A New Look at an Old Friend

KAERU Conference

Kavli IPMU, March 26 , 2015

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My recent involvement

CEPC-SppC Preliminary Conceptual Design Report

Volume I: Physics and Detector

To be available soon. Please check back on April 8th or later.

Volume II: Accelerator

Download the pdf (12.3MB)
(Last updated 24-Mar-2015)

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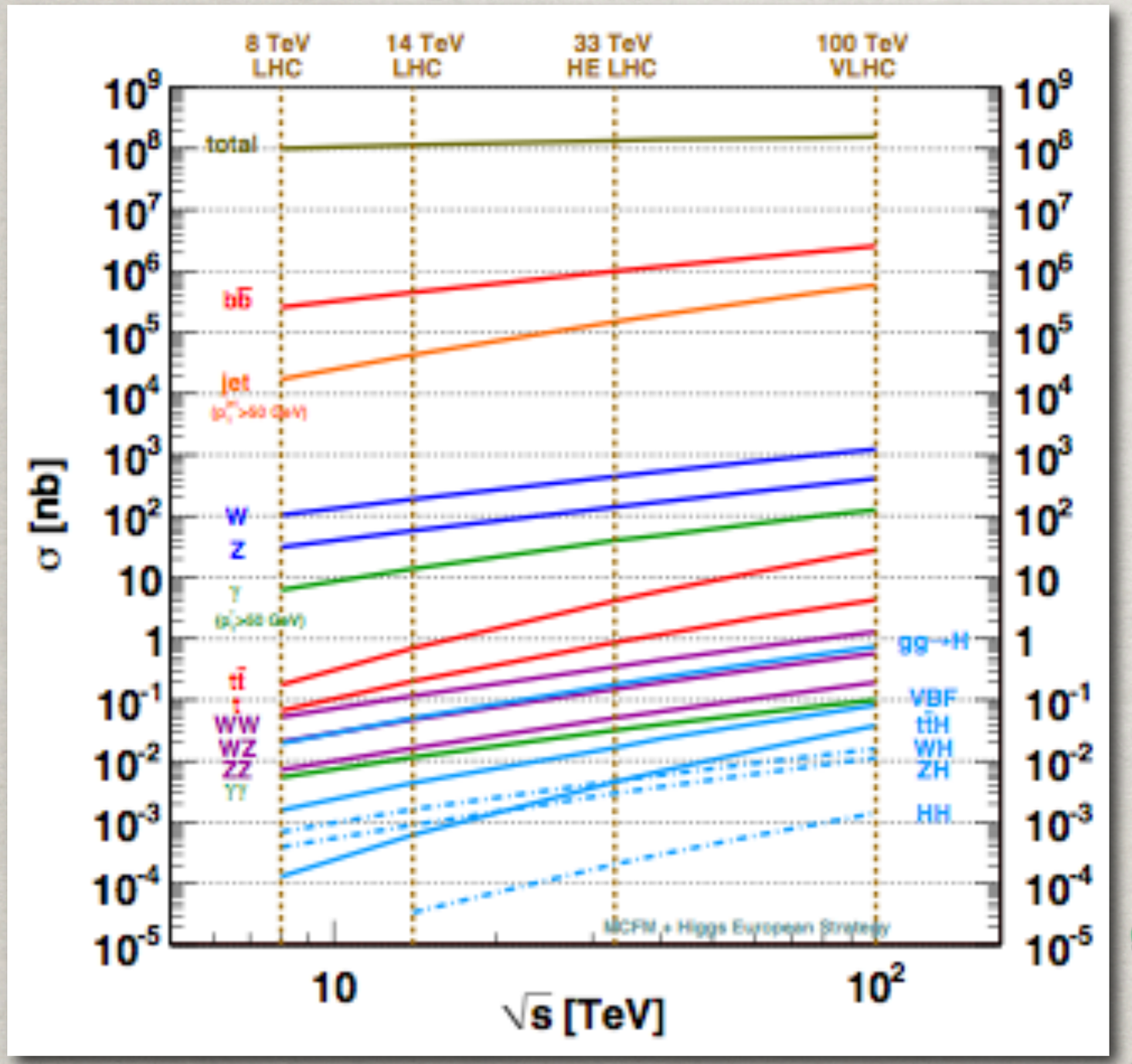
A new look at “old physics”

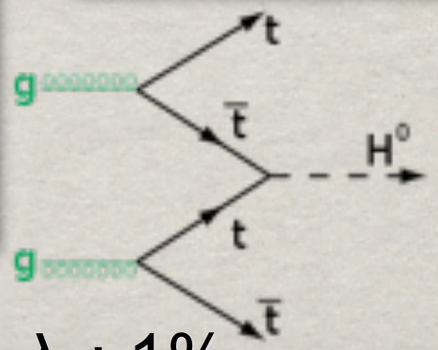
VLHC LEADS ENERGY FRONTIER

"Old Physics" still rich at 100 TeV

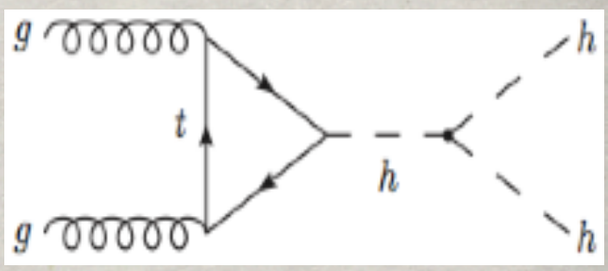


Interesting scaling:

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)	~10³



λ_t : 1%



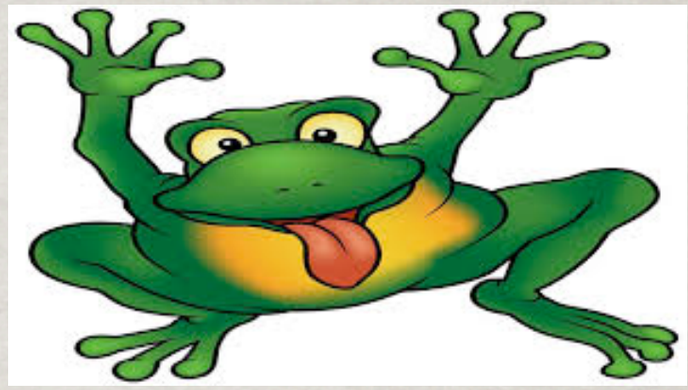
λ : 8%

Snowmass QCD Working Group: 1310.5189

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*±/*Z*/*H*/*top*

→ Studying *W*±/*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

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

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

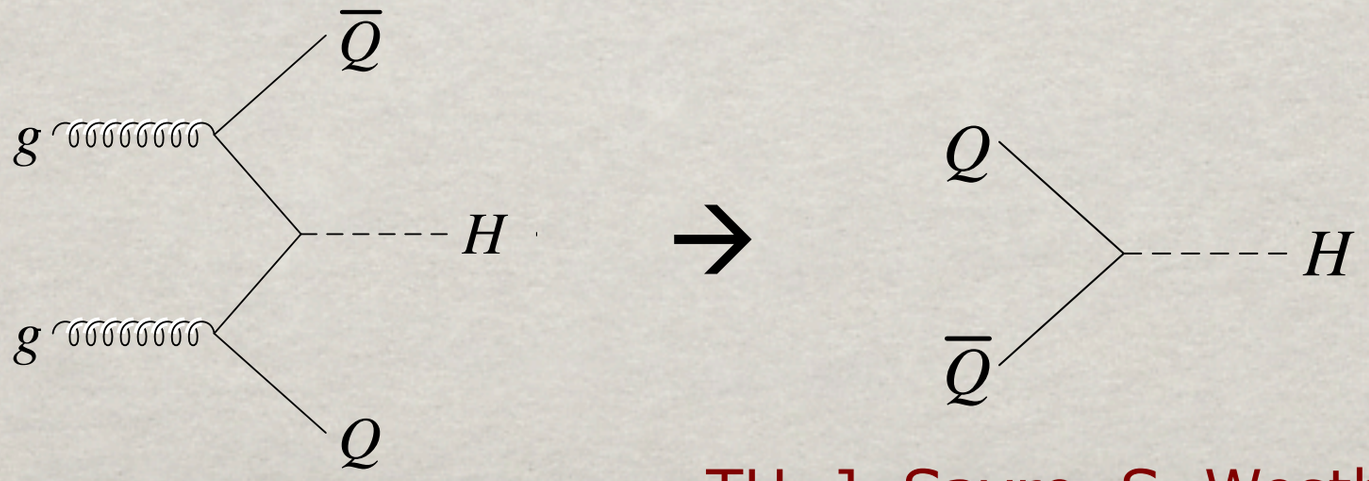
$$m_t / E_{VLHC} \sim 160/50\text{x}10^3 \sim 3.2\text{x}10^{-3}$$

