Physics At VLHC

Tao Han
Pittsburgh Particle physics, Astrophysics and Cosmology Center

Exploring the Physics Frontier with Circular Colliders
ACP Winter Conference, Jan. 27, 2015

Photo credit:
Hitoshi Murayama

FERMILAB-CONF-97/ 318-T

Summary of the Very Large Hadron Collider Physics and Detector Workshop

Physics at the high energy frontier beyond the LHC

March 13-15, 1997

Fermi National Accelerator Laboratory, Batavia, Illinois

(Bill Foster's initiative)

G. Anderson (Fermilab), U. Baur (SUNY at Buffalo), M. Berger (Indiana University), F. Borcherding (Fermilab), A. Brandt (Fermilab), D. Denisov (Fermilab, Co-Chair and Co-editor), S. Eno (University of Maryland), T. Han (University of California–Davis), S. Keller (Fermilab, Co-Chair and Co-editor), D. Khazins (Duke University), T. LeCompte (Argonne National Laboratory), J. Lykken (Fermilab), F. Olness (Southern Methodist University), F. Paige (Brookhaven National Laboratory), R. Scalise (Southern Methodist University), E. H. Simmons (Boston University), G. Snow (University of Nebraska–Lincoln), C. Taylor (Case Western Reserve University), J. Womersley (Fermilab).

PHYSICS AT 100-200 TeV

Tao Han, Univ. of Wisconsin-Madison

(1999 VLHC Annual Meeting, June. 28)

I. Brief Introduction:
- Particle Physics and Colliders

II. Physics Expectations at the VLHC:
- Representative SM Physics
- Physics Beyond the SM

III. Physics at the High-Energy Frontier
- Beyond the Naive Expectation

PHYSICS AT THE VLHC

Tao Han, Univ. of Wisconsin-Madison

(July 17, Snowmass 2001)

VLHC: The True Energy Frontier
- Invitation to Innovative Ideas for New Physics

Beyond the SM Physics
- New Threshold and Extended Reach

Theory Overview in the light of future hadron colliders

Tao Han

Univ. of Wisconsin - Madison

VLHC workshop, Fermilab, Oct. 16, 2003

The Standard Model as It Is

The Need For Going Beyond SM

The Role of Future Hadron Colliders

Physics Issues in 1999
(TH's list)

✔ • $M_W, \ M_Z$? (Gauge symmetry breaking)

✔ • $M_H \sim \mathcal{O}(M_Z)$? (natural EW scale)

? • Supersymmetry? ($M_Z - M_{pl}$ hierarchy)

? • $m_t, \ m_f, \ m_\nu$? (fermion masses and mixing)

? ✕ • Techni-/top-color? (dynamical symm. brkng)

? • extra dimensions/low-scale gravity? (gravity+hierarchy)

? • Superstring? (quantum gravity/Theory of everything?)

? • ... ...? (... ...) DM

Chris Quigg, IAS-HKUST
Jan. 19, 2015

Issues for the Future *(Starting now!)*

1. What is the agent of EWSB? *There is a Higgs* Might there be several?
2. Is the Higgs boson elementary or composite does it interact with itself? What triggers EWSI
3. Does the Higgs boson give mass to fermions only to the weak bosons? What sets the masse mixings of the quarks and leptons? *(How) is ferm mass related to the electroweak scale?*
4. Are there new flavor symmetries that give in into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

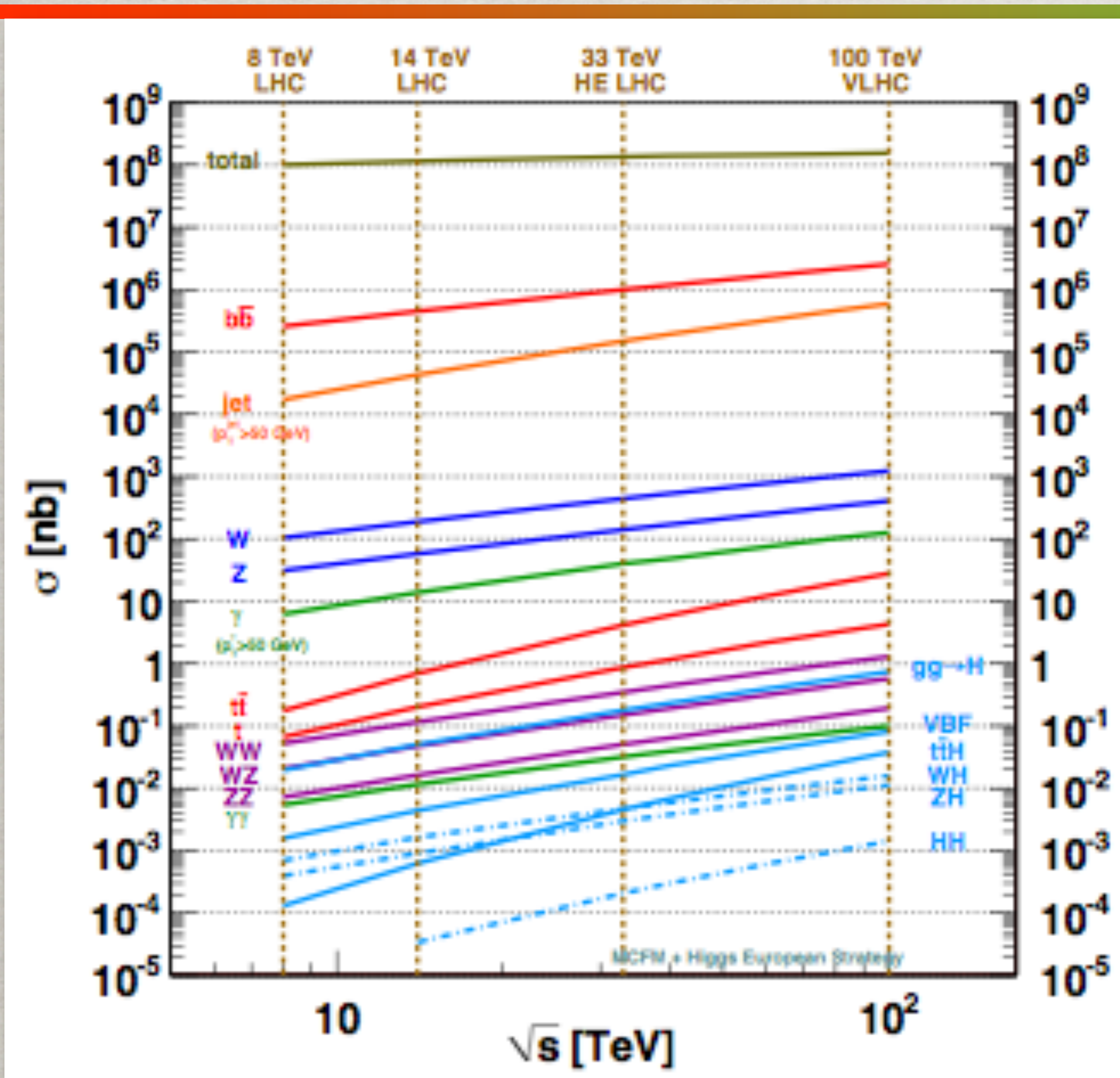
11. What are the dark matters? Any flavor str
12. Is EWSB an emergent phenomenon conn with strong dynamics? How would that alter conception of unified theories of the strong, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy proble
15. (When we understand the origin of EWS lessons does EWSB hold for unified theories inflation? … for dark energy?

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, …?

20. How are we prisoners of conventional thinking?

VLHC LEADS ENERGY FRONTIER

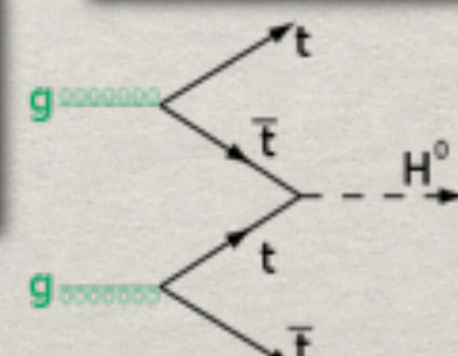
Rich Physics @ VLHC



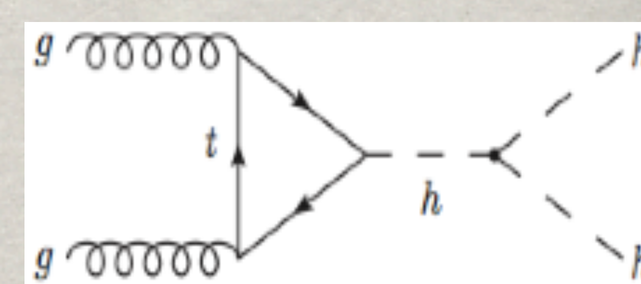
Snowmass QCD Working Group: 1310.5189

Interesting scaling:

