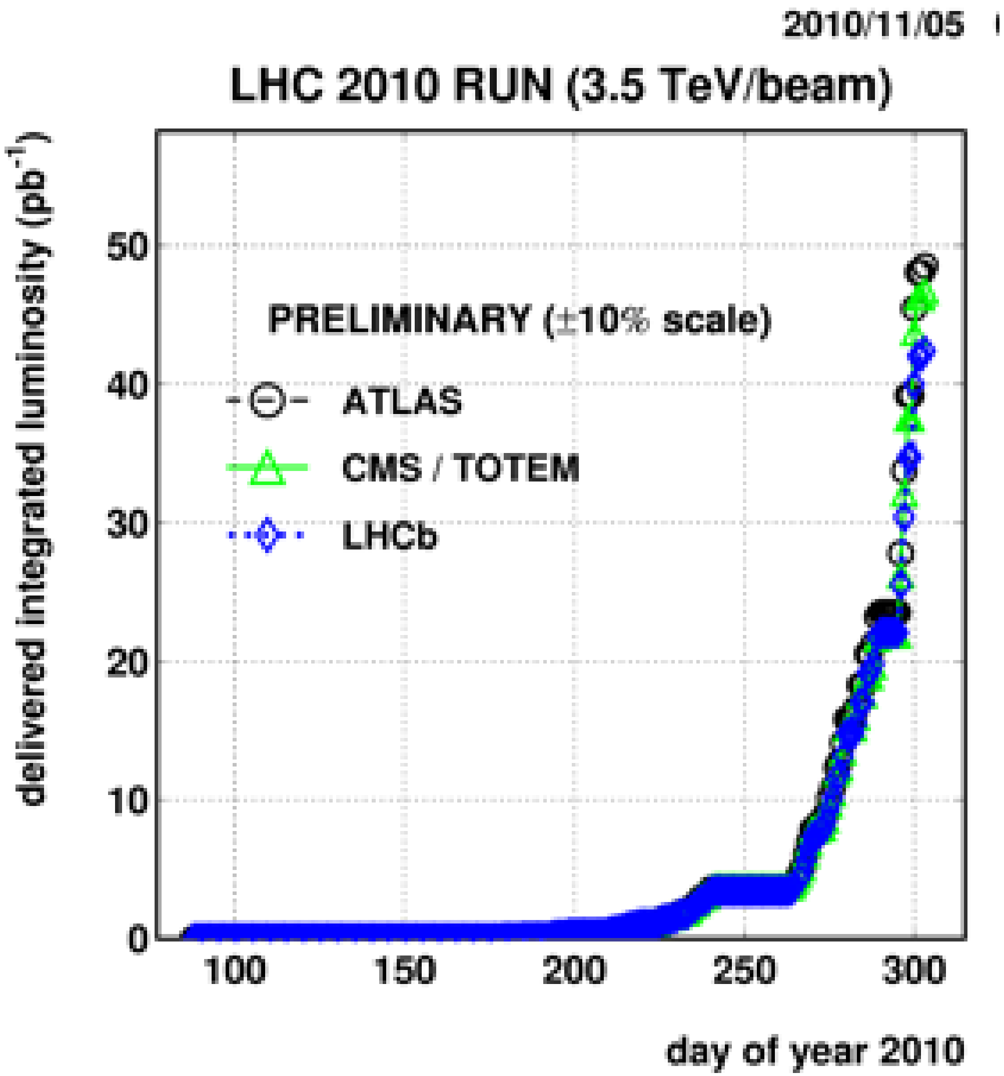
Paris, FRIF, 18 December '10

Conclusion and Outlook

Guido Altarelli
Roma Tre/CERN

In 2010 the LHC has worked well
(both in p-p and HI)



Total integrated p-p luminosity so far
47 pb^{-1}

Peak luminosity
~ 2 10^{32} $cm^{-2}s^{-1}$
344 bunches

1 fb^{-1} by end 2011 realistic

Possible continuation in 2012 envisaged, to be decided soon (Chamonix, January '11)

The detector performance has also been superb from the very beginning!

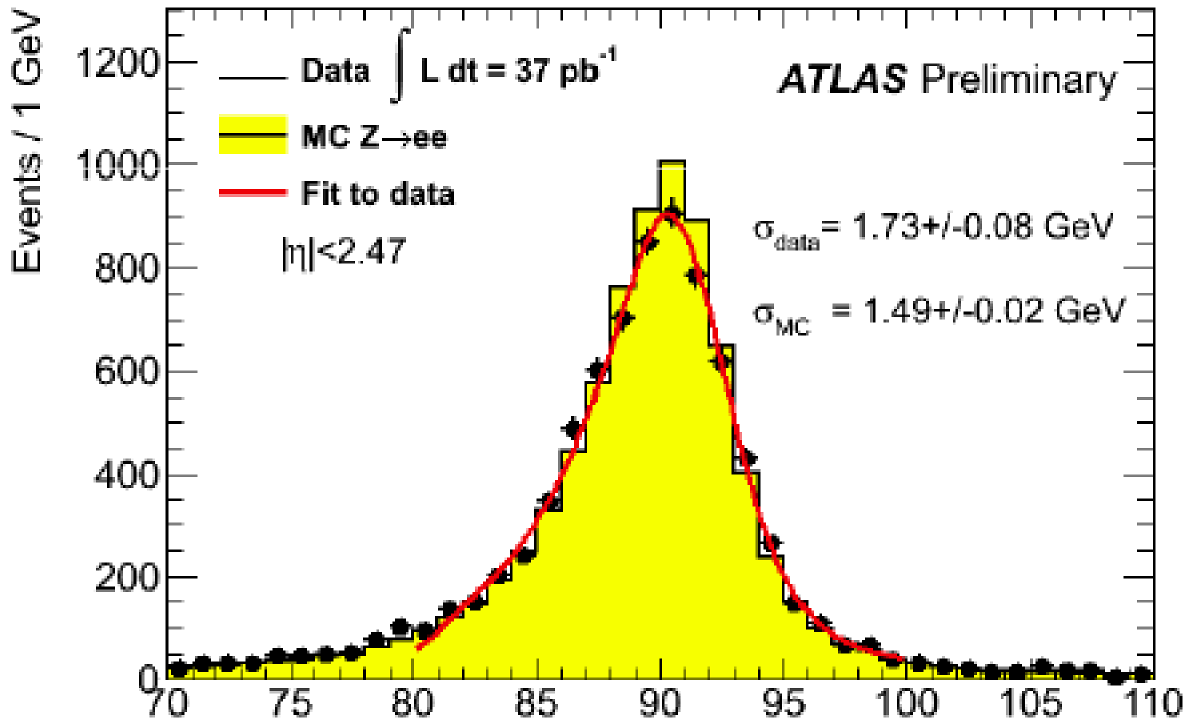
The distributions shown are remarkably clean and the resolution is astonishing.

Good prospects for precision physics

Just a few examples follow

Z -> dileptons

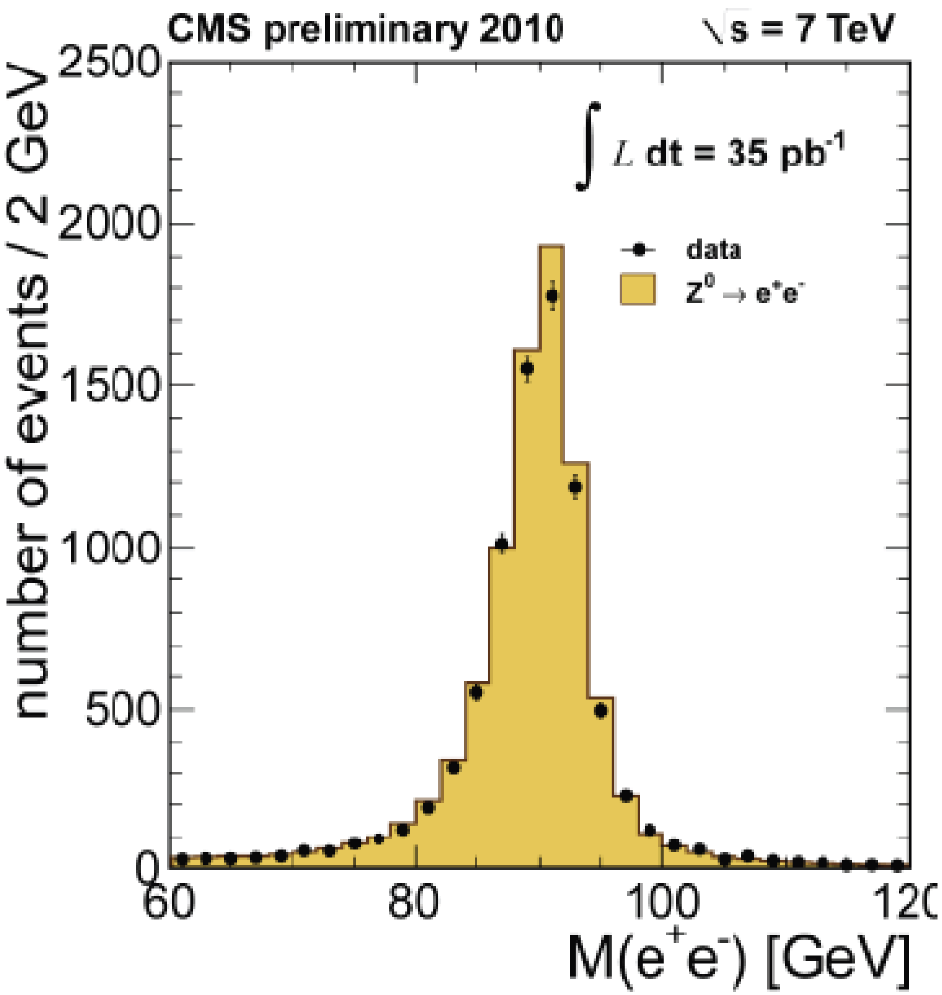
ATLAS
B. Mansoulie'