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



TH, J. Sayre, S. Westhoff: 1411.2588

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

With $m_t \sim v$,

Top quark may hold the key to new physics:

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

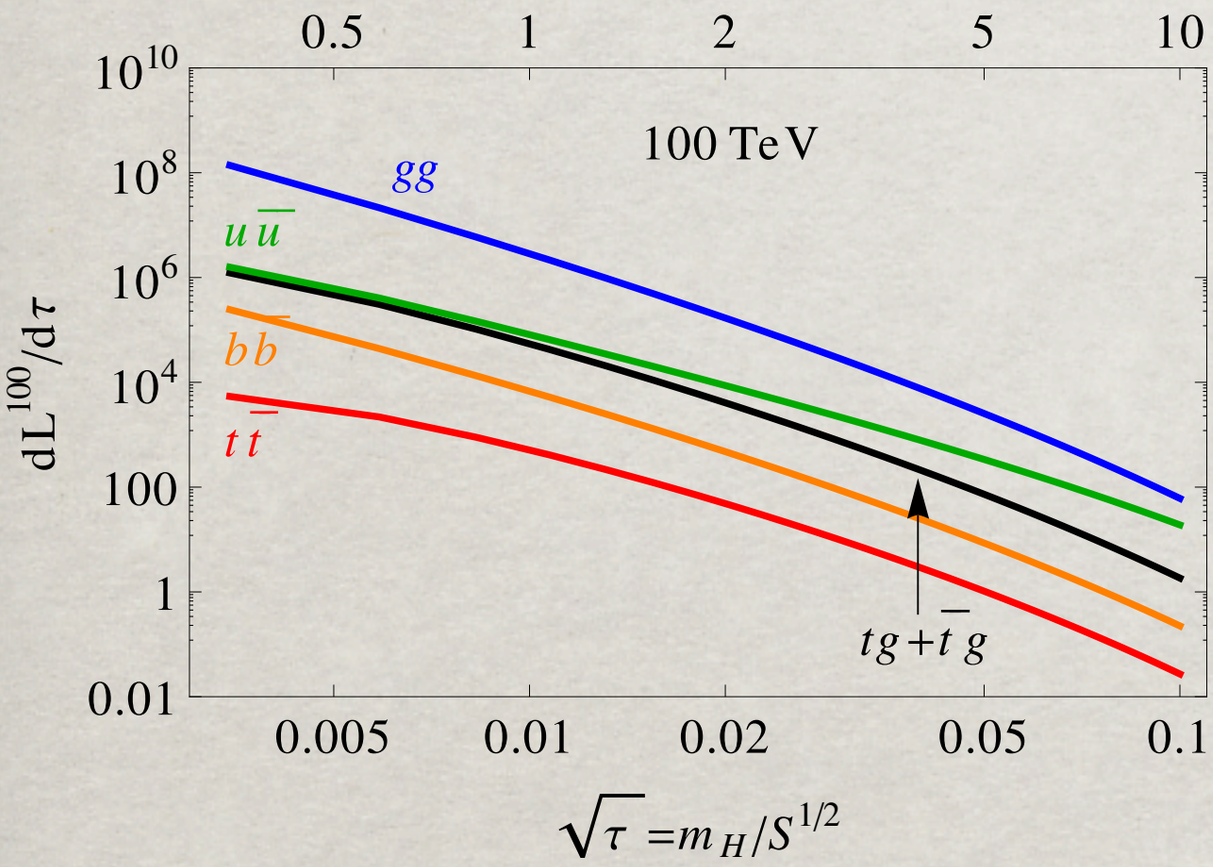
TH, J. Sayre, S. Westhoff: 1411.2588

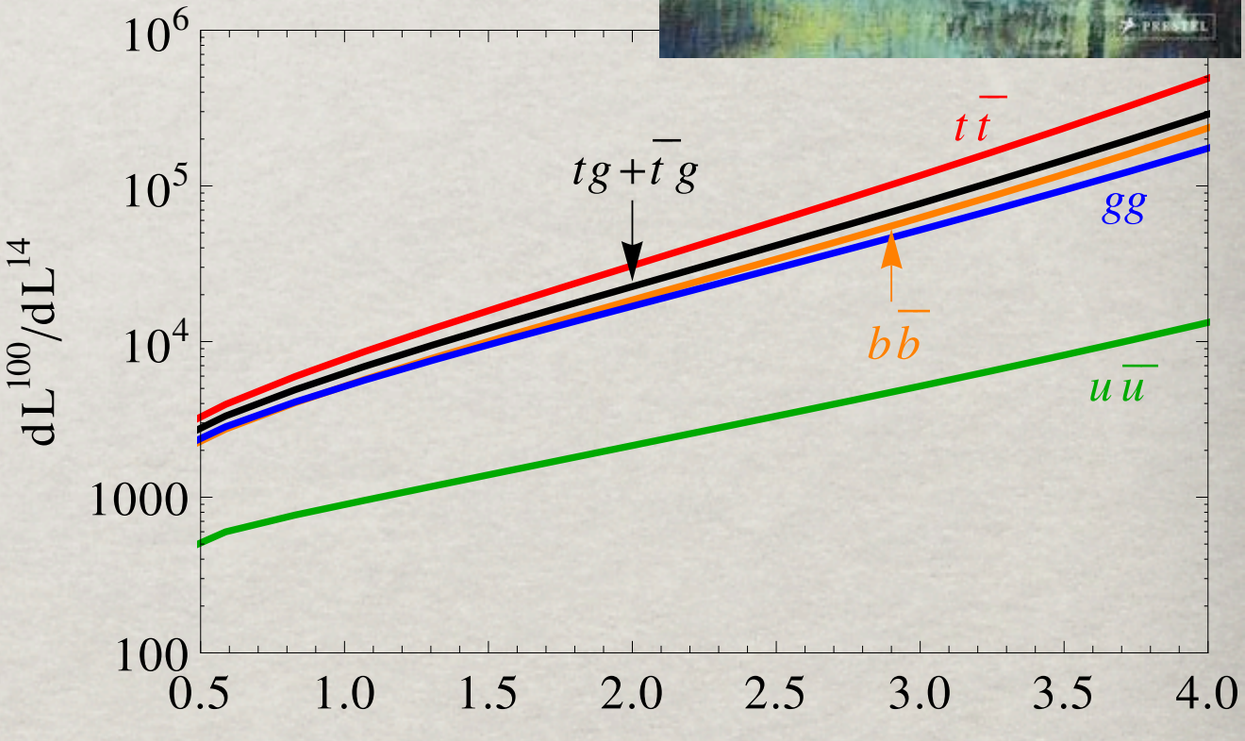
process	$\overline{\sum}\lvert\mathcal{M}\rvert^2$	threshold behavior
$t\bar{t} \to H^0$	$\frac{y^2 s}{4N_c}\ \beta_{t\bar{t}}^2$	P-wave
$t\bar{t} \to A^0$	$\frac{y^2 s}{4N_c}$	S-wave
$t\bar{b} \to H^+$	$\frac{y^2 s}{4N_c}\ (g_S^2 \beta_{t\bar{b}}^2/\ell_{t\bar{b}} + g_P^2 \ell_{t\bar{b}})$	same as H^0, 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
$t\bar{b} \to W_T'^+$	$\frac{g^2 s}{N_c}\ \left(g_V^2 \ell_{t\bar{b}} + g_A^2 \beta_{t\bar{b}}^2/\ell_{t\bar{b}}\right)$	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
$t\bar{t} \to G$	$\frac{\kappa^2 s^2}{32 N_c}\ (1 + 8m_t^2/3s)\beta_{t\bar{t}}^2$	P-wave

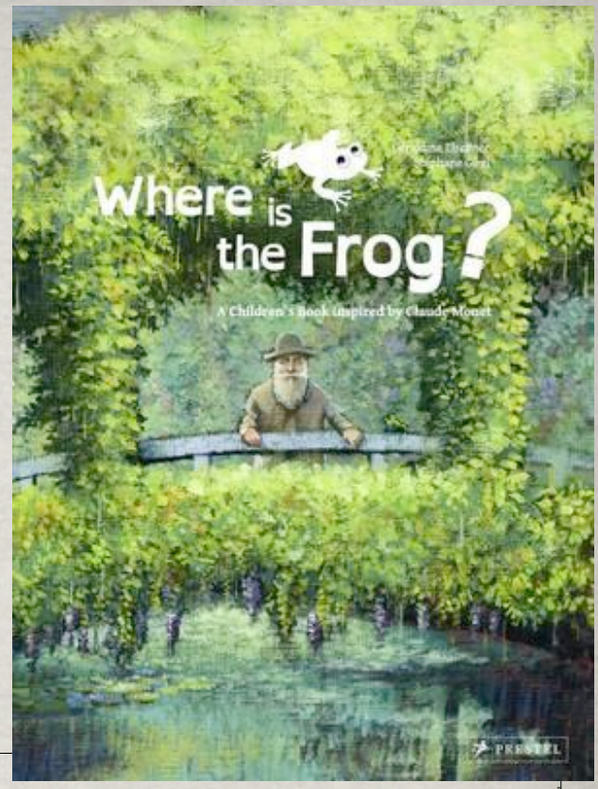
Partonic luminosities

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

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







Top lumi tracking gg, reaching few% of bb!

