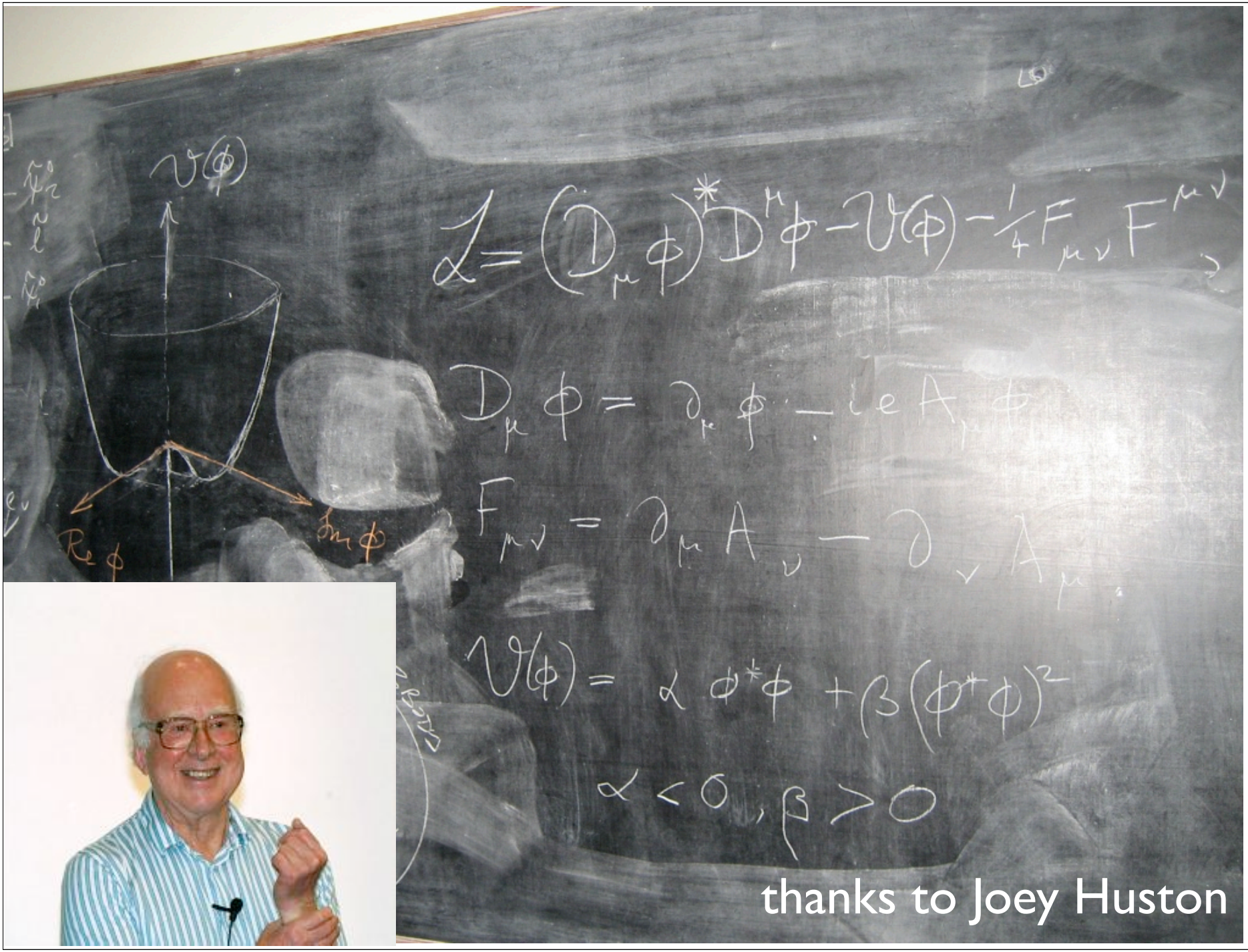
Higgs physics at the Large Hadron Collider