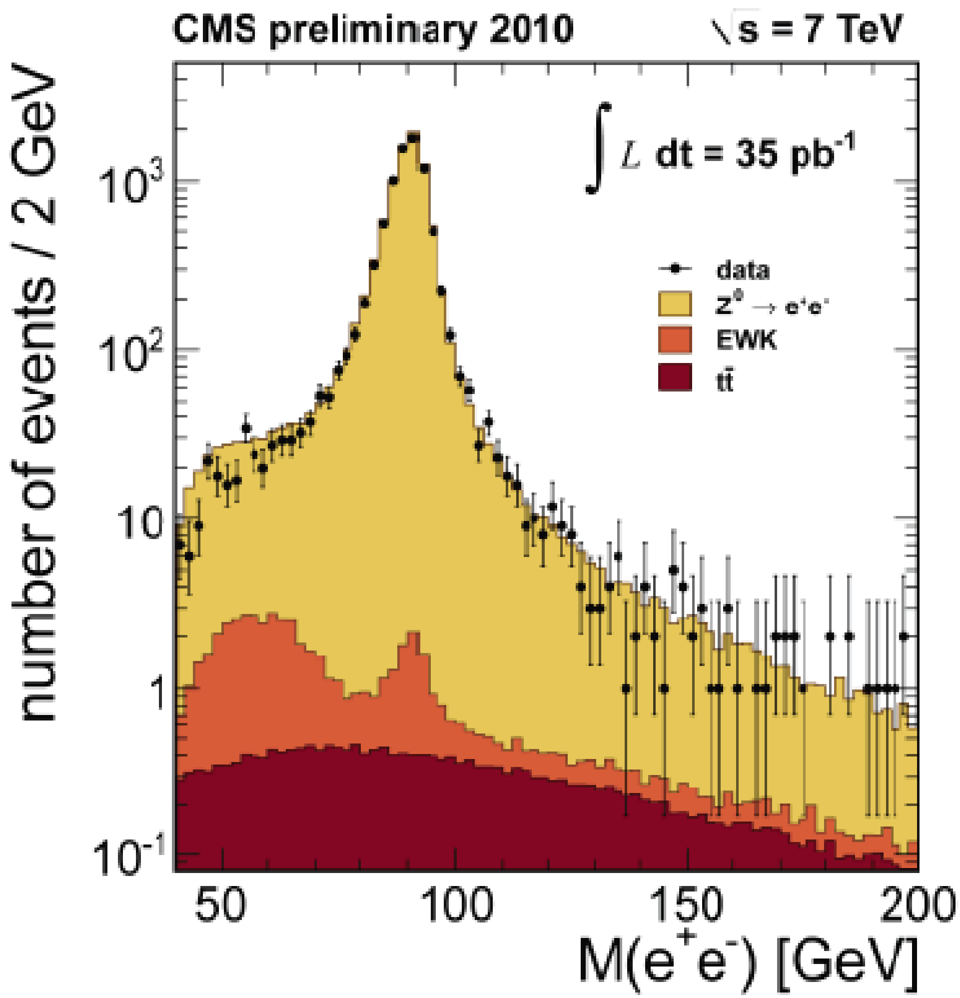


m_{ee}

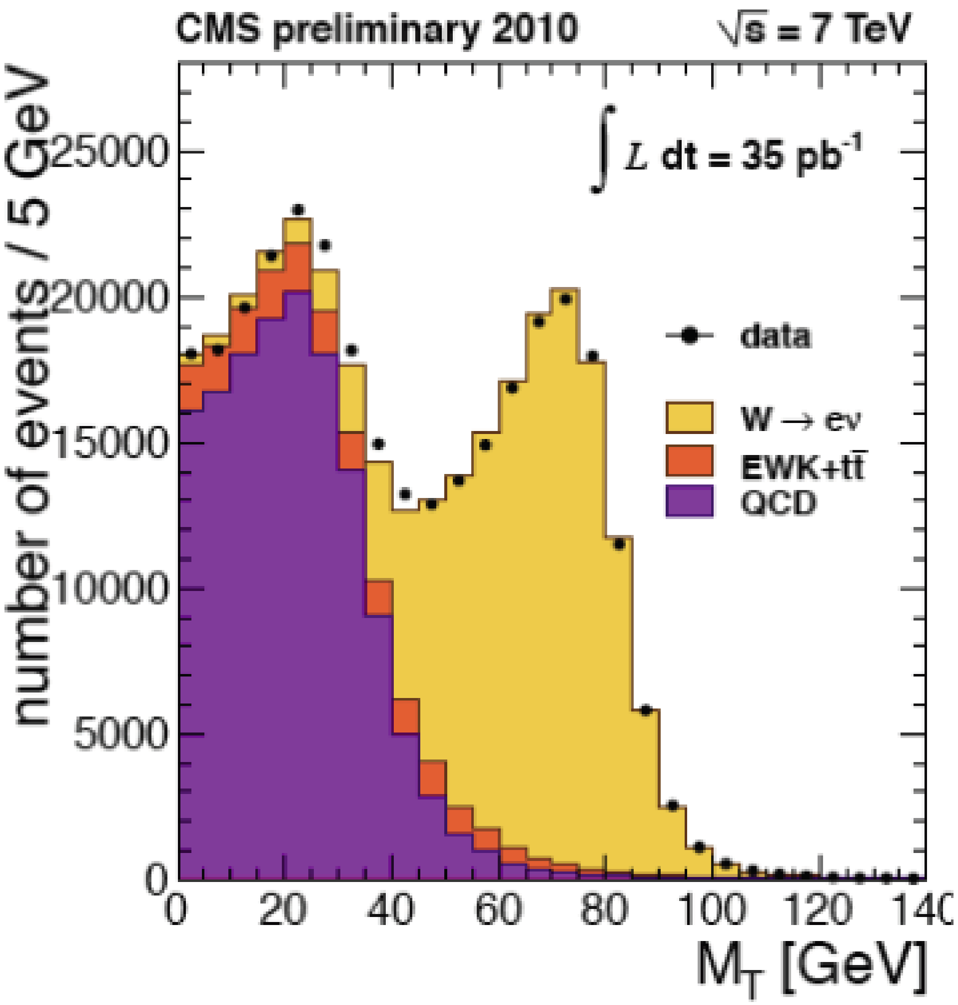
Z ee mass spectrum

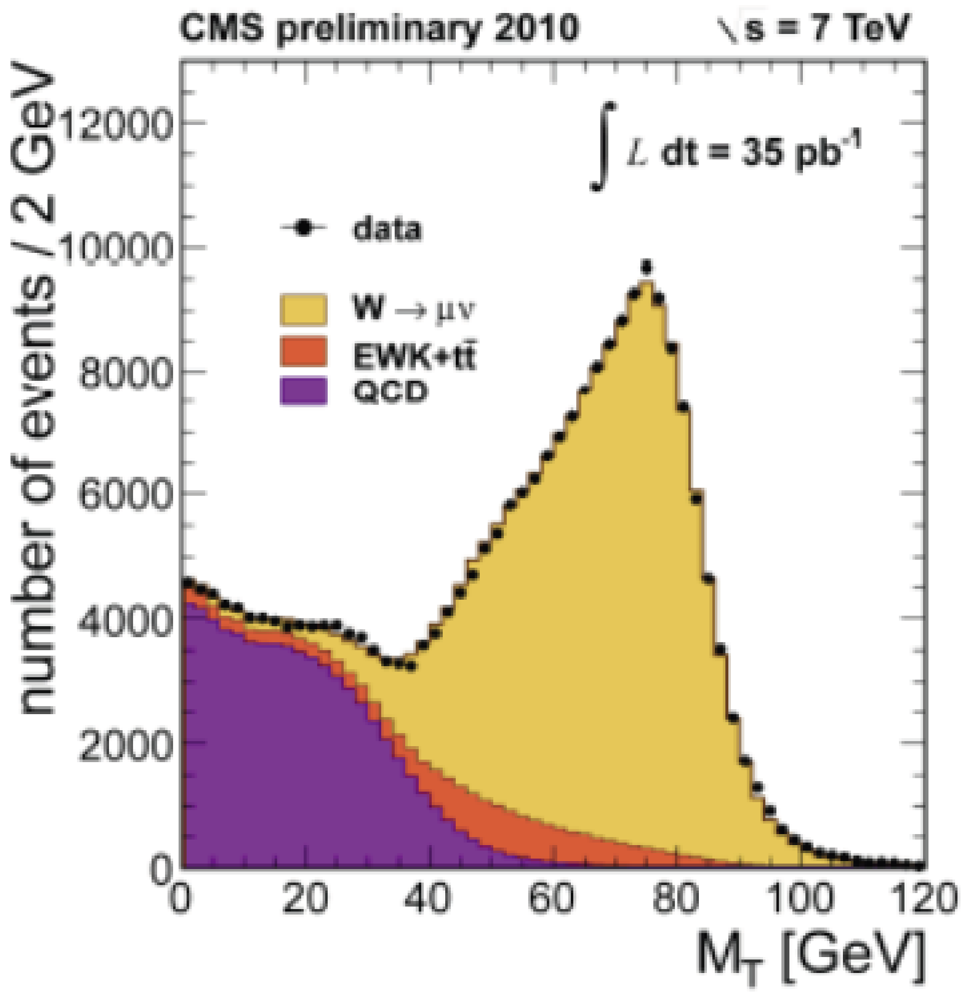
CMS
L. Rolandi





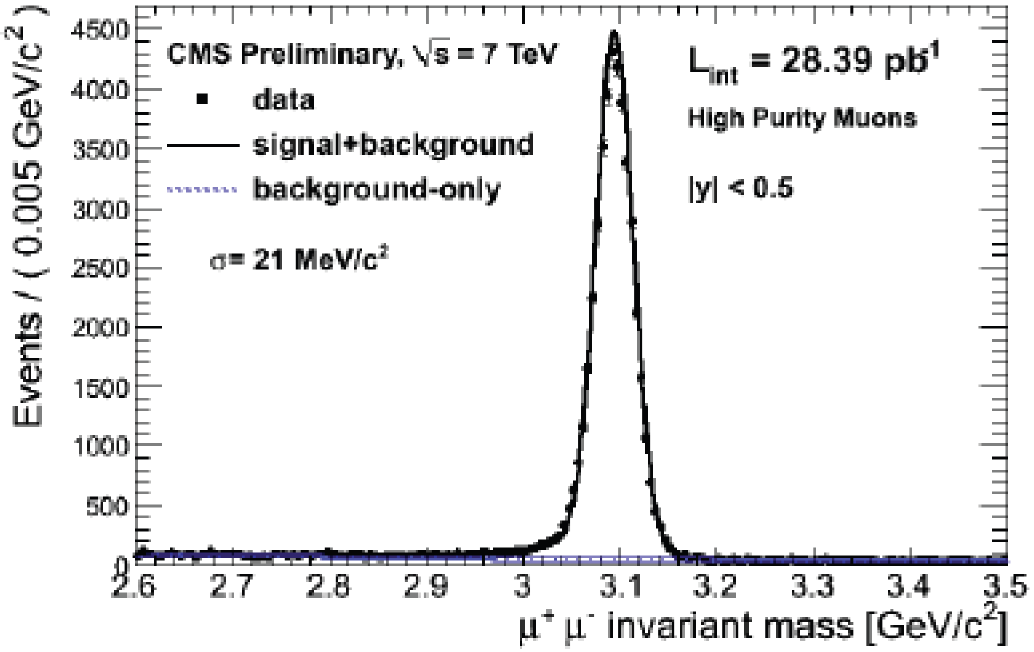
W Jacobian peaks



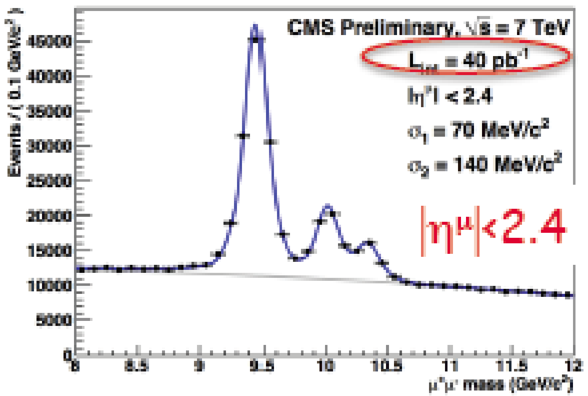


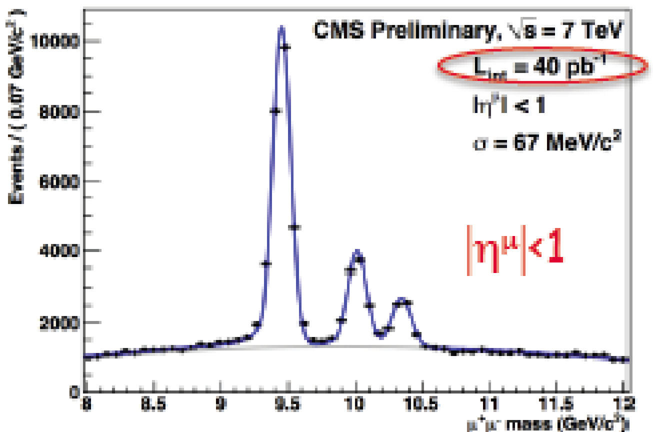
M_T =transverse mass

J/ψ producti



Y producti

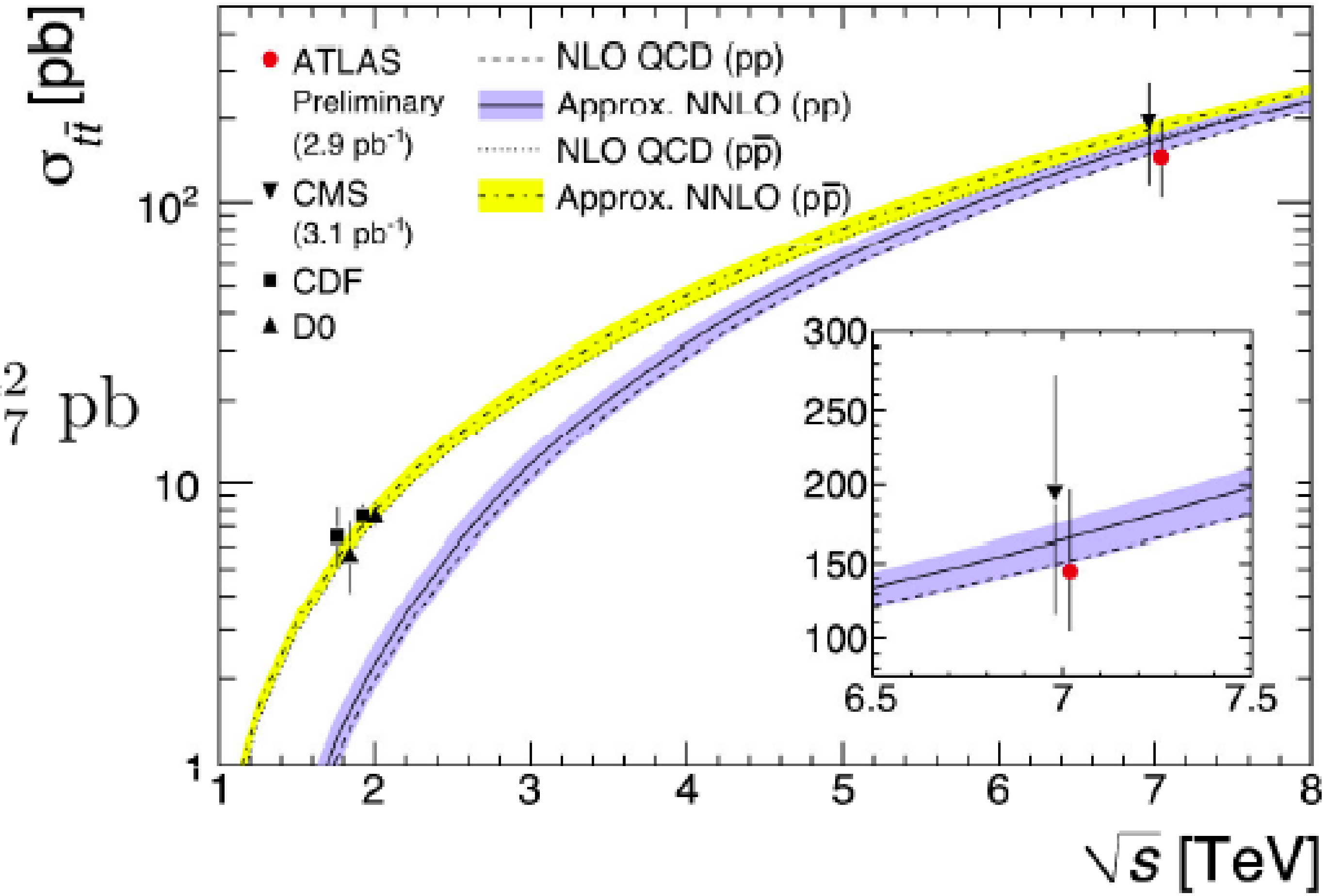




U1

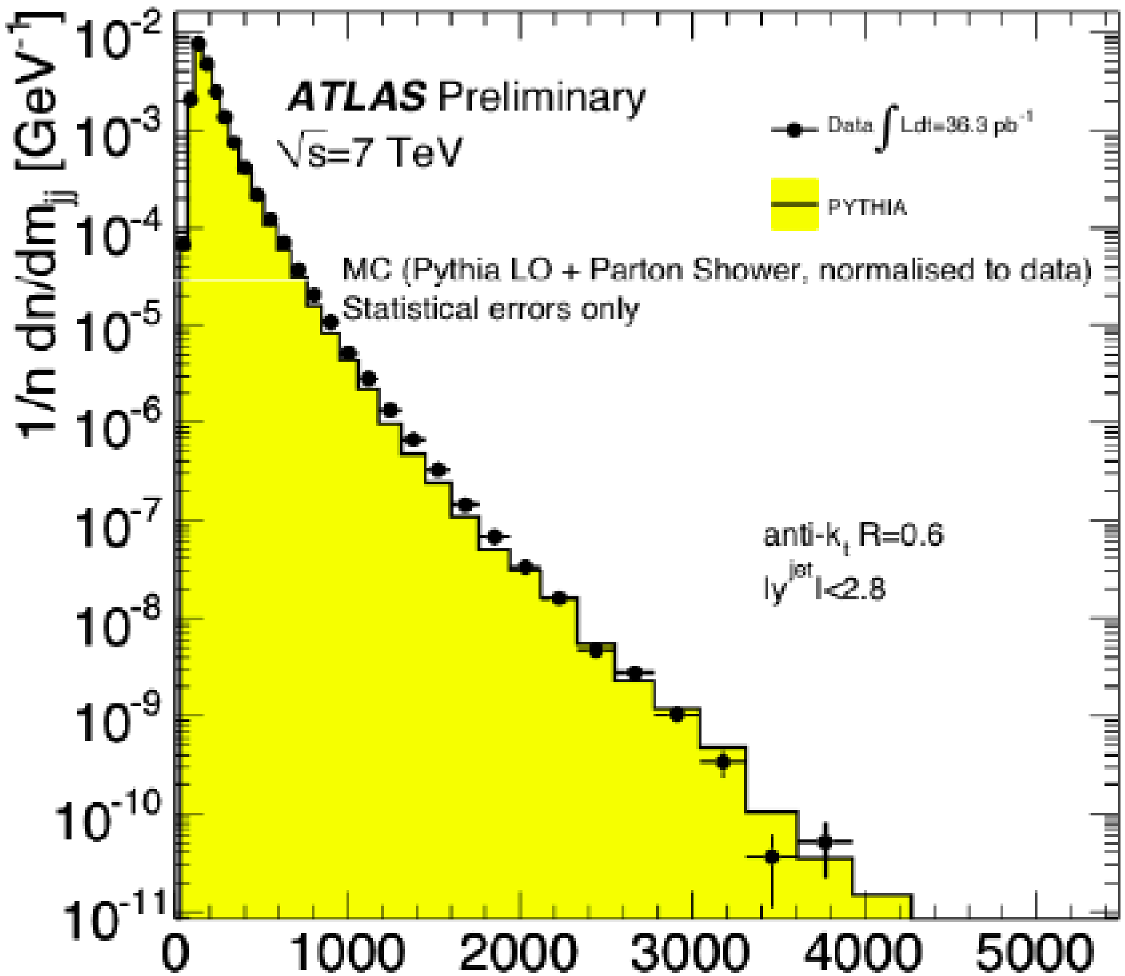
Top cross-section (combined)

$$\sigma_{t\bar{t}} = 145 \pm 31^{+42}_{-27}\ \mathrm{pb}$$



- **Significance ~4.8 σ (with respect to background only hypothesis).**

Jets

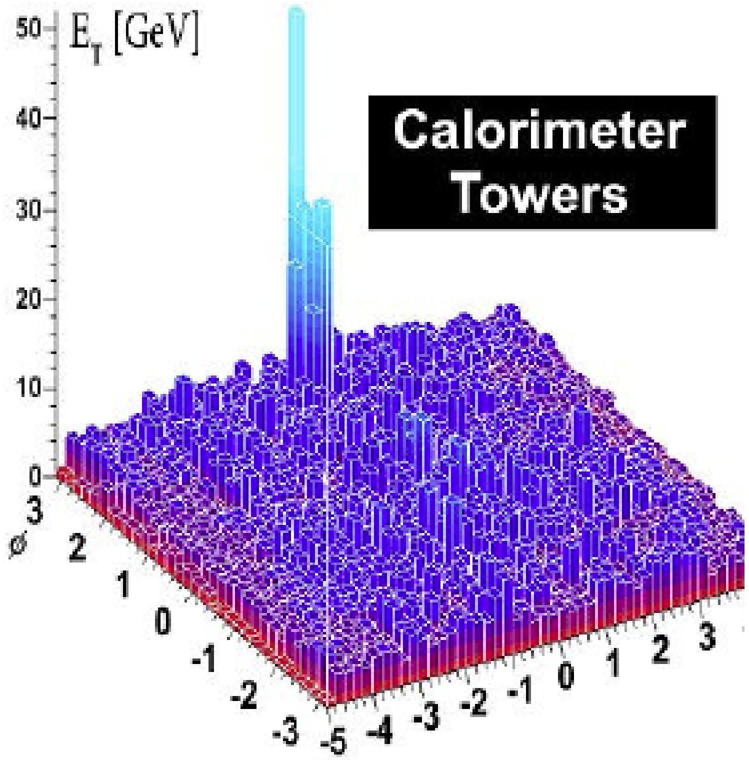

ATLAS Preliminary
$\sqrt{s}$=7 TeV
Data $\int$Ldt=36.3 pb^{-1}
PYTHIA
MC (Pythia LO + Parton Shower, normalised to data)
Statistical errors only
anti-k$_t$ R=0.6
$|y^{jet}|$<2.8
1/n dn/dm$_{jj}$ [GeV^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0
1000
2000
3000
4000
5000

m_{jj}(GeV)

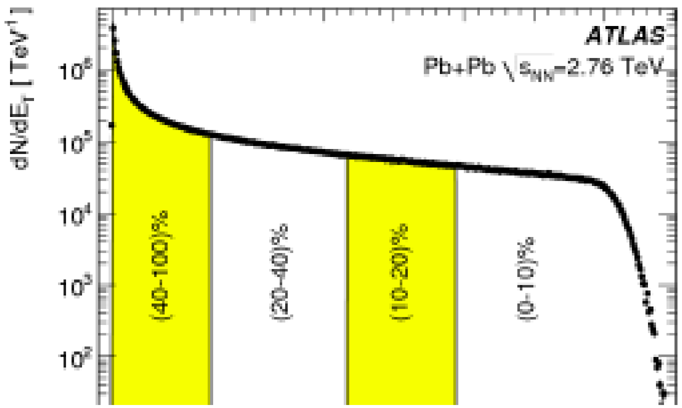
ATLAS
B. Mansoulie'

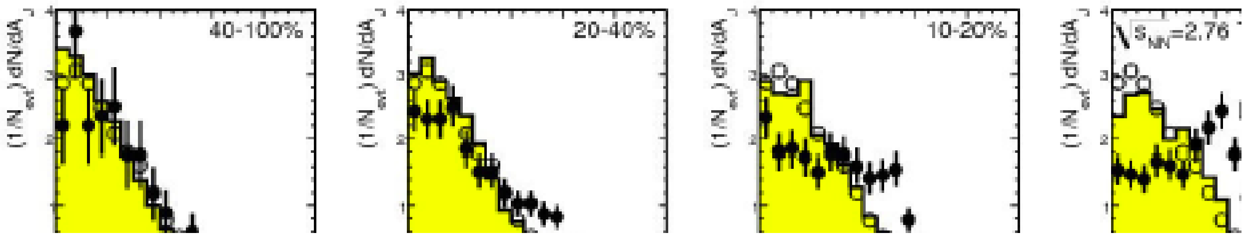
Heavy Ions

- **Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at √s(NN) = 2.76 TeV**



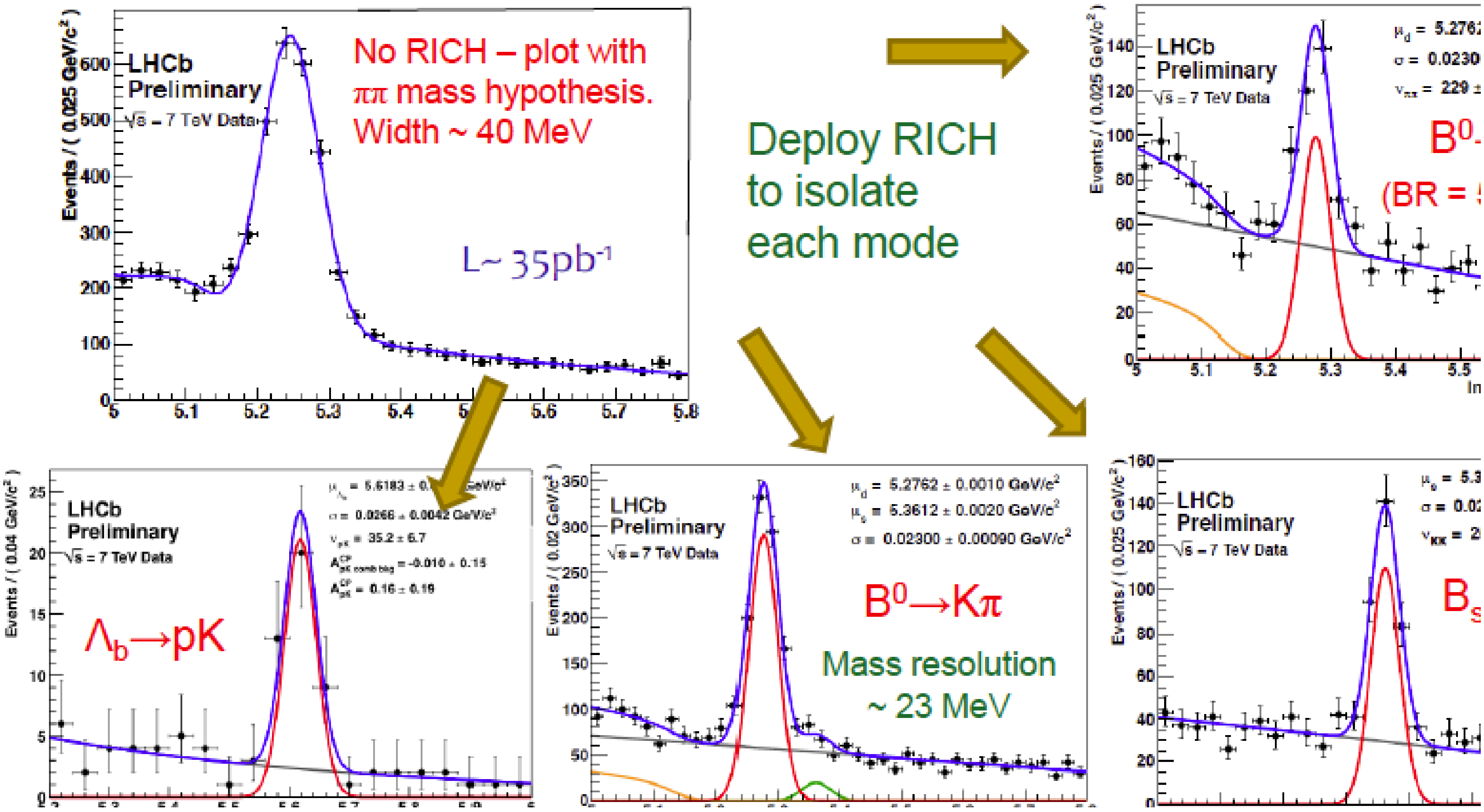
- **Use of the excellent jet and hadron calorimetry**





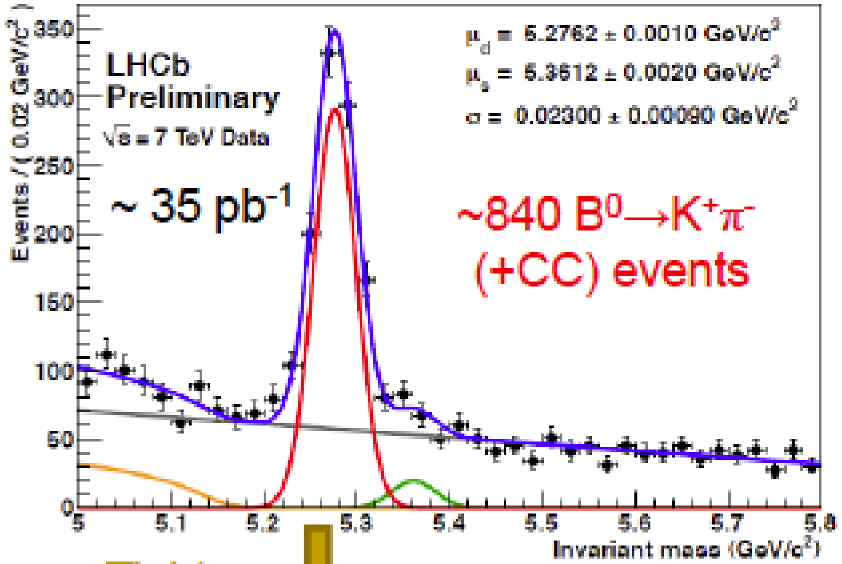
Two-body charmless B-decays central to LHCb physics. Significant contribution of Penguin diagrams provide entry points for new physics.

