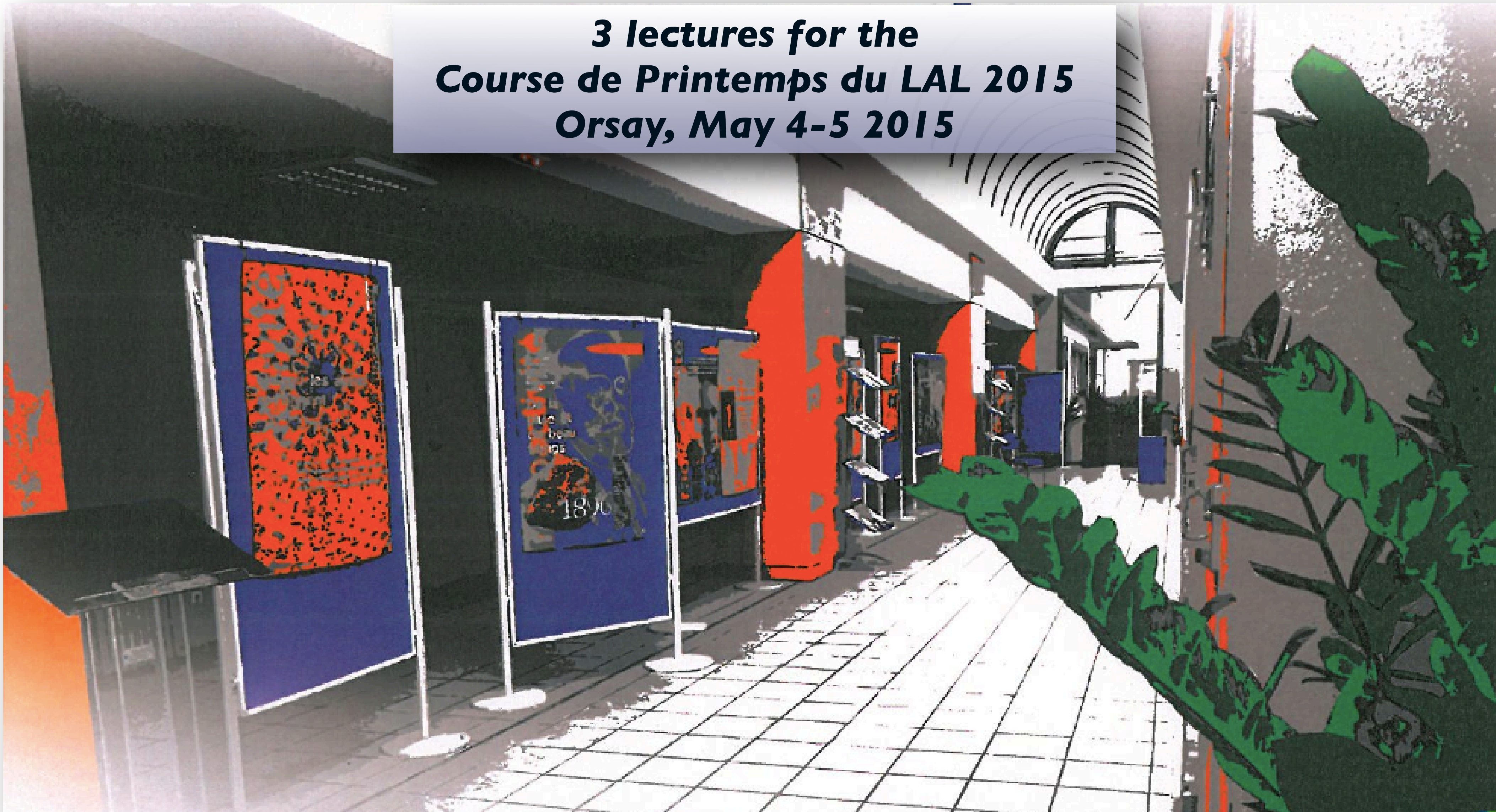
SM and BSM physics after the Higgs discovery

3 lectures for the
Course de Printemps du LAL 2015
Orsay, May 4-5 2015



Lecture 2

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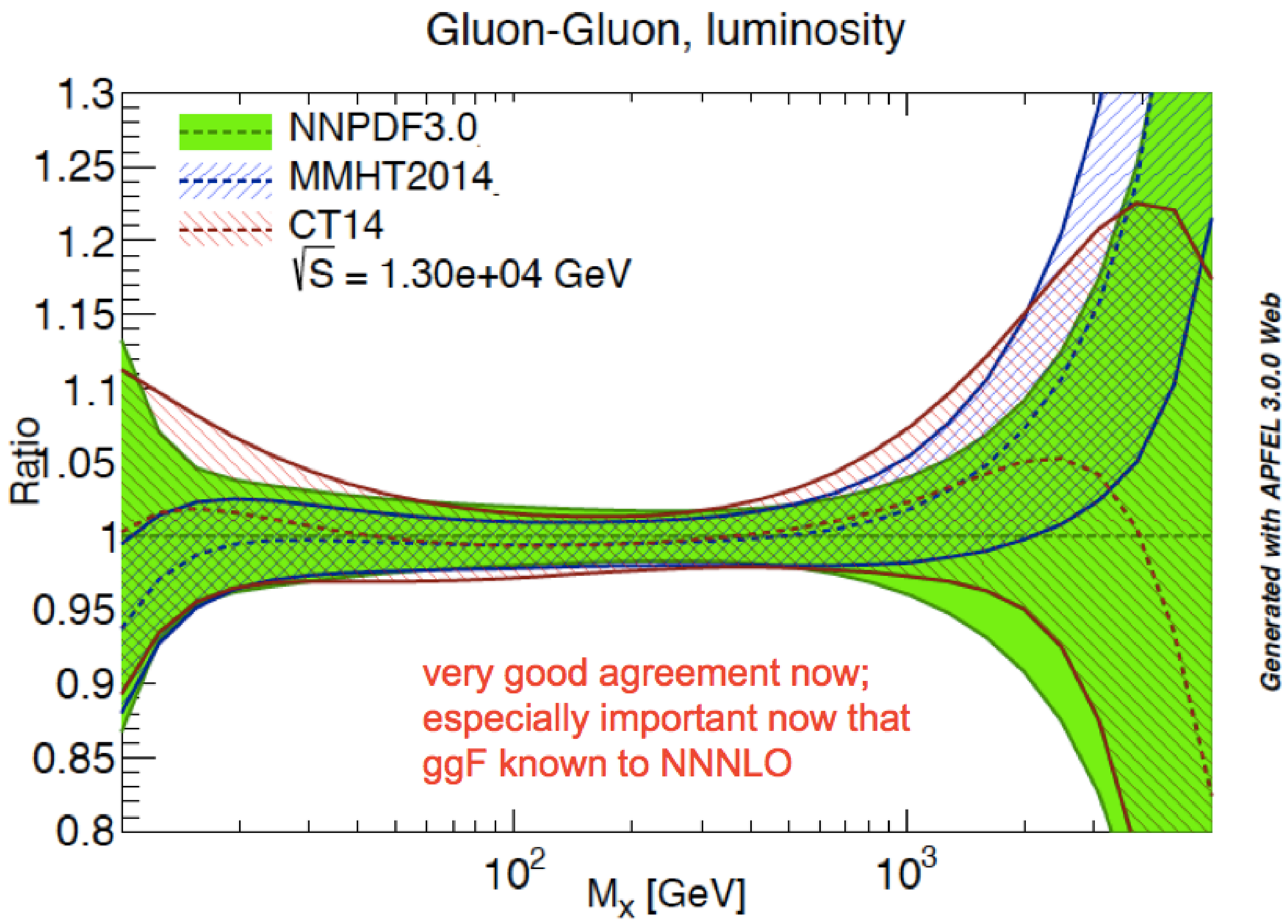
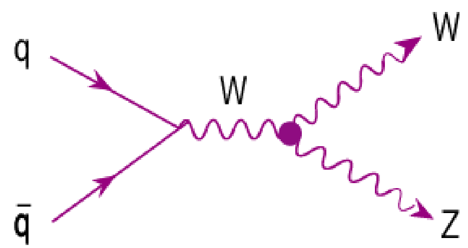
more or PDF prospects, status

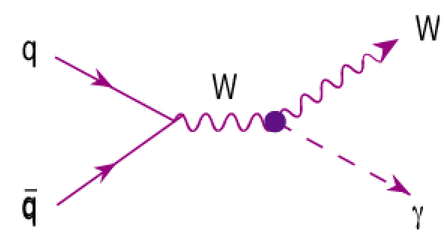
See PDF4LHC mtg, Apr 13 2015



	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

Precise determinations of the self-couplings of EW gauge bosons





5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision

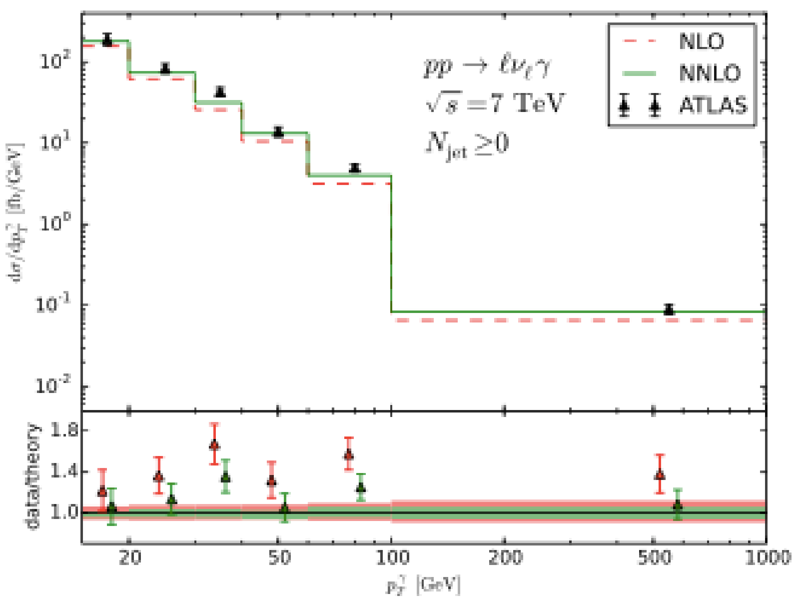
Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050

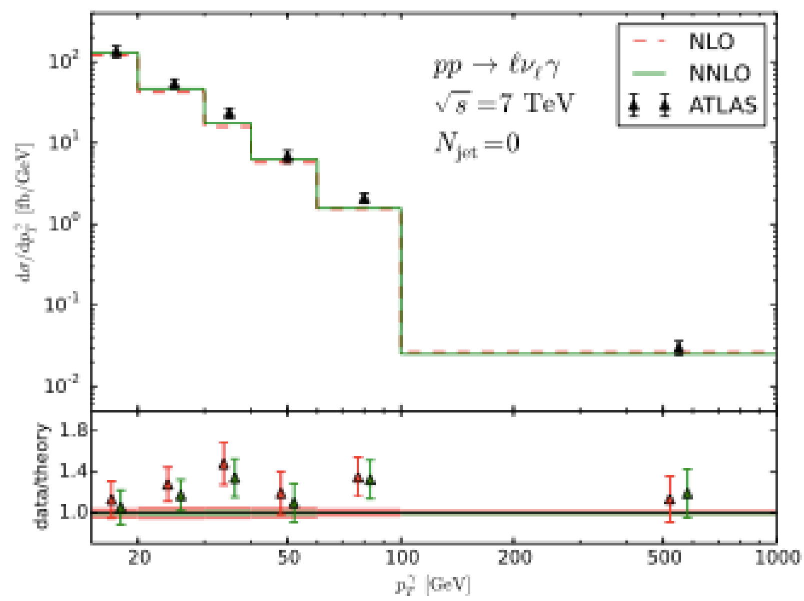
Wγ production

- results for $pp \to \ell^{\pm}\nu_{\ell}\gamma + X$
- ATLAS cuts [ATLAS collaboration (2013)]
  - $p_T^{\gamma} > 15$ GeV, $|\eta^{\gamma}| < 2.37$
  - $p_T^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.47$
  - $p_{T,\mathrm{miss}} > 35$ GeV
  - $\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
  - Frixione isolation with $\varepsilon = 0.5$, $R = 0.4$

Inclusion of NNLO QCD corrections
Grazzini, Kallweit, Rathlev
1504.01330

	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\mathrm{jet}} \geq 0$	$0.8726^{+6.8\%}_{-8.1\%}$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)
$N_{\mathrm{jet}} = 0$		$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)



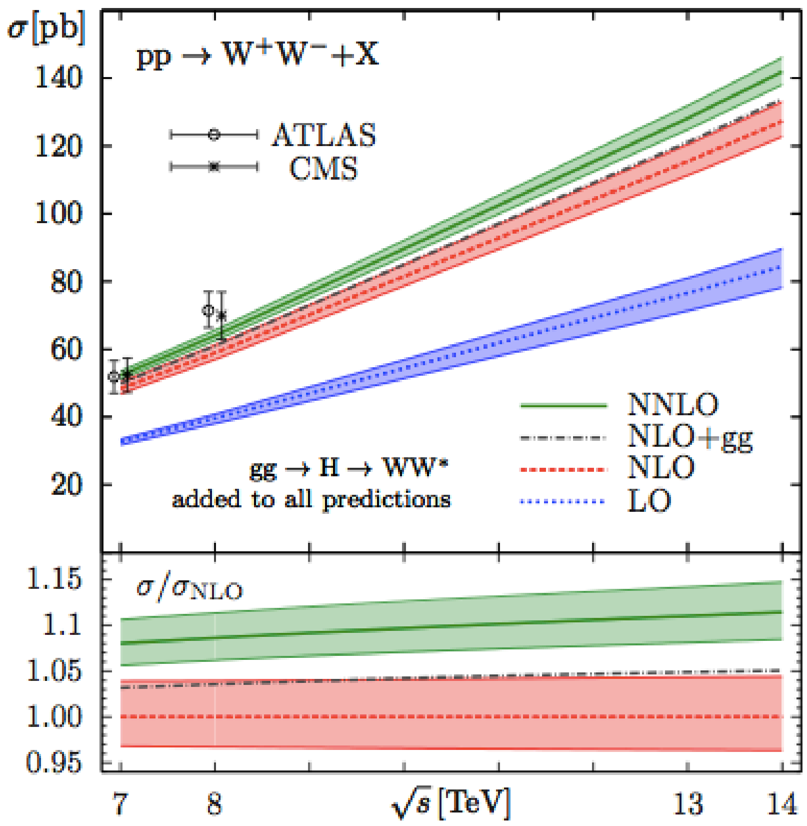


WW production

	$\sigma\,(pp \to W^+W^-)$ [pb]	SM NLO [pb]
ATLAS 7 TeV [ATLAS collaboration (2012)]	51.9 ± 4.8	$44.7^{+2.1}_{-1.9}$
CMS 7 TeV [CMS collaboration (2013)]	52.4 ± 5.1	
ATLAS 8 TeV [ATLAS collaboration (2014)]	71.4 ± 5.3	$57.3^{+2.4}_{-1.6}$
CMS 8 TeV [CMS collaboration (2013)]	69.9 ± 7.0	

Inclusion of NNLO QCD corrections

Gehrmann, Grazzini, Kallweit, Maierhoefer, von Manteuffel, Pozzorini, Rathlev, Tancredi; 1408.5243



- NNLO corrections range from 9% to 12%
- gg fusion contribution is about 35% of the NNLO correction

New CMS result (2015): σ_{W+W-} =61.1 ± 4.8 pb CMS-PAS-SMP-14-016

NNLO: σ_{W+W-} = 59.8 ± 1.2 pb

Dominant theoretical uncertainty on integrated cross section now from gg contribution:

