Theoretical Summary

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Rencontres de Moriond 2017

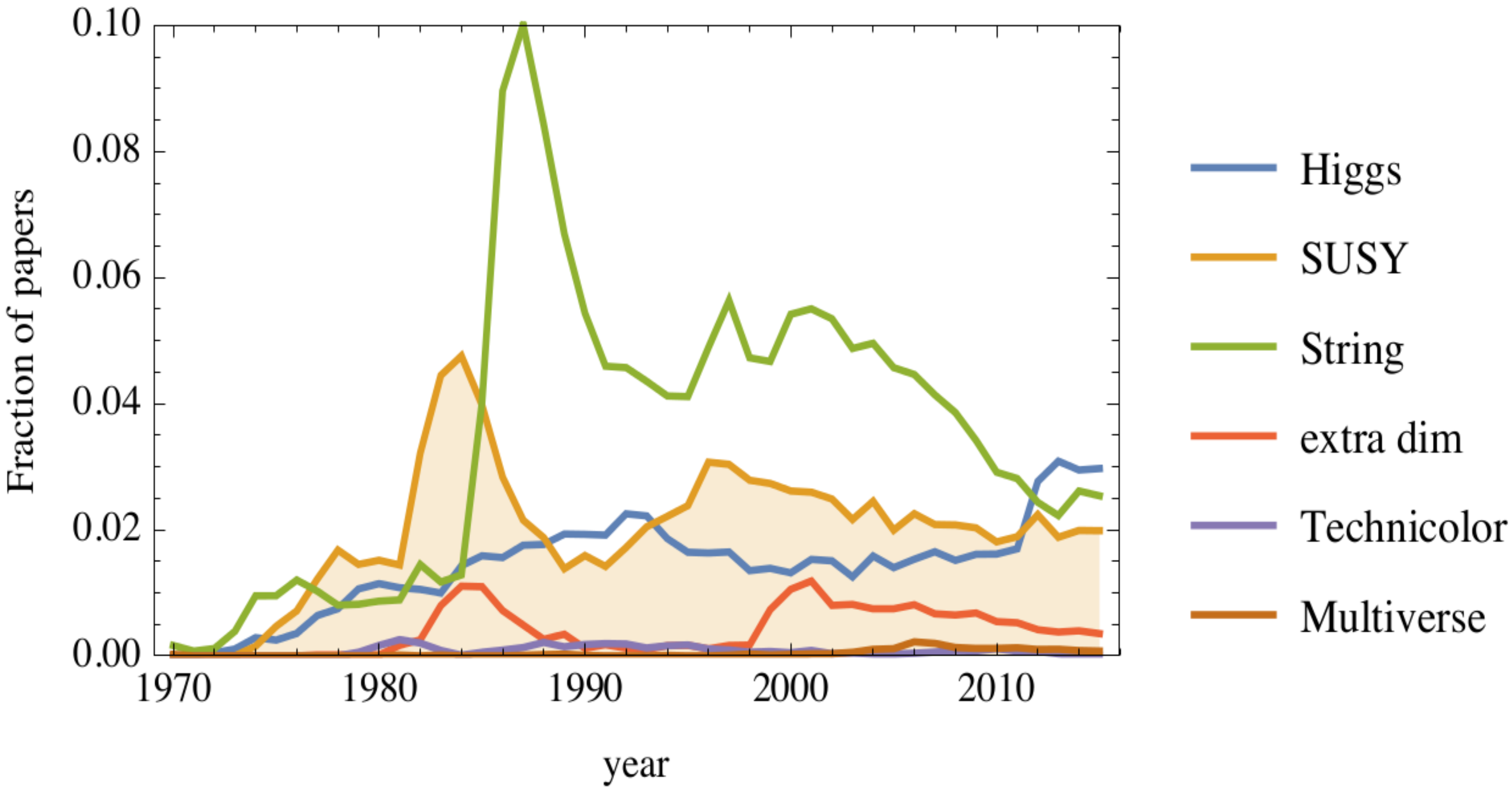
QCD and High Energy Interactions

Sessions:

- *Higgs*
- *Electroweak*
- *Heavy Flavour*
- *New Phenomena*
- *Top*
- *QCD*
- *Heavy Ion*
- *Special talk: neutrinos + Higgs*

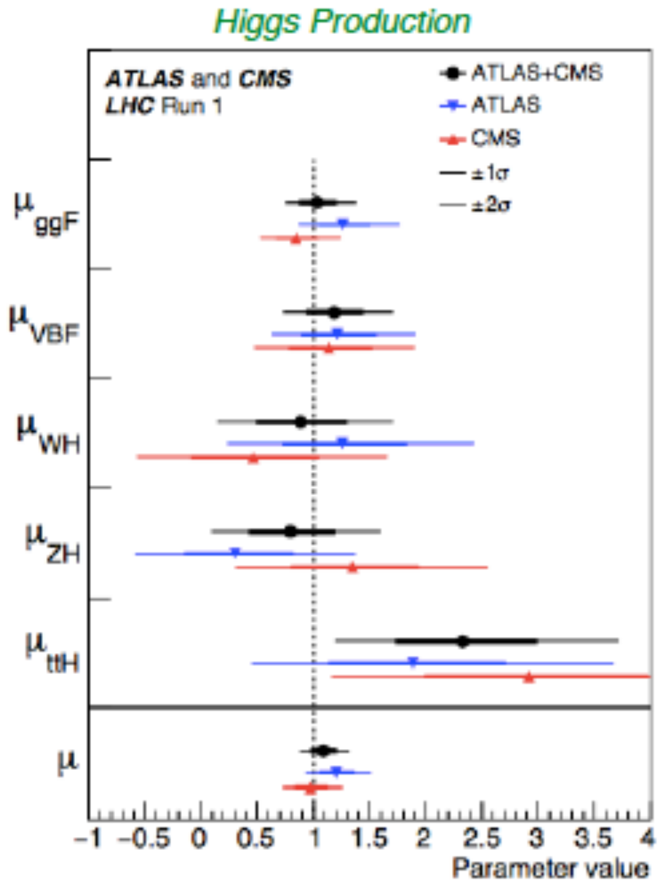
QCD: beauty or beast?

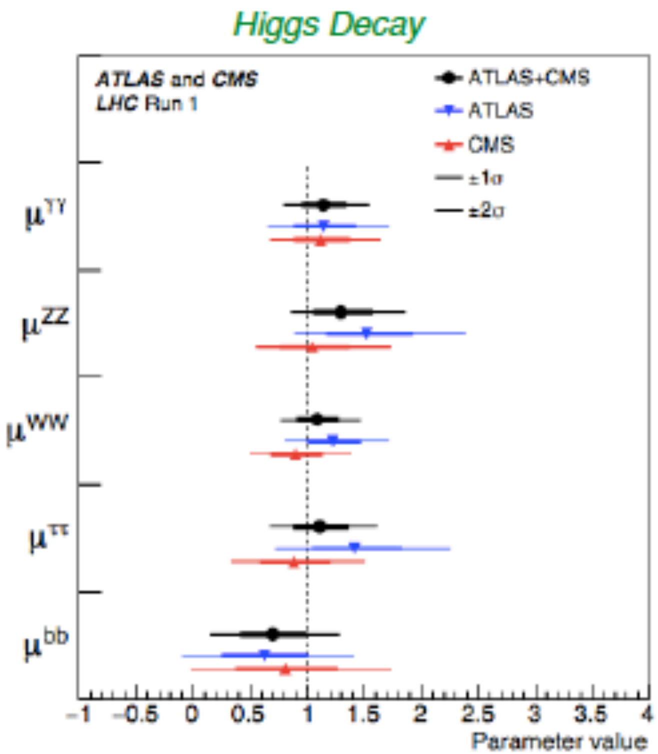
Higgs physics: still more popular than string theory



Courtesy A. Strumia

HIGGS PHYSICS





- *Production signal strengths assuming SM decay BR*
- *B signal strengths assuming SM production*

Electroweak symmetry breaking appears to be as in the SM

Higgs issues covered:

- triple Higgs coupling

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

- EFT Higgs couplings

$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_H = \tfrac{1}{2} (\partial_\mu |H|^2)^2$$

