Theory overview of LHC physics

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The Lagrangian of Nature?

- With the discovery of a scalar particle having properties consistent with the SM Higgs boson, the Lagrangian of Nature appears complete.

$$\boxed{\mathcal{L}_h^{SM} = |D_\mu H|^2 - \left(y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R + y_e \bar{L}_L H e_R + h.c.\right) - \lambda \left(H^\dagger H - \frac{v^2}{2}\right)^2}$$

- The SM is *predictive*: given m_H, all couplings of the Higgs are now fixed.

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV}$$

(ATLAS+CMS, 1503.07589, fit to 4l+2γ)

Tree-level couplings:

$$g_{hf^if^j} = -\frac{gm_f}{2m_W}\delta^{ij}$$

$$g_{hVV} = g_V m_V$$

$$g_{hhh} = -\frac{3m_H^2}{2m_W}$$

Failures of the Standard Model I

- Numerous outstanding problems exist in the SM, both aesthetic and experimental, that demand explanation.

No hierarchy between input, "bare" value and quantum corrections ➪ *Naturalness*

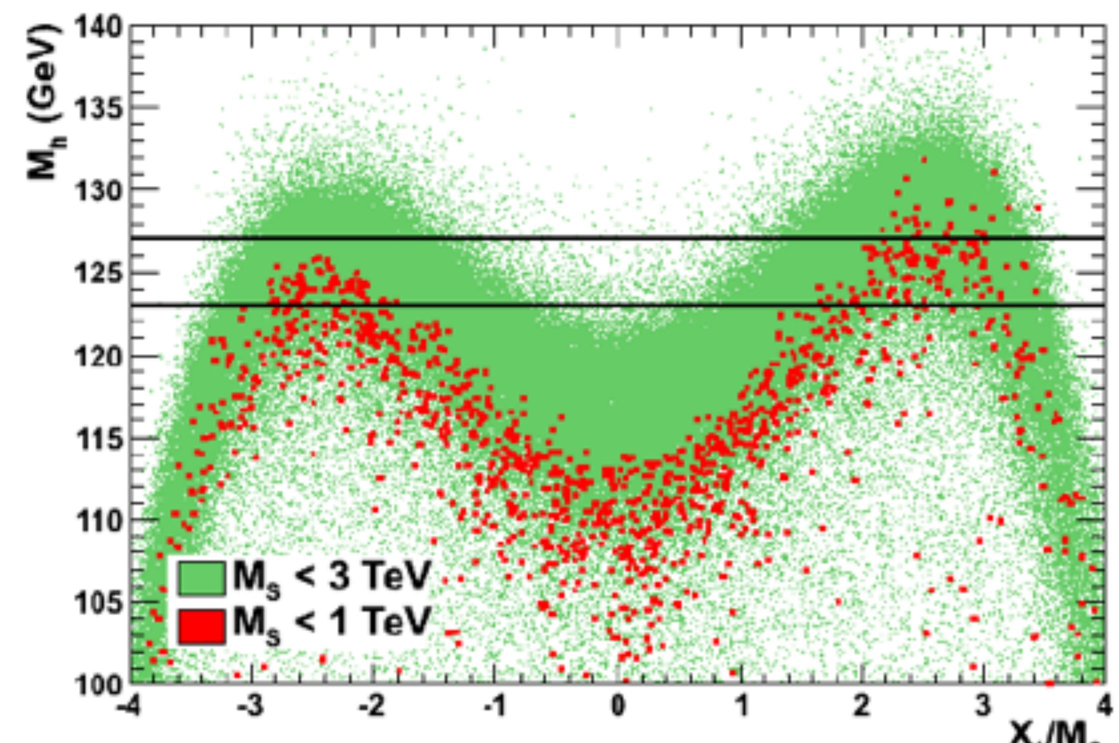
- [x] True for gauge bosons ➪ gauge symmetry
- [x] True for the fermions ➪ chiral symmetry
- [ ] Not true for the Higgs!

$$M^{\text{gauge,ferm}} \sim M^{\text{bare}}\{1 + a \ln \Lambda/M\}$$

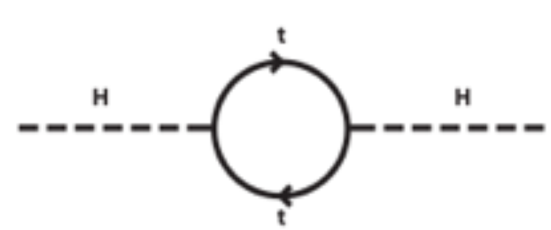
$$(M^{\text{Higgs}})^2 \sim (M^{\text{bare}})^2 + \Lambda^2$$

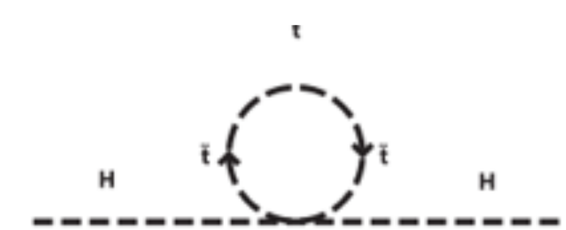
Precision Higgs mass measurement influencing our search for TeV-scale SUSY

Does TeV-scale SUSY resolve this problem?



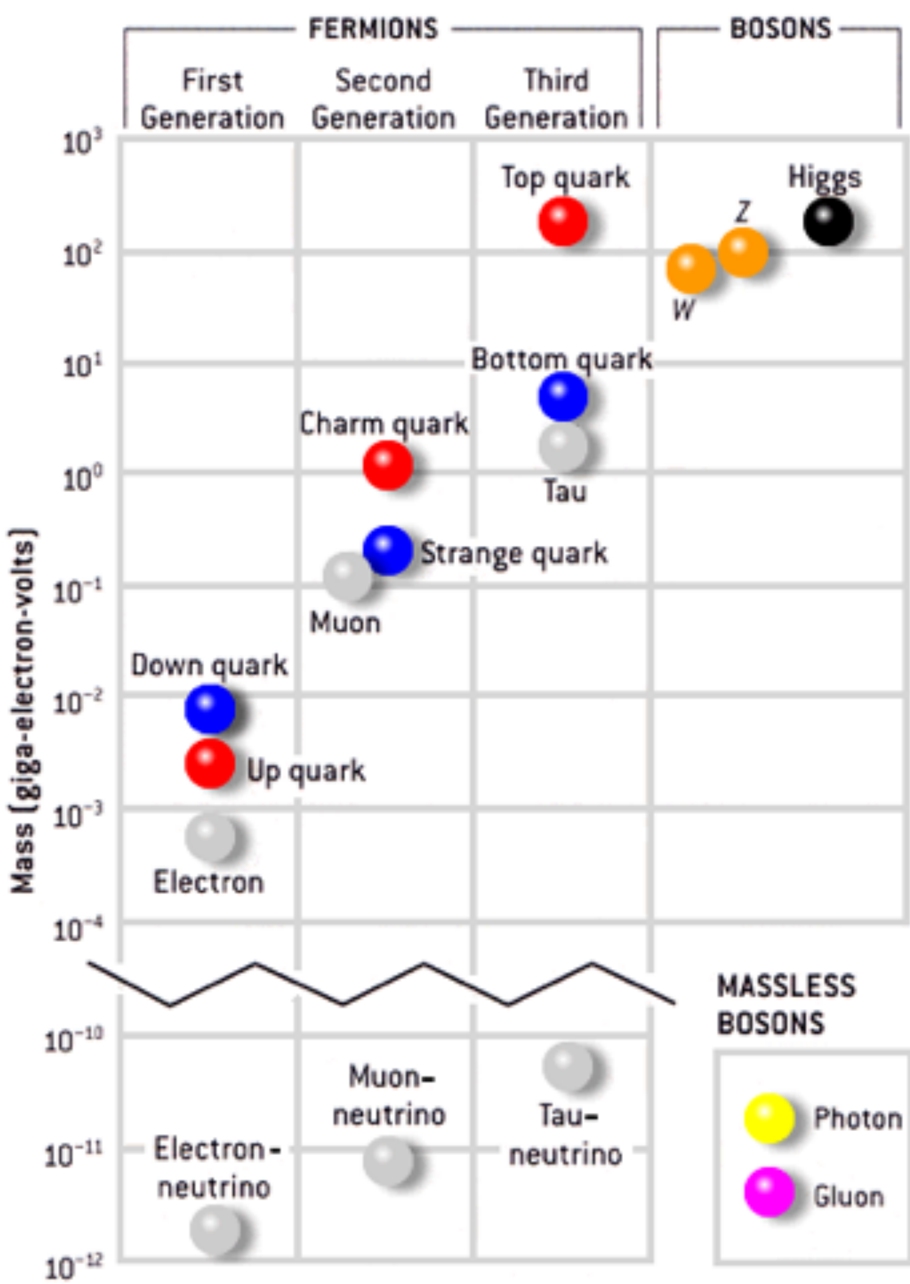
Arbey, Battaglia, Djouadi, Mahmoudi 1211.4004



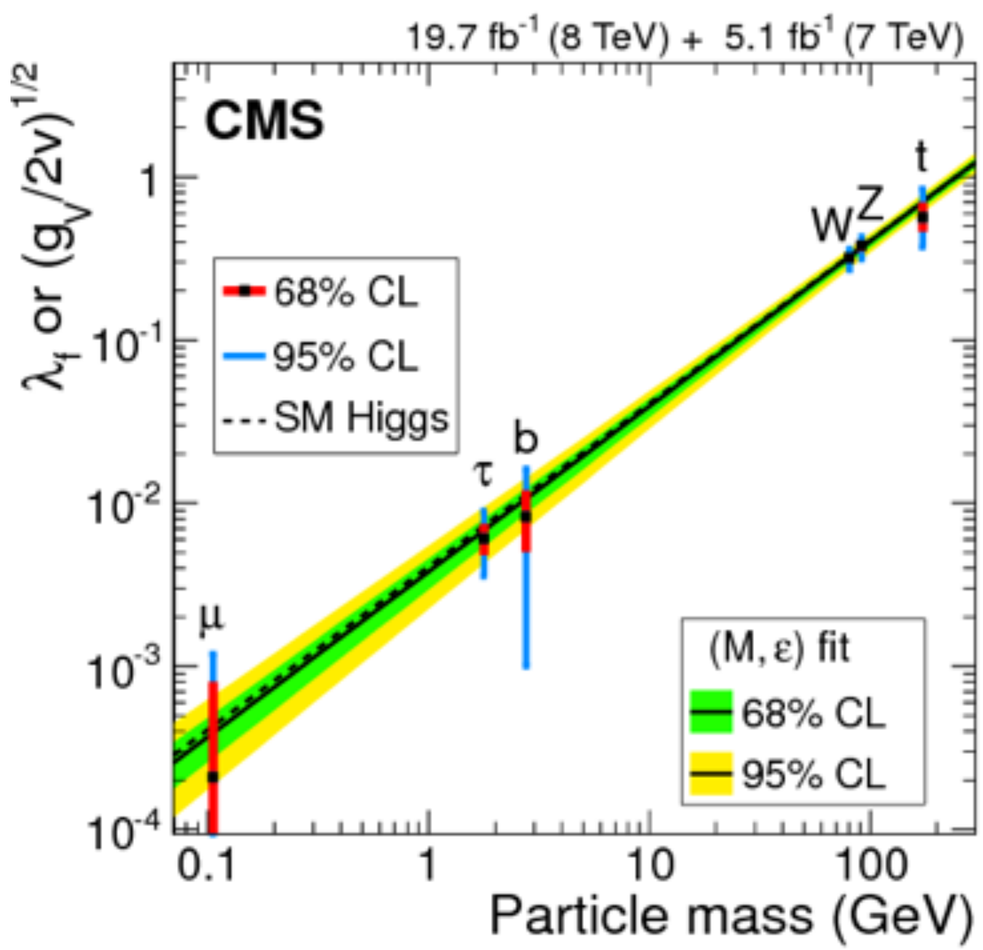


Failures of the Standard Model II

- Numerous outstanding problems exist in the SM, both aesthetic and experimental, that demand explanation.



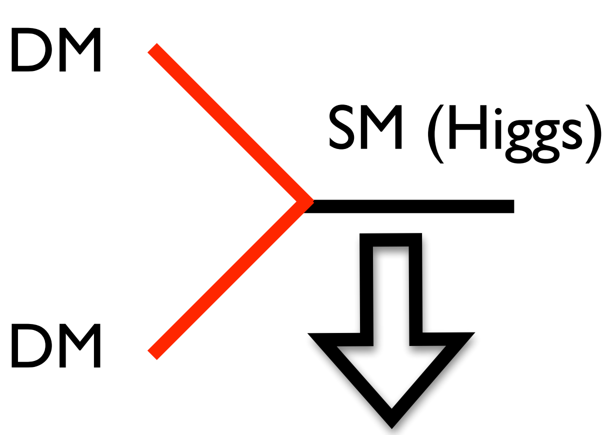
➪The SM Higgs does not explain the observed masses and mixings of fermions.



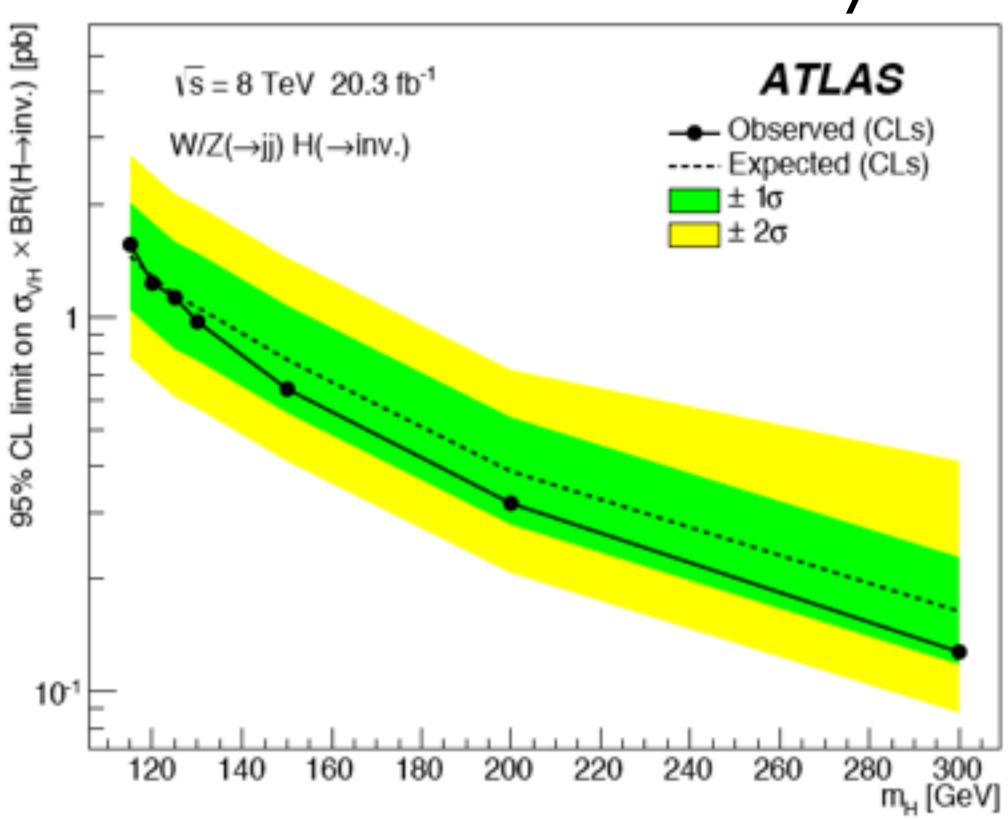
Is new insight hiding in the lighter fermion couplings, or buried in the errors?

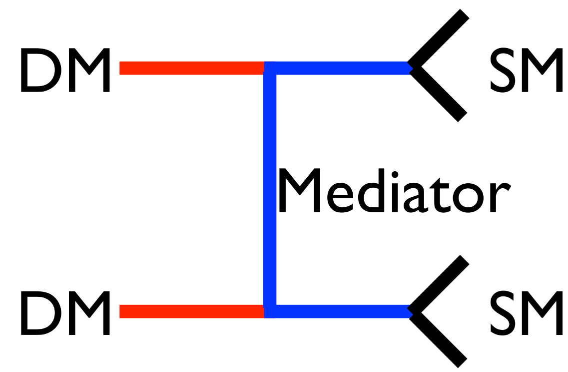
Failures of the Standard Model III

- Doesn't have dark matter! Assuming non-gravitational DM couplings, can imagine two possible scenarios for DM coupling to the SM.



Predicts invisible decays





Only three renormalizable possibilities:

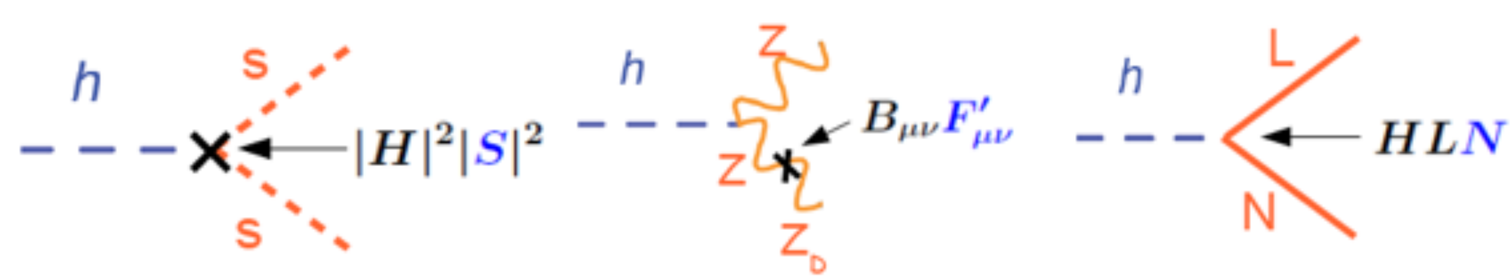
Schabinger, Wells hep-ph/0509209;
Patt, Wilczek hep-ph/0605188

$$\Delta\mathcal{L}_1 = |H|^2 S^2$$

$$\Delta\mathcal{L}_2 = HLN + h.c.$$

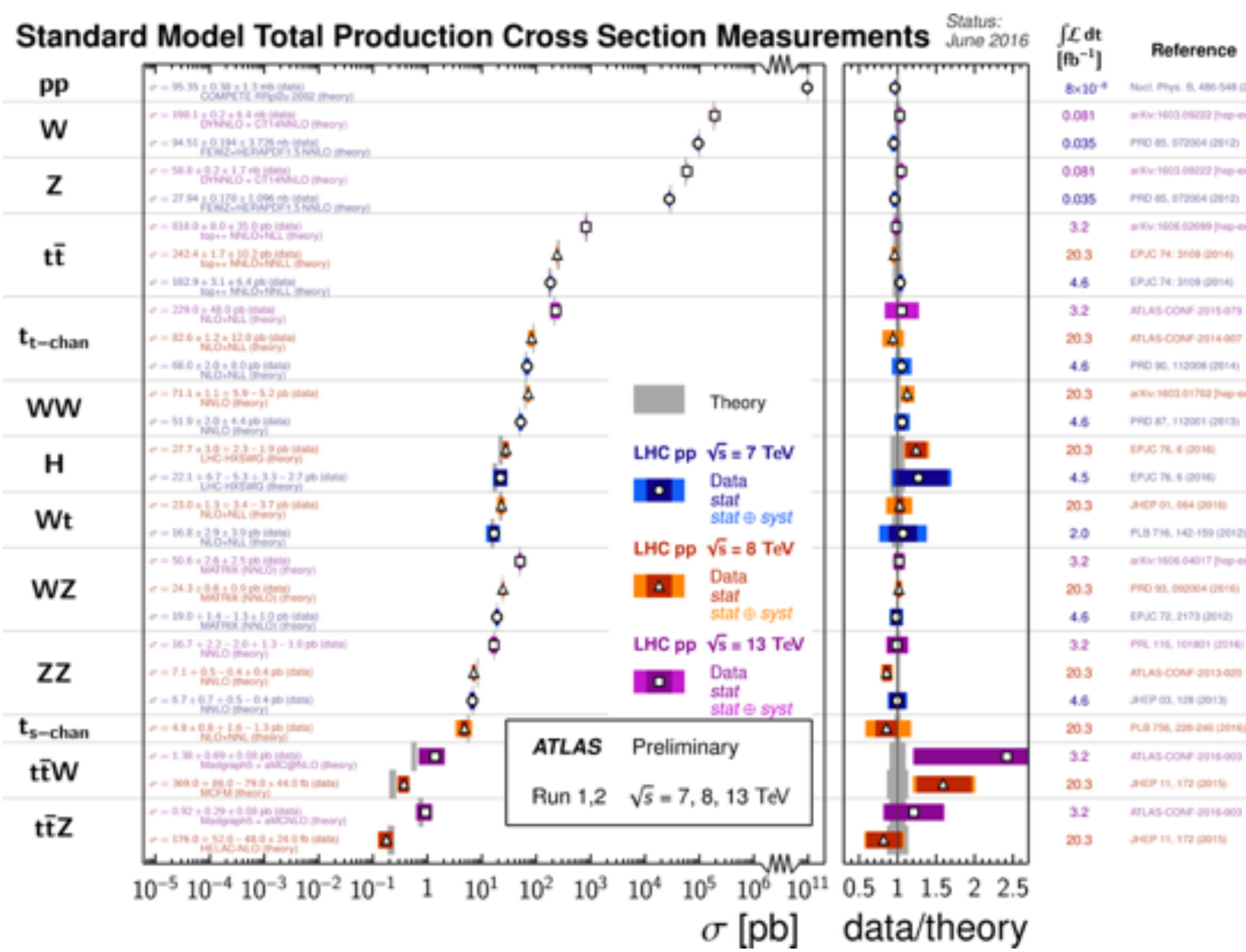
$$\Delta\mathcal{L}_3 = F'_{\mu\nu} B^{\mu\nu}$$

