Xth Rencontre du Vietnam
Physics at LHC and Beyond:
Theory Summary and Grand Vision

Benjamin Grinstein

UCSD

2014

Xth Rencontre du Vietnam Physics at LHC and Beyond: *Theory Summary*

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Physics at LHC and Beyond

The LHC is primarily a discovery machine

It can be and has been used for other purposes

- top factory
- heavy ions
- B_d/B_s factory
- pp total elastic/inelastic cross section
- precision "standard" physics

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The LHC did make a discovery: a $J^{PC}=0^{++}$ resonance at ~125 GeV

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We would like a roadmap to further discoveries

How we look is informed by

- Computation of signal & background
- New Observables
- New Techniques
- New Tests
- ? (what am I missing)

Where to look is informed by

- Precision physics
  - EWPD
  - Flavor
  - QED, ...
  - ? (what am I missing?)

- Theoretical Prejudice
  - EFT
  - Models
    - Anomaly driven
    - Principled

How we look is informed by ... computation of signal and background

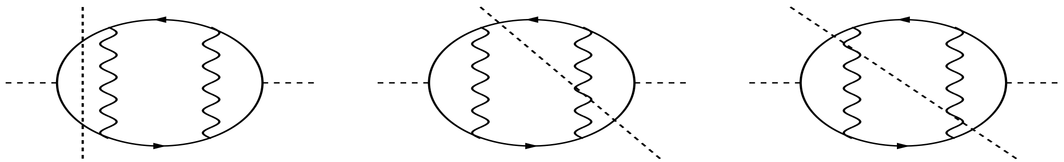
Beware of common hidden assumptions! They lead to wrong computations [Giampero Passarino]

Example: $\mathrm{Br}(H \to \bar{f} f \bar{f} f) \neq \mathrm{Br}(H \to VV) \times \mathrm{Br}^2(V \to \bar{f} f)$

This holds exactly in the narrow width approximation. At best

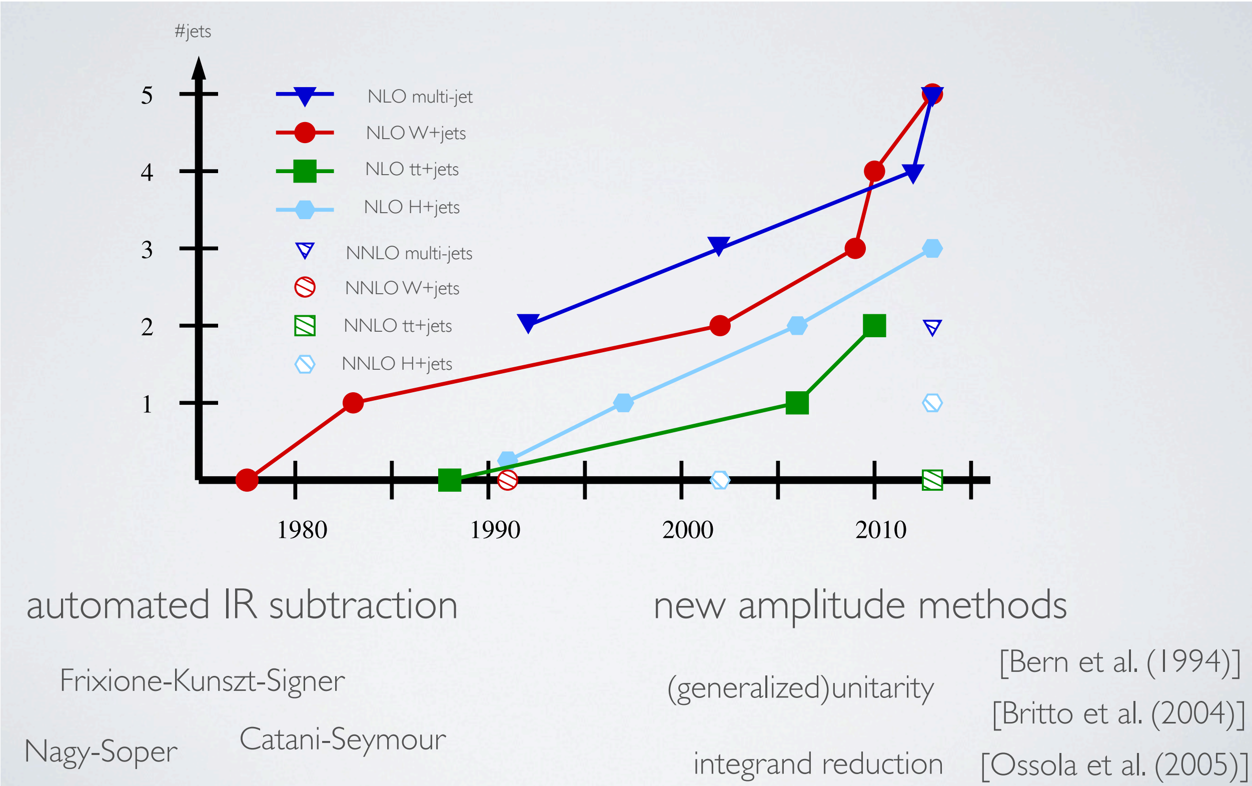
$$\text{correction} \sim 2\frac{\Gamma_V}{M_V} \approx 6\% \text{ for } V = Z, W$$

Much worse: “Dalitz Decay”



$\mathbf{H \to \bar{f}f}$ NNLO or $\mathbf{H \to \bar{f}f\gamma}$ NLO

[Simon Badger]

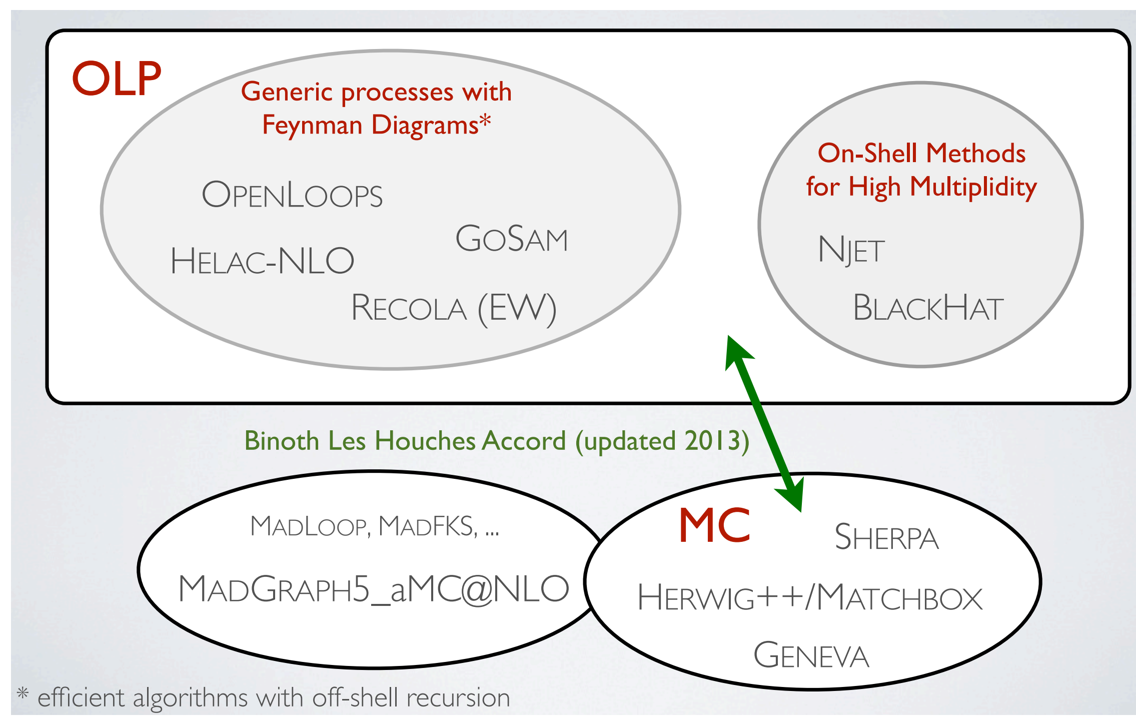


Tremendous progress

NLO “Revolution”

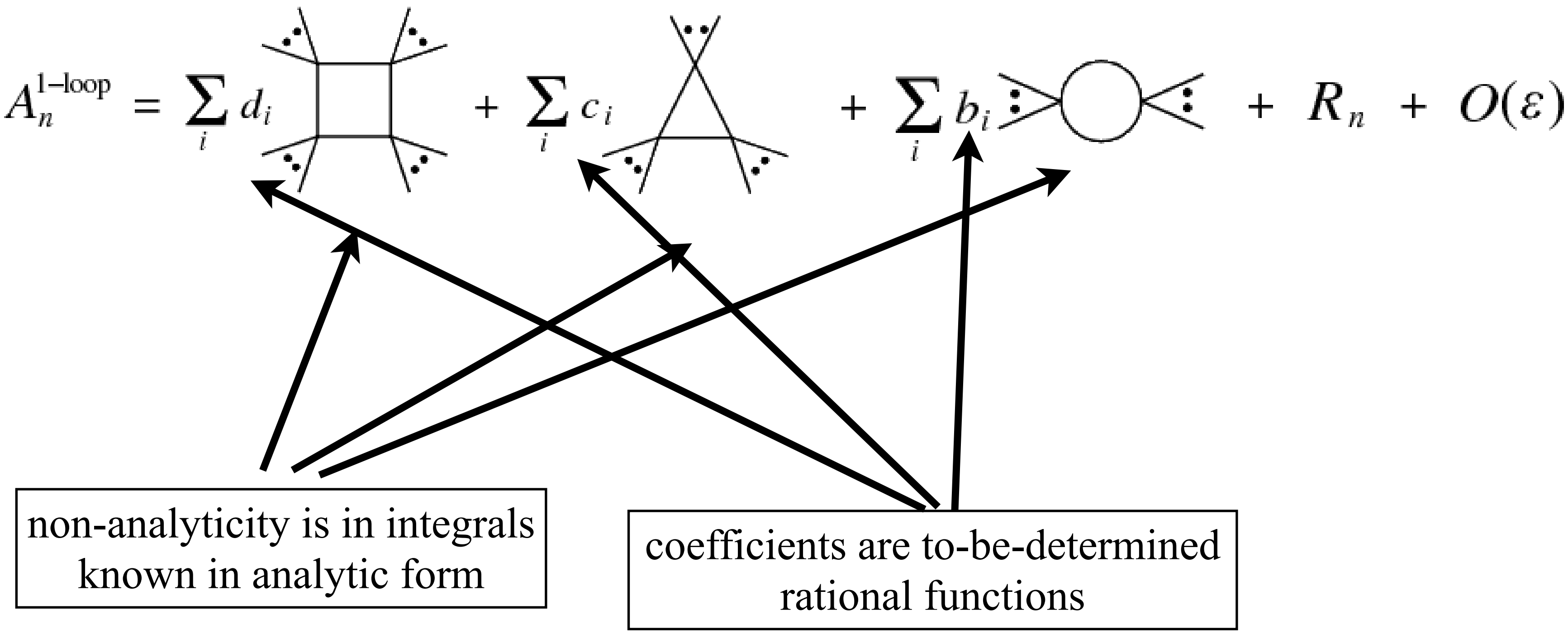
Automated NLO:

- Generic: QCD corrections to $2 \to$ 4-anything
- On-Shell: Specific processes at $2 \to$ 5/6 specific (eg, W?Z+jets)

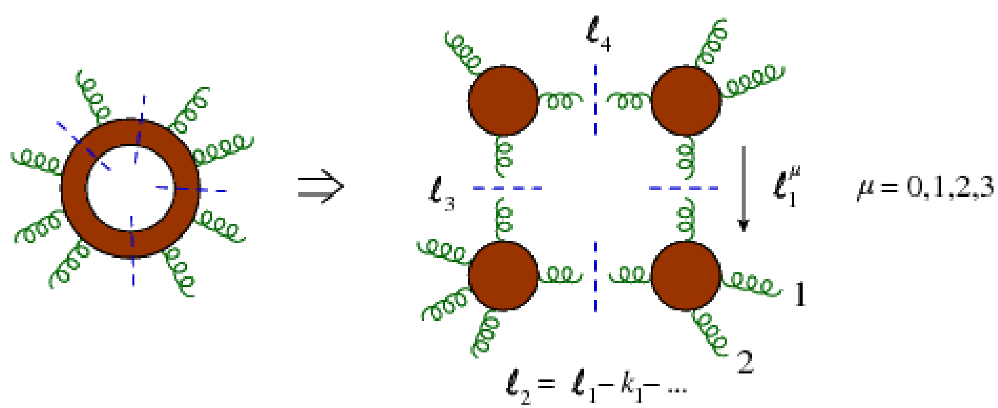


[Giampero Passarino, Simon Badger]

Peak under the hood: amplitude methods



Much progress in algorithmic computation of coefficients by:



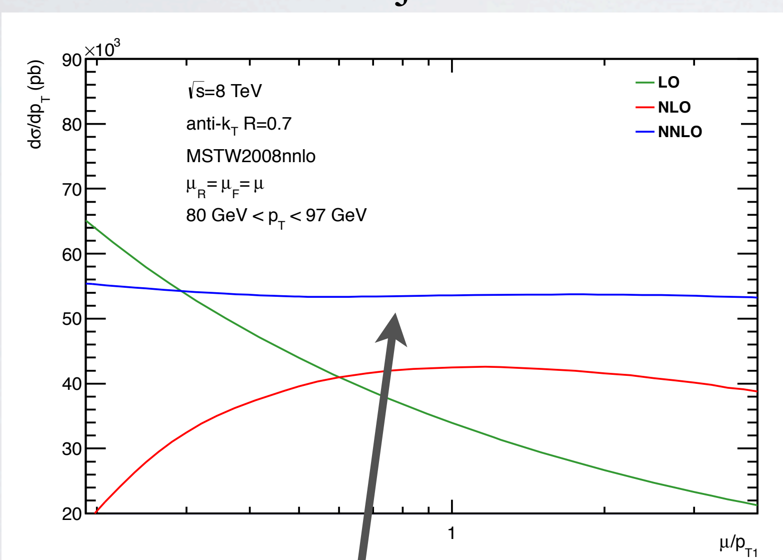
But wait, there is more! [Simon Badger]

NNLO recent progress ($2 \to 2$)

$pp \to \gamma\gamma$	[Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
$pp \to WH$	[Ferrera, Grazzini, Tramontano (2011)]
$gg \to gg$	[Currie, Gehrmann de Ridder, Gehrmann, Glover, Pires (2013)]
$pp \to t\bar{t}$	[Czakon, Fiedler, Mitov (2013)]
$gg \to Hg$	[Boughezal, Caola, Melnikov, Petriello, Schulze (2013)]
$pp \to Z\gamma$	[Grazzini, Kallweit, Rathlev, Torre (2013)]
$pp \to tj$	[Bruchseifer, Caola, Melnikov (2014)]
$pp \to ZZ$	[Cascioli, Gehrmann, Grazzini, Kallweit, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs (2014)]
$pp \to HH$	[de Florian, Mazzitelli (2014)]
$pp \to ZH$	[Ferrera, Grazzini, Tramontano (2014)]

loop integrals only recently available: new approach to DE [Henn (2013)]

Ex: dijets



flat scale dependence

NNLO $2 \to 3$ needs new tools

Future

unknown loop integrals

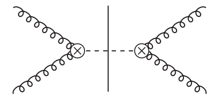
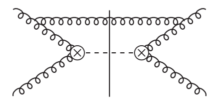
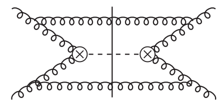
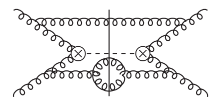
highly non-trivial kinematics

reduction algorithms

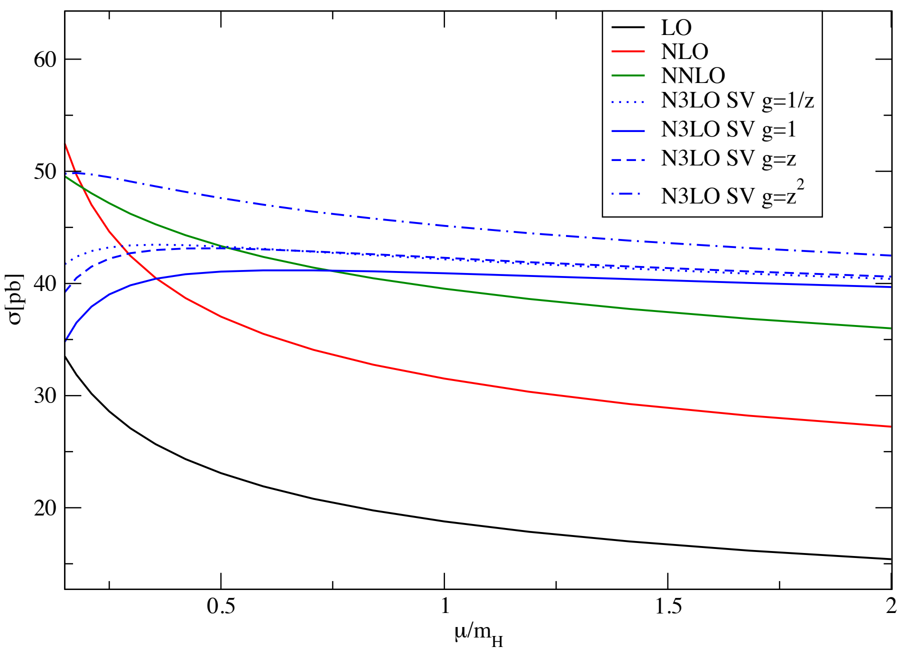
Wait, even more!! Progress towards NNNLO

[Claude Duhr]

A daunting task!