- BSM Higgses

2HDM, composite Higgs, …

- CP properties in multi-Higgs models

H, A, …

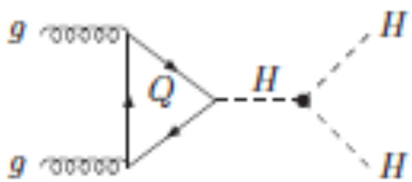
- Dark Matter in multi-Higgs models

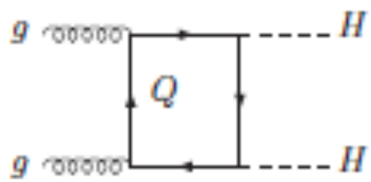
$$Z_2 : \ H_I \rightarrow - H_I$$

- Higgs as the only scalar in Nature

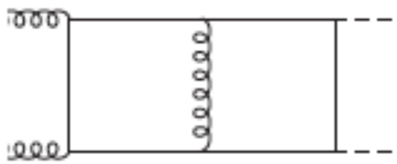
$$\Delta L = \xi R |H|^2$$

[Higgs boson pair production](#): Stephen Jones





New result: NLO m_t dependence →

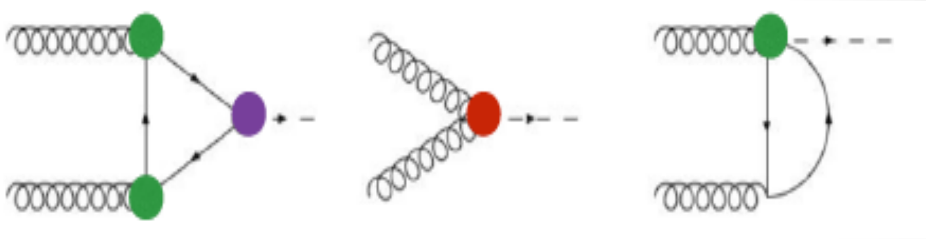


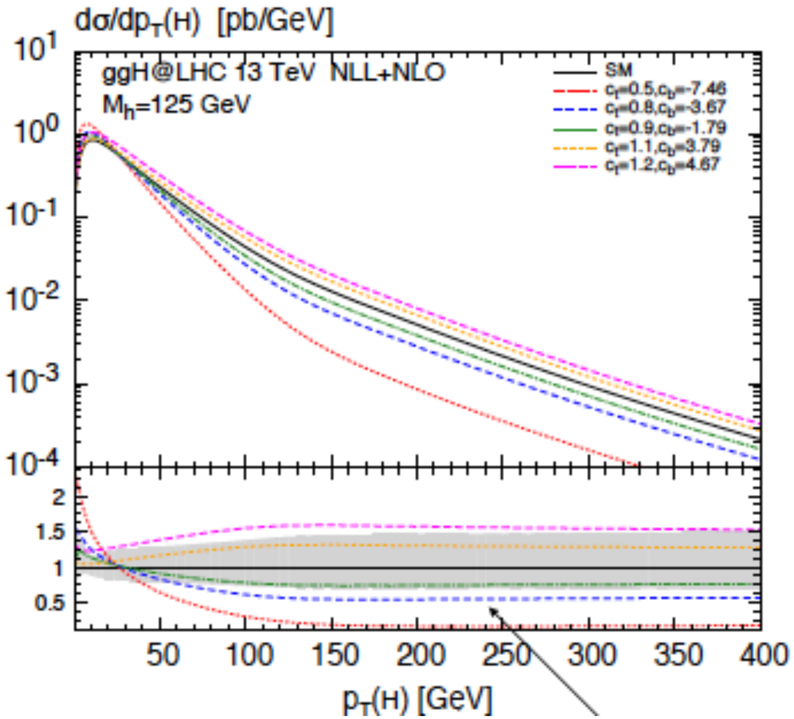
Gluon Fusion

- Key measurement for probing the self coupling (HL-LHC era)
- NLO deviates from Born Improved HEFT
  -14% @ 14 TeV, -24% @ 100 TeV
- Distributions altered significantly

Higgs EFT and p_T dependence: Agnieszka Ilnicka

$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$$
$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.$$
$$\mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$
$$\mathcal{O}_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + h.c.$$





Peculiar new physics dependence compared to that of σ

BSM Higgs : Marcela Carena

2HDM:

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+\left\{\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)]\Phi_1^\dagger \Phi_2 + \text{h.c.}\right\} ,$$

Alignment:

- *heavy BSM Higgses*
- *alignment w/o decoupling*

$\eta = \cos_{\beta-\alpha} t_\beta$ →

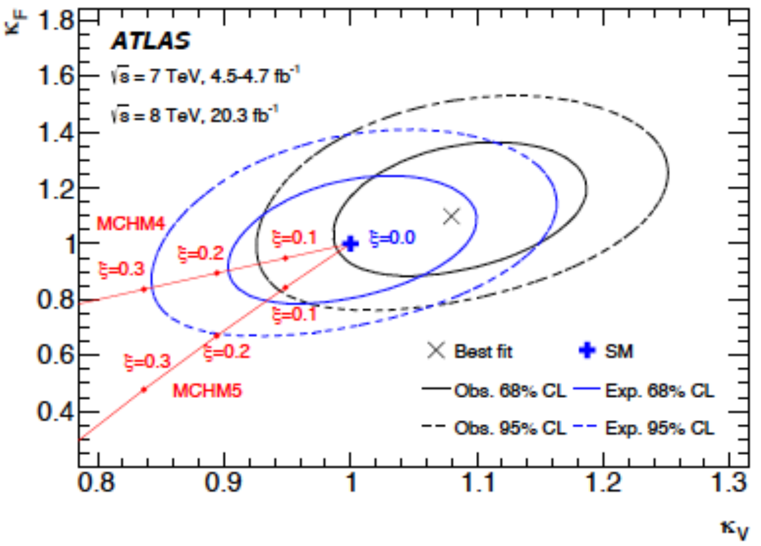
$$g_{hVV} \approx \left(1 - \frac{1}{2} t_\beta^{-2} \eta^2\right) g_V$$
$$g_{hdd} \approx (1 - \eta)\, g_f ,$$
$$g_{huu} \approx (1 + t_\beta^{-2} \eta)\, g_f ,$$

Composite models:

$\xi = v^2/f^2$ << 1 (f = strong dynamics scale)

Higgs coupling modifications:

$$\kappa_V = \sqrt{1-\xi} \qquad \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$



Model	Lower limit on f	
	Obs.	Exp.
MCHM4	710 GeV	510 GeV
MCHM5	780 GeV	600 GeV

CERN-PH-EP-2015-191

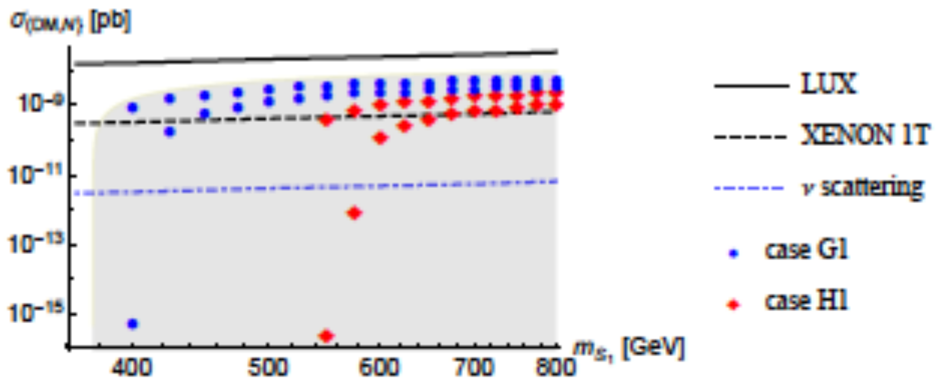
Dark Matter in multi-HDM: Dorota Sokolowska

Inert 2HDM:

Z_2: H -> H , H_I -> $-H_I$ ➡ DM, but quite constrained

I(2+1) HDM:

Add an extra inert doublet ➡ open up efficient co-annihilation



Generalized CP in 3HDM: Igor Ivanov

$$J:\ \phi_i \xrightarrow{CP} X_{ij}\phi_j^*\,,\quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}$$

Mass degenerate neutral scalars H,A and h,a:

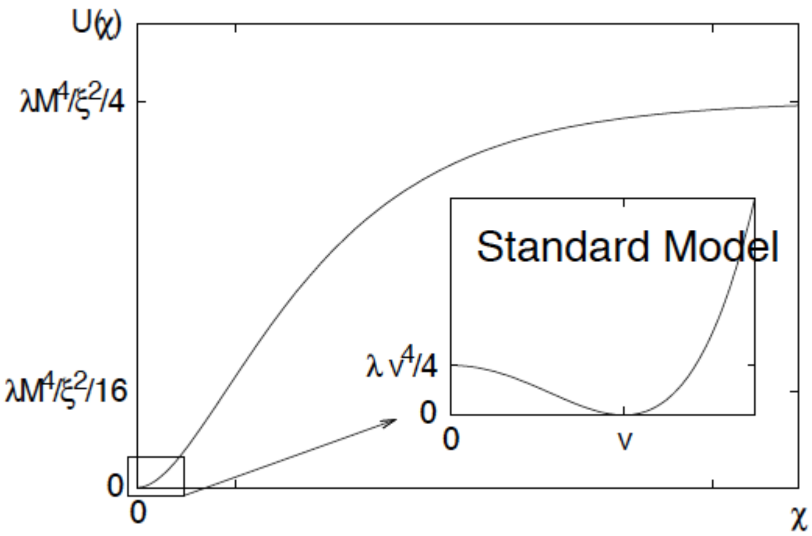
$$H \xrightarrow{CP} A,\quad A \xrightarrow{CP} -H\,,\quad h \xrightarrow{CP} -a,\quad a \xrightarrow{CP} h\,.$$

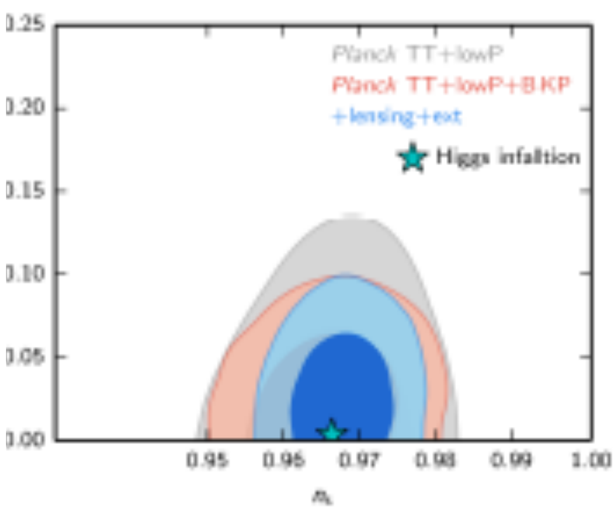
$$\Phi = \frac{1}{\sqrt{2}}(H - iA)\,,\quad \varphi = \frac{1}{\sqrt{2}}(h + ia)\,,\quad \Phi \xrightarrow{CP} i\Phi\,,\quad \varphi \xrightarrow{CP} i\varphi\,.$$