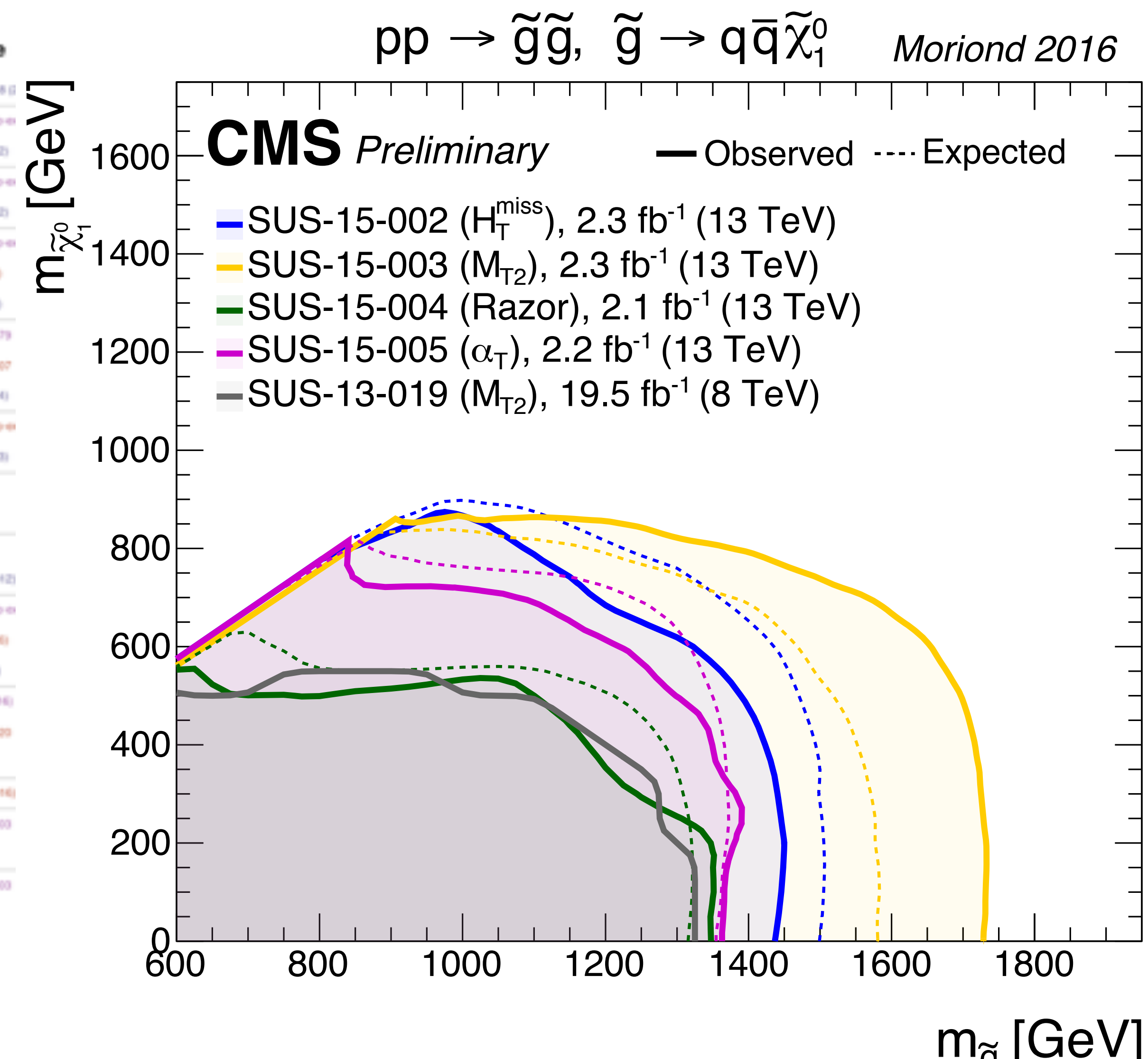
Hidden-sector dark matter leads to rich Higgs phenomenology (surveyed in Curtin et al, 1312.4992)



Experimental guidance

- No convincing evidence of new particles or BSM effects; Higgs looks SM-like, limits on SUSY and other new states over a TeV and increasing



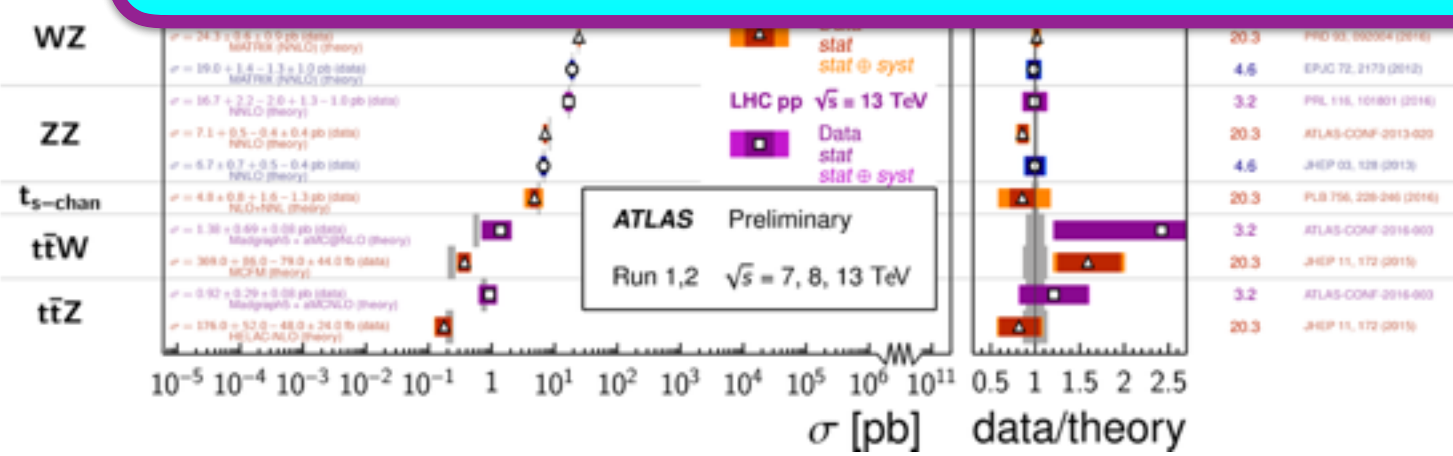


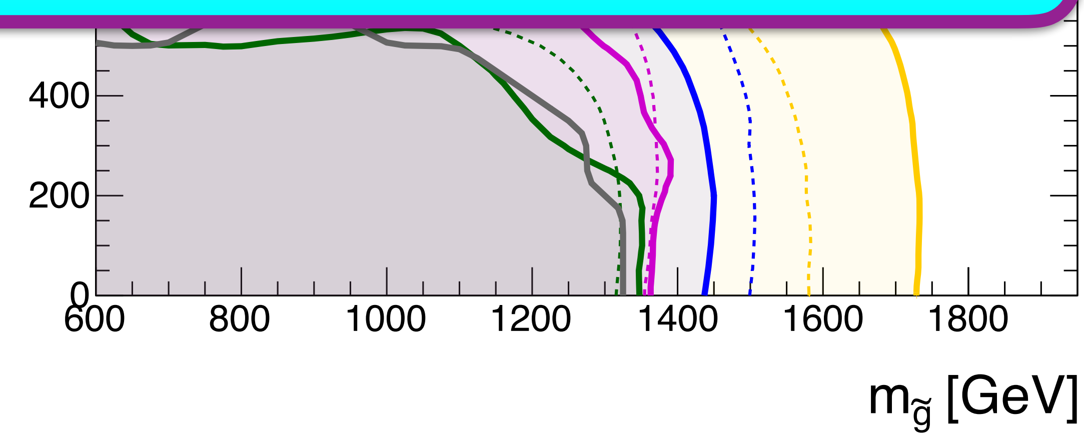
Experimental guidance

No convincing evidence of new particles or BSM effects; Higgs look SM-like

What is the path forward at Run II?

- Precision may be the key to Run II discoveries
- The Higgs is a likely portal to Beyond the SM physics
- Leave no stone unturned: rare, exotic production and decays
- Novel observables and ideas⇒boosted topologies and jet substructure

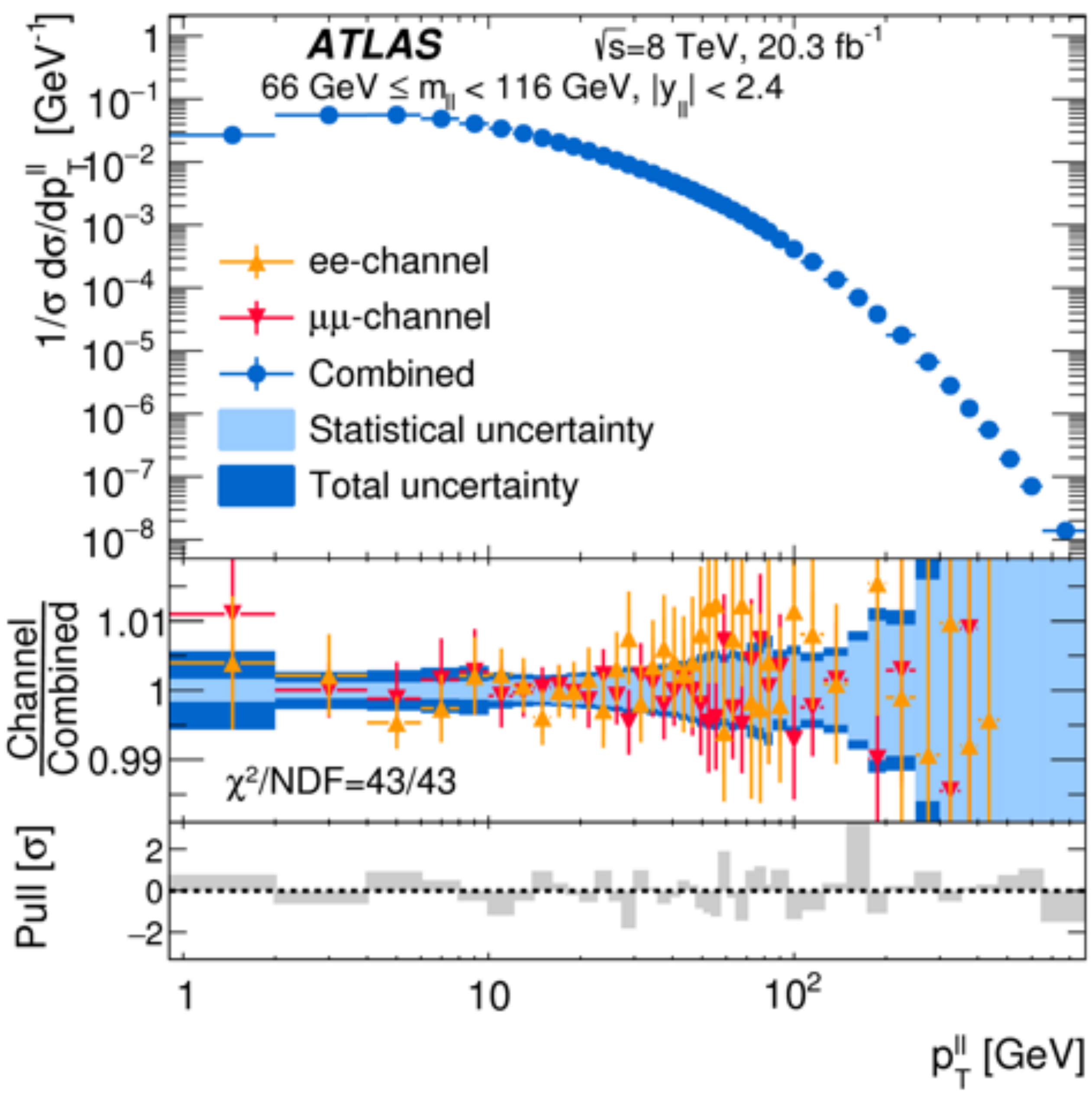




Precision tests of the Standard Model

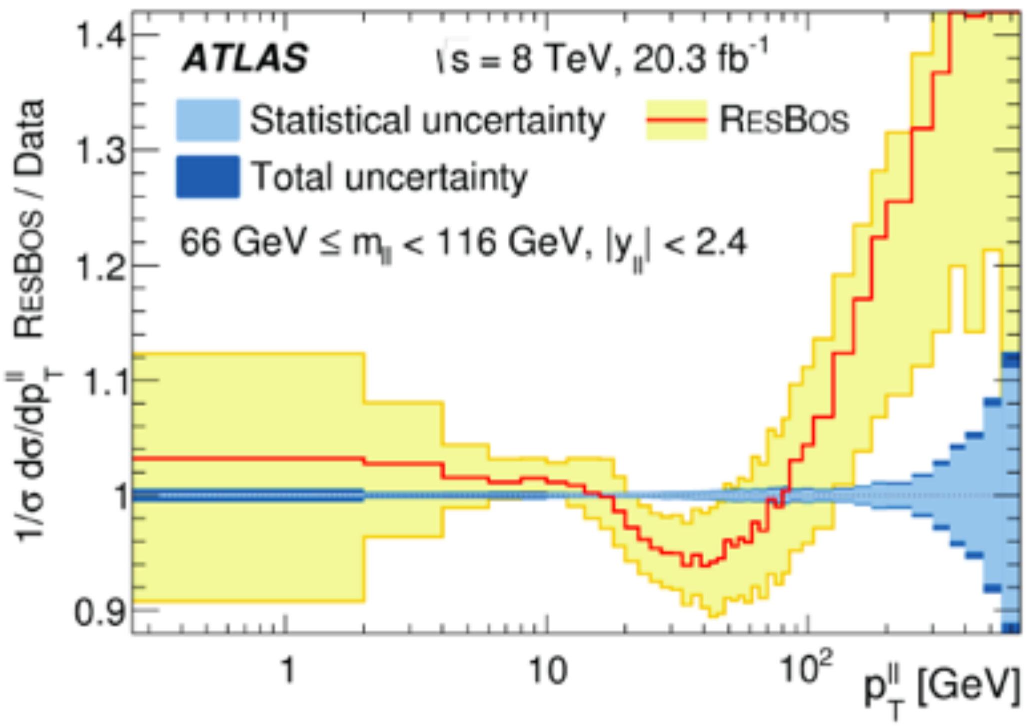
The experimental challenge

- The experimental precision achieved at the LHC in multiple channels is challenging our ability to calculation precisely enough to compare theory to data

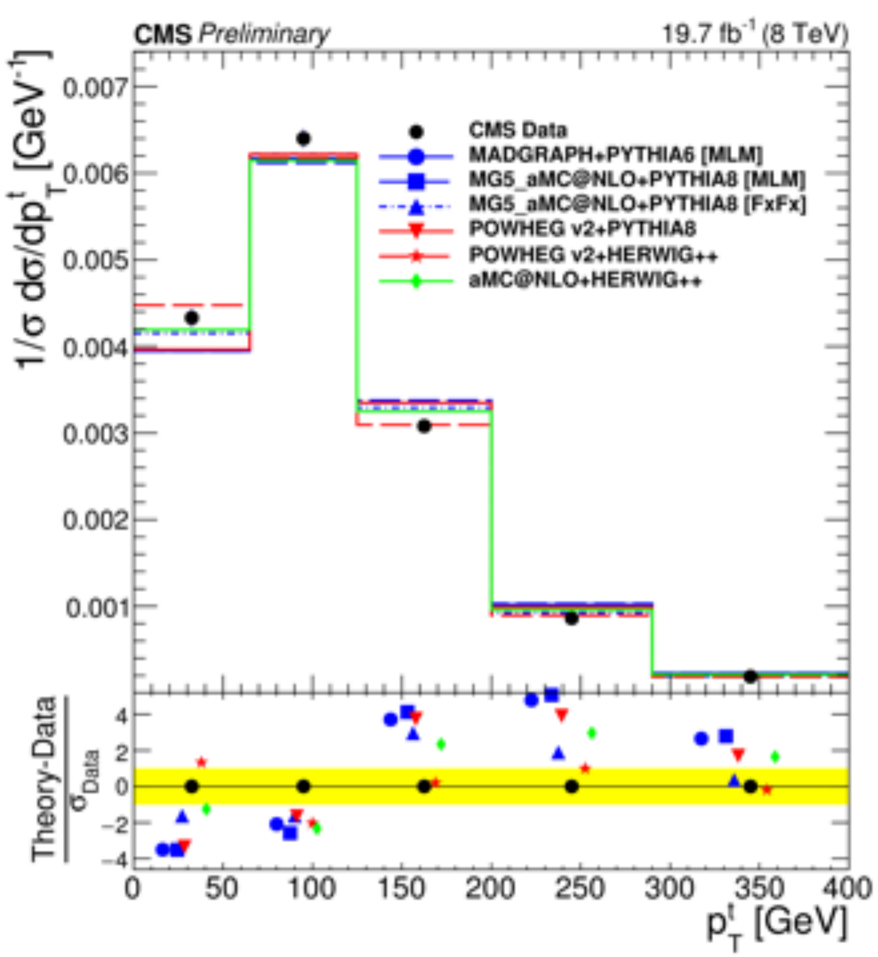


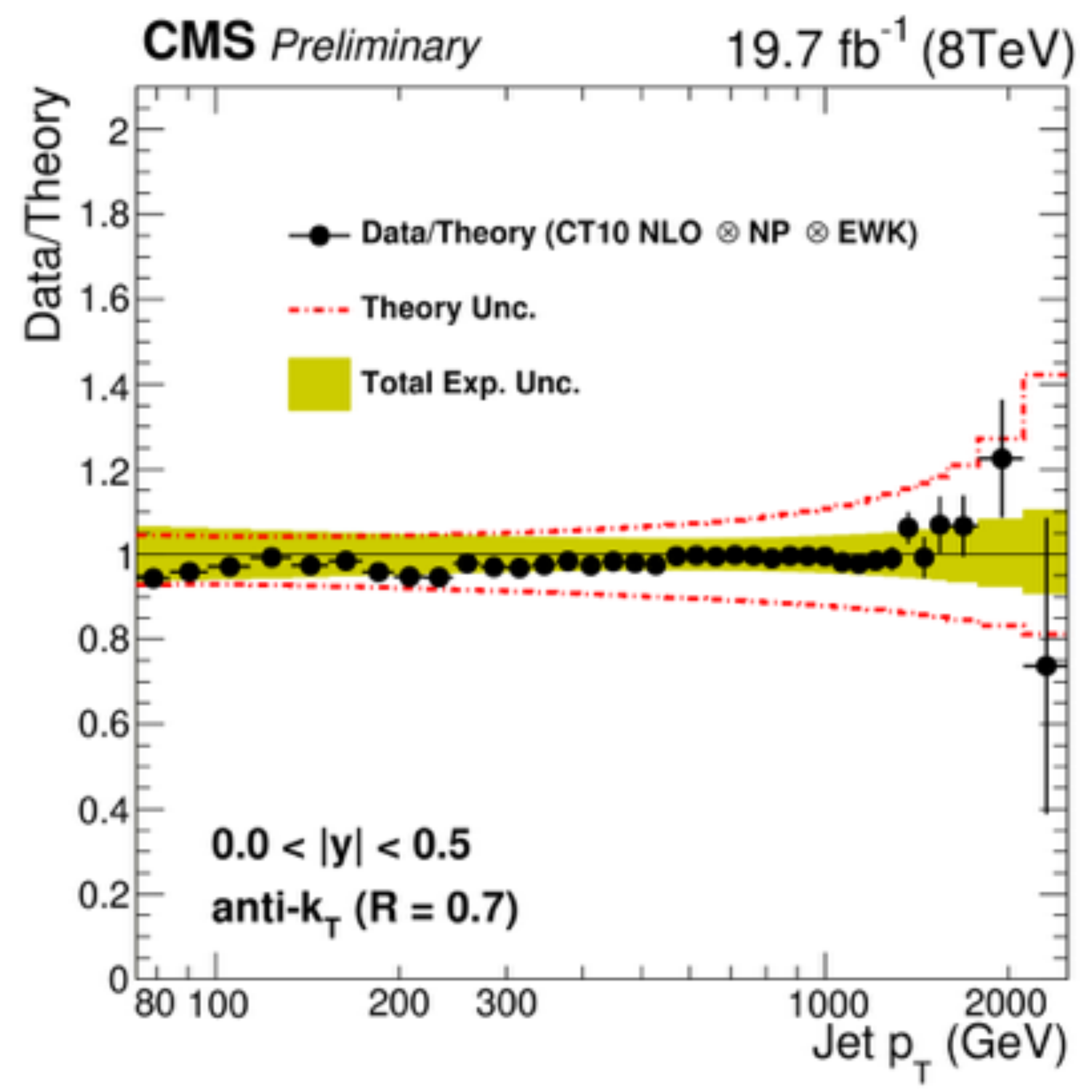
- Experimental errors on inclusive p_T spectrum of lepton pairs in Z-production under 1%
- Important input into PDF fits; detector calibration
- Scale uncertainties at NLO at the 10% level