LO		1 diagram	1 integral
NLO		10 diagrams	1 integral
NNLO		381 diagrams	18 integrals
N3LO		26565 diagrams	~500 integrals

But under way:
NNNLO Higgs soft-virtual



Some new strategies needed, eg, "threshold expansion"

$$\hat{\sigma}(z) = \sigma_{-1} + \sigma_0 + (1-z)\,\sigma_1 + \mathcal{O}(1-z)^2$$

where $z = \dfrac{m^2}{s}$

Source of ambiguity:

$$\int dx_1\, dx_2\, \left[f_i(x_1)\, f_j(x_2) z g(z)\right] \left[\frac{\hat{\sigma}_{ij}(s,z)}{z g(z)}\right]_{\text{threshold}}$$

$$\lim_{z\to 1} g(z) = 1$$

With NLO-cross sections corresponding need for new MC simulations [Simon Badger, Claude Duhr]

NLO is the new standard for SM simulations

Precise SM backgrounds

shower matching

MC@NLO, POWHEG

Frixione, Webber, Nason

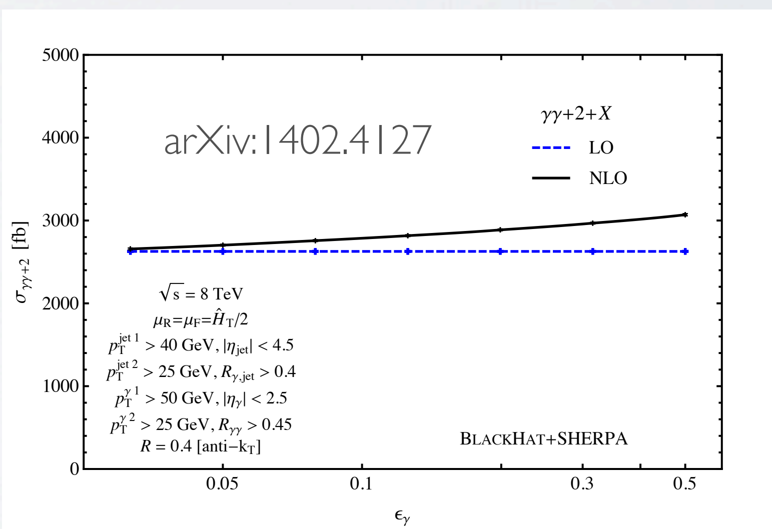
multi-jet merging

MEPS@NLO, FxFx, UNLOPS, MiNLO, Geneva

Hoeche, Krauss, Schoenherr, Siegert, Frixione, Frederix, Lonnblad, Prestel, Platzer, Hamilton, Nason, Oleari, Zanderighi, Alioli, Baur, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi

now being implemented into MCs

SHERPA, HERWIG++/MATCHBOX, POWHEG-BOX, GENEVA, MADGRAPH5_aMC@NLO,...



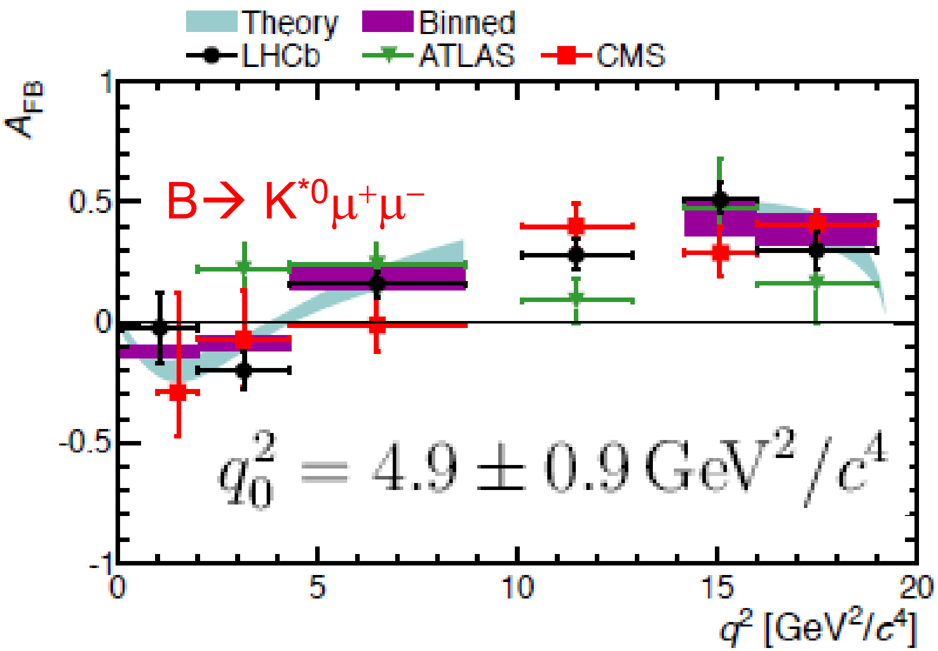
$pp \to H \to \gamma\gamma$

mild dependence on smooth isolation cone parameters

How we look is informed by ... New Observables

There are many examples. In QCD many types of transverse masses are now common.
Time allows for two:

[Sanjay Swain, George Hou]



CLEAN observable: zero

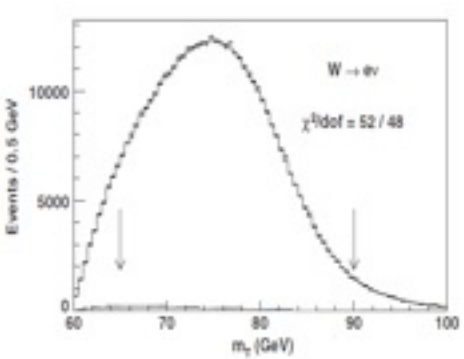
$$q_0^2 \text{ such that } A_{\rm FB}(q_0^2) = 0$$

G. Burdman, PRD 57, 4254 (1998).
non-resonance interference:
BG & Pirjol, PRD 73, 094027 (2006)

New approach for the precision measurement of the *W* and *t*-quark masses [Kiwoon Choi]

The time tried standard:

$$M_T^2 = 2P_T^l P_T^\nu (1 - \cos(\phi^l - \phi^\nu)$$

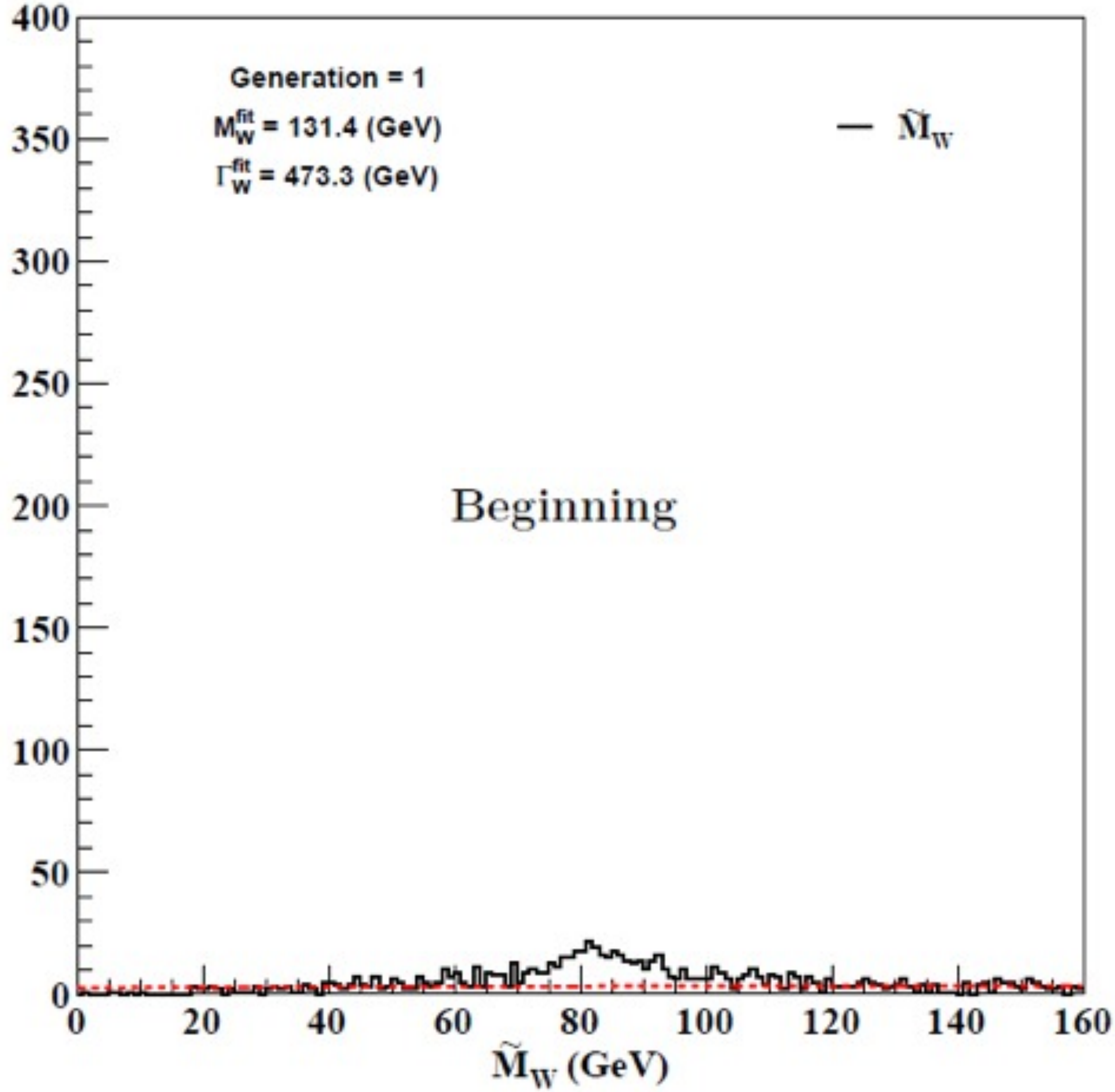


Include info on longitudinal (along beam) momentum

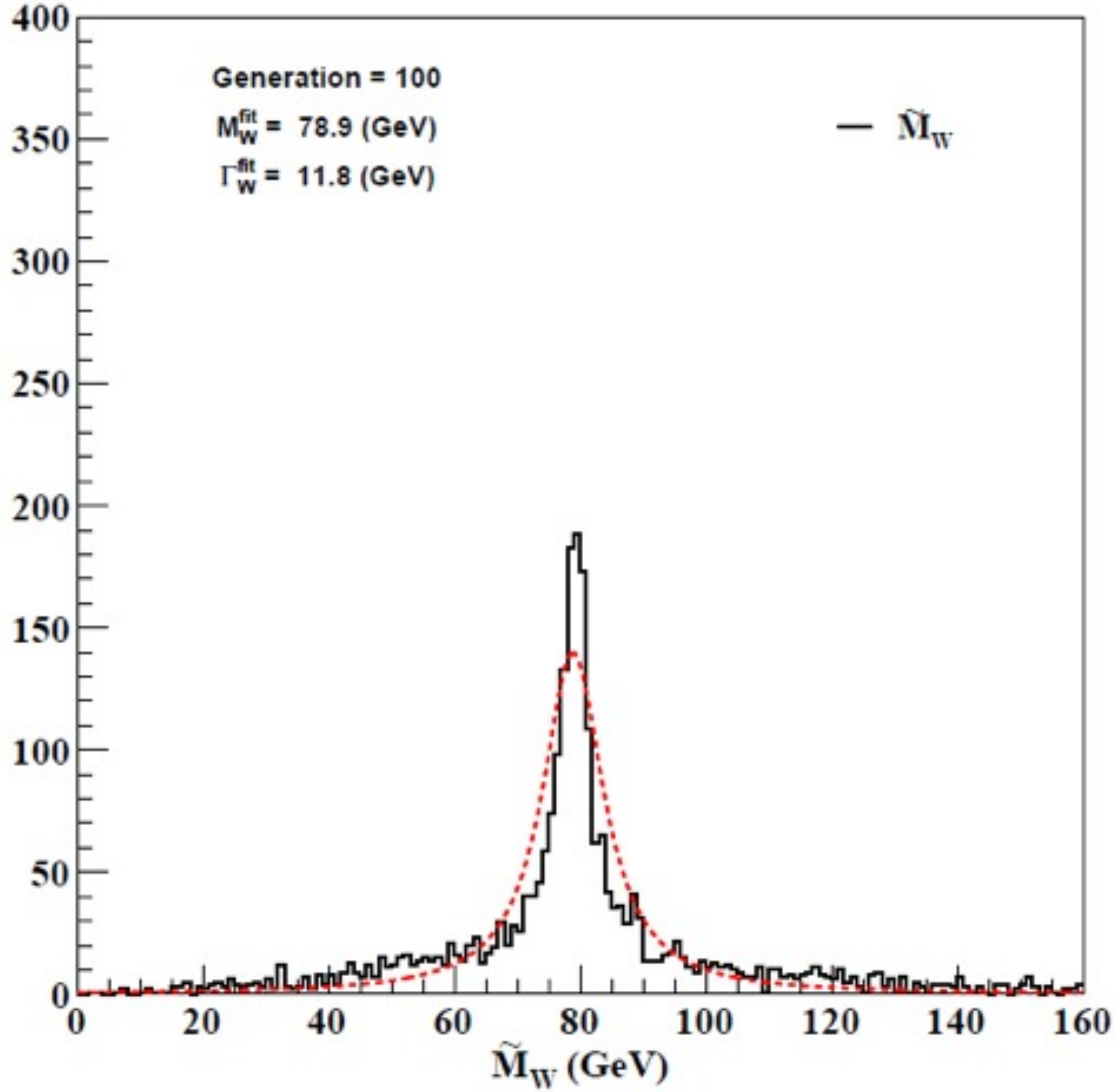
$$\boxed{\tilde{M}_W^2 = \left(P_\mu^\ell + \tilde{P}_\mu^\nu\right)^2 = 2P_T^\ell P_T^\nu\left(\cosh(\eta_\ell - \tilde{\eta}_\nu) - \cos(\phi_\ell - \phi_\nu)\right)}$$

Neutrino rapidity reconstructed by collective stochastic optimization process through a genetic algorithm

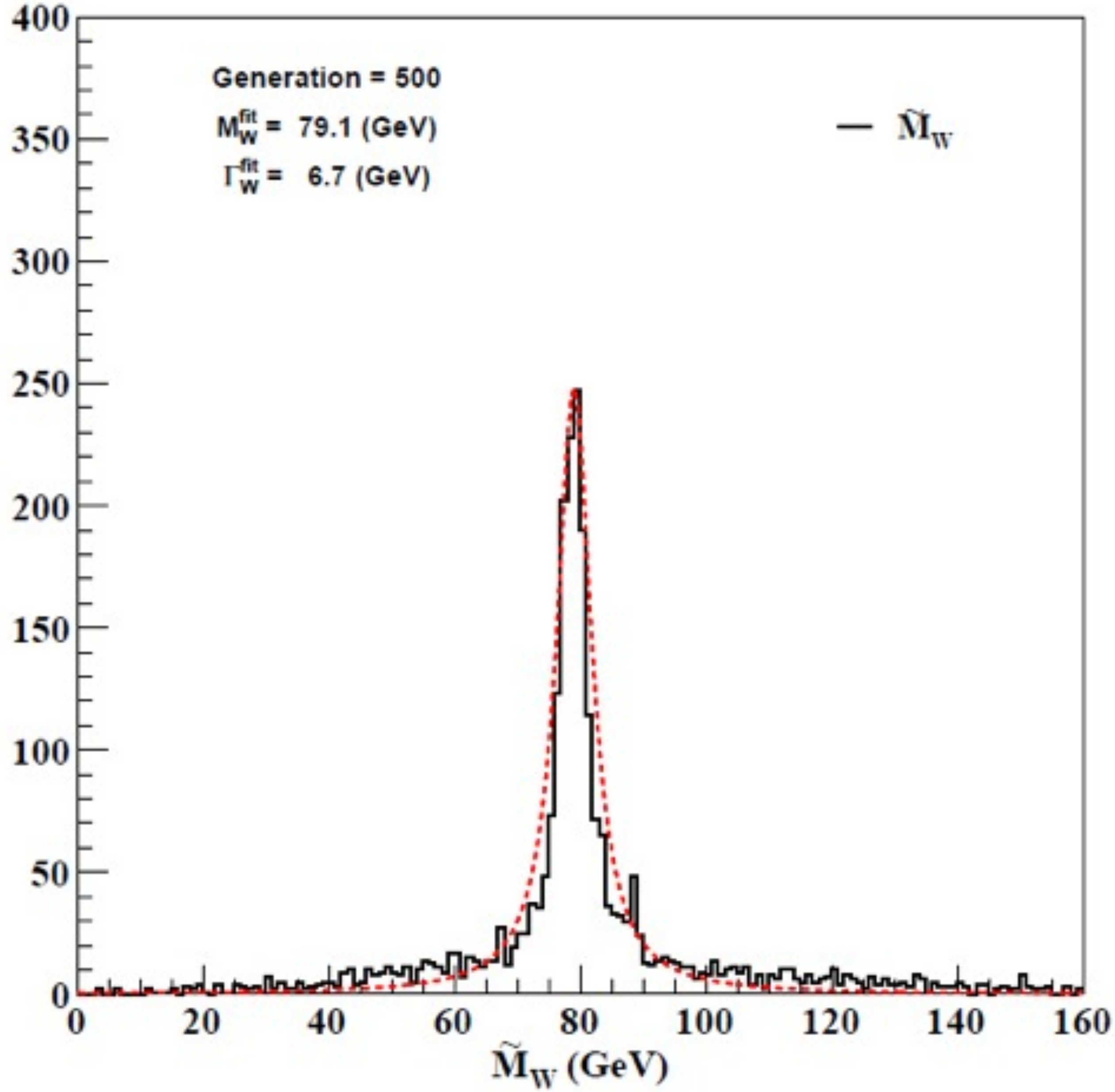
Preliminary test for 10 independent sets of 200 events