→ CP-half-odd scalars (CP is order 4)

νMSM: Mikhail Shaposhnikov

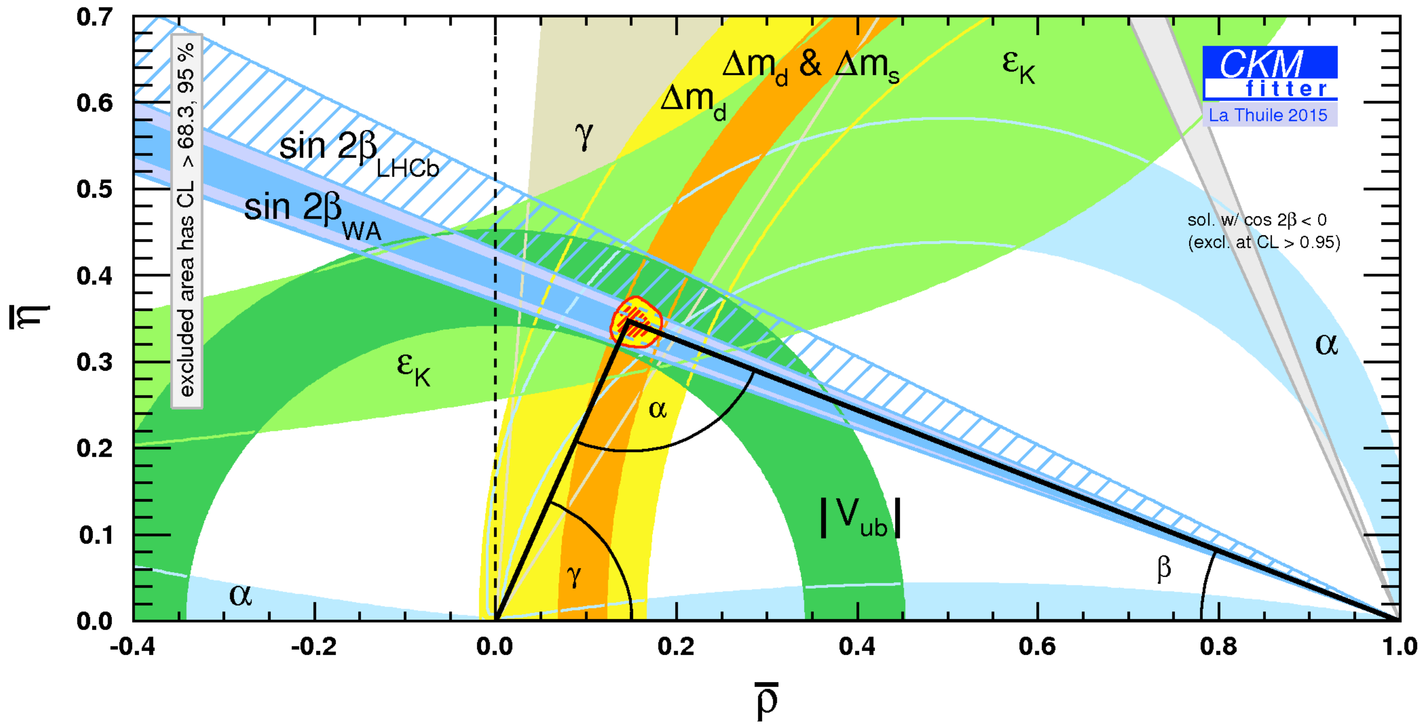
Higgs-gravity coupling: $$\mathcal{L}_G = -\left(M_P^2 + 2\xi_h \varphi^\dagger \varphi\right) \frac{R}{2}$$





χ = canonically normalized Higgs = inflaton

FLAVOR PHYSICS



CKM picture is in excellent agreement with data

Flavor issues covered:

- B-physics anomalies/new insights

R_D , R_K , …

- Lattice progress

$\varepsilon' / \varepsilon$

- Heavy flavor production at the LHC

σ_{bb} , σ_{cc}

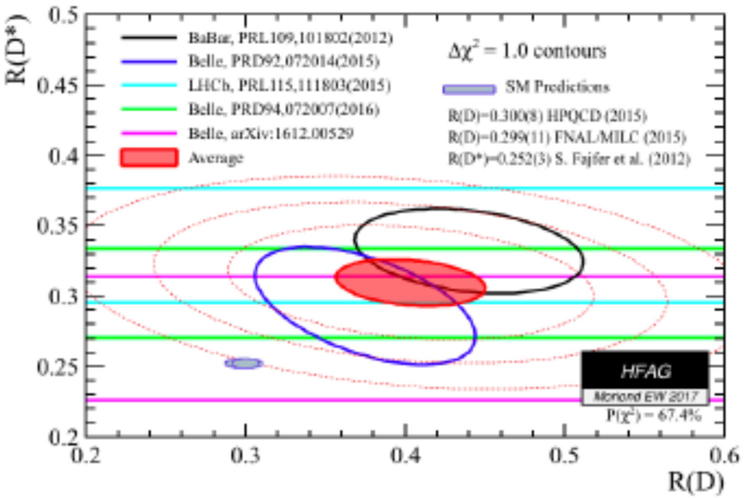
- CP violation

ϕ_s

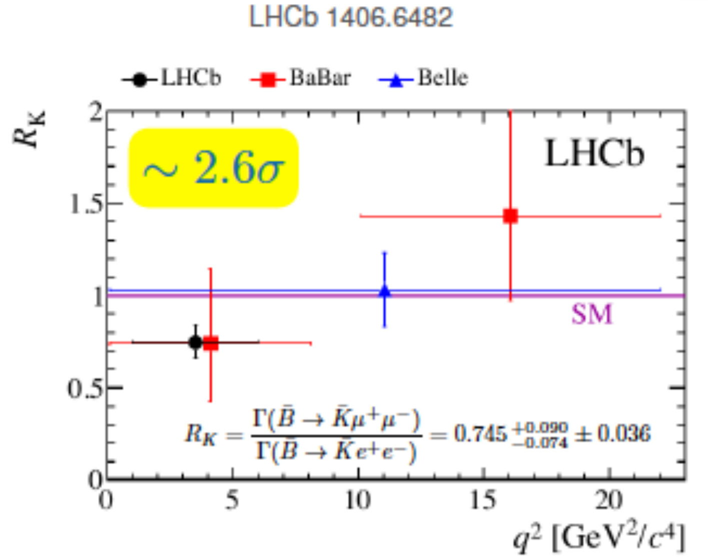
- Hadronic B decays

$B \to PP$, …

Anomalies: Matthias Neubert, Javier Virto

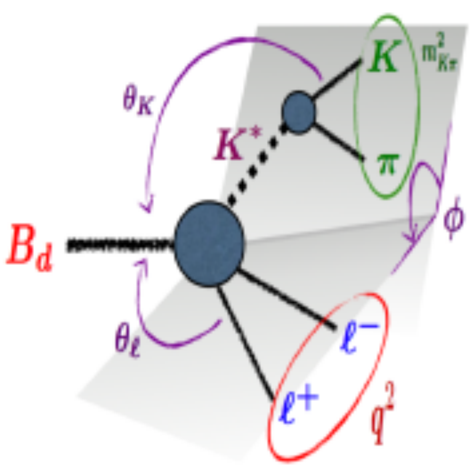


$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}; \quad \ell = e, \mu$$



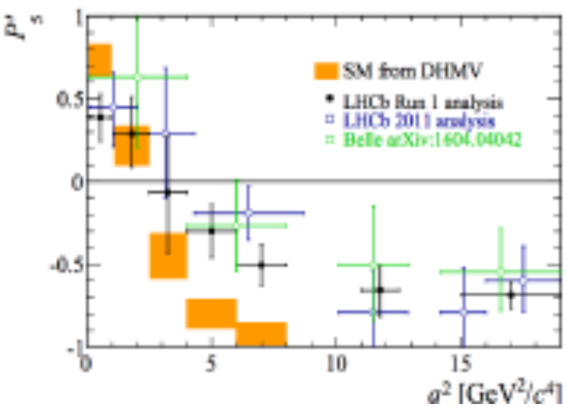
Clean observables!

