The Physics Horizon

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2013 US LHC Users Organization Annual Meeting
November 7, 2013

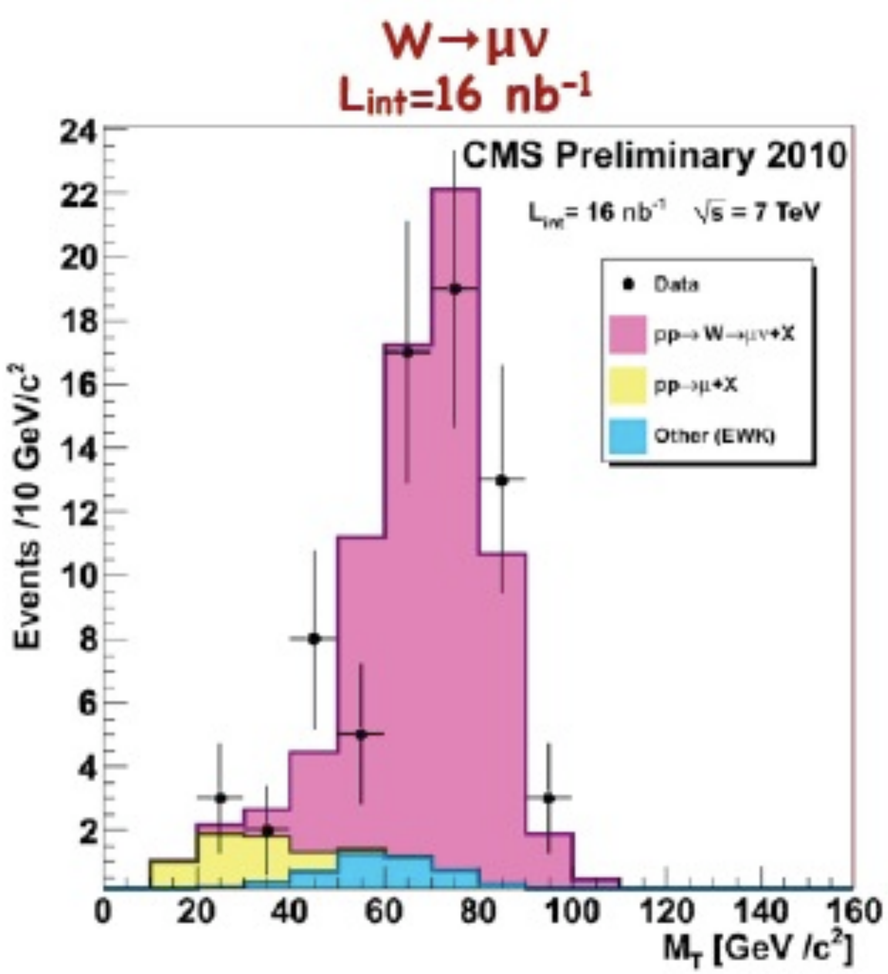
Outline

- A pictorial history of the LHC, and HEP, circa 2013
- What the BBC has to teach us about physics at the smallest scales
- Tools for hadron-collider physics, from the Stone Age through the Middle Ages to now
- A Higgs-centric view of LHC Run II

Apologies in advance for the biases and limited coverage!

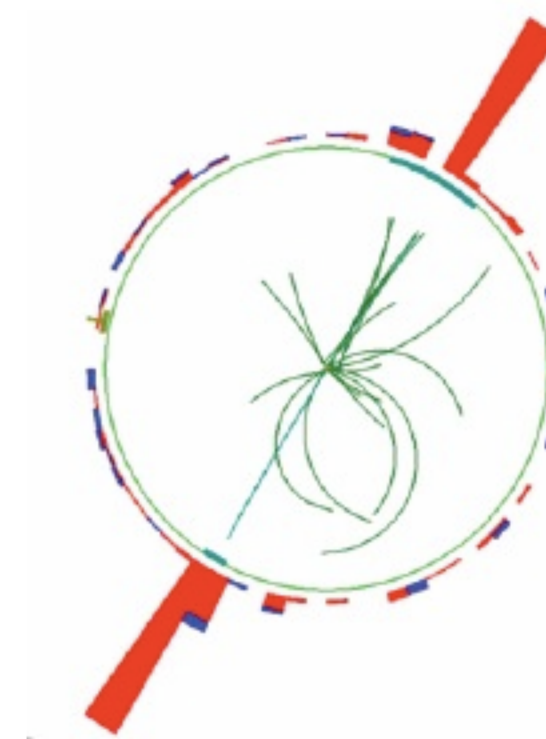
The LHC circa 2010

ATLAS, J. Guimares, pLHC 2010



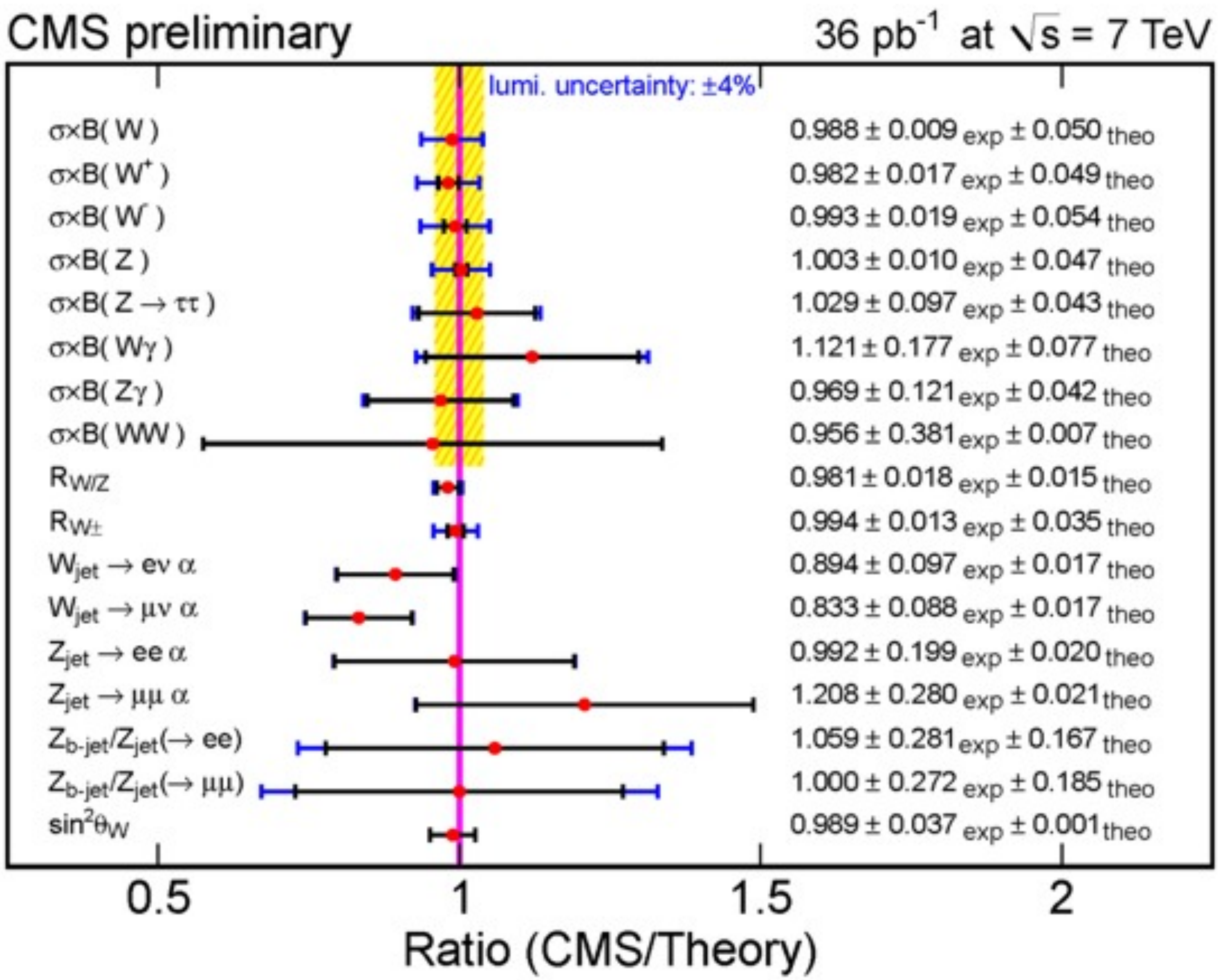
CMS, E. Di Marco, pLHC 2010

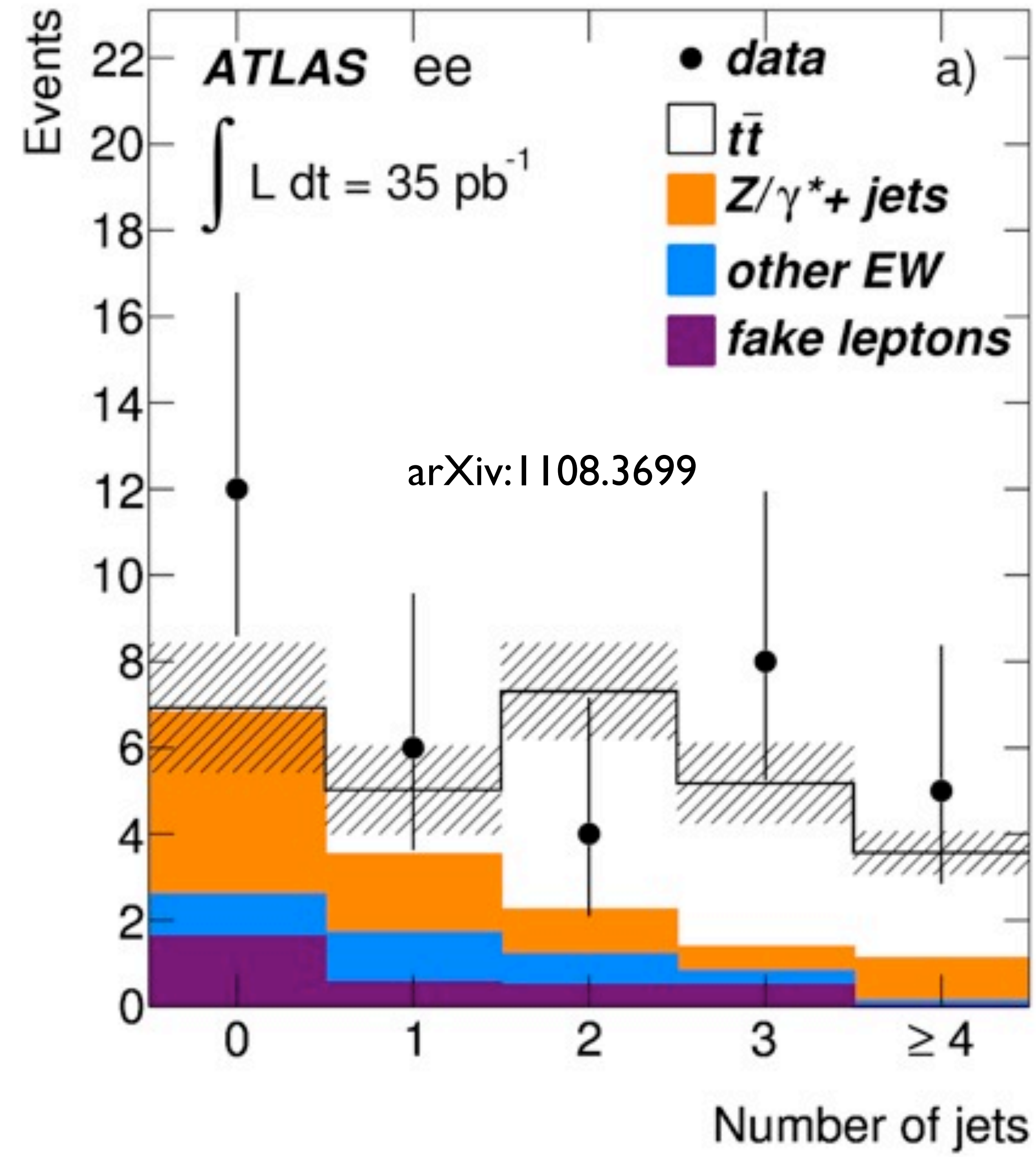
- W, Z candidate events feature prominently in talks
- A few sparsely populated $p_{T,W}$ and M_T distributions