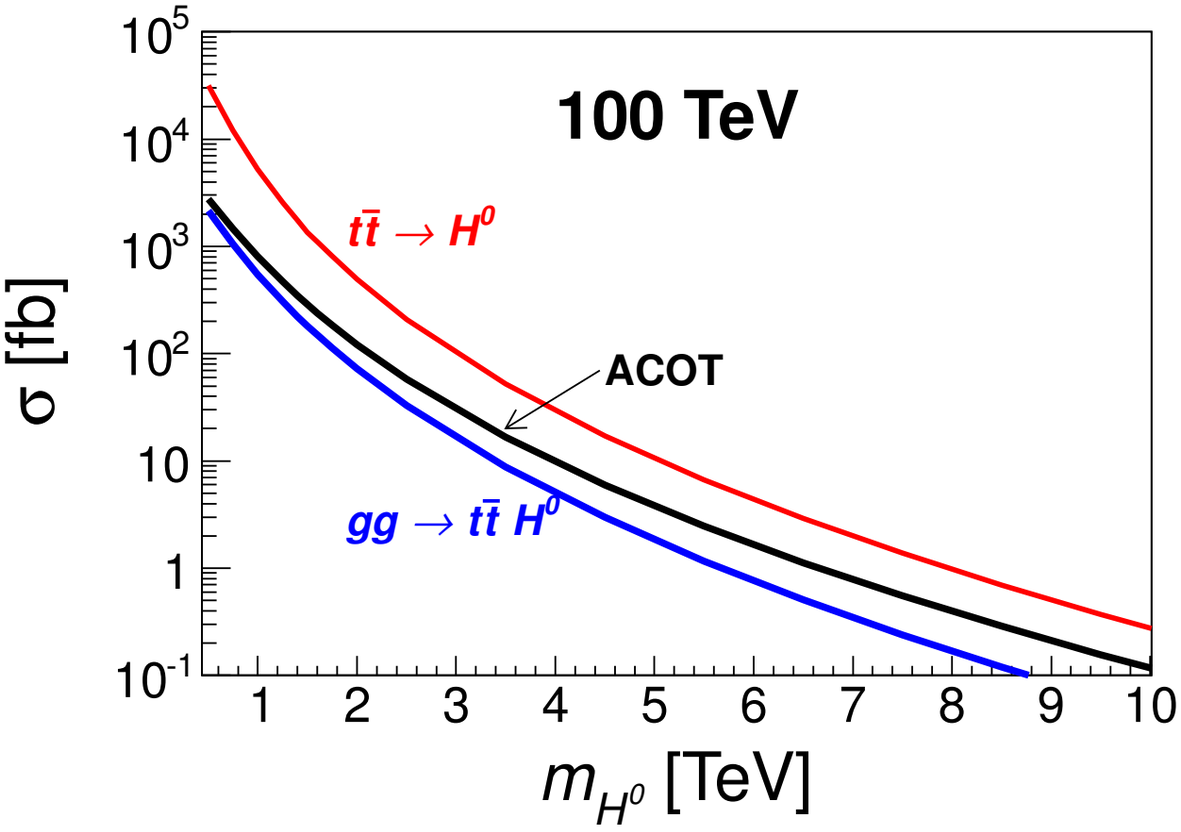
Relevant range: $0.002 \lesssim \bar{x} \lesssim 0.1, \quad \text{for} \quad 200\ \text{GeV} \lesssim \sqrt{s} \lesssim 10\ \text{TeV}.$

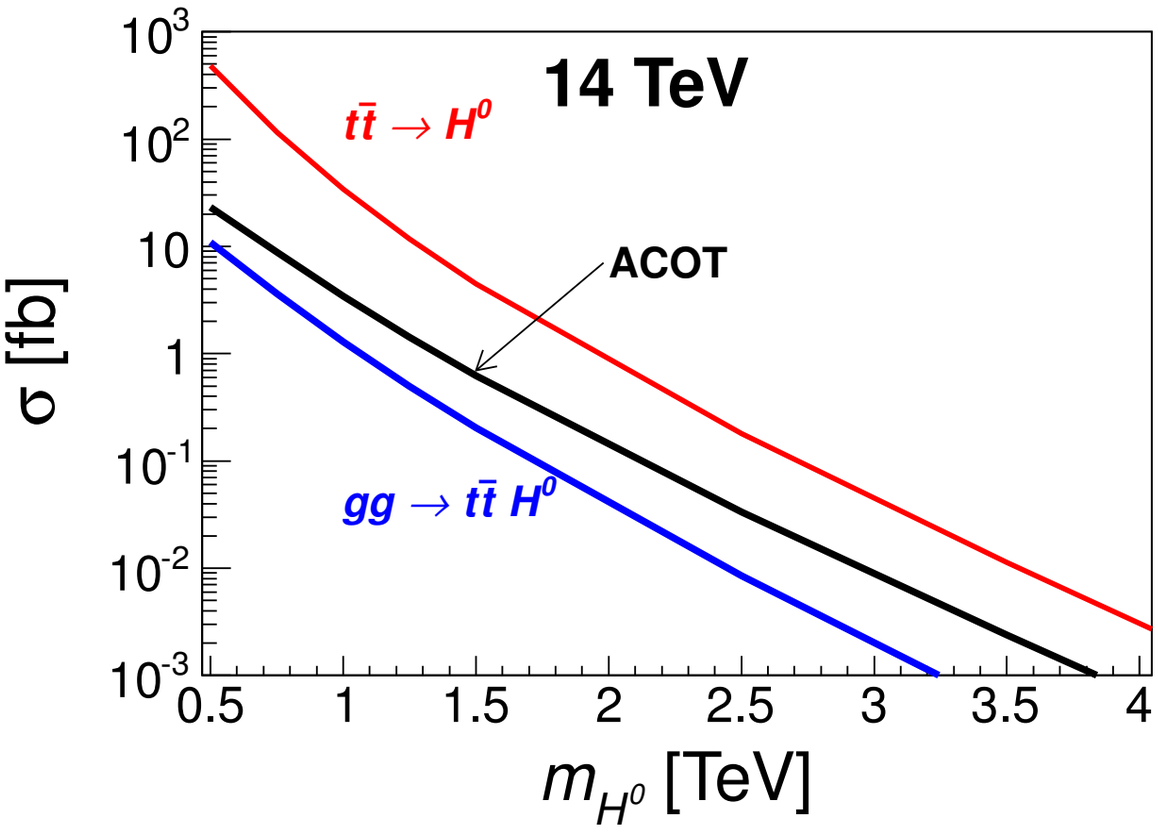
Lumi(gg, bb, tt @100/14) increased by

10^3 – 10^5 for 500 GeV - 4 TeV!

TH, J. Sayre, S. Westhoff: 1411.2588

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



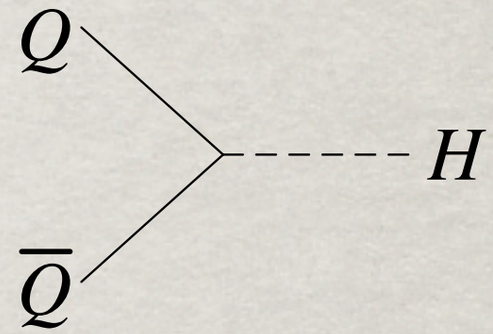


- 5-flavors usually underestimate the rate (better at low M)
- 6-flavors usually overestimate the rate (better at high M) (too much resummation) → proper treatment needed
- Higher CM Energies better approximation