Babis Anastasiou
ETH Zürich

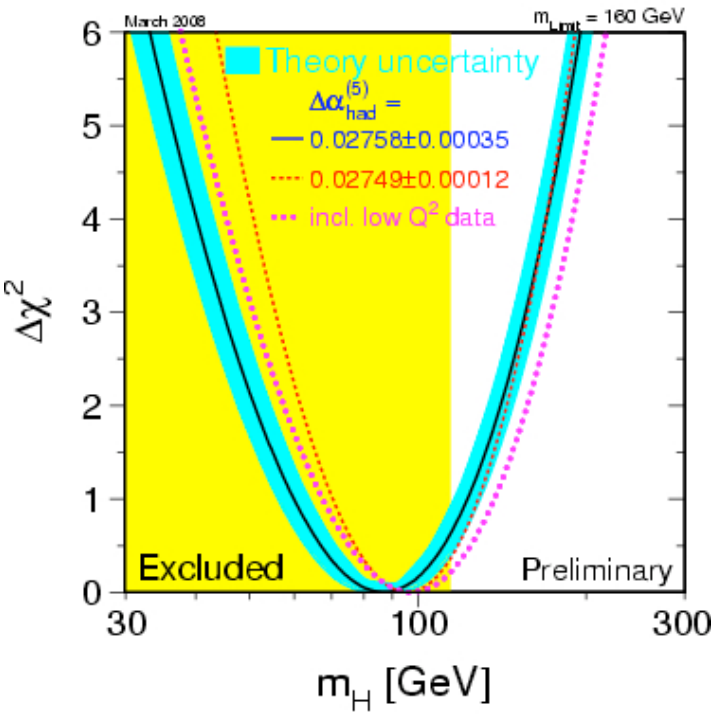
Debrecen, August 2008

$$M_{HIGGS} = ?$$

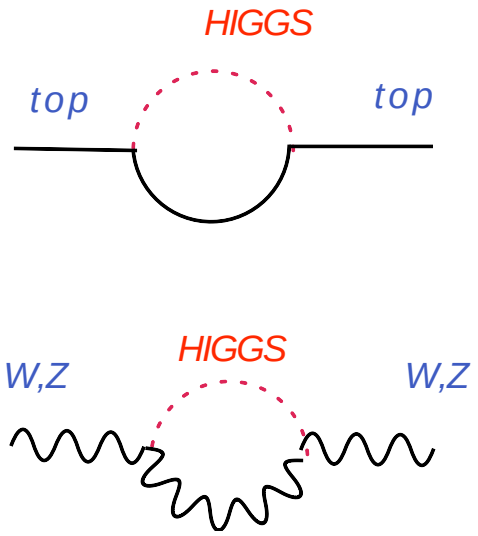


thanks to Joey Huston

Precision EWK tests



Our window to new particles: quantum fluctuations



A SM Higgs boson must be light.

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Clinton fights on amid president Obama's second Iraq visit.
Democratic presidential hopeful Hillary Clinton's campaign chief denies she is to concede...

UN sets out food crisis measures
The UN secretary general calls for revitalising agriculture as a way of tackling the world's worsening food crisis.

Bardot fined over racial hatred
Former film star Brigitte Bardot is fined 15,000 euros by a French court for inciting racial hatred in a letter on her website.

God's particle found in Geneva
It is a relatively light particle with a mass of 116 GeV.

Just a number away...

- The mass of the Higgs boson may be the only parameter missing to explain everything that we will see at the LHC!
- If the SM is true, this will be the most spectacular triumph of the physicists of the 20th century.

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God's particle found in Geneva. It is not alone!
It is a relatively light particle with a mass of 116 GeV. The top quark is antagonized by mystery particles. It produced only half the expected number of Higgs bosons.

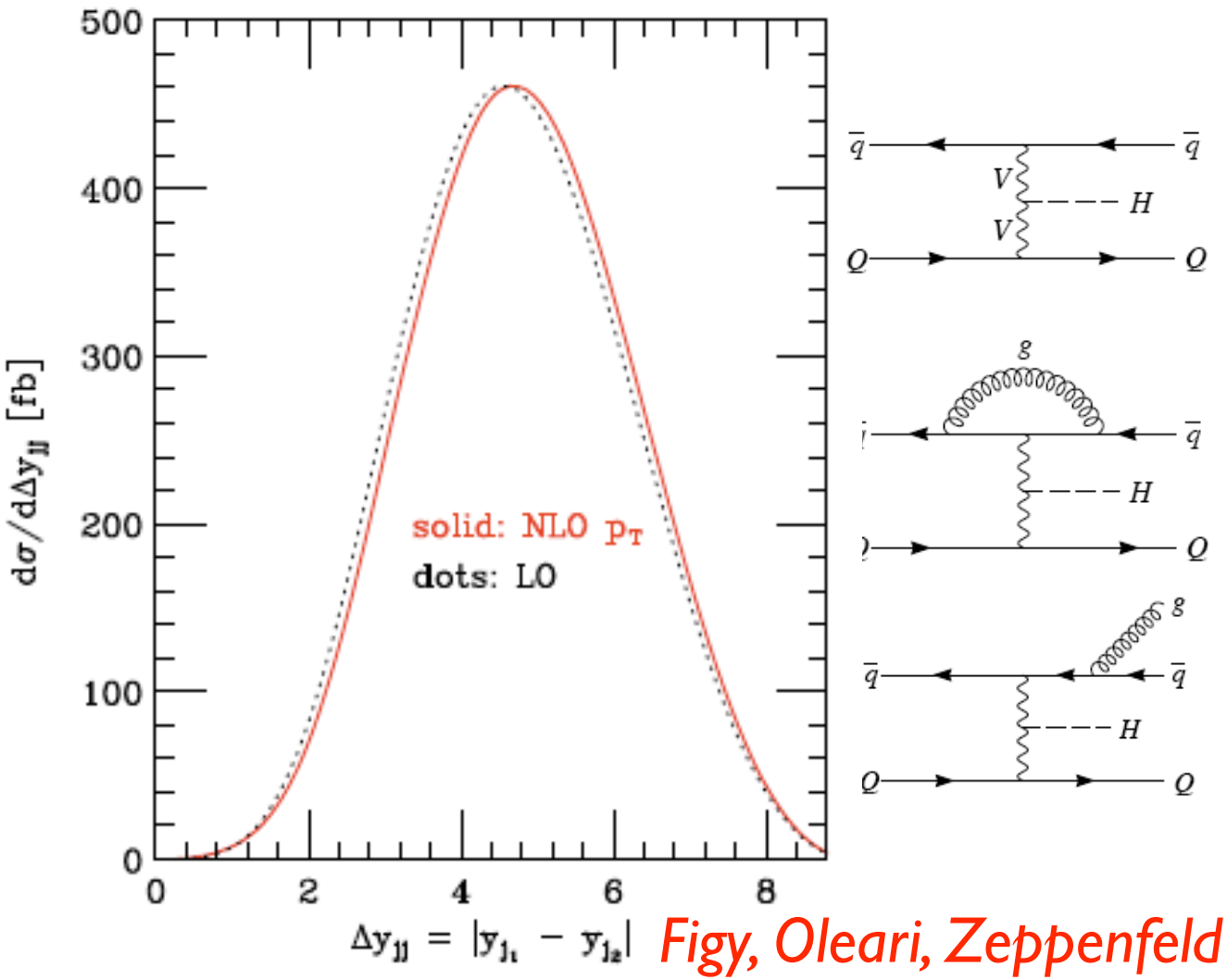
What if $\sigma_{HIGGS} = 50\% \sigma_{SM}$?

