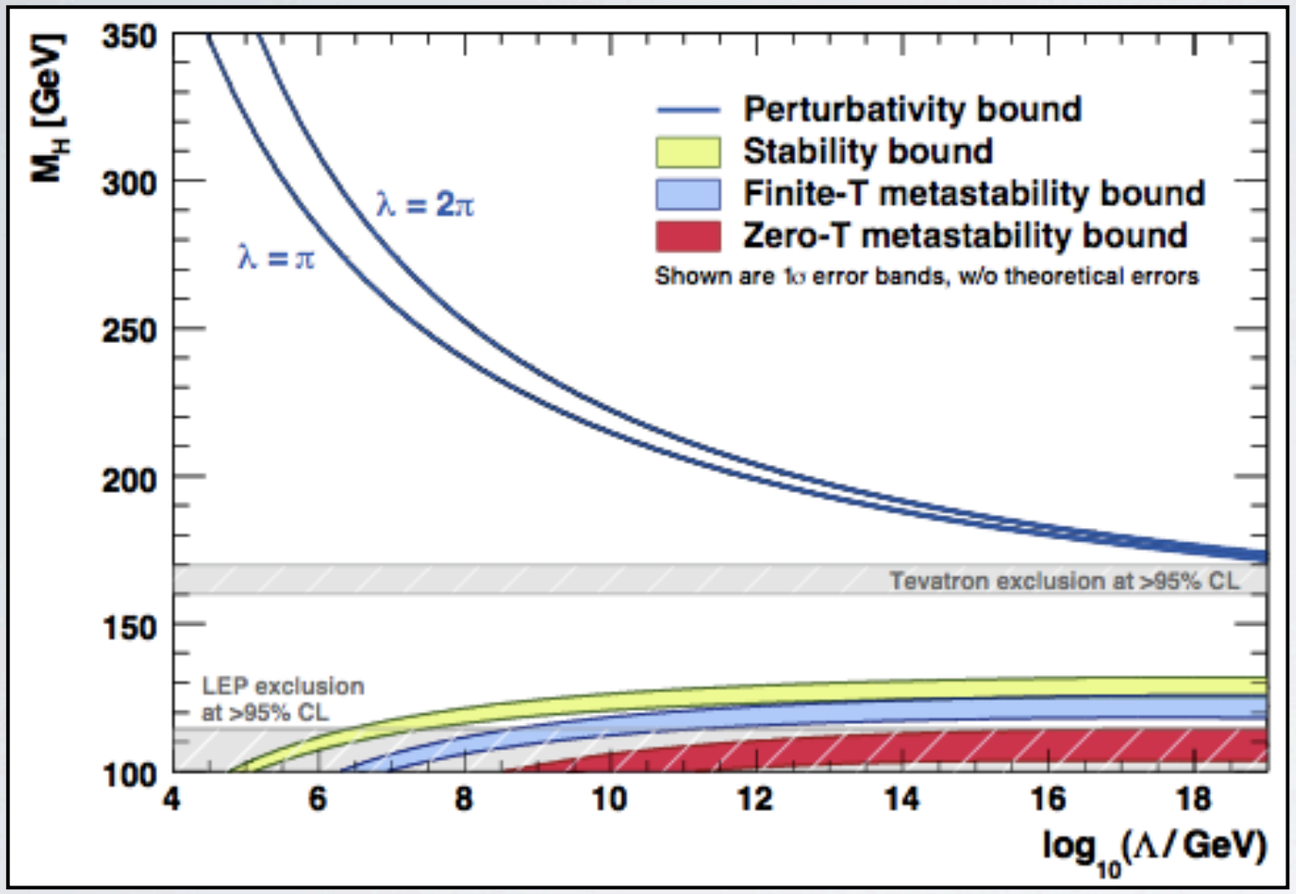
HIGGS HUNTING 2011 THEORY VIEWS

Babis Anastasiou

ETH Zurich

THE LHC IS MAKING HISTORY

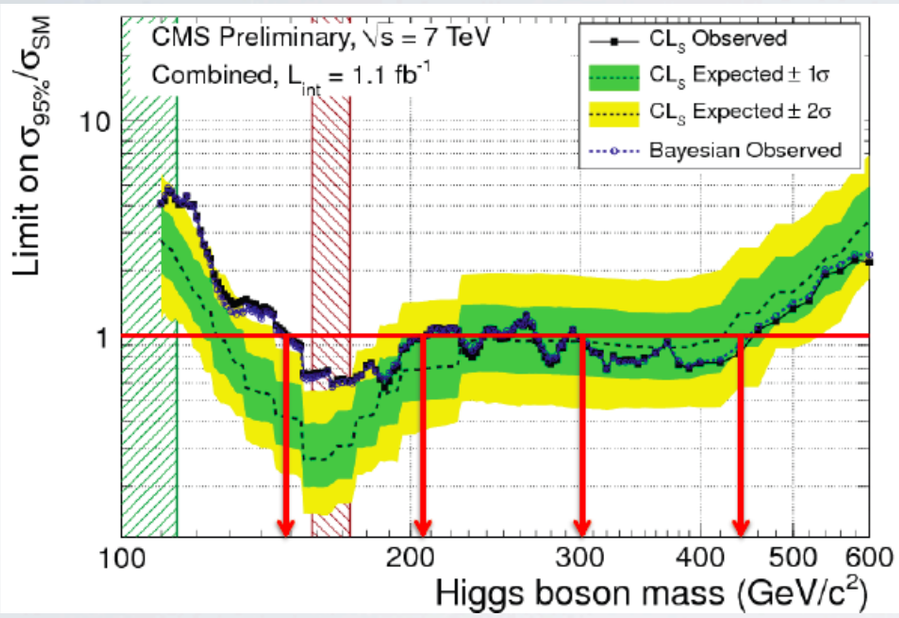


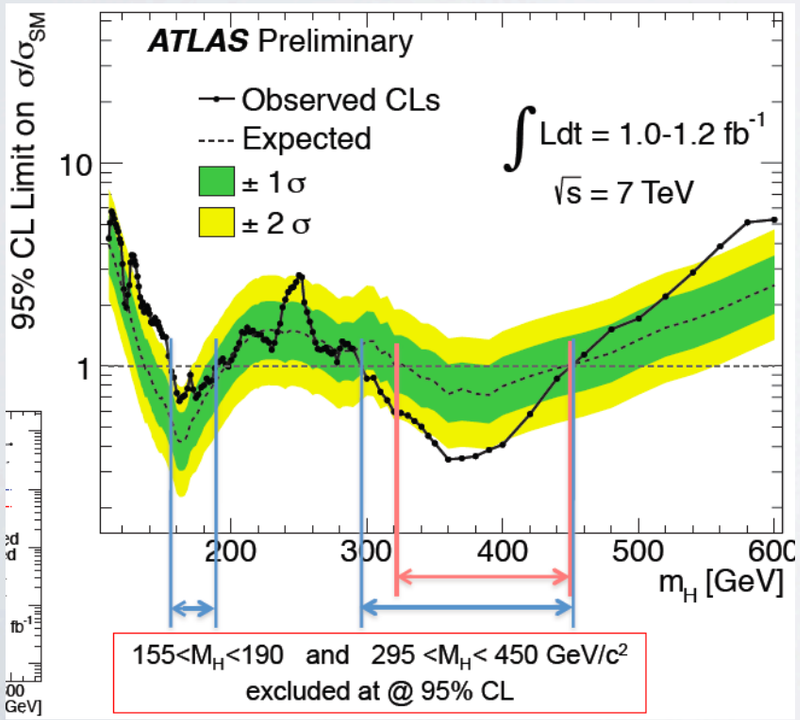
- unearthing extremely rare phenomena
- making a classic contribution to science
- writing the most dramatic chapter in particle physics history
- proving a complete story in particle physics to tell for the next generations
- ….or getting us to an exciting frontier in physics governed by different laws.

John Ellis

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A TRIUMPH OF EXPERIMENTAL PHYSICS

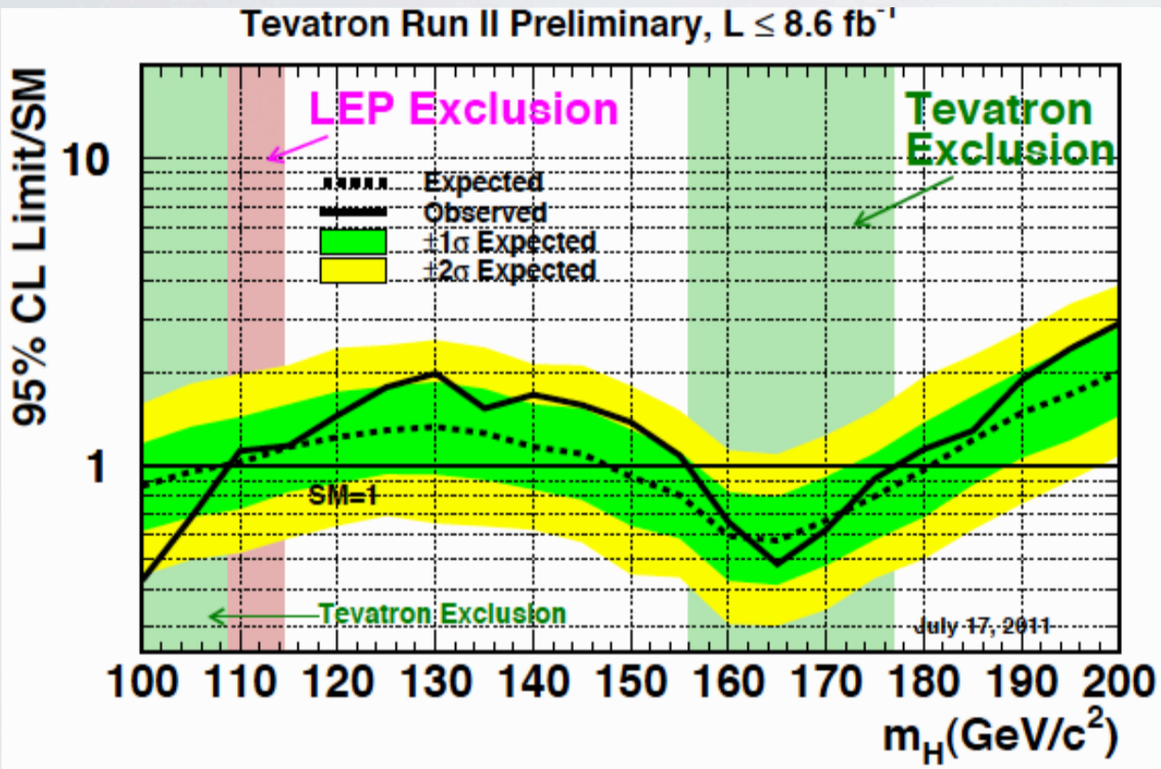




- A technology marvel has been created.
- The LHC machine and detectors have proven themselves with amazing confidence.
- Performing excellent.
- *At first LHC workshops, it was not anticipated that one can get so close to a Higgs boson discovery as we are now with only 7TeV.*

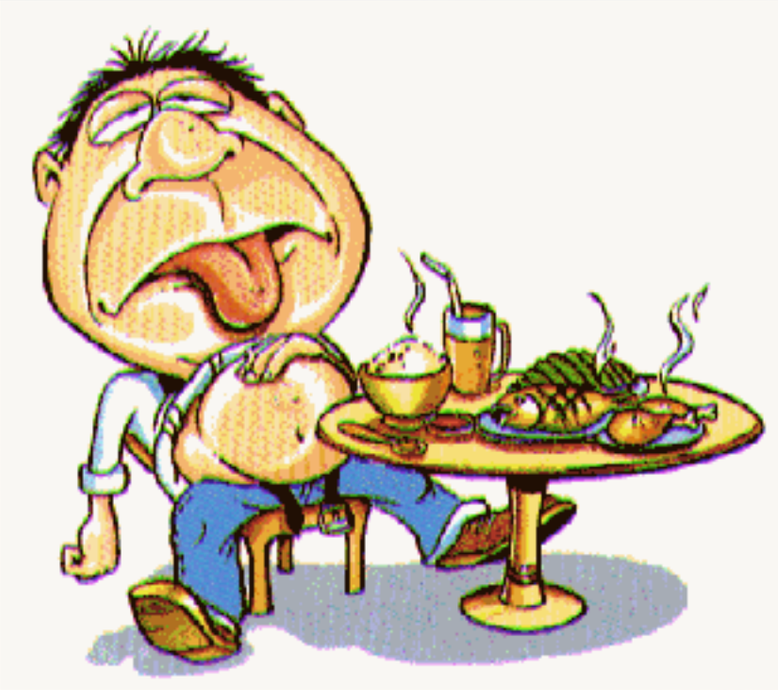
Zoltan Kunszt,
"limited audience" dinner talk

CONGRATULATIONS



- As "theory bystanders" we are amazed with what has been achieved so far in the experimental frontier and congratulate.
- Not only the LHC teams, but also LEP and the TEVATRON.
- CDF and D0 have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders.