The experimental challenge



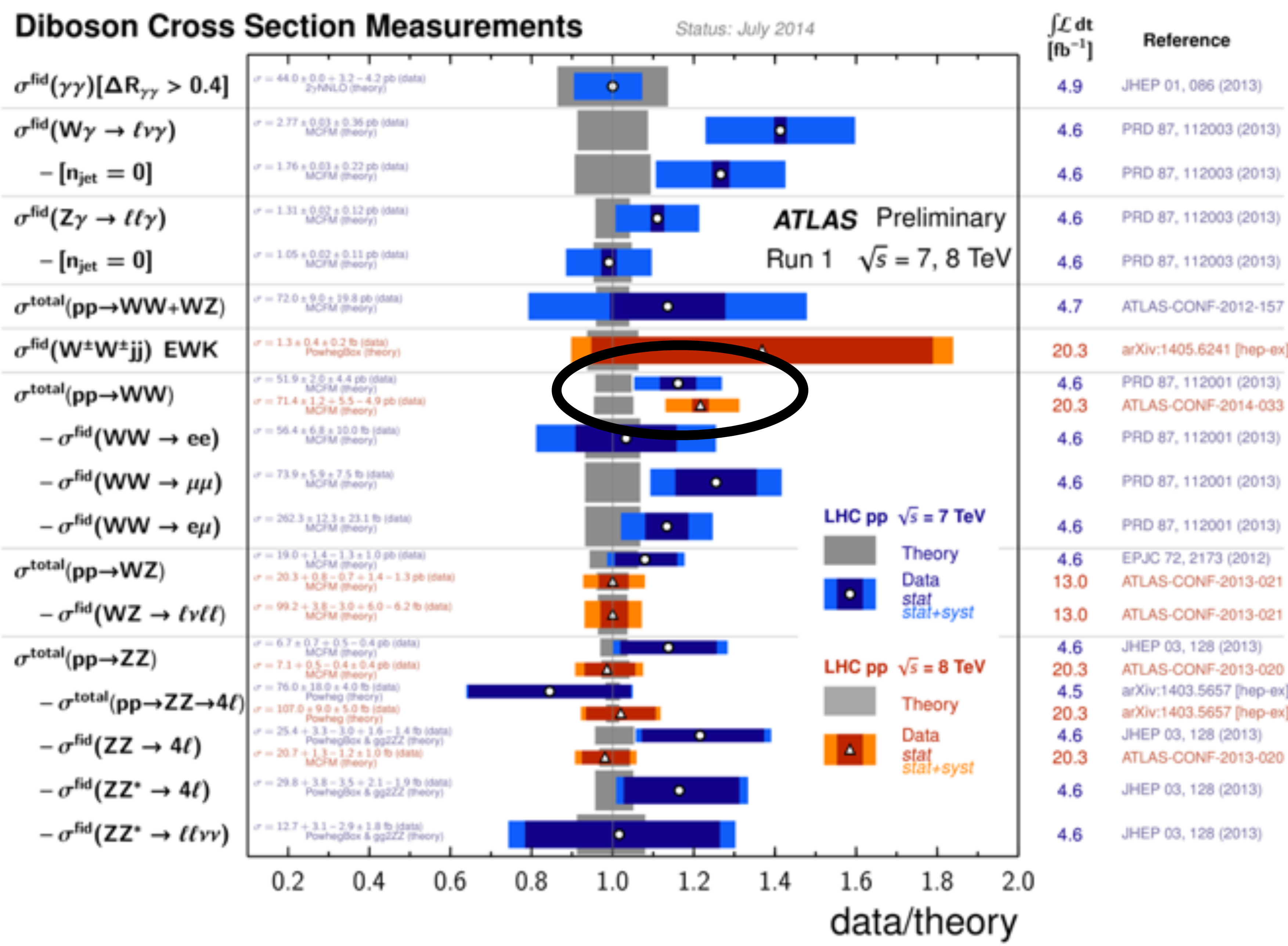
Theory errors are exceeding experimental errors in multiple channels





Why we need NNLO precision

- The precision standard for most processes so far has been NLO
- NNLO is needed to avoid misinterpretation of experimental data
- An example: the WW cross section



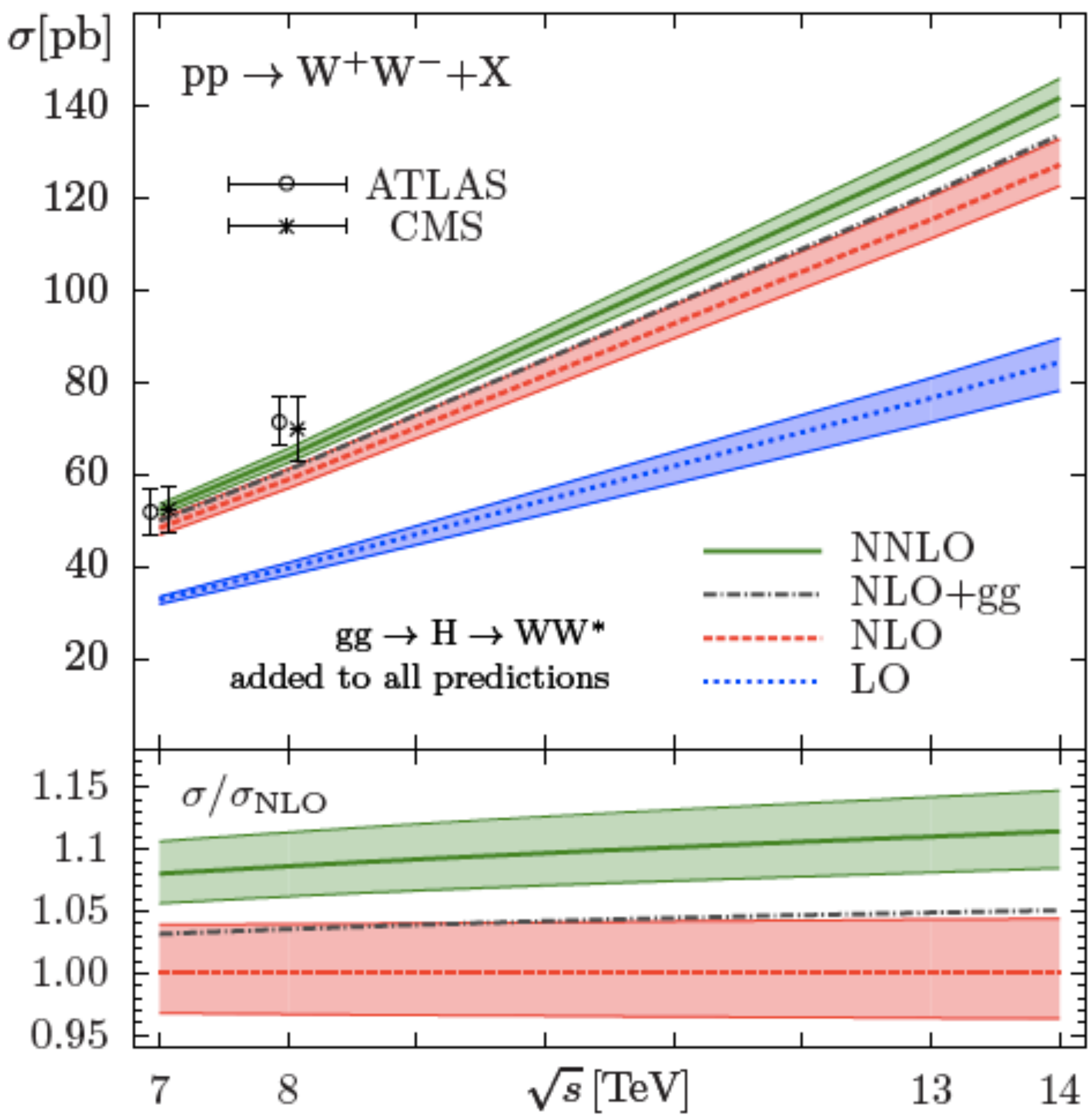
Could it be light charginos?

(Curtin, Jaiswal, Meade 1206.6888, and others)

The WW cross section now

- Sizable NNLO QCD corrections! Theory within 1σ agreement of ATLAS and CMS for both CM energies

Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi (2014)

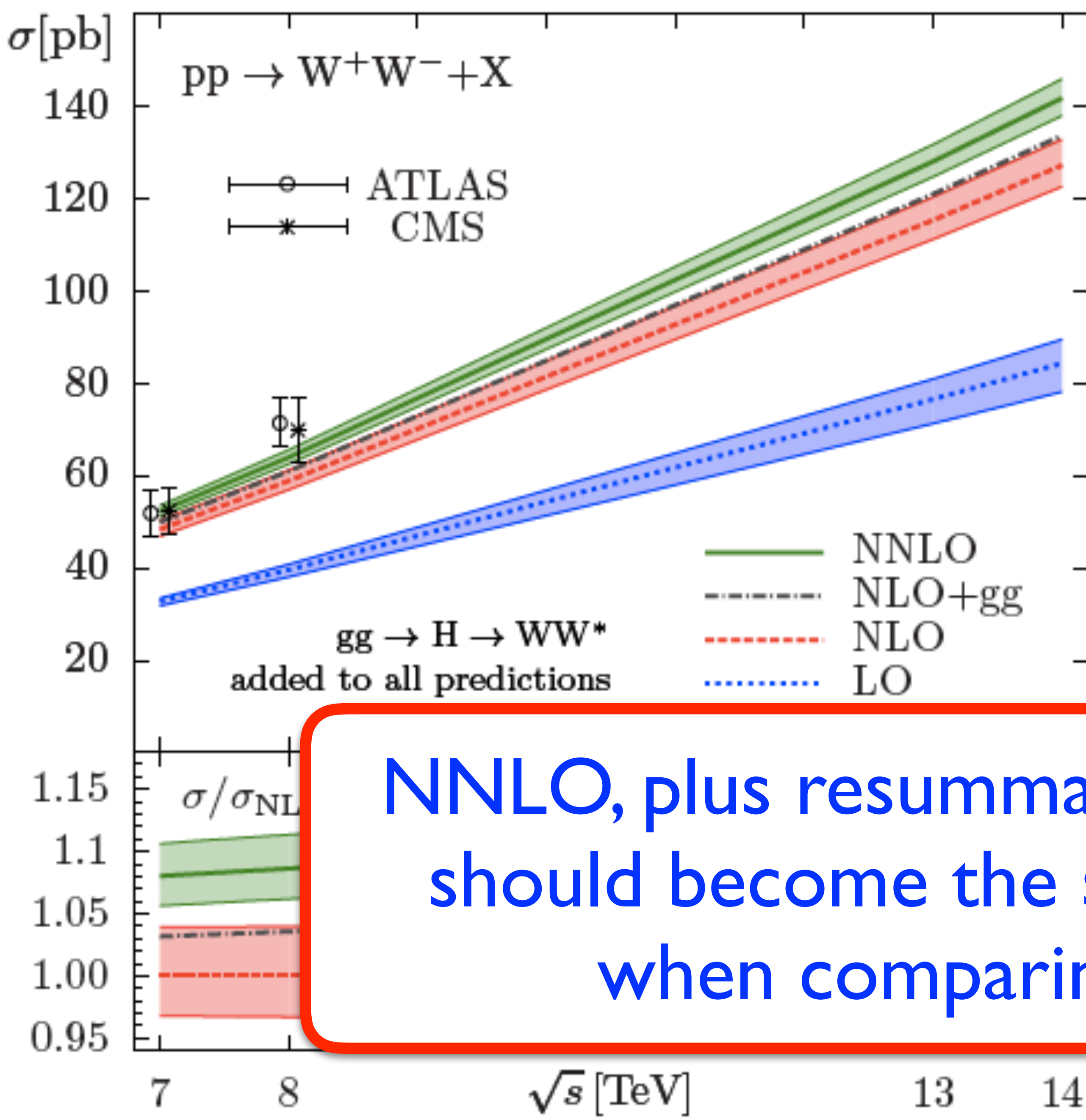


- Enhancement of theory is expected when the extrapolation from the fiducial region is properly modeled, further improving agreement

Monni, Zanderighi (2014) (see also Jaiswal, Okui, Curtin, Meade, Tien (2014))

The WW cross section now

- Sizable NNLO QCD corrections! Theory within 1σ agreement of ATLAS and CMS for both CM energies Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi 1408.5243



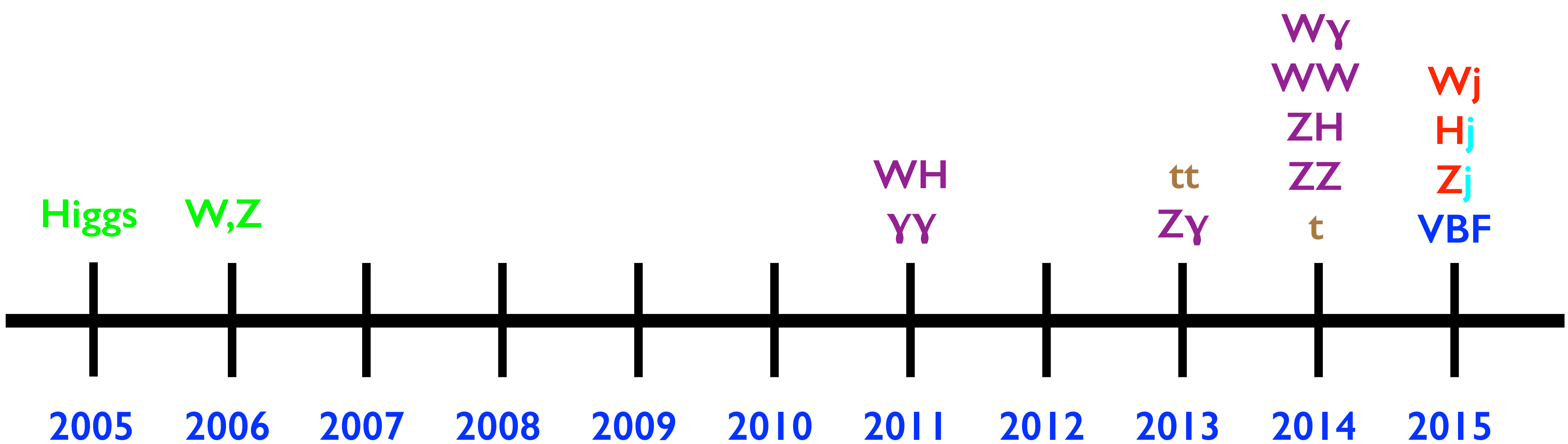
- Enhancement of theory is expected when the extrapolation from the fiducial region is properly modeled, further improving agreement

Monni, Zanderighi 1410.4745 (see also Jaiswal, Okui, 1407.4537; Curtin,

NNLO, plus resummation when cuts require, should become the standard during Run II when comparing theory to data

A timeline of NNLO hadron collider cross sections

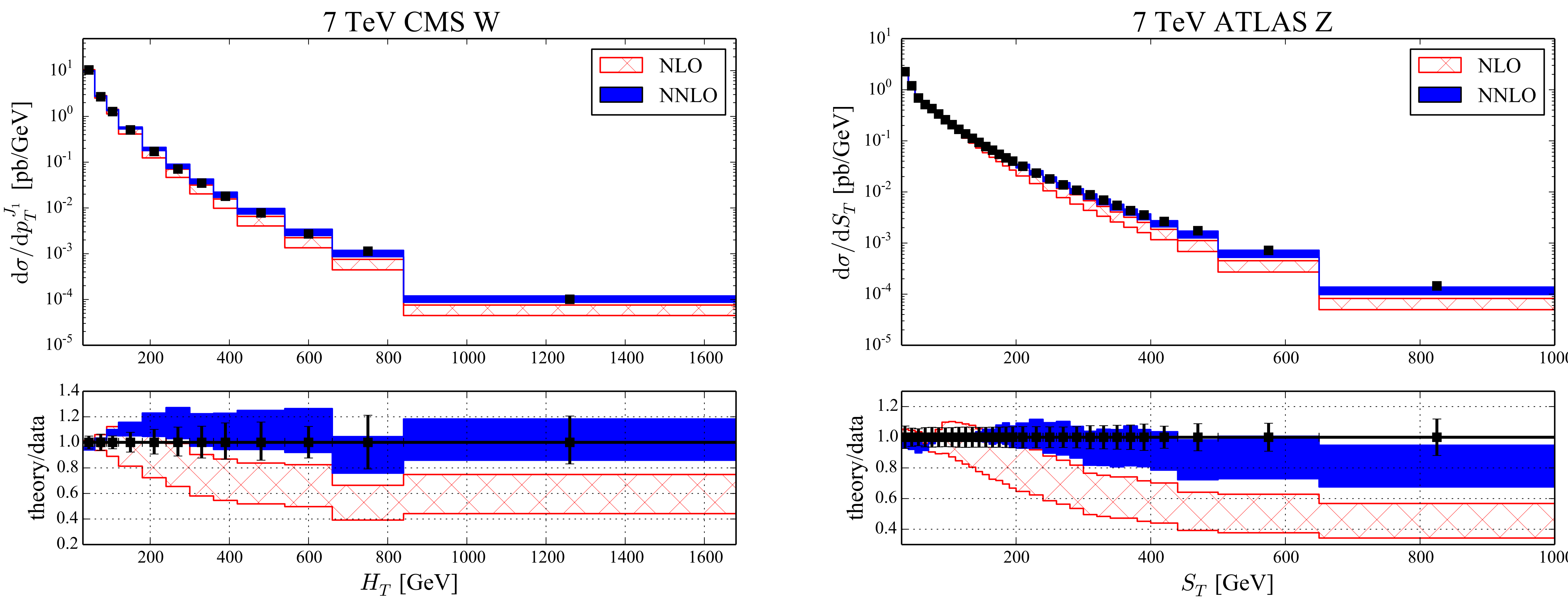
- Complete NNLO hadron-collider cross sections with control over kinematics:



NNLO, including for jets, becoming available for 2→2 scattering in time for high-precision Run II data