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3



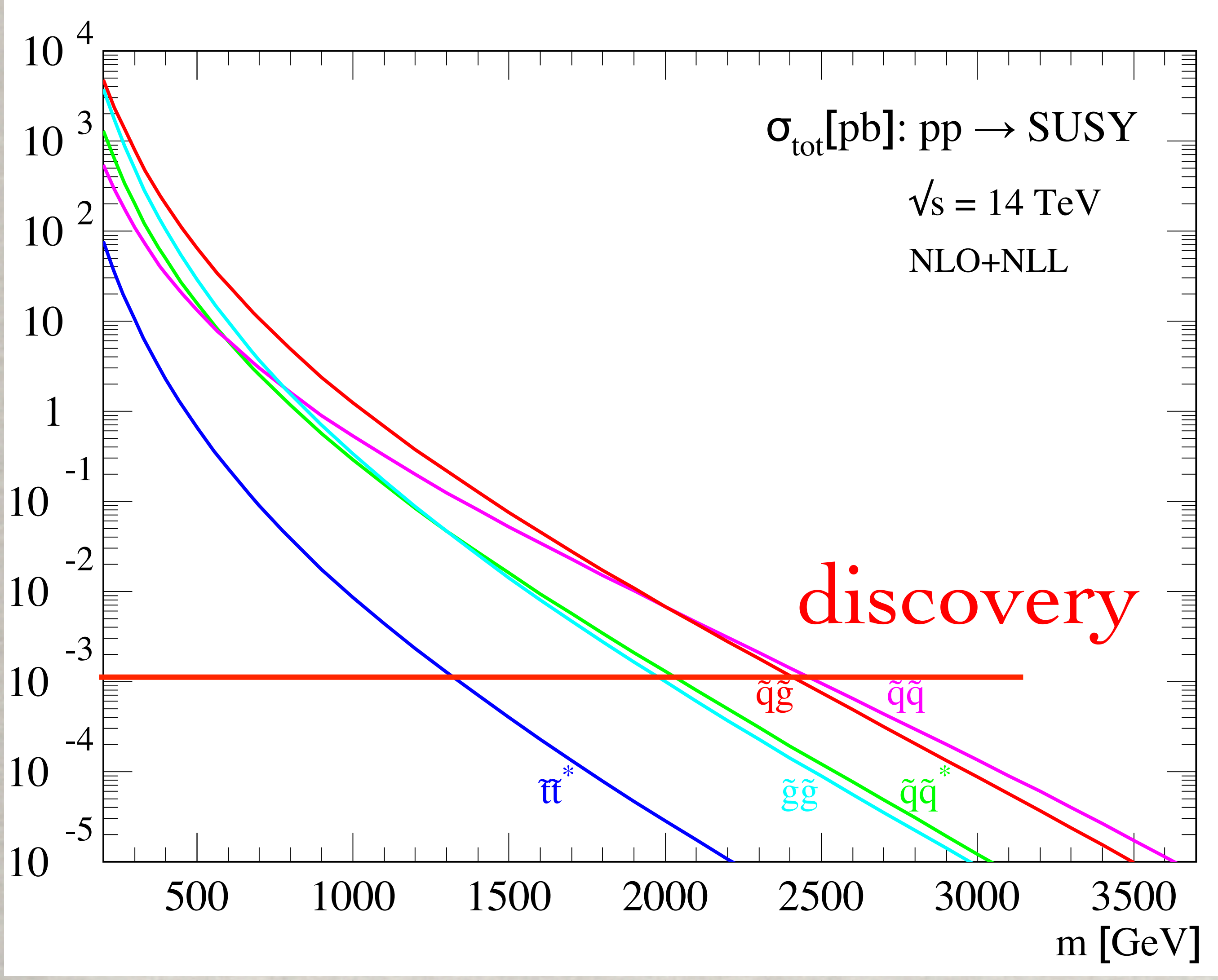
λ_t : 1%

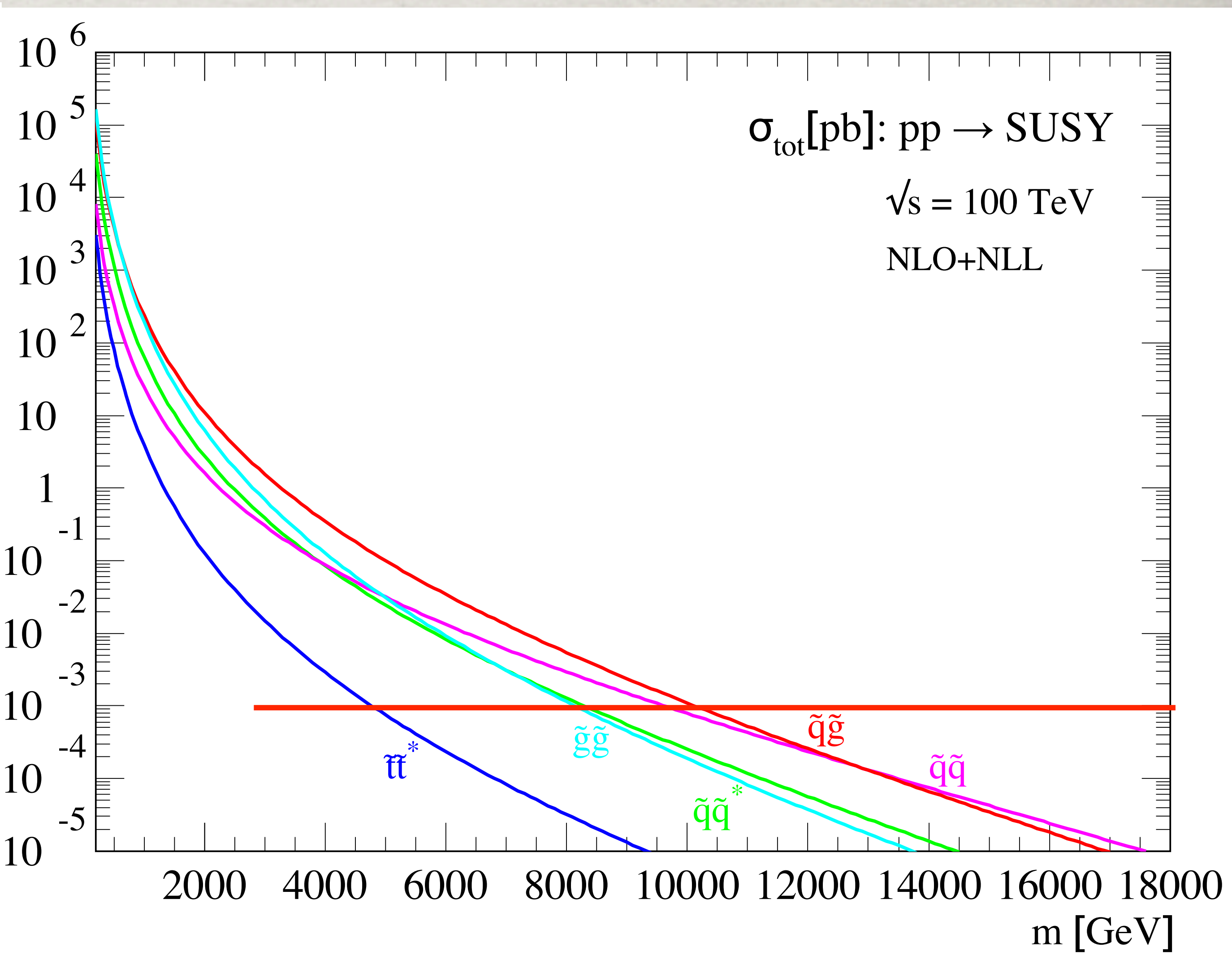


λ : 8%

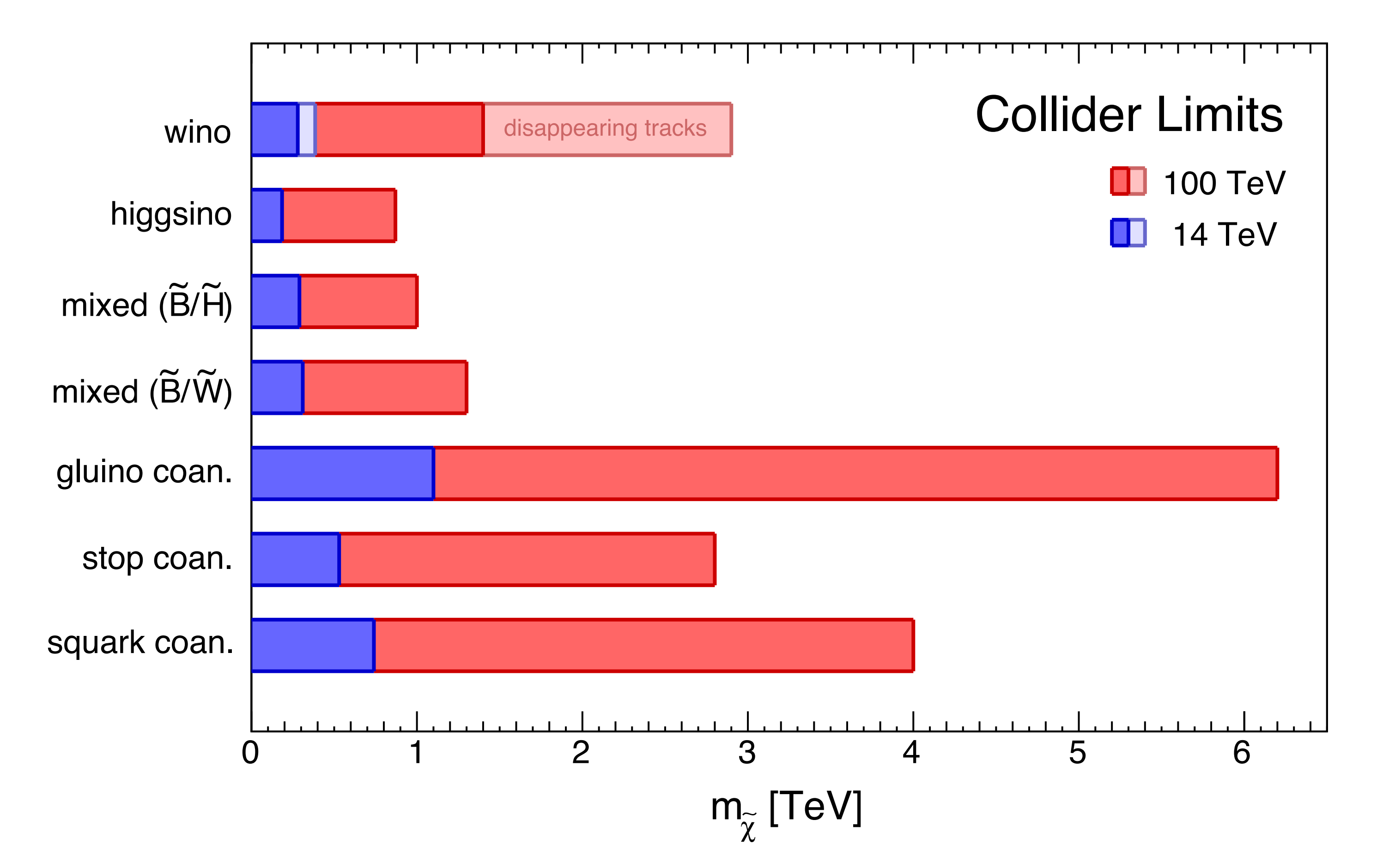
SUSY @ VLHC

M.Mangano, T.Plehn et al.: 1407.5066



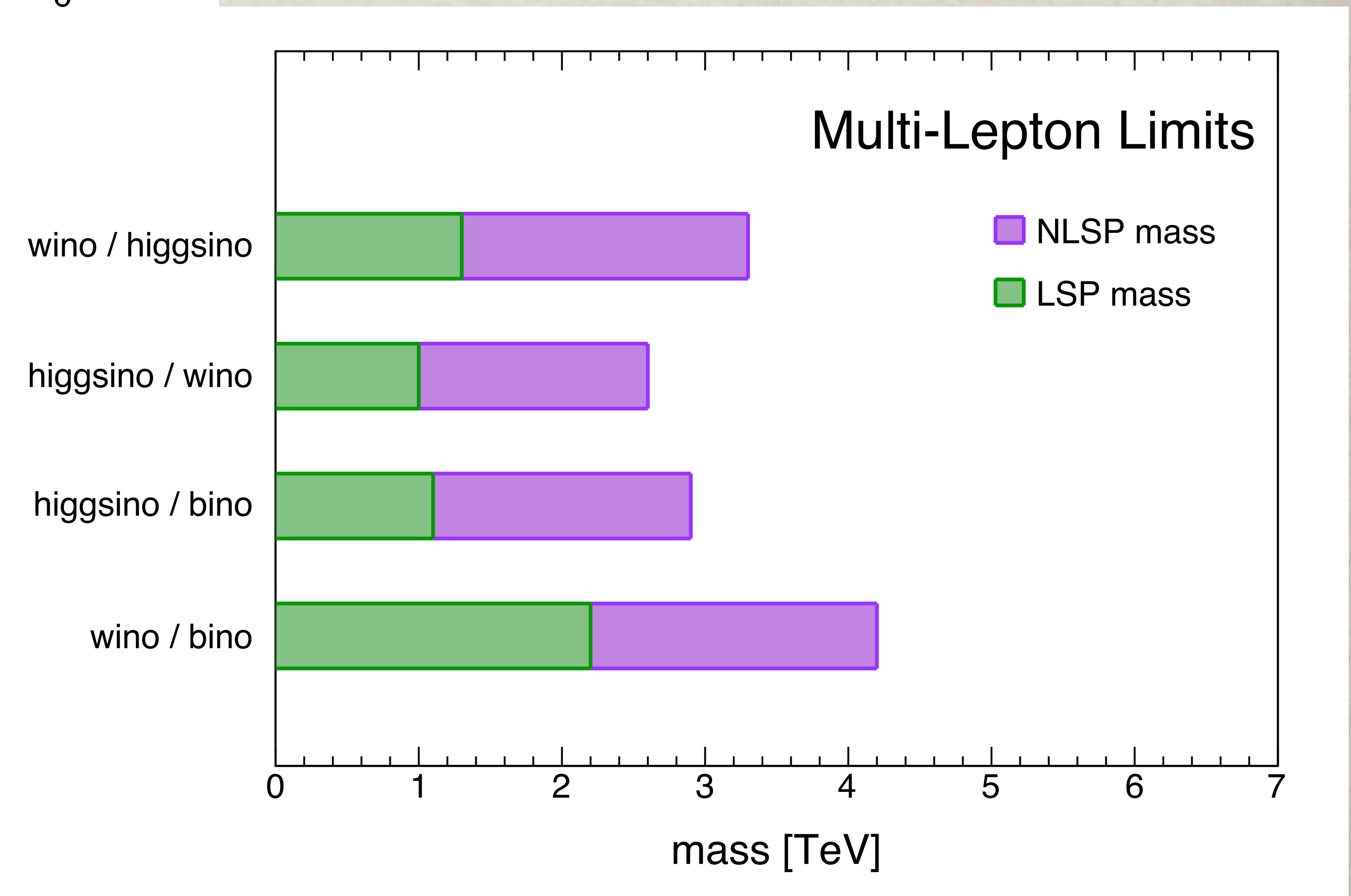


SUSY DM @ VLHC



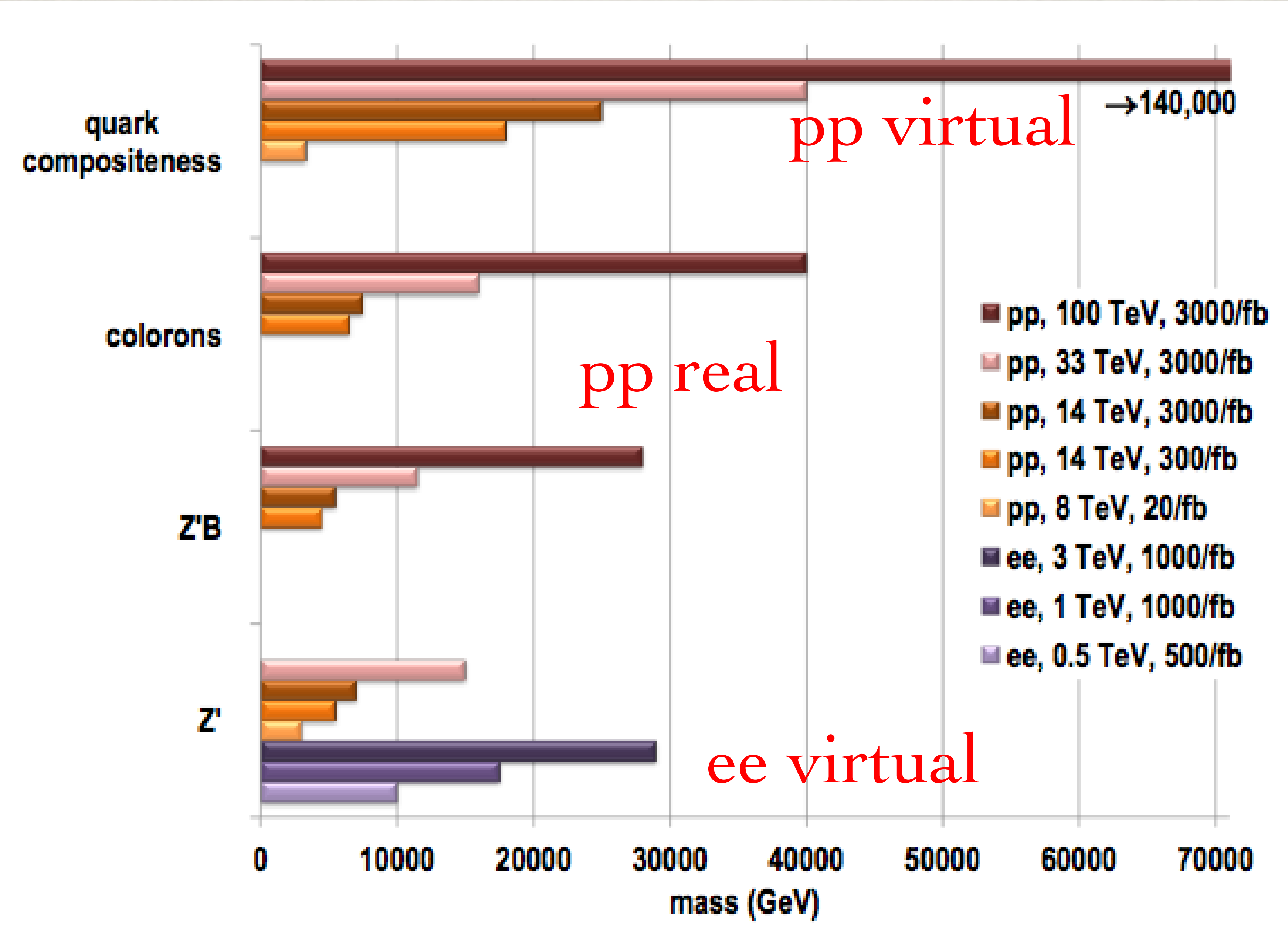
M. Low & L.T. Wang: 1404.0682

S. Gori et al.: 1410.6287



New Particle Searches at VLHC

Snowmass NP report, 1311.0299



VLHC leads for broad searches at the energy frontier.

Look forward to the many inspiring talks this week!

New behavior of "old physics"

At the new energy frontier VLHC:

$$v/\sqrt{s} \sim 2.5 \times 10^{-3}$$

The EW gauge bosons & the top quark pretty much "massless": the EW symmetry is "restored"

In the collision processes

- Initial particles → partons
- Final state particles → narrow jets, radiations
- New physics @ heavier scales → *$W^{\pm}$/Z/H/top*

→ Studying *$W^{\pm}$/Z/H/top* at higher energies:

- bread & butter (new) phenomena within SM
- first step toward understanding O(10 TeV) scale physics

Top quark Initiated Processes

TH, J. Sayre, S. Westhoff: 1411.2588

With $m_t << E_{cm}$, The top quark *IS* as massless at the VLHC as *b*-quark at the Tevatron:

$$m_b / E_{TeV} \sim 3.5/1\text{x}10^3 \sim 3.5\text{x}10^{-3}$$

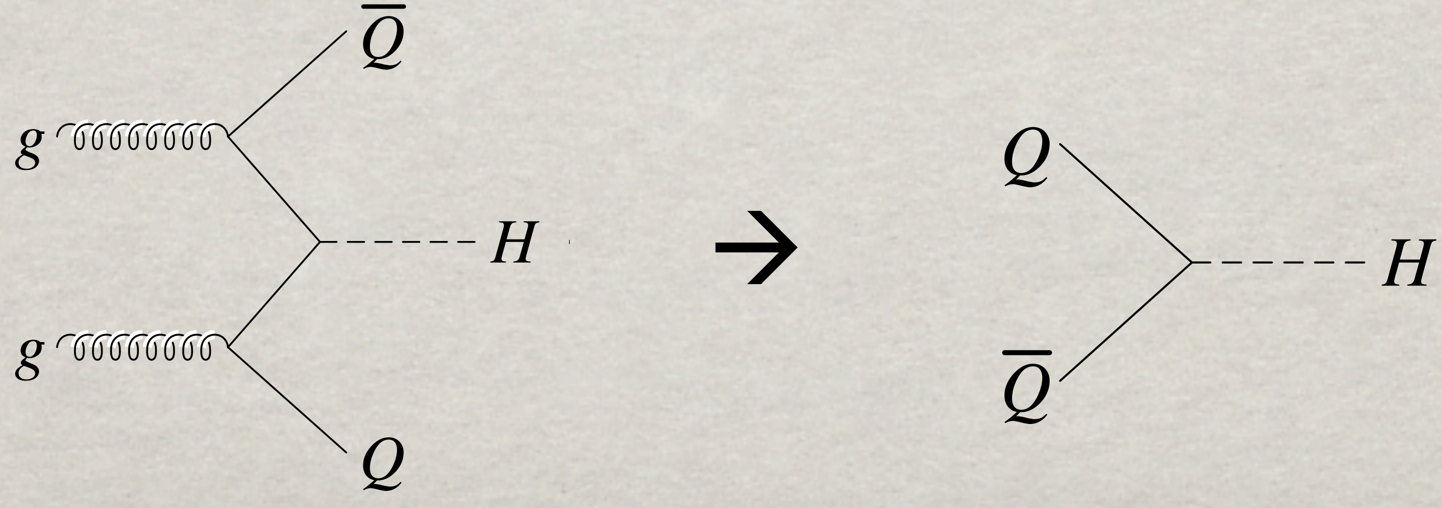
$$m_t / E_{VLHC} \sim 160/50\text{x}10^3 \sim 3.2\text{x}10^{-3}$$

When a heavy scale M is involved, so that

$$\alpha_s \ln(M^2/m_t^2) \sim O(1) \rightarrow M \sim (50\text{-}100)\, m_t$$

then the collinear large logs need to be resummed

→ top quarks as partons



Top quark Initiated Processes

With $m_t \sim v$,
The top quark may hold the key to new physics:

- Most sensitive to the "naturalness" issue.
- Vacuum stability
- … …

TH, J. Sayre, S. Westhoff: 1411.2588

Examples for new physics: $t\bar{t} \to X$

$$\text{spin } 0: \quad \text{neutral scalar } H^0: \quad i\frac{y}{\sqrt{2}}; \quad \text{pseudo scalar } A^0: \quad i\frac{y}{\sqrt{2}}\gamma_5;$$

$$\text{charged scalar } H^+: \quad i\frac{y}{\sqrt{2}}(g_L P_L + g_R P_R);$$

$$\text{spin } 1: \quad \text{color} - \text{singlet vector/axial vector } Z'^0, W'^+: \quad ig\gamma^\mu(g_V - g_A\gamma_5);$$

$$\text{color} - \text{octet vector/axial vector } g_{KK}: \quad ig_s\gamma^\mu(g_V - g_A\gamma_5)\, t^a;$$

$$\text{spin } 2: \quad \text{tensor } G: \quad -i\frac{\kappa}{8}[\gamma^\mu(p_t - p_{\bar{t}})^\nu + \gamma^\nu(p_t - p_{\bar{t}})^\mu - 2g^{\mu\nu}(\not{p}_t - \not{p}_{\bar{t}} - 2m_t)].$$