Recollection: Double-counting and subtraction

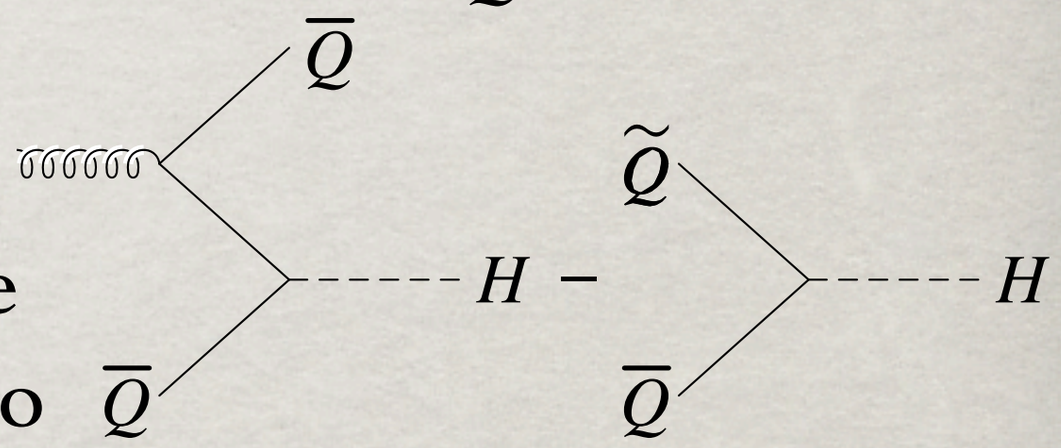
For $m_H >> m_b$ ($m_H > 100$ GeV), (Maltoni, Stelzer, Sullivan, Willenbrock)
it would be justifiable to start with 5-flavors

$$b\bar{b} \to H$$



NLO correction at α_s

$$gb \to b\ H,\ g\bar{b} \to \bar{b}\ H$$

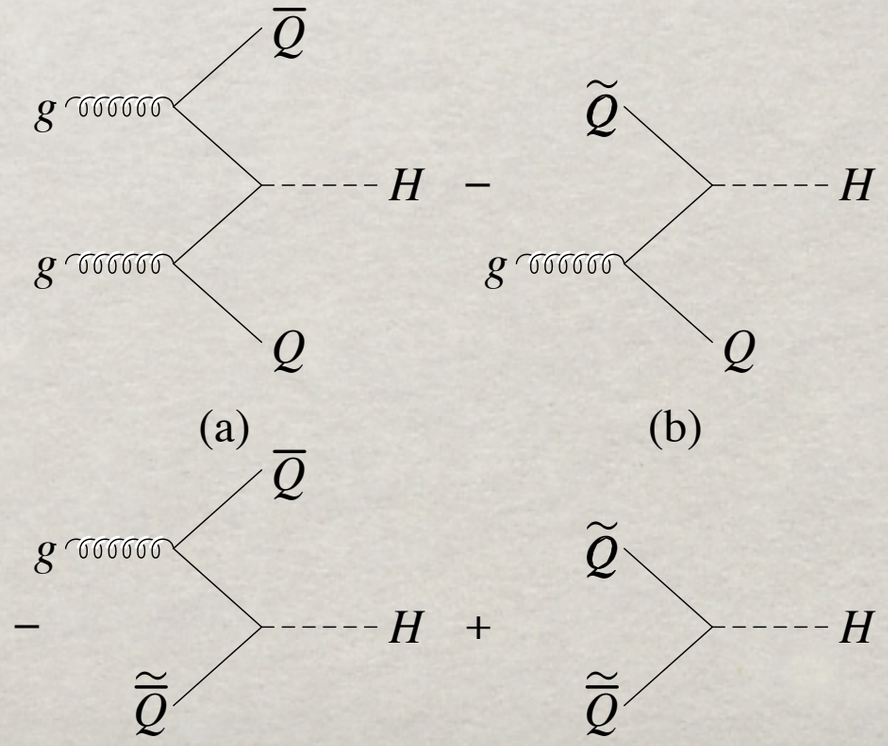


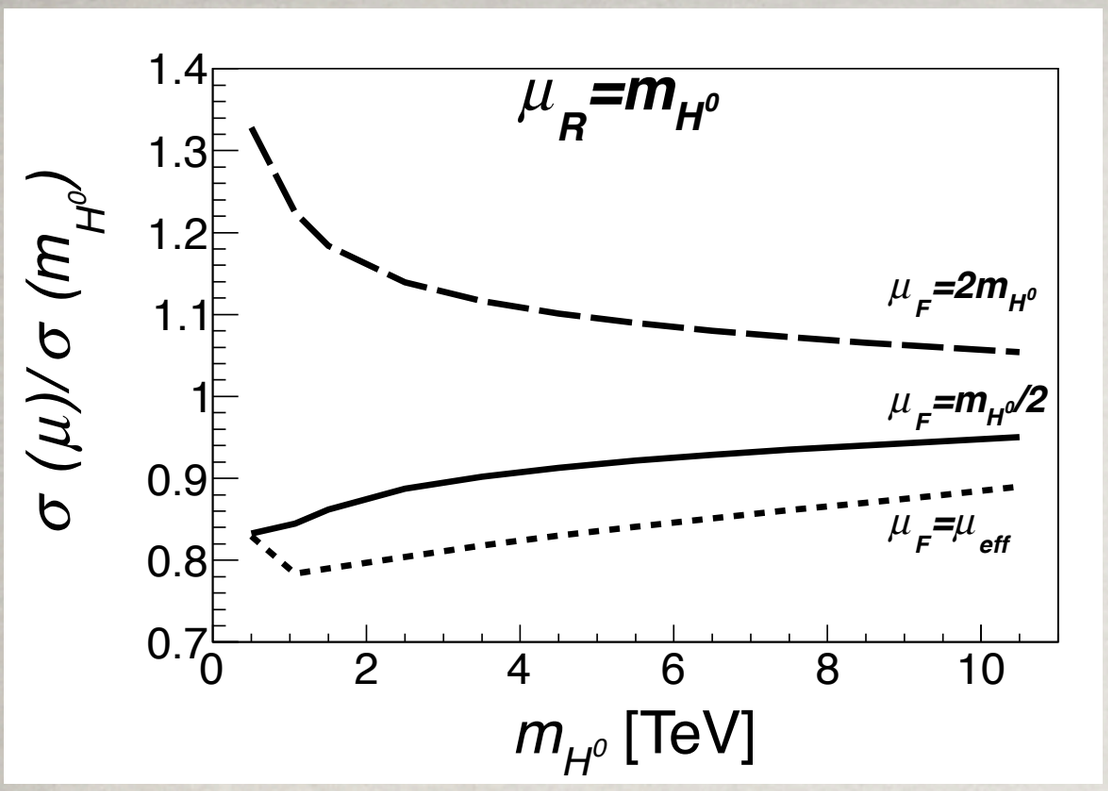
But near the collinear regions, there exists double-counting, that needs to be subtracted out