Vector boson plus jet production

- Important background process to SUSY, dark matter searches, VH production

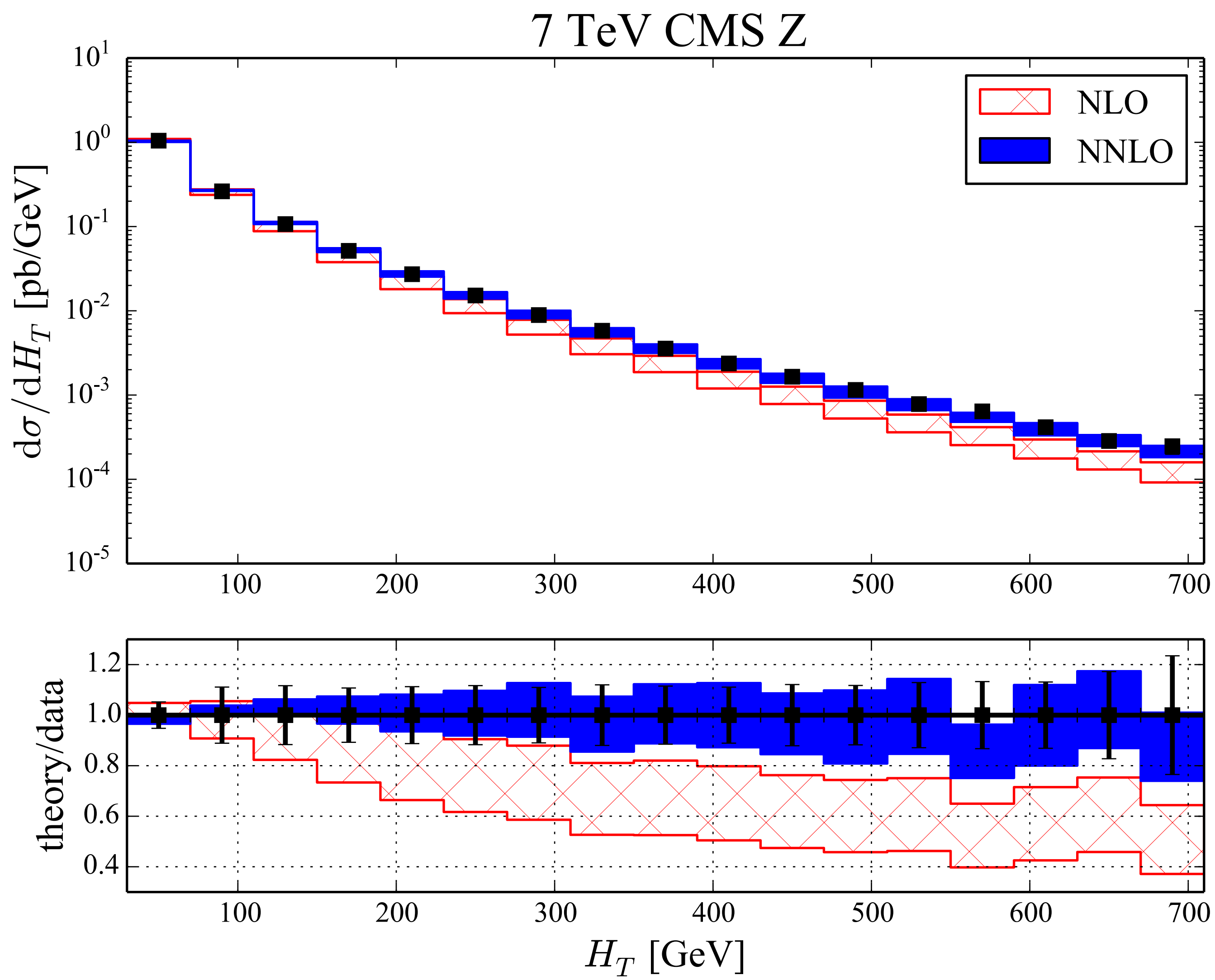


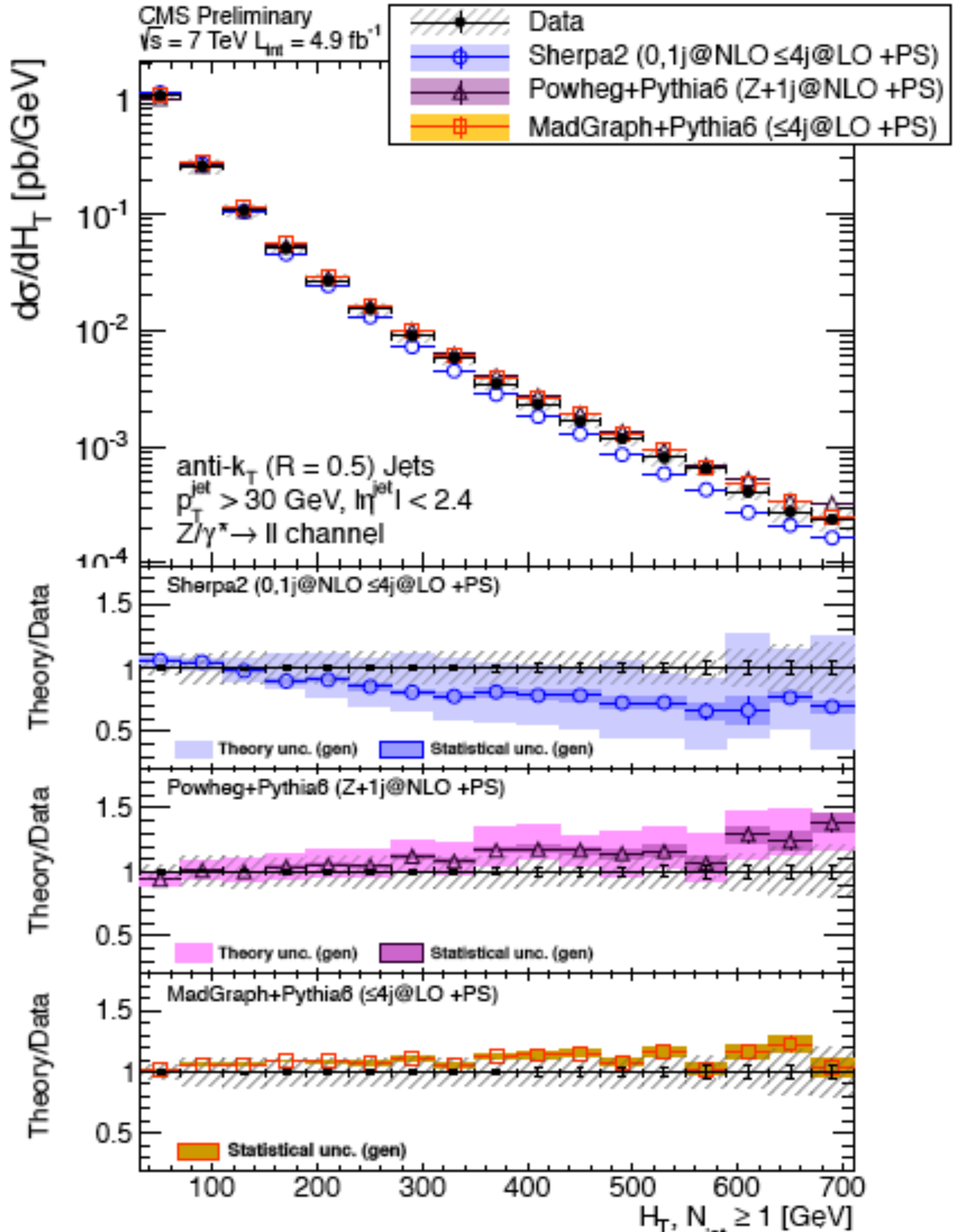
Boughezal, Liu, FP 1602.05612

NNLO corrections mandatory to properly describe measured H_T distributions in both W+j and Z+j production

Vector boson plus jet production

Boughezal, Liu, FP 1602.05612

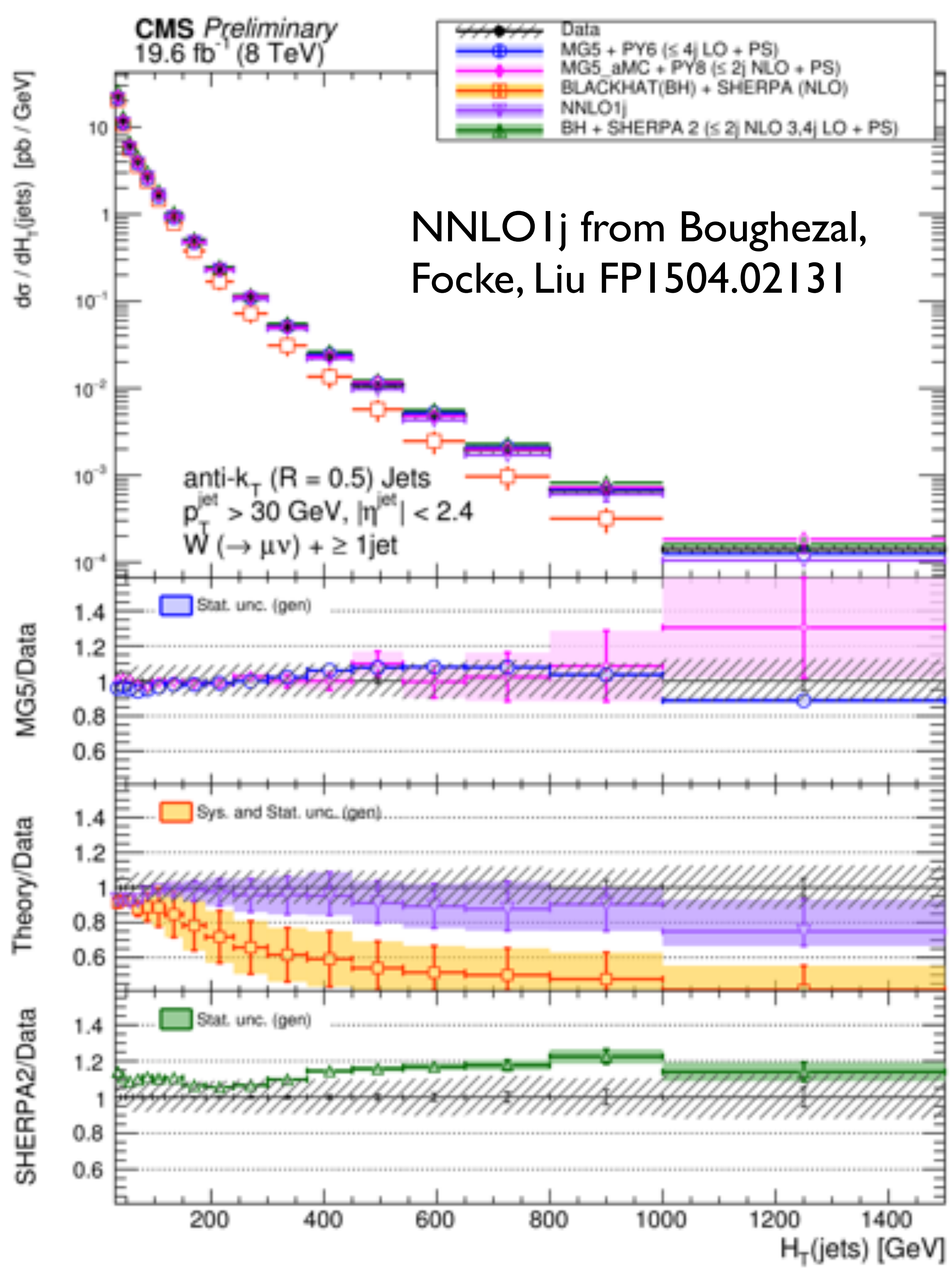


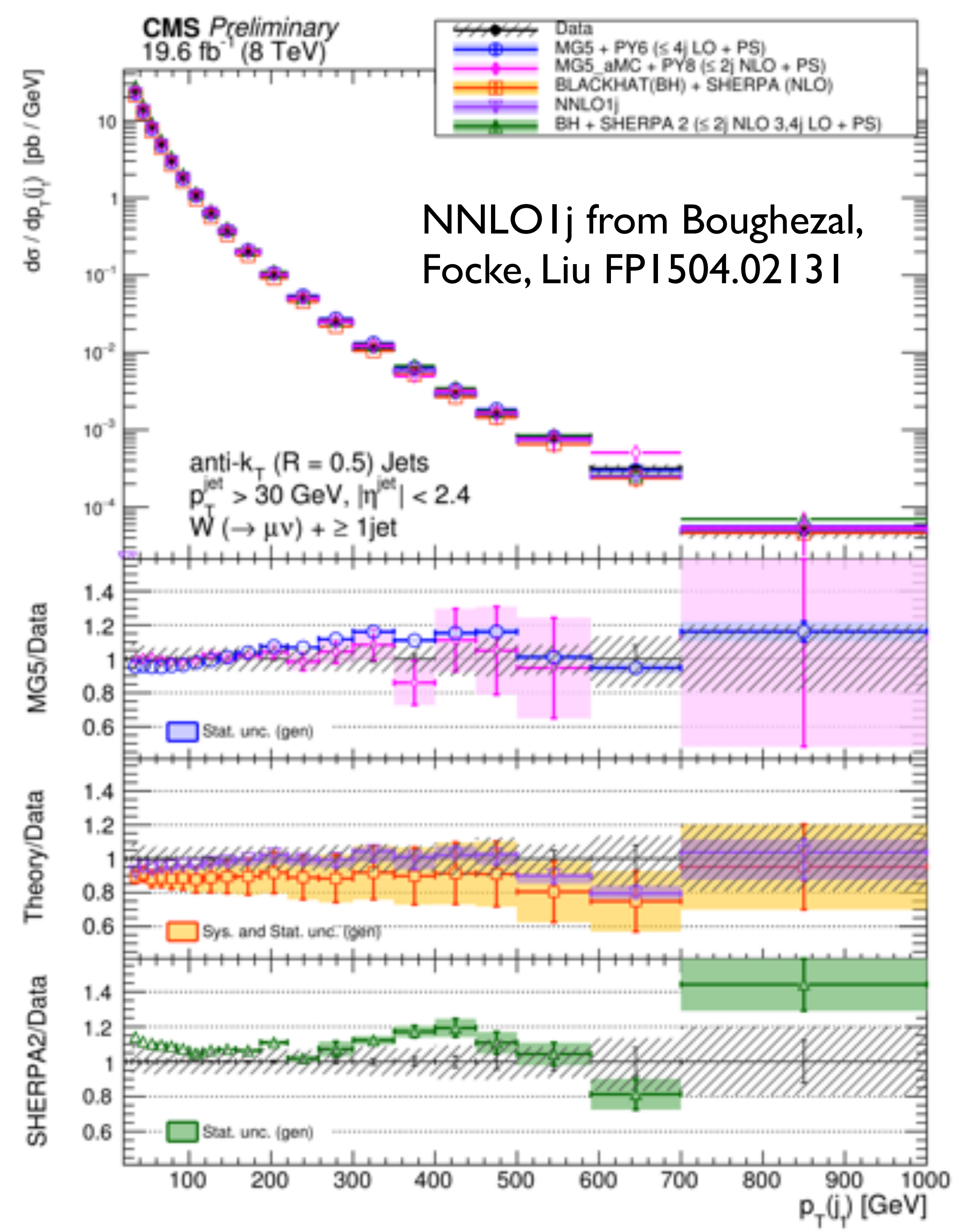


Only NNLO correctly describes shape and normalization via a controlled, systematically improvable expansion

Comparisons with 8 TeV data

- NNLO again offers an excellent description of both shape and normalization





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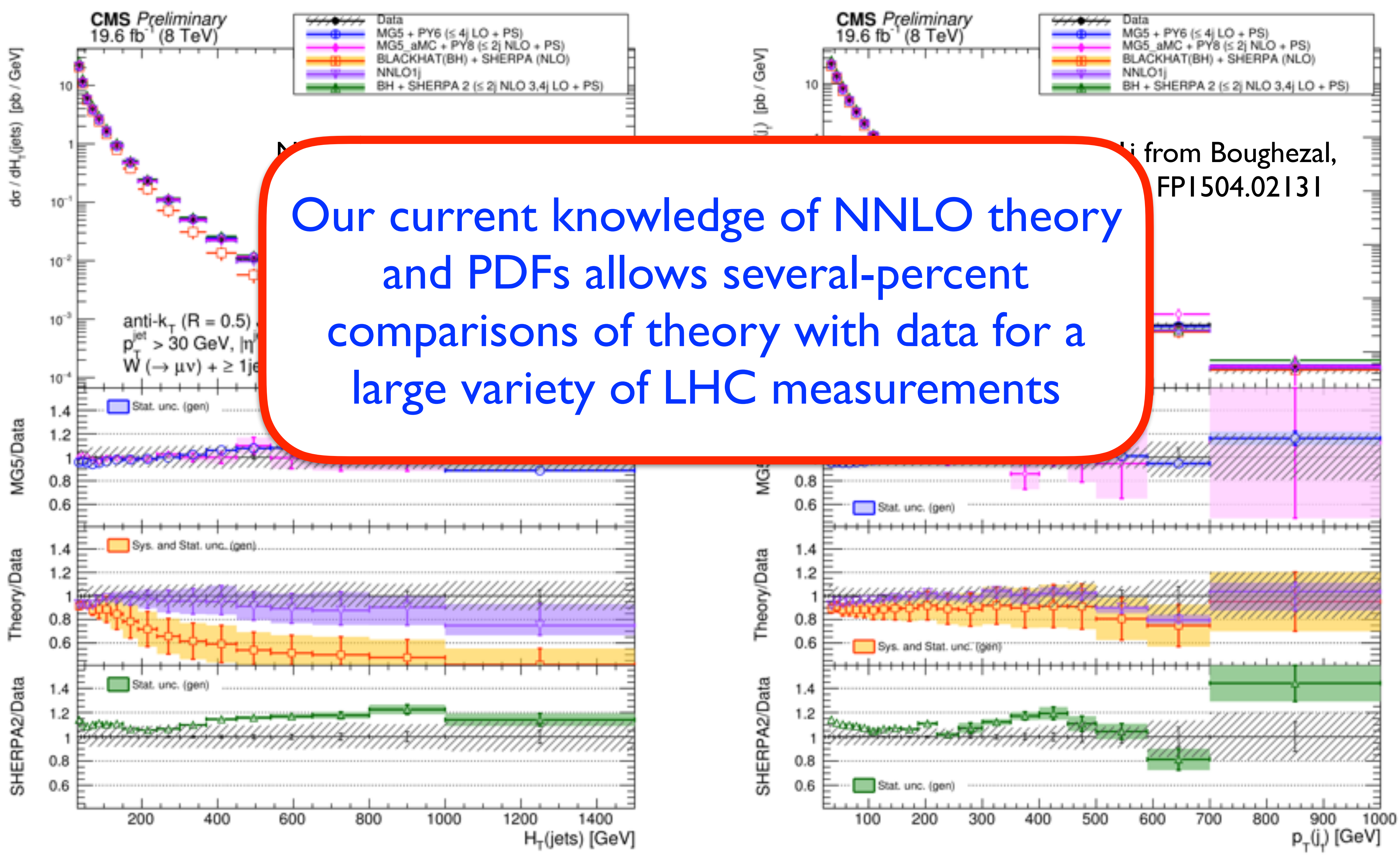
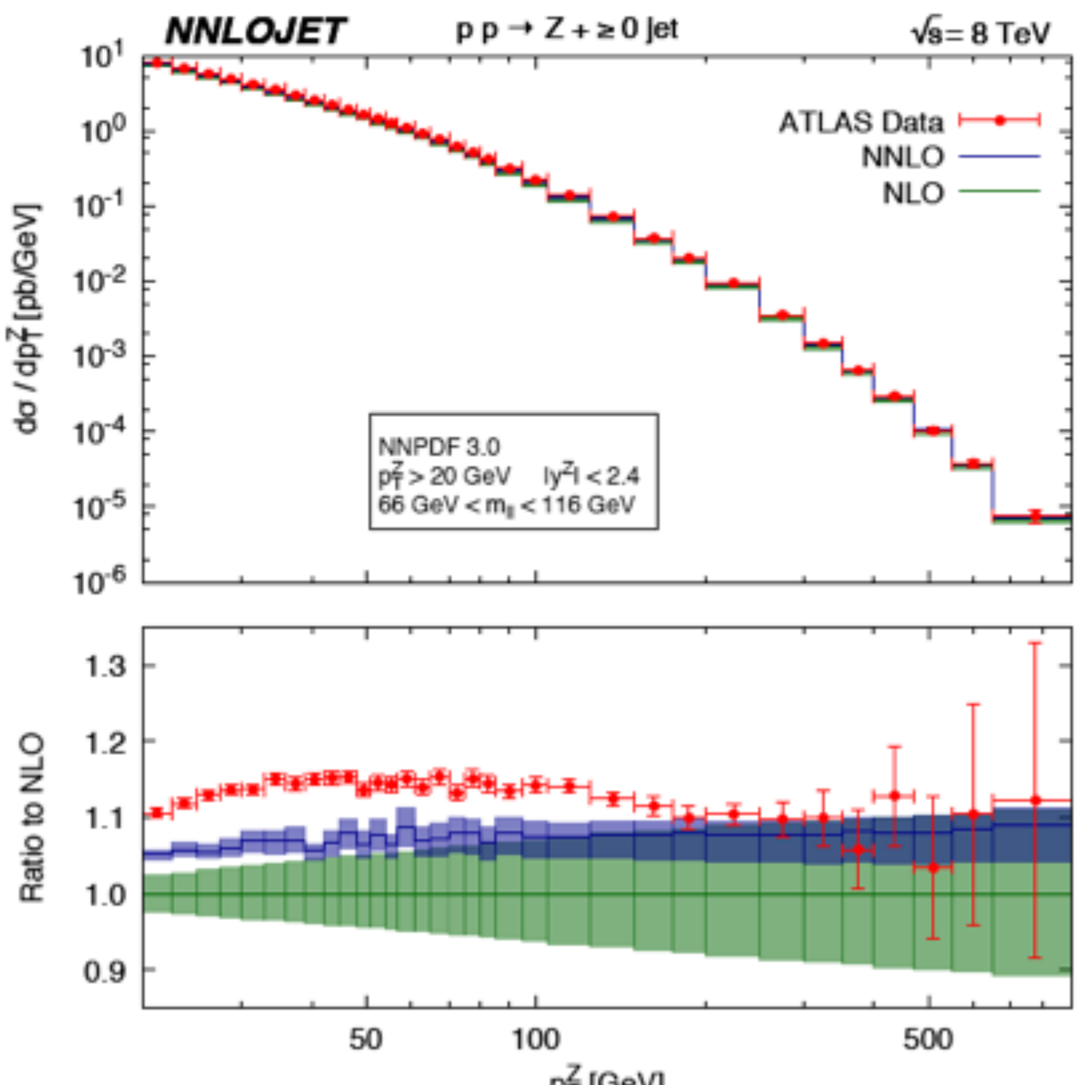