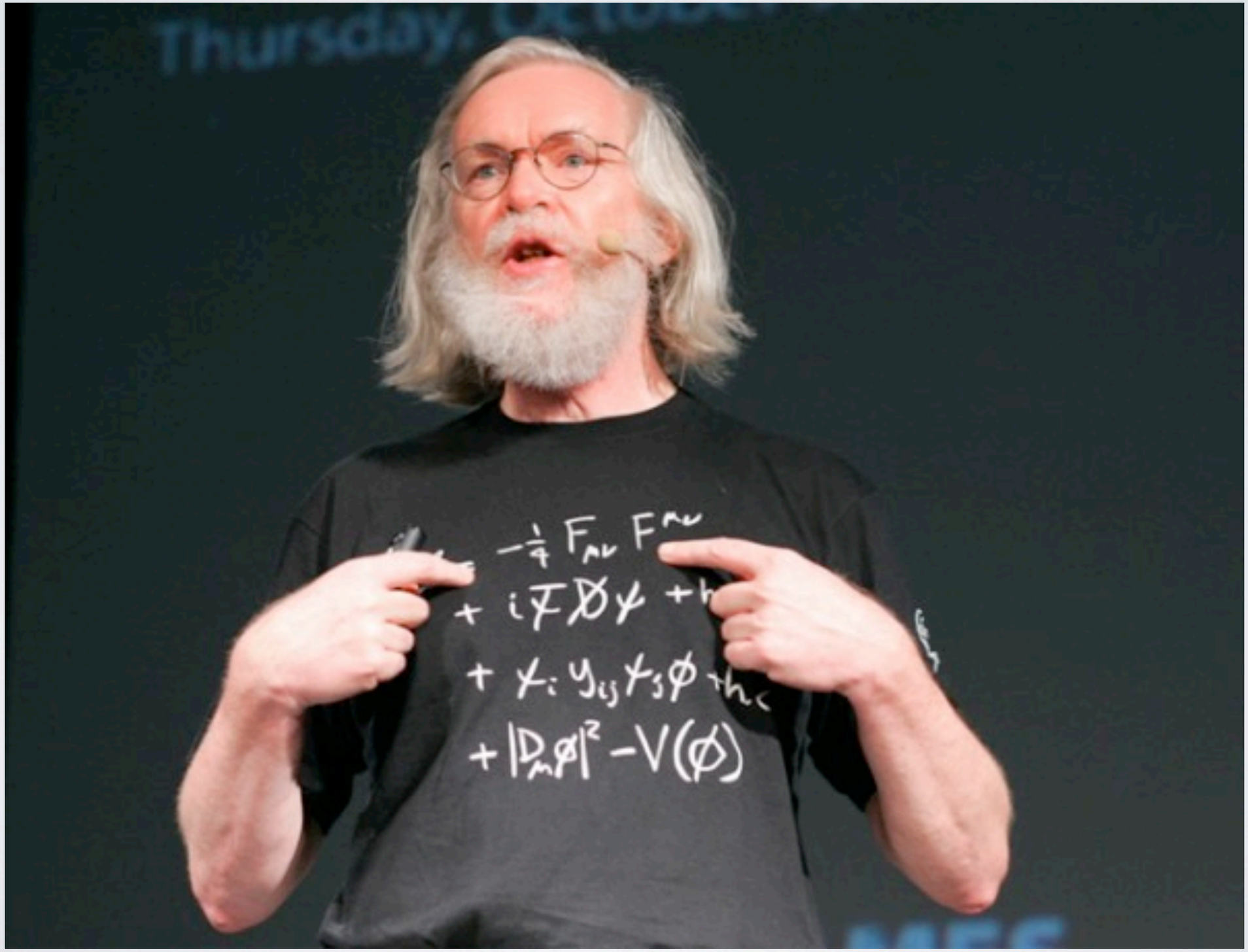
THEORY MENU



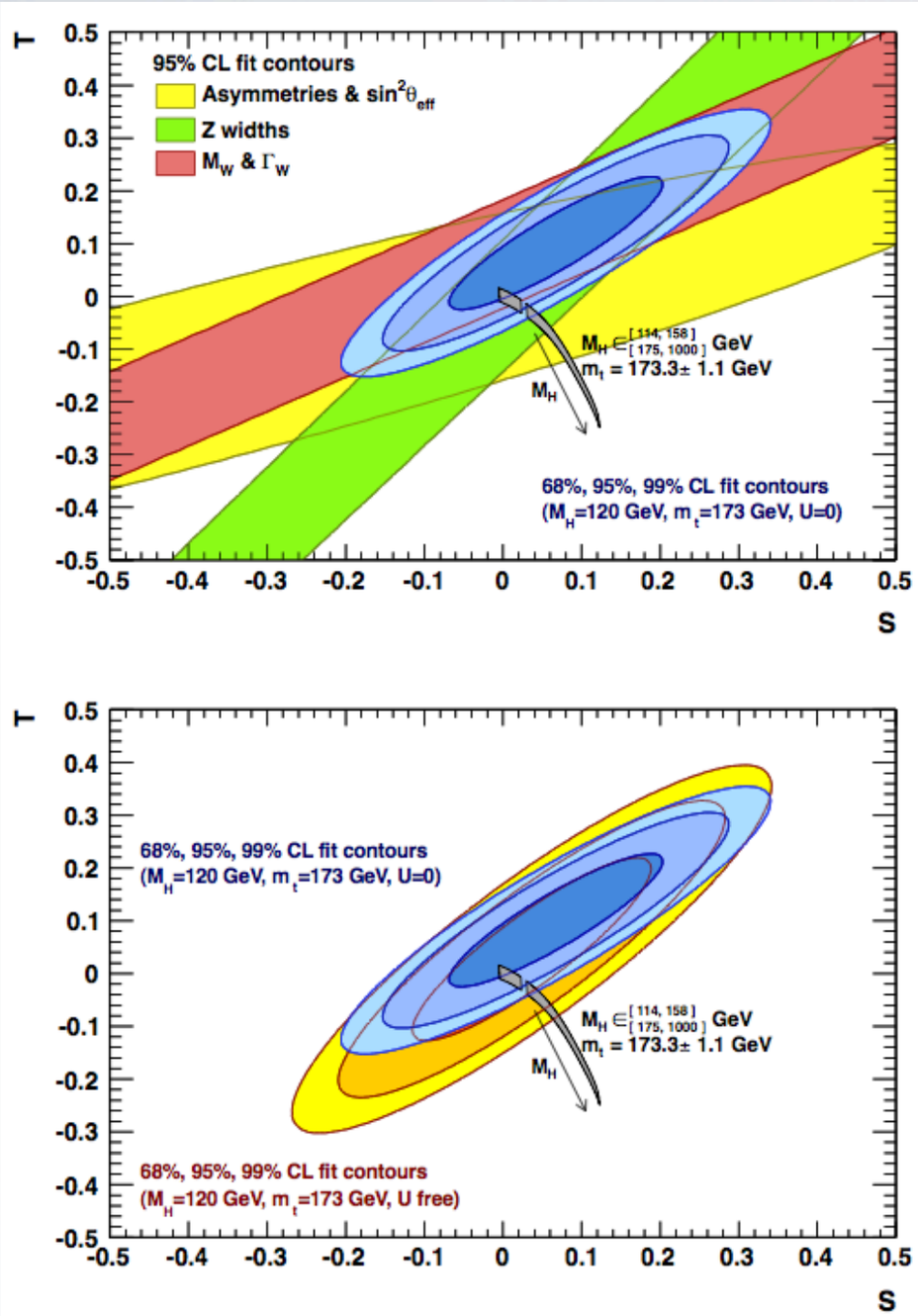
- hypotheses, models and ideas on what to search for
- ideas on how to best search for certain signatures
- simulation tools
- a little bit of healthy "paranoia"
- precision and confidence
- ``final'' interpretation

HYPOTHESES
WHAT TO SEARCH FOR?

THE STANDARD MODEL

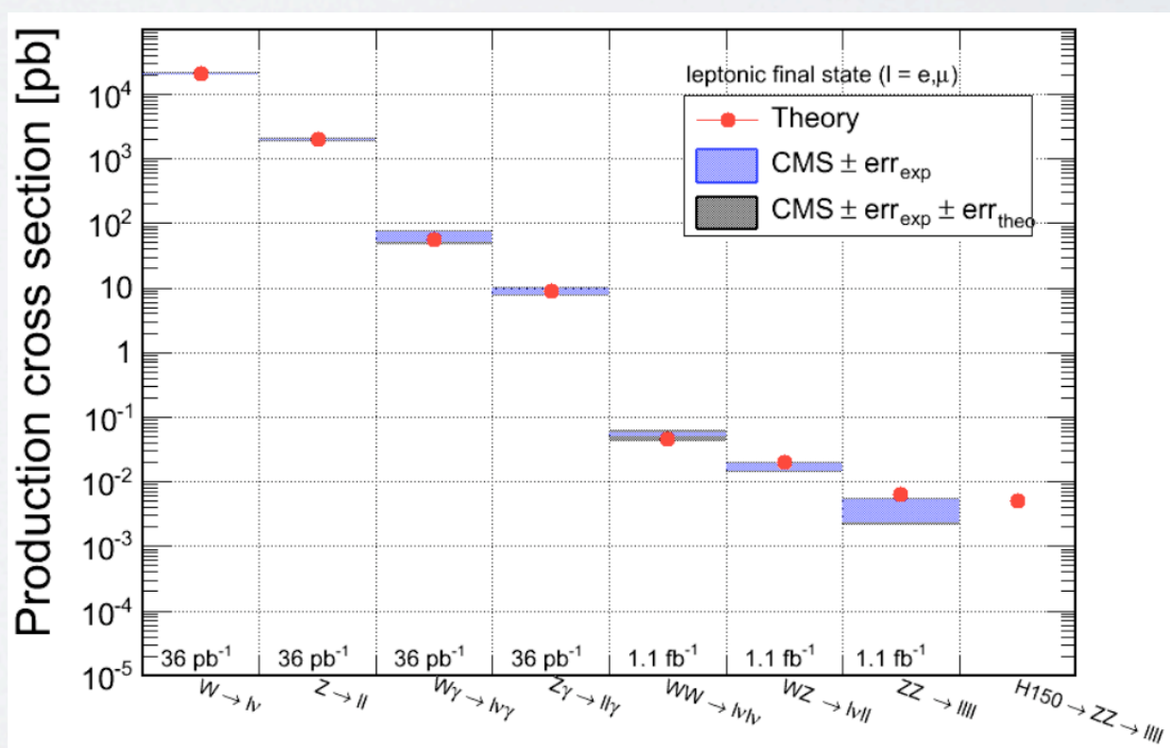


STANDARD MODEL TESTS



M. Schott, for Gfitter

- A light Standard Model Higgs hypothesis is in agreement with all indirect tests
- More important: no spectacular novel phenomenon has emerged yet at the new LHC energy frontier.