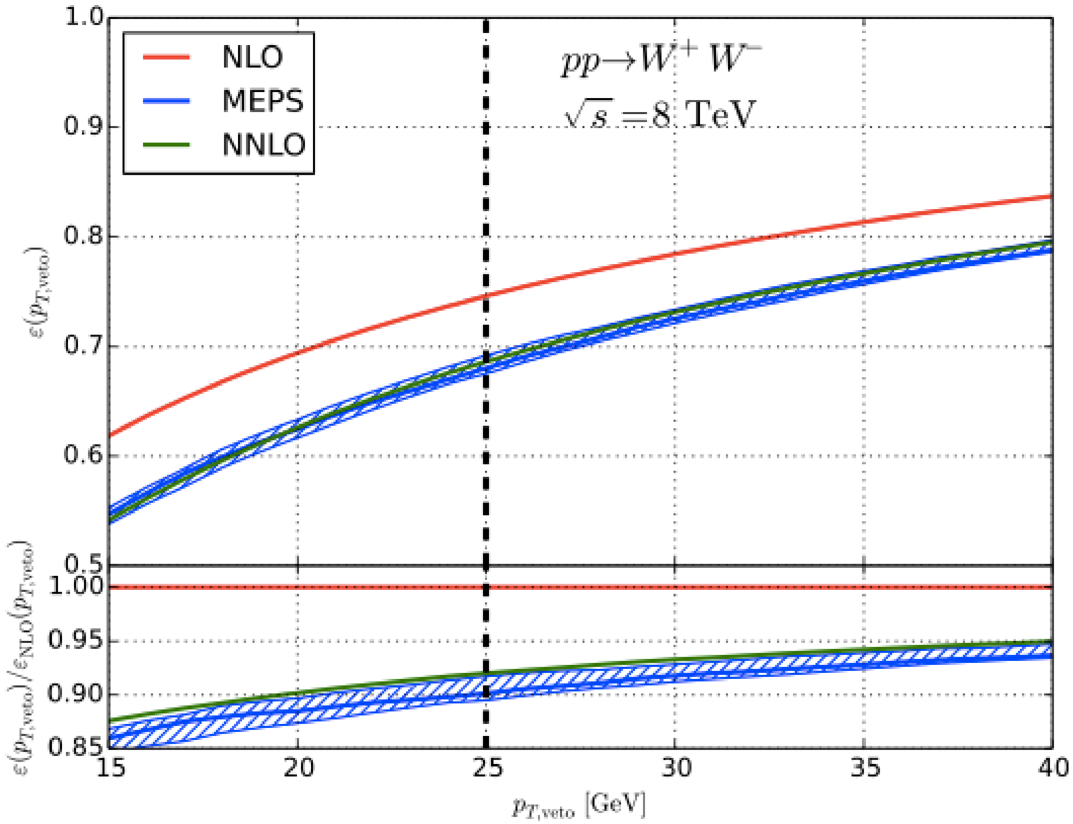
- 1.6 pb at LO (8 TeV), possible corrections up to 100% NNLO ⇒
  - ~ 3% uncertainty on σ_{W+W-}
- expect NLO result soon

Diboson cross section ratios

8 over 7 TeV	$R^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	δ_{scales} (%)	
WW	1.223	± 0.1	−0.4 – 0.2	
$gg \to WW$	1.330	± 0.2	−0.0 – 0.0	(scale errors missing)
WW/W	1.057	± 0.1	−0.3 – 0.2	
WZ	1.209	± 0.4	−1.2 – 0.4	
ZZ	1.165	± 0.4	−0.6 – 1.1	
$gg \to ZZ$	1.218	± 1.2	−0.0 – 0.0	(scale errors missing)
ZZ/Z	1.000	± 0.4	−0.5 – 1.1	
WW/WZ	1.012	± 0.4	−0.2 – 1.0	
WW/ZZ	1.050	± 0.4	−0.9 – 0.7	
WZ/ZZ	1.038	± 0.5	−1.7 – 0.4	

W^+W^-: jet-veto effects, MEPS

[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- first emission with NLO accuracy
- agrees with NNLO
- but missing higher log effects might still be sizeable

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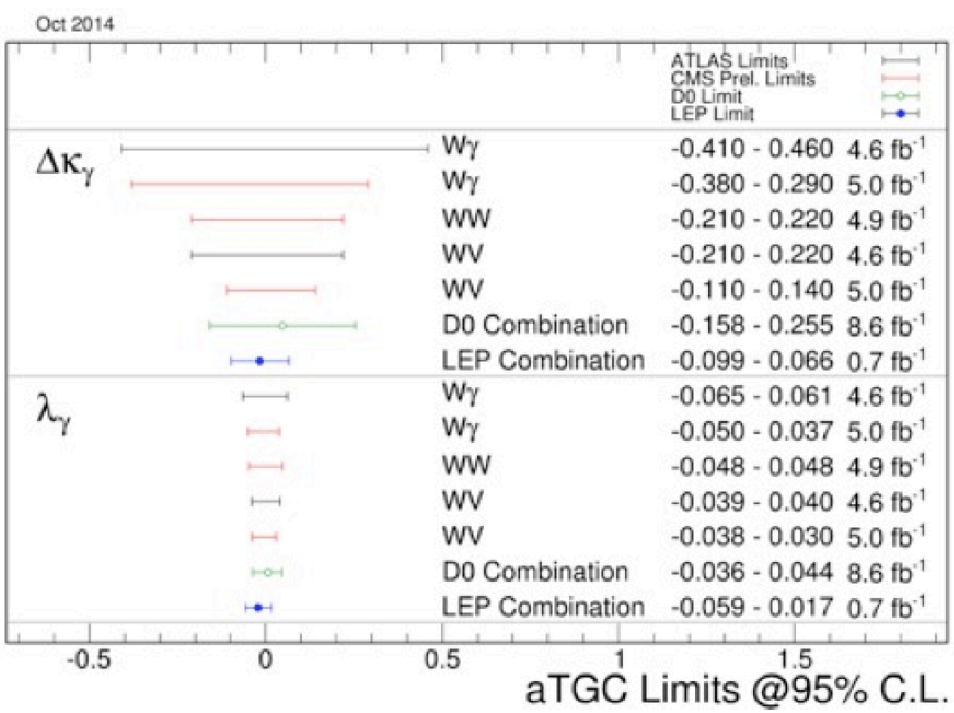
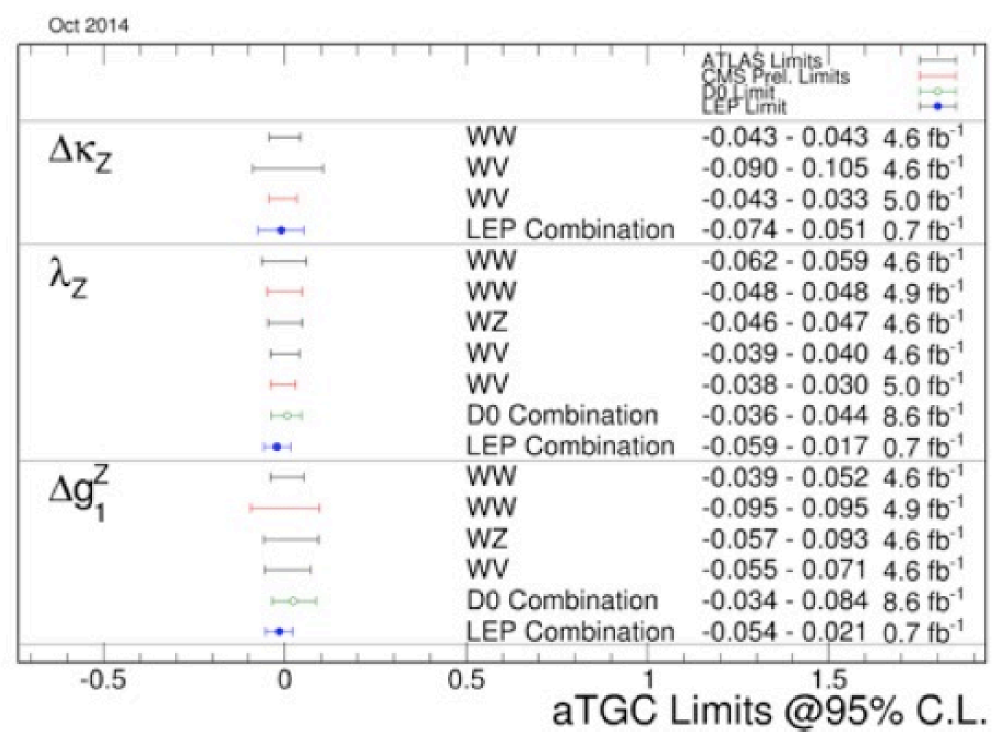
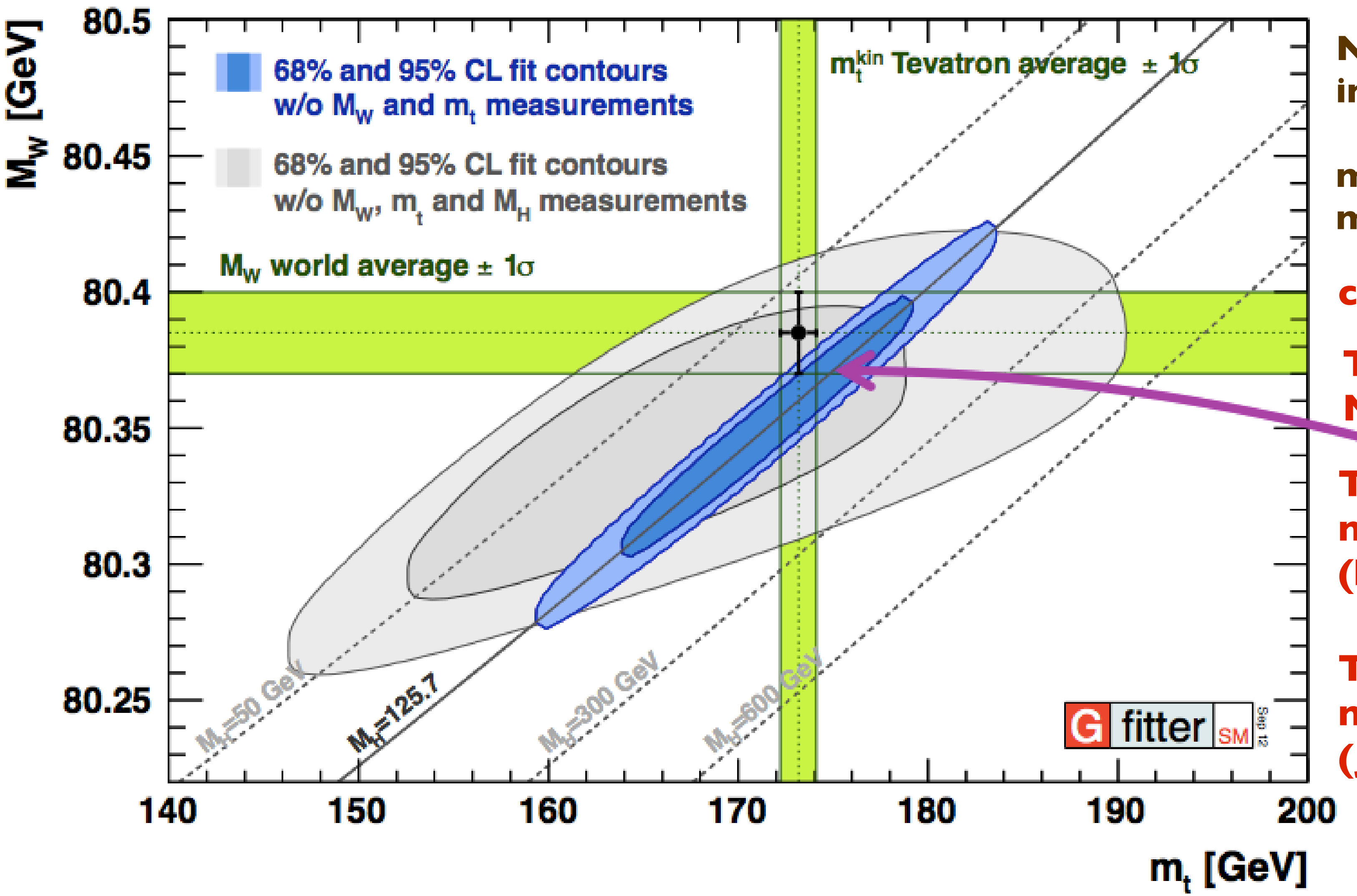




Top quark and W mass

Inclusion of m_H in EW fits greatly tightens correlation between m_W and m_{top}
introducing perhaps a slight tension ?



New EW fit results, including m_{Higgs} :

$m_{top} = 175.8^{+2.7}_{-2.4}$ GeV
m_W = 80359 ± 11 MeV

cfr:

Tevatron+LEP2:
M_W =80385±15 MeV

Tevatron+LHC:
m_t =173.34±0.76 GeV
(Mar 2014)

Tevatron:
m_t =174.34±0.64 GeV
(Jul 2014)

Continued improvement in the direct determination of m_W and m_{top} remains a high priority