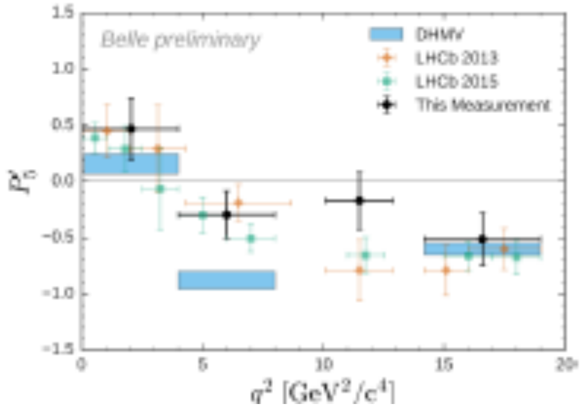
:: $B \to K^{\star}\mu\mu$ Angular Observables



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\times$$
$$\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + J_{2s}\sin^2\theta_K\cos 2\theta_l$$
$$+J_{2c}\cos^2\theta_K\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+J_{6s}\sin^2\theta_K\cos\theta_l + J_{6c}\cos^2\theta_K\cos\theta_l$$
$$+J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

: $P_5' = J_5/(2\sqrt{-J_{2c}J_{2s}})$





about 3σ anomaly

Javier Virto:

$$\mathcal{O}_{9\ell} = \frac{\alpha}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

1. Assuming KMPW is the right ballpark for $c\bar{c}$.
2. Assuming Fact. PCs are $\sim 10-20\%$ (supported by LCSR calculations).
3. Assuming the OPE for the large-q^2 bin is correct up to $\sim 10\%$

then, a NP contribution $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$ gives a substantially improved fit for

- $B \to K\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \Phi\mu\mu$
- BRs and angular observables (including P_5')
- Low q^2 and large q^2
- R_K

Siavash Neshatpour: **hadronic corrections do not improve the fit**

Hadronic power correction effect:

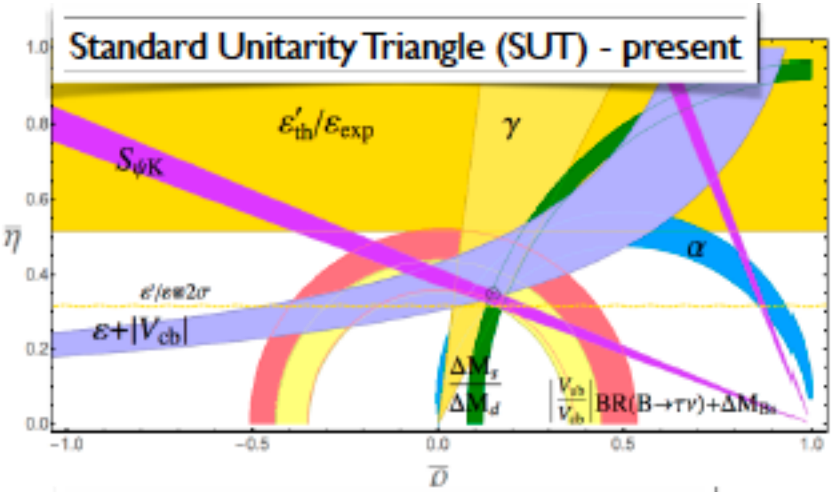
$$\delta H_V^{\rm p.c.}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_\lambda(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2}\left(h_\lambda^{(0)} + q^2 h_\lambda^{(1)} + q^4 h_\lambda^{(2)}\right)$$

New Physics effect:

$$\delta H_V^{C_9^{\rm NP}}(\lambda) = -iN' \tilde{V}_\lambda(q^2) C_9^{\rm NP} = iN' m_B^2 \frac{16\pi^2}{q^2}\left(a_\lambda^{\tilde{V}} C_9^{\rm NP} + q^2 b_\lambda^{\tilde{V}} C_9^{\rm NP} + q^4 c_\lambda^{\tilde{V}} C_9^{\rm NP}\right)$$

Lattice calculation progress: Enrico Lunghi

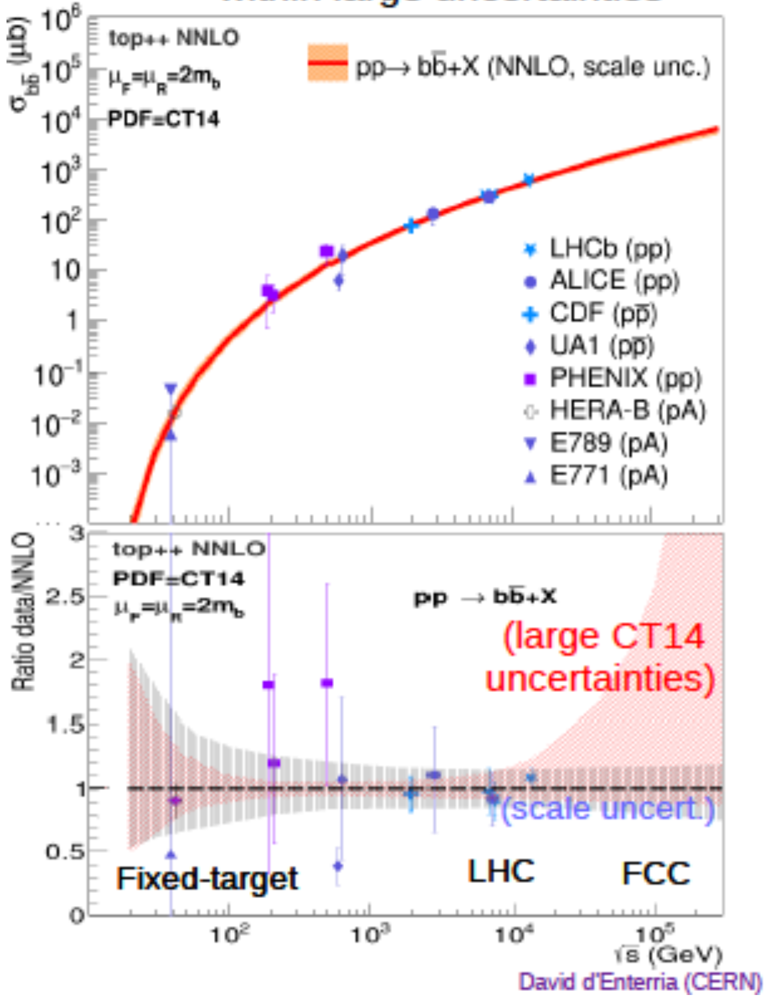
The long standing mysterious enhancement of the $\Delta I=1/2$ channel (the so-called $\Delta I=1/2$ rule) is explained as an accidental cancellation between contributions to $\mathrm{Re}(A_2)$ which does not occur for $\mathrm{Re}(A_0)$

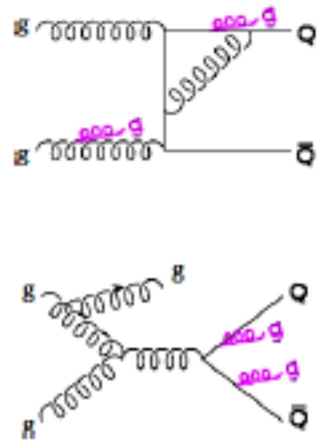


$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \begin{cases} (16.6 \pm 2.3) \times 10^{-4} & \text{exp} \\ (1.36 \pm 5.15 \pm 4.59) \times 10^{-4} & \text{th} \end{cases}$$

Total bottom/charm σ at NNLO: **David d'Enterria**

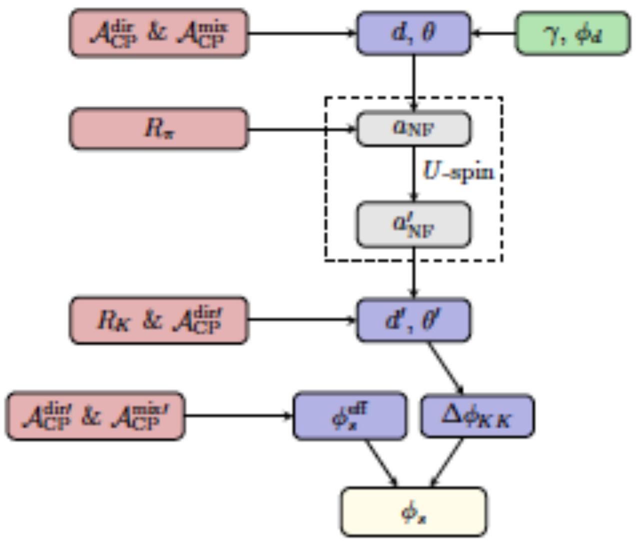
■ Bottom: Very good agreement at all √s within large uncertainties





Charm production σ not as good

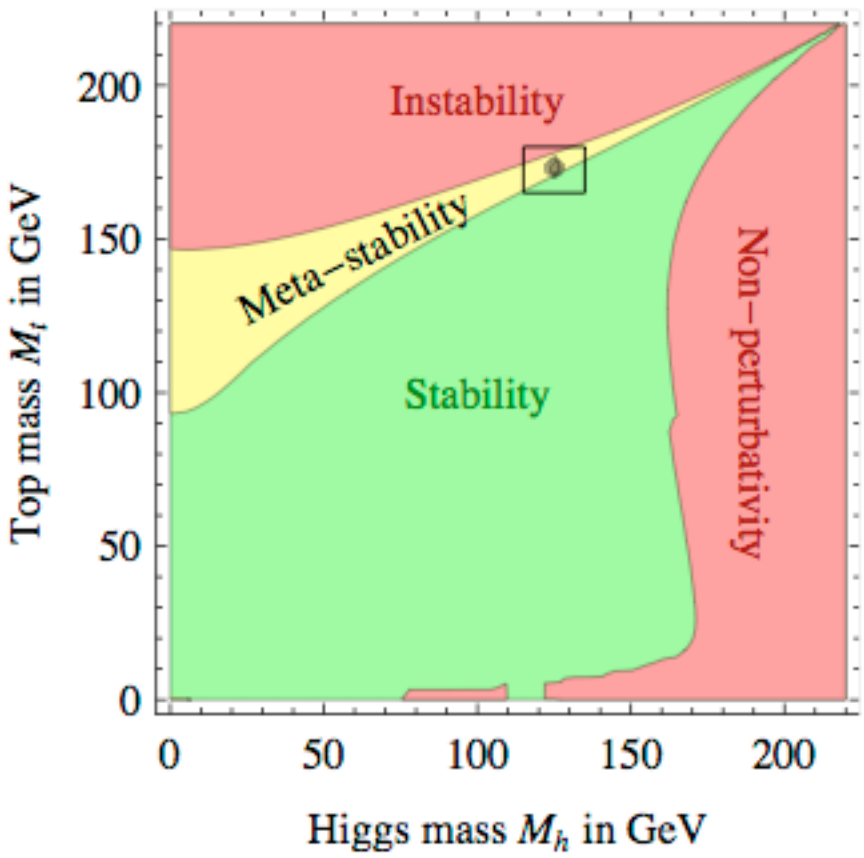
Determination of ϕ_s to 0.5%: Keri Vos



Hadronic B decays: Cai-Dian Lu

- Only 14 universal non-perturbative parameters to be fitted from all $B \to PP$, VP and PV *decay channels*, more predictive power than ever
- Results are consistent with data. SU(3) breakings are studied.
- Predictions for more than 100 channels to be tested by future exp. Power corrections are needed