New Physics Examples: $t\bar{t} \to X$

TH, J. Sayre, S. Westhoff: 1411.2588

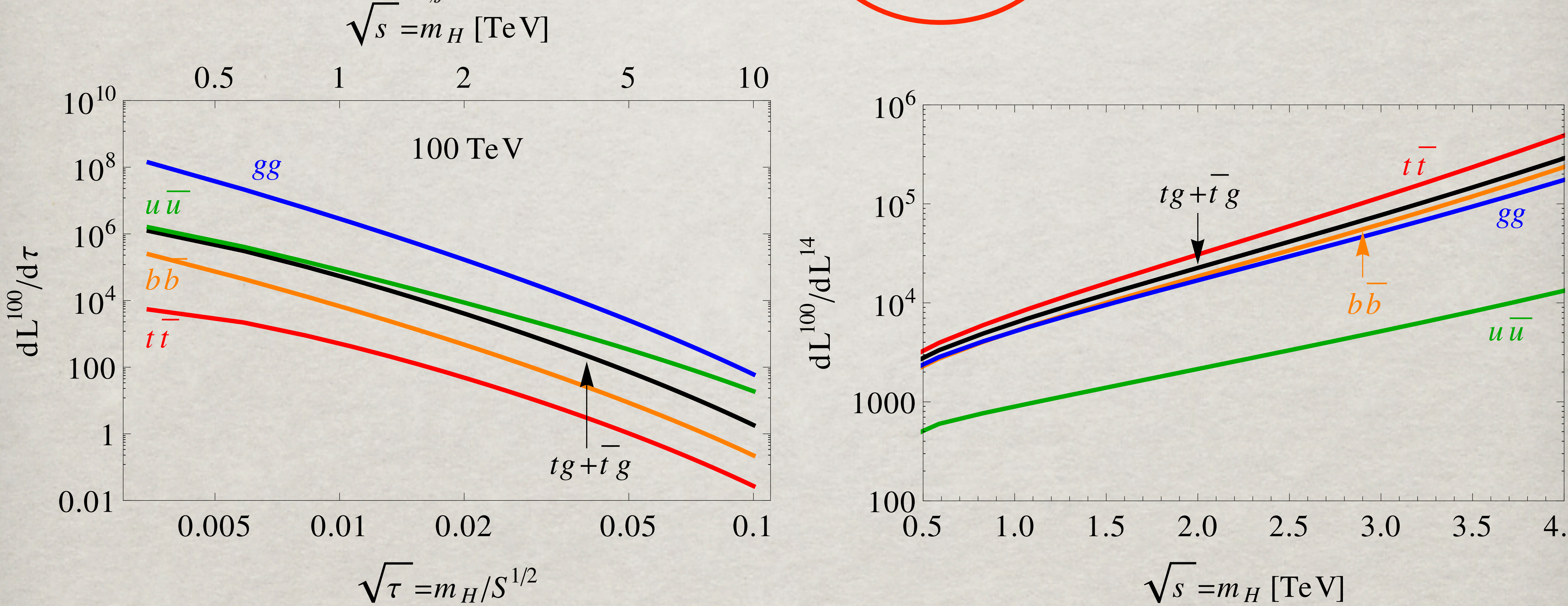
Table 1: Spin- and color-averaged squared matrix elements for the production of an on-shell heavy particle of mass $m_H = \sqrt{s}$ from heavy-quark fusion and the corresponding threshold behavior. The number of colors is denoted by N_c and the SU(3) invariant as $C_F = 4/3$. Subscripts T and L indicate transverse and longitudinal polarization, respectively. The kinematic factors are $\beta_{ij}^2 = \ell_{ij}(1-(m_i+m_j)^2/s)$ and $\ell_{ij} = 1-(m_i-m_j)^2/s$, as well as the couplings $g_{S,P} = (g_L \pm g_R)/2$ in terms of chiral couplings g_L and g_R.

process	$\overline{\sum}\lvert\mathcal{M}\rvert^2$	threshold behavior
$t\bar{t} \to H^0$	$\frac{y^2 s}{4N_c}\ \beta_{t\bar{t}}^2$	P-wave
$t\bar{t} \to A^0$	$\frac{y^2 s}{4N_c}$	S-wave
$t\bar{b} \to H^+$	$\frac{y^2 s}{4N_c}\ (g_S^2 \beta_{t\bar{b}}^2/\ell_{t\bar{b}} + g_P^2 \ell_{t\bar{b}})$	same as H^0, A^0, with an extra ℓ
$t\bar{t} \to Z_T'^0$	$\frac{g^2 s}{N_c}\ (g_V^2 + g_A^2 \beta_{t\bar{t}}^2)$	vector: S-wave; axial-vector: P-wave
$t\bar{t} \to Z_L'^0$	$\frac{g^2 s}{N_c}\ g_V^2(2m_t^2/s)$	fermion mass suppression
$t\bar{b} \to W_T'^+$	$\frac{g^2 s}{N_c}\ (g_V^2 \ell_{t\bar{b}} + g_A^2 \beta_{t\bar{b}}^2/\ell_{t\bar{b}})$	same as $Z_T'^0$, with an extra ℓ
$t\bar{b} \to W_L'^+$	$\frac{g^2 s}{N_c}\ \left(g_V^2 \ell_{t\bar{b}}\ \frac{(m_t+m_b)^2}{2s} + g_A^2 \beta_{t\bar{b}}^2\ \frac{(m_t-m_b)^2}{2s\ell_{t\bar{b}}}\right)$	fermion mass suppression
$t\bar{t} \to g_{KK}$	$C_F \frac{g_s^2 s}{N_c}\ (g_V^2(1+2m_t^2/s) + g_A^2 \beta_{t\bar{t}}^2)$	same as Z'^0
$t\bar{t} \to G$	$\frac{\kappa^2 s^2}{32N_c}\ (1+8m_t^2/3s)\beta_{t\bar{t}}^2$	P-wave

Partonic luminosities

$$\sigma_{pp\to H+X}(S) = \sum_{i,j} \int_{m_H^2/S}^{1} dx_1 \int_{m_H^2/(x_1 S)}^{1} dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat\sigma_{ij\to H}(s)$$

$$\equiv \sum_{i,j} \int_{m_H^2/S}^{1} d\tau\, \frac{dL_{ij}}{d\tau}\, \hat\sigma_{ij}(s), \qquad \frac{dL_{ij}}{d\tau}(\tau,\mu) = \int_{\tau}^{1} \frac{\mathrm{d}x}{x} f_i(x,\mu) f_j(\tau/x,\mu)$$



Top lumi tracking gg, reaching few% of bb!

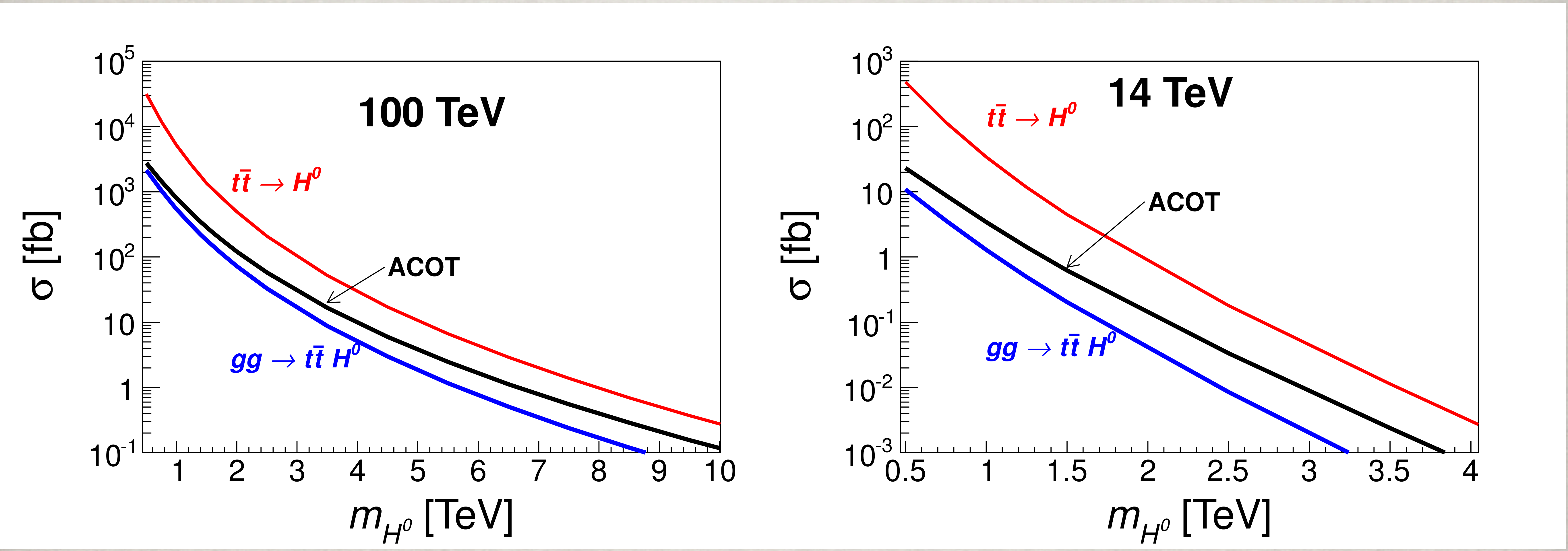
Relevant range: $0.002 \lesssim \bar{x} \lesssim 0.1, \quad \text{for} \quad 200\ \text{GeV} \lesssim \sqrt{s} \lesssim 10\ \text{TeV}.$

Lumi(gg, bb, tt @100/14) increased by

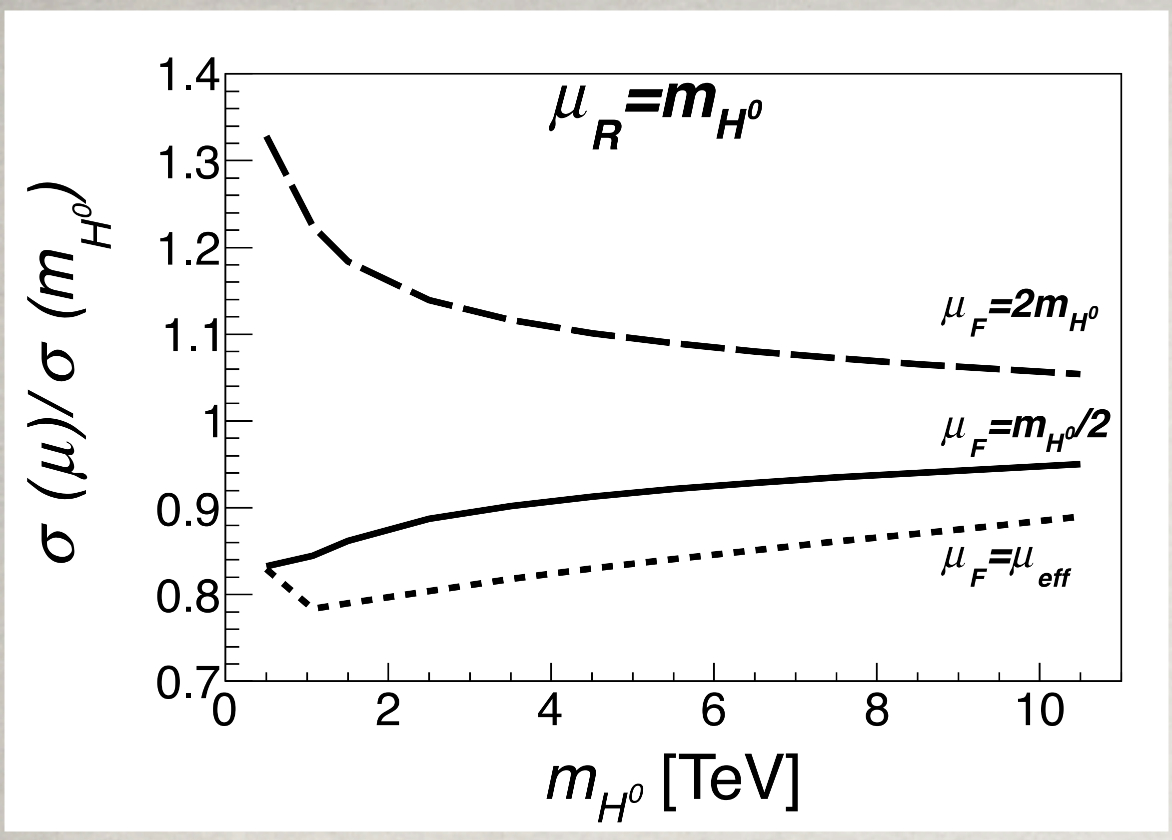
$1000 - 10^5$ for 500 GeV - 4 TeV!