Tevatron combined W mass: M_W =80387±16 MeV

Tevatron+LEP2 combined W mass: M_W =80385±15 MeV

Uncertainties

Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

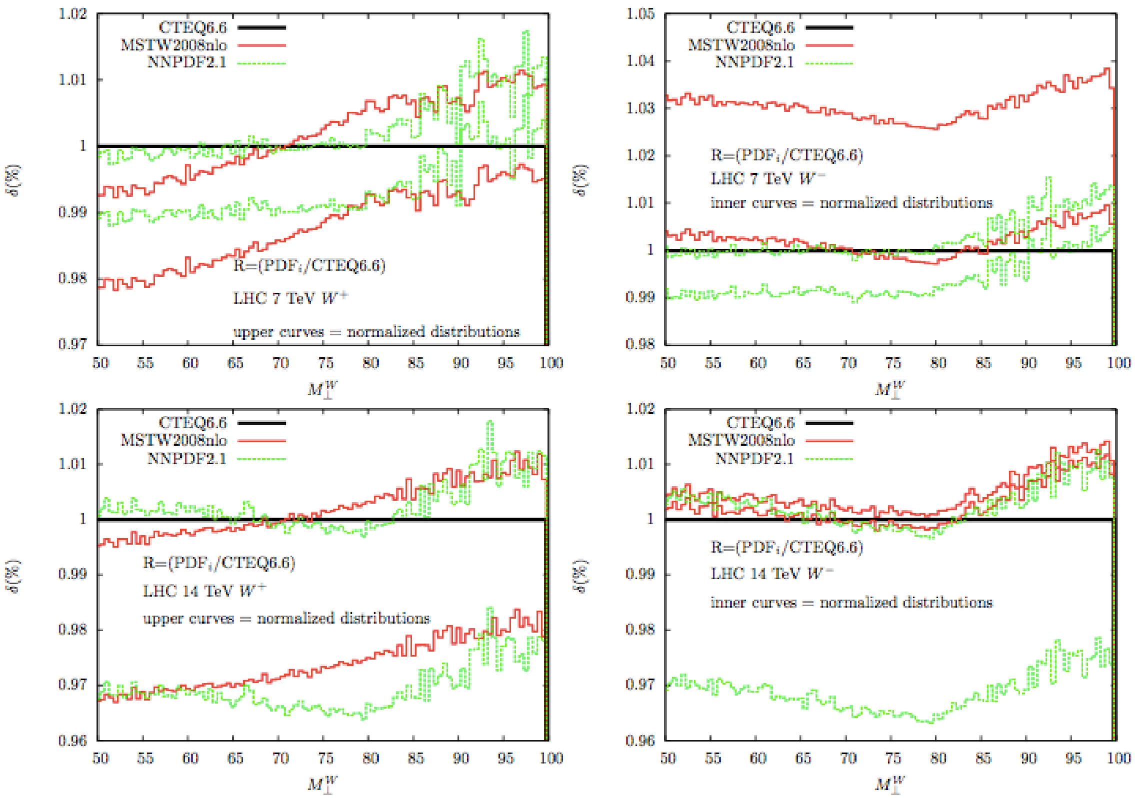
Largely stat. in origin → **10 MeV**

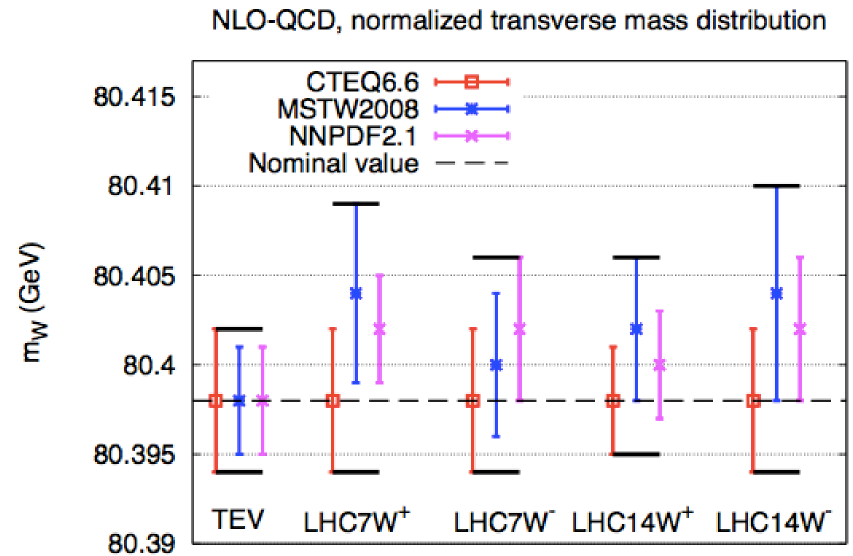
Largely theory in origin → **12 MeV**

90% of M_W information is in transverse mass

Predictions for PDF-induced TH syst at the LHC

Bozzi, Rojo, Vicini, arXiv:1104.2056, updated in arXiv:1309.1311





Theory syst:
$\Delta m_W \simeq \pm$ 8 MeV

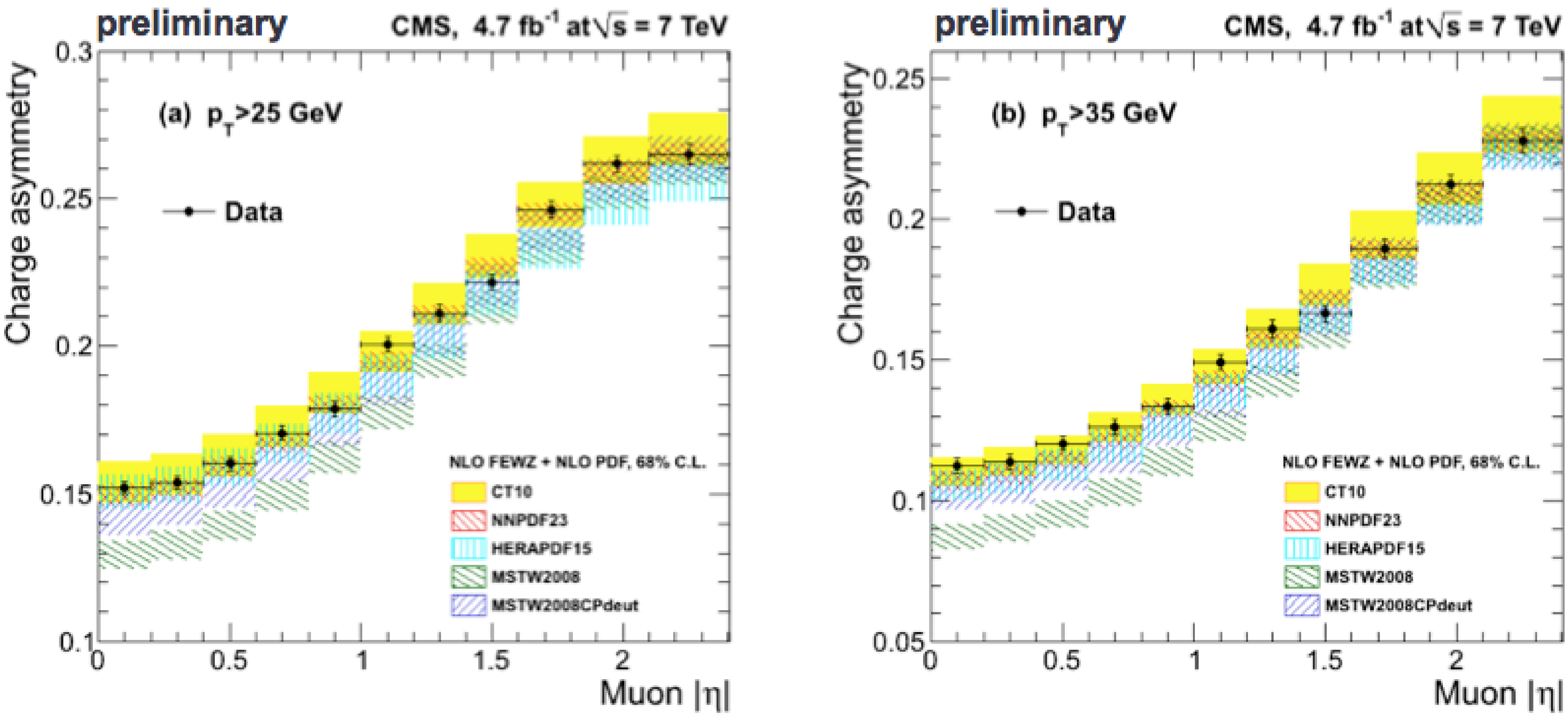
- This uncertainty should be further reduced, to be confident that it's negligible in the context of a measurement with a total systematics of less than ± 20 MeV

- These systematics should be validated through dedicated measurements: can one extract at the same time PDF and m_W from the fit of the relevant distributions (e.g. pt(e))?

- there remain issues raised by Krasny et al, Eur. Phys. J. C 69, 379 (2010) which are not fully addressed by this study (e.g. the impact of the charm mass in using pt(Z) to model pt(W)

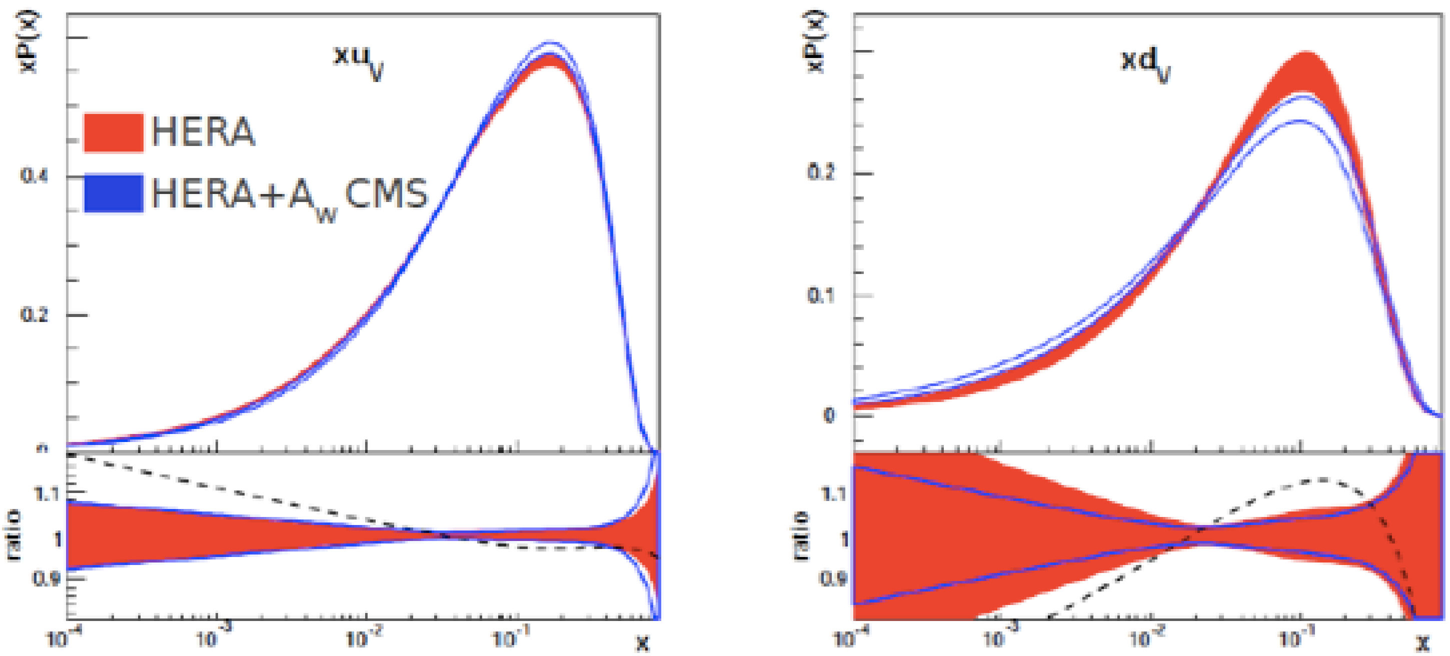
There is still room to further constrain PDF distributions relevant for W/Z production properties.

CMS-PAS-SMP-12-021



Questions:
- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements?
- Would this have an impact in the extraction of m_W ?

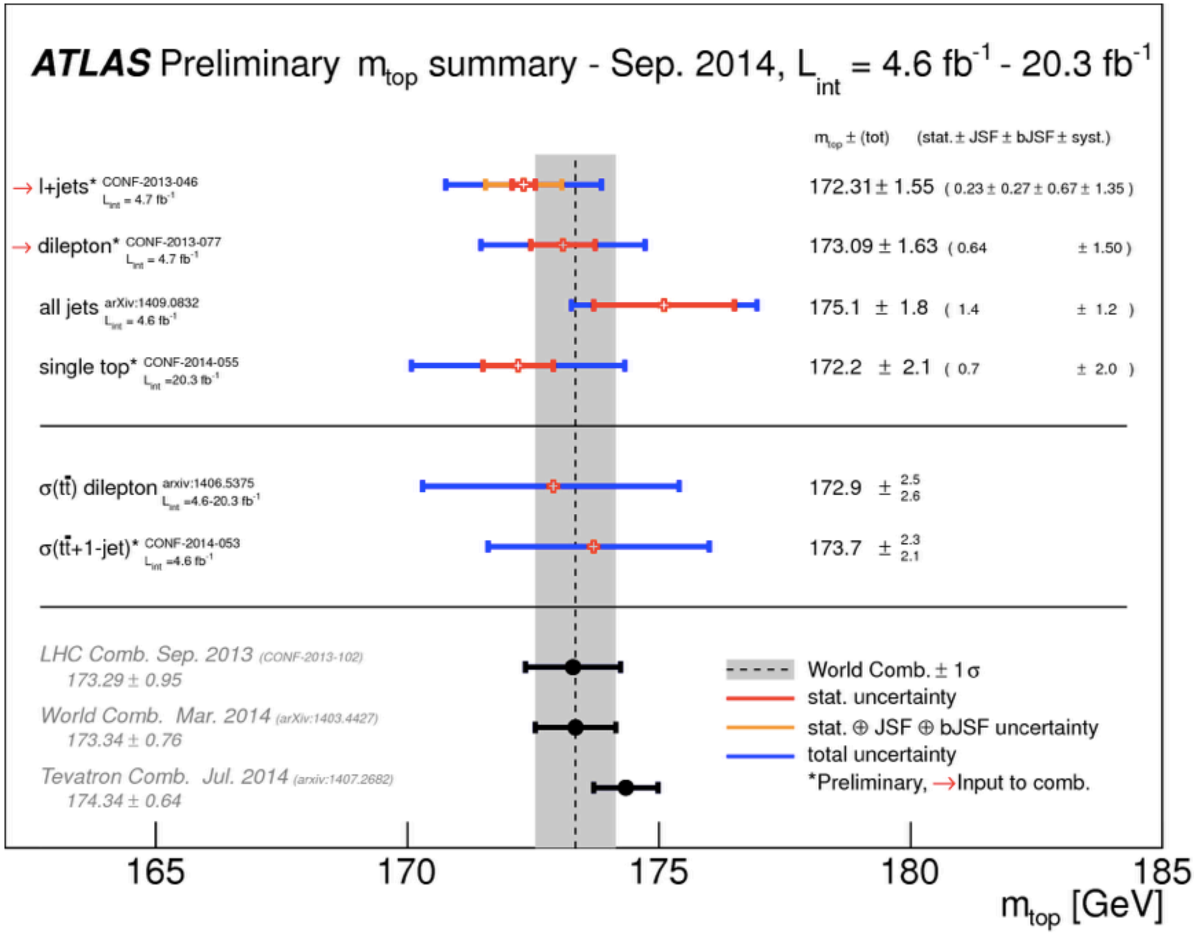
Impact of CMS W-asymmetry data on the fit of u,d(x) using HERA data only

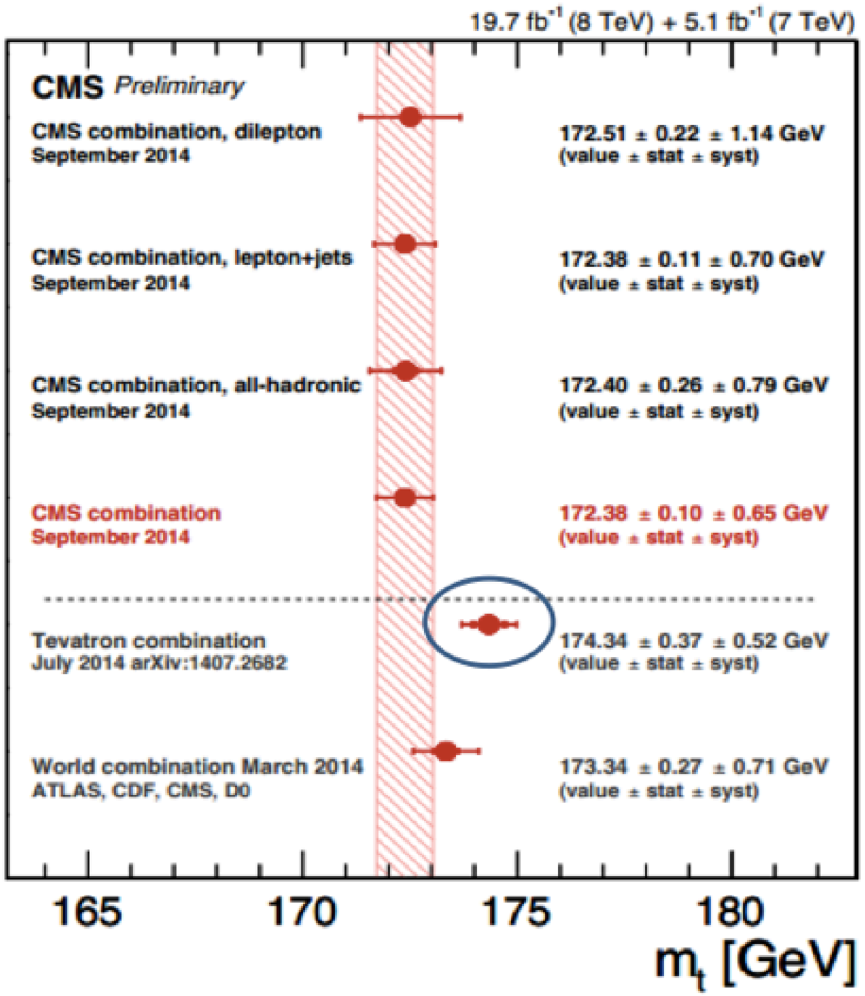


HERAfitter bands represent experimental uncertainties only

R. Placakyte, A. Vargas, http://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=238762
A.Khukhunaishvili, CCT Sept 12, http://indico.cern.ch/conferenceDisplay.py?confId=270169

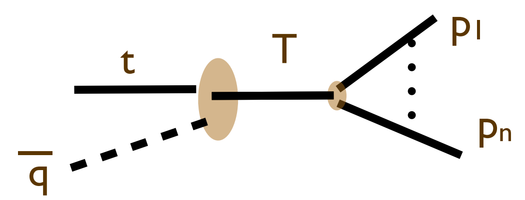
Top quark mass





Why is it hard to measure/define m_{top} at the LHC ?

