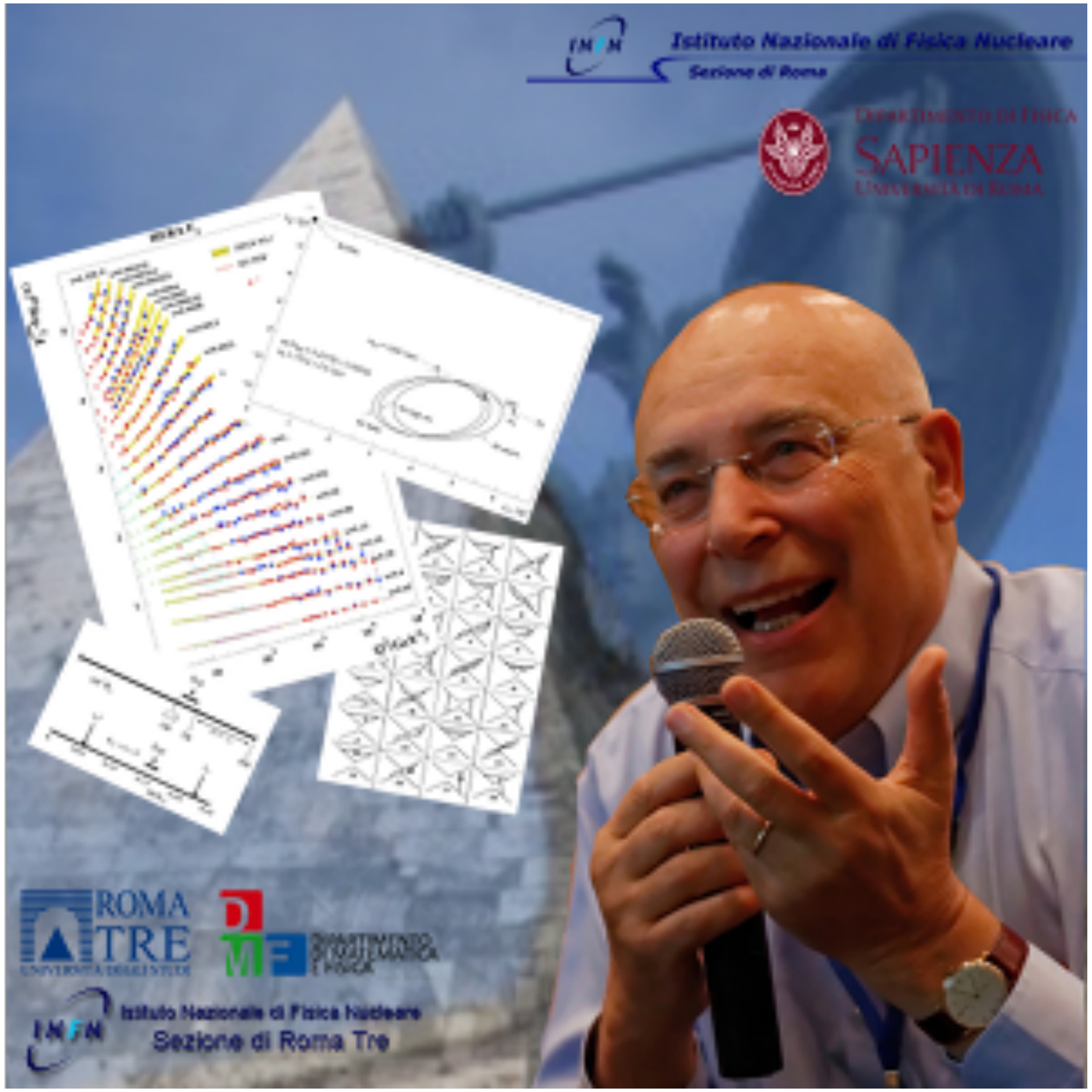
The many roles of QCD in the exploration of fundamental interactions



Michelangelo L. Mangano
CERN, Theory Department
19 December, 2016

European Research Council

Foreward

- The **known** fundamental particles and interactions play a double role

  1. they are objects of study, to measure their properties, to test our understanding of the dynamics, and to test the compatibility with existing predictions
  2. they are tools for the discovery of the **unknown**

- The depth of knowledge we can acquire from (1) defines the strength and power of these tools to accomplish (2)

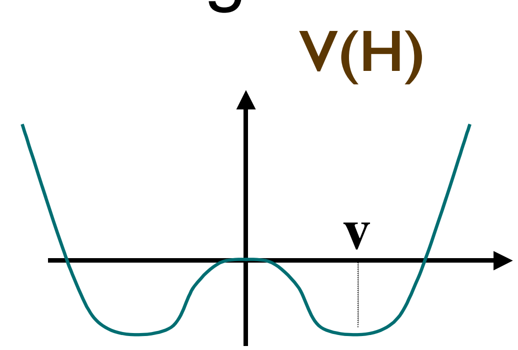
EW interactions hold the secret of the most puzzling aspects of the SM: ***symmetry breaking*** and ***flavour***

$$\mathcal{L}_{EW} = -\frac{1}{4g^2} W_a^{\mu\nu} W^a_{\mu\nu} - \frac{1}{4g'^2} B^{\mu\nu} B_{\mu\nu} + i \sum_F \bar{F}\, \gamma_\mu D^\mu\, F + |D_\mu H|^2$$

$$- \boxed{V(H)} - \boxed{Y_u^{ij}}\, \bar{Q}_i H^*\, u_j^c - \boxed{Y_d^{ij}}\, \bar{Q}_i H\, d_j^c - \boxed{Y_\ell^{ij}}\, \bar{L}_i H\, \ell_j^c$$

who ordered those ?? *the answer is worth a Nobel prize ….*

Given the EW lagrangian, however, the study of its dynamics is "straightforward".
In particular, finding the ground state is a high-school exercise:



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

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

QCD, in comparison, is conceptually rather dull:

$$\mathcal{L}_{QCD} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{\mu\nu}_a + i \sum_f \bar{q}_f \, D_\mu \gamma^\mu \, q_f$$

Its perturbative dynamics is controlled by the scale evolution of the coupling

$$\frac{\partial \alpha_s(\mu^2)}{\partial \log \mu^2} = \beta(\alpha_s) \qquad \alpha_s = \frac{g^2}{4\pi}$$

$$\langle (gG)^2 \rangle \stackrel{\text{def}}{=} \langle g^2 G_{\mu\nu} G^{\mu\nu} \rangle \simeq 0.5 \text{ GeV}^4$$

$$\langle \bar{\psi}\psi \rangle \simeq (-0.23)^3 \text{ GeV}^3$$

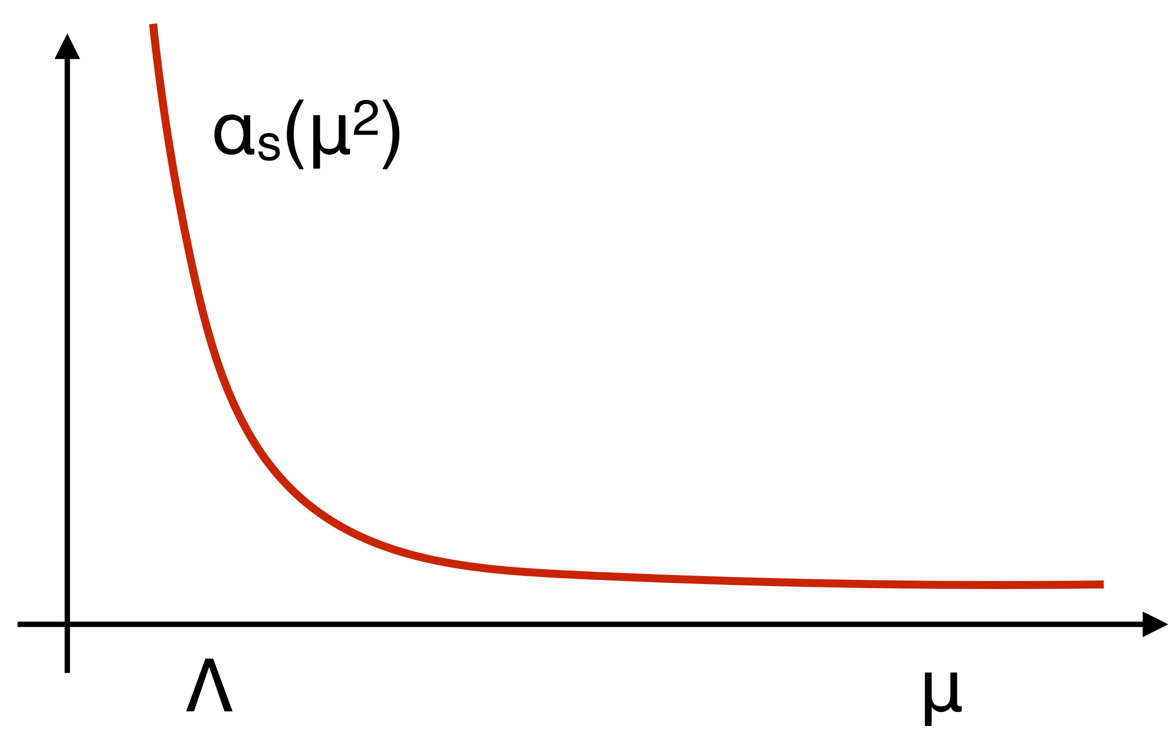
$$\langle (gG)^4 \rangle \simeq 5:10 \langle (gG)^2 \rangle^2$$

At the lowest order,

$$\beta(\alpha_s) = -b_0 \alpha_s^2 \quad , \quad b_0 = \frac{33 - 2n_f}{12\pi}$$

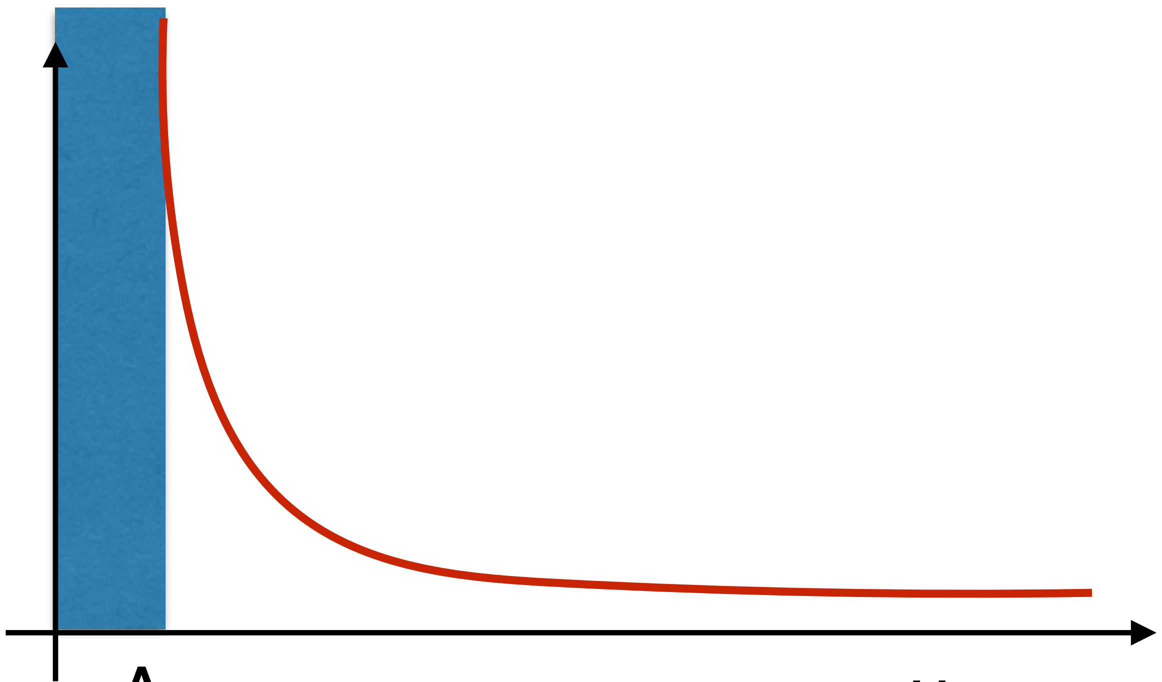
and

$$\alpha_s(\mu^2) = \frac{1}{b_0 \, \log(\mu^2/\Lambda^2)}$$



See G.Altarelli,
http://pos.sissa.it/archive/conferences/177/002/Corfu2012_002.pdf

The problem is that the “real” world sits in the deep infrared, at μ < Λ !!



The identification of the QCD **vacuum state** and the formal proof of its properties (mass gap, confinement, chiral symmetry breaking) is one of the outstanding “millennium” problems, worth a Nobel prize (and loads of money from the Clay foundation* ….)

* http://www.claymath.org/sites/default/files/yangmills.pdf

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What makes QCD highly non-trivial, therefore, is the challenge (intellectual and technical) to develop frameworks that allow up to make quantitative, and precise, predictions for hadronic phenomena, in spite of our limited control from first principles of the vacuum and the spectrum

QCD in the non-PT regime: phenomenological issues interesting "per se"

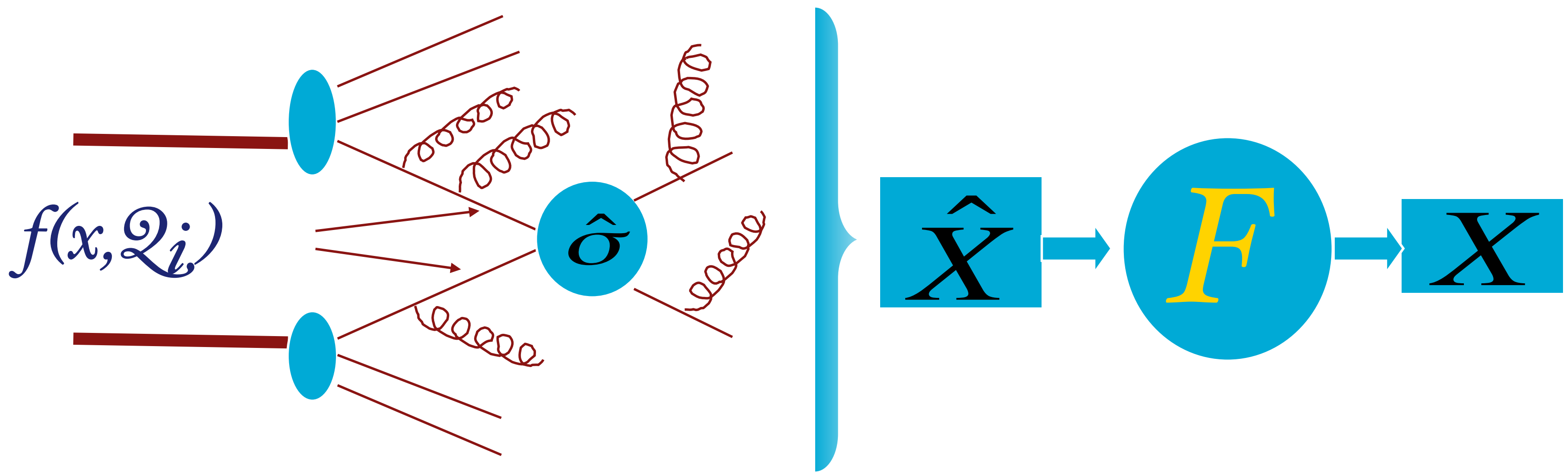
- Issues that used to be classified as "chemistry", have become exciting fields of research, addressed also using powerful theoretical frameworks such as AdS/CFT or supersymmetry
- They may not be relevant for applications of QCD as a tool to explore the puzzles of the SM, but testify to the richness of the dynamics emerging from QCD
- Examples:
  - Exotic states in the hadronic spectrum: tetra- and pentaquarks, glueballs, …
  - The phase diagram at finite density and temperature: deconfinement, the quark-gluon plasma, strange matter, the equation of state of neutron stars, …
  - …

QCD in the non-PT regime: role in the exploration of the SM and its limits

- Quark flavour physics: extraction of CKM parameters and CP violation, rare decays and FCNC transitions, heavy meson decay dynamics, etc etc: crucial role of non-PT QCD => lattice QCD, HQET, sum rules, …
- $(g-2)_\mu$: role of light hadrons in the evolution of α_{QED}, light-by-light scattering
- Measurement of α_s and its evolution from
  - hadronic τ decays
  - quarkonium spectroscopy
  - jet shapes in $e^+e^- \to$ hadrons
- LHC physics => proton structure
- …

Factorization in hadronic collisions

$$\frac{d\sigma}{dX} = \sum_{j,k}\int_{\hat{X}} f_j(x_1,Q_i)\, f_k(x_2,Q_i)\, \frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}}\, F(\hat{X}\to X;Q_i,Q_f)$$



$f_j(x,Q)$ Parton distribution functions (PDF)

- sum over all initial state histories leading, at the scale Q, to:

$$\vec{p}_j = x\,\vec{P}_{proton}$$

$F(\hat{X}\to X;Q_i,Q_f)$

- transition from partonic final state to the hadronic observable (hadronization, fragm. function, jet definition, etc)
- Sum over all histories with *X* in them

Universality of parton densities and factorization, an intuitive picture

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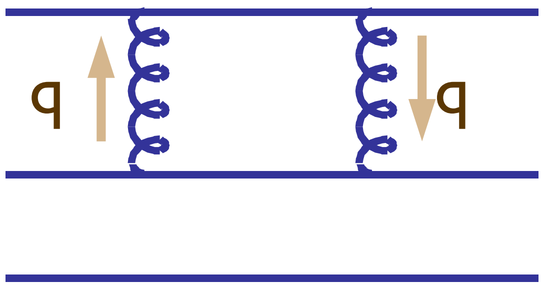
1) Exchange of **hard gluons** among quarks inside the proton is suppressed by powers of $(m_p/Q)^2$



$$\overset{q>Q}{\sim} \int_Q^\infty \frac{d^4q}{q^6} \sim \frac{1}{Q^2}$$

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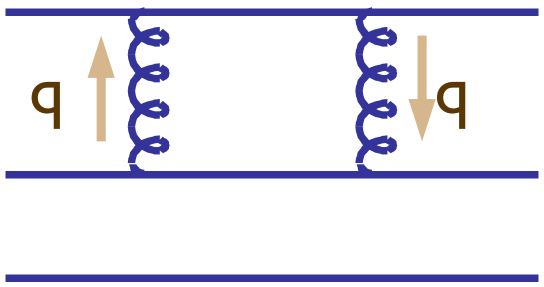

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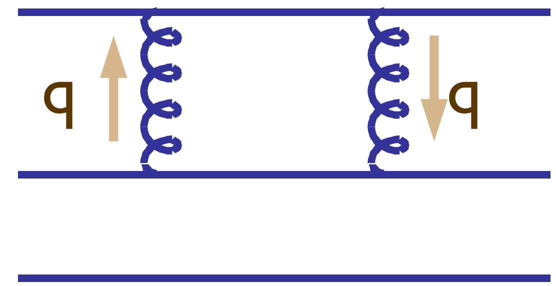
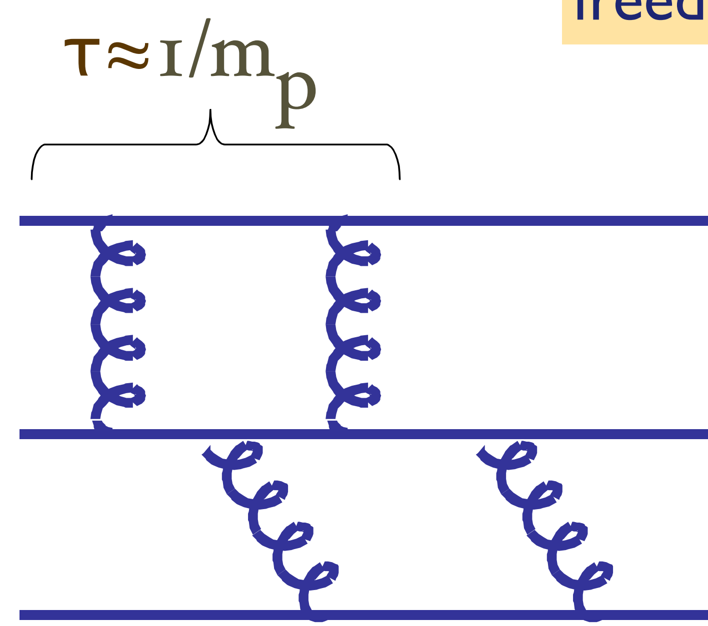


$$\overset{q>Q}{\sim} \int_Q^\infty \frac{d^4q}{q^6} \sim \frac{1}{Q^2}$$

Assuming asymptotic freedom!

2) **Typical time-scale of interactions binding the proton** is therefore of $O(1/m_p)$ (in a frame in which the proton has energy E, $\tau = \gamma/m_p = E/m_p^2$)



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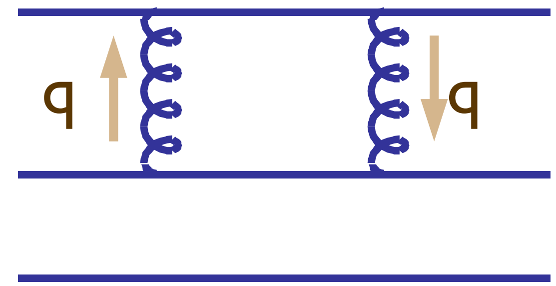

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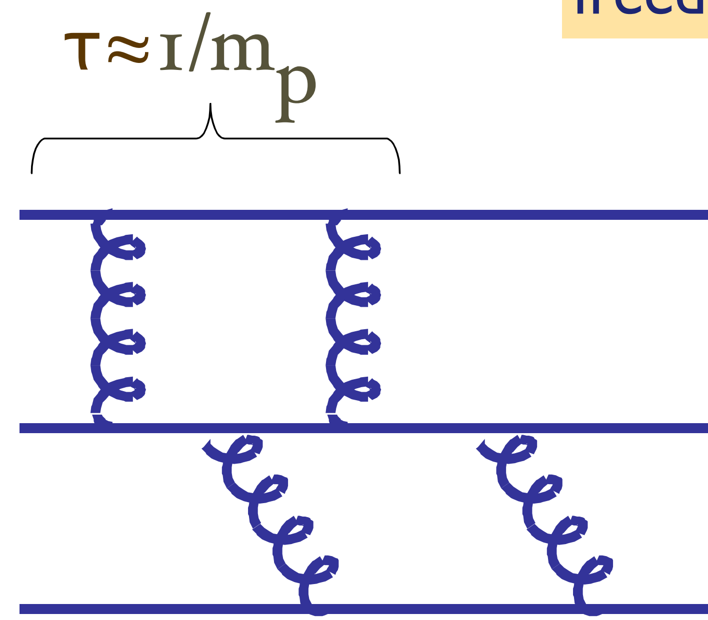

2) **Typical time-scale of interactions binding the proton** is therefore of $O(1/m_p)$ (in a frame in which the proton has energy E, $\tau = \gamma/m_p = E/m_p^2$)

3) If a hard probe ($Q \gg m_p$) hits the proton, on a time scale $=1/Q$, there is no time for quarks to negotiate a coherent response. The struck quark receives no feedback from its pals, and acts as a free particle

As a result, to study inclusive processes at large Q it is sufficient to consider the interactions between the external probe and a single parton:

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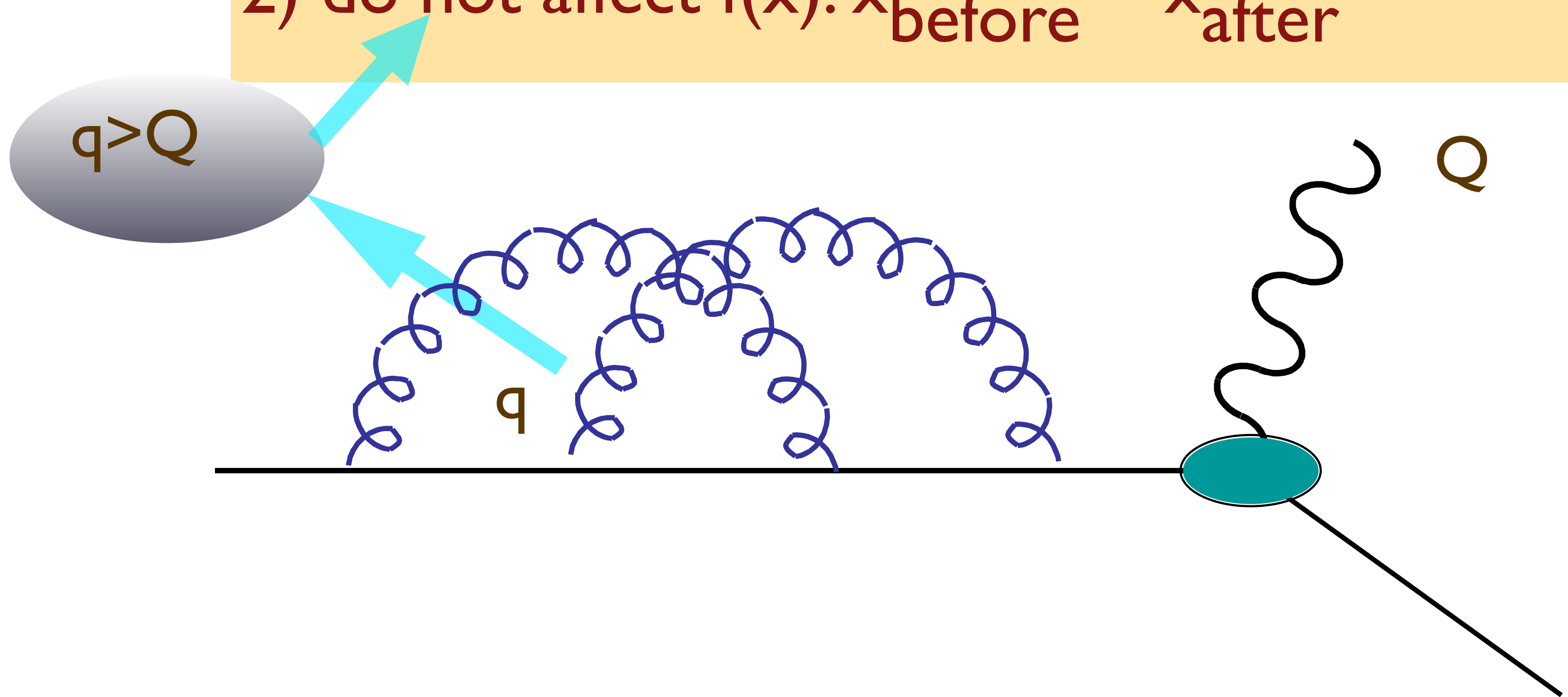

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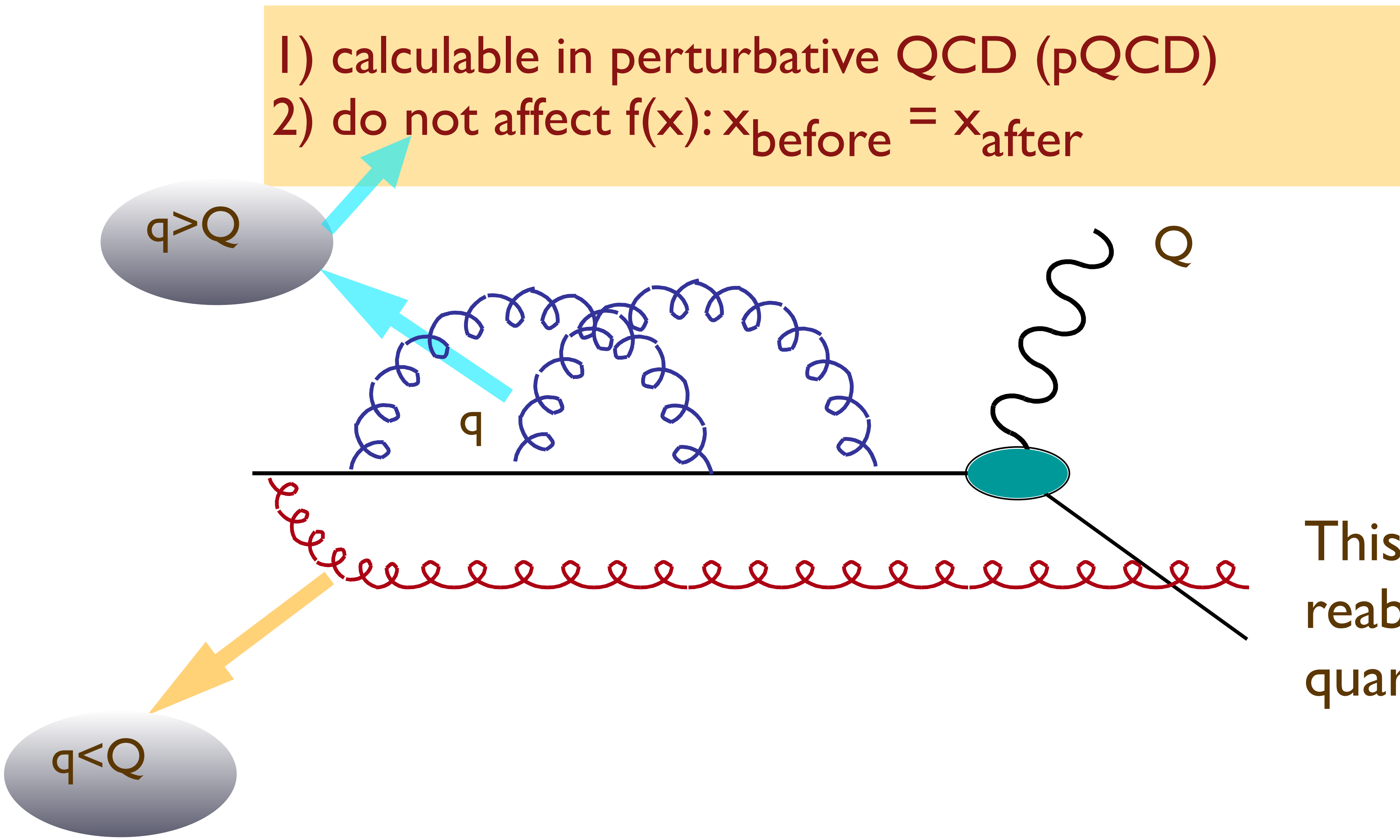

This gluon cannot be reabsorbed because the quark is gone

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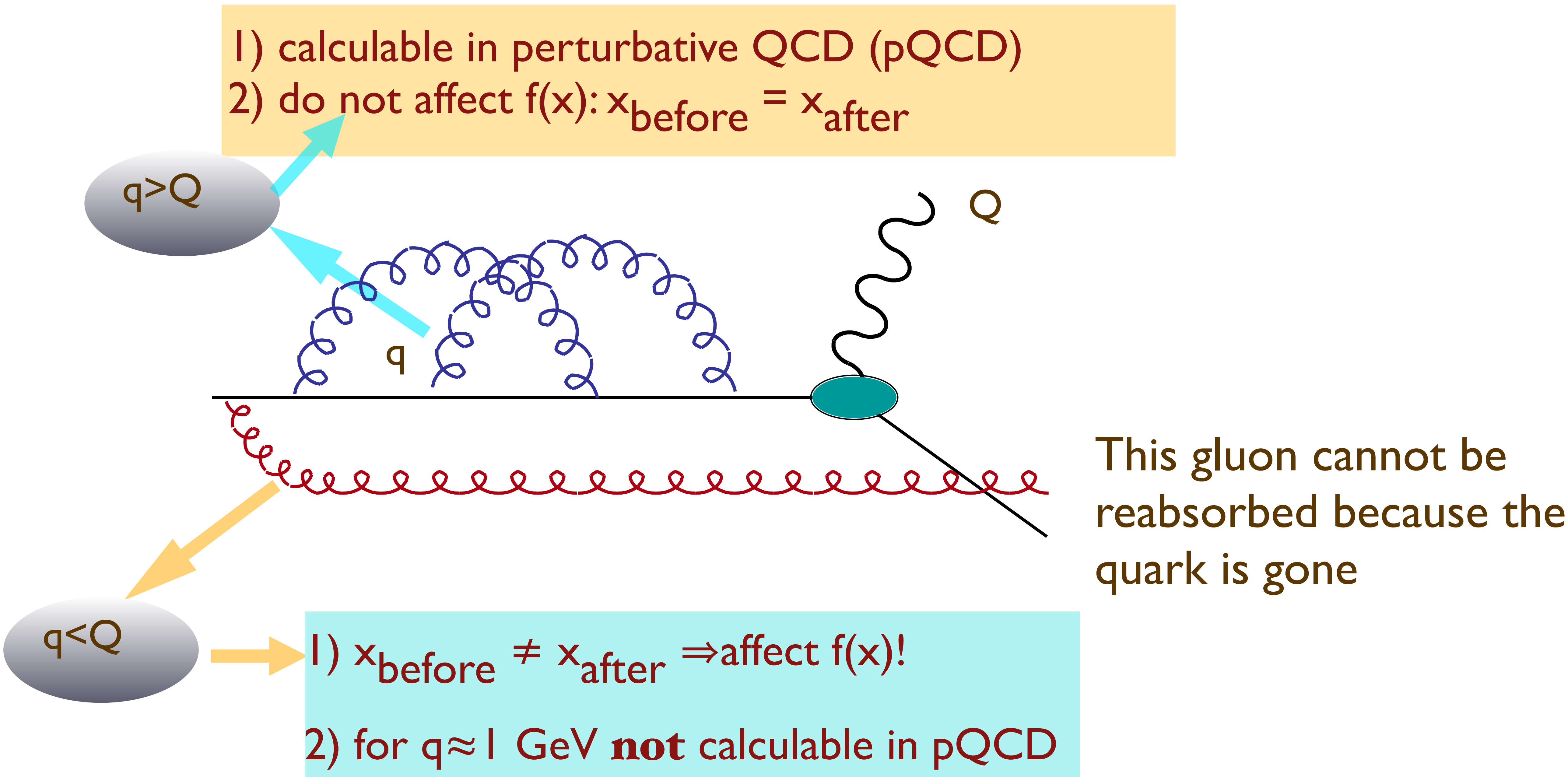

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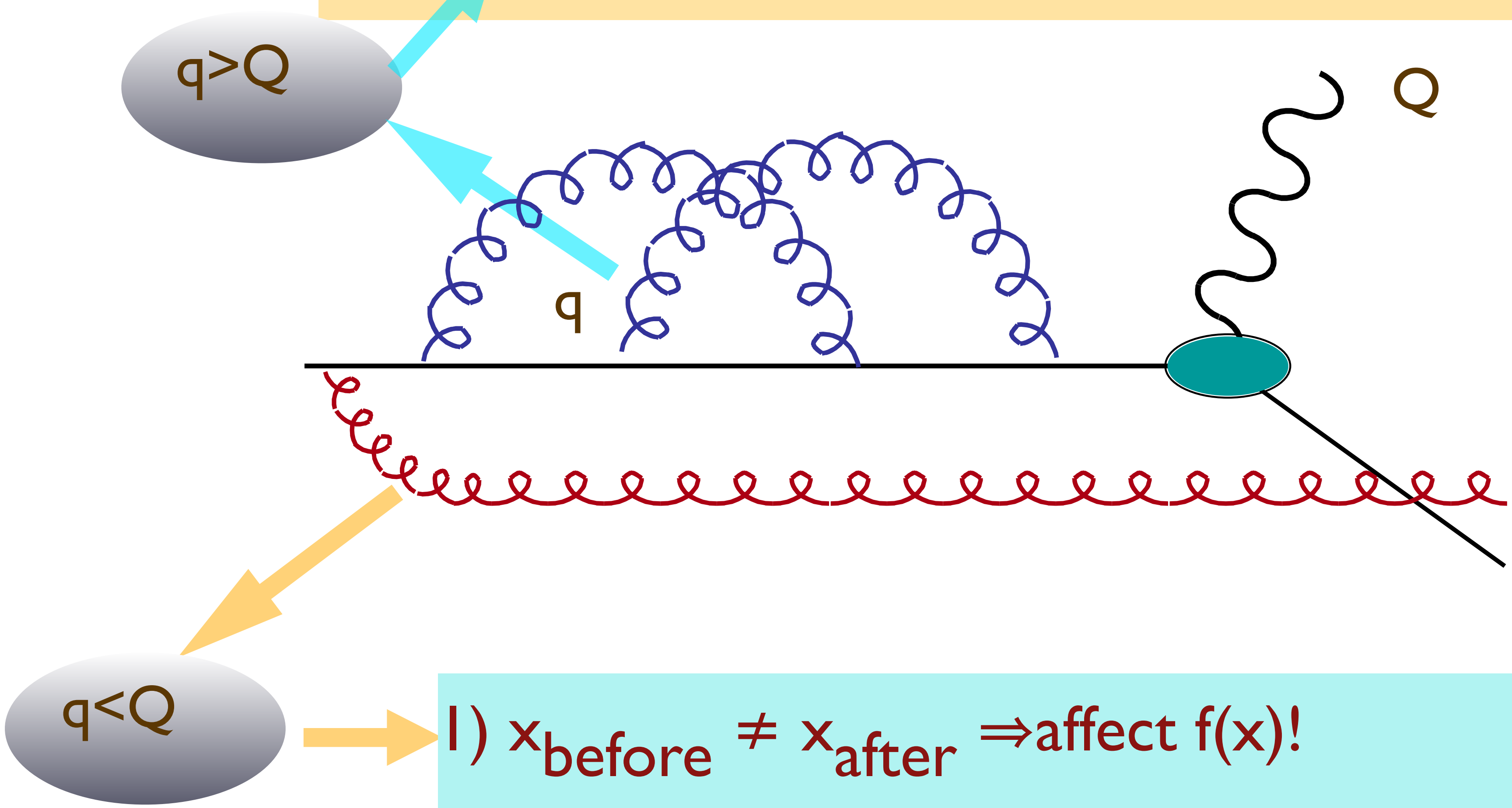


This gluon cannot be reabsorbed because the quark is gone

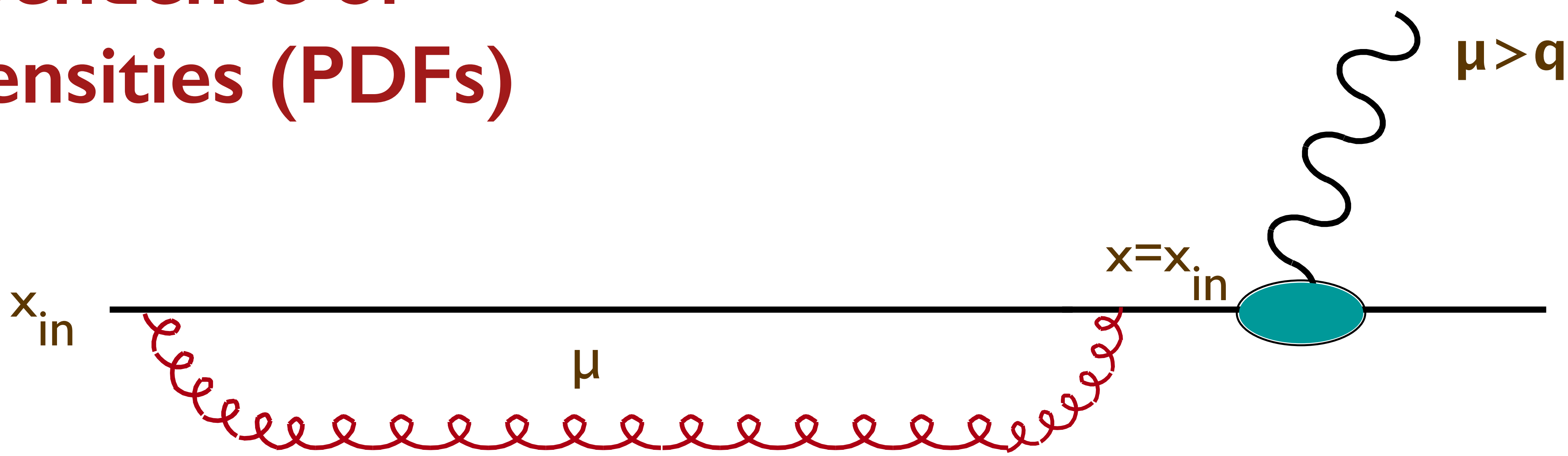
1) $x_{before} \neq x_{after}$ ⇒affect f(x)!