- QCD?
- Kaluza-Klein tower of 5-D quark? (Djouadi, Moreau; Falkowski,...)
- "Sweet-spot" supersymmetry? (Kitano, Nomura; Perelstein; Dermisek, Low; Cho;...)
- Higgs dependent Yukawa couplings? (Giudice, Lebedev)
- We shall need to check very many cases!

Well behaved perturbation

Small perturbative corrections in Weak boson fusion.

Interesting theoretically set of experimental cuts: How "clean" is central region?

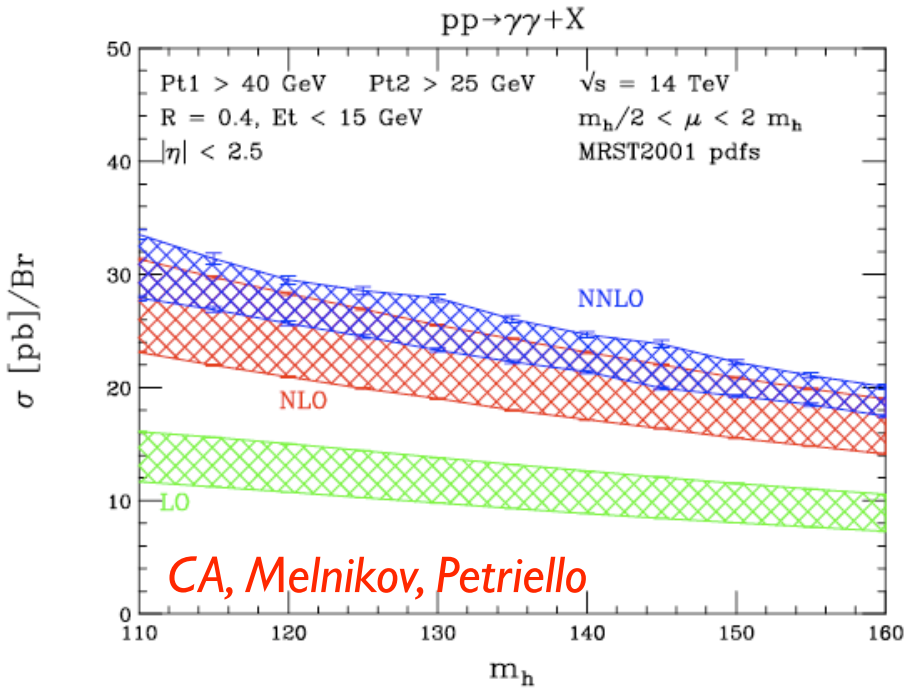


Figy, Oleari, Zeppenfeld

Gluon-fusion cross-section

- A new precision test for ALL models which aspire to explain LHC data...
- If SM cross-section estimate is roughly correct, then it may be measured with a 10-15% precision. Comparable to theory!
- We should be prepared for surprises.
  All SM extensions modify the Higgs sector one way or another!

"Misbehaving" perturbation



- A very large K-factor

Could we confuse this with a new family of heavy quarks or a new gauge boson?

- pp→H+X→γγ+X

$$\sigma\left(\mu = 2M_h\right) = \mathrm{LO}\left(1 + 0.9 + 0.35\right)$$

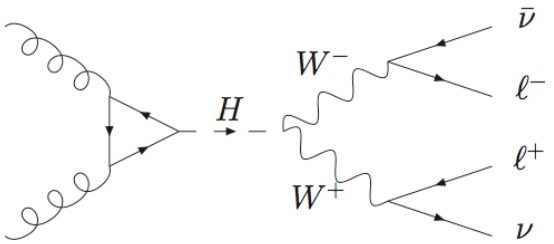
$$\sigma\left(\mu = M_h/2\right) = \mathrm{LO}\left(1 + 0.75 + 0.13\right)$$

Cuts and K-factors

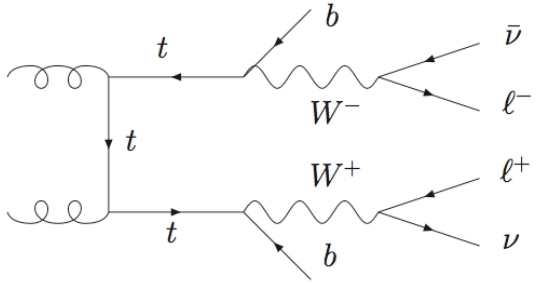
m_h, GeV	$\sigma^{\rm cut}_{\rm NNLO}/\sigma^{\rm inc}_{\rm NNLO}$	$K^{(2)}_{\rm cut}/K^{(2)}_{\rm inc}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

- p_t and η cuts are responsible for the cross-section reduction
- isolation is a mild cut $< 5\%$ for $R_{cone} = 0.4$
- cuts less drastic for larger Higgs masses (photons are produced with larger p_t)
- $K^{(2)} = \sigma^{NNLO}/\sigma^{NLO}$
- Can we approximate $\sigma^{cut}_{NNLO} \sim \sigma^{cut}_{NLO} K^{(2)}_{incl}$? Within 5%

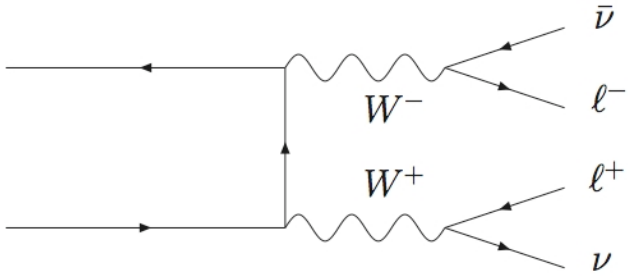
Signal and background

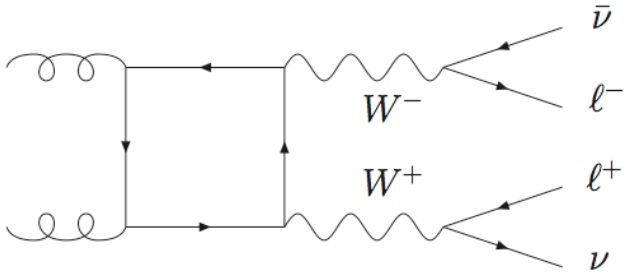


Gluon fusion signal



Top pair background





Direct W-pair production

Aggressive cuts!