Higgs mechanism is the most plausible solution
(not a surprise)

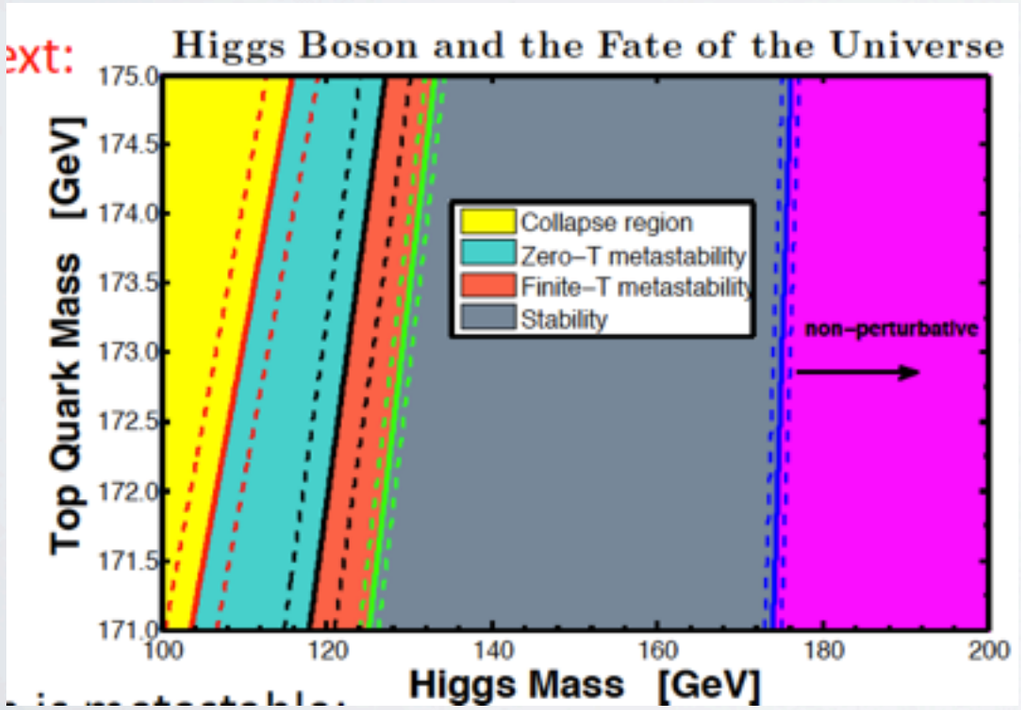
A discovery not to be trivialized:

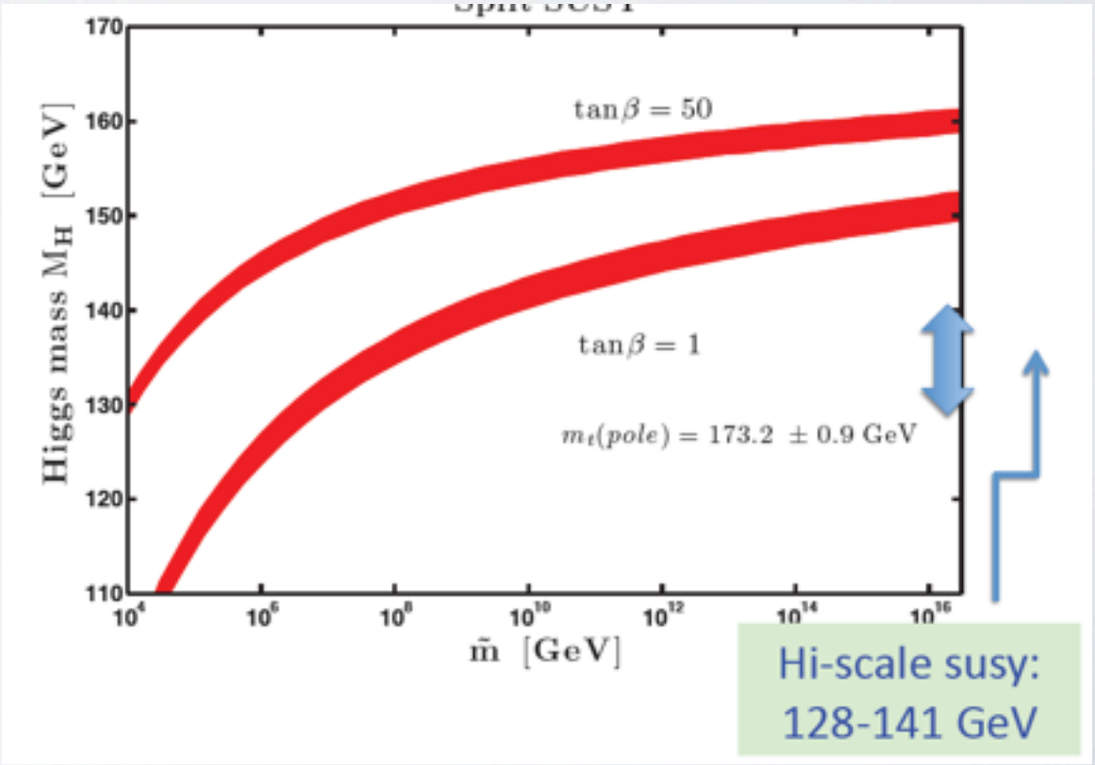
- A new guise of the gauge principle
- A new force of nature (non-gauge?)
- Propagating particles do not share the full symmetry of interactions
- Boost for precision studies at a LC
- New information from Higgs mass and couplings

G. Giudice

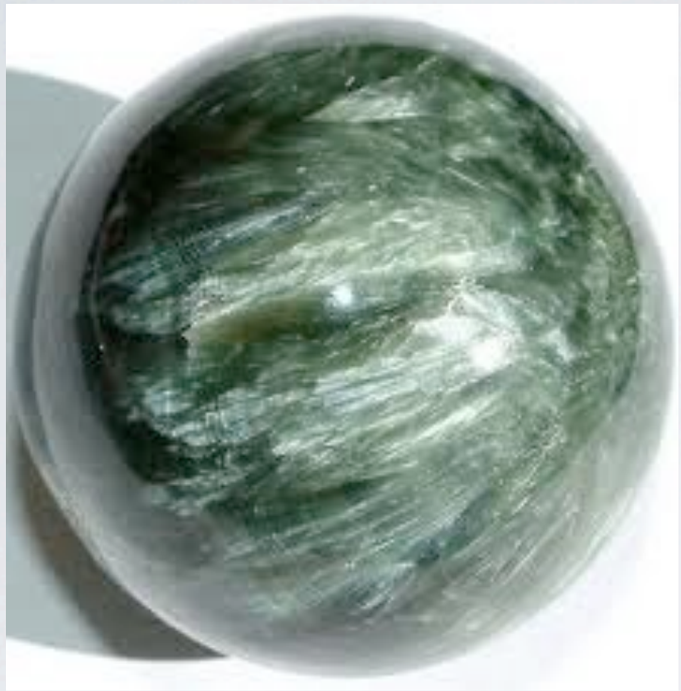
HIGGS MASS

- The last missing parameter in the Standard Model
- But its value may matter a lot for physics at many orders of magnitude higher than the LHC reach and cosmology. *G. Giudice*





LOW ENERGY SUPERSYMMETRY



- A beloved theory by both theorists and experimentalists
- A conceptually beautiful idea which makes physics at very high energies simple and largely explicable.
- It offers the opportunity for a bonus discovery at the LHC, by explaining dark matter and electroweak symmetry breaking simultaneously.

THE MERRY AND LONGEVITY

"Longevity Project participants who were the most cheerful and had the best sense of humor as kids lived shorter lives, on average, than those who were less cheerful and joking. It was the most prudent and persistent individuals who stayed healthiest and lived the longest." *The Longevity Project*

- SUSY models are very exciting, offering an explanation about (almost) everything.
- The SM is also exciting but less cheerful and a little bit conservative…

LHC IS A MODEL ASSASSIN… …BUT

- it is early for SUSY to be pronounced "dead"
- well motivated scenaria yet to be constrained
  - almost degenerate sparticle spectrum
  - only third family squarks are light
  - *also studies by A. Weiler*
- Exciting interplay of Higgs physics and direct supersymmetry searches

Example: "*Lambda-SUSY*"

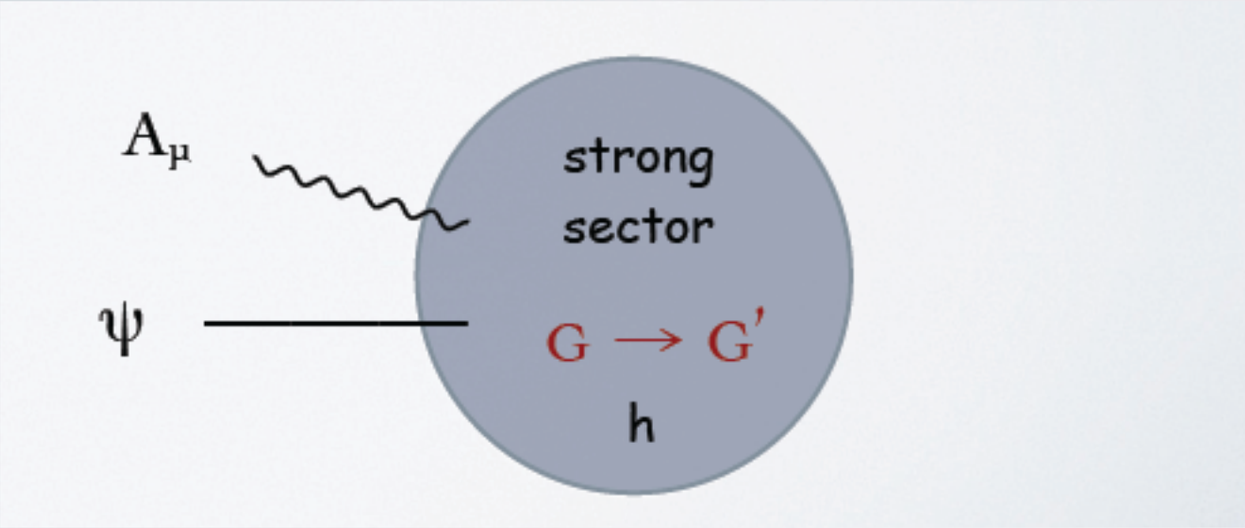
$$W_\lambda = \lambda S H_1 H_2$$

Barbieri, Hall, Nomura, Rychkov

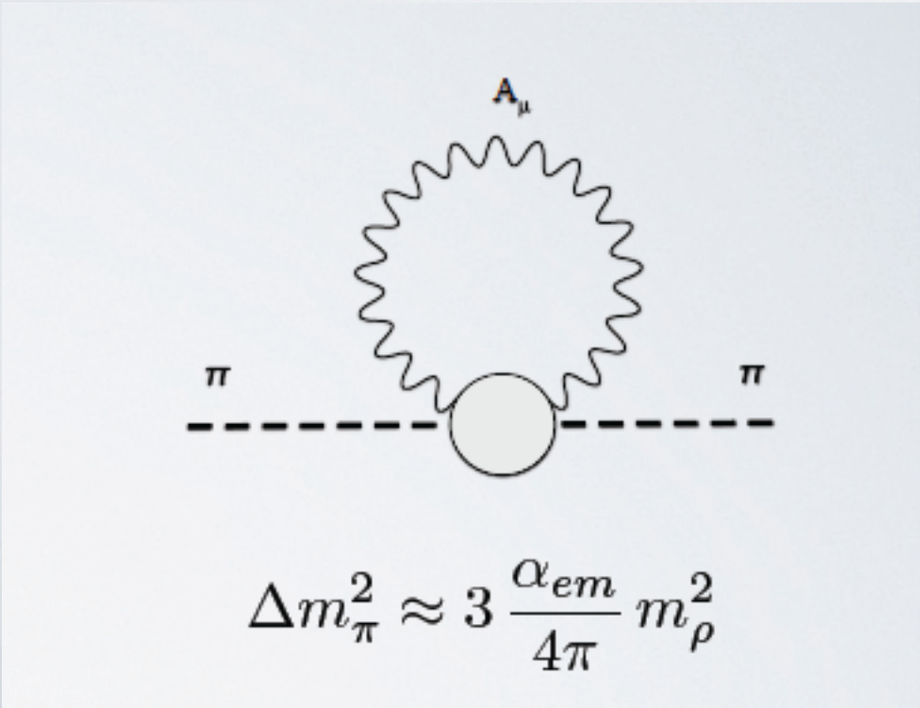
http://arXiv.org/pdf/hep-ph/0607332

- Rather strongly coupled scalar chiral multiplet
- Higgs bosons from ~200-700 GeV
- heavier squarks, small tanb, ….
- "sacrifices":
  - not complete theory as it requires a new threshold at ~10-20 TeV,
  - not manifest gauge coupling unification