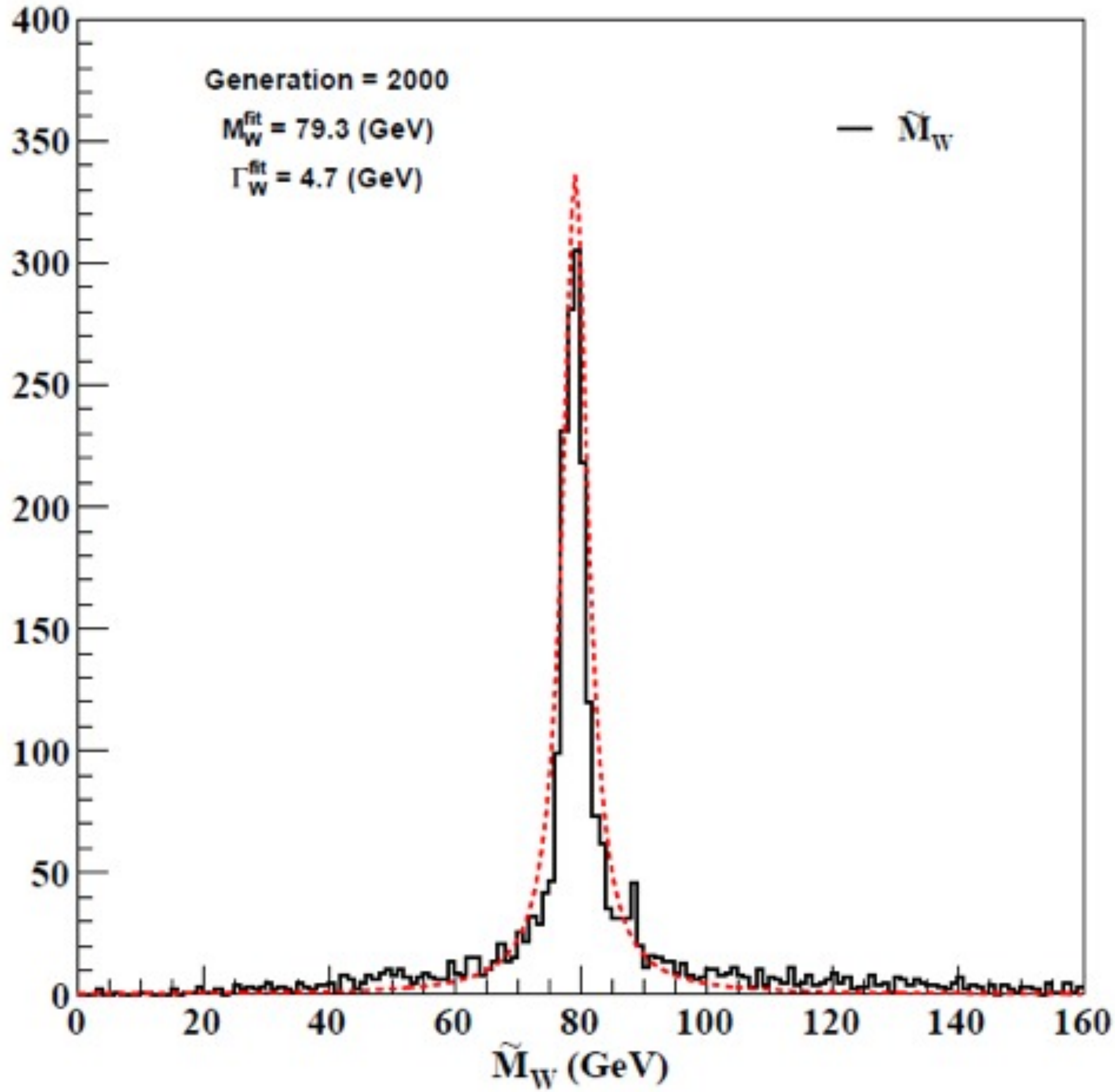
After 100 evolutions



After 500 evolutions



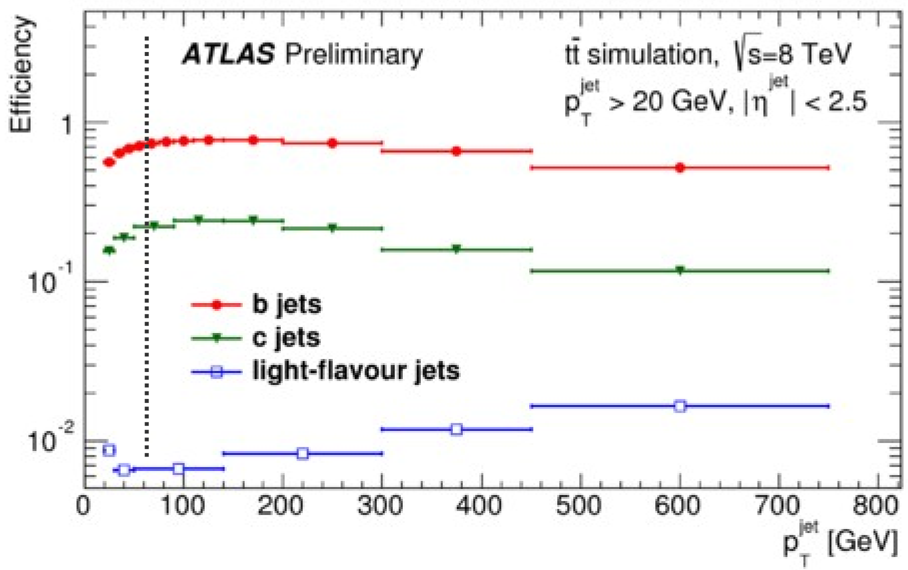
After 2000 evolutions



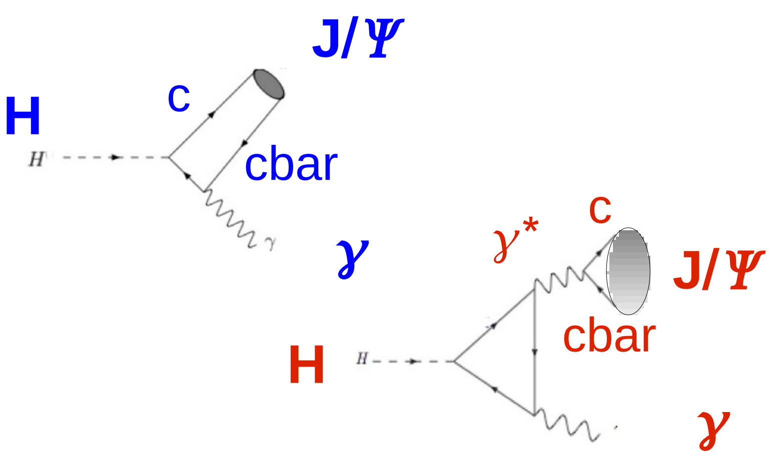
How we look is informed by ... New Techniques

$hc\bar{c}$ coupling measurement by interference [Stoyan Stoynev]

Various models exist where this coupling alone could be enhanced relative SM, eg, 2HDM and General Minimal Flavor Violation Scenario with one Higgs Doublet.



"There needs to be a significant improvement in c-tagging for direct use for Higgs. Many people consider this hard to do. Work is on-going in both ATLAS and CMS."



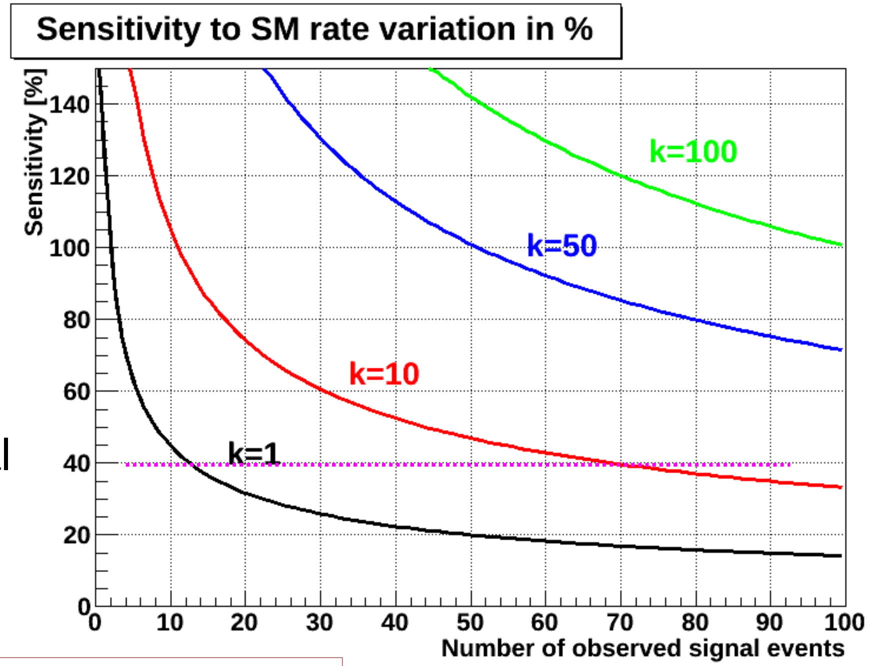
$$\boxed{\Gamma(H \to V\gamma) = \frac{1}{8\pi}\frac{m_H^2 - m_V^2}{m_H^2}|\mathcal{A}_{\rm direct} + \mathcal{A}_{\rm indirect}|^2}$$

Theory well understood. Errors under good control:

$$\boxed{\Gamma_{\rm SM}(H \to J/\psi + \gamma) = 1.17^{+0.05}_{-0.05} \times 10^{-8}\ {\rm GeV}}$$

Experimental sensitivity ($H \rightarrow J/\Psi + \gamma$)

We estimate that if both lepton and muon channels are reconstructed with 50% acceptance x efficiency we'll see ~50 signal events from combined ATLAS and CMS data from 3000 fb^{-1} LHC. This is ~14% statistical error on the Br and ~40% on k_c.



Defining Sensitivity as S/sqrt(B+S) and using the k=B/S we can try to judge about the experimental perspectives. The observation in the $H \rightarrow \gamma\gamma$ channel was announced at Sensitivity ~ 40%

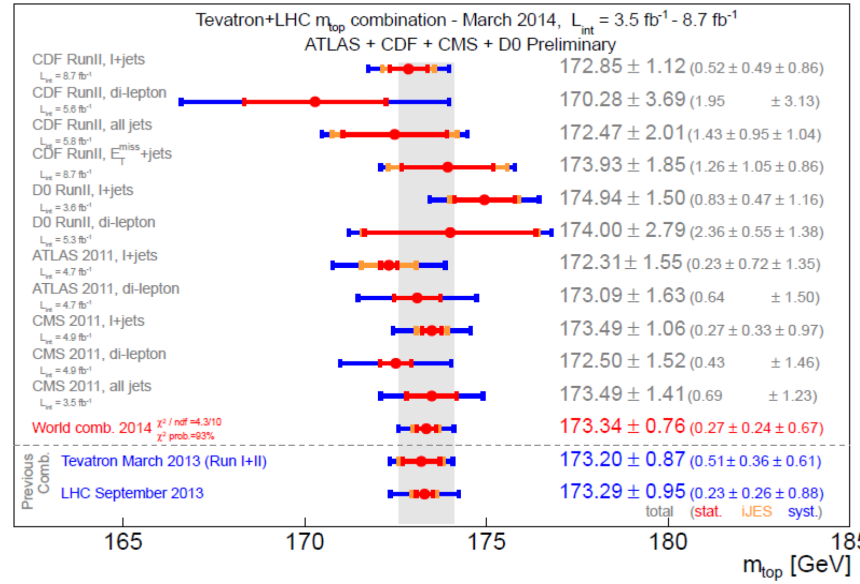
- The main uncertainty will be statistical (from background)
- We can assume k<40 as a *current* working estimate
- Categorization of events and kinematic handles against background typically (in past) increase sensitivity by 10-20%
- On the other hand it may be more difficult to get high efficiency for the electron channel (both trigger and off-line)

It is an assumption that experiments will plan accordingly to record the relevant data.

We are at the limit to observe the (SM) decay with full LHC data.
In any case strong limits on the Hccbar Yukawa coupling can be set.

Top Mass: New techniques

[Hiroshi Yokoya]



Good experimental determination however ... of something not understood theoretically (ie, how to relate to MS, or any SD, mass)

Need

- Avoid to use jet momenta to determine the well-defined top-quark mass.
- Good for cross check by various methods which have different systematic errors.
  - Kinematical Endpoint (M_{T2})

    $$m_t \;=\; 173.9 \pm 0.9\ (\mathrm{stat})^{+1.2}_{-1.8}\ (\mathrm{syst})\ \mathrm{GeV}$$

    Tevatron, CMS, EPJC73,2494
  - B-hadron lifetime (L_{xy}) Hill,Incandela,Lamb (05)

    $$m_t = 173.5 \pm 1.5\ (\mathrm{stat}) \pm 1.3\ (\mathrm{syst}) \pm 2.6\ (p_T^{top})\ \mathrm{GeV}$$

    CMS-PAS-TOP-12-030
  - J/ψ method Kharchilava (00)
  - tt + 1-jet invariant-mass distribution Alioli et. al (13),
  - Boost invariant energy peak Agashe,Franceschini,Kim (13)

Leptonic Observable Methods

- J/ψ methods : $M_{\mu\mu\ell}$, J/ψ frag fnc from b-quark

  Kharchilava (00)
- Mellin moments of E_l, p_{Tl} ,,, :

  Frixione,Mitov (14), Biswas,Melnikov,Shulze (10),
- Weight function methods :

  Kawabata,Shimizu,Sumino,HY (14)

[Hiroshi Yokoya]

Weight Function Method

$$I(m) = \int dE_\ell \, \mathcal{D}(E_\ell) \, W(E_\ell, m)$$

D(E$_l$) : energy distribution of lepton.