NNLO correction at α_s^2

$$q\bar{q},\ gg \to b\bar{b}\ H$$

Subtraction as well





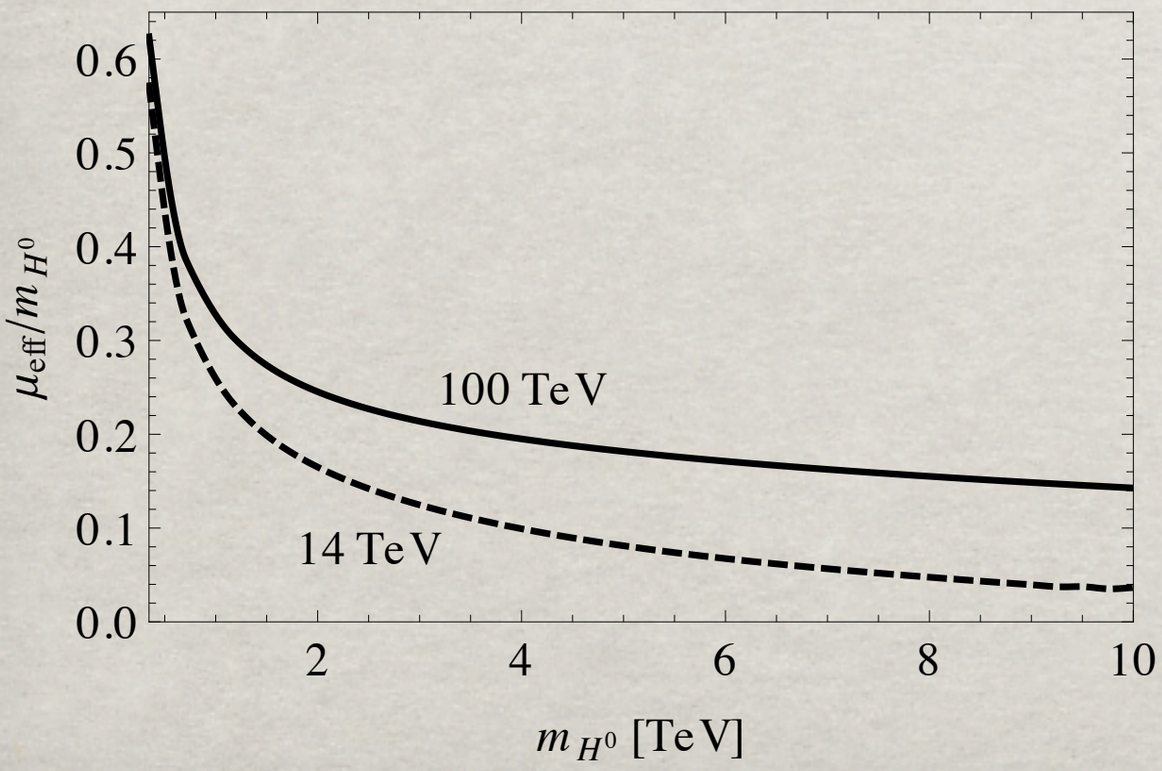
"Natural" factorization scale

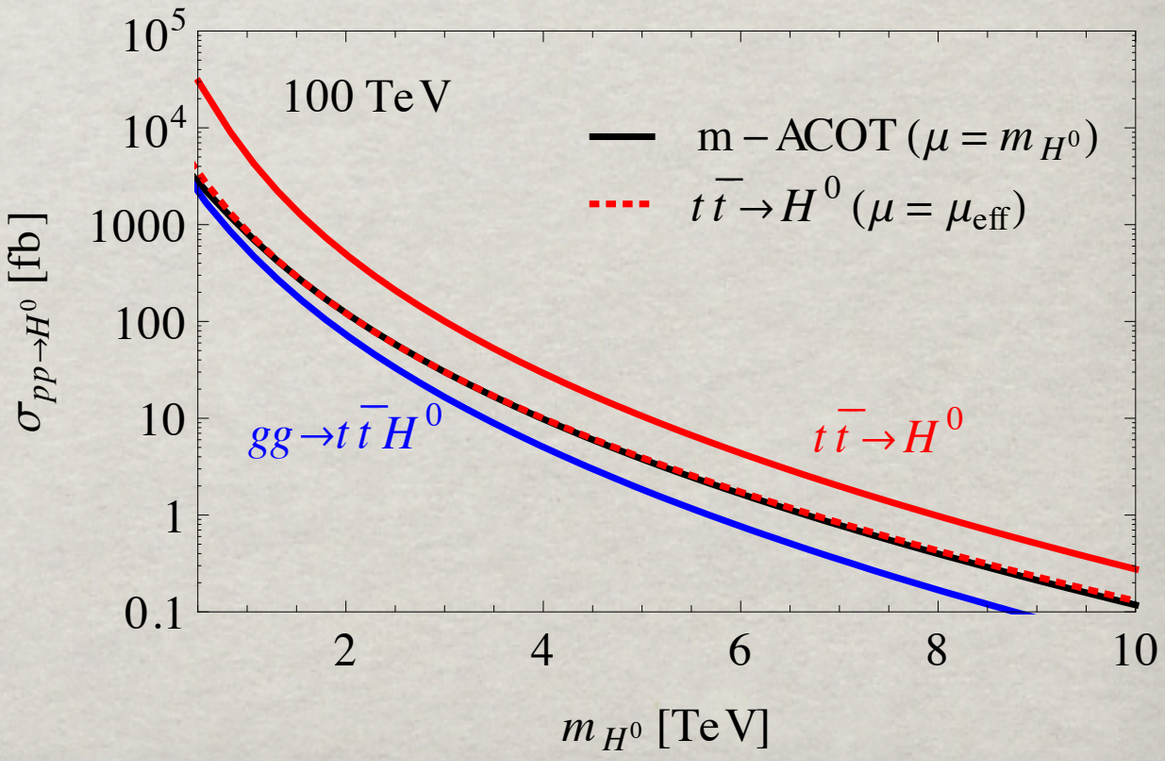
$$\mu^2 \approx m_H^2$$

"Effective" factorization scale

(Early discussions: Maltoni, Willenbrock)

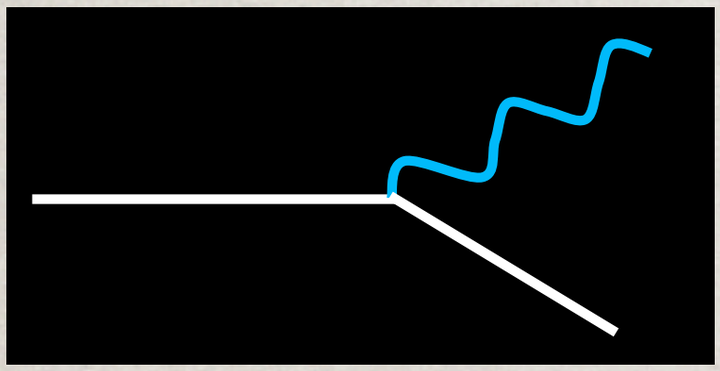
$$\log\left(\frac{\mu_{\rm eff}^2}{m_t^2}\right) = \frac{\int \frac{{\rm d}x}{x} f_t(x, m_{H^0}) \int \frac{{\rm d}z}{z} P_{tg}(z) \log\left(\frac{m_{H^0}^2}{m_t^2} \frac{(1-z)^2}{z}\right) f_g\left(\frac{\tau}{zx}, m_{H^0}\right)}{\int \frac{{\rm d}x}{x} f_t(x, m_{H^0}) \int \frac{{\rm d}z}{z} P_{tg}(z)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





Gauge-boson Initiated Processes

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



"Effective W-Approximation"
S. Dawson, 1985;
G. Kane et al., 1984;
Chanowitz & Gailard, 1984

(Full treatment for VBF: Dieter's talk)

In the EW theory:

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

"forward-jet tagging"

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

"central-jet vetoing"

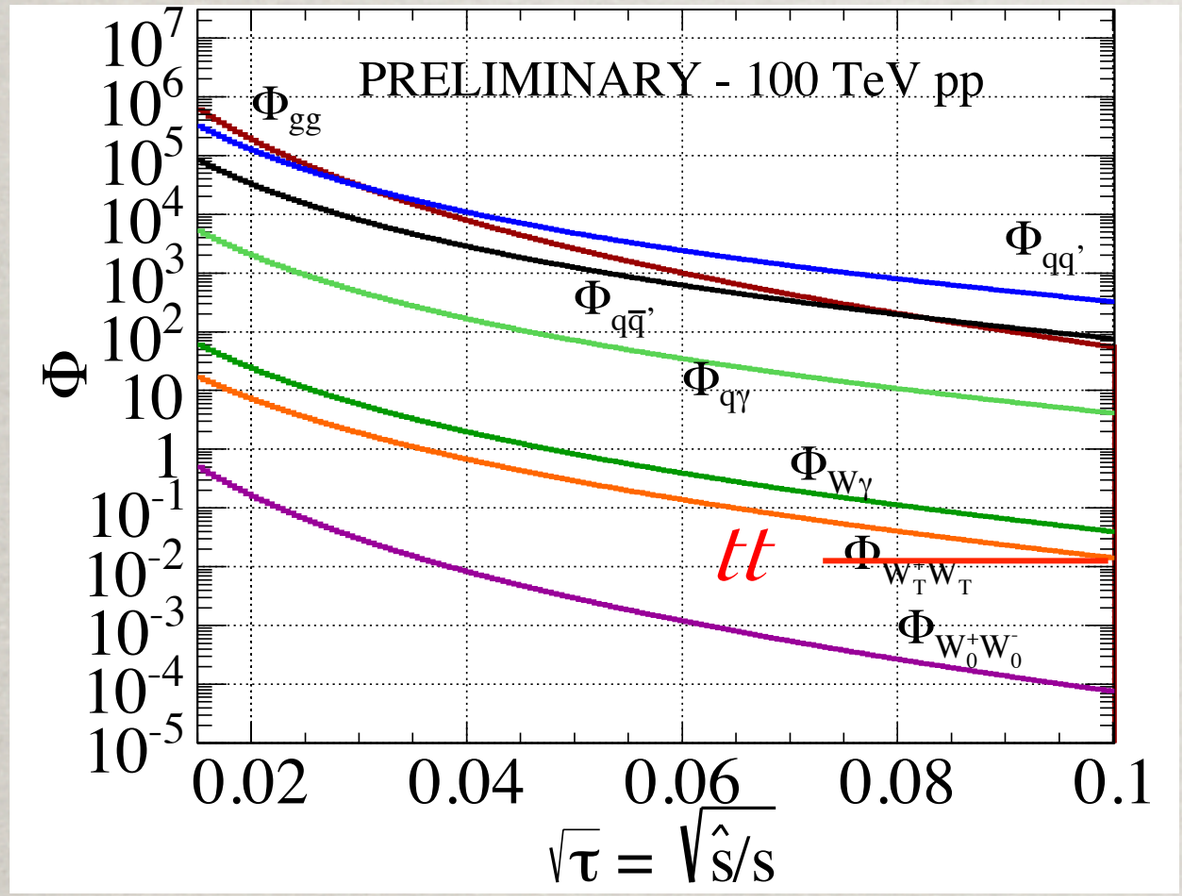
- V_T radiation the same as g, γ : $|\mathcal{M}|^2 \sim p_T^2$:
  - "dead cone" at $p_T \to 0$
  - log-enhancement at high p_T & soft x
- V_L radiation no collinear enhancement/suppression, not the same as a scalar radiation.