2) for q≈1 GeV **not** calculable in pQCD

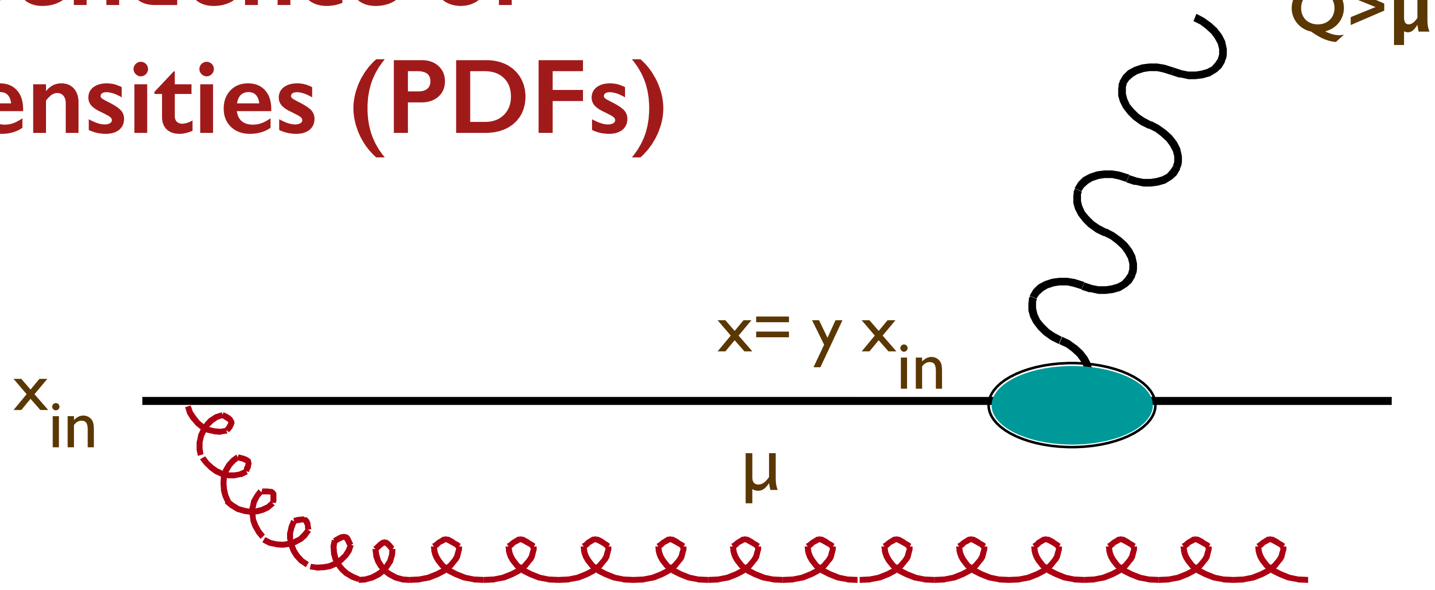
However, since τ(q≈1GeV)>>1/Q, the emission of low-virtuality gluons will take place long before the hard collision, and therefore cannot depend on the detailed nature of the hard probe. While it is not calculable in pQCD, f(q<<Q) can be measured using a reference probe, and used elsewhere

➡ **Universality of f(x)**

Q dependence of parton densities (PDFs)



Q dependence of parton densities (PDFs)



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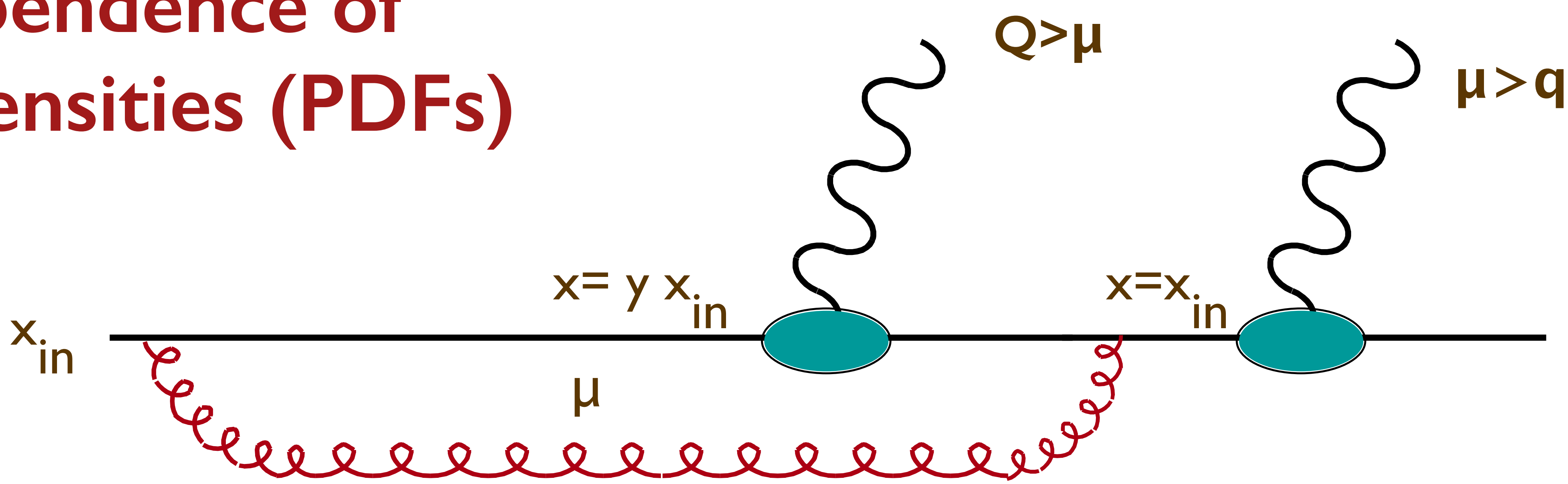

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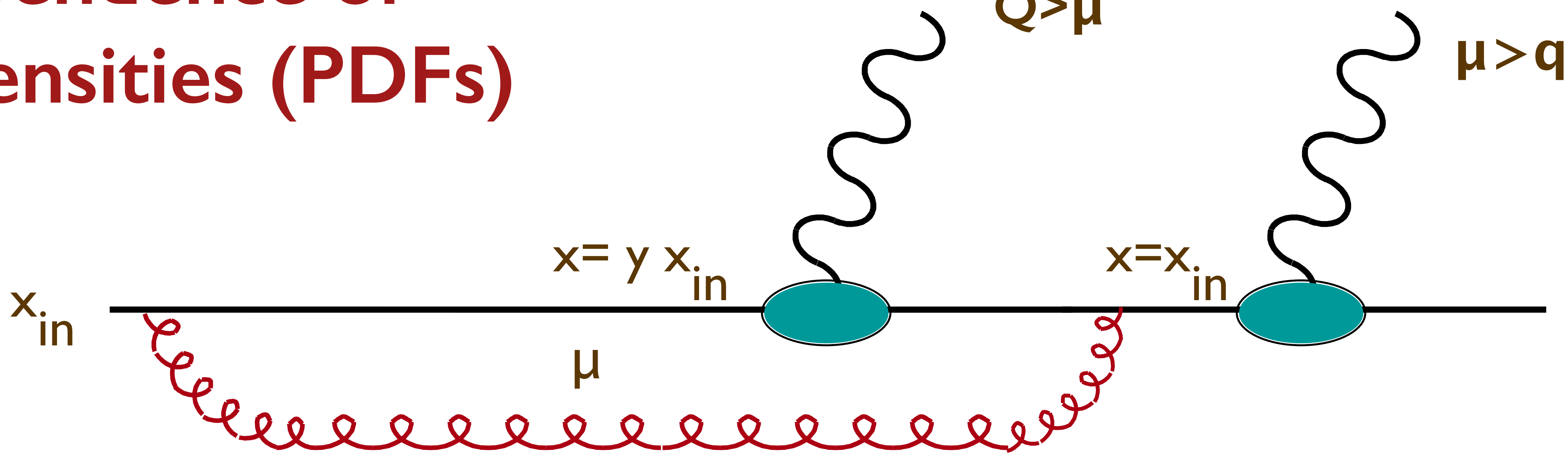


The larger is Q, the more gluons will **not** have time to be reabsorbed

PDF's depend on Q!

$$f(x,Q) = f(x,\mu) + \int_x^1 dx_{in}\, f(x_{in},\mu) \int_\mu^Q dq^2 \int_0^1 dy\, P(y,q^2)\, \delta(x - yx_{in})$$

$$f(x,Q) = f(x,\mu) + \int_x^1 dx_{in} f(x_{in},\mu) \int_\mu^Q dq^2 \int_0^1 dy\, P(y,q^2)\, \delta(x - y x_{in})$$

f(x,Q) should be independent of the intermediate scale μ considered:

$$\frac{d f(x,Q)}{d\mu^2} = 0 \quad \Rightarrow \frac{d f(x,\mu)}{d\mu^2} = \int_x^1 \frac{dy}{y} f(y,\mu)\, P(x/y,\mu^2)$$

One can prove that:

calculable in pQCD

$$P(x,Q^2) = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} P(x)$$

and finally (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi DGLAP equation):

$$\frac{d f(x,\mu)}{d \log \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} f(y,\mu)\, P(x/y)$$

Nuclear Physics B126 (1977) 298–318

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, Paris, France*

G. PARISI ***

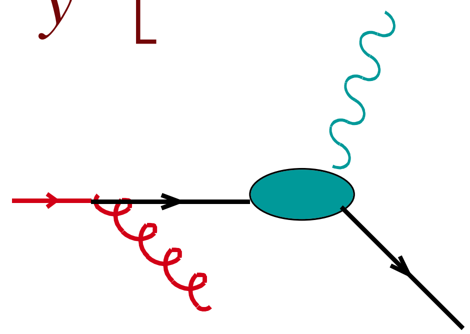
Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

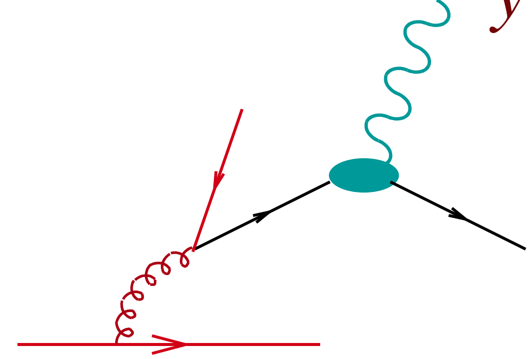
Received 12 April 1977

More in general, one should consider additional processes which lead to the evolution of partons at high Q ($t=\log Q^2$):

$$[g(x)]_+ : \quad \int_0^1 dx\, f(x)\, g(x)_+ \equiv \int_0^1 [f(x) - f(1)]\, g(x)\, dx$$

$$\frac{dq(x,Q)}{dt} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[q(y,Q)\, P_{qq}(\frac{x}{y}) + g(y,Q)\, P_{qg}(\frac{x}{y}) \right]$$

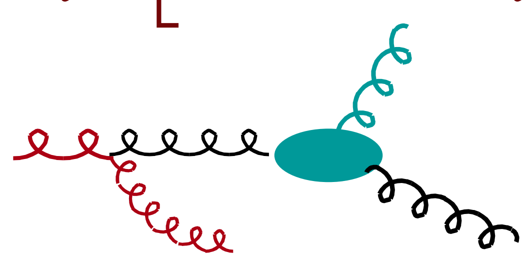


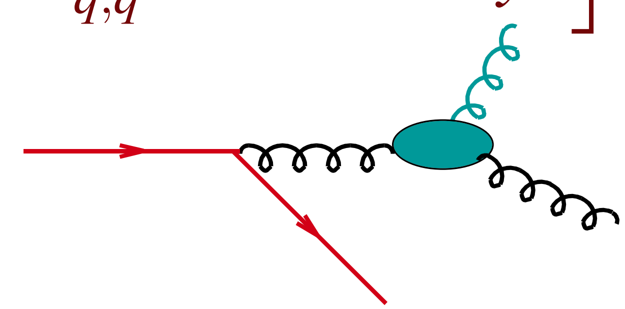


$$P_{qq}(x) = C_F \left(\frac{1+x^2}{1-x} \right)_+$$

$$P_{qg}(x) = \frac{1}{2} \left[x^2 + (1-x)^2 \right]$$

$$\frac{dg(x,Q)}{dt} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[g(y,Q)\, P_{gg}(\frac{x}{y}) + \sum_{q,\bar{q}} q(y,Q)\, P_{gq}(\frac{x}{y}) \right]$$





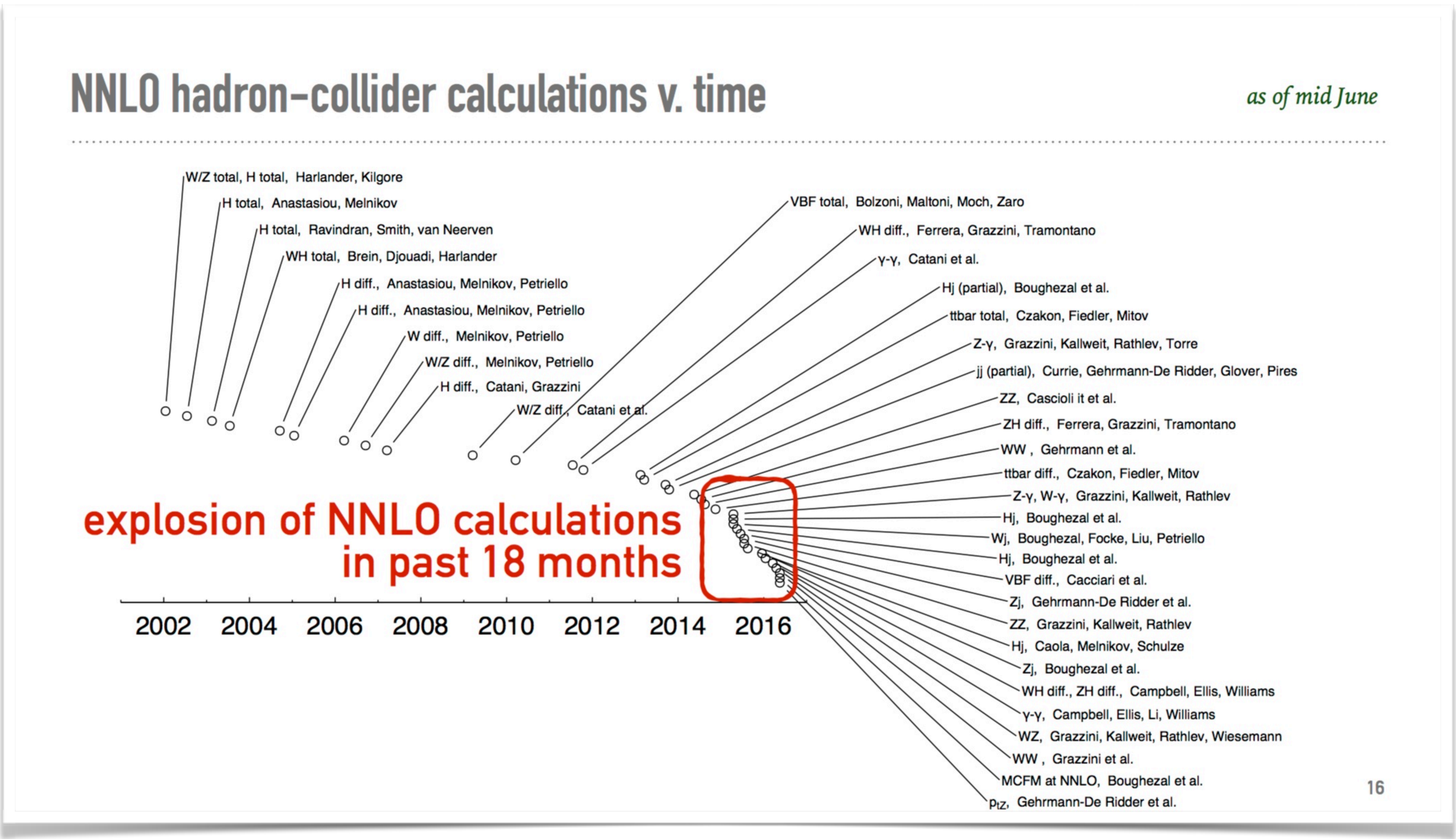
$$P_{gq}(x) = C_F \left(\frac{1+(1-x)^2}{x} \right)$$

$$P_{gg}(x) = 2N_c \left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) \right] + \delta(1-x) \left(\frac{11N_c - 2n_f}{6} \right)$$

Directions for progress

- Improve the determination of the PDFs, using LHC data
- Improve the calculations of partonic matrix elements (N^nLO)
- Improve the description of the full final state:
  - higher-order corrections to the matrix element (resummation, parton shower)
  - transition from partons to hadrons
  - modeling the interaction of the proton fragments
- Validate the theoretical progress against data, test validity/limitations of factorization

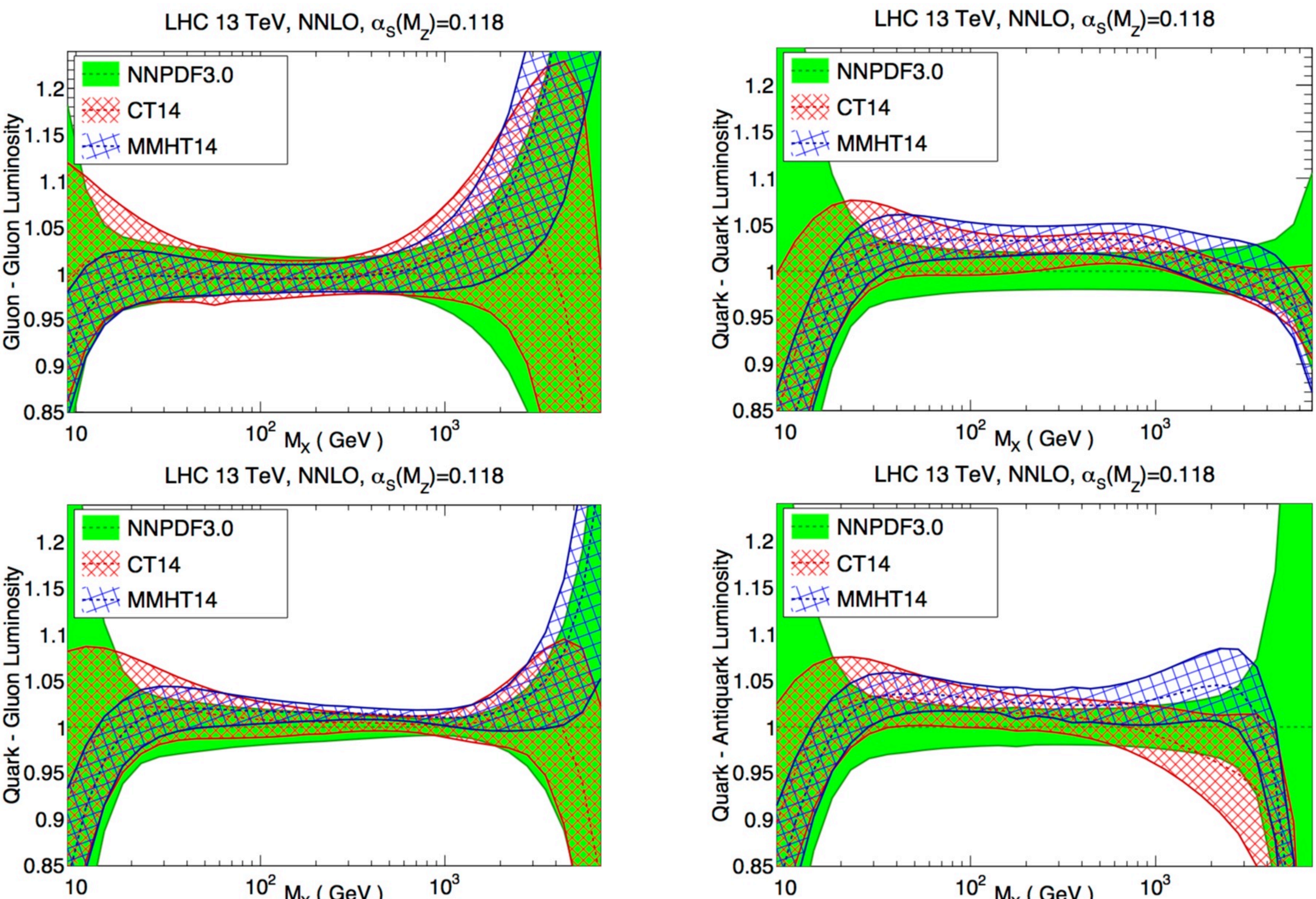
TH is rapidly making progress



Courtesy of G.Salam

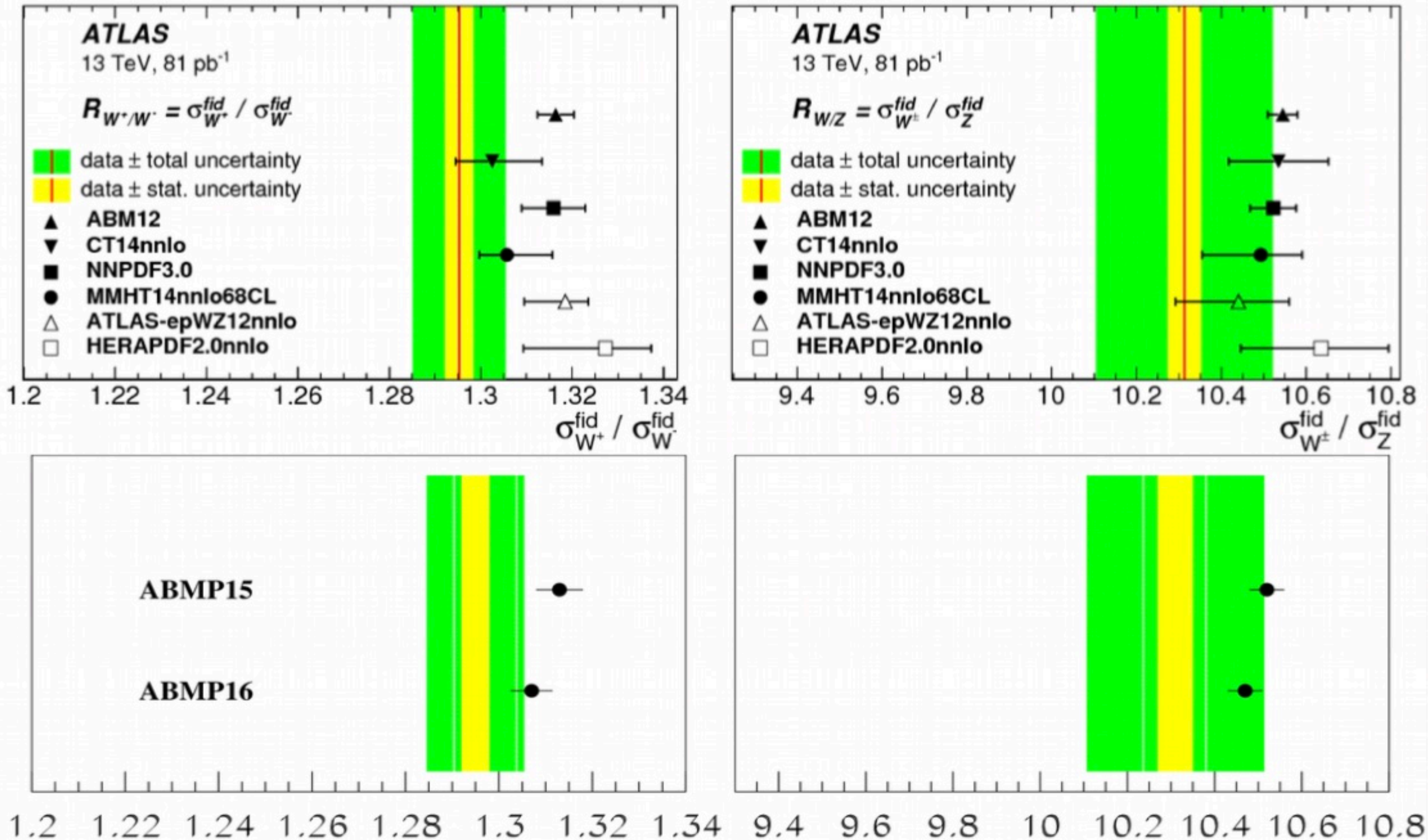
Status of PDF luminosity uncertainties

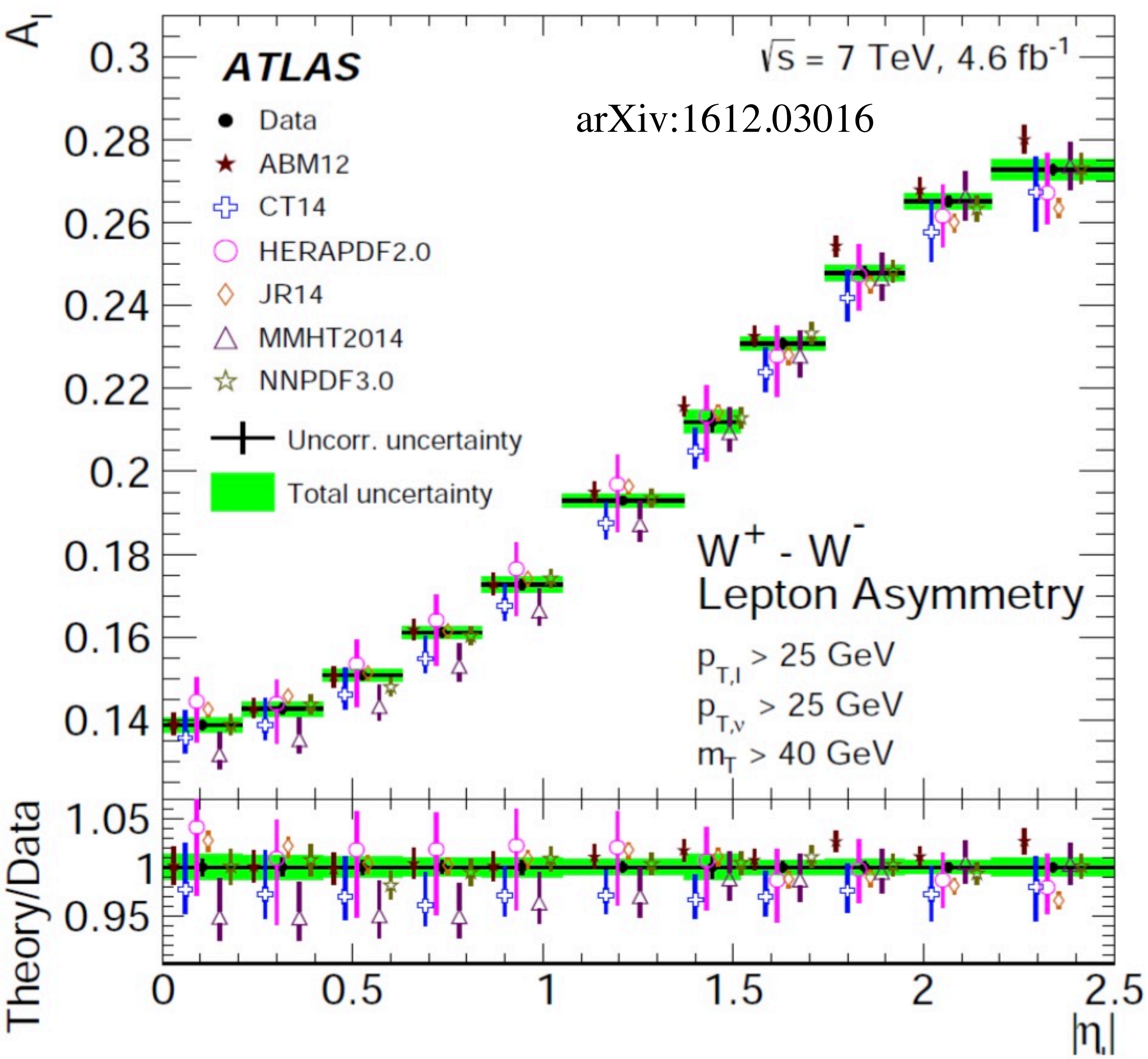
$$\frac{dL_{ij}}{d\tau} \equiv \frac{1}{1+\delta_{ij}} \int_\tau^1 \frac{dx}{x} [f_i(x) f_j(\frac{\tau}{x}) + f_j(x) f_i(\frac{\tau}{x})] \qquad \tau = M^2/S$$



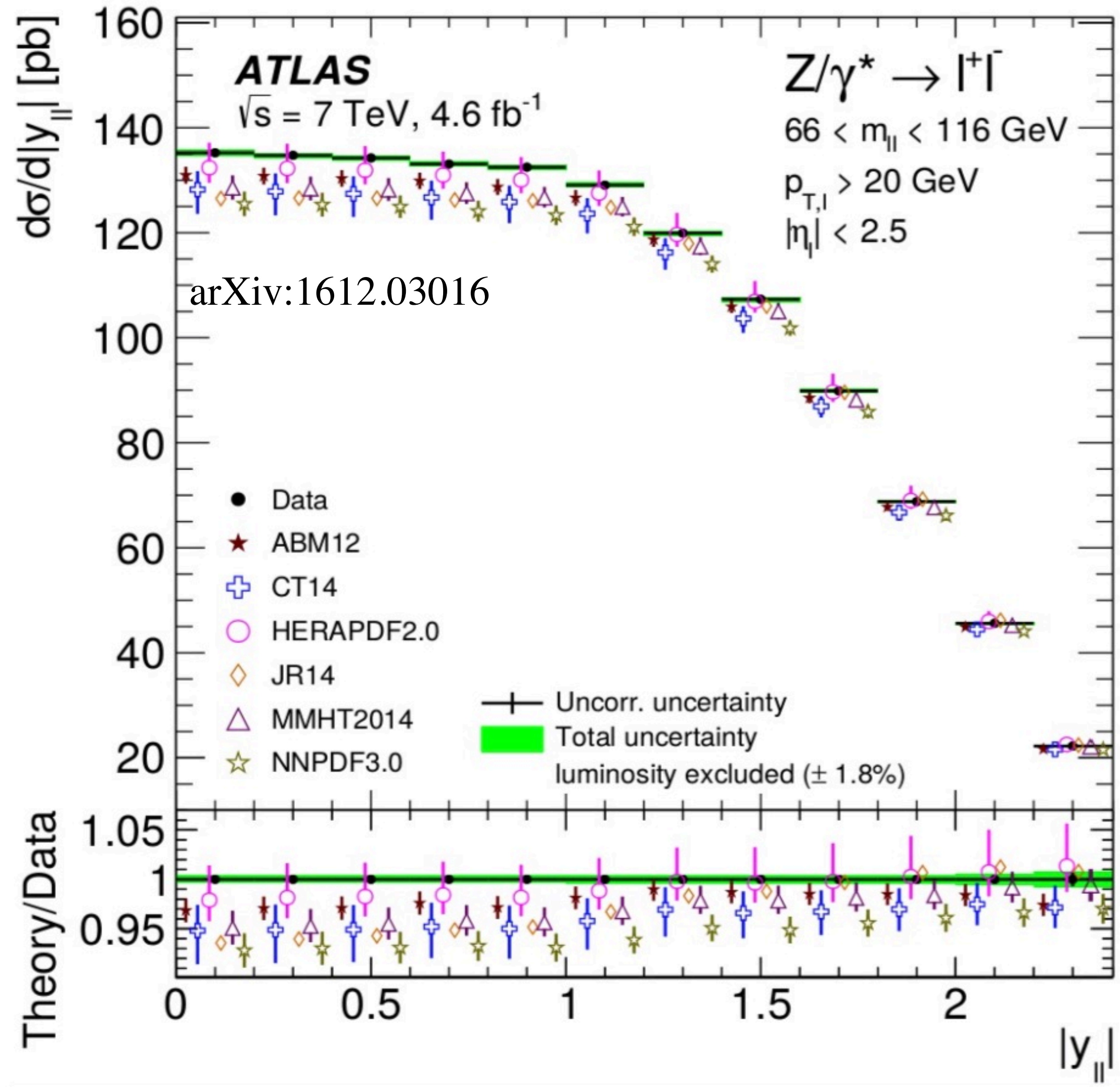
ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222





ATLAS
√s = 7 TeV, 4.6 fb-1
arXiv:1612.03016
Data
ABM12
CT14
HERAPDF2.0
JR14
MMHT2014
NNPDF3.0
Uncorr. uncertainty
Total uncertainty
W+ - W-
Lepton Asymmetry
pT,l > 25 GeV
pT,ν > 25 GeV
mT > 40 GeV
Al
Theory/Data
|ηl|



ATLAS
√s = 7 TeV, 4.6 fb-1
Z/γ* → l+l-
66 < mll < 116 GeV
pT,l > 20 GeV
|ηl| < 2.5
arXiv:1612.03016
Data
ABM12
CT14
HERAPDF2.0
JR14
MMHT2014
NNPDF3.0
Uncorr. uncertainty
Total uncertainty
luminosity excluded (± 1.8%)
dσ/d|yll| [pb]
Theory/Data
|yll|