COMPOSITE HIGGS



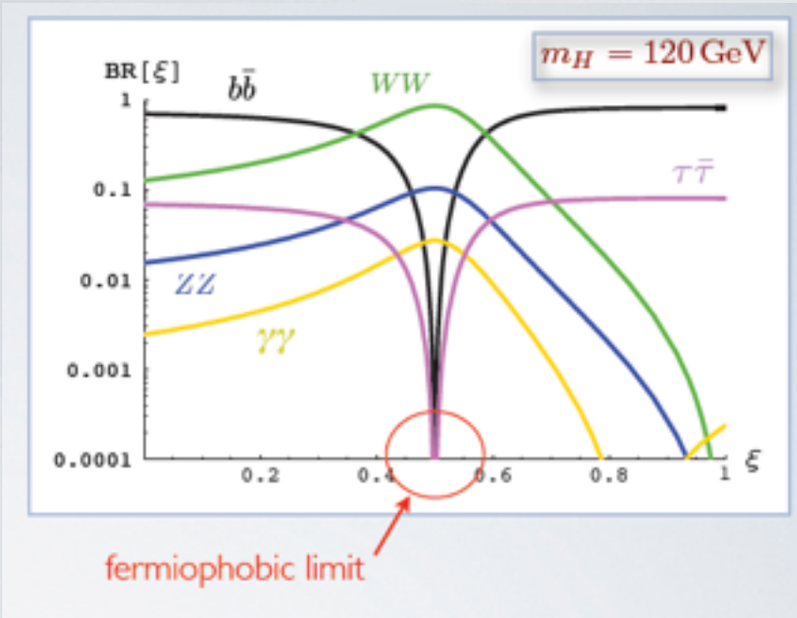
R. Contino



- Light Higgs from strong dynamics at the TeV scale
- No elementary scalar.
- Cures the hierarchy problem.
- Similar mechanism from QCD (pion mass)
- UV completions with warped extra dimensions.

COMPOSITE HIGGS

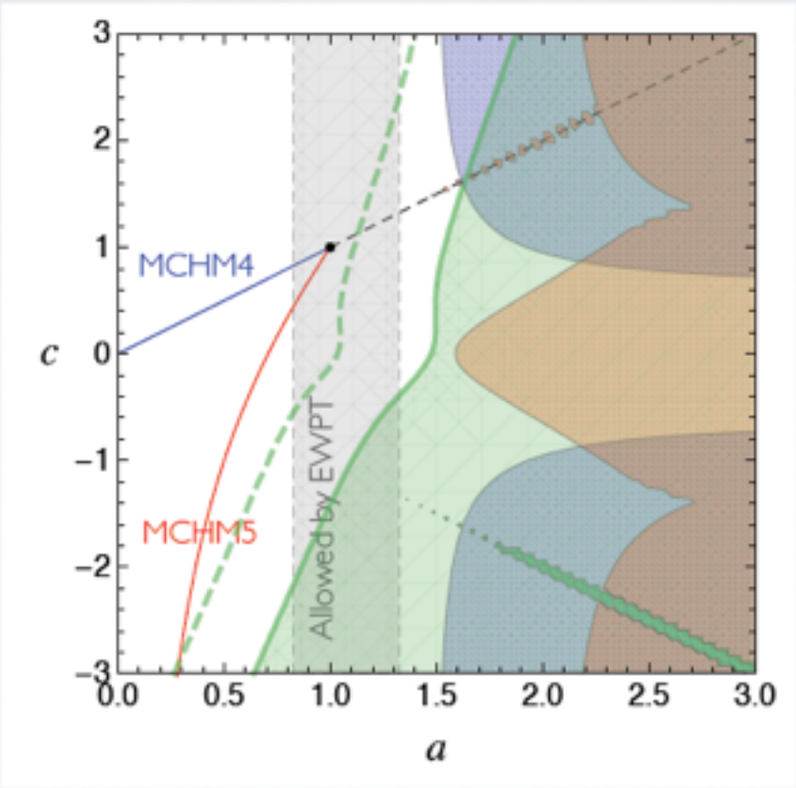
R. Contino



$$y_q = y_q^{SM} \times \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$g_{hVV} = g_{hhVV}^{SM} \times \sqrt{1-\xi}$$

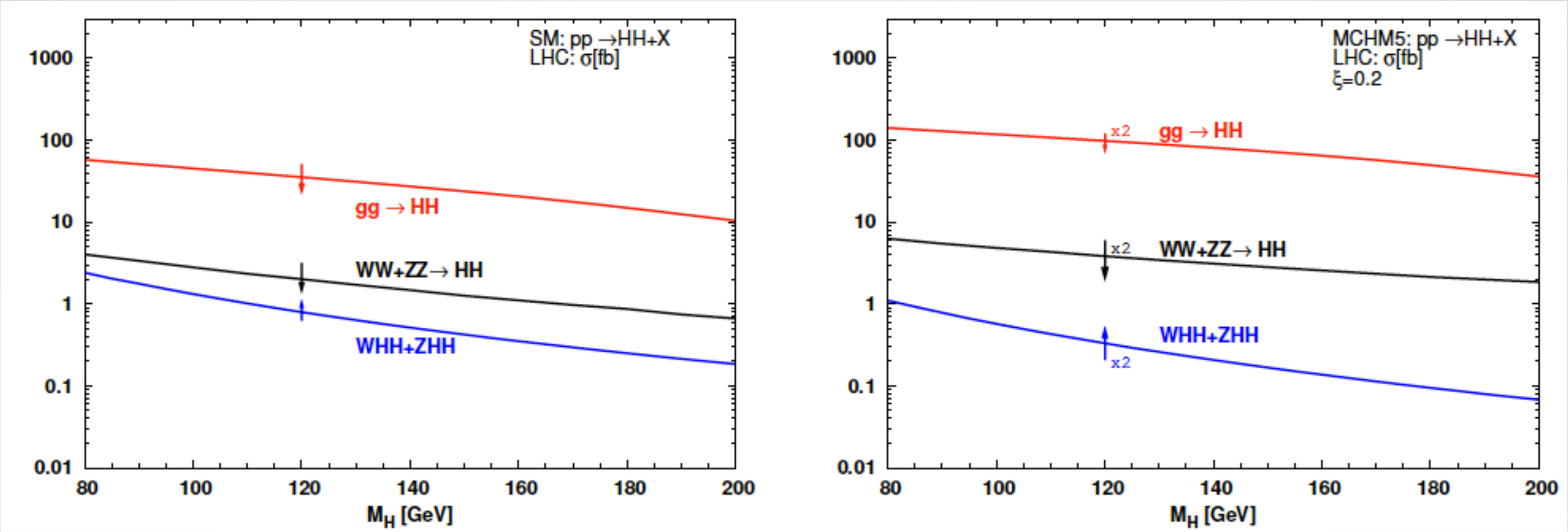
- Suppressed coupling of the Higgs boson to EWK gauge bosons
- Higgs-fermion couplings are model dependent.
- A fermiophobic Higgs is also possible
- Discovery of the Higgs boson may be more challenging (reduced production cross-sections)
- but not a "nasty" model... one generally expects additional signatures (top-quark partners)



$m_h = 120\,\mathrm{GeV}$

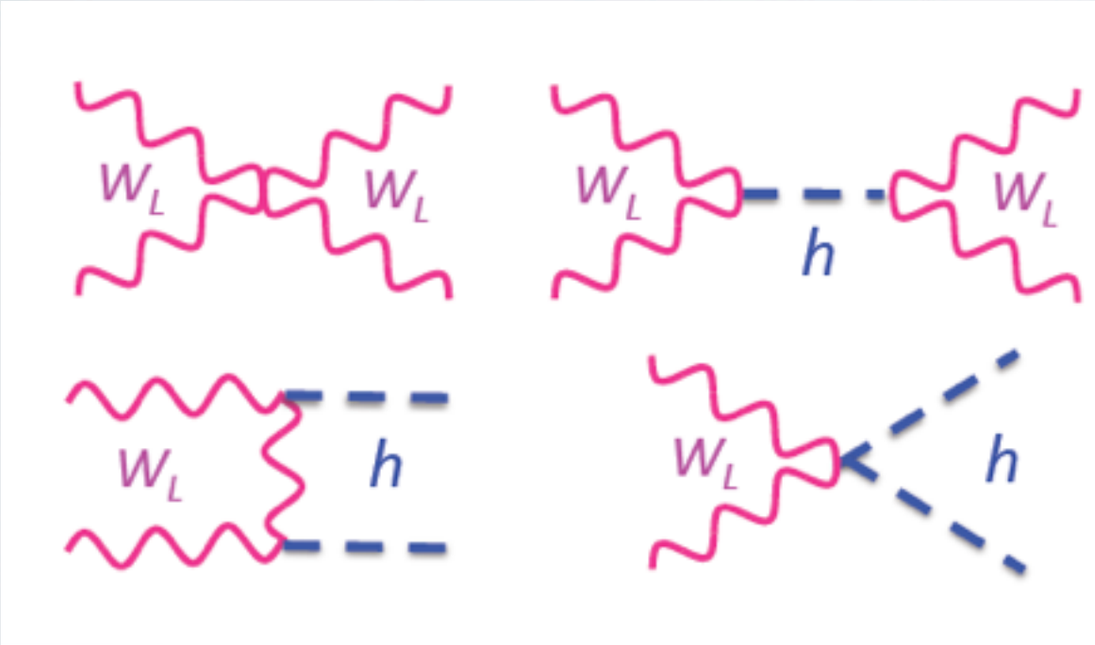
COMPOSITE HIGGS

R. Groeber



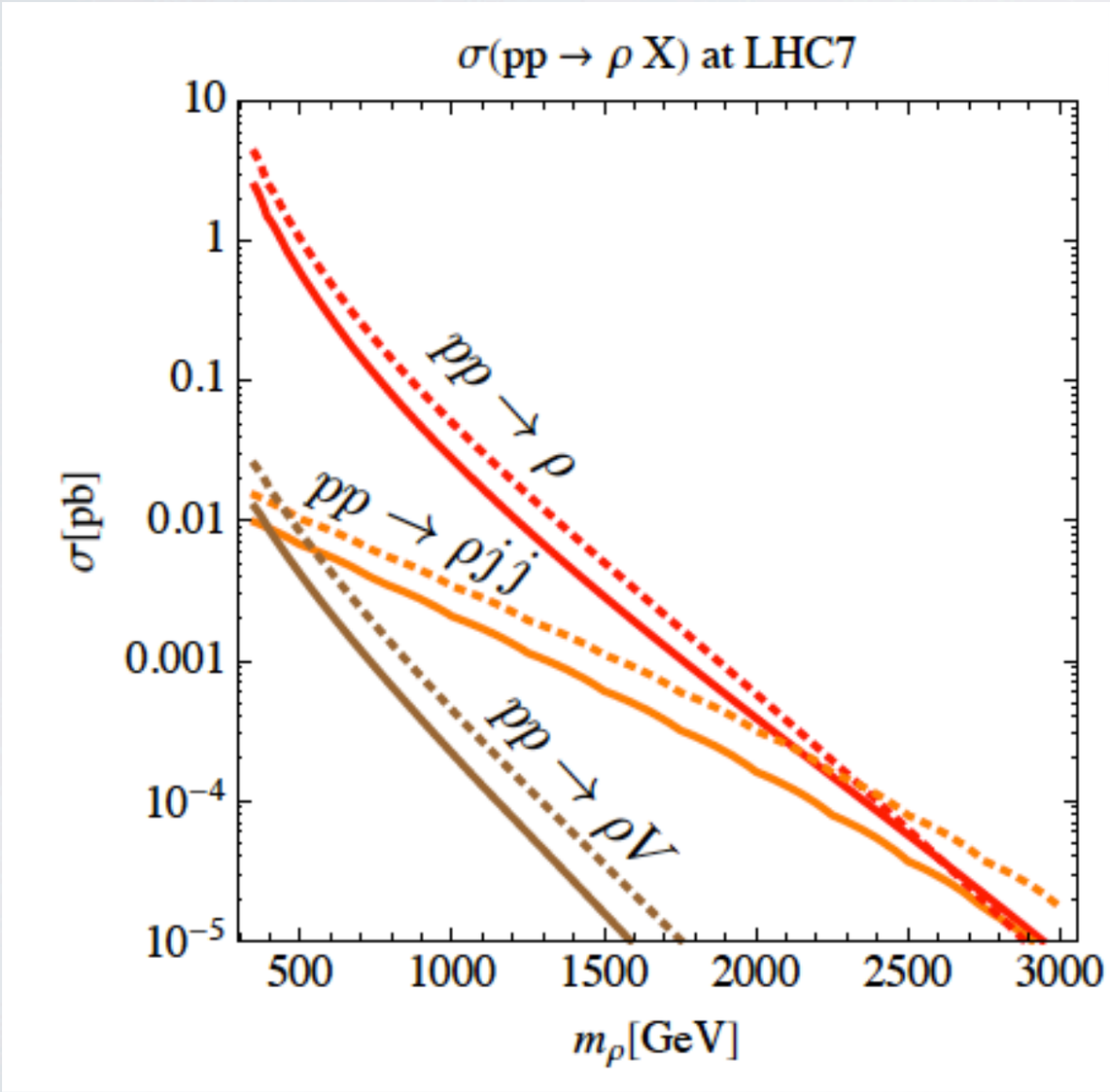
Higgs pair production is typically enhanced
(non-standard Higgs self-coupling)