CMS $Z \to e^+e^-$

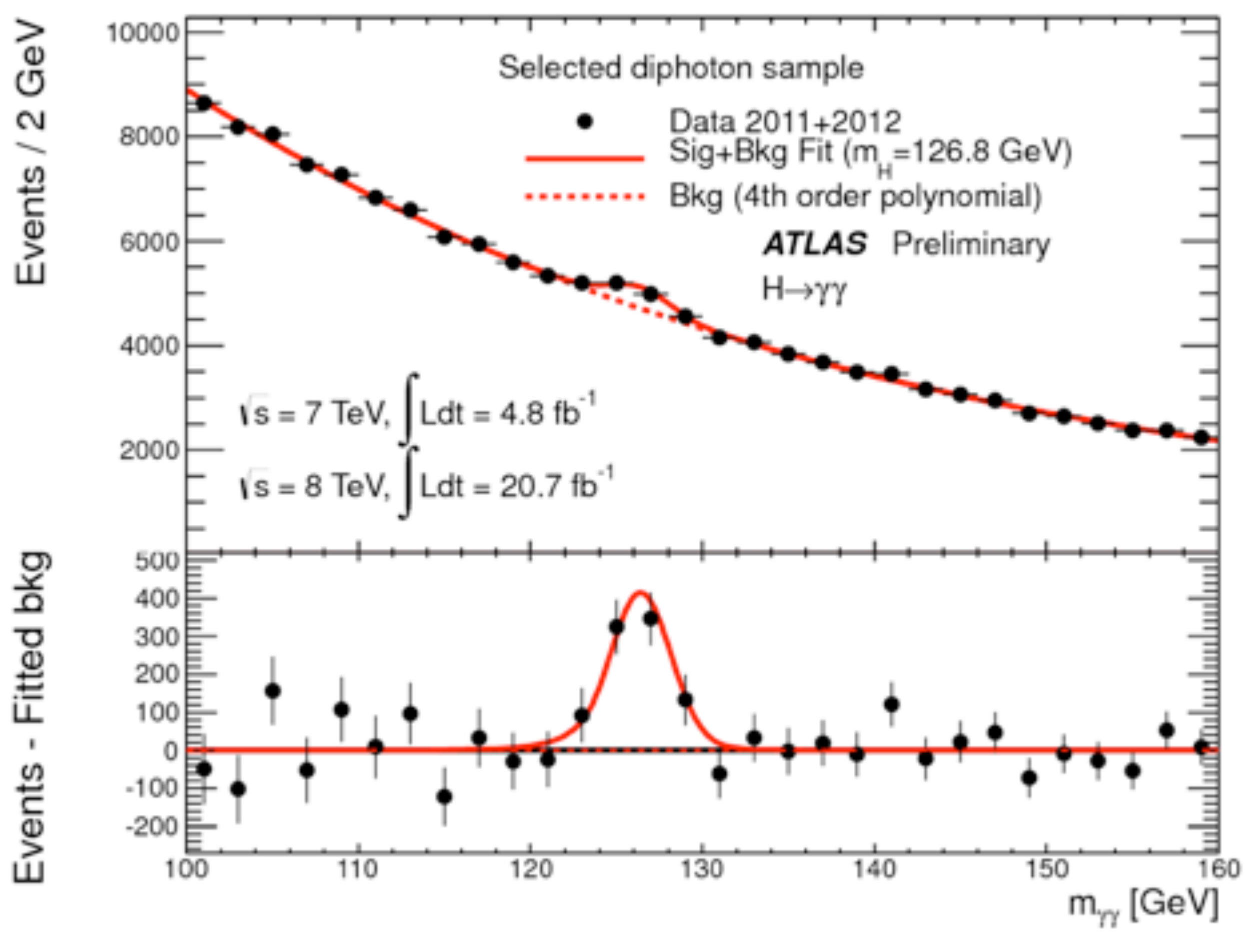
The LHC circa 2011

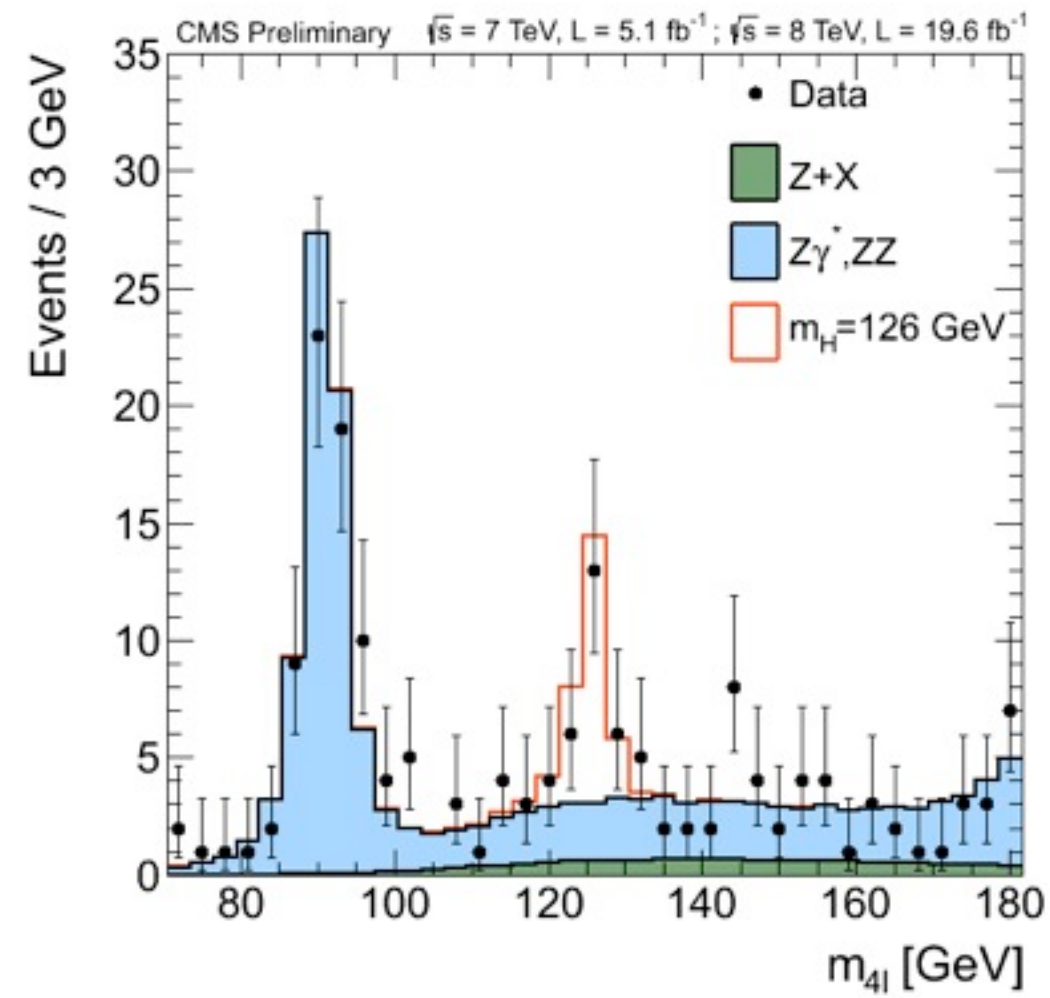




- Rediscovery of the Standard Model well on its way

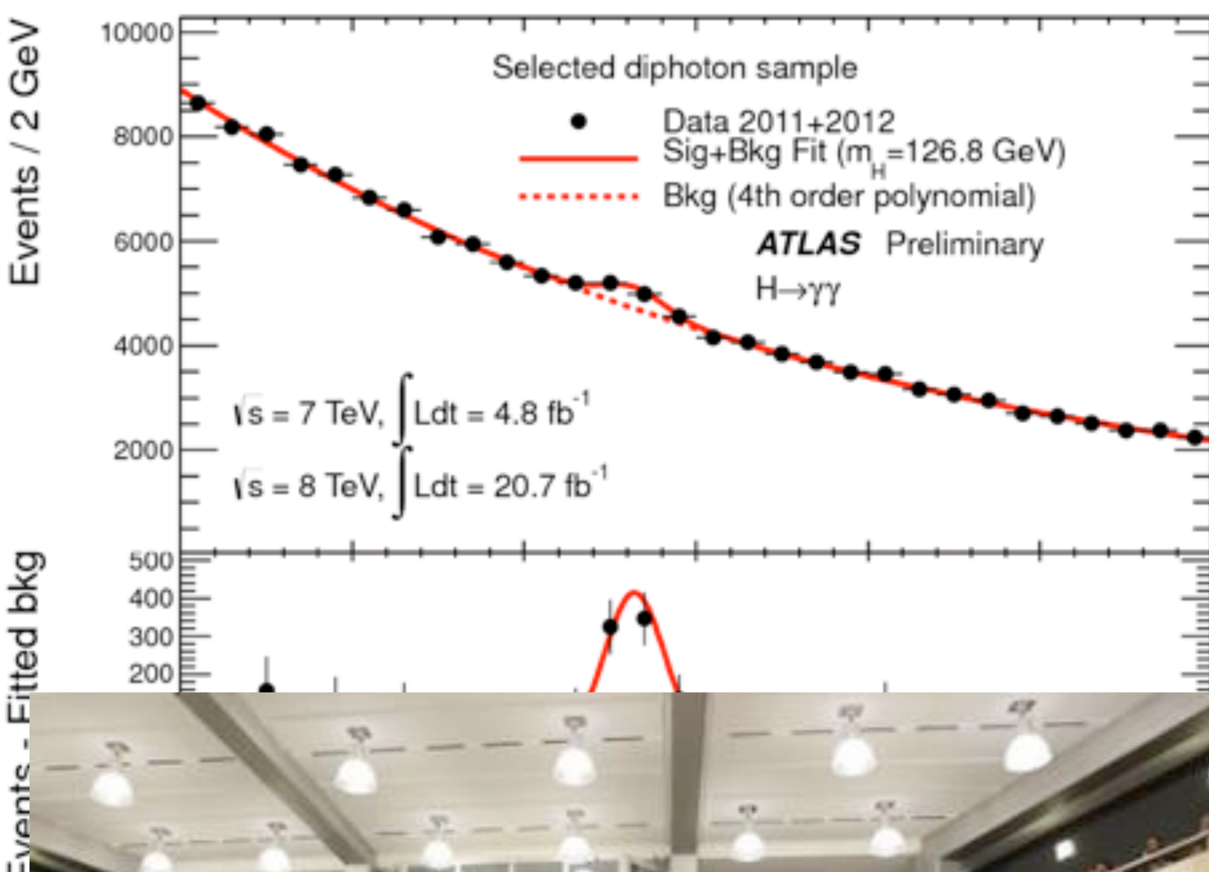
The LHC circa 2012

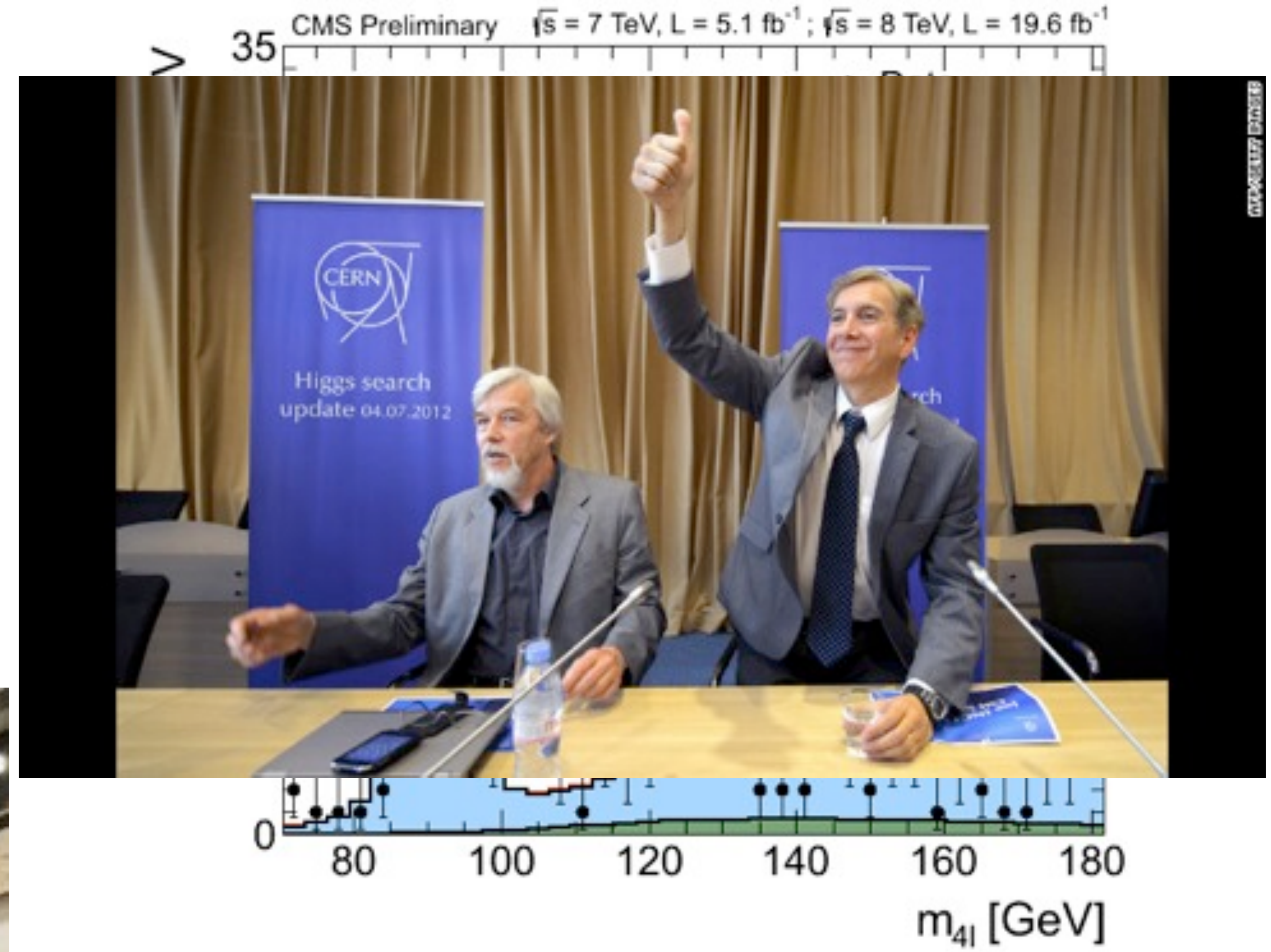




- July 4, 2012: a new member added to the family

The LHC circa 2012

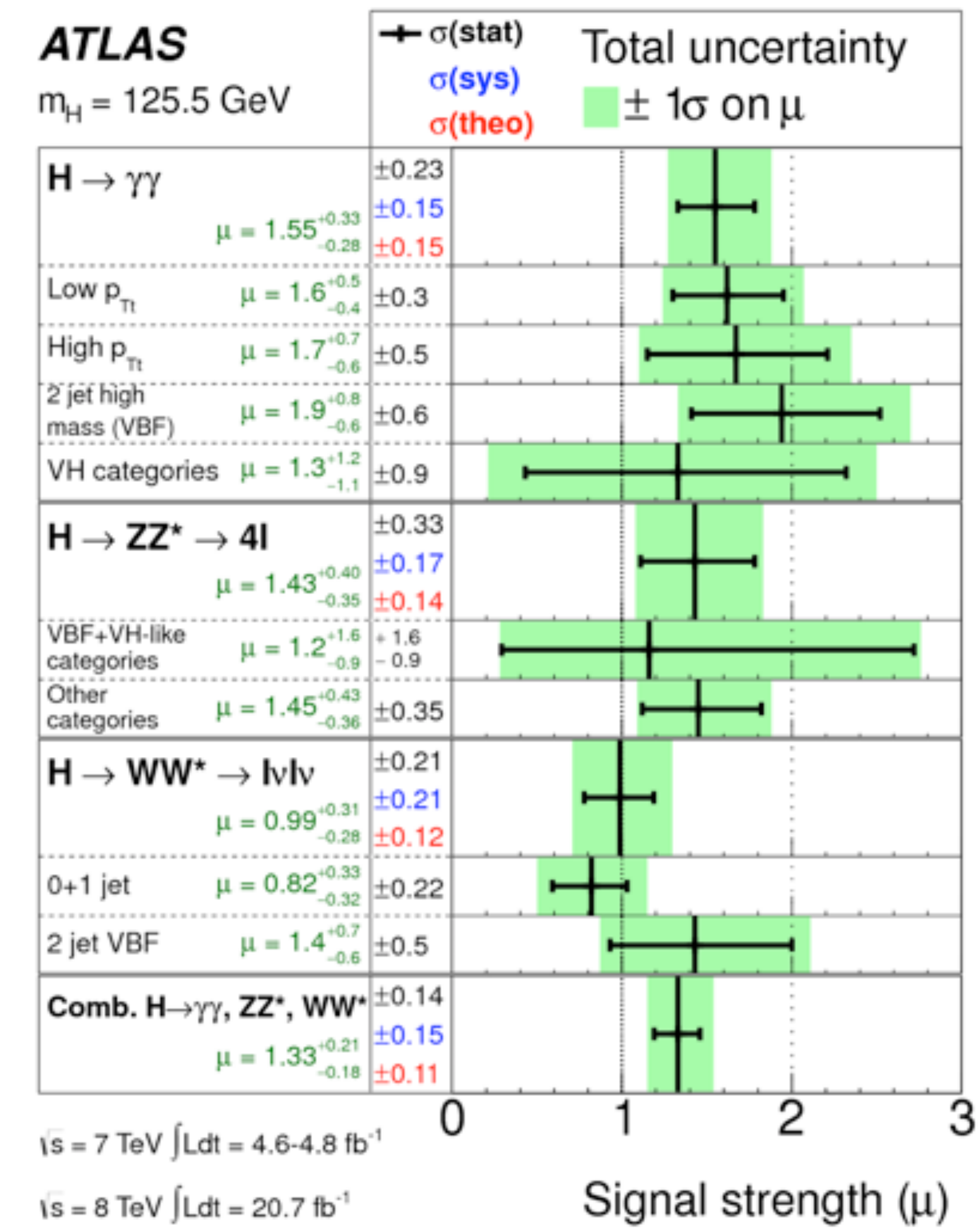


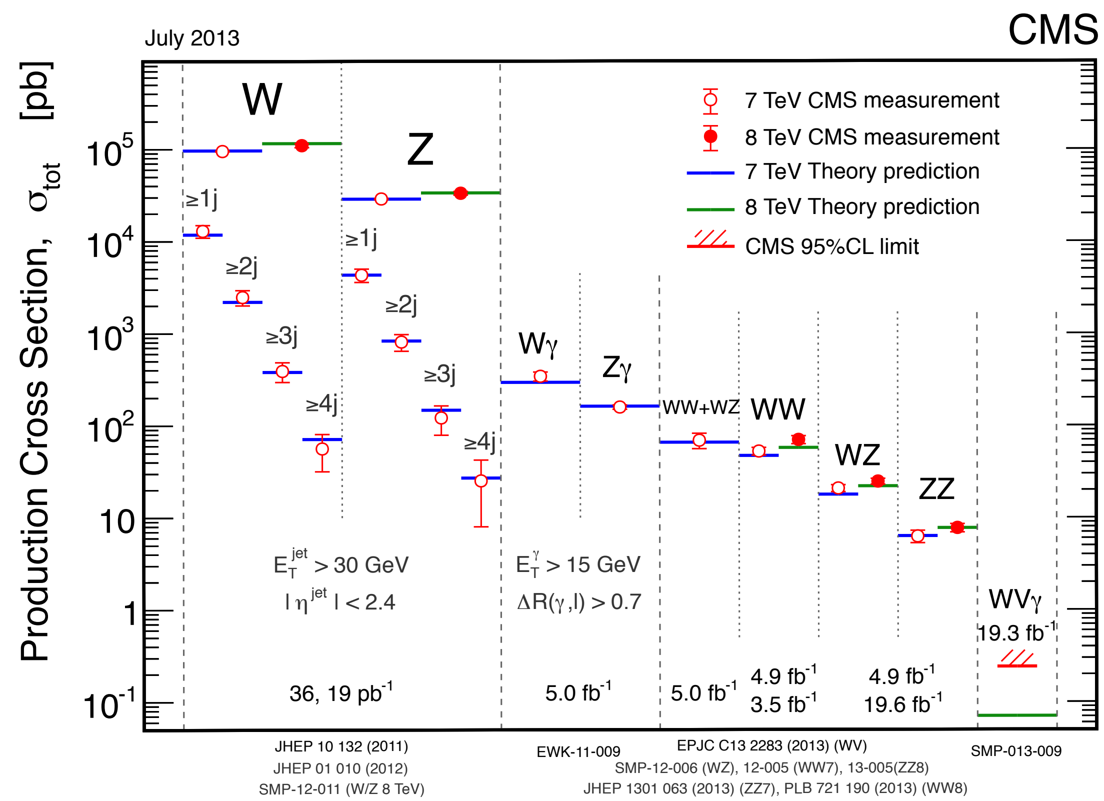


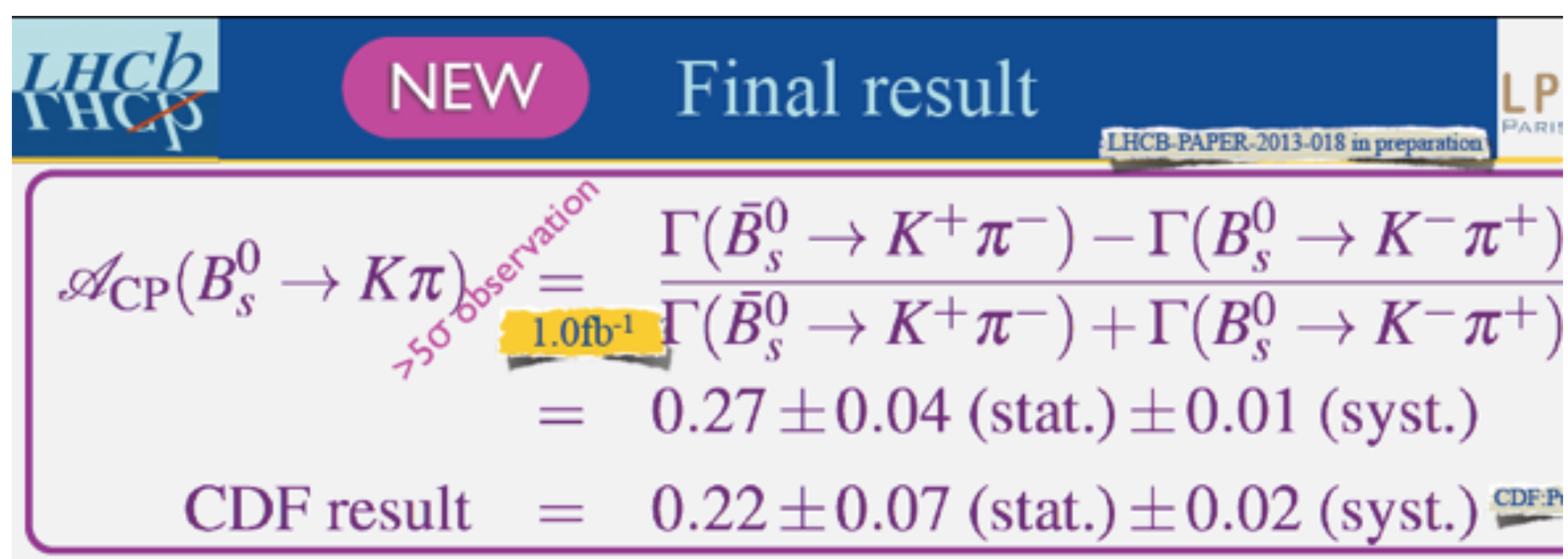
- July 4, 2012: a new member added to the family