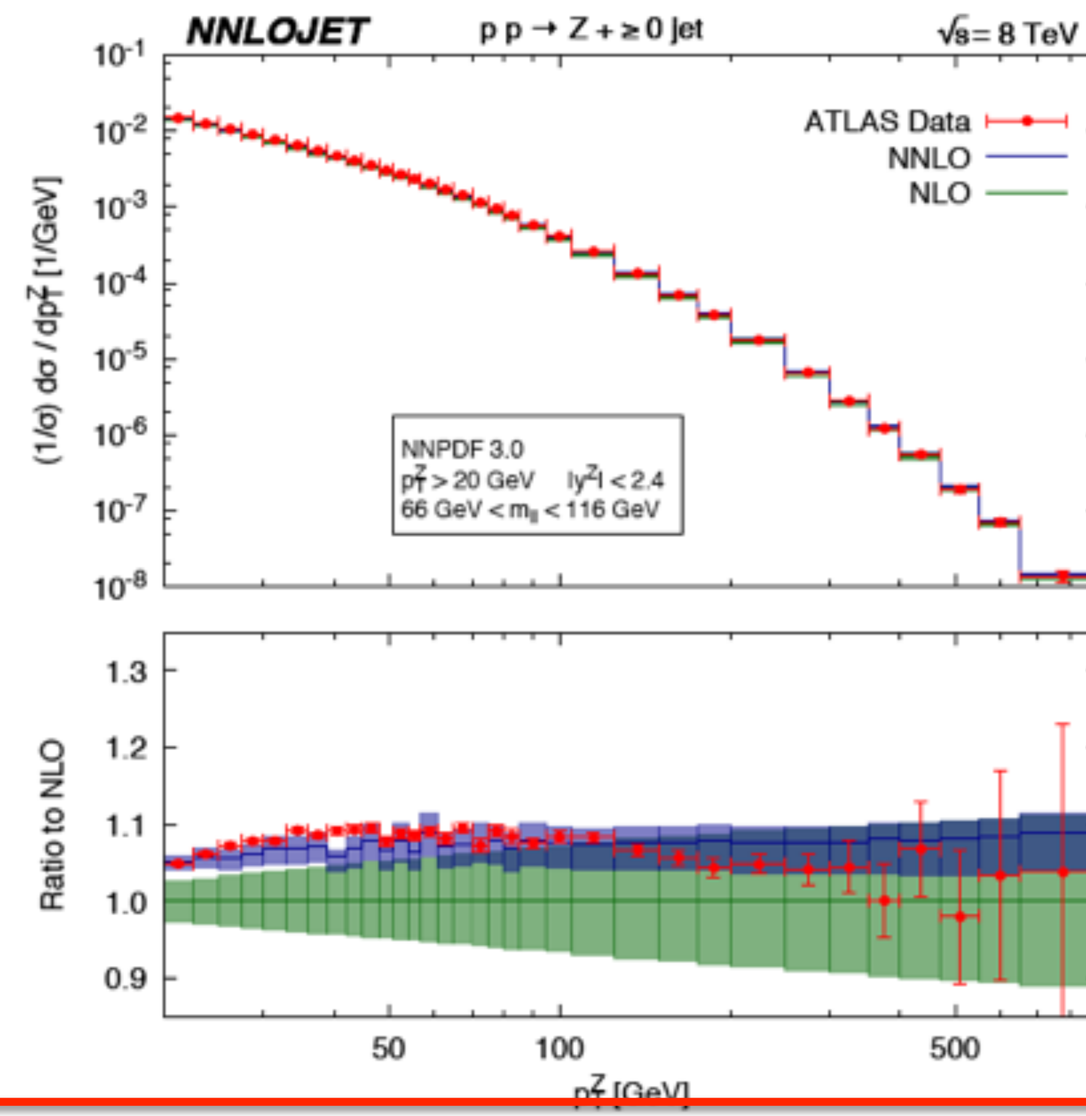
Our current knowledge of NNLO theory and PDFs allows several-percent comparisons of theory with data for a large variety of LHC measurements

The Z-boson p_T spectrum

- The sub-percent experimental precision make this a stringent precision test of the SM, and illustrates the challenges to further improving precision at Run II

Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan 1605.04295





Normalizing to the fiducial Z cross section affects theory/data agreement

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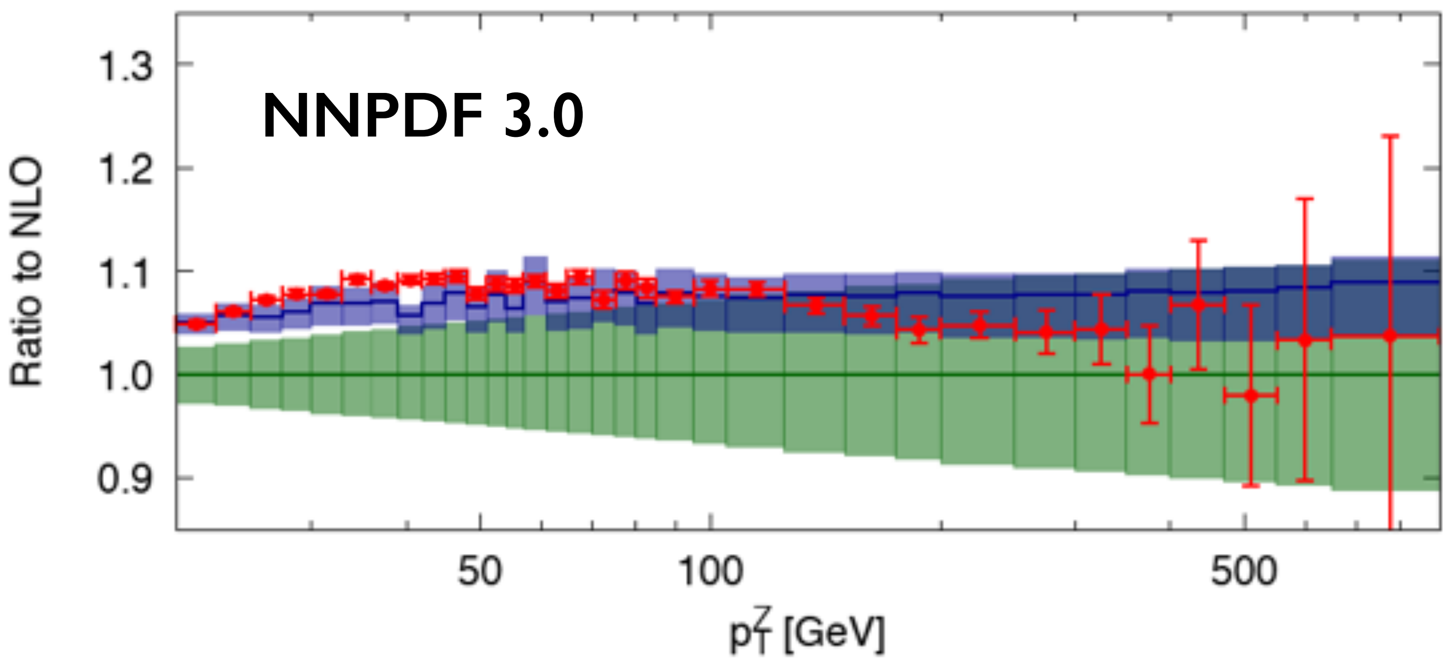
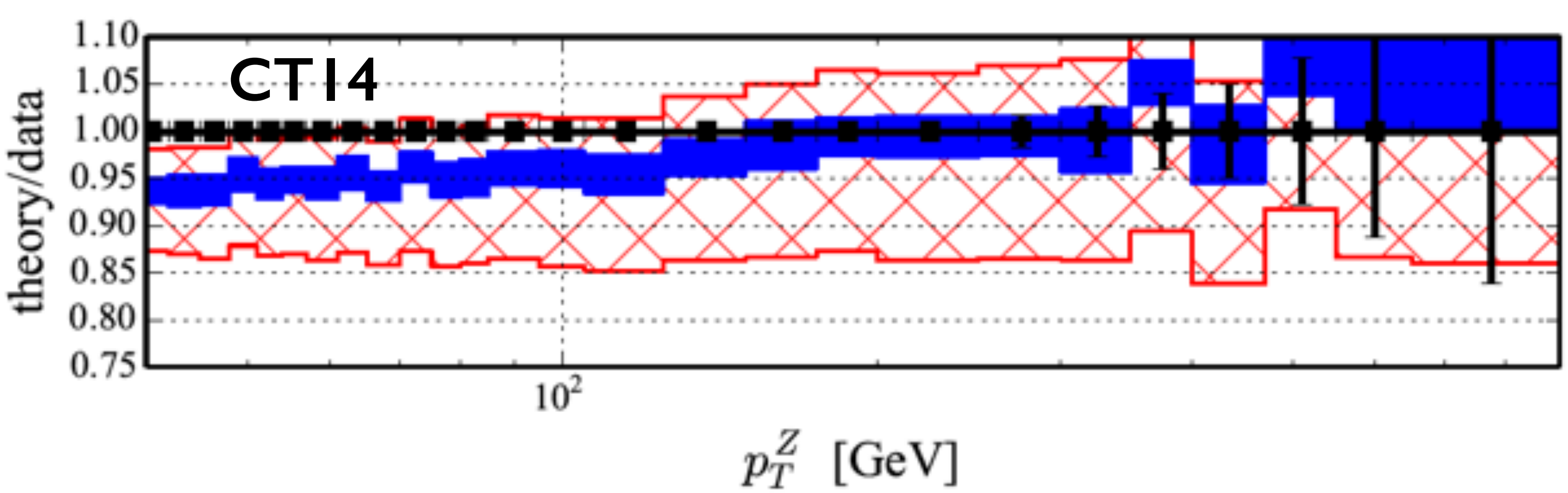
Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan 1605.04295



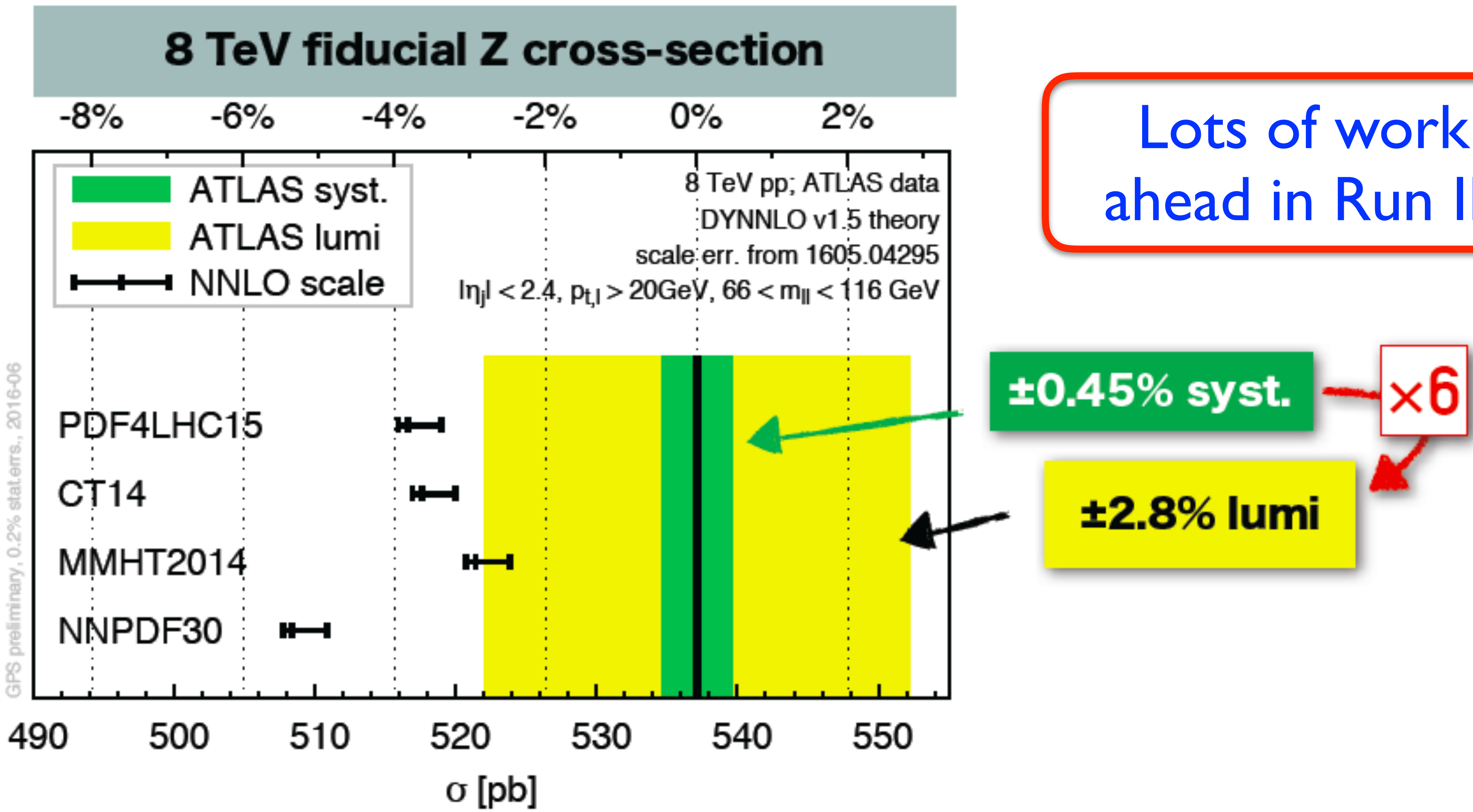
Choice of PDF set affects theory/data agreement

Boughezal, Liu, FP (based on Boughezal et al. 1512.01291)



The Z-boson fiducial cross section

- Everything must be in place to achieve percent-level precision at Run II: theory, PDFs, parameters such as α_S, luminosity and experimental systematics

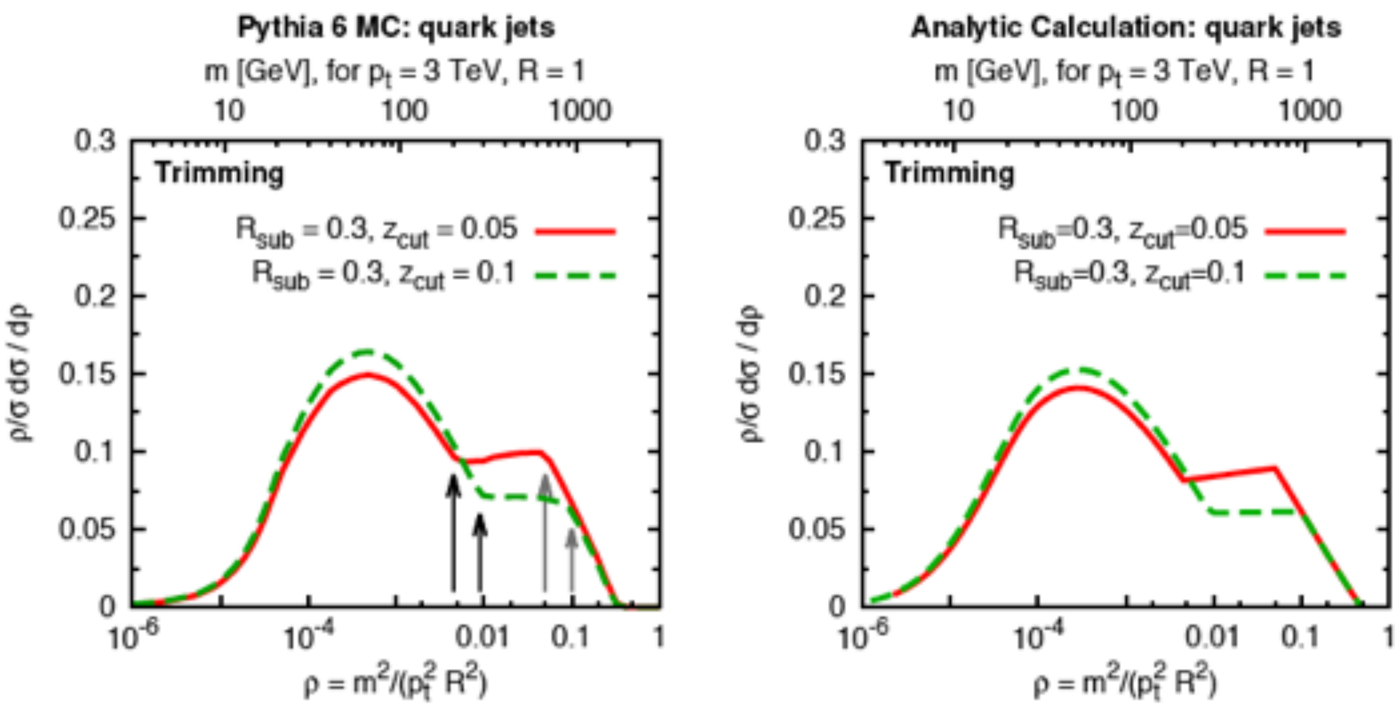


from G. Salam, LHCP 2016

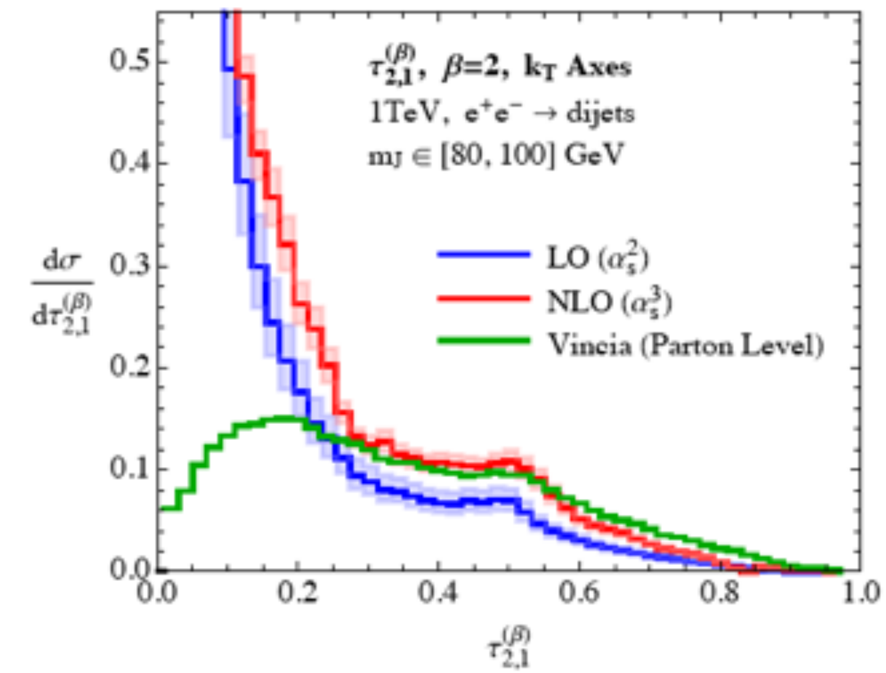
Lots of work ahead in Run II!