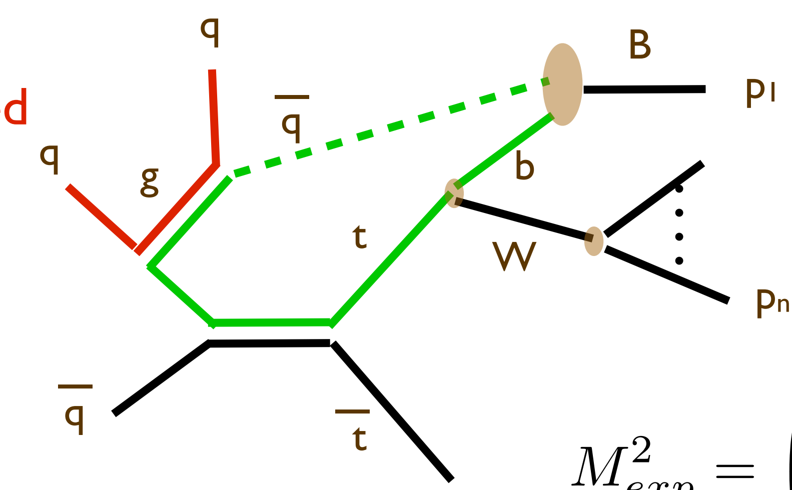
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

$m_t = F_{lattice/potential\ models}(m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

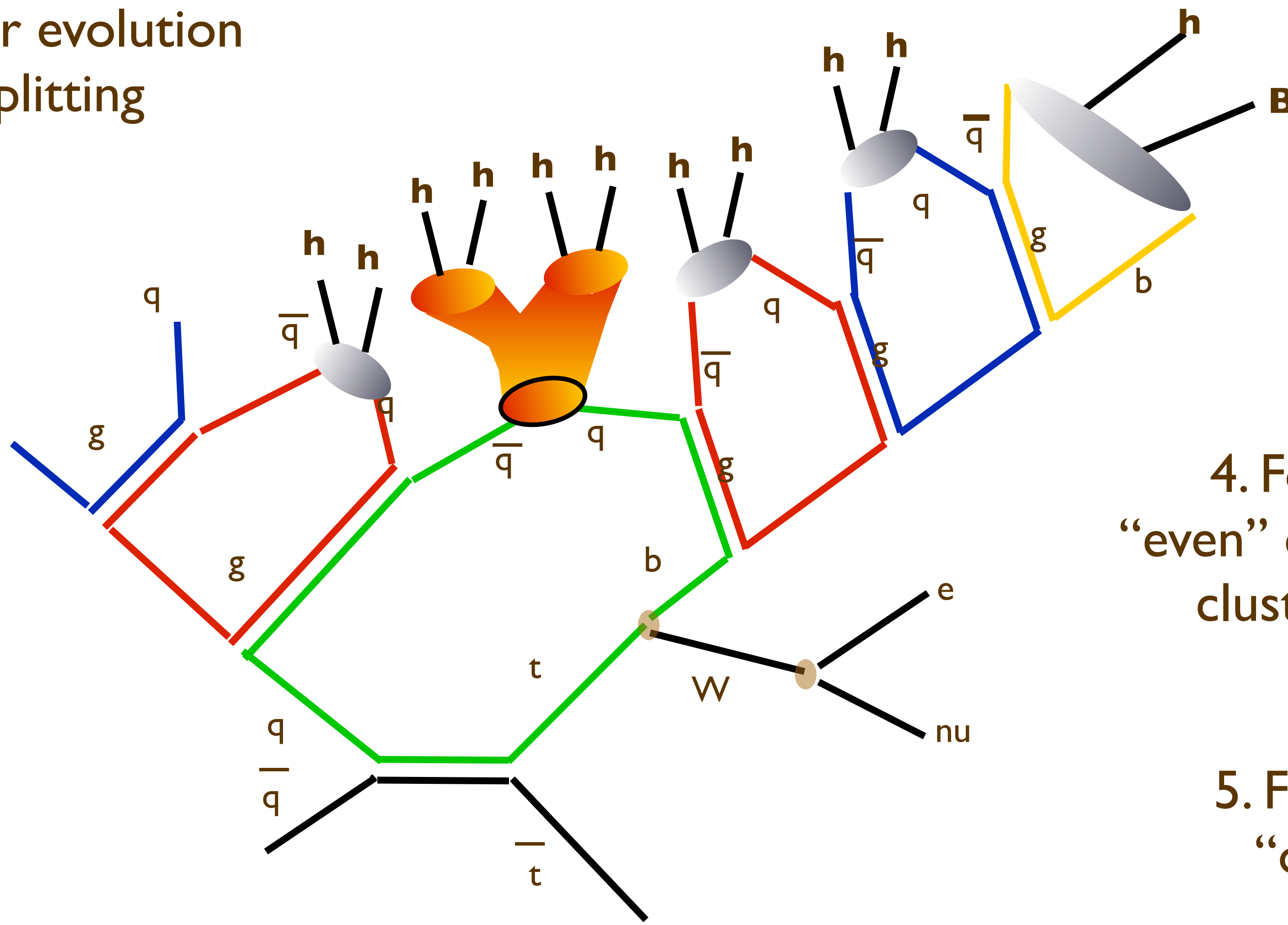
The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top})$~ 1 GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

1. Hard Process

2. Shower evolution

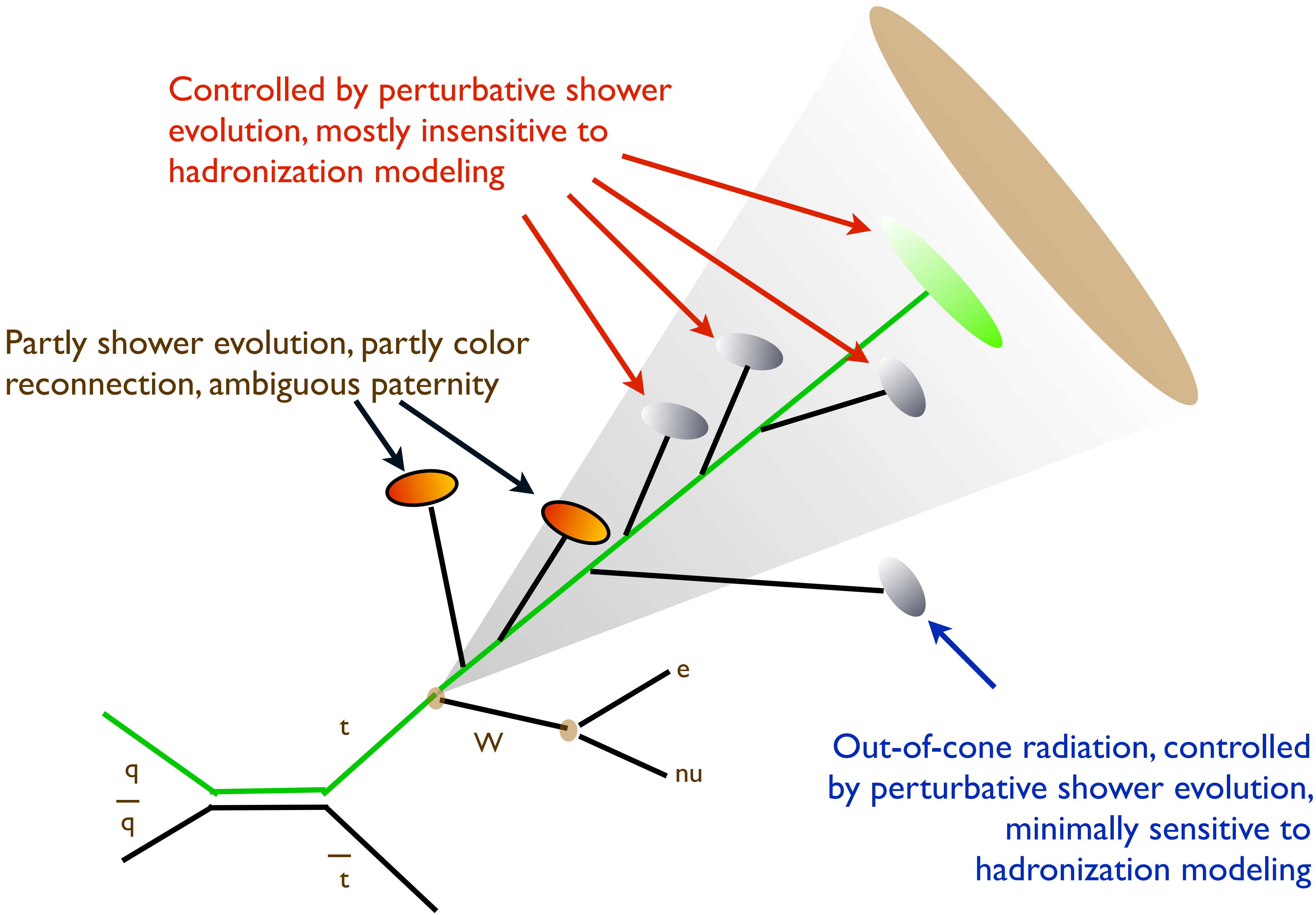
3. Gluon splitting



4. Formation of "even" clusters and cluster decay to hadrons

5. Formation of "odd" cluster

6. Decay of "odd" clusters, if large cluster mass, and decays to hadrons



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling
Partly shower evolution, partly color reconnection, ambiguous paternity
t
W
e
nu
q
q
t
Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling

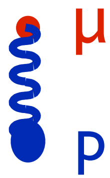
m_{MC} vs m_{pole}

Consider a simplified example

Take $\mu \to e\nu\nu$.

$m_\mu = m_{pole}$ and $m_\mu{}^2 = [p(e)+p(\nu)+p(\nu)]^2$

Take μ interacting with an external field, e.g. bound with a proton in an atom:

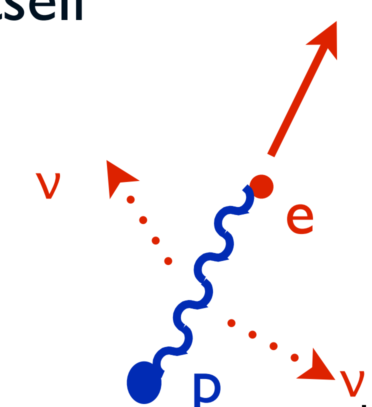


$$E = m_p + m_\mu + (K + V)_\mu = m_p + m_\mu - m_\mu \alpha^2/2 = m_p + m_\mu^*$$

$m_\mu^* = m_\mu\,(1 - \alpha^2/2)$ absorbs part of the potential energy into itself

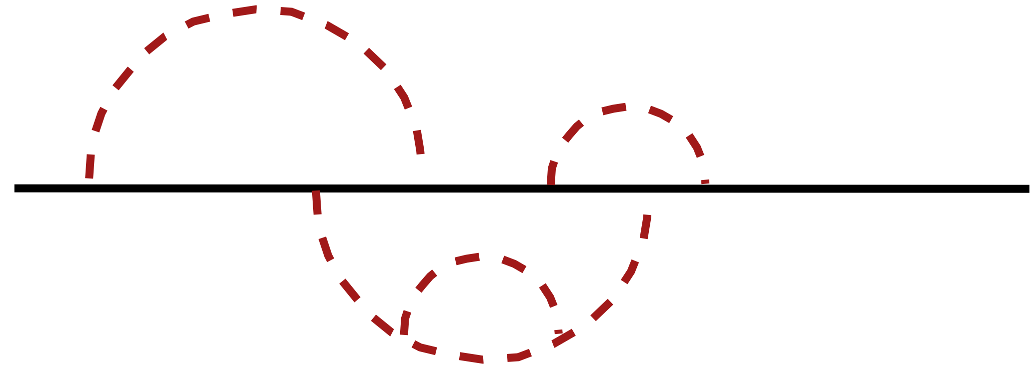
It is a "useful" mass, since, once the muon decays,

$[p(e)+p(\nu)+p(\nu)]^2 = m_\mu^{*\,2}$, which $\neq m_\mu^2$ by $O(\alpha^2)$



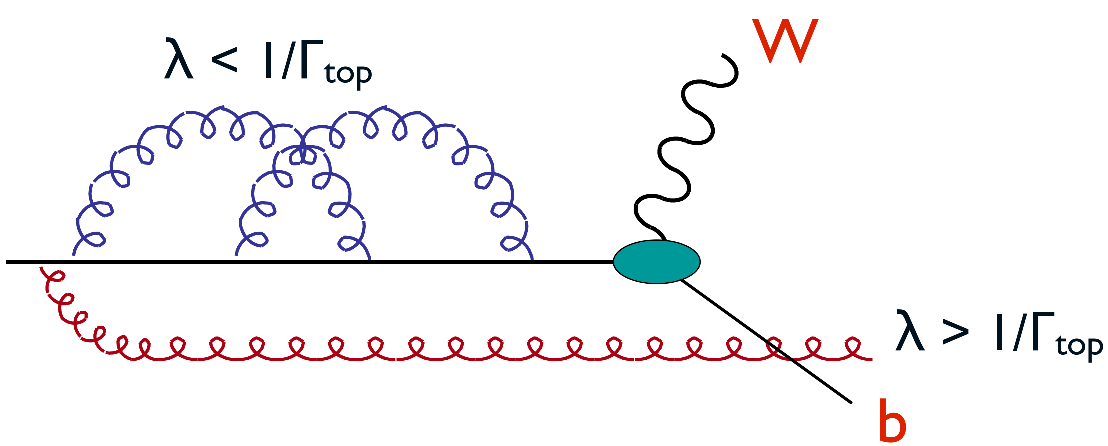
The reason is that the electron, to escape, must overcome the Coulomb potential, and its energy will be shifted by $V = -m_\mu\alpha^2$

In the case of a quark, the potential is the due to the interaction with its own gluon field



The pole mass is defined by resumming the effects of all these diagrams, absorbing all divergences. However, we know that we find problems if we integrate the loop momenta below the scale Λ_{QCD}, where perturbation theory breaks down. If we do it, to define m_{pole}, the perturbative series can only be resummed up to a ("renormalon") ambiguity. If we stop before, at some scale, we dump into a m^* mass the self-energy potential due to modes with wavelength above that scale.

This is further justified for the top, which anyway only lives $1/\Gamma_{top}$, so gluons with wavelength > $1/\Gamma_{top}$ are cutoff:

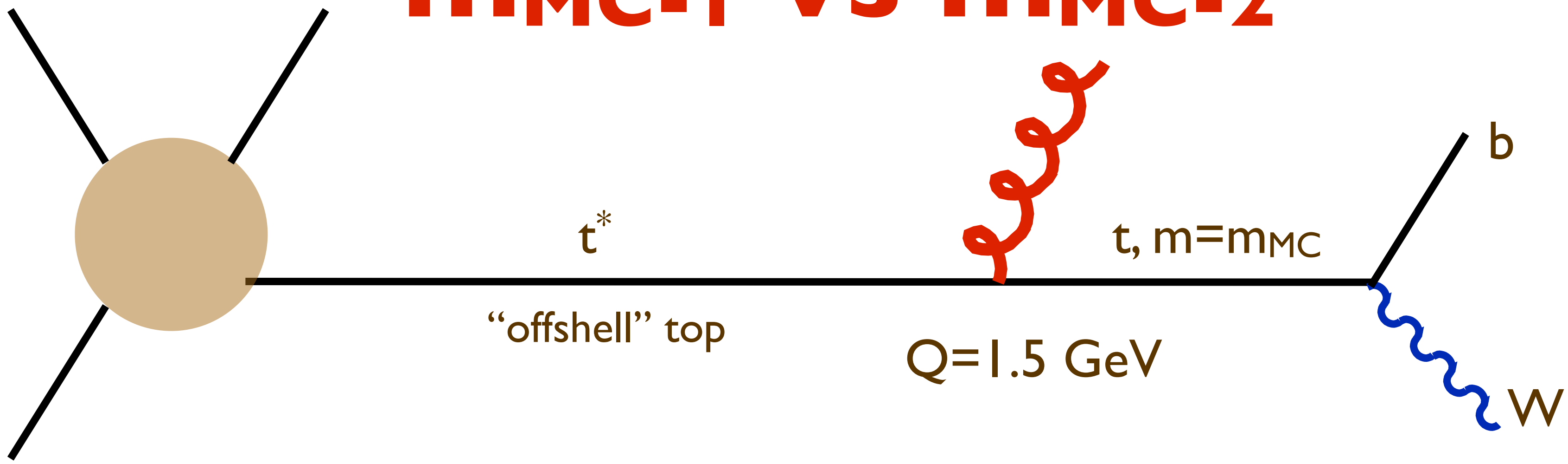


In this case,

$$\delta m \sim \alpha_S \, \Gamma_{top}$$

what is the coefficient ?

m_{MC-1} vs m_{MC-2}



This emission at scale Q=1.5 GeV may or may not be present in the MC, depending on the IR cutoff scale of the shower (e.g. 1 GeV vs 2 GeV). One may consider this is as using m_{MSR} defined at different scales, or as using different top-mass definitions.