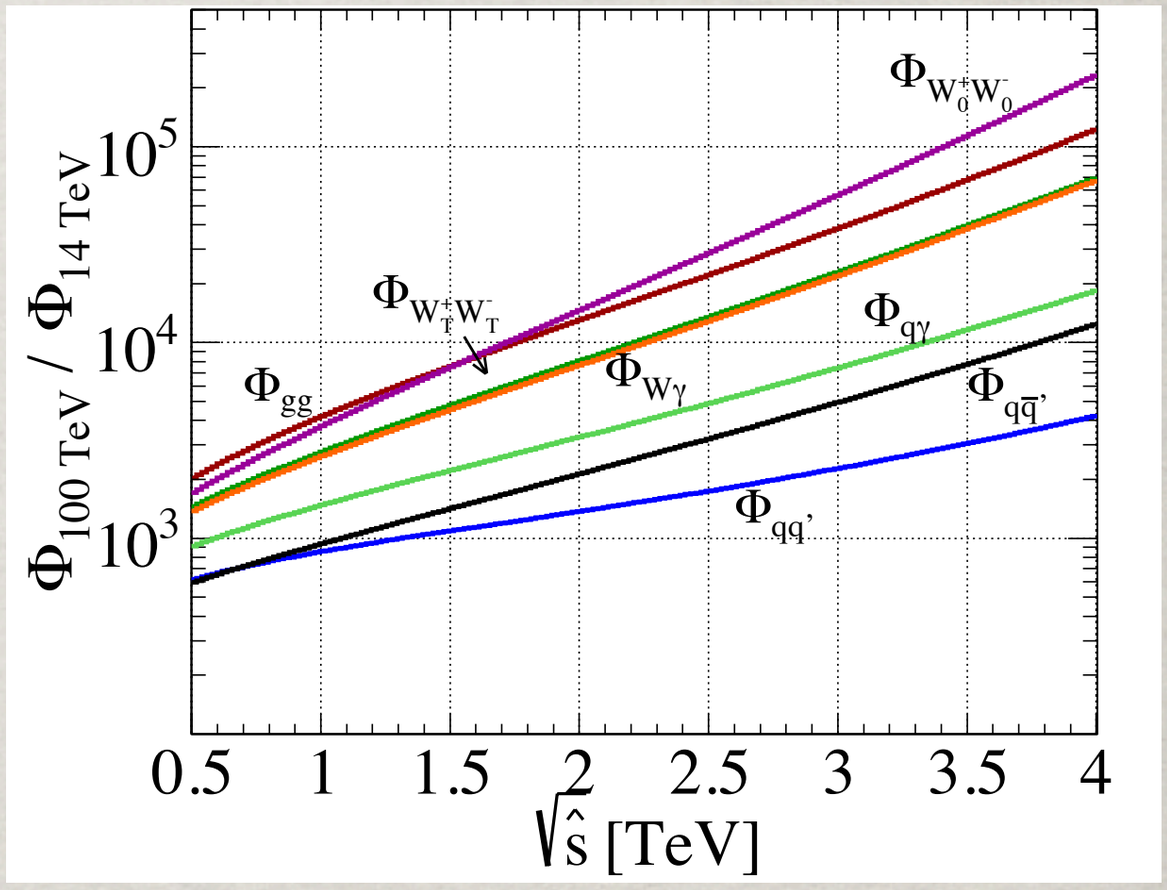
WW Partonic luminosities

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

$$\Phi_{VV'}(\tau) = \frac{1}{(\delta_{VV'}+1)} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \sum_{q,q'} \tag{7}$$

$$\times \left[f_{V/q}(z_2) f_{V'/q'}(z_1)\ f_{q/p}(\xi) f_{q'/p}\left(\frac{\tau}{\xi z_1 z_2}\right) + f_{V/q}(z_2) f_{V'/q'}(z_1)\ f_{q/p}\left(\frac{\tau}{\xi z_1 z_2}\right) f_{q'/p}(\xi) \right]$$





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

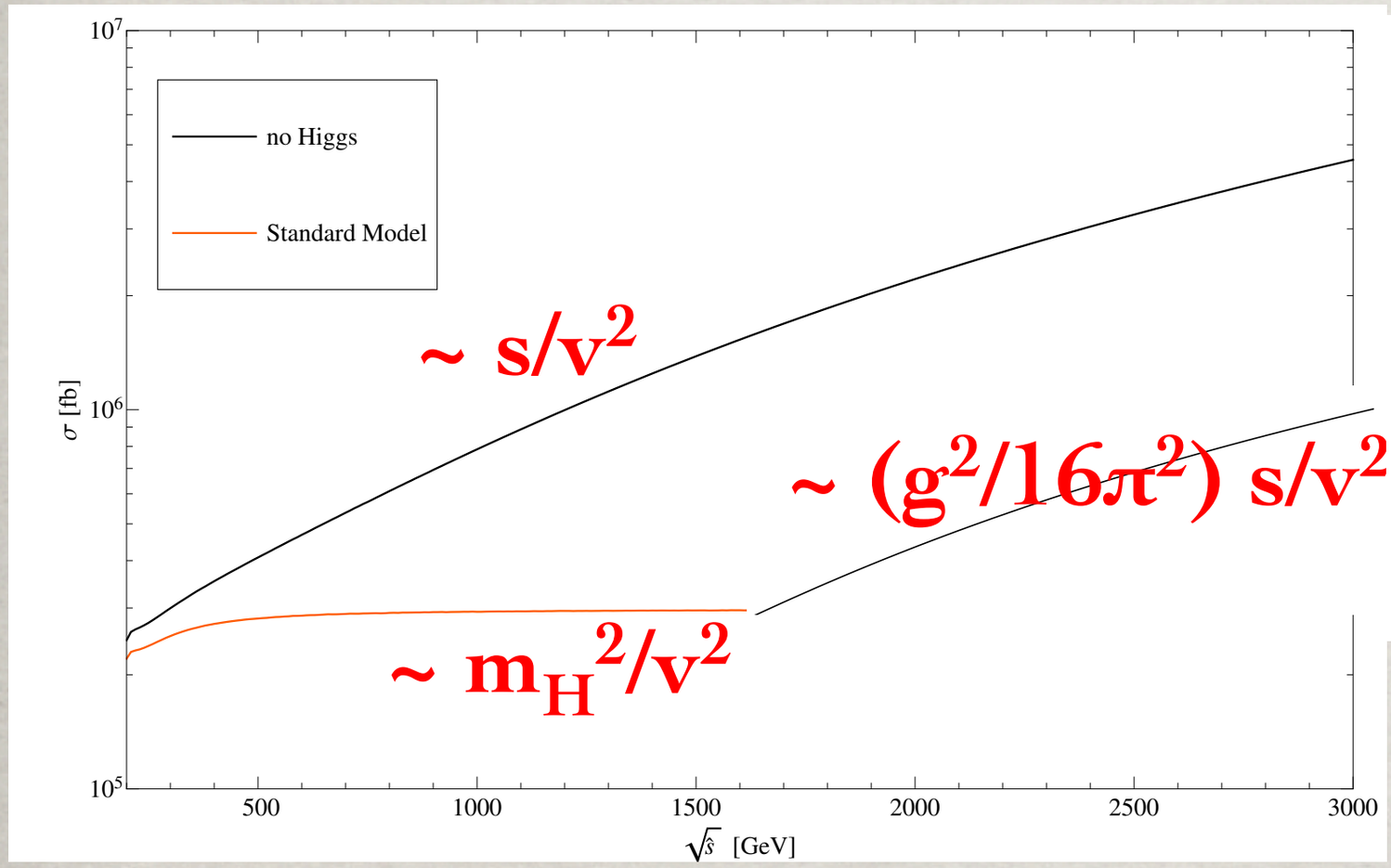
Lumi($W^+_T W^-_T$) ~ Lumi($W^\pm \gamma$), Electro=weak