Precision QCD for jet substructure

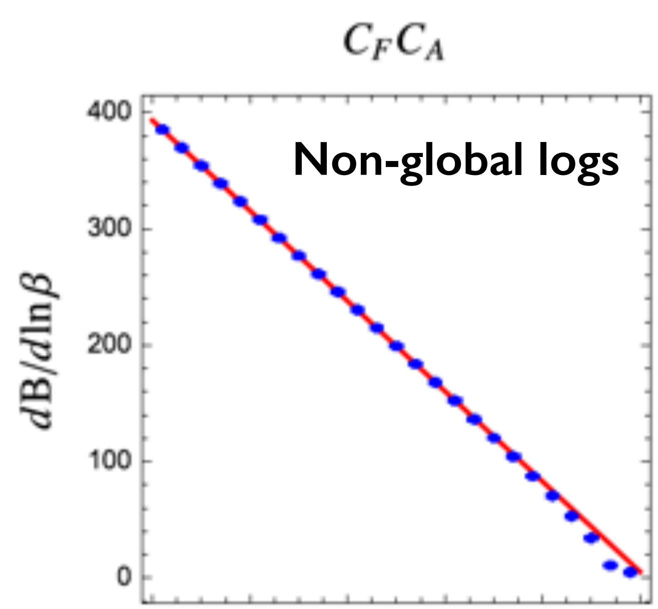
- Newly-developing precision QCD calculations of jet substructure observables



Dasgupta, Fregoso, Marzani, Salam 1307.0007



Larkoski, Moult 1510.08459



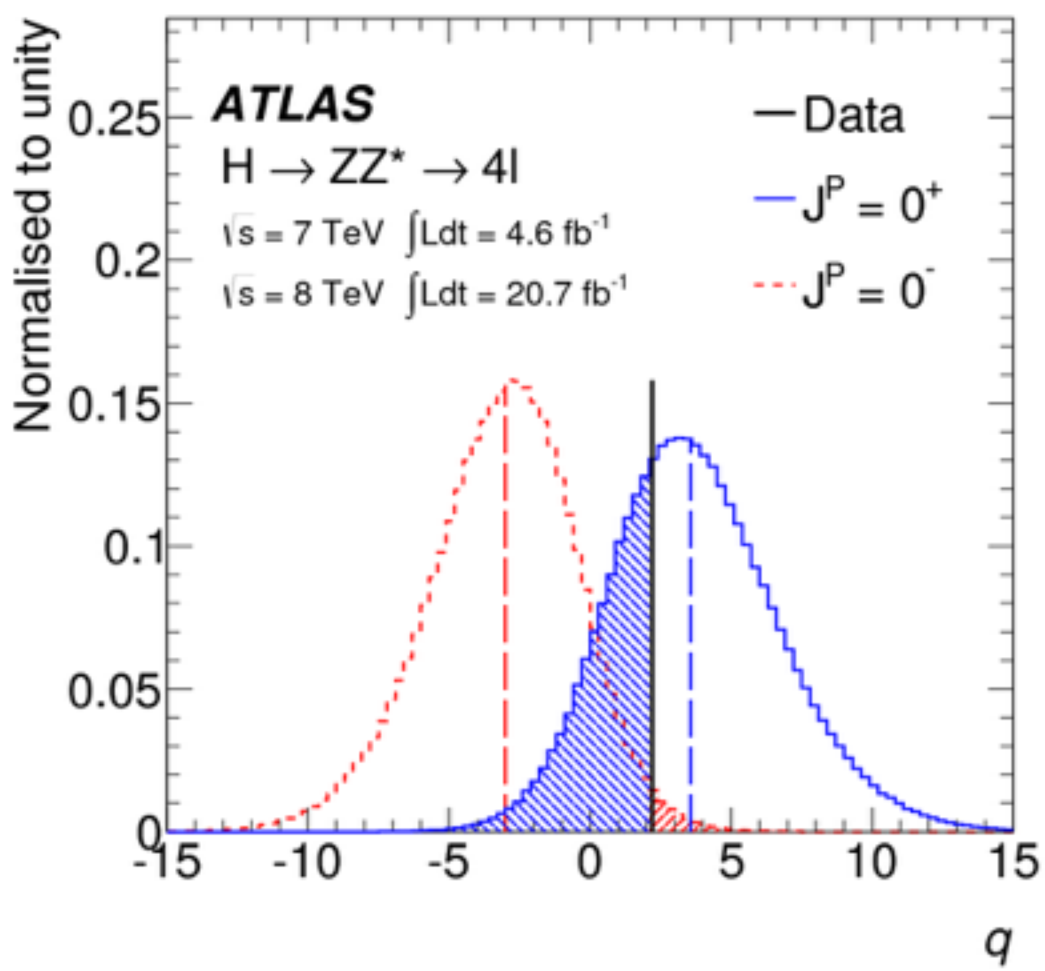
Becher, Neubert, Rothen, Shao 1605.02737

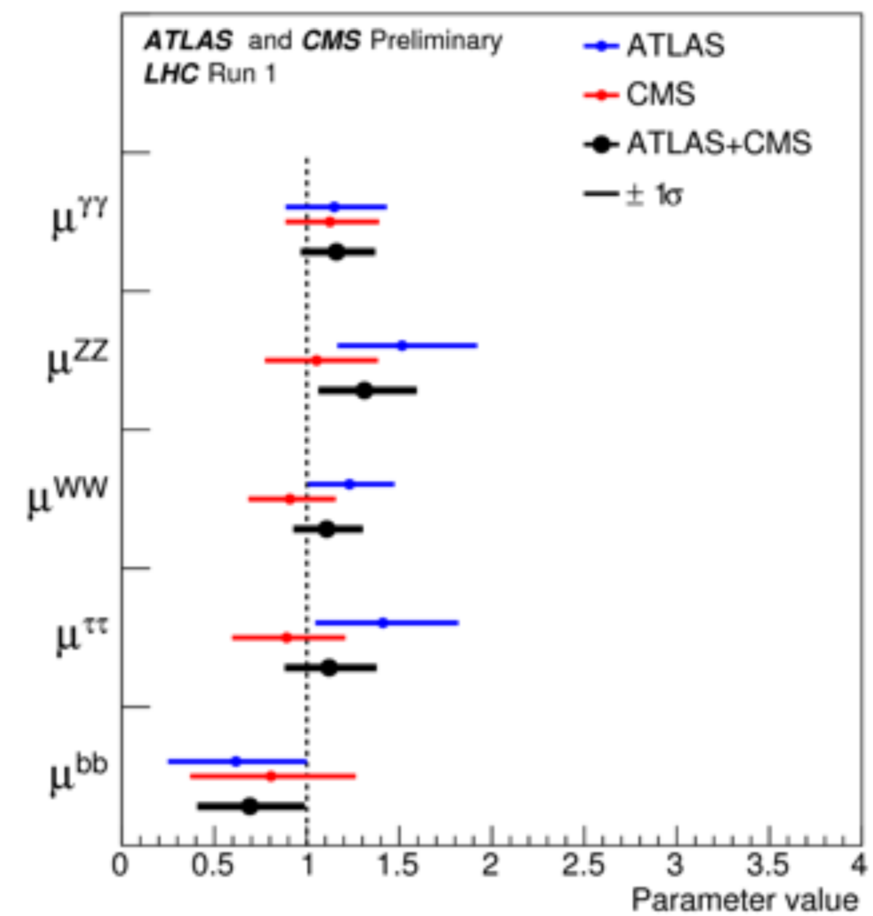
Looking forward to hearing more at this conference!

Exploring the Higgs sector in Run II

Framework for Run II Higgs studies

- We haven't yet seen anything beyond the SM, although hints exist. The Higgs appears SM-like. Motivates interpretation of Run II results in EFT framework.





$$\boxed{\mathcal{L} = \mathcal{L}^{SM} + \mathcal{L}^{UV} \Rightarrow \mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2}\mathcal{O}_i}$$

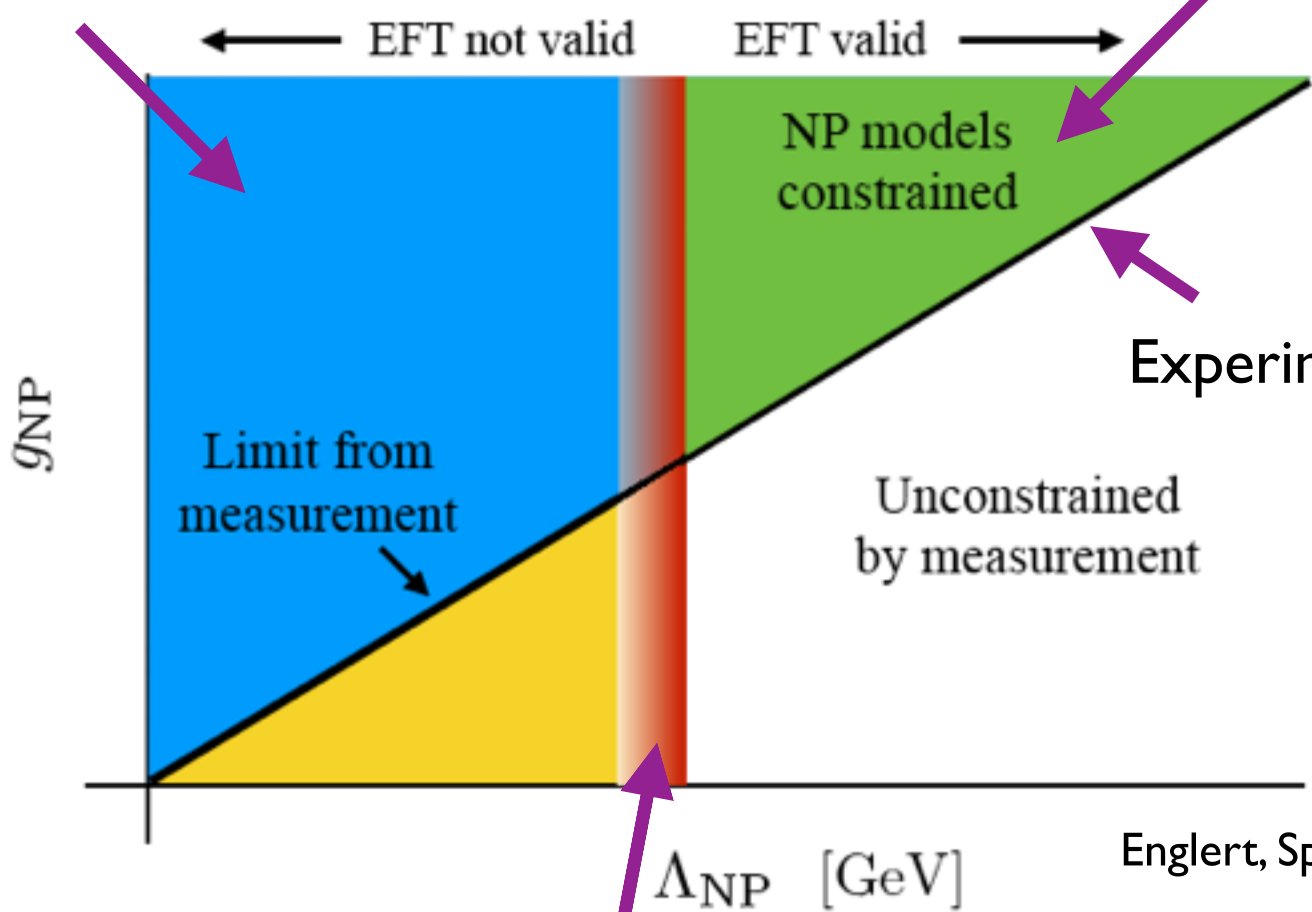
EFTs for Higgs physics

- Complete N_F=1, baryon-number conserving D=6 EFT contains 59 operators; N_F=3 contains 2499 operators (Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884); Alonso, Jenkins, Manohar, Trott 1312.2014). Various basis choices and simplifications have been discussed.
  - Warsaw basis (Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884)
  - SILH basis (Giudice, Grojean, Pomarol, Rattazzi hep-ph/0703164; Contino, Ghezzi, Grojean, Muhlleitner, Spira 1303.3876)
  - Higgs basis (Gupta, Pomarol, Riva 1405.0181)
  - Chiral EW Lagrangian (Buchalla, Cata, Krause 1307.5017)
- Higher-order corrections in EFT important to disentangle new physics effects from RG-running (Englert, Spannowsky 1408.5147). Full NLO EFT calculations appearing (Hartmann, Trott 1507.03568)
- Can investigate EFT validity in toy models (Contino, Falkowski, Goertz, Grojean, Riva 1604.06444)

Sketch of an EFT analysis

Must compare explicit UV models against data in the region

Can map heavy NP models into this constraint plane



Experiment bounds g^2/Λ^2

Englert, Spannowsky 1408.5147

Measure maximum energy scale that goes into measurement to set lower limit on EFT region of validity

Sketch of an EFT analysis

Must compare explicit UV models against data in the region

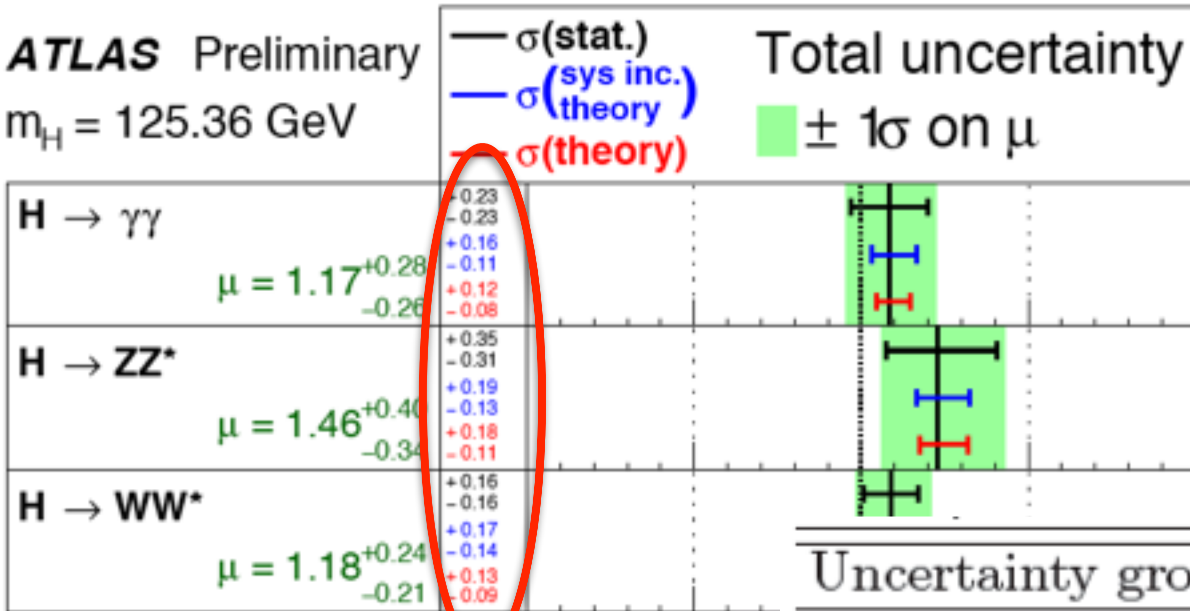
Can map heavy NP models into this constraint plane

Measurement  EFT

Several bridges between experiment and EFT interpretation have been proposed to simplify analyses:

- Pseudo-observables (Gonzalez-Alonso, Greljo, Isidori, Marzocca 1412.6038; Ghezzi, Gomez-Ambrosio, Passarino, Uccirati 1505.03706)
- Template cross sections (Duehrssen-Debling, Francavilla, Tackmann, Tackmann LHCHXSWG-2016-006)

Measure maximum energy scale that goes into measurement to set lower limit on EFT region of validity



Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
QCD scale uncertainty	6.5%
PDF, α_s uncertainty	6.0%
$H \to ZZ^*$ branching ratio uncertainty	4.0%

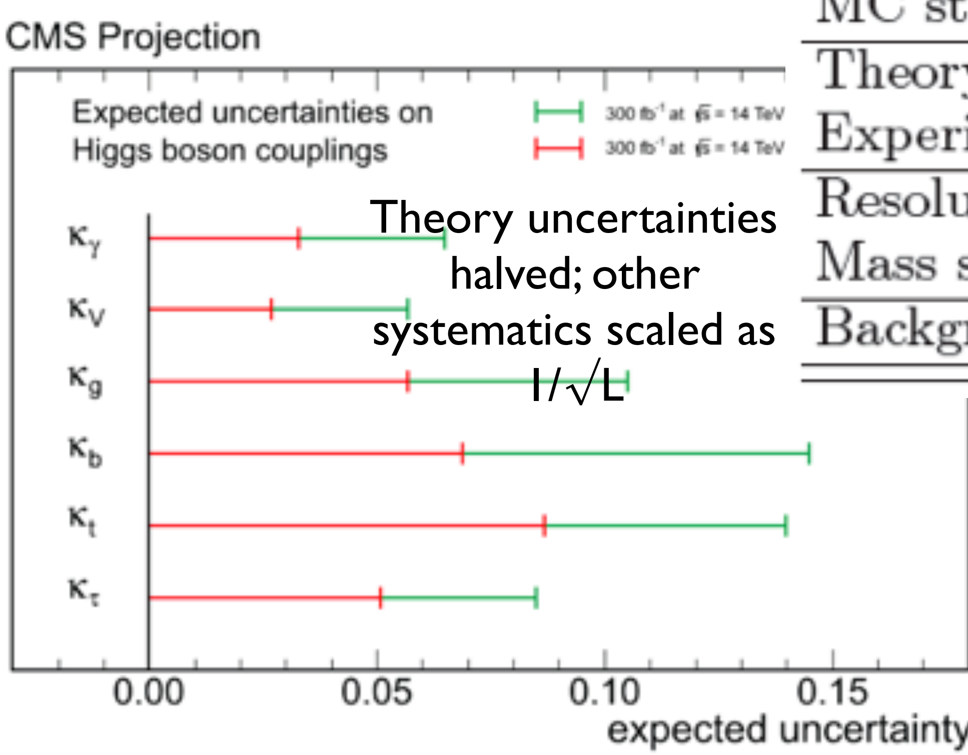
ZZ

Uncertainty group	$\sigma_\mu^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

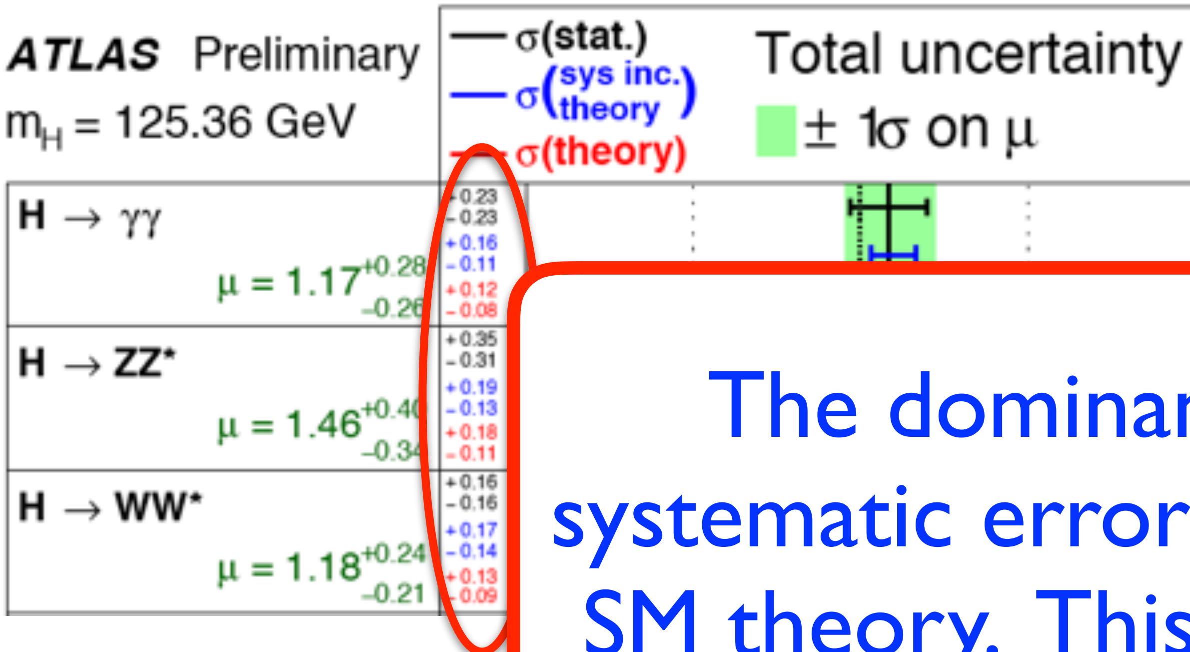
γγ

Source	Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	

WW



Theory uncertainties halved; other systematics scaled as 1/√L



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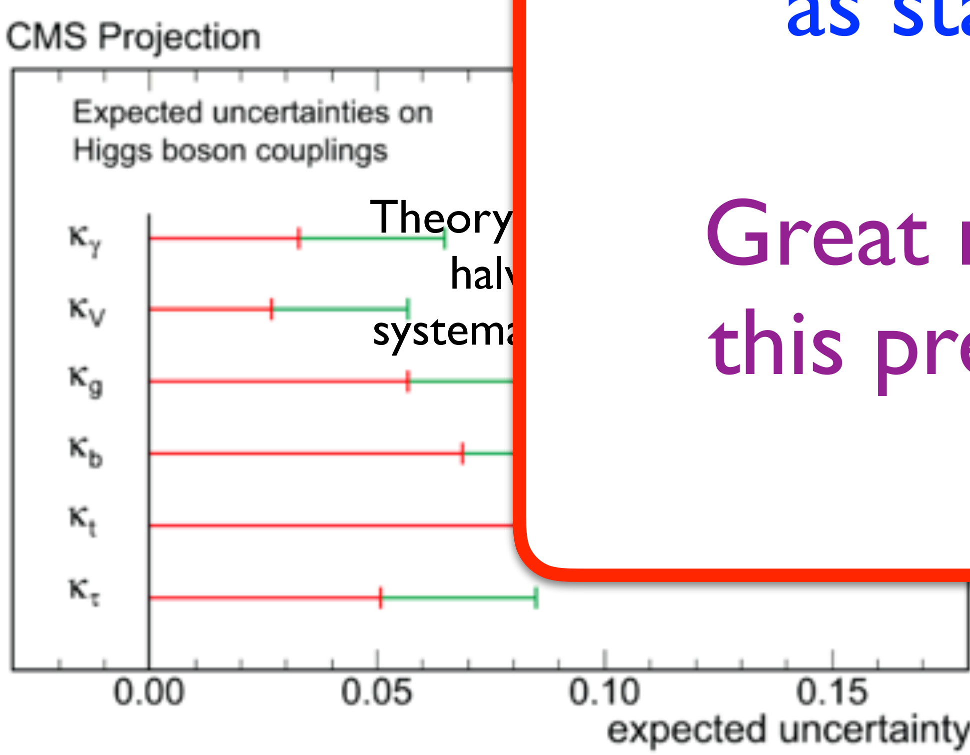
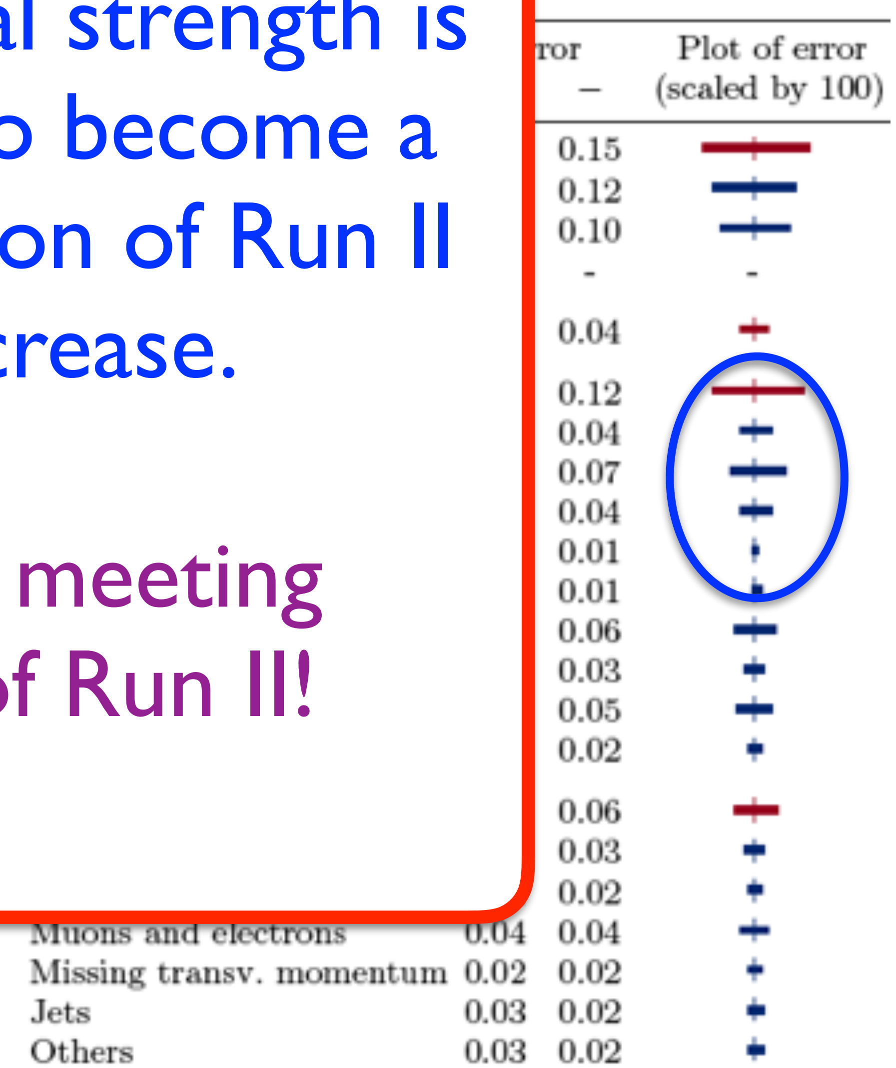
$\ell\ell + \mu\mu$ backgrounds	1.2%
	6.5%
	6.0%
	4.0%





