

SM physics at the LHC: relevance, challenges and prospects

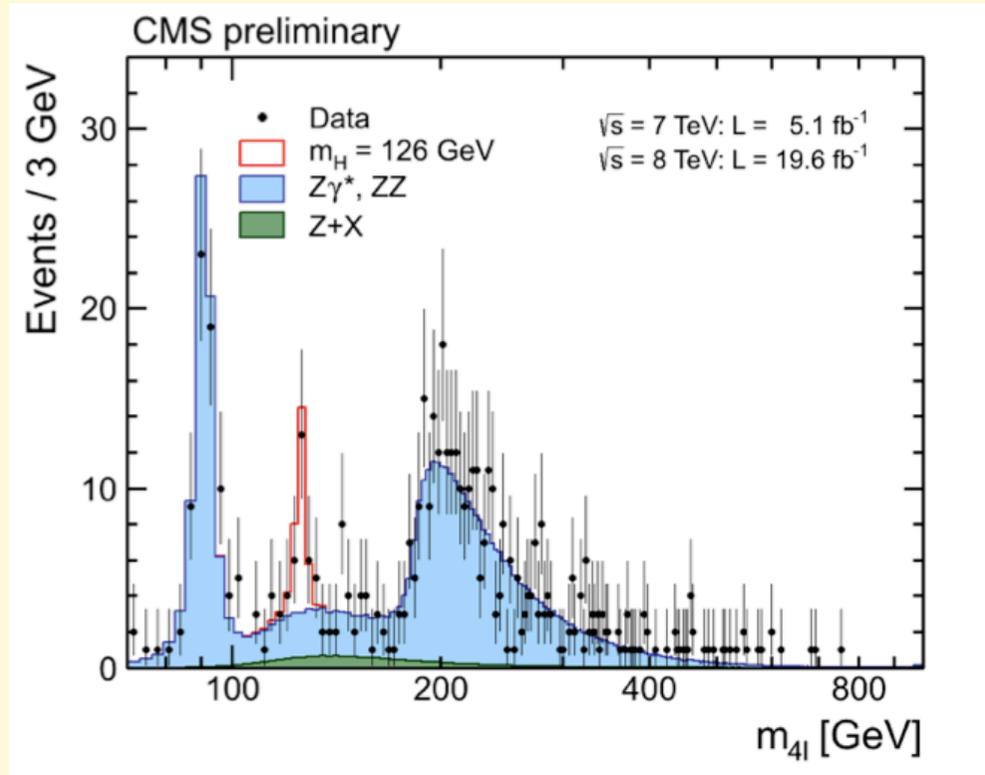
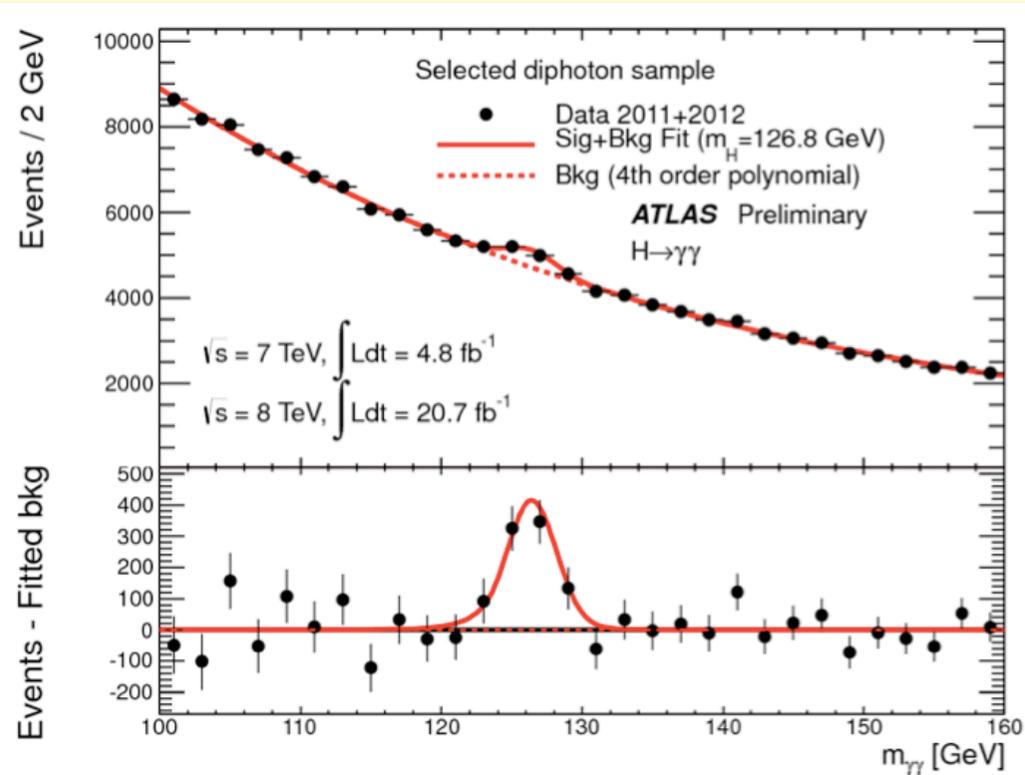
**Département de physique nucléaire et corpusculaire,
Université de Genève
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Key outcomes of 3 yrs at the LHC: I

I: The Higgs signal has been detected through sharp mass peaks in several channels

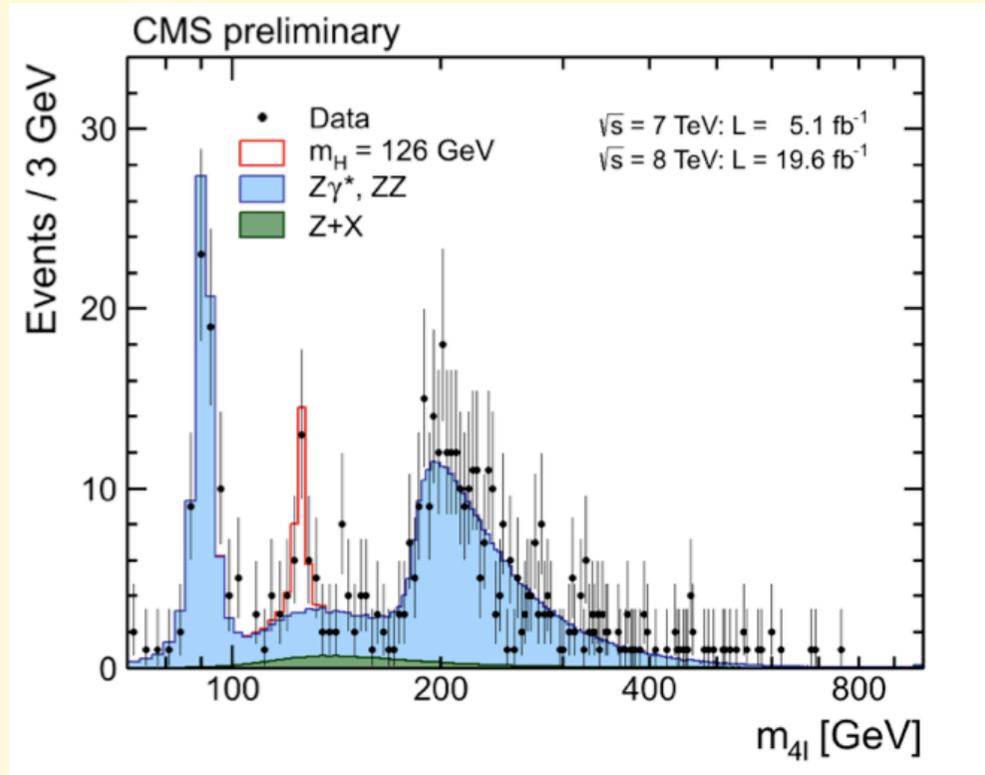
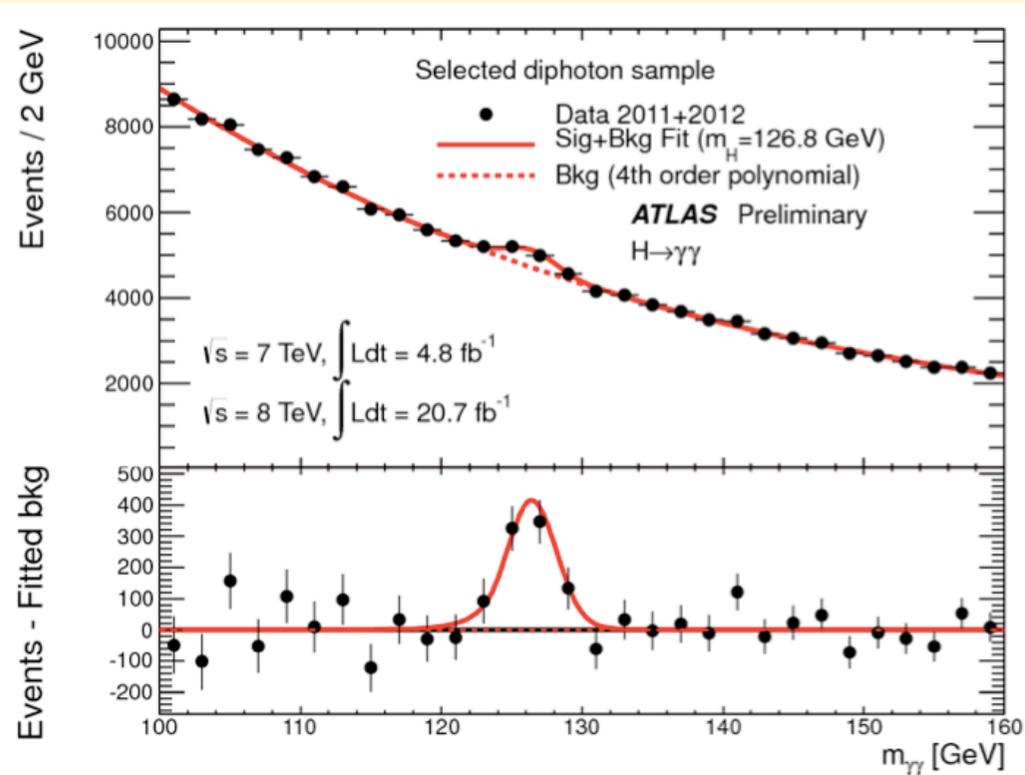
II: Its production and decay rates are consistent with the SM expectation, at the $\pm 20\%$ level



Key outcomes of 3 yrs at the LHC: I

I: The Higgs signal has been detected through sharp mass peaks in several channels

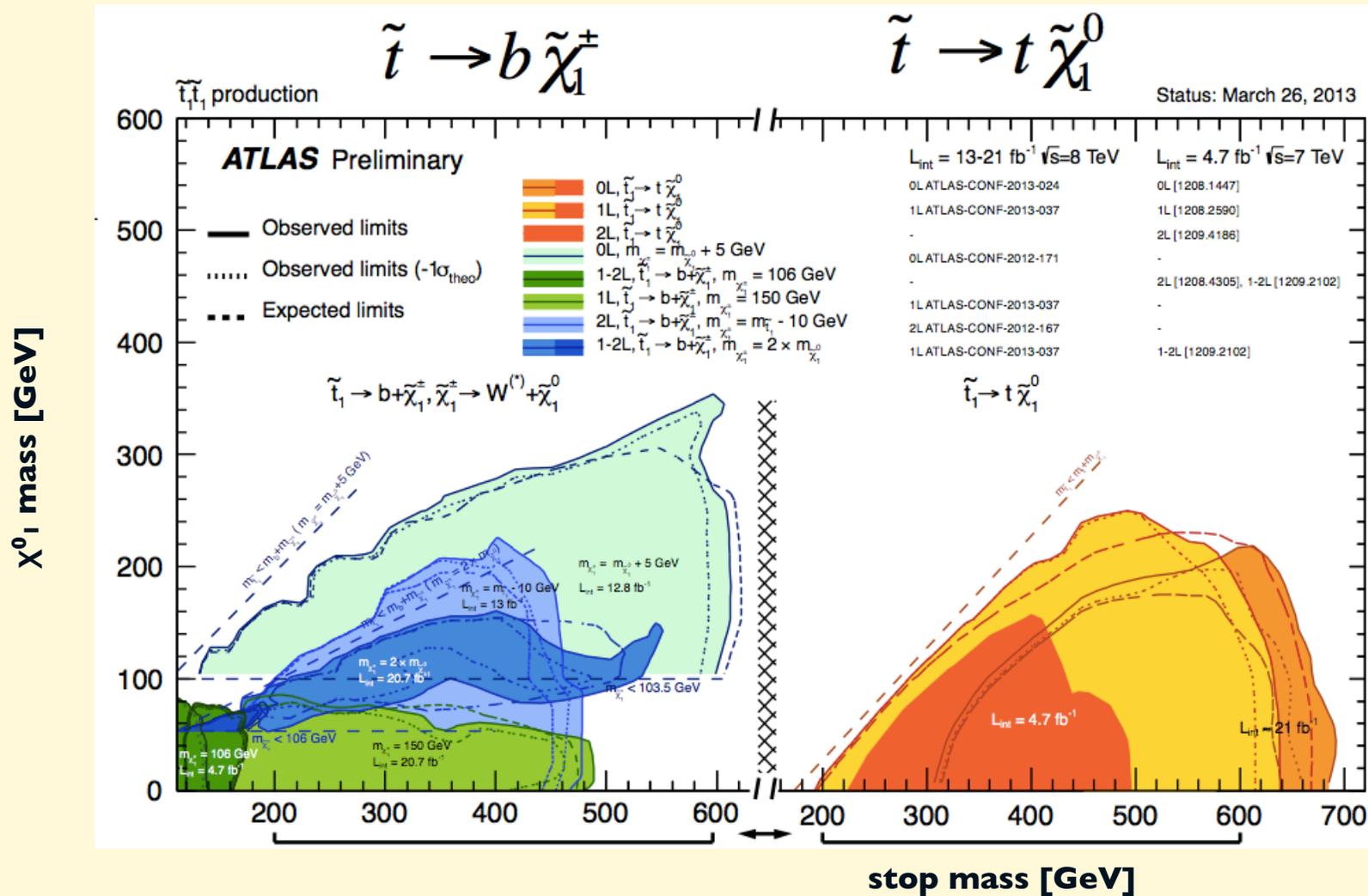
II: Its production and decay rates are consistent with the SM expectation, at the $\pm 20\%$ level



.... how far can we push the accuracy of these tests, and probe the mechanism of EWSB ?

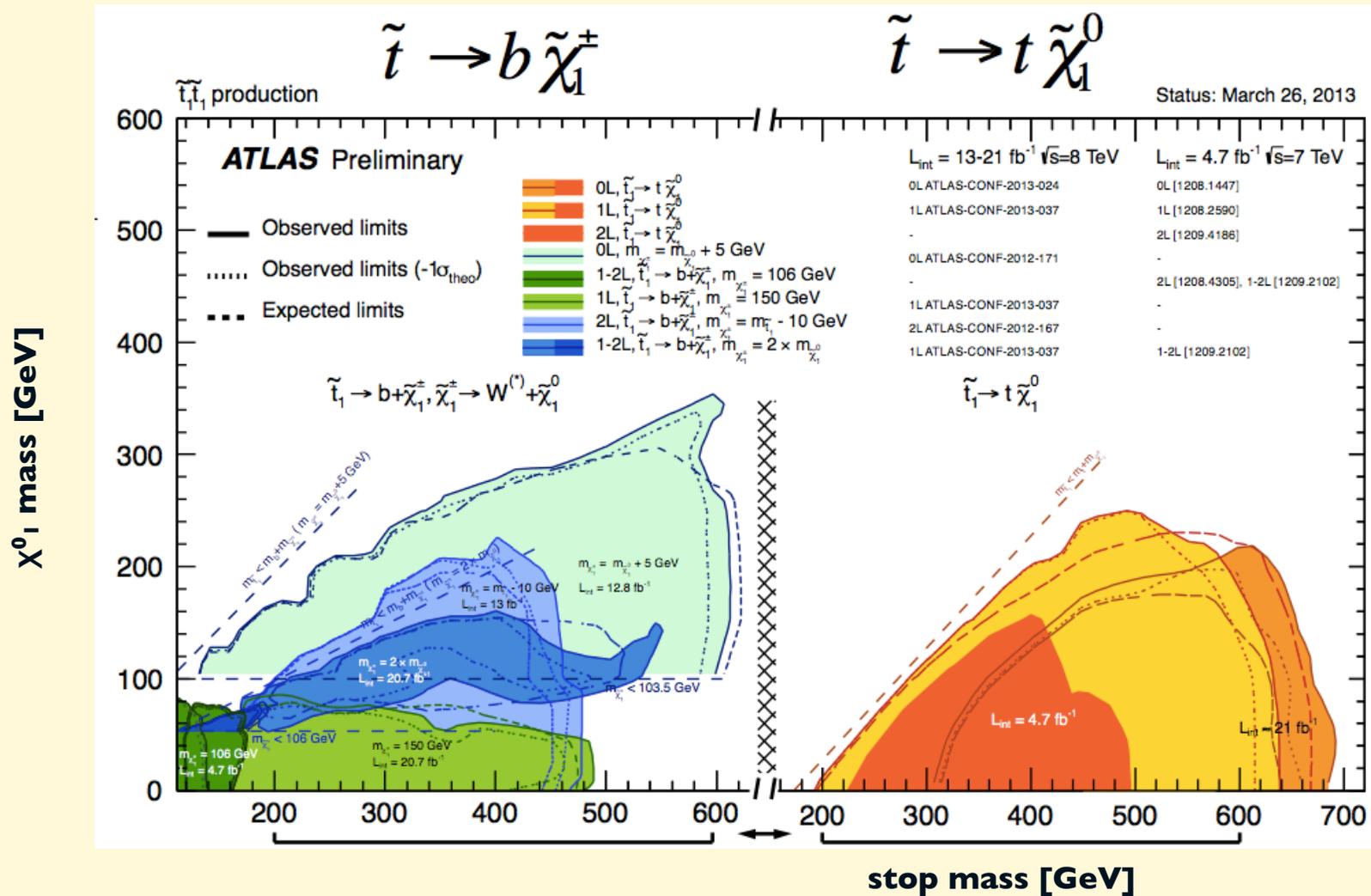
Key outcomes of 3 yrs at the LHC: 2

No sign of BSM, in all places the experiments have looked



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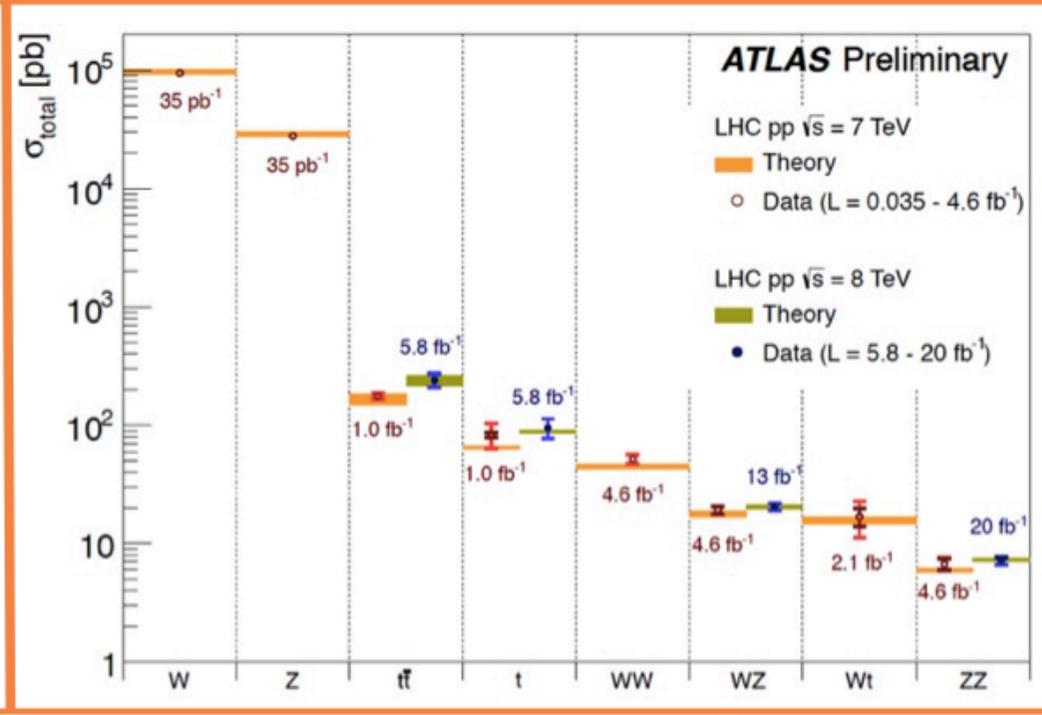
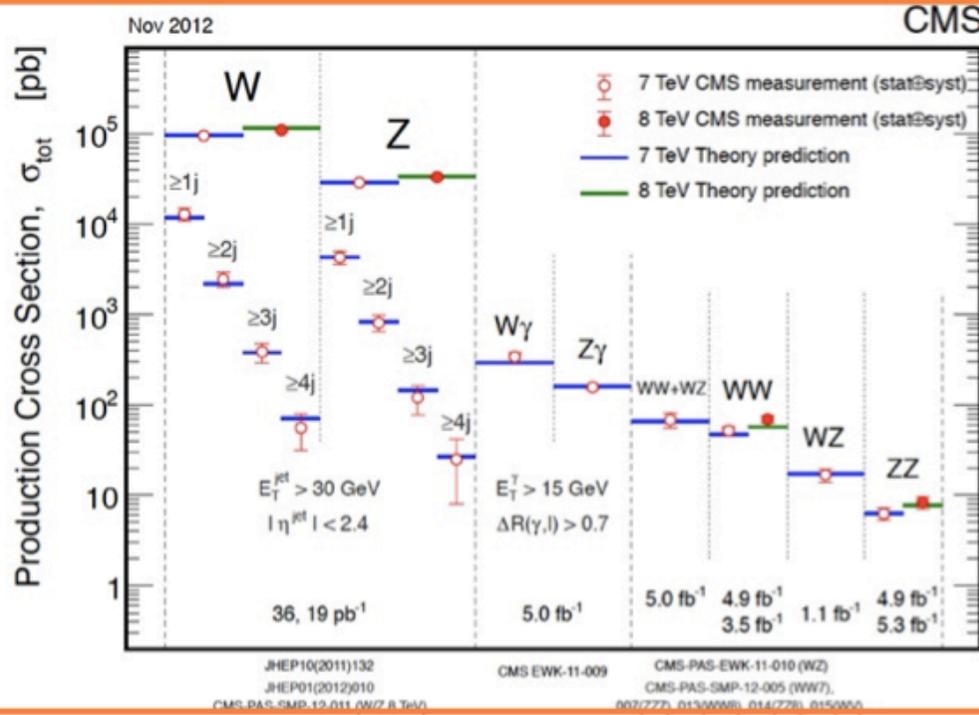
No sign of BSM, in all places the experiments have looked



.... how to access regions of parameters of BSM models where the sensitivity is low?

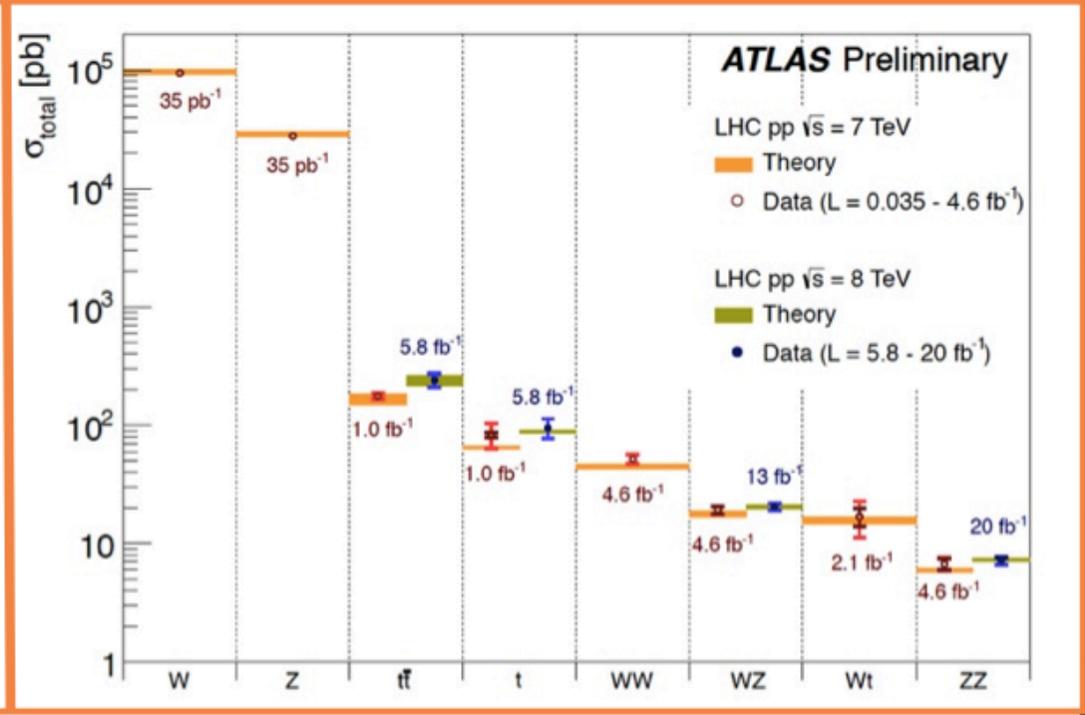
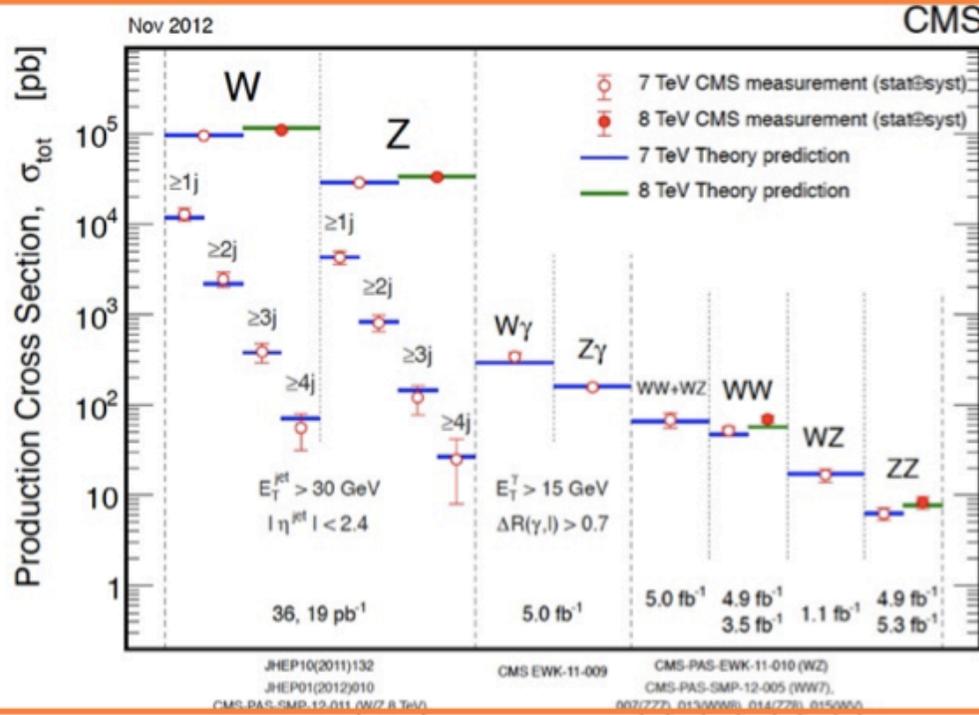
Key outcomes of 3 yrs at the LHC: 3