NO HIGGS OR INVISIBLE HIGGS



- The Higgs boson in the Standard Model tames the cross-section growth for the scattering of longitudinal W's.
- If no Higgs, then something else must be happening:
- Higgs is in the theory, but it is the portal of the SM to a hidden sector and thus invisible *G. Giudice*
- Higgs is not in the theory, but other visible phenomena take place

NO HIGGS



- Forming of extended longitudinal W field configurations, decaying into multiple W,Z bosons. *R. Gupta*

- Spin-1 resonaances at the TeV scale *A. Kaminska*

HOW TO SEARCH FOR “STUFF” ?

THEORY INPUT FOR SEARCH STRATEGIES

How to find a Higgs Boson with a Mass between 155–180 GeV at the LHC

M. Dittmar[1], H. Dreiner[2]

Extracting Higgs boson couplings from LHC data

M. Dührssen[1•], S. Heinemeyer[2†], H. Logan[3‡], D. Rainwater[4§], G. Weiglein[5¶] and D. Zeppenfeld[3,6‖]

Effective K-factors for $gg \to H \to WW \to \ell\nu\ell\nu$ at the LHC

G. Davatz[1], G. Dissertori[1], M. Dittmar[1], M. Grazzini[2], F. Pauss[1]

Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

- An optimal search strategy is usually shaped through hands on experience, which is lacking from the classical education of a typical theorist.
- But synergy and collaboration among theorists and experimentalists on search strategies has boosted progress.
- An important example is the classic paper of Dittmar and Dreiner on finding a Higgs signal in the WW channel.
- Many other examples: Higgs coupling extractions, reweighting methods, jet substructure,...

FAT JETS

T. Plehn

Fat jets — made for the LHC

- VH: bringing back 2/3 of light Higgses
- $t\bar{t}H$: curing combinatorics and backgrounds
- SUSY cascades: curing lack of analysis idea

  ...

- Z' etc: improving mass resolution
- $\tilde{t}\tilde{t}^*$: curing backgrounds

  ...

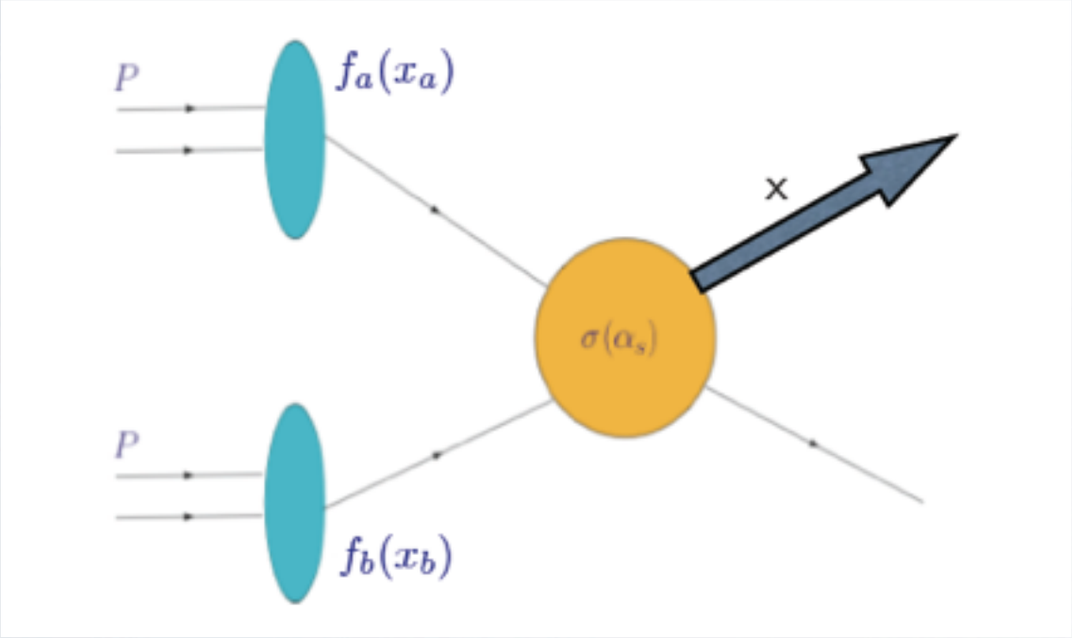
- $H \to aa \to 4g$: making it possible

  ...

- The anatomy of boosted jets (collimated hadrons) can reveal heavy fast moving parent particles, such as a Higgs boson or a top-quark
- Has revived the WH and ZH channels at the LHC, and brings hope for the ttH
- Ideas to deal with increasing pile-up

SIMULATIONS

A SIMULATION OF MANY SCALES



- Non-perturbative parton densities
- Hard scattering cross-sections
- Radiative collinear cascades
- Hadronization, underlying event,...

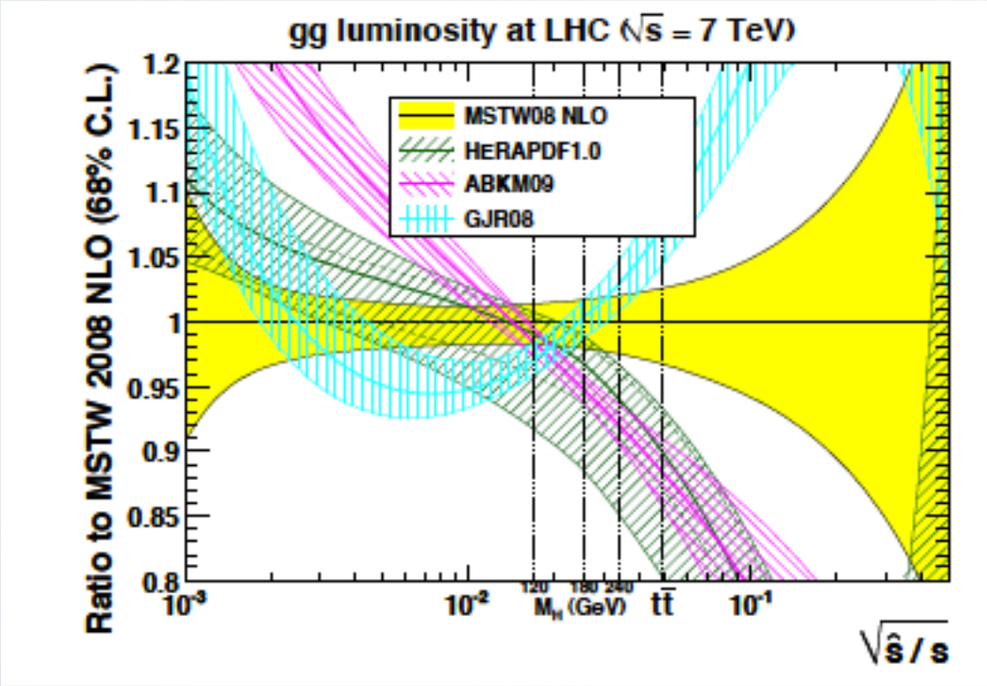
set	order	data	$\alpha_s(M_Z)$	uncertainty	HQ	
MSTW 2008	NNLO	global	fitted (+ external variations)	Hessian (dynamical tolerance)	GM-VFN (ACOT +TR')	Martin, Stirling, Thorne, Watt
CT10	NLO	global combined HERA	external (several values & older fit)	Hessian (dynamical tolerance)	GM-VFN (SACOT-X)	CTEQ, Lai et al.
NNPDF 2.1	NEW NNLO	global combined HERA	external (several values & recent fit)	Monte Carlo (pdf replicas)	GM-VFN (FONLL)	NNPDF, Ball et al.
AB(K)M	NNLO	DIS+DY(f.t.)	fitted	Hessian	FFN +matching	Alekhin, Blümlein, Klein, Moch
(G)JR	NNLO	DIS+DY(f.t.)+ some jet	fitted	Hessian	FFN (VFN massless)	Glück, Jimenez Delgado, Reya
HERA PDF	NNLO	only DIS HERA	external	Hessian	GM-VFN (ACOT +TR')	H1 & Zeus collaborations

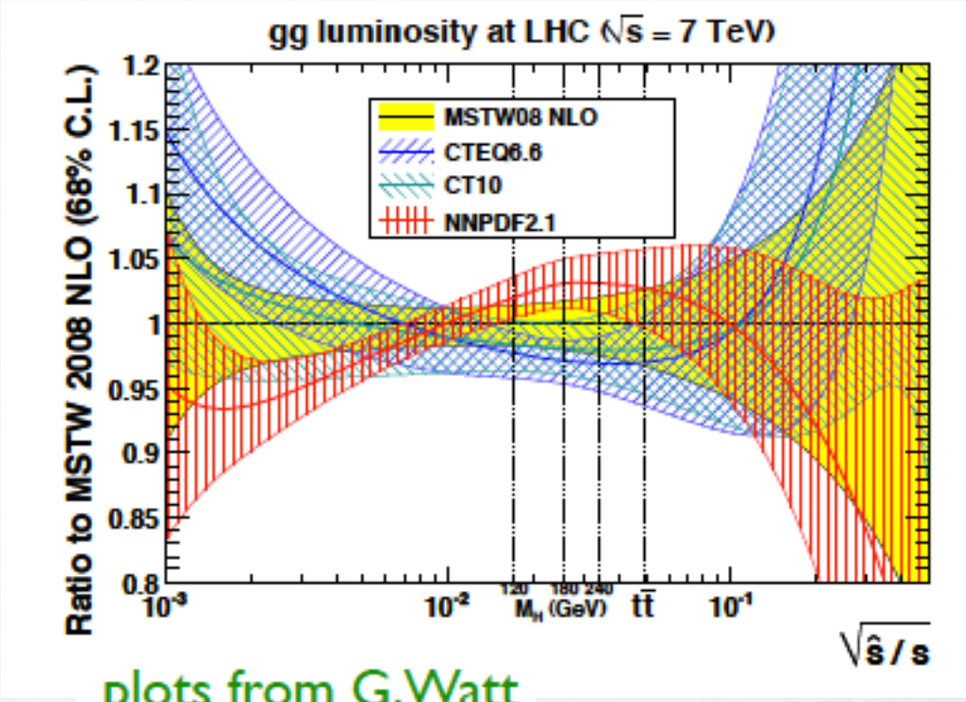
Each group one provides a number of sets to compute central values and pdfs, pdf+coupling uncertainties

D. de Florian

PDF ISSUES

- A generally very good precision.
- But with some discrepancies beyond the estimated uncertainties: strong coupling, gluon density.
- Affect mainly Tevatron gluon-fusion, but also LHC





plots from G.Watt

Conclusions *D. de Florian*

- Everything looks pretty solid and coming LHC data will help to constrain PDFs much better!