Heavy quarks and PDFs

Nuclear Physics B308 (1988) 724–752
North-Holland, Amsterdam

TOTAL CROSS SECTIONS FOR HEAVY FLAVOUR PRODUCTION IN HADRONIC COLLISIONS AND QCD

G. ALTARELLI

CERN, Geneva, Switzerland

M. DIEMOZ

Dipartimento di Fisica, Università di Roma, INFN, Sezione di Roma, Italy

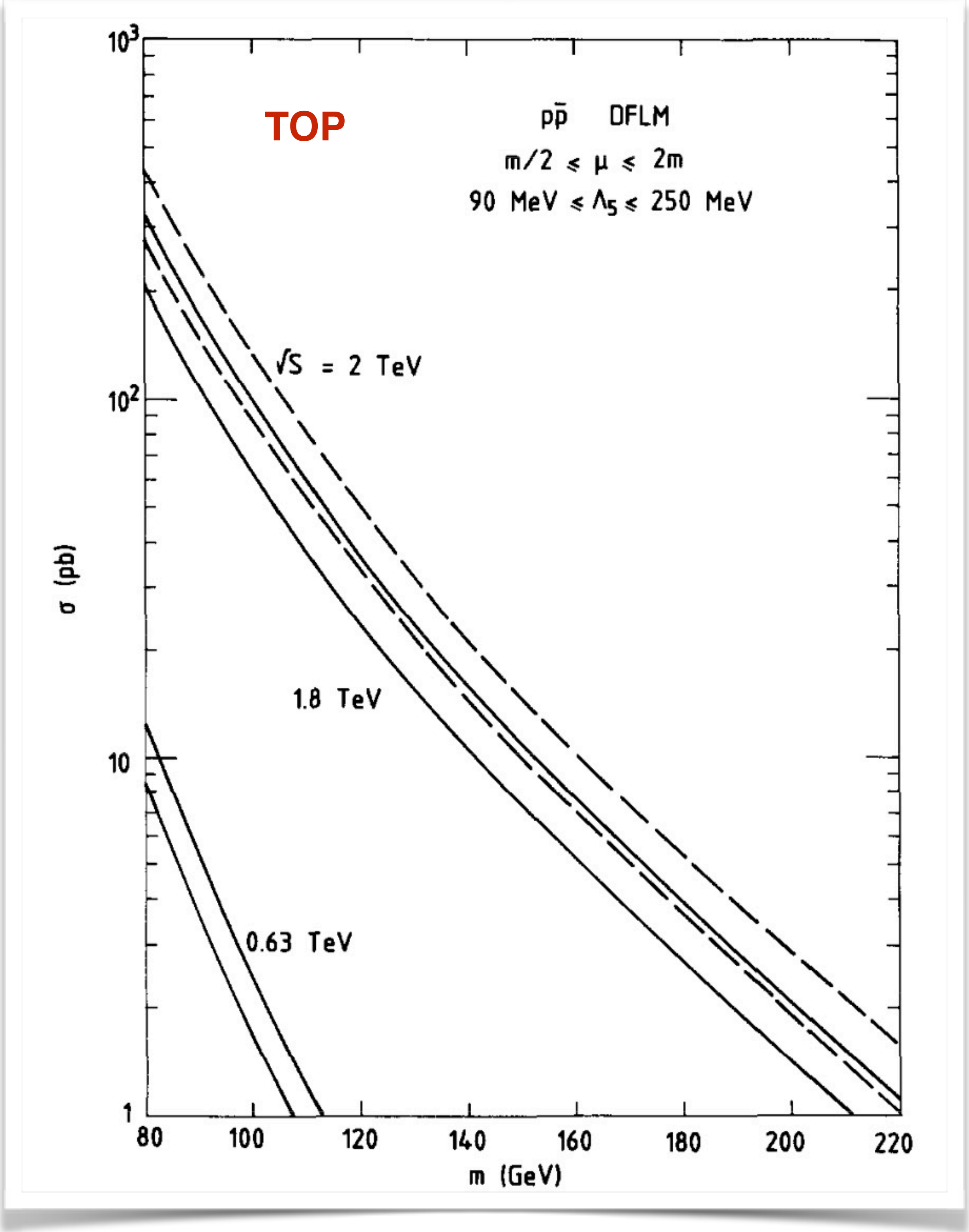
G. MARTINELLI

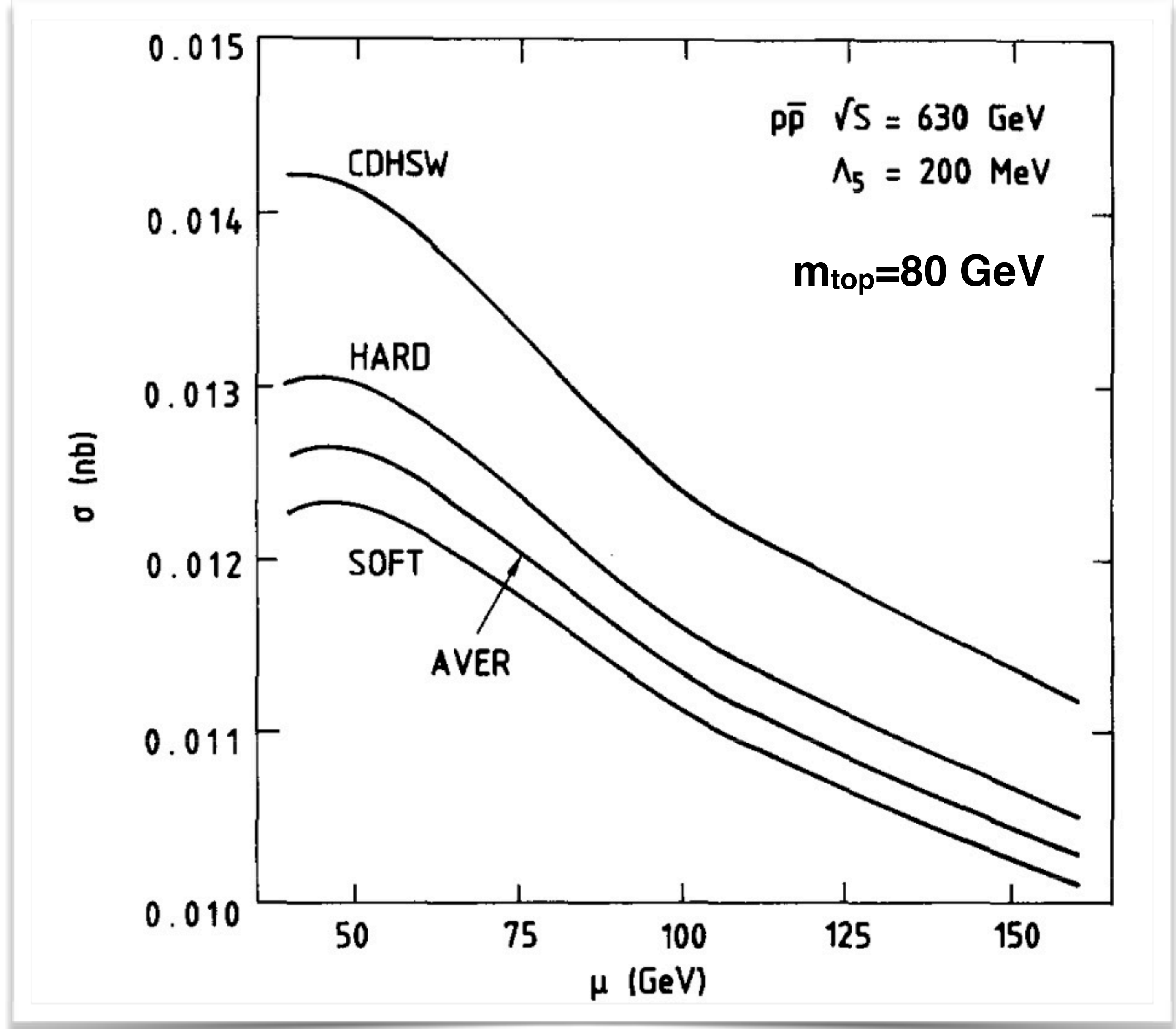
CERN, Geneva, Switzerland

P. NASON*

ETH, Zürich, Switzerland

Received 5 April 1988


TOP
pp̄ DFLM
m/2 ≤ μ ≤ 2m
90 MeV ≤ Λ5 ≤ 250 MeV
√S = 2 TeV
1.8 TeV
0.63 TeV
σ (pb)
m (GeV)
10³
10²
10
1
80
100
120
140
160
180
200
220


pp̄ √S = 630 GeV
Λ5 = 200 MeV
mtop=80 GeV
CDHSW
HARD
SOFT
AVER
σ (nb)
μ (GeV)
0.015
0.014
0.013
0.012
0.011
0.010
50
75
100
125
150

CHARM

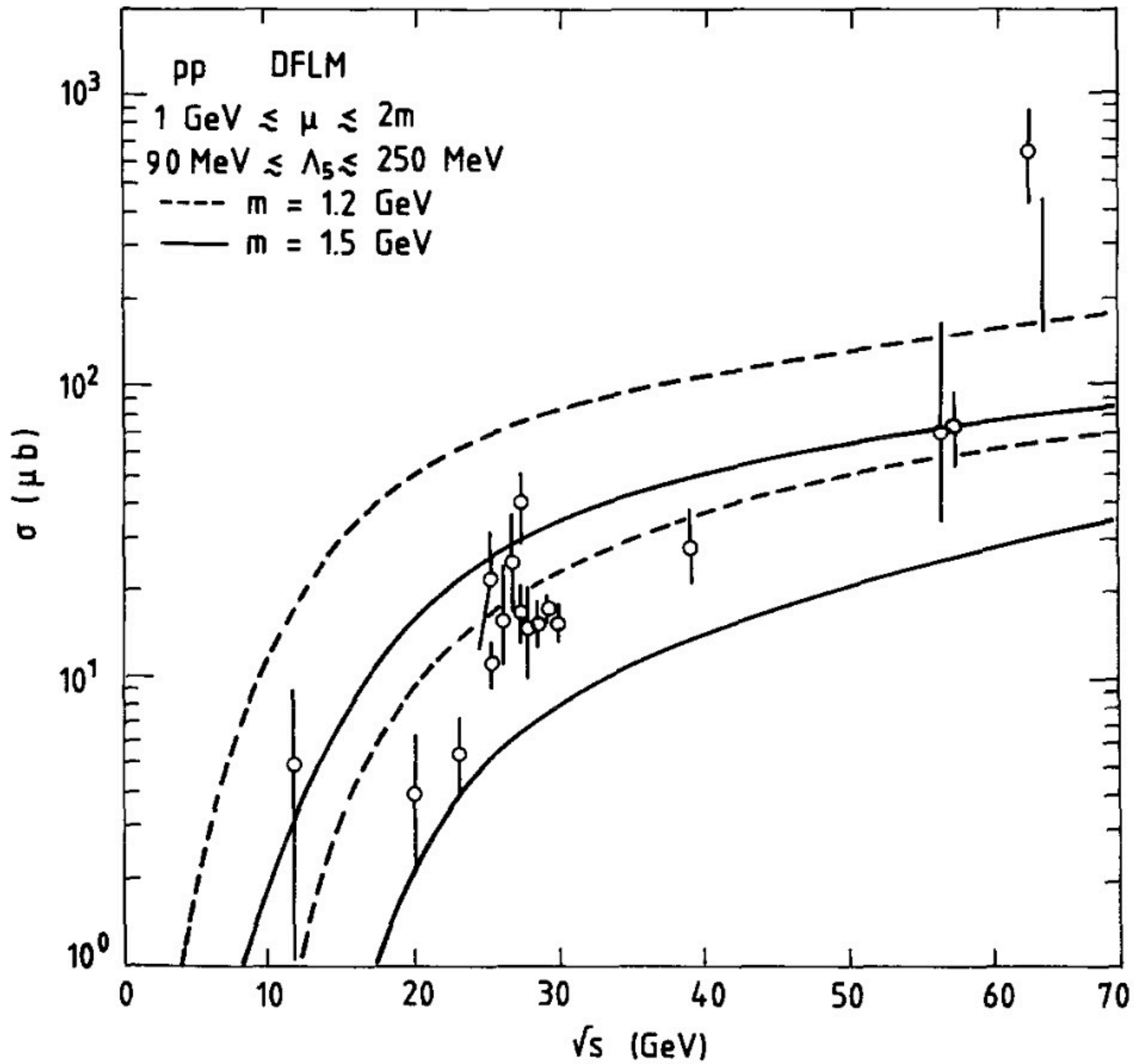
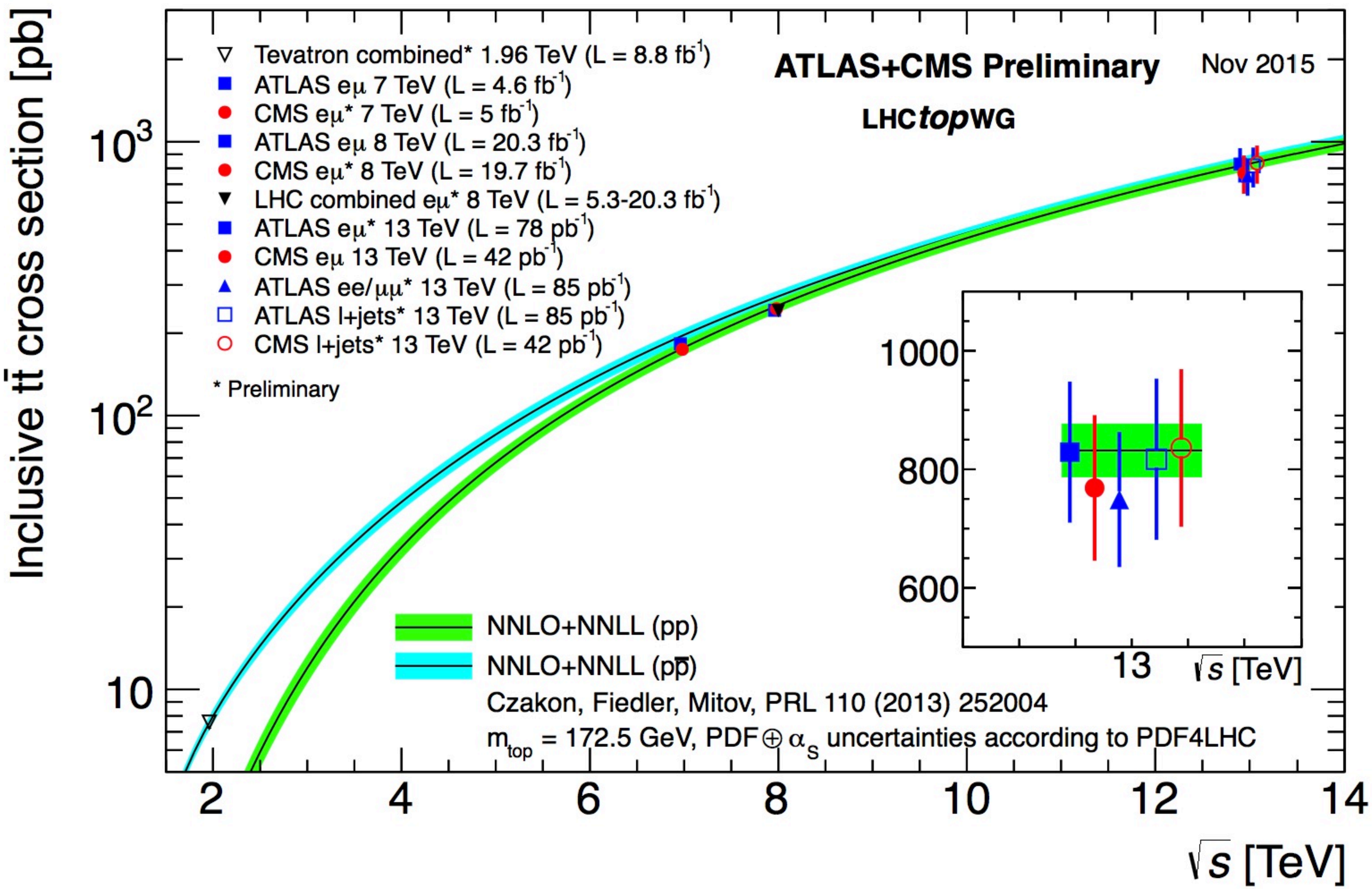
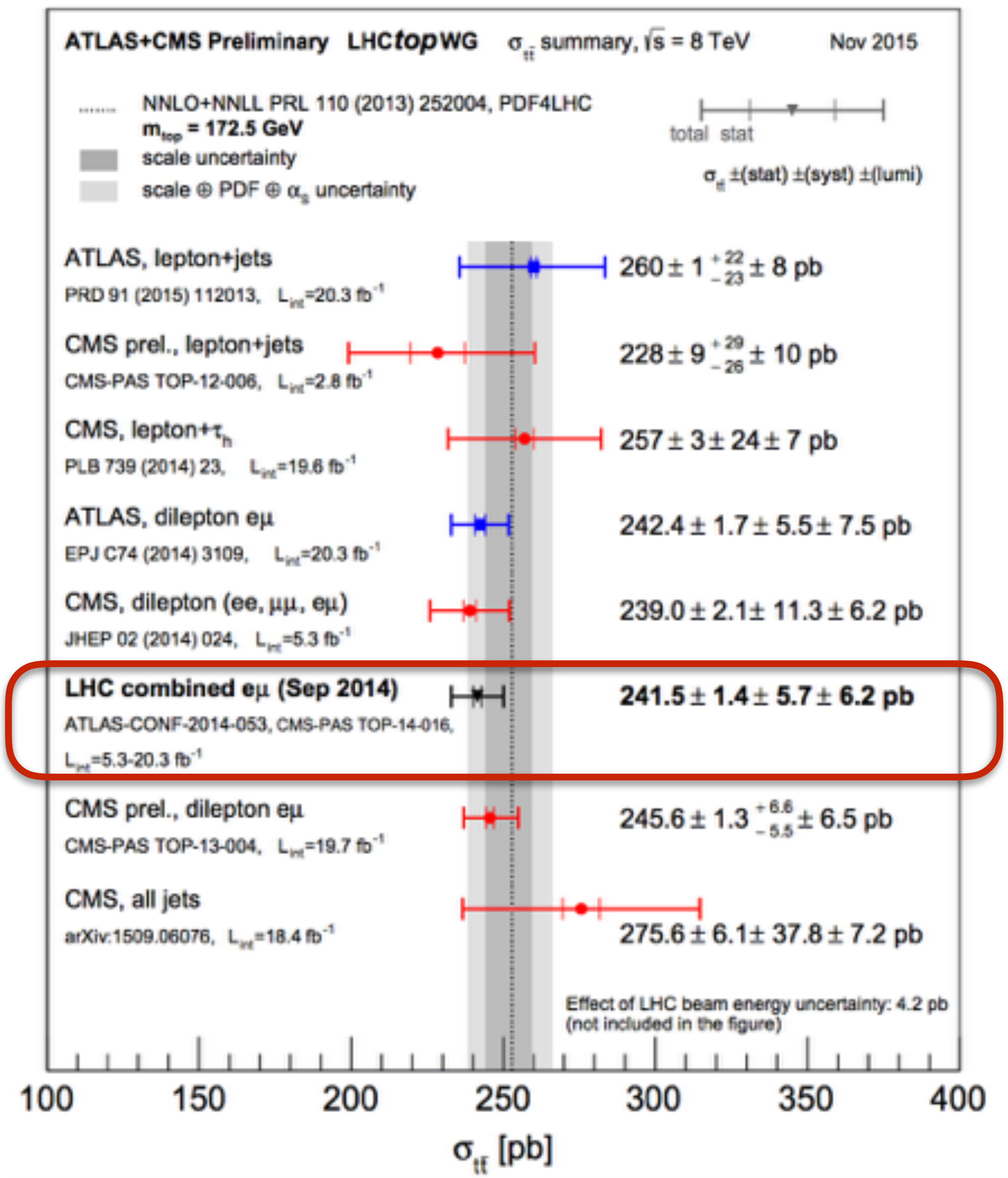
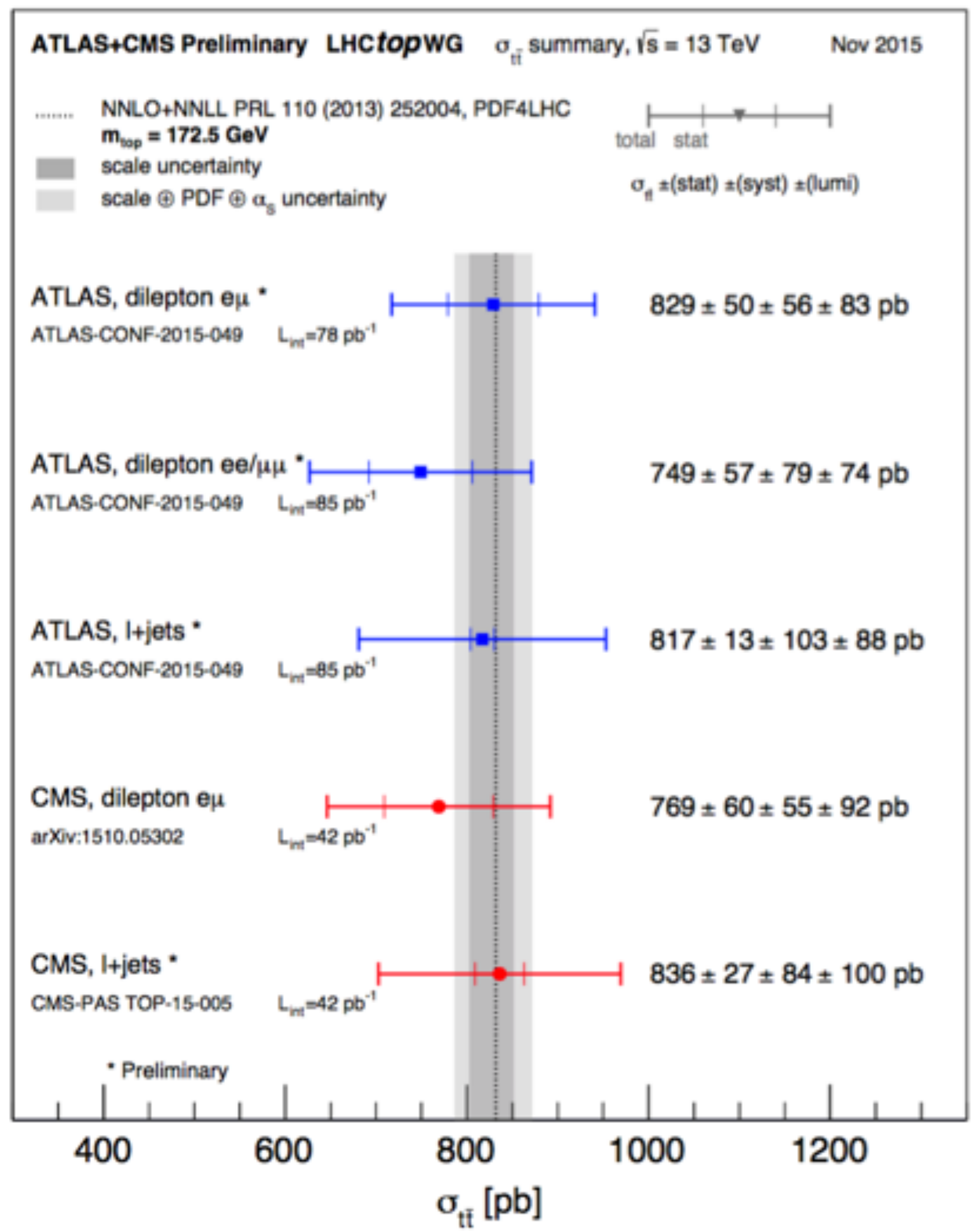


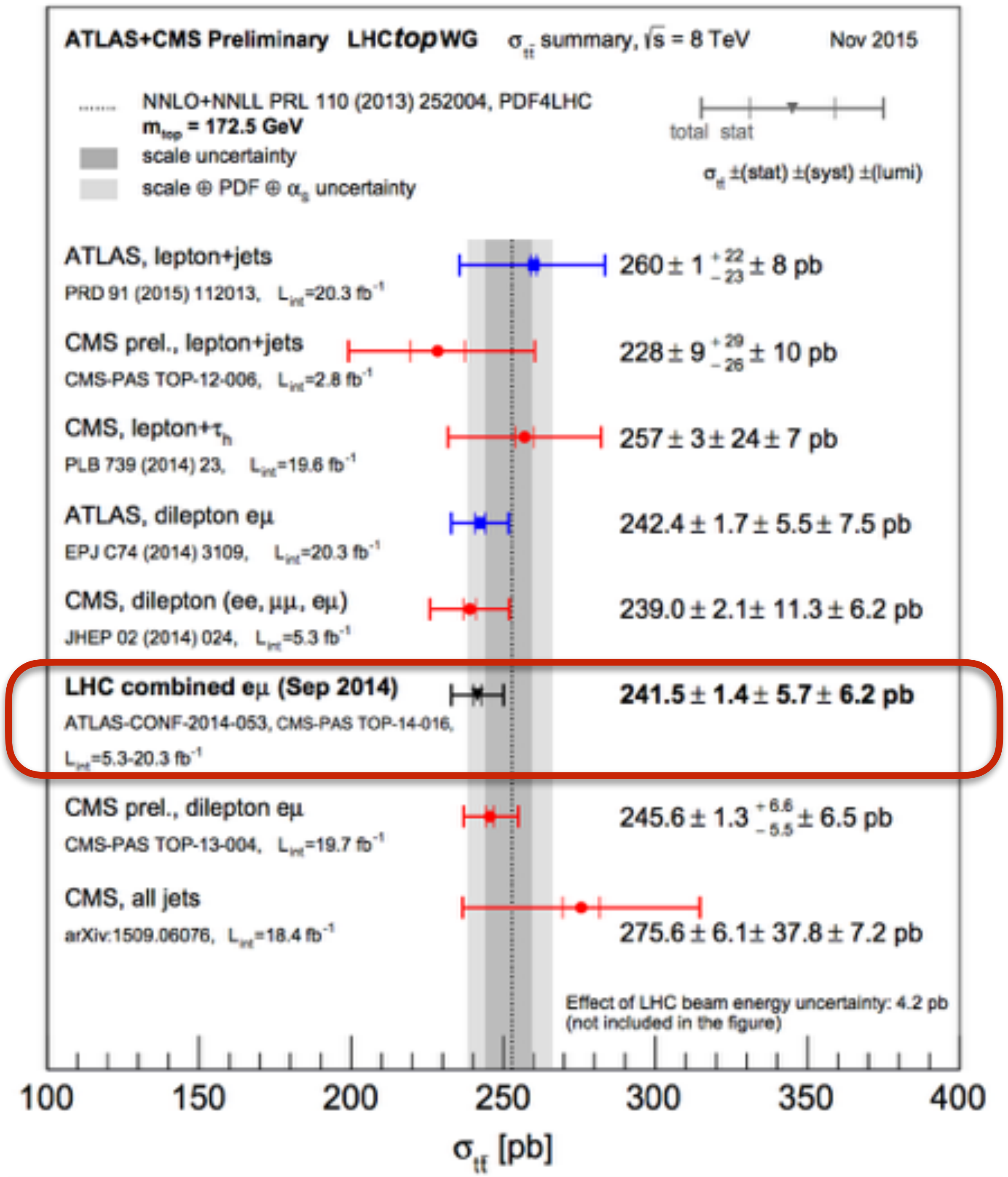
Fig. 18. Total cross section for charm production in pp collisions. The data compilation is taken from ref. [38]. The solid (dashed) curves determine the band, obtained for $m_c = 1.5$ GeV (1.2 GeV), by combining the theoretical uncertainties deriving from independent variations of μ and Λ_5 in the given ranges (added in quadrature).

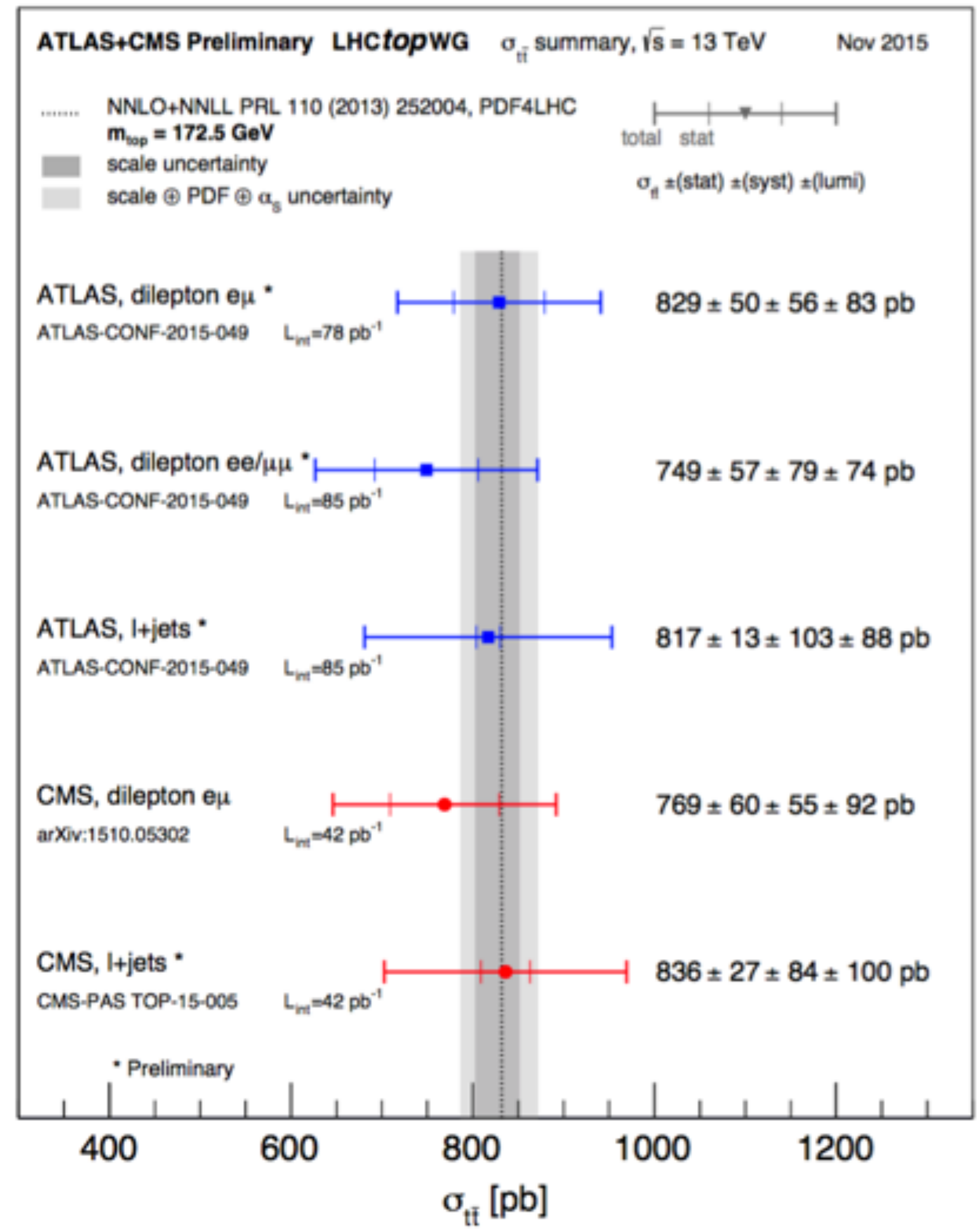
Top quark production at LHC




ATLAS+CMS Preliminary LHCtopWG σtt̄ summary, √s = 8 TeV Nov 2015
NNLO+NNLL PRL 110 (2013) 252004, PDF4LHC
mtop = 172.5 GeV
scale uncertainty
scale ⊕ PDF ⊕ αs uncertainty
total stat
σtt̄ ±(stat) ±(syst) ±(lumi)
ATLAS, lepton+jets
PRD 91 (2015) 112013, Lint=20.3 fb-1
260 ± 1 +22 −23 ± 8 pb
CMS prel., lepton+jets
CMS-PAS TOP-12-006, Lint=2.8 fb-1
228 ± 9 +29 −26 ± 10 pb
CMS, lepton+τh
PLB 739 (2014) 23, Lint=19.6 fb-1
257 ± 3 ± 24 ± 7 pb
ATLAS, dilepton eμ
EPJ C74 (2014) 3109, Lint=20.3 fb-1
242.4 ± 1.7 ± 5.5 ± 7.5 pb
CMS, dilepton (ee, μμ, eμ)
JHEP 02 (2014) 024, Lint=5.3 fb-1
239.0 ± 2.1 ± 11.3 ± 6.2 pb
LHC combined eμ (Sep 2014)
ATLAS-CONF-2014-053, CMS-PAS TOP-14-016,
Lint=5.3-20.3 fb-1
241.5 ± 1.4 ± 5.7 ± 6.2 pb
CMS prel., dilepton eμ
CMS-PAS TOP-13-004, Lint=19.7 fb-1
245.6 ± 1.3 +6.6 −5.5 ± 6.5 pb
CMS, all jets
arXiv:1509.06076, Lint=18.4 fb-1
275.6 ± 6.1 ± 37.8 ± 7.2 pb
Effect of LHC beam energy uncertainty: 4.2 pb
(not included in the figure)
100 150 200 250 300 350 400
σtt̄ [pb]

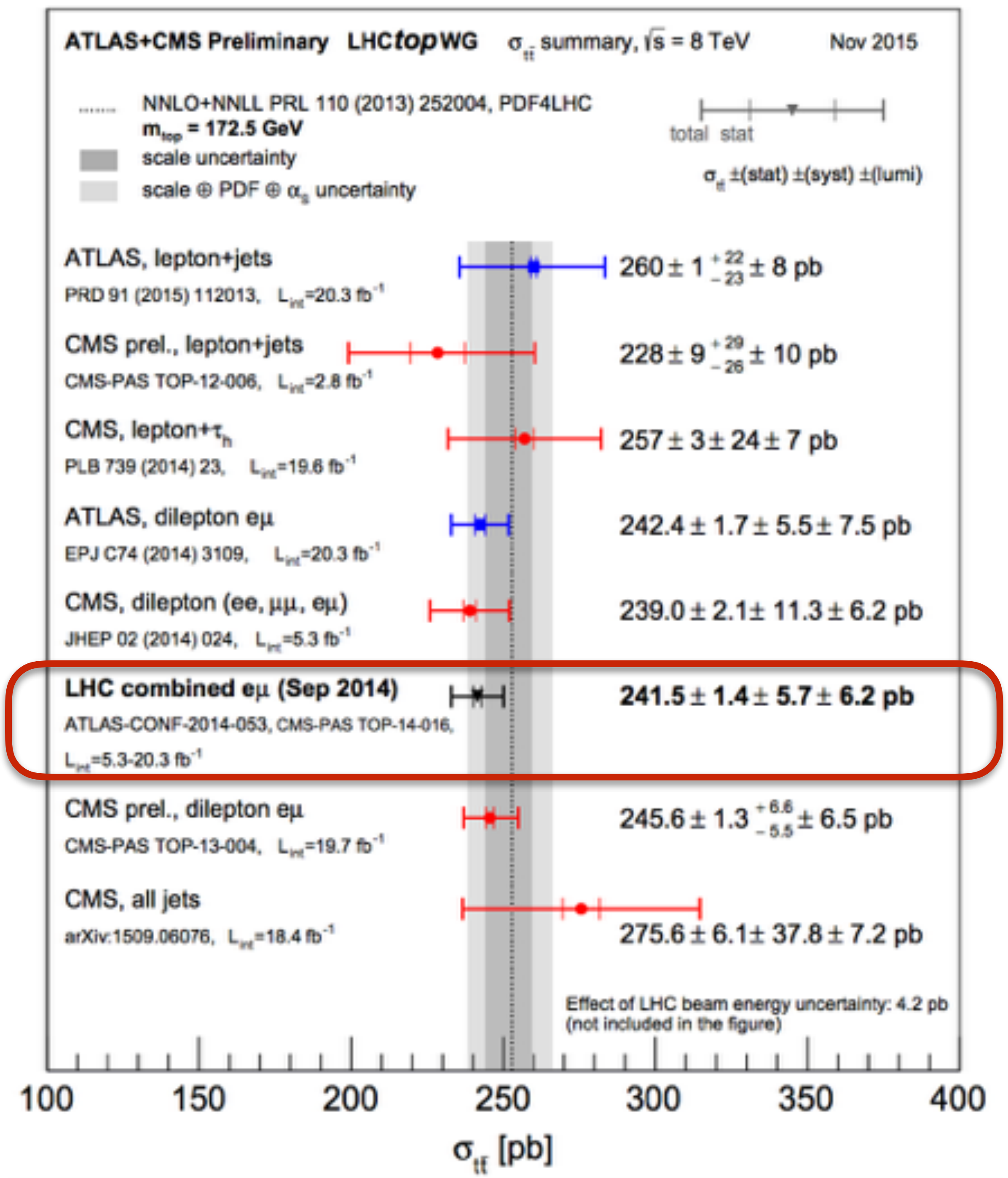

ATLAS+CMS Preliminary LHCtopWG σtt̄ summary, √s = 13 TeV Nov 2015
NNLO+NNLL PRL 110 (2013) 252004, PDF4LHC
mtop = 172.5 GeV
scale uncertainty
scale ⊕ PDF ⊕ αs uncertainty
total stat
σtt̄ ±(stat) ±(syst) ±(lumi)
ATLAS, dilepton eμ *
ATLAS-CONF-2015-049 Lint=78 pb-1
829 ± 50 ± 56 ± 83 pb
ATLAS, dilepton ee/μμ *
ATLAS-CONF-2015-049 Lint=85 pb-1
749 ± 57 ± 79 ± 74 pb
ATLAS, l+jets *
ATLAS-CONF-2015-049 Lint=85 pb-1
817 ± 13 ± 103 ± 88 pb
CMS, dilepton eμ
arXiv:1510.05302 Lint=42 pb-1
769 ± 60 ± 55 ± 92 pb
CMS, l+jets *
CMS-PAS TOP-15-005 Lint=42 pb-1
836 ± 27 ± 84 ± 100 pb
* Preliminary
400 600 800 1000 1200
σtt̄ [pb]