PRECISION CALCULATIONS

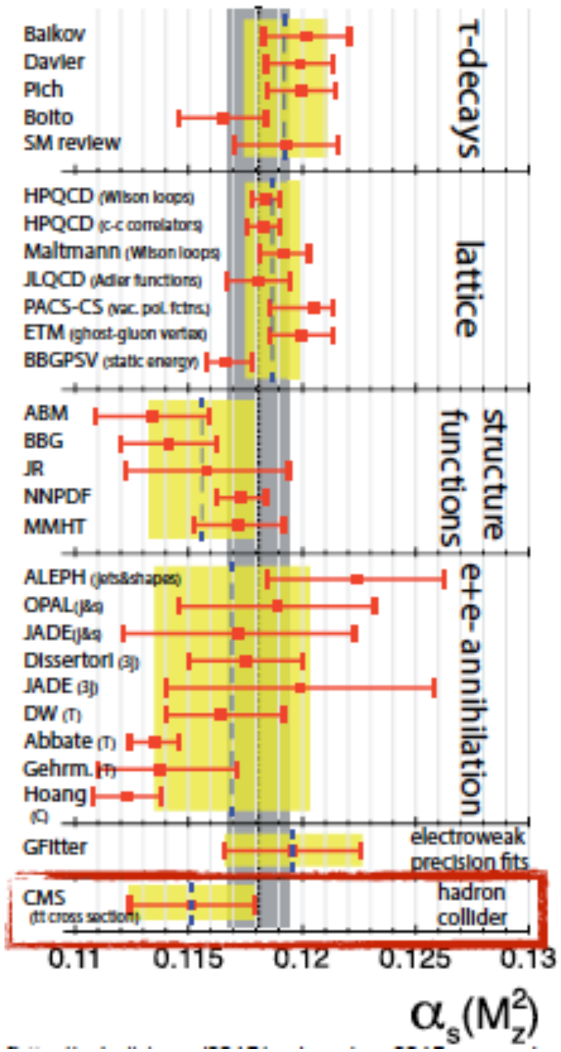


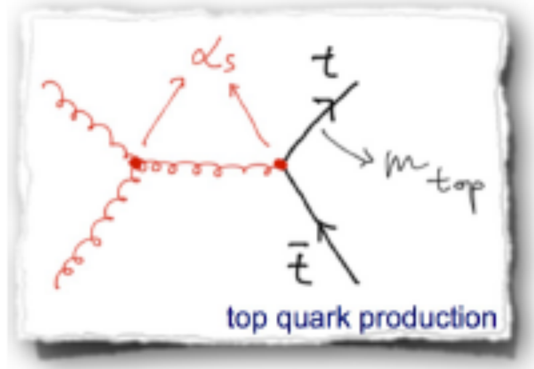
Matter of life and death

Topics covered:

- α_s extraction
- top mass at LHC
- single top production
- PDFs
- jet production in DIS and at LHC
- vector boson pair production at LHC

Strong coupling from top production: Thomas Klijnsma





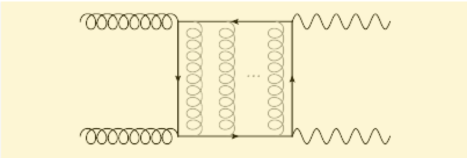
ATLAS + CMS + Tevatron

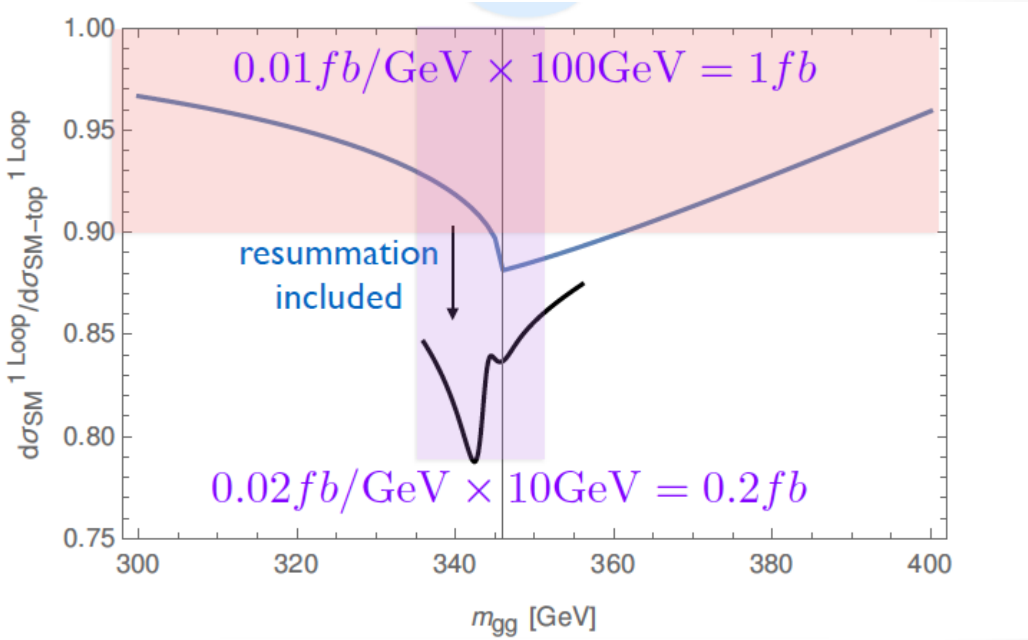
⇓

3.8% precision depending on PDF

Top mass from di-photons: Hyung Do Kim

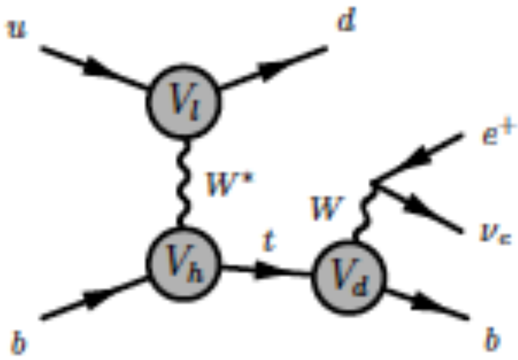
Toponium production
at the threshold





There is a hope for $\Delta m_t < 0.5$ GeV from a single channel measurement

Single top production and decay: Hua-Xing Zhu



Direct probe of Wtb vertex in *both* production and decay

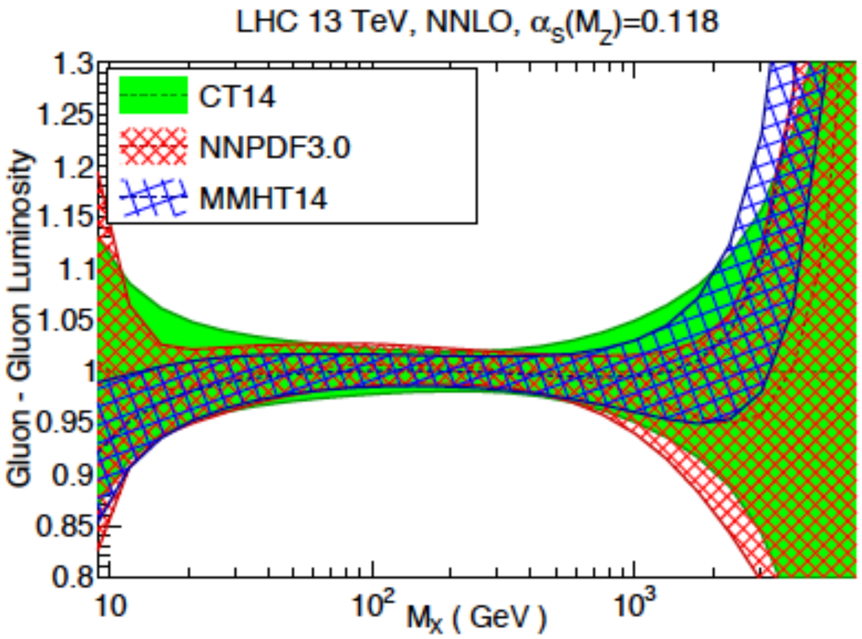
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

Direct measurement of $|V_{tb}|^2$

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.0\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13
$\bar{t}$ quark	total	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	$1.62^{+1.2\%}_{-0.8\%}$
	corr. in pro.		-0.46	-0.15
	corr. in dec.		-0.21	-0.08

