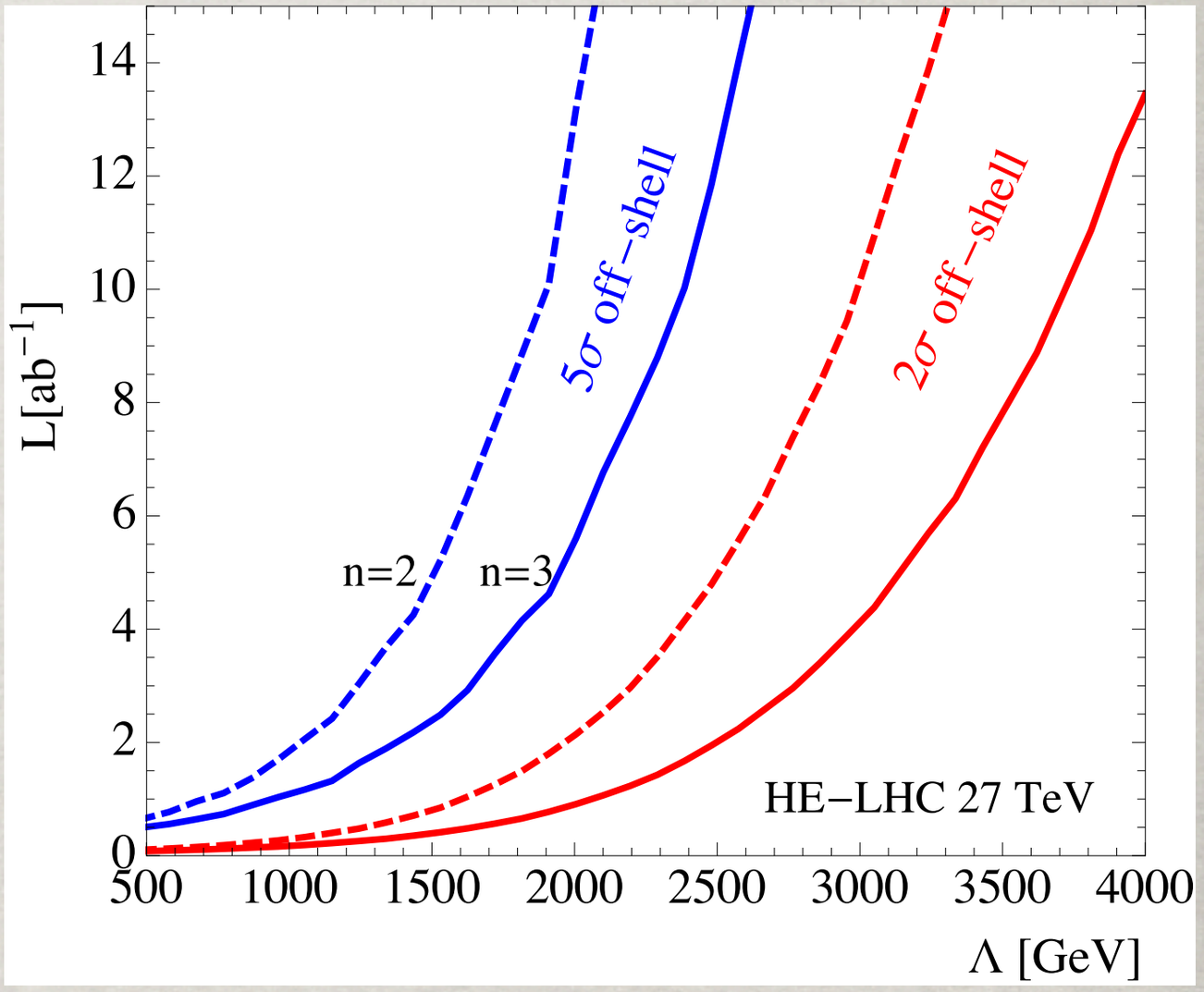
Leading to a suppressed ttH
→ Enhanced ZZ signal!



LHC Sensitivity: top-Higgs Form Factor

pp → h* → ZZ → 4 leptons





HL-LHC: Λ_c ~0.8 TeV @ 2σ

HE-LHC: Λ_c ~3.3 TeV @ 2σ; 2.1 TeV @ 5σ.

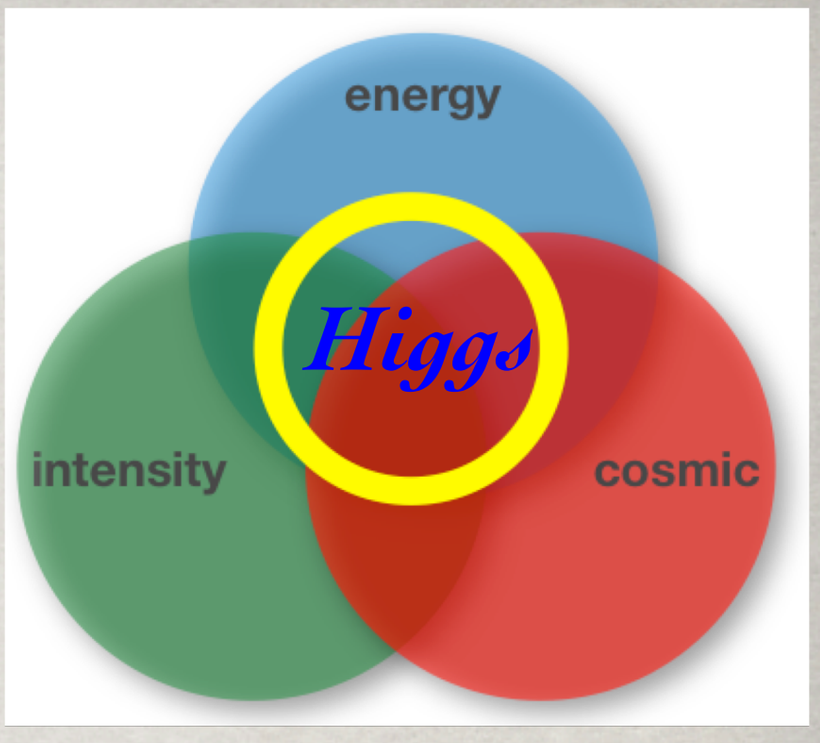
LHC physics is extremely rich!

I have omitted a LOT:

- Rare decays
- Exotic decays
- Top quark as a window to new physics
- Neutrino mass connection
- $W_L W_L$ interactions
- Test discrete symmetries: CPv etc.
- … …

Summary:

- HL-LHC / HE-LHC will take us to a new territory at the energy / intensity / cosmic & technology frontiers.



- Great potential to answer fundamental questions:
  - Higgs couplings ~ 1% → sensitive to TeV new physics.
  - λ_{HHH} ~ 30% @ 2$\boldsymbol{\sigma}$ → EWPT & sensitive to new physics.
  - Stop / gluino up to 3 - 5 TeV → "unnatural fine-tune" ~10^{-3}.
  - WIMP (SUSY) DM up to: 0.5 - 2 TeV.
  - New resonances Z' ~ 6 TeV; Colored states ~ 10 TeV.
  - Unprecedented accuracies in flavor physics/rare decays.

An exciting journey ahead!