Experimentally, rely on good performance of hadron trigger and RICH syst



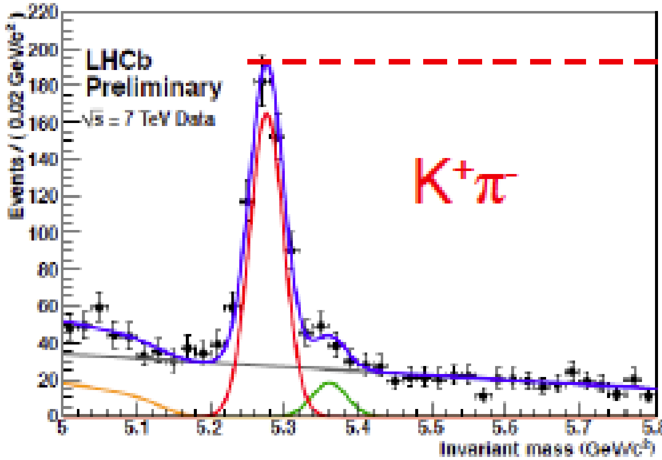
A closer look at B→Kπ

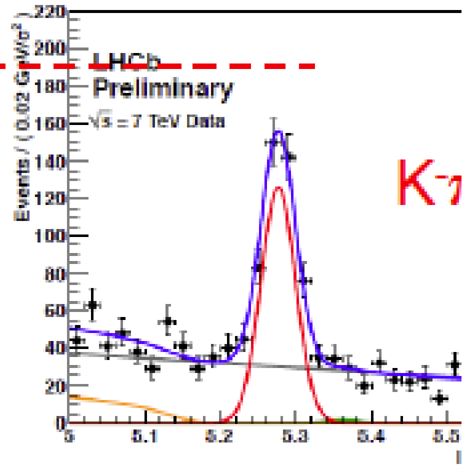
LHCb
G. Wilkins

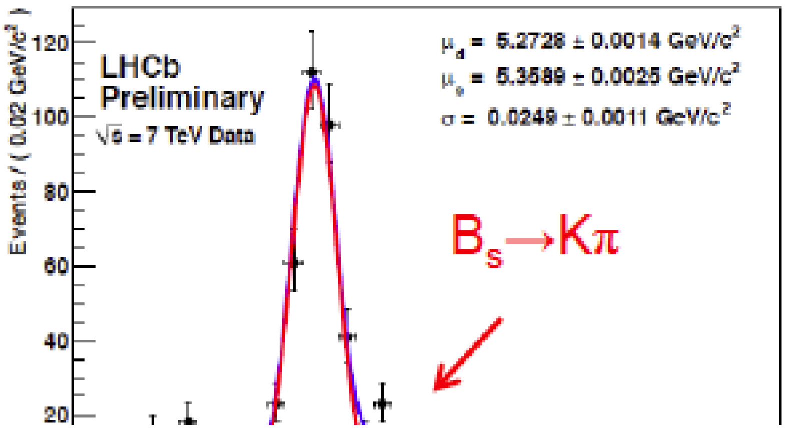


Divide into B^0 and B^0-bar

Tighter selection







Raw result shows CP-violation at > 3 σ wi
central value consistent with world-averag

Analysis being optimised & account being
of (small) production and detector asymm

Top physics priorities at the LHC (ATLAS&CMS):

- Clarify the EW symmetry breaking sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

Also:

- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram
- TOTEM, LHCf: forward pp physics

$\oplus$ At this point, fresh input from experiment is badly needed

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable, hence highly predictive.
And is well supported by the data.

However, we expect corrections from higher energies

not only from the GUT or Planck scales
but also from the TeV scale (LHC!)

But even as a low energy effective theory it is not satisfactory

QCD + the gauge part of the EW theory are fine,
but the Higgs sector is so far only a conjecture

The Higgs problem is central in particle physics today

A review: G.A. ArXiv:1003.3180

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

Origin of quadratic
divergences.
Hierarchy problem

Possible instability
depending on m_H

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

The Standard EW theory: $\mathcal{L} = \mathcal{L}_{symm} + \mathcal{L}_{Higgs}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W_\nu^A - \partial_\nu W_\mu^A - ig\varepsilon_{ABC} W_\mu^A W_\nu^B]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + gW_\mu^A t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = |[\partial_\mu - igW_\mu^A t^A - ig' B_\mu \frac{Y}{2}]\phi|^2 +$$

$$+ V[\phi^\dagger\phi] + \bar{\psi}\Gamma\psi\phi + \mathrm{h.c}$$

with $V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{symm}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{Higgs}$: ~ untested

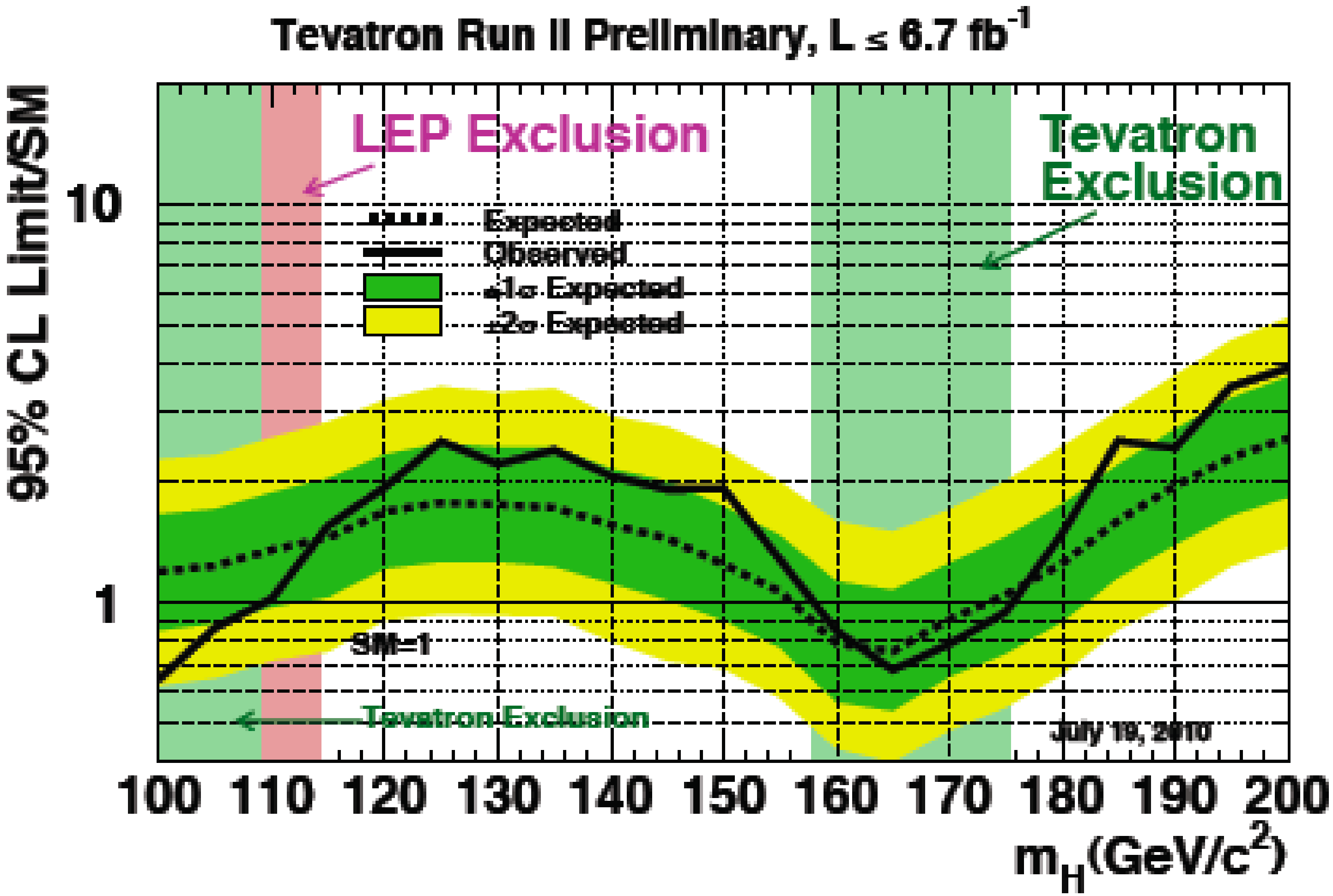
All we know from experiment about the SM Higgs:

No Higgs seen at LEP2 -> $m_H > 114.4$ GeV (95%cl)

Rad. corr's -> $m_H < 186$ GeV (95%cl, incl. direct search bound)

$v = \langle\phi\rangle = \sim 174$ GeV ; $m_W = m_Z \cos\theta_W$ $\longrightarrow$ doublet Higgs

In the H search the Tevatron has now reached the SM sensitivity



Excluded at 95%cl: $158 < m_H < 175$ GeV

10 fb^{-1} by '11: could perhaps exclude $145 < m_H < 185$ GeV !!!

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

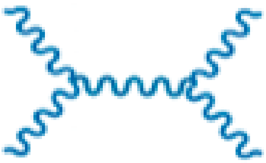
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

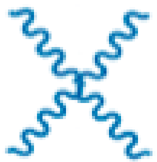
In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints

[Veltman, 1977; Lee-Quigg-Thacker, 1977; ...]

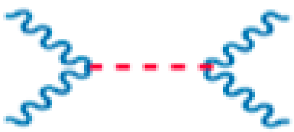
Zwirner

An example: $\mathcal{A}(W_L^+ \, W_L^- \longrightarrow Z_L \, Z_L) \quad (s \gg m_W^2)$





$$i \frac{s}{v^2}$$



$$-i \frac{s^2}{v^2(s-m_h^2)}$$

$$\rightarrow \quad -i \frac{m_h^2}{v^2} \frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

  W′, Z′
  KK recurrences
  resonances from a strong sector
  ......

At the Terascale something new must be found:
either the Higgs or new physics or both

Is it possible that the Higgs is not found at the LHC?

Here "Higgs" means the "the EW symmetry breaking mechanism"

Looks pretty unlikely!!

The LHC discovery range is large enough: $m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

A heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > \sim$ TeV)

e.g. strongly interacting WW or WZ scattering

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

The SM good agreement with the data favours forms of new physics that keep at least some Higgs light

Why precision? What for?

To me precision at the LHC is

first, a tool for enhancing
the discovery potential of new physics

better PDF, more precise α_s, N^nLO calculations in SM
and beyond, better jet finding algorithms....

second, as we can profit of this beautiful instrument,
the possibility of doing all intelligent possible use of it

m_W, m_t, $\sin^2\theta_W$ to unprecedented precision is a
formidable experimental/intellectual challenge

Plot m_W vs m_H

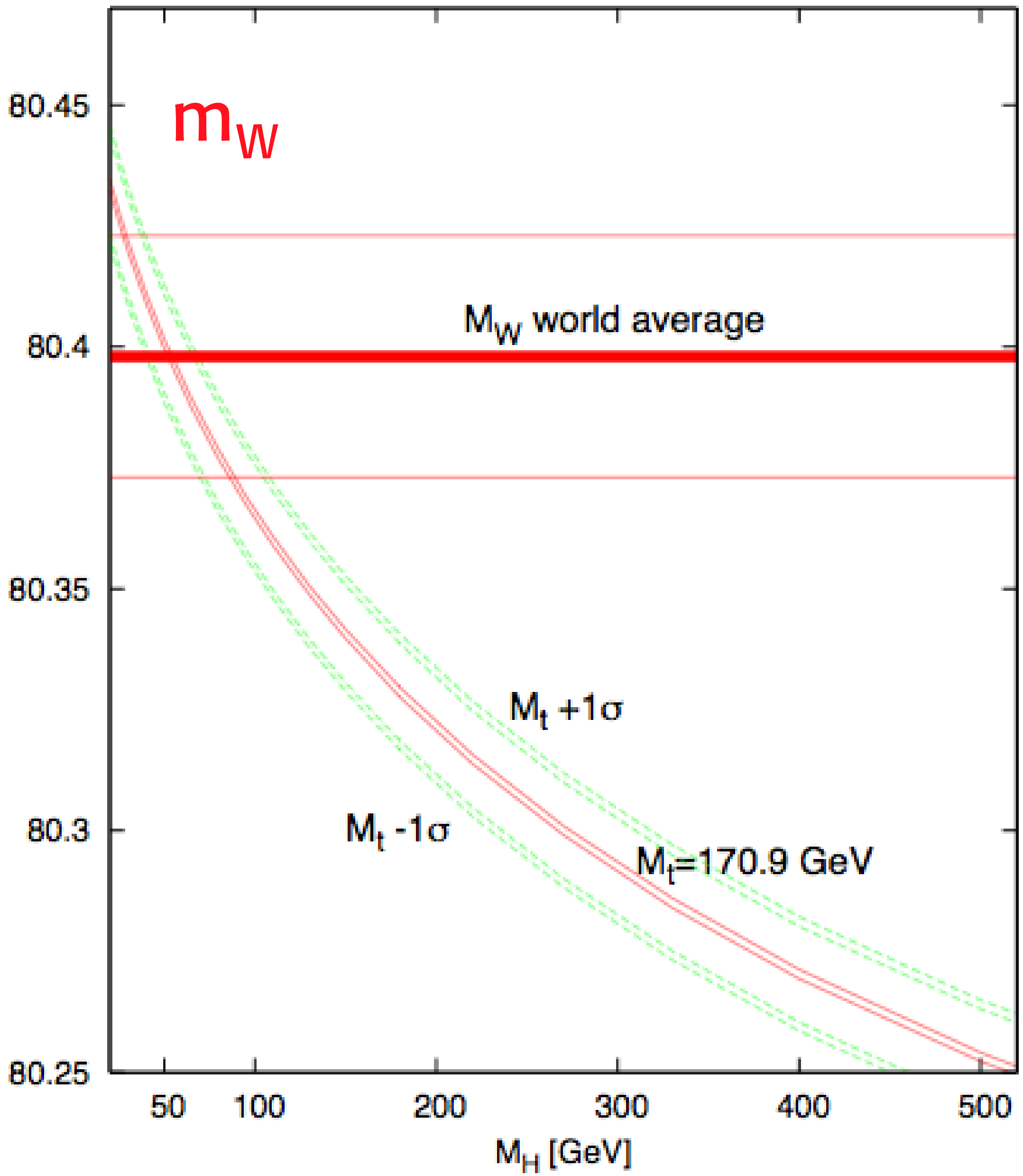
P. Gambino

m_W points to a light Higgs!

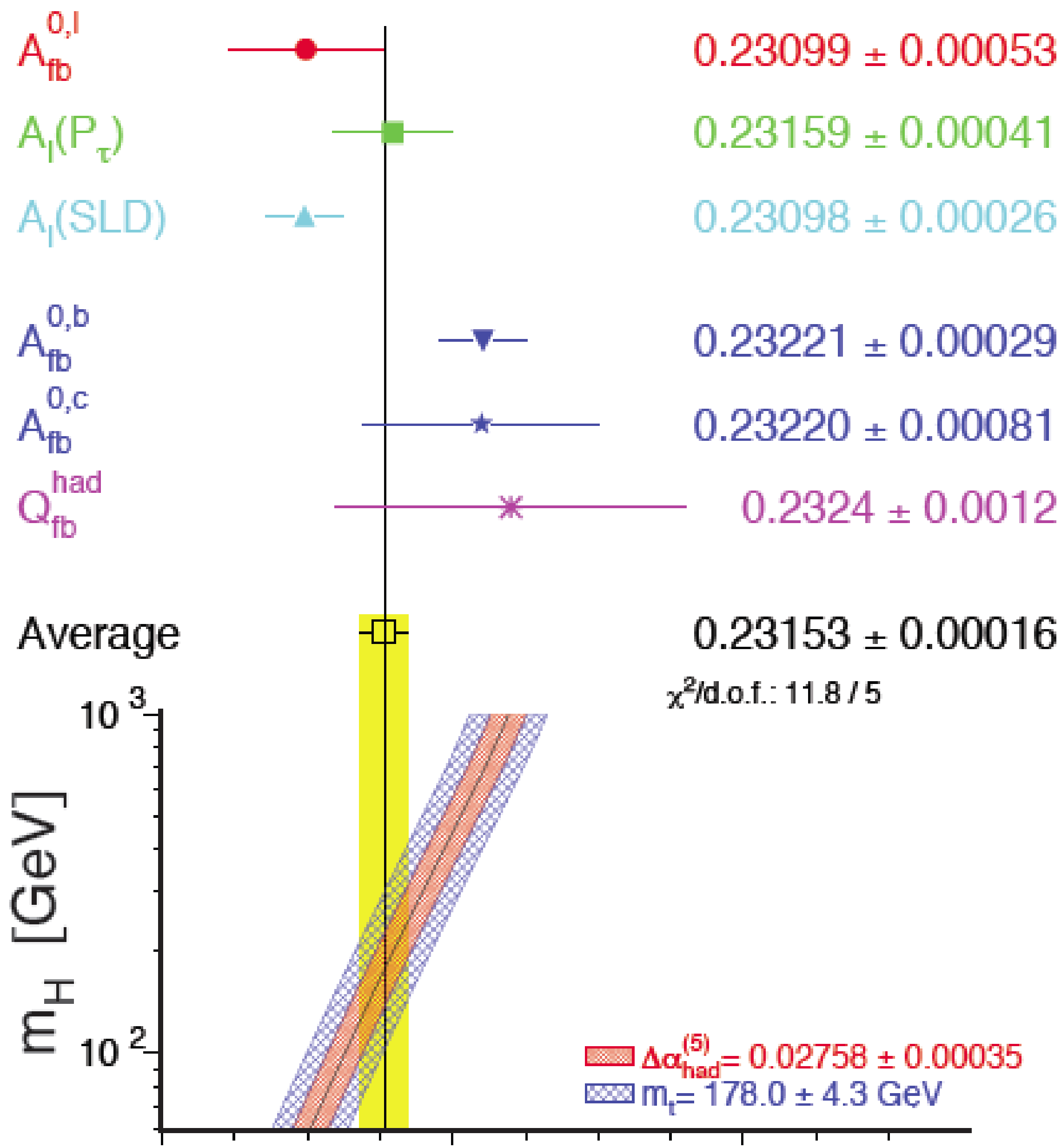
Like $[\sin^2\theta_{eff}]_l$

2008:
m_W=80399(25)MeV
m_t=170.9 (1.3)GeV

2010:
m_W=80399(23)MeV
m_t=173.3 (1.1)GeV



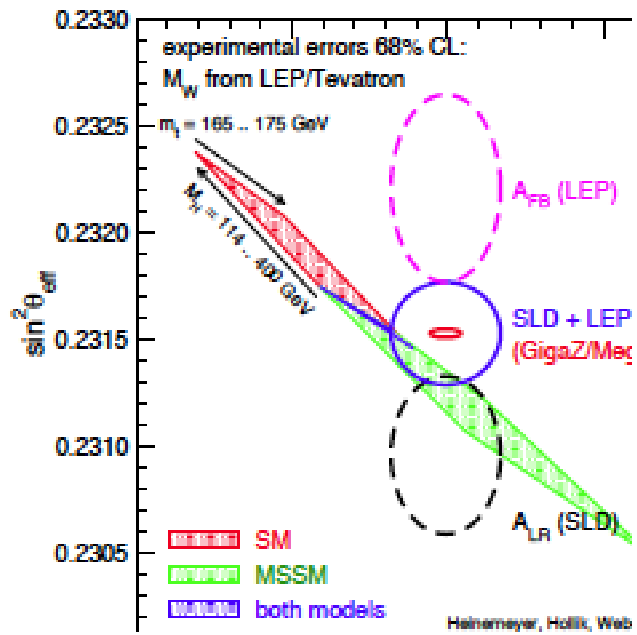
Summary $\sin^2\theta_{eff}$ Measurements



- Very precise measurer
- Average dominated by A_{LR}(SLD) and A^b_{FB}

  … which agree margin

  (3.2σ, but overall average χ^2 = 11.8 / 5 dof → 2.0 σ)
-

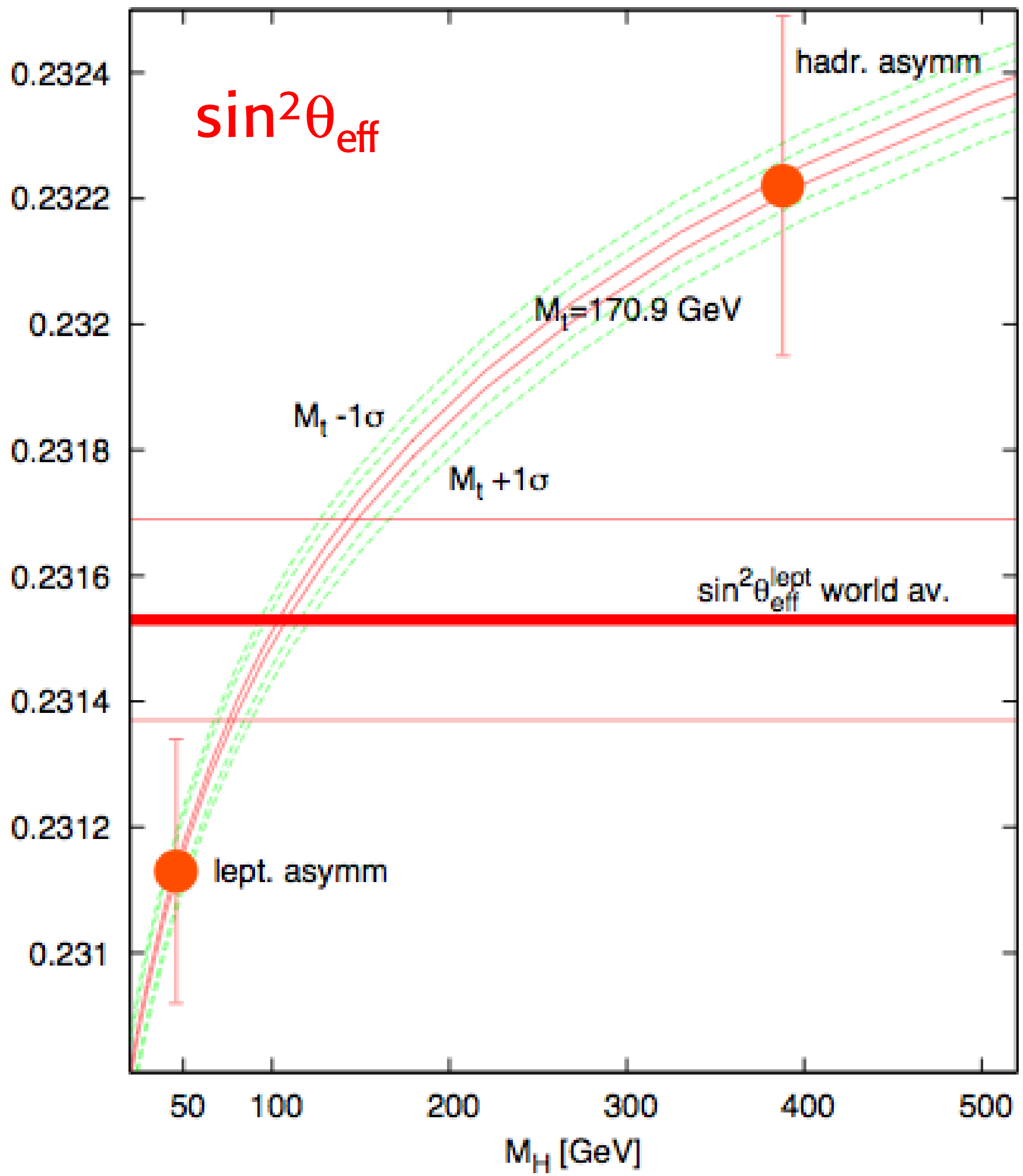


P. Gambino

Plot $\sin^2\theta_{eff}$ vs m_H

Exp. values are plotted at the m_H point that better fits given m_{texp}

Clearly leptonic and hadronic asymm.s push m_H towards different values



A^b_{FB} vs $[\sin^2\theta]_{lept}$: New physics in Zbb vertex?