The theoretical description of high- Q^2 processes at the LHC is very good



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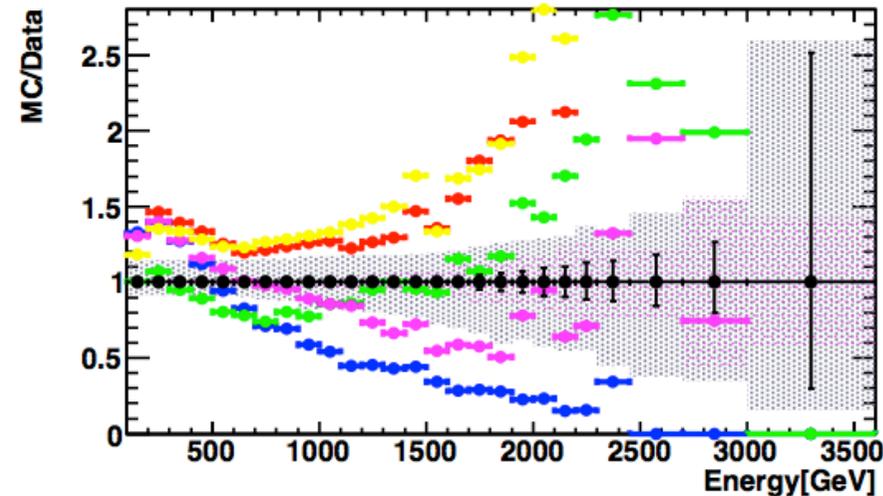
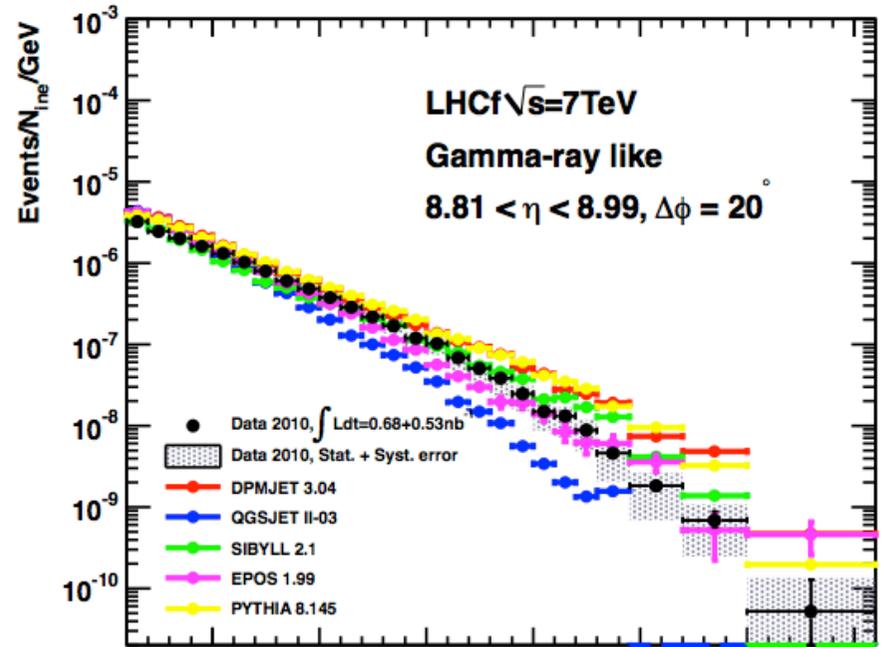
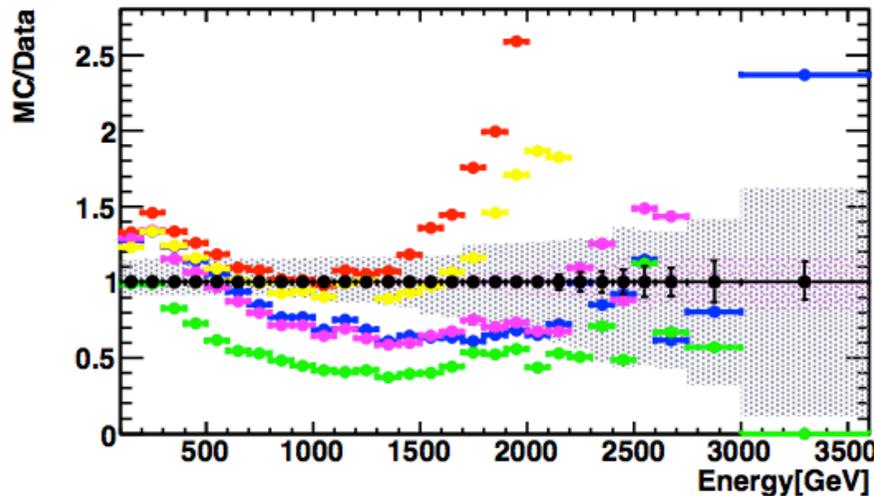
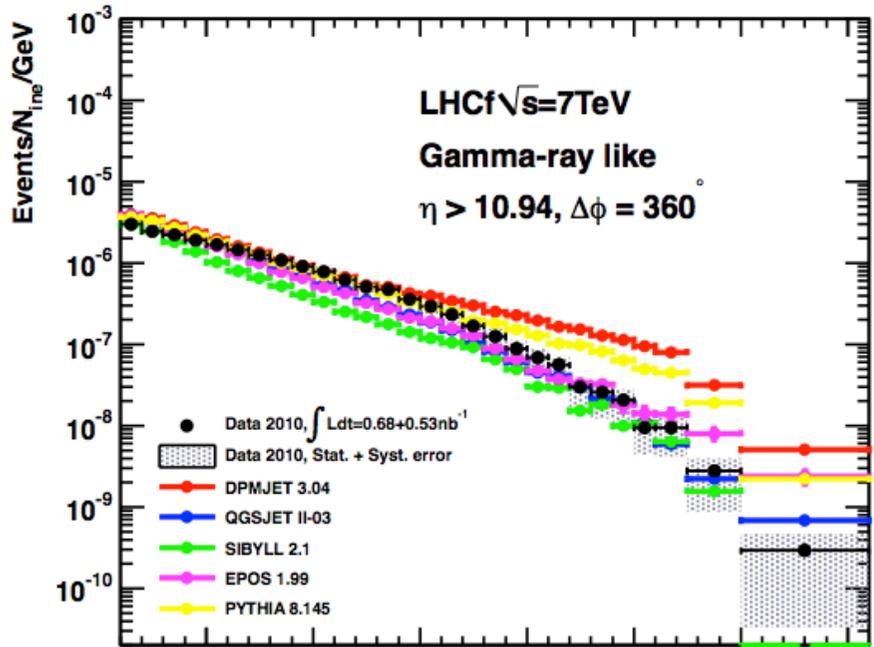
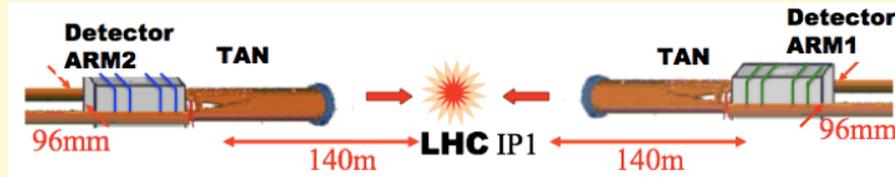
.... but must and can be improved

SM studies at the LHC:

- improve and validate our ability to model final states and make predictions, increasing the potential for precise measurements and for more sensitive BSM searches
- provide opportunities for the exploration of new and complex dynamical regimes of the SM, both in the QCD and EW sectors
- feed back into the HEP community valuable and often unique knowledge

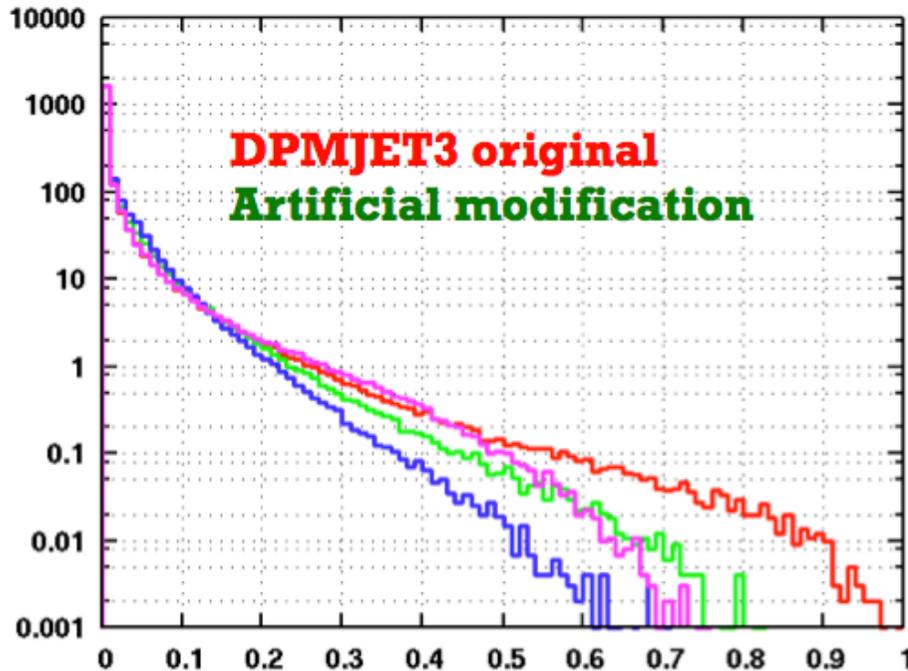
LHCf: Very forward energy flow

“Measurement of zero degree single photon energy spectra for $\sqrt{s} = 7$ TeV proton-proton collisions at LHC”
PLB 703 (2011) 128



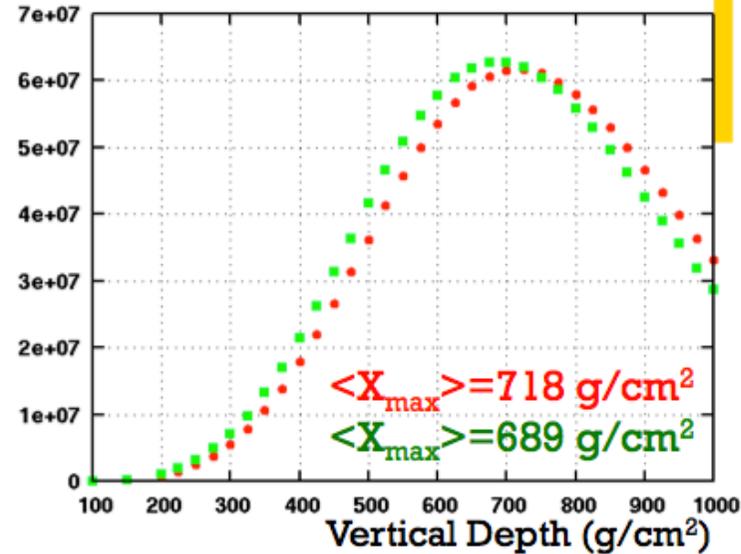
+ π^0 spectrum and air shower

14

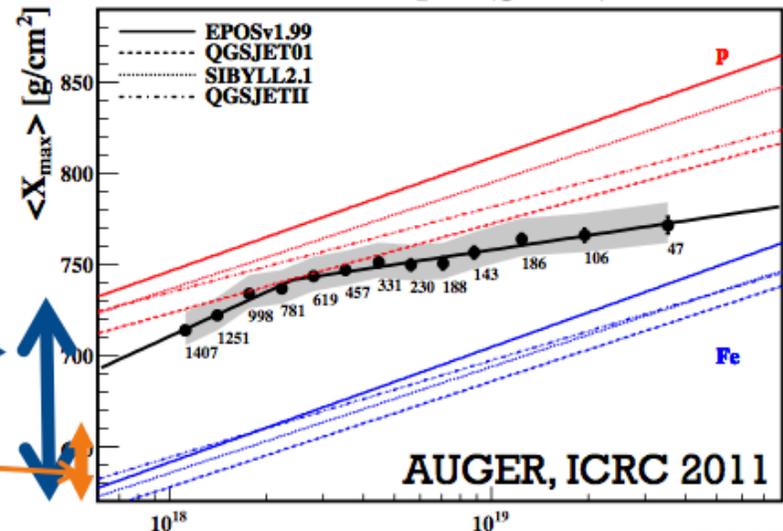


π^0 spectrum at $E_{lab} = 10^{17} eV$

Longitudinal AS development



- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta \langle X_{max}(p-Fe) \rangle \sim 100 \text{ g/cm}^2$
- ✓ Effect to air shower $\sim 30 \text{ g/cm}^2$



Open challenge:

To prove that the underlying mechanisms of multiparticle production at high energy are understood, in addition to being simply properly modeled

Back to large Q^2

Current challenges for the field: precision

Ex: Future precision in the determination of Higgs coupling ratios

L(fb ⁻¹)	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s} = 14$ TeV using an integrated dataset of 300 fb⁻¹ at LHC, and 3000 fb⁻¹ at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and for [Scenario2, Scenario1] in the case of CMS.

CMS Scenario 1: same systematics as 2012 (TH and EXP)

CMS Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as LC@500GeV !!

Current challenges for the field: precision

Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

14 TeV	$\delta(\text{pert. theory})$	$\delta(\text{PDF, } \alpha_s)$
$gg \rightarrow H$	$\pm 10\%$	$\pm 7\%$
VBF ($WW \rightarrow H$)	$\pm 1\%$	$\pm 2\%$
$qq \rightarrow WH$	$\pm 0.5\%$	$\pm 4\%$
$(qq, gg) \rightarrow ZH$	$\pm 2\%$	$\pm 4\%$
$(qq, gg) \rightarrow ttH$	$\pm 8\%$	$\pm 9\%$

Improve with higher-loop
calculations:

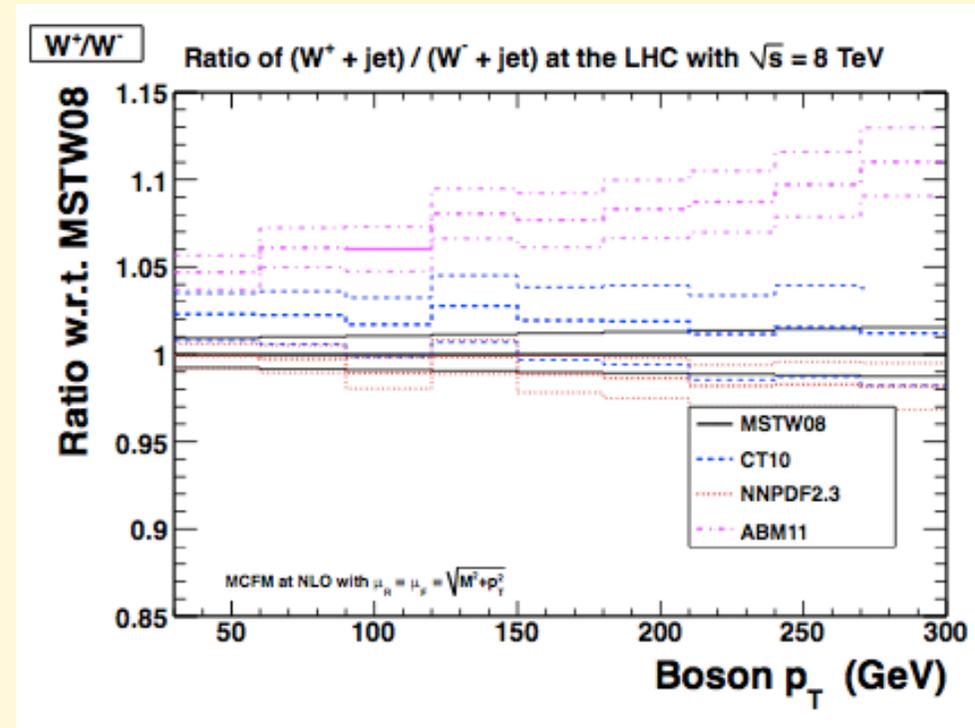
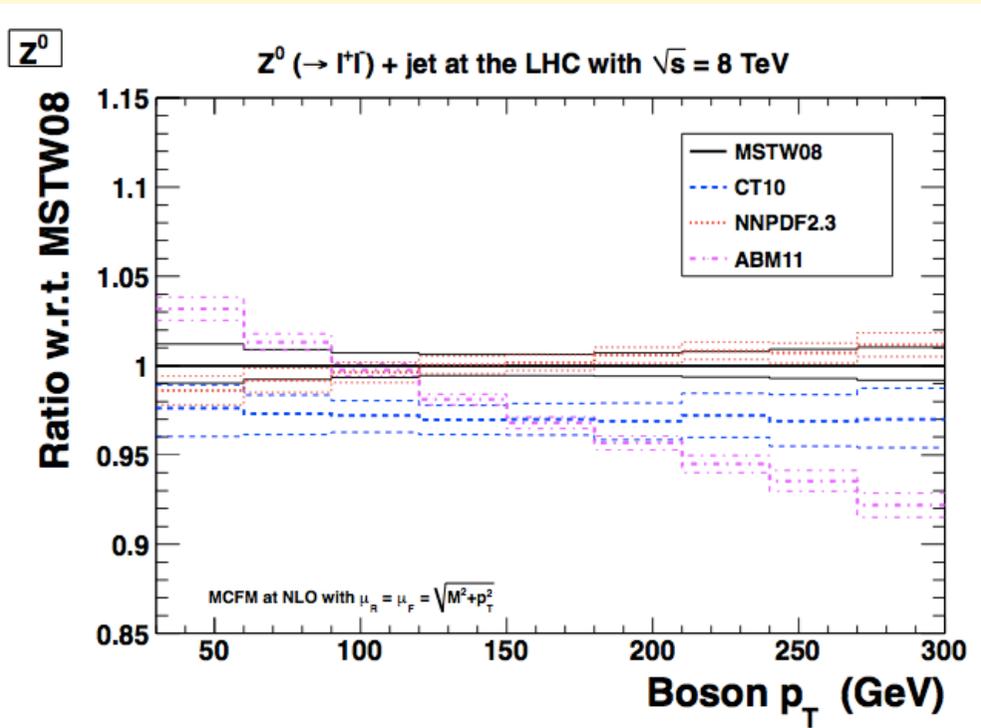
$gg \rightarrow H$ @ **NNLO**

ttH @ **NNLO**

Improve with
dedicated QCD
measurements,
and appropriate
calculations

Example: Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to $gg \rightarrow H$ production

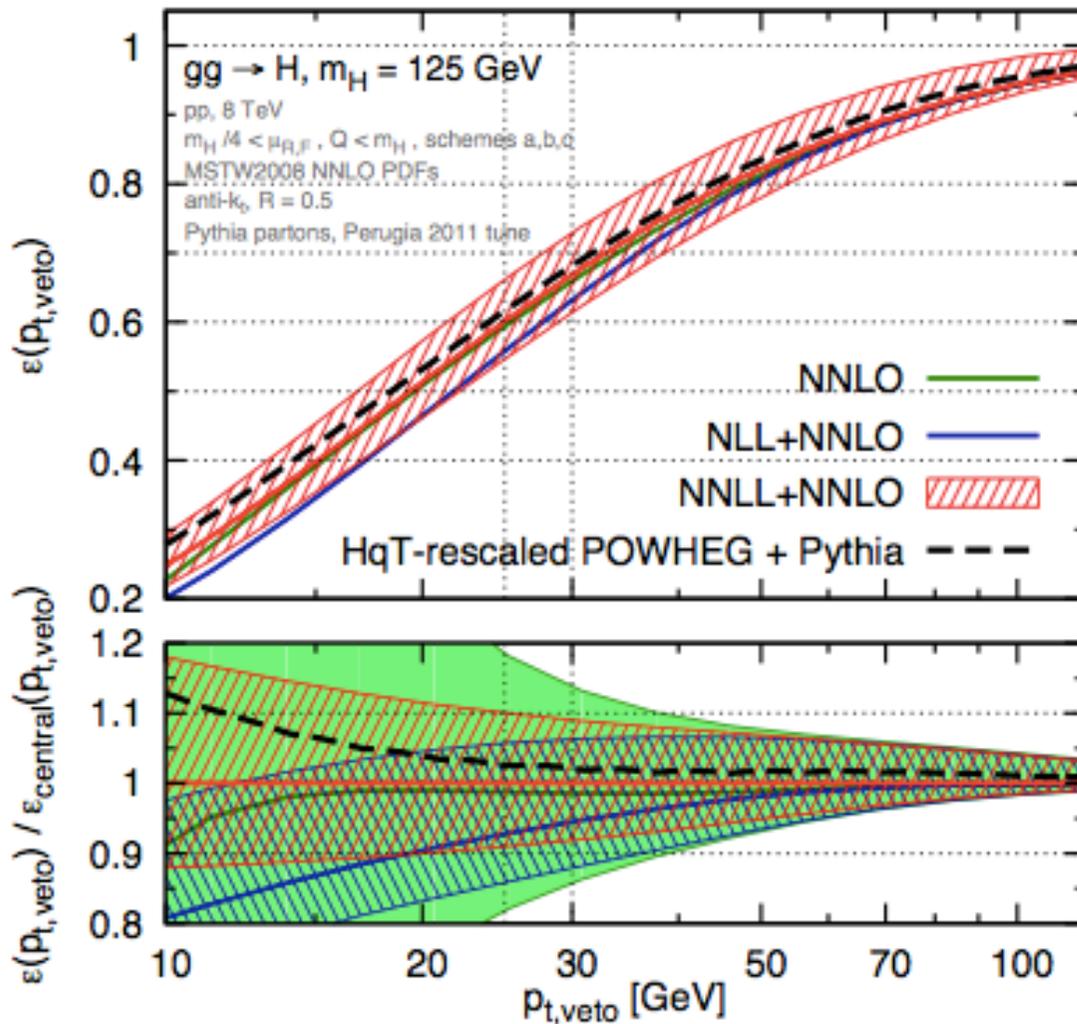
S.Malik and G.Watt, arXiv:1304.2424



⇒ excellent motivation to undertake the calculation of $d\sigma/dp_T(V)$ at NNLO !!

Current challenges for the field: accurate description of final states

- to properly model experimental selection cuts
- to properly model the separation between signals and background
- to improve the sensitivity to rare and “stealthy” final states in BSM searches



Ex. jet veto efficiency, required to reduce bg's to $H \rightarrow WW^*$

Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

Goals of the SM LHC programme

- Precise determination of fundamental SM parameters:
 - $m(\text{top})$, $m(W)$, α_s , $\sin^2\theta_W$, CKM
 - Higgs properties
- Determination of the PDFs
- Validation of the reliability/precision/uncertainties of the modeling of SM dynamics (QCD and EW), for applications to:
 - the measurements above
 - the search for new phenomena, through deviations from established SM behaviour

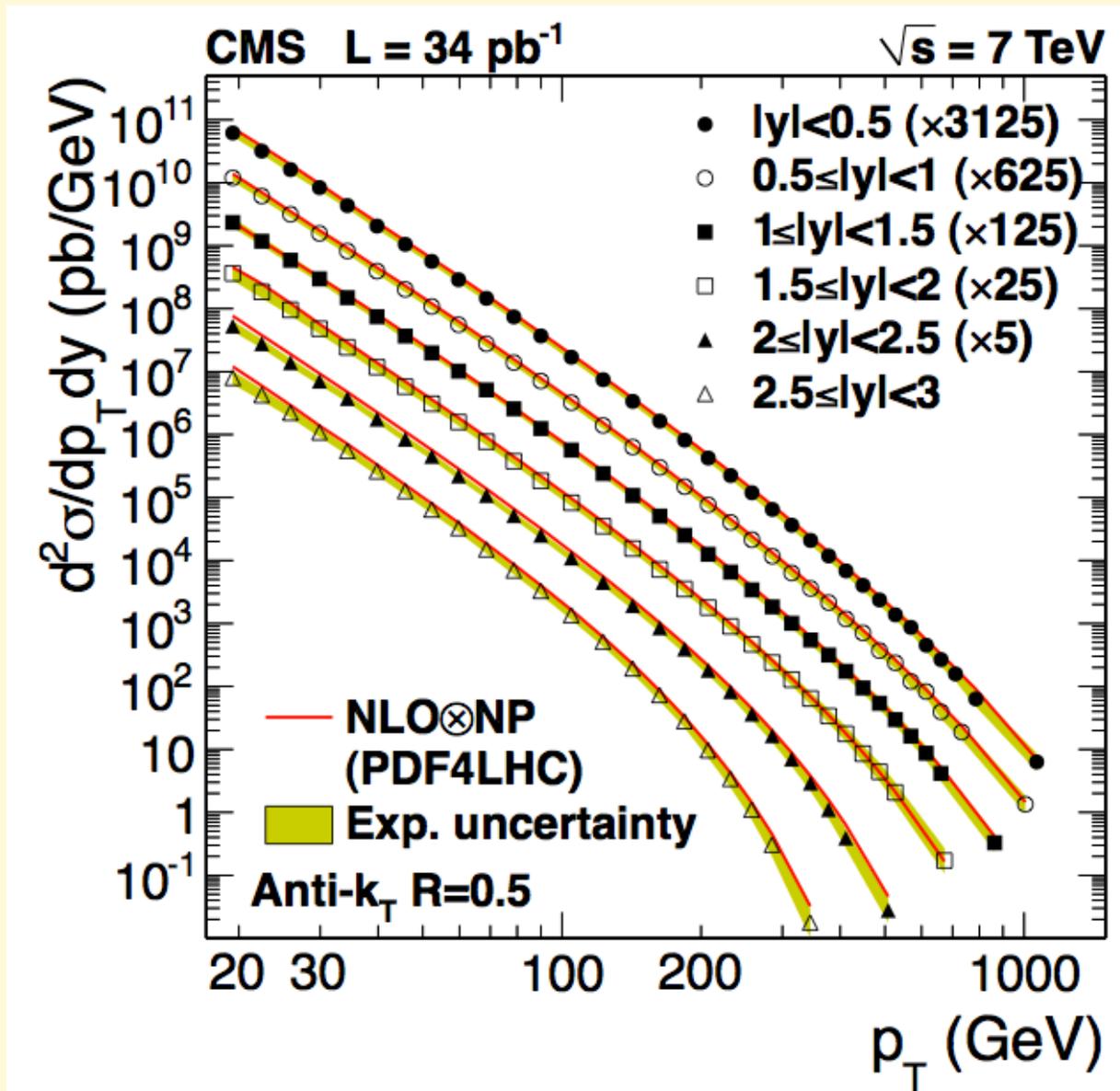
Means:

- Precise measurement of ancillary quantities, necessary to
 - improve the inputs of theory calculations
 - validate the theoretical precision and systematics
- This includes what may otherwise be considered as **“and now what?”** measurements, whose key purpose is to build confidence in the theoretical modeling, for applications to the precision physics programme and to the searches

Opportunities opened by LHC data

- High statistics and superior experimental precision
- Access to small rates:
 - rare final states (multijets, associated production of multiple EW and QCD objects)
 - high-energy final states (highest pt jets, highest mass DY,)
 - VBF final states
- EW radiative corrections:
 - impact on EW observables (V, VV production - V=W,Z)
 - impact on QCD observables (jet cross sections)
- New probes of PDFs:
 - large-x gluons (jet, top production)
 - heavy quarks (γQ , ZQ, WQ associated production)
- Correlations:
 - ratios of cross sections for different processes
 - ratios of cross sections at 7 vs 8 vs 14 TeV

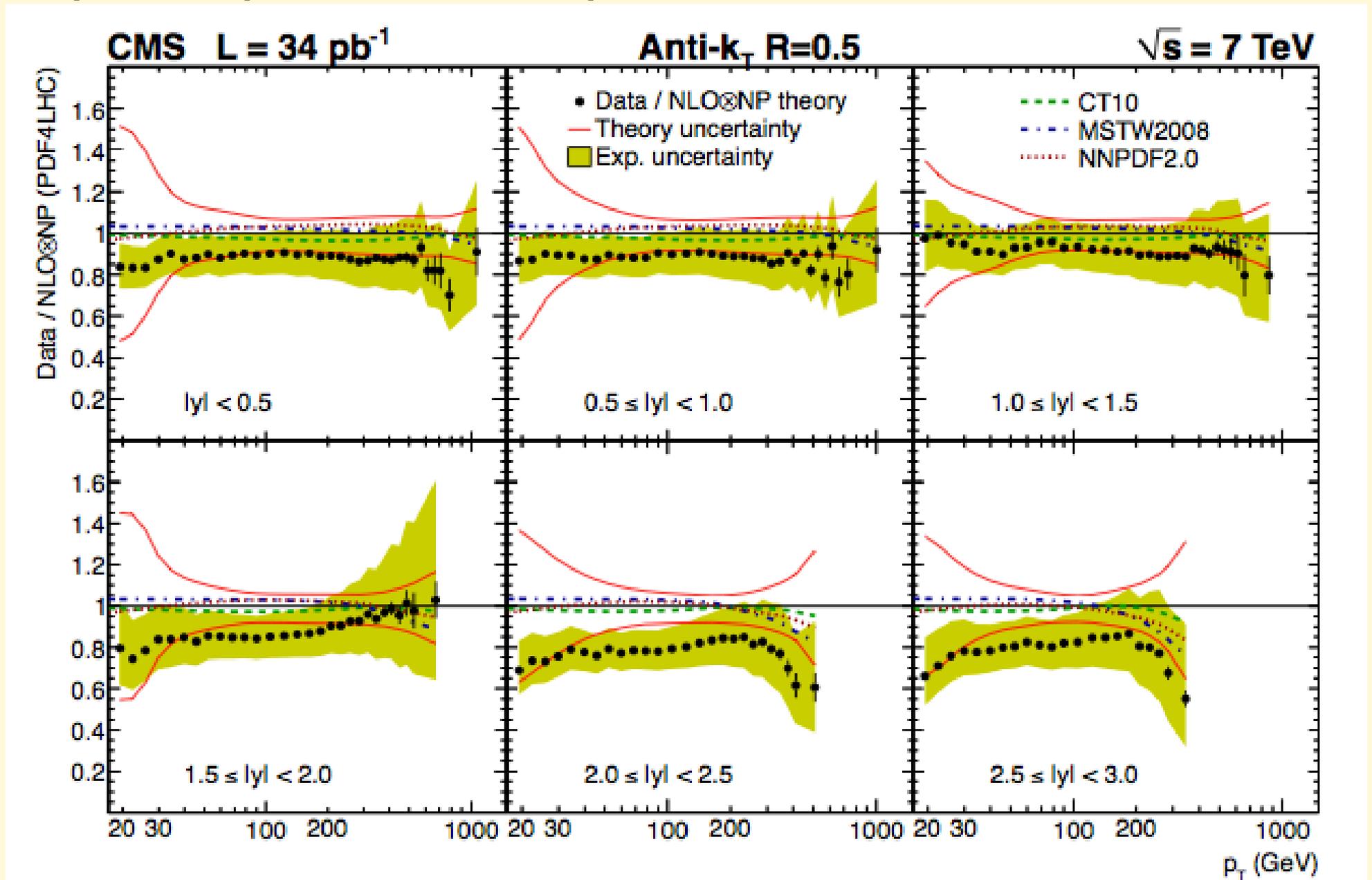
Example: Jet cross section



Rates span 10 orders of magnitude!