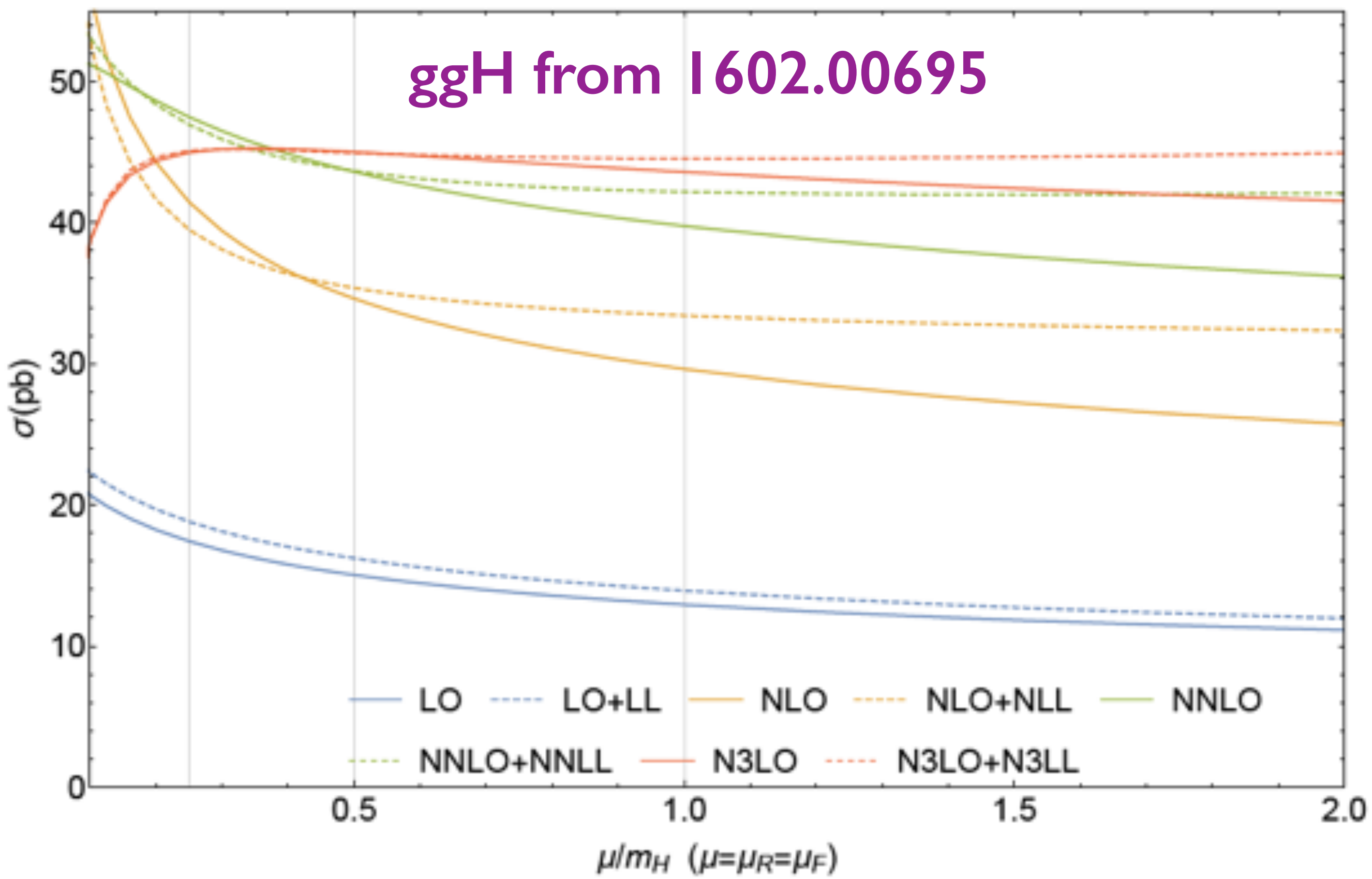
The dominant component of the systematic error on the signal strength is SM theory. This threatens to become a limiting factor in interpretation of Run II as statistical errors decrease.

Great recent progress in meeting this precision challenge of Run II!

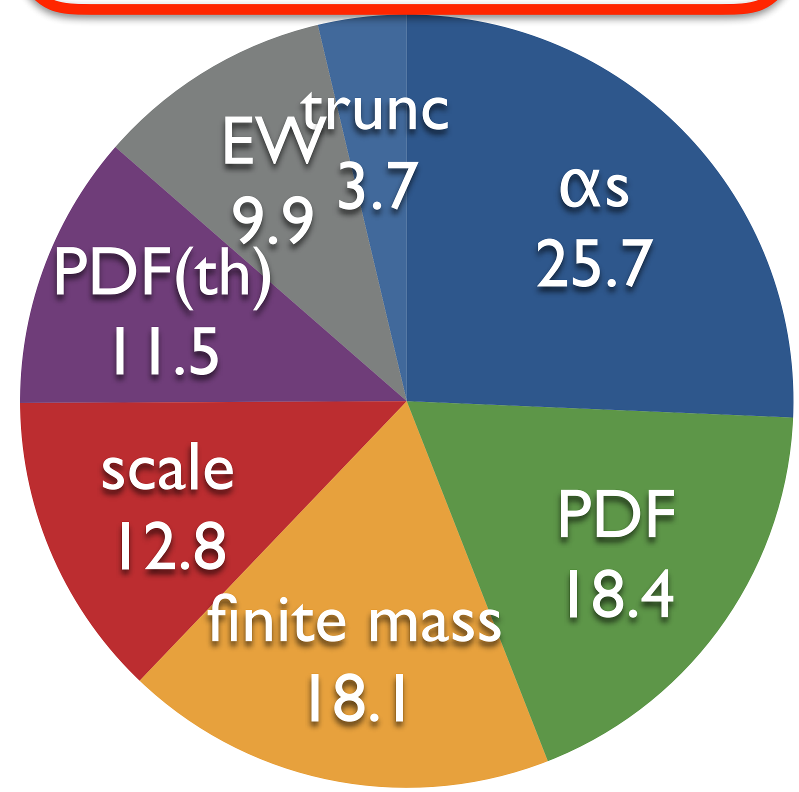
Higgs production in gluon-fusion and VBF

- Inclusive gluon-fusion Higgs production known at N^{3}LO! Important part of all coupling analyses (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger 1602.00695)

- VBF production known at N^{2}LO differentially, and N^{3}LO inclusively (Cacciari, Dreyer, Karlberg, Salam, Zanderighi 1506.02660; Dreyer, Karlberg 1606.00840)



Approximate error budget (percentage of total error):

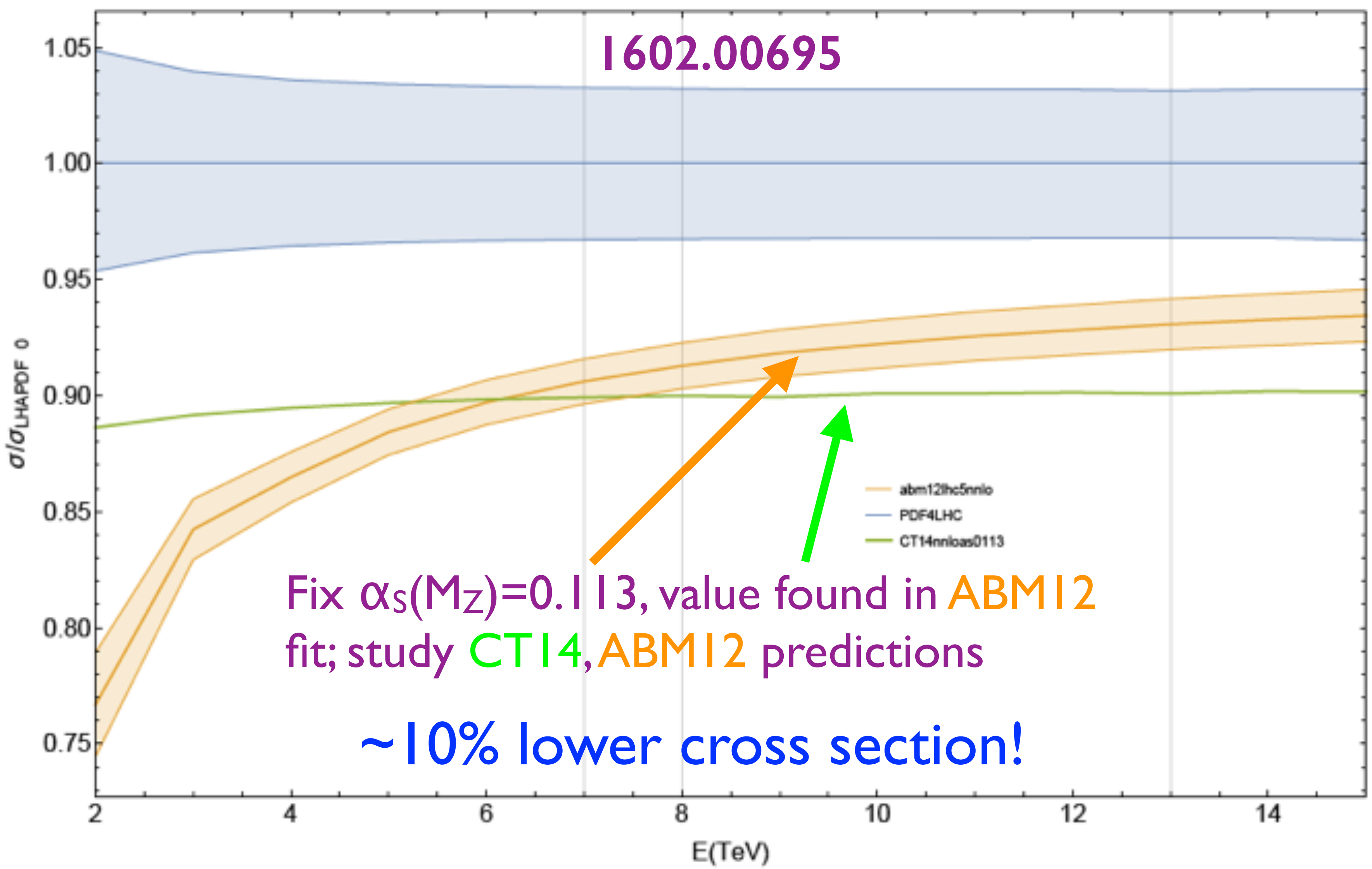


13 TeV:

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\mathrm{PDF}+\alpha_s)\,.$$

Higgs production in gluon-fusion and VBF

- This assumes PDF4LHC $\alpha_S(M_Z)$ recommendation: 0.1180±0.0015
- DIS fits prefer lower $\alpha_S(M_Z)$; LO ggH~α_S^2⇒strong parametric dependence!



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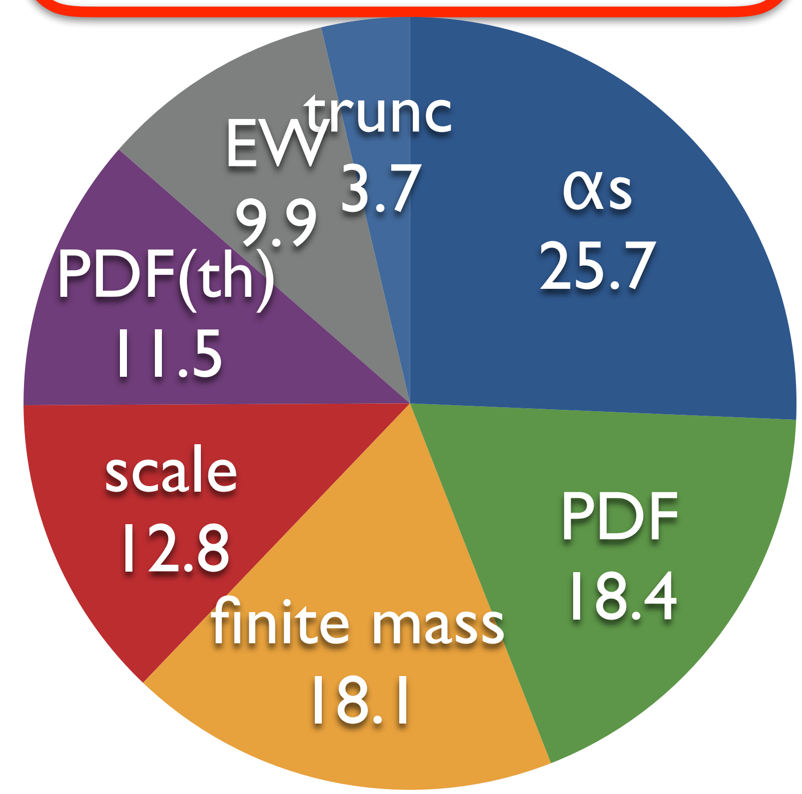

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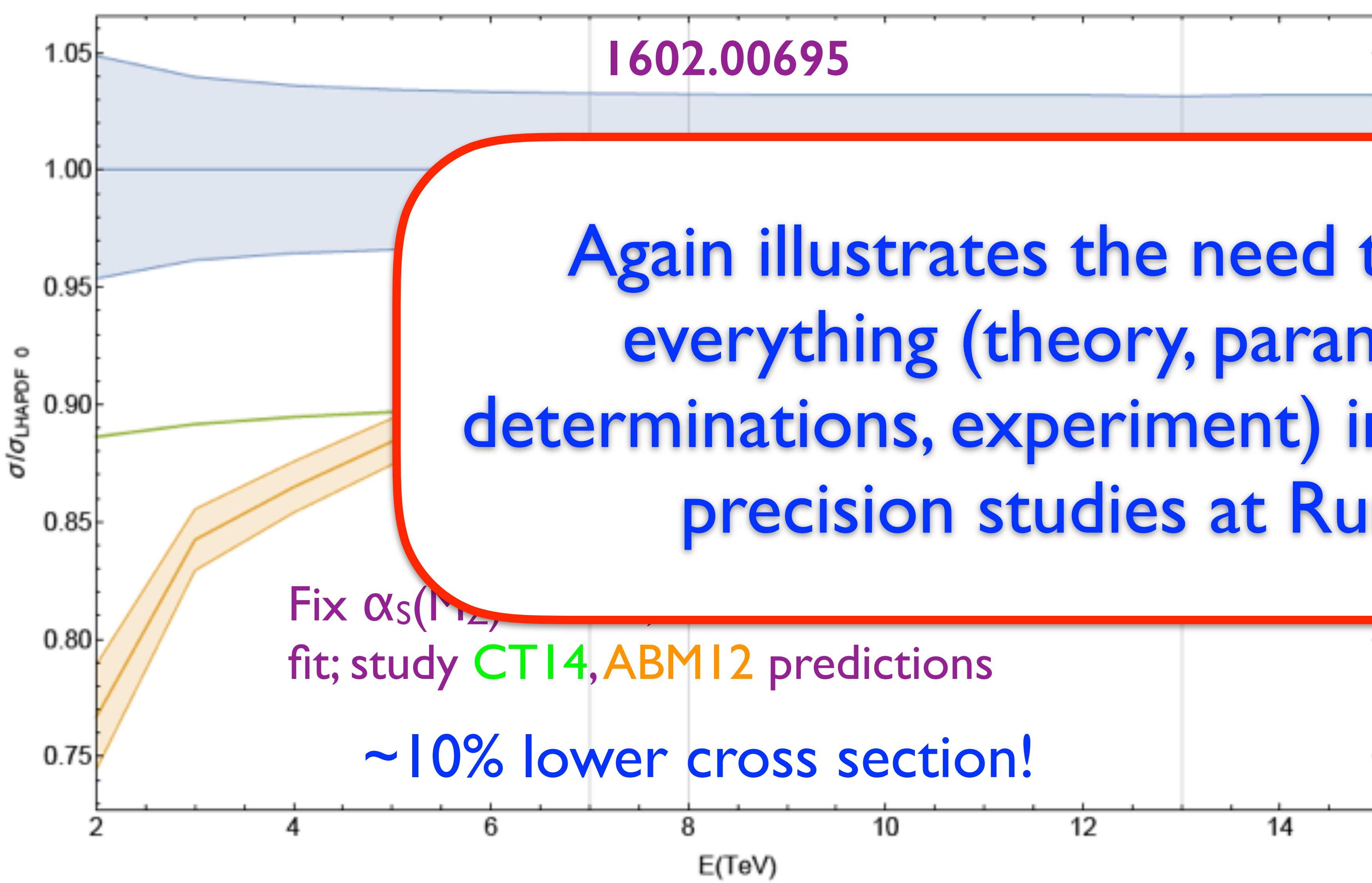


Approximate error budget
(… of total error):

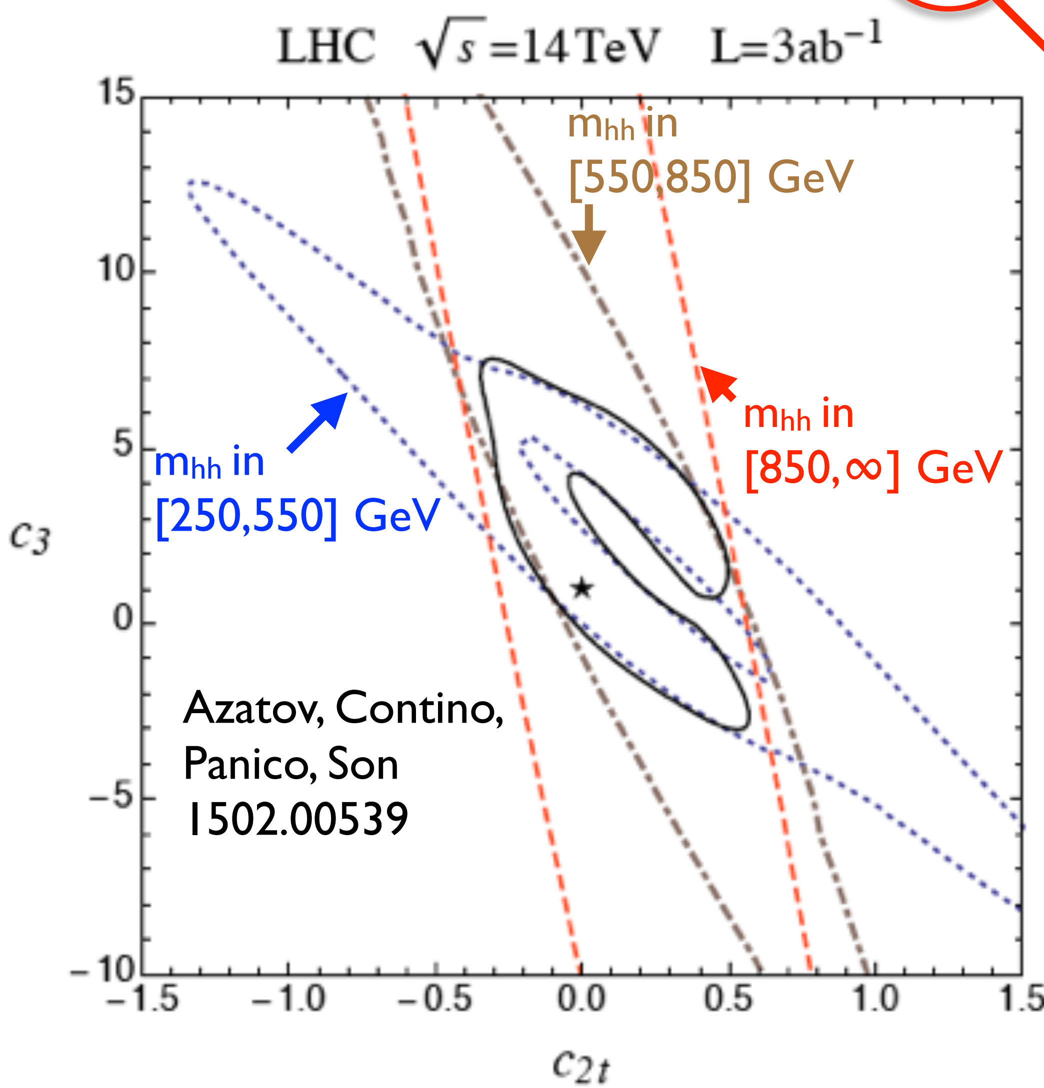
Again illustrates the need to have everything (theory, parameter determinations, experiment) in place for precision studies at Run II

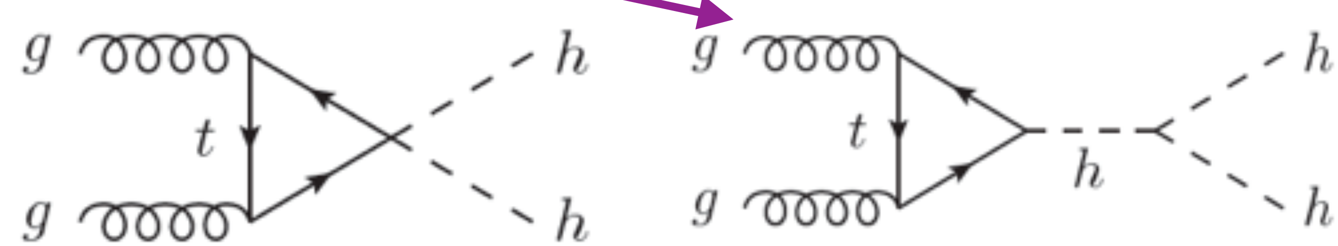
Di-Higgs production

- Question: Is the Higgs potential the one predicted in the SM, which depends only on m_h?