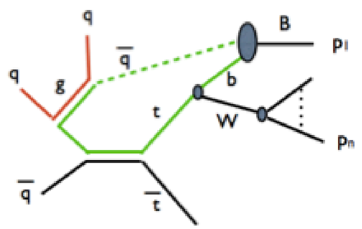
The question is whether the emission of the extra gluons in the region ($cutoff_{MC-1}$ – $cutoff_{MC-2}$) affects the observables used to measure m_{MC} and change the measured value

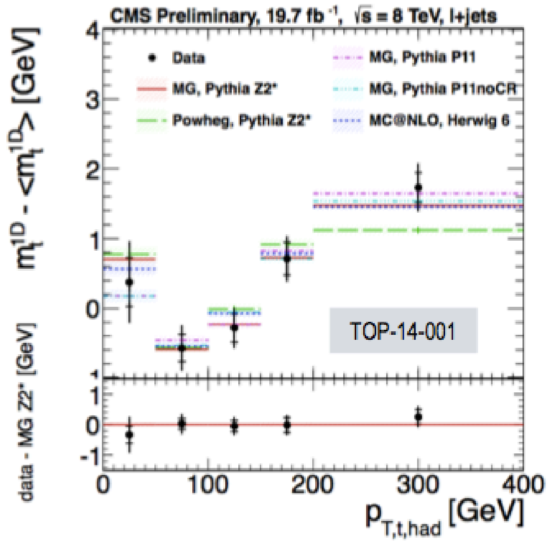
Typically we consider these possible differences as part of the shower/hadronization systematics. There is no evidence that they exceed the 100 MeV level.

Studies like those shown by CMS (mtop vs different production configurations) are crucial to understand the sensitivity to these effects, the consistency of the modeling in different MC, with data and with themselves

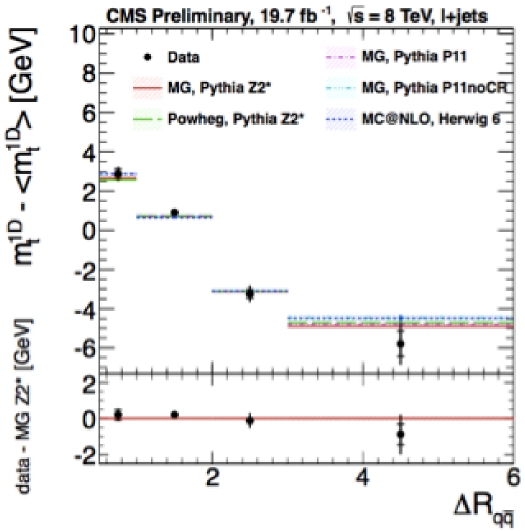
Top Mass: Kinematic Dependence

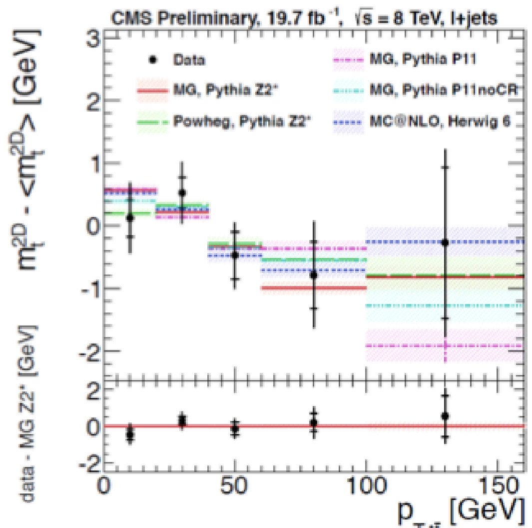
- Probe for issues with QCD modeling or Mass Definition by looking for kinematic dependence in extracted top mass
- Investigate distributions with sensitivity to
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics
- Figures: $m_{top} - \langle m_{top} \rangle$
- Check 14 variables; ≈ 50 total bins





Observable	$m_t^{1D}\ \chi^2$	JSF χ^2	$m_t^{2D}\ \chi^2$	Ndf
$\Delta R_{q\bar{q}}$	2.87	3.66	0.83	3
$p_{T,t,had}$	0.89	12.03	5.76	4
$\lvert\eta_{t,had}\rvert$	5.56	1.22	1.14	3
H_T^4	6.19	9.18	7.54	4
$m_{t\bar{t}}$	2.16	4.69	4.22	5
$p_{T,t\bar{t}}$	1.02	1.22	1.33	4
Jet multiplicity	4.24	0.10	1.16	2
$p_{T,b,had}$	2.57	5.80	2.17	4
$\lvert\eta_{b,had}\rvert$	1.15	0.08	0.72	2
$\Delta R_{b\bar{b}}$	0.37	1.63	1.77	3
$p^1_{T,q,had}$	4.04	8.39	1.28	4
$\lvert\eta^1_{q,had}\rvert$	3.36	3.79	6.27	2
$p_{T,W,had}$	1.59	8.06	1.60	4
$\lvert\eta_{W,had}\rvert$	1.41	1.09	1.35	3
Total	37.43	60.94	37.15	47





No significant deviations between data and various models w.r.t their kinematic dependence

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CMS-PAS-TOP-12-031

$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat) \pm 122\ (syst.)\ MeV$$

remarks

QCD effects depend on how long the top actually lives. Should one change m_{MC} as a function of lifetime, event by event ?

When a top lives longer than $1/\Lambda_{QCD}$ (prob ~ $\exp(-\Gamma_{top}/\Lambda_{QCD})$) it likely hadronizes

Rare/forbidden top decays

<table>
<tr><th>EXP</th><th>$\sqrt{s}$TeV</th><th>$\mathcal{L}(fb^{-1})$</th><th>Br</th><th>(q=u)%</th><th>(q=c)%</th></tr>
<tr><td>ATLAS</td><td>7&8</td><td>25</td><td rowspan="2">$t \to Hq$</td><td colspan="2">0.79</td></tr>
<tr><td>CMS</td><td>8</td><td>19.5</td><td colspan="2">0.56</td></tr>
<tr><td>CDF</td><td>1.8</td><td>0.11</td><td rowspan="2">$t \to \gamma q$</td><td colspan="2">3.2</td></tr>
<tr><td>CMS</td><td>8</td><td>19.1</td><td>0.0161</td><td>0.182</td></tr>
<tr><td>CDF</td><td>1.96</td><td>2.2</td><td rowspan="5">$t \to gq$</td><td>0.039</td><td>0.57</td></tr>
<tr><td>D0</td><td>1.96</td><td>2.3</td><td>0.02</td><td>0.39</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.56</td><td>7.12</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.035</td><td>0.34</td></tr>
<tr><td>ATLAS</td><td>8</td><td>14.2</td><td>0.0031</td><td>0.016</td></tr>
<tr><td>CDF</td><td>1.96</td><td>1.9</td><td rowspan="5">$t \to Zq$</td><td colspan="2">3.7</td></tr>
<tr><td>D0</td><td>1.96</td><td>4.1</td><td colspan="2">3.2</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.51</td><td>11.40</td></tr>
<tr><td>ATLAS</td><td>7</td><td>2.1</td><td colspan="2">0.73</td></tr>
<tr><td>CMS</td><td>7&8</td><td>24.7</td><td colspan="2">0.05</td></tr>
</table>

R.Goldouzian, arXiv:1412.2524

FB asymmetry at CDF/D0

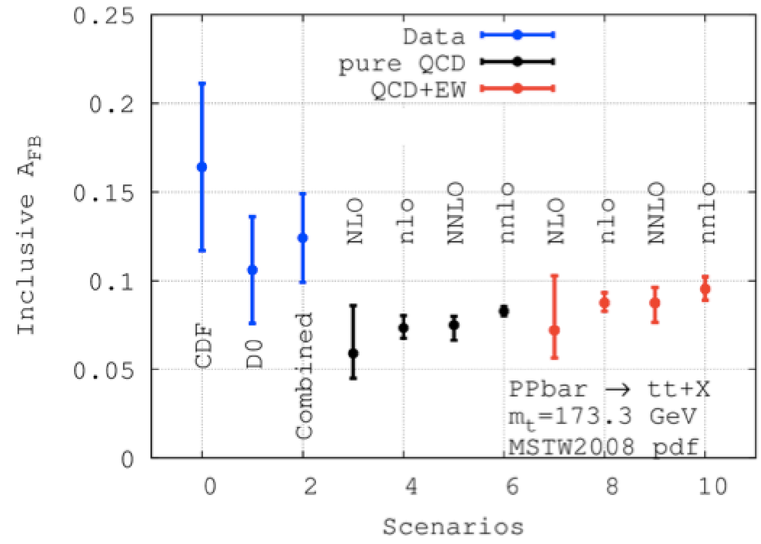
$$A_{FB} = \frac{N_{EW} + \alpha_S^3 N_3 + \alpha_S^4 N_4 + \mathcal{O}(\alpha_S^5)}{\alpha_S^2 D_2 + \alpha_S^3 D_3 + \alpha_S^4 D_4 + \mathcal{O}(\alpha_S^5)}$$

(N)NLO

$$= \alpha_S \frac{N_3}{D_2} + \frac{N_{EW}}{\alpha_S^2 D_2} + \alpha_S^2 \left(\frac{N_4}{D_2} - \frac{N_3 D_3}{D_2^2} \right) - \frac{N_{EW} D_3}{\alpha_S D_2^2} + (\alpha_S^3)$$

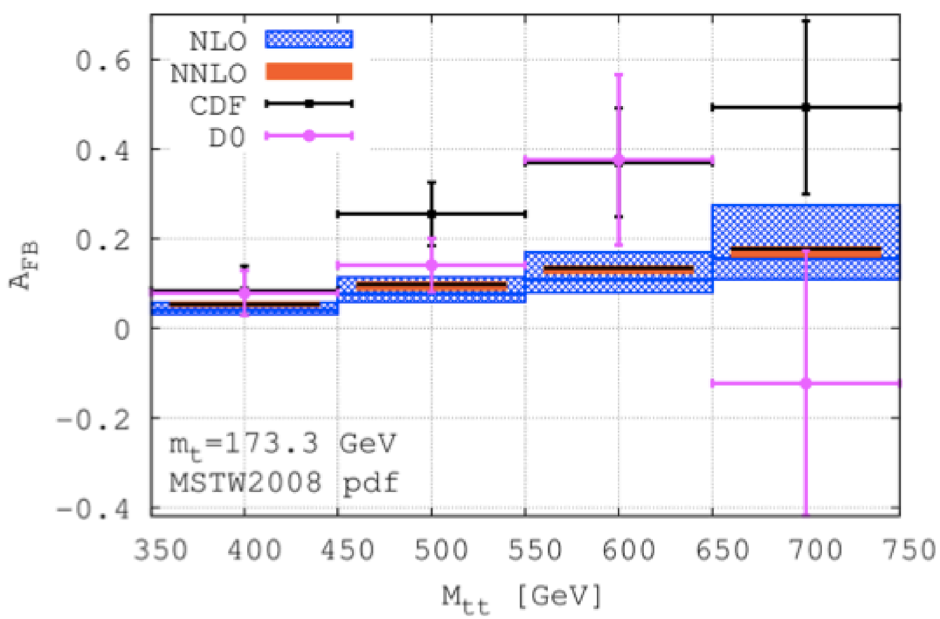
(n)nlo

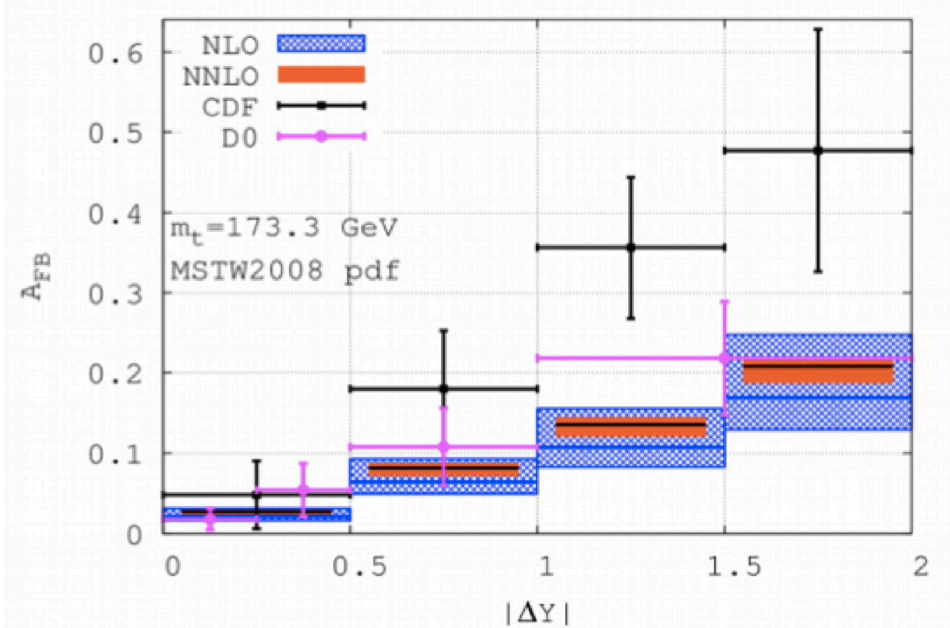
[Czakon, Fiedler, Mitov; 2014]



- Differential asymmetry

[Czakon, Fiedler, Mitov; 2014]





NNLO calculation for A_C at the LHC in progress (Czakon et al)

Other SM/dynamics issues I did not discuss

- Production of jets
  - multijet final states, α_S measurements, ...
- Production of c/b quarks
  - use to constrain gluon PDF
  - charmonium/bottomonium, onia polarization
- Top quarks:
  - prodution propoerties (pt spectra, Mtt distribution, ...)
  - single top production (V_{tb} constraints)
  - W polarization, spin correlations, anomalous couplings, ...
- DY:
  - high mass Z
  - associated production of W/Z and jets; high-pT W/Z production
  - associated production of W+charm (strange PDF)
  - Associated production of W/Z and bbar, ccbar (bg to V+H → V+ Q Qbar)
- Diffraction (low mass / high mass)
- Heavy flavours: spectroscopy (X,Y, Z states), decays, CPV, ...
- .....

What's to be learned from the Higgs, now that's been found?

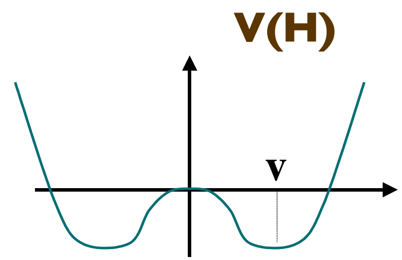
The Higgs boson is directly connected to several key questions:

- What's the real origin of the Higgs potential, which breaks EW symmetry?
  - underlying strong dynamics? composite Higgs?
  - RG evolution from GUT scales?
  - Are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
- The hierarchy problem: what protects the smallness of m_H / $m_{Plank,GUT,...}$?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?
  - is there a relation between EW baryogenesis and DM?
- Is there a relation between Higgs, EWSB and Dark Matter?