Example: Jet cross section

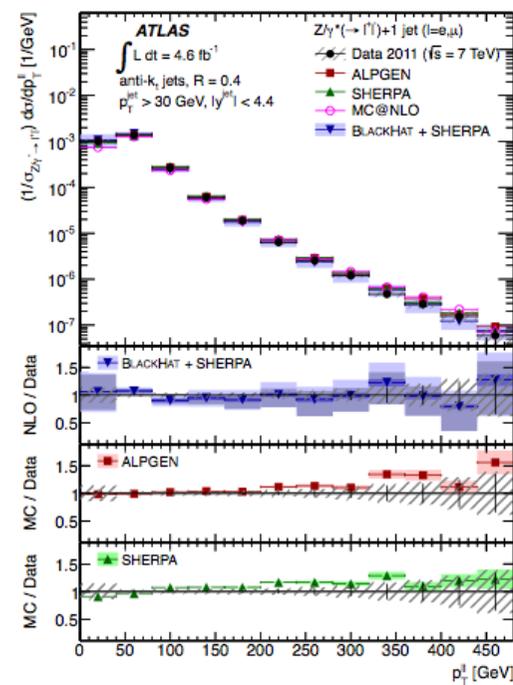
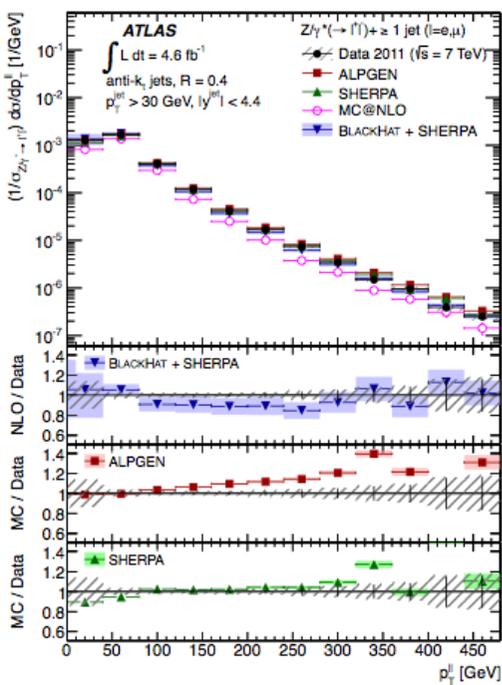
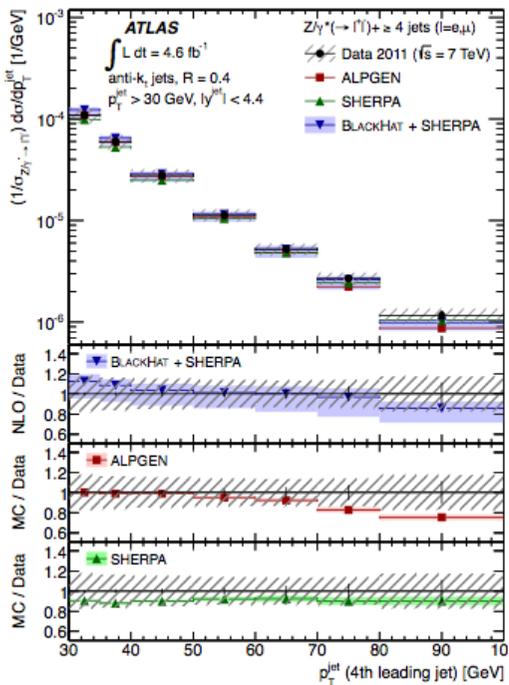
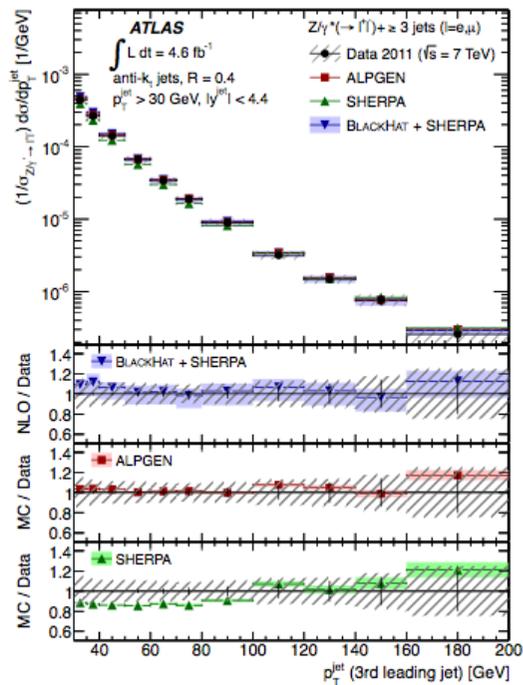
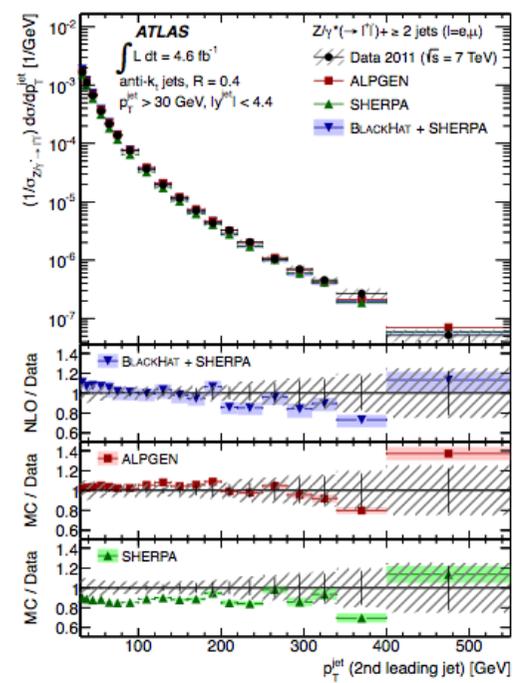
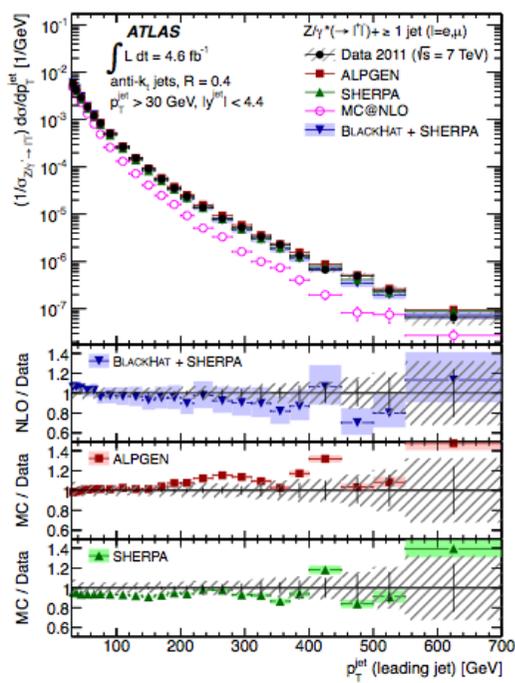
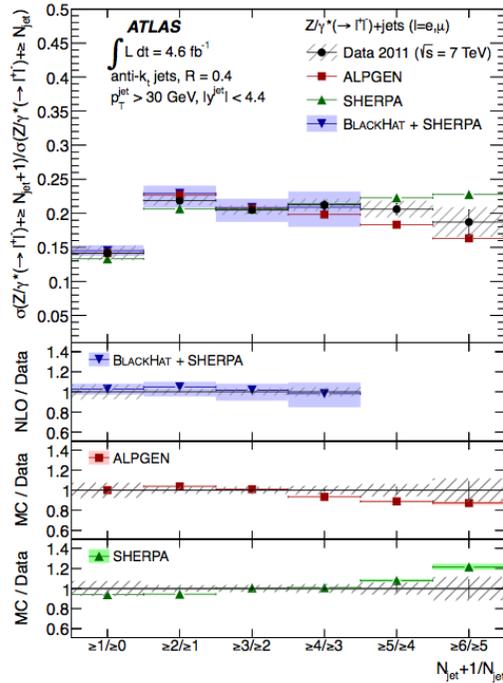
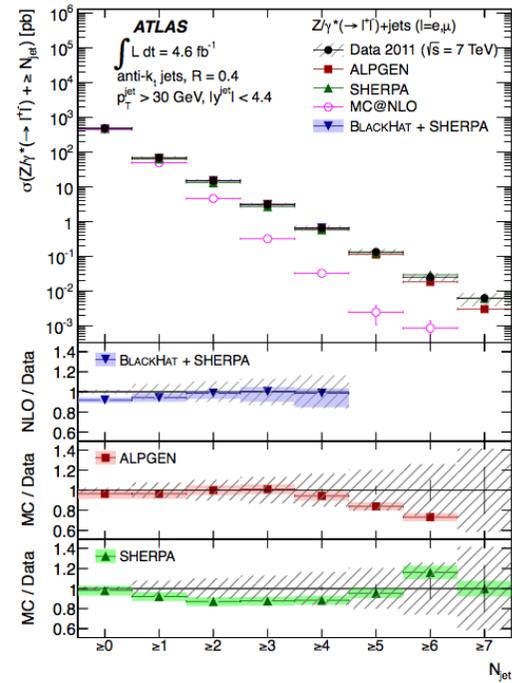
Theory: absolute prediction for both shape and normalization



Agreement to within 20% (over 10 orders of magnitude!)

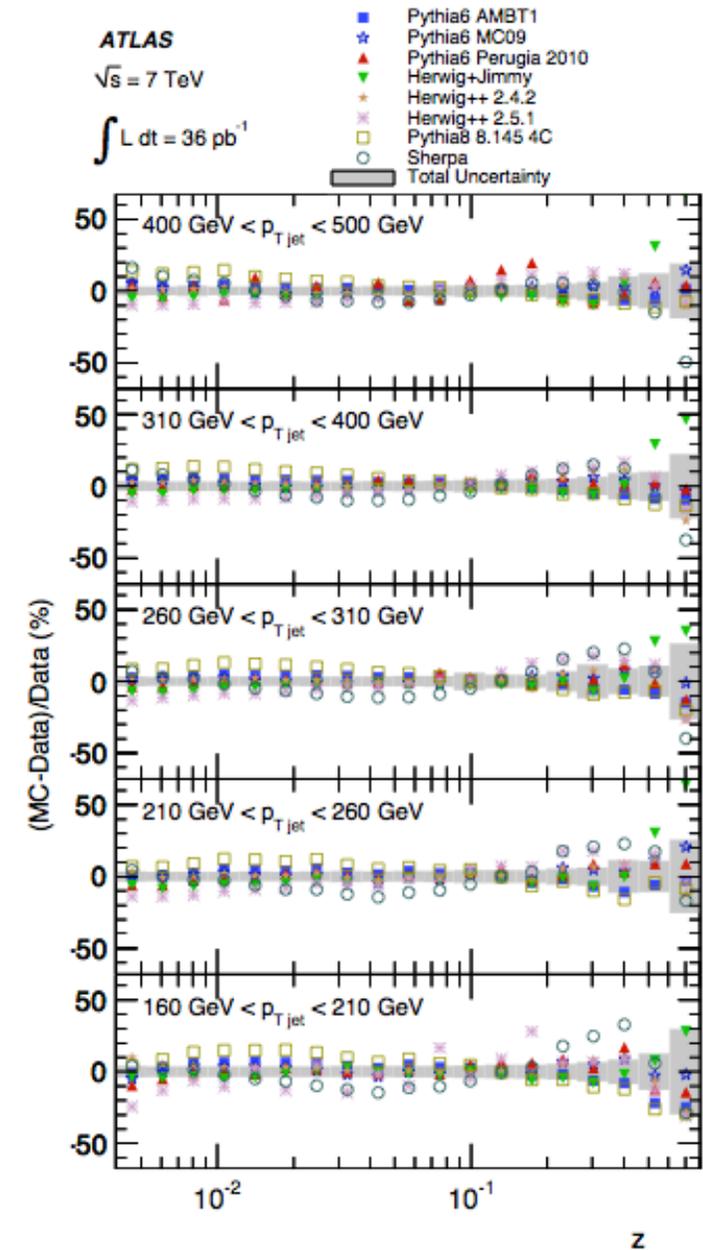
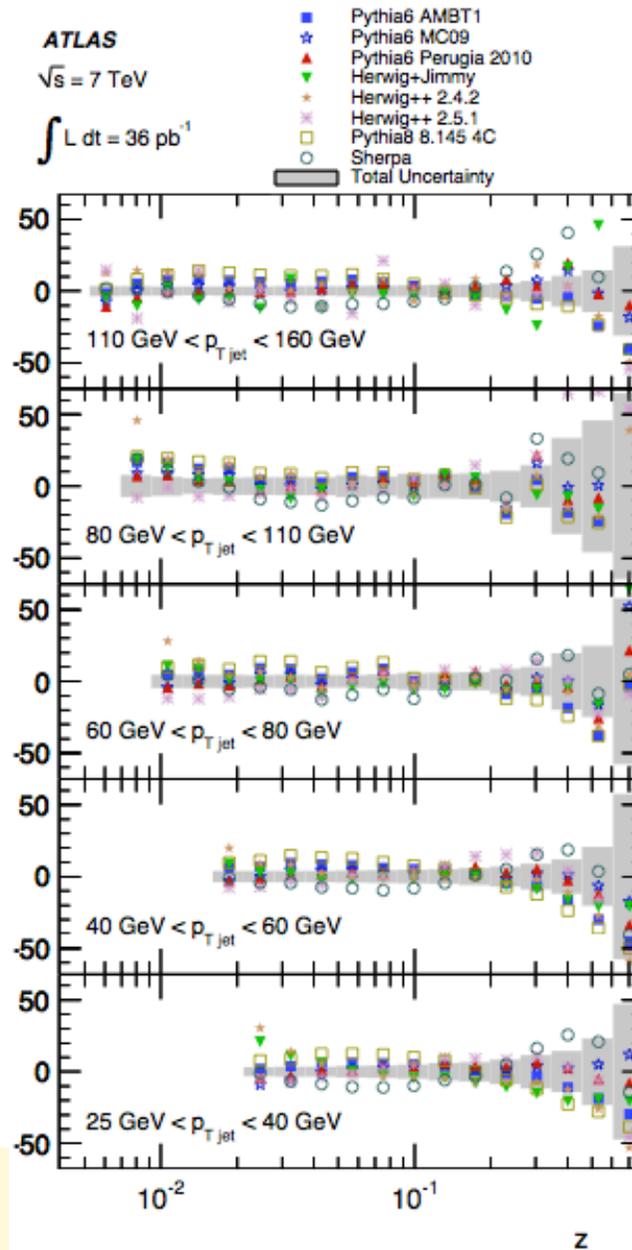
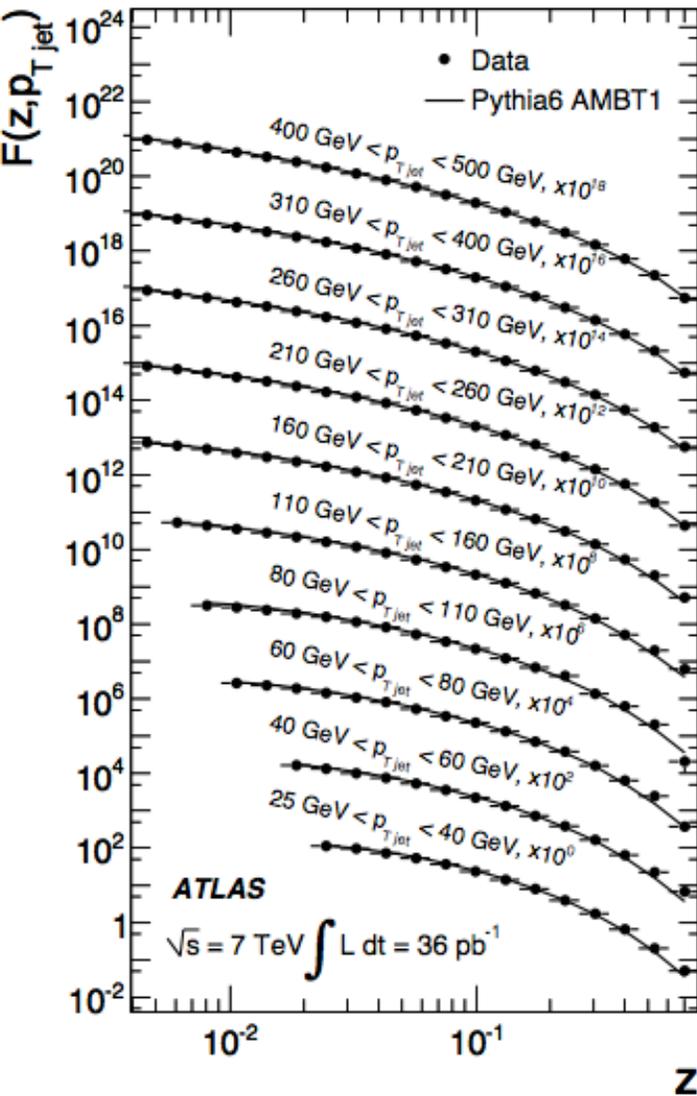
Residual discrepancy consistent with PDF and perturbative NLO uncertainties

Example: Z+jets



Example: Jet fragmentation function

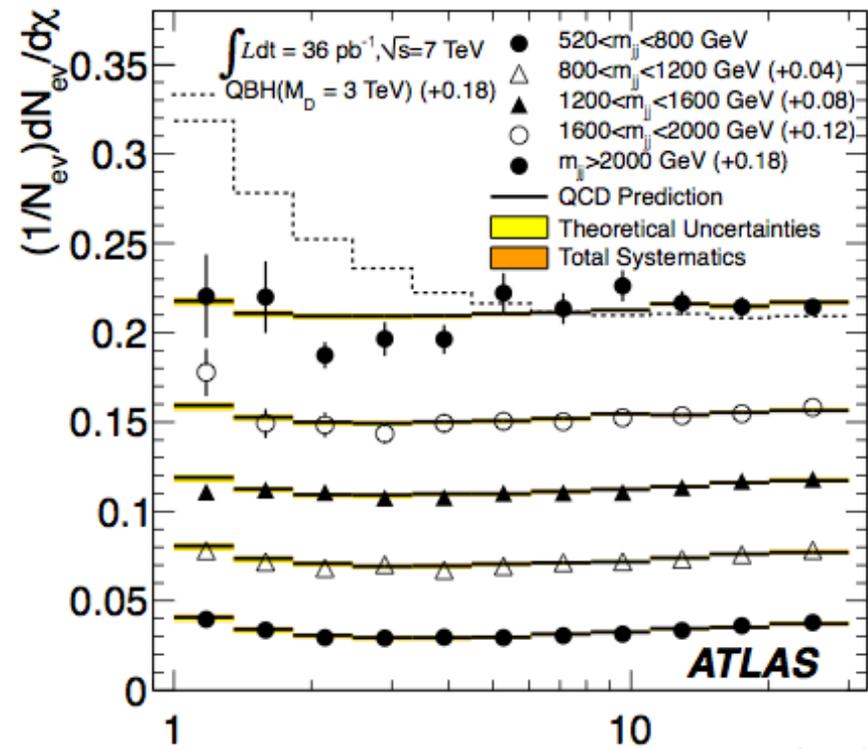
ATLAS, arXiv:1109.5816



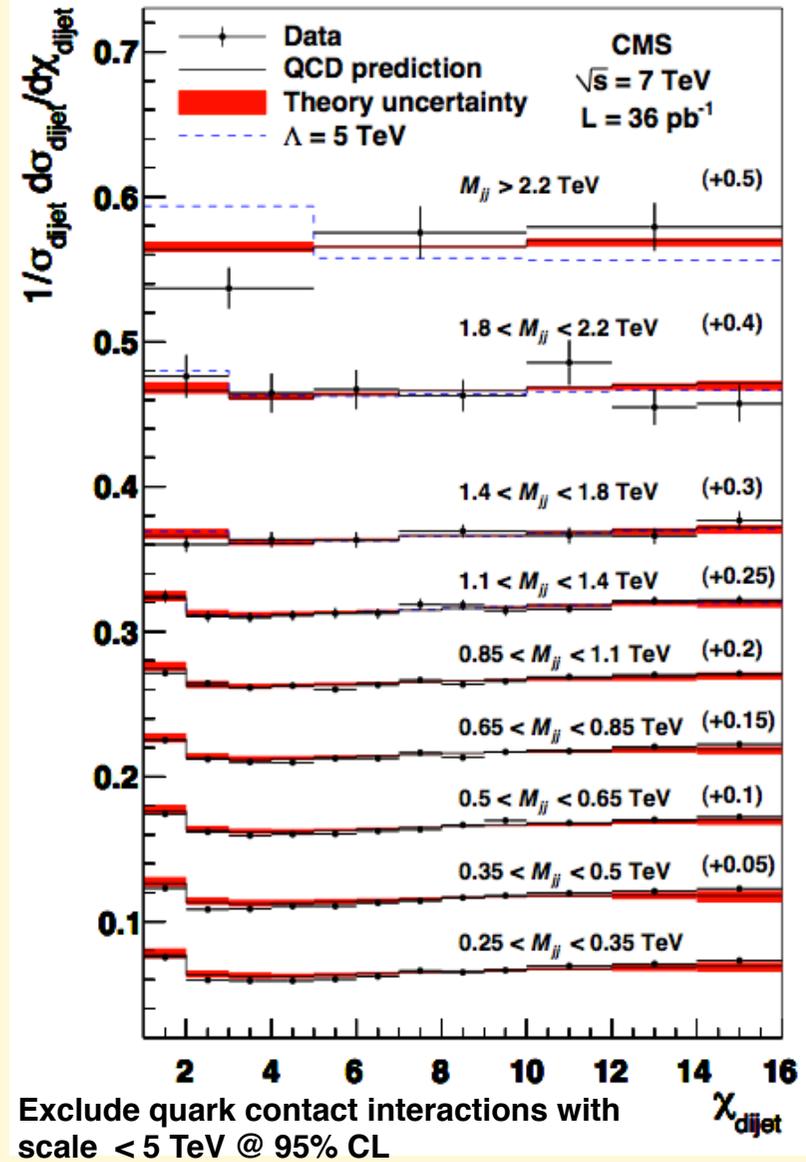
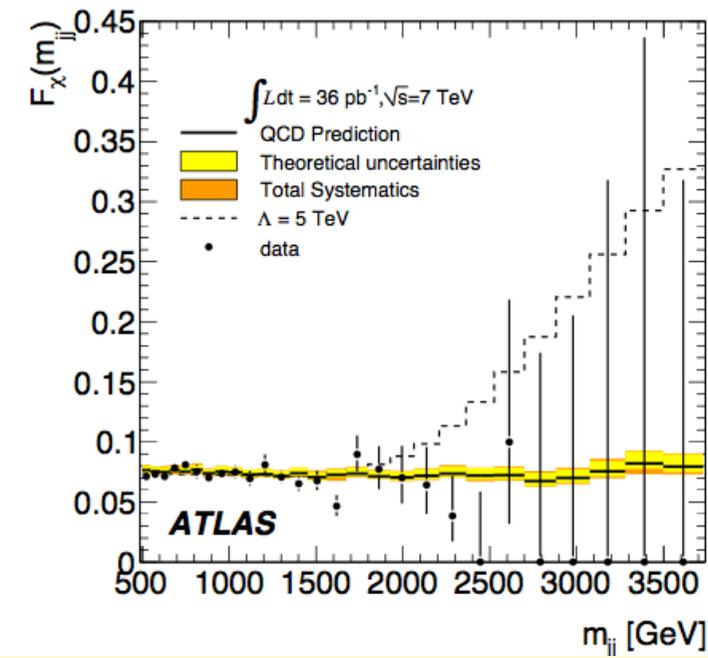
- plus
- jet shapes
- p_Trel spectra
- <N_{ch}> and <z> distributions,
-

Constraints on quark contact interactions

$$\chi = \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|}$$



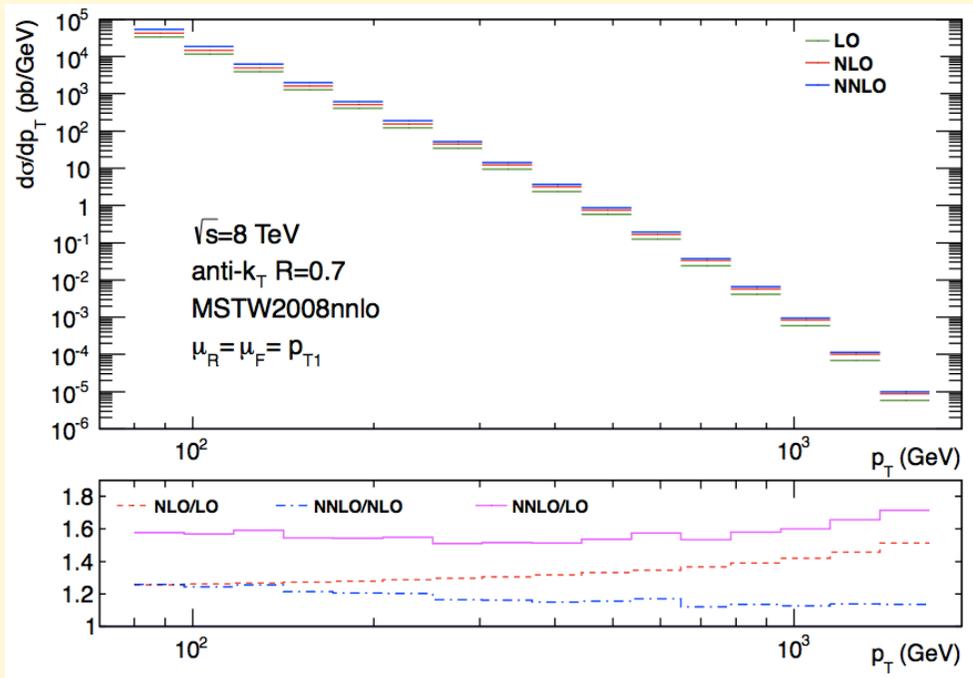
$$\chi = e^{|y_1 - y_2|}$$



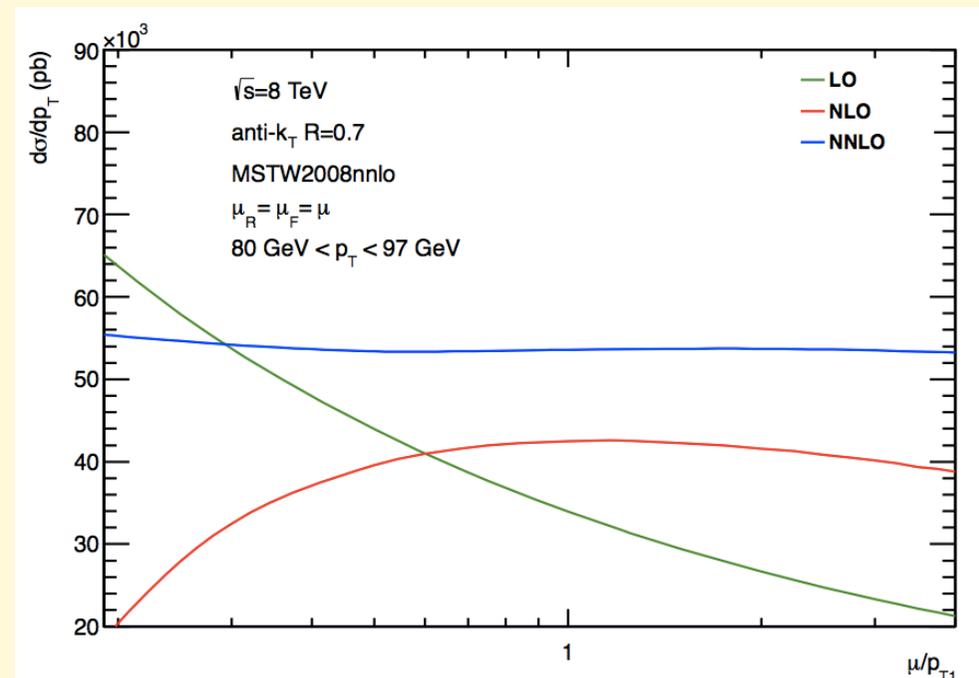
Quarks appear pointlike even at the distances probed by the LHC

Inclusive jet cross section at NNLO

“Second order QCD corrections to jet production at hadron colliders: the all-gluon contribution”, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J. Pires, arXiv:1301.7310



NNLO/NLO ~ 1.2



NNLO scale systematics ~ few % ...
- does this survive if $\mu_F \neq \mu_R$?

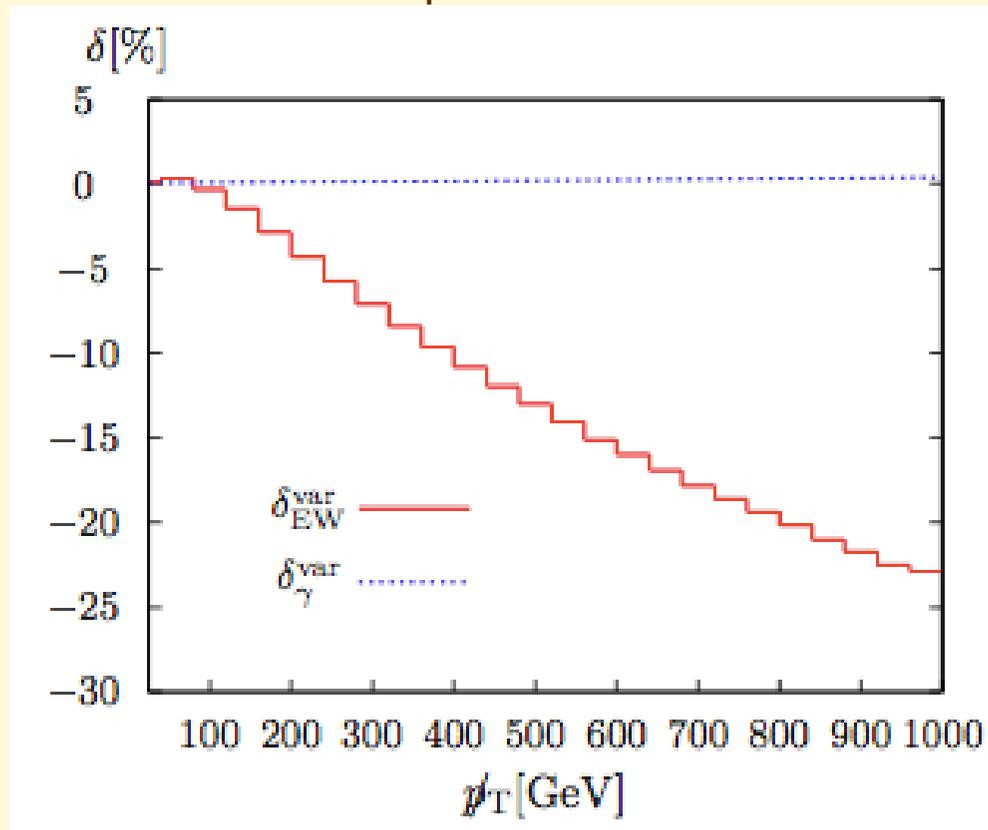
Notice that NNLO outside the NLO scale-variation band

At this level of precision, there are other things one should start considering. E.g. non-perturbative systematics and [EW corrections](#)

Impact of EW radiative corrections, example:

Jet+MET spectrum from ($Z \rightarrow \nu\nu$)+jet: corrections due to pure EW and pure EM corrections

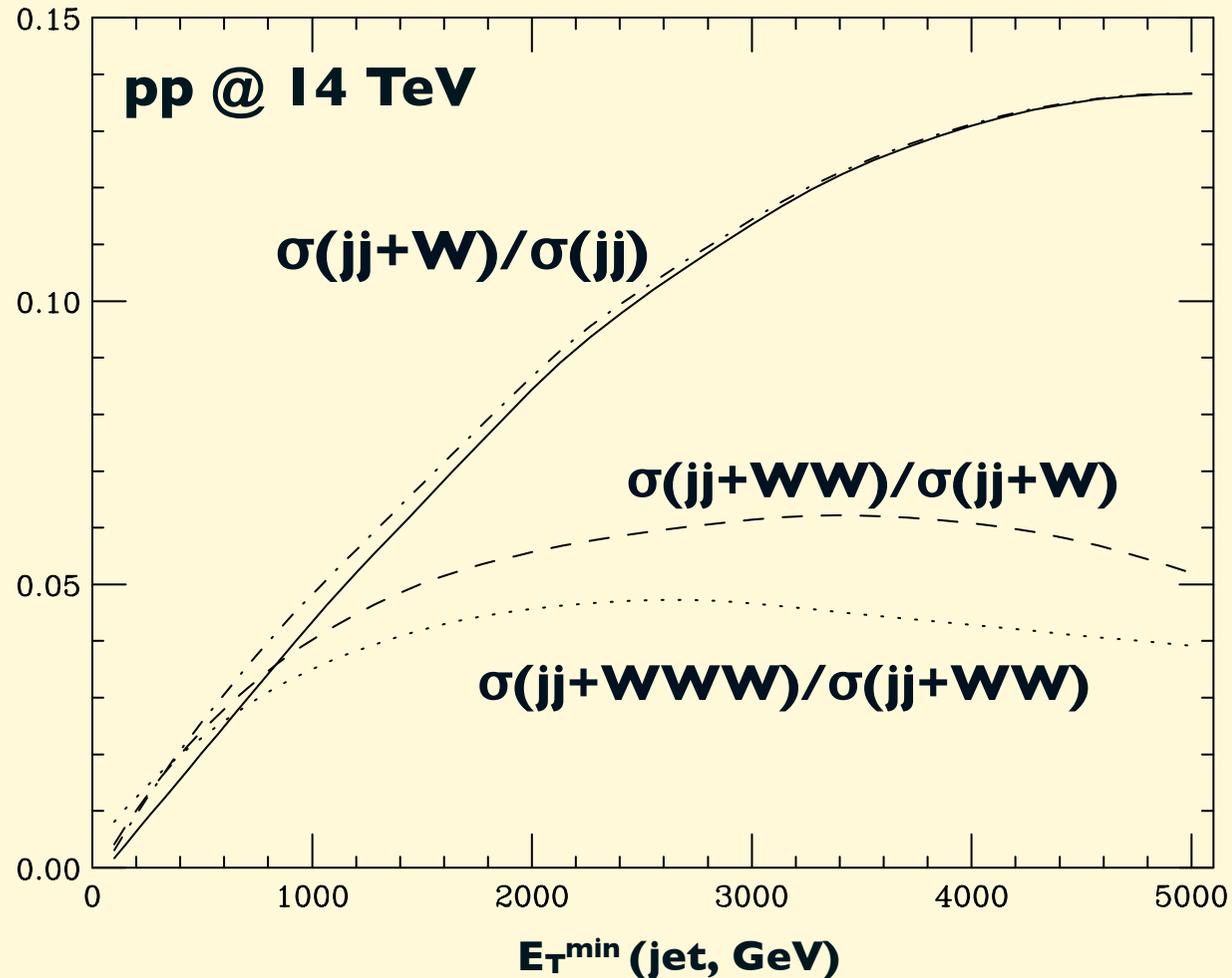
Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2



Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the Z p_T spectrum by retuning the QCD MCs!