After trigger and some basic cuts on the leptons:

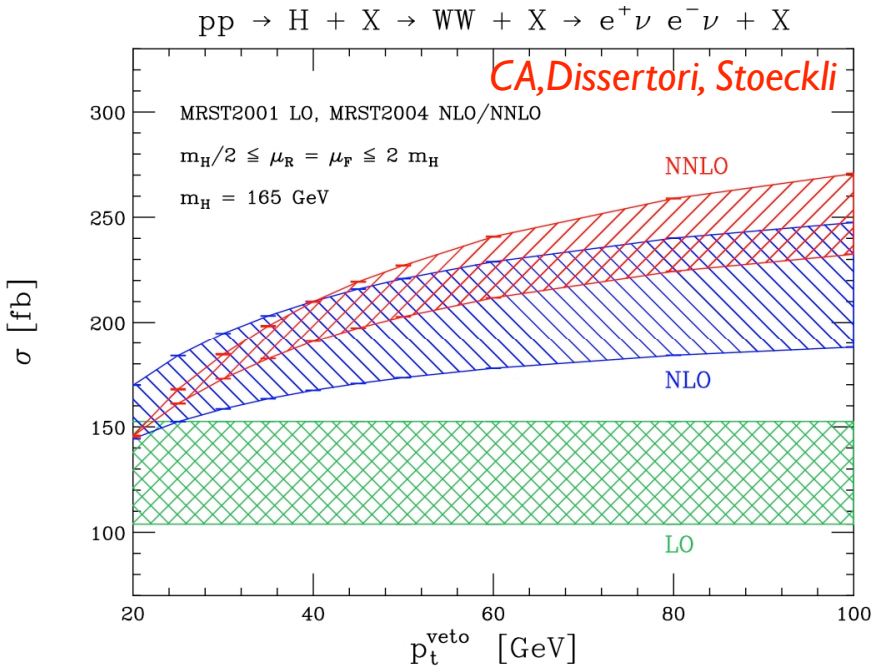
process	m_H=165 GeV	tt	qq→WW	gg→WW
σ [pb]	0.4	15.7	1.4	0.1

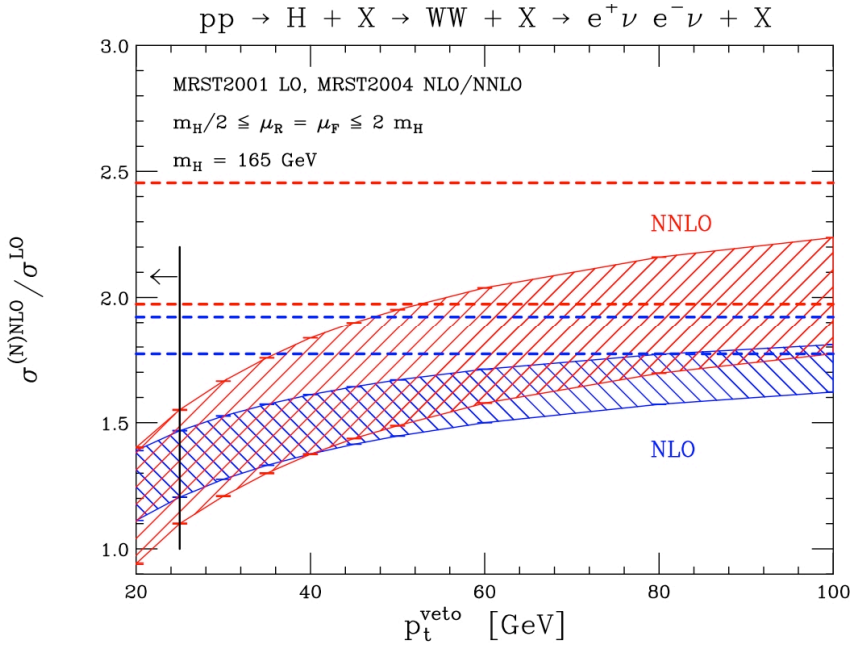
After signal selection cuts (jet-veto, lepton angle, missing energy, ...):

process	m_H=165 GeV	tt	qq→WW	gg→WW
σ [fb]	46	10	12	4

At what order in perturbation theory are these cut efficiencies accurately predicted?