TH, J. Sayre, S. Westhoff: 1411.2588

5-flavor vs. 6-flavor:
(ACOT: massive top with careful subtraction)



- 5-flavors usually underestimate the rate (better at low M)
- 6-flavors usually overestimate the rate (better at high M) (too much resummation) → proper treatment needed
- Higher CM Energies better approximation



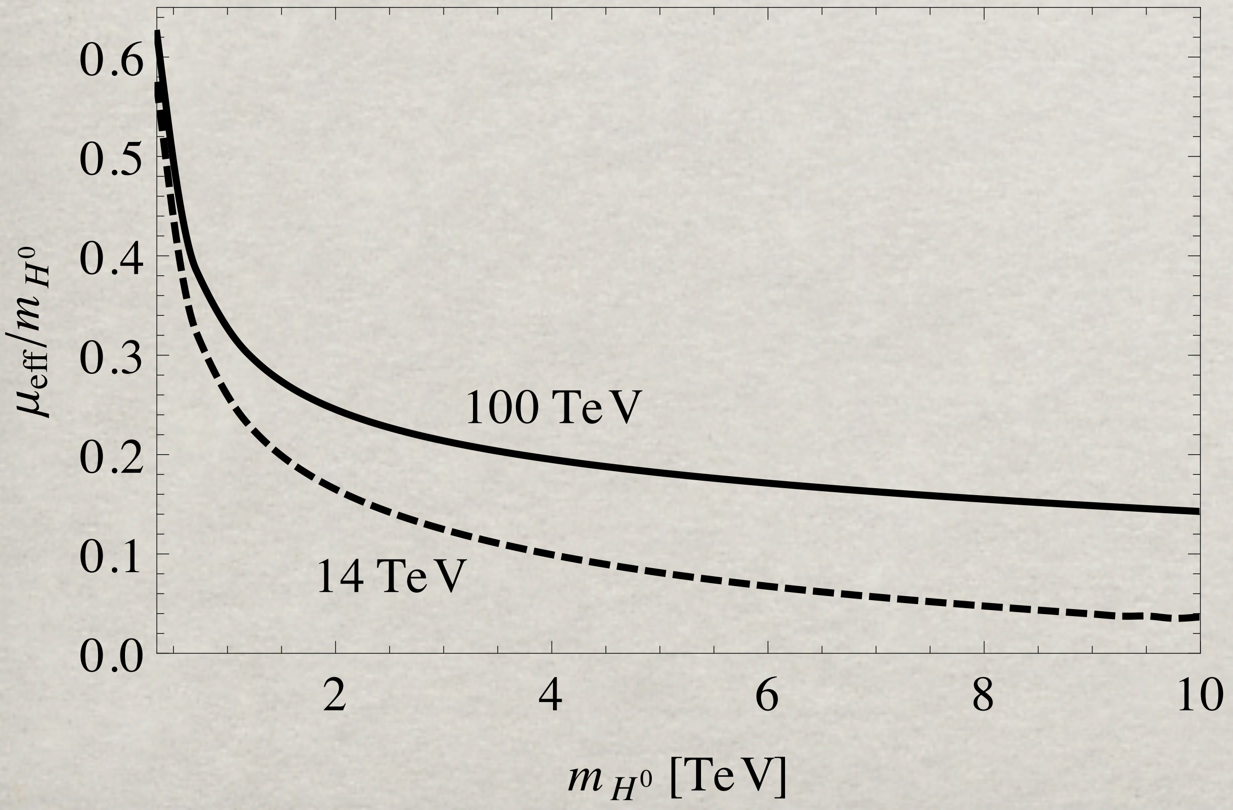
"Natural" factorization scale

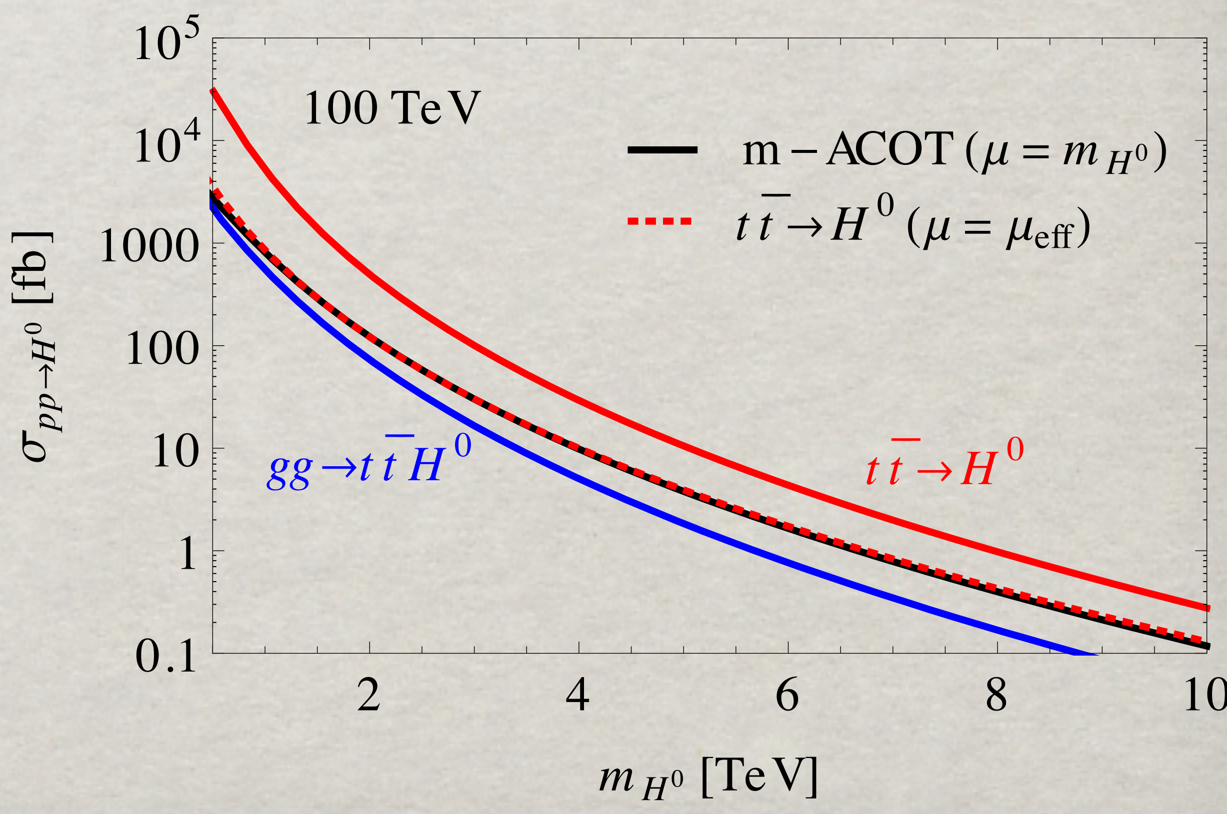
$$\mu^2 \approx m_H^2$$

"Effective" factorization scale

(Early discussions: Maltoni, Willenbrock)

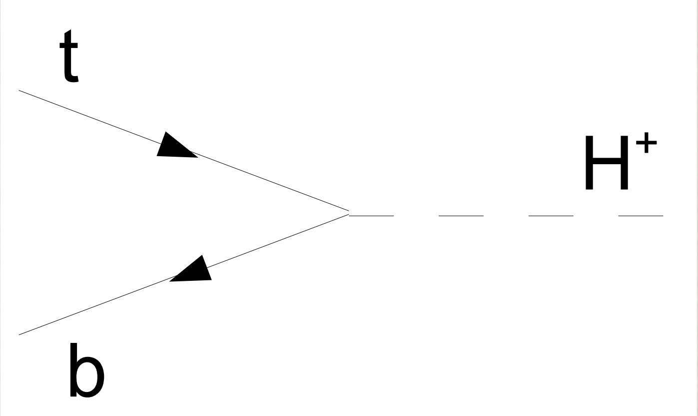
$$\log\left(\frac{\mu_{\rm eff}^2}{m_t^2}\right) = \frac{\int \frac{dx}{x} f_t(x, m_{H^0}) \int \frac{dz}{z} P_{tg}(z) \log(\frac{m_{H^0}^2}{m_t^2}\frac{(1-z)^2}{z}) f_g(\frac{\tau}{zx}, m_{H^0})}{\int \frac{dx}{x} f_t(x, m_{H^0}) \int \frac{dz}{z} P_{tg}(z) f_g(\frac{\tau}{zx}, m_{H^0})}$$



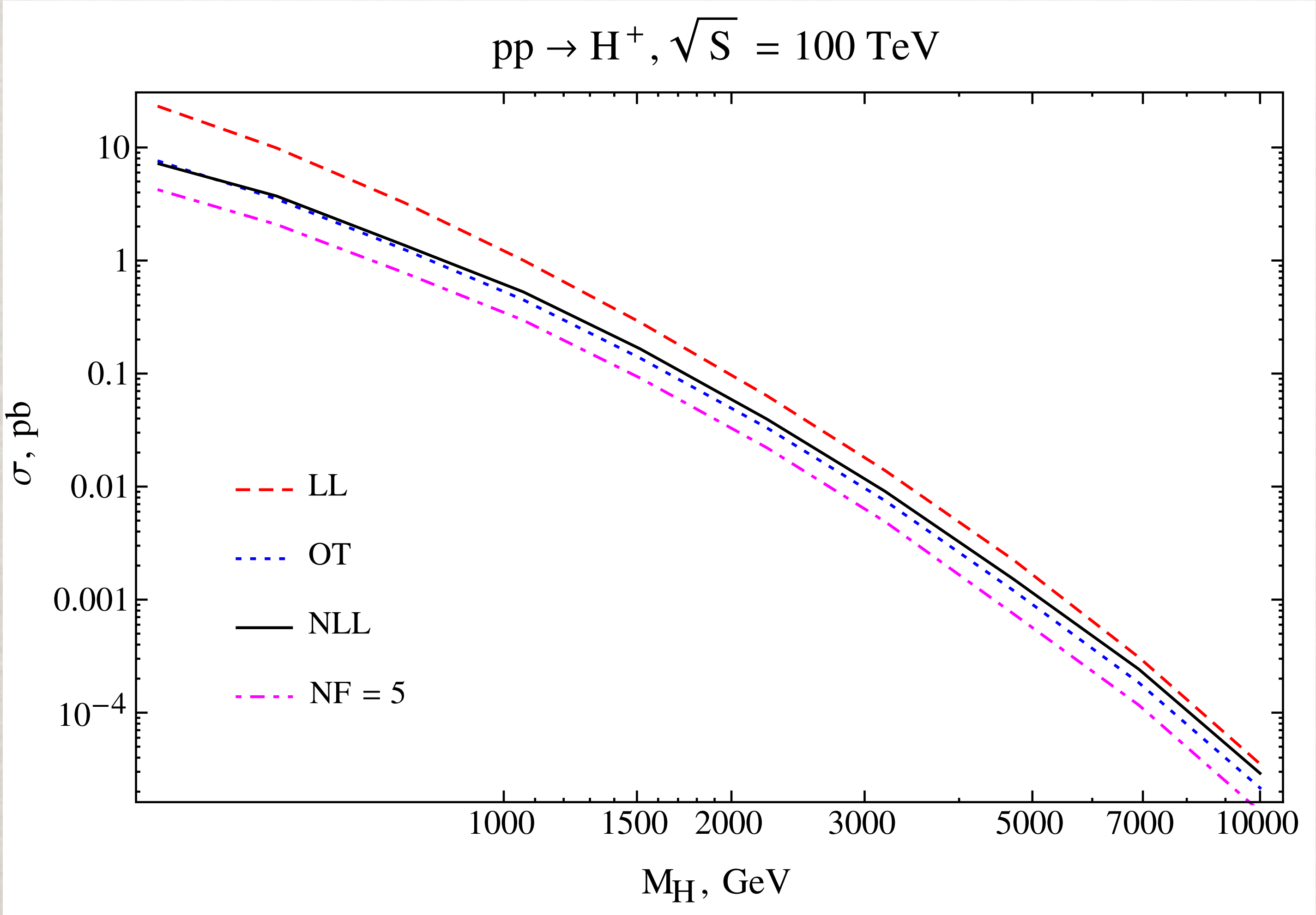


Another recent work *

$$t\bar{b} \to H^+$$



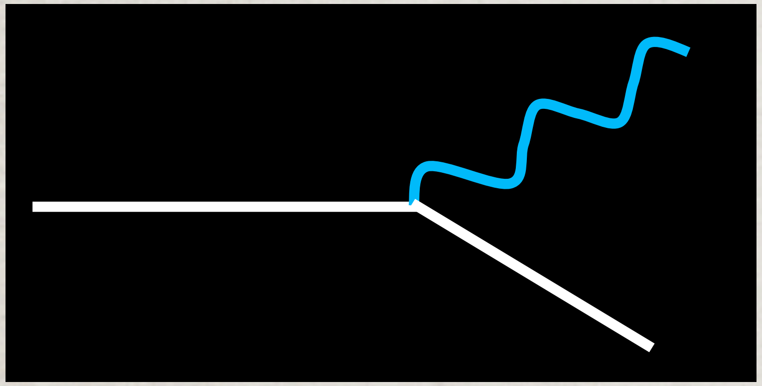
Full NLO $O(\alpha_s)$ calculations, including NLO PDF's.