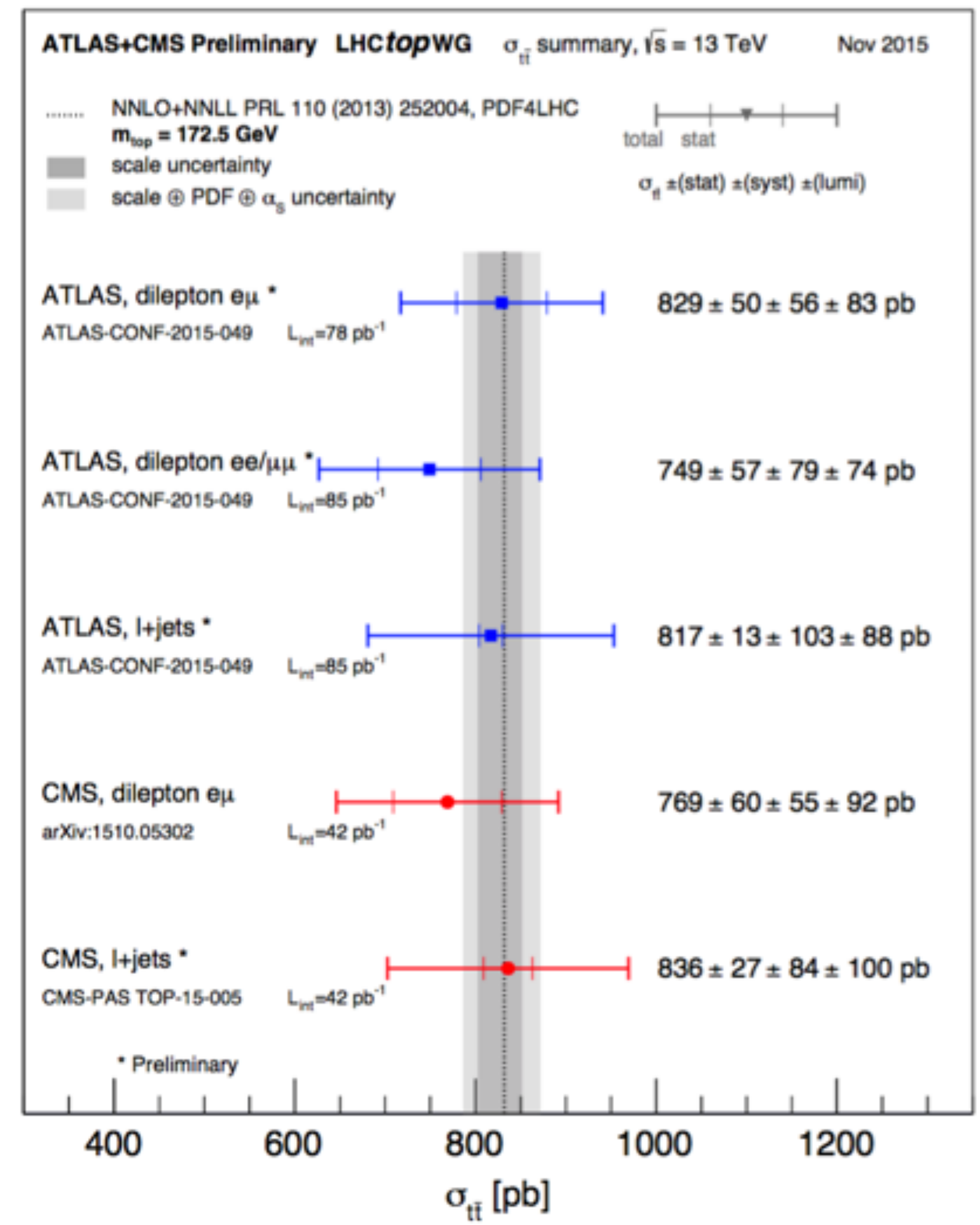




(pb)	σ(172.5 GeV)	δ_{scale}	$\delta_{PDF+\alpha s}$	δ_{mtop}
8 TeV	253	$^{+6}_{-9}$	± 12	± 7.5
13 TeV	832	$^{+20}_{-29}$	± 35	± 23

Czakon, Fiedler, Mitov, arXiv:1303.6254





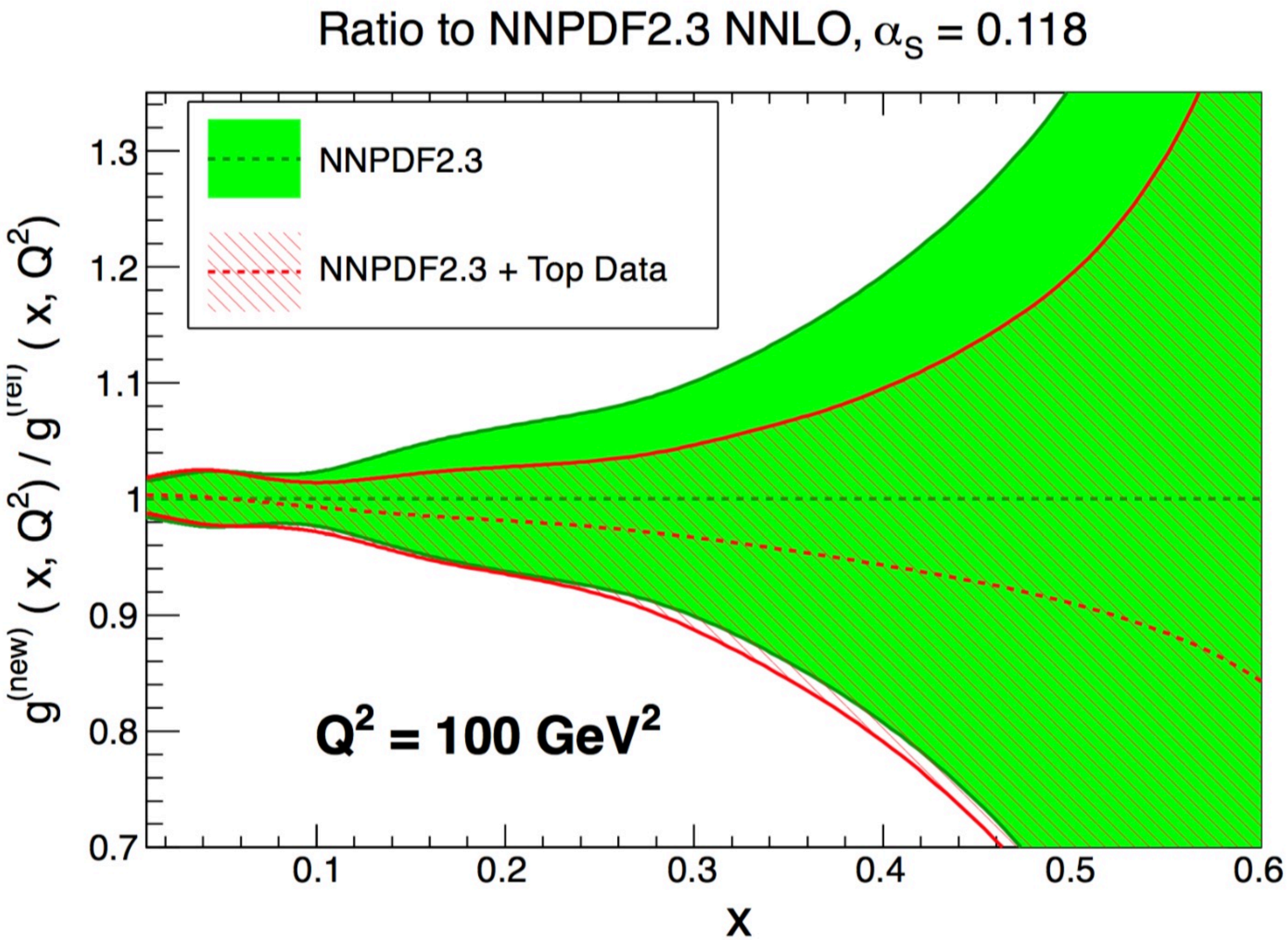
(pb)	σ(172.5 GeV)	δ_{scale}	$\delta_{PDF+\alpha s}$	δ_{mtop}
8 TeV	253	+6 −9	± 12	± 7.5
13 TeV	832	+20 −29	± 35	± 23

Czakon, Fiedler, Mitov, arXiv:1303.6254

Pinning down PDF and parametric uncertainties is becoming more important than dealing with uncertainties from higher-order corrections

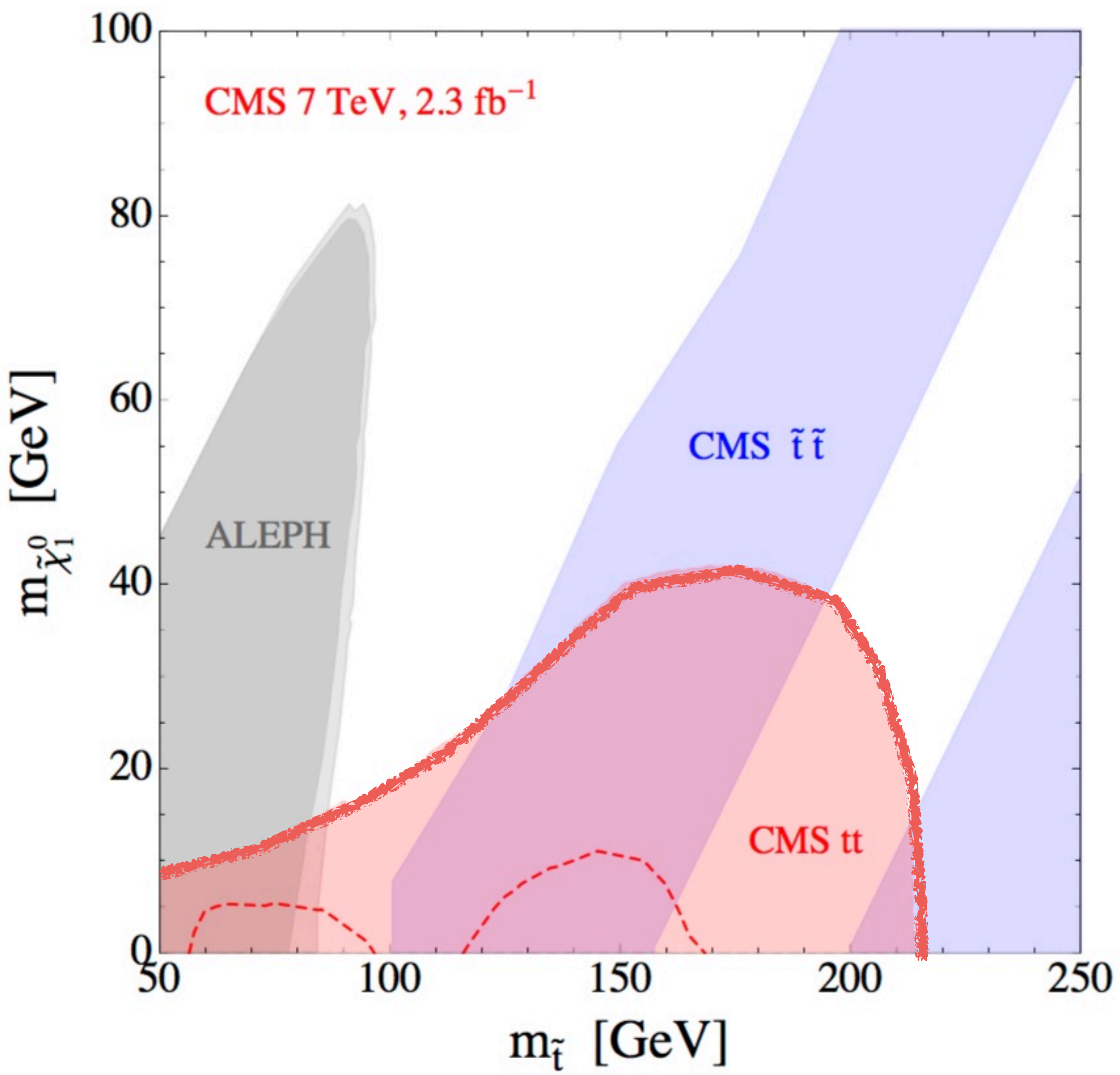
Some applications

Improved determination of gluon density



Czakon, et al
arXiv:1407.1043

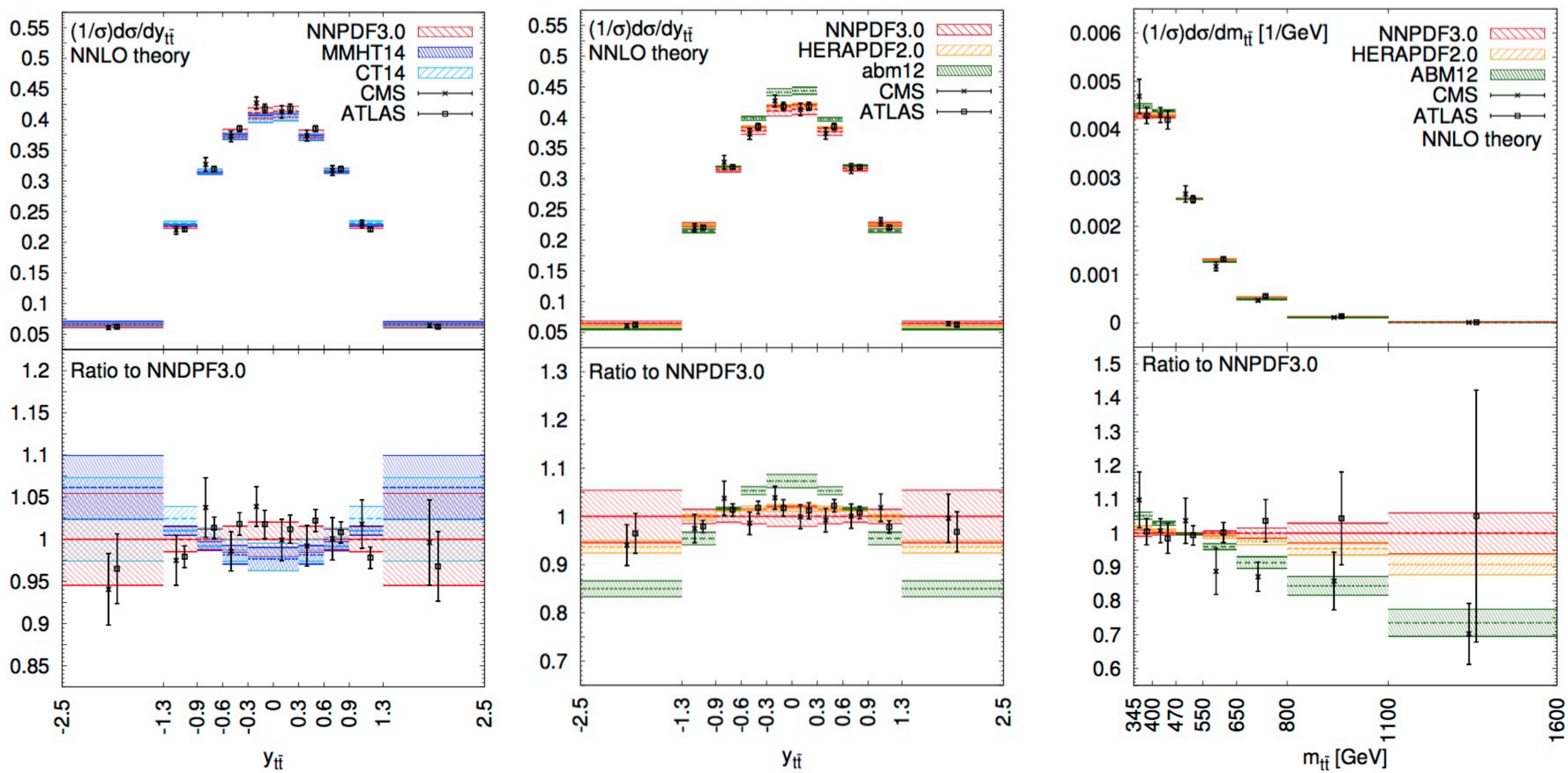
Limits on stop from $\sigma_{TH}(tt)$ vs $\sigma_{exp}(tt)$



Czakon, Papucci Mitov Rudermann Weiler,
arXiv:1407.1043

Top quark spectra @ NNLO vs PDF fits

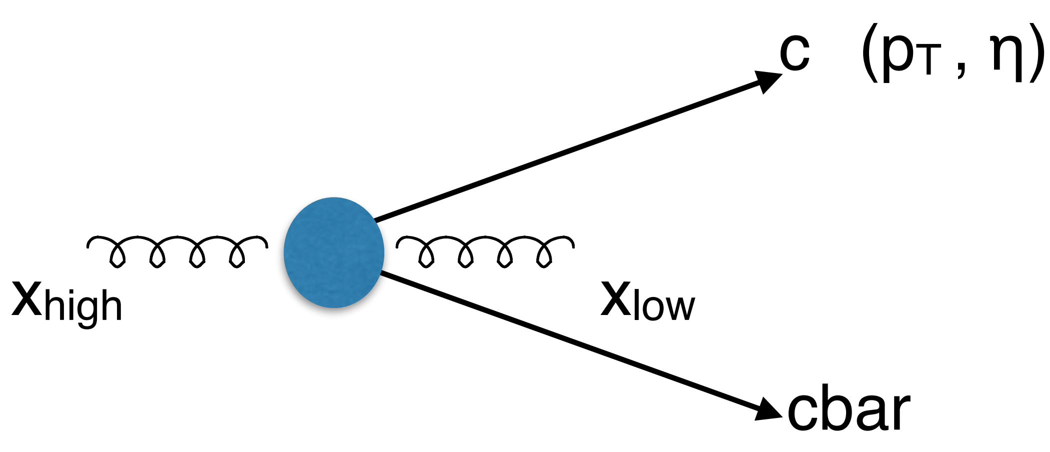
M.Czakon et al, arXiv:1611.08609



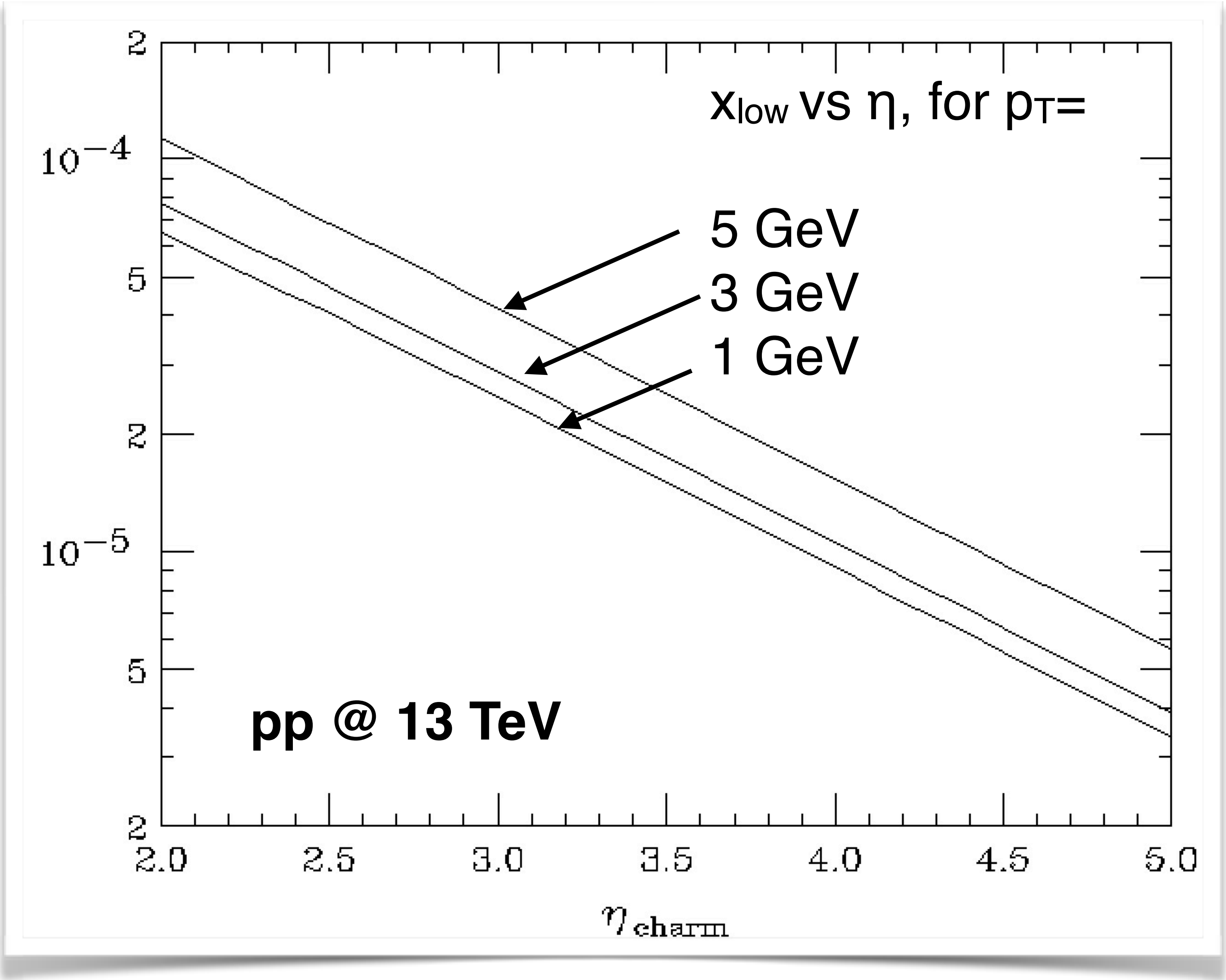
The sensitivity of measurements and TH has reached the few-% level also for complex processes like t-tbar production.

The measurement of distributions complement the total XS info, in sorting out PDF effects vs possible new physics effects

Forward charm as a probe of small-x gluons

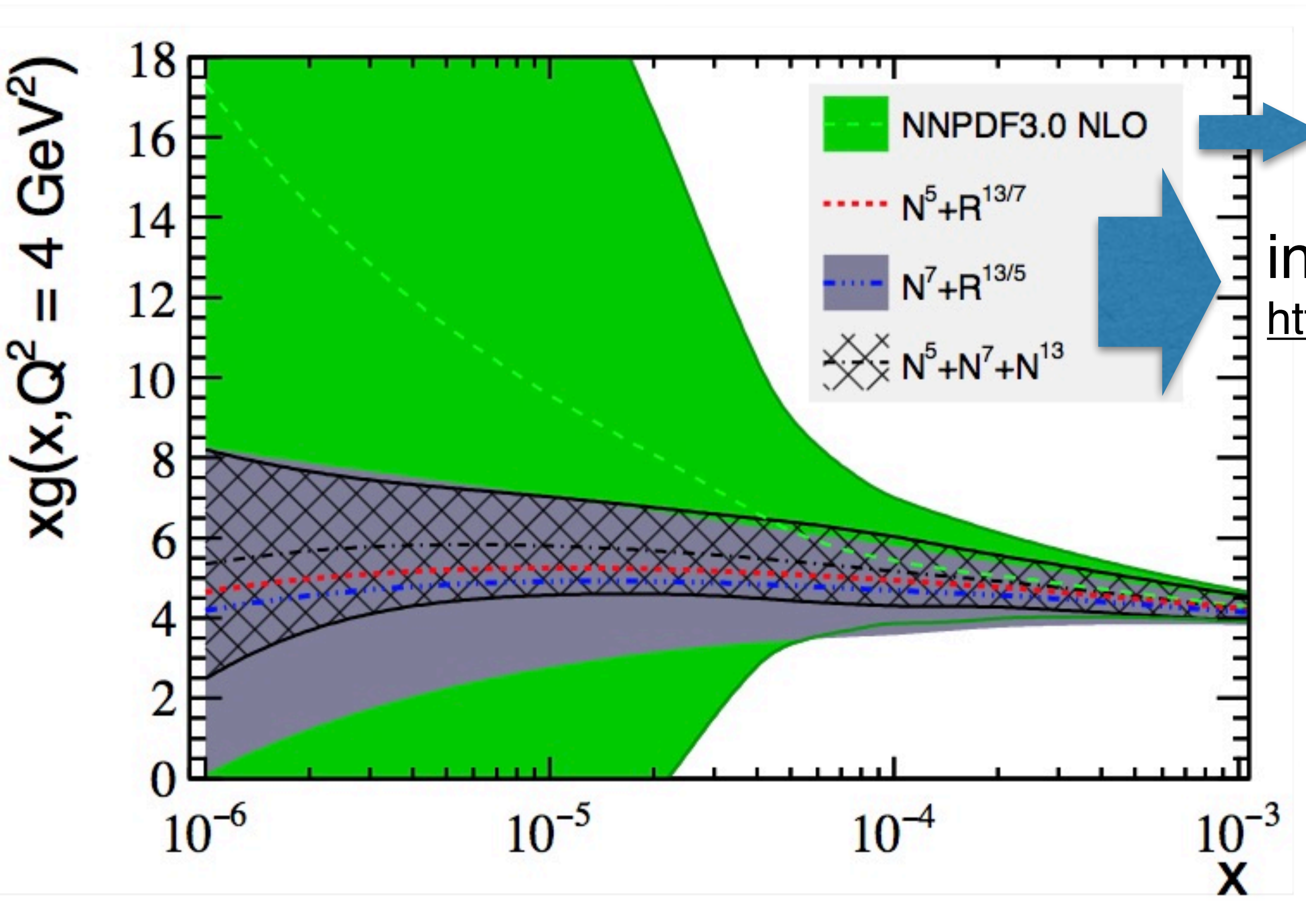


The **LHCb** experiment, with coverage for 2.5<η<5, has a reach in the 10^{-6} range



Forward charm production at LHCb, implications for cosmic ray physics

Gauld, Rojo: http://arxiv.org/abs/arXiv:1610.09373



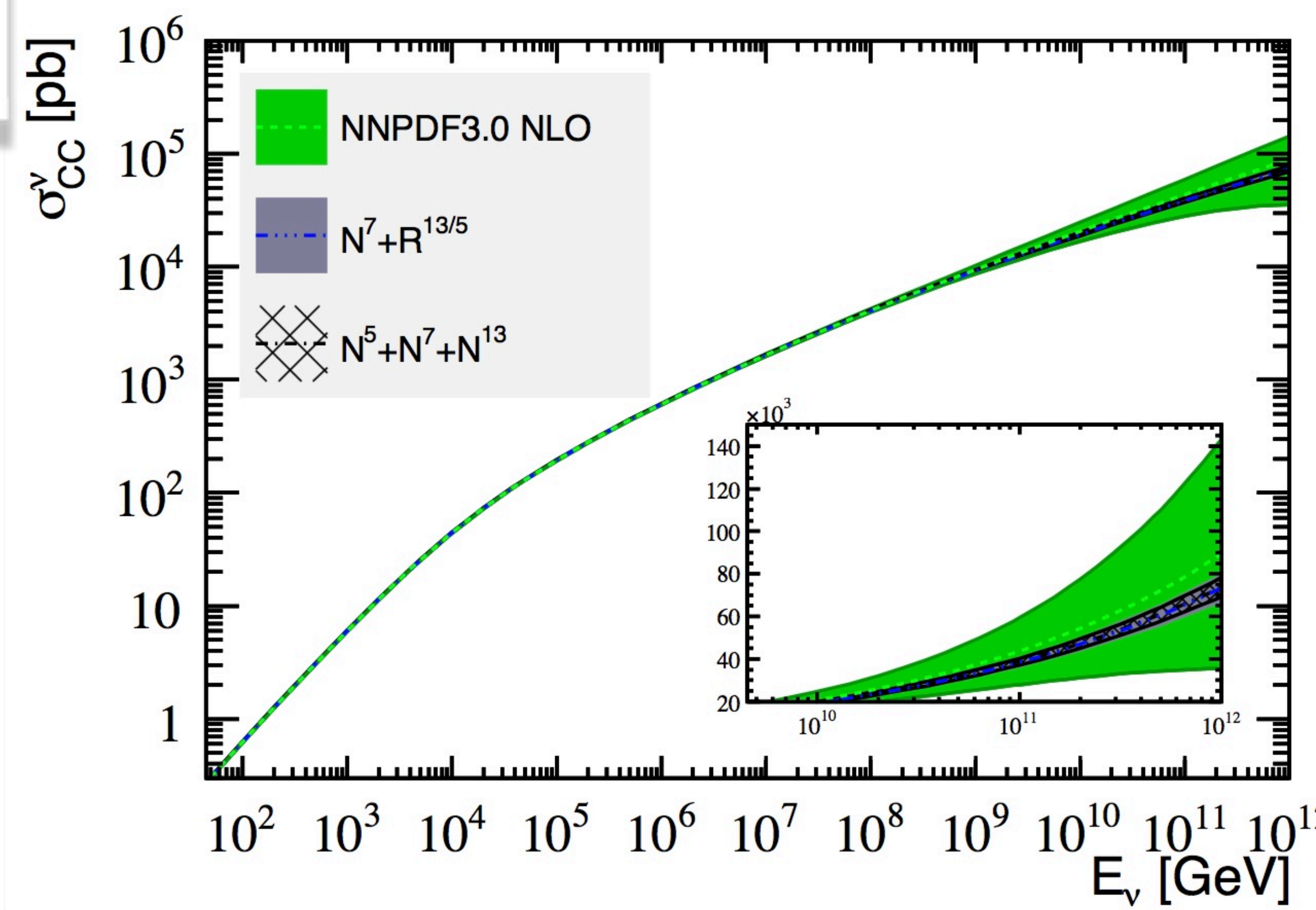
only HERA small-x data

inclusion of LHCb charm data in the fits
http://arxiv.org/abs/arXiv:1610.02230

$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j} ,$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} ,$$

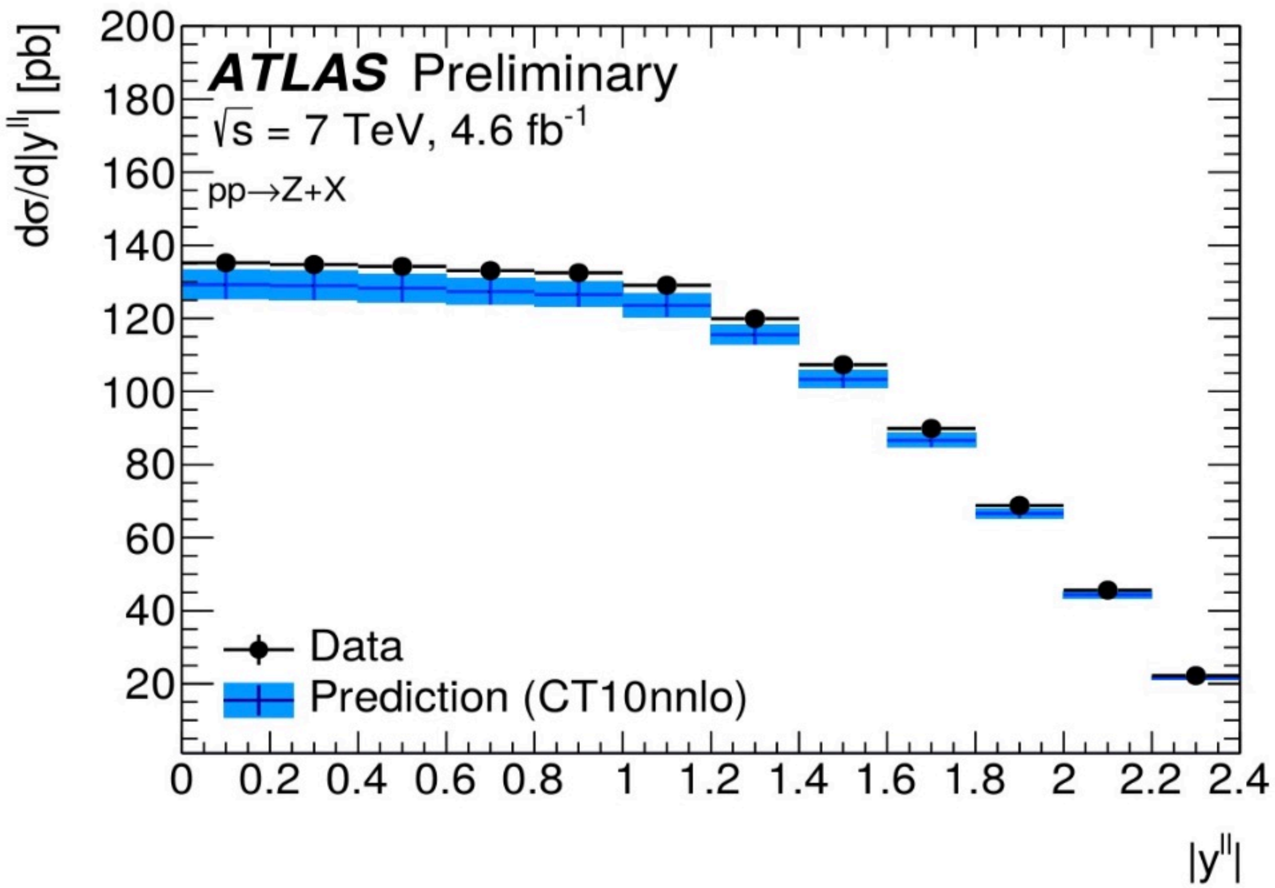
The reduction in small-x gluon PDF uncertainty leads to a reduction in systematics for the calculation of the cross sections of cosmic high-energy neutrinos