Jet Veto





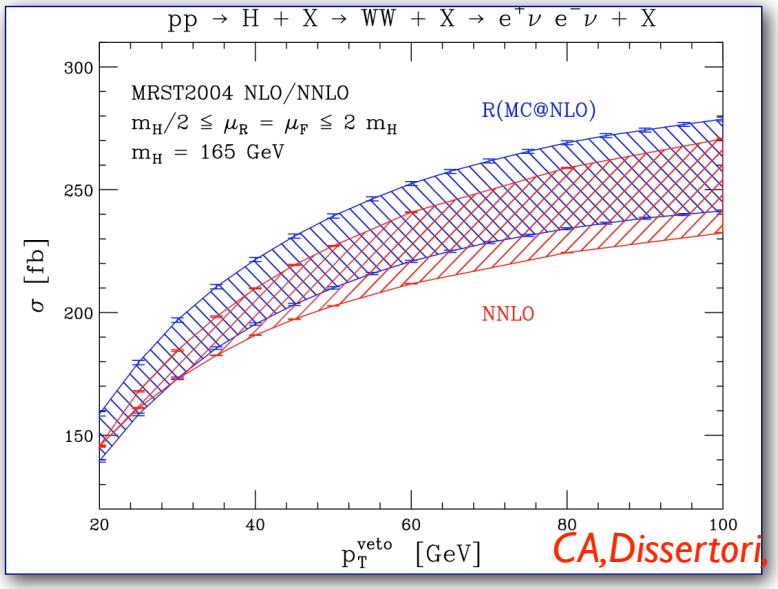
Jet-veto has no impact at LO

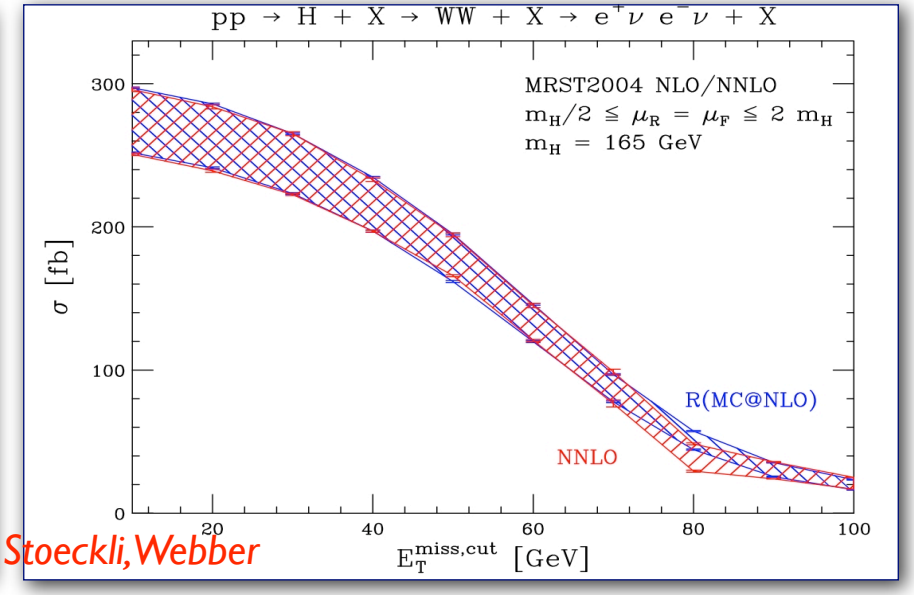
At NLO corresponds to a cut on the Higgs pt.

K-factors ($\sigma^{(N)NLO}/\sigma^{LO}$) depend heavily on cut-value

Inclusive K-factors would fail to predict the cross-section reliably

How good are generators?





CA,Dissertori, Stoeckli,Webber

Generators (MC@NLO & HERWIG) agree very well with NNLO efficiencies

We can approximate:

$$\sigma_{cuts} \approx \sigma^{nnlo}_{cuts} \approx \sigma^{generator}_{cuts} \times \frac{\sigma^{nnlo}_{incl}}{\sigma^{generator}_{inc}}$$

QCD and Higgs physics

- NLO and (some) NNLO calculations for signal and backgrounds
- Threshold and transverse momentum resummation methods
- New computational methods for computing amplitudes/ cross-sections
- Even if we don't find a Higgs boson, its hypothesis has triggered an immense technical progress
- APOLOGIES FOR NOT BEING ABLE TO REVIEW THESE DEVELOPMENTS AND THE HARD WORK THAT MANY PEOPLE HAVE MADE

The physics beyond...

What if it is not "the" "Mexican hat"?

In the SM: $\vec{\phi} = (\phi_1, \phi_2, \phi_3, \phi_4)$

Barbieri, Bellazzini, Rychkov, Varagnolo

An extended SO(5) model: $\phi = \left(\vec{\phi}, \phi_5\right)$

$$V = V_0 f^2 \delta(\phi^2 - f^2) - A f^2 \vec{\phi}^2 + B f^3 \phi_5$$

A strong force sets in at the scale f

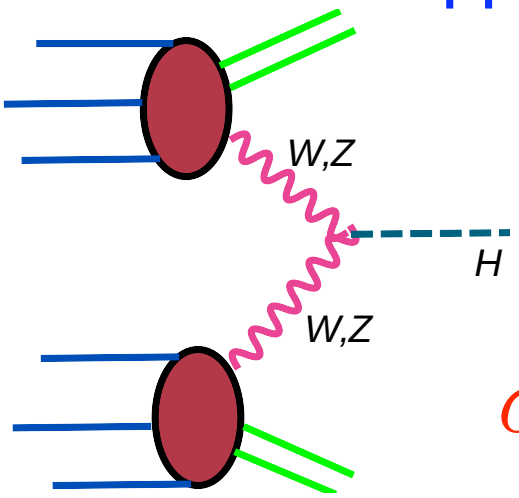
Breaks SO(5) to custodial SO(4)

$\vec{\phi}$ gauged as usual under SU(2)xU(1)

$$\left\langle \vec{\phi}^2 \right\rangle = v^2 = f^2 \left[1 - \left(\frac{B}{2A}\right)^2\right]$$

Consequences

All couplings of the Higgs boson to other SM particles suppressed by a factor: $\sqrt{1-\frac{v^2}{f^2}}$



$$f \simeq 500\mathrm{GeV}$$

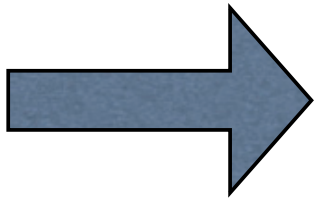
$$\sigma_{WBF} \approx 75\% \quad \sigma_{WBF}^{SM}$$

Common effective theory for
Little Higgs/ Randall-Sundrum / technicolor models

Giudice, Grojean, Pomarol, Rattazzi

“But the SM should be enough...” NO!