* Dawson, Ismail, Low, 2014

Gauge-boson Initiated Processes

At colliding energies $E >> M_W$,
EW gauge bosons are new "gluons"!



"Effective W-Approximation"
(VBF → h is seen by ATLAS/CMS)
S. Dawson, 1985;
G. Kane et al., 1984;
Chanowitz & Gailard, 1984

In the EW theory:

$$P_{q\to qV_T} = (g_V^2 + g_A^2)\ \frac{\alpha_2}{2\pi}\ \frac{1+(1-x)^2}{x} \ln\frac{Q^2}{\Lambda^2}$$

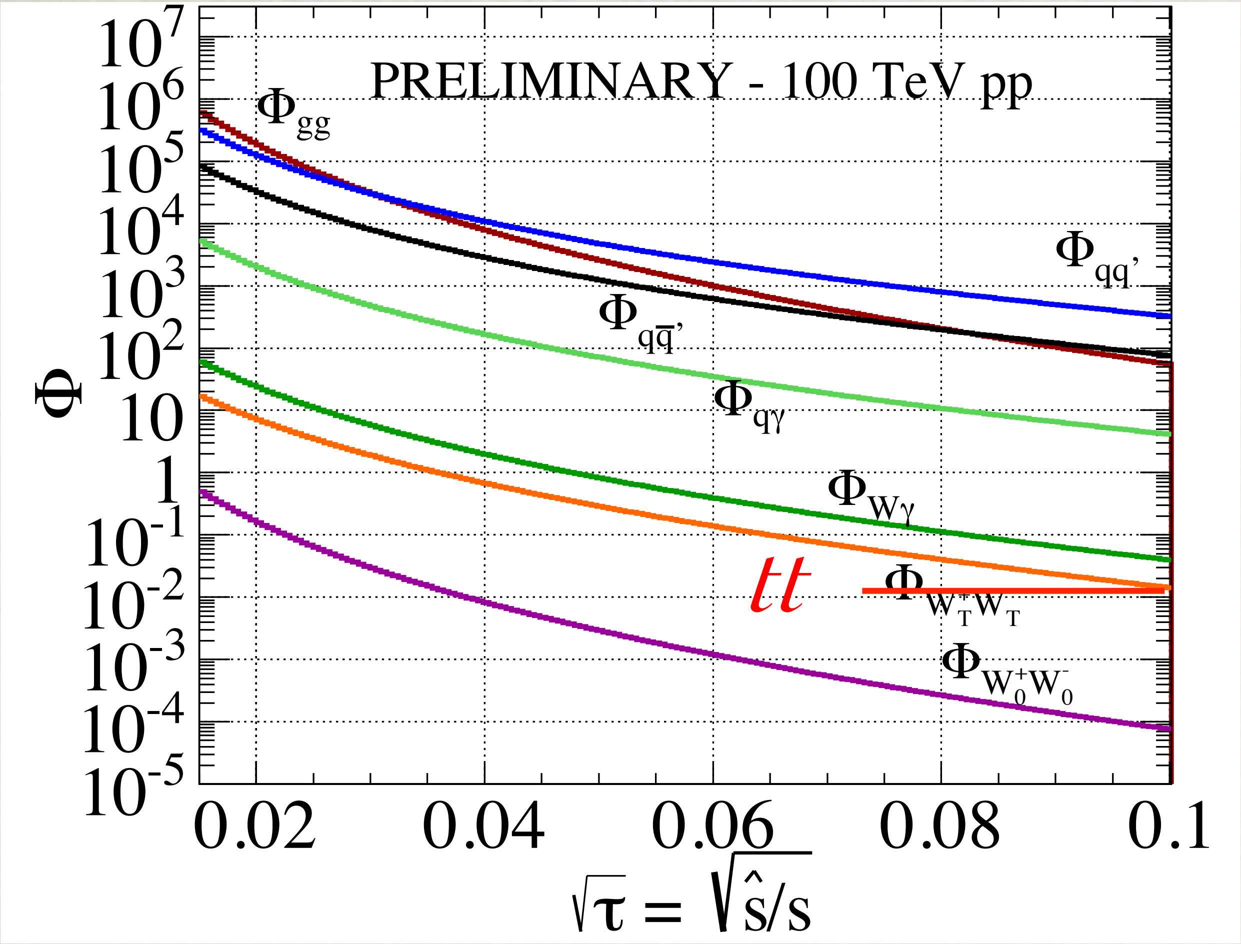
$$P_{q\to qV_L} = (g_V^2 + g_A^2)\ \frac{\alpha_2}{\pi}\ \frac{1-x}{x}$$

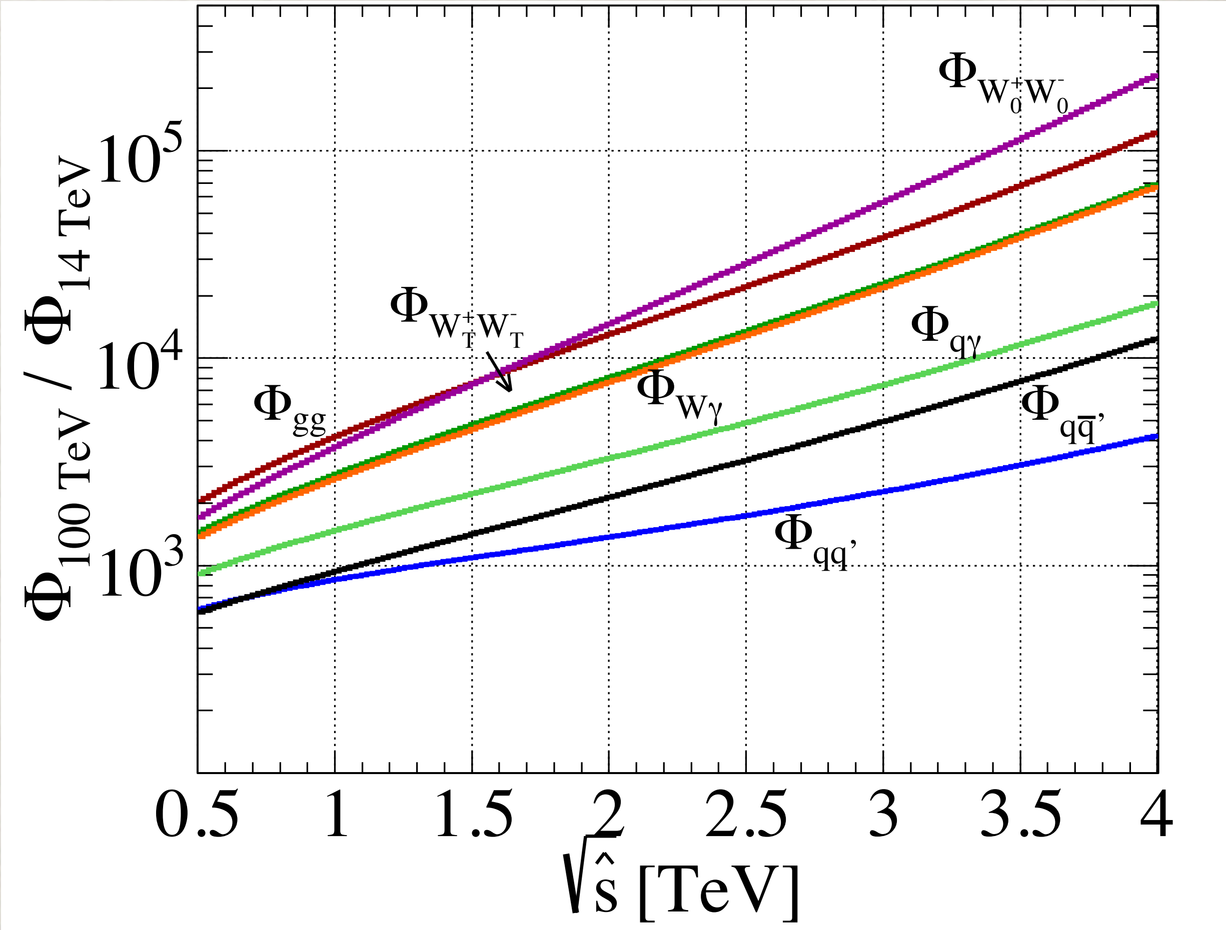
- V_T radiation the same as g, γ : $|\mathcal{M}|^2 \sim p_T^2$:
  - "dead cone" at $p_T \to 0$
  - log-enhancement at high p_T & soft x
- V_L radiation no collinear enhancement/suppression, not the same as a scalar radiation.

WW Partonic luminosities

TH, R. Ruiz, B. Tweedie, in prep

$$\Phi_{VV'}(\tau) = \frac{1}{(\delta_{VV'}+1)} \int_{\tau}^{1} \frac{d\xi}{\xi} \int_{\tau/\xi}^{1} \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^{1} \frac{dz_2}{z_2} \sum_{q,q'} \times \left[f_{V/q}(z_2) f_{V'/q'}(z_1)\, f_{q/p}(\xi) f_{q'/p}\left(\frac{\tau}{\xi z_1 z_2}\right) + f_{V/q}(z_2) f_{V'/q'}(z_1)\, f_{q/p}\left(\frac{\tau}{\xi z_1 z_2}\right) f_{q'/p}(\xi) \right] \quad (7)$$





Lumi($W^+_T W^-_T$) similar size to lumi(tt);