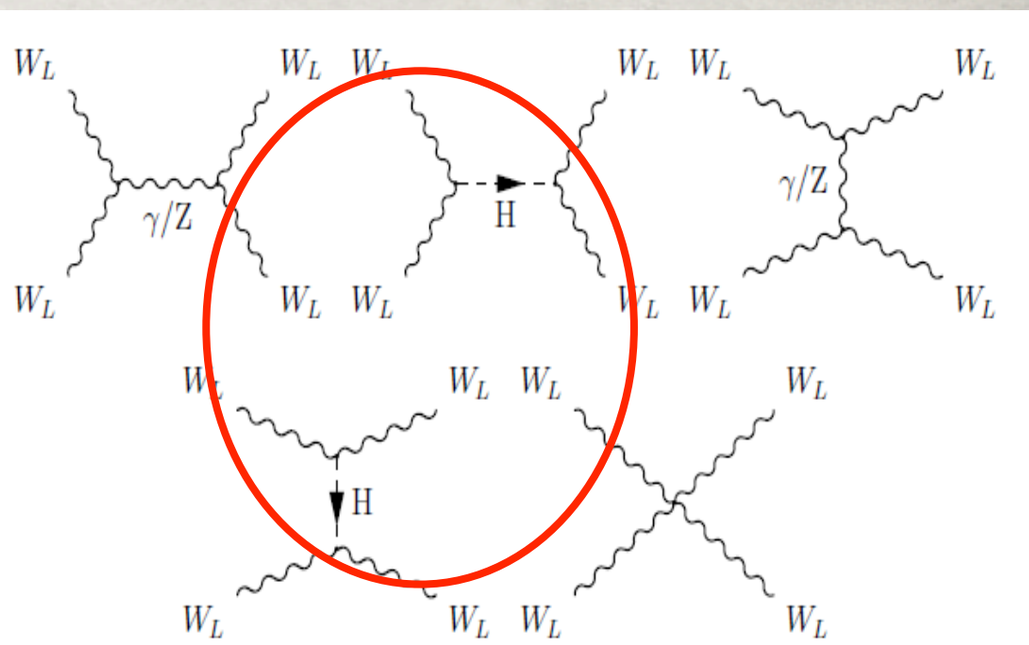
Lumi($W^+_L W^-_L$) 100 times smaller: Goldstones

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	.	ρ^-,ρ^0,ρ^+	.
2	f^0	.	$t^{--},t^-,t^0,t^+,t^{++}$
...	...	...	...

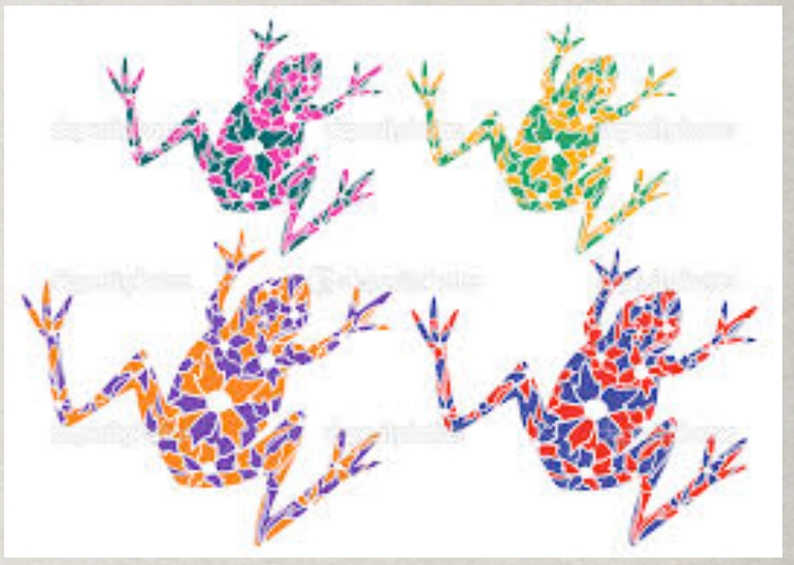
- $I=0$: resonant in W^+W^- and ZZ scattering
- $I=1$: resonant in W^+Z and W^-Z scattering
- $I=2$: resonant in W^+W^+ and W^-W^- scattering

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

Multi Gauge-boson Production From prompt production

At 100 TeV:

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
....	



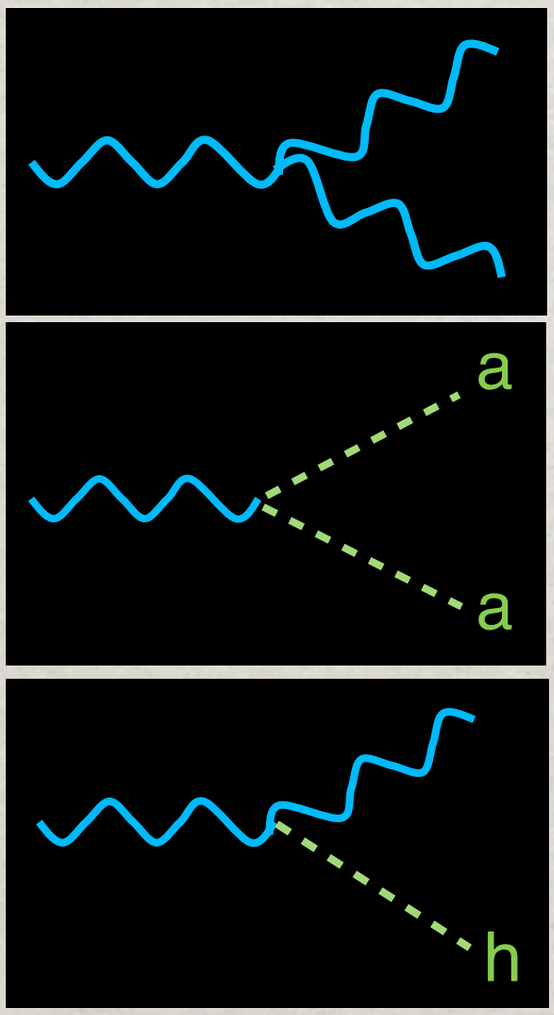
(M. Mangano)

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:



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

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

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

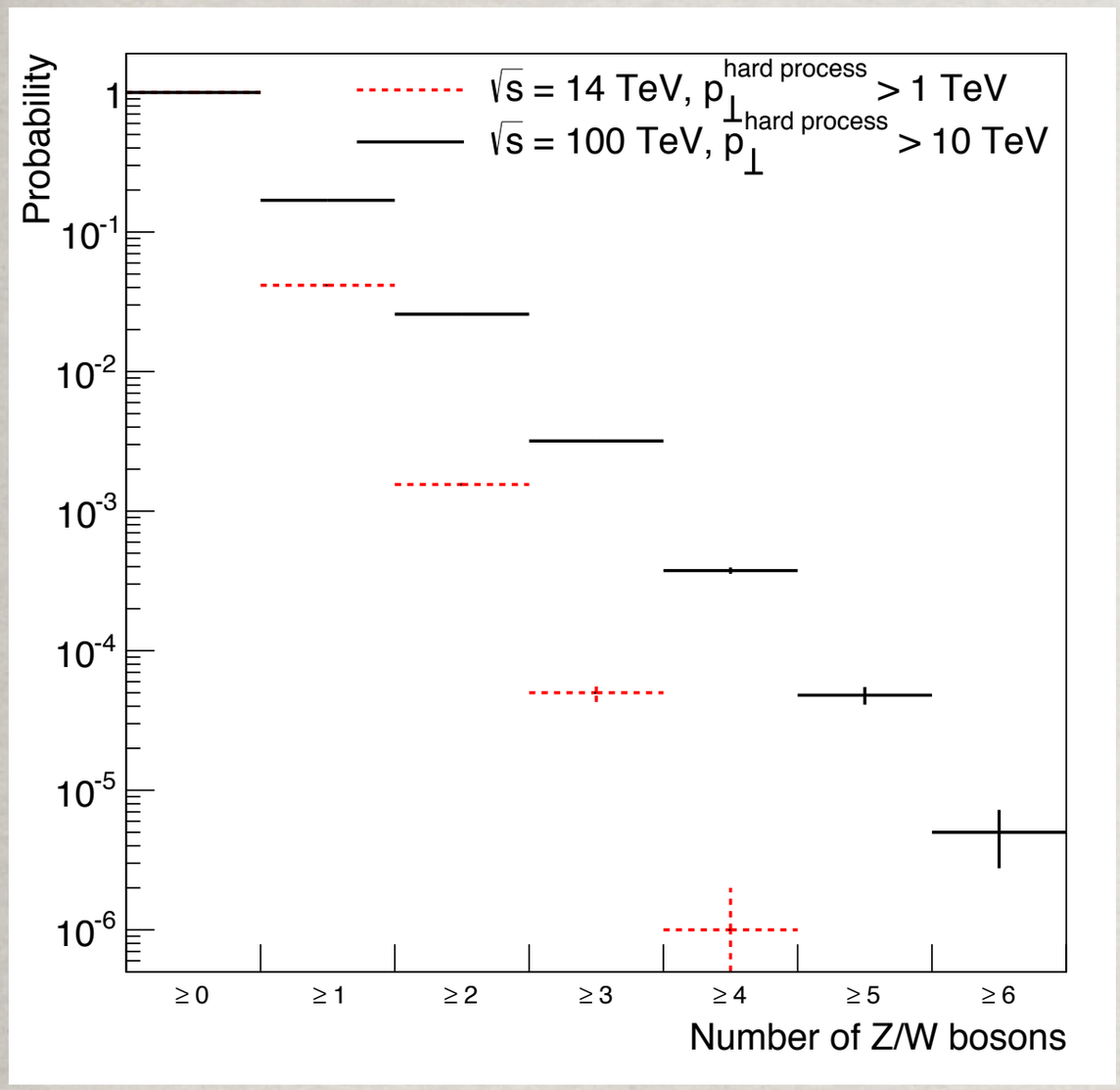
- V_T the "new gluons"!
- V_L/H radiations the Goldstone Eq. Theo.