The LHC circa 2013

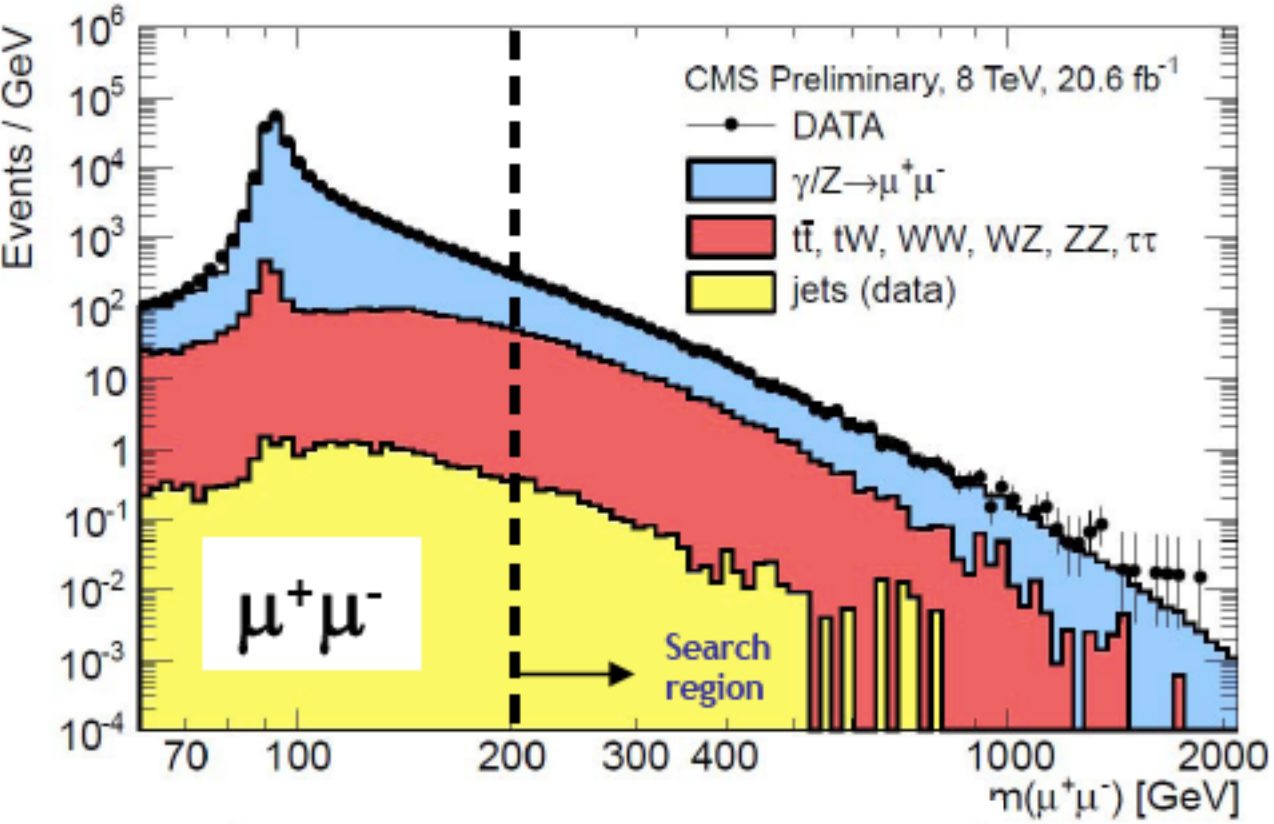
- Remarkable in both breadth and depth of coverage
- Underlying identity of the Higgs being slowly revealed

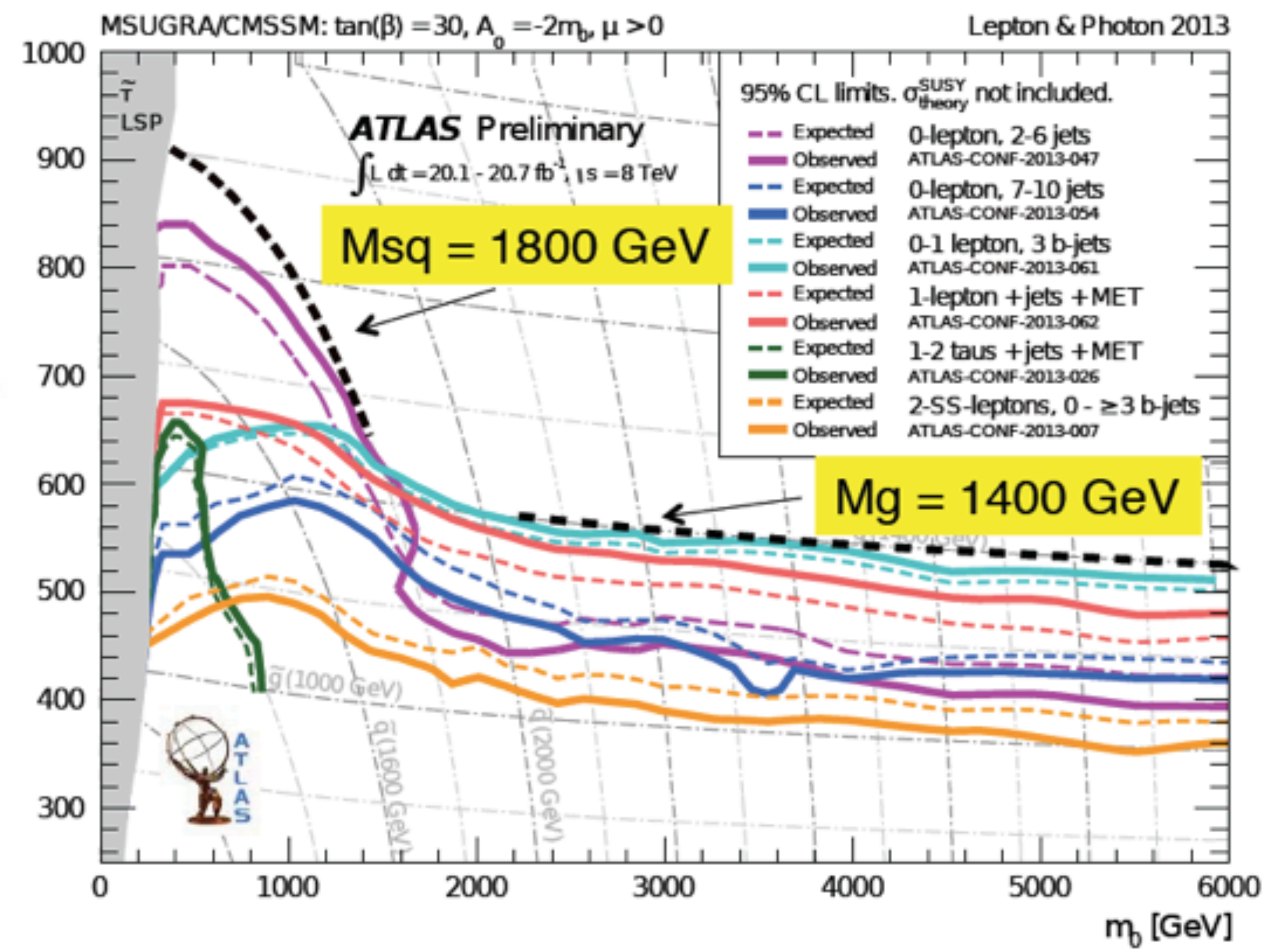


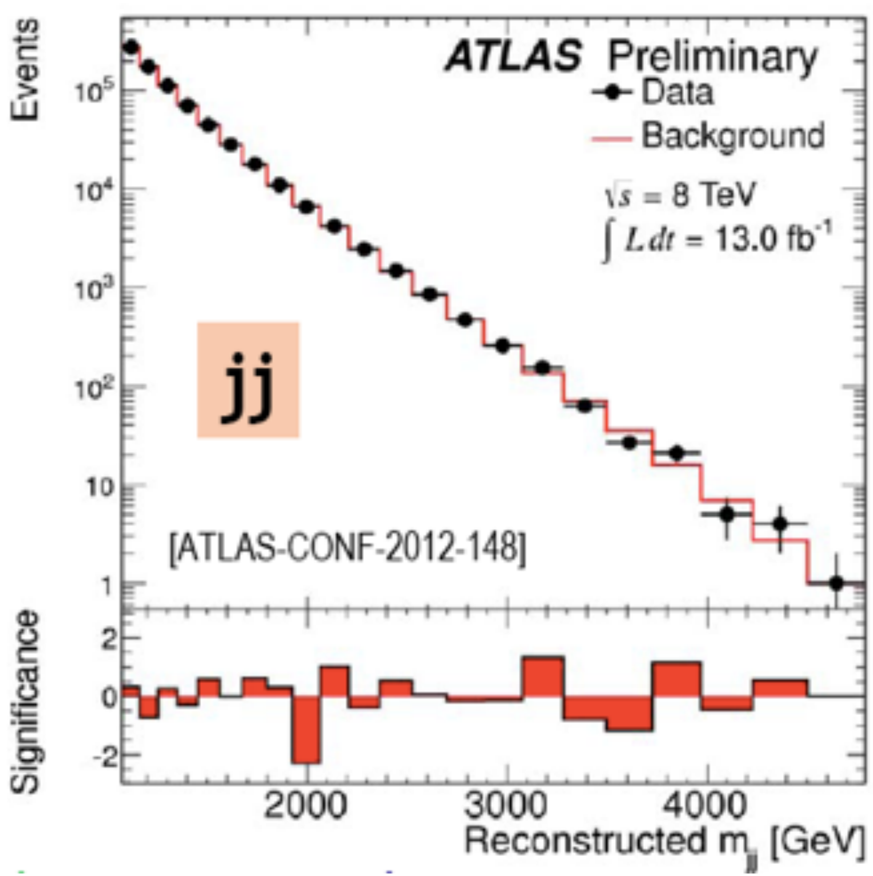




The LHC circa 2013







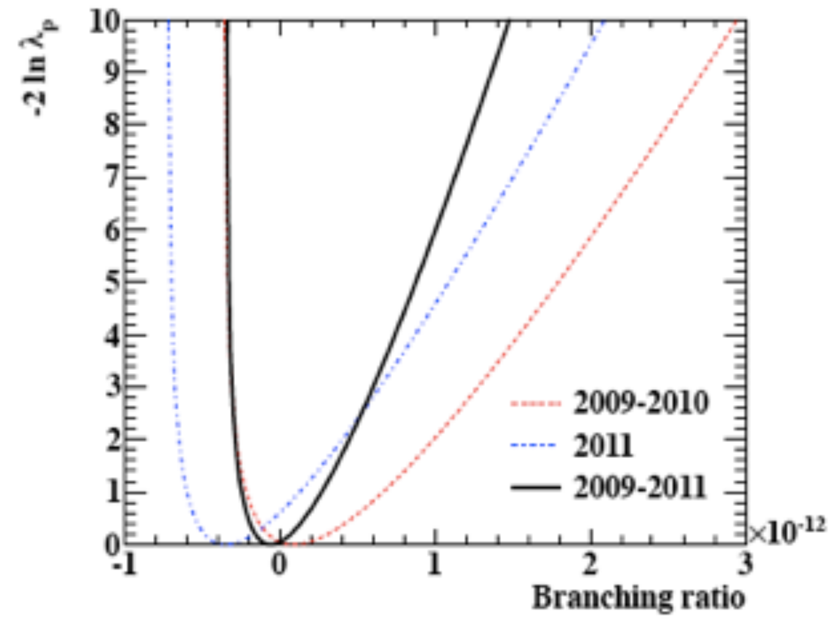
- Nothing besides the Higgs; limits reaching multi-TeV in some channels

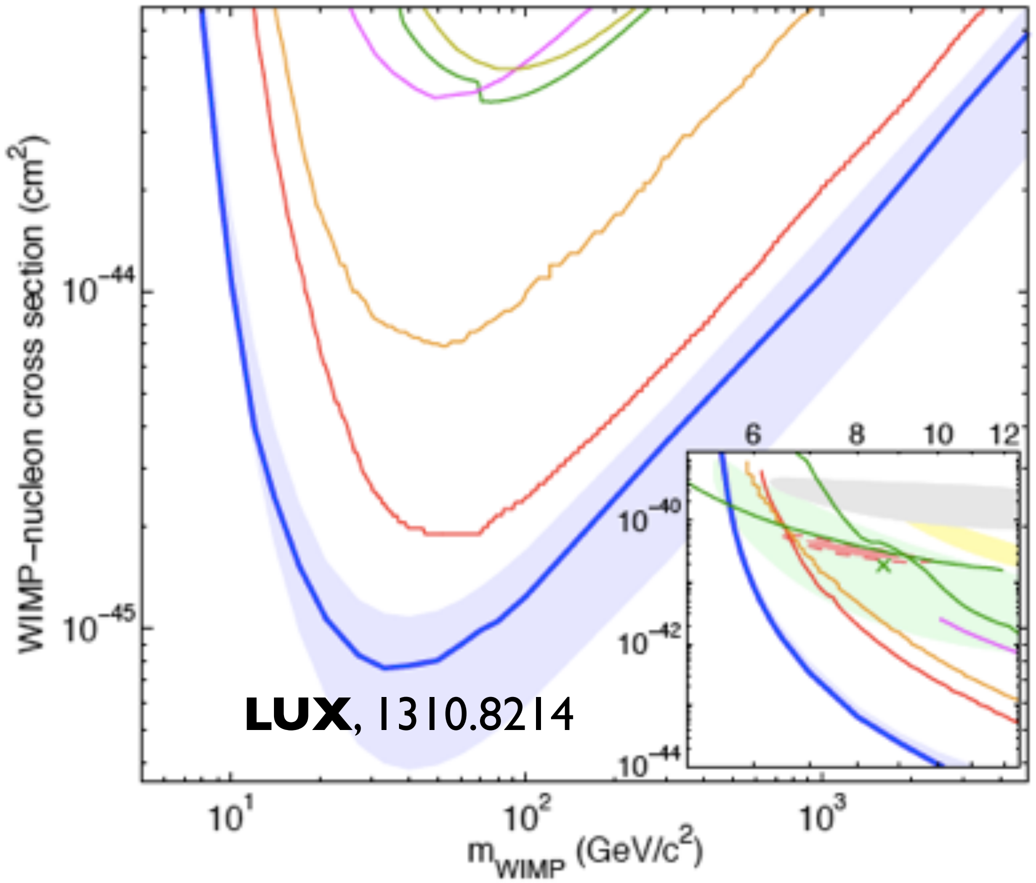
HEP circa 2013

- A more global view of the current landscape

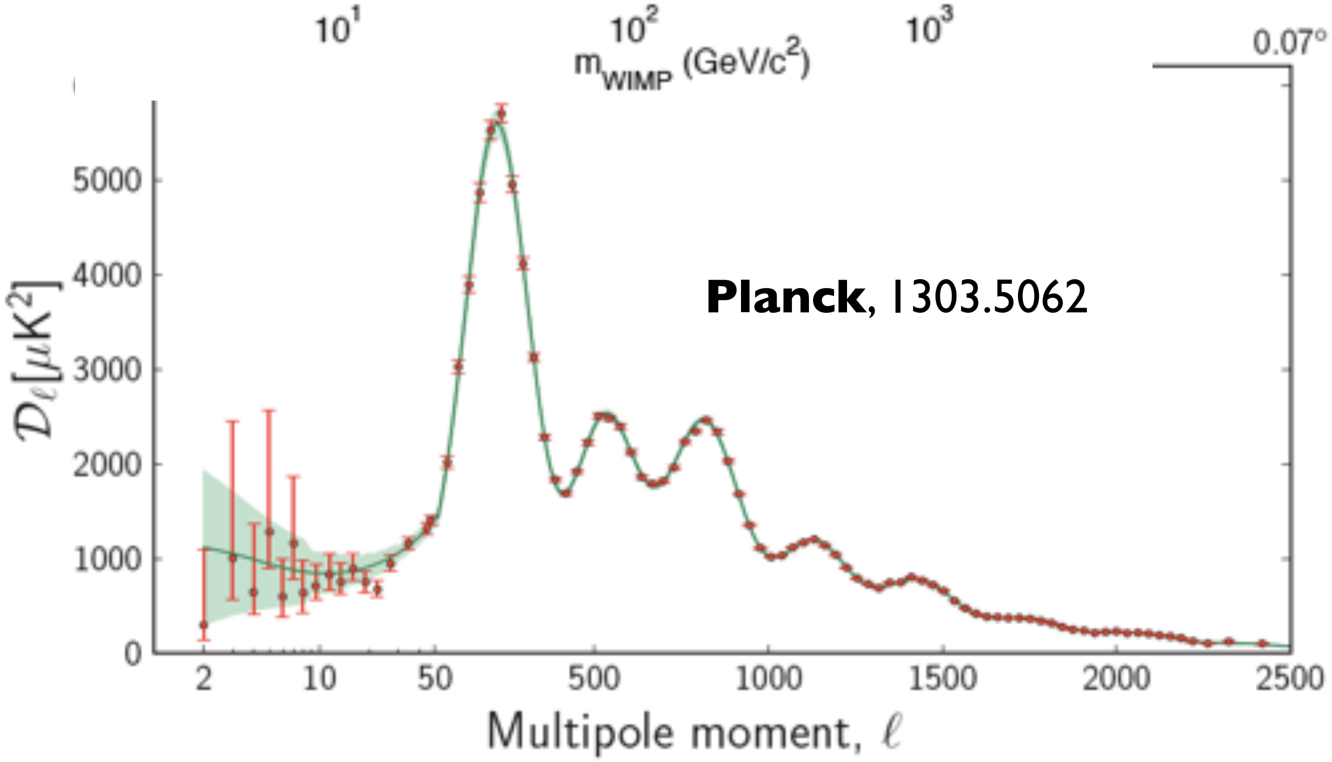
Dataset	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