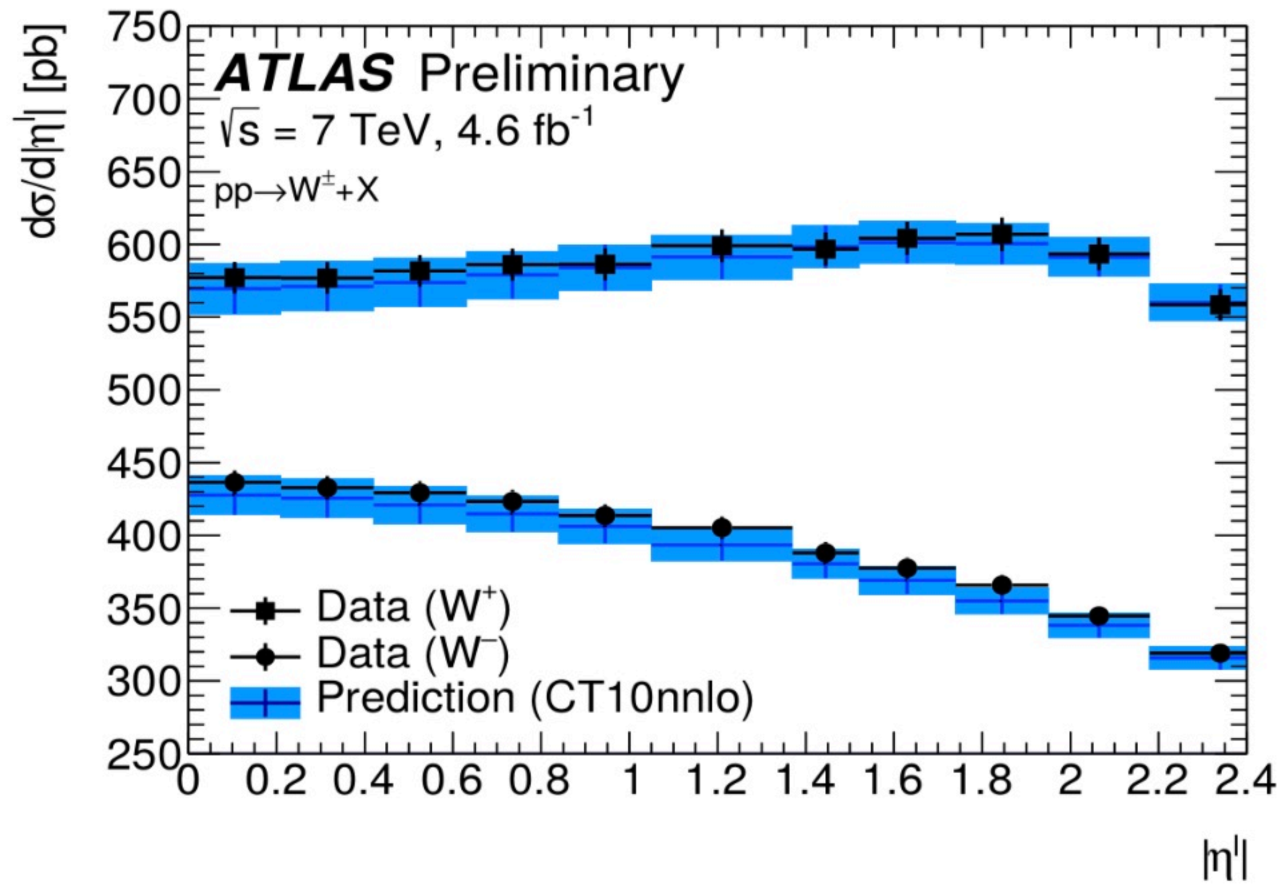


Examples of PDF-sensitive precision measurements of SM parameters

W mass

ATLAS-CONF-2016-113





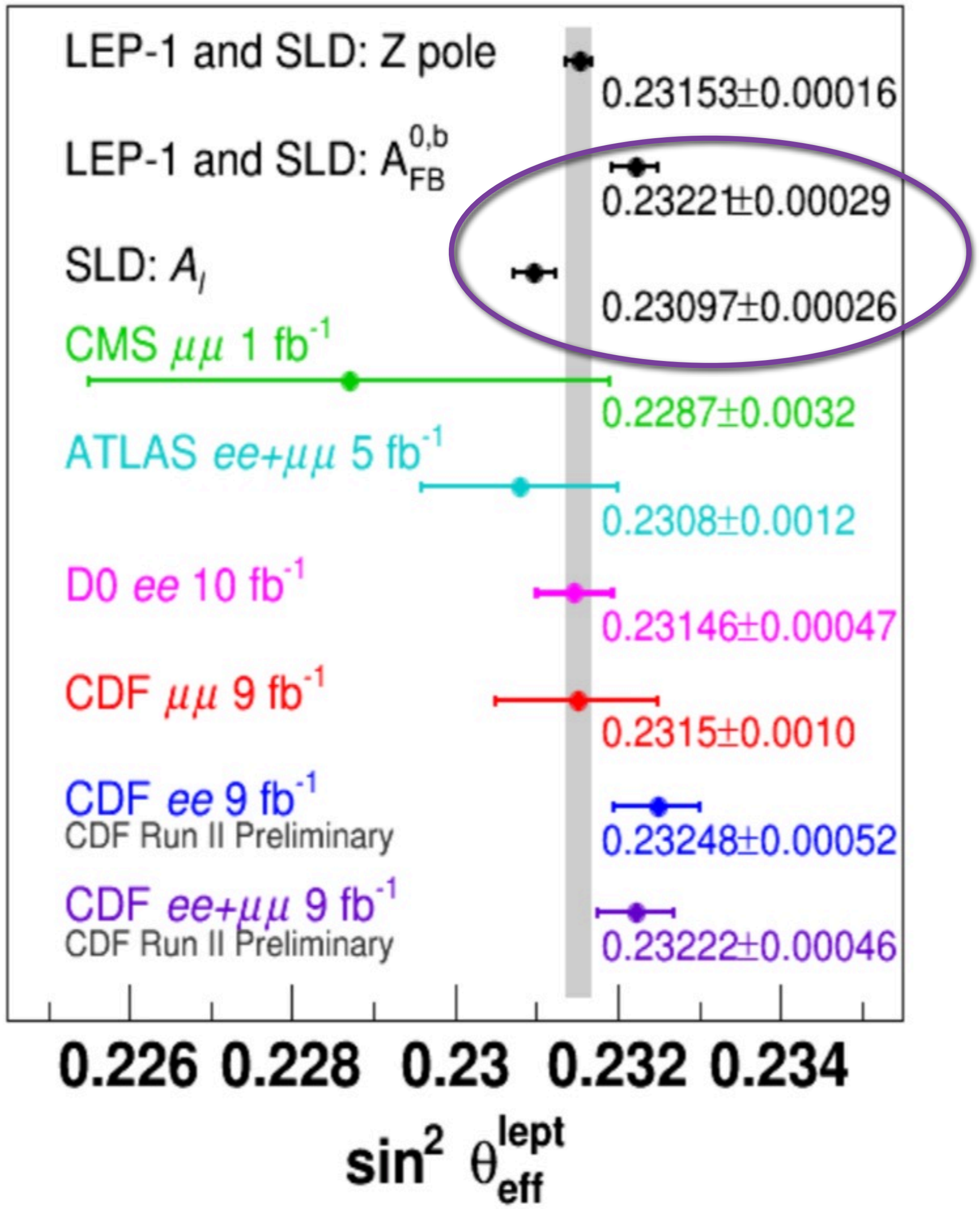
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

m_W = 80.370 ± 0.007 (stat.) ± 0.011 (exp.syst.) ± 0.014 (mod.syst.) GeV

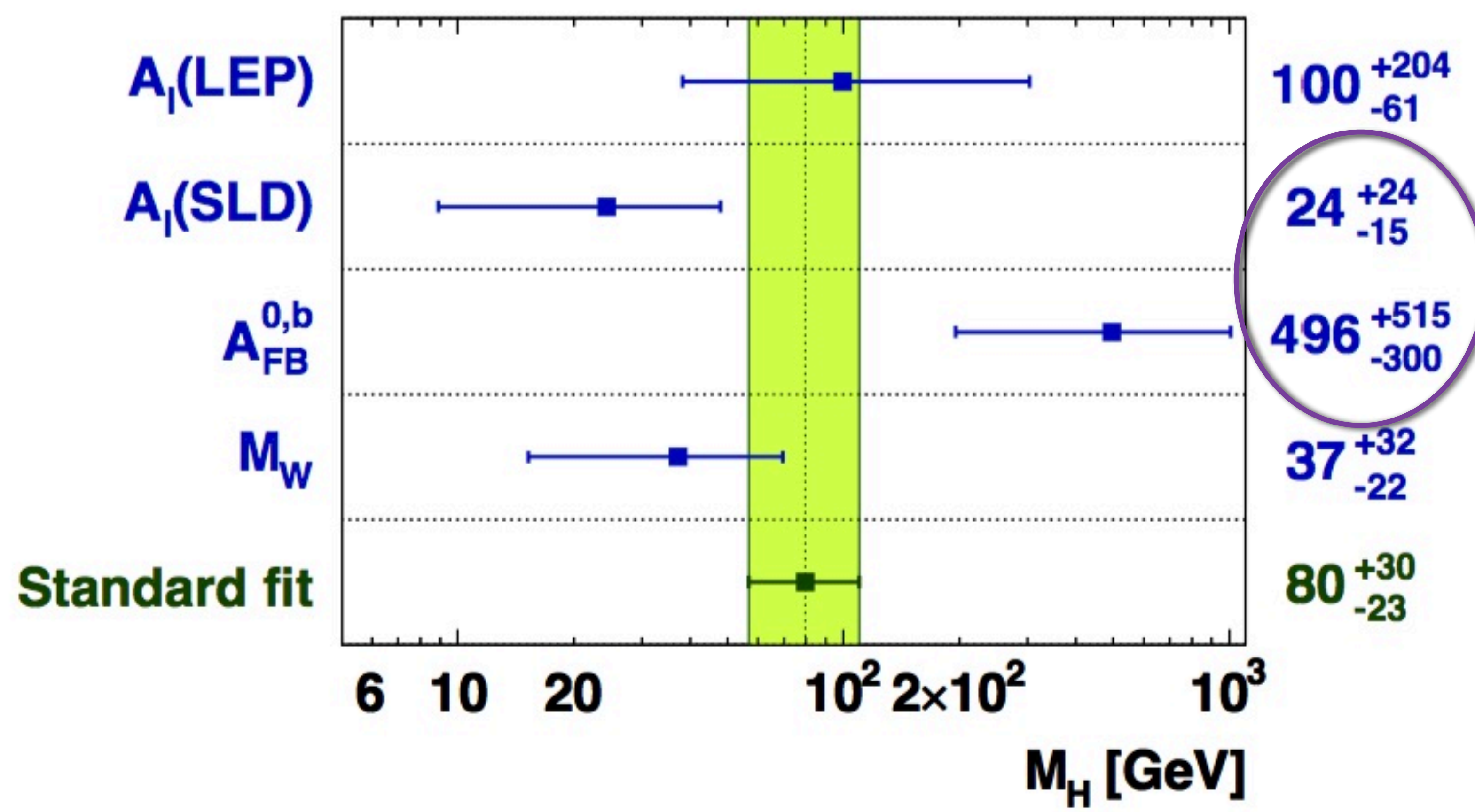
= 80.370 ± 0.019 GeV

$\sin^2\theta_W$

Δ = 0.00123 ± 0.00040
=> ~ 3 σ

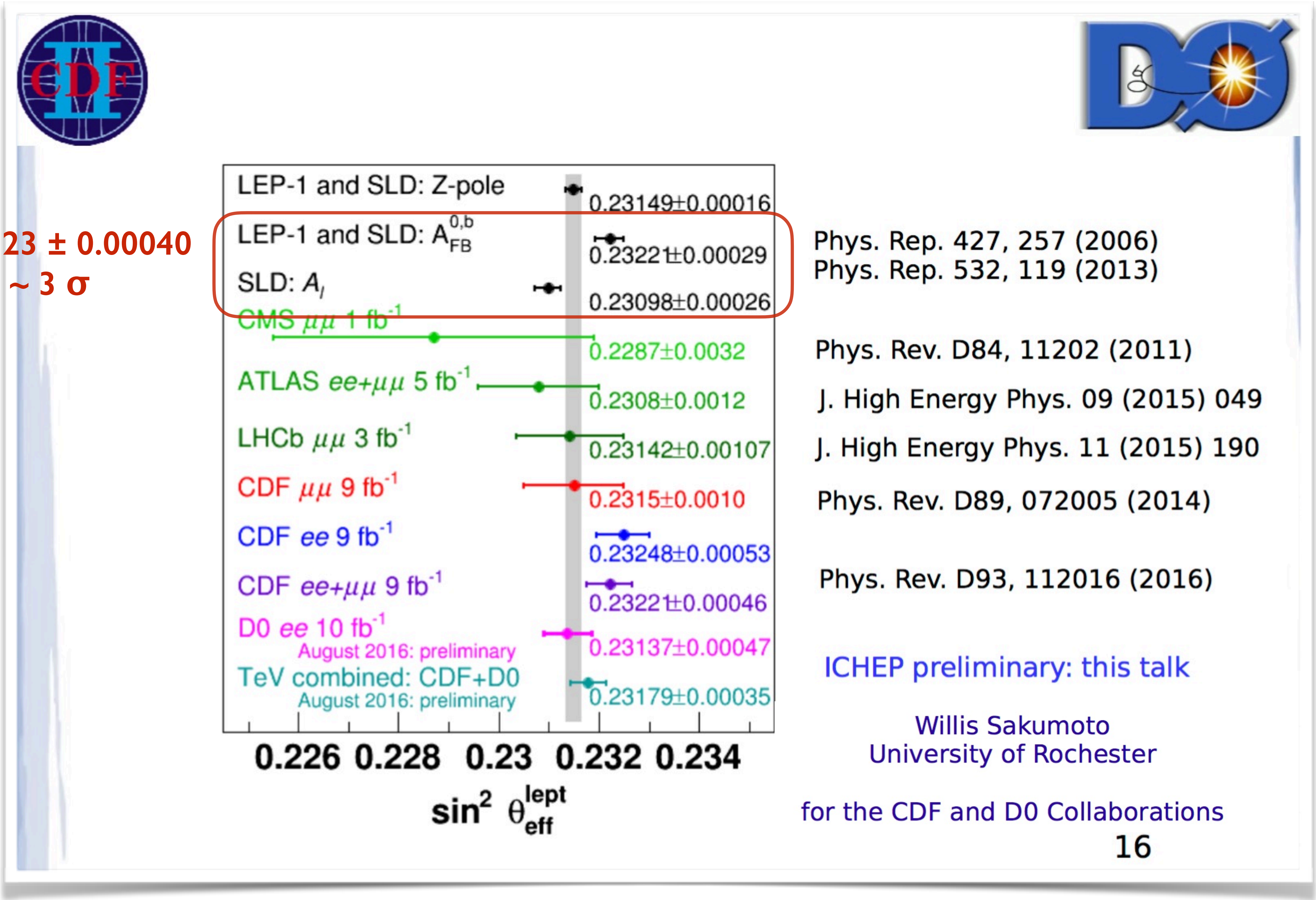


Gfitter, arXiv:0811.0009

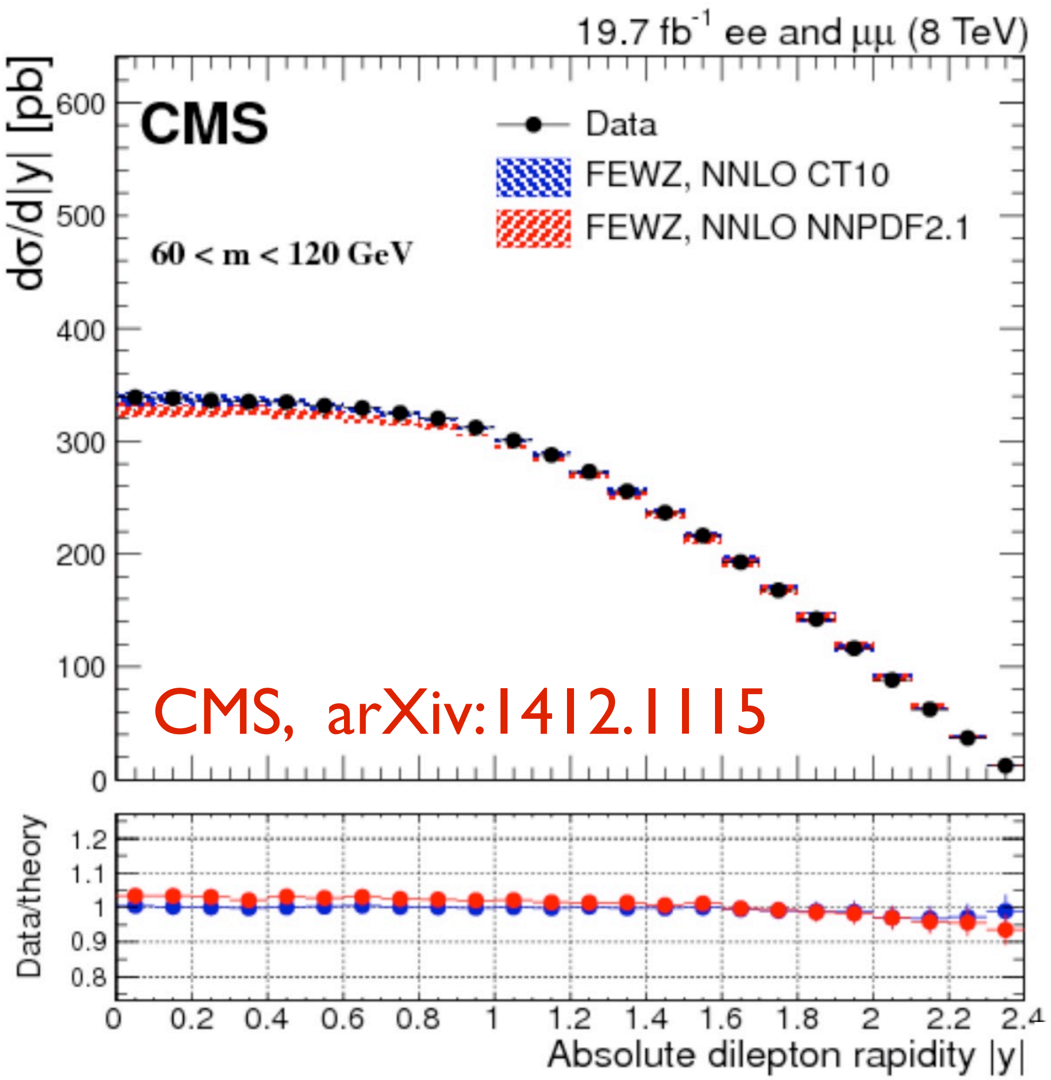


$\sin^2\theta_W$ at the Tevatron

$\Delta = 0.00123 \pm 0.00040$
=> ~ 3 σ



$\sin^2\theta_W$ at the LHC ?

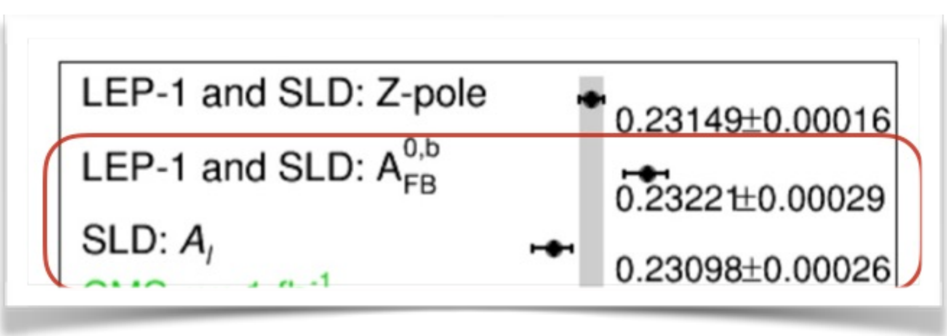


CMS, arXiv:1412.1115

⇒ opens prospects for a precise

measurement of $\sin\theta_W$ from FB lepton asymmetry in Z^0 decays at large y

CMS like detector Energy data sample	20 fb^{-1} 8 TeV current	≈ 200 fb^{-1} 13-14 TeV future
Number of reconstructed events	8.2M $\mu^+\mu^-$ 6.8M e^+e^-	≈ 120M $\mu^+\mu^-$
$\Delta\sin^2\theta_W$ CT10 PDF error $\Delta\sin^2\theta_W$ NNPDF3.0 NNLO error	± 0.00090 ± 0.00050	± 0.00090 ± 0.00050
$\Delta\sin^2\theta_W$ χ^2 Weighted PDF error $\Delta\sin^2\theta_W$ statistical error	± 0.00022 ± 0.00034	± 0.00014 ± 0.00011
Stat+ χ^2 weighted PDF error	± 0.00040	± 0.00018

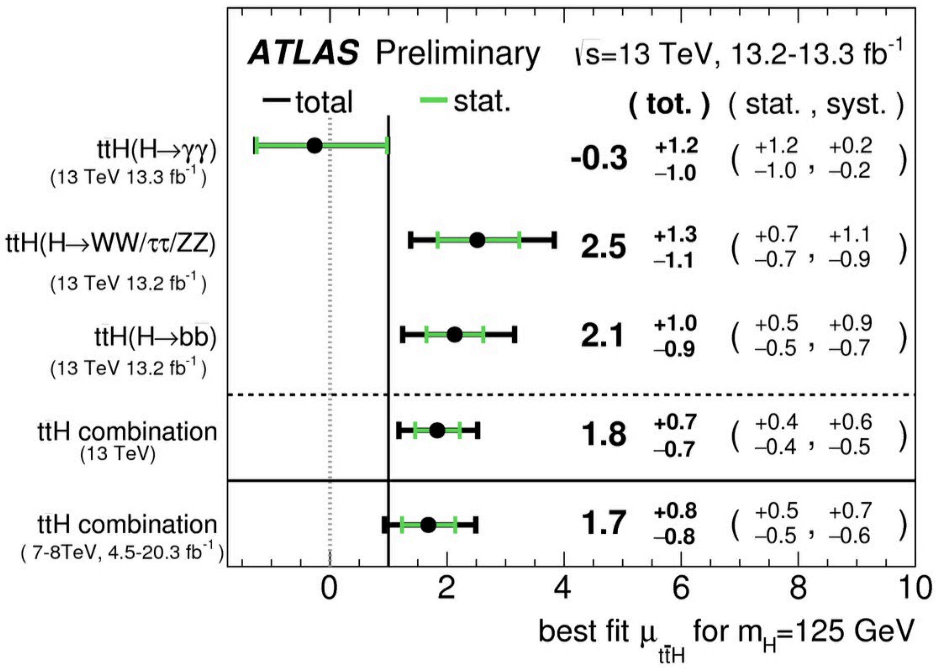


Bodek, Han, Khukhunaishvili, Sakumoto, arXiv:1507.02470

QCD and progress in the measurement of the Higgs boson properties

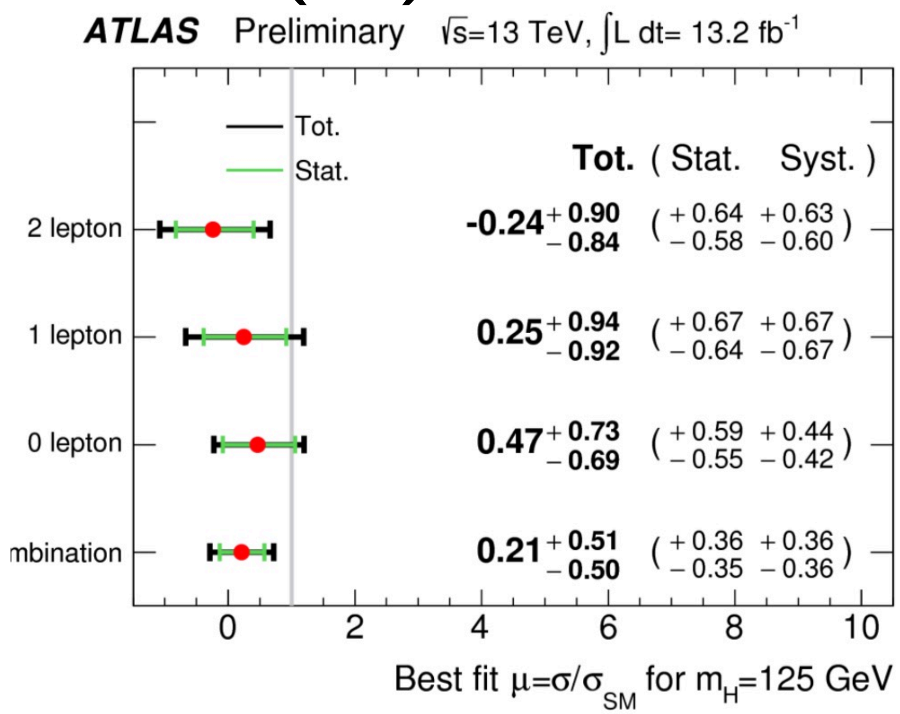
Highlights of 2015-16 Higgs measurements

ttH



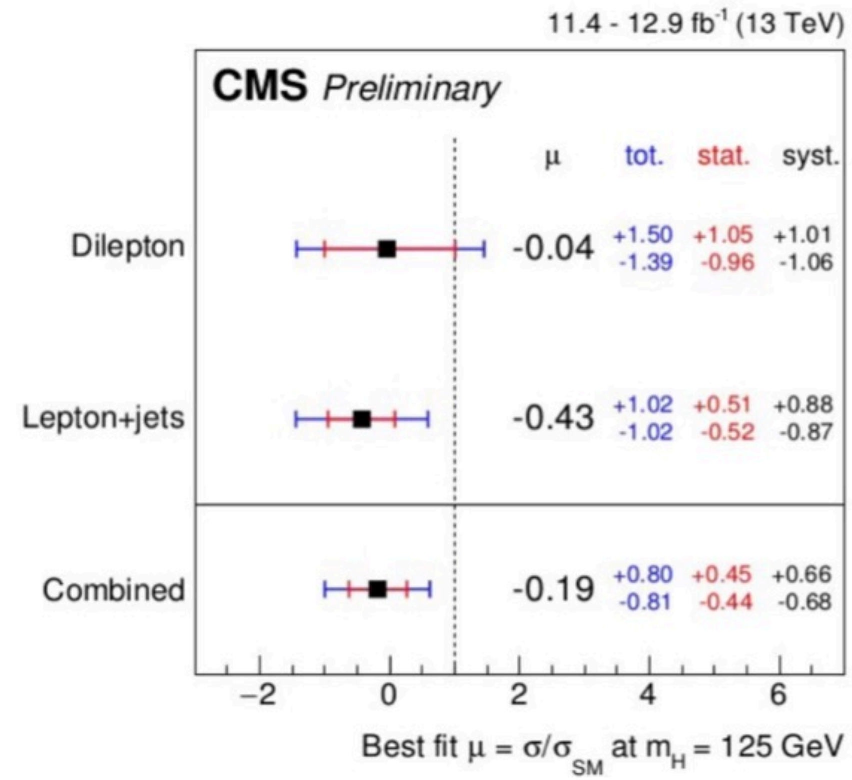
too much ….

VH(bb)



too little ….

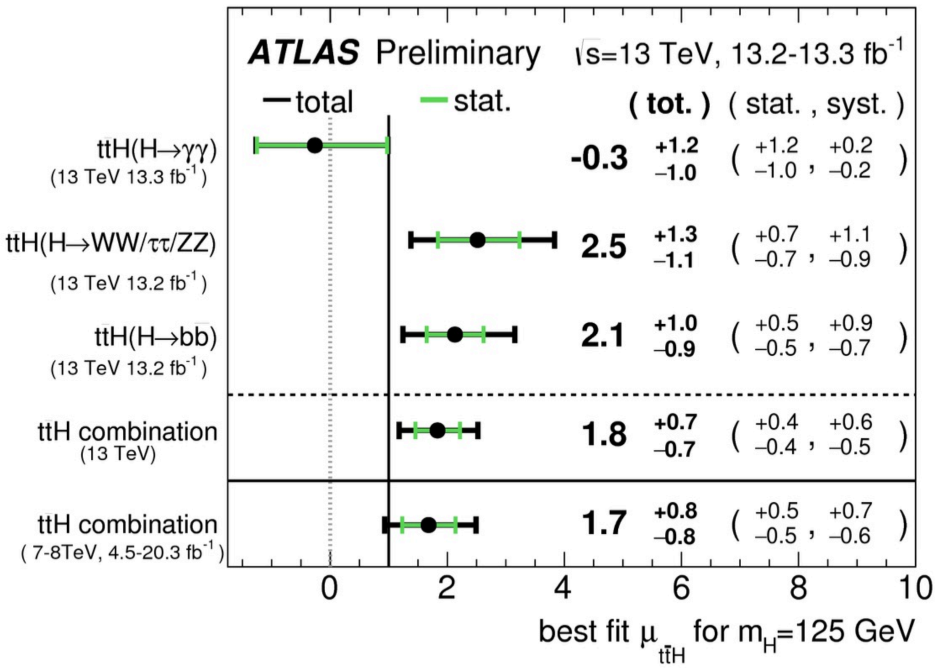
ttH (→bb)



….

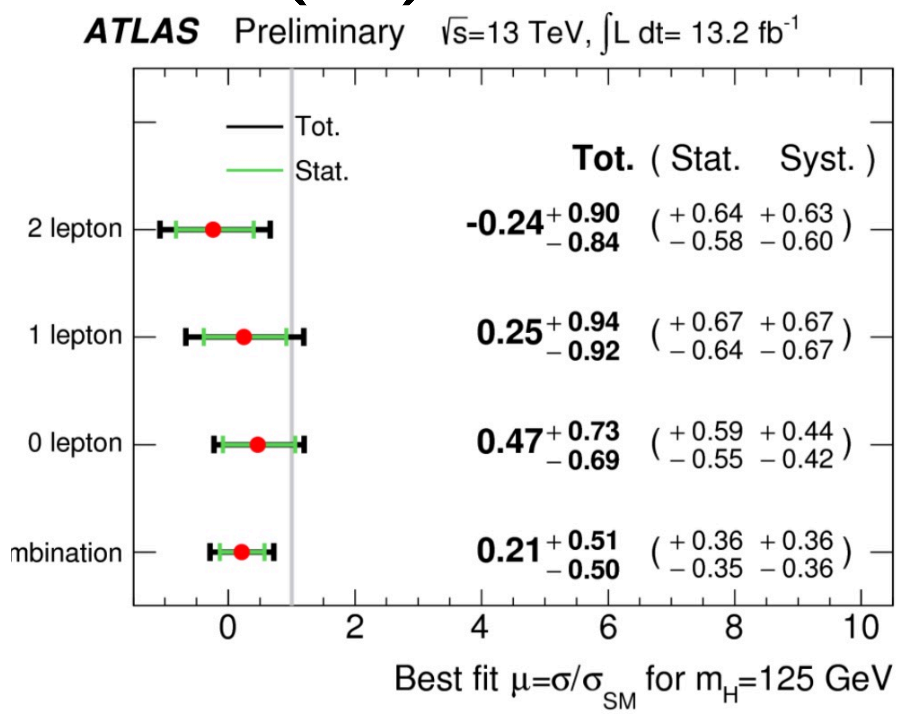
Highlights of 2015-16 Higgs measurements

ttH



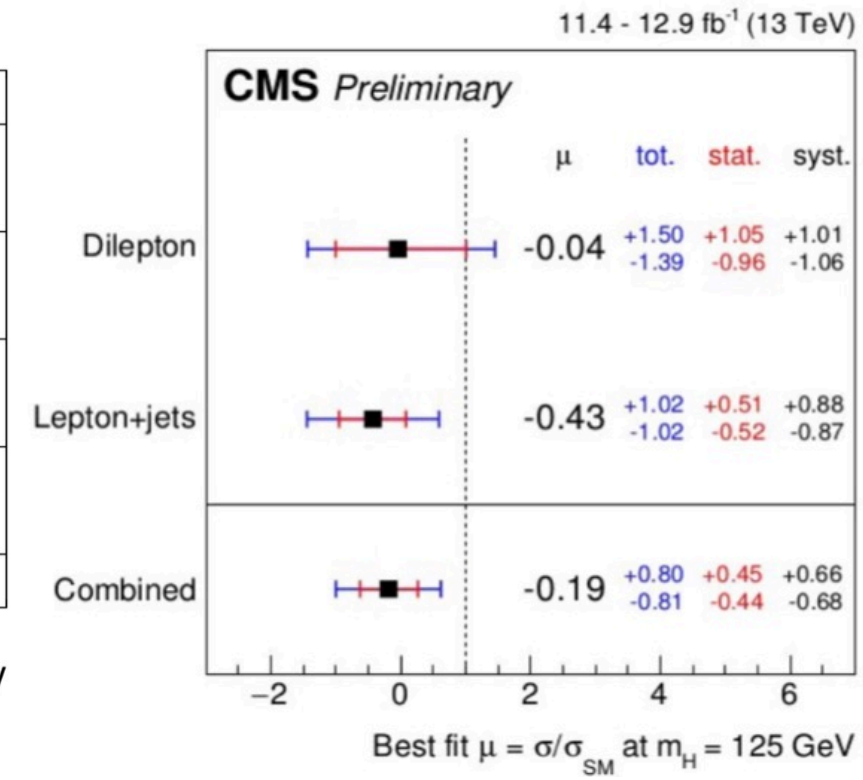
too much ….

VH(bb)

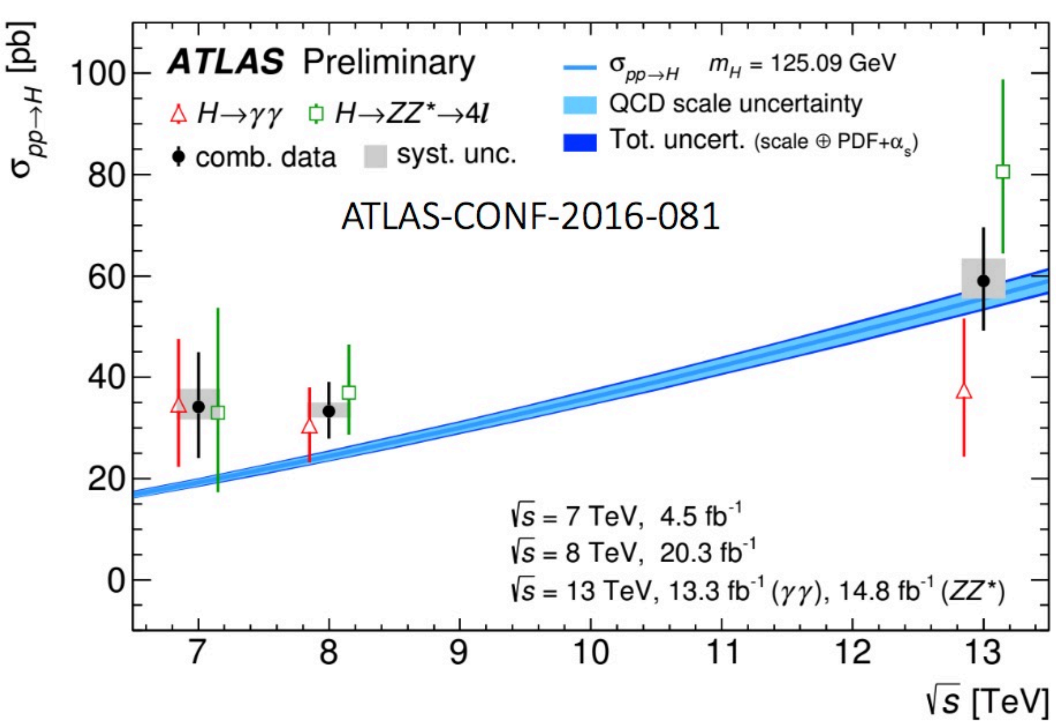


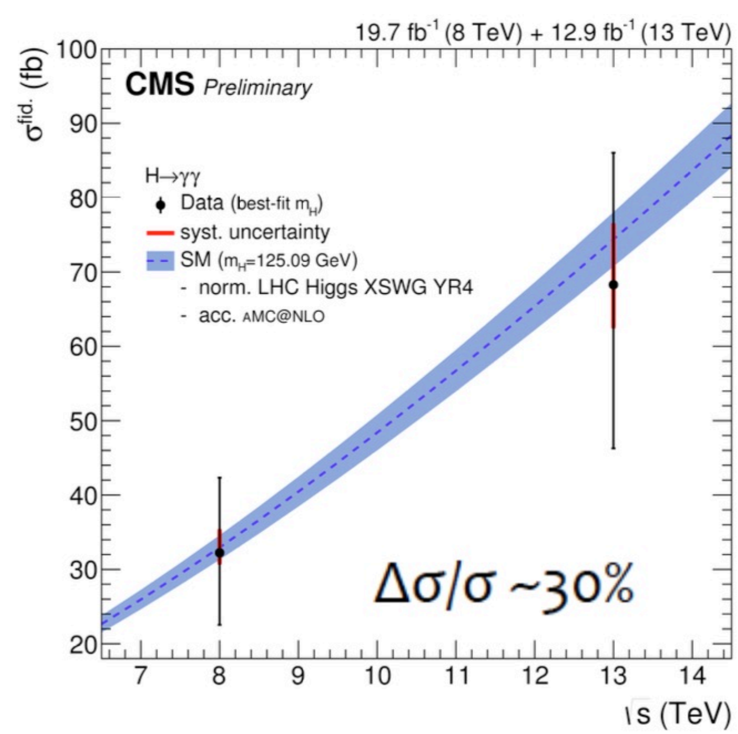
too little ….