NNLO: -6% correction

Progress in PDFs: Pavel Nadolsky

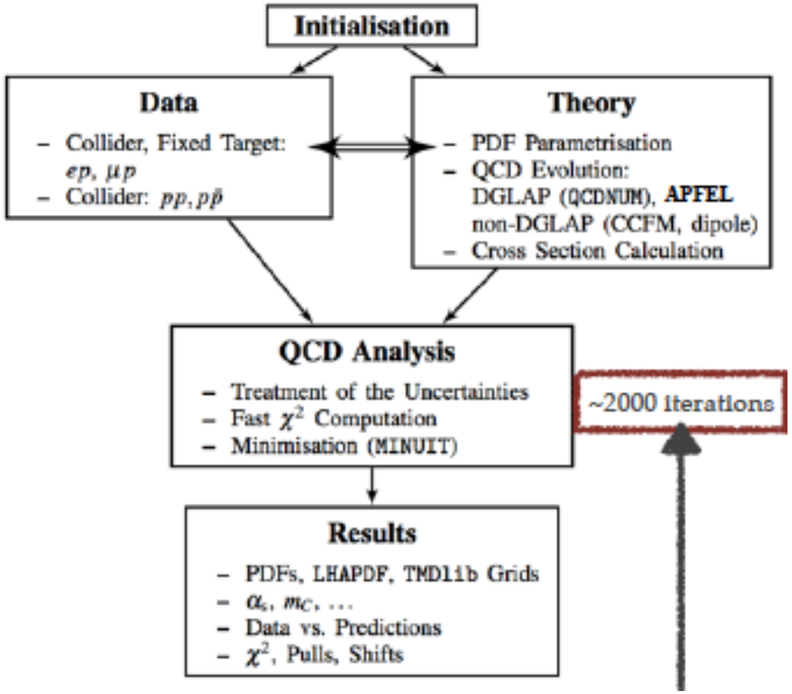


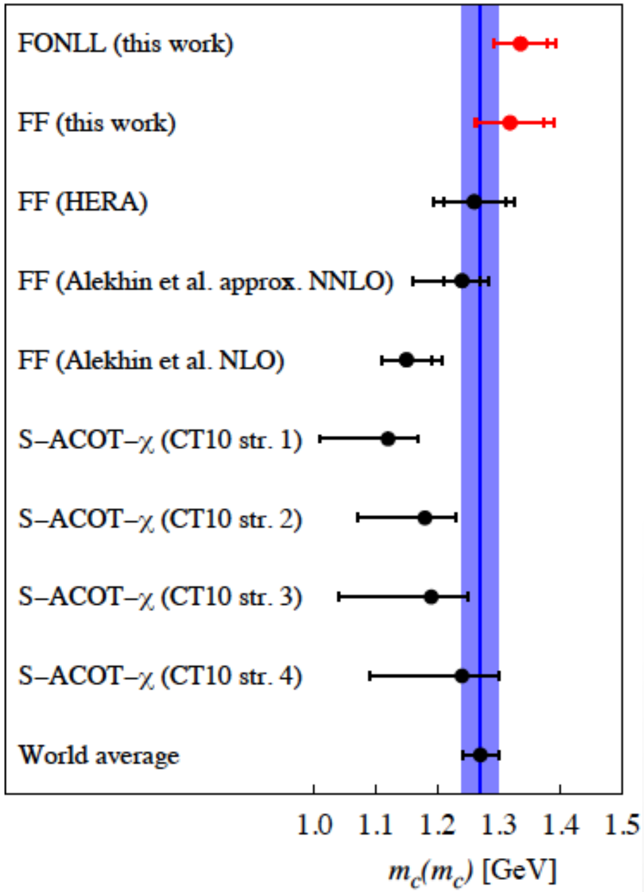
In the Higgs production region (MX=125 GeV), all PDFs now **agree** as a result of **dedicated benchmarking**. The uncertainty on sigma_tot(Higgs) was reduced from 7% in 2012 to 3% in 2015. Can we reduce it more?

NNLO PDFs **CT17**, **MMHT'16, NNPDF3.1** to be released

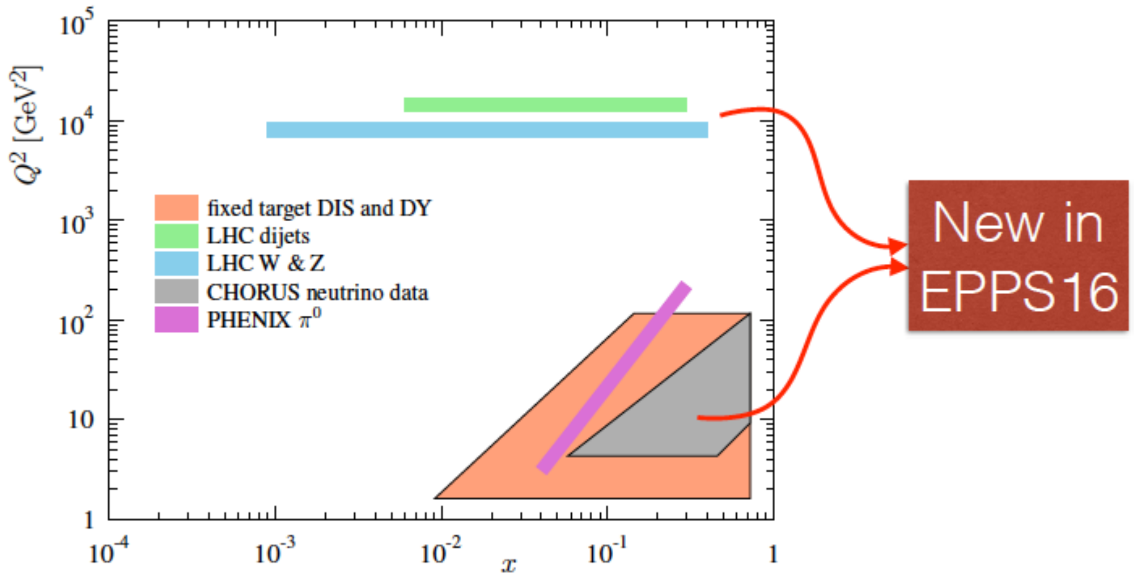
xFitter: Valerio Bertone

- provides a unique QCD framework to address theoretical differences:
  —> benchmark exercises / collaborative efforts / topical studies
- provides means to the experimentalists to optimise the measurements:
  —> assess impact / consistency of new data

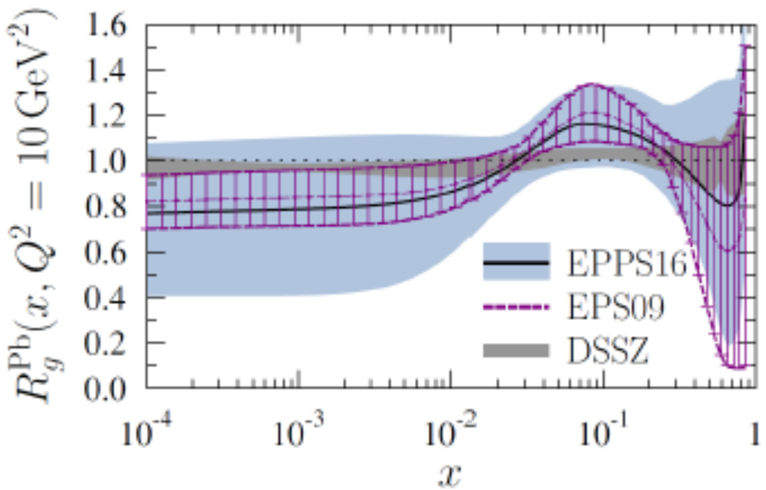




EPPS16 nuclear PDFs: Carlos Salgado

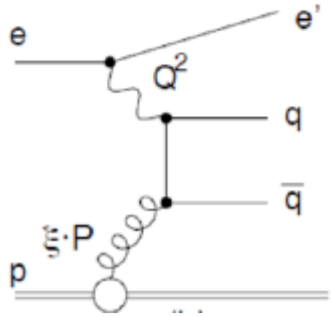


Supersedes EPS09

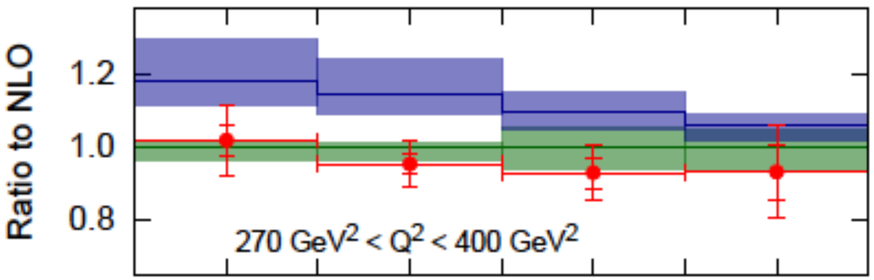


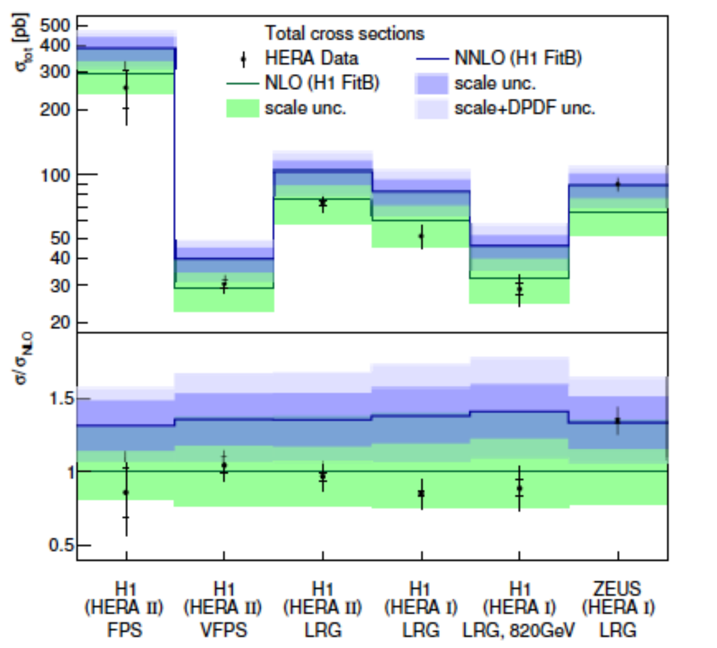
Larger uncertainties reflect more realistic analysis
more freedom in parametrization