MEG, 1303.0754

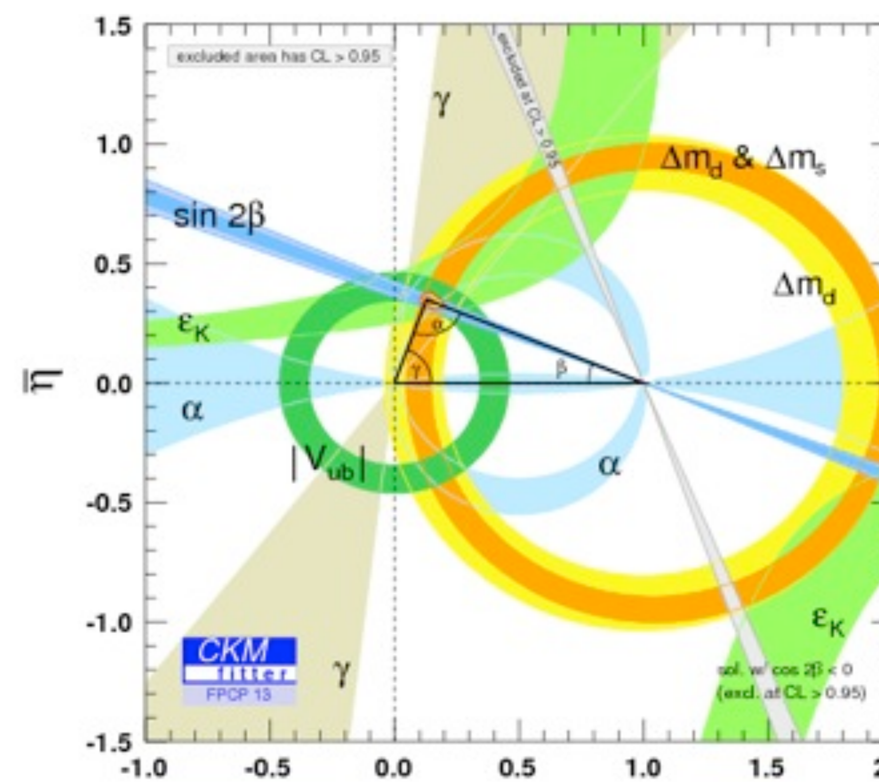




LUX, 1310.8214



Planck, 1303.5062



Everything we've measured so far is consistent with the following picture of fundamental physics at a few/tens of TeV

Gobi desert:

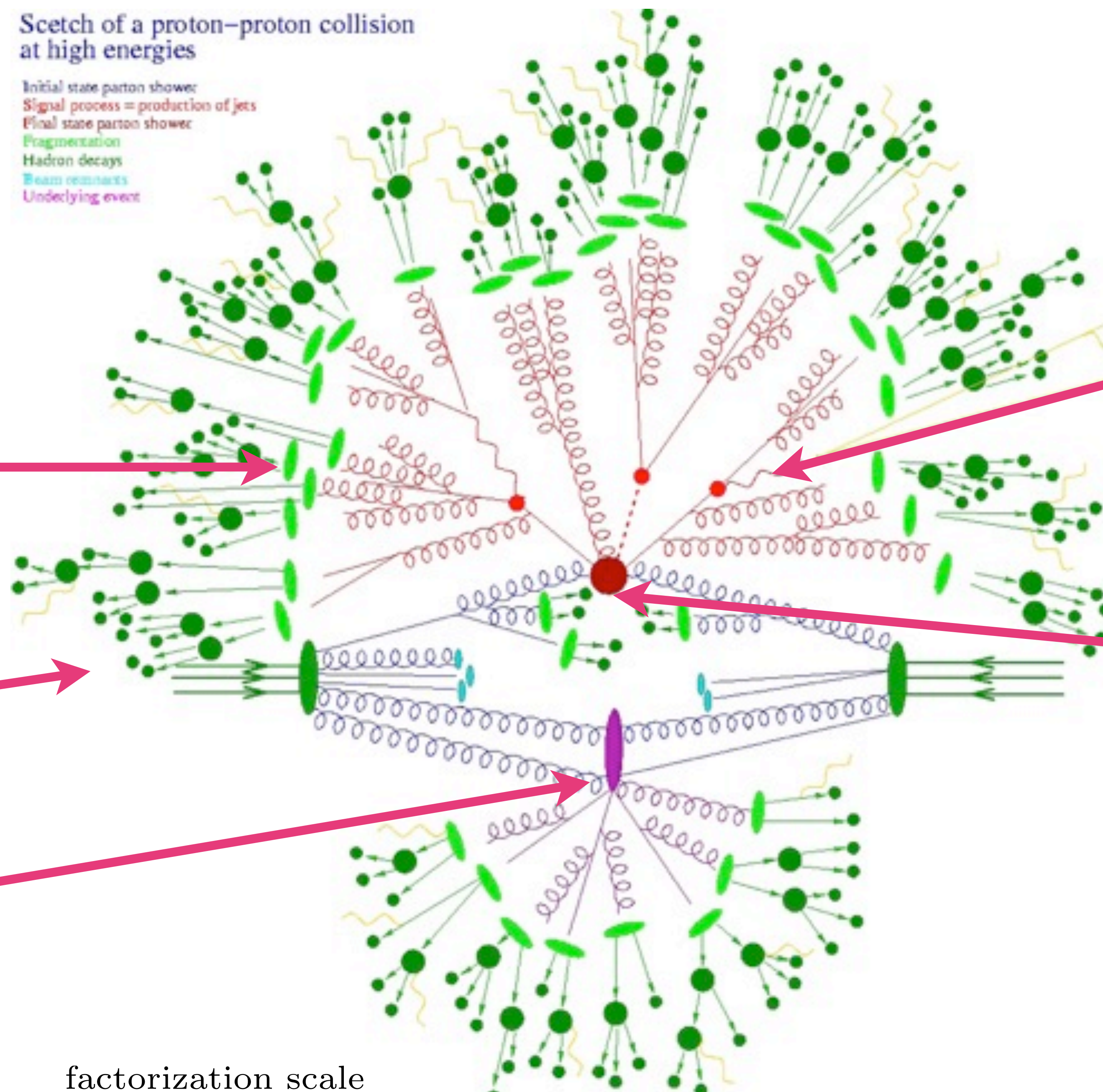
- Temperature ranges from -40°F to 122°F
- Daily variations reach 63°F
- 8in rainfall in entire desert/year

- Bactrian camel: critically endangered, <1000 estimated in the wild
- Can survive months without water; in winter eats ice/snow instead
- To film: 2-month journey in Mongolia; carry in all food, water, fuel to desert
- Need spare parts to rebuild vehicle engine
- 1500 mile drive to find the area in which the camels live
- Fun along the way: Interpreter headbutts local authorities when drunk... Driver, also drunk, punches interpreter in the face...

- Moral: There can be fascinating life hidden in a desert... but it can be rare and difficult to find (the background to SUSY is ***not*** SUSY... the LHC inverse problem turned out to not be a big deal)
- Takes persistence and the ability to sift through lots of background to find what is new and exciting
- Hopefully LHC_{14} resurrects the LHC inverse problem and SUSY backgrounds, but if not we should be ready for the challenge

QCD at the LHC

- From a theorist's perspective, the challenge is dealing with QCD



Hadronization at Λ_{QCD}

Hadron decays

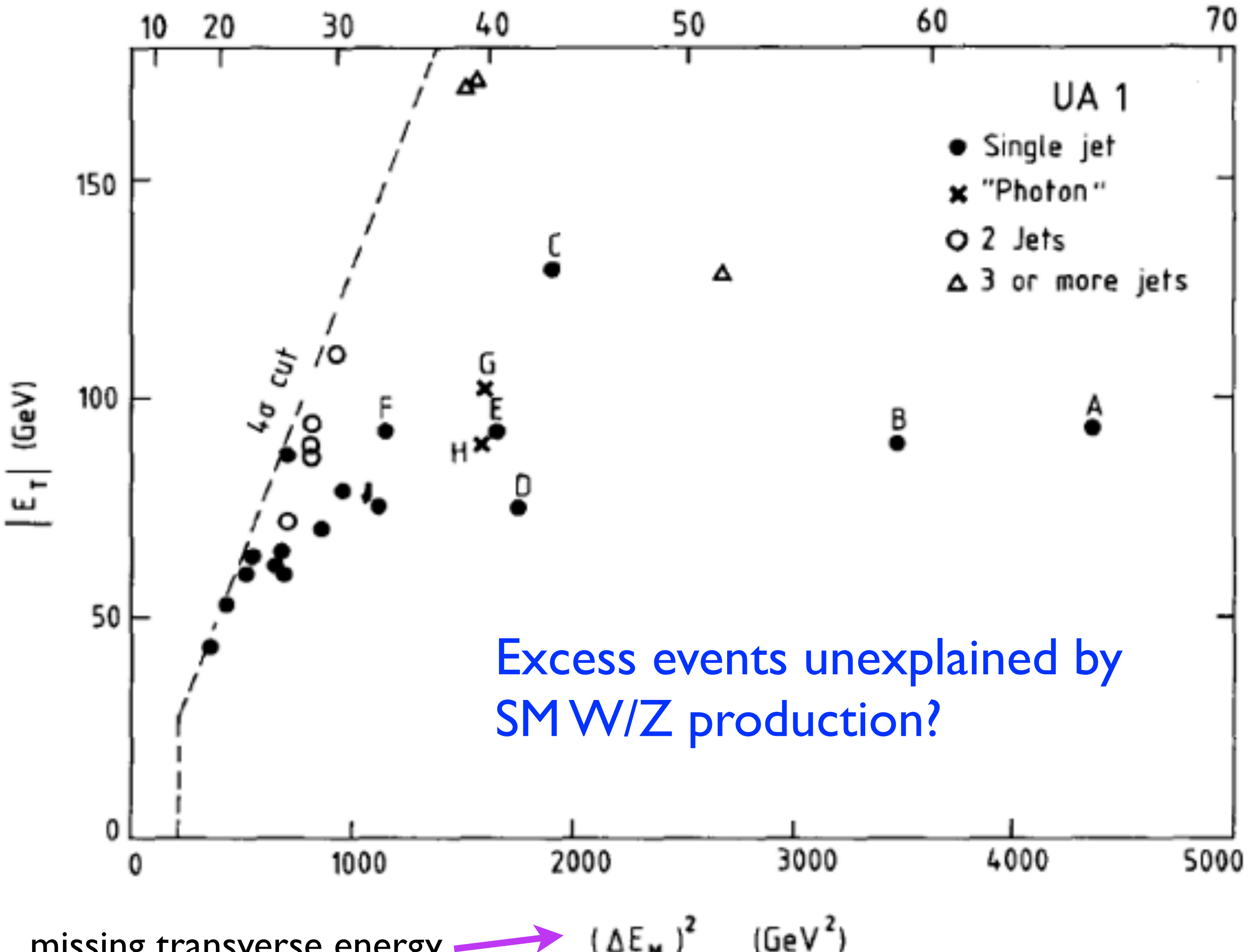
Multiple parton interactions

Parton-shower evolution to low energies

Hard collision (Higgs production) at short distances/ high energies

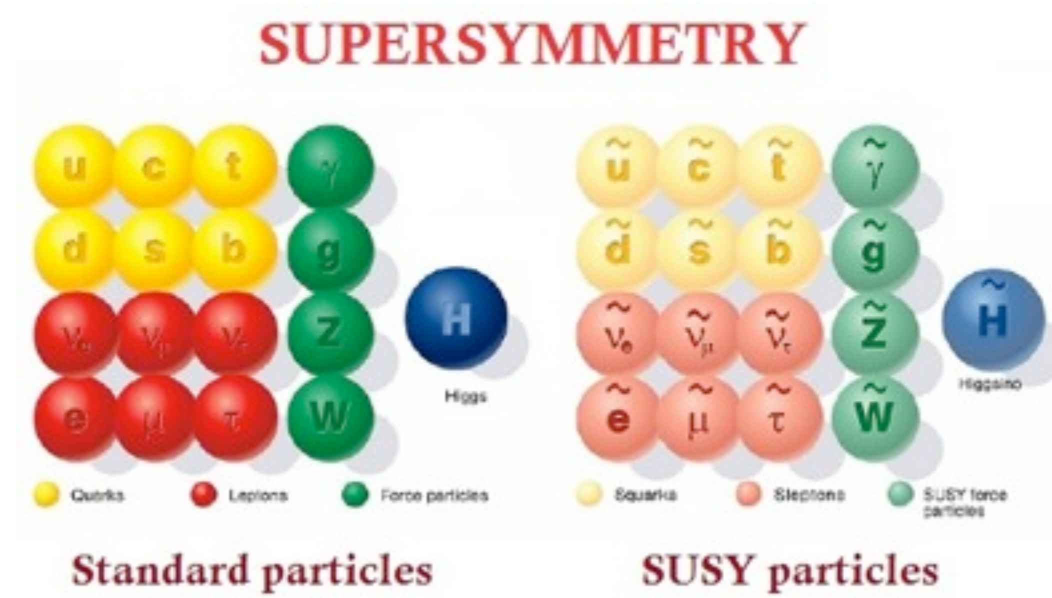
$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij\to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

QCD simulation circa 1986

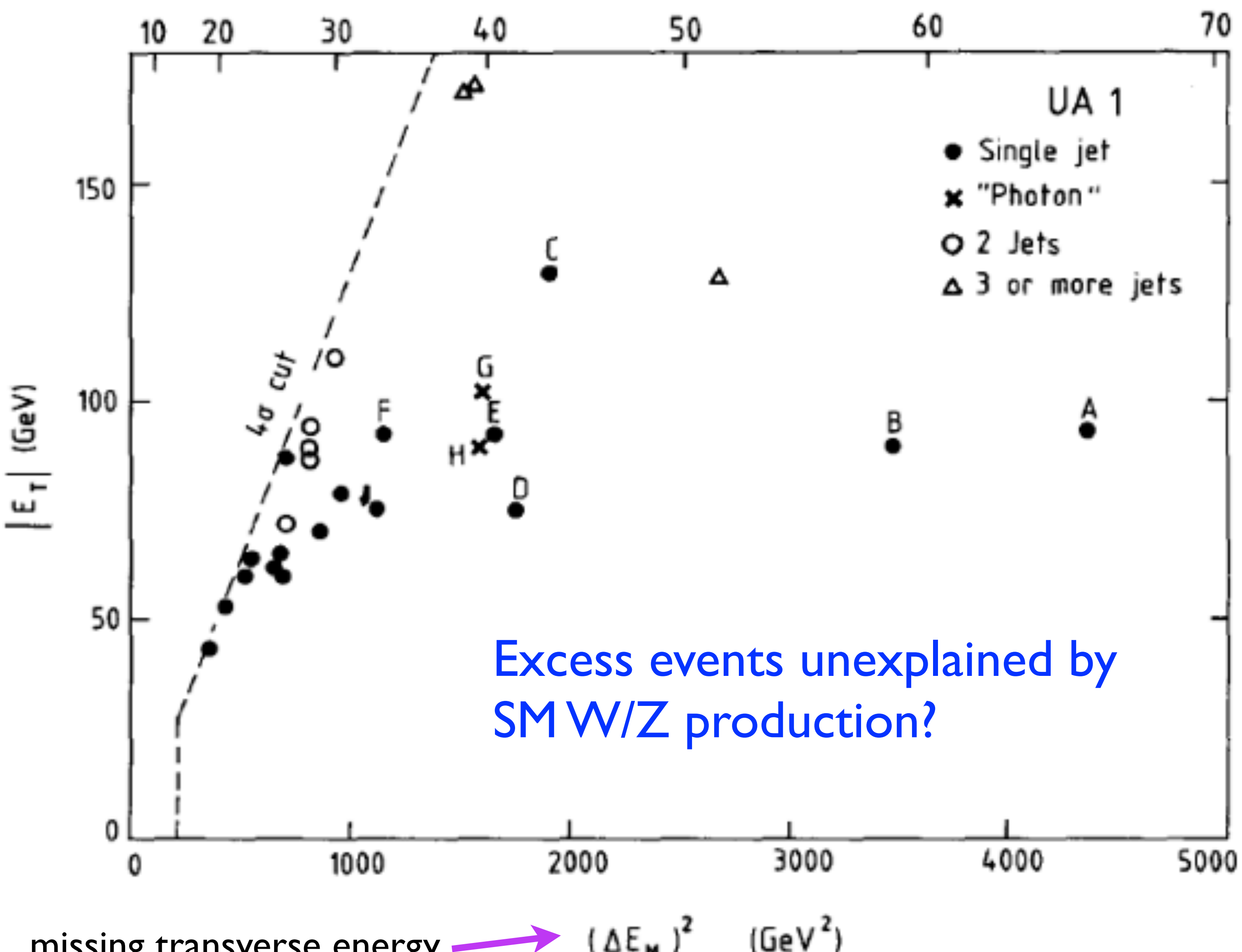


Excess events unexplained by SM W/Z production?