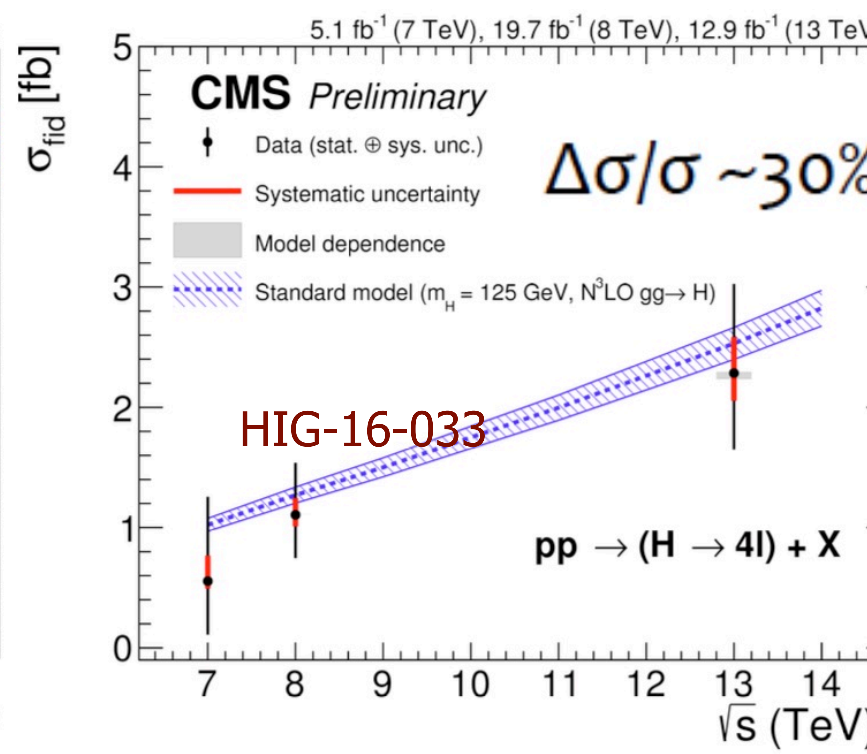
ttH (→bb)



….







just about right …

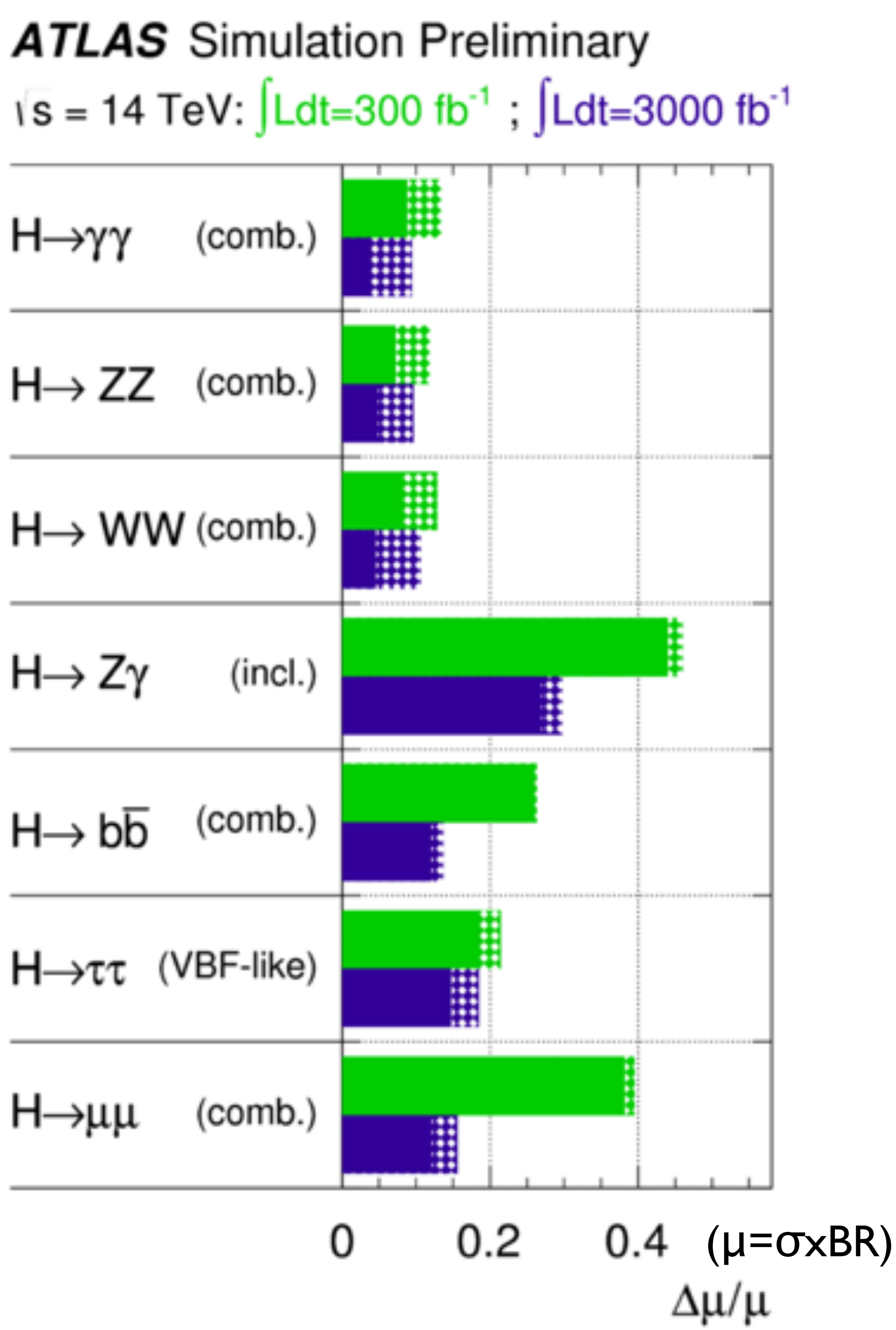
Future evolution of Higgs statistics

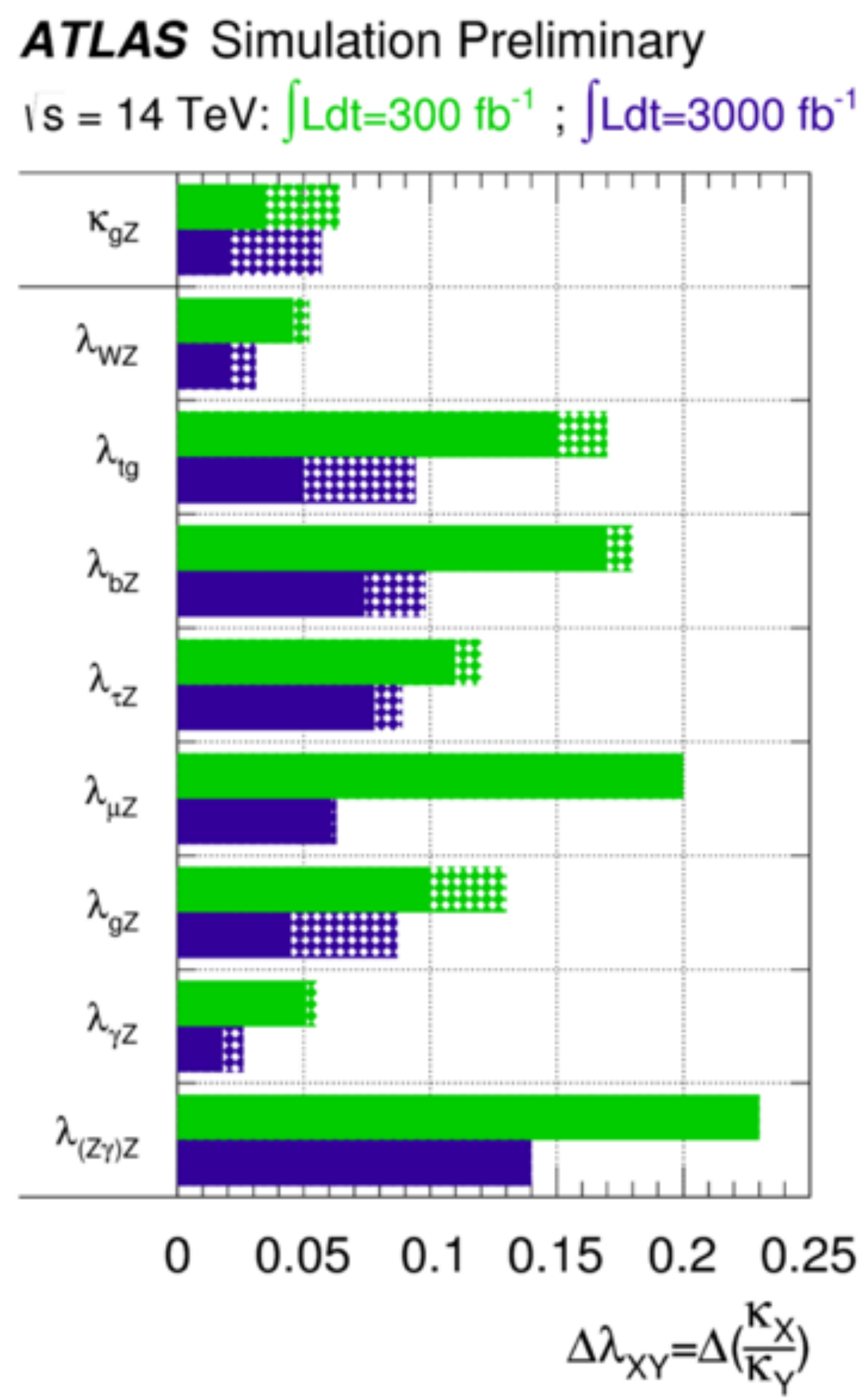
	$\mathcal{L}$ [fb^{-1}]	All	$H\to\gamma\gamma$	$H\to ZZ\to 4l$	$H\to WW^*\to l\nu l\nu$
July '16	13.3	0.75M	600	20	400
End '18	120	7M	6,000	200	4,000
End '23	300	17M	14,000	500	10,000
~ 2035	3000	170M	140,000	5,000	100,000

include estimates of analysis cuts and efficiencies

Projected precision on H couplings

ATL-PHYS-PUB-2014-016





solid areas: no TH systematics

shaded areas: with TH systematics

On theory uncertainties

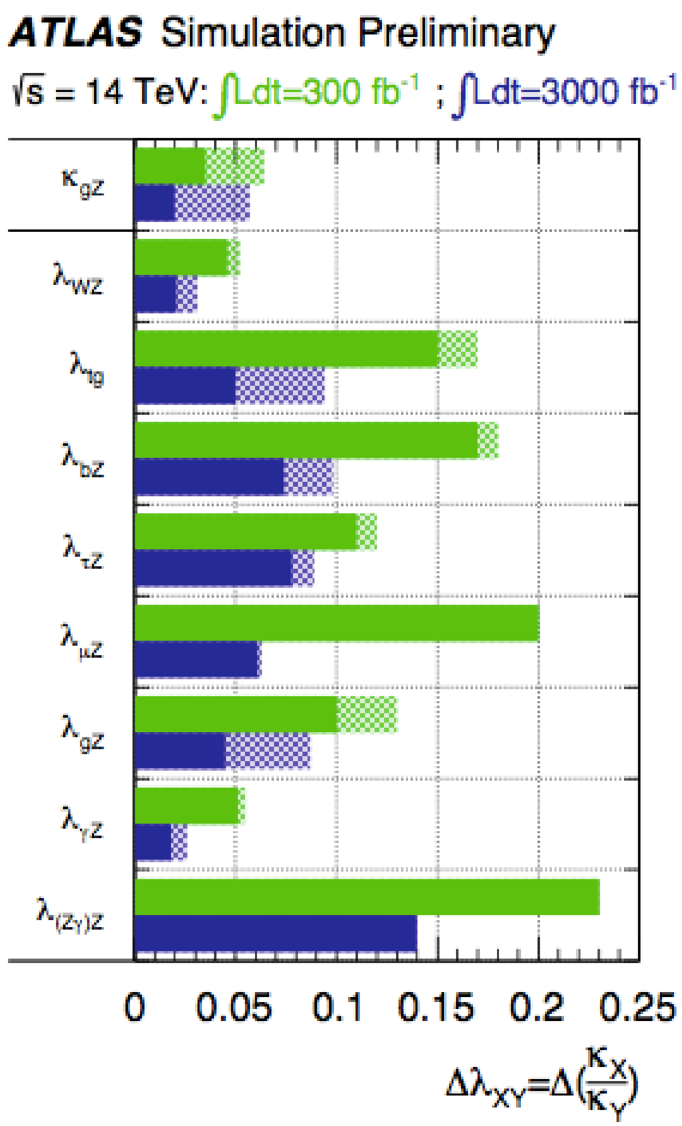


Figure 3: Relative uncertainty expected for the determination of coupling scale factor ratios λXY in a generic fit without assumptions, assuming a SM Higgs boson with a mass of 125 GeV and with 300 fb^{-1} or 3000 fb^{-1} of 14 TeV LHC data. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties.

Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. A dash "-" indicates that the theory uncertainty from existing calculations [10–12] is already sufficiently small to fulfill the condition above for some measurements. The same applies to theory uncertainties not mentioned in the table for any measurement. The impact of the jet-bin and p_T related uncertainties in $gg \to H$ depends on analysis selections and hence no single number can be quoted. Therefore the range of uncertainty values used in the different analysis is shown.

dominated by modeling

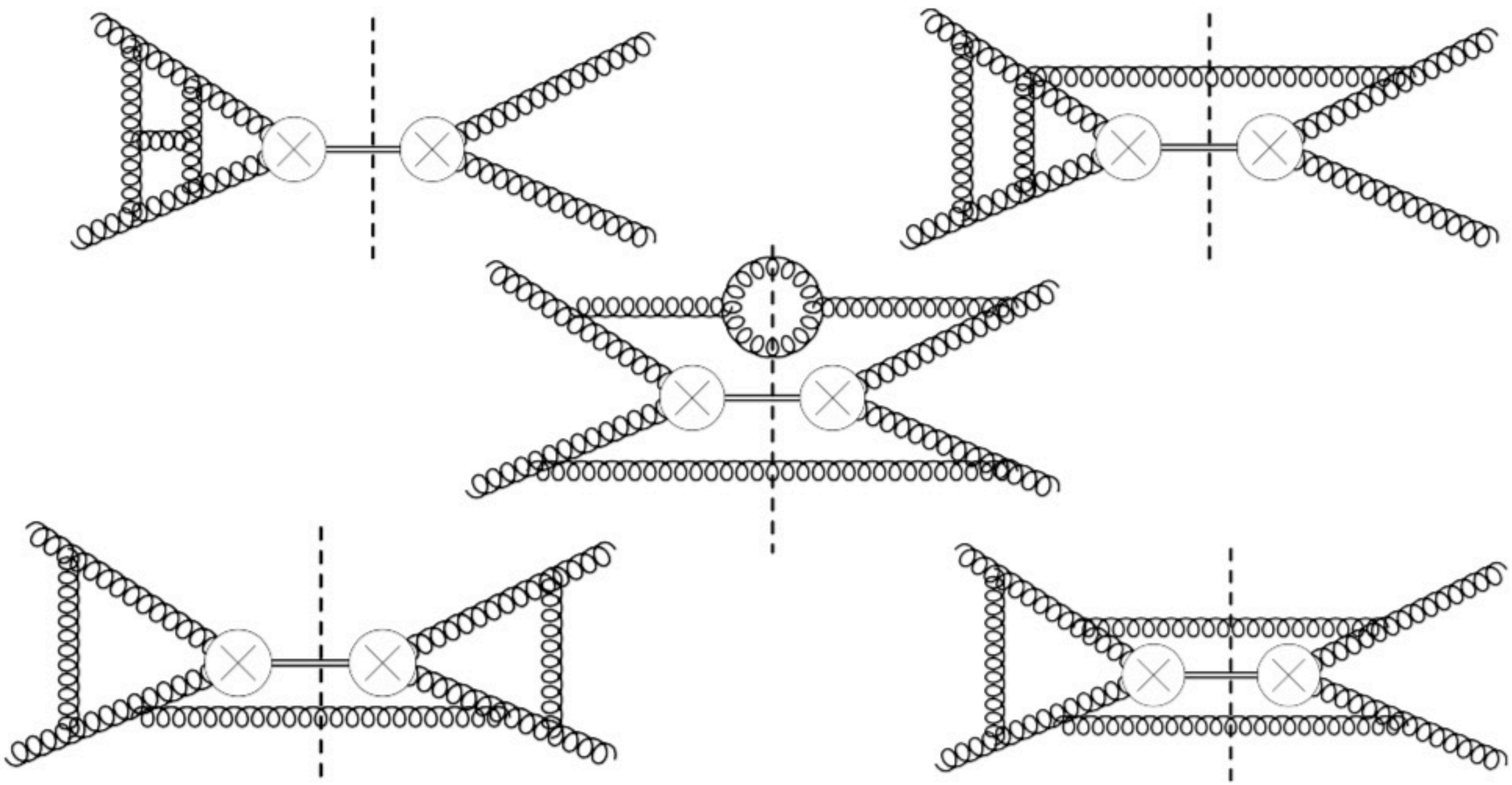
ATL-PHYS-PUB-2014-016

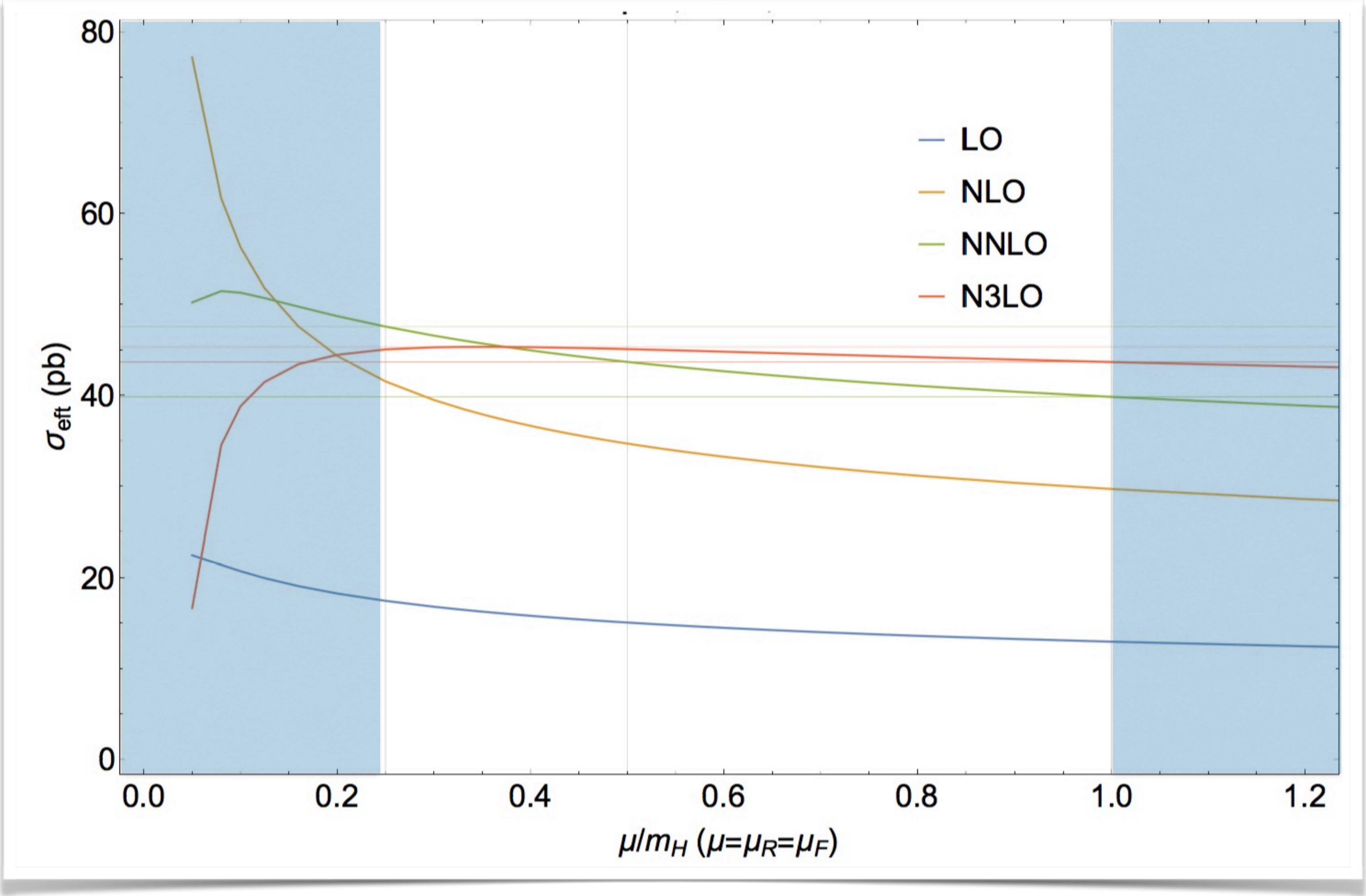
Example in TH progress: pp→Higgs, via gg fusion, at N^{3}LO

High precision determination of the gluon fusion Higgs boson cross-section at the LHC

Charalampos Anastasiou[a], Claude Duhr[b,c]*, Falko Dulat[a], Elisabetta Furlan[a], Thomas Gehrmann[e], Franz Herzog[f], Achilleas Lazopoulos[a], Bernhard Mistlberger[b]

arXiv:1602.00695





NB $\sigma(gg \to H) \propto y_t^2 \quad \Longrightarrow \delta y_t / y_t \propto 0.5\ \delta\sigma_{TH} / \sigma_{TH}$

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\;\;2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\;\;9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\;\;0.34\,\text{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)
	$+\;\;2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\;\;1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)

Lack of NNNLO in PDF evolution

Higher-order EW and mt corrections

PDF fits syst's

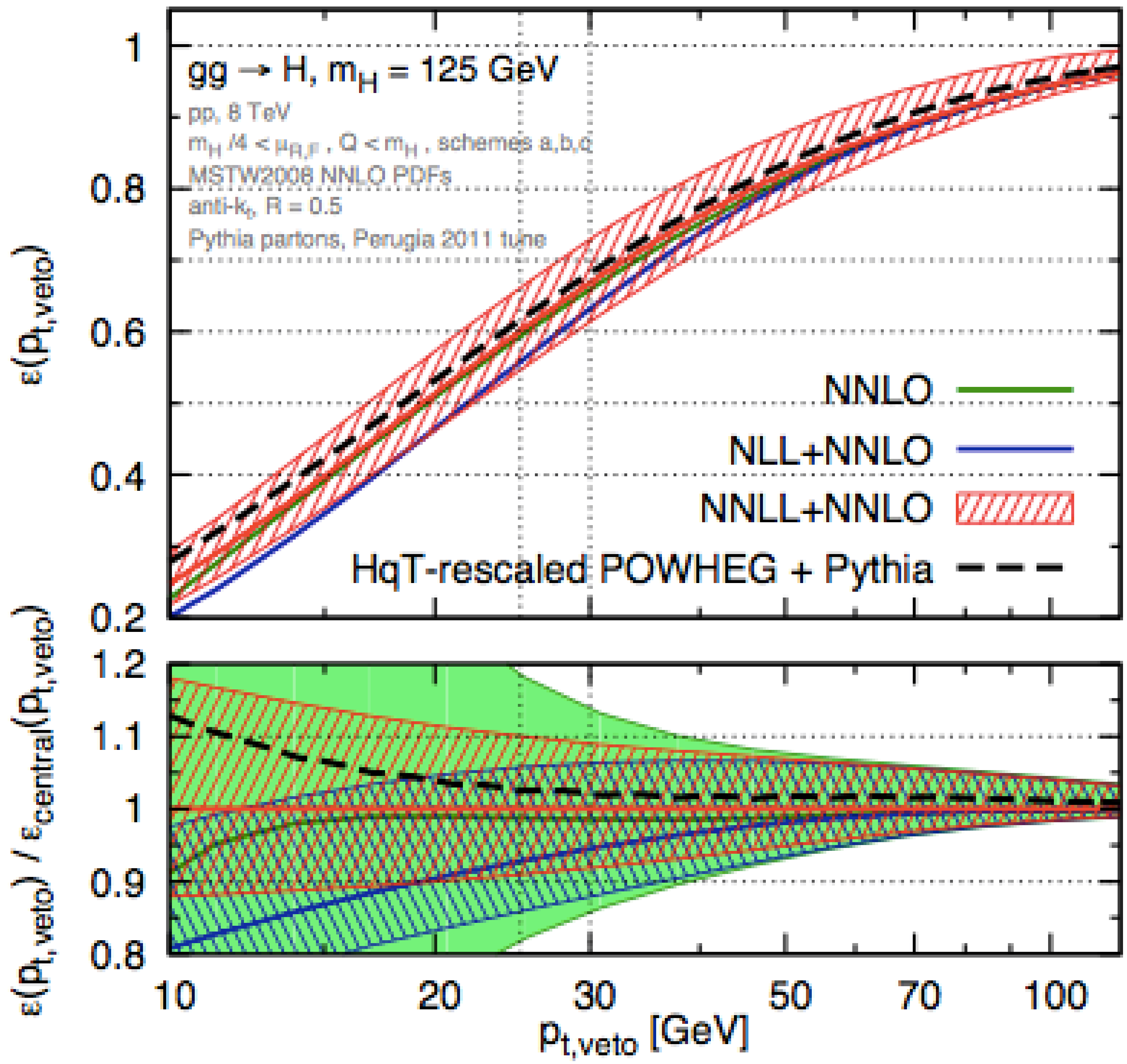
αs Ssyst's

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$	δ(PDF)	$\delta(\alpha_s)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb	± 0.90 pb	$^{+1.27\text{pb}}_{-1.25\text{pb}}$
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$	$\pm 1.86\%$	$^{+2.61\%}_{-2.58\%}$

E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.58 pb	$^{+2.22\text{pb}}_{-3.27\text{pb}}\left(^{+4.56\%}_{-6.72\%}\right)$	$\pm$ 0.90 pb ($\pm$ 1.86%)	$^{+1.27\text{pb}}_{-1.25\text{pb}}\left(^{+2.61\%}_{-2.58\%}\right)$

Example of theoretical modeling systematics in the interpretation of Higgs measurements: jet vetoes

Jet veto required to reduce ttbar bg's to H→WW*



Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

Digression: the importance of EW bosons' p_T distributions in hadronic collisions

Nuclear Physics B246 (1984) 12–44

VECTOR BOSON PRODUCTION AT COLLIDERS: A THEORETICAL REAPPRAISAL

G. ALTARELLI

CERN, Geneva, Switzerland and Dipartimento di Fisica, Università "La Sapienza", Roma, Italy
INFN, Sezioue di Roma, Italy

R.K. ELLIS*

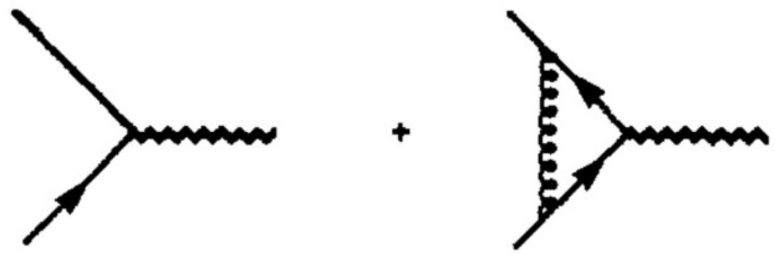
INFN, Sezione di Roma, Italy

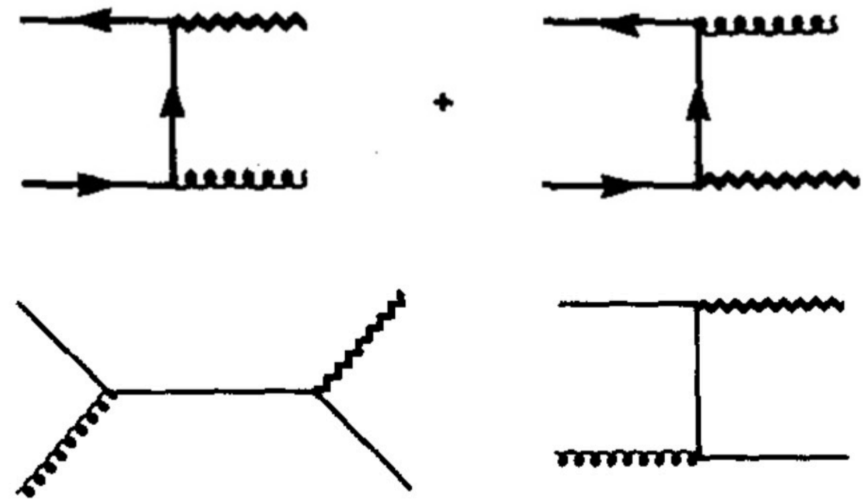
M. GRECO and G. MARTINELLI

INFN, Laboratori Nazionali di Frascati, Italy

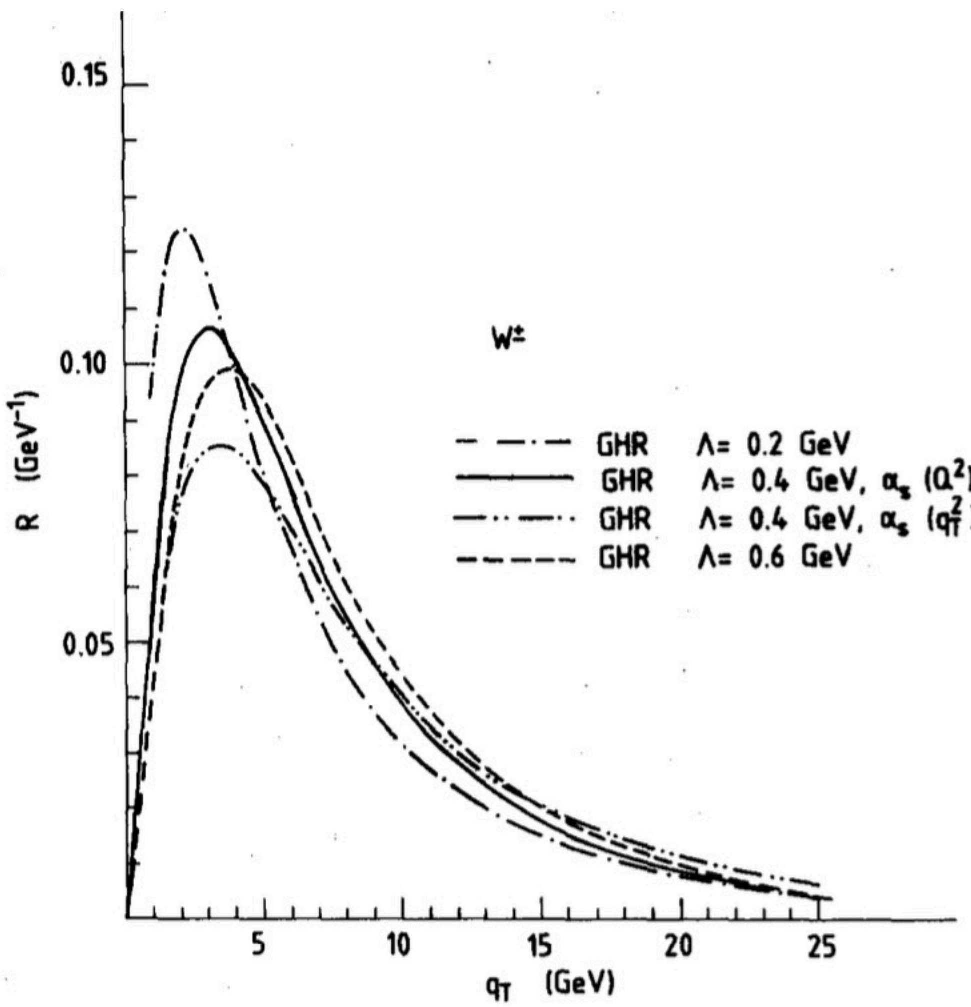
Received 2 May 1984
(Revised 13 June 1984)

p_T(W) spectrum at LO



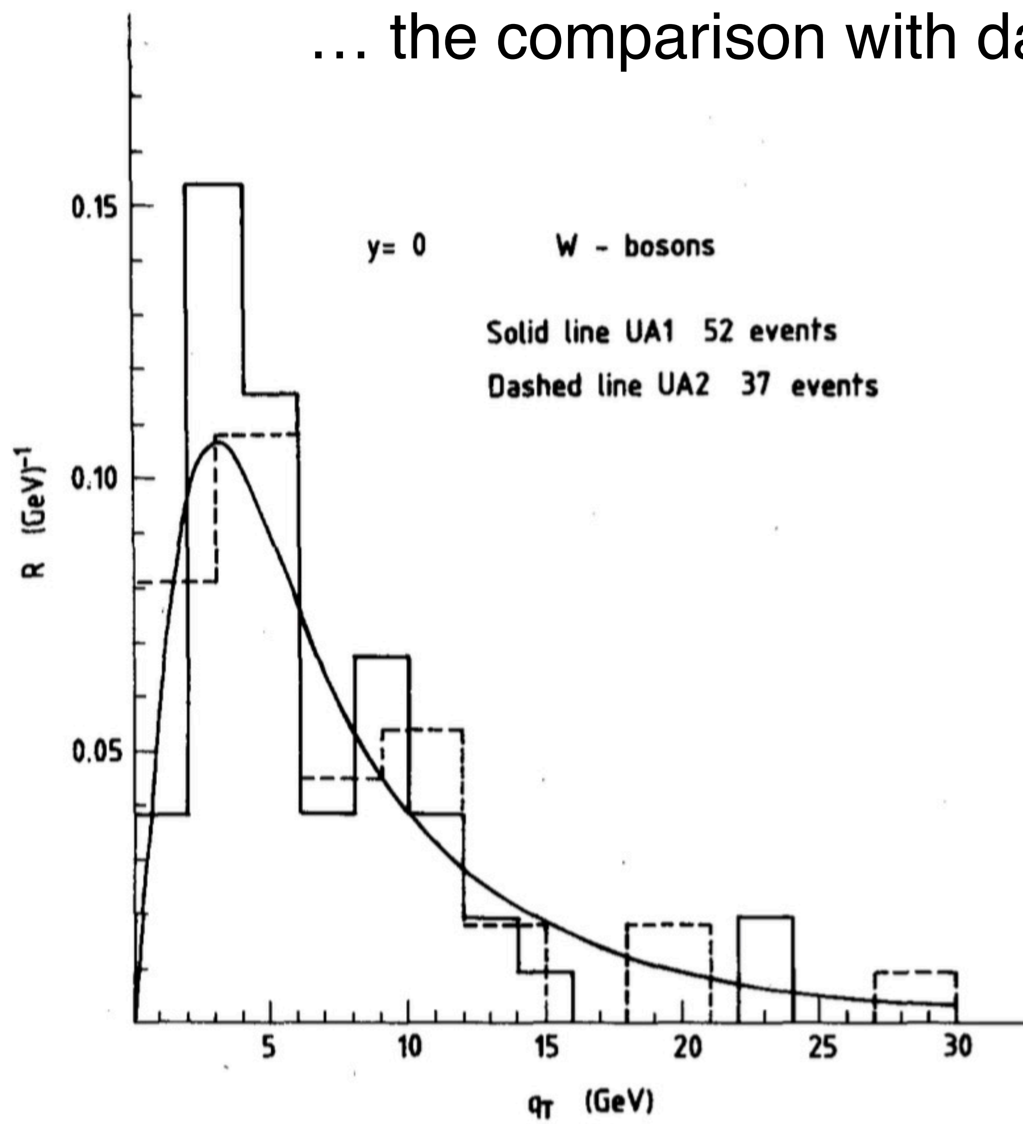


The theoretical systematics ….



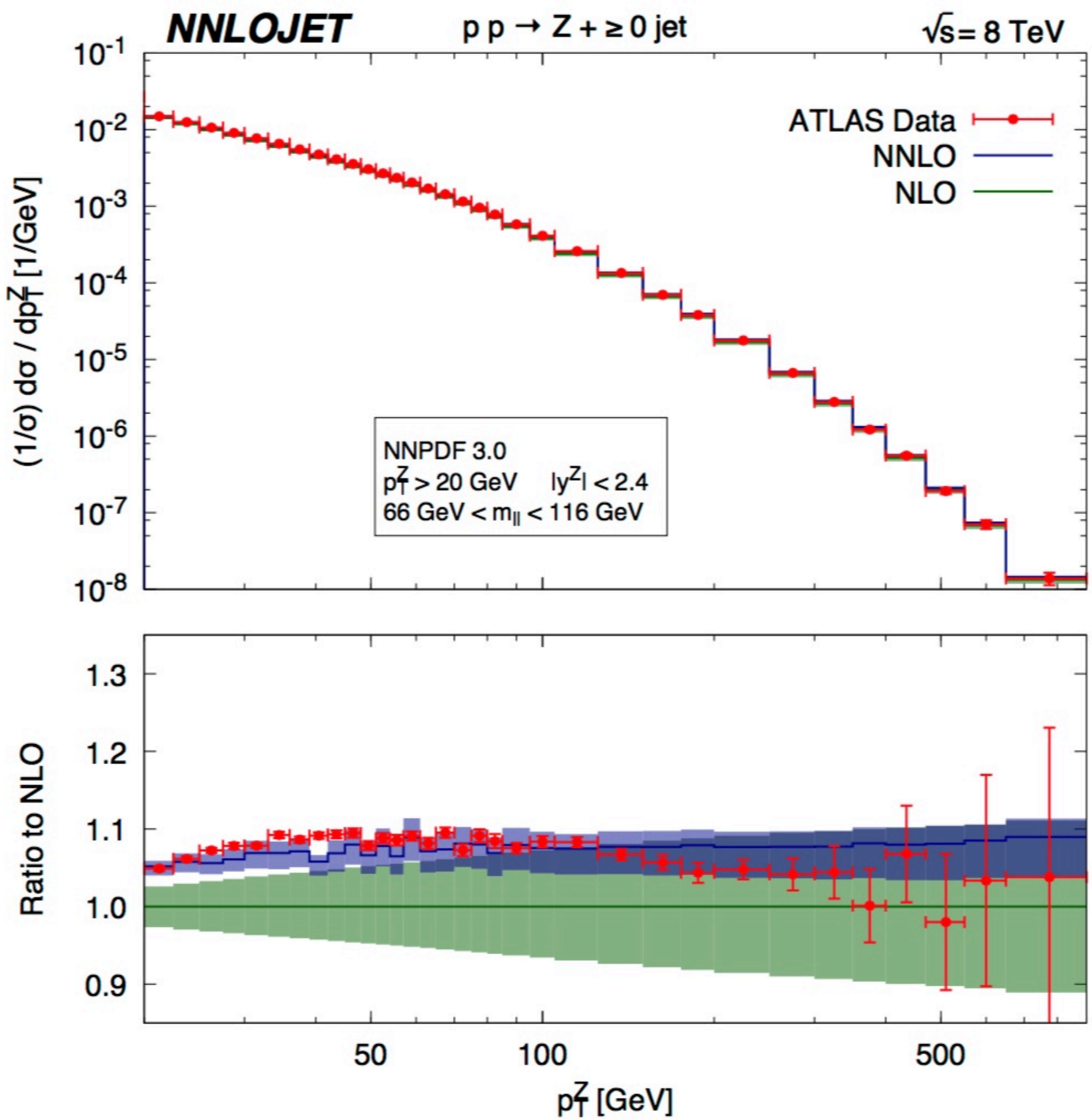
ig. 4. The ratio $R=(\mathrm{d}\sigma/\mathrm{d}q_T\,\mathrm{d}y)/(\mathrm{d}\sigma/\mathrm{d}y)$ at rapidity $y=0$ using the densities of GHR. The two urves with $\Lambda=0.4$ GeV differ by the choice of scale in terms of order α_s which is taken either as Q^2 or q_T^2 (other values of Λ correspond to the choice Q^2).

… the comparison with data

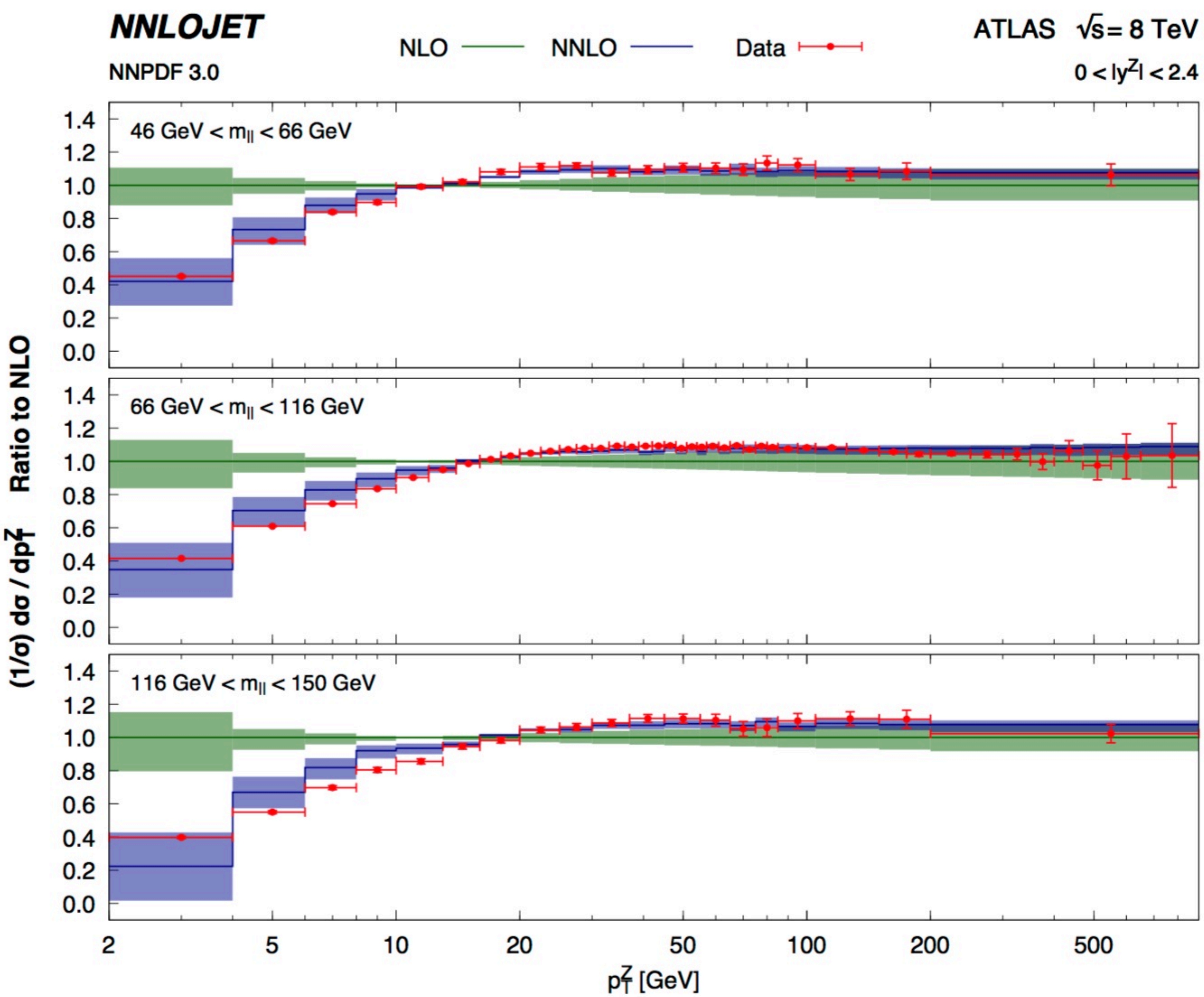


The data for $W^\pm$ boson production suitably normalized and plotted against q_T. Also shown is our prediction for GHR, $\Lambda=0.4$ GeV, $y=0$, $\alpha_s(Q^2)$.