NNLO dijet production in DIS: Jan Niehues (+ Daniel Britzger)



- sensitive to α_s
- sensitive to gluon PDF



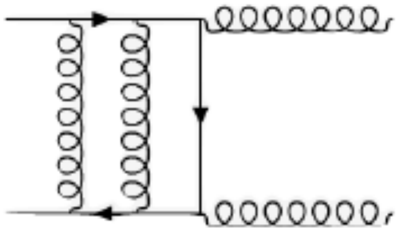


[D. Britzger et al. 2017]

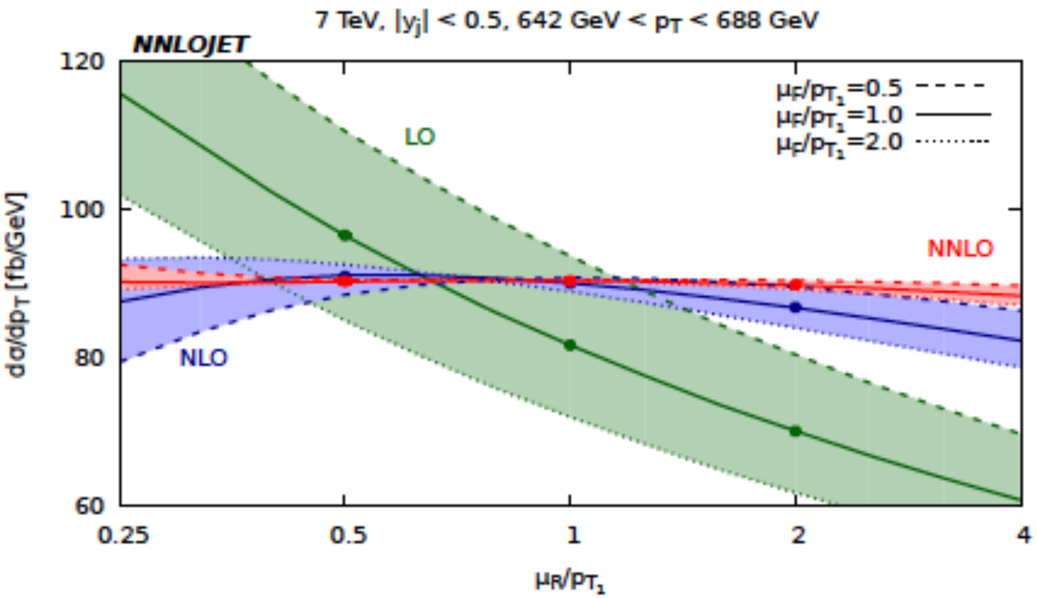
σ_{tot} at NNLO: - reduced scale uncertainty

- normalization issue (30%) → PDF

Single jet production at NNLO at LHC: Joao Pires

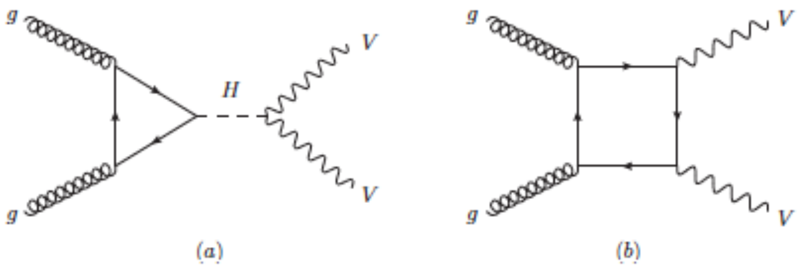


- Rigorous tests of pQCD dynamics across a huge range of kinematics
- Constrain PDF's
- Determine $\alpha_s(M_Z)$ and running coupling from a single experiment



Percent level scale uncertainty!

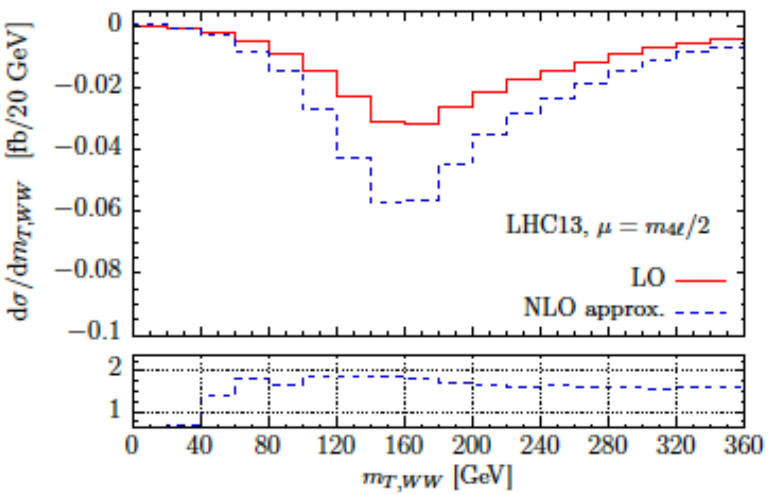
Vector boson pair production at NLO: Raoul Röntsch



Strong destructive interference
(probe unitarizing behavior of Higgs)

$$|A_{ZZ}|^2 = |A_H|^2 + |A_b|^2 + 2\mathrm{Re}[A_H A_b^*]$$

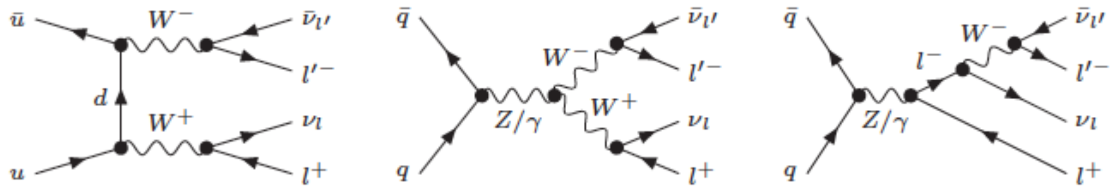
$$\rightarrow \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

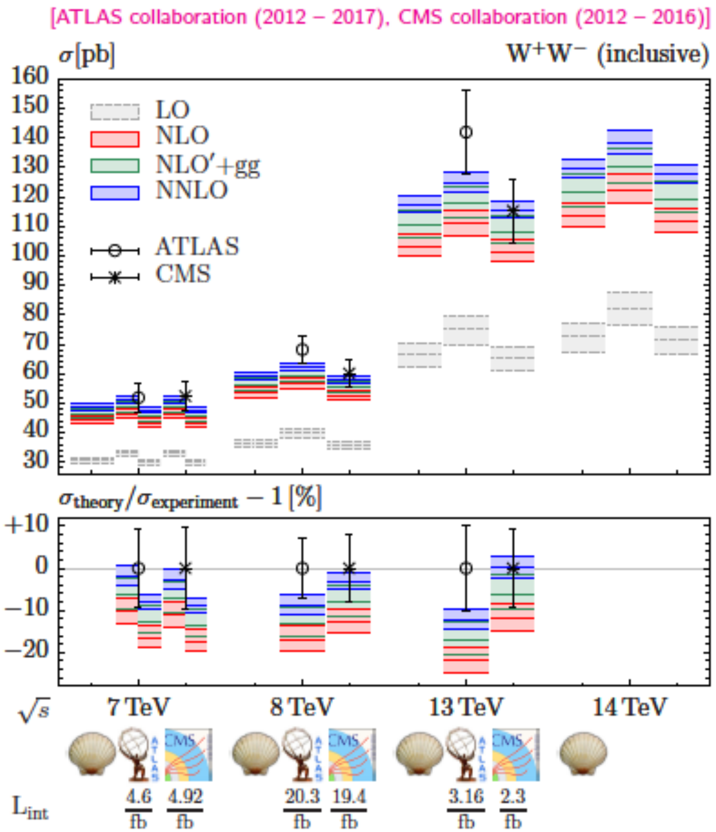


Interference effects ~ 5%

Scale uncertainty reduced to 10%

WW,WZ production at NNLO QCD: Stefan Kallweit, Marius Wiesemann

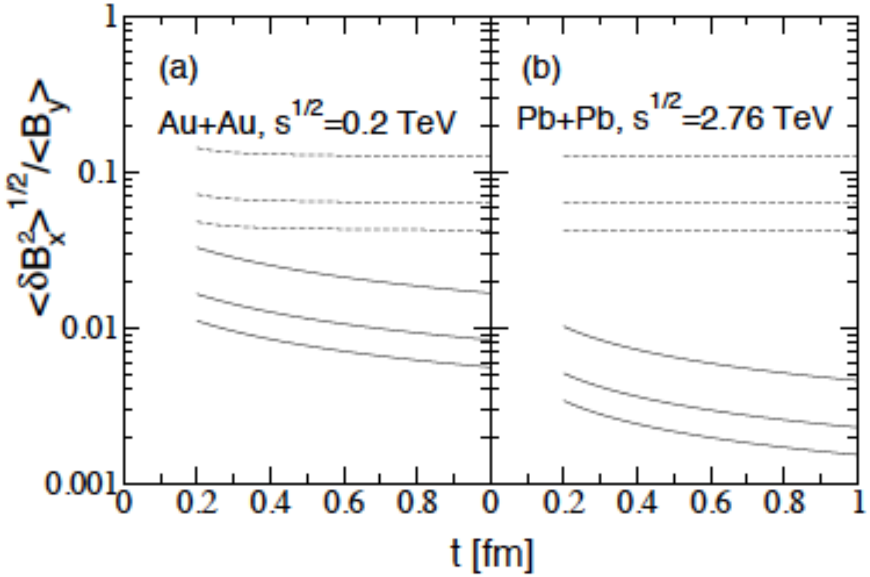




- NNLO/NLO ranges from 10% to 14% (7 TeV to 14 TeV).
- NNLO scale variation ≈ ±3%.