How does one convince himself that possible deviations of this size from the QCD expectation are indeed the result of EW corrections? E.g. compare Z p_T , W p_T and γ p_T (different EW effects)

W production, in events with high- E_T jets



Dotdashes: $\sigma(jj)$ in the denominator replaced by $\sigma(jj, \text{no } gg \rightarrow gg)$

- Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!
- It would be interesting to go after these W and Zs, and verify their production properties

Multi-gauge boson production:

WWW → 3lept's

$$\sigma(W) = 100 \text{ nb}$$

$$\sigma(WW) = 50 \text{ pb} \quad \sigma(WW) / \sigma(W) = 0.5 \times 10^{-3}$$

$$\sigma(WWW) = 60 \text{ fb} \quad \sigma(WWW) / \sigma(WW) = 10^{-3}$$

$$\sigma(WWW \rightarrow 3 \ell) = 0.7 \text{ fb} \Rightarrow \mathbf{20 \text{ events}/30 \text{ fb}^{-1}} \quad \ell = e, \mu$$

ZWW → 4lept's

$$\sigma(Z) = 30 \text{ nb}$$

$$\sigma(ZW) = 20 \text{ pb} \quad \sigma(ZW) / \sigma(Z) \sim 10^{-3}$$

$$\sigma(ZWW) = 50 \text{ fb} \quad \sigma(ZWW) / \sigma(ZW) \sim 2 \times 10^{-3}$$

$$\sigma(ZWW \rightarrow 4 \ell) = 0.15 \text{ fb} \Rightarrow \mathbf{5 \text{ events}/30 \text{ fb}^{-1}} \quad \ell = e, \mu$$

$$\sigma(W) / \sigma(Z) \sim 3$$

$$\sigma(WW) / \sigma(ZW) \sim 2.5$$

$$\sigma(WWW) / \sigma(ZWW) \sim 1.2$$

Ratio determined by couplings to quarks, u/d PDF

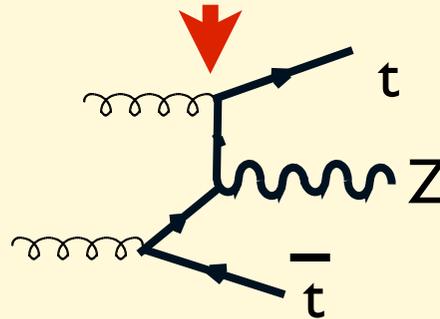


Ratio determined by couplings among W/Z, SU(2) invariance₂₄

Multi-gauge boson production:

ttZ → WWZ → 4lept's

$$\sigma(\text{Ztt}) = 100 \text{ fb} = 40_{(\text{uub} + \text{d} \bar{\text{d}})} \text{ fb} + 60_{(\text{gg})} \text{ fb} = 100 \text{ fb}$$



The gg part is directly proportional to the ttZ coupling. **First** “direct” measurement (indirect: virtual corrections to Z self-energy)

$$\sigma(\text{Ztt}) \times \text{B}(\text{Z} \rightarrow \ell\ell) \times \text{B}(\text{tt} \rightarrow \ell'\ell'') = 0.3 \text{ fb} \Rightarrow \mathbf{10 \text{ events/30}}$$

$$\ell = e, \mu$$

fb⁻¹

ttW → 3W → 3lept's

$$\sigma(\text{Wtt}) = 110 \text{ fb}$$

Notice $\sigma(\text{Wtt}) \sim \sigma(\text{Ztt})$, while typically $\sigma(\text{W}) \sim 3 \sigma(\text{Z})$. The reason is that Wtt cannot have a gg production channel!!

$$\sigma(\text{Wtt}) \times \text{B}(\text{W} \rightarrow \ell) \times \text{B}(\text{tt} \rightarrow \ell'\ell'') = 1.2 \text{ fb} \Rightarrow \mathbf{40 \text{ events/30}}$$

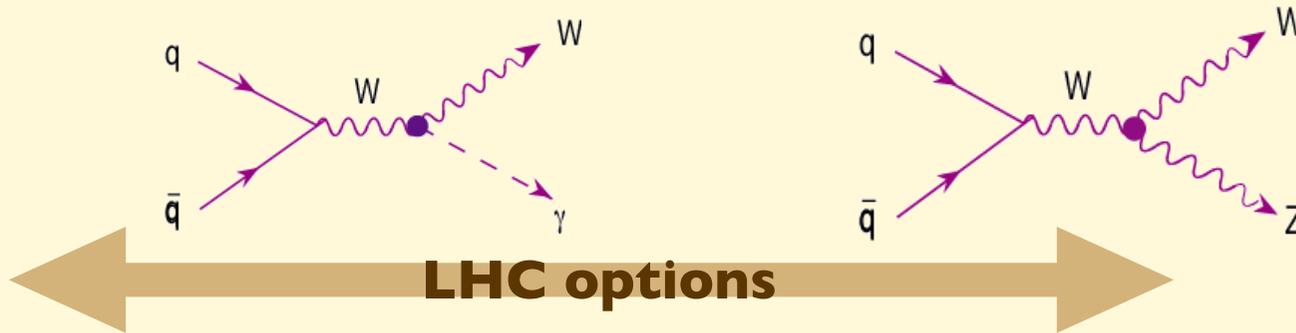
$$\ell = e, \mu$$

fb⁻¹

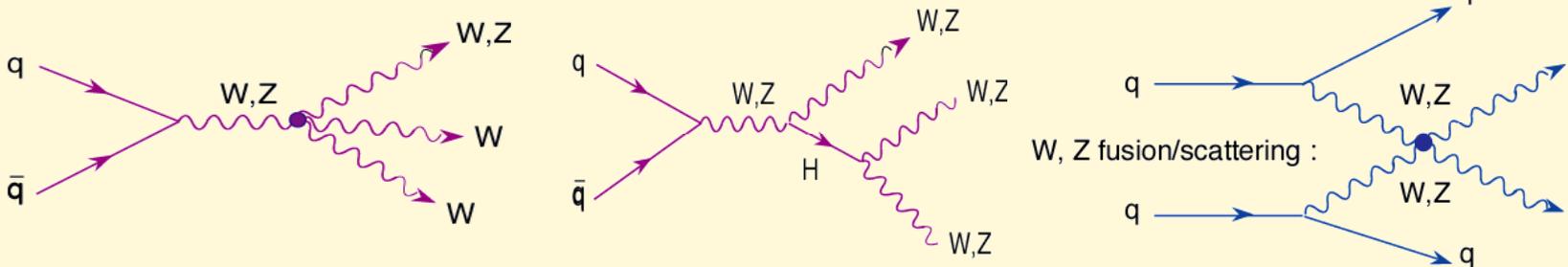
$$\sigma(\text{Wtt}) / \sigma(\text{tt}) = 0.7 \times 10^{-3}$$

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_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

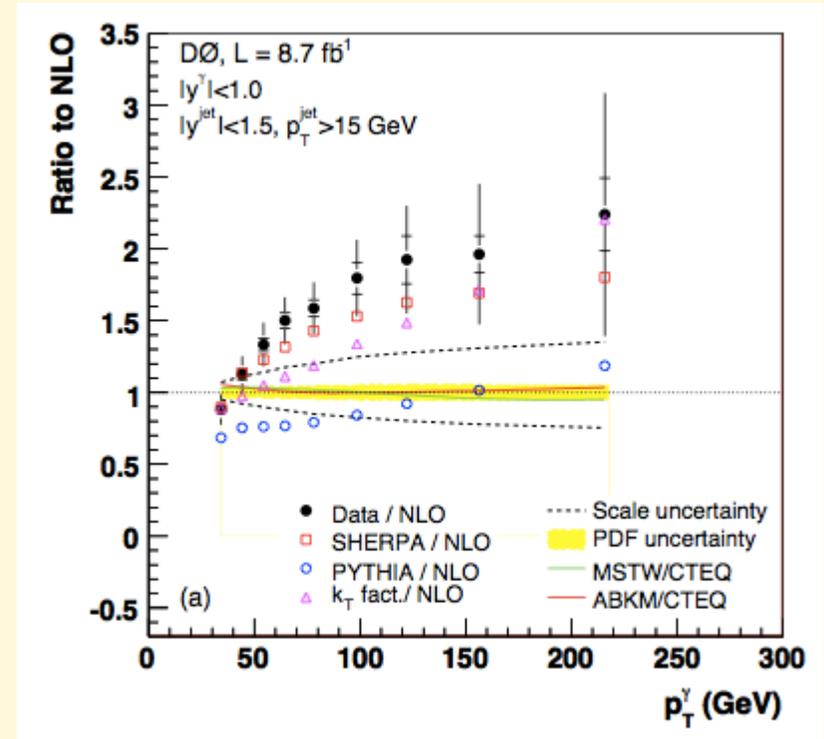
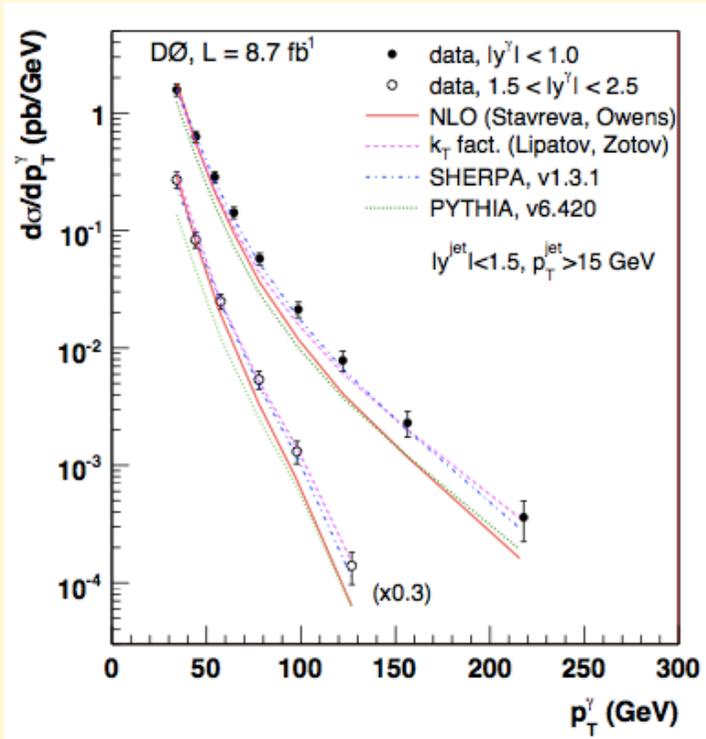


(LO rates, CTEQ5M, $k \sim 1.5$ expected for these final states)						
Process	WWW	WWZ	ZZW	ZZZ	WWWW	WWWZ
N($m_H = 120$ GeV)	2600	1100	36	7	5	0.8
N($m_H = 200$ GeV)	7100	2000	130	33	20	1.6

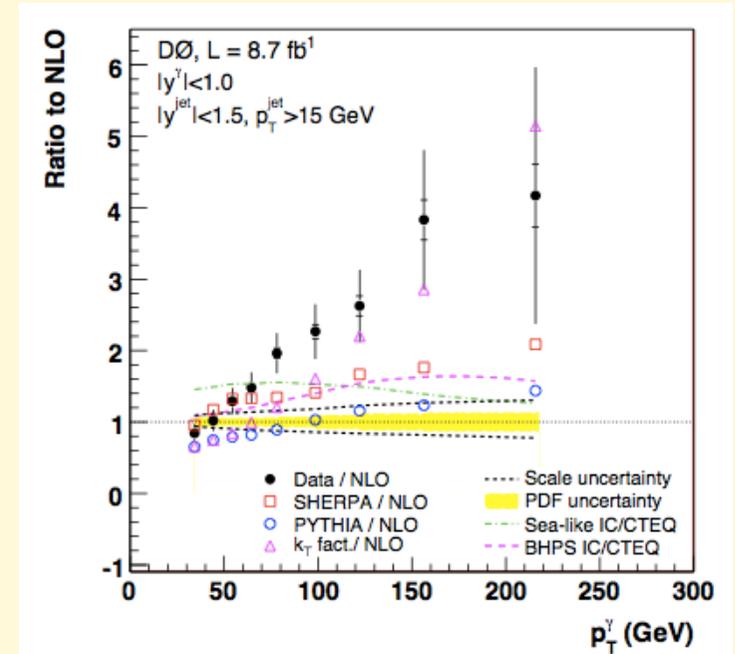
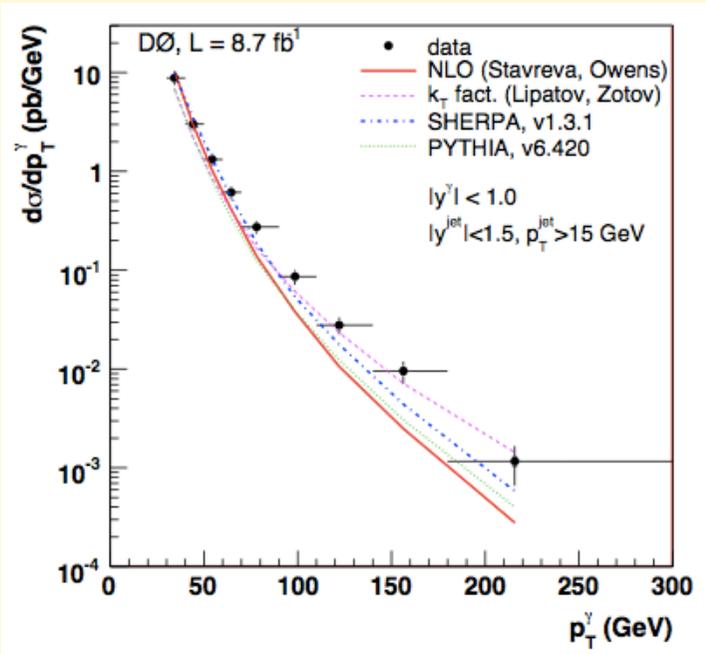
Examples of open issues

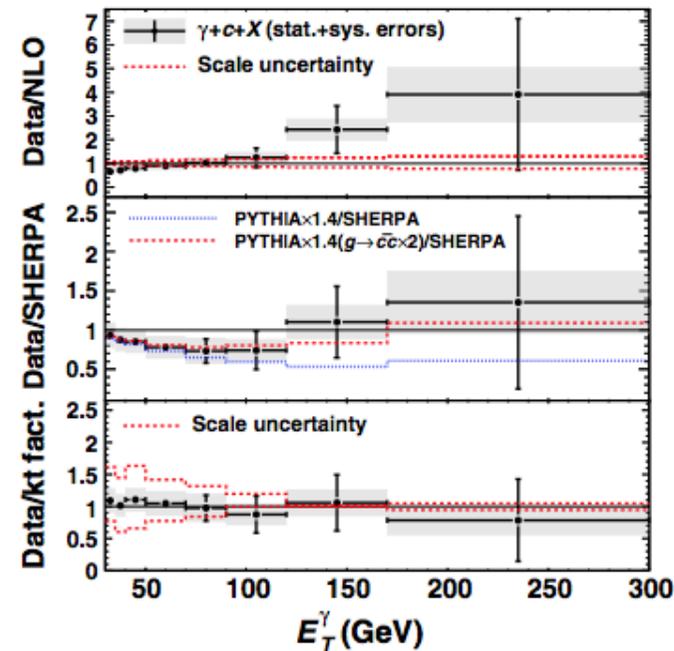
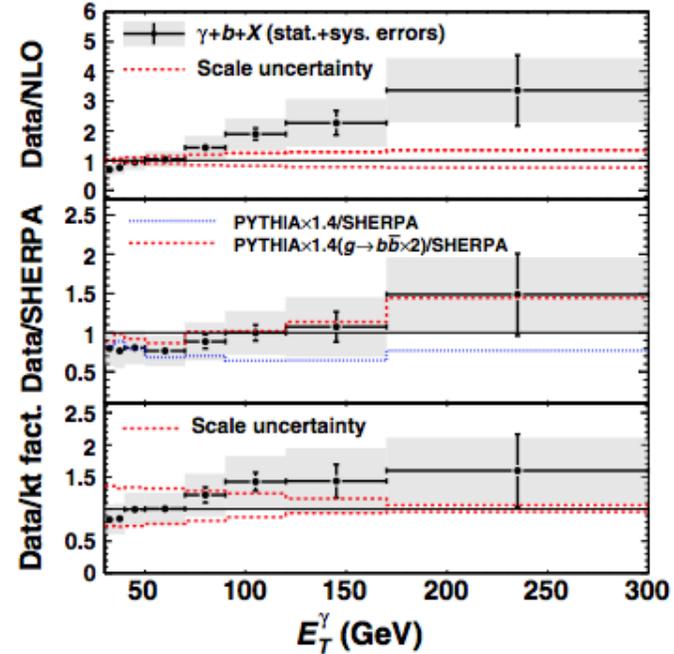
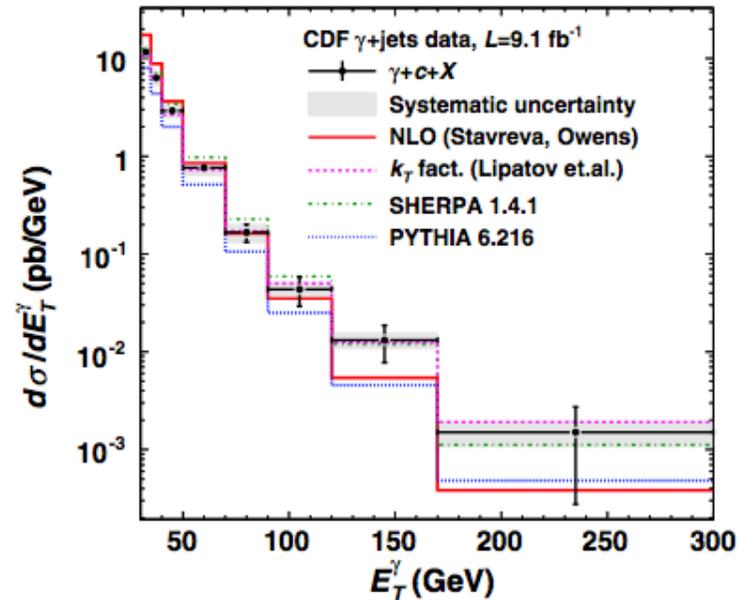
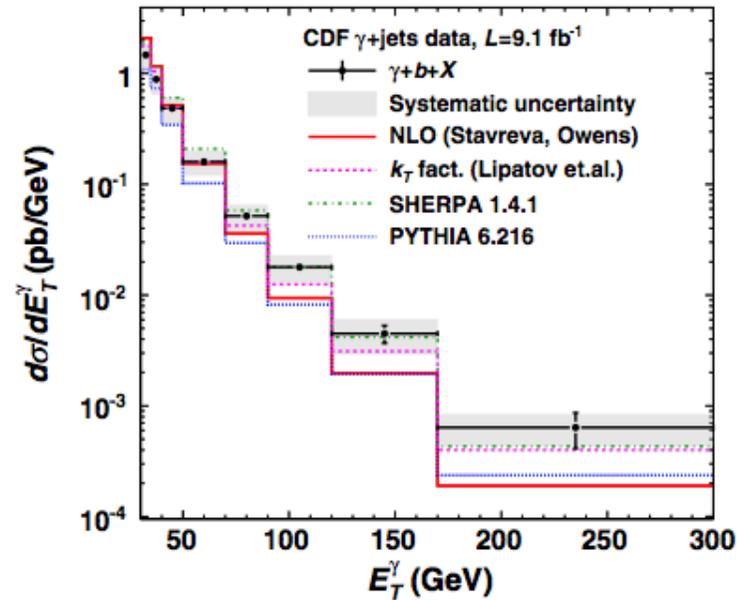
D0 results

$\gamma+b$



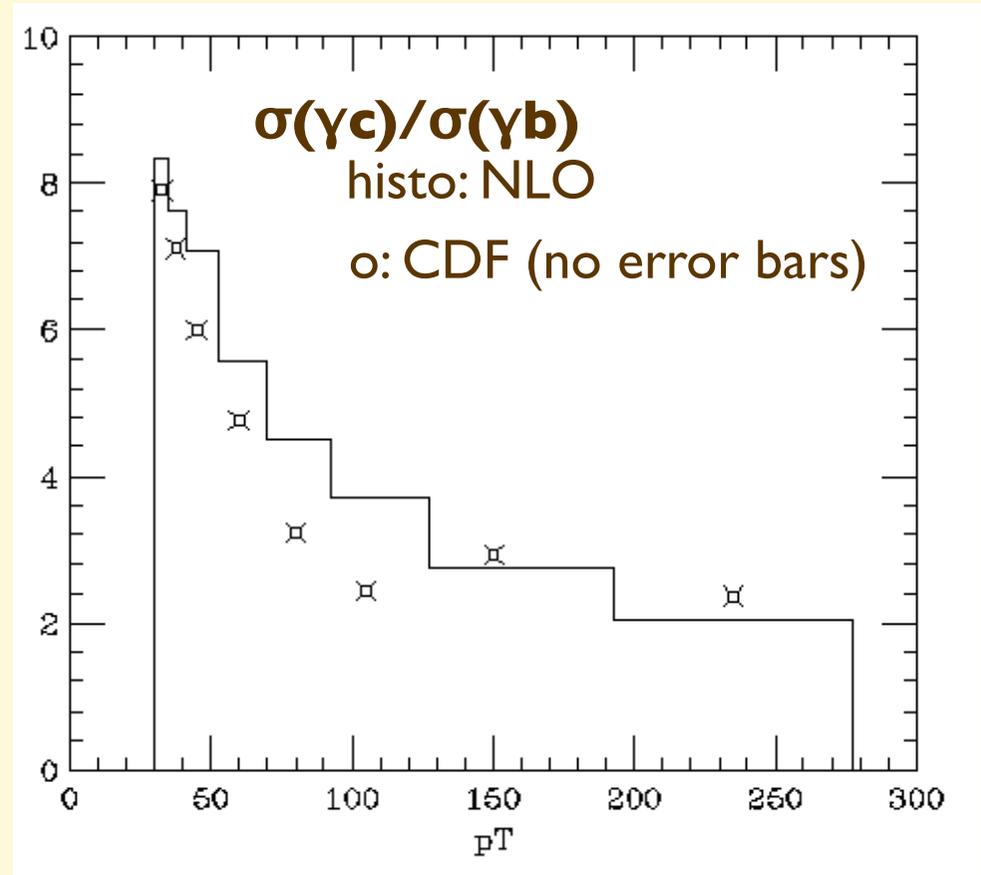
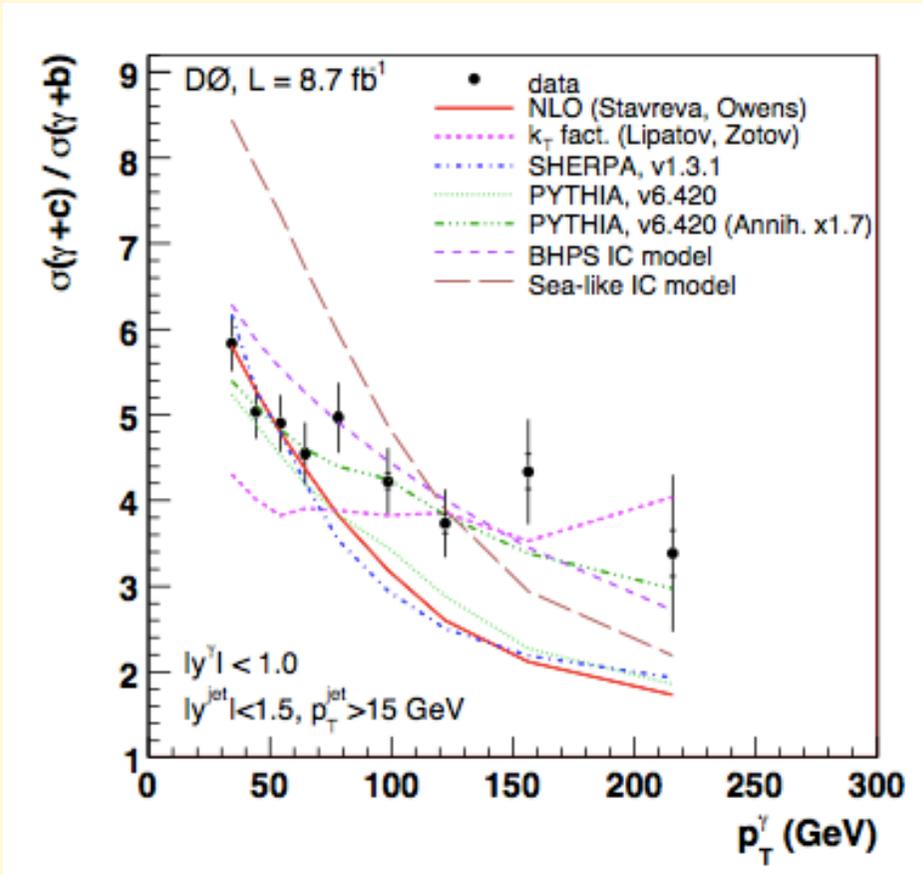
$\gamma+c$





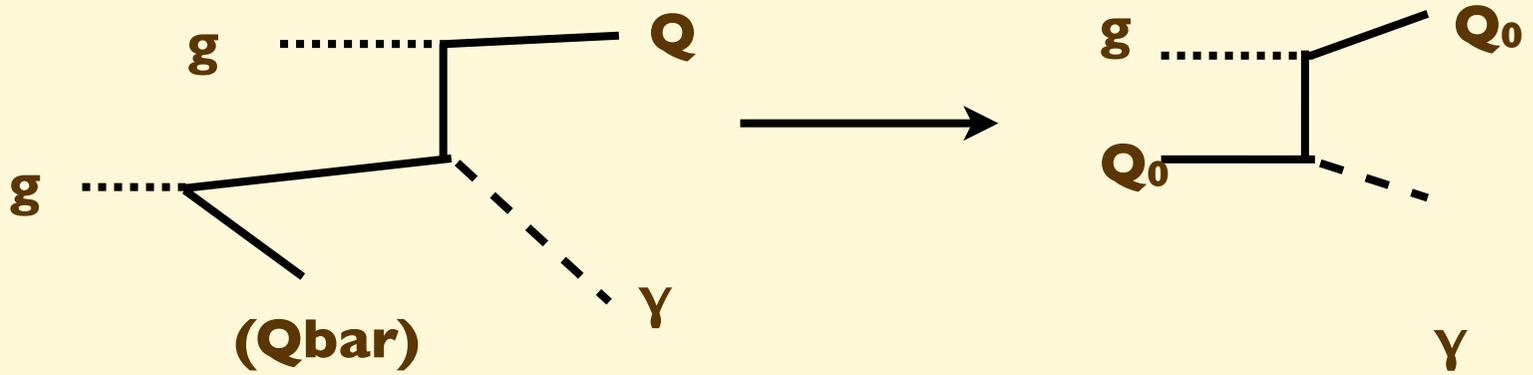
Similar trend in cdf and D0: an excess in both c and b.