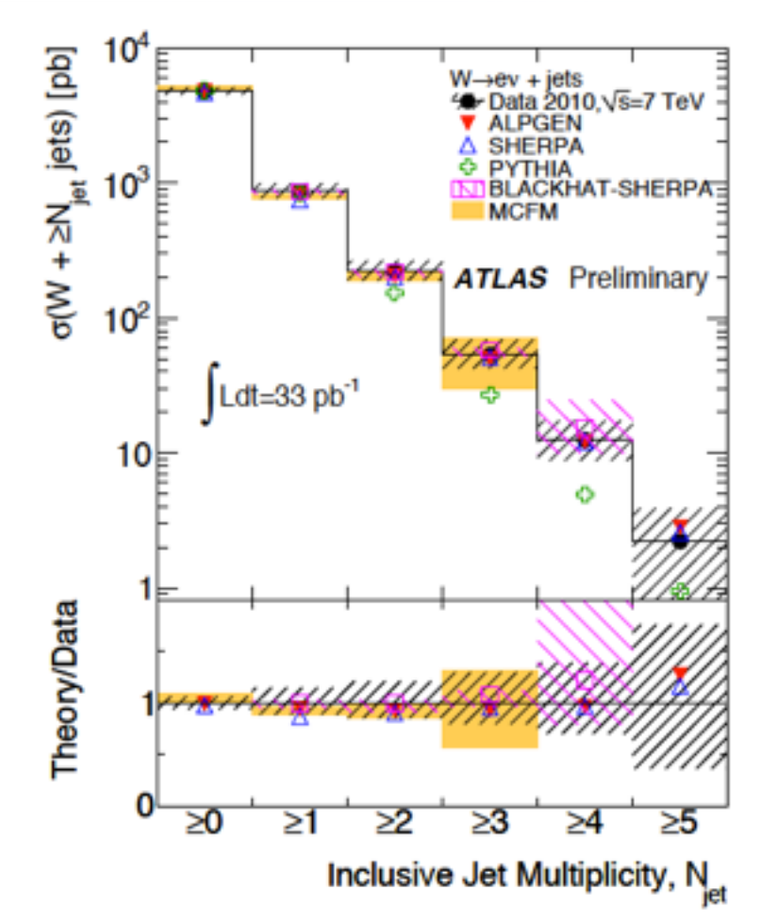
- PDFs play a role in setting exclusion limits for Higgs, but limit can not depend of pdf set used

- We know recent examples (e.g. MRST-06 vs MSTW-08) where TH improvements produced considerable change in PDFs (and Higgs cross section)

Do not expect such big modification in the future. But to be safer, I would recommend try PDF4LHC prescription with larger uncertainty to leave room for possible TH/EXP improvements (mostly on jets!)

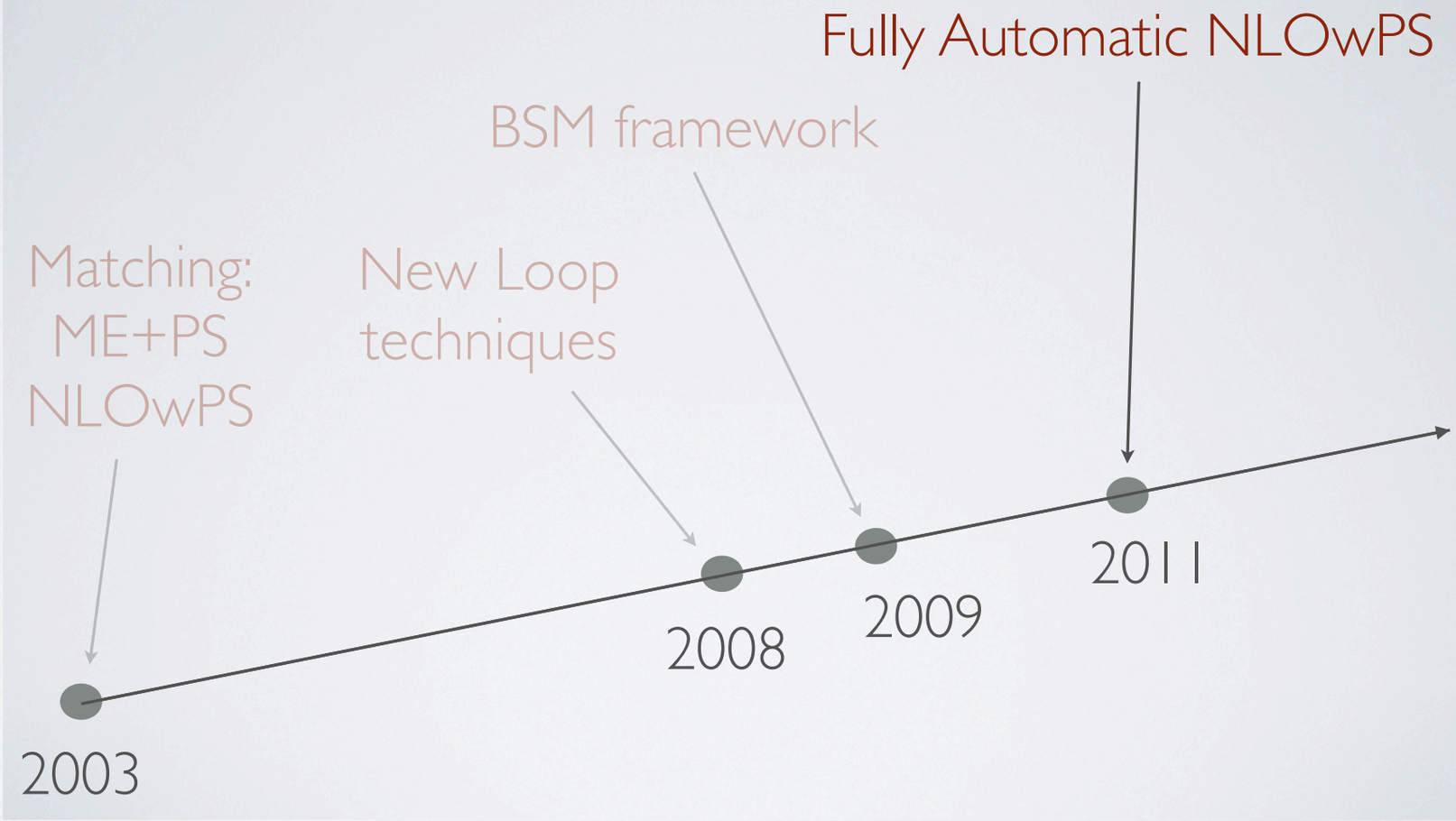
FANTASTIC LEAP FORWARD: TWO COMPLETE ORDERS IN THE PERTURBATIVE EXPANSION ALWAYS ACCOUNTED FOR.

L. Reina *F. Maltoni*



Blackhat+Sherpa: W+3j, W+4j at NLO

QCD AND MC (SIMPLIFIED) PROGRESS



AUTOMATION

- Cost saving

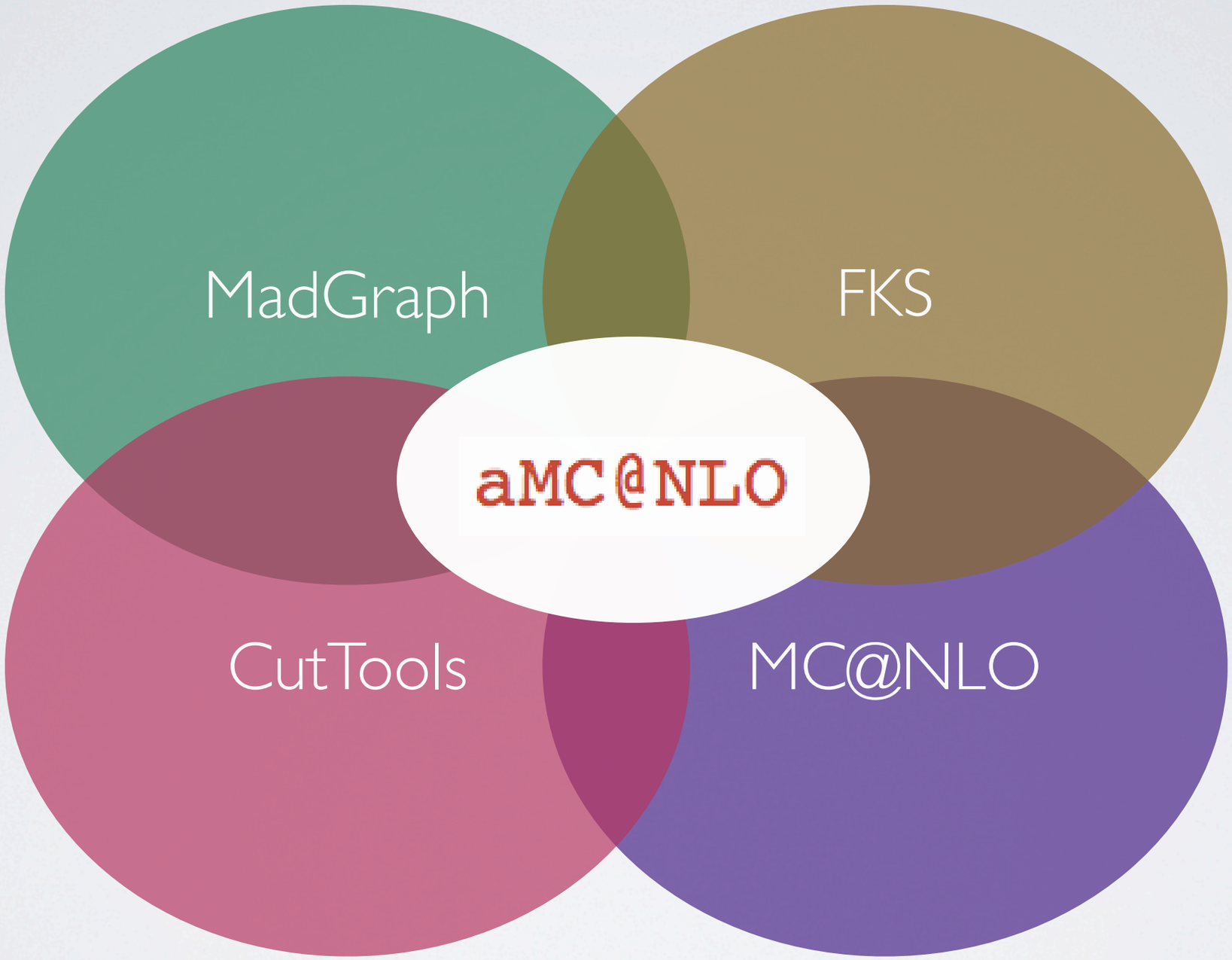
  Trade human time and expertise spent on computing one process at the time with time on physics and pheno.

- Robustness

  Programs are modular and computations based on elements that can be systematically and extensively checked. Trust can be easily built.

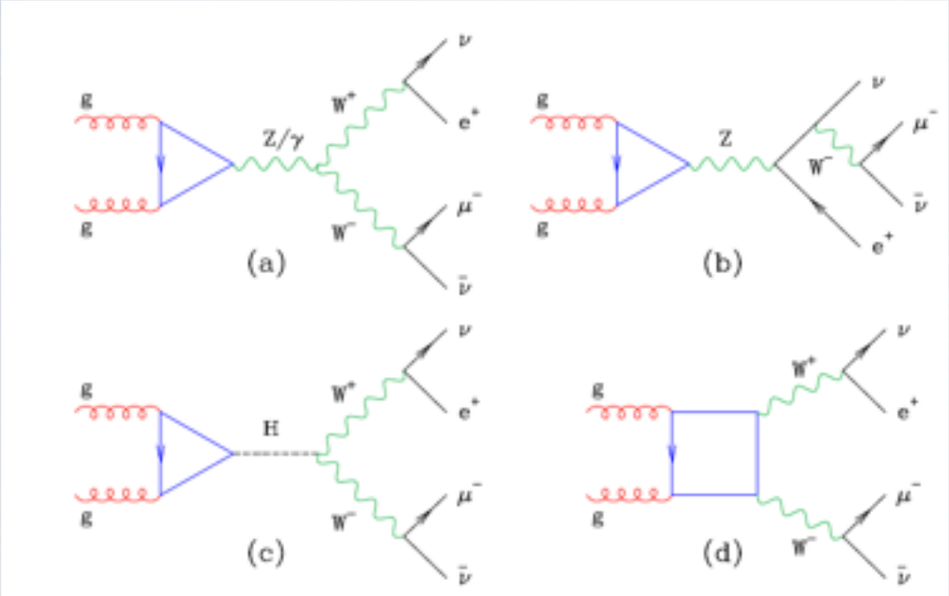
- Wide accessibility

  One framework for all. Available to everybody for an unlimited set of applications for all. Suitable to EXP collaboration.