Higgs selfcouplings

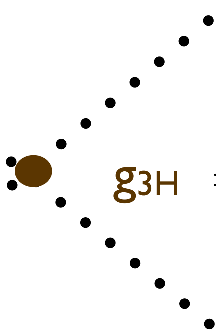
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

$$V_{SM}(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

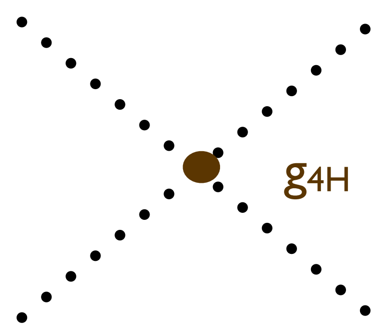


$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \dfrac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



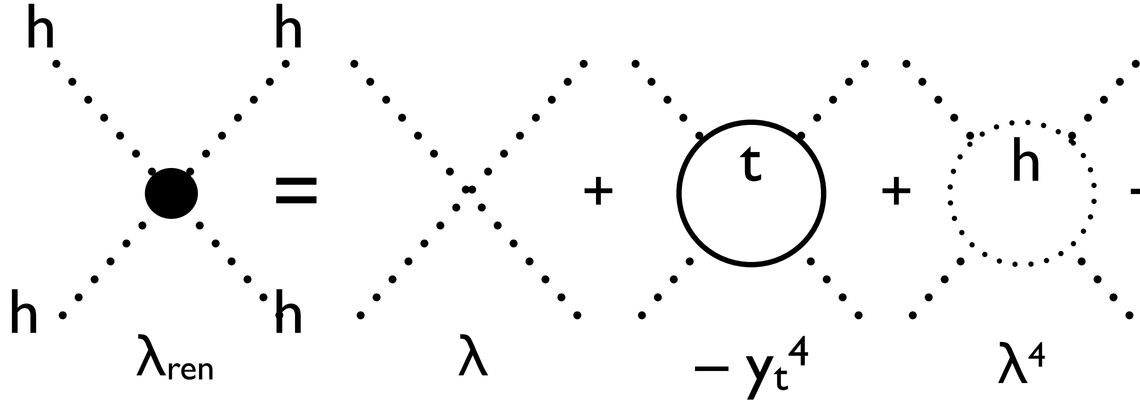
$g_{3H} \Rightarrow 6\lambda\, v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

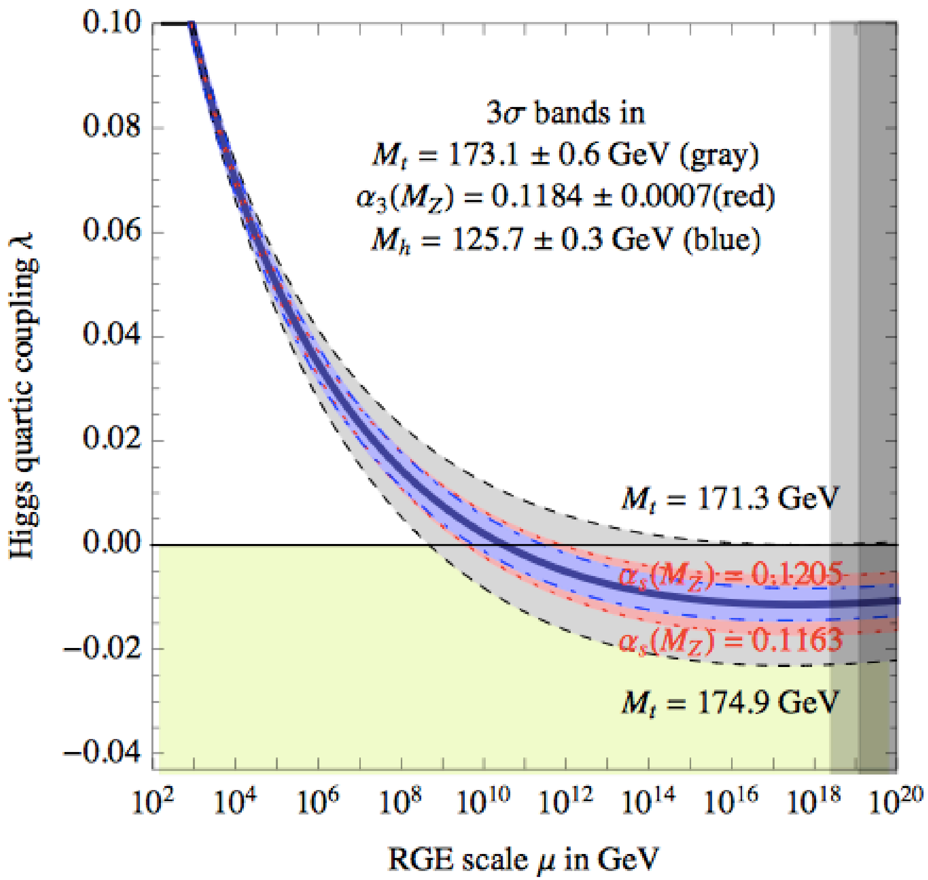
(meta)Stability of the Higgs potential

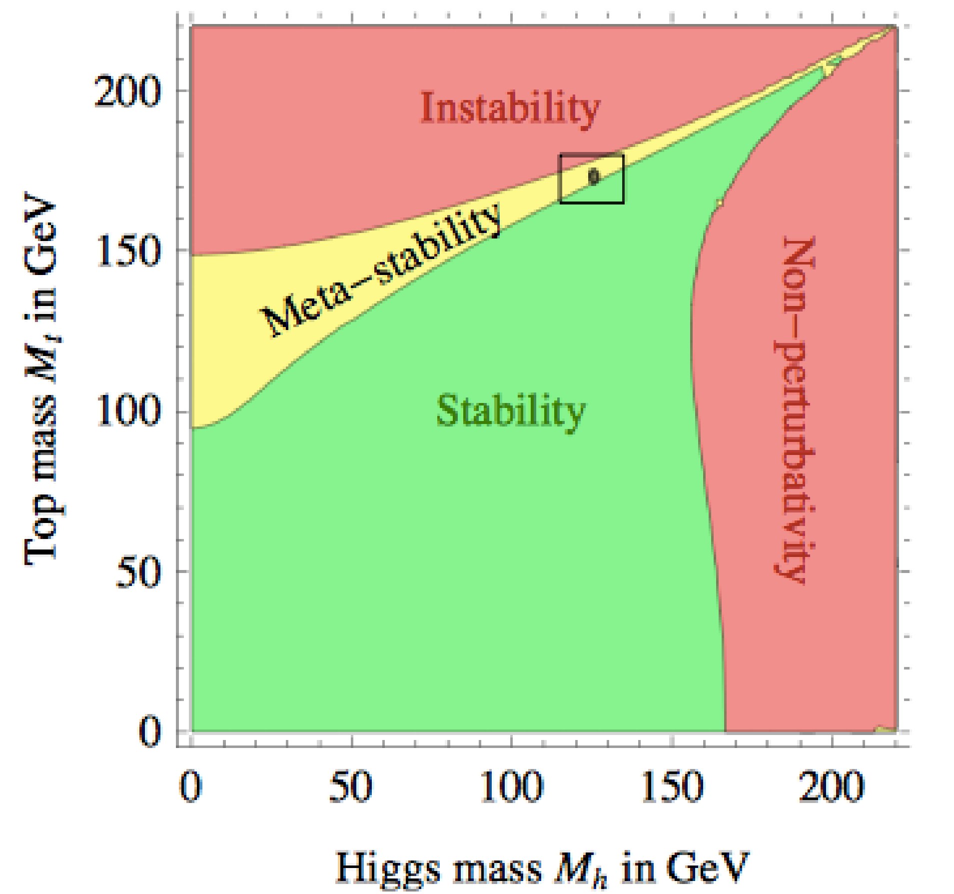


$$\Rightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4 \propto a\, m_H^4 - b\, m_t^4$$

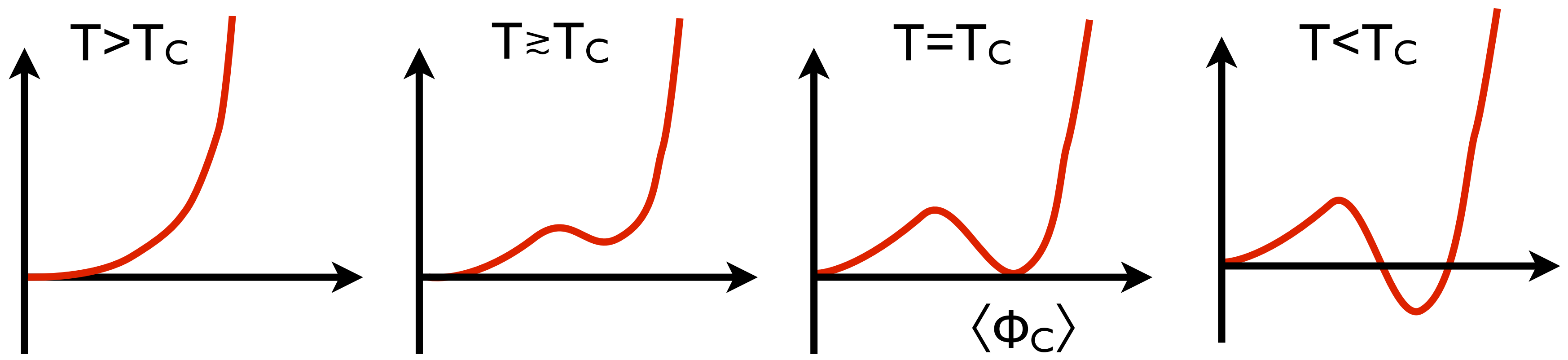
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential

Degrassi et al, http://arxiv.org/pdf/1205.6497





The nature of the EW phase transition



Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV ⇒ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible

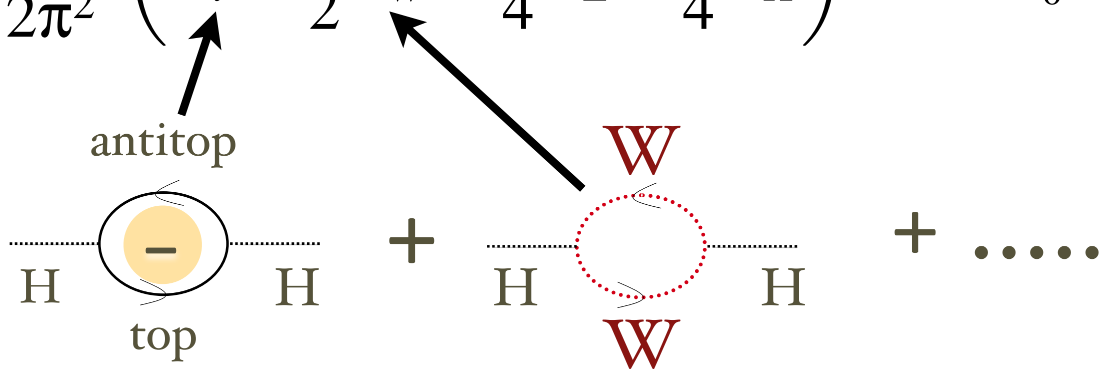
Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for future accelerators

- Experimental probes:
  - study of triple-Higgs couplings (... and quadruple, etc)
  - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
  - search for new sources of CP violation, originating from (or affecting) Higgs interactions

H, the hierarchy problem, and physics beyond the SM

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (125\,\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$



Λ= scale up to which the SM is valid

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\mathrm{GeV}$$

Assuming Λ can extend up to the highest energy beyond which quantum gravity will enter the game, 10^{19} GeV, keeping m_H below 1 TeV requires a fine tuning among the different terms at a level of 10^{-34}:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

extremely **unnatural** if it is to be an accident !!

hierarchy, or **fine tuning**, problem

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

Utrecht, The Netherlands

Naturalness is not a recent "fashion": it's an original sin of the SM itself ... See e.g.

Aug **1979**. 28 pp.

NATO Adv.Study Inst.Ser.B Phys. 59 (1980) 135

As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Pursuing naturalness beyond 1000 GeV will require theories that are immensely complex compared with some of the grand unified schemes.

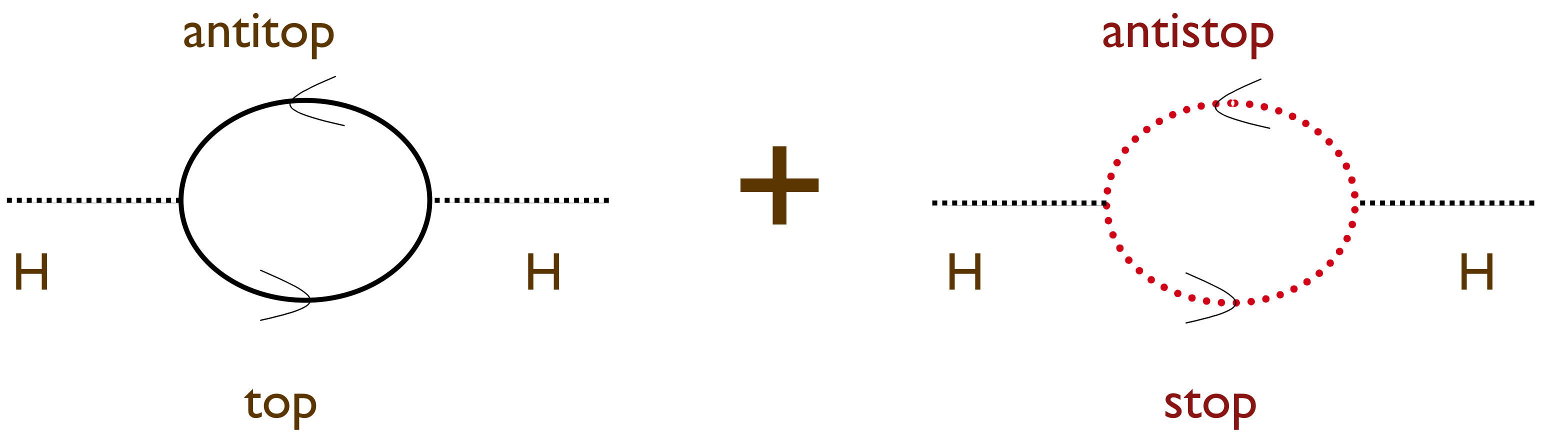
We're finally there, at 1 TeV, facing the fears about a light SM Higgs anticipated long ago

A remarkable attempt towards a natural theory was made by Dimopoulos and Susskind [2]. These authors employ various kinds of confining gauge forces to obtain scalar bound states which may substitute the Higgs fields in the conventional schemes. In their model the observed fermions are still considered to be elementary.

Most likely a complete model of this kind has to be constructed step by step. One starts with the experimentally accessible aspects of the Glashow-Weinberg-Salam-Ward model. This model is natural if one restricts oneself to mass-energy scales below 1000 GeV. Beyond 1000 GeV one has to assume, as Dimopoulos and Susskind do, that the Higgs field is actually a fermion-antifermion composite field. Coupling this field to quarks and leptons in order to produce their mass, requires new scalar fields that cause naturalness to break down at 30 TeV or so.

- The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack of BSM phenomena up to the TeV scale, make the ***naturalness issue as puzzling as ever***
- Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of ***naturalness will ultimately require an understanding***.
- Naturalness remains a guiding principle to drive the search of new phenomena at the LHC

Higgs self-energy, Susy fix



(I)

$$\Delta m_H^2 \propto G_F\, m_t^4 \log(m_t/m_{stop})$$ → stability of the natural scale of the Higgs mass restored!

$$m_H \leq M_Z + \text{ radiative corrections } (\propto \log(m_t/m_{stop})) \leq 135 \text{ GeV}$$

More in general ....