However, if we look at the ratios c/b:



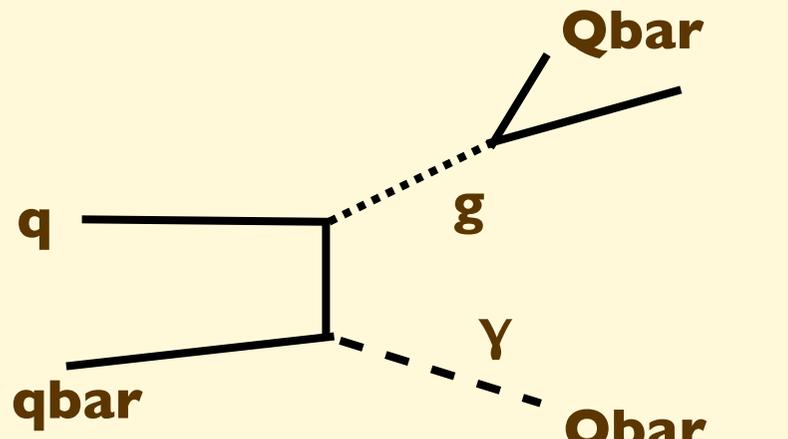
Are the CDF and D0 results consistent with each other?

$gg \rightarrow QQ\gamma$

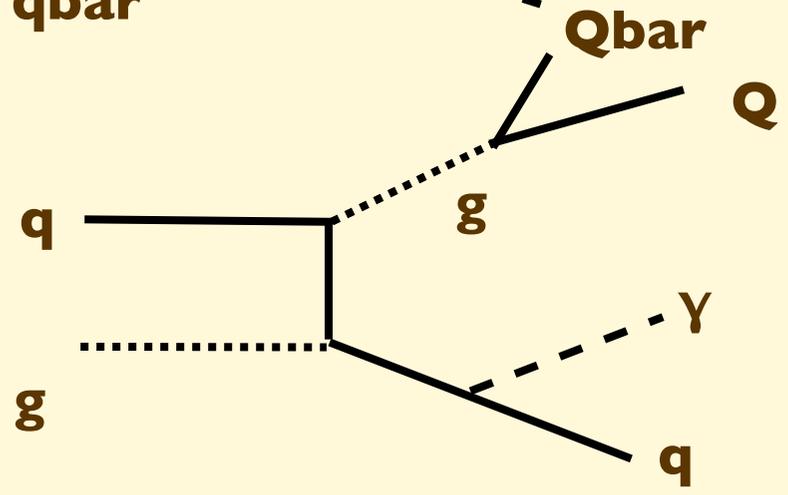


$R_{gg} = \sigma(c) / \sigma(b) \sim 4 * f(c)/f(b) \sim 4 \log(p_T/m_c) / \log(p_T/m_b)$

$q qbar \rightarrow QQ\gamma$

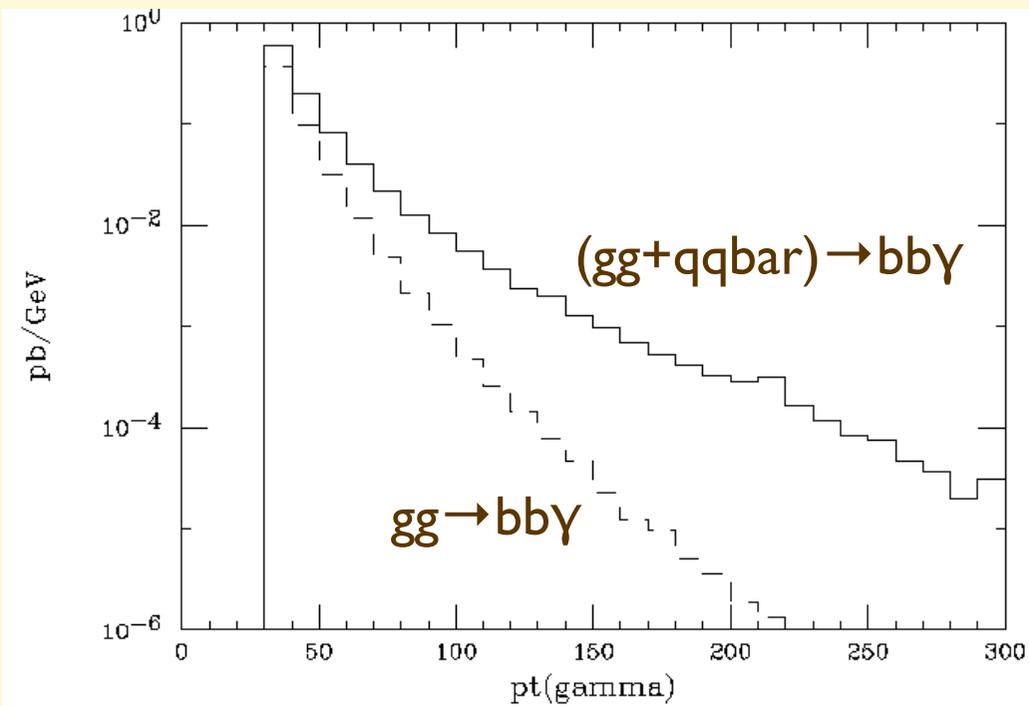
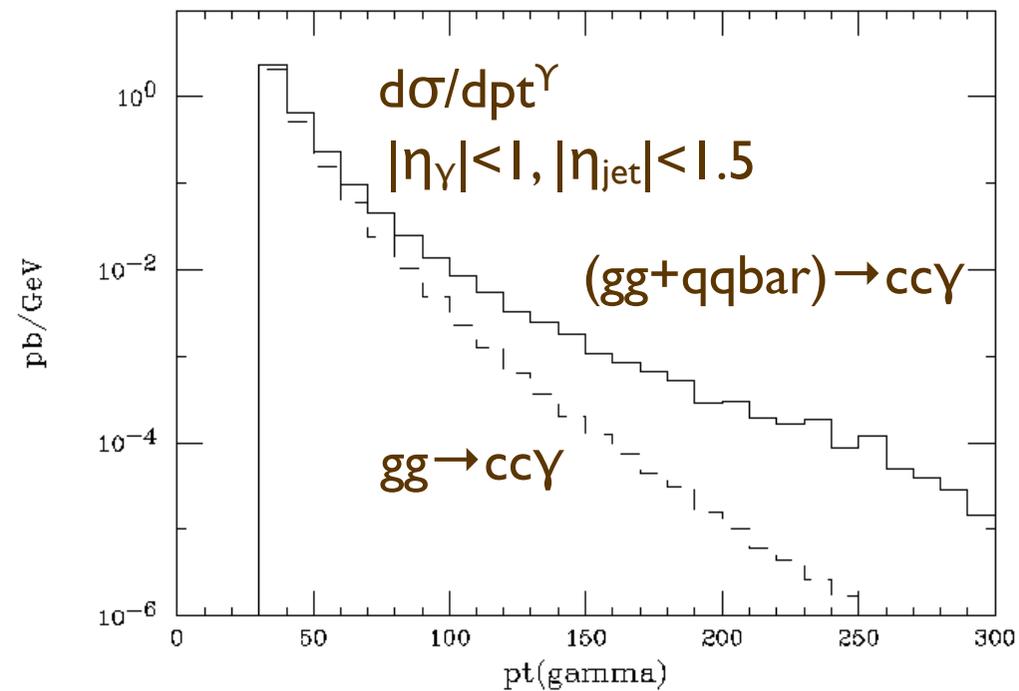


$q g \rightarrow QQ (q \rightarrow \gamma)$

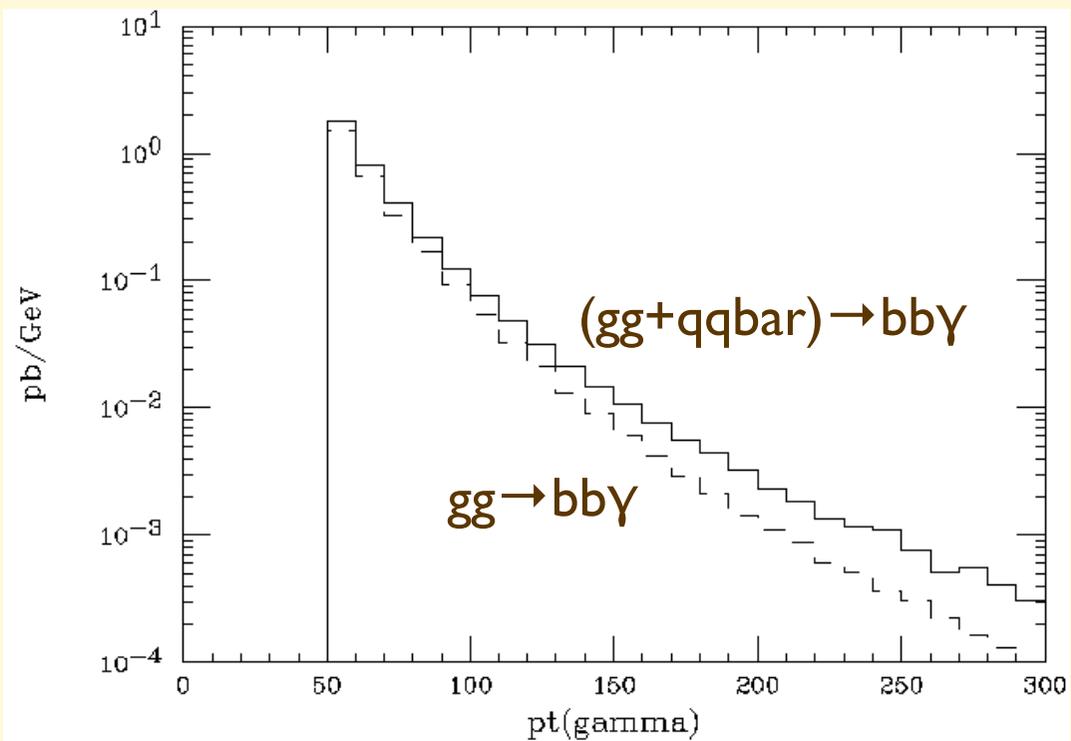
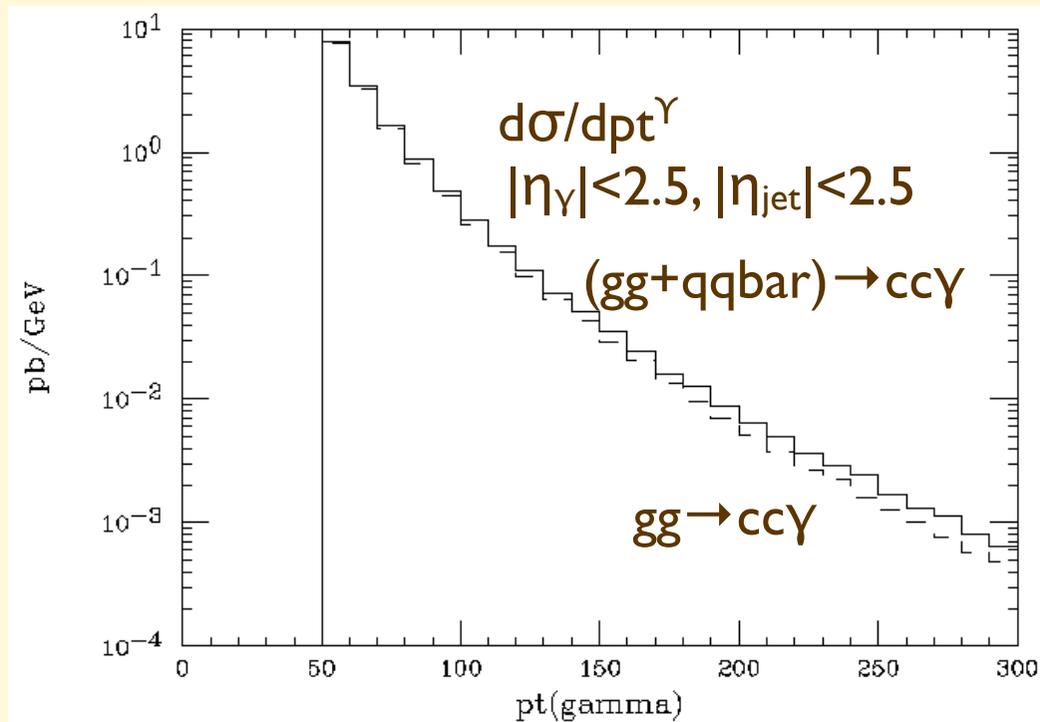


$R_{qq} = \sigma(c) / \sigma(b) \sim \log(p_T/m_c) / \log(p_T/m_b) = 1/4 R_{gg}$

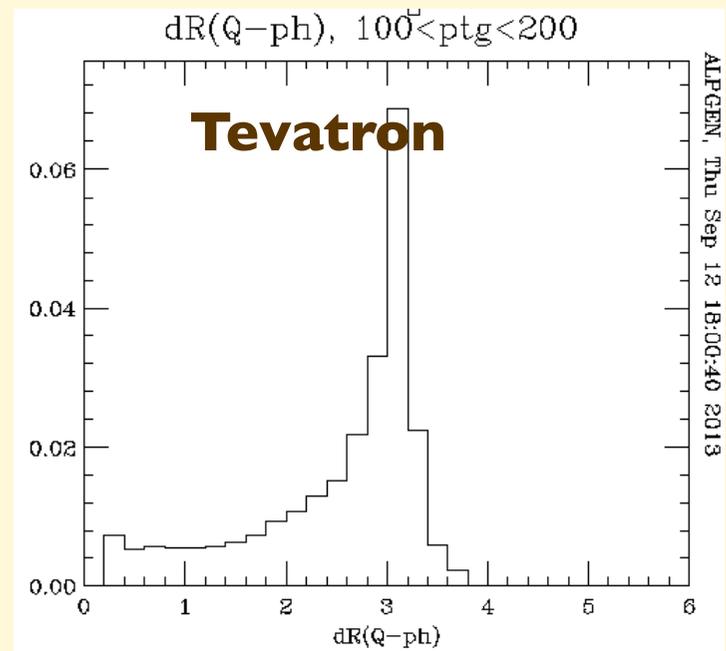
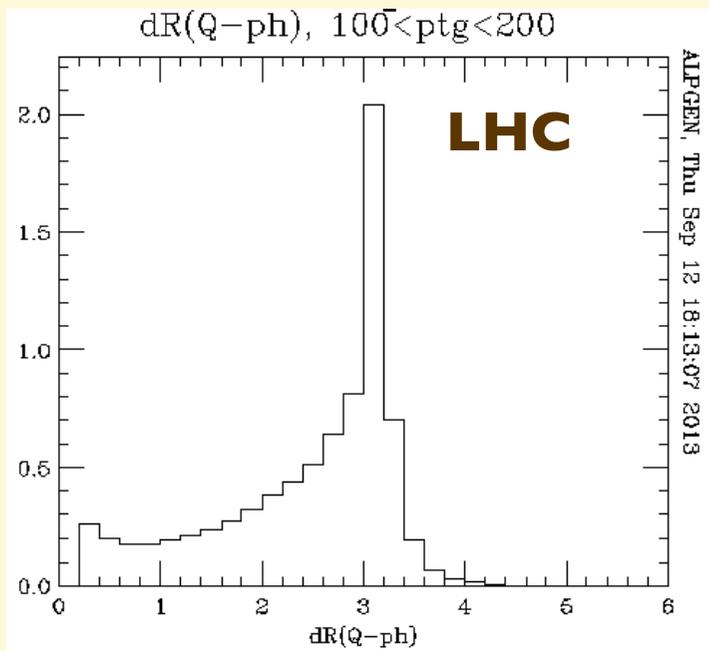
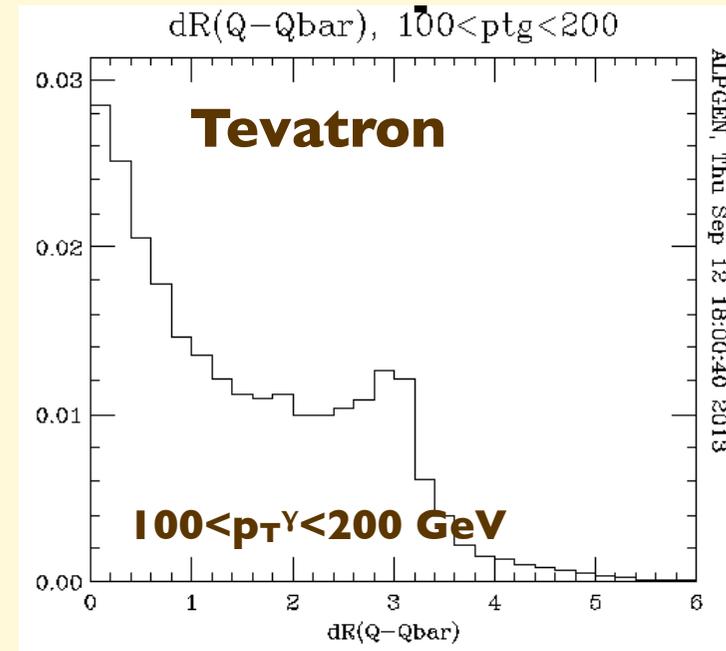
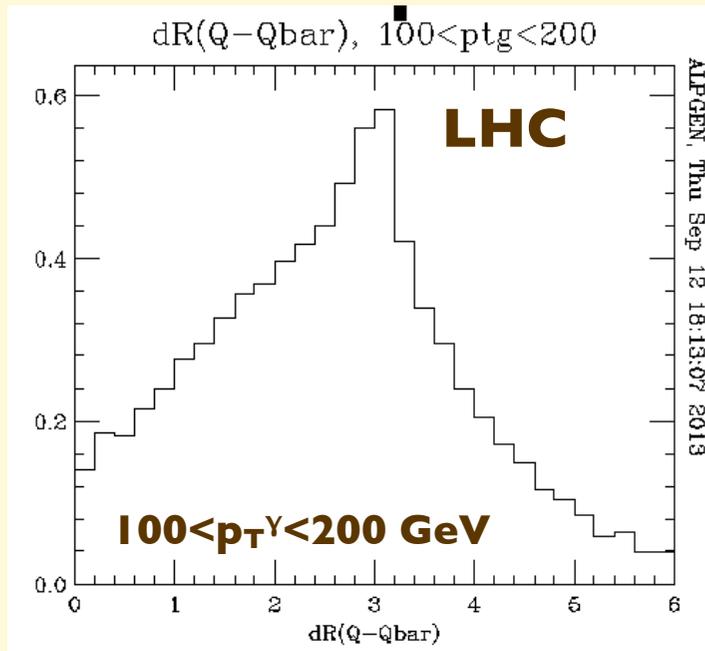
Tevatron



LHC

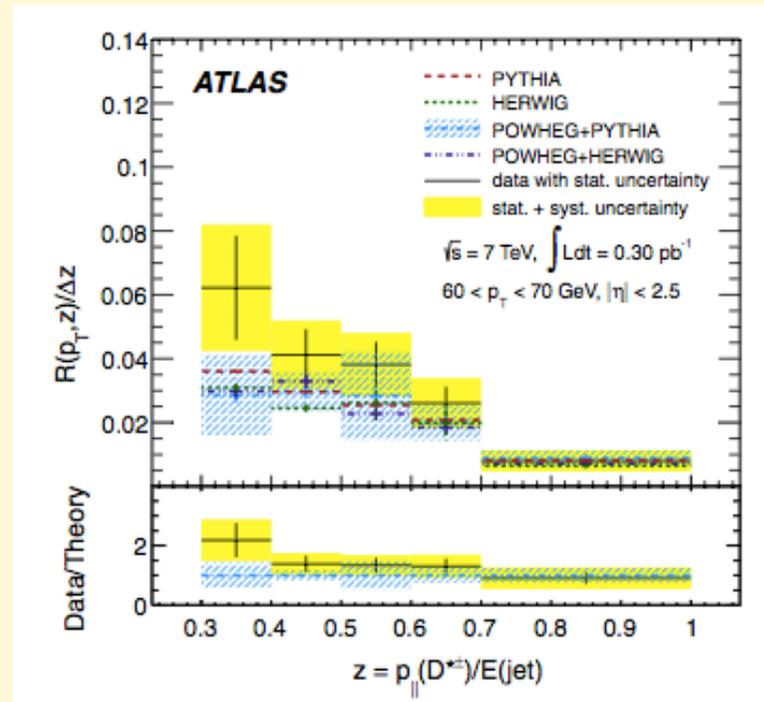
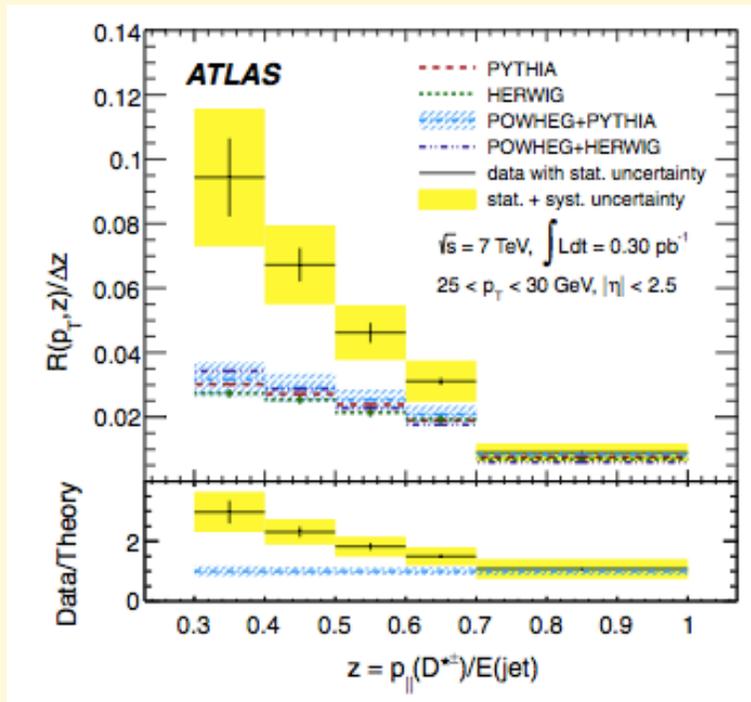
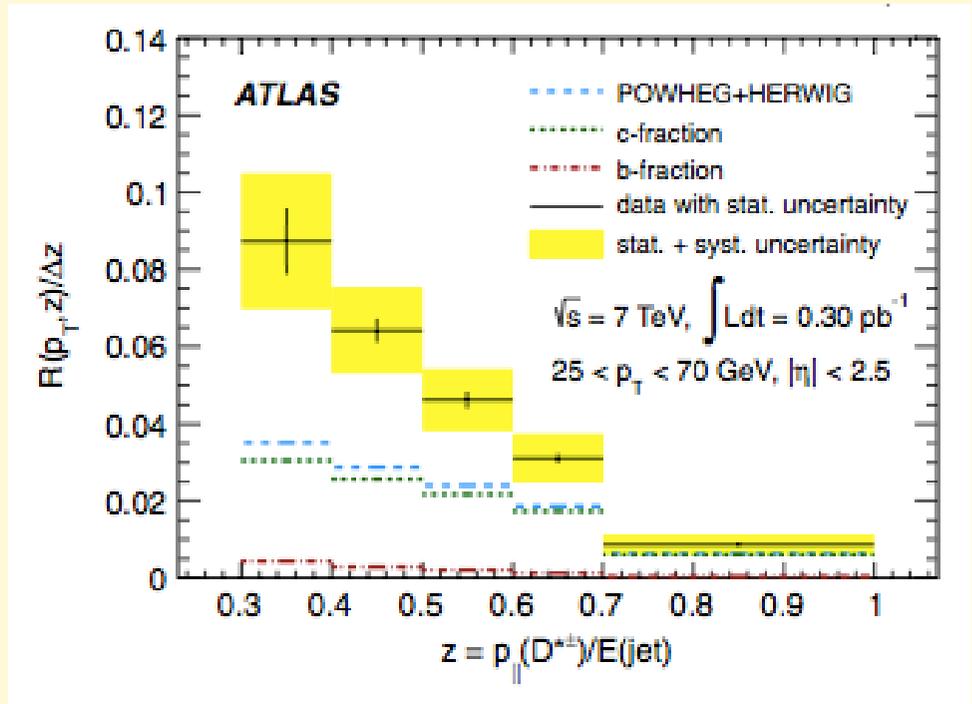


Thus γc production at large p_t at the LHC is more sensitive to the charm PDF than at the Tevatron, where gluon splitting has a major role at large p_t .

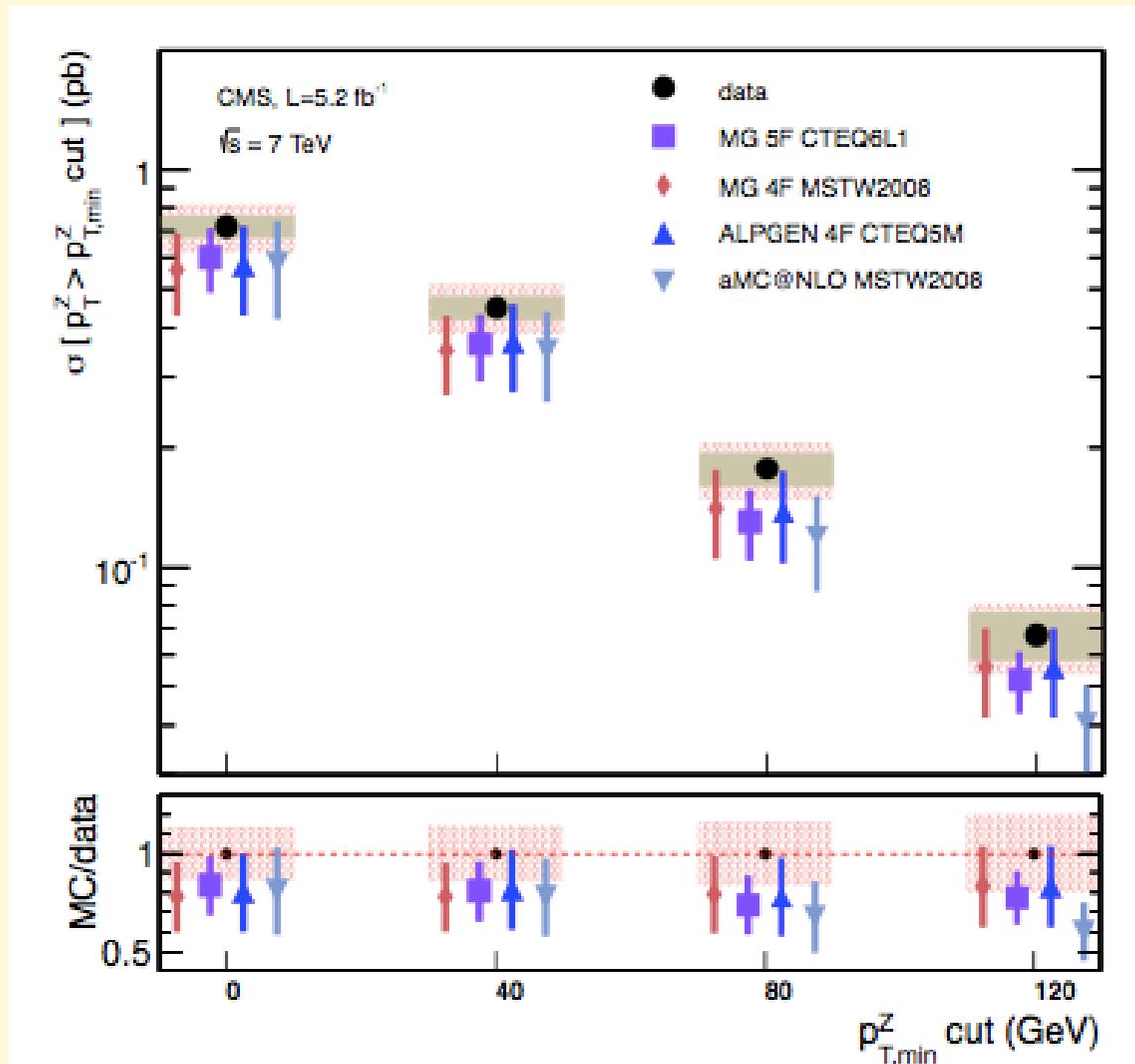


Ancillary handles: D* in jets, fragmentation function

PHYSICAL REVIEW D 85, 052005 (2012)



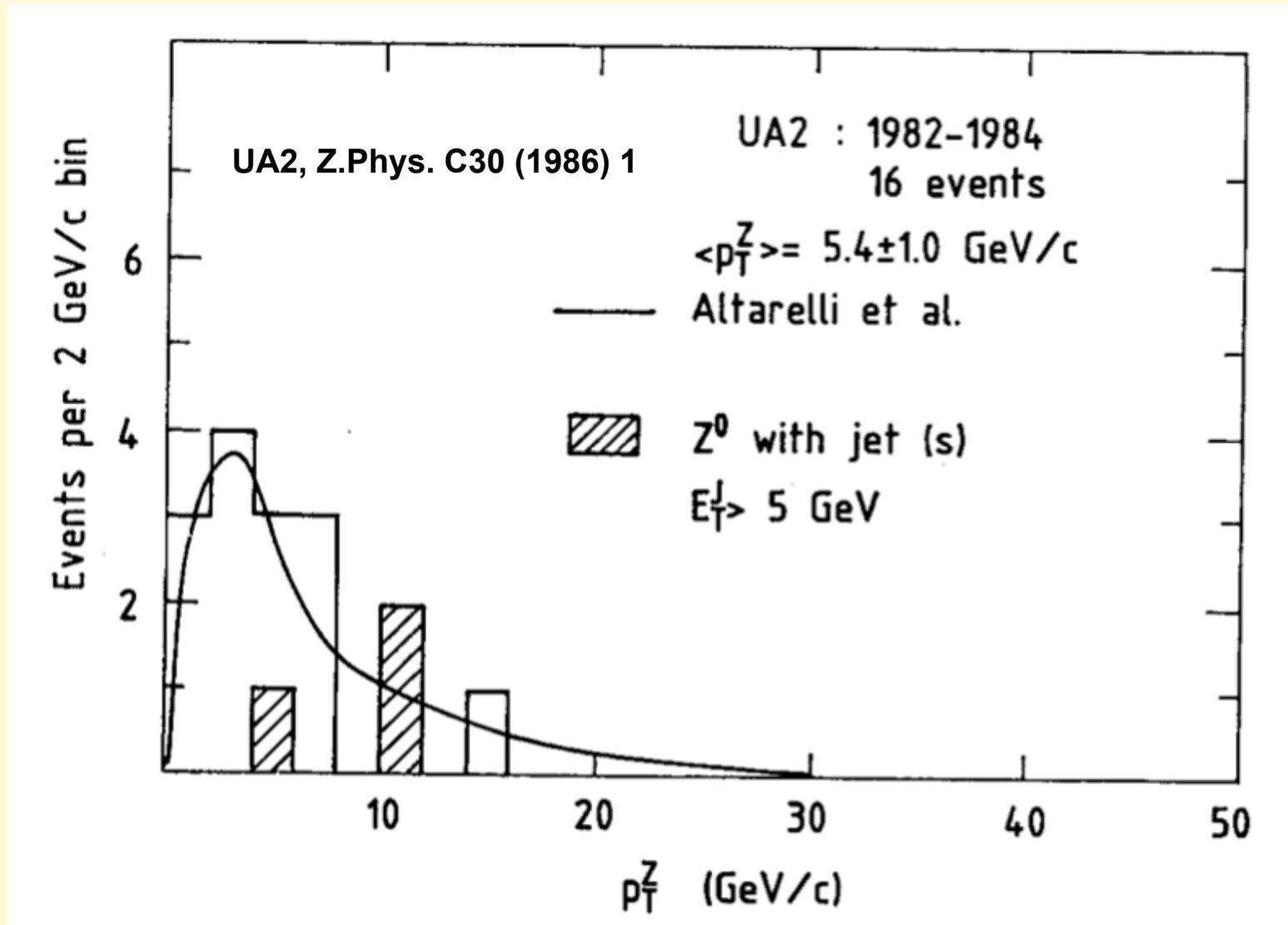
CMS, Z+b jets, arXiv:1310.1349v1: rate and correlations OK to ~20%