$p_T(Z)$ spectrum at NNLO

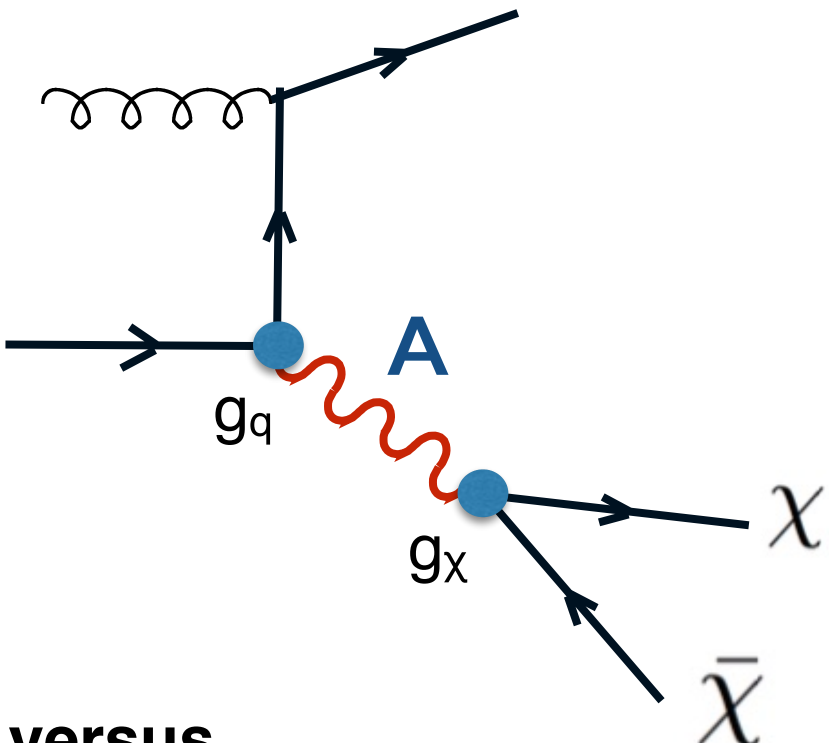


Gehrmann–De Ridder, Gehrmann, Glover, Huss, Morgan, arxiv:1610.01843

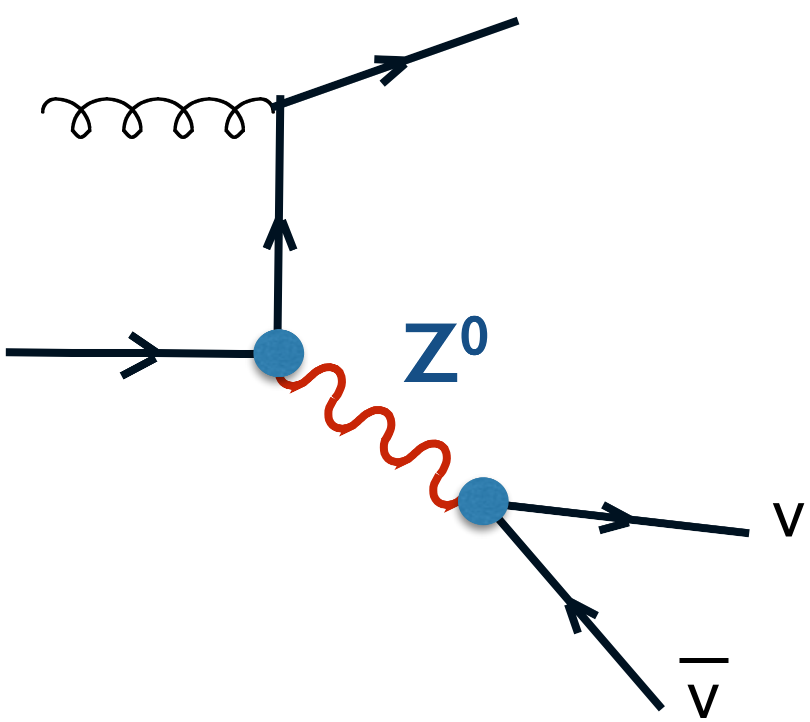


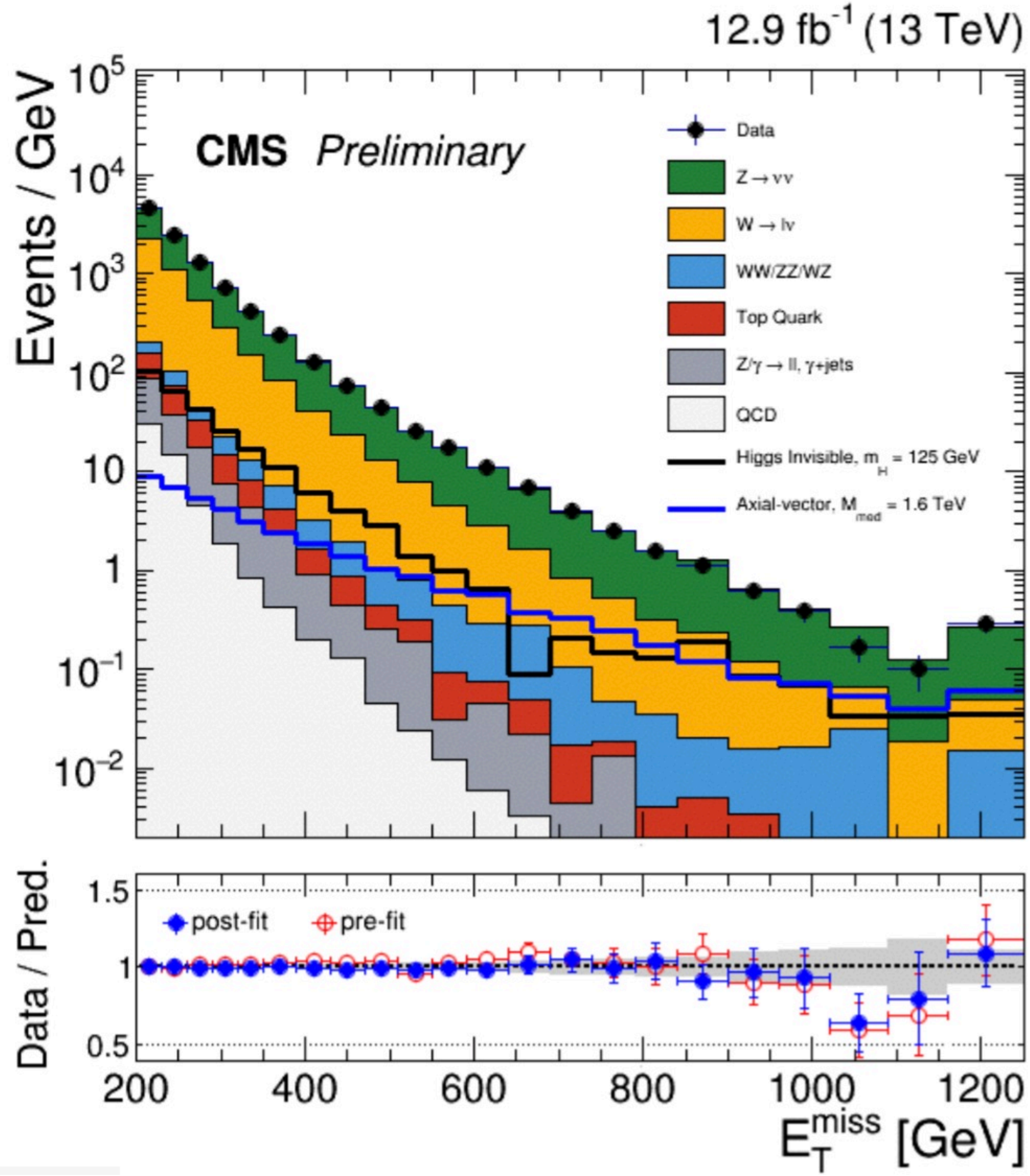
Gehrmann–De Ridder, Gehrmann, Glover, Huss, Morgan, arxiv:1610.01843

Understanding the p_T of gauge bosons in the search for DM signatures



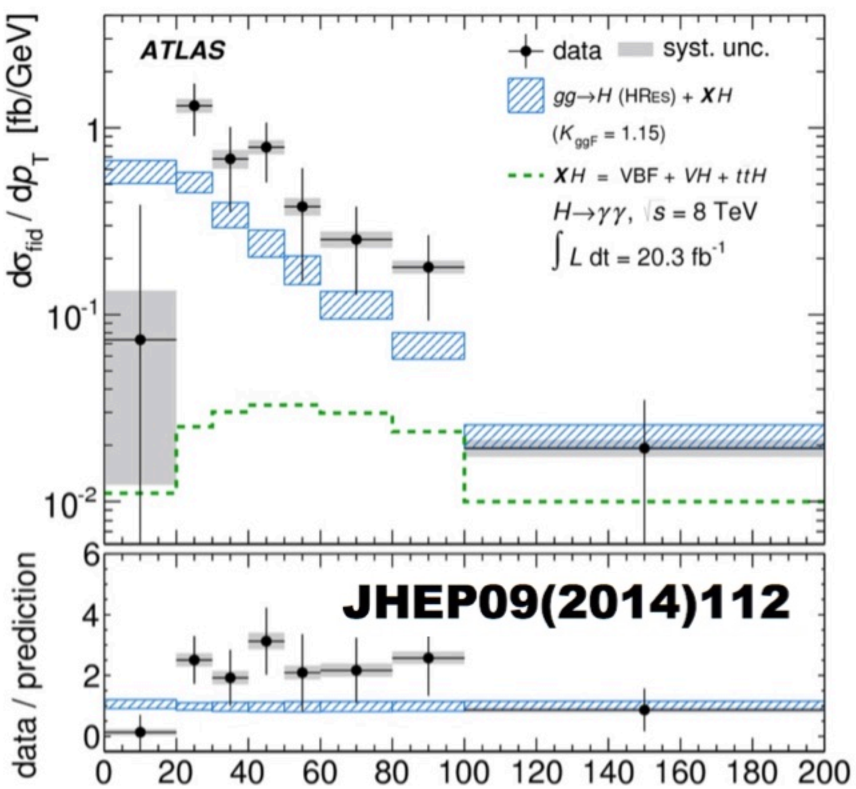
versus



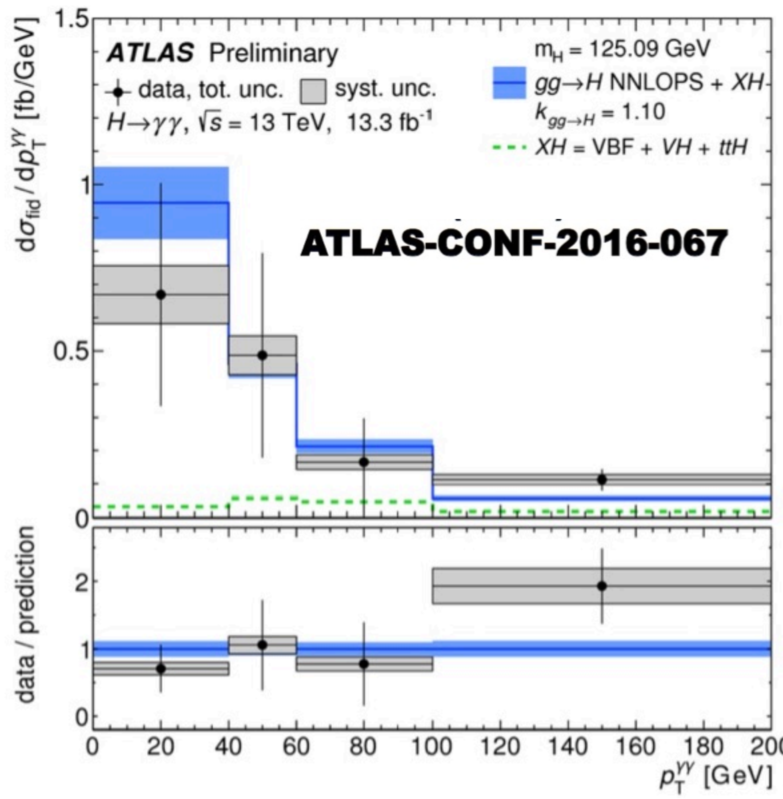


back to the Higgs: first probes of production dynamics, $p_T(H)$ spectrum

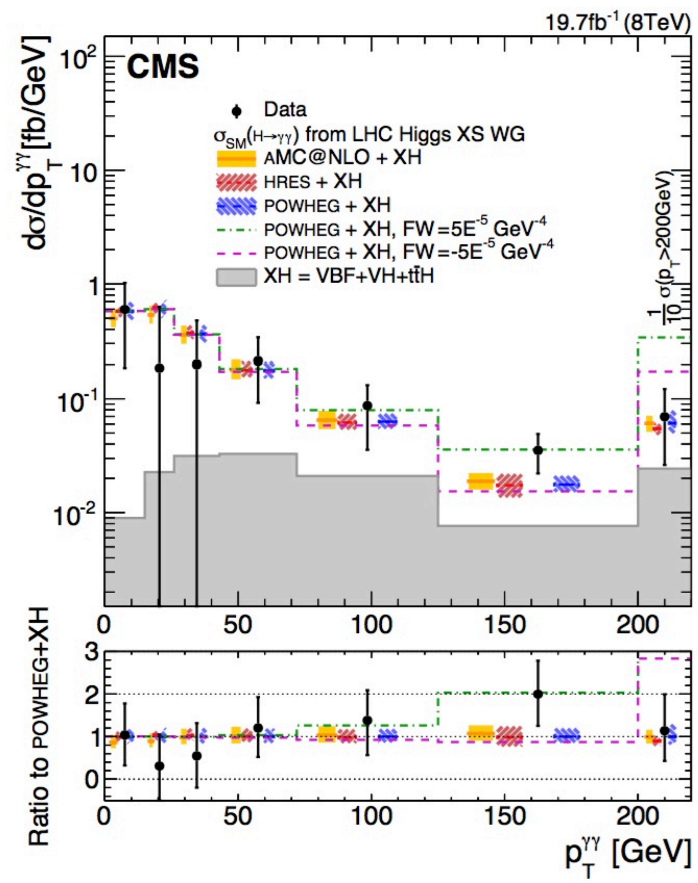
ATLAS γγ run 1



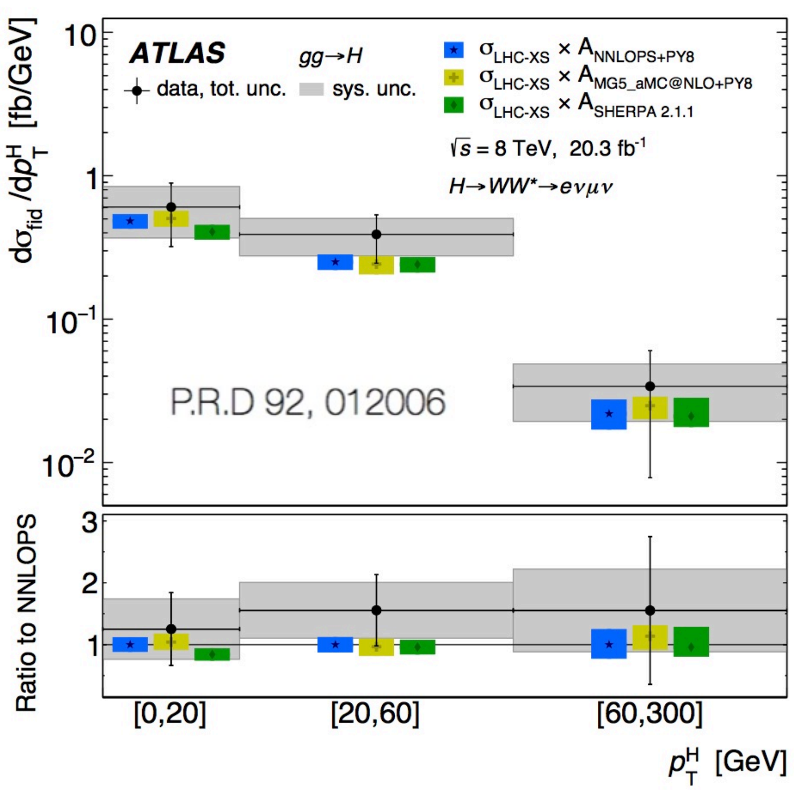
ATLAS γγ run 2



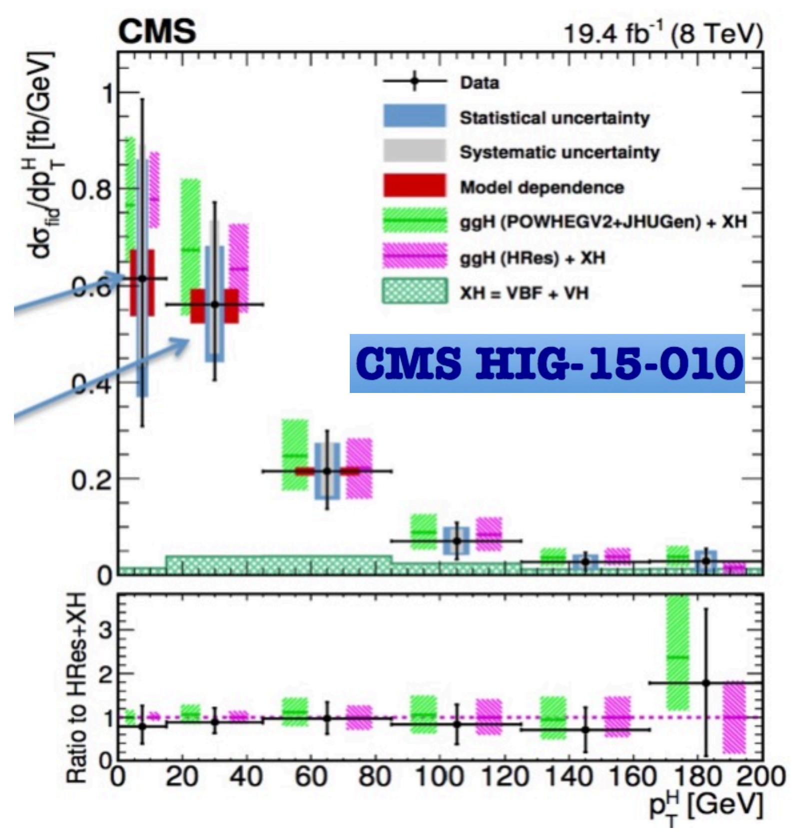
CMS γγ run 1



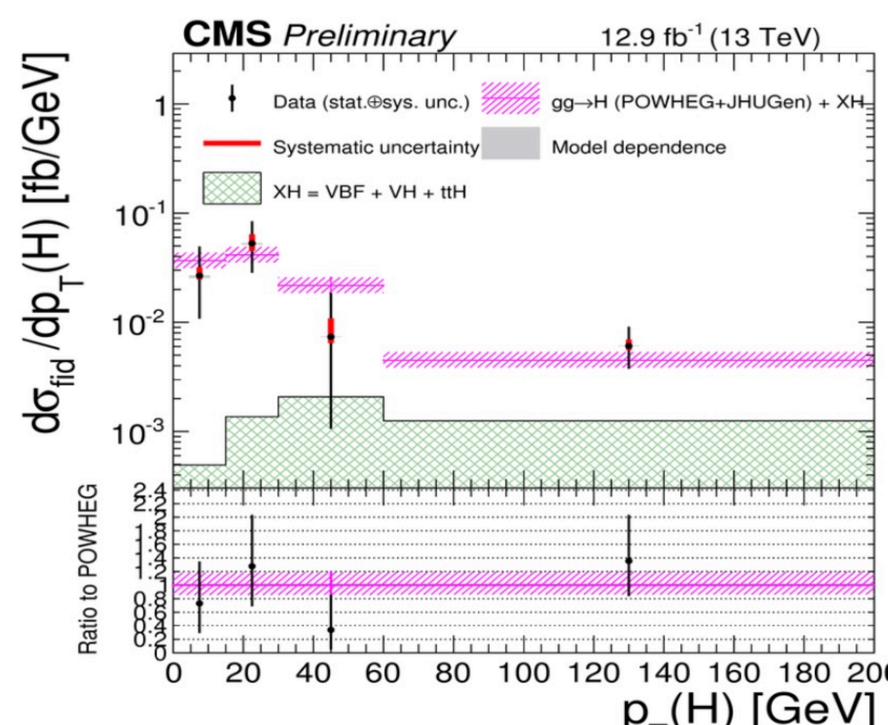
ATLAS 2l2ν run 1

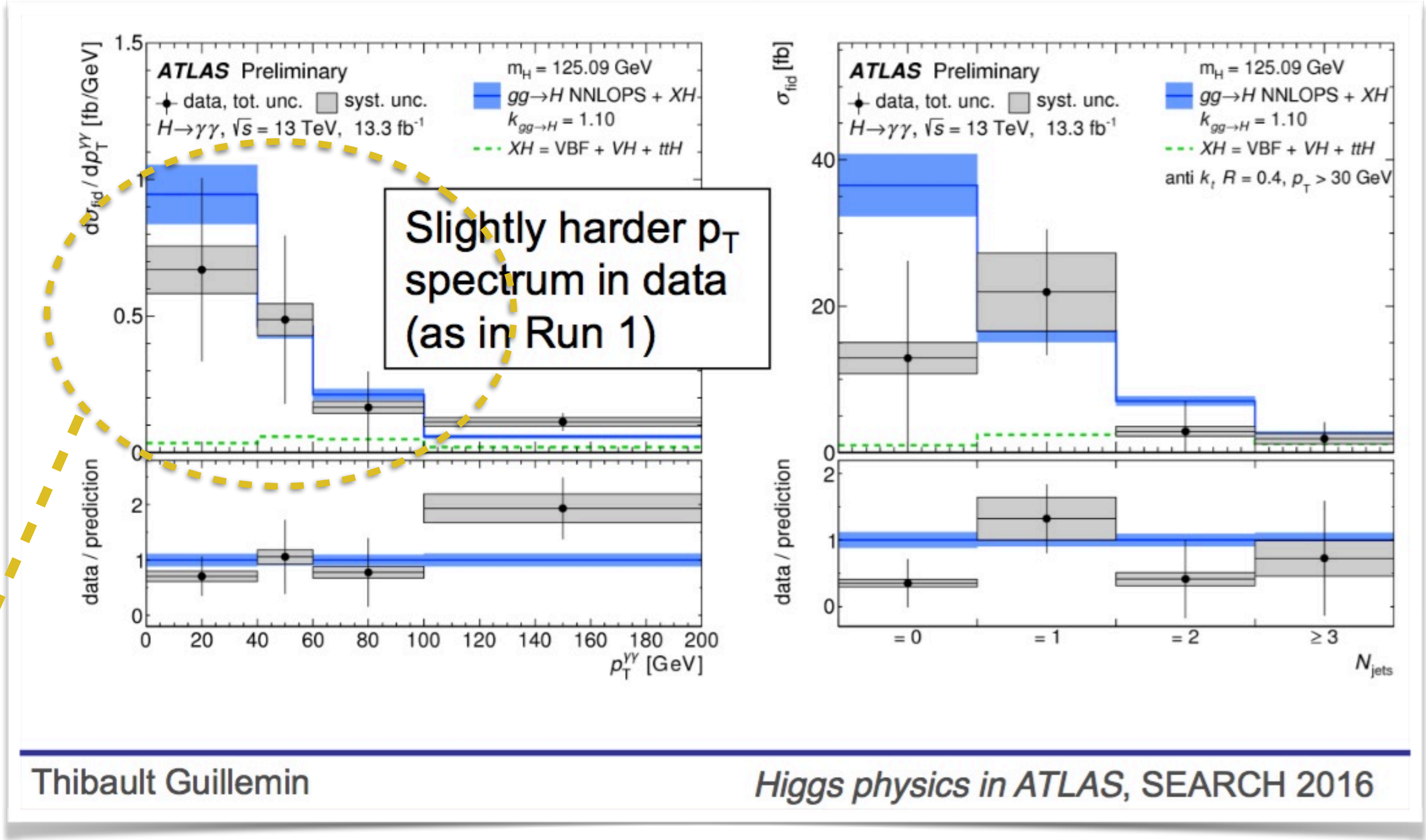


CMS 2l2ν run 1



CMS 4l run 2





- δstat ~ 5 δexp => ~25xL ~300fb^{-1} to equalize exp&stat uncert'y
- O(ab^{-1}) will provide an accurate, purely exptl determination of $p_T(H)$ in the theoretically delicate region 0-50 GeV, and strongly reduce/suppress th'l modeling systematics affecting other measurements (e.g. WW*)
- More in general, a global programme of higher-order calculations, data validation, MC improvements, PDF determinations, etc, will push further the TH precision….

Indirect Higgs probes of new physics at large statistics

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.

- We often talk about "**precise**" Higgs measurements. What we actually aim at, is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.

- *Sensitivity* may not require extreme precision
    - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

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For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

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For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

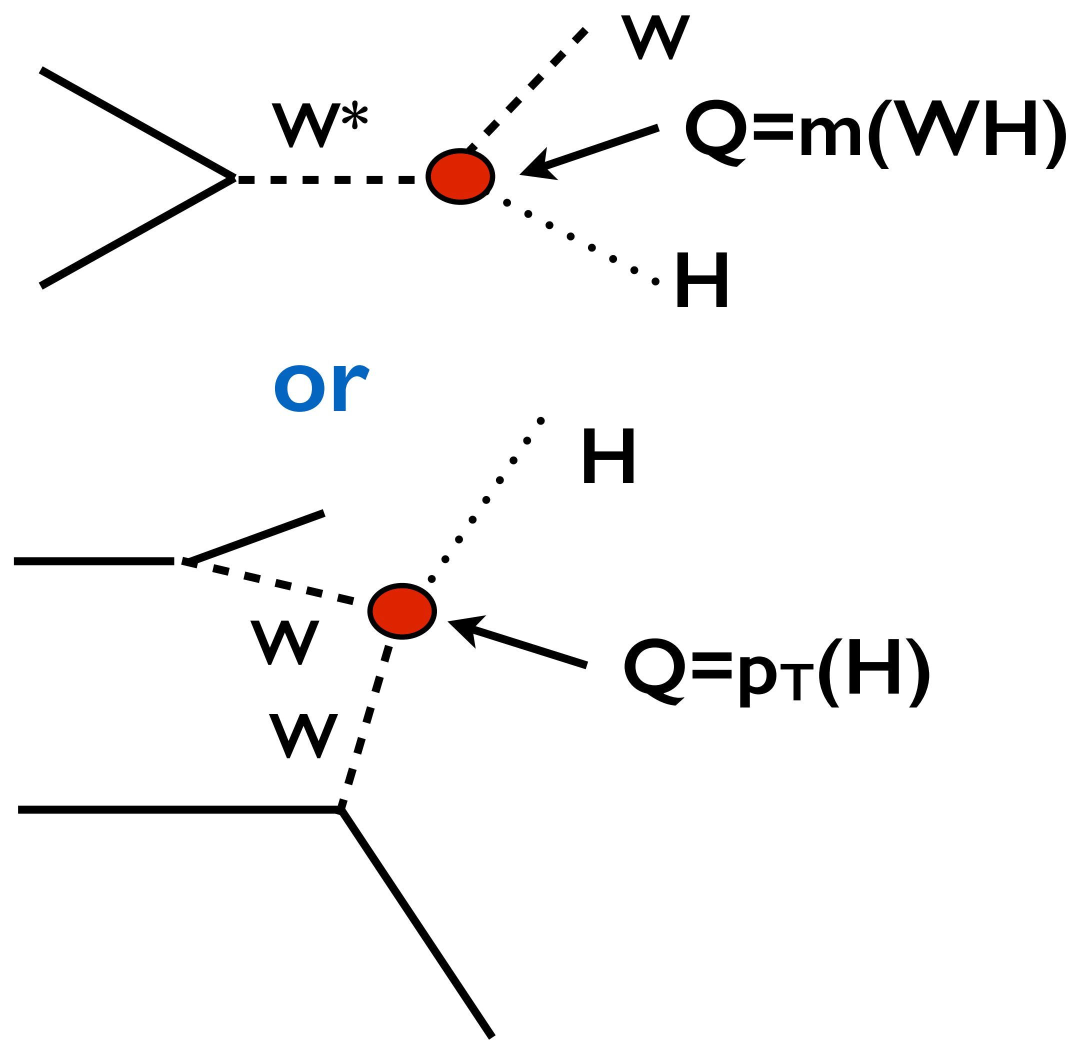
$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

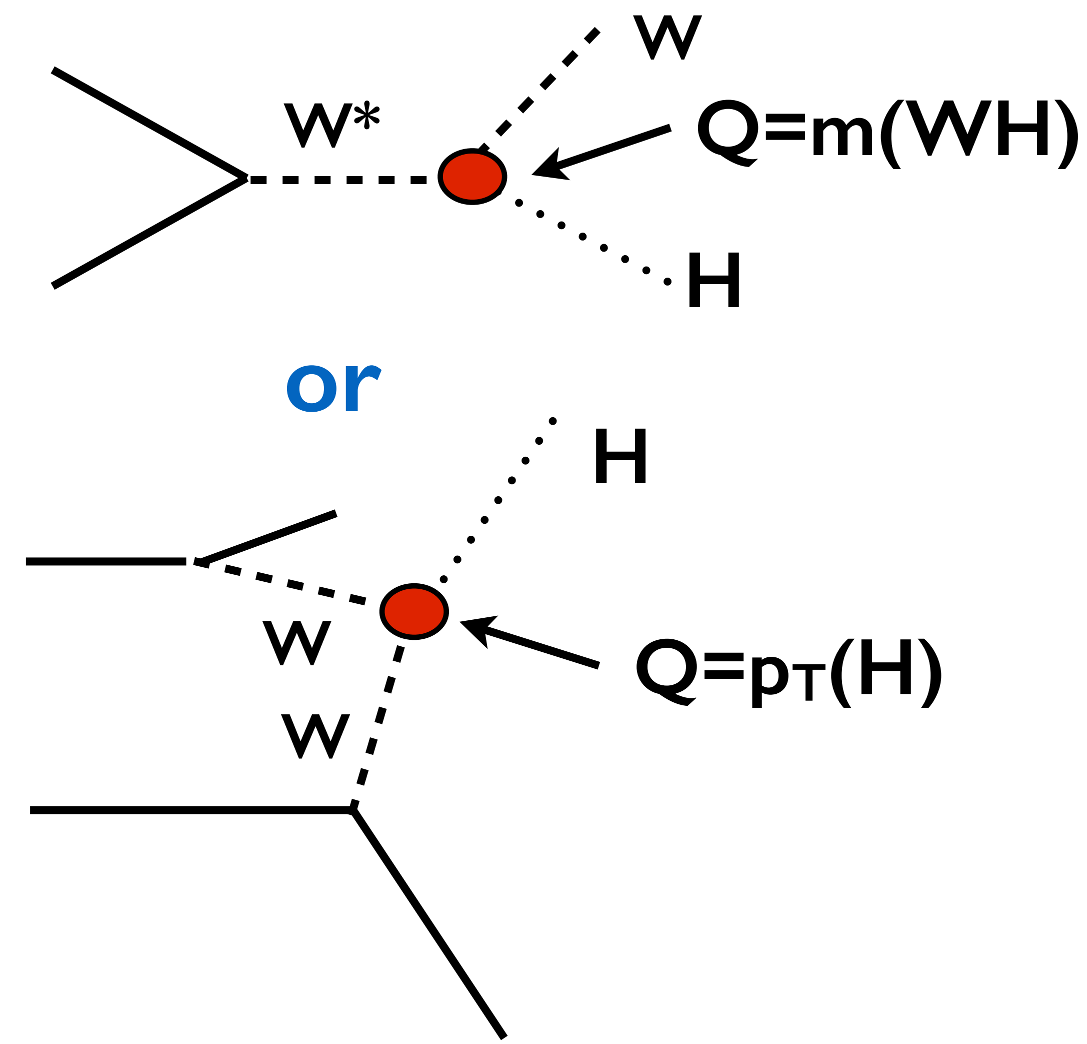
e.g. $\delta O_Q = 10\%$ at Q=750 GeV ⇒ $\Lambda \sim 2.5$ TeV

Examples

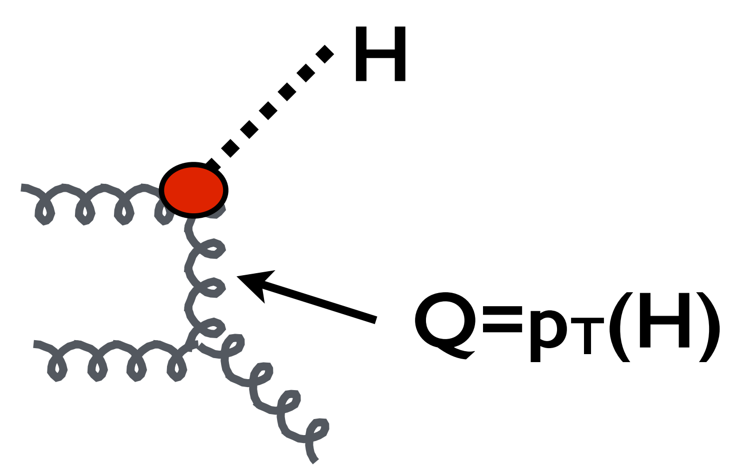
$\delta BR(H \to WW^*)$



Examples

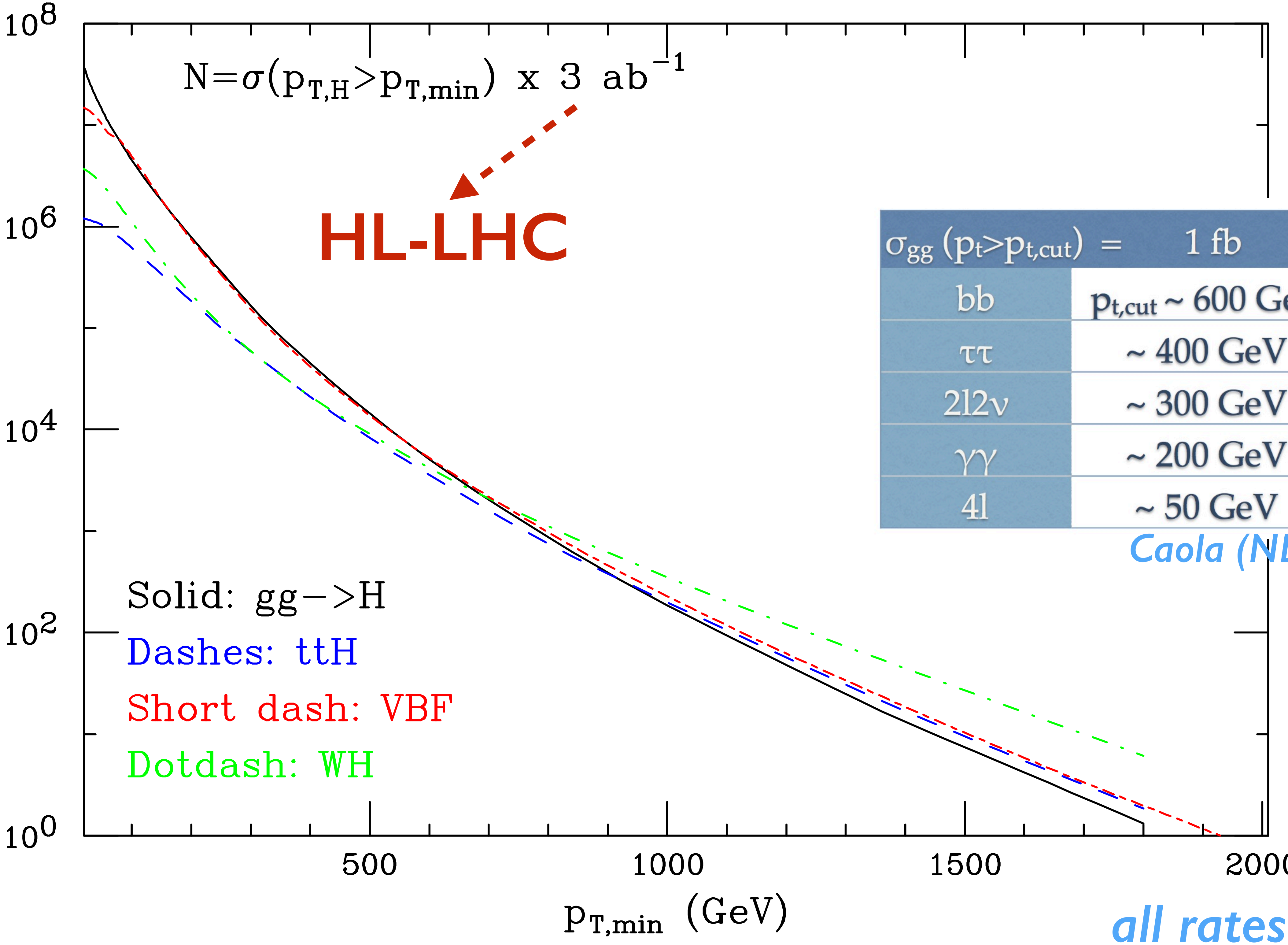


$\delta BR(H \rightarrow WW^*)$



$\delta BR(H \rightarrow gg)$

Probing large Q:
Higgs production at large p_T



$\sigma_{gg}(p_t>p_{t,cut})$ =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