- MATRIX results with NNPDF3.0 PDF sets.

Fluctuations of EM field in heavy ion collisions : Bronislav Zakharov



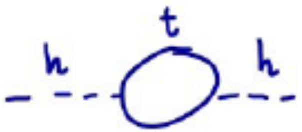
quantum effects reduce magnetic field fluctuations (!)

NEW PHENOMENA

Fine-tuned?

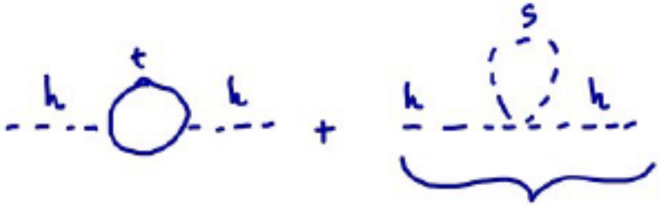
Beyond the Standard Model : Aldo Deandrea

SM:



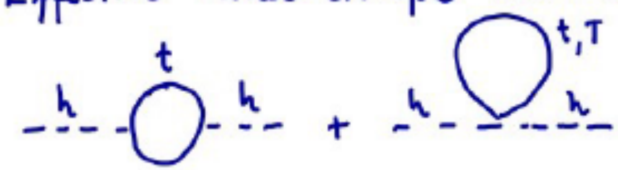
$\sim \Delta m_h^2 = -\frac{y_t^2}{16\pi^2}\left(2\Lambda^2 + 6\, m_t^2 \log(\Lambda/m_t)\right)$

a) Renormalizable theory example (susy):



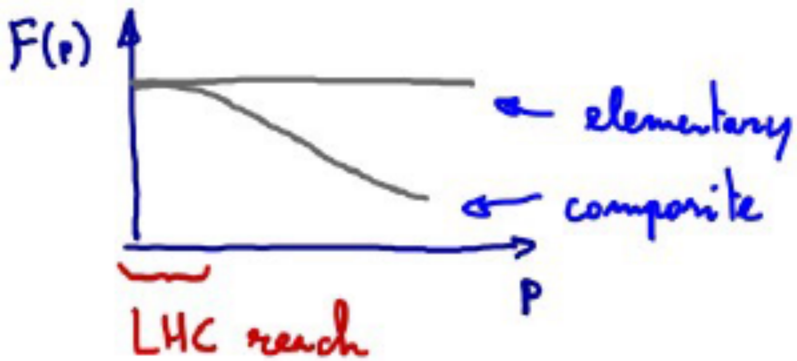
$$\frac{\lambda_S}{16\pi^2}\left(\Lambda^2 - 2\, m_S^2 \log(\Lambda/m_S) + \dots\right)$$

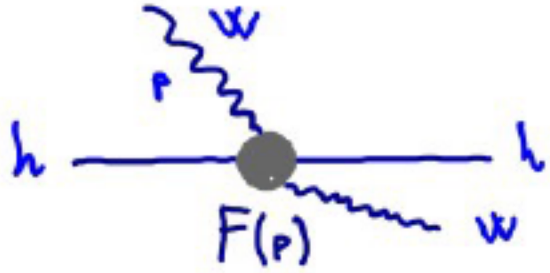
b) Effective model example (with a fermion, as in composite higgs):

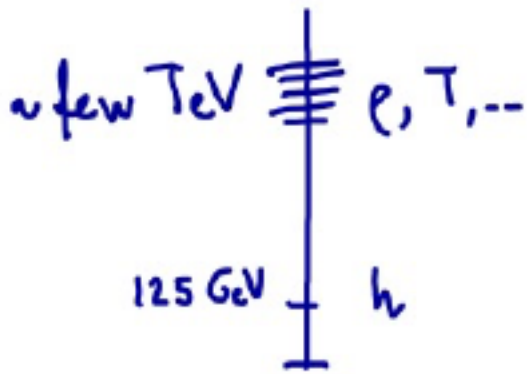


Λ cut-off, but here physical meaning

Probe the form factor :







Supersymmetry : **Werner Porod**

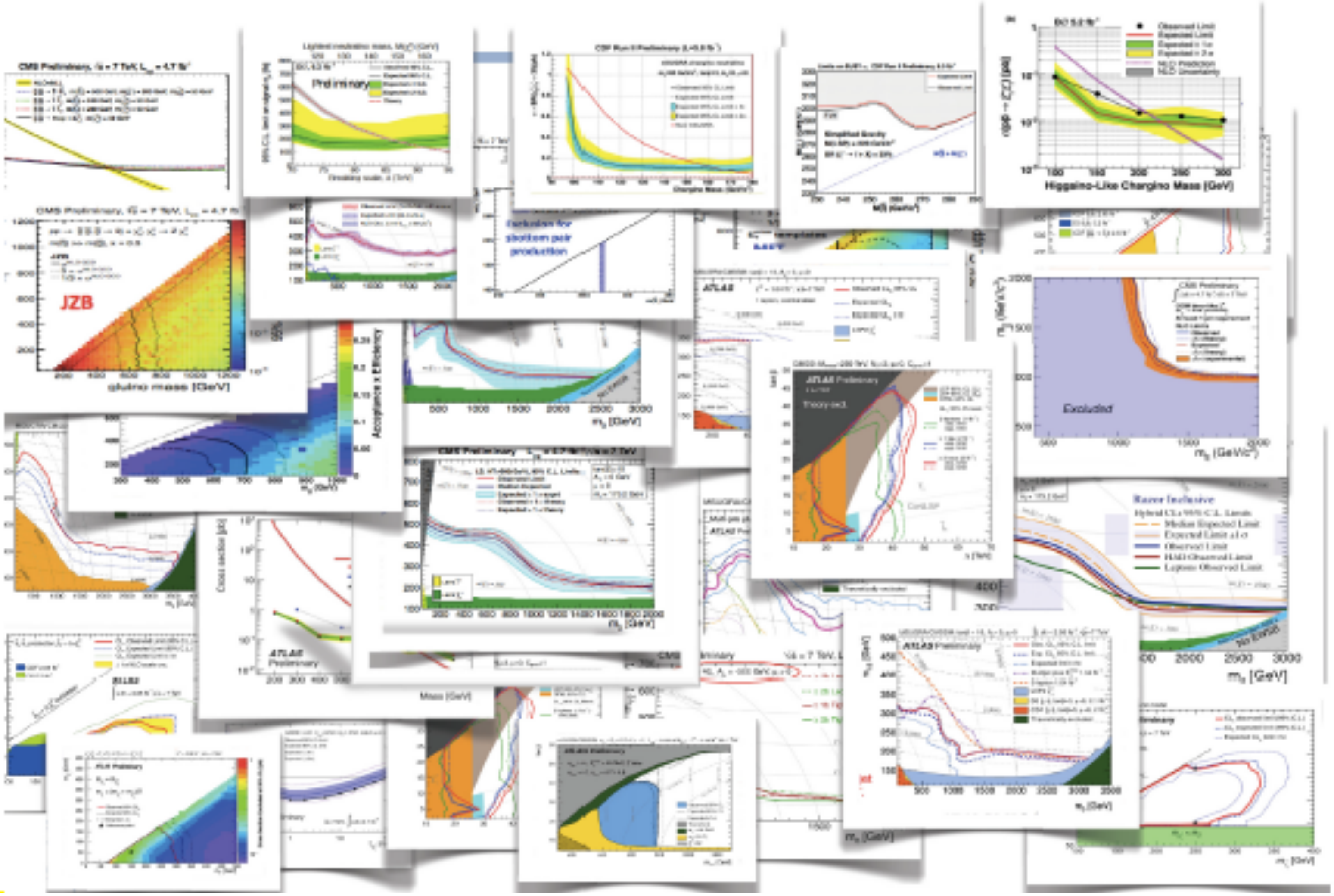
$(125\ \text{GeV})^2 \simeq m_Z^2 + (86\ \text{GeV})^2 \Rightarrow$ large corrections within MSSM

- GMSB, CMSSM, NUHM: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV
- CMSSM, NUHM: large A_0, danger of color and charge breaking minima

- general MSSM: SUSY particles with masses of few 100 GeV still allowed if spectra compressed, in particular light $\tilde{t}_1$ still allowed
- 'Natural SUSY': take only those states light which contribute to EWSB: $\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_i$

$$m_Z^2 \simeq -1.8\,\mu^2 + 5.9\,M_3^2 - 0.4\,M_2^2 - 1.2\,m_{H_u}^2 + 0.9\,m_{q_L^{(3)}}^2 + 0.7\,m_{u_R^{(3)}}^2 - 0.6\,A_t\,M_3 + 0.4\,M_2\,M_3 + \ldots\ ,$$

SUSY Searches :



BSM theories so far: *“We tried to do good, but it turned out as usual.”*

Виктор Черномырдин

SUMMARY OF SUMMARY

✧ Remarkable progress in calculations: NNLO = commonplace

✧ Intriguing B-physics anomalies

✧ Higgs precision era

✧ Data-driven theory: test “unmotivated” ideas