After all the 3rd generation is somewhat special

The difficulty is that:

- No deviations are seen in A_b (SLD) and R_b
- A quite large shift in g_R, the Zbb right-handed coupling is needed (by ~30%: a tree level effect)

$$A^b_{FB} = \frac{3}{4} A_e A_b \qquad A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}$$

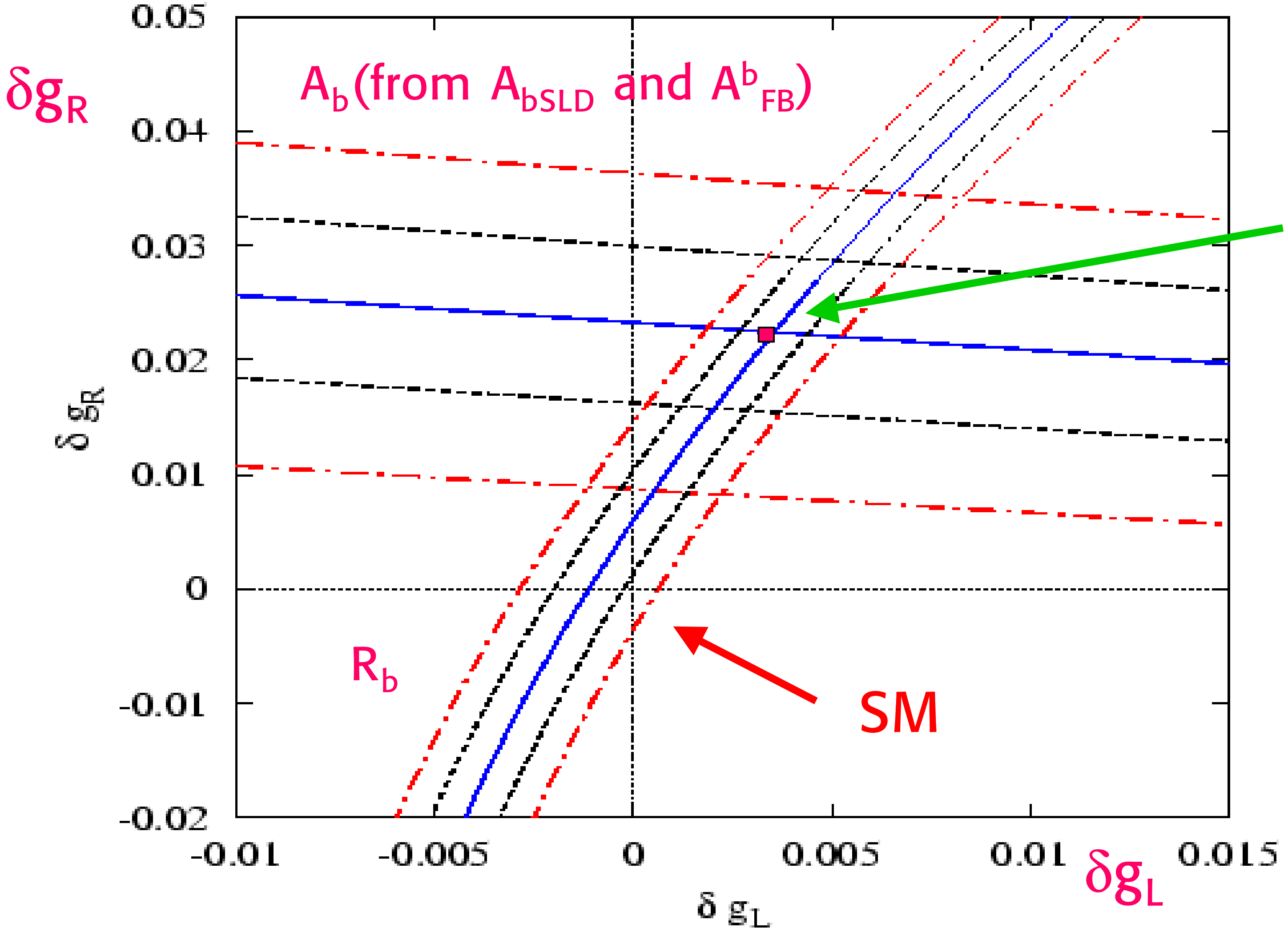
SM: $g_L^2 \approx 0.72 >> g_R^2 \approx 0.02$ $\qquad (A_b)_{SM} \approx 0.936$

from A^b_{FB} $\rightarrow (A_b)_{SM} - A_b = 0.055 \pm 0.018 \rightarrow \sim 3\,\sigma$

But note: $(A_b)_{SLD} = 0.923 \pm 0.020$, $\qquad R_b \sim g_L^2 + g_R^2$

also $R_b = 0.21629 \pm 0.00066$ $(R_{bSM} \sim 0.2157)$

Choudhury, Tait, Wagner '01



$0.992\ g_L(SM)$, $1.26\ g_R(SM)$

Too large for a loop effect. Needs a ad hoc tree level effect

There are many models where this can happen

(not easy: a large change in g_R and a small one in g_1)

Mixing of the b quark with a vectorlike doublet (ω,χ) with charges (2/3, -1/3) or (-1/3, -4/3)

Choudhury,Tait, Wagner '01

Or mixing of Z with Z' and KK recurrences in extra dim models

Djouadi, Moreau, Richard '06

Composite Higgs models where the 3rd generation is also mostly composite

Agashe, Contino, Pomarol '07;

A. Hoecker anomalous magnetic moment of the muon

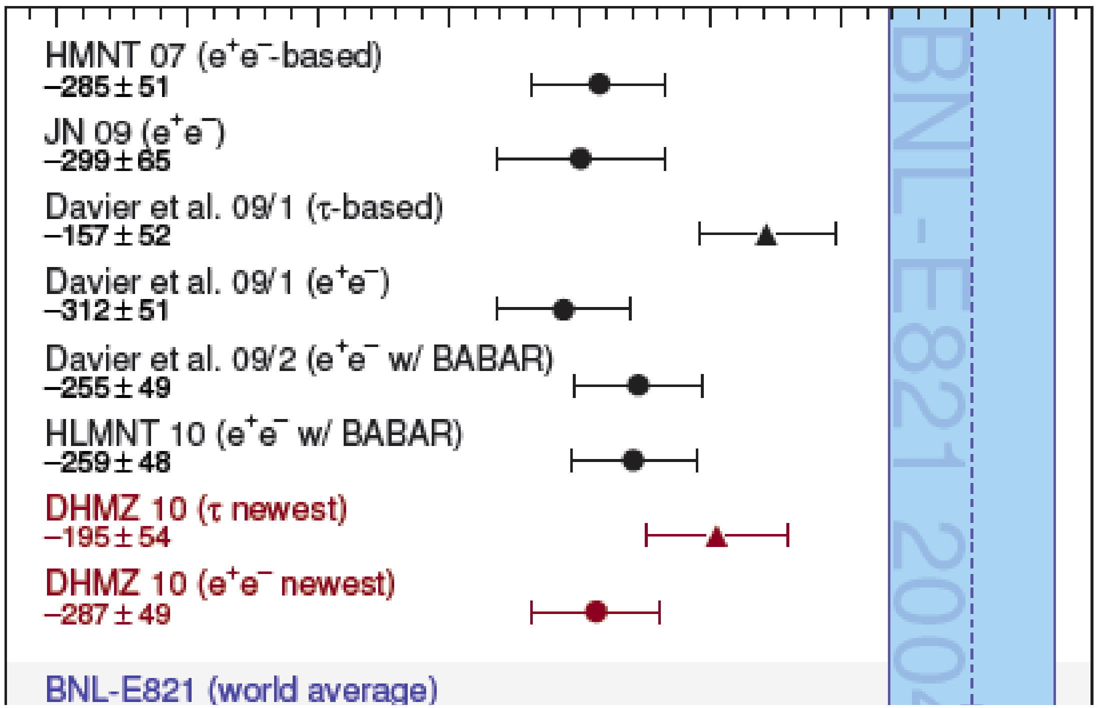
Experimental result (E821-BNL, 2004): $a_\mu = (11\,659\,208.9 \pm 5.4 \pm 3.3) \times 10^{-10}$ E82 072

Standard Model Prediction:

$$a_\mu^{SM}[e^+e^-\text{-based}] = (11\,659\,180.2 \pm 4.2_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

$$a_\mu^{SM}[\tau\text{-based}] = (11\,659\,189.4 \pm 4.7_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

DMHZ, arXiv:1010.4180



Observed Difference with Experim

$$a_\mu^{exp} - a_\mu^{SM} = (28.7 \pm 8.0)\ \times$$
$$= (19.5 \pm 8.3)\ \times$$

➡ 3.6 / 2.4 "standard devi

Davier-Hoecker-Malaescu-Zhang, arXiv

The deviation is in the ball pa
of SUSY expectations with

Muon g-2 and SUSY

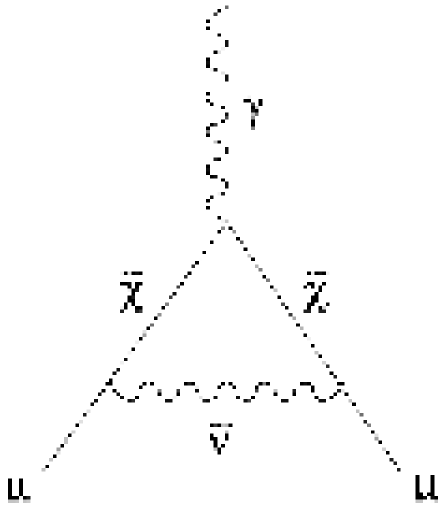
Observed Difference with Experiment:

$$a_\mu^{\exp} - a_\mu^{SM} = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 ”standard deviations“

Could be new physics
eg light SUSY

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100 GeV}{M_{SUSY}} \right)^2 tg\beta$$



a_μ is a plausible location for a new physics signal!!

Why precision? What for?

To me precision at the LHC is

first, a tool for enhancing
the discovery potential of new physics

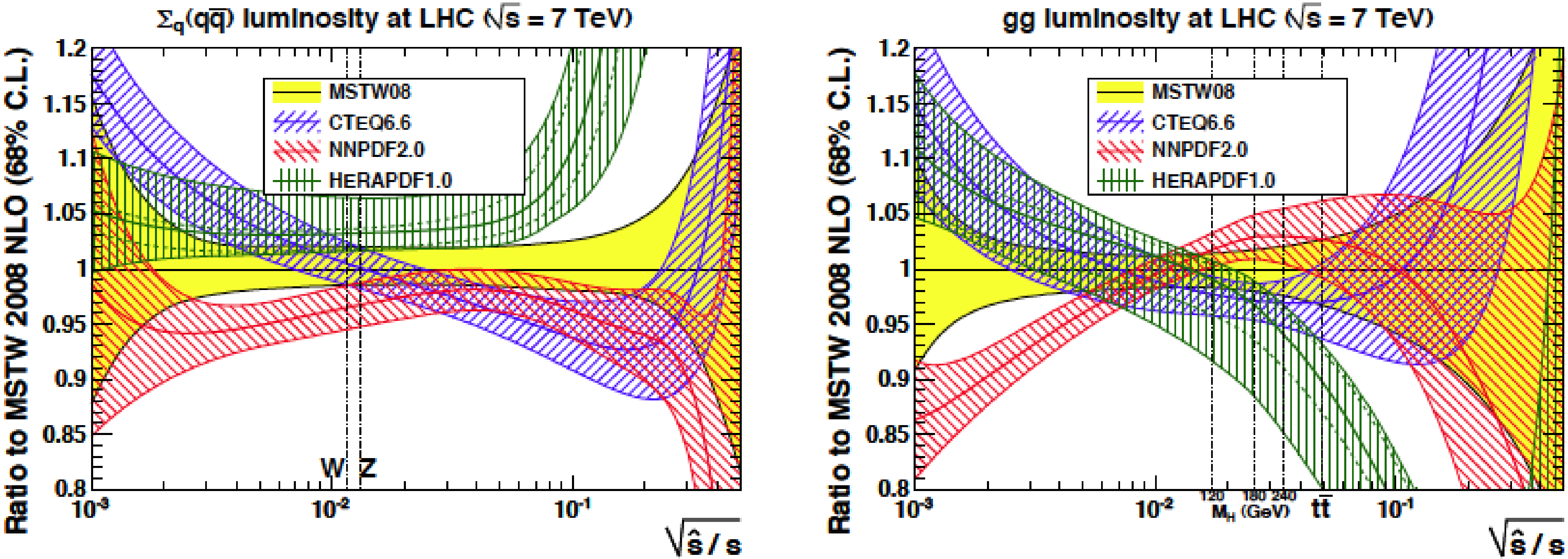
better PDF, more precise α_s, N^nLO calculations in SM
and beyond, better jet finding algorithms....

second, as we can profit of this beautiful instrument,
the possibility of doing all intelligent possible use of it

m_W, m_t, $\sin^2\theta_W$ to unprecedented precision is a
formidable experimental/intellectual challenge

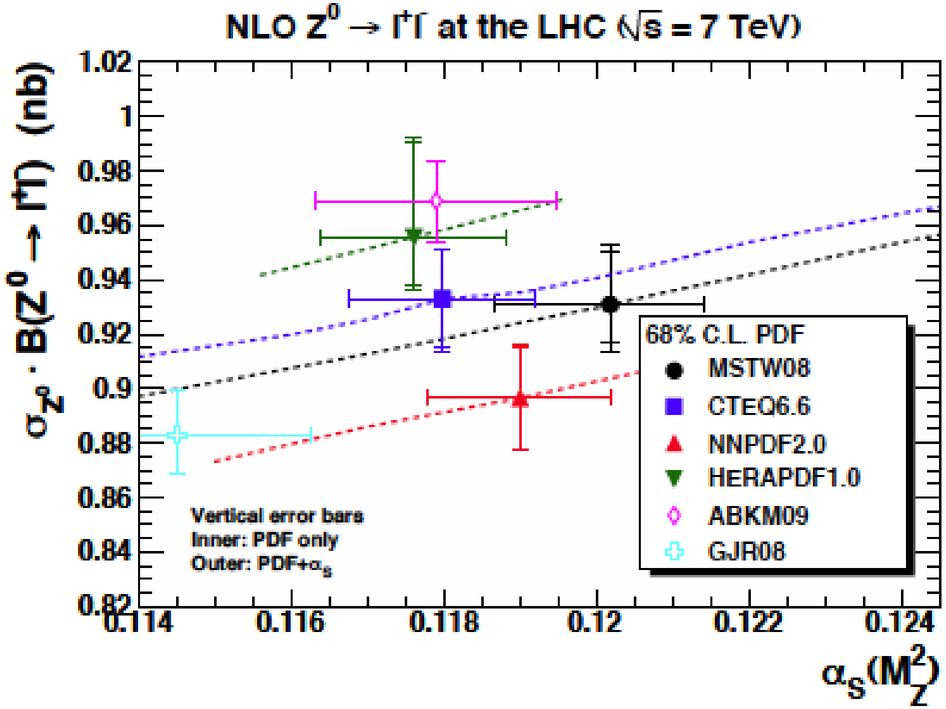
P. Slavich

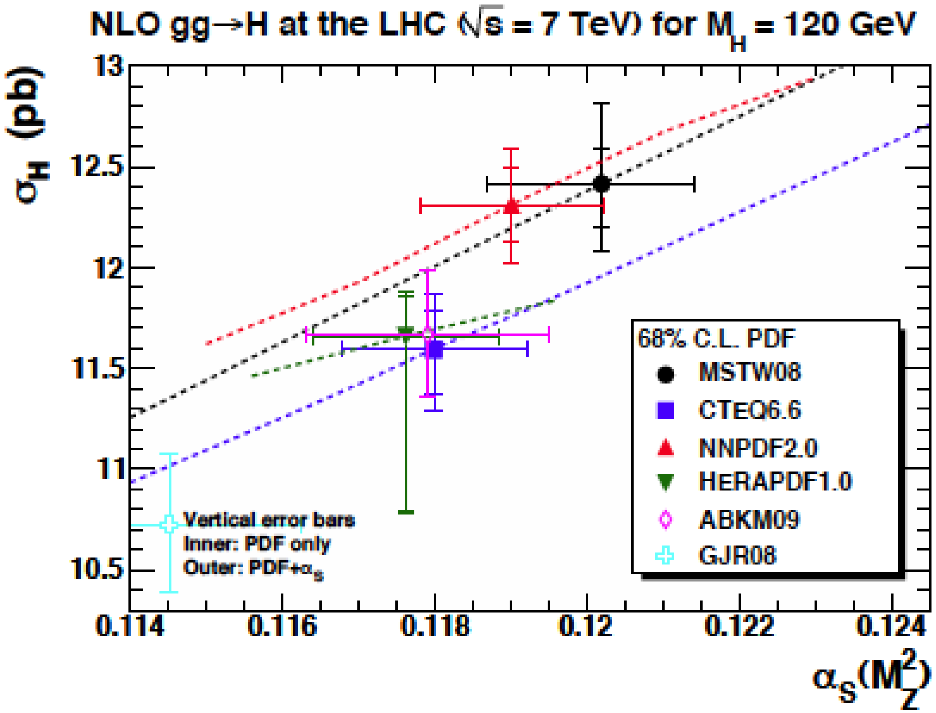
importance of improving the pdf's



parton luminosities: $$\frac{\partial \mathcal{L}_{ab}}{\partial(\hat{s}/s)} = \int_0^1 dx_a dx_b \, f_a(x_a,\hat{s}) f_b(x_b,\hat{s}) \, \delta(x_a x_b - \hat{s}/s)$$