missing transverse energy →



QCD simulation circa 1986



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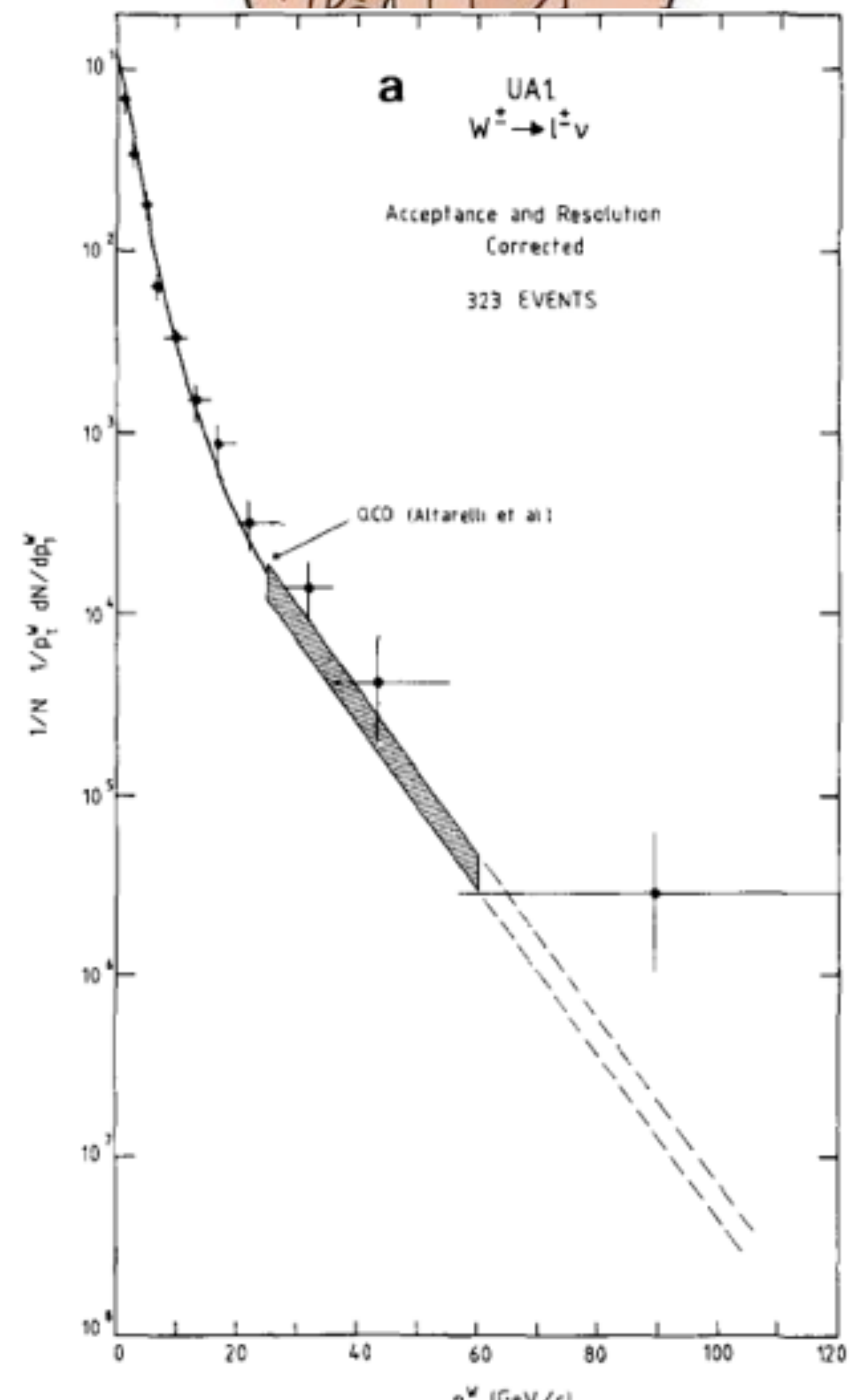
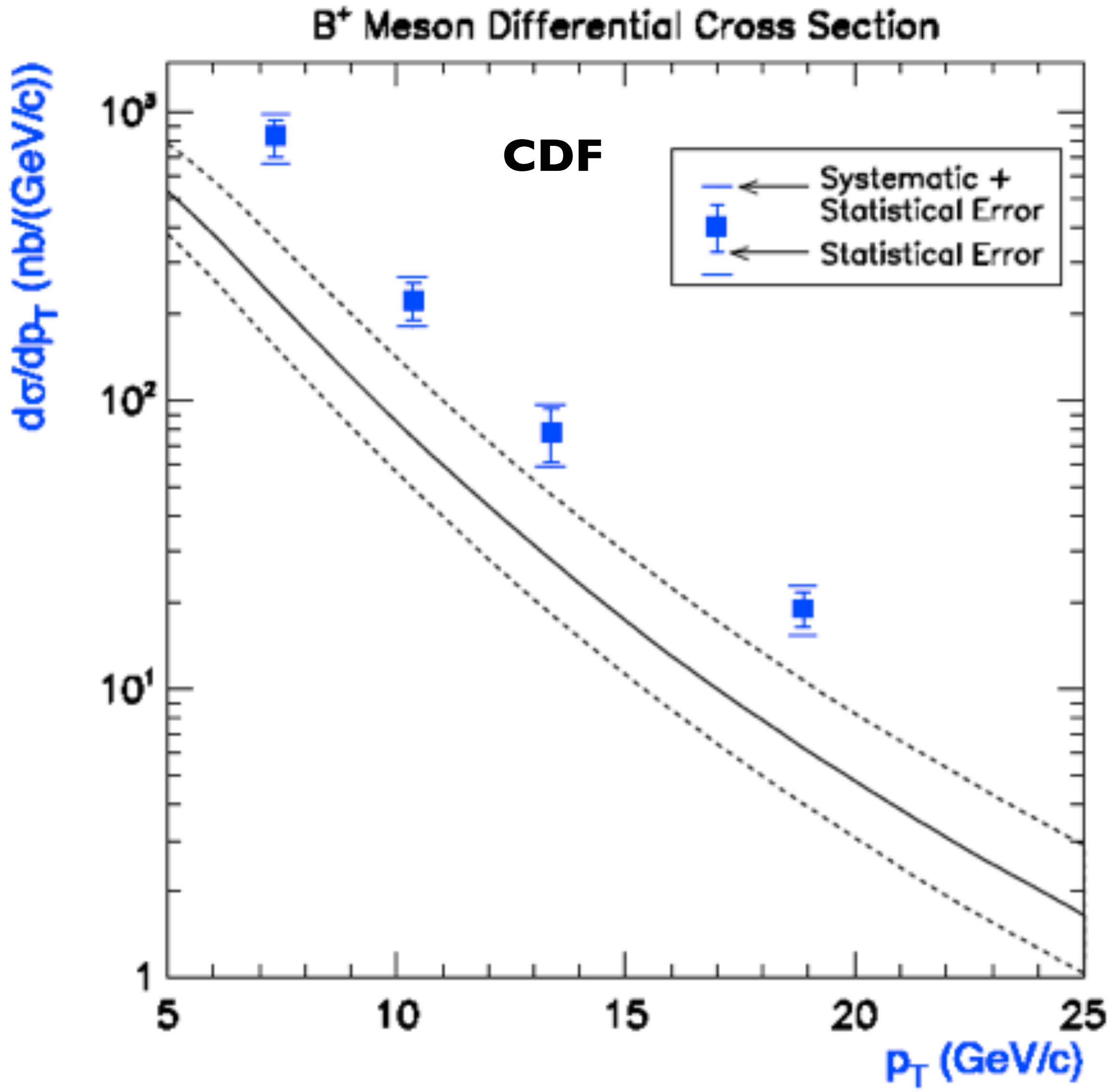
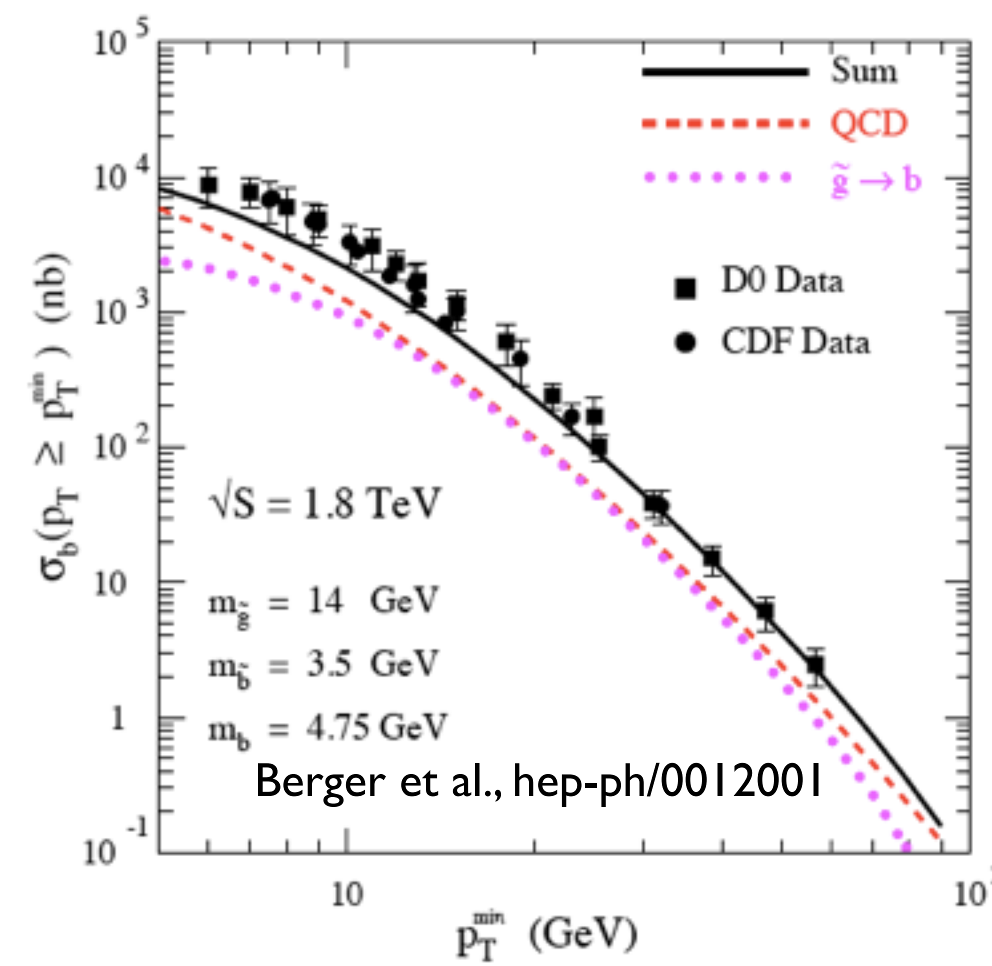


Parton shower ≠ QCD

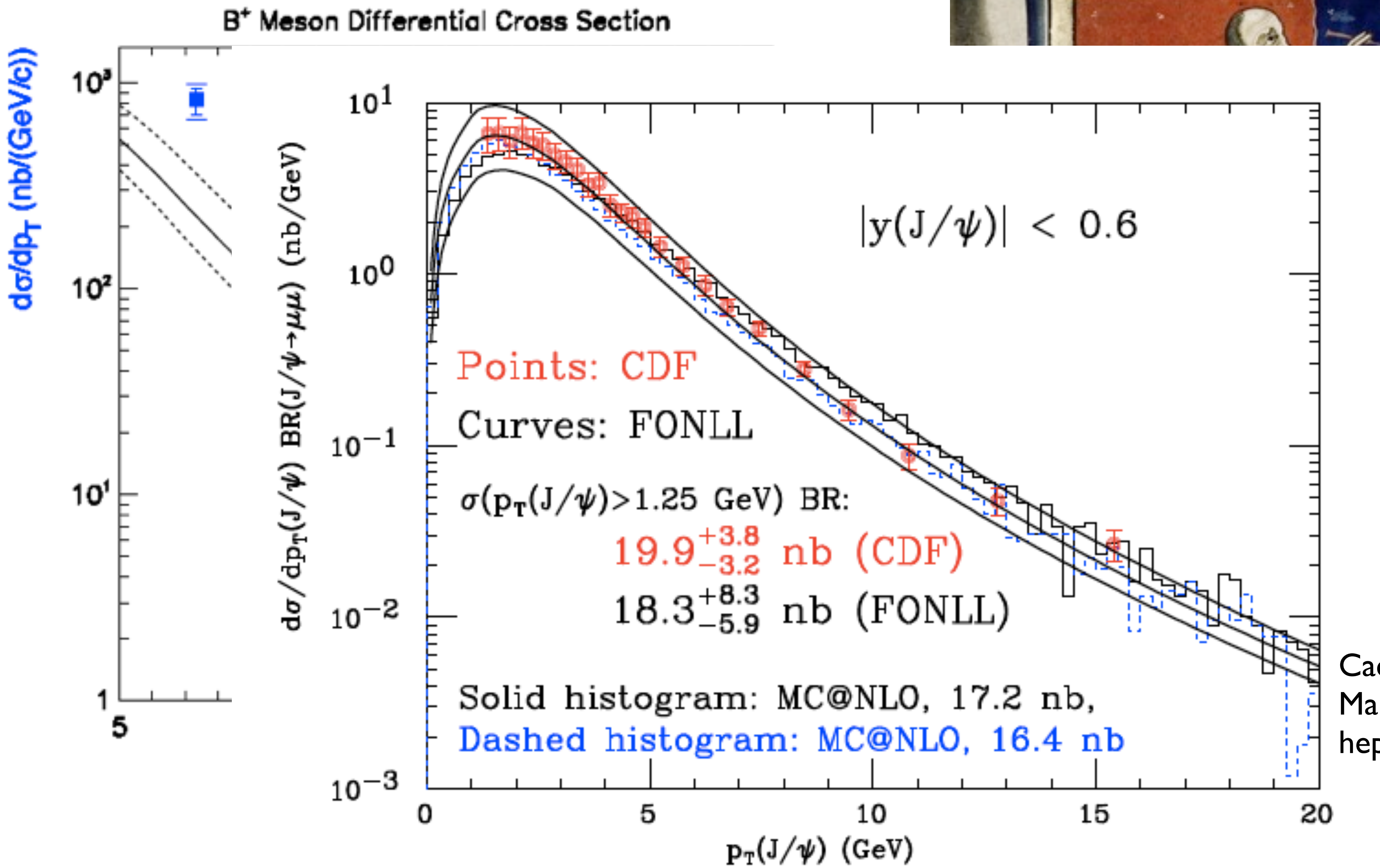
QCD simulation circa 2001

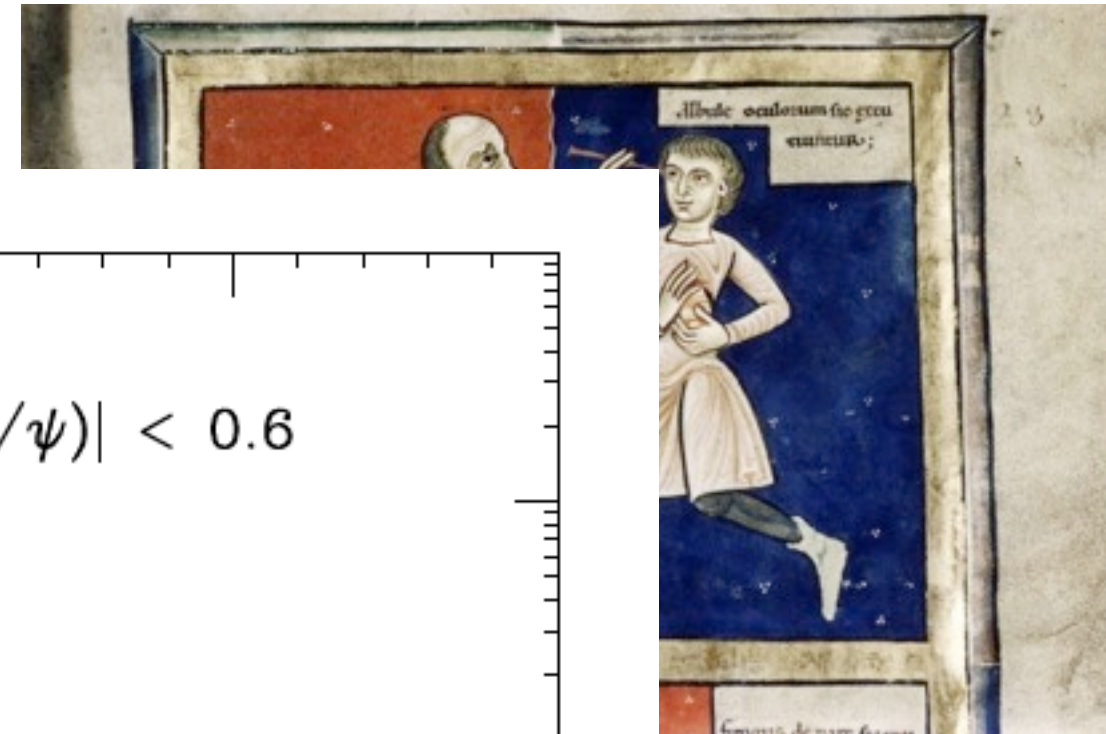




"The differential cross section is measured to be 2.9±0.2±0.4 times higher than the NLO QCD predictions with agreement in shape."