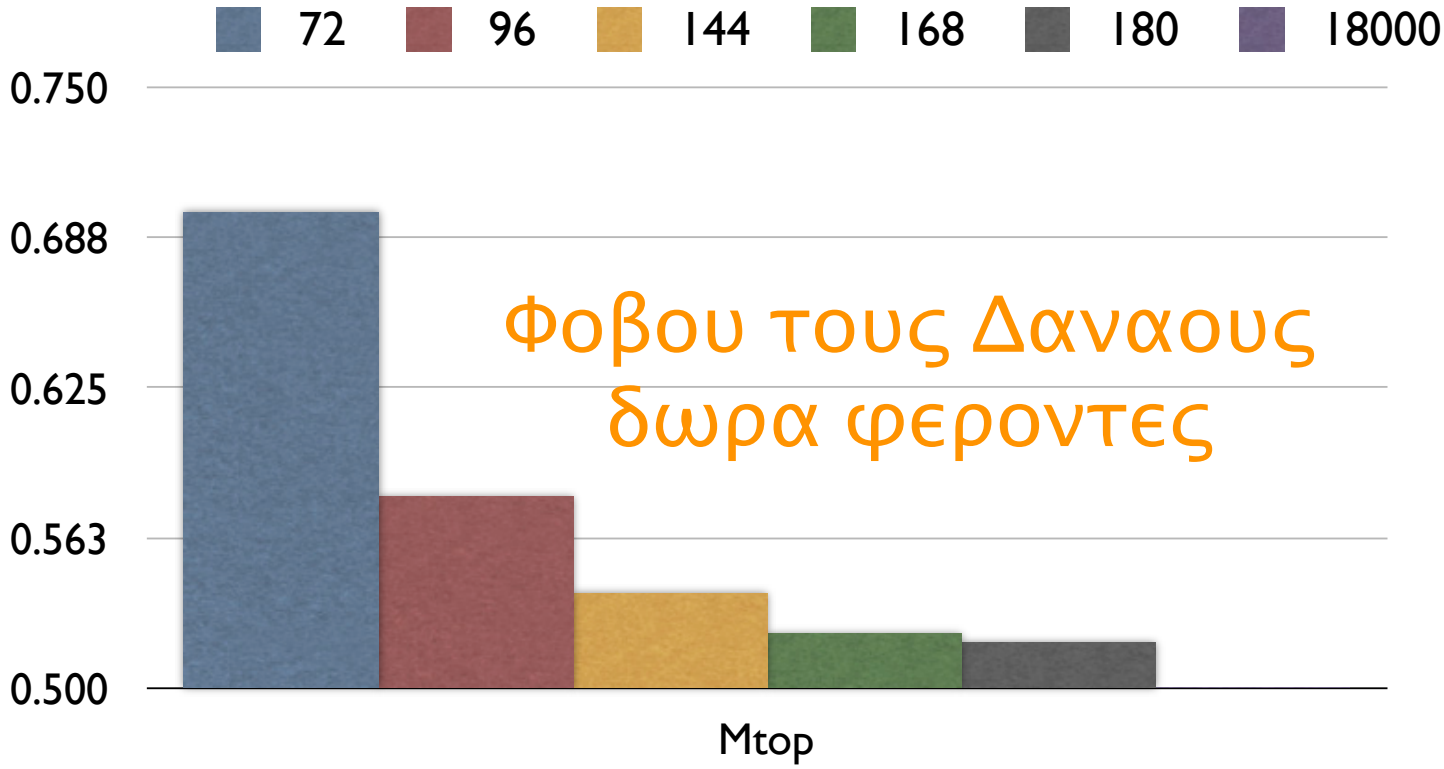
It does not account for dark matter... at some point (energy scale) we must extend it!



HIERARCHY PROBLEM

This is not an aesthetic problem.
IT AFFECTS MEASURABLE OBSERVABLES

A "present" from the hierarchy problem



Φοβου τους Δαναους
δωρα φεροντες

Infinitely heavy states contribute the same as lights in gluon fusion. Is this natural?

The hierarchy problem

Thanks to Jose Santiago

Lets extend the SM naively (e.g. not based on a symmetry principle):

$$\mathcal{L} \ni \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi^2}{2}\phi^2$$

the Higgs scalar: $m_\phi \sim 10^2 \mathrm{GeV}$

$$+\frac{1}{2}\left(\partial_\mu S\right)^2 - \frac{m_S^2}{2}S^2$$

new heavy scalar: $m_S \sim 10^{15}\mathrm{GeV}$

$$+\bar{\psi}\left(i\not{\partial} - m_f\right)\psi$$

light fermion: $m_f \sim 10^2 \mathrm{GeV}$

$$-\frac{1}{4}\lambda\phi^2\Phi^2 - y_\phi \phi\bar{\psi}\psi - y_\Phi \Phi\bar{\psi}\psi$$

Interactions

The hierarchy problem

MSbar mass shifts:

$$\delta m_\phi^2 = \frac{y_\phi^2}{4\pi^2} m_\psi^2 \left[1 - 2\ln\frac{m_\psi^2}{\mu^2} + \mathcal{O}(m_\phi^2/m_\psi^2)\right]$$

$$- \frac{\lambda}{32\pi^2} m_\Phi^2 \left[1 - \ln\frac{m_\Phi^2}{\mu^2}\right] \qquad \frac{\delta m_\phi}{m_\phi} \sim 10^{15}$$

$$\delta m_\psi = m_\psi \left[\frac{5}{4} - \frac{3}{2}\ln\frac{m_\Phi^2}{\mu^2} + \mathcal{O}(m_\psi^2/m_\Phi^2)\right] + (\Phi \to \phi)$$

$$\frac{\delta m_\psi}{m_\psi} \sim 1$$

Solving the problem

Luck: "Yukawa" coupling of order $\sim 10^{-15}$

multiverse, anthropic principle

We really do not have so many model building ideas. The high multiplicity of models is due to how these principal are implemented.