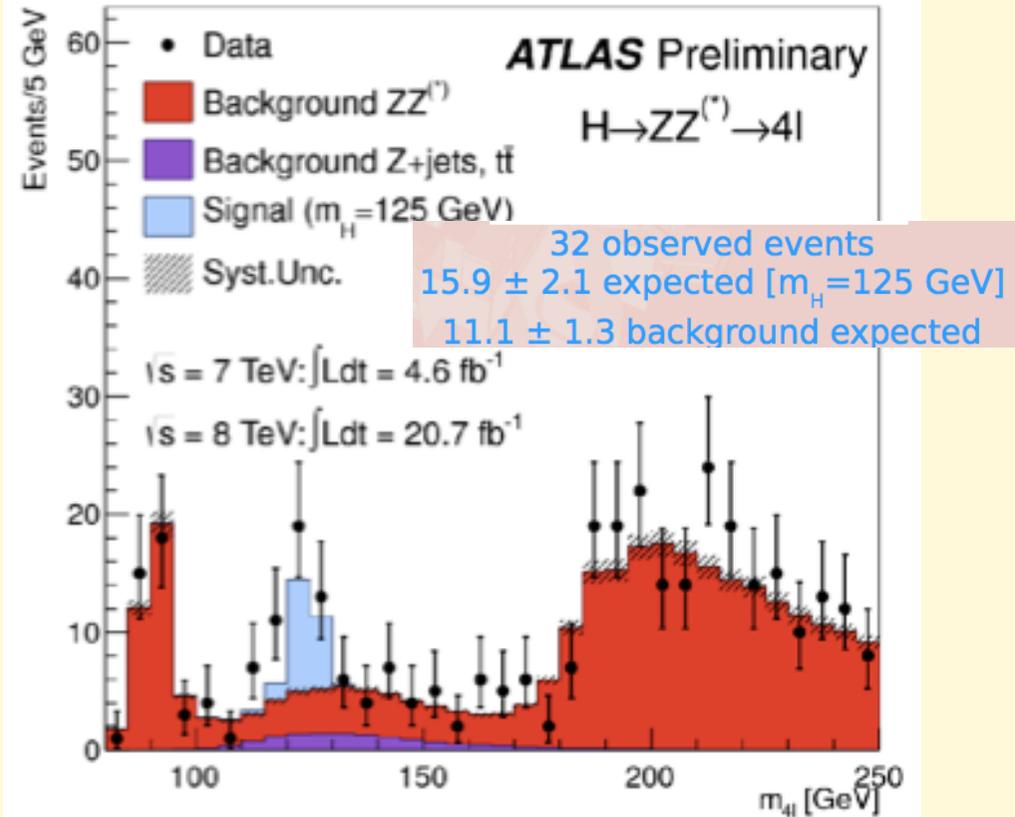
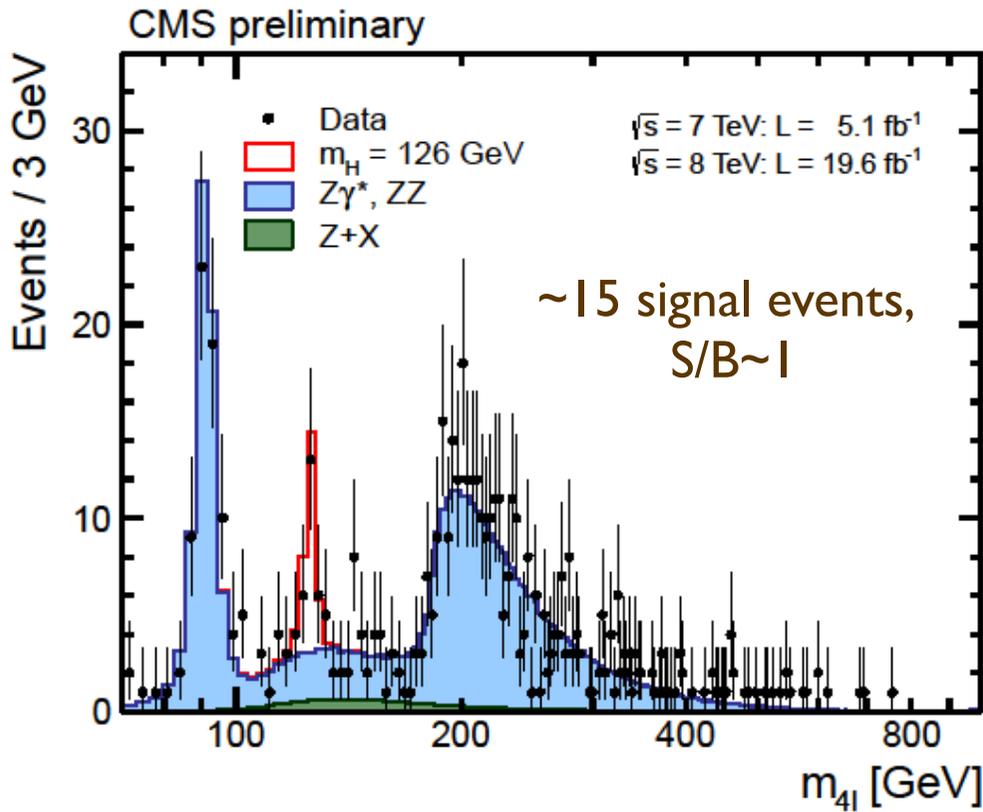


Would be nice to see a complete comparative study of Z+c, Z+b, γ +c, γ +b at the LHC !!

Towards experimental constraints on Higgs production dynamics ...

To put it in perspective, W/Z physics started like this, from a score of events:



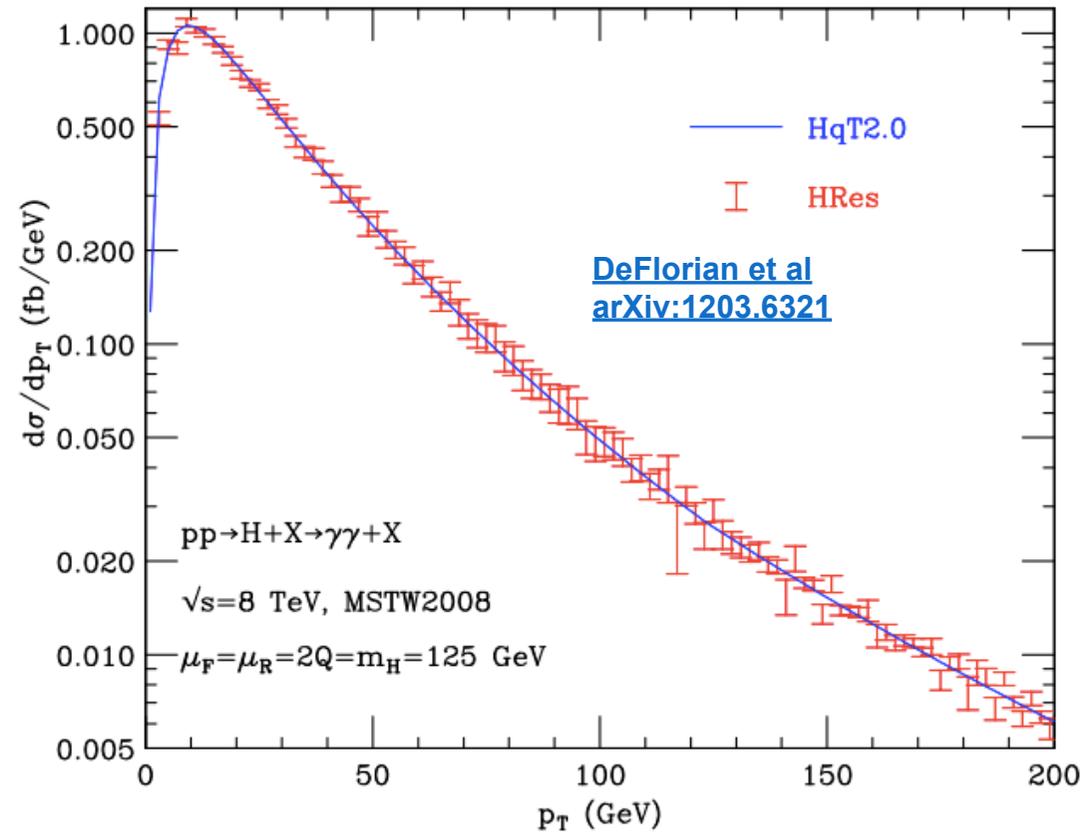
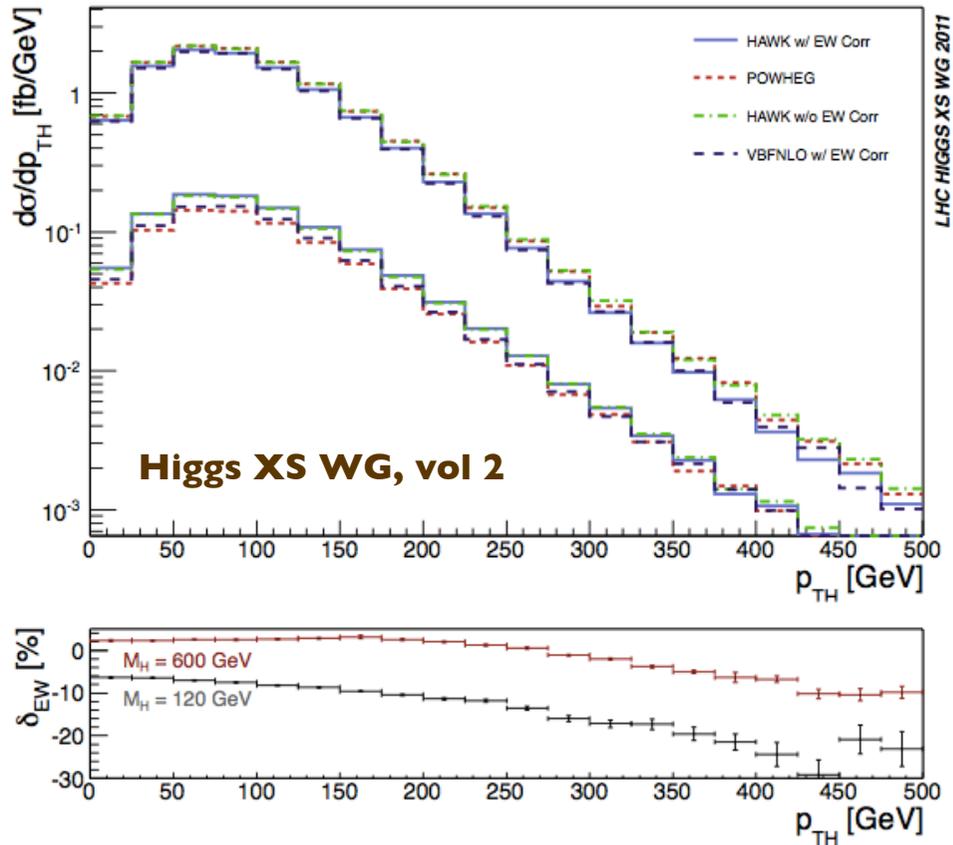


There is enough to start plotting $pt(H)$, N_{jet} distribution in H production, etc.

$p_T(H): qq \rightarrow qq H$ vs $gg \rightarrow H$

$qq \rightarrow qq H$

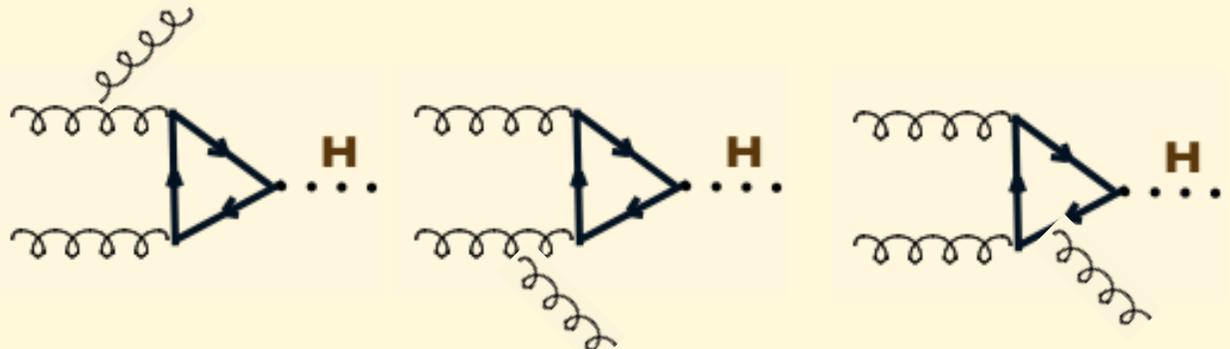
$gg \rightarrow H$



- $p_T(\text{peak}) \sim 60$ GeV
- Large size of EW corrections

- $p_T(\text{peak}) \sim 10$ GeV

$gg \rightarrow H$ at $p_T > m_{\text{top}}$ resolves the inside of the production triangle, an alternative probe to its components



8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

E_{1,2}: different beam energies

X,Y: different hard processes

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X, E_2)}{\sigma(X, E_1)}$$



- TH: reduce “scale uncertainties”
- TH: reduce parameters’ systematics: PDF, m_{top}, α_s, ... at E₁ and E₂ are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst’s from acceptance, efficiency, JES, ...

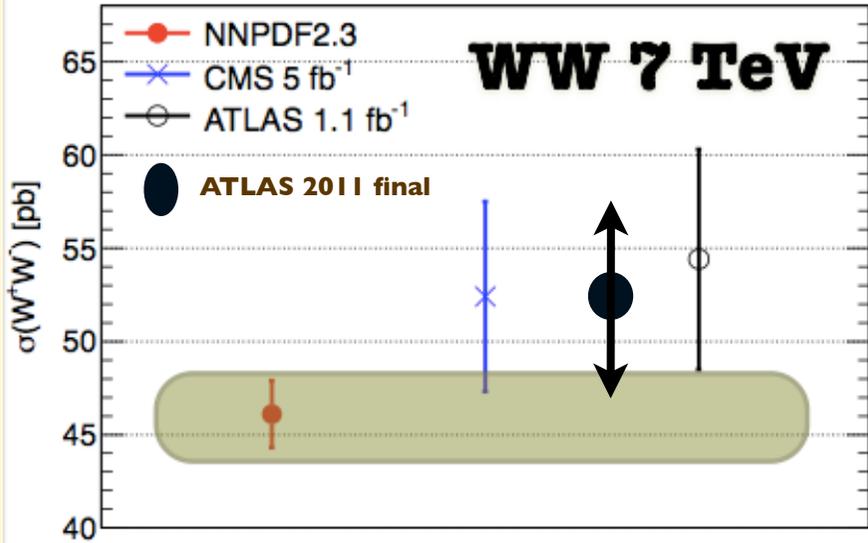
$$R_{E_2/E_1}(X, Y) \equiv \frac{\sigma(X, E_2)/\sigma(Y, E_2)}{\sigma(X, E_1)/\sigma(Y, E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)}$$



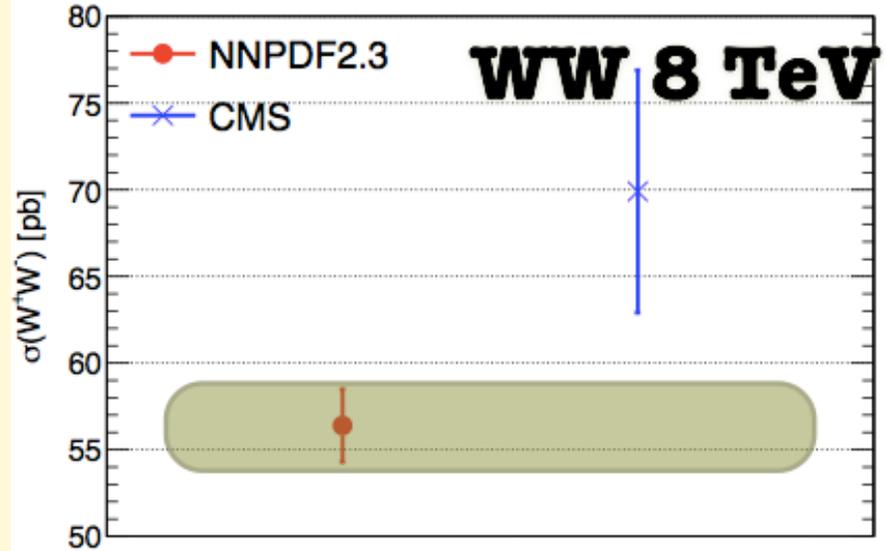
- TH: possible further reduction in scale and PDF syst’s
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst’s (e.g. X,Y=W⁺,W⁻)

Following results obtained using best available TH predictions: NLO, NNLO, NNLL
resummation when available

LHC 7 TeV $\sigma(W^+W^-)$ - MCFM6.3 PDF+scales - $\alpha_s = 0.119$



LHC 8 TeV $\sigma(W^+W^-)$ - MCFM6.3 PDFs+scales - $\alpha_s = 0.119$



Diboson cross section ratios

8 over 7 TeV	$R^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$\delta_{\text{scales}}(\%)$
WW	1.223	± 0.1	-0.4 - 0.2
$gg \rightarrow WW$	1.330	± 0.2	-0.0 - 0.0
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
$gg \rightarrow ZZ$	1.218	± 1.2	-0.0 - 0.0
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

(scale errors missing)

(scale errors missing)

14 TeV / 8 TeV: NNPDF results

CrossSection	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$\delta_{\alpha_s}(\%)$	$\delta_{\text{scales}}(\%)$
$t\bar{t}/Z$	2.121	1.01	-0.84 - 0.75	0.42 - 1.10
$t\bar{t}$	3.901	0.84	-0.51 - 0.66	0.38 - 1.07
Z	1.839	0.37	-0.10 - 0.34	0.28 - 0.18
W^+	1.749	0.41	-0.03 - 0.27	0.31 - 0.18
W^-	1.859	0.39	-0.08 - 0.26	0.32 - 0.13
W^+/W^-	0.941	0.28	0.00 - 0.05	0.00 - 0.04
W/Z	0.976	0.09	-0.07 - 0.04	0.04 - 0.02
ggH	2.564	0.36	-0.10 - 0.09	0.89 - 0.98
$ggH/t\bar{t}$	0.657	0.75	-0.56 - 0.41	1.38 - 1.05
$t\bar{t}(M_{t\bar{t}} \geq 1\text{TeV})$	8.215	2.09	0.00 - 0.00	1.61 - 2.06
$t\bar{t}(M_{t\bar{t}} \geq 2\text{TeV})$	24.776	6.07	0.00 - 0.00	3.05 - 1.07
$\sigma_{\text{jet}}(p_T \geq 1\text{TeV})$	15.235	1.72	0.00 - 0.00	2.31 - 2.19
$\sigma_{\text{jet}}(p_T \geq 2\text{TeV})$	181.193	6.75	0.00 - 0.00	3.66 - 5.76

- $\delta < 10^{-2}$ in W^\pm ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta \sim 10^{-2}$ in $\sigma(t\bar{t})$ ratios
- $\delta_{\text{scale}} < \delta_{\text{PDF}}$ at large p_T^{jet} and $M_{t\bar{t}}$: constraints on PDFs

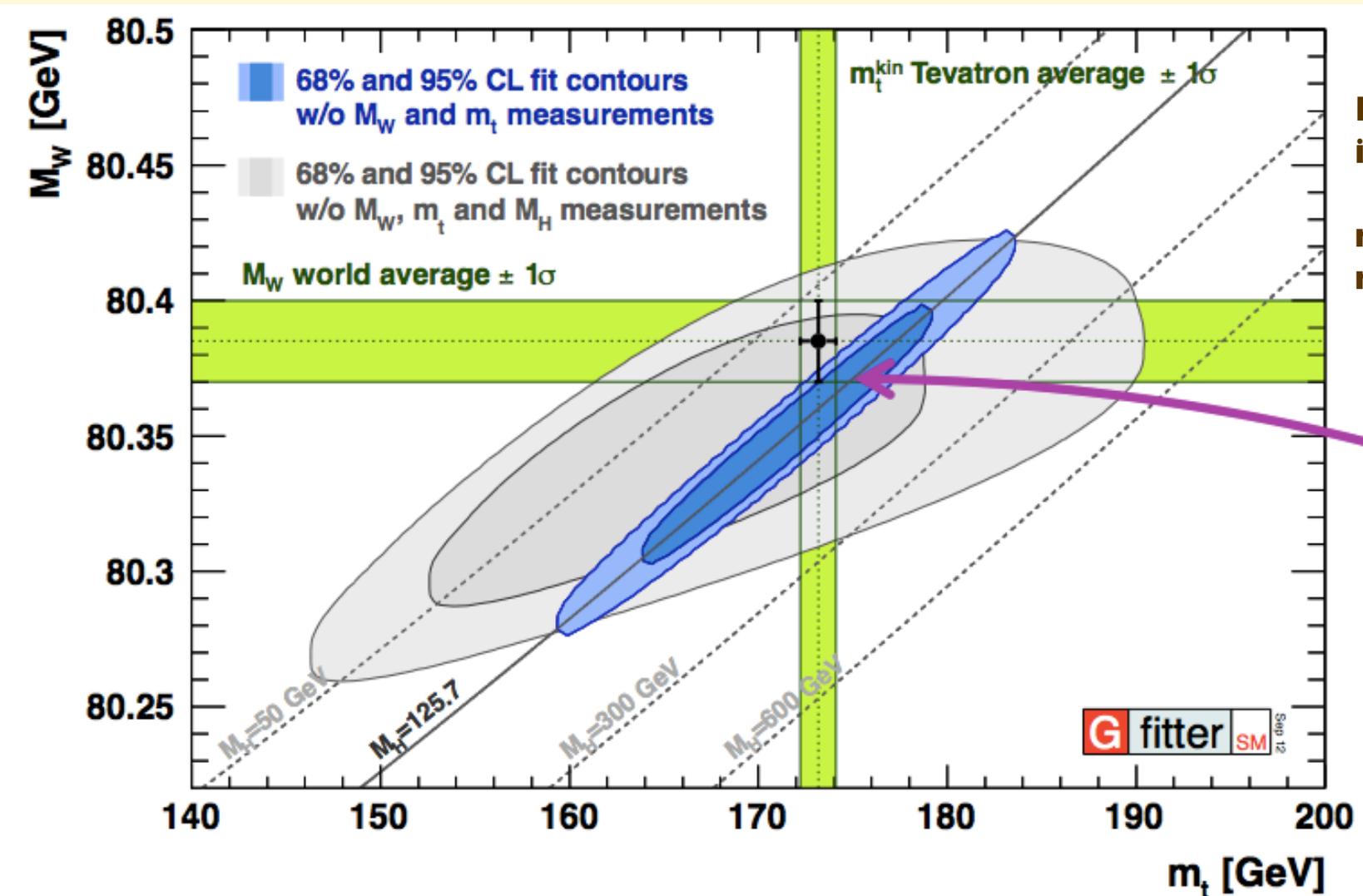
14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

Ratio	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$r^{\text{th,mstw}}$	$\delta_{\text{PDF}}(\%)$	$\Delta^{\text{mstw}}(\%)$	$r^{\text{th,abkm}}$	$\delta_{\text{ABKM}}(\%)$	$\Delta^{\text{abkm}}(\%)$
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
W^-	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
W^+/W^-	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
W/Z	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
ggH	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{t\bar{t}} \geq 1\text{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{t\bar{t}} \geq 2\text{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma_{\text{jet}}(p_T \geq 1\text{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma_{\text{jet}}(p_T \geq 2\text{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of 3-4 σ discrepancies between predictions of different PDF sets, even in the case of W and Z rates

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 ?

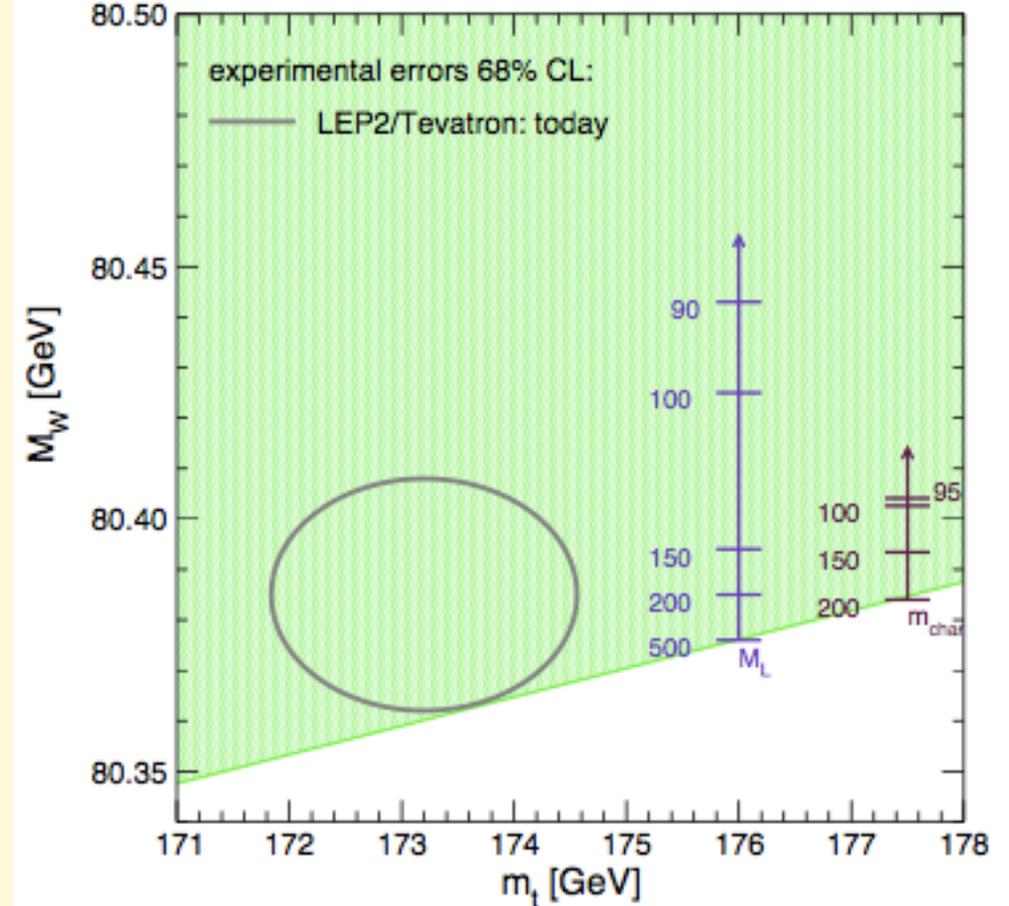
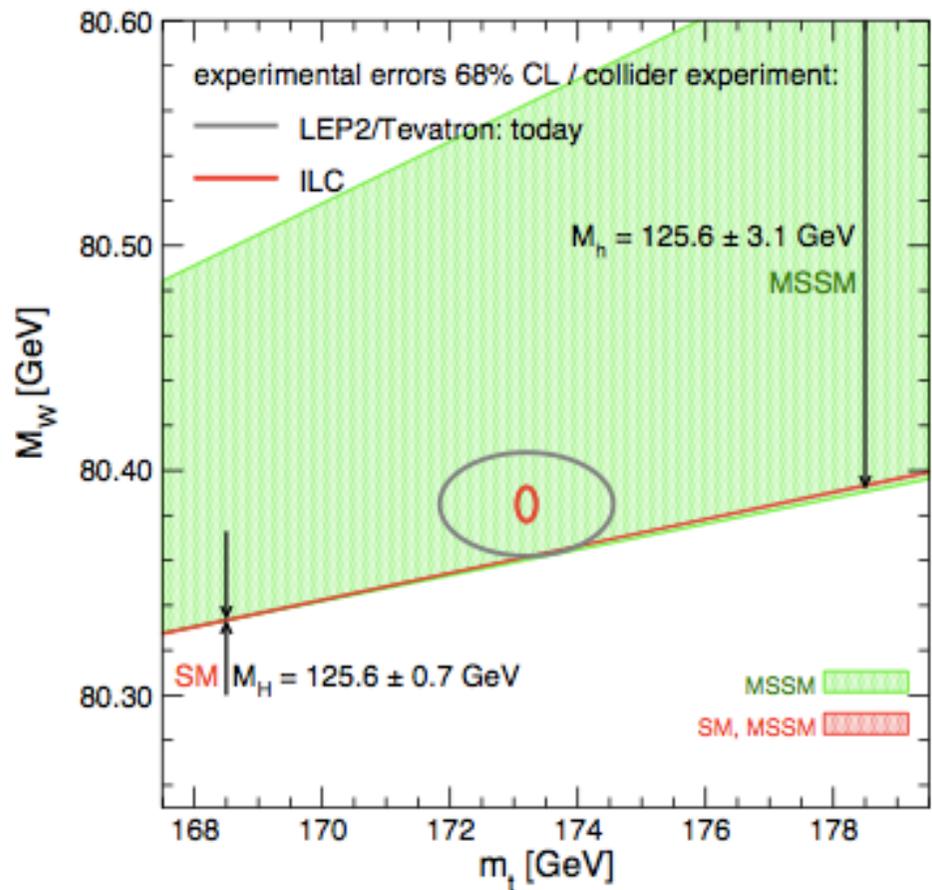