Tie the Higgs mass to some symmetry which protects it against quadratic divergencies

Supersymmetry

H (scalar) ↔ fermion

Gauge symmetry

H (scalar) ↔ 5th component of a gauge bosons in 5 dimensions or more

=> extra dimensional theories

Global symmetry

$H \rightarrow H + a \Rightarrow L(H)=L(\partial H)$

=> Little Higgs theories, Technicolor
H=pseudo-goldstone boson

The manifestations of these new symmetries (e.g. new particles, new interactions) cannot be too far from the TeV scale, in order to solve the Higgs fine tuning issue in a **natural** way

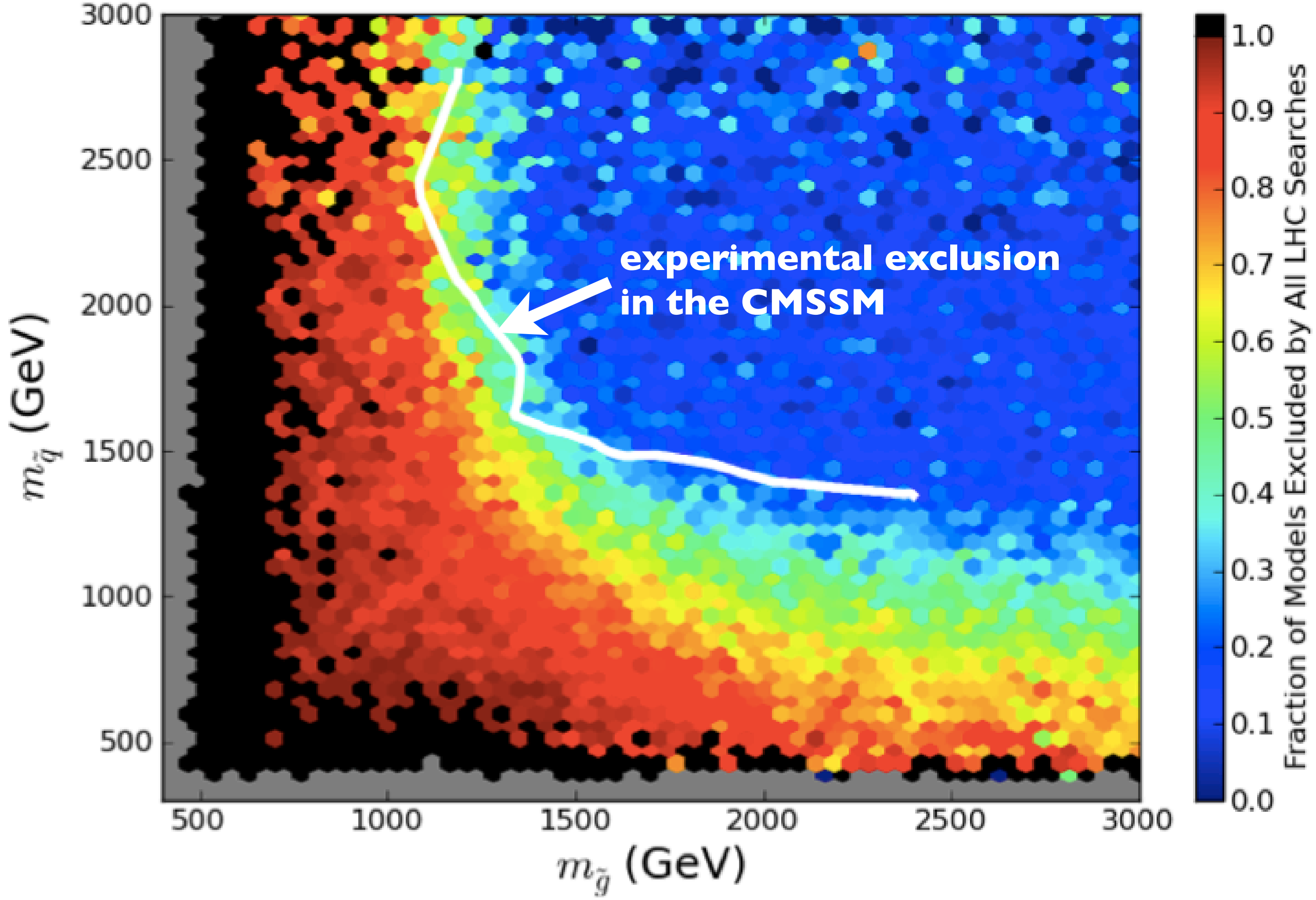
- So far, no search of new particles possibly related to the solution of the hierarchy problem or otherwise has led to positive results.
- So, where is everyone?

Ways out

- new particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....
- Physics beyond the SM (BSM) is more subtle than "conventional" models => fine-tuning or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....
- The scale at which naturalness is restored is higher than the TeV: acceptable, but becoming less and less "natural" as the scale grows ....
- **Naturalness** is an ill guided principle to solve the fine-tuning problem $\Rightarrow$ Anthropic principle, ???

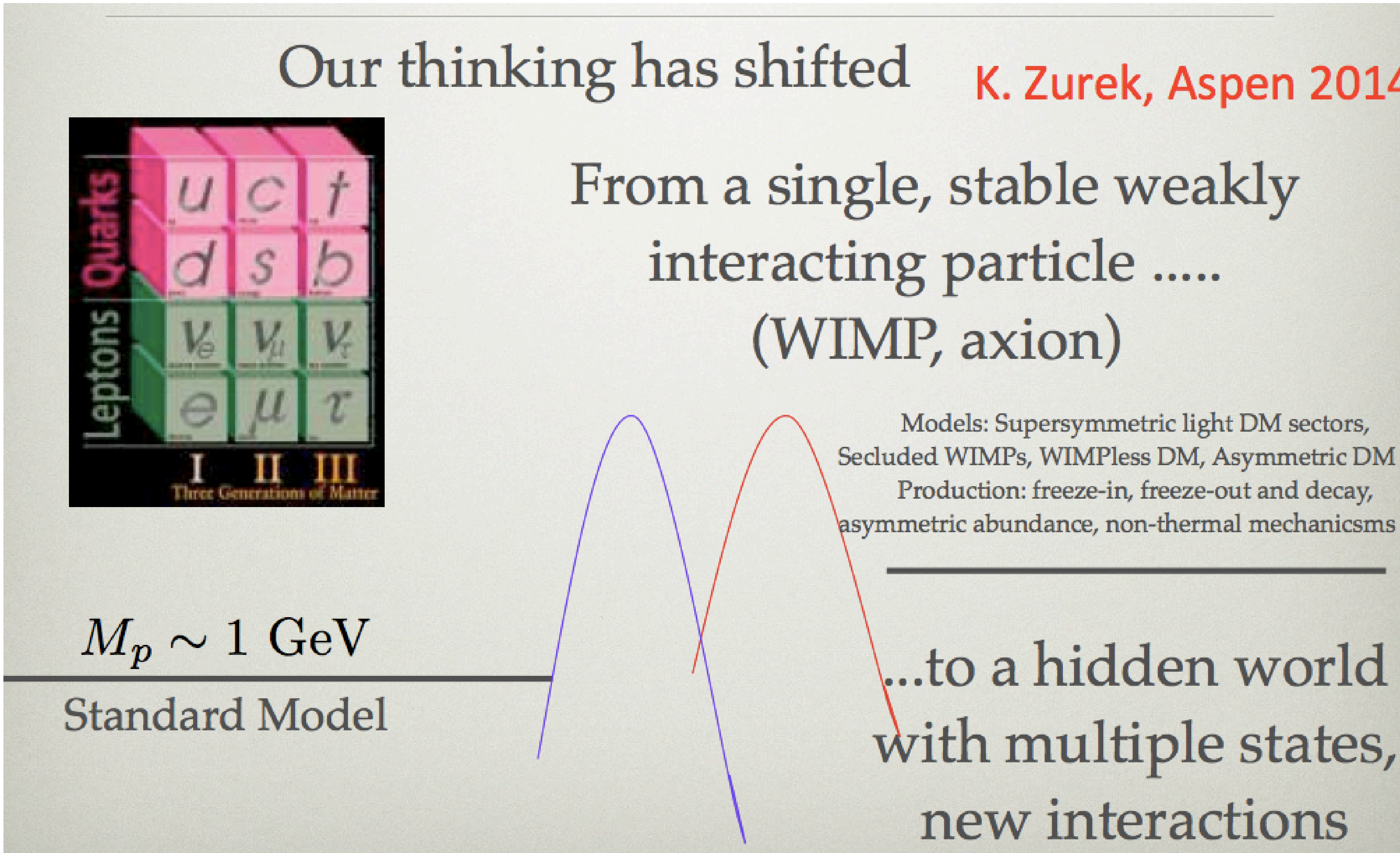
Example of ways out: explore less constrained SUSY models

Fraction of excluded models in the pMSSM (19 parameters MSSM)



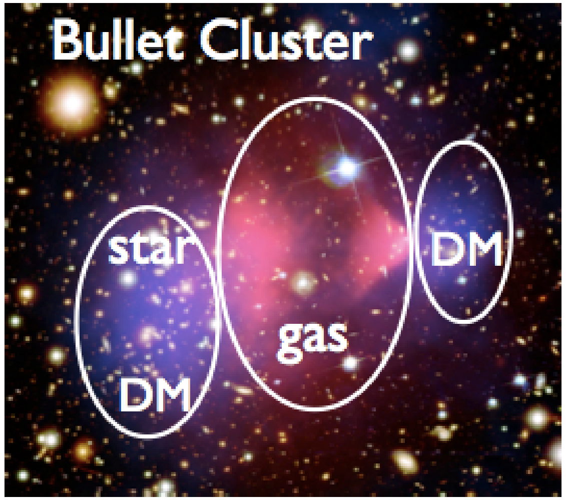
Rizzo et al, arXiv:1211.1981

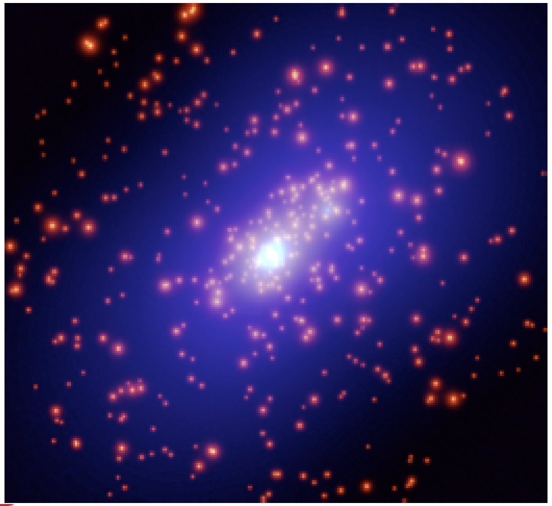
Dark Matter



ASPEN 2014: https://indico.cern.ch/event/276476/

Evidence building up for self-interacting DM





- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

For a WIMP: $\sigma \sim 10^{-38}\,\mathrm{cm}^2\,(m_X/100\,\mathrm{GeV})$

SIDM indicates a new mass scale

Hai-Bo Yu, ASPEN 2014:
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via weakly interacting "portals"

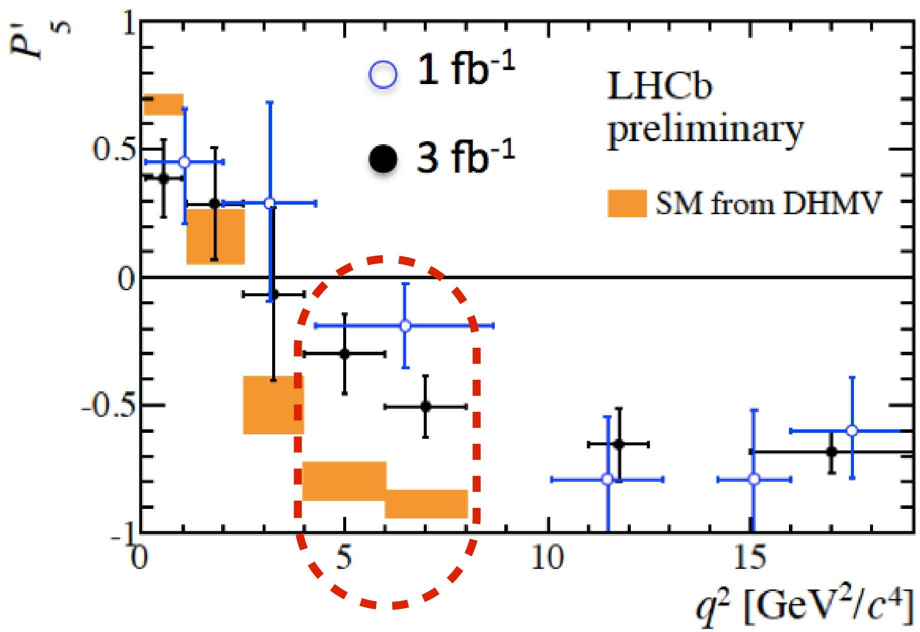
Anomalies left over from run 1, some examples

$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\,\%$$

CMS-PAS-HIG-14-005

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to K e^+ e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb, arXiv:1406.6482