Caola (NLO rates for gg->H)

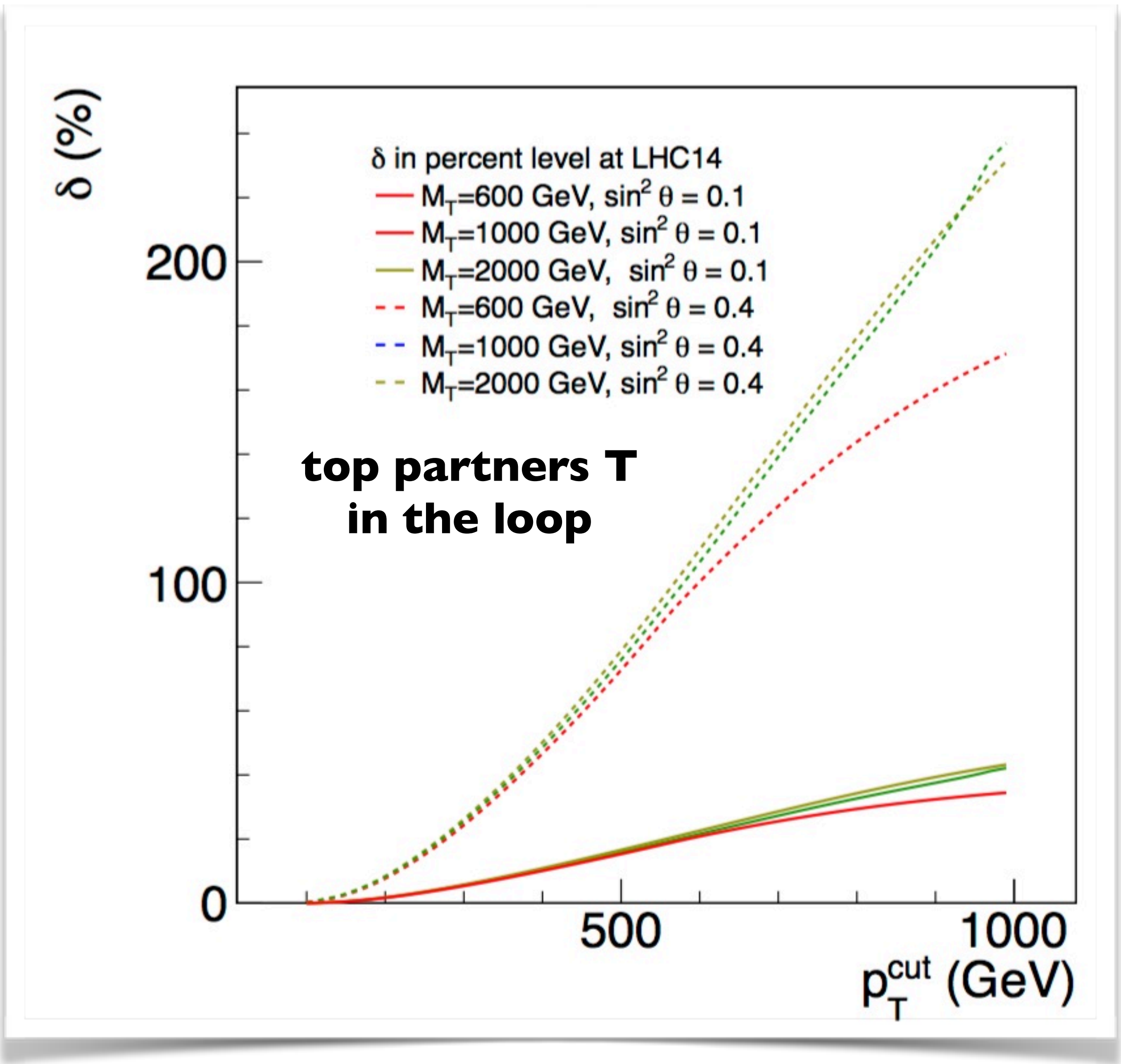
all rates LO

Examples: gg-> H at large p_T

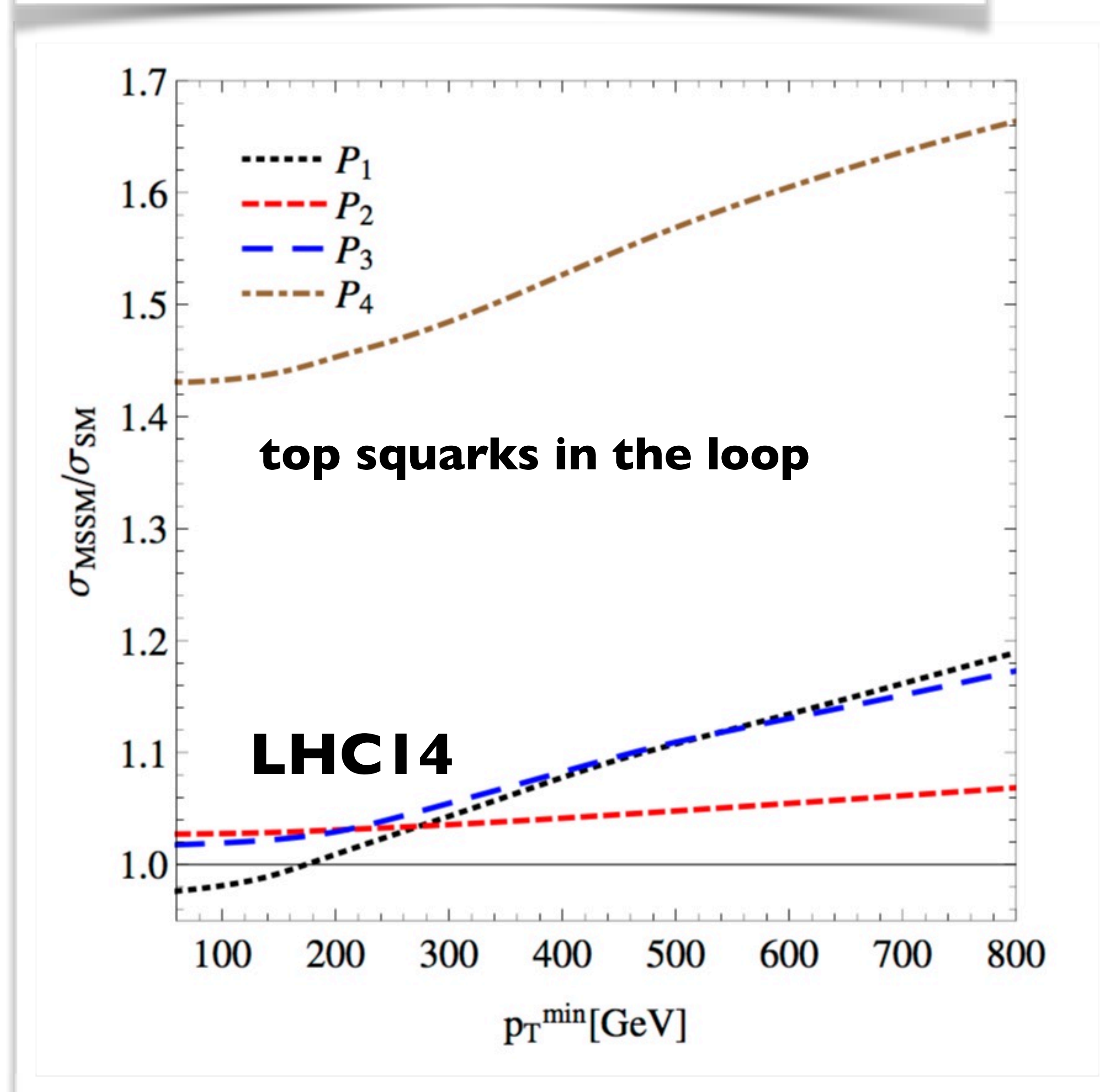
Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\text{GeV}$, $M_2 = 1000\,\text{GeV}$, $\mu = 200\,\text{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was set to 125 GeV.

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

(See also
Azatov and Paul arXiv:1309.5273v3)



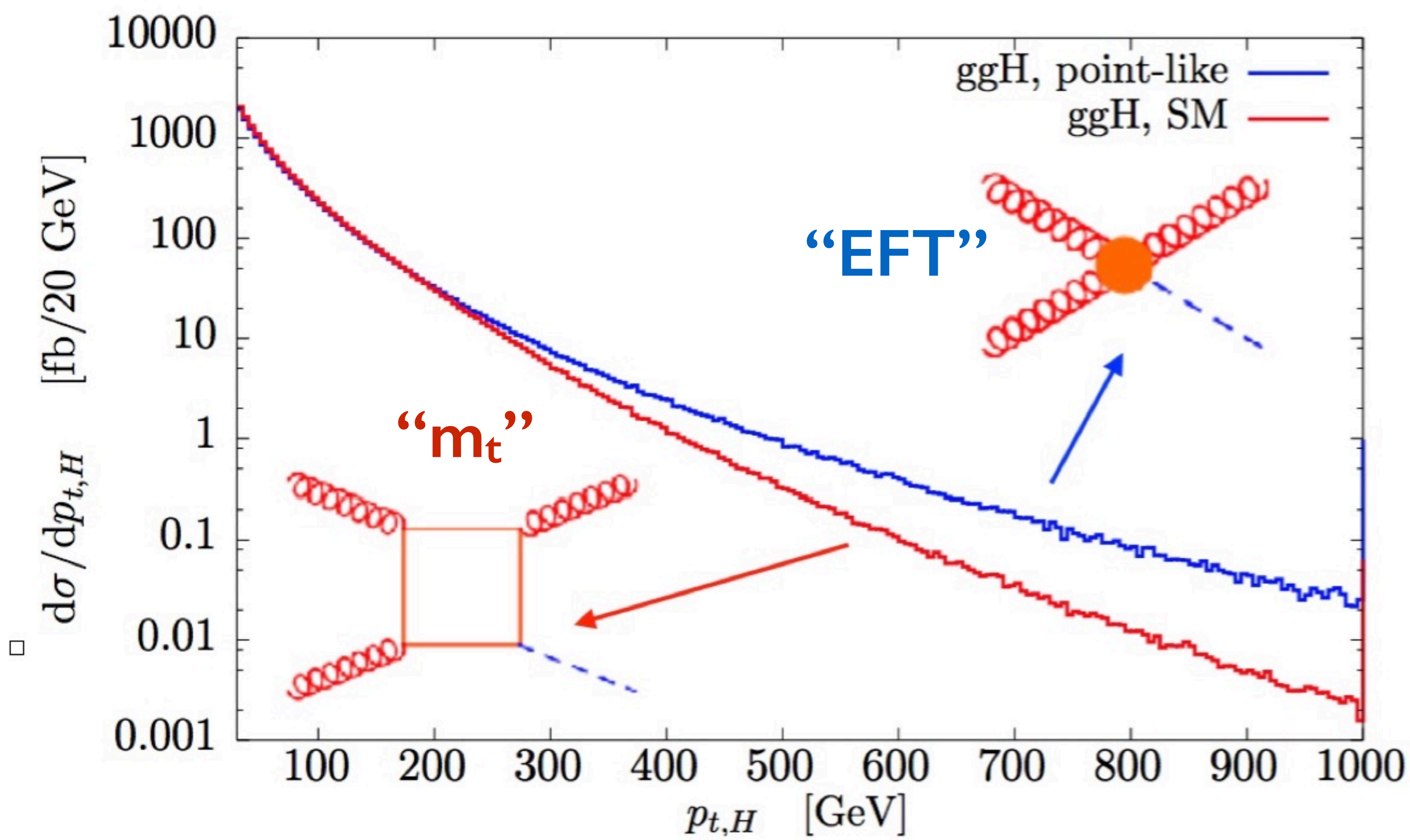
Banfi Martin Sanz, arXiv:1308.4771

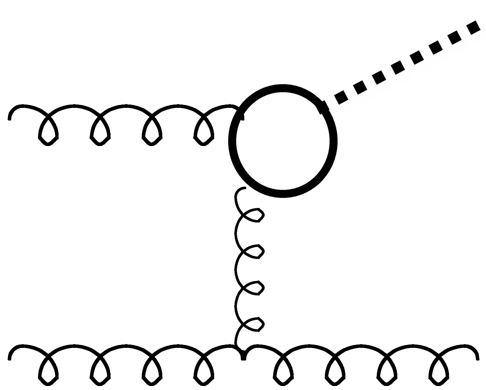


Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

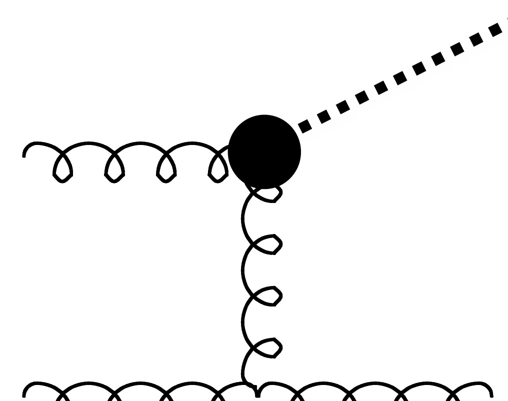
10% sensitivity at $p_T(H)$~1TeV is compatible with $3ab^{-1}$ rates in previous page

TH syst's at large p_T^H





~ $f(p_T/m)$ x

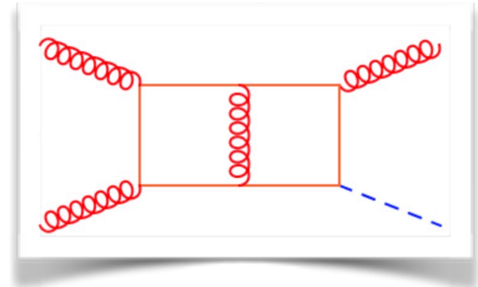


$$f \sim \frac{4m^2}{4m^2 + p_T^2} \quad \begin{array}{l} \rightarrow 1 \text{ for } p_T \ll m \\ \rightarrow 1/p_T^2 \text{ for } m \ll p_T \end{array}$$

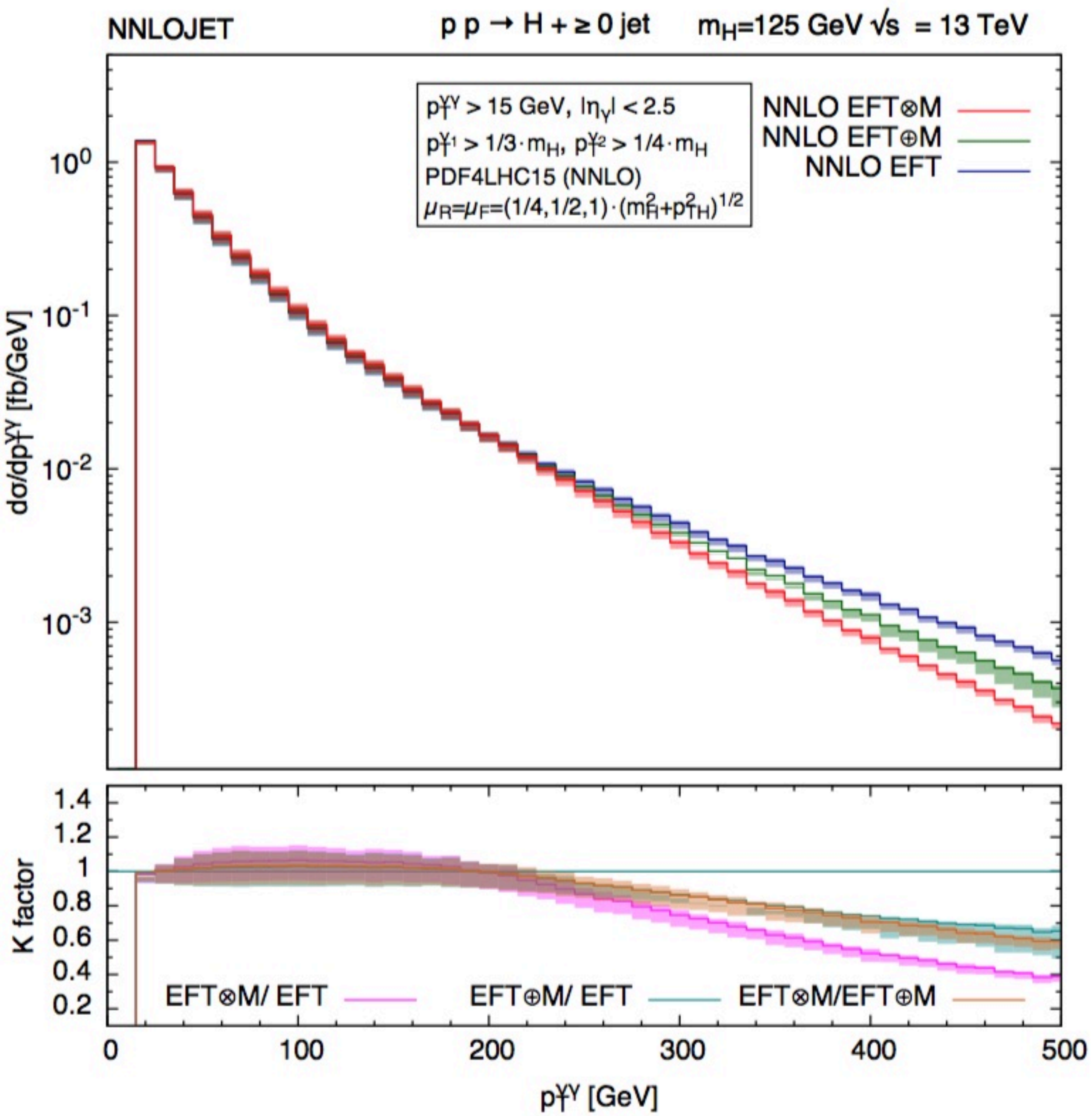
NNLO p_T spectrum available in EFT…

Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier,
https://arxiv.org/pdf/1607.08817v2

… but for finite m_{top} , not even at NLO



- NLO at high momentum transfer: 2-loop amplitudes with several external (s, p_t, m_h) and internal (m_t) mass scales → *significantly more complicated than any amplitude computed so far*

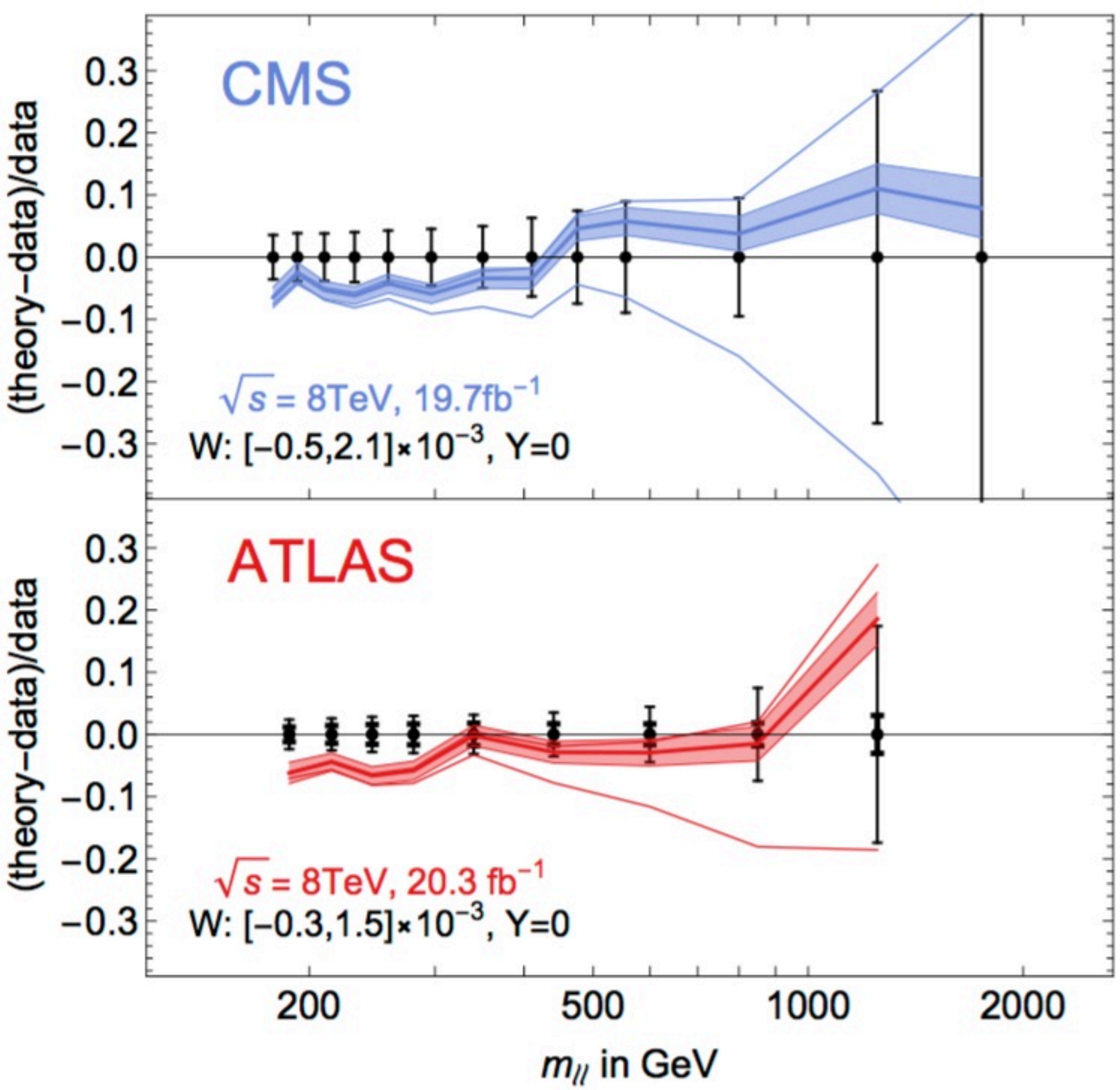


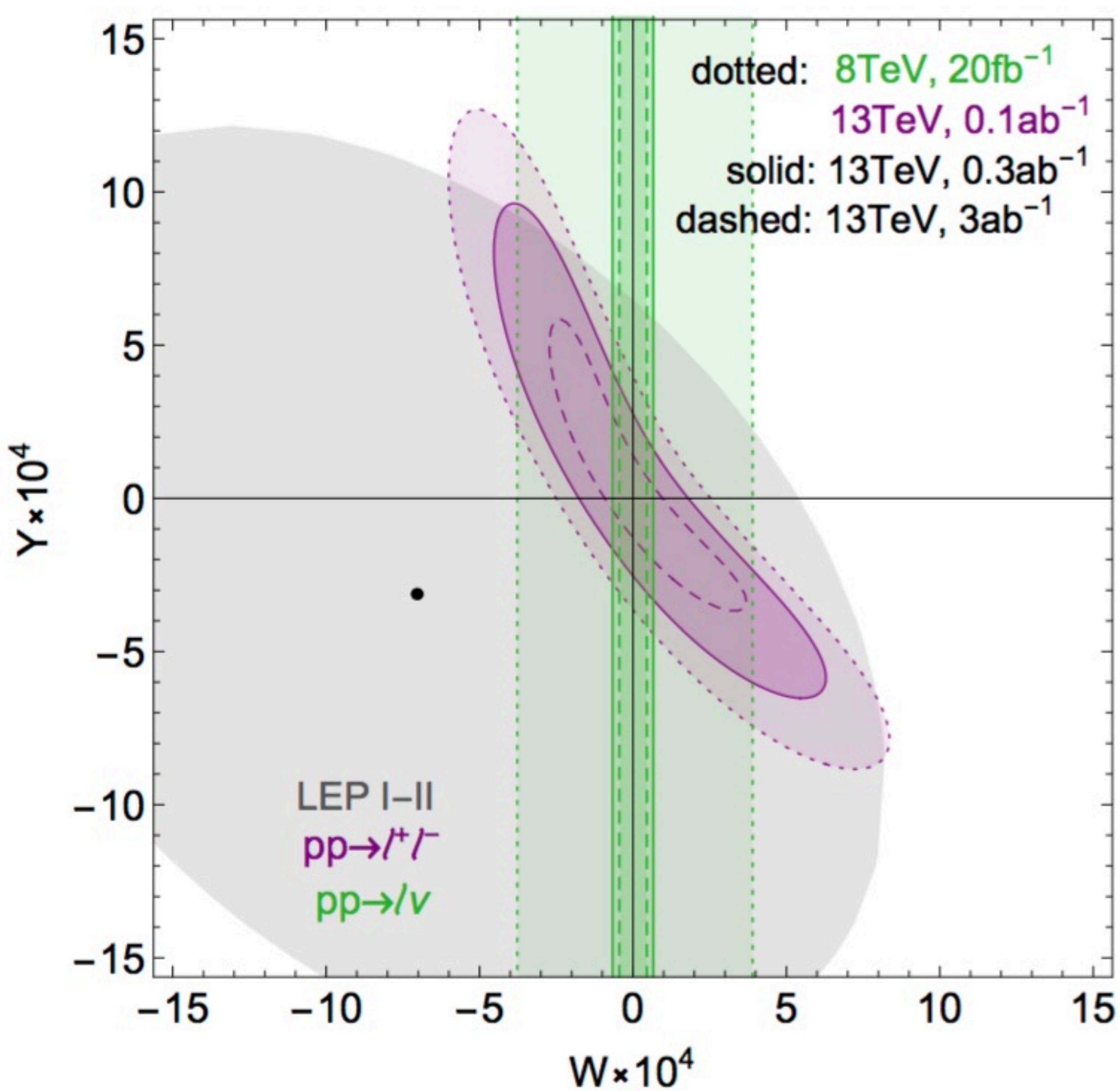
=> important systematics due to finite m_{top} effects at large p_T

Ex: Probes of dim-6 op's with high-mass DY

M.Farina et al, arXiv:1609.08157

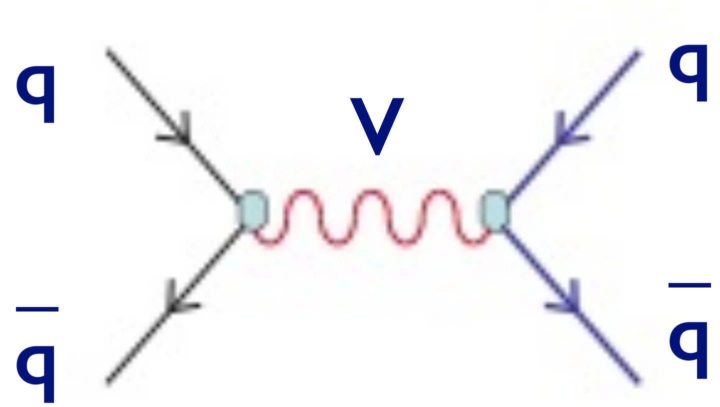
	universal form factor ($\mathcal{L}$)
W	$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$





Physics with hadronic W/Z(/H) decays ?

Example: search for low-mass resonances V→2 jets



search impossible at masses below few hundred GeV, due to large gg→gg bg's and trigger thresholds

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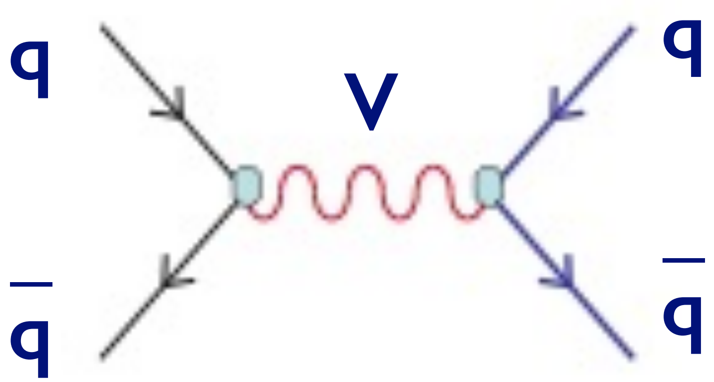
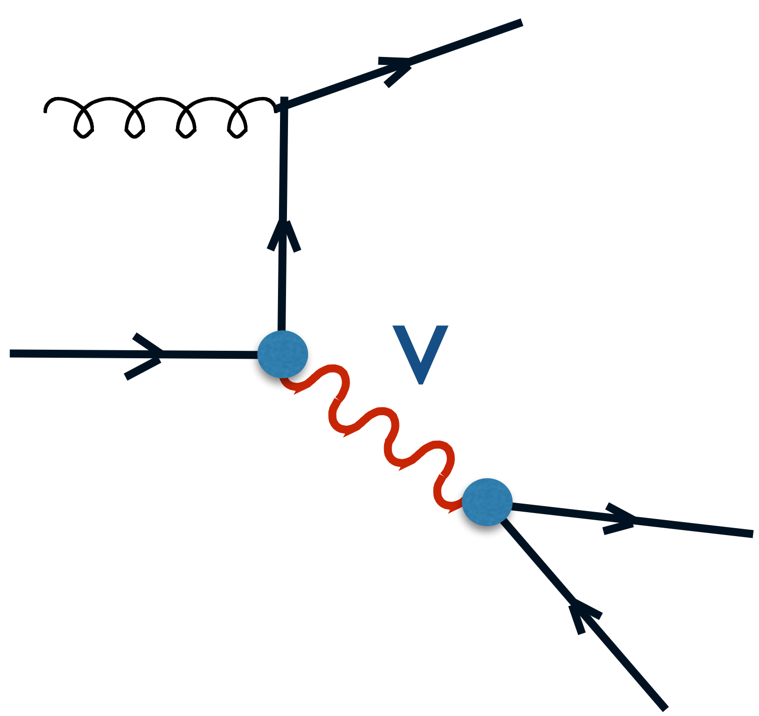


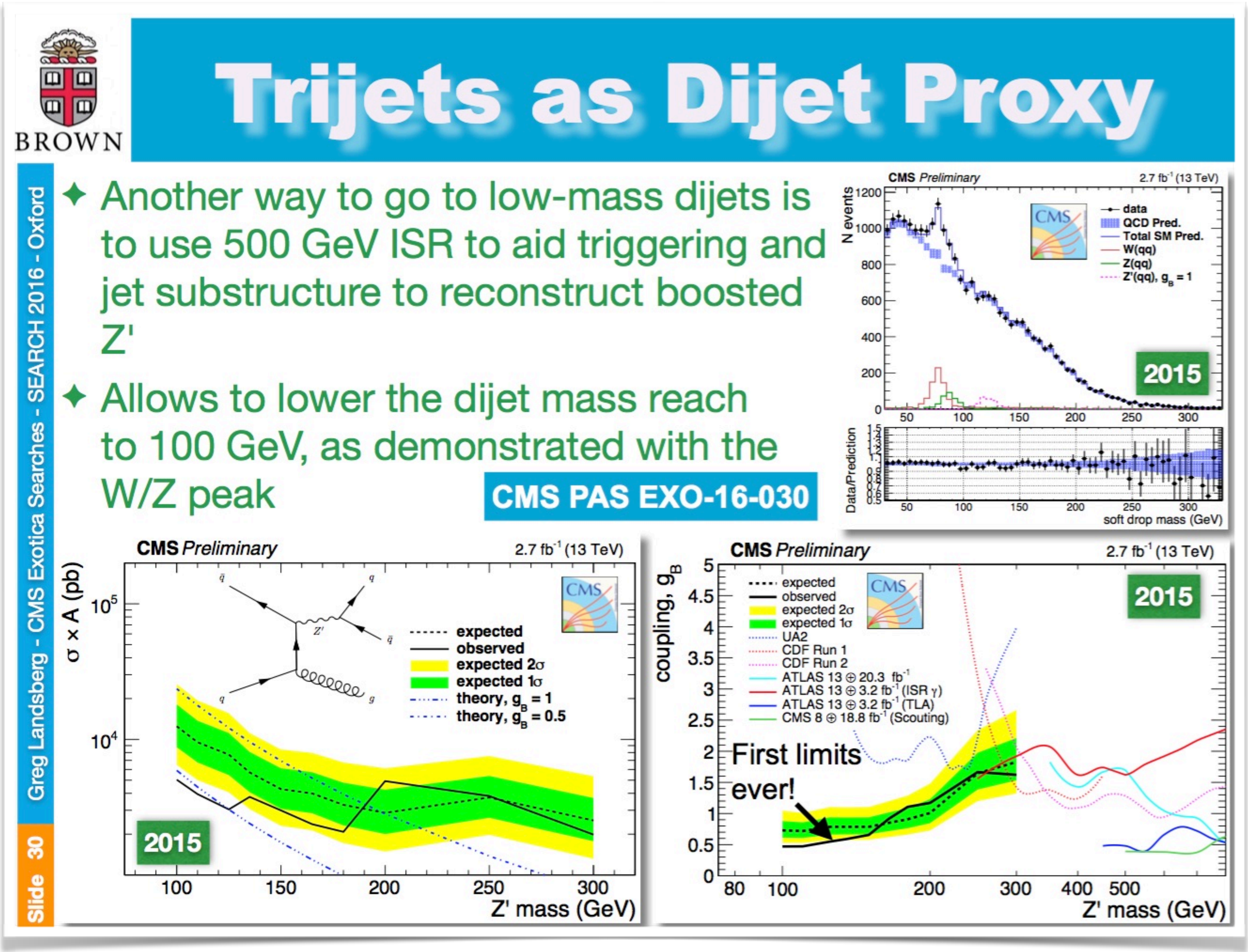
search impossible at masses below few hundred GeV, due to large gg→gg bg's and trigger thresholds



At large p_T

- S/B improves (qg initial state dominates both S and B)
- use boosted techniques to differentiate V→qq vs QCD dijets
- ε_{trig} ~ 100%

Example: search for low-mass dijet resonances



Final remarks

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Key question after few yrs of LHC:

why don't we see the new physics we expected to be present around the TeV scale ?

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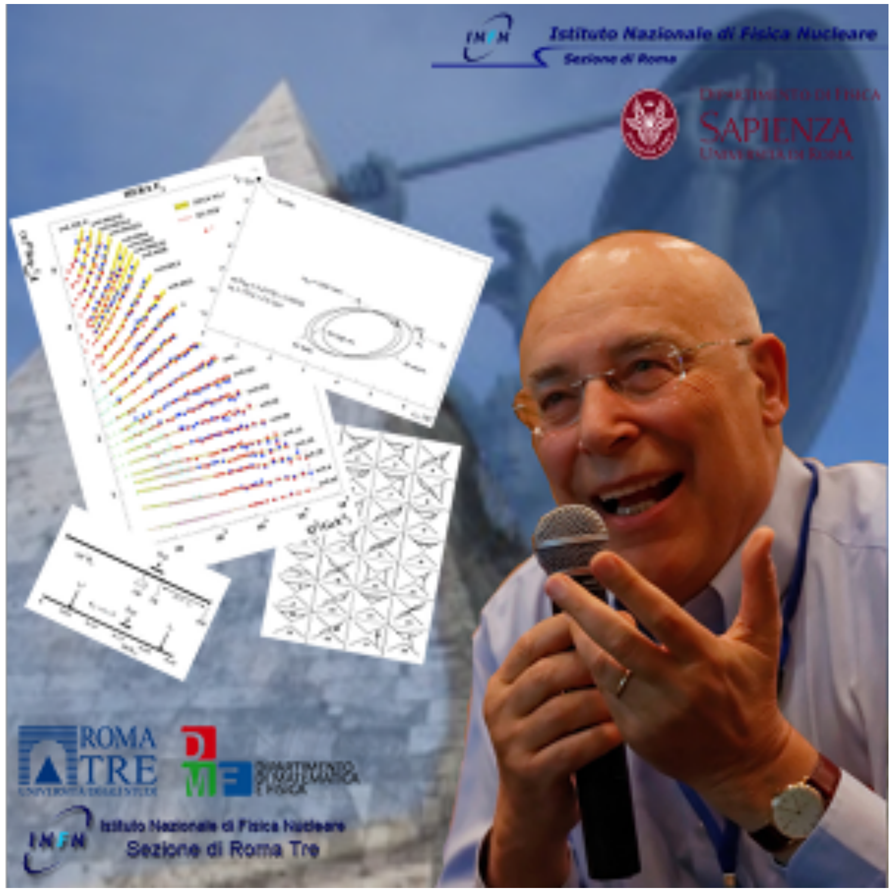

In either case, if new physics is there to be found, better understanding and control of QCD will play a crucial role in revealing it, and studying its properties

While we wait for the discoveries, improving our knowledge of QCD via calculations and measurements remains greatly challenging and rewarding