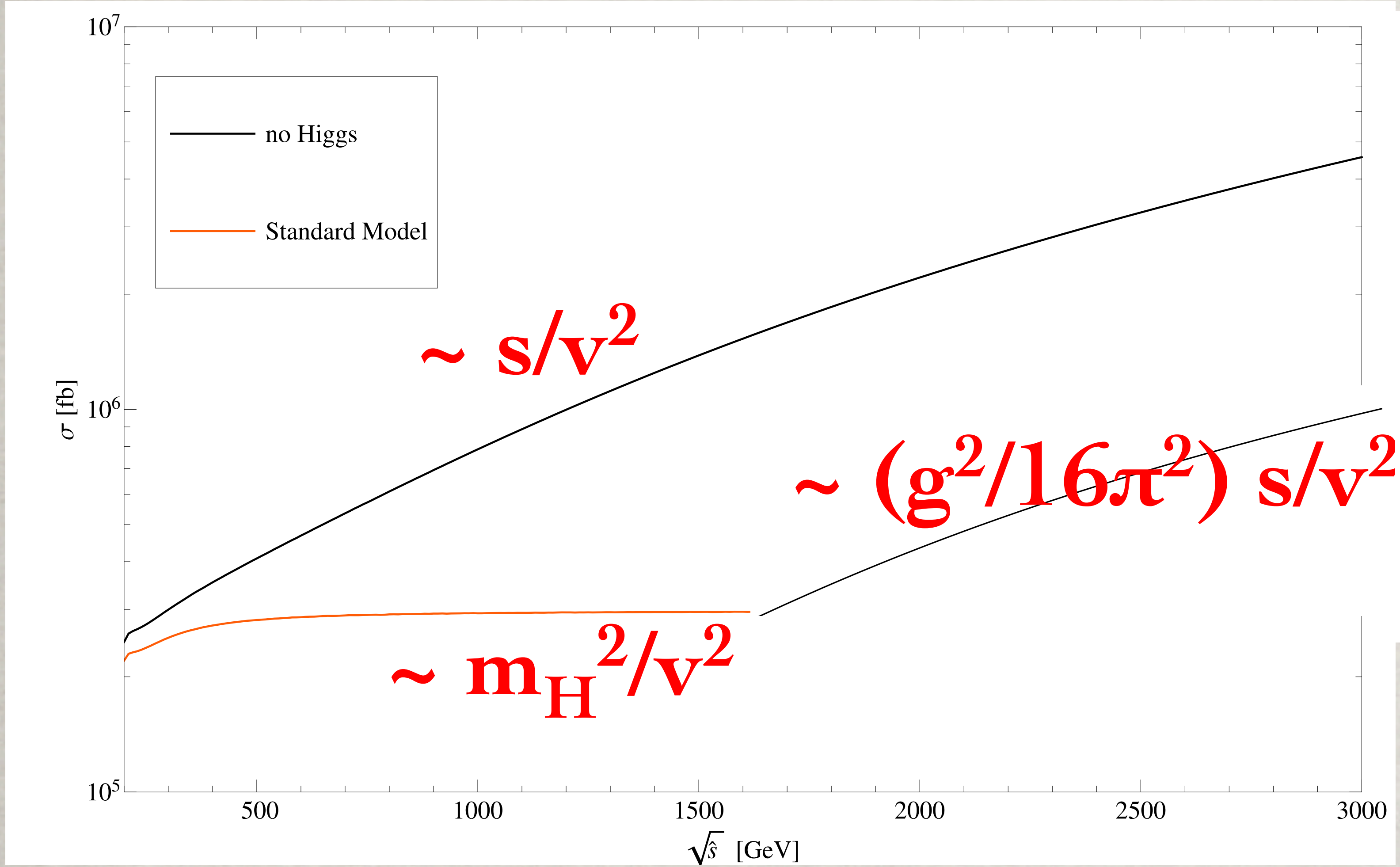
Lumi($W^+_T W^-_T$) ~ Lumi($W^\pm \gamma$), Electro=weak

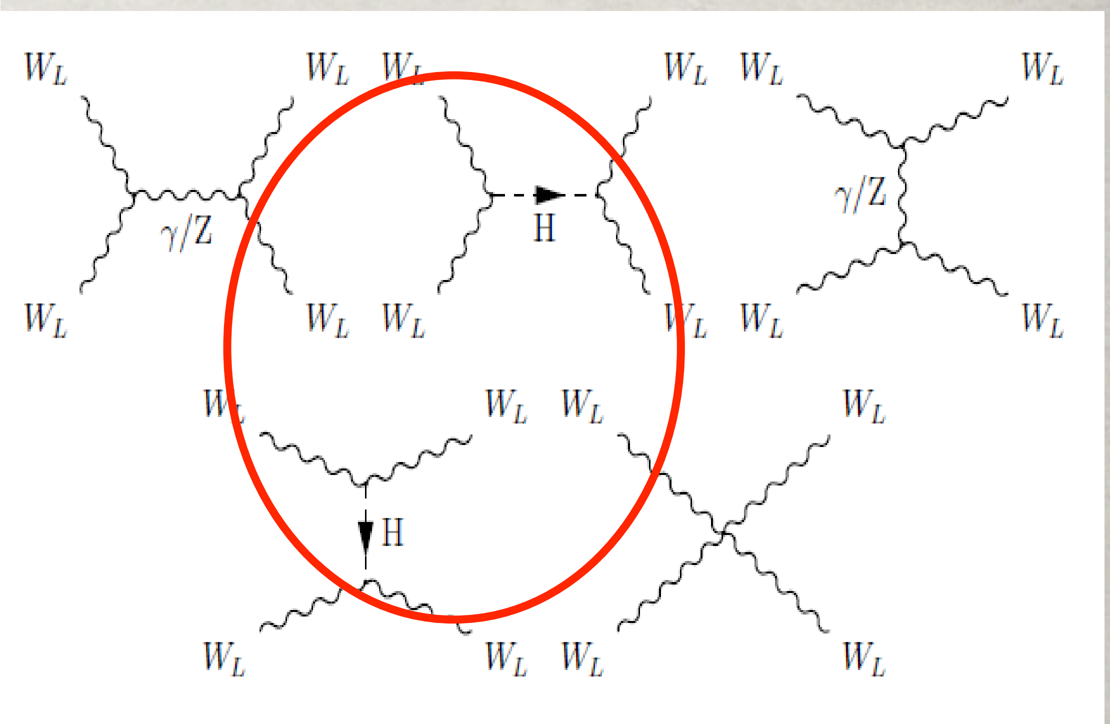
Lumi($W^+_L W^-_L$) 100 times smaller: Goldstones

Lumi(100/14) increased by 1000 – 10^5 for 500 GeV - 4 TeV!

$W_L W_L$ Scattering:

- The existence of a light, weakly coupled Higgs boson unitarize the WW amplitude:





- Consistent perturbative theory up to Λ (?)
- New strong dynamics effects may still exist, but "delayed" to v^2/Λ^2.

$W_L W_L$ Scattering:

Different channels are sensitive to different physics:

I	0	1	2
$J=0$	σ^0	.	$\phi^{--}, \phi^{-}, \phi^{0}, \phi^{+}, \phi^{++}$
1	.	$\rho^{-}, \rho^{0}, \rho^{+}$	.
2	f^0	.	$t^{--}, t^{-}, t^{0}, t^{+}, t^{++}$
...	...	...	...

- $I=0$: resonant in W^+W^- and ZZ scattering
- $I=1$: resonant in W^+Z and W^-Z scattering
- $I=2$: resonant in W^+W^+ and W^-W^- scattering

Equally important: *WW → HH, tt* for H^3 & top couplings.

Multi Gauge-boson Production From prompt production

At 100 TeV:

M. Mangano's talk

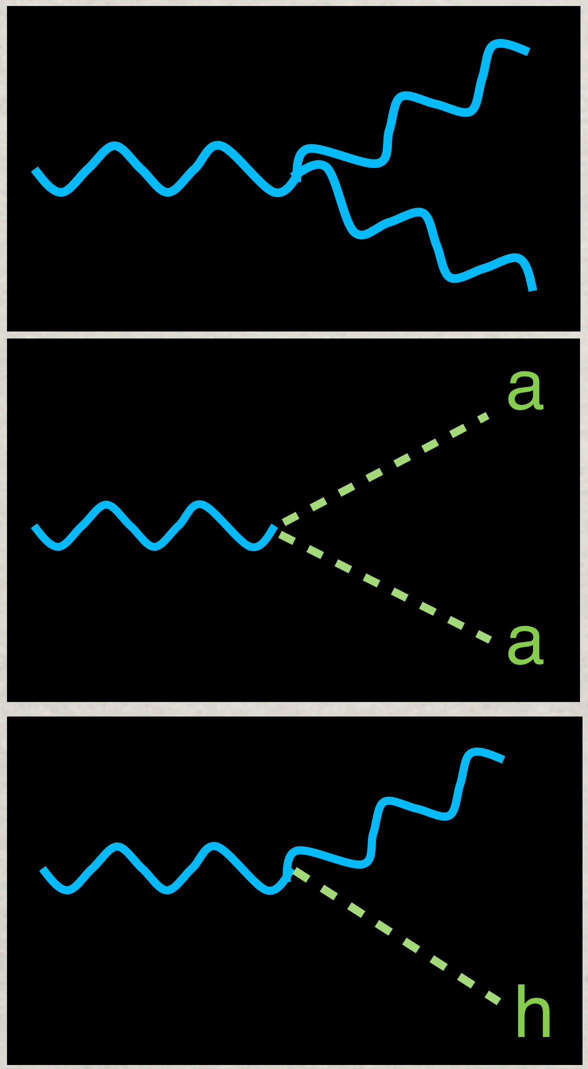
W W	σ=770 pb
W W W	σ=2 pb
W W Z	σ=1.6 pb
W W W W	σ=15 fb
W W W Z	σ=20 fb
....	

Each W costs you a factor of ~ 1/100 (EW coupling)

Multi Gauge-boson Production From splitting/showering:

At colliding energies E >> M_V,

In EW gauge boson splitting: J. Chen, TH, B. Tweedie, in prep



$$P_{V_T \to V_T V_T'} = \frac{\alpha_2}{2\pi}\left[\frac{1}{x(1-x)} + x(1-x)\right] \ln \frac{Q^2}{M_W^2}$$

$$P_{V_T \to V_L V_L'} = \frac{\alpha_2}{4\pi} x(1-x) \ln \frac{Q^2}{M_W^2}$$

$$P_{V_T \to V_T H} = \frac{\alpha_2}{4\pi} \frac{1-x}{x}$$

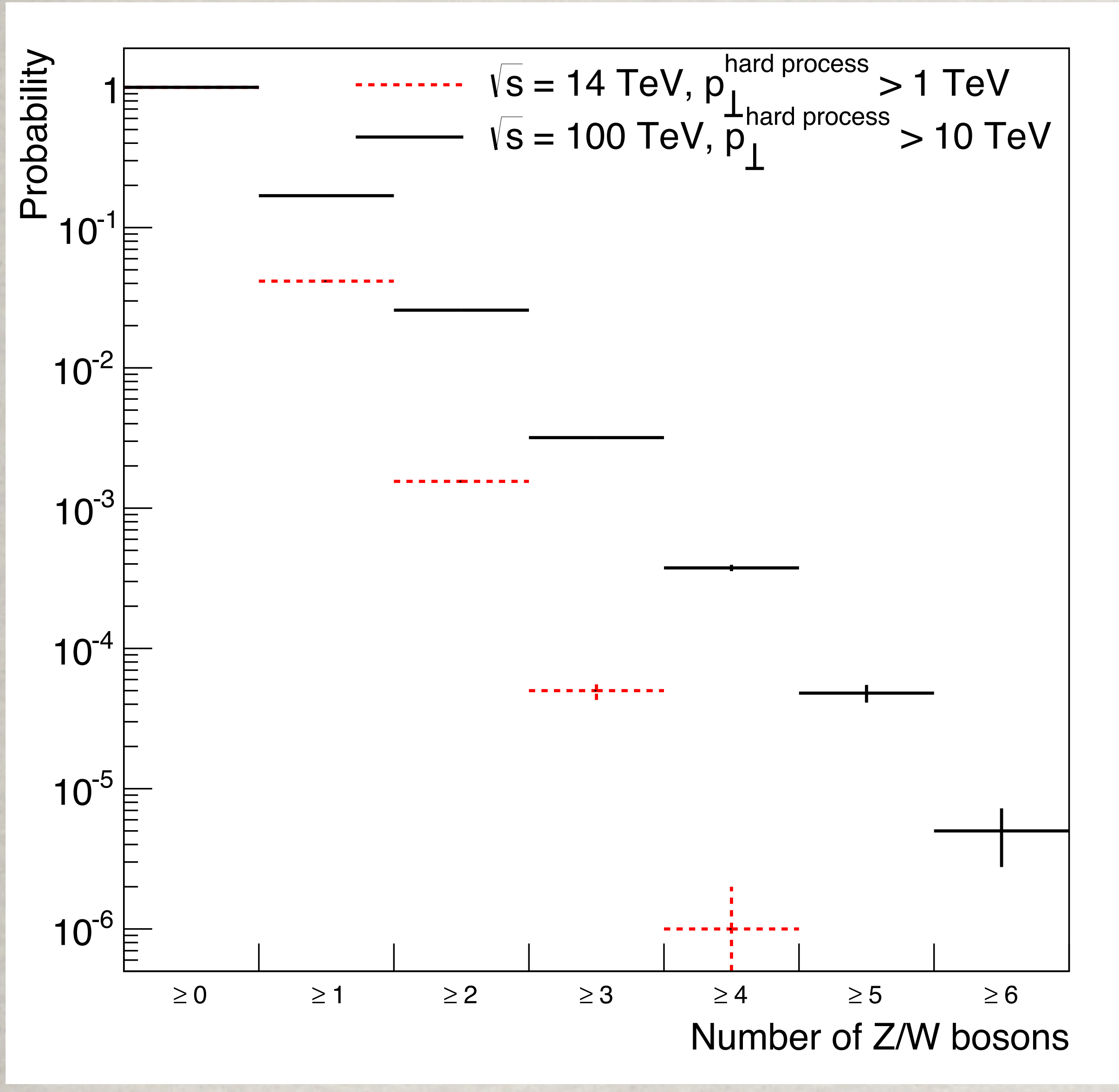
- V_T the “new gluons”!
- V_L/H radiations the Goldstone Eq. Theo.