(These two c_i chosen for illustration)

$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^a G^{a\,\mu\nu}$$



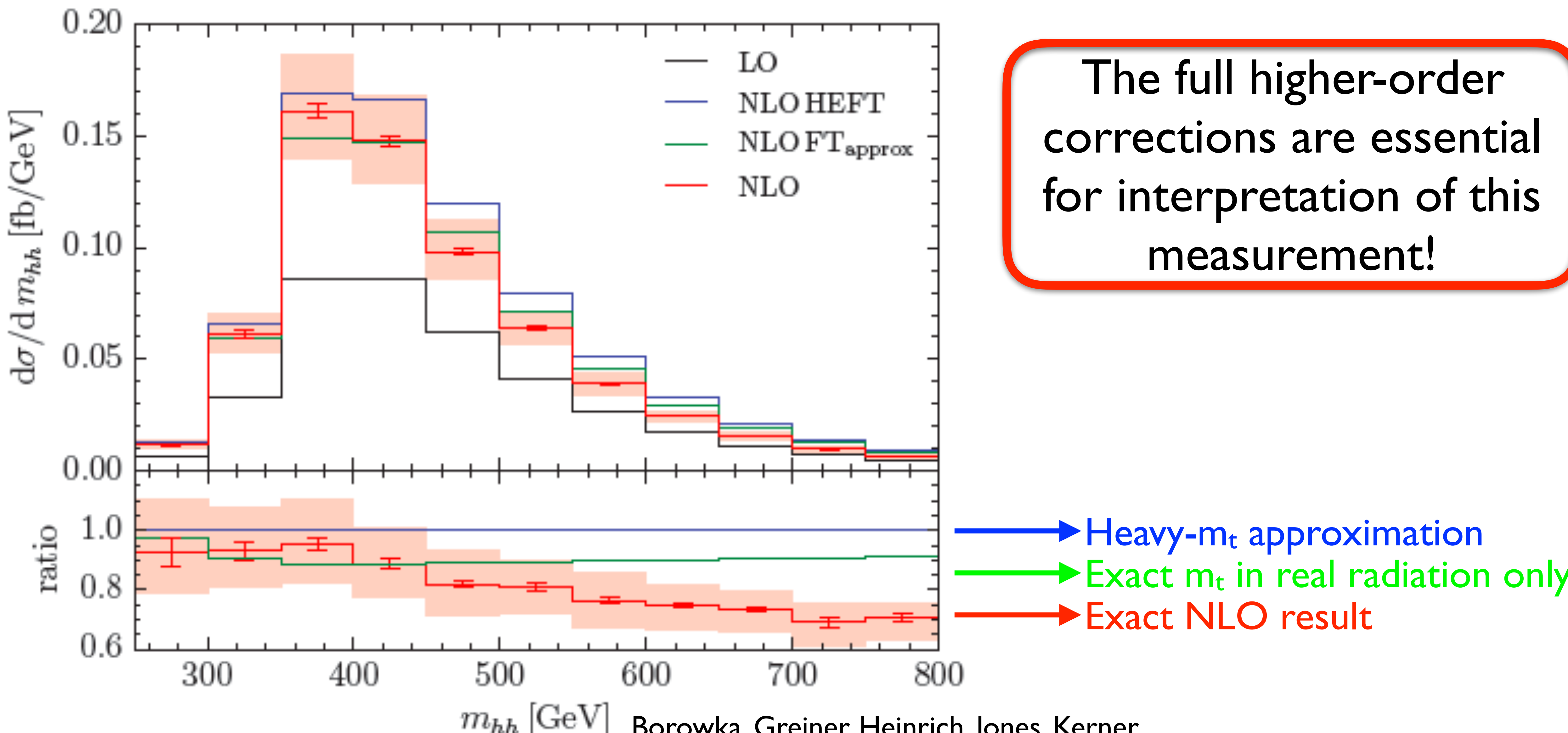


- Critical to use m_{hh} to break degeneracies between couplings. First higher-order QCD corrections were in heavy-m_t approximation

Plehn, Spira, Zerwas (1996); Dawson, Dittmaier, Spira (1998); Grigo, Hoff, Melnikov, Steinhauser (2013); Maltoni, Vryonidou, Zaro (2014); Degrassi, Giardino, Groeber (2016)

Di-Higgs production

- Large corrections not captured by heavy-m_t approximation! In particular, a strong dependence of the NLO corrections on m_{hh} is missed in the approximation approach



The full higher-order corrections are essential for interpretation of this measurement!

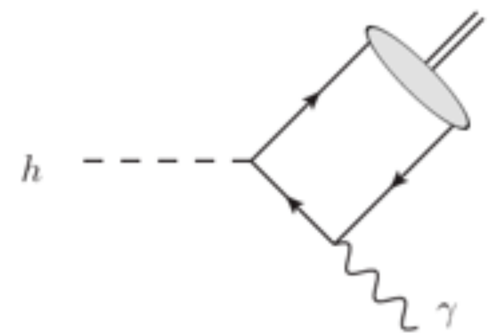
Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 1604.06447

The Higgs and flavor

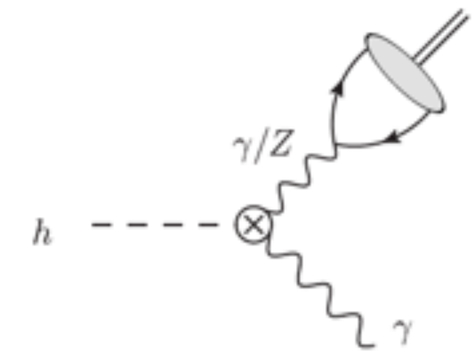
- We have no understanding of the Higgs Yukawa structure in the SM; measurements mostly constrain 3rd-generation couplings
- Need ideas to measure Higgs couplings to light fermions!

One idea: Use exclusive decays to constrain!

(Bodwin, FP, Stoynev, Velasco 1306.5570; Kagan et al. 1406.1722; Koenig, Neubert 1505.03870)



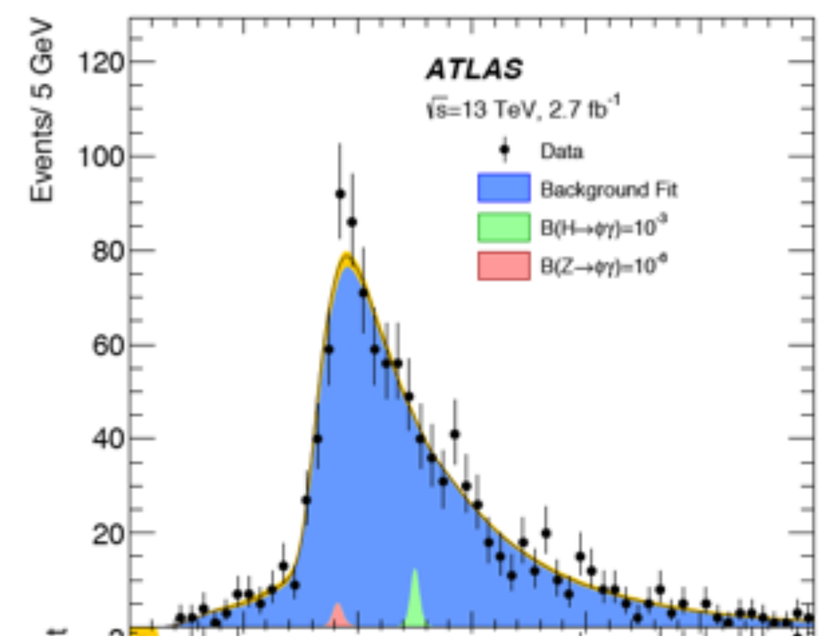
Direct production, which is sensitive to Hff coupling, is small



Indirect production is larger; interferes quantum-mechanic with direct production

Mode Method	Branching Fraction $[10^{-6}]$ NRQCD [171]	LCDA LO [170]	LCDA NLO [173]
$\mathrm{Br}(H \to \rho^0\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(H \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(H \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(H \to J/\psi\,\gamma)$	$2.79\,^{+0.16}_{-0.15}$	–	2.95 ± 0.17
$\mathrm{Br}(H \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(H \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(H \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

from 1606.09408



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\,\gamma)\,[\,10^{-3}\,]$	$1.5^{+0.7}_{-0.4}$	1.4

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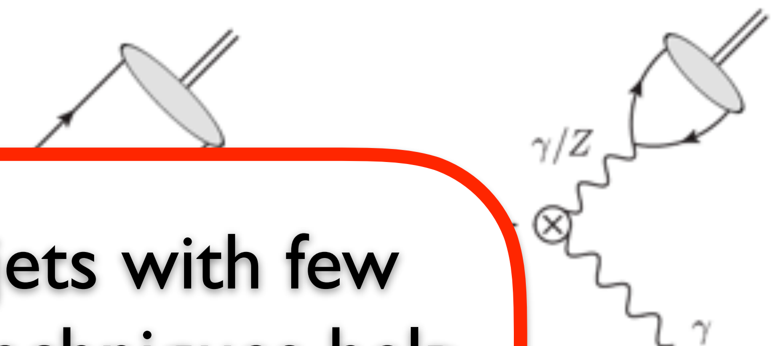

One idea: Us

(Bodwin, FP, Stoyne

Koenig, Neubert 15

The φ, ω, ρ, J/Ψ appear as narrow jets with few charged tracks; can jet substructure techniques help control backgrounds?

ct production is larger;

feres quantum-mechanic

h direct production

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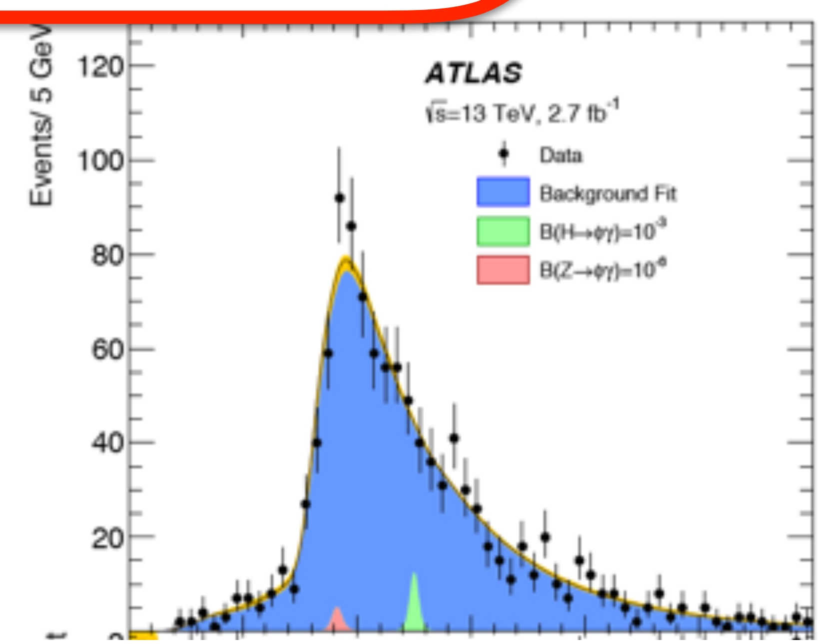

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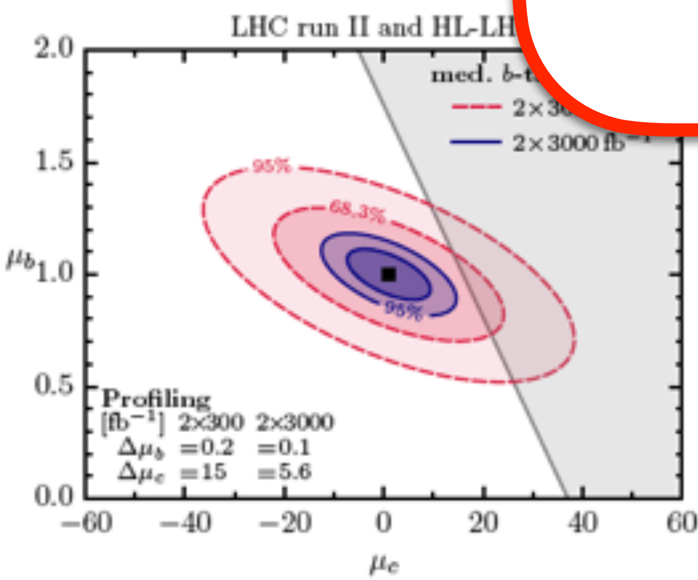
$m_{K^+K^-\gamma}$ [GeV]

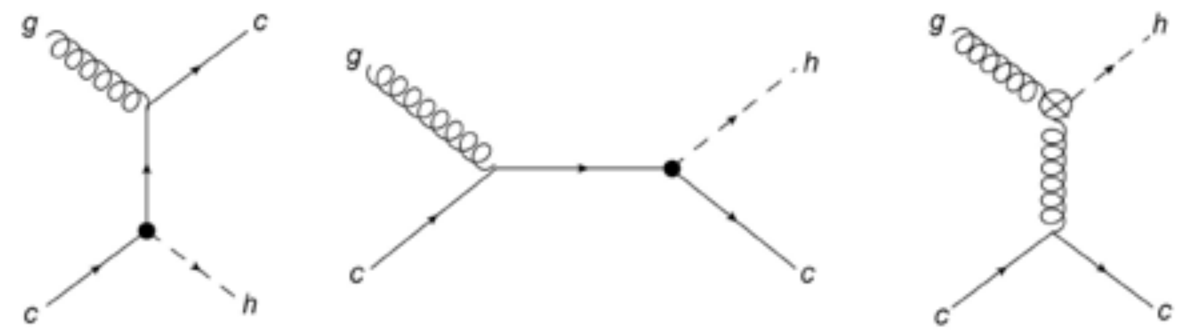
The Higgs and flavor

Exciting new area for Run II, lots of new ideas!



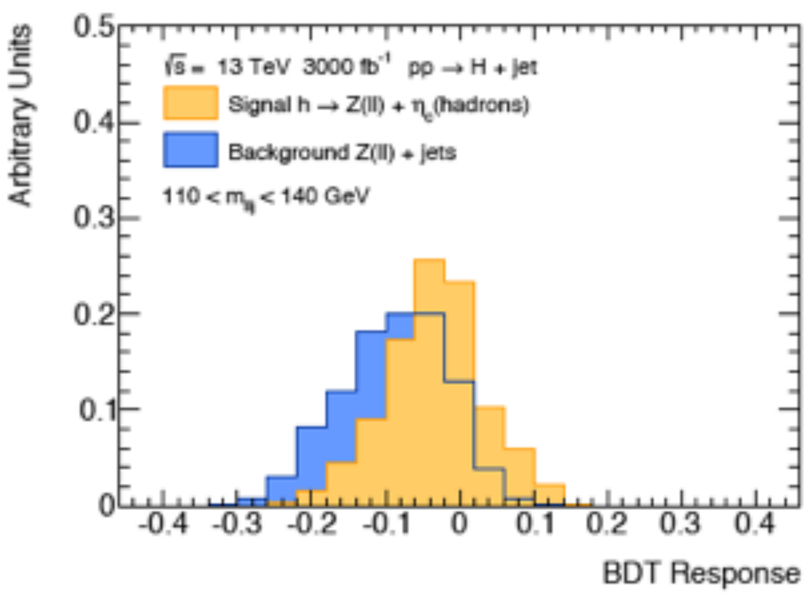
Recast of h→bb searches

Perez, Soreq, Stamou, Tobioka 1505.06689



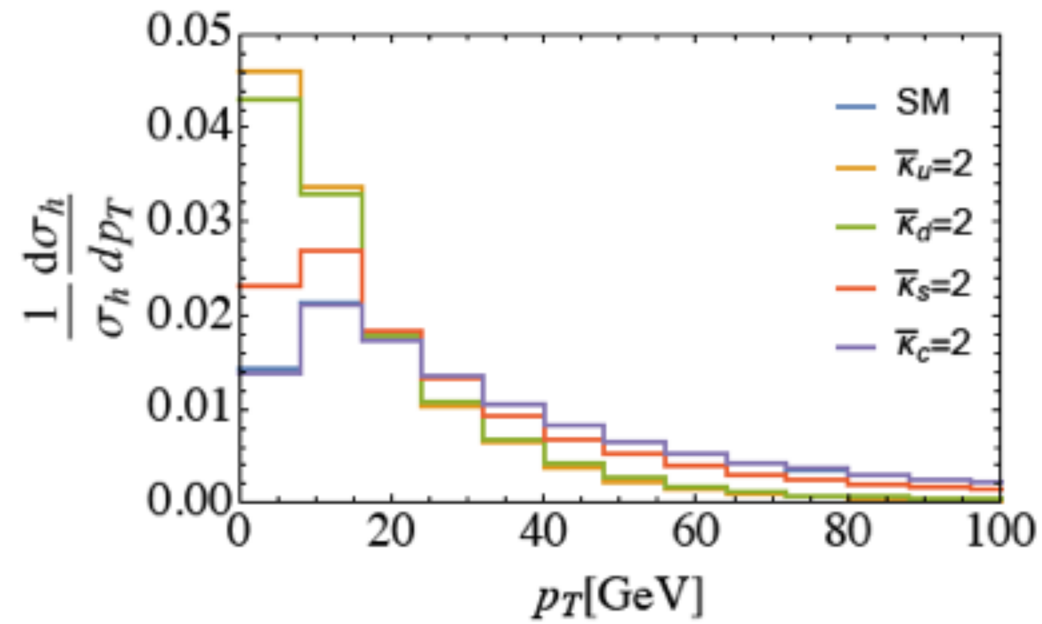
Higgs in association with charm-tagged jet

Brivio, Goertz, Isidori 1507.02916



Track-based jet substructure techniques

Chisholm, Kuttimalai, Nikolopoulos, Spannowsky 1606.90177



Higgs kinematic distributions

Bishara, Haisch, Monni, Re 1606.09253;
Soreq, Zhu, Zupan 1606.09621

We eagerly await the answers to many questions during Run II

- Does SUSY, or another mechanism, stabilize the EW scale?
- Will the LHC measurements uncover the origin of flavor?
- Will the Higgs guide us to a new Standard Model?

Let's find the answers!