Splitting Probabilities:

J. Chen, K. Hagiwara, TH, B. Tweedie

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

Multi Gauge-boson From showering:

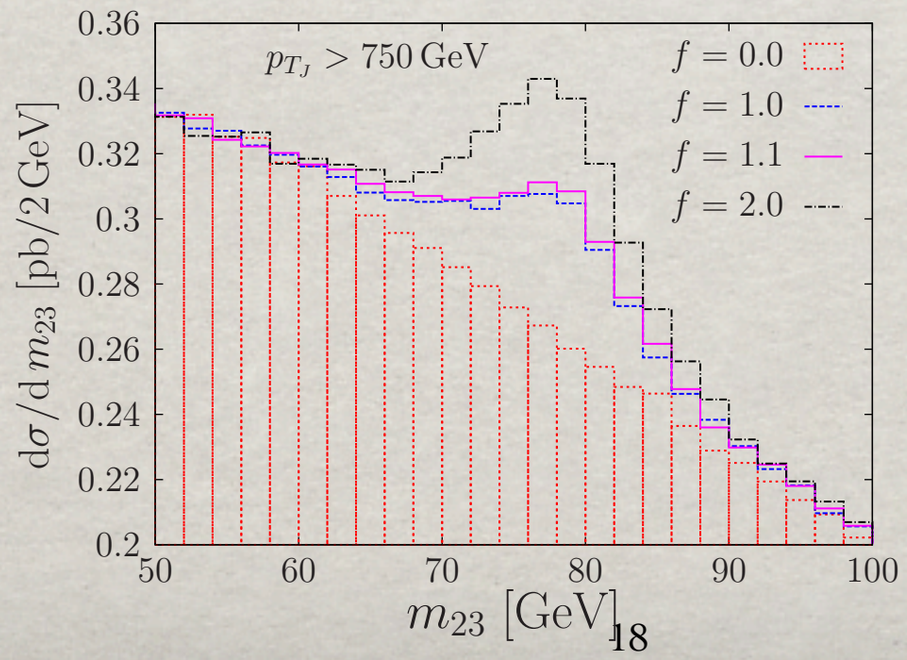


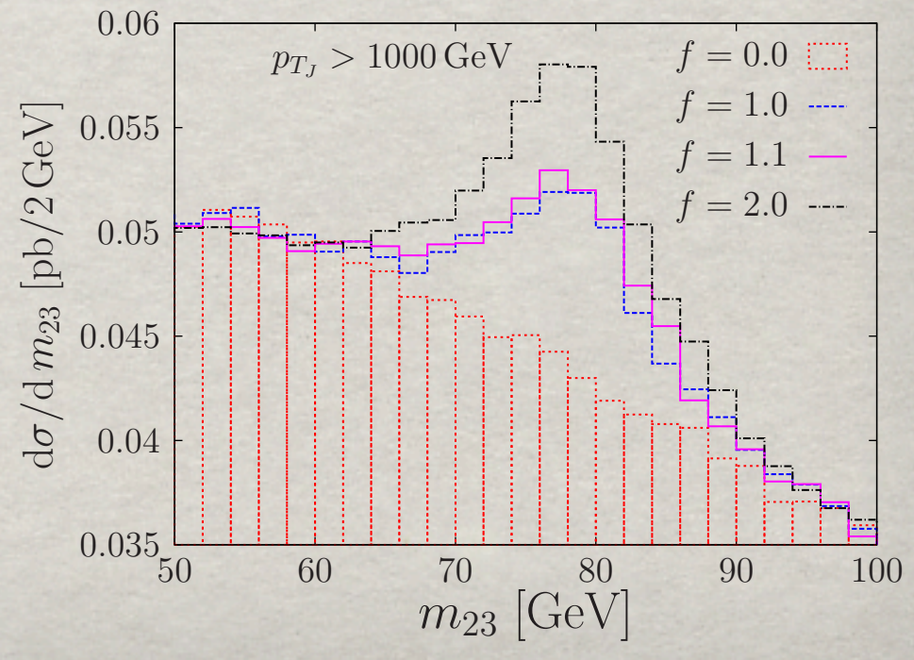
Christiansen, Sjostrand: 1401.5238

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.

Kruass, Petrov, Schonher, Spannowsky: 1403.4788





New Physics Window 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*±, *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 $\Lambda \sim ?$

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

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

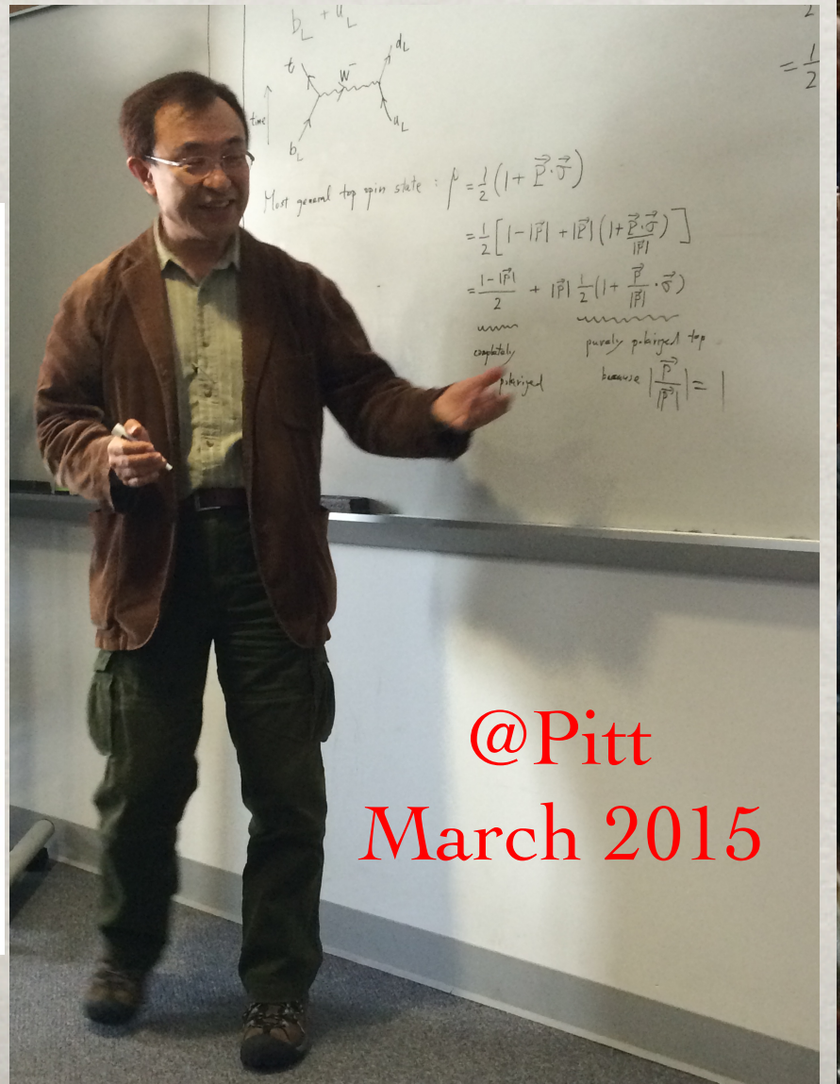
- Searching for new physics starts from understanding old physics in the new regime:
  - *top,W,Z* may behave as partons to produce new heavy states;
  - *top,W,Z,H* may serve as new radiation sources; and may help reveal new heavy states.
  - Thus, need precise understanding of the dynamics/kinematics

While new physics searches exciting, "Old Physics" Remains rich at VLHC!

Special Thanks to Kaoru!

A mentor, a teacher, an old friend

A fresh look:



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