QCD simulation circa 2001

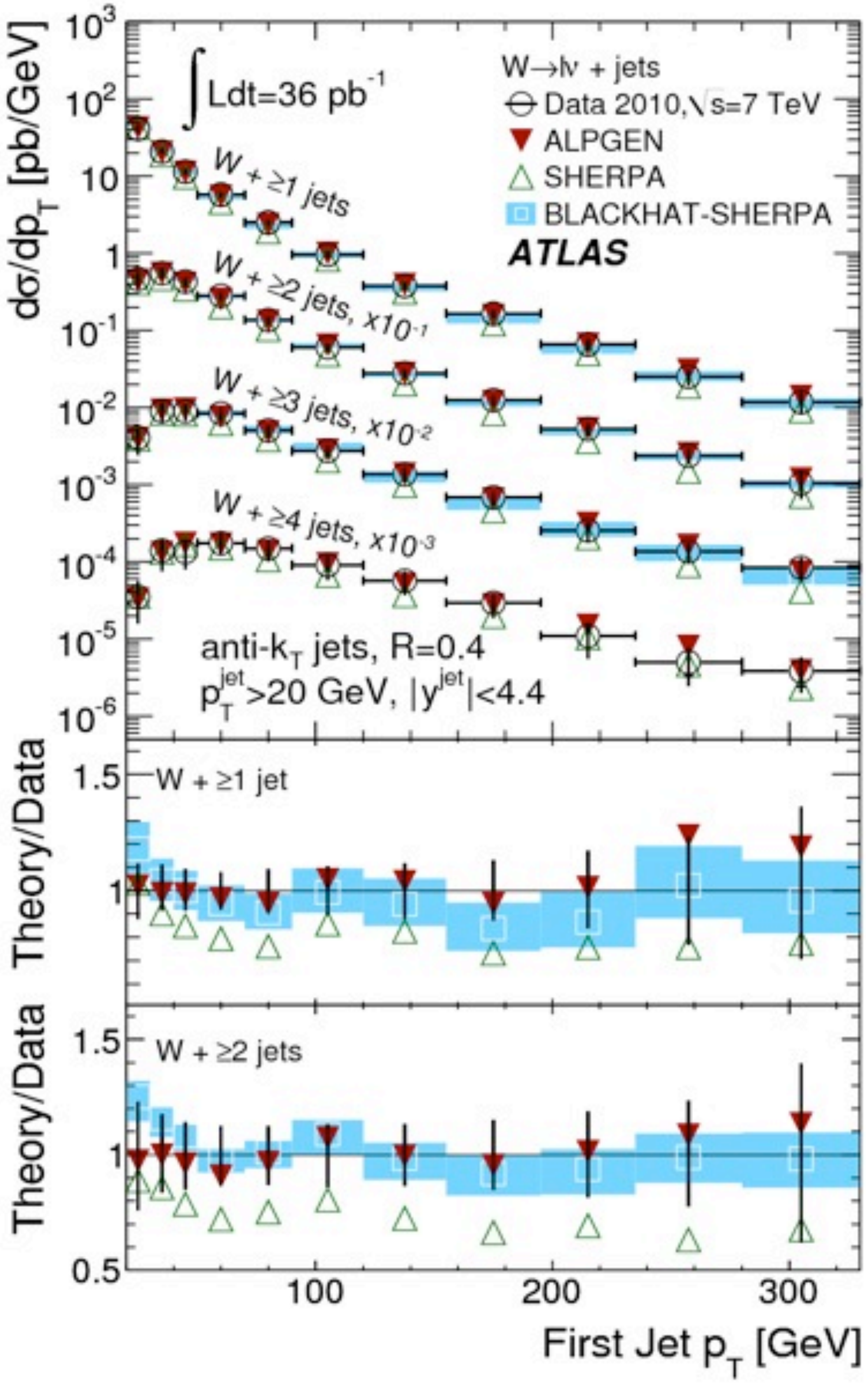




Cacciari, Frixione, Mangano, Nason, Ridolfi hep-ph/0312132

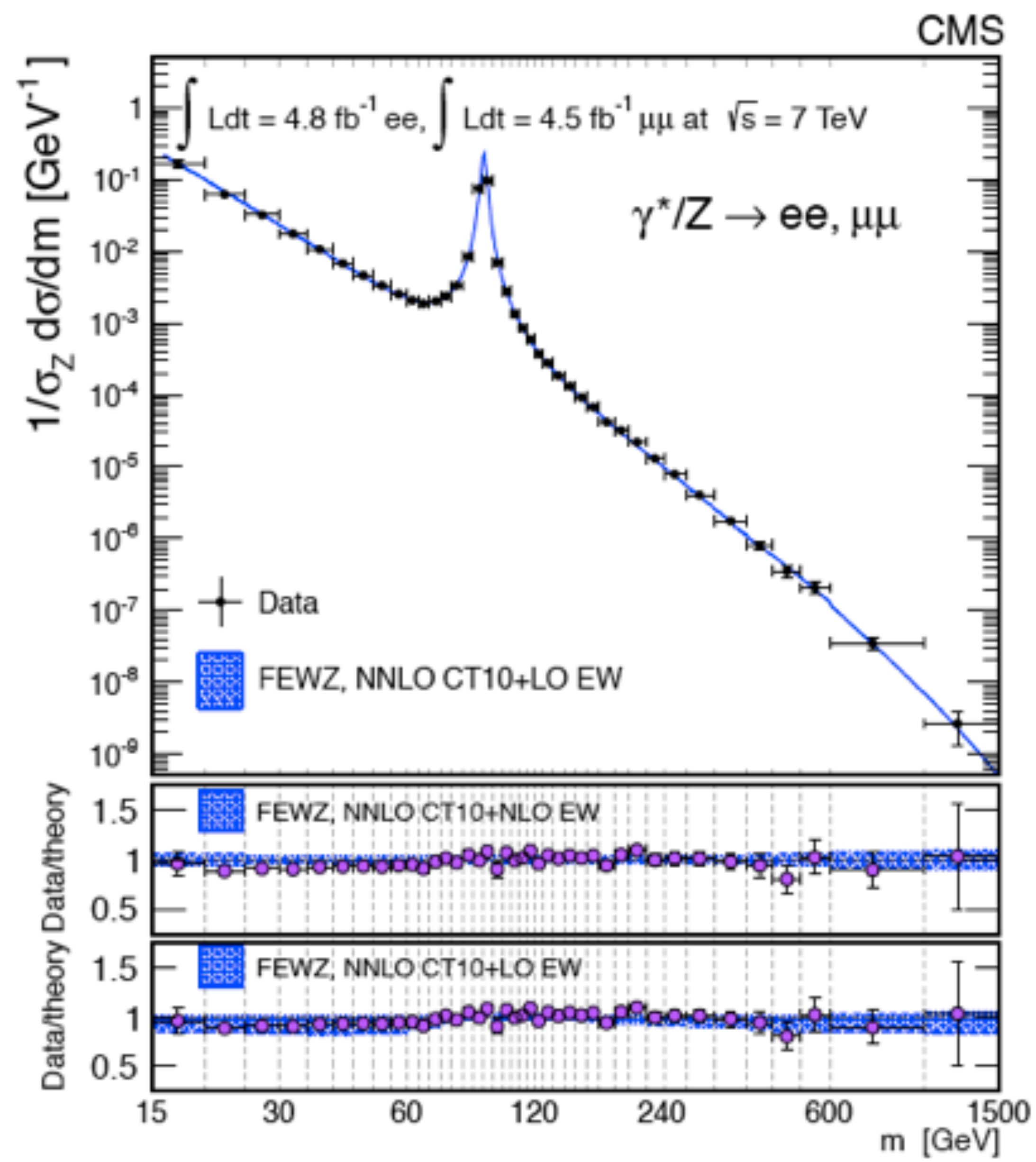
- Consistent combination of fragmentations functions and pQCD, more proper accounting of theoretical errors, better PDFs, all reduce the discrepancy

QCD today



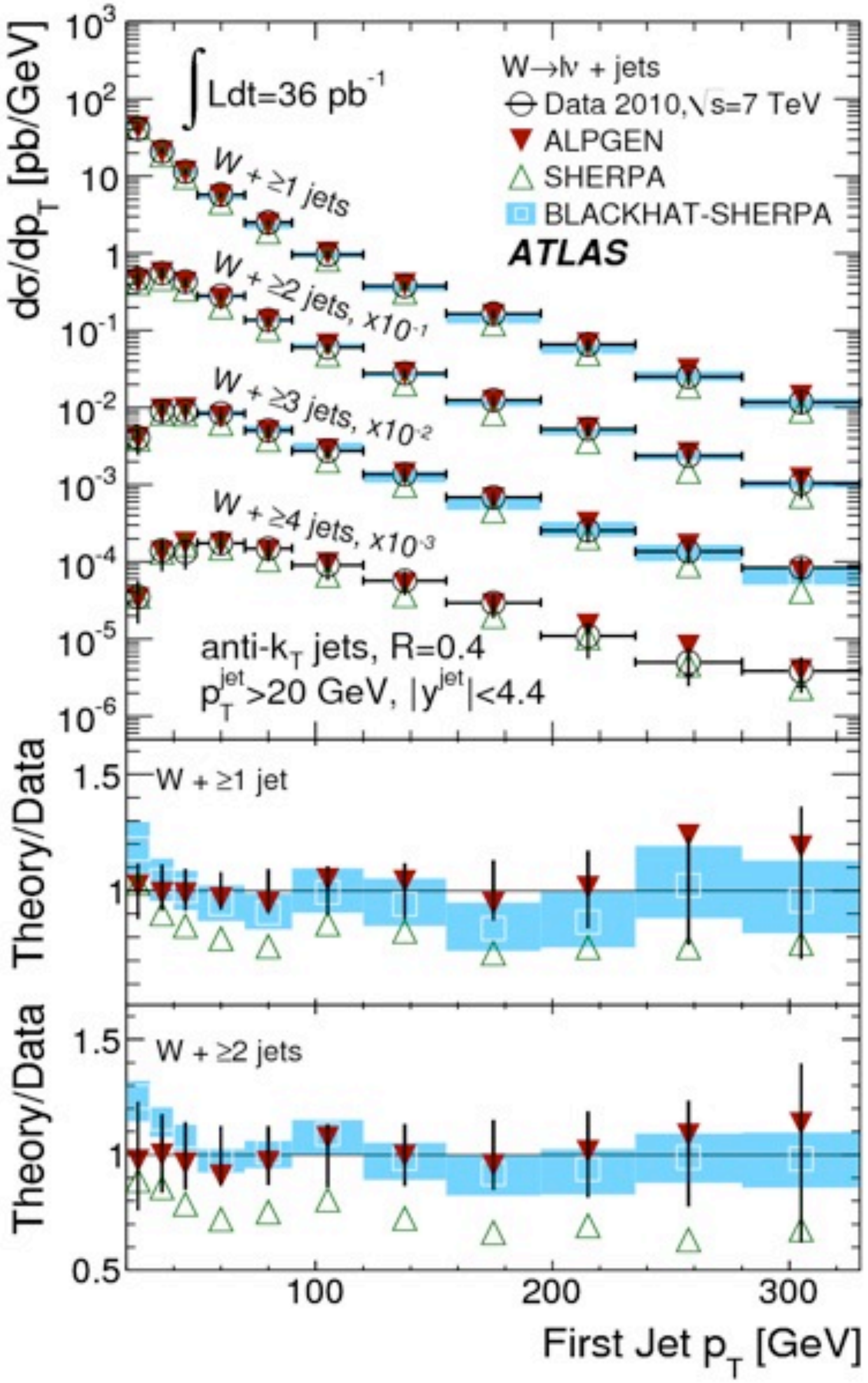
W→lν + jets
Data 2010, √s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
∫Ldt=36 pb⁻¹
W + ≥1 jets
W + ≥2 jets, x10⁻¹
W + ≥3 jets, x10⁻²
W + ≥4 jets, x10⁻³
anti-kT jets, R=0.4
pT jet>20 GeV, |y jet|<4.4
dσ/dpT [pb/GeV]
Theory/Data
W + ≥1 jet
W + ≥2 jets
First Jet pT [GeV]

DEWALT

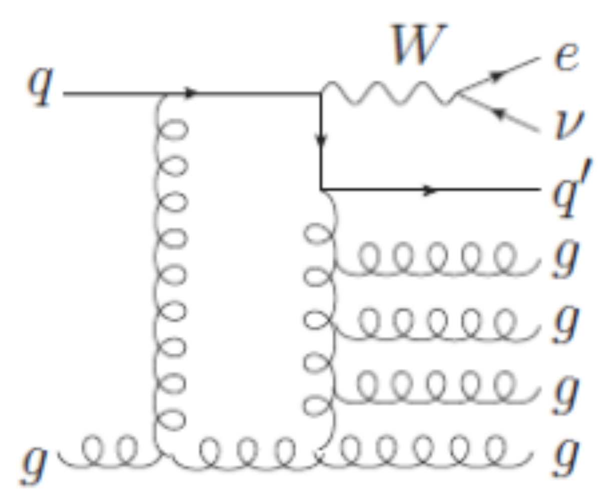


CMS
∫ Ldt = 4.8 fb⁻¹ ee, ∫ Ldt = 4.5 fb⁻¹ μμ at √s = 7 TeV
γ*/Z → ee, μμ
Data
FEWZ, NNLO CT10+LO EW
FEWZ, NNLO CT10+NLO EW
1/σZ dσ/dm [GeV⁻¹]
Data/theory Data/theory
m [GeV]

QCD today

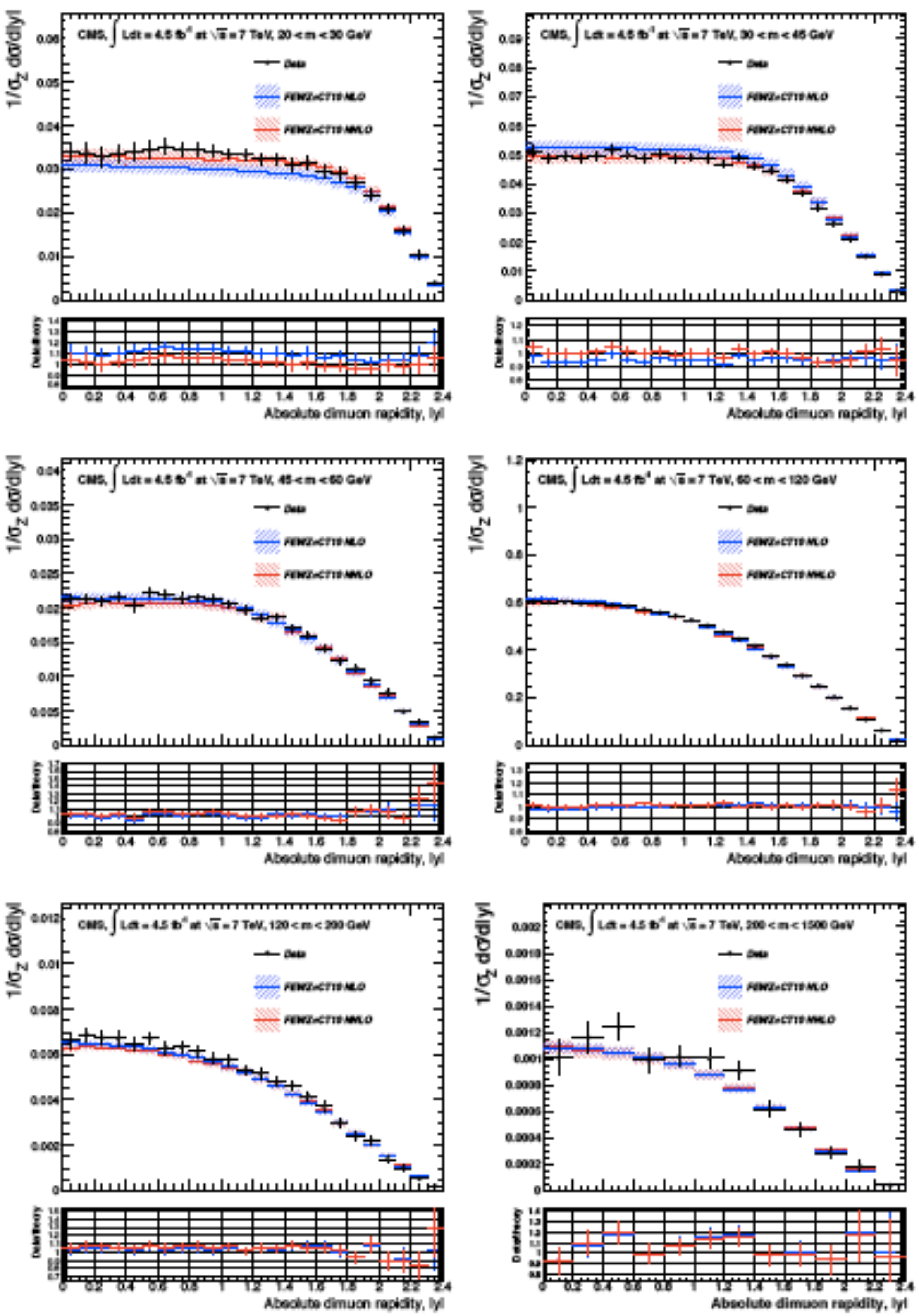


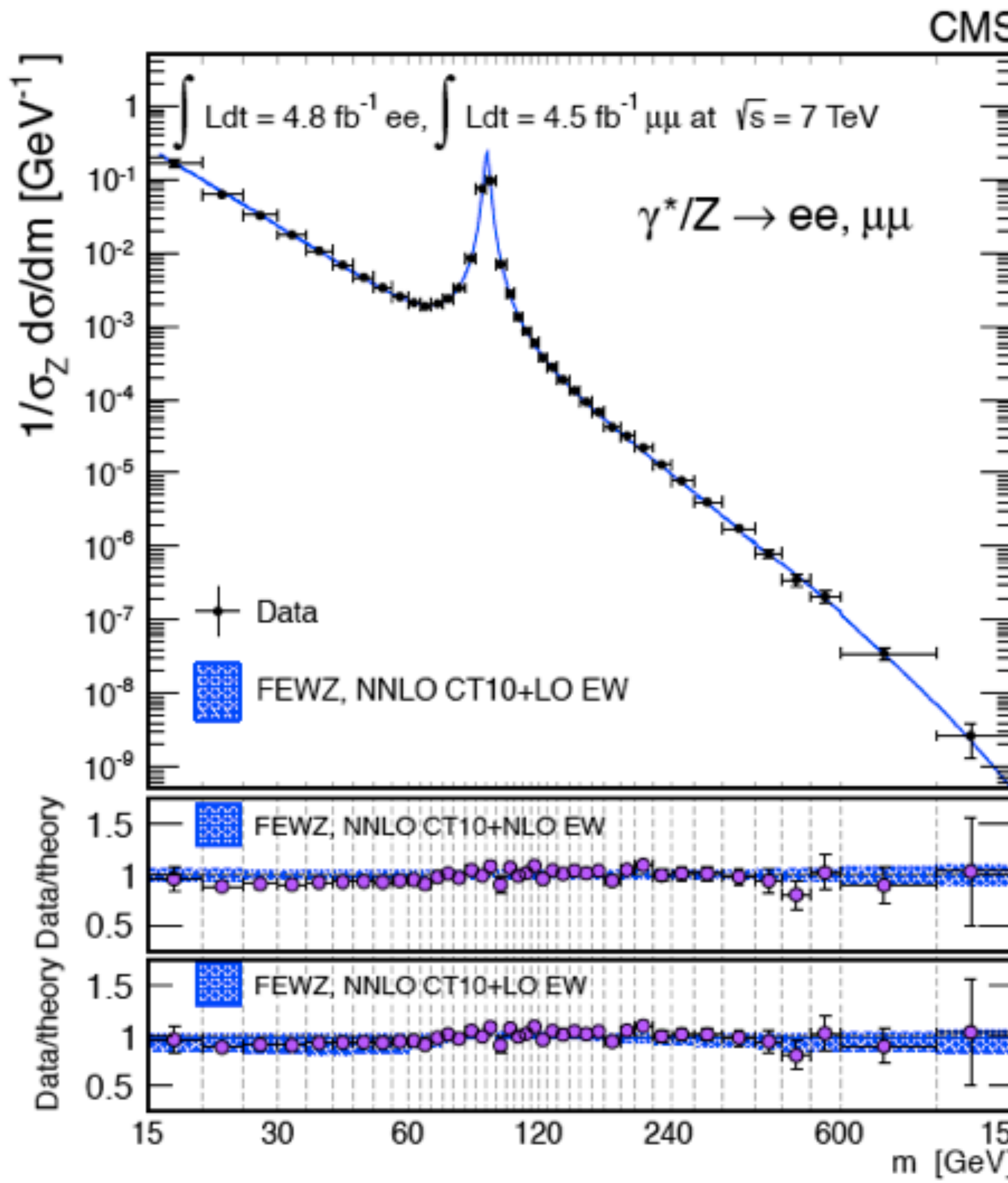
- NLO+parton shower tools now standard tools used in analyses
- NNLO QCD, sometimes with NLO EW combined, are becoming available for more and more channels
- Several global NNLO PDF extractions with robust errors now available