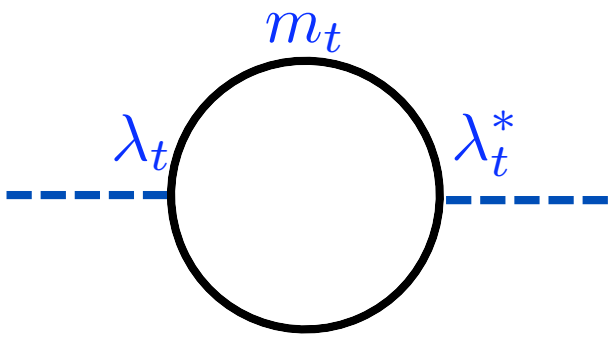
Don't allow scalars (strongly coupled theories)

Protect scalars with chiral symmetry (using supersymmetry)

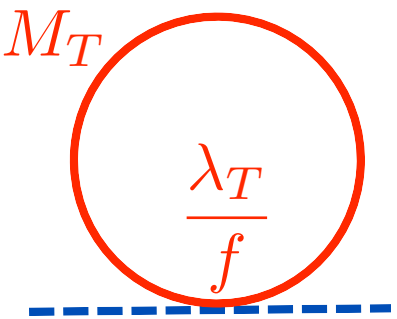
Geometry in extra-dimensions (Randall-Sundrum models)

All are "ingredients" of string theory

Canceling the UV sensitivity

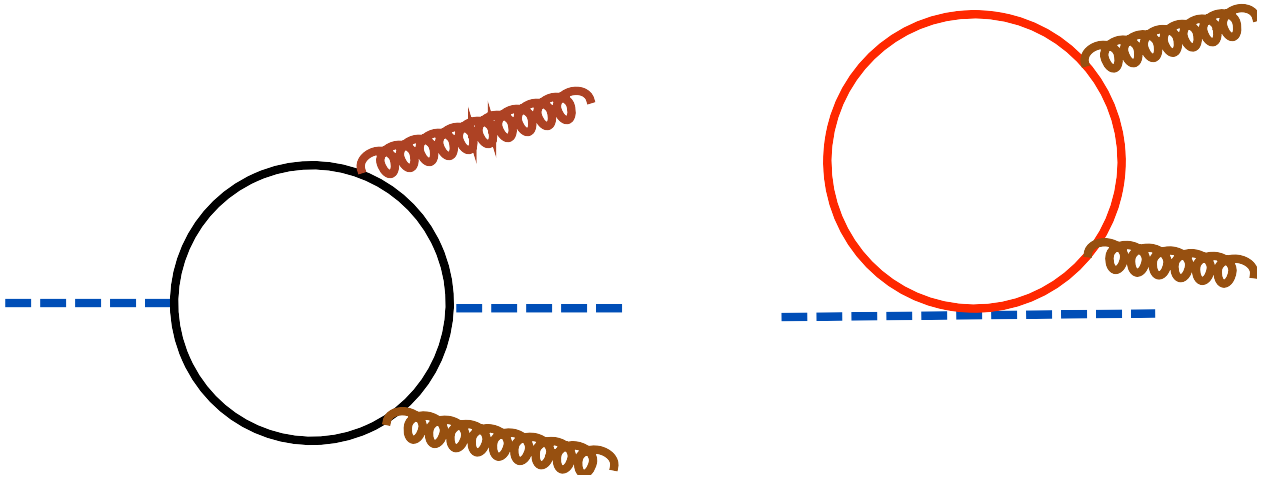


$$-\frac{3}{8\pi^2}\left|\lambda_t\right|^2\Lambda_{NP}^2$$



$$-\frac{3}{8\pi^2}\left(-M_T\frac{\lambda_T}{f}\right)\Lambda_{NP}^2$$

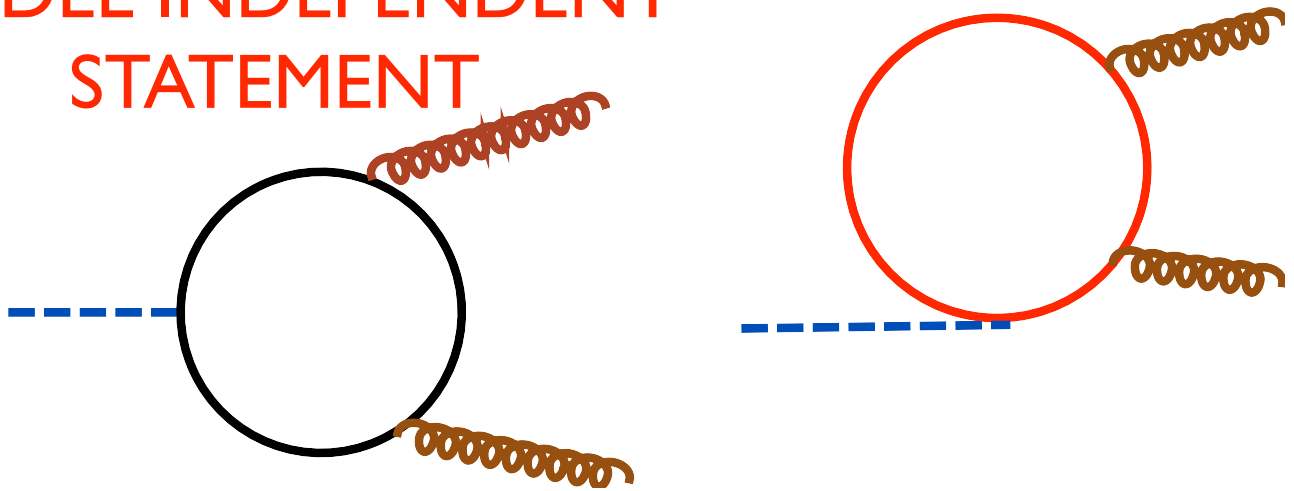
Cancelation and gluon fusion



ADDING TWO GLUONS DOES NOT CHANGE THE RELATIVE SIGN

Cancelation also in gluon fusion

MODEL INDEPENDENT STATEMENT



ADDING TWO GLUONS DOES NOT CHANGE THE RELATIVE SIGN

(Take momentum of second Higgs to zero)