Splitting Probabilities:

J. Chen, TH, B. Tweedie, in prep

Split	Form	Rate: E=1TeV	10 TeV
$q \to qV_T$	$2.8\times10^{-3}\ln^2(E/M_W)$	1.7%	7%
$q \to qV_L$	*ET* $1.4\times10^{-3}\ln(E/M_W)$ proportional to gv	0.5%	1%
$V_T \to V_TV_T$	$0.01\times\ln^2(E/M_W)$	6%	22%
$V_T \to V_LV_L$	$4\times10^{-4}\ln(E/M_W)$	0.15%	0.3%
$\to V_Lh$	*ET* same		
	pure gauge couplings		
$V_L \to V_TV_L$	$2\times10^{-3}\ln^2(E/M_W)$	1%	4%
$\to V_Th$	same		
$h \to V_TV_L$	same *ET*		
$V^*_T \to f\,f'$	$0.04\times\ln(E/M_W)$	5%	10%
$V_T \to V_TV_L$	$0.01\times\ln(E/M_W)$	2%	5%
$\to V_Th$	*ET* 3×10^{-4} proportional to gv	0.03%	0.03%

Multi Gauge-boson From showering:



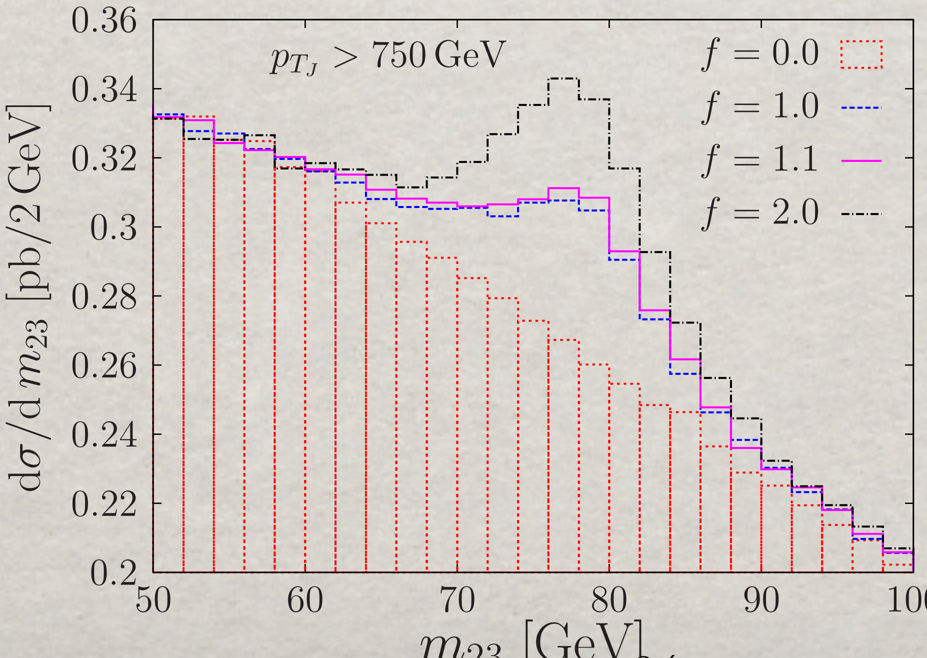
Christiansen, Sjostrand: 1401.5238

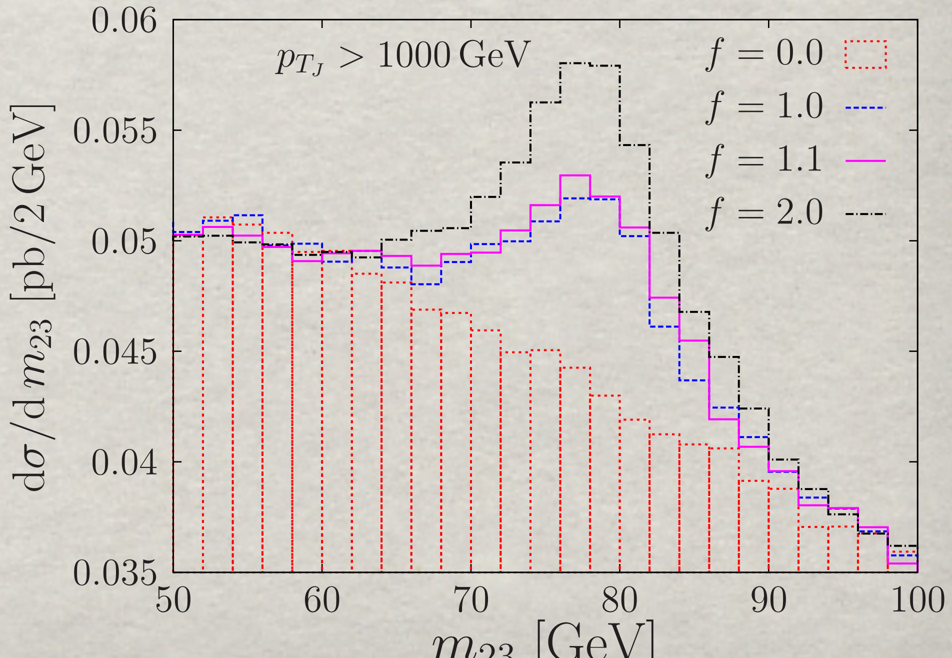
At higher energies, each *W* costs you a factor of ~ 1/10 !

We are in the process of developing a more complete EW showering code.

J. Chen, TH, B. Tweedie

Kruass, Petrov, Schonher, Spannowsky: 1403.4788





New Physics with energetic/ Multi tops/Gauge-bosons

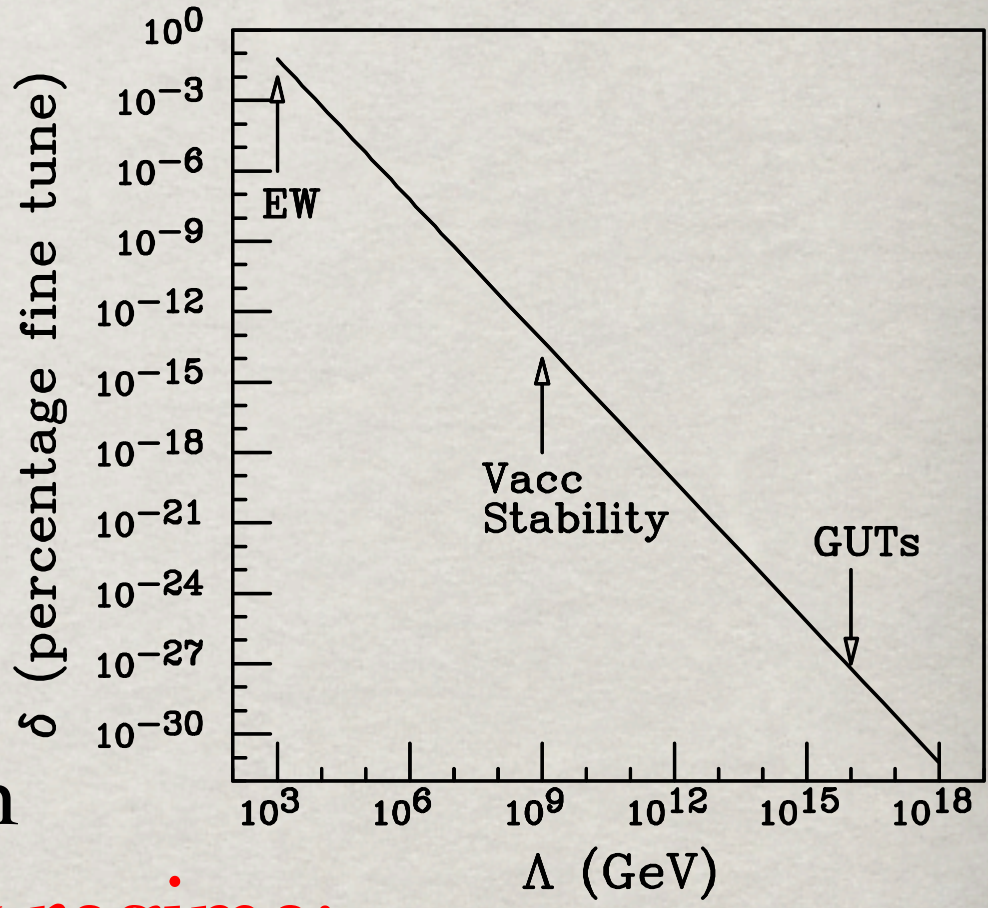
SUSY examples: $\tilde{b}\tilde{b}^* \to t\chi^- \ \bar{t}\chi^+, \ \tilde{t}W^- \ \tilde{t}^* W^+ \to 4W^\pm \ b\bar{b}.$

Heavy quark examples: *TT', BB', ...*

Energetic $W^\pm$, Z, H, t as new radiation sources from heavy W', *Z'* decays & $W_L W_L$ scattering

OVERALL

* With the Higgs discovery, the SM is healthier than ever, valid to a scale up to $\Lambda \sim$?
  But the Higgs sector fine-tuned δ :



* VLHC will take the lead for searches:
  $\tilde{g},\ \tilde{t},\ \tilde{b},\ \chi^{\pm,0}$, …$H^{\pm}$, A^0; $W^{\pm\prime}$, Z' …

The *top, W,Z,H* may hold the key for discovery!

- Searching for new physics starts from understanding old physics in the new regime:
  - *top, W,Z* may behave as partons to produce new heavy states;
  - *top, W,Z,H* may serve as new radiation sources; and may help reveal new heavy states.
  - Thus, need precise understanding of the dynamics/kinematics

WHILE NEW PHYSICS SEARCHES EXCITING, SM PHYSICS REMAINS RICH AT VLHC!