New EW fit results, including m_{Higgs} :

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

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

Tension released in the MSSM:



S.Heinemeyer et al, arXiv:1311.1663v1

Tevatron combined W mass: $M_W = 80387 \pm 16$ MeV

Tevatron+LEP2 combined W mass: $M_W = 80385 \pm 15$ 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

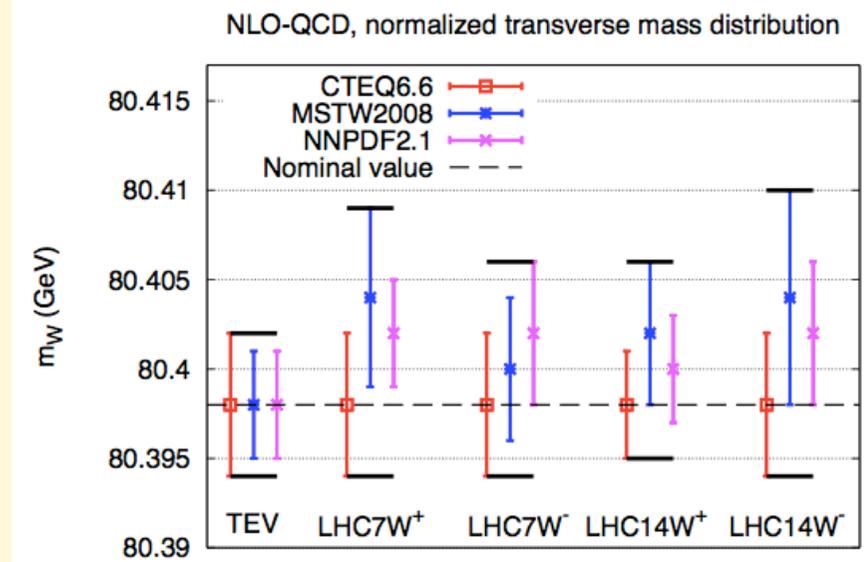
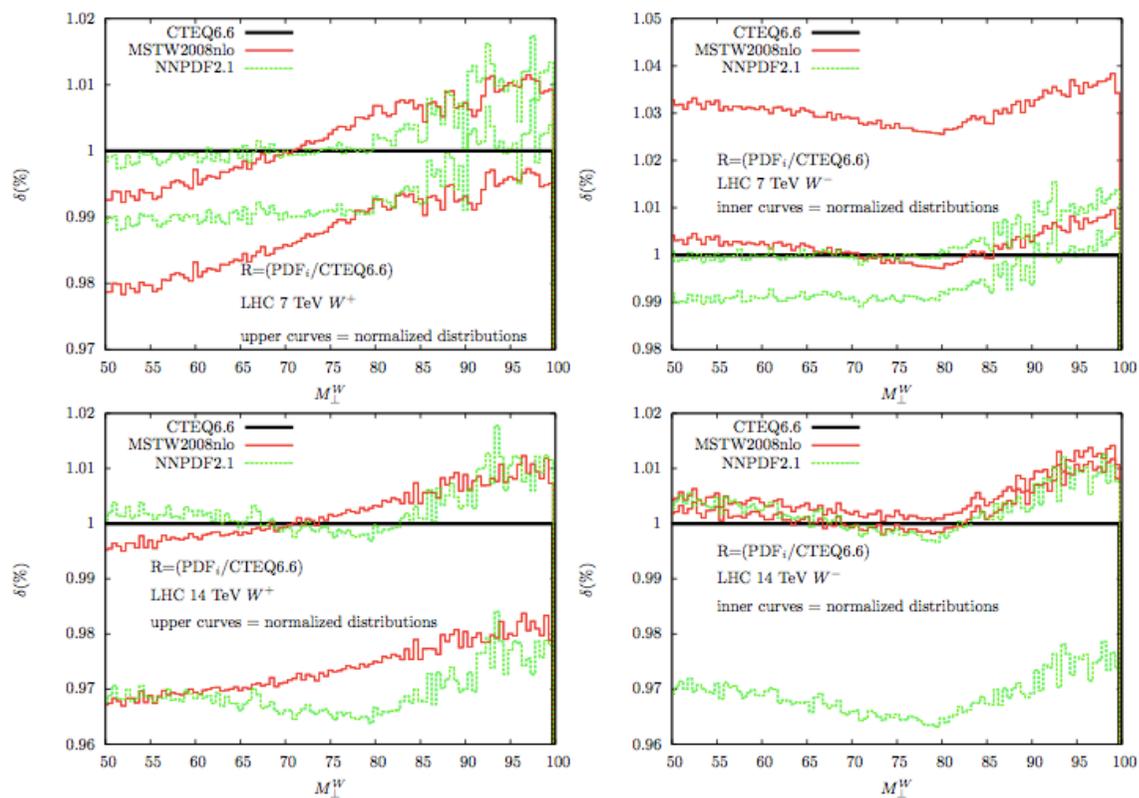
*Largely theory
in origin*

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

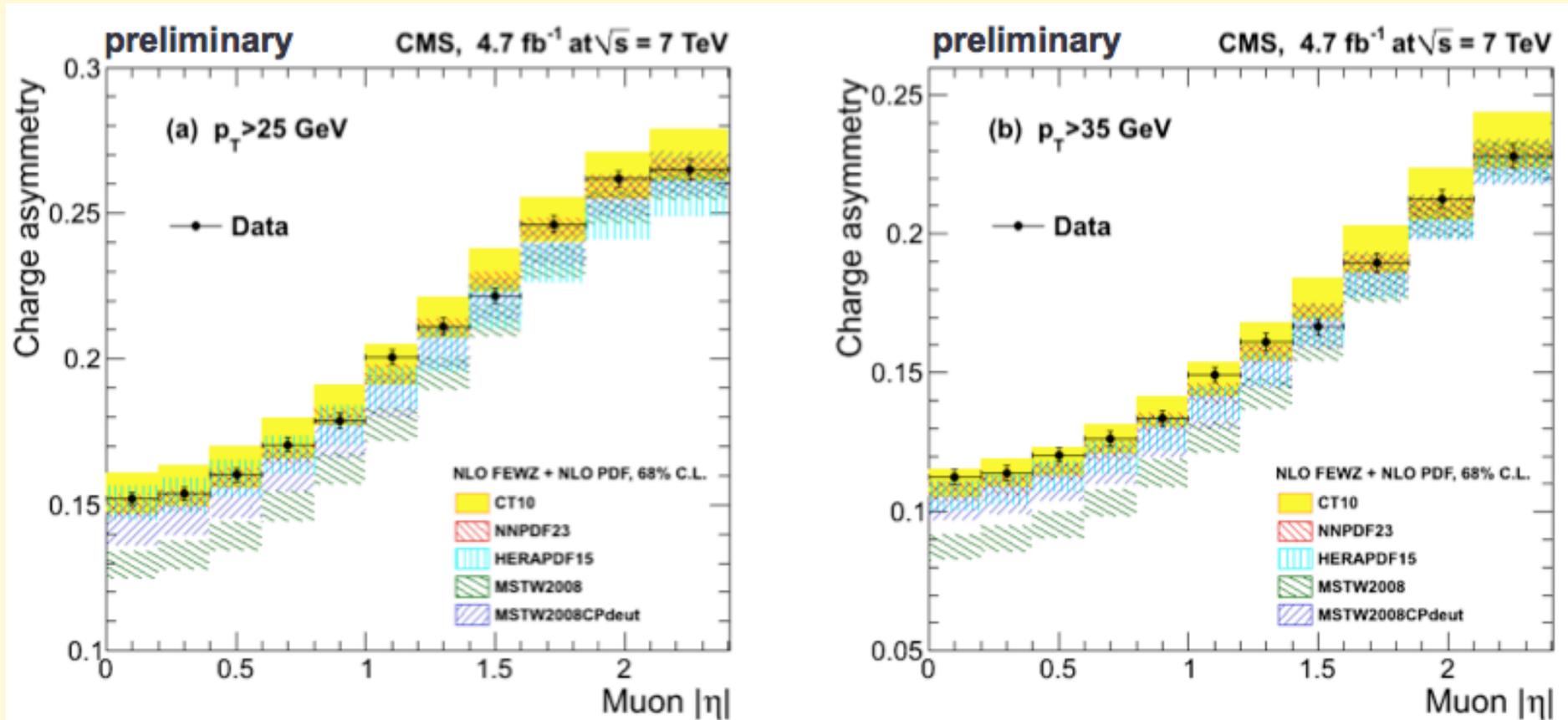


Theory syst:
 $\Delta m_W \approx \pm 8 \text{ MeV}$

- 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 $\pm 20 \text{ MeV}$
- 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. $p_t(e)$)?
- 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 $p_t(Z)$ to model $p_t(W)$)

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

CMS-PAS-SMP-12-021



Questions:

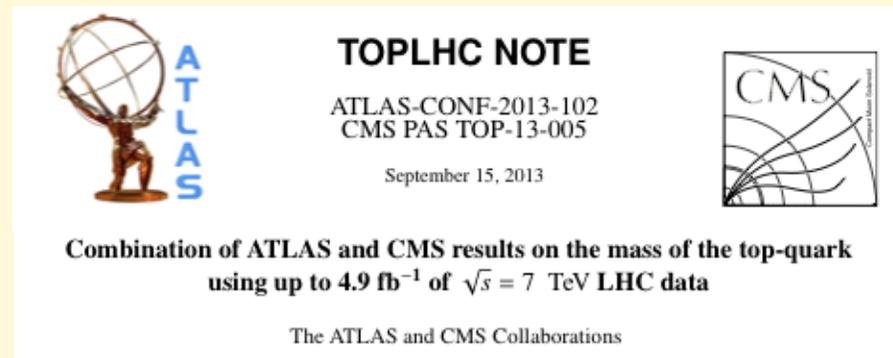
- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements?
- Would this have an impact in the extraction of m_W ?

Top quark mass

Tevatron combination:

$$m_{\text{top}} = 173.20 \pm 0.51 \text{ (stat)} \pm 0.71 \text{ (syst)} = 173.20 \pm 0.87 \text{ GeV}$$

LHC combination:

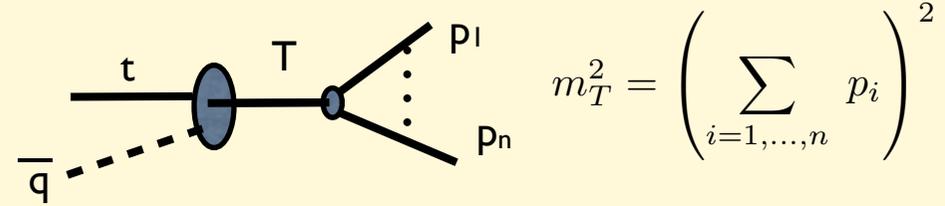


$$m_{\text{top}} = 173.29 \pm 0.23 \text{ (stat)} \pm 0.92 \text{ (syst)} = 173.29 \pm 0.95 \text{ GeV}$$



Definition of m_{top}

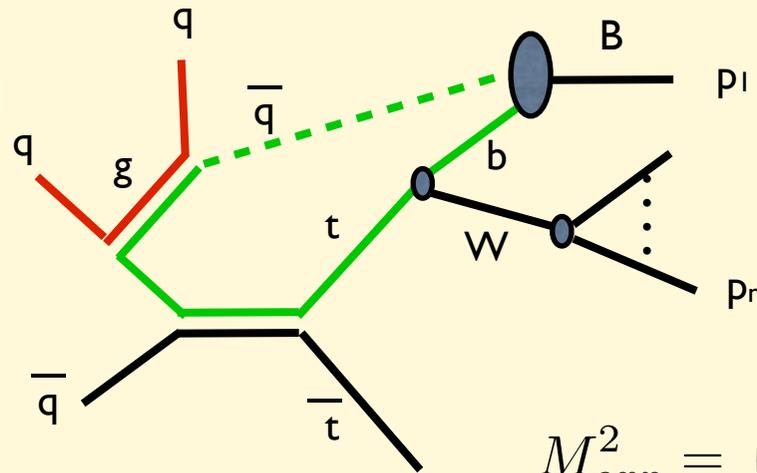
If $\Gamma_{top} < 1 \text{ GeV}$, top would hadronize before decaying. Same as b-quark



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

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

But Γ_{top} is $> 1 \text{ GeV}$, 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



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

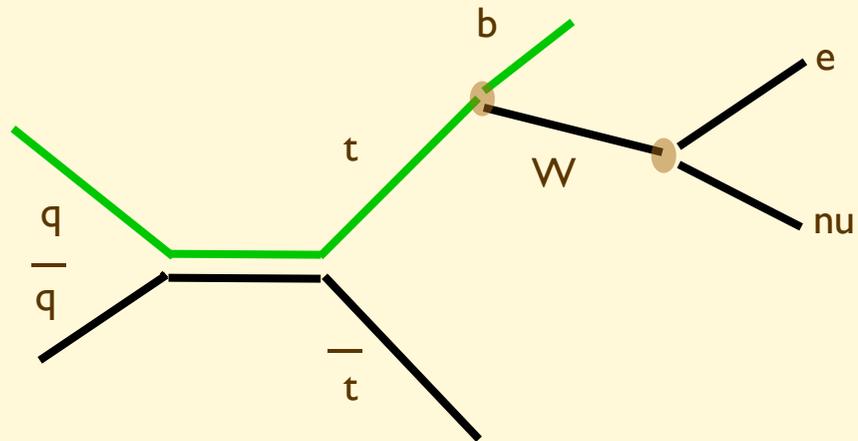
As a result, M_{exp} is not equal to m_{top}^{pole} , and will vary in each event, depending on the way the event has evolved.

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

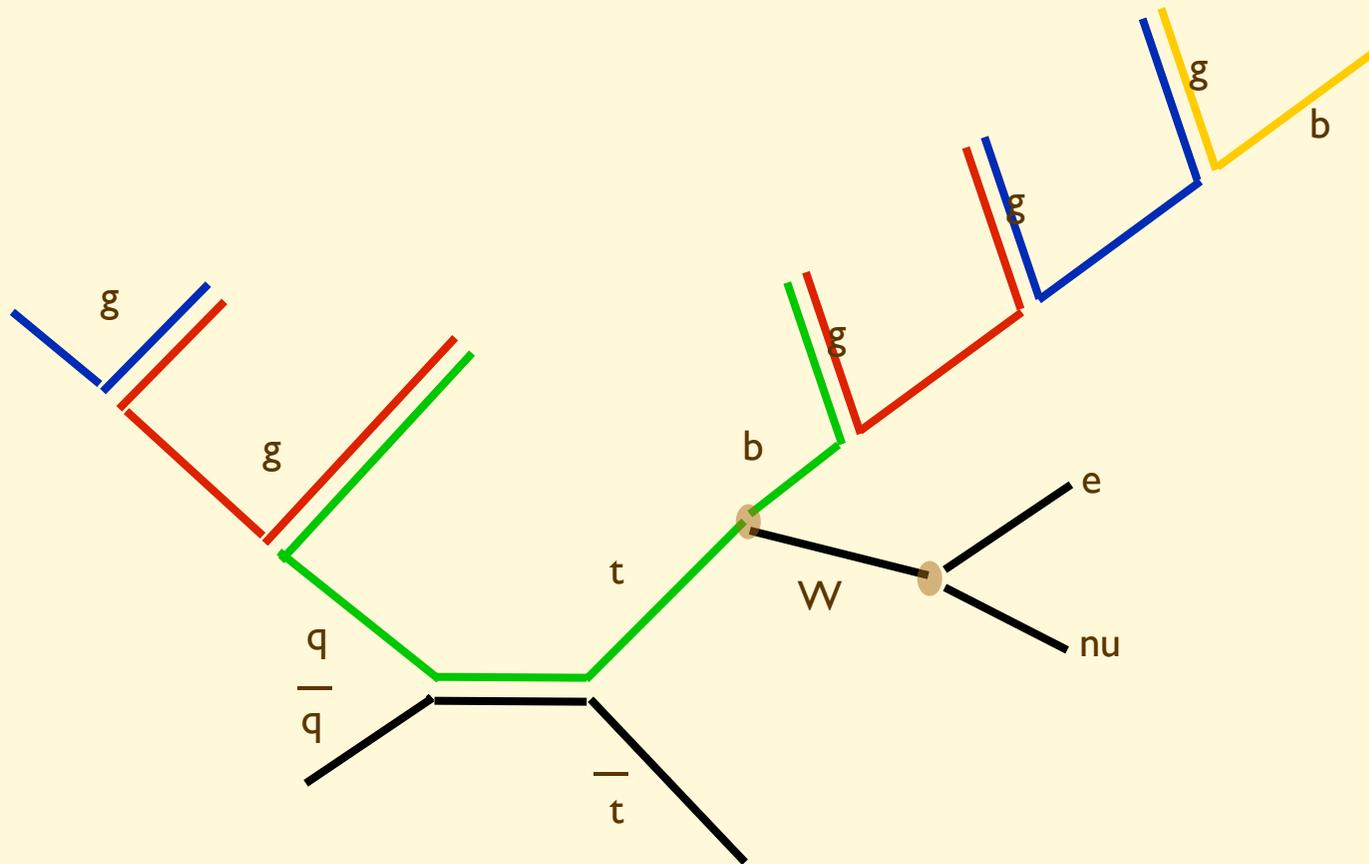
Goal:

- 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

I. Hard Process



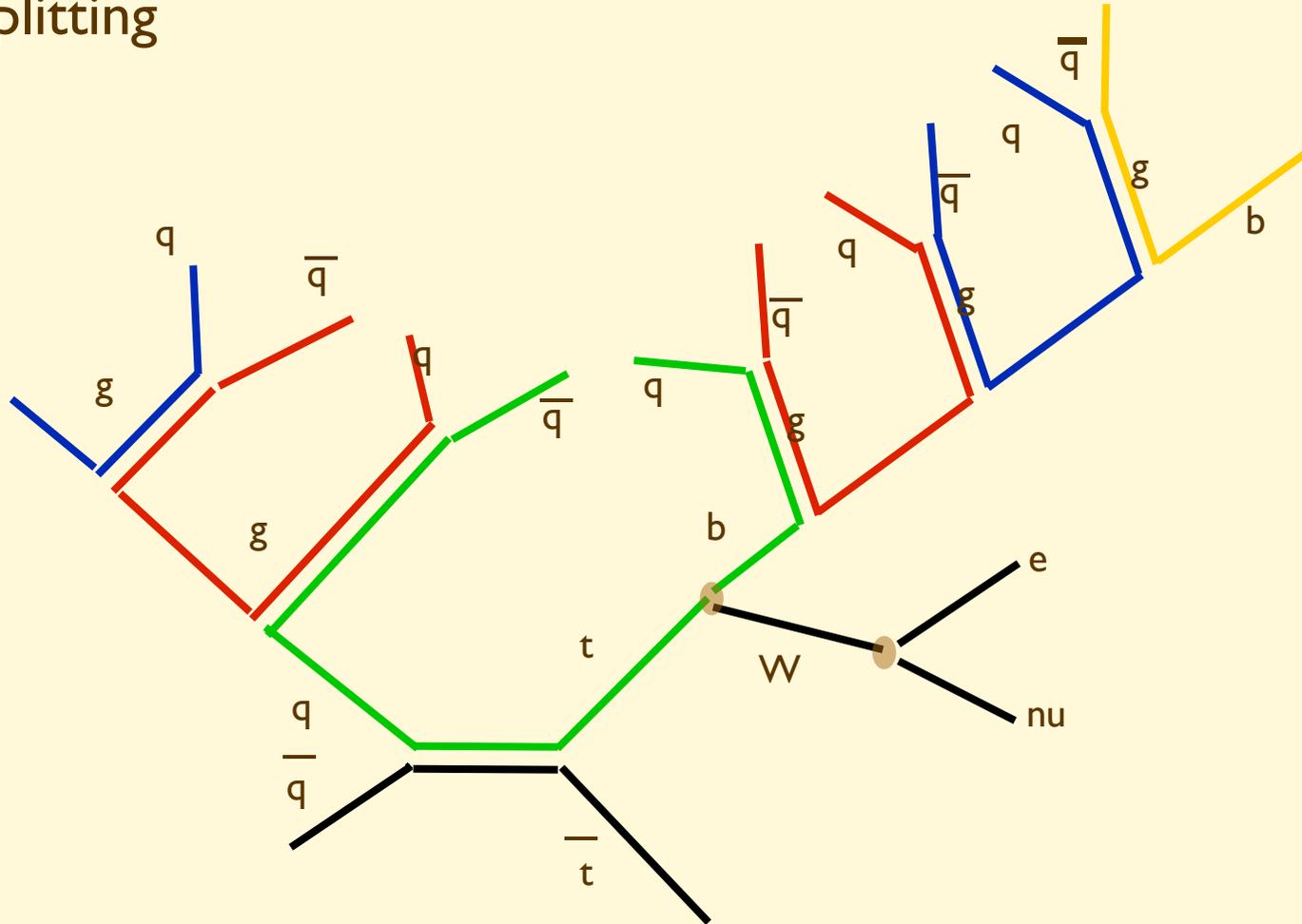
1. Hard Process
2. Shower evolution



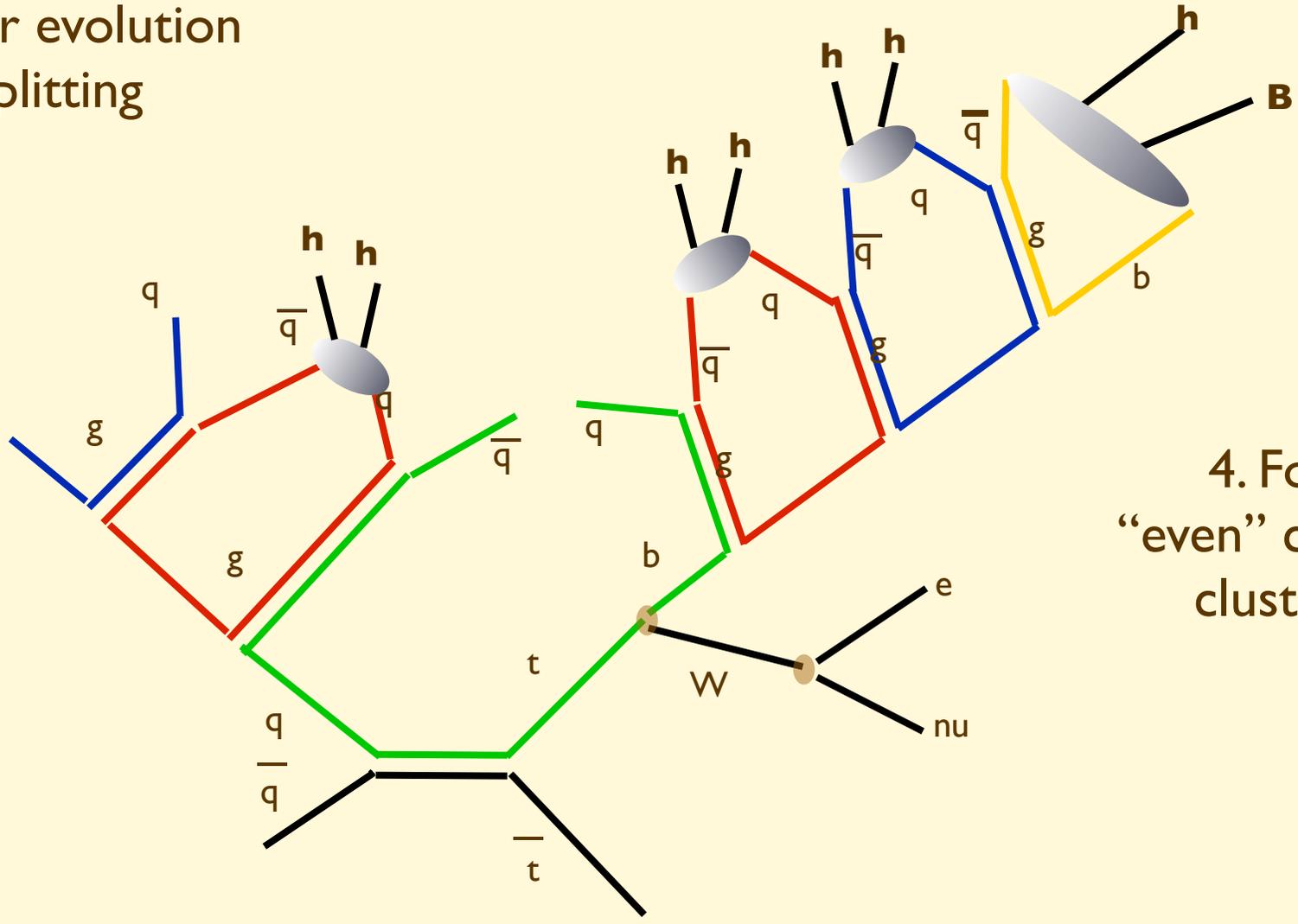
1. Hard Process

2. Shower evolution

3. Gluon splitting

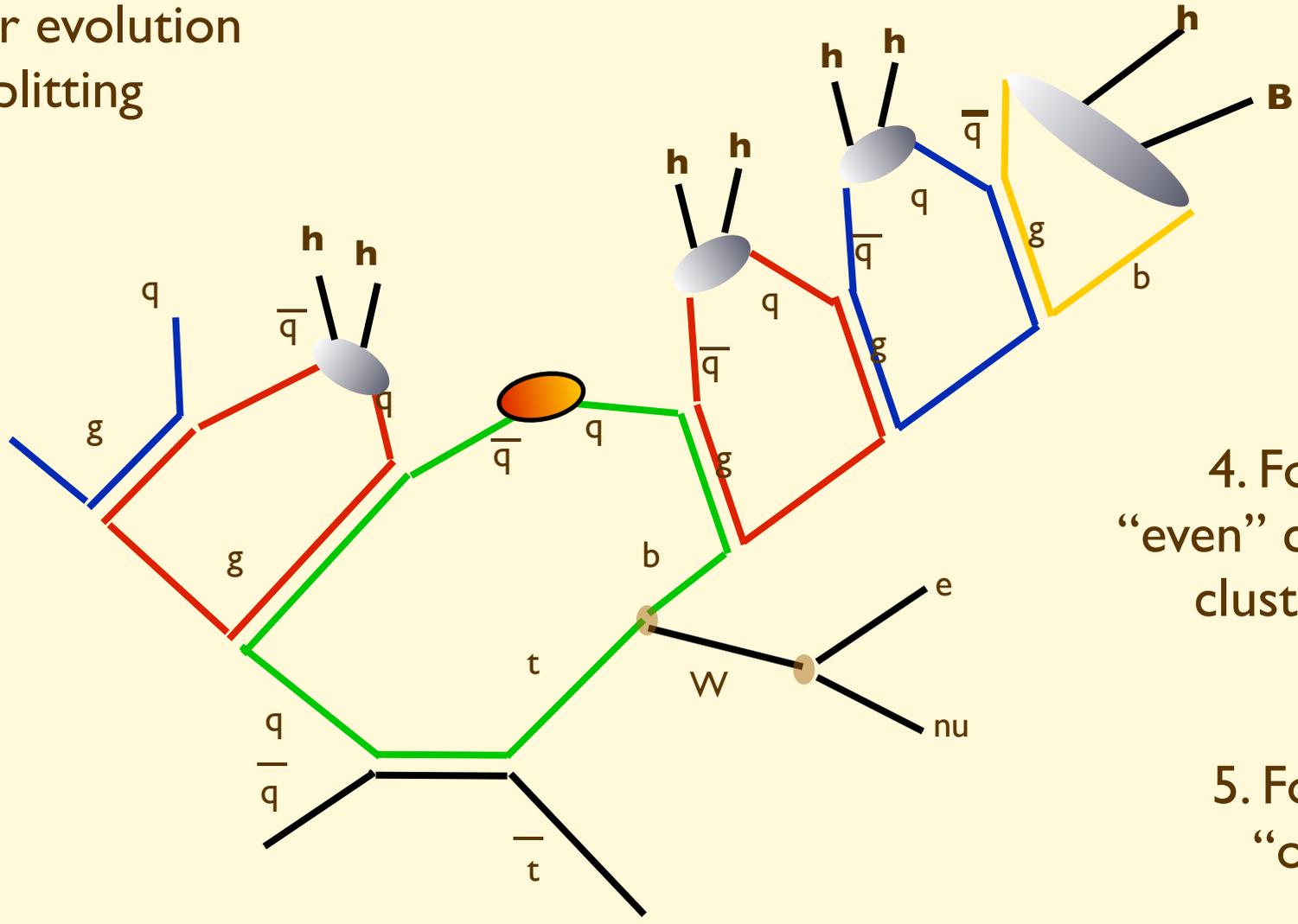


1. Hard Process
2. Shower evolution
3. Gluon splitting



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

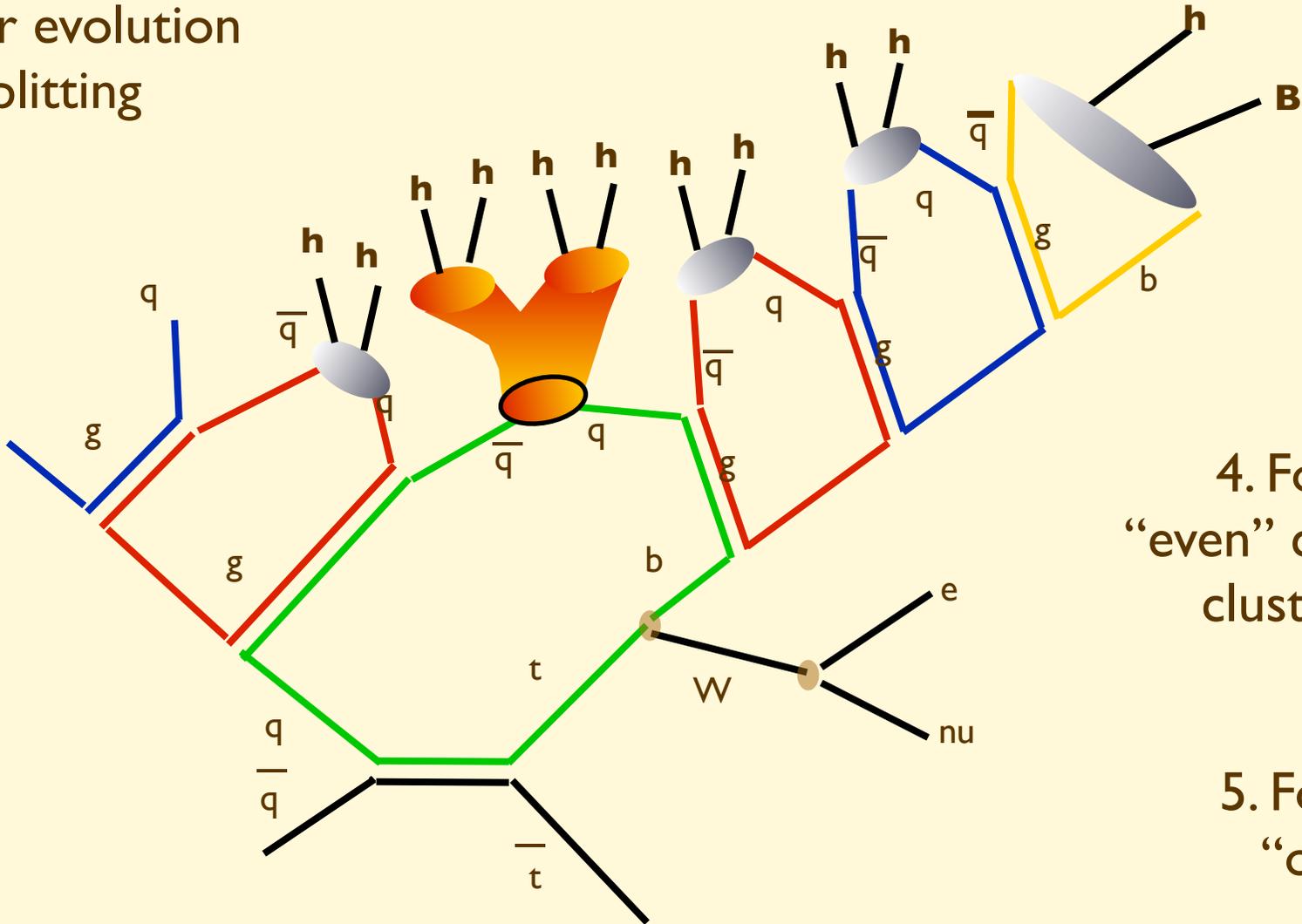
1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of “even” clusters and cluster decay to hadrons