W+5 jets from BLACKHAT, Bern et al. 1304.1253

QCD and experiment, hand-in-hand



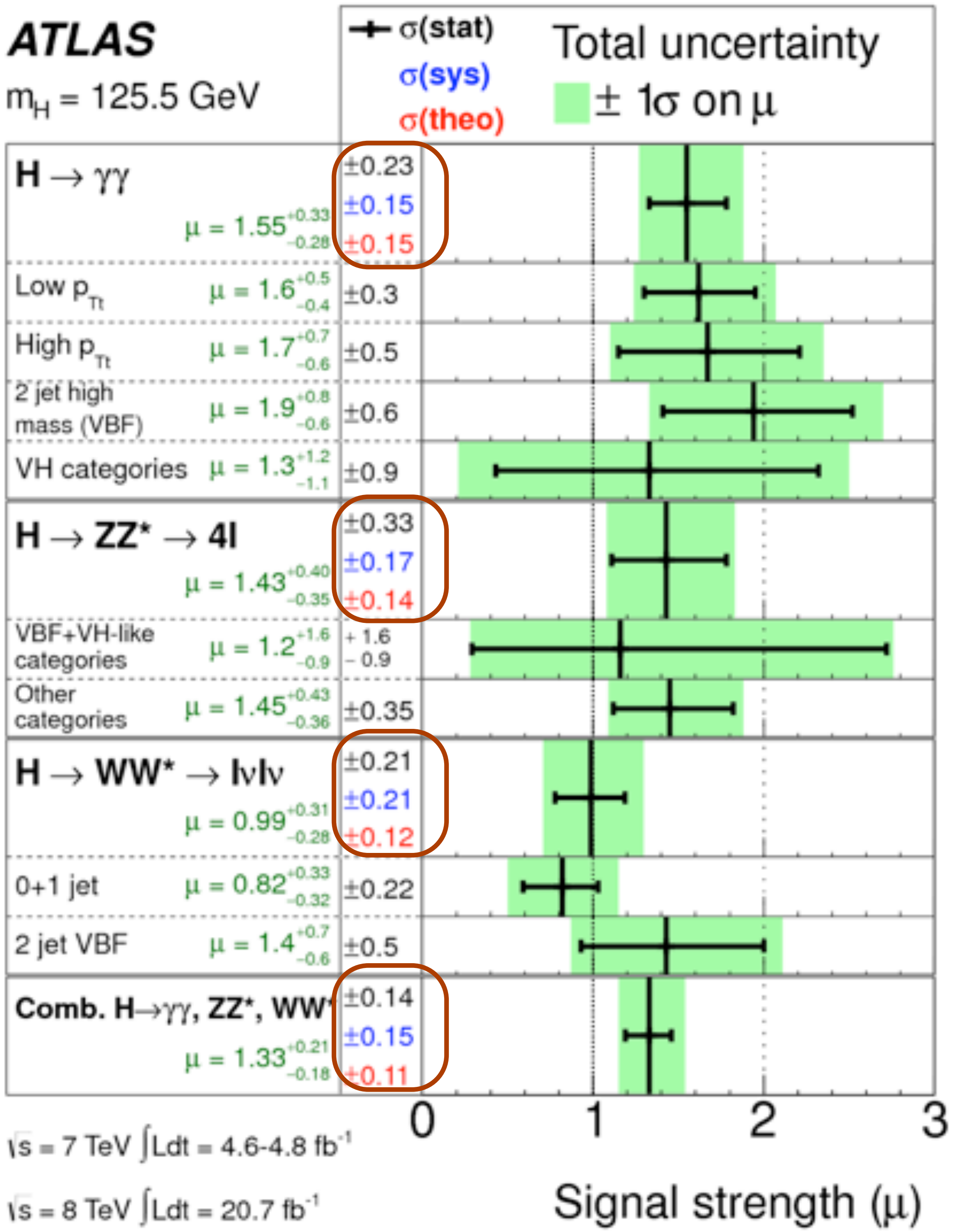


QCD and experiment, hand-in-hand

- Take a second to appreciate the magnitude of the success indicated by this measurement
- ~130 bins spanning 9 orders of magnitude in cross section
- Total experimental error: 2-3% in all but the highest mass bins
- Acceptance, PDF errors, and modeling errors: under 3% for all but the first and last bins
- Inspires great confidence that we are ready for whatever Nature may try to hide from us in the 14 TeV run

m (GeV)	Eff. ρ (%)	Det. resol. (%)	Bkgr. est. (%)	FSR (%)	Total (%)	Acc.+PDF (%)	Modeling (%)
15–20	1.90	0.03	0.28	0.54	2.09	2.29	9.70
20–25	2.31	0.24	0.63	0.47	2.47	3.15	3.10
25–30	2.26	0.27	2.95	0.40	3.76	2.73	1.90
30–35	1.48	0.17	1.94	0.46	2.50	2.59	0.70
35–40	1.19	0.09	1.26	0.66	1.88	2.61	0.50
40–45	1.12	0.07	0.97	0.30	1.54	2.49	0.30
45–50	1.10	0.07	0.86	0.44	1.50	2.51	0.10
50–55	1.07	0.10	0.67	0.58	1.42	2.44	0.10
55–60	1.07	0.15	0.69	0.77	1.52	2.36	0.20
60–64	1.06	0.19	0.35	0.94	1.50	2.27	0.20
64–68	1.06	0.22	0.24	1.06	1.55	2.22	0.30
68–72	1.06	0.30	0.20	1.13	1.60	2.20	0.20
72–76	1.05	0.51	0.15	1.13	1.65	2.18	0.20
76–81	1.06	0.94	0.25	1.01	1.77	2.15	0.20
81–86	1.11	1.56	0.10	0.69	2.06	2.18	0.10
86–91	1.07	2.21	0.01	0.23	2.48	2.12	0.20
91–96	1.08	2.55	0.01	0.12	2.78	2.14	0.20
96–101	1.29	2.32	0.08	0.15	2.68	2.12	0.30
101–106	1.31	1.69	0.14	0.19	2.17	2.07	0.30
106–110	1.32	1.05	0.28	0.22	1.76	2.01	0.50
110–115	1.34	0.65	0.34	0.25	1.59	1.97	0.60
115–120	1.33	0.47	0.43	0.27	1.55	1.95	0.60
120–126	1.36	0.37	0.56	0.29	1.60	1.91	0.50
126–133	1.35	0.33	0.70	0.30	1.65	1.88	0.60
133–141	1.31	0.42	0.90	0.32	1.75	1.85	0.70
141–150	1.29	0.64	1.08	0.35	1.91	1.81	1.00
150–160	1.36	0.87	1.20	0.39	2.13	1.82	1.10
160–171	1.42	0.99	1.48	0.39	2.39	1.82	1.10
171–185	1.53	0.96	1.72	0.41	2.61	1.75	1.10
185–200	1.60	0.77	1.80	0.51	2.67	1.75	1.10
200–220	1.71	0.52	1.82	0.42	2.64	1.53	1.00
220–243	1.75	0.39	2.28	0.44	3.01	1.48	1.50
243–273	1.86	0.49	2.46	0.46	3.23	1.40	1.40
273–320	1.90	0.72	2.37	0.50	3.24	1.31	1.30
320–380	1.90	0.96	2.88	0.57	3.73	1.28	1.50
380–440	1.93	1.31	3.54	0.57	4.44	1.45	1.20
440–510	1.97	1.74	4.64	0.57	5.50	1.60	1.30
510–600	2.02	1.79	4.48	0.57	5.28	0.50	2.10
600–1000	2.01	1.13	5.07	0.57	5.61	0.41	2.40
1000–1500	2.14	0.48	15.34	0.57	15.51	0.24	3.10

QCD and the Higgs, run II

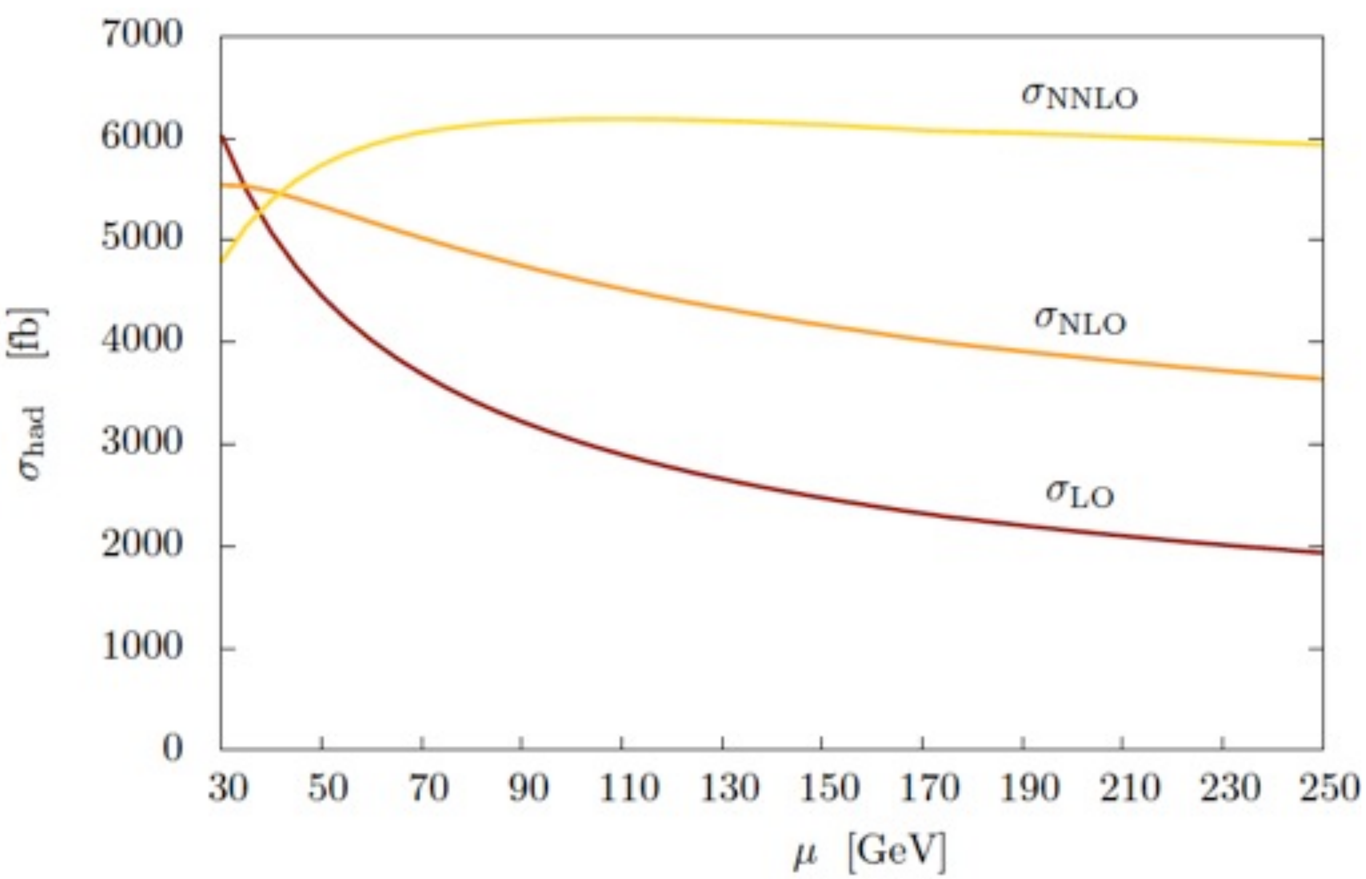


- Systematic errors already approaching statistical ones; will overtake with 14 TeV data
- Systematic error shown is the combination of experimental and theoretical systematics; theory is already the dominant systematic error

Source	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{jet} \geq 0$	+13	-	-
QCD scale for ggF, $N_{jet} \geq 1$	+10	−27	-
QCD scale for ggF, $N_{jet} \geq 2$	-	−15	+4
QCD scale for ggF, $N_{jet} \geq 3$	-	-	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
WW transfer factors (theory)	±1	±2	±4
Jet energy scale and resolution	2	3	7
b-tagging efficiency	-	+7	+2
f_{recoil} efficiency	±4	±2	-