P. Slavich
A. Glazov

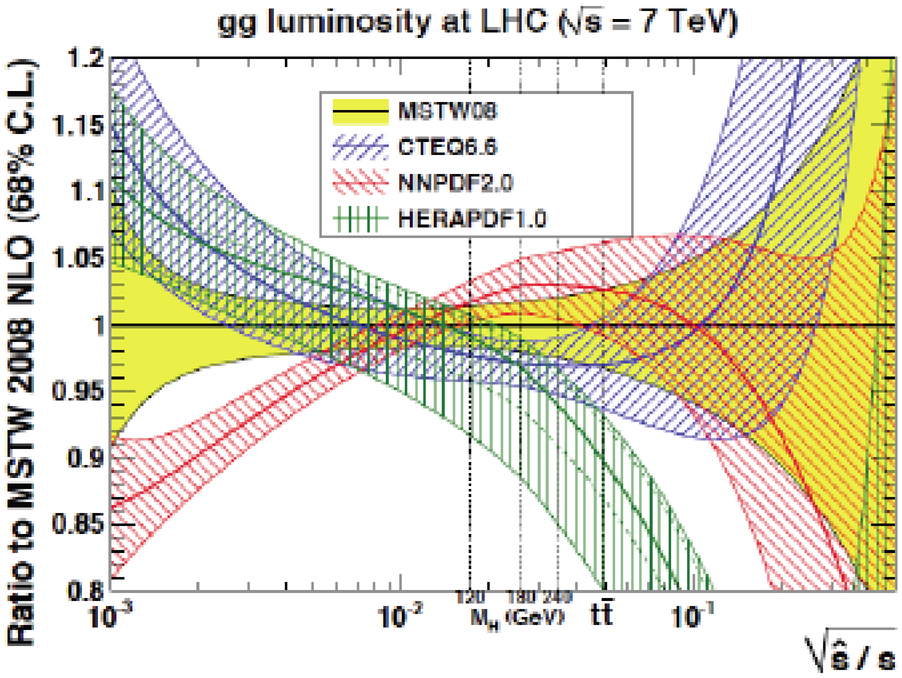


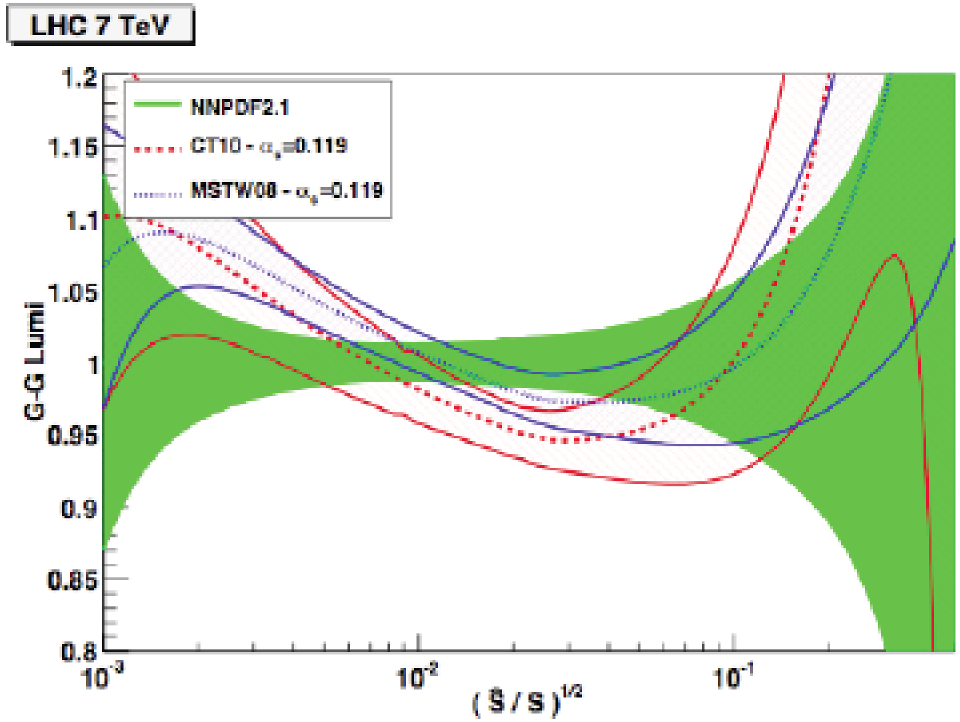


PDFs @ the LHC

S. Forte
M. Ubiali

Towards an increasing agreement





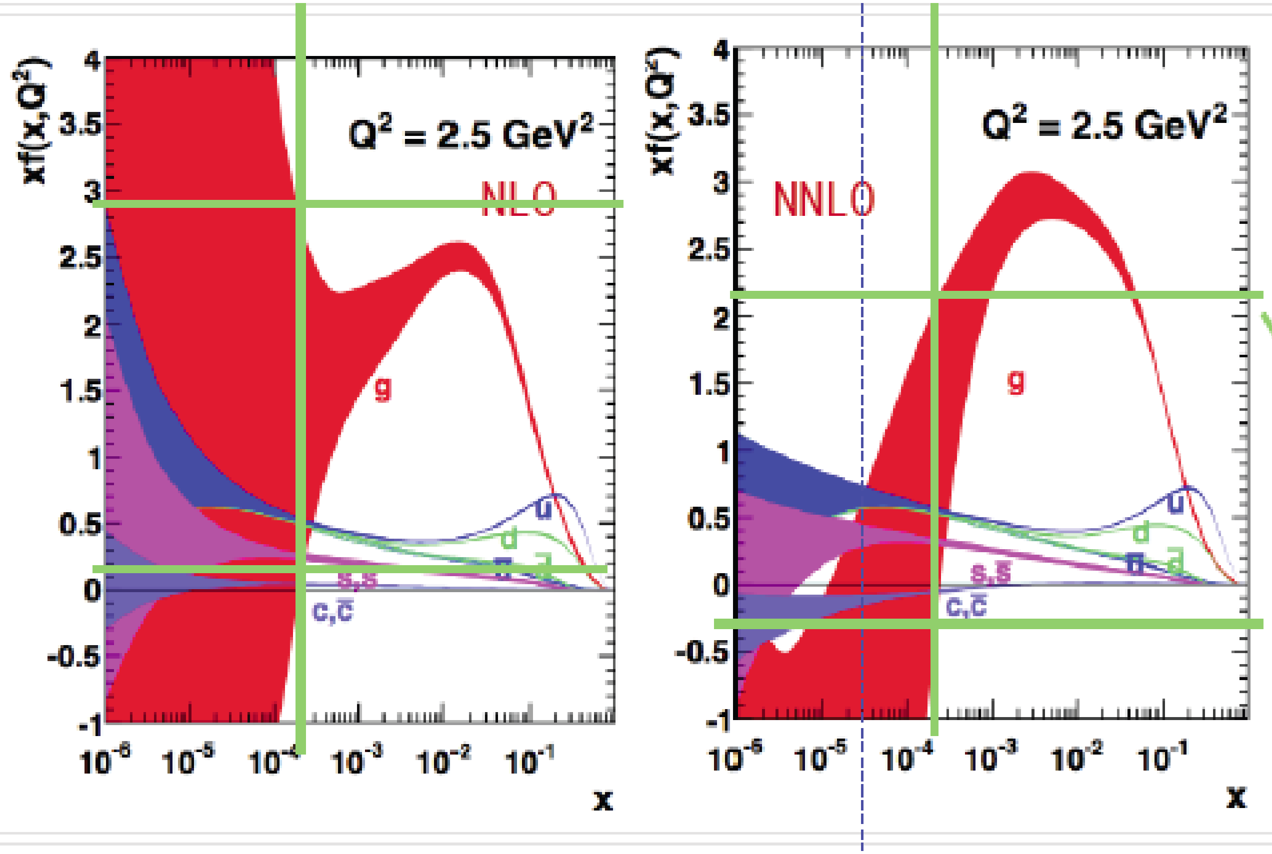
$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$

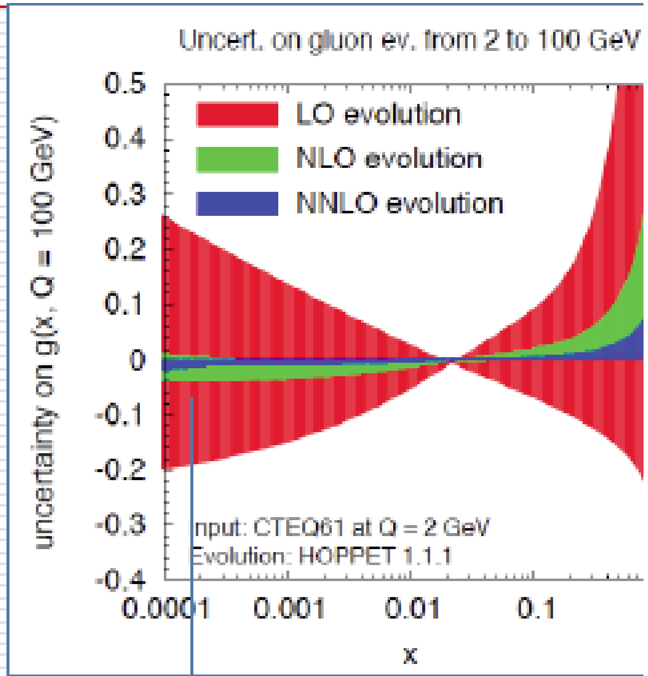
Parton luminosities

Theoretical error
Higher orders: NNLO

S. Forte
M. Ubiali

- ✓ NNLO parton sets to match NNLO theoretical predictions
- ✓ NNLO evolution reduces theoretical uncertainty
- ✓ Caveat: jets cross-sections and coefficient functions for massive heavy quark production still at NLO
- ✓ NNLO partons: only slight improvement of global χ^2, and uncertainty in data region.





Salam, 1011.513

scale variation

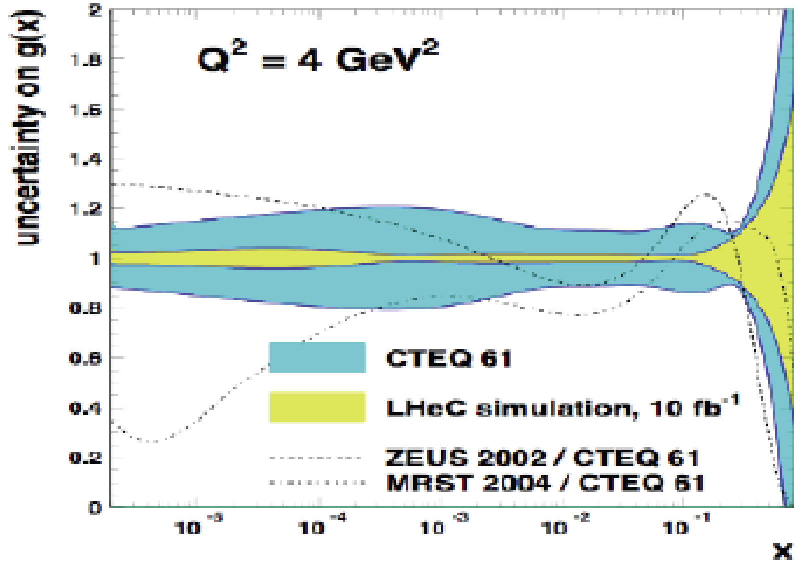
PDFs uncertainty

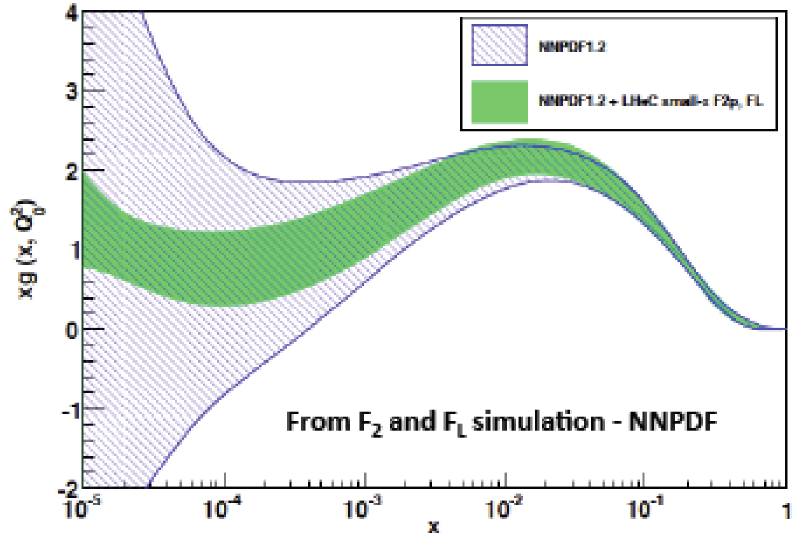
MSTW08, 0901.0002

The LHeC would be the solution

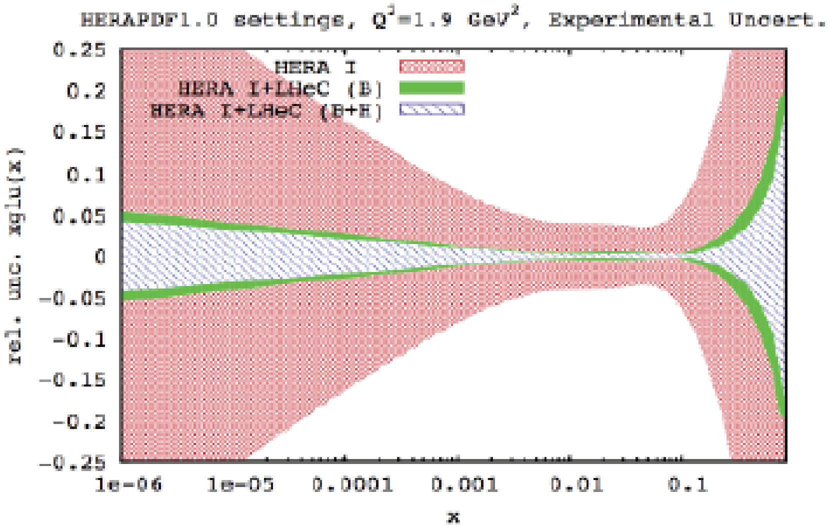
Gluon Distribution

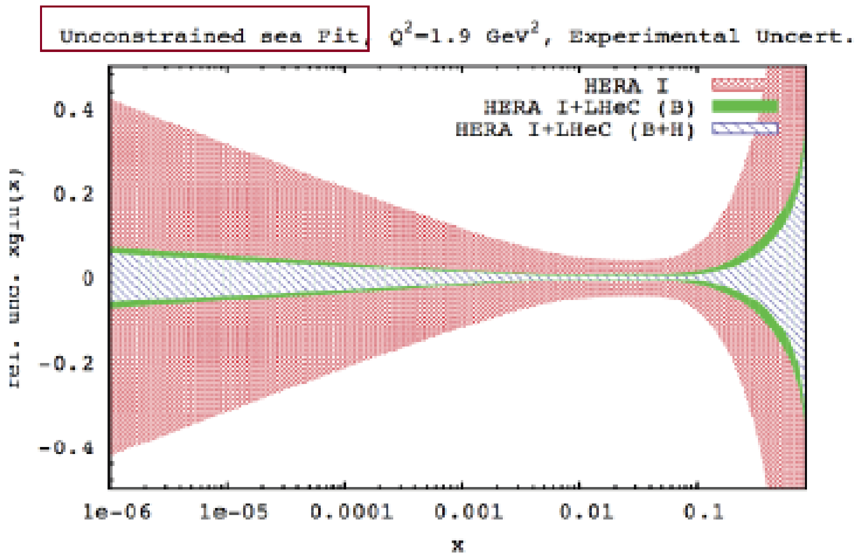
M. Klein





NLO QCD “Fits” of LHeC simulated data





For precision physics extremely accurate calculations are needed

A great effort has been made in computational techniques, both analytic and numerical, and in event simulation

Terrific work by QCD theorists for LHC

New powerful techniques for loop calculations

G. Salam, ICHEP'10

F. Boudjema

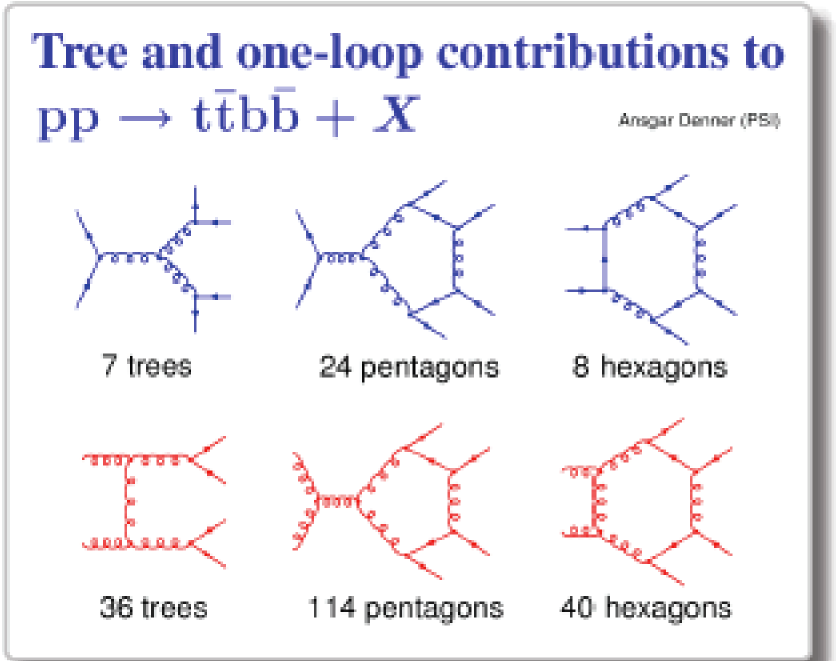
Feynmanians

Unitarians

Traditional

Draw all Feynman diagrams with 1 loop. Work out formulae for them.

Work hard to reduce integrals to known forms (+ tricks).



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams

Some main ideas:

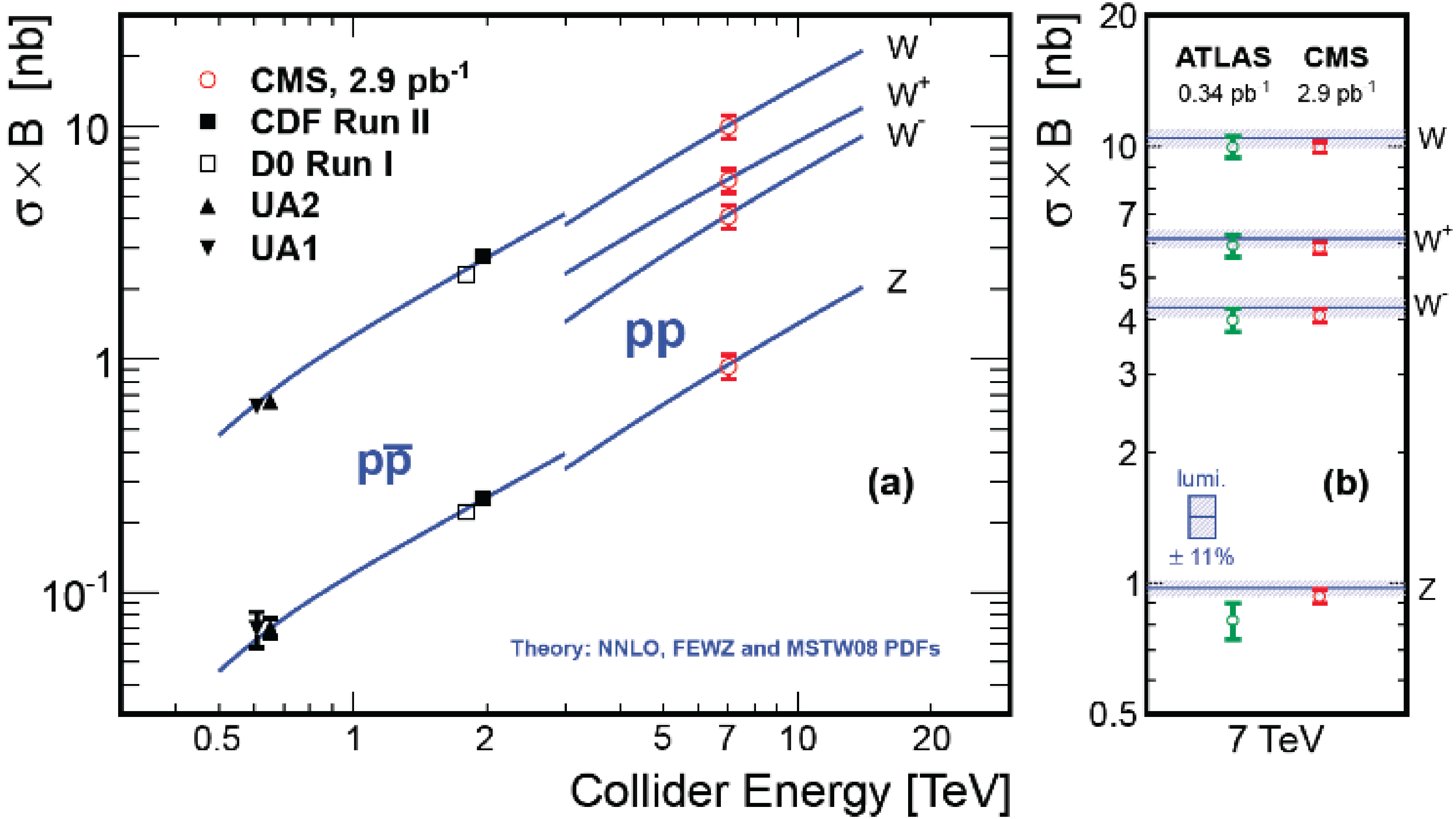
Bern, Dixon & Kosower '93
[sewing together trees]