5. Formation of “odd” cluster

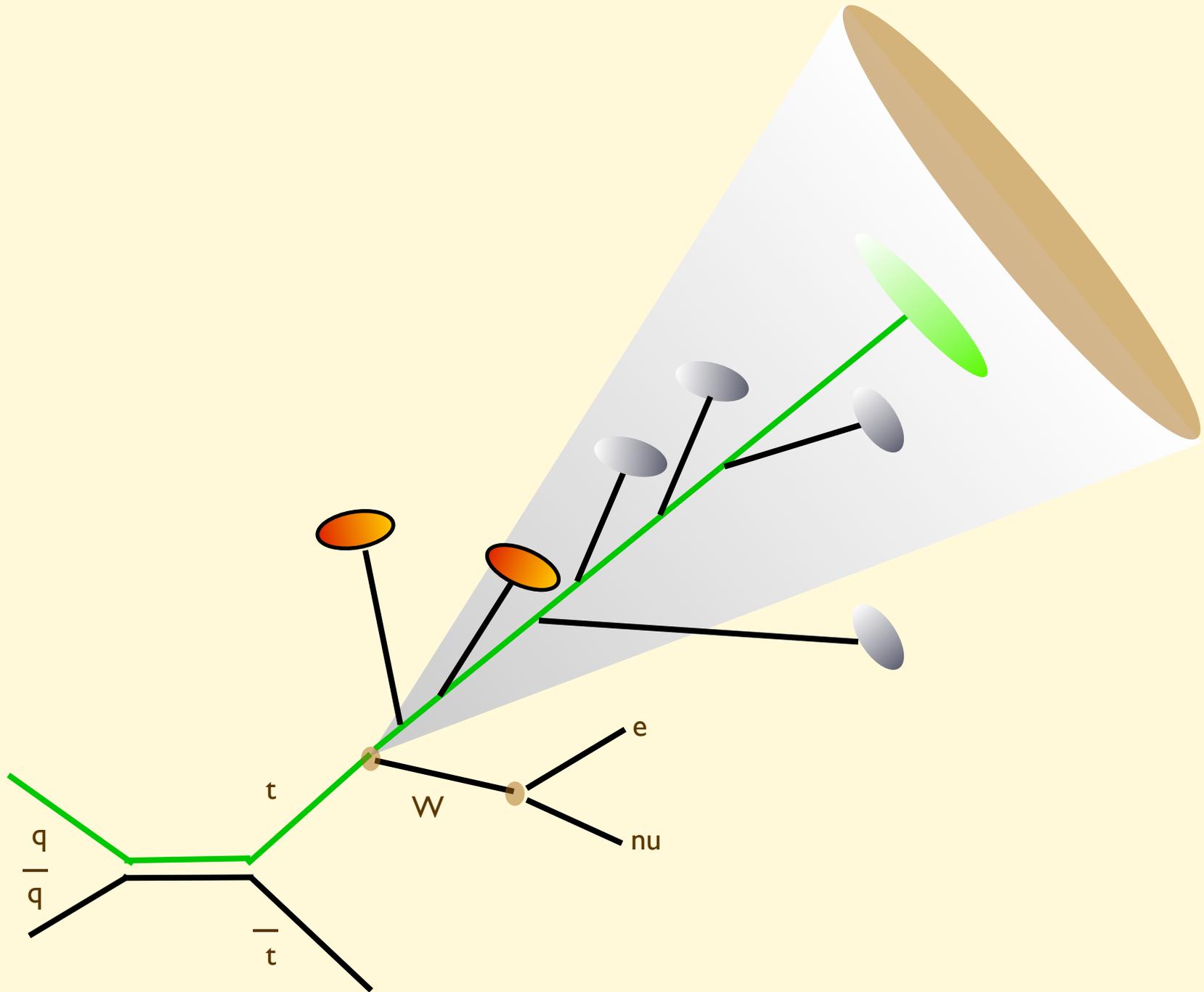
1. Hard Process
2. Shower evolution
3. Gluon splitting



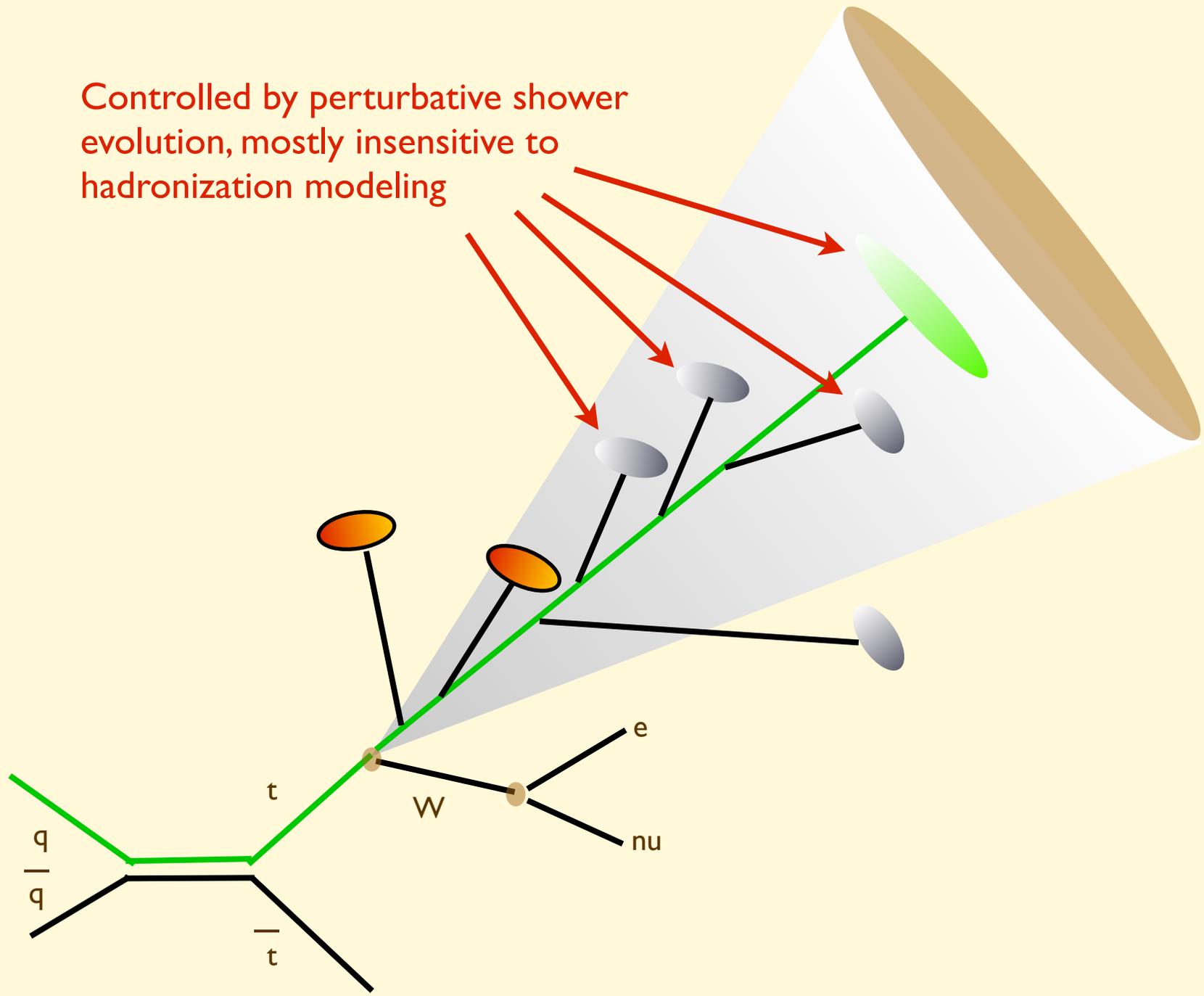
4. Formation of “even” clusters and cluster decay to hadrons

5. Formation of “odd” cluster

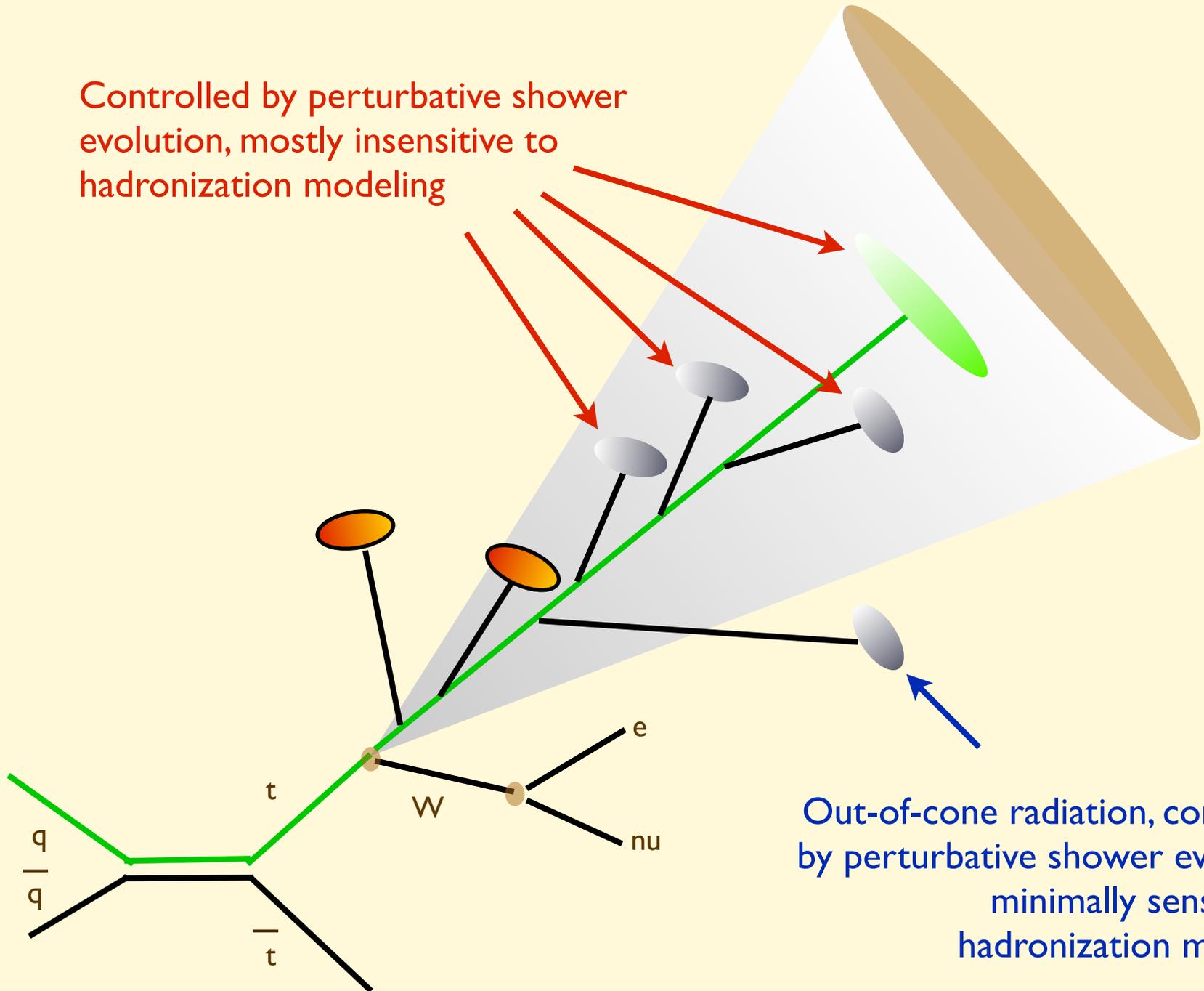
6. Decay of “odd” clusters, if large cluster mass, and decays to hadrons



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling



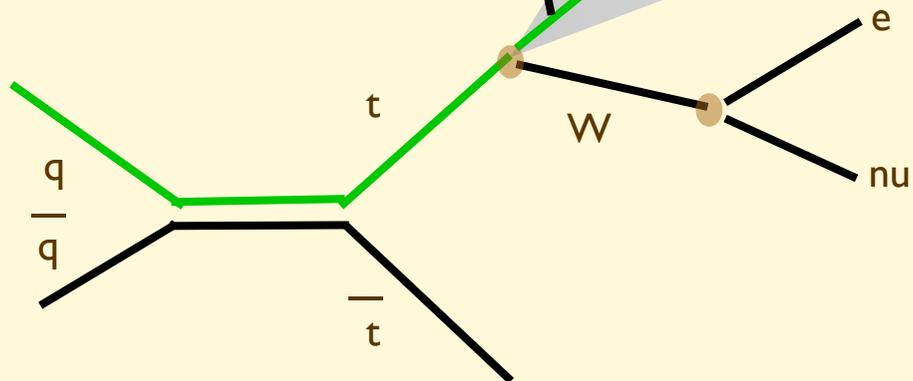
Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling



Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling

Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling

Partly shower evolution, partly color reconnection, ambiguous paternity



Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling

A good way to assess the relevance of these effects and the reliability of the MC modeling is to monitor the dependence of the reconstructed m_{top} on the production environment. E.g.

- m_{top} vs pt

- $pp \rightarrow t \bar{t}$ implies that hadronization of top decay products differs from hadronization of \bar{t} decay products $\Rightarrow m_t$ vs $m_{\bar{t}}$ at the LHC

probes possible hadronization systematics

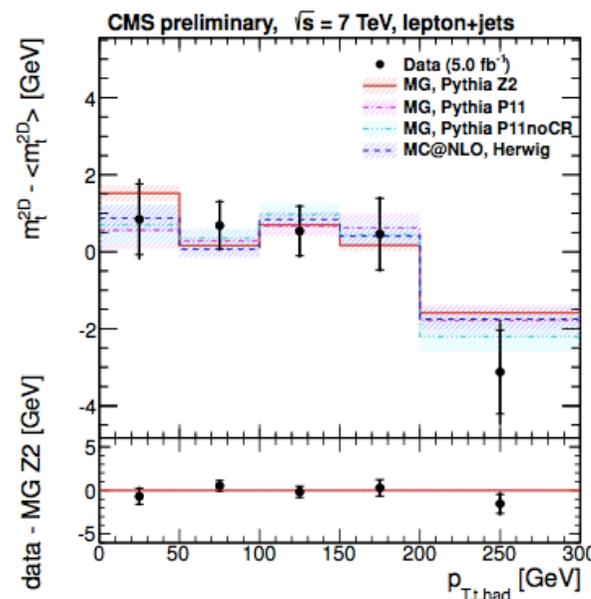
- $q \bar{q} \rightarrow t \bar{t}$ vs $gg \rightarrow t \bar{t} \Rightarrow m_{\text{top}}(\text{Tevatron})$ vs $m_{\text{top}}(\text{LHC})$ is a probe of hadronization systematics

- ditto for m_{top} from single top events

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t, \text{had}}$
	4	$ \eta_{t, \text{had}} $
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
b-quark kin.	8	Jet multiplicity
	9	$p_{T,b, \text{had}}$
	10	$ \eta_{b, \text{had}} $
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



- First top mass measurement binned in kinematic observables.
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
 - ◆ color reconnection, ISR/FSR, b-quark kinematics, difference between pole or $\overline{\text{MS}}$ masses.

10

CMS-PAS-TOP-12-031

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

52

Pole vs MSbar masses

$$m_{pole} = \bar{m} \times \left[1 + g_1 \frac{\bar{\alpha}}{\pi} + g_2 \left(\frac{\bar{\alpha}}{\pi} \right)^2 + g_3 \left(\frac{\bar{\alpha}}{\pi} \right)^3 \right] \quad \text{where}$$

Melnikov, van Ritbergen, Phys.Lett. B482 (2000) 99

$$\bar{m} = m_{MS}(m_{MS})$$

$$\bar{\alpha} = \alpha(\bar{m})$$

$$g_1 = \frac{4}{3}$$

$$g_2 = 13.4434 - 1.0414 \sum_k \left(1 - \frac{4}{3} \frac{\bar{m}_k}{\bar{m}} \right)$$

$$g_3 = 0.6527 n_l^2 - 26.655 n_l + 190.595$$

In the range $m_{top} = 171 - 175$ GeV, α_s is \sim constant, and, using the 3-loop expression above,

$$m_{pole} = \bar{m} \times [1 + 0.047 + 0.010 + 0.003] = 1.060 \times \bar{m}$$

showing an excellent convergence. In comparison, the expansion for the bottom quark mass behaves very poorly:

$$m_{pole}^b = \bar{m}^b \times [1 + 0.09 + 0.05 + 0.04]$$

Assuming that after the 3rd order the perturbative expansion of m_{pole} vs m_{MS} start diverging, the smallest term of the series, which gives the size of the uncertainty in the resummation of the asymptotic series, is of $O(0.003 * m)$, namely $O(500 \text{ MeV})$, consistent with Λ_{QCD}

This same $O(\alpha_s^3)$ term gives also: $\bar{m}^{(3-loop)} - \bar{m}^{(2-loop)} = 0.49 \text{ GeV}$

Meson vs heavy-Q masses

Heavy meson \Rightarrow (point-like color source) + (light antiquark cloud): properties of “light-quark” cloud are independent of m_Q for $m_Q \rightarrow \infty$

$$m_M = m_Q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_Q}$$

$$m_{M^*} = m_Q + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_Q}$$

where $\bar{\Lambda}$, λ_1 , λ_2 are independent of m_Q

$$\begin{aligned} \langle M | \bar{h}_Q (iD)^2 h_Q | M \rangle &= -\lambda_1 \text{tr}\{ \bar{\mathcal{M}} \mathcal{M} \} = 2M \lambda_1, \\ \langle M | \bar{h}_Q s_{\alpha\beta} G^{\alpha\beta} h_Q | M \rangle &= -\lambda_2(\mu) \text{tr}\{ i\sigma_{\alpha\beta} \bar{\mathcal{M}} s^{\alpha\beta} \mathcal{M} \} = 2d_M M \lambda_2(\mu), \end{aligned}$$

$$d_{M^*} = -1, \quad d_M = 3$$

See e.g. Falk and Neubert, arXiv:hep-ph/9209268v1

From the spectroscopy of the B-meson system:

$$m(B^*) - m(B) = 2 \lambda_2/m_b \Rightarrow \lambda_2 \sim 0.15 \text{ GeV}^2$$

$$\text{QCD sum rules: } \lambda_1 \sim 1 \text{ GeV}^2$$

$$\text{QCD sum rules: } \Lambda = 0.5 \pm 0.07 \text{ GeV}$$

thus corrections of $O(\lambda_{1,2}/m_{\text{top}})$ are of $O(\text{few MeV})$ and totally negligible

Separation between m_Q and Λ is however ambiguous:
renormalon ambiguity on the pole mass:

$$\begin{aligned}\delta m_{pole} &= \frac{C_F}{2N_f|\beta_0|} e^{-C/2} m(\mu = m) \exp\left(\frac{1}{2N_f\beta_0\alpha(m)}\right) \\ &= \frac{C_F}{2N_f|\beta_0|} e^{-C/2} \Lambda_{QCD} \left(\ln \frac{m^2}{\Lambda_{QCD}^2}\right)^{\beta_1/(2\beta_0^2)},\end{aligned}$$

where $\beta_1 = -1/(4\pi N_f)^2 \times (102 - 38N_f/3)$ is the second coefficient of the β -function

$\delta m_{pole} = 270$ MeV for m_{top} .

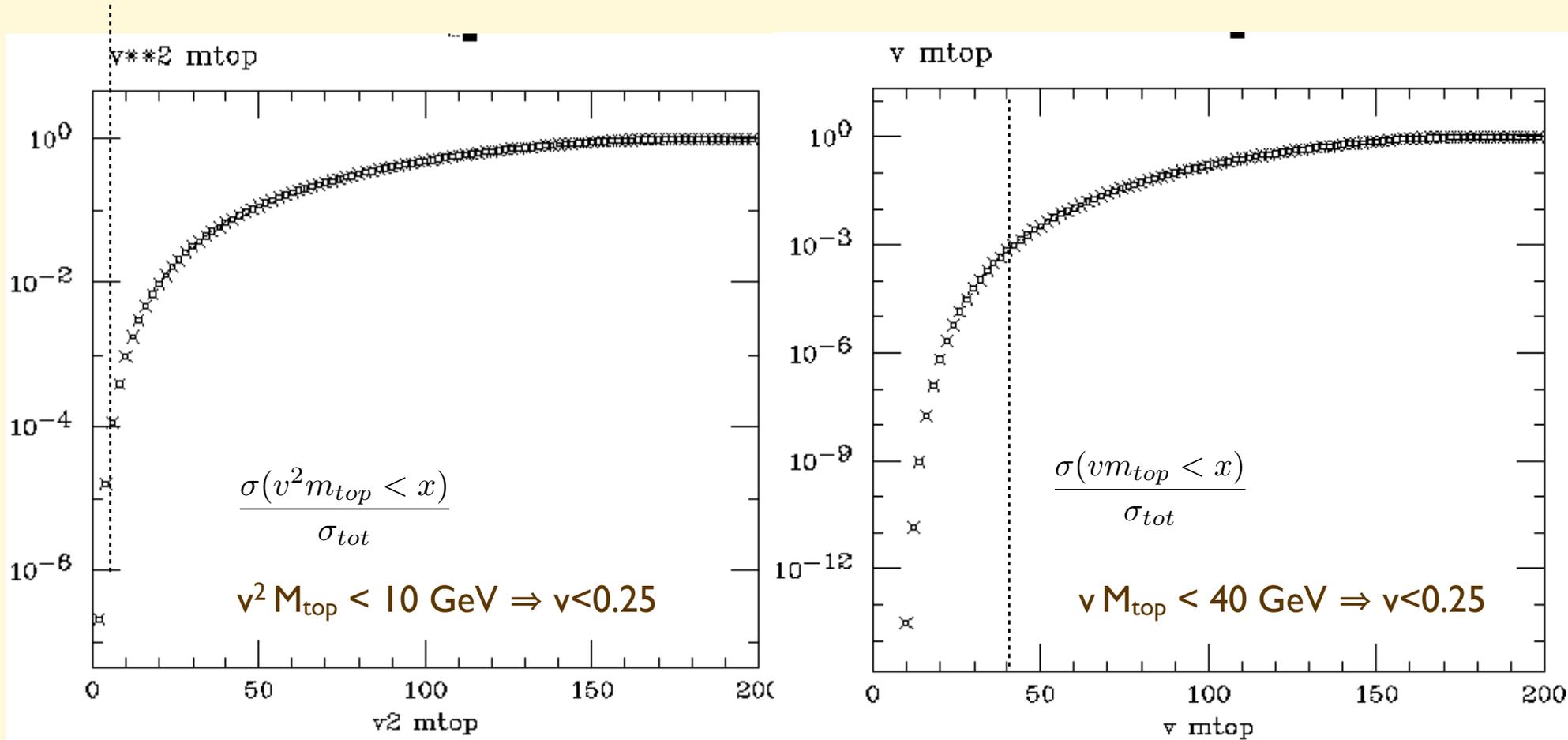
This is smaller than the difference between MSbar masses obtained using the 3-loop or 2-loop MSbar vs pole mass conversion.

It would be very interesting to have a 4-loop calculation of MSbar vs m_{pole} , to check the rate of convergence of the series, and improve the estimate of the m_{pole} ambiguity for the top

Beneke and Braun, Nucl. Phys. B426, 301 (1994)

Bigi et al, 1994

Impact of IR sensitive phase-space regions on $\sigma(tt)$

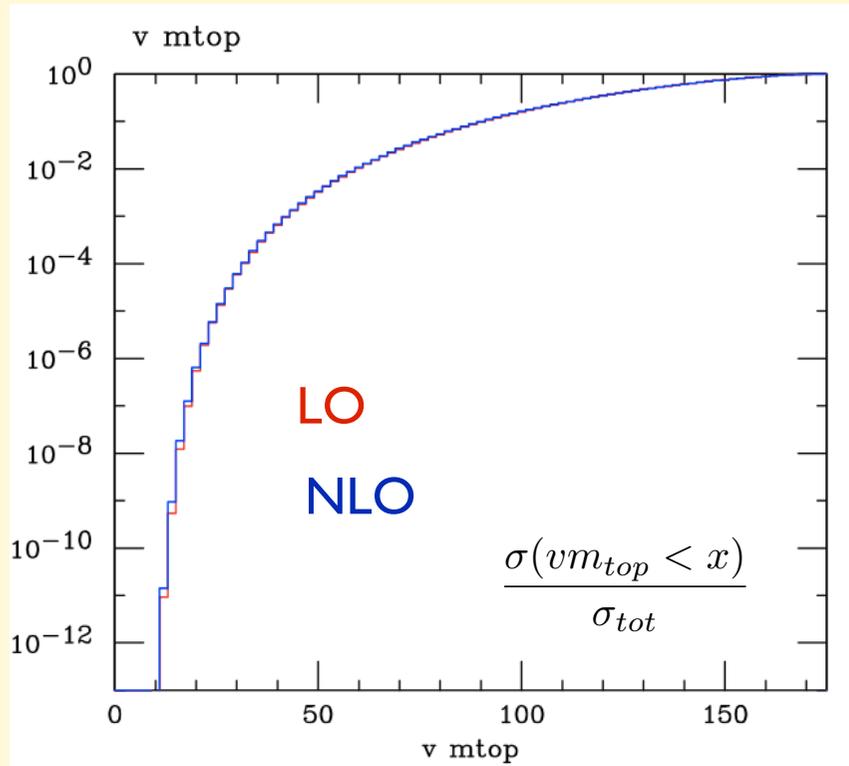


$$\frac{1}{\sigma} \frac{\Delta\sigma}{\Delta m} \sim 0.03 \text{ GeV}^{-1}$$

$$v^2 M_{top} < 10 \text{ GeV}$$

The region possibly sensitive to IR effects, $v^2 M_{top} < 10 \text{ GeV}$, or $v < 0.25$, contributes only 10^{-3} of the total rate.

Uncertainties of the order of 100% in the description of this region only change the extraction of M_{top} from the total rate at the level of 30 MeV



The impact of Coulomb corrections (which first appear at NLO) is confined to values of v that contribute very little to the total cross section

\Rightarrow no evidence that the relation between $m_{pole}(top)$ and total tt cross section in $pp(\bar{p})$ collisions is subject to the same IR problems that enter as main systematics in the extraction of m_{top} from the threshold scan in e^+e^-

All in all I believe that it is correct to assume that MC mass parameter is interpreted as m_{pole} .

We are left with the ambiguity intrinsic in the definition of m_{pole} , thus at the level of $\sim 250\text{-}500$ MeV (uncertainty to be reduced by a future $\mathcal{O}(\alpha_s^4)$ calculation of m_{pole} vs m_{MS}

$B_s \rightarrow \mu^+ \mu^-$

(LHCb+CMS) : $B(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

Intrinsic TH uncertainty **below 1%**, after recent calculation of 3-loop NNLO QCD and 2-loop NLO EW effects:

arXiv:1311.0903v2

FLAVOUR(267104)-ERC-53, LTH 990,
SFB/PPP-13-82, TTP13-033

$B_{s,d} \rightarrow \ell^+ \ell^-$ in the Standard Model

Christoph Bobeth,¹ Martin Gorbahn,^{2,1} Thomas Hermann,³
Mikołaj Misiak,^{4,5} Emmanuel Stamou,^{1,6} and Matthias Steinhauser³

Uncertainty dominated by f_{B_s} (lattice)

⇒ November 2013:

(Theory) : $B(B_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

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- **The Higgs is there ... but where is everyone else ??**

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- These improvements will come not only from progress in theoretical calculations, but will need to rely on a robust programme of experimental validation
- SM measurements are thus a flagship component of the LHC physics, and in particular a crucial and indispensable part of a successful BSM programme.