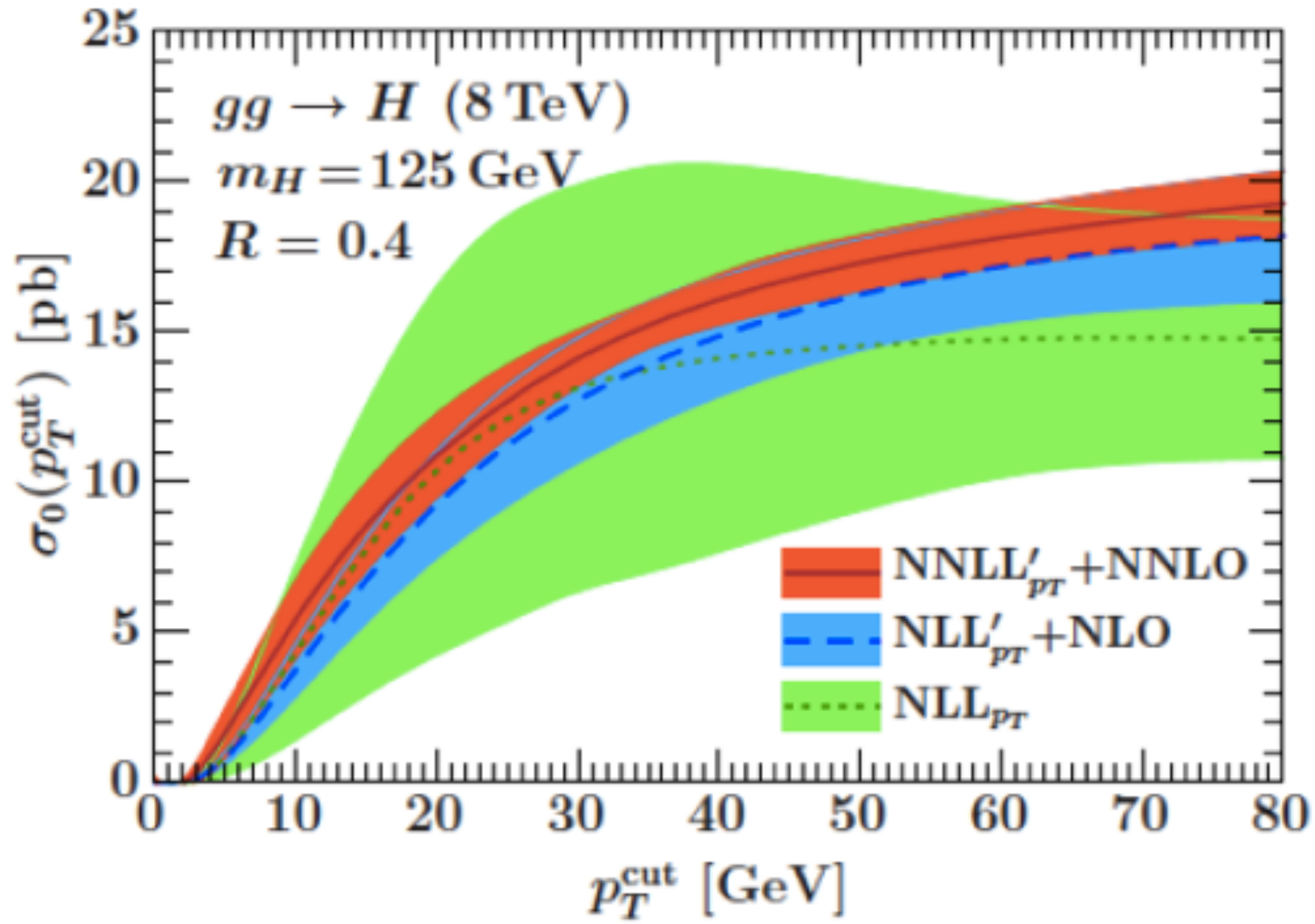
QCD for the Higgs

Boughezal, Caola, Melnikov, FP, Schulze, 1302.6216



H+jet, p_{TH} at NNLO

Stewart, Tackmann, Walsh, Zuberi 1307.1808

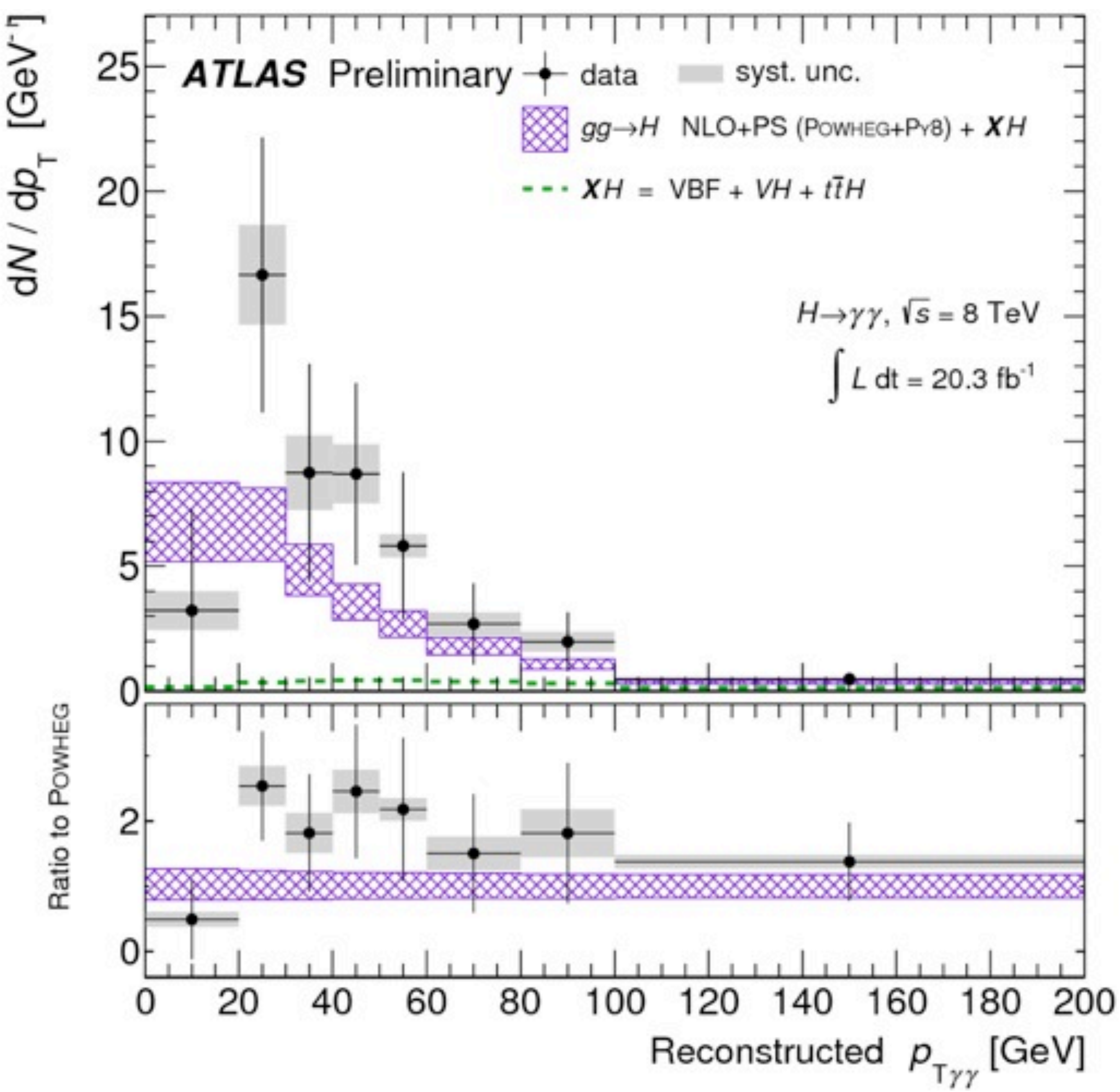


Resummation of H+0-jet logarithms

(also see work by Banfi, Monni, Salam, Zanderighi; Becher, Neubert)

- New calculations coming online to address these issues, in time for 14 TeV (and hopefully for some 8 TeV analyses)

Differential measurements



Azatov, Paul 1309.5273

$$\mathcal{L} = c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

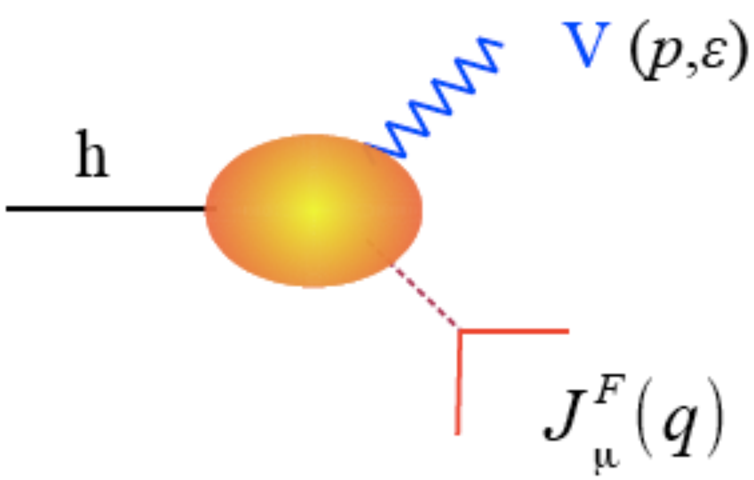
$$O_g(m_H) \approx \frac{g_s^2}{48\pi^2} (c_g + c_t) \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

$$\frac{d\sigma}{dp_T} = \alpha(p_T) c_t^2 + \beta(p_T) c_g^2 + 2\gamma(p_T) c_t c_g$$

- Measurements of such spectra can break degeneracies that exist in inclusive Higgs production
- Should be a focus of LHC_{14}, and QCD is ready!

Rare Higgs decays

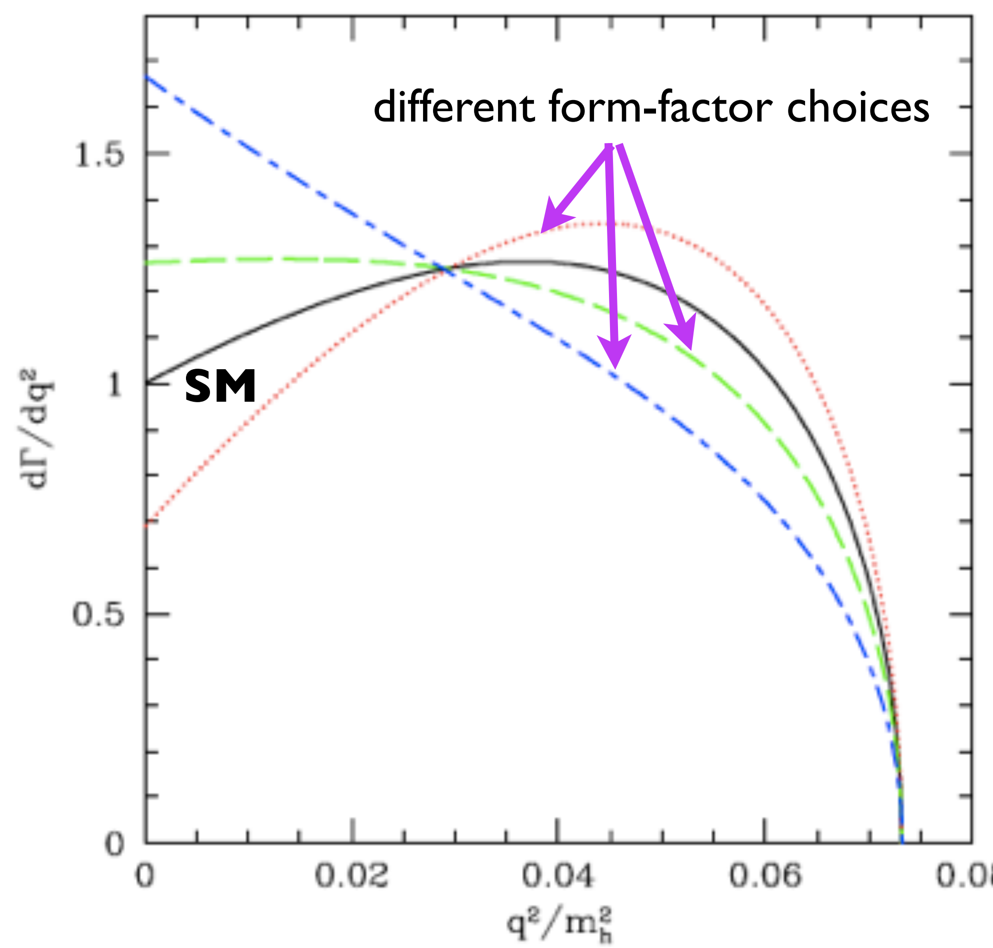
- We've only begun to use the full potential of the LHC to probe the richness of the Higgs effective Lagrangian
- This area should be a focus during the 14 TeV run!



$$\mathcal{A}^{\mathcal{F}}_V = C_V g_V^2 m_V \frac{\varepsilon_\mu J^{\mathcal{F}}_\nu}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p \cdot q\; g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

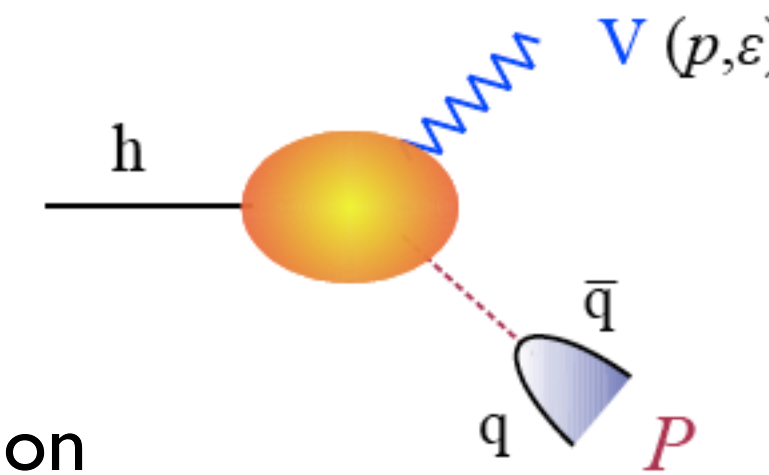
- Significant structure present in the H→Vff decay that can be accessed via differential measurements at the LHC

Isidori, Manohar, Trott 1305.0663



Rare Higgs decays

$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu \right.$$
$$\left. + f_3^V(q^2)(p \cdot q\, g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2)\epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$



- Difficult to access f_2 with continuum fermion production due to $q_\nu J^\nu=0$ for fermion vector couplings
- These terms are picked out by the exclusive production of a meson, H→VP (pseudoscalar meson in this case)

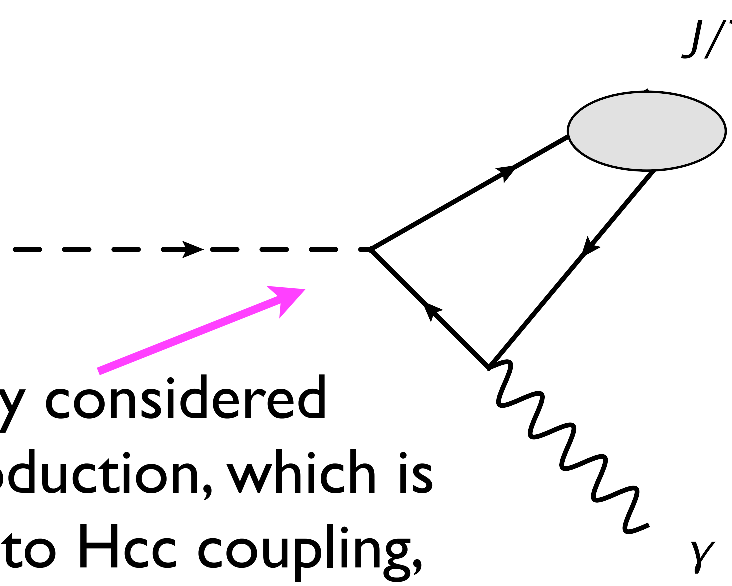
Isidori, Manohar, Trott 1305.0663

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	0.4×10^{-5}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	0.4×10^{-5}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.4×10^{-5}

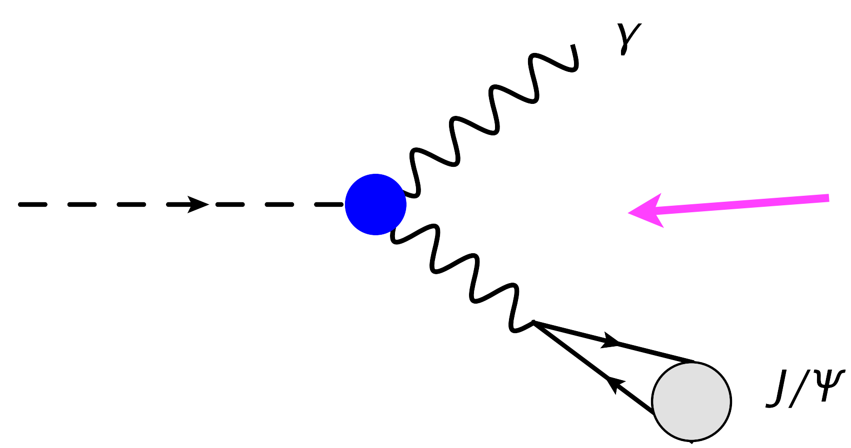
Need a luminosity upgrade to access this information!

Rare Higgs decays and Hcc, Hbb couplings

- Rare decays offer unique windows onto other properties of the Higgs
- Can we measure second-generation quark couplings at the LHC?
- Recent result: it may be possible to measure the Hcc coupling at a high-luminosity LHC, using $H \to J/\Psi + \gamma$ Bodwin, FP, Stoynev, Velasco 1306.5770
- The mode $H \to \Upsilon(1S) + \gamma$ provides additional information on hbb



previously considered *direct* production, which is sensitive to Hcc coupling, is small



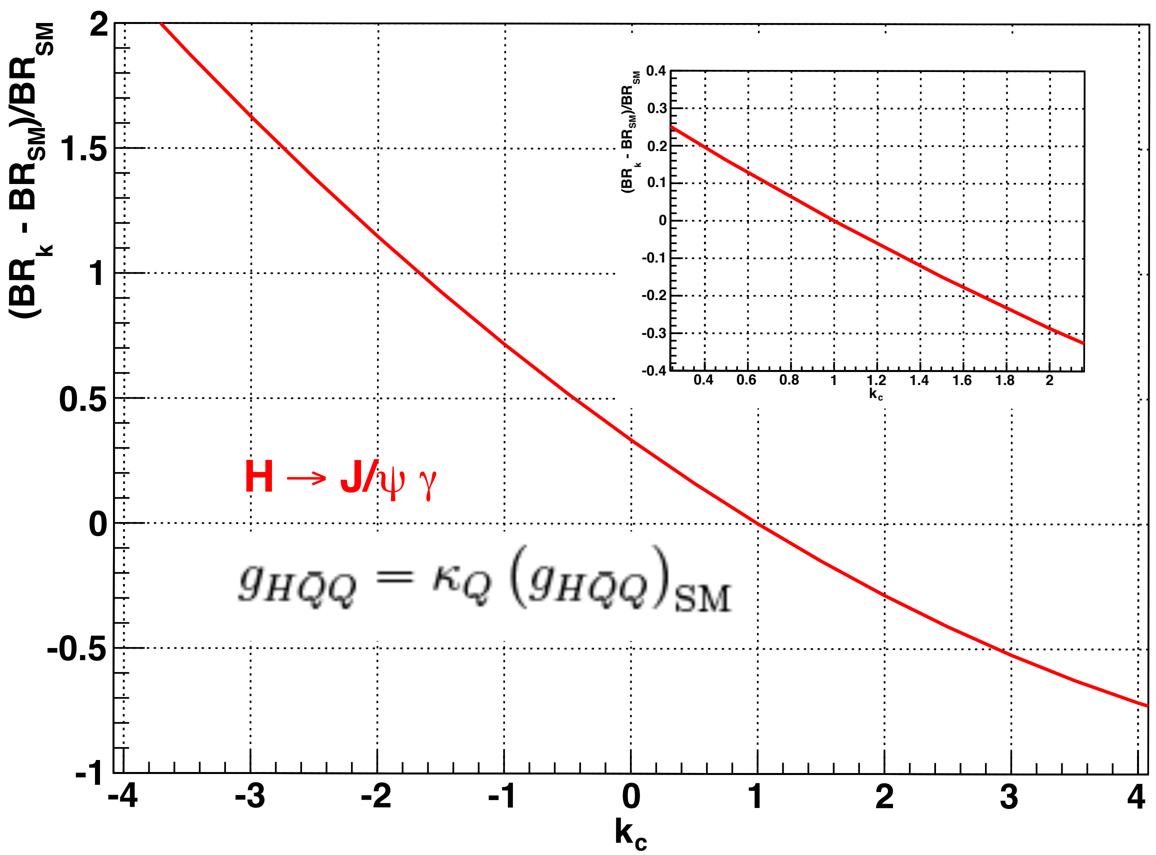
newly identified *indirect* production is larger; interferes quantum-mechanically with direct production