Gluon fusion and the hierarchy problem

Low, Rattazzi

"*Conclusion:*

- If at the LHC we measure

$$\frac{B\sigma^{\rm BSM}(gg \to h \to \gamma\gamma)}{B\sigma^{\rm SM}(gg \to h \to \gamma\gamma)} > 1$$

then unnatural models such as UEDs and MSSM with small mixing in the stop sector are favored.

- If on the other hand we measure

$$\frac{B\sigma^{\rm BSM}(gg \to h \to \gamma\gamma)}{B\sigma^{\rm SM}(gg \to h \to \gamma\gamma)} < 1$$

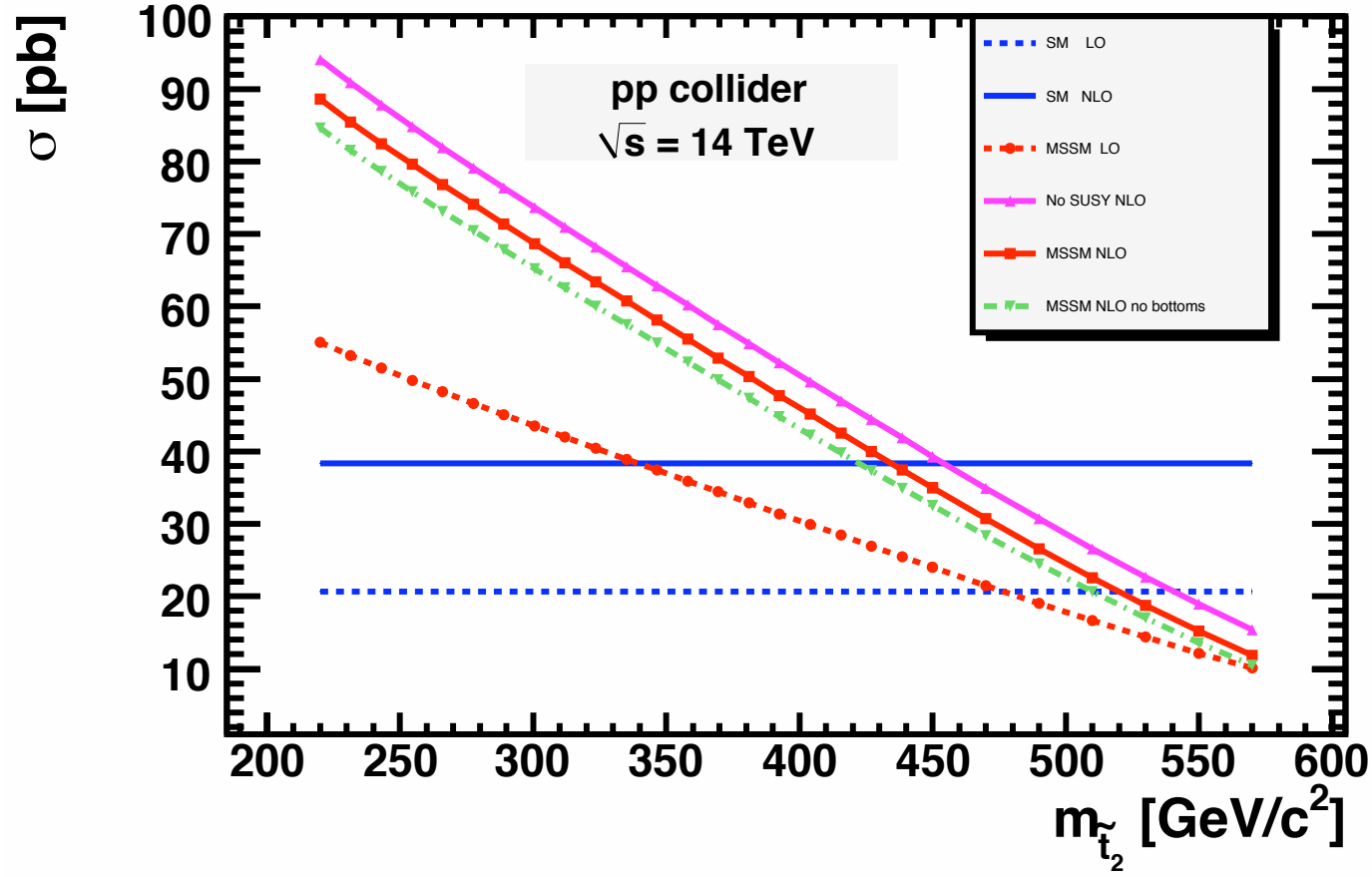
then natural models such as composite Higgs and MSSM with large mixing in the stop sector are favored.

"

for MSSM with large stop mixing

CA, Beerli, Bucherer, Daleo, Kunszt

Preliminary



Conclusions

- Higgs physics at the LHC is new physics!
- A comprehensive program to discover a SM Higgs boson
- Solid theoretical predictions from QCD
- Enormous effort to optimize search strategies
- BSM physics AFFECTS Higgs boson phenomenology profoundly!