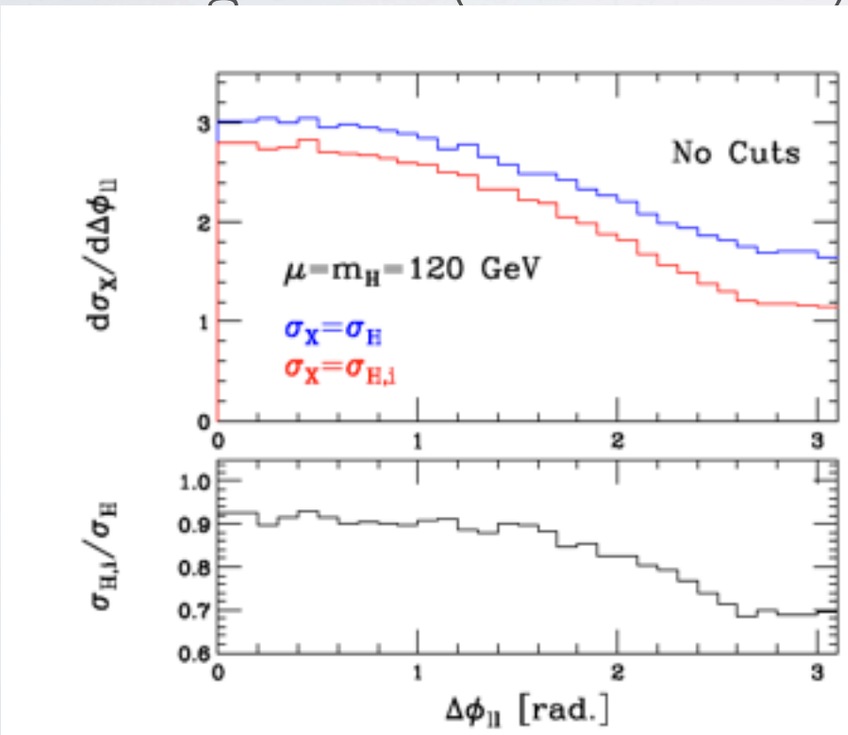


Hirshi,Frederix,Frixione,Maltoni,Garzelli,Pittau,Torrielli

STANDING OF SIMULATIONS



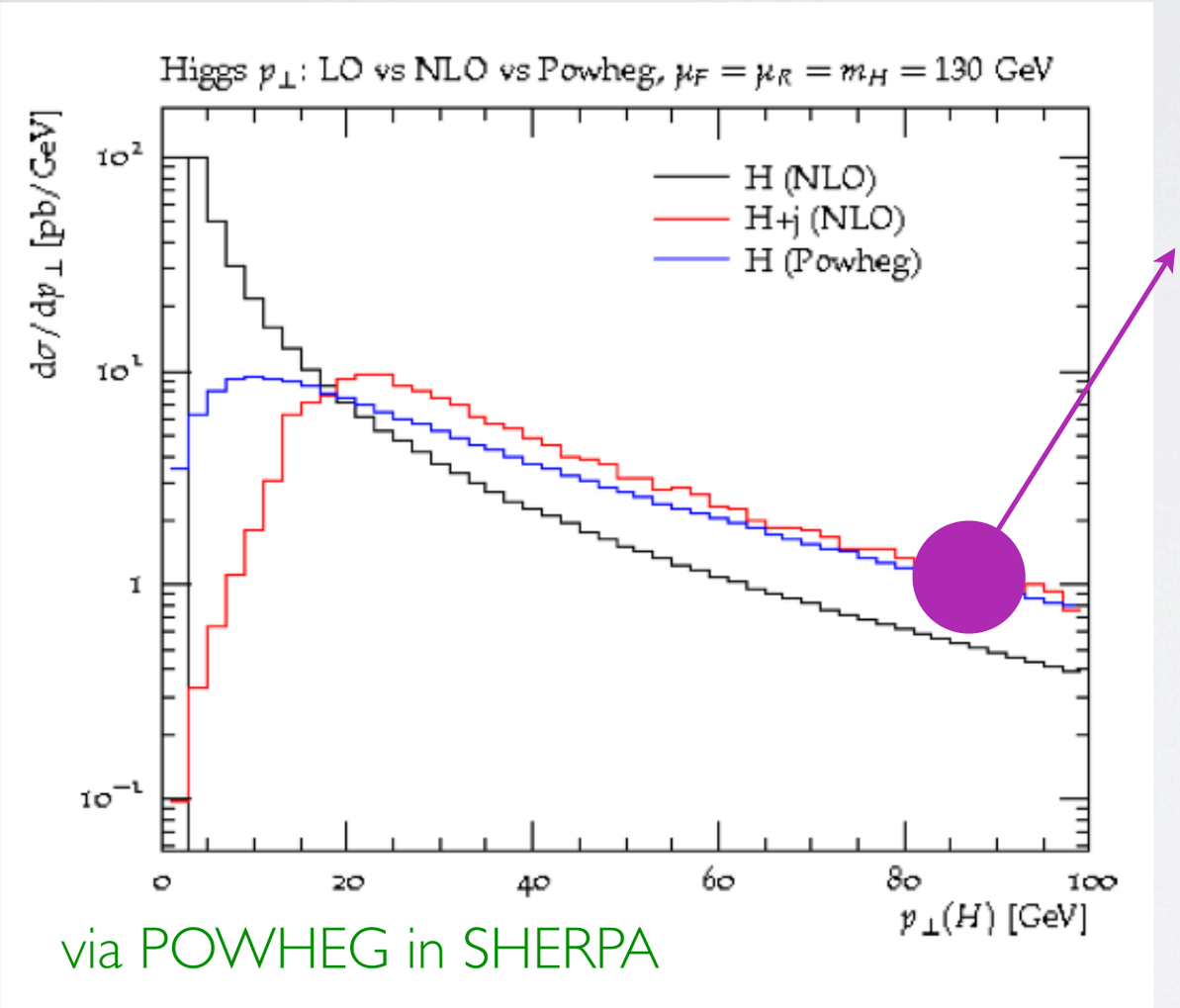
A leading order (interference) effect

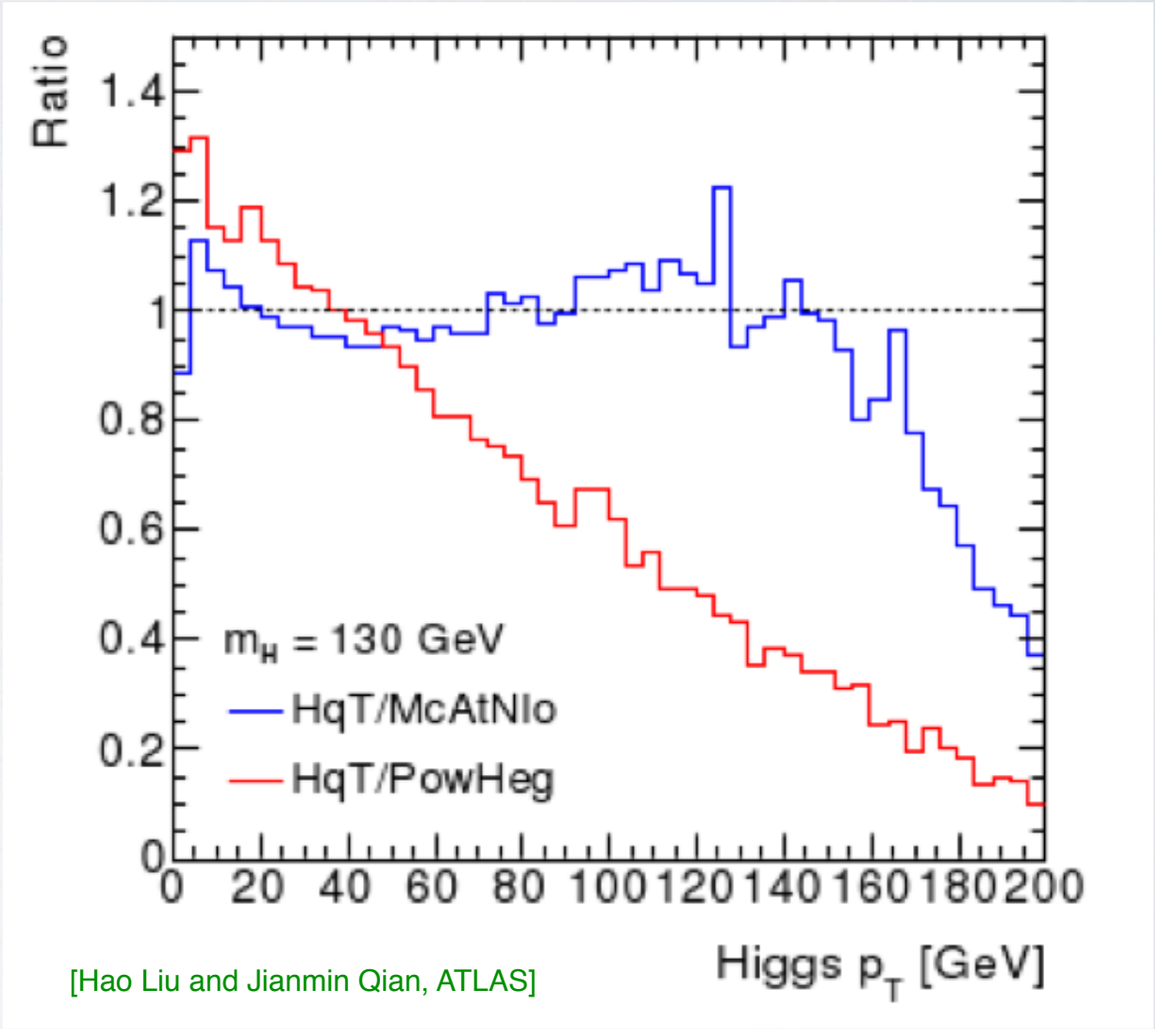


Campbell,Ellis,Williams

- The precision of generic Monte-Carlo tools is improving continuously and it is already impressive!
- including NLO (POWHEG, MC@NLO), improving parton showers (J.Lopez-Villarejo), etc
- Still, some vigilance is needed for "special" effects.
- Very recent example, finite width and signal-background interference effects.

Formally equivalent matching methods treat differently sub-leading effects. These are important in Higgs physics and generally processes with significant NLO corrections.





"Artificial" enhancement at large pt :
By chance on the NLO result for this observable.

Well known agreement between MC@NLO +HERWIG and the resummed result. Not quite for POWHEG.

(ONE/TWO-LOOP) NLO AND NNLO

Grazzini, Reina, Muehlleitner, Vazquez Acosta

- Higgs observables are typically predicted with two and three-loop accuracy

- gluon-fusion,vector boson fusion, bottom-quark fusion, associated Drell-Yan total cross-sections are known at NNLO in the Standard Model

- Higgs decays are mostly known at NNNLO.

- In BSM, it is not always possible to reach completely NNLO (Heavy Higgs, more complicated virtual corrections).

- In the MSSM, all ingredients are there for NLO and even NNLO for a light Higgs (Muehlleitner,Rzhak,Spira;Degrassi,Slavich,Pak, Steinhauser.Zerf,Harlander,Hofman,Mantler,...)

- If it can be done for the MSSM, it can be done for any other model!