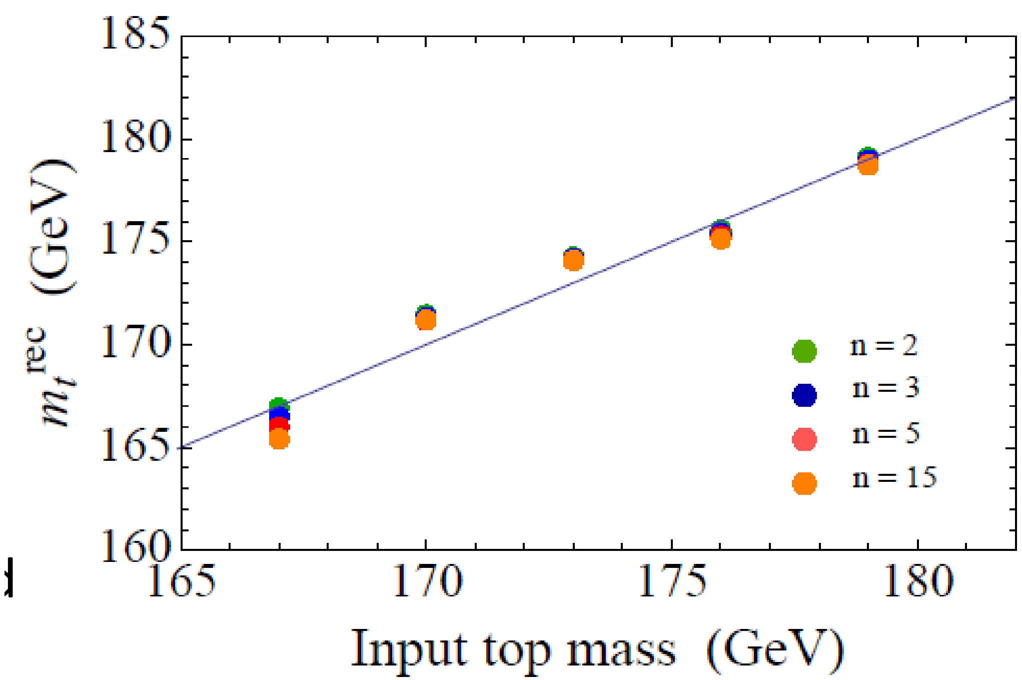
The point: one can construct weight function such that $I(m = m_{\text{true}}) = 0$

- Free from production mechanism (top has to be unpolarized)
- Free from the PDF uncertainty, initial-state radiation
- Free from hadronization modeling (because it uses only lepton)

Simulation analysis in LO

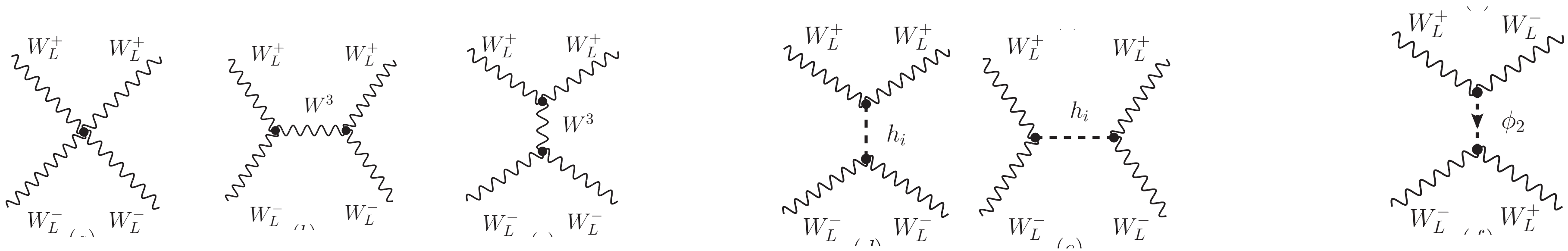
Uncertainties [GeV] (100 fb^{-1}, e+μ)

Signal stat. error	0.4
μ_F scale	+1.5/-1.6
Jet energy scale	+0.0/-0.1
BG stat. error	0.4



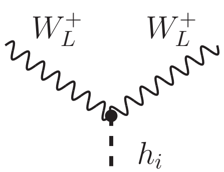
How we look is informed by ... New Tests

$W_L^+ W_L^- \to W_L^+ W_L^-$ Perturbative Unitarity, a la Lee-Quigg-Thacker, but allowing for many “higgses”

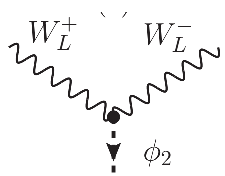


neutrals

charge ++



$= igM_W a_i$



$= igM_W b_r$

gives test:

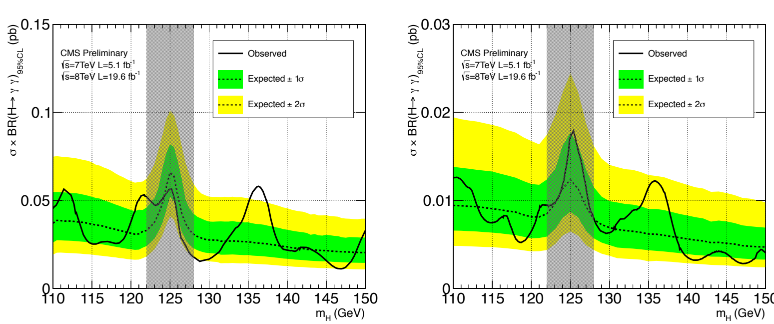
$$\boxed{\sum_i a_i^2 - 4\sum_r b_r^2 = 1}$$

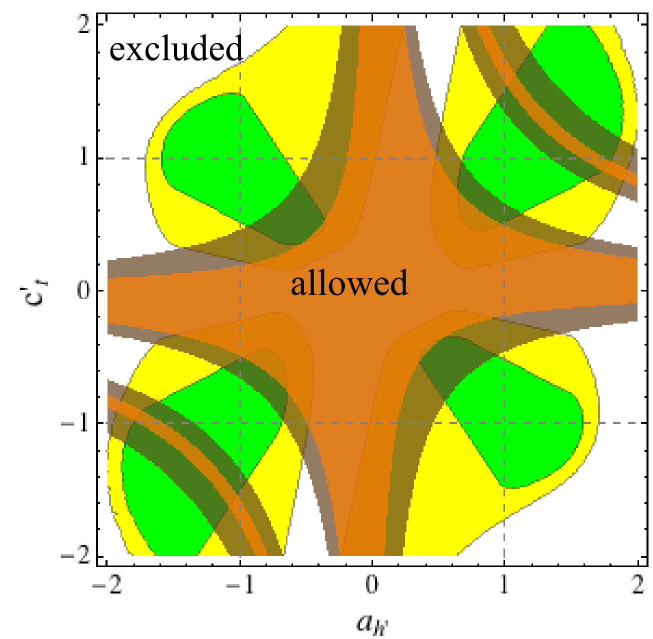
Precision test: If $|a_1| > 1$ a doubly charged higgs must exist
if $|a_1| < 1$ a second neutral higgs must exist

$W_L^+ W_L^- \to t\bar{t}$ similarly gives $\sum_i a_i c_{ti} = 1.$

Suppose there are two neutral higgs:

$a_{h'} c'_t = 1 - a_h\, c_t.$



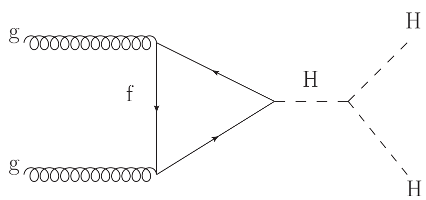


Is the 125GeV-scalar the higgs? (the minimal, 1HDM, of the SM) [José Francisco Zurita]

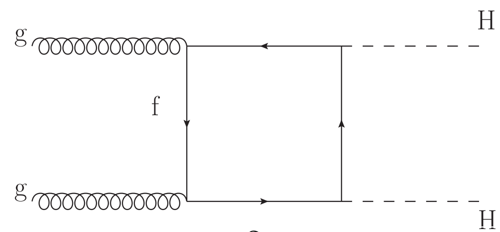
$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

SM: $\lambda_{HHH}^{SM} = \lambda_{HHHH}^{SM} = (M_H^2/2v^2) \approx 0.13$

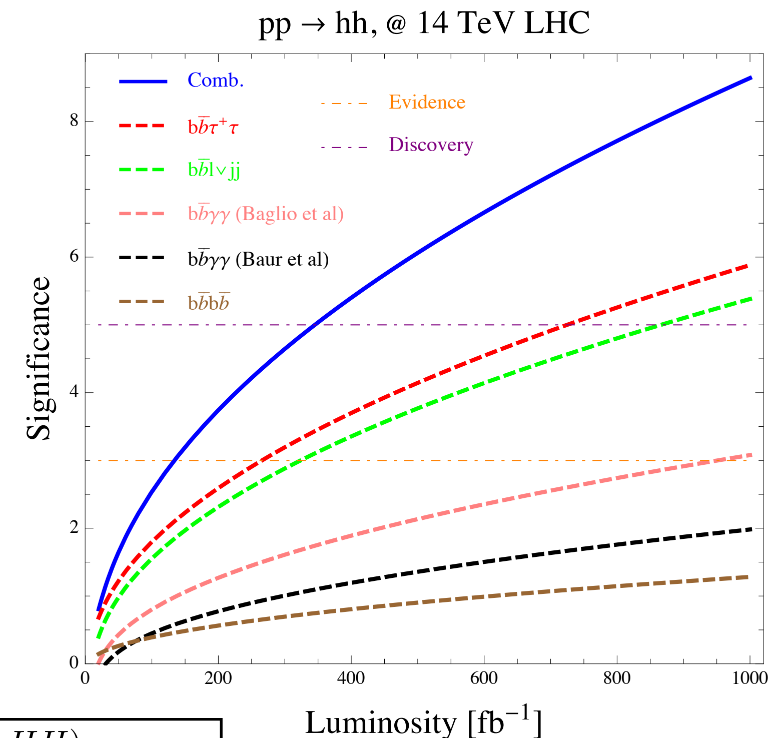
(we'll use $\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ here)

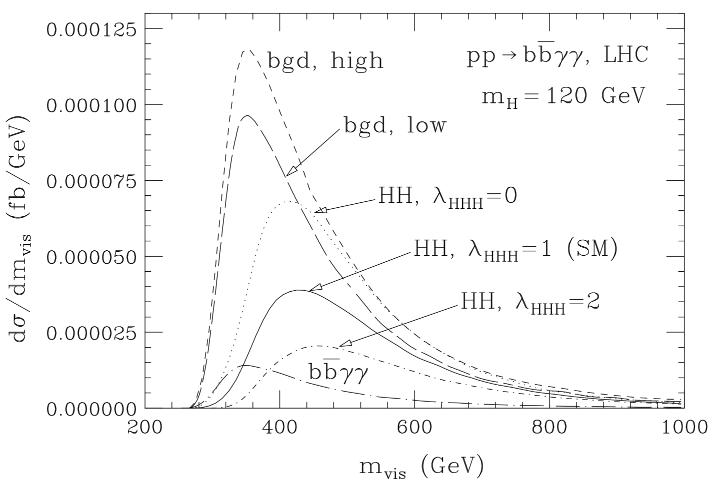


$\sim \lambda y_t$



$\sim y_t^2$



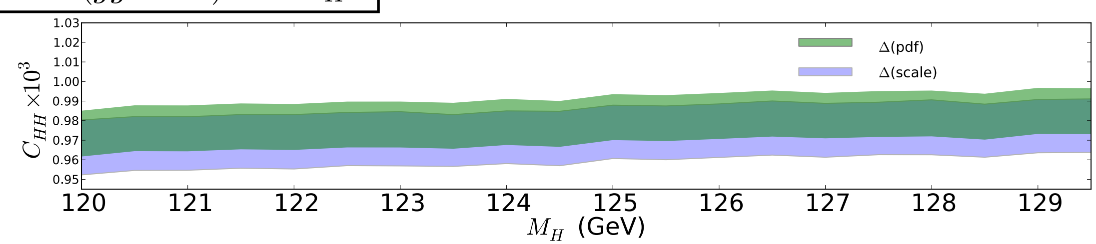


Traditional method:
fitting a distribution

A few events in a few bins:
poor statistics

$$\boxed{C_{HH} = \frac{\sigma(gg\to HH)}{\sigma(gg\to H)} \equiv \frac{\sigma_{HH}}{\sigma_H}}$$

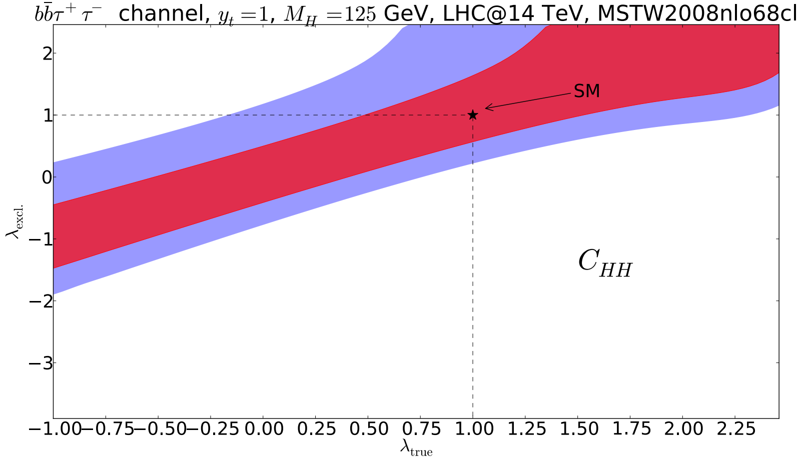
NLO theory



idea:
from
sensitive
observables

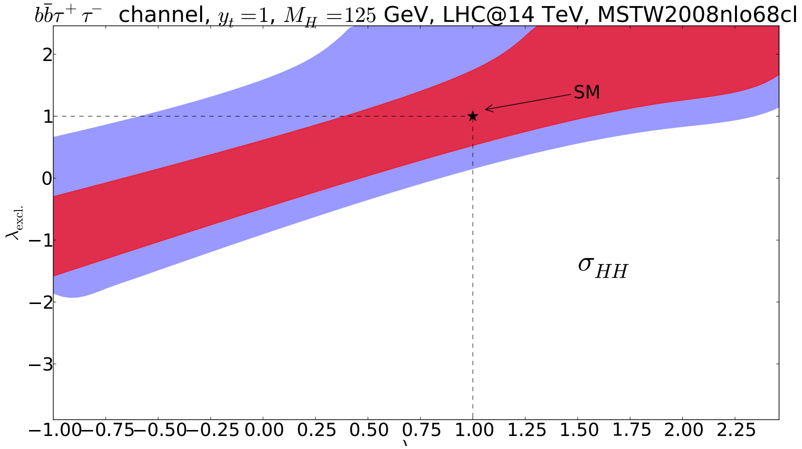
$$\sigma_{HH}^{b\bar{b}xx} \equiv \sigma_{HH} \times 2 \times \mathrm{BR}(b\bar{b}) \times \mathrm{BR}(xx)$$
$$\sigma_H^{b\bar{b}} \equiv \sigma_H \times \mathrm{BR}(b\bar{b})$$

$$C_{HH}^{\text{exp.}} = \left.\frac{\sigma_{HH}^{b\bar{b}xx}}{\sigma_H^{b\bar{b}} \times 2 \times BR(xx)}\right|_{\text{exp.}}$$



- Given an assumption for the "true" value of the self-coupling ($\lambda_{\rm true}$) what is the constraint we can impose on λ ?

$$1\sigma : \lambda \in (0.57 - 1.64)$$
$$2\sigma : \lambda \in (0.22 - 4.70)$$



$$1\sigma : \lambda \in (0.54 - 1.78)$$
$$2\sigma : \lambda \in (0.17 - 4.75)$$

This method:

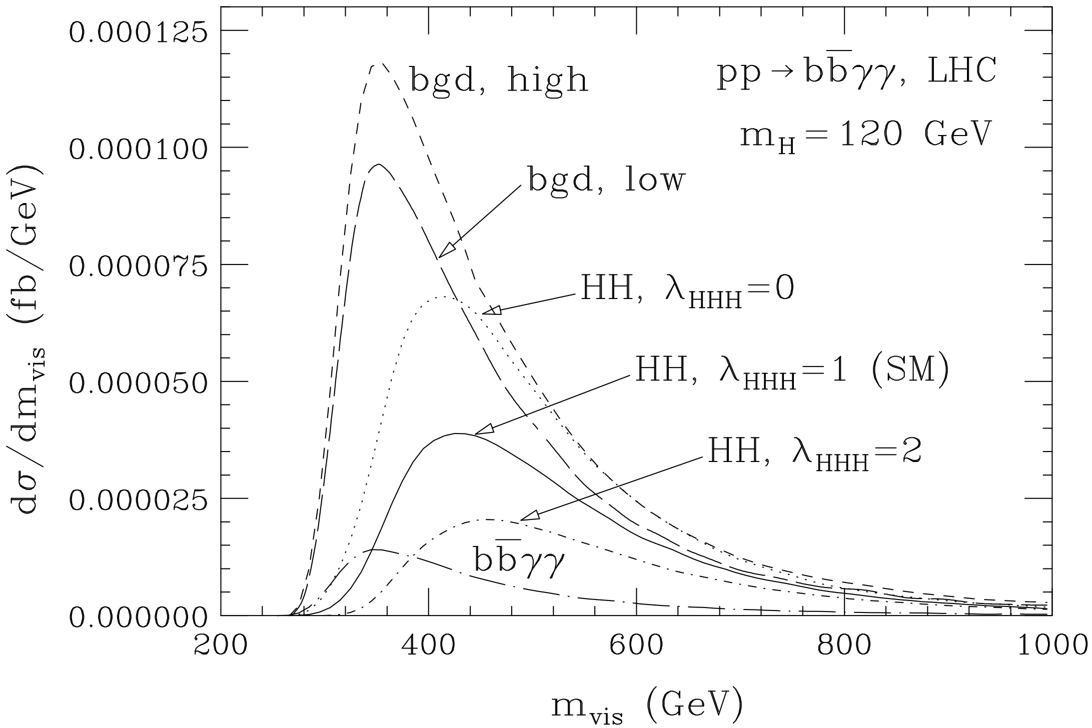
Process	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} 2σ	3000 fb^{-1} 1σ
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
$b\bar{b}W^+W^-$	(0.04, 4.88)	(0.46, 1.95)	(0.36, 4.56)	(0.65, 1.46)
$b\bar{b}\gamma\gamma$	(-0.56, 5.48)	(0.09, 4.83)	(0.08, 4.84)	(0.48, 1.87)

"Traditional" method:

LHC: **(0.26-1.94)** $\sqrt{s} = 14$ TeV, 600 fb^{-1} (1σ)

Digresion.
Fun remark:

(and an instance
of bad choice
of example
as illustration of
a valuable new
idea:
BG&Trott
PRD 76, 073002 (2007))



Tougher for larger coupling!

On the other hand
At large enough coupling
higgs mediated Yukawa potential
binds *hh* into “higgsinium”
(hissonium?)

This is little understood:
1. is binding time shorter than lifetime
2. search phenomenology

Future

How we look is informed by ... ?? what am I missing

How we look is informed by ... ?? what am I missing

How we look is informed by ... ?? what am I missing

How we look is informed by ... ?? what am I missing

How we look is informed by ... ?? what am I missing

Where to look is informed by ... precision physics: EWPD

[Max Baak]

The minimal (1HDM) Electroweak Standard Model is in FINE SHAPE!

Even at high precision, which requires theory to NNLO!!

Fit is overconstrained. With 125GeV resonance as Higgs, all parameters known precisely.

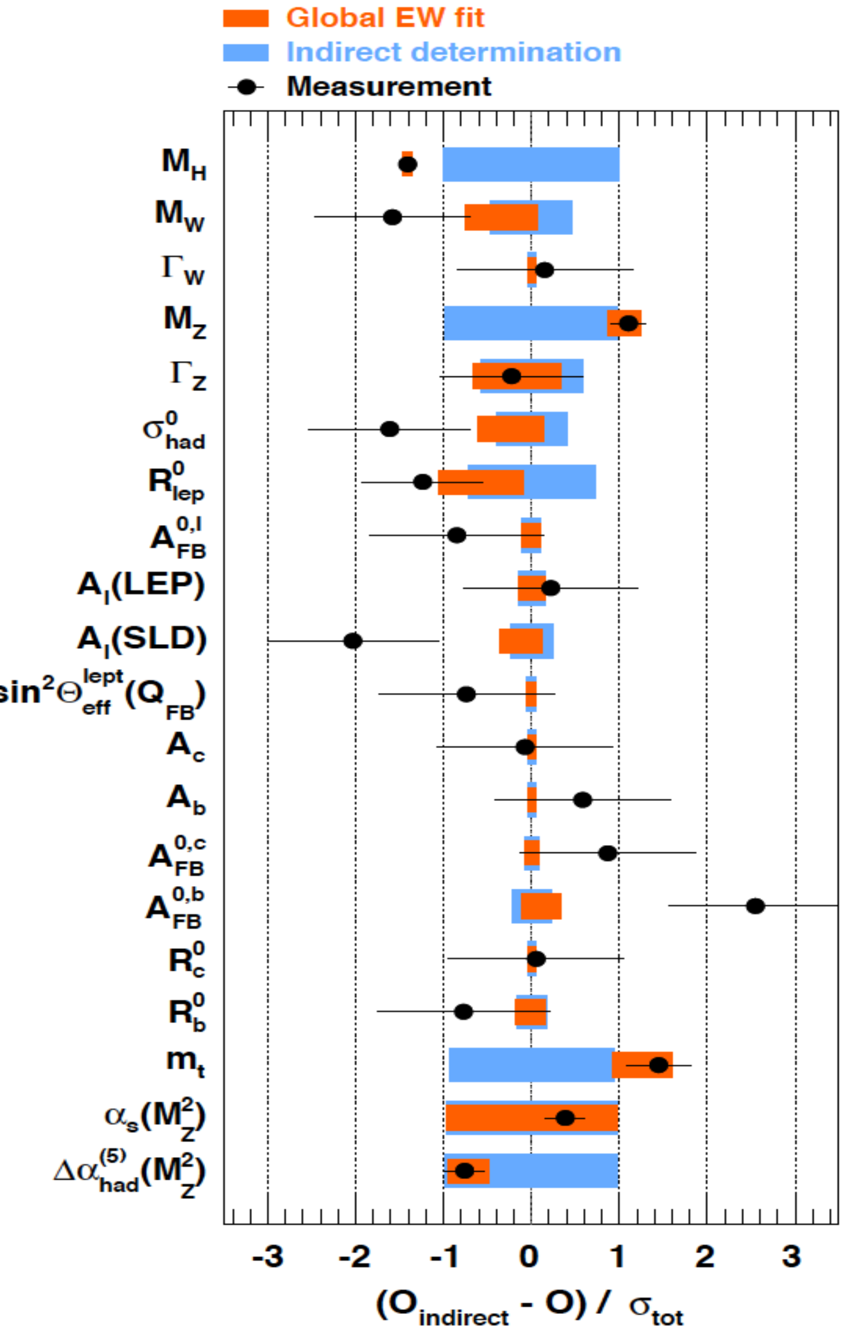
7 (+10) free fit parameters:

- M_H, M_Z, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, m_c, m_b
- 10 theory nuisance parameters
  - e.g. δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7×10^{-5})

Fit Inputs

Fit Inputs		
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	Tevatron
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP, SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP, SLC
R^0_b	0.21629 ± 0.00066	LEP, SLC
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	Tevatron + LHC
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	

[Max Baak]



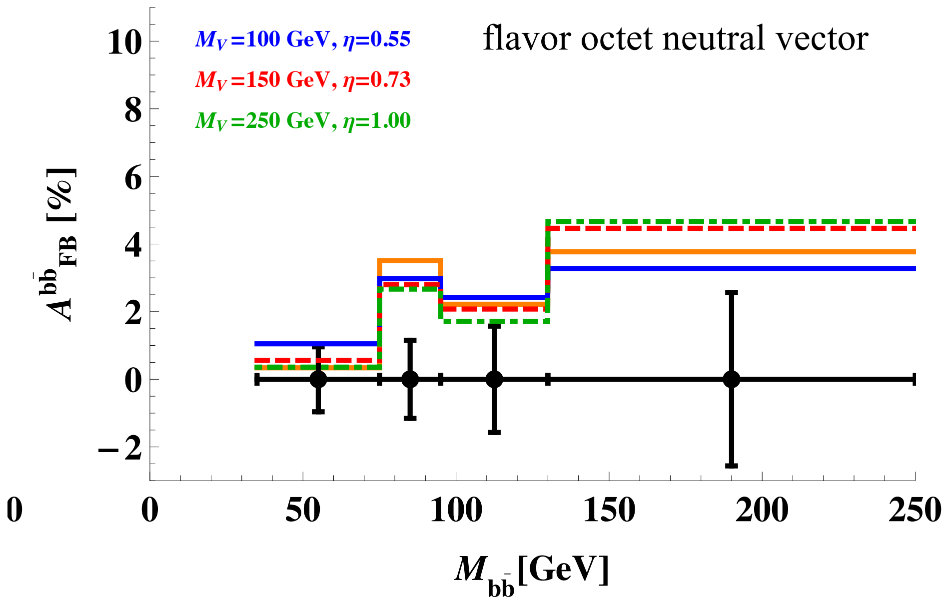
Black: direct measurement (data)

Orange: full fit

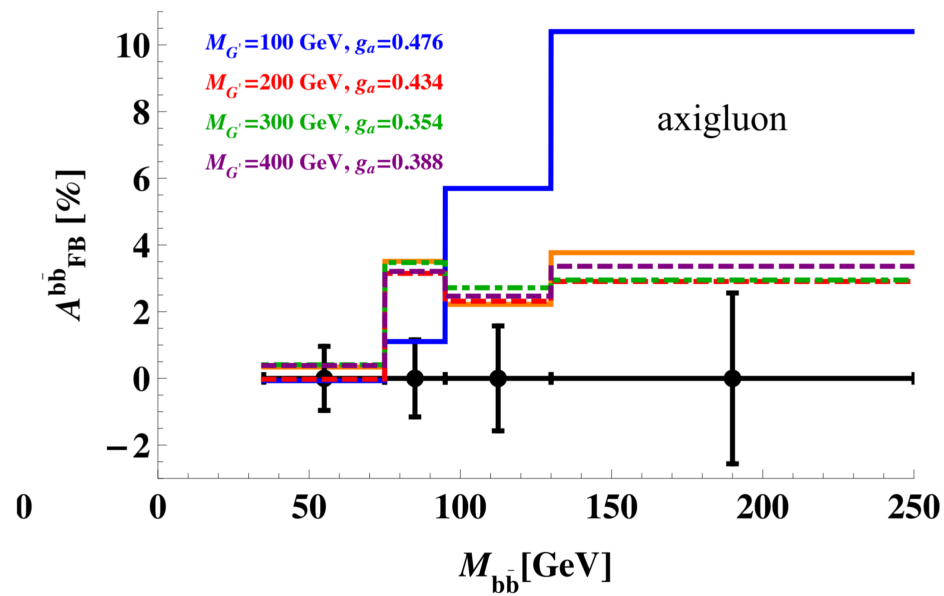
Light-blue: fit excluding input from the row

- No individual value exceeds 3σ
- Largest deviations in b-sector: $A^{0,b}_{FB}$ with 2.5σ
  - → largest contribution to χ^2
- Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$ indicate that input accuracies exceed fit requirements
- Goodness of fit – p-value:
  - χ^2_{min}= 17.8 → Prob(χ^2_{min}, 14) = 21%
  - Pseudo experiments: 21 ± 2 (theo) %
- Only small changes from switching between 1 and 2-loop calc. for partial Z widths and small M_W correction.
  - χ^2_{min}(1-loop Z width) = 18.0
  - χ^2_{min}(no M_W correction) = 17.4
  - χ^2_{min}(no extra theory errors) = 18.2

LHC/Tevatron should test for asymmetry (charge/FB) in $Z \to bb$
The Tevatron anomaly in A_{FB} in $Z \to tt$ is not completely resolved.



Tevatron, binned (with cuts).
SM in orange.



BG&Murphy, PRL 111(2013) 062003

DIGRESSION

[Martin Holthausen]

FATE OF THE UNIVERSE

DIGRESSION

[Martin Holthausen]

Fate of the Universe

DIGRESSION

[Martin Holthausen]

Fate of the Universe

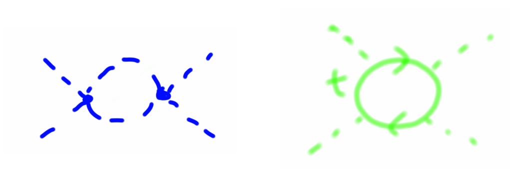
DIGRESSION

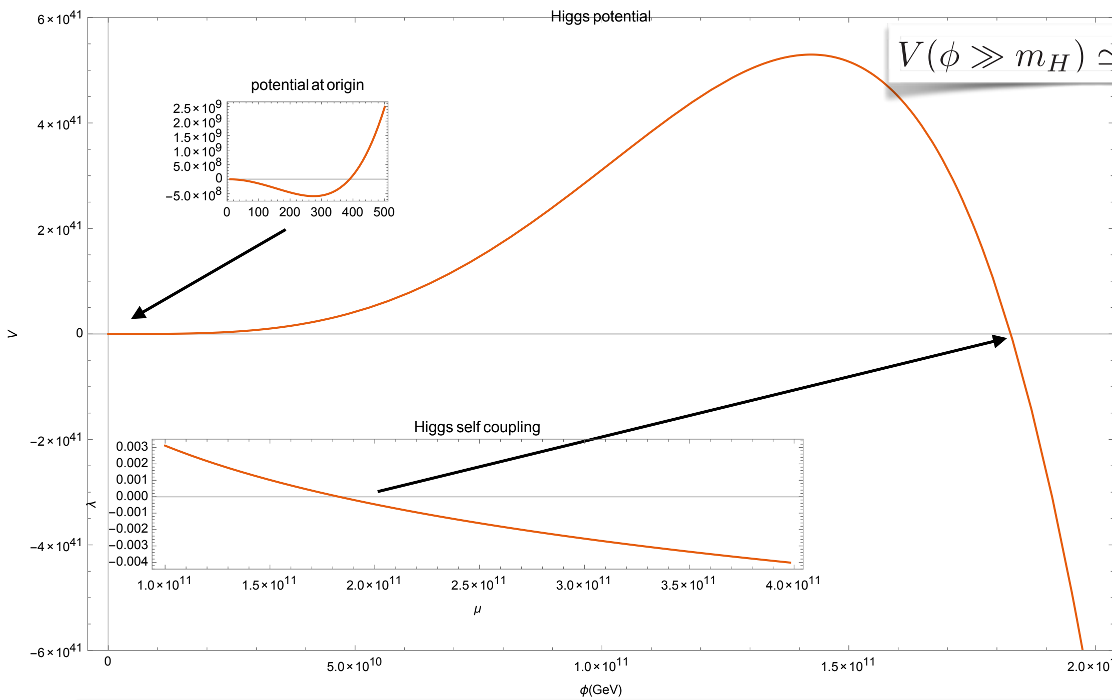
[Martin Holthausen]

Fate of the Universe

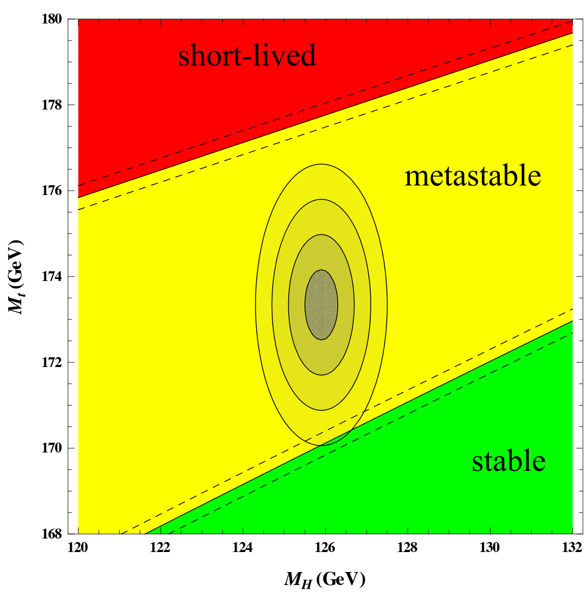
Big assumption:
NO NEW PHYSICS

$$\mu\frac{d}{d\mu}\lambda \approx \frac{1}{16\pi^2}\left(24\lambda^2 - 6y_t^4\right)$$





$$V(\phi \gg m_H) \simeq \lambda(\mu \simeq \phi)\phi^4$$



NNLO:
2-loop matching
3-loop running

Caveat:
top-mass
uncertainty

no reason to worry about vacuum decay from a practical point of view

interesting question: is the SM stable, meta-stable or what?

Many have suggested classical scale invariance at Planck Scale.

[Hiroshi Yokoya]

Where to look is informed by ... precision physics: Flavor

Where to look is informed by ... precision physics: Flavor

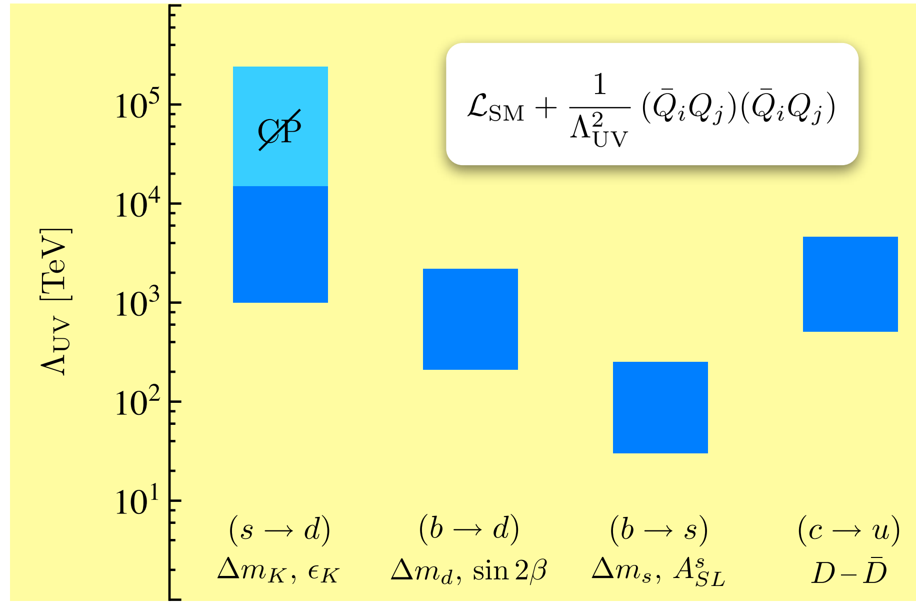
Agh!! A killer!

Flavor suggests, GENERICALLY,

no NP anywhere we are looking

nor anywhere we are likely to look
in the foreseeable future

Generic EFT bounds



EFT bounds with flavor alignment (Minimal Flavor Violation)

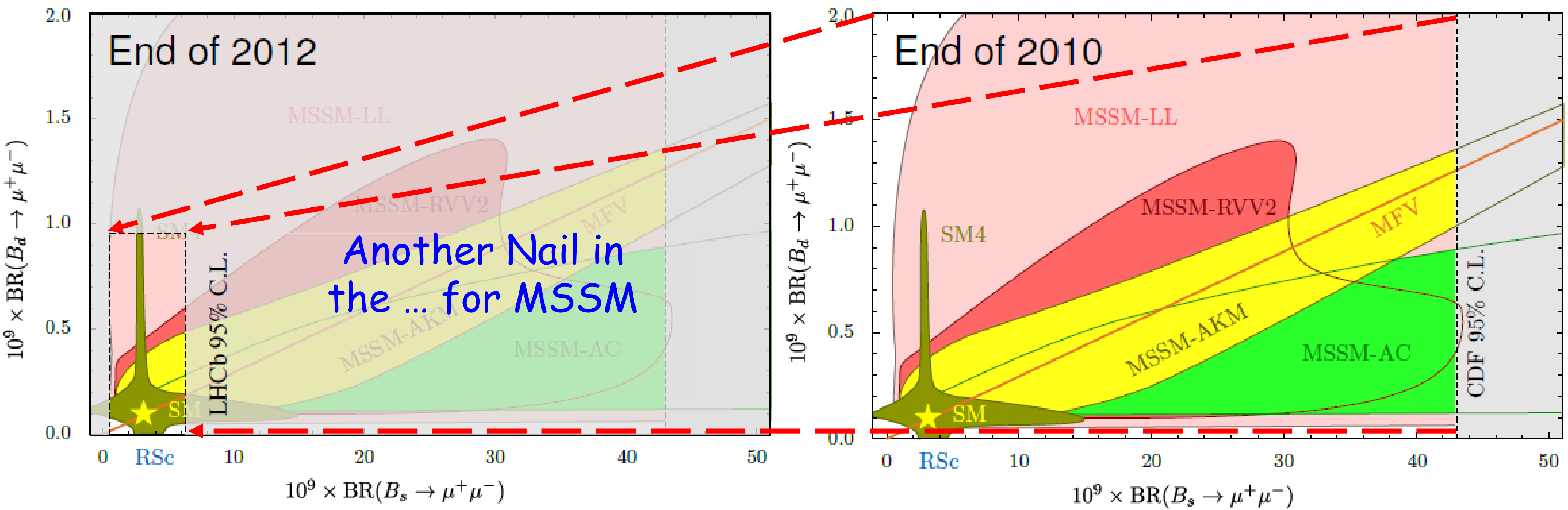
Minimally flavour-violating dimension-six operator	Main observables	Λ [TeV] $-$	Λ [TeV] $+$	
$\mathcal{O}_0 = \frac{1}{2}(\overline{Q}_L \lambda_{FC} \gamma_\mu Q_L)^2$	$\epsilon_K,\quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger(\overline{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} Q_L) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger(\overline{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} T^a Q_L) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\overline{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\overline{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\overline{Q}_L \lambda_{FC} \gamma_\mu \tau^a Q_L)(\overline{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\overline{Q}_L \lambda_{FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\overline{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\overline{D}_R \gamma_\mu D_R)$	$B \to K\pi,\quad \epsilon'/\epsilon, \ldots$	~ 1		

From G. D'Ambrosio et al. NPB 645 (2002) 155–187, outdated (sorry no time to find update)

There is hope: with MFV and weak coupling, and assuming NP only through loops $\frac{1}{\Lambda_{\rm UV}^2} \sim \frac{g^2}{16\pi^2 M_{\rm NP}^2}$

$$M_{\rm NP} \sim \frac{g\Lambda_{\rm UV}}{4\pi} = \left(\frac{g}{0.3}\right)\left(\frac{\Lambda_{\rm UV}}{10\ \rm TeV}\right) = 240\ \rm GeV$$

This is much like in any SUSY-model with flavor-blind SUSY breaking (eg, gauge mediation).
(This is why flavor-blind SUSY breaking is a must).
And even then:

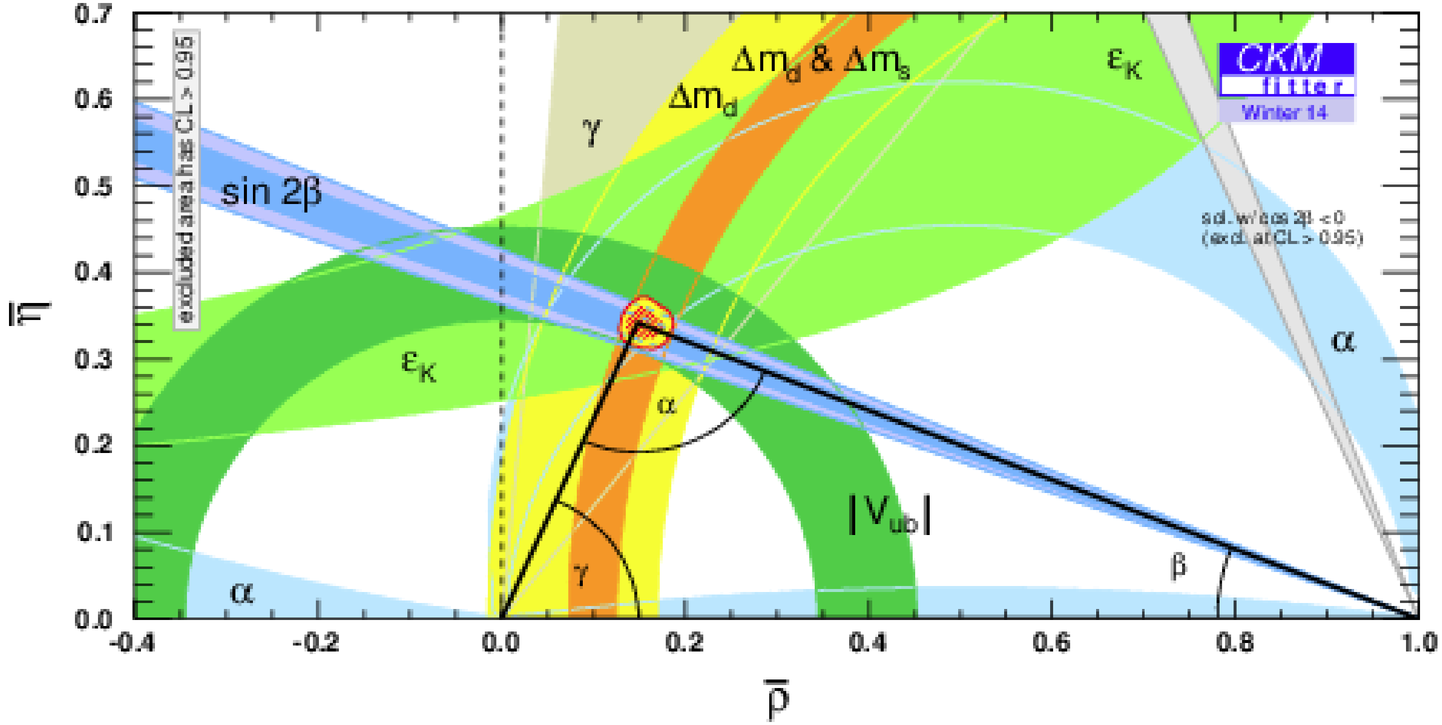


[George Hou]

Note: if $B_d \to \mu\mu$ is high, SM4 and MSSM-LL favored
(MSSM-LL is Hall and Murayama's all left handed currents in Phys. Rev. Lett. 75 (1995) 3985)

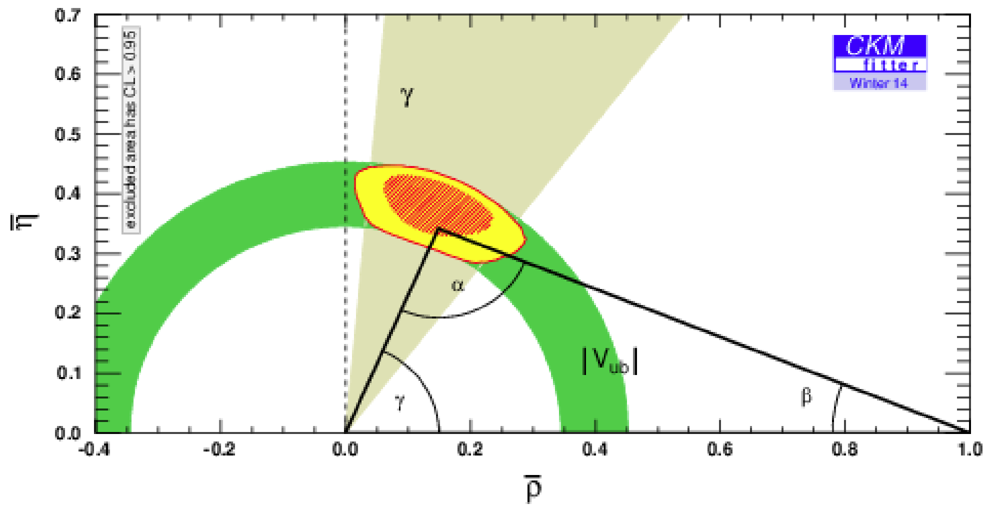
This suggests (at least SM4) to test Unitarity Triangle more precisely.

Already impressive:



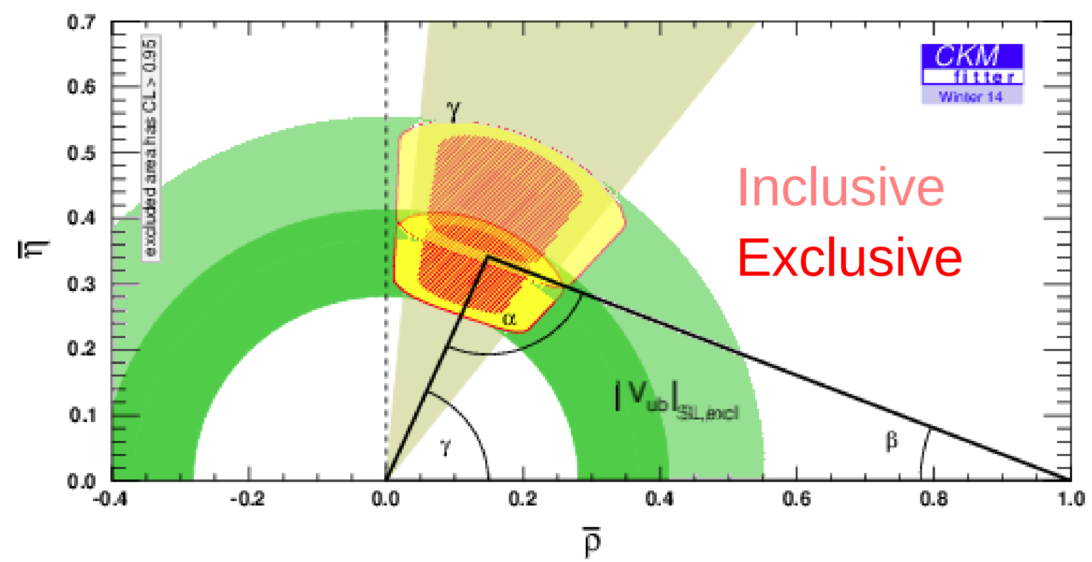
How to improve? [Ulrik Egede]

Largest uncertainties are coming from left side ($|V_{ub}|/|V_{cb}|$) and the angle γ



- Angle γ : Best in $B^- \to D^0(\bar{D}^0)K^-$ followed by $D^0(\bar{D}^0) \to K^+\pi^-, K^+\pi^-\pi^0, \ldots$ Statistical reach for Belle-II is 2 degrees, for LHCb 1degree.

- V_{ub} is theory limited, at the momen



Exclusive measurement: $B^0 \to \pi^- \mu^+ \upsilon$

Inclusive measurement : $B^0/B^+ \to X_u \mu^+ \upsilon$

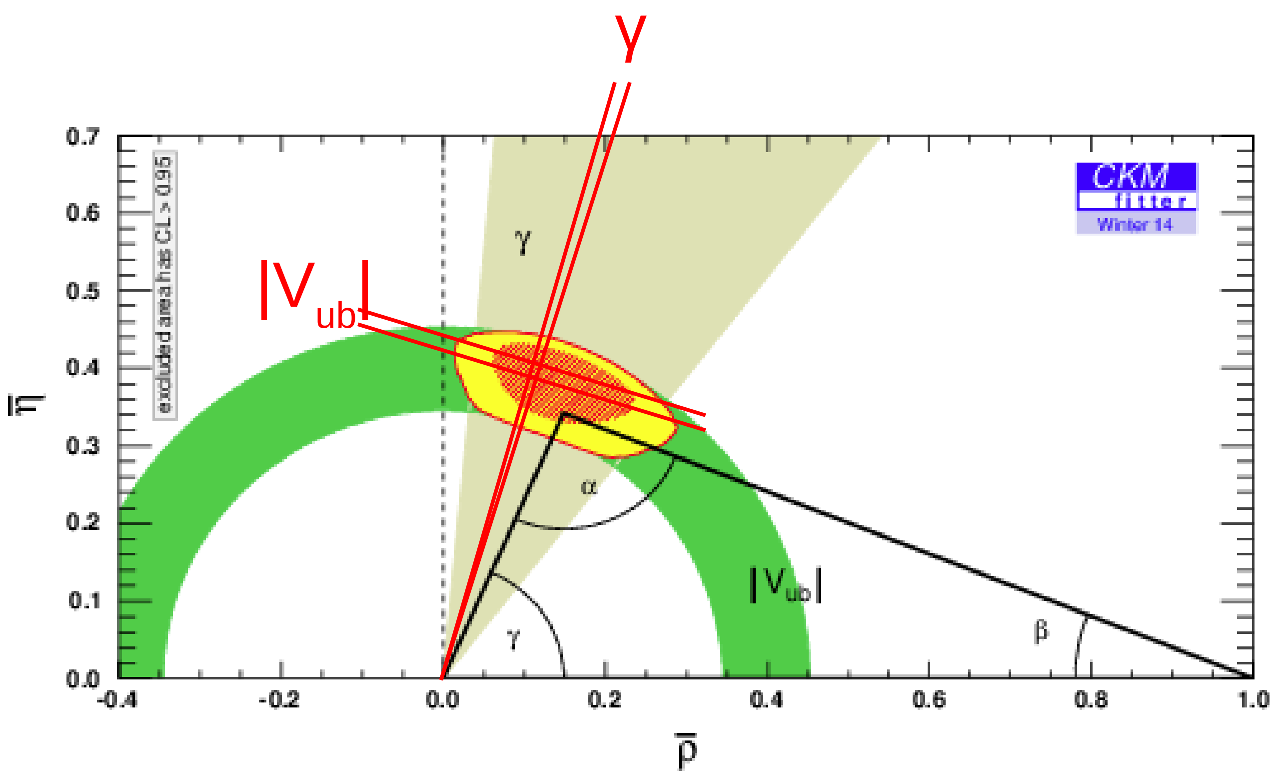
Need alternate methods for V_{ub}:

- $\Lambda_b \to p\,\mu^- \nu$
  - In progress with LHCb – rely on new $\Lambda_b \to p$ form factors from lattice
- $B^+ \to \tau^+ \nu$
  - At the moment statistics limited, Belle-II will much improve
- Inclusive measurement
  - Large gain in hadron tagged sample with Belle-II
- $B_c^+ \to D^0 \mu^+ \nu$
  - Possible at LHCb or LHCb upgrade. Interesting?

[Ulrik Egede]

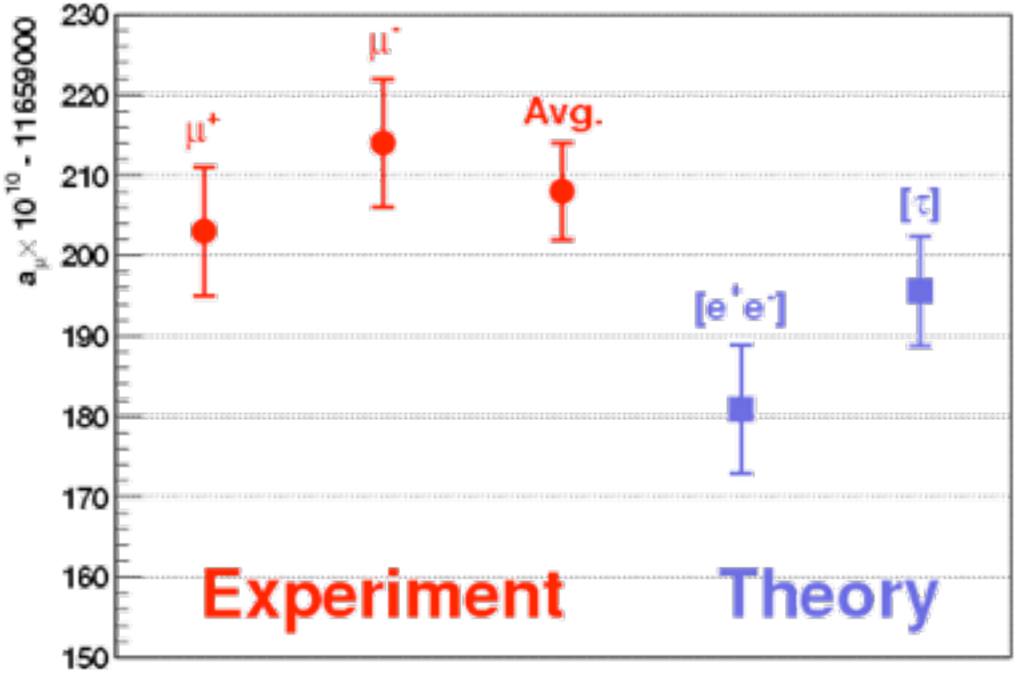
Several other are discussed (including double ratios)

If a 1% determination in both is reached:



Where to look is informed by ... QED, ...

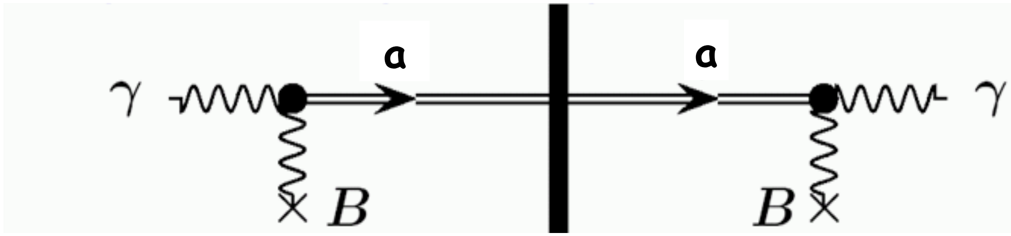
No talks here. But should not forget, for example, *g*-2



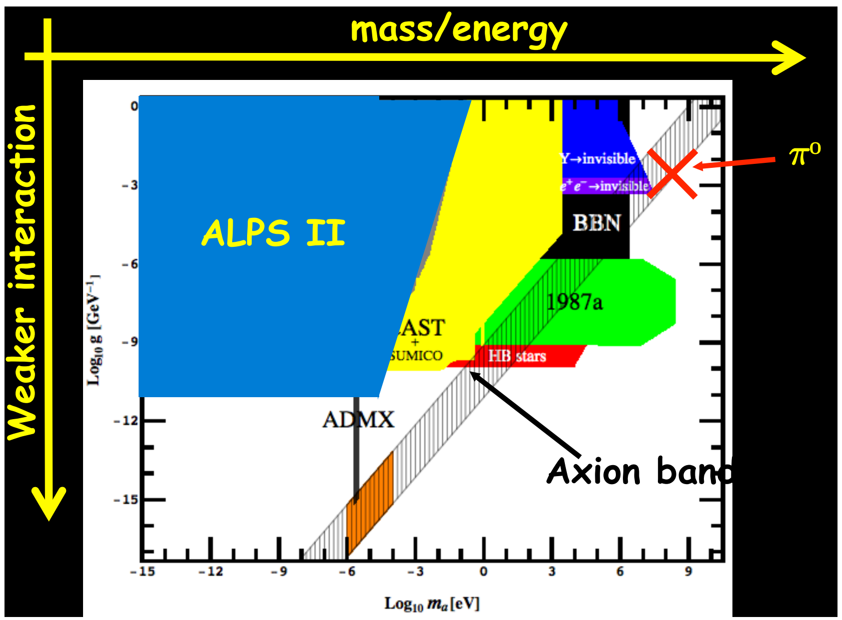
$$a_\mu \sim \left(\frac{m_\mu}{\Lambda}\right)^2 \quad \Rightarrow \quad \Lambda \sim 10\ \mathrm{TeV}$$ just as in Flavor Physics!

So we already know, for weakly coupled, radiative (loop) process $M_{\rm NP} \gtrsim 250\ \mathrm{GeV}$

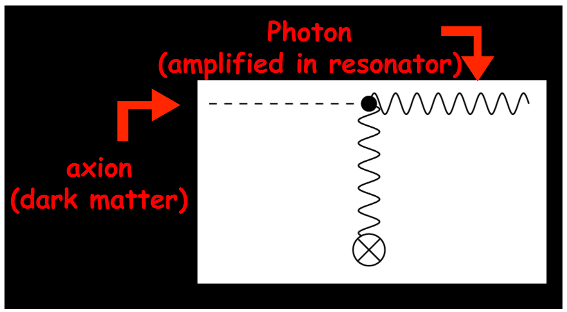
Speaking of QED, can you shine light through a wall? [J. Jaeckel]

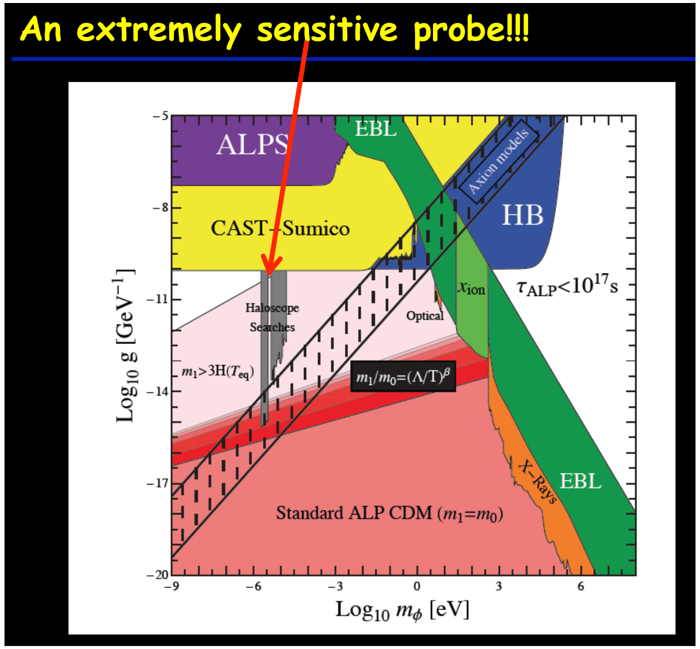


ANS: Yes! Caveat: you have to have a coupling to axions. $P_{\gamma\to a\to\gamma} \sim N_{\text{pass}} \left(\frac{BL}{M}\right)^4$



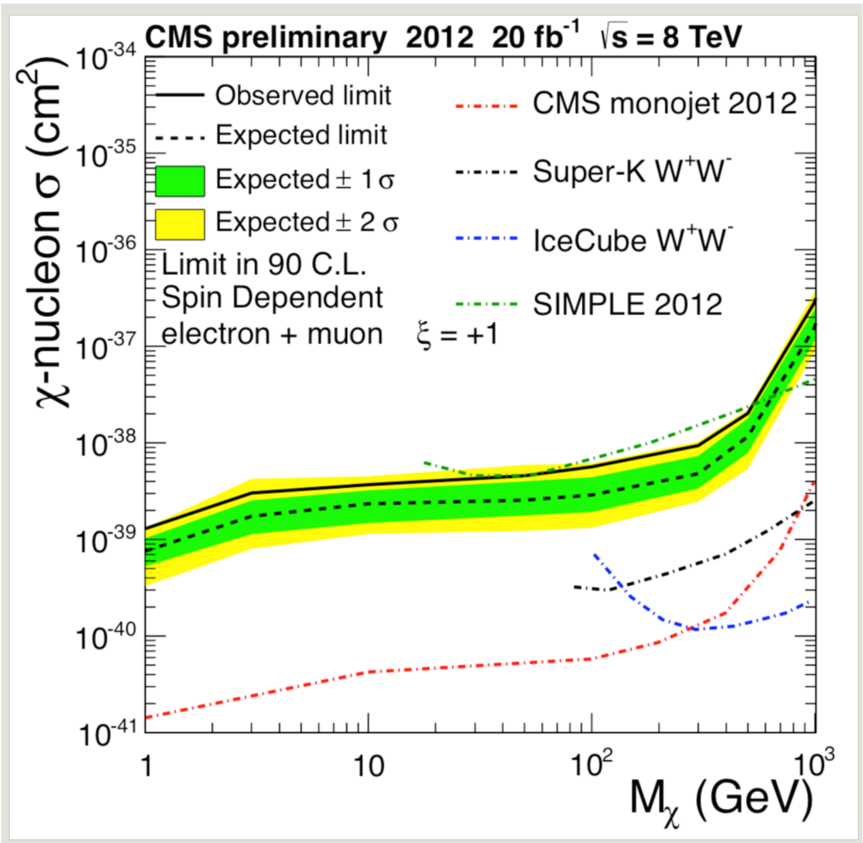
And what if axions are the DM?



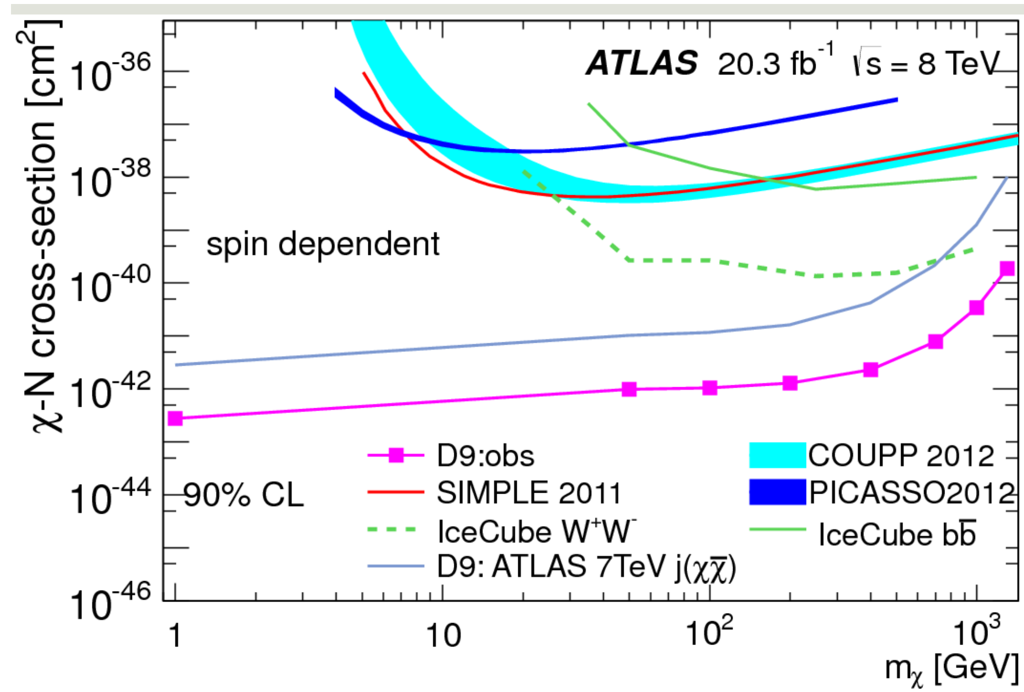


Of course, LHC experiments also place bounds on DM pair production

$$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$$



$$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$$



(taken from Sarah Eno, Moriond 2014)

We would like a roadmap to further discoveries

How we look is informed by

- Computation of signal & background
- New Observables
- New Techniques
- New Tests
- ? (what am I missing)

Where to look is informed by

- Precision physics
  - EWPD
  - Flavor
  - QED, ...
  - ? (what am I missing?)

- Theoretical Prejudice
  - EFT
  - Models
    - Anomaly driven
    - Principled

Theoretical Prejudice?

- Theoretical Prejudice
  - EFT
  - Models
    - Anomaly driven
    - Principled

EFT:

- How can this be *wrong*?
  - It can't be wrong *if* it contains all particles $m < \Lambda$
  - It can place very strong bounds on C/Λ, with C = dimensionless coefficient
  - BUT, We can keep Λ TeVish by making C small, if necessary
  - We can then find "principled reasons" for the smallness of C
    - Example: Minimal Flavor Violation, brings Λ down from 10,000 TeV to 10 TeV

- How can this be *useful*?
  - Suggests NP has to satisfy the "principled reasons" that keep C small
    - BUT, only "suggests."
      - Examples exist of non-MFV TeVish physics that is not inconsistent with Flavor
  - Gives correlated deviations from SM
    - Many processes from same small set of operators (and their coefficients)
    - Violations to these determine scale of NP (requires establishing deviation!), as in

$$A = \frac{1}{\Lambda}X + \frac{1}{\Lambda^2}Y$$

observables

correlation

correlation breakdown

$$B = \frac{1}{\Lambda}X + \frac{1}{\Lambda^2}Z$$

Caveats:

- Scale of NP must be not too large, not too small (like Goldie Locks's soup, just right)
- Coefficients of X, Y/Z may be anomalously small/large

Digression

Many times in this conference: what precision?

Often answered 1% is $\Lambda_{NP} \sim 1$ TeV (will call Λ_{NP} just Λ below)

This is back-of-the-envelope EFT.

And wrong!

To SM operator with coupling g add operator with additional H^2/Λ^2 and coefficient C:

$$\delta g \sim C\frac{v^2}{\Lambda^2} \quad \Rightarrow \quad \Lambda \sim \sqrt{\frac{C}{\delta g}}\, v = \sqrt{\frac{C}{g}}\, \frac{v}{\sqrt{\delta g/g}}$$

So for 1% errors

$$\Lambda \sim 2.5 \text{ TeV}\sqrt{\frac{C}{g}}$$

SAME DAMNED BOUND AS FROM aligned-FLAVOR AND QED!!!!

But what if g is small, as in *hbb* coupling? $\Lambda_{hbb} \sim 25 \text{ TeV}\sqrt{C_{hbb}}$ $\Lambda_{h\mu\mu} \sim 250 \text{ TeV}\sqrt{C_{h\mu\mu}}$

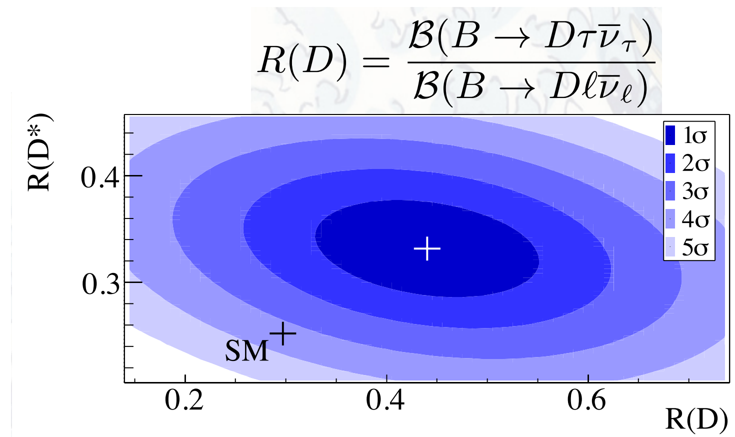
(Similar to flavor)

Theoretical Prejudice?

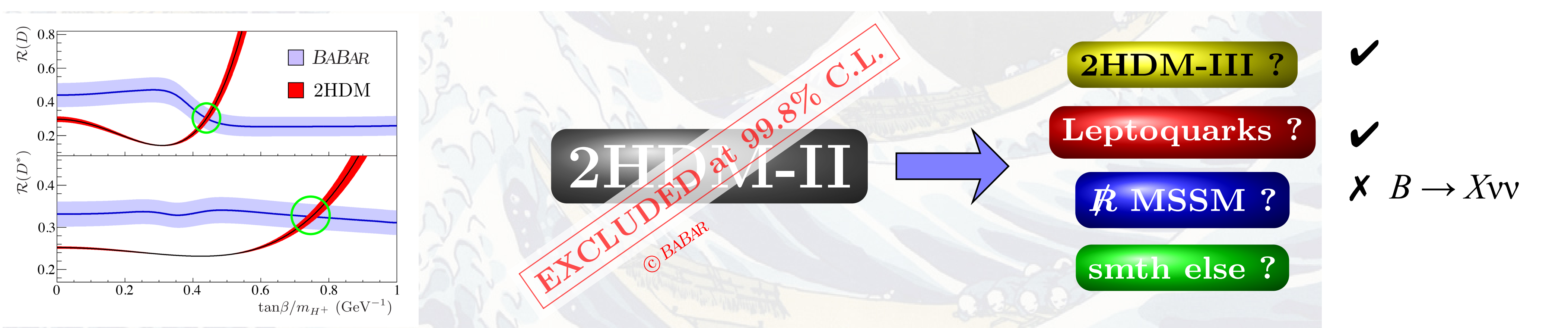
- Theoretical Prejudice
  - EFT
  - Models
    - Anomaly driven
    - Principled

Anomaly Driven Models:

- How can this be *wrong*?
  - Anomaly disappears
    - High-Y
    - ζ(8.3)
    - mid-80s monojets
    - Simpson's 17 keV neutrino
    - ...
- How can this be *useful*?
  - Gives idea of plausibility
  - Challenges theorists to break with orthodoxy
  - Pushes principled models into unchartered regions of parameter space



[Andrey Tayduganov]



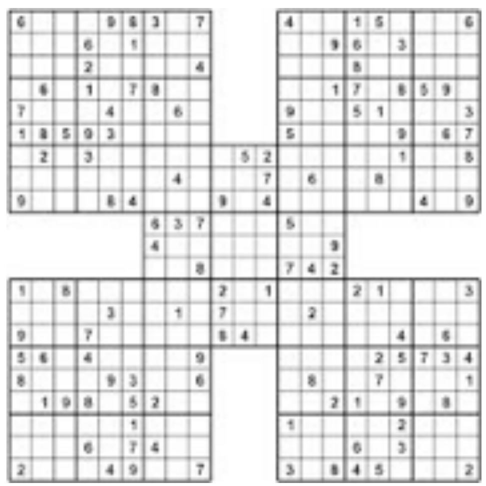
Theoretical Prejudice?

- Theoretical Prejudice
  - EFT
  - Models
    - Anomaly driven
    - Principled

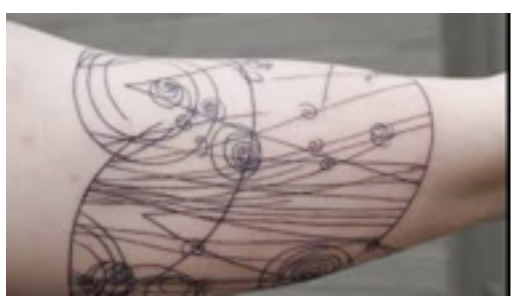
Principled Models:

- How can this be *wrong*?
  - At most one is correct!
    (I resist temptation to show much overused compilations of bounds on models ATLAS/CMS)

- How can this be *useful*?



- Keeps us entertained
- Keeps us busy
- Keeps us employed
- ...



- New particles: Suggest signatures
  (many HEX talks this conference)
- Low energies: Suggest further correlations
- Suggest observables (eg, black hole searches)

Theoretical Prejudice?

Principles

Big Questions

The two faces of **Principles**

Principles are cherished fundamental statements
about reality

...

but only inasmuch as they are correct in describing reality!

P and then PC symmetries were principles that are no more

Experiment constantly puts us at risk of *loosing* principles.

Are we comfortable giving up...

- Locality
- Causality
- Principle of Relativity
- Principle of Equivalence
- ...

(there are serious examples of these)

and retain them only as emerging principles at "long" distances?

The answer is **YES**, but only if nature twists our arm.

Are we ready to introduce **new** principles?

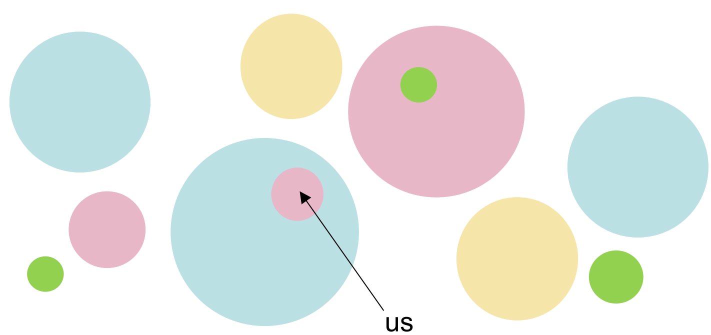
- Naturalness
- Typicality
- Anthropic (mandatory?)
- Complementarity
- Doubly special relativity
- ...

[Yasunori Nomura]

Again, **YES**, but only if nature twists our arm.

- Eternal inflation

Inflation is (generically) future eternal → populate all the vacua



… Anthropic considerations **mandatory** (not an option)

⟹ Eternally inflating multiverse

But in a somewhat bizarre turn of events,
we have invented some principles (e.g., naturalness)
to guide us in theory/experiment

.... before we have any evidence to support them!

Should we be surprised if, in the end, the higgs mass seems fine tuned to high accuracy?

"Heretic!"

The aloofness of Big Questions

Only sure bet there is New Physics
(by definition!!)

Dark Matter
Accelerated Expansion of the Universe
Matter-Antimatter asymmetry in Universe
...

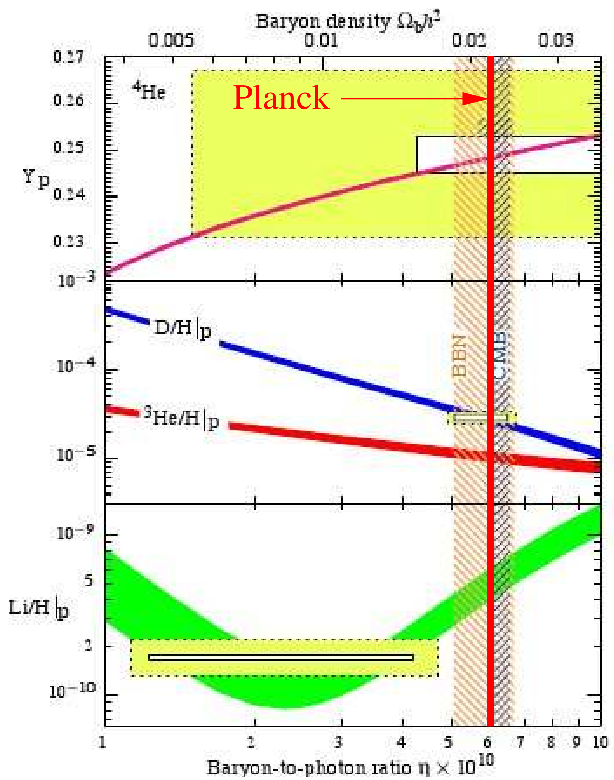
Big questions don't seem to care
at what energy we build our accelerators.

Need to look everywhere

This is not easy

So, for example... what is the scale of baryogenesis?

[Kimmo Kainulainen]

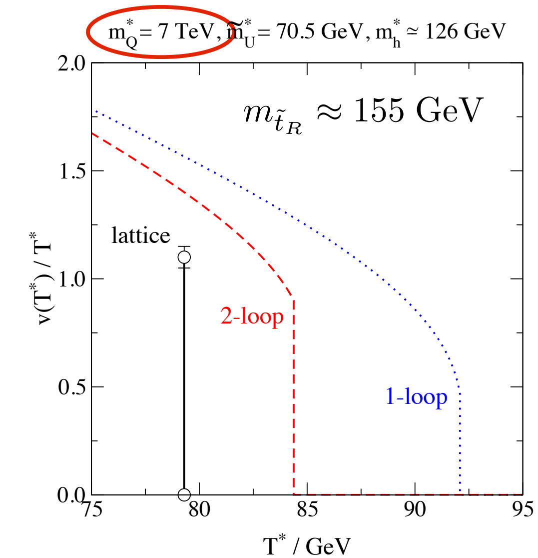


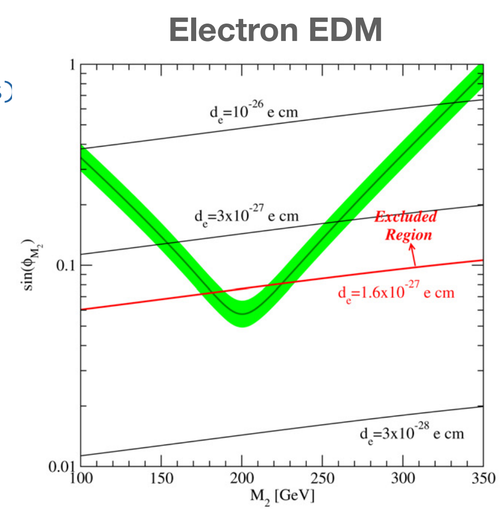
$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

P.Ade et al, ArXiv:1303.5076
(Planck 2013 Cosmological Parameters)

In MSSM,
"looks awkward at best.
Probably not working."

(RGE-improved potential metastable against color breaking; from LHC, tension with light stop-enhanced gg-fusion Higgs production; phase transition may not be 1st order, or too weak; CPV insufficient form EDM constraints)



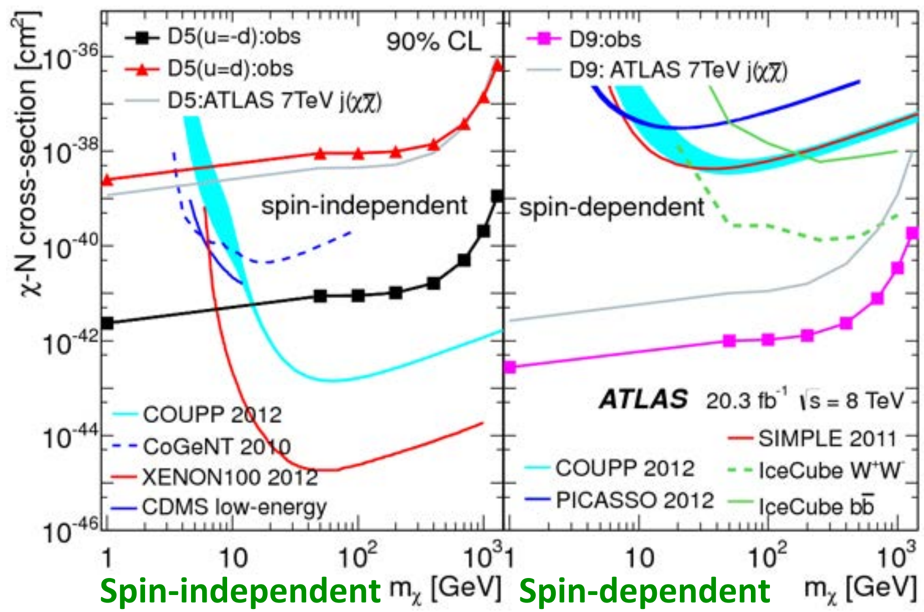


But EW baryogenesis
does not have to be
the explanation for baryogenesis.

Some other process
(leptogenesis?)
at some other **unknown** scale
could be at work.

[Norraphat Srimanobhas]

Likewise with DM.



WIMP “Miracle”

may very well be just numerology

Very Light or Heavy DM is a possibility.

[J. Jaeckel,Yasunori Nomura]

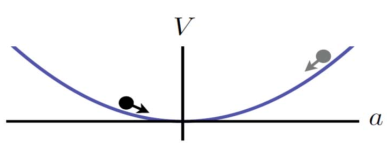
Axion (DM) with Planck/GUT scale f_a

… attractive possibility suggested by string theory e.g. Svrček, Witten, hep-th/0605206

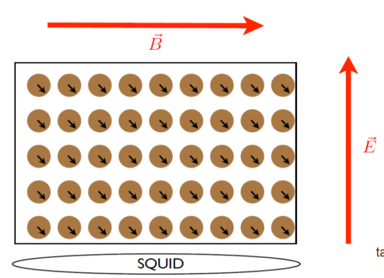
(outside the standard “axion window”)

- Solid state magnetometry Budker, Graham, Ledbetter, Rajendran, Sushkov ('13)

Axion DM

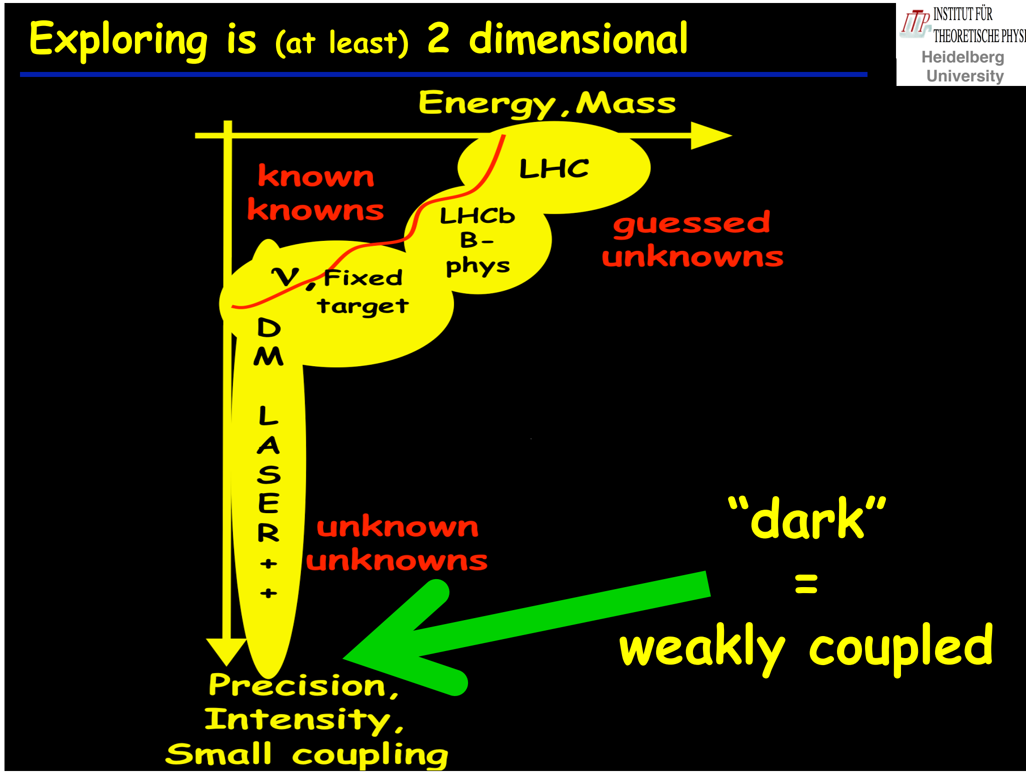


→ time-dependent EDMs

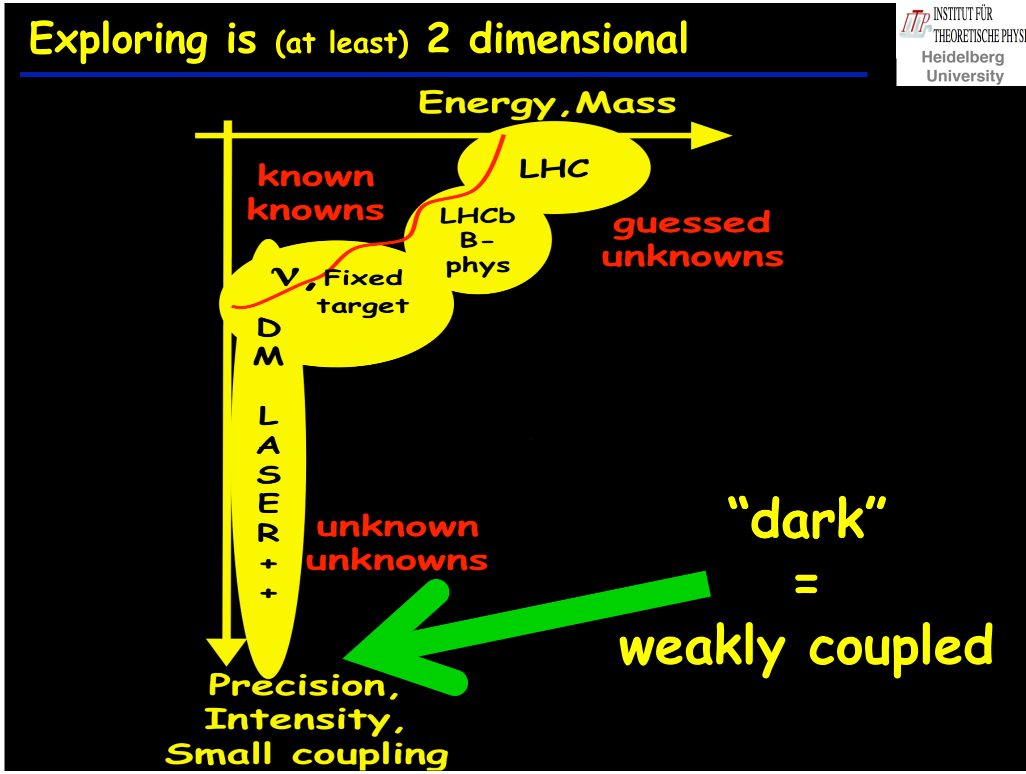


talk by Rajendran ('13)

[Jaeckel]


Exploring is (at least) 2 dimensional
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University
Energy, Mass
known knowns
LHC
LHCb B-phys
guessed unknowns
ν, Fixed target
DM
LASER++
unknown unknowns
"dark" = weakly coupled
Precision, Intensity, Small coupling

[Jaeckel]



The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

Donald Rumsfeld
—Feb. 12, 2002, Department of Defense news briefing

A Confession

Once in a while,
I'm standing here, doing something.
And I think,
"What in the world am I doing here?"
It's a big surprise.

Donald Rumsfeld
—May 16, 2001, interview with the New York Times

Dream:

No model is correct, not even close.

Run II discovers totally unexpected phenomena.

We stop Sudoku. We loose sleep.

Dream:

No model is correct, not even close.

Run II discovers totally unexpected phenomena.

We stop Sudoku. We loose sleep.

So:

Go Home!　　　　Continue the Good Work

Dream:

No model is correct, not even close.

Run II discovers totally unexpected phenomena.

We stop Sudoku. We loose sleep.

So:

Go Home! Continue the Good Work

See you soon in Quy Nhon.

Thank you Organizers.
Thank you Lydia and Amie.

And thank you Prof. and Mrs. Jean Tran Thanh Van