Britto, Cachazo & Feng '04
[on-shell complex loop momenta]

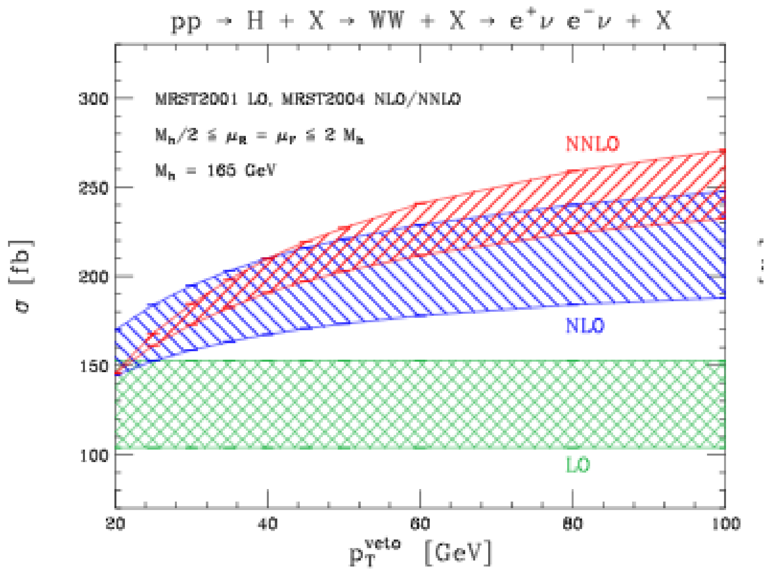
Ossola, Pittau & Papadopoulos '06
[handful of loop momentum choices give full amplitude]

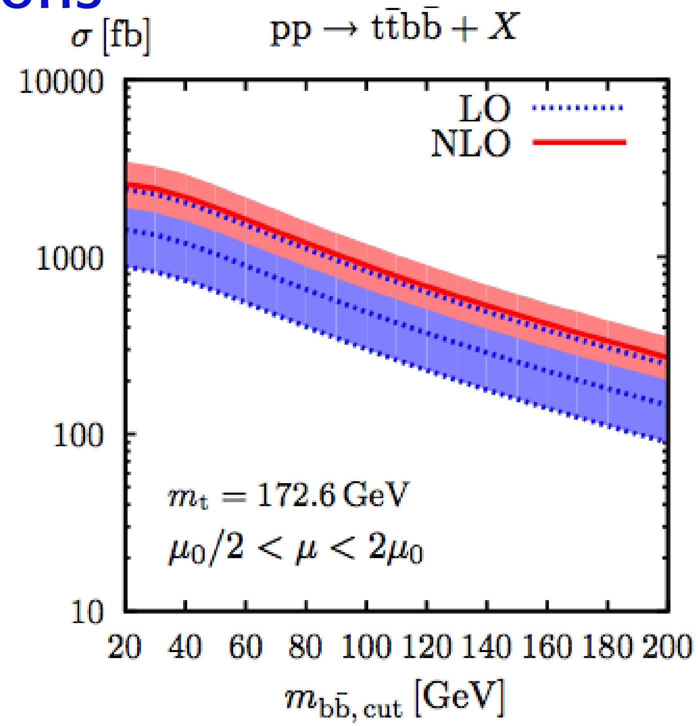
S. Kesisoglou

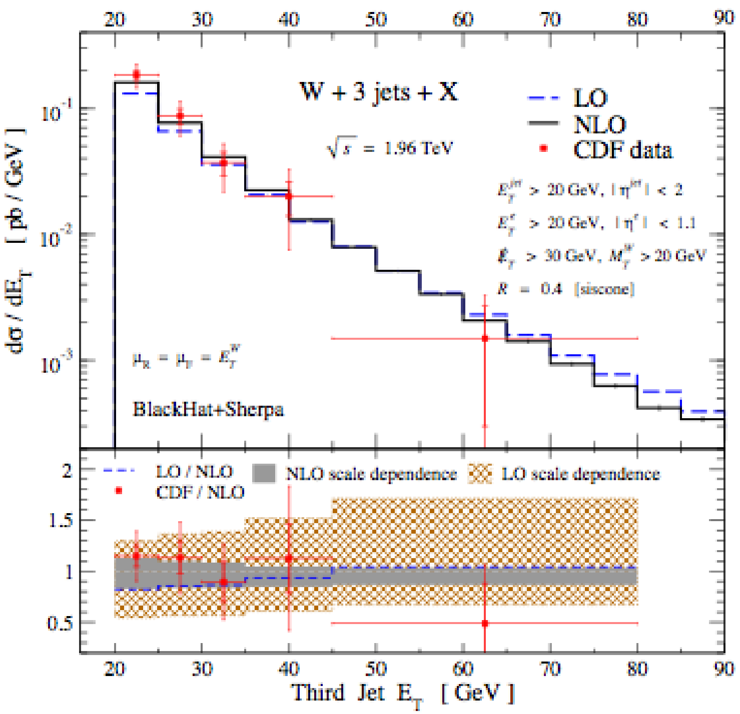
NNLO QCD W, Z production



QCD for LHC: very difficult calculations

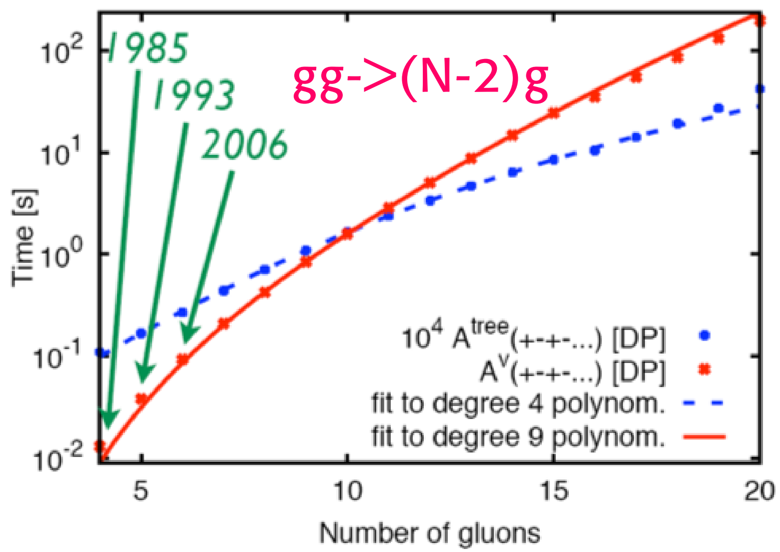






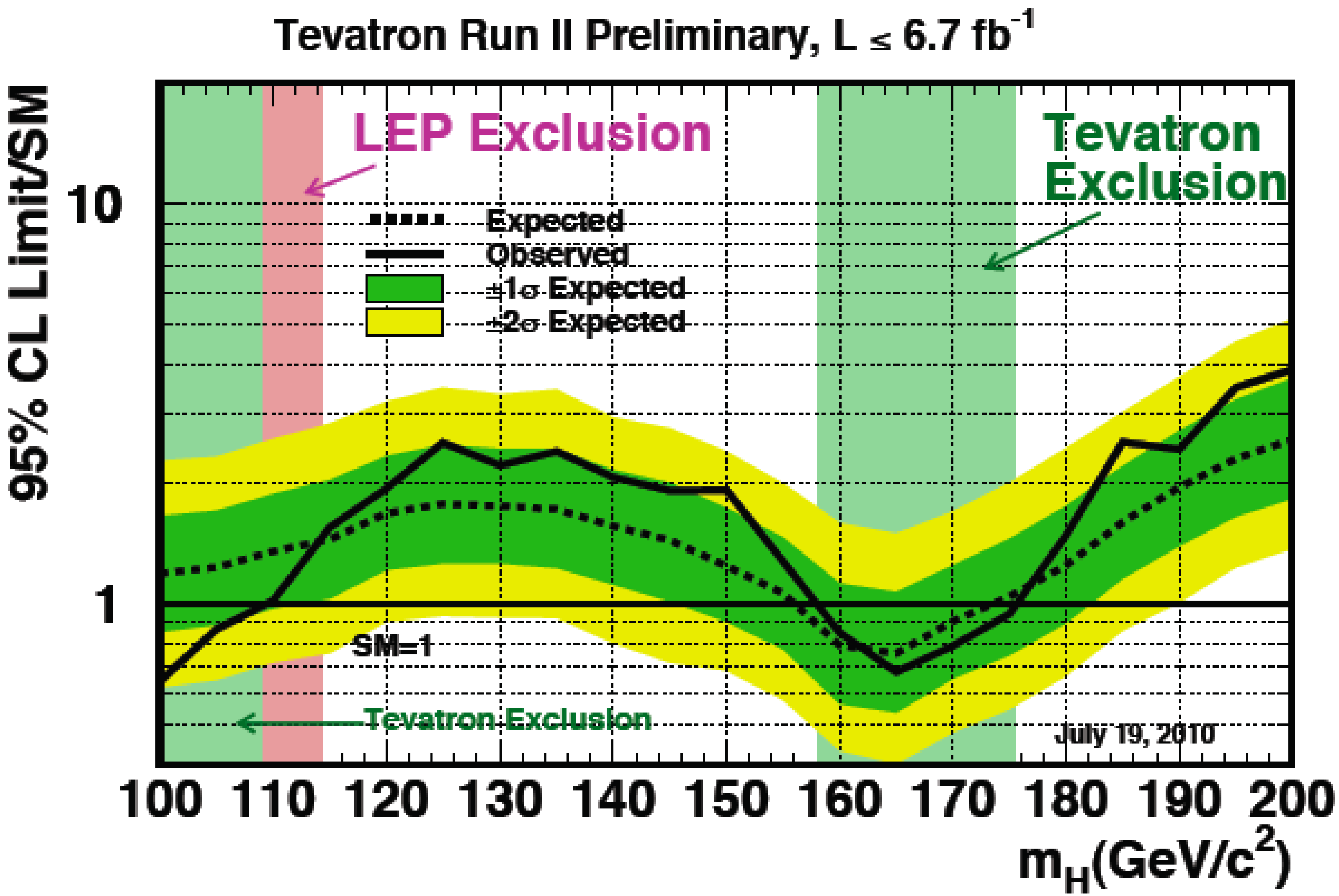
Fantastic technical skill!!

Essential for the LHC

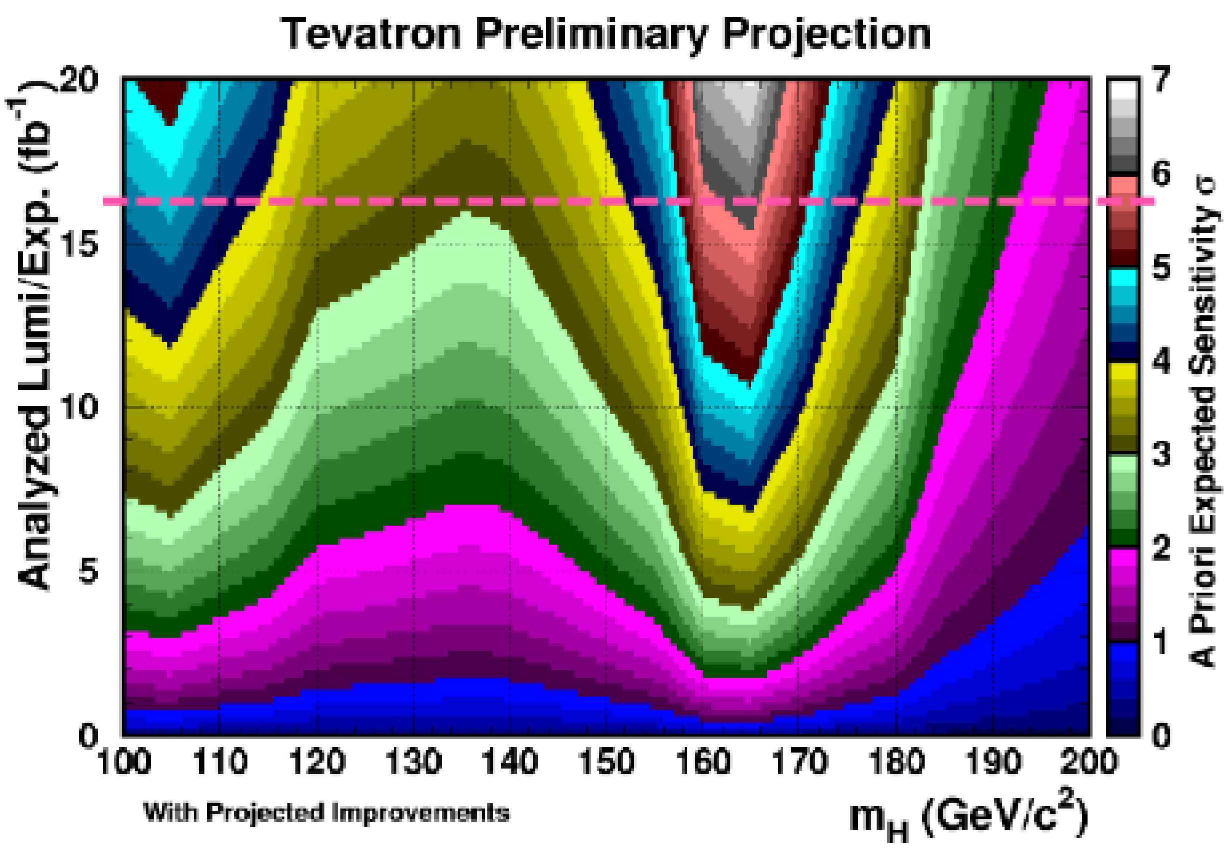


The Tevatron bounds depend on what is assumed for the relevant cross-sections

see e.g. Baglio, Djouadi'10



$158 < m_H < 175$ GeV at 95%

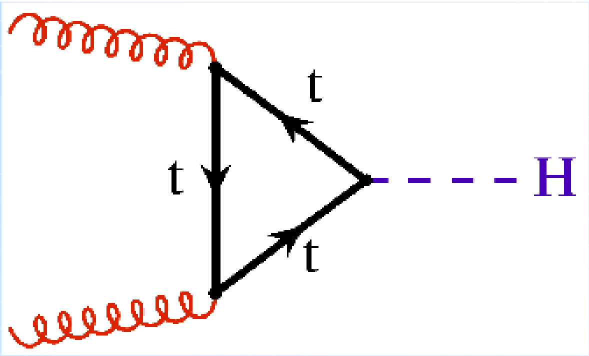


With 16 fb-1 at the Tevatron, expect:

- 95% CL exclusion (and stronger) over whole range m_H<190 GeV
- 3σ evidence, in 100 < m_H < 180 GeV
- 4σ evidence for m_H=115 GeV

Higgs production via g+g -> H

Very important for the LHC



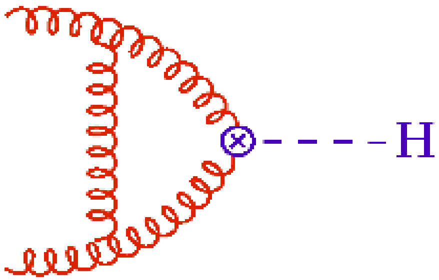
Effective lagrangian (m_t -> infinity)

$$\mathscr{L} = C_1 \, H \, G^{\mu\nu} G_{\mu\nu}$$

C_1 known to α_s^4

Chetyrkin, Kniehl, Steinhauser'97

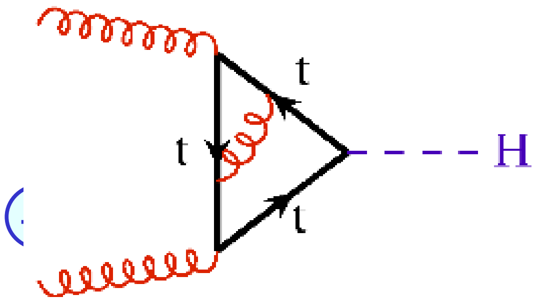
NLO corr.s computed with effective lagrangian

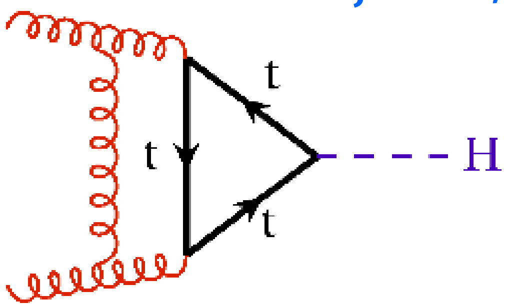


Dawson
Djouadi, Spira, Graudenz, Zerwas

AND the full theory

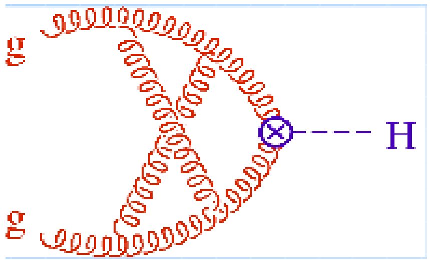
Djouadi, Spira, Graudenz, Zerwas

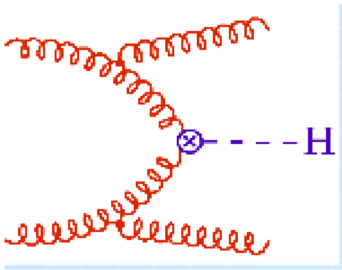




They agree very well

More recently the NNLO calculation was completed (analytic)

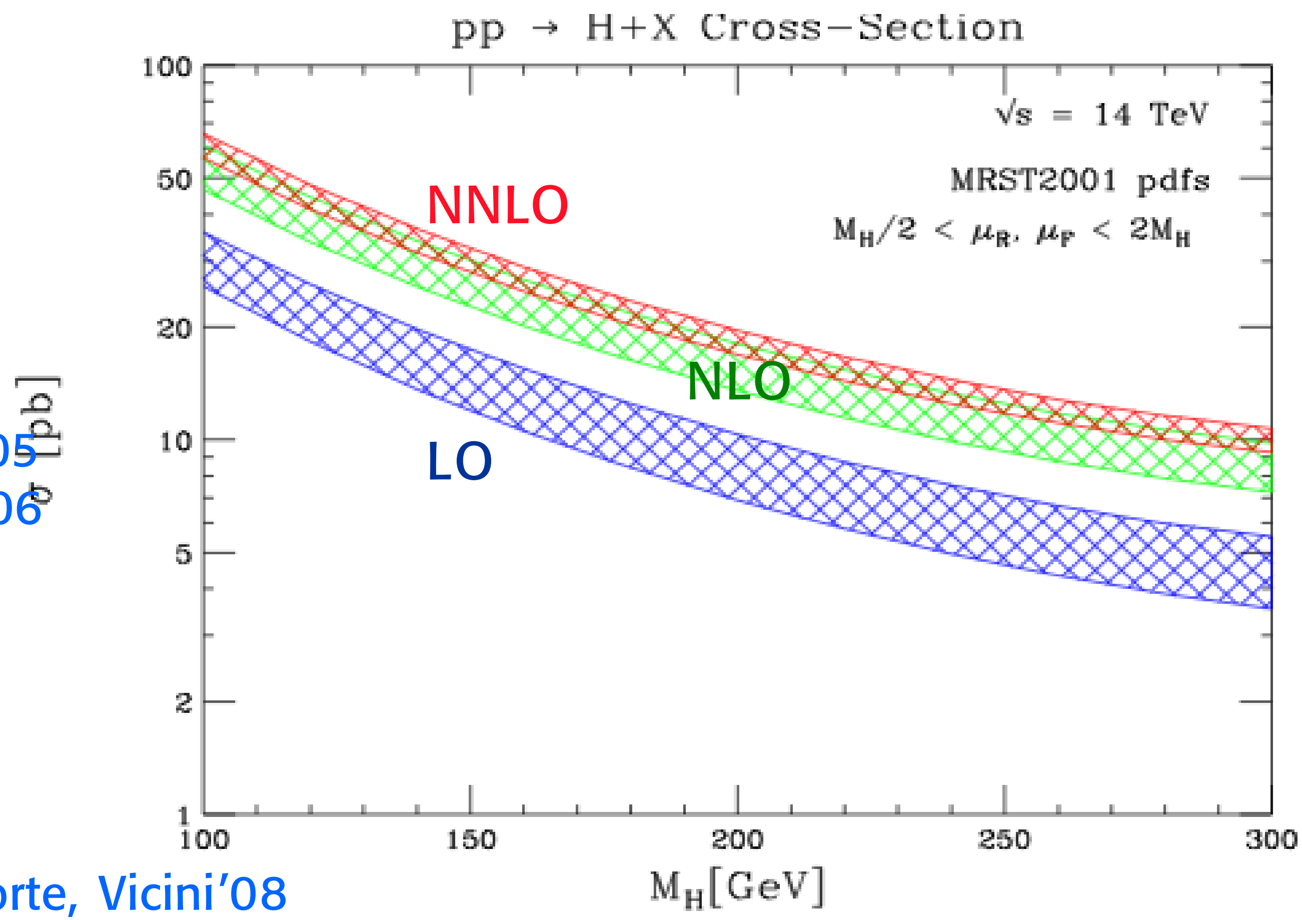




Catani, de Florian, Grazzini '01.
Harlander, Kilgore '01, '02
Anastasiou, Melnikov'02
Ravindran, Smith, van Neerven '03

Also NLO y and p_T distributions have been computed

De Florian, Grazzini, Kunszt '99
Glosser, Schmidt'02
Anastasiou, Melnikov, Petriello'05
Ravindran, Smith, van Neerven'06



Recent progress:
Resummation of large partonic-energy logs
DeMarzani, Ball, Del Duca, Forte, Vicini'08

Higgs p_T distribution: $[\log(p_T/m_H)]^n$ resummed

Bozzi, Catani, De Florian, Grazzini'03-'08

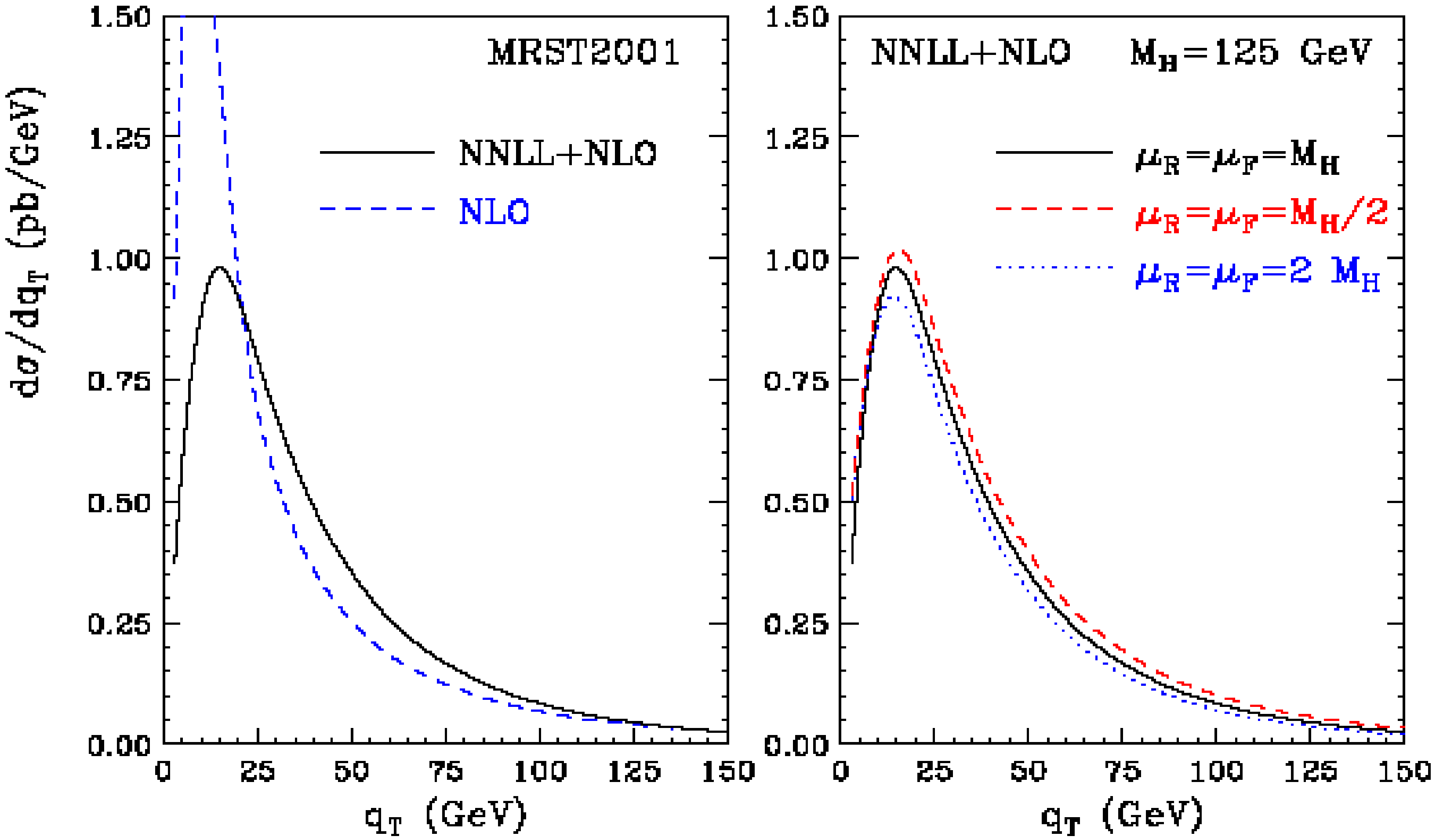
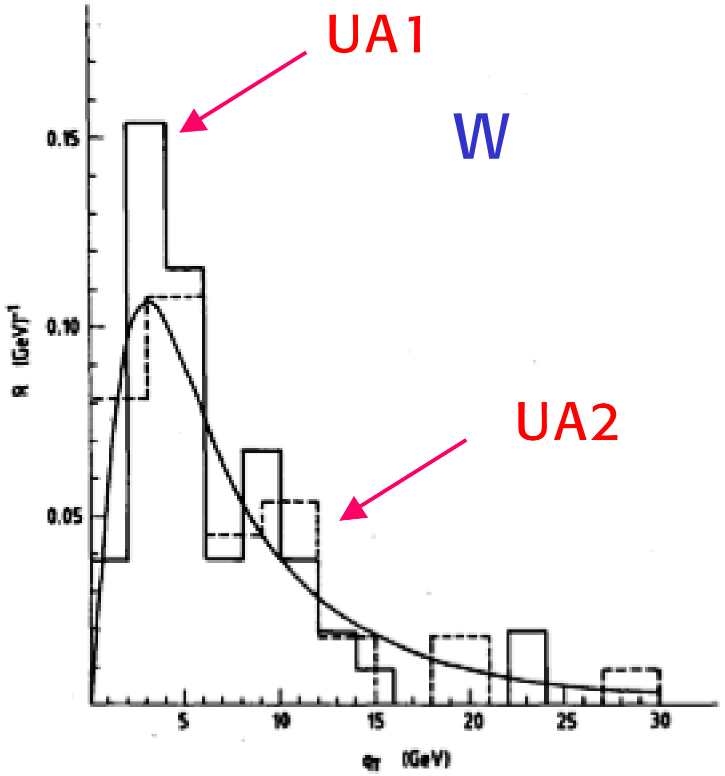


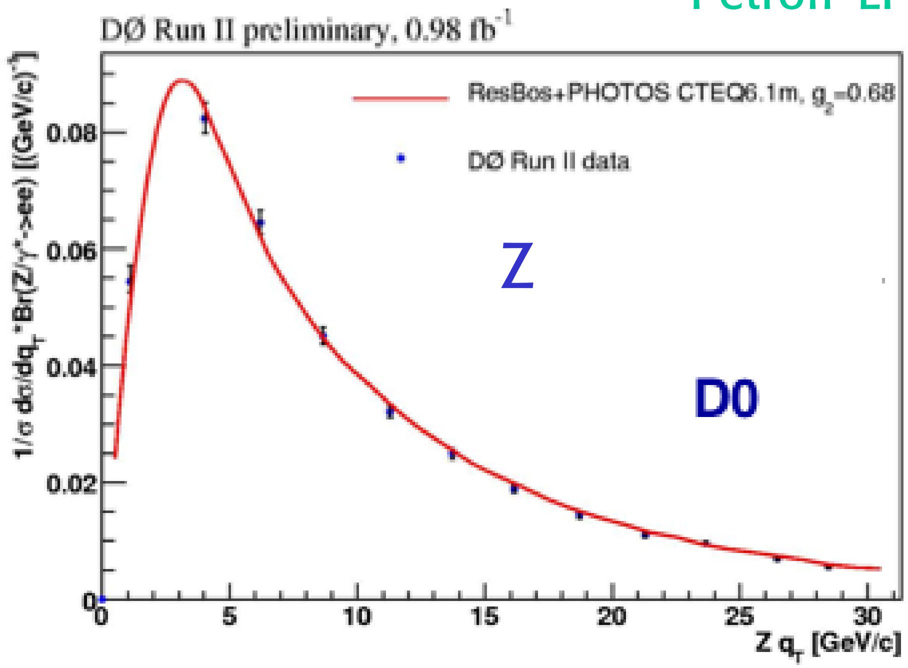
Figure 7. Resummed pQCD prediction for the Higgs transverse momentum distribution at the LHC, from Bozzi *et al.*[25]

~25 years ago I started at CERN by computing the W and Z p_T distribution in QCD

Petroff LP'07



GA, K.Ellis, M. Greco, G.Martinelli '84



In agreement with perturbative QCD augmented by Collins-Soper-Sterman (CSS) resummation at low q_T

J. Collins, D. Soper, G. Sterman, Nucl. Phys. B250 (1985) 199.

ResBos describes data well up to ~ 30 GeV

F. Landry, R. Bock, P.Nadolsky, C.P. Yuan
Phys. Rev. D 67, 073016 (2003)

NNLO describes better above 30 GeV

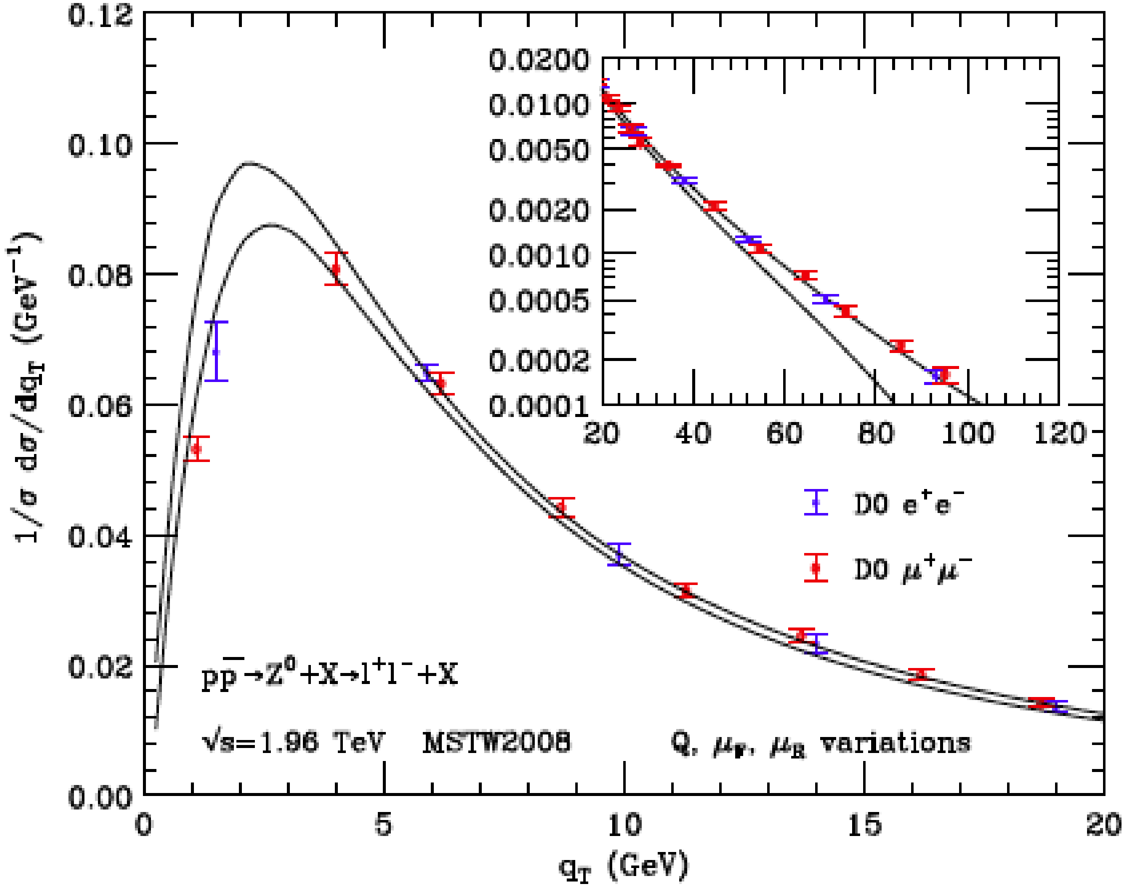
K. Melnikov and F. Petriello Phys. Rev. D74 114017 (2006)

Yesterday the W&Z
today the Higgs!

G. Ferrera

The state of the art p_T distribution of the W

Bozzi, Catani, Ferrera, de Florian, Grazzini'10



QCD event simulation

B. Webber, S. Jadach

A big boost in the preparation to LHC experiments

General algorithms for computer NLO calculations

eg the dipole formalism — Catani, Seymour,.....

the antenna pattern — Kosower....

Matching matrix elements and parton showers

e.g. MC@NLO based on HERWIG — Frixione, Nason, Webber

POWHEG — Nason, Ridolfi

Perturbative (+ resumm.s)

$$d\sigma = A\alpha_S^N [\, 1 + (c_{1,1}L + c_{1,0})\alpha_S + (c_{2,2}L^2 + c_{2,1}L + +c_{2,0})\alpha_S^2 + \dots \,]$$

L= large log eg L=log(p_T/m)

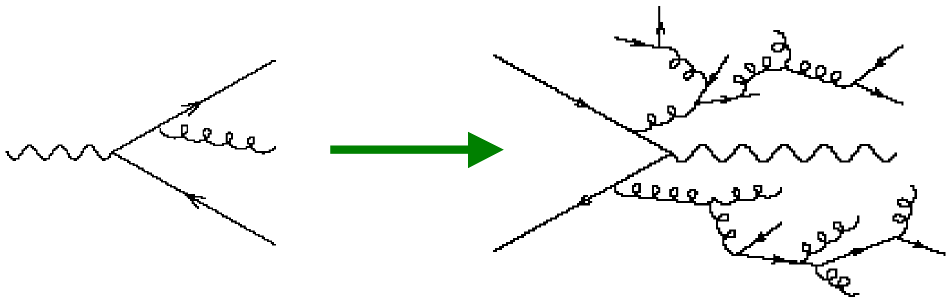
Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

collinear emissions factorize

$$d\sigma_{q\bar{q}g} = d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

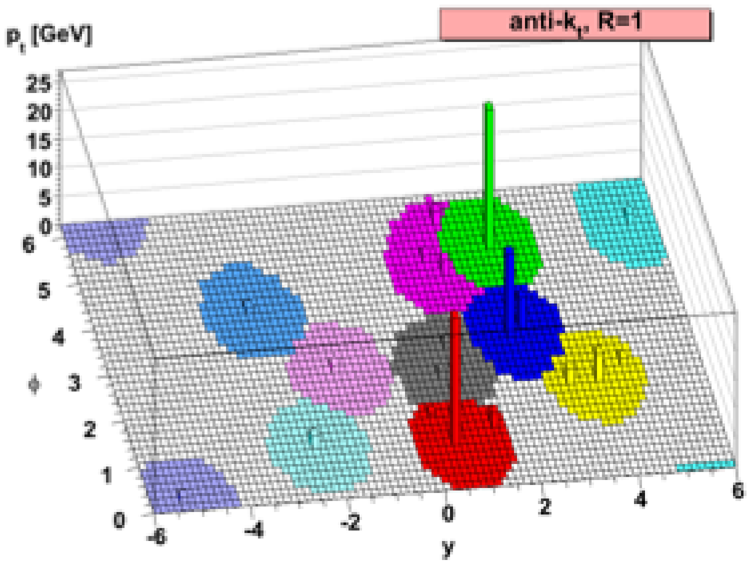
$$t = (p_q + p_g)^2 \longrightarrow 0$$

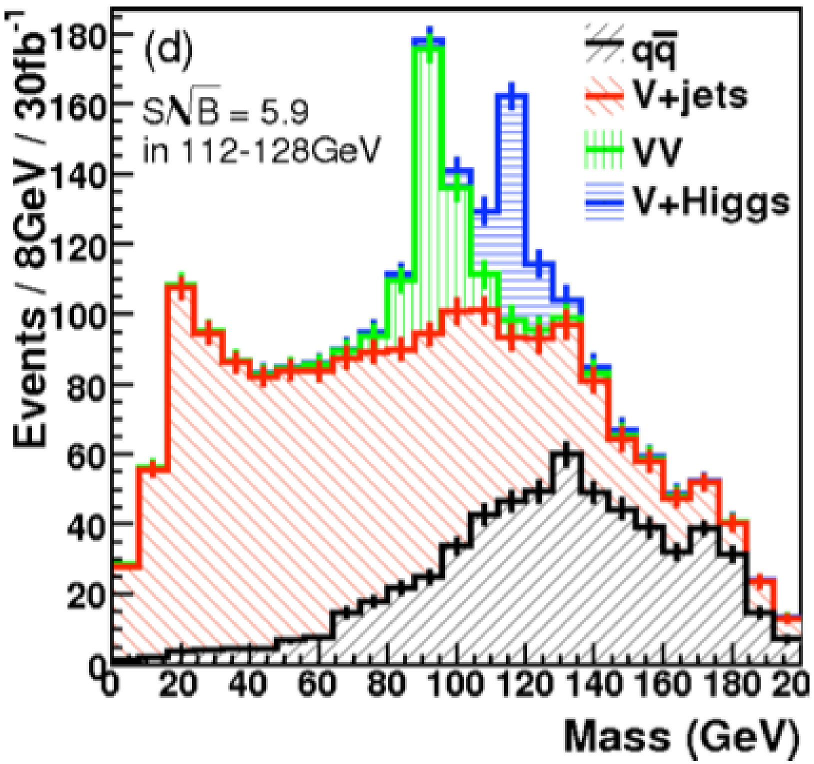


hadronization added

Important recent work on jet recombination algorithms SISCone, anti-k_T

G. Salam et al





It is essential that a correct jet finding is implemented by LHC experiments for an optimal matching of theory and experiment

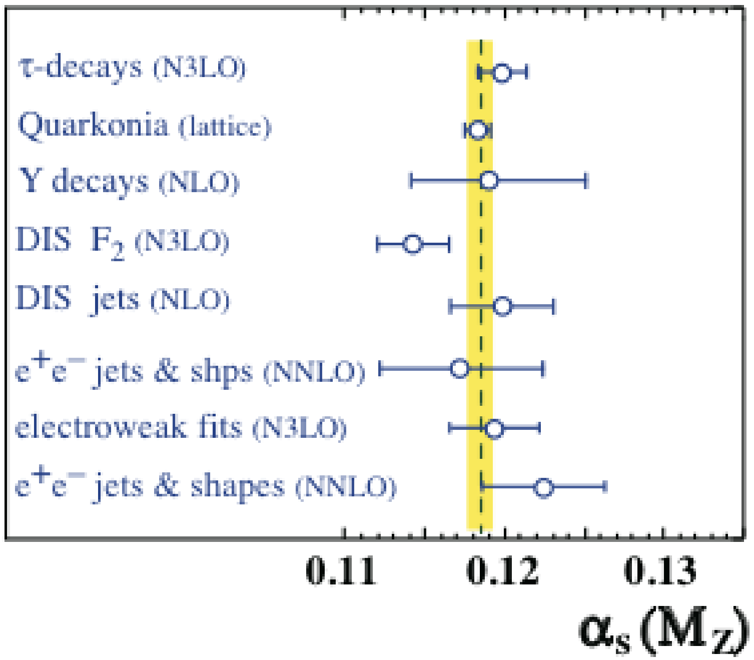
What is the best value of α_s ?

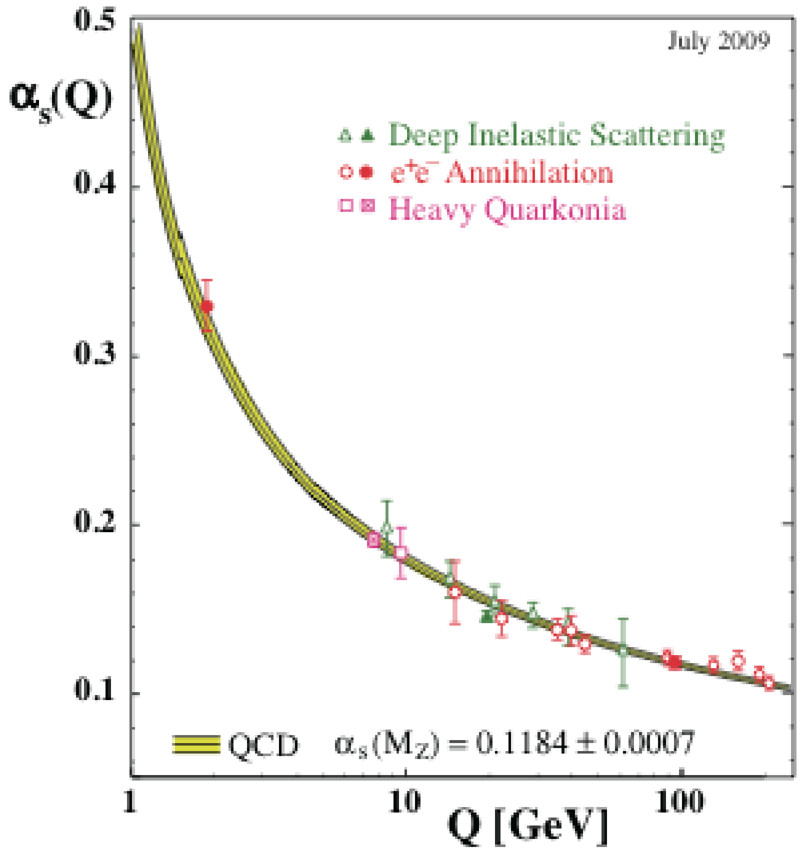
The standard reference is the compilation by S. Bethke [ArXiv: 0908.1135] also adopted by the PDG '10:

$$\alpha_s(m_Z) = 0.1184 \pm 0.0007$$

This is obtained by taking all allegedly precise measures of $\alpha_s(m_Z)$, in most cases taking the quoted errors for granted.

S. Bethke '09





so small?

$\alpha_s(m_Z)=0.1184\pm0.0007$

Alternatively we could order the measurements in order of decreasing in-principle-control of theoretical errors.

We can take a few to measure α_s and keep the other ones as QCD tests

In principle the golden processes for α_s should be those at large Q^2, totally inclusive, certified by the light cone operator expansion plus the renormalization group

- e+e- ---> hadrons
- Deep Inelastic Scattering (DIS)

In practice LEP has produced a precise and reliable measurement of α_s

For DIS the situation is more difficult and the result is still affected by considerable uncertainties

From LEP: Z decays (plus m_t and m_W) lead to

- $\alpha_s(m_Z)=0.1191\pm0.0028$ (N^3LO)

LEPEWG, Summer 2010

This is the most reliable measurement!
The effects of possible new physics are really negligible after so much negative searches

α_s from DIS : more complicated

The scaling violations of non-singlet str. functs. would be ideal: less dependence on input parton densities

$$\frac{d}{dt}\log F(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 dy \frac{F(y,t)}{yF(x,t)} P_{qq}\left(\frac{x}{y}\right)$$

But

- for F_p-F_n exp. errors add up in the difference,
- $F_{3\nu N}$ is not terribly precise

  (ν data only from CCFR, NuTeV)
- neglecting sea and glue in F_2 for $x > x_0$ decreases the sample and introduces a dependence on x_0

Neutrinos. For xF_3 at NNLO:

Using Bernstein moments

A combination of Mellin moments which emphasizes a value of x and a given spread in order to be sensitive to the interval where the measured points are

- $\alpha_s(m_Z)=0.1153\pm0.0063$

  Santiago, Yndurain '01

- $\alpha_s(m_Z)=0.1174\pm0.0043 \pm ?$

  Maxwell, Mirjalili '02

Here the error from scale dep. not included (a model dep. scale fixing is chosen)

Using Mellin moments

- $\alpha_s(m_Z)=0.1190\pm0.0060$

  Kataev, Parente, Sidorov '02

Good overall agreement. Not very precise:
(as expected from ν's) Total error $\sim\pm0.006$

Non singlet electron/muon production

From a recent analysis of eP and eD data, neglecting sea and gluons at $x > 0.3$ (error to be evaluated)

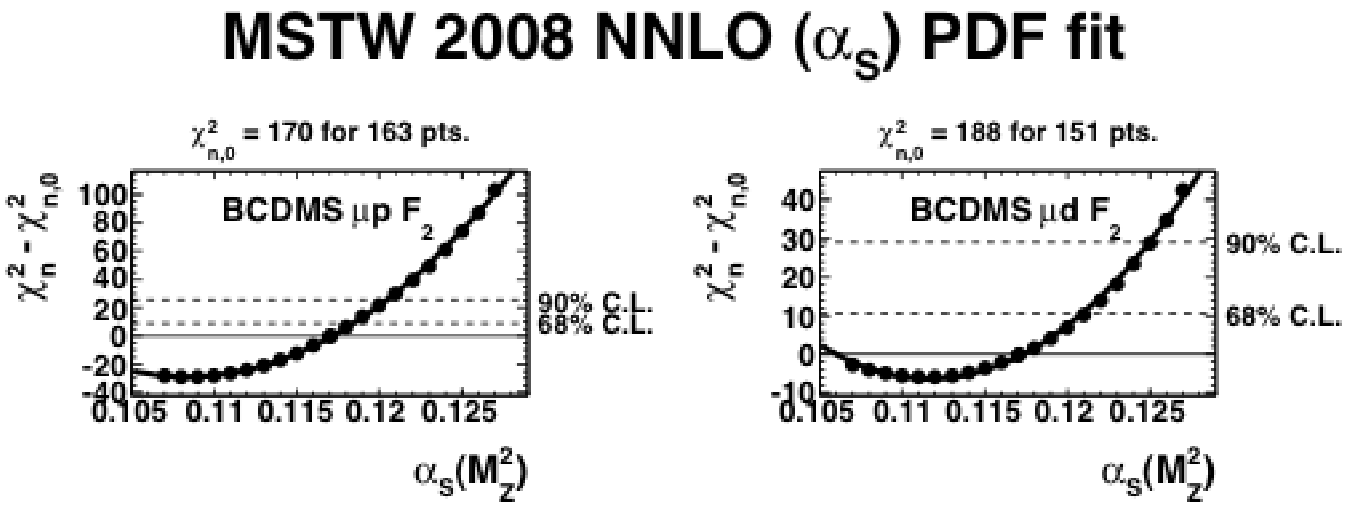
- Non singlet DIS: $\alpha_s(m_Z)=0.1148\pm0.0019$ (exp)+? (NLO)
  $\alpha_s(m_Z)=0.1134\pm0.0020$ (exp)+? (NNLO)

Bluemlein et al '06

- a rather small central value
- not much difference between NLO and NNLO

According to Watt the contribution of singlet to F2 at $x \sim 0.3$ is still $\sim$ 10%

BCDMS data push towards small α_s



According to Watt 162/280 exp points at $x > 0.3$ are from BCDMS

When one measures α_s from scaling viols. in F_2 from e or μ beams, data are abundant, exp. errors small but:

$\alpha_s \Longleftrightarrow$ gluon correlation

$$dF/d\log Q^2 \sim \alpha_s\, g$$

There is a strong feedback on α_s of the parametrisation of g

A too rigid param'n of gluon may strongly bias α_s

It appears that including Tevatron jets is essential to constrain g at large x (and then, via momentum conservation, also at small x)

Recent $\alpha_s(m_Z)$ determinations at NNLO

$$\alpha_s(m_Z) = 0.1128 \pm 0.0015 \text{ (exp)} + ?$$

Alekhin, Melnikov, Petriello '06

$$\alpha_s(m_Z) = 0.1129 \pm 0.0014 \text{ (exp)} + ?$$

Alekhin, Blumlein, Klein, Moch '09

$$\alpha_s(m_Z) = 0.1158 \pm 0.0035 \text{ (exp)} + ?$$

Jimenez-Delgado, Reya '08

V. Radescu, DIS 2010, Florence

From combined H1+ZEUS data

$$\alpha_s(m_Z) = 0.1145 \pm 0.0042 \text{ (exp)} + ? \quad \text{(NNLO)}$$

For HERA data the NLO evolution should be improved by a correct treatment of small x effects (negative g at small x and Q^2 is a symptom)

Global fit to α_s and PDF

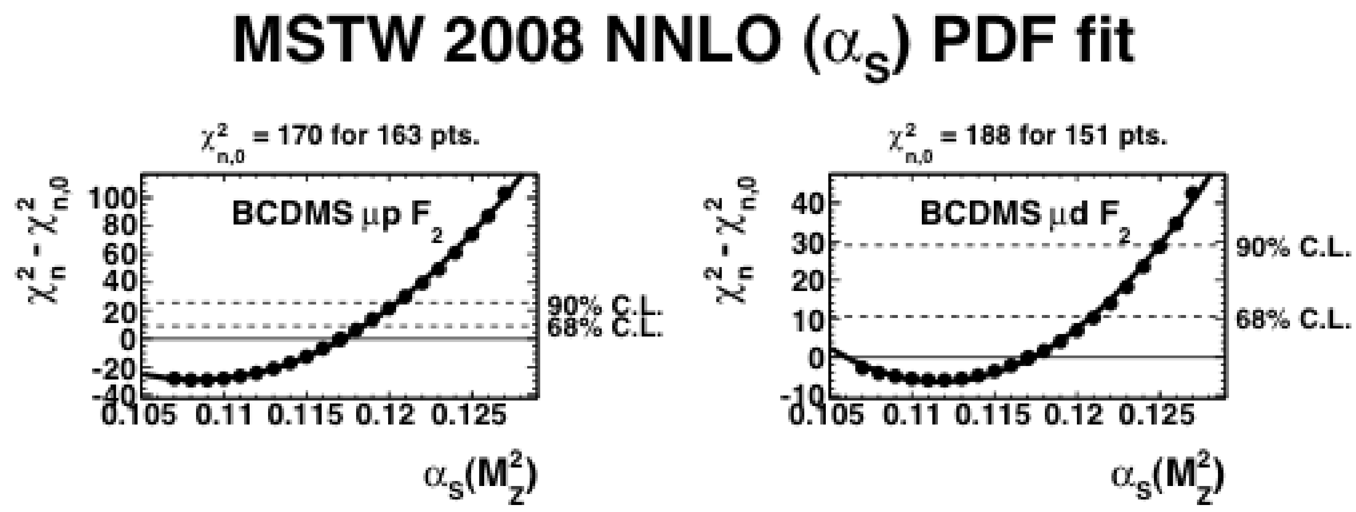
dominated by DIS but not only DIS

$$\alpha_s(m_Z) = 0.1171 \pm 0.0037 \text{ (exp)} \qquad \text{(NNLO)}$$

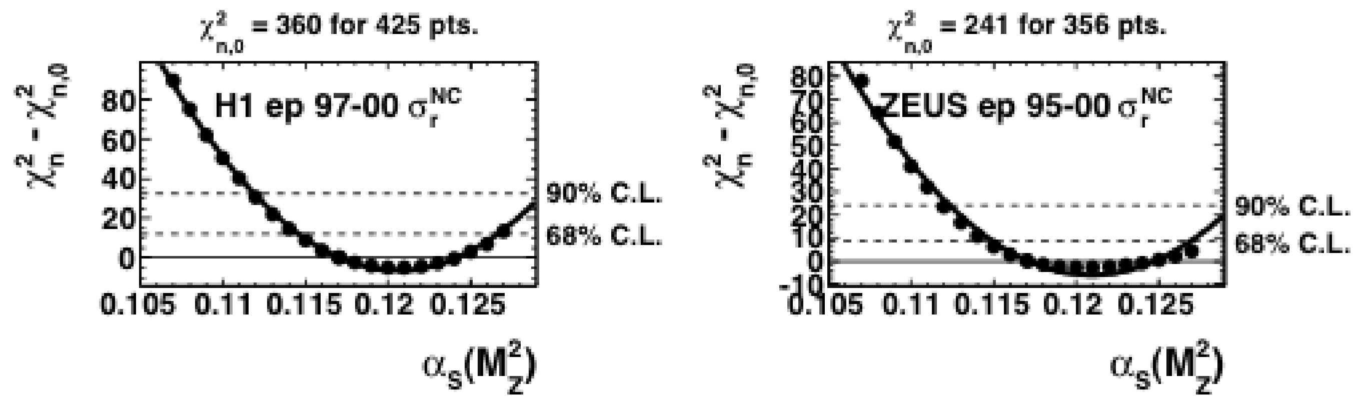
Martin, Stirling, Thorne, Watt '09

MRST attribute their larger value of α_s to a more flexible parametrisation of the gluon and claim that the Tevatron jets are needed to fix g at large x

BCDMS data push towards small α_s



By comparison HERA points at larger α_s



In conclusion, for DIS

Bethke takes $\alpha_s(m_Z) = 0.1142 \pm 0.0023$ from non-singlet and this is what he puts in his average from DIS

From the global fit, a more reliable result

$$\alpha_s(m_Z) = 0.1171 \pm 0.0037$$

Here removing BCDMS makes 0.117 - > 0.118

α_s from Rτ

$$R_\tau = \frac{\Gamma(\tau \Rightarrow \nu_\tau + hadrons)}{\Gamma(\tau \Rightarrow \nu_\tau + leptons)}$$

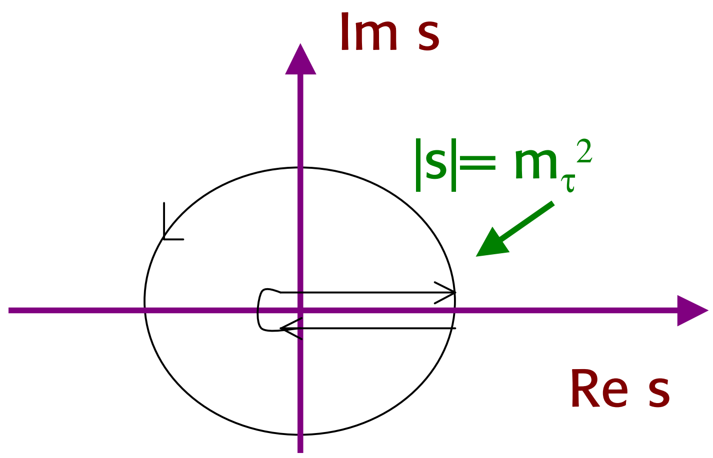
R_τ has a number of advantages that, at least in part, compensate the smallness of m_τ=1.777 GeV:

- R_τ is more inclusive than $R_{e+e-}(s)$.

$$R_\tau = \frac{1}{\pi}\int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1 - \frac{s}{m_\tau^2}\right)^2 Im\,\Pi_\tau(s)$$

- one can use analiticity to go to $|s| = m_\tau^2$

$$R_\tau = \frac{1}{2\pi i}\oint_{|s|=m_\tau^2} \frac{ds}{m_\tau^2}\left(1 - \frac{s}{m_\tau^2}\right)^2 \Pi_\tau(s)$$



- factor $(1-s/m_\tau^2)^2$ kills sensitivity to Re s$= m_\tau^2$ (thresholds)

Still the quoted result looks a bit too precise

Bethke '09 $\alpha_s(m_Z)=0.1197\pm0.0016$

This precision is obtained by taking for granted that corrections suppressed by $1/m_\tau^2$ are negligible.

$$R\tau \sim R\tau^0[1+\delta_{pert}+\delta_{np}]$$

This is because in the massless theory:

$$\delta_{np} = \frac{ZERO}{m_\tau^2} + c_4 \cdot \frac{<O_4>}{m_\tau^4} + c_6 \cdot \frac{<O_6>}{m_\tau^6} + \ldots$$

In fact there are no dim 2 operators (e.g. $g_\mu g^\mu$ is not gauge invariant) except for light quark m^2 ($m\sim$few MeV) .

Most people believe that. I am not sure that the gap is not filled by ambiguities of $o(\Lambda^2/m_\tau^2)$ from δ_{pert}.

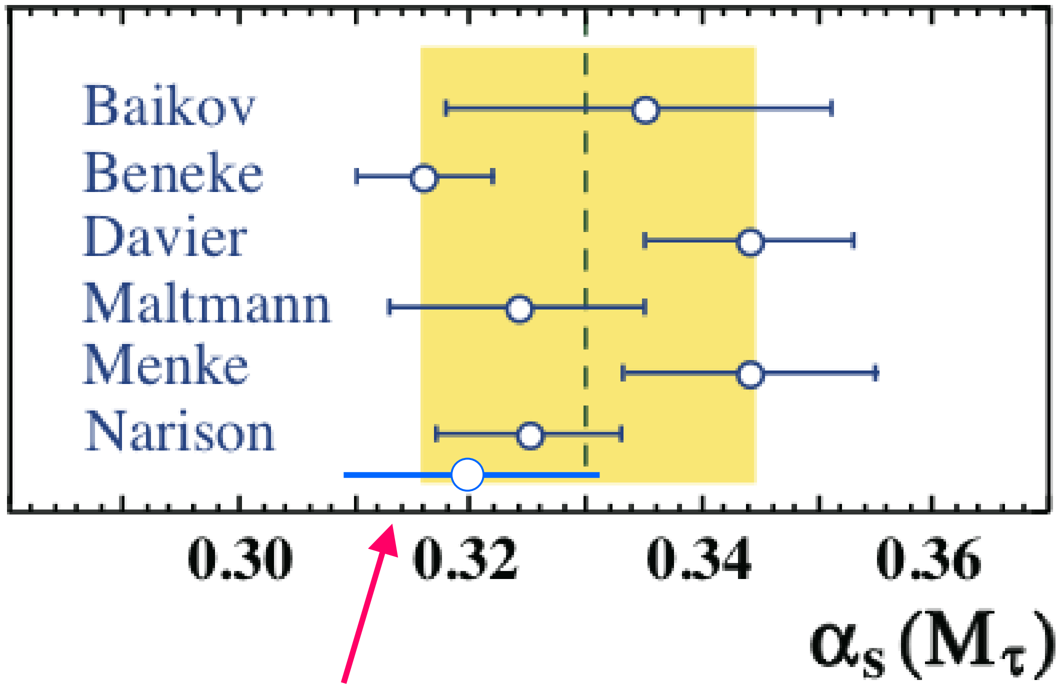
eg effect of ultraviolet renormalons

GA, Nason, Ridolfi '95; Chetyrkin, Narison,Zakharov '98

The yellow band is Bethke conclusion

$$\alpha_s(M_\tau) = 0.330 \pm 0.014$$

$$\alpha_s(M_Z) = 0.1197 \pm 0.0016$$



Caprini' 0.320 ± 0.011

I would add an error from possible $(\Lambda_{QCD}/m_\tau)^2$ terms

Summarising

From LEP

- Z inclusive decay: $\alpha_s(m_Z)=0.1191\pm0.0028$ (N^3LO)
- τ inclusive decay: $\alpha_s(M_Z) = 0.1197\pm0.0016 \pm ?$ (N^3LO))

From DIS +DY+ Tevatron

- $\alpha_s(m_Z) = 0.1171 \pm 0.0037$

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it! → LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

•••••

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy

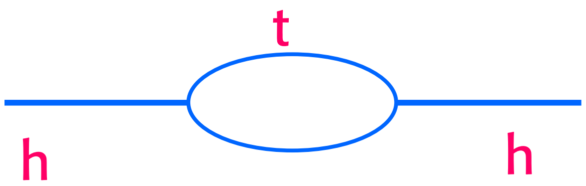
•••••

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter (perhaps)

For the low energy theory: the “little hierarchy” problem:

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

$\Lambda \sim o(1\text{TeV})$

This hierarchy problem demands new physics near the weak scale

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be so close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top
- some new fermion

  t'

  KK recurrences of the top

  ......

Precision Flavour Physics

J. Chauveau

Another area where the SM is good, too good.....

With new physics at ~ TeV one would expect
the SM suppression of FCNC and the CKM
mechanism for CP violation to be sizably modified.

But this is not the case

an intriguing mystery and a major challenge for models of
new physics

Adding effective operators to SM generally leads to very large Λ

$$M(\mathrm{B_d}\text{-}\overline{\mathrm{B}}_\mathrm{d}) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP} \frac{1}{\Lambda^2}$$

G. Isidori

c_{NP}:

- $\sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5$ TeV [K & B]

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{NP} \sim (y_t V_{tb}{}^* V_{td})^2$ (or anyway small)

we get a bound on Λ in the TeV range

eg in Minimal Flavour Violation (MFV) models

D'Ambrosio, Giudice, Isidori, Strumia'02

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY}\text{-}m_{ord}$ → top loop $\Lambda \sim m_{stop}$

  The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

  Strongly disfavoured by LEP. Coming back in new forms

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

  "Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that "bring" M_{Pl} down to o(1TeV)

  Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

And to conclude

On behalf of all participants I most warmly thank the Organisers, and, in particular, Witek Krasny, for this very informative and interactive Workshop

THANK YOU!