Grazzini

The NNLO revolution

Total cross section is thus OK but....more exclusive observables are needed !

examples in the talk of Laura

At LO we don't find problems: compute the corresponding matrix element and integrate it numerically over the multiparton phase-space

Beyond LO the computation is affected by **infrared singularities**

Although these singularities cancel between real and virtual contributions, they prevent a straightforward implementation of numerical techniques

In particular, at NNLO, only few fully exclusive computations exist, due to their extreme technical complications

- gg→H FEHIP, HNNLO — C.Anastasiou, K.Melnikov, F.Petrello (2005)
- Drell-Yan FEWZ, DYNNLO — S.Catani, MG (2007); MG(2008); K.Melnikov, Petriello (2006); R.Gavin et al. (2010); L.Cieri et al. (2009)

Catani,Cieri,de Florian,Ferrera,Grazzini

FIRST EVER DIFFERENTIAL "2 TO 2" NNLO CROSS-SECTION

NEW: $pp \to \gamma\gamma$ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera, MG (in progress)

Two loop amplitude available

C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans (2002)

$\gamma\gamma$ +jet at NLO available

Z.Nagy et al. (2003)

➡ We can perform the NNLO calculation using hard coefficients obtained for Drell-Yan

Use Frixione isolation ➡ no fragmentation contribution

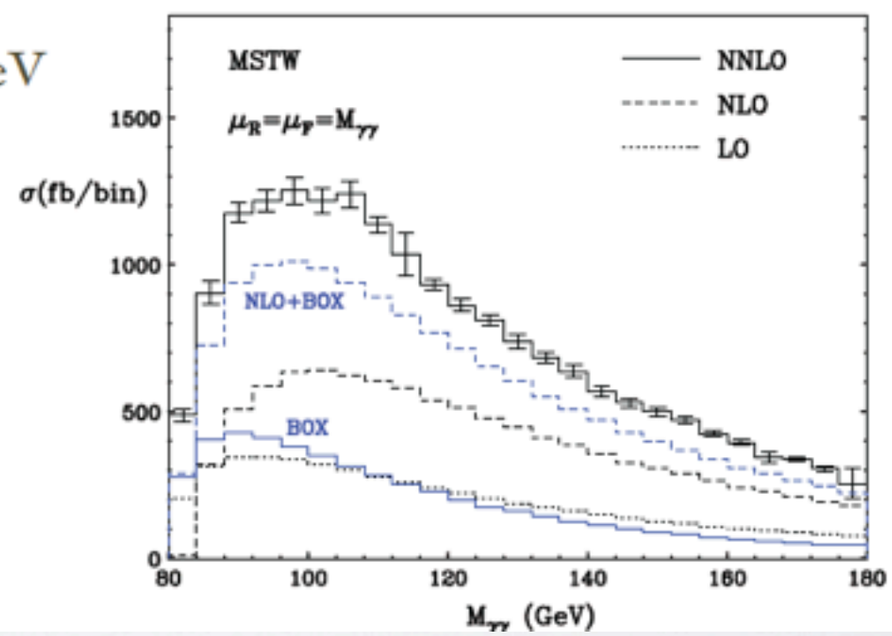
PRELIMINARY RESULTS LHC, $\sqrt{s}$=14 TeV

$p^{\gamma}_T \geq 40$ GeV $\quad |\eta^{\gamma}| \leq 2.5$

$60 \text{ GeV} \leq M_{\gamma\gamma} \leq 180 \text{ GeV}$

$$E_T^{had}(\delta) \leq \chi(\delta)$$

$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \qquad n=1,\ \epsilon_\gamma = 0.5,\ R_0 = 0.4$$



Ferrera, Tramontano, Grazzini

ASSOCIATED WH,ZH PRODUCTION

NEW: WH at NNLO

G.Ferrera, F.Tramontano, MG (2011)

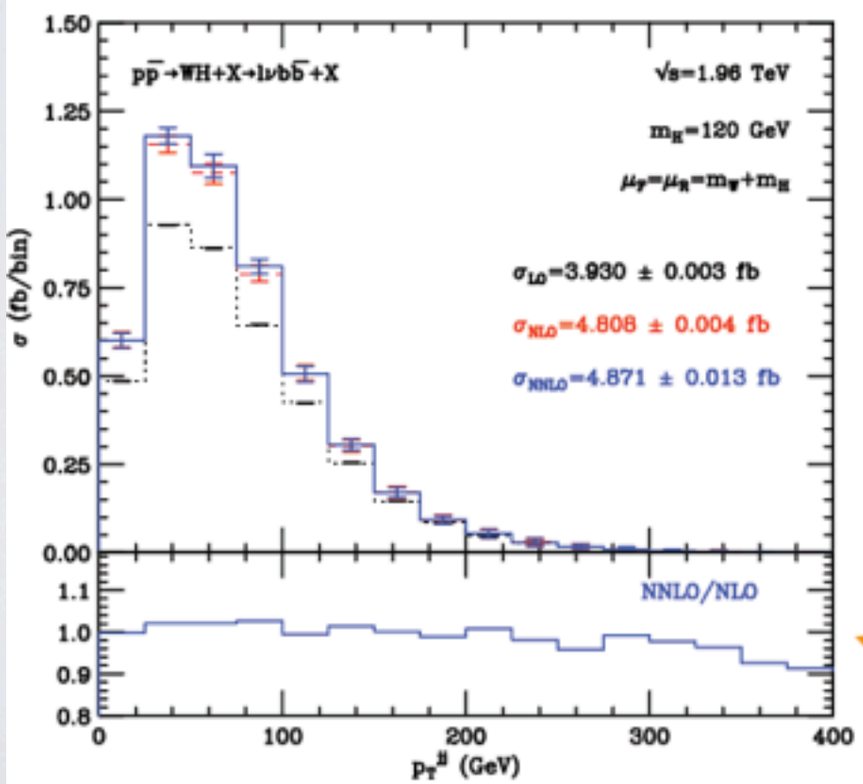
Results at the Tevatron

Cuts:
lepton: $p_T > 20$ GeV and $|\eta|<2$
$p_T^{miss} > 20$ GeV

Jets: k_T algorithm with R=0.4

We require exactly 2 jets with $p_T >$ 20 GeV and $|\eta|<2$

One of the jets has to be a b-jet with $|\eta|<1$



σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = (m_W + m_H)/2$	4.266 ± 0.003	4.840 ± 0.005	4.788 ± 0.013
$\mu_F = \mu_R = m_W + m_H$	3.930 ± 0.003	4.808 ± 0.004	4.871 ± 0.013
$\mu_F = \mu_R = 2(m_W + m_H)$	3.639 ± 0.002	4.738 ± 0.004	4.908 ± 0.010

Fixed-order results appear to be under good control

Scale dependence at the 1% level both at NLO and NNLO

Shape of p_T spectrum of dijet system is stable

A "NON-SUMMARY" SLIDE
FULLY DIFFERENTIAL NNLO H->BB

Herzog,Lazopoulos,CA

$$\Gamma^{NNLO}_{H\to b\bar{b}}(\underset{y_{cut}=0.01}{\text{2JetRate}}) = \Gamma^{LO}_{H\to b\bar{b}}\left[1-\left(\frac{\alpha_s}{\pi}\right)13.591(6)-\left(\frac{\alpha_s}{\pi}\right)^2 307(2)+\mathcal{O}(\alpha_s^3)\right]$$

Numerically

$$\Gamma^{NNLO}_{H\to b\bar{b}} = \Gamma^{LO}_{H\to b\bar{b}}\left[1+\left(\frac{\alpha_s}{\pi}\right)5.6666(4)+\left(\frac{\alpha_s}{\pi}\right)^2 29.12(4)+\mathcal{O}(\alpha_s^3)\right]$$

Analytically

$$\Gamma^{NNLO}_{H\to b\bar{b}} = \Gamma^{LO}_{H\to b\bar{b}}\left[1+\left(\frac{\alpha_s}{\pi}\right)5.6666666..+\left(\frac{\alpha_s}{\pi}\right)^2 29.146714..+\mathcal{O}(\alpha_s^3)\right]$$

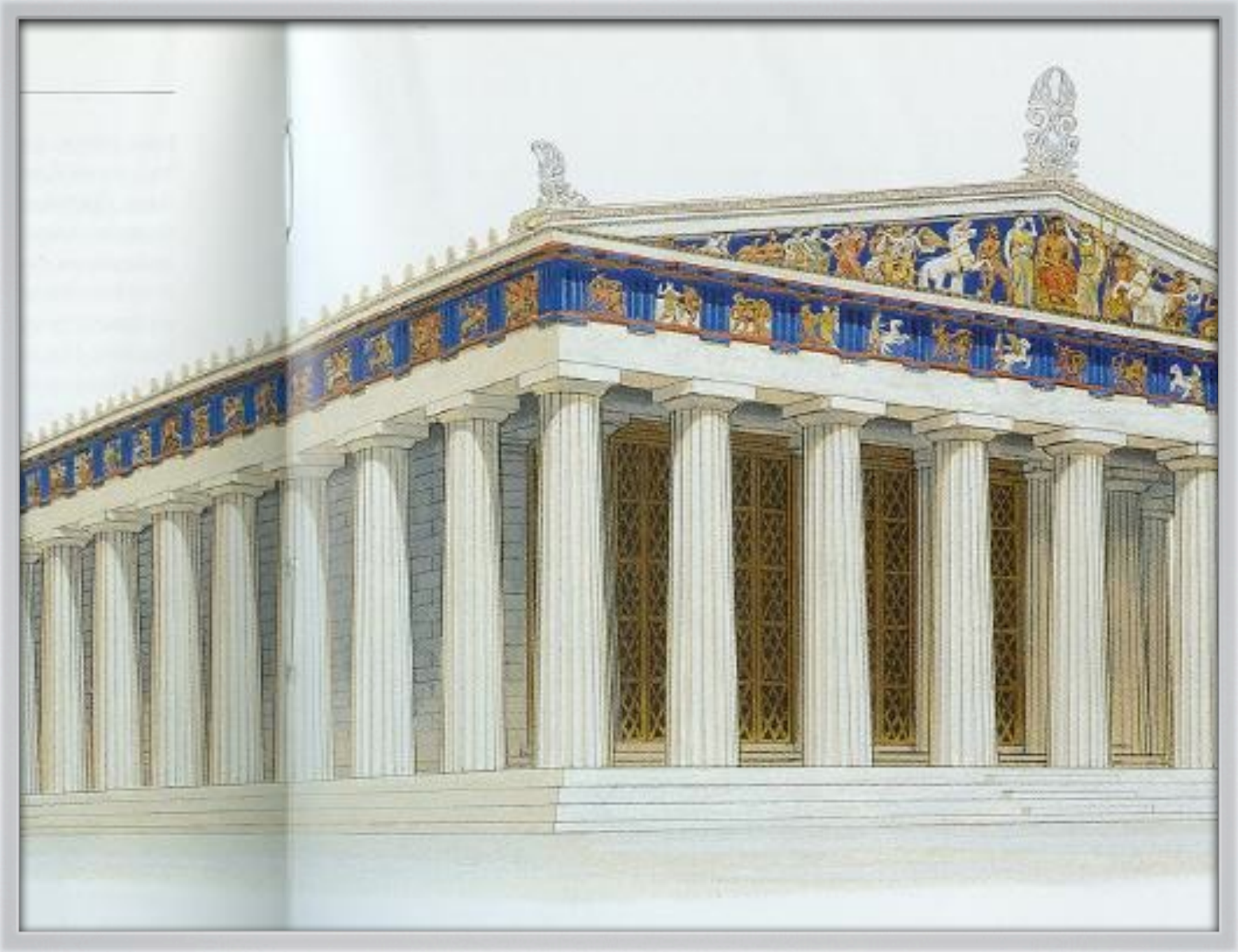
- Yet another method for real radiation at NNLO (non-linear mappings)
- First physical application
- Radiation from the final state in the Higgs decay to bottoms may play a role for jet substructure, etc
- The NNLO revolution is growing with the influx of a bright younger generation in the field.

WE HAVE A PARTIAL VIEW OF PARTICLE PHYSICS

- but we should not worry or be anxious.

it already looks beautiful!
And the LHC will reveal a full picture which...

WILL REMAIN CLASSIC



...WHATEVER IT IS!