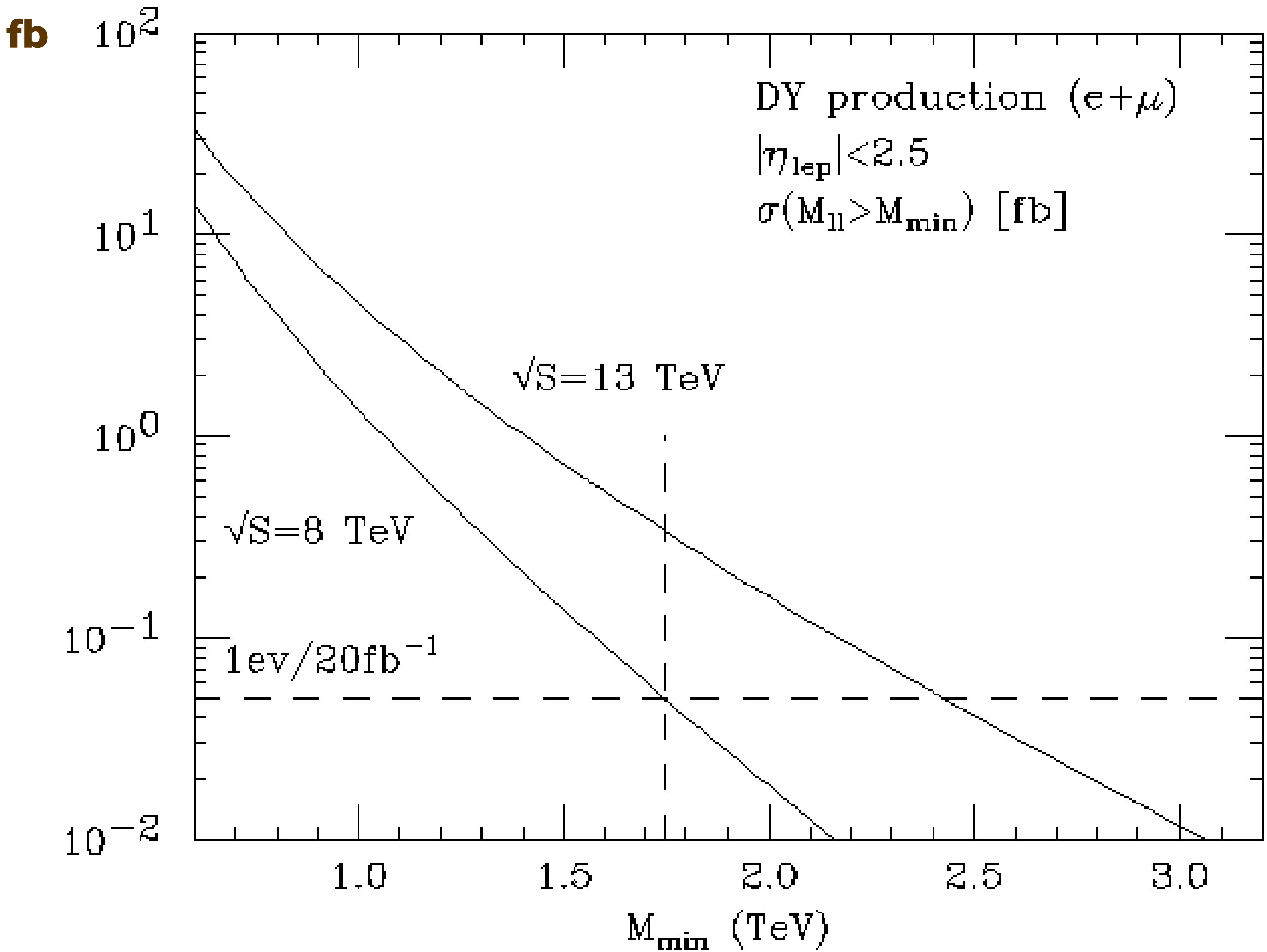
- $B \to K_* \mu^+\mu^-$ anomaly

LHCb, arXiv:1308.1707 and 3fb^{-1}
update LHCb--CONF--2015--002

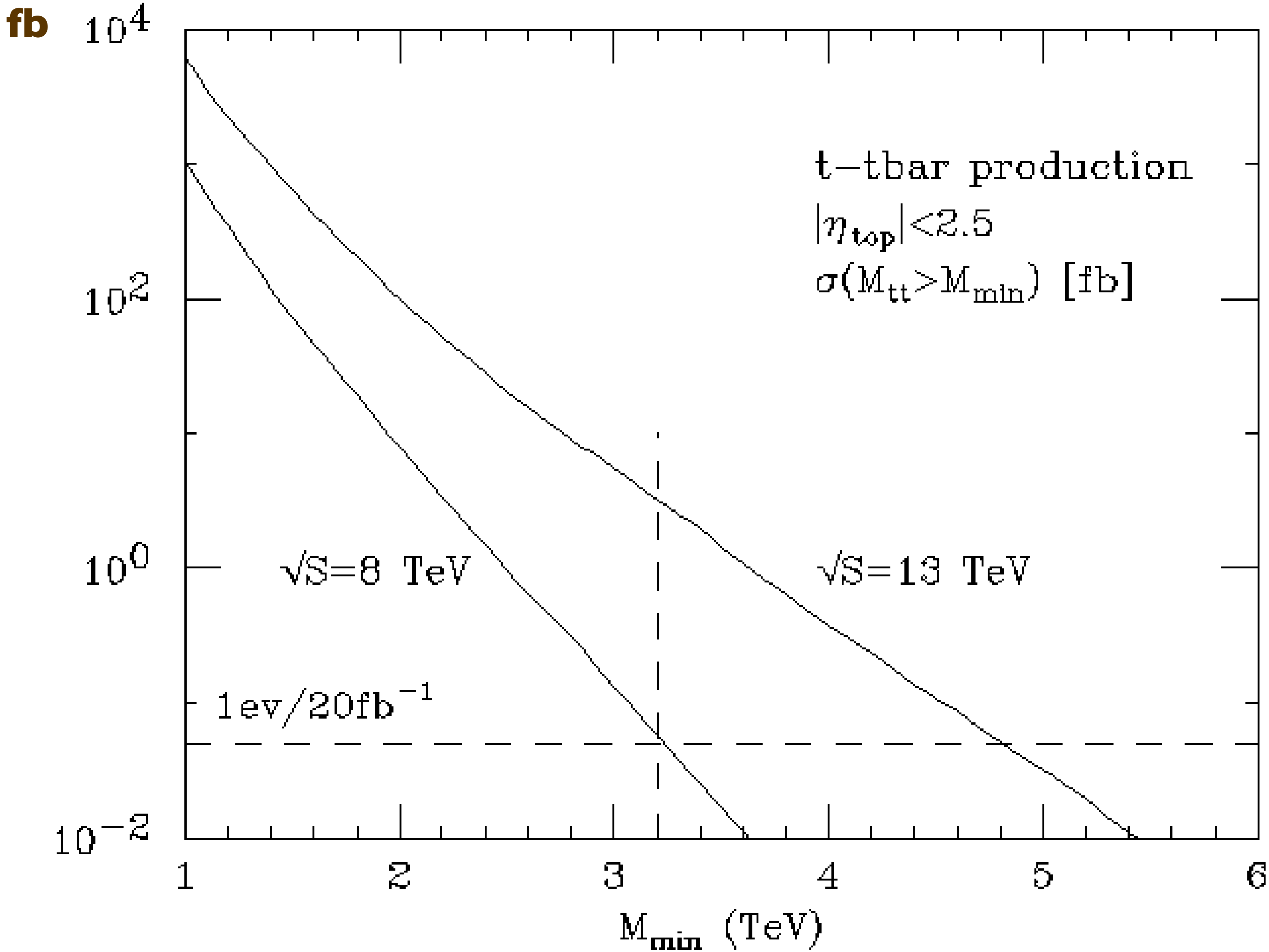
For possible interpretation within a single BSM model
see e.g. Crivellin, D'Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged L_μ–L_τ)

How long before run 2 extends the discovery reach of run 1?

Rate comparison 8 vs 13 TeV: Drell-Yan production



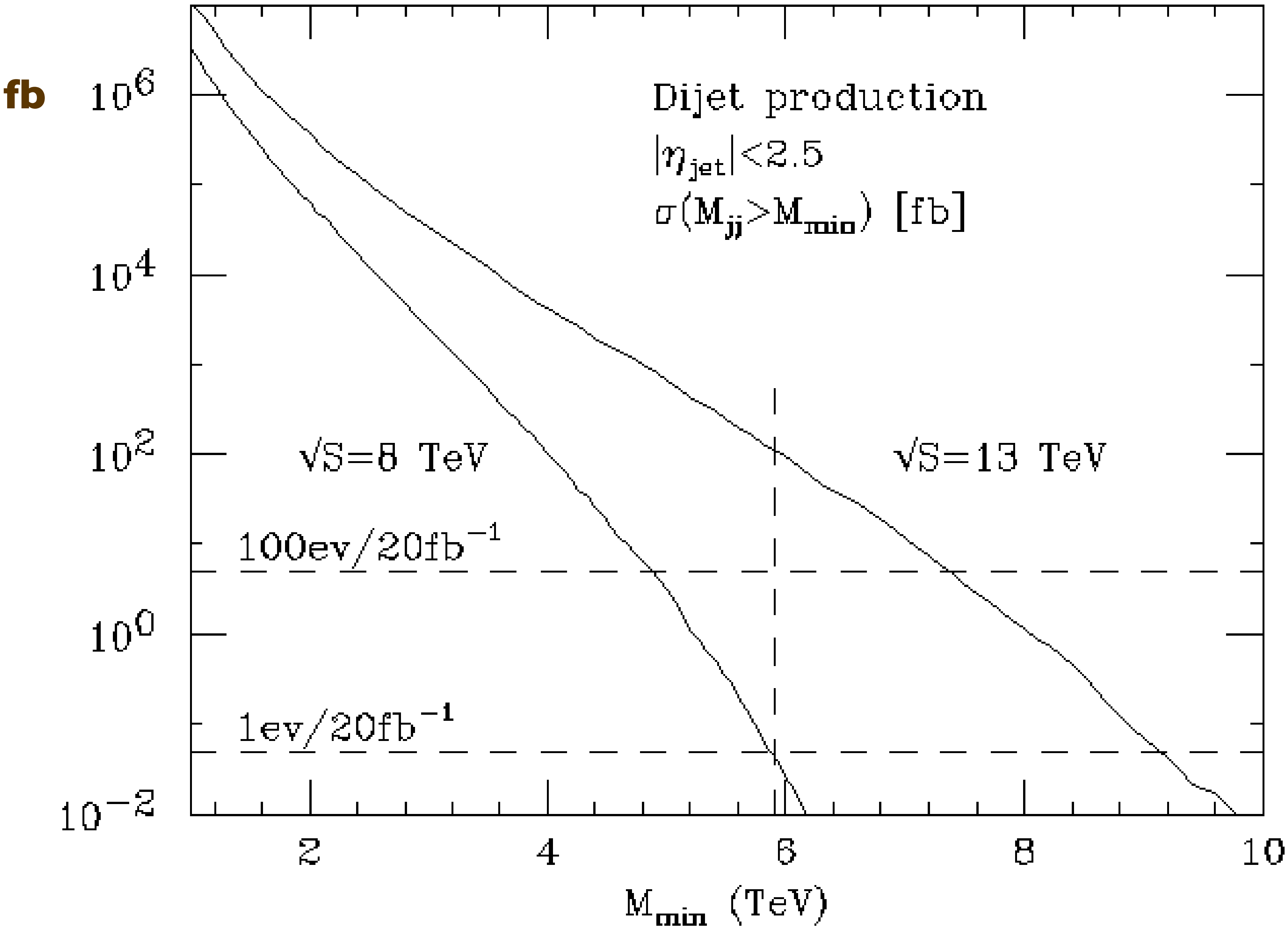
Rate comparison 8 vs 13 TeV: t tbar production



Remarks

- Top quark E_T probed above 2-3 TeV =>
  - Lorentz factor γ larger than 10:
    - top jet ~ b jet at LEP !
  - all top decay products within a cone with R<0.1
    - "hyper"-boosted regime for top tagging ...

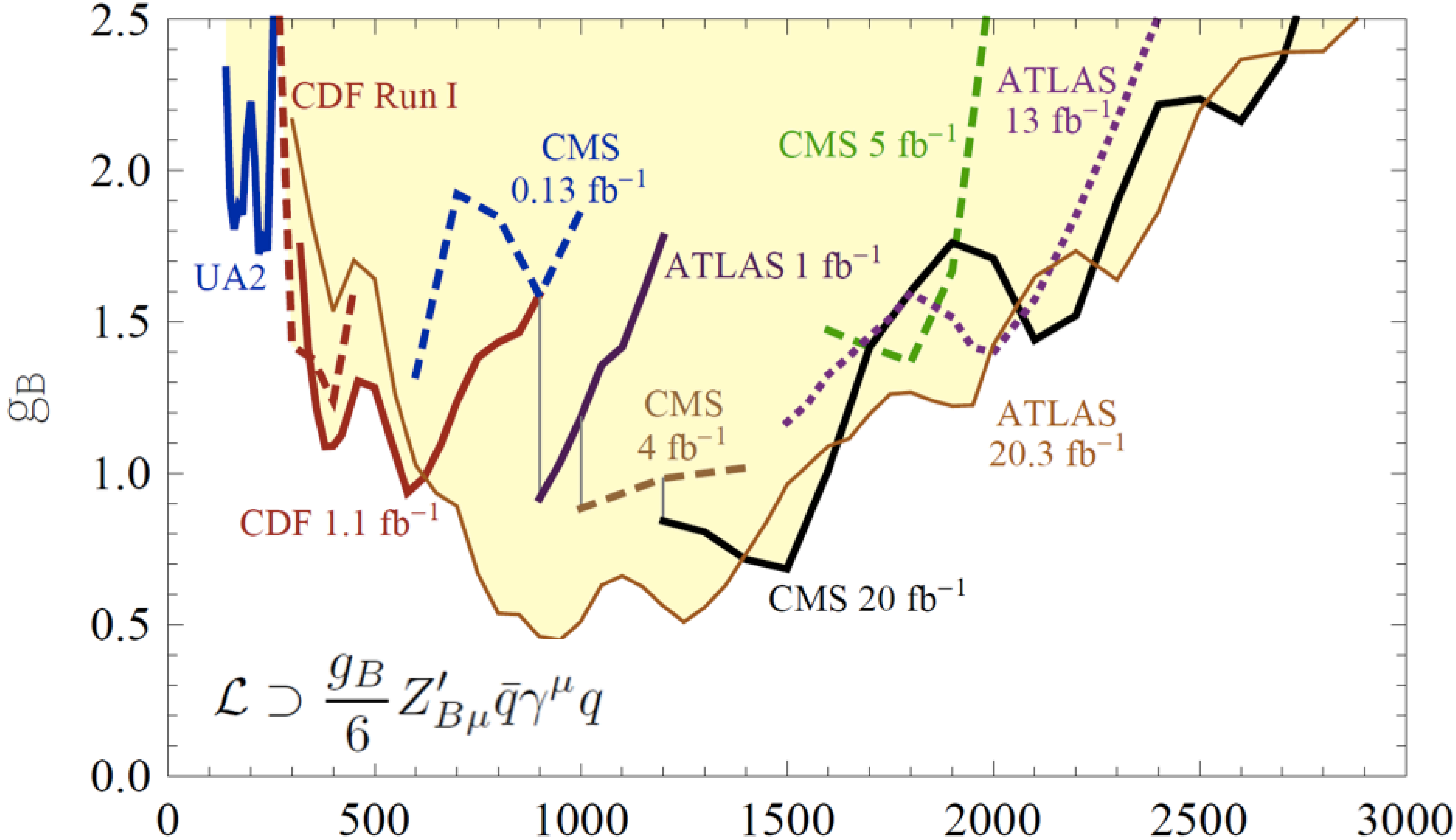
Rate comparison 8 vs 13 TeV: dijet production



Remarks

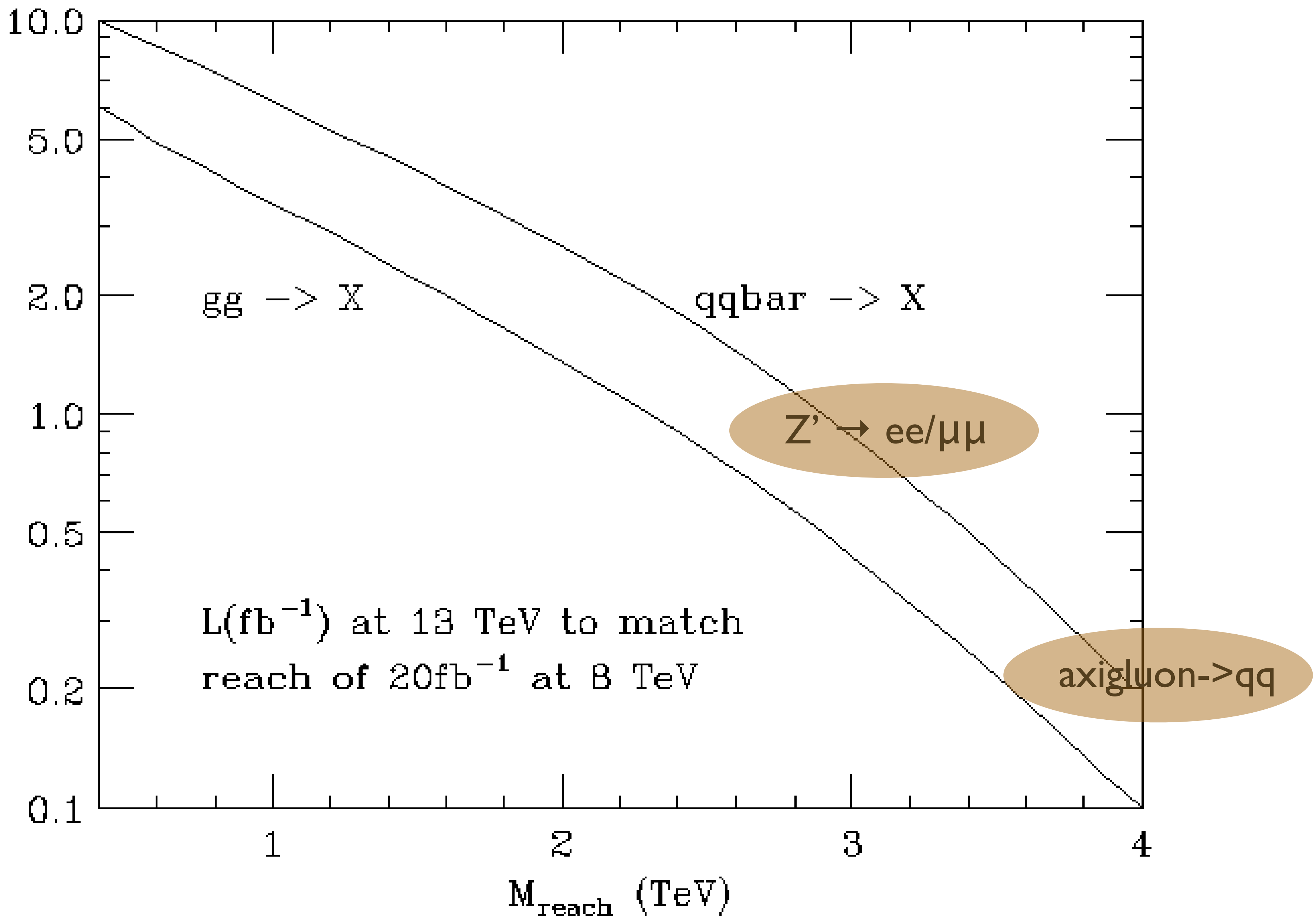
- Further studies at high energy/luminosity should not just focus on pushing the high mass end, but also on exploring low-couplings at low mass

Current g_B vs. $M_{Z'}$ limits: Z'_B dijet resonance



B. Dobrescu, F. Yu arXiv:1306.2629, updated (F.Yu) with new ATLAS arXiv:1407.1376 results

13 TeV luminosity required to match sensitivity reached so far (20fb^{-1}) at 8 TeV



See also http://collider-reach.web.cern.ch, by Salam and Weiler

Remarks

- For what concerns the extension of the discovery reach, nothing in the future of the LHC programme will match the step forward from 20 fb^{-1} at 8 TeV to 100 fb^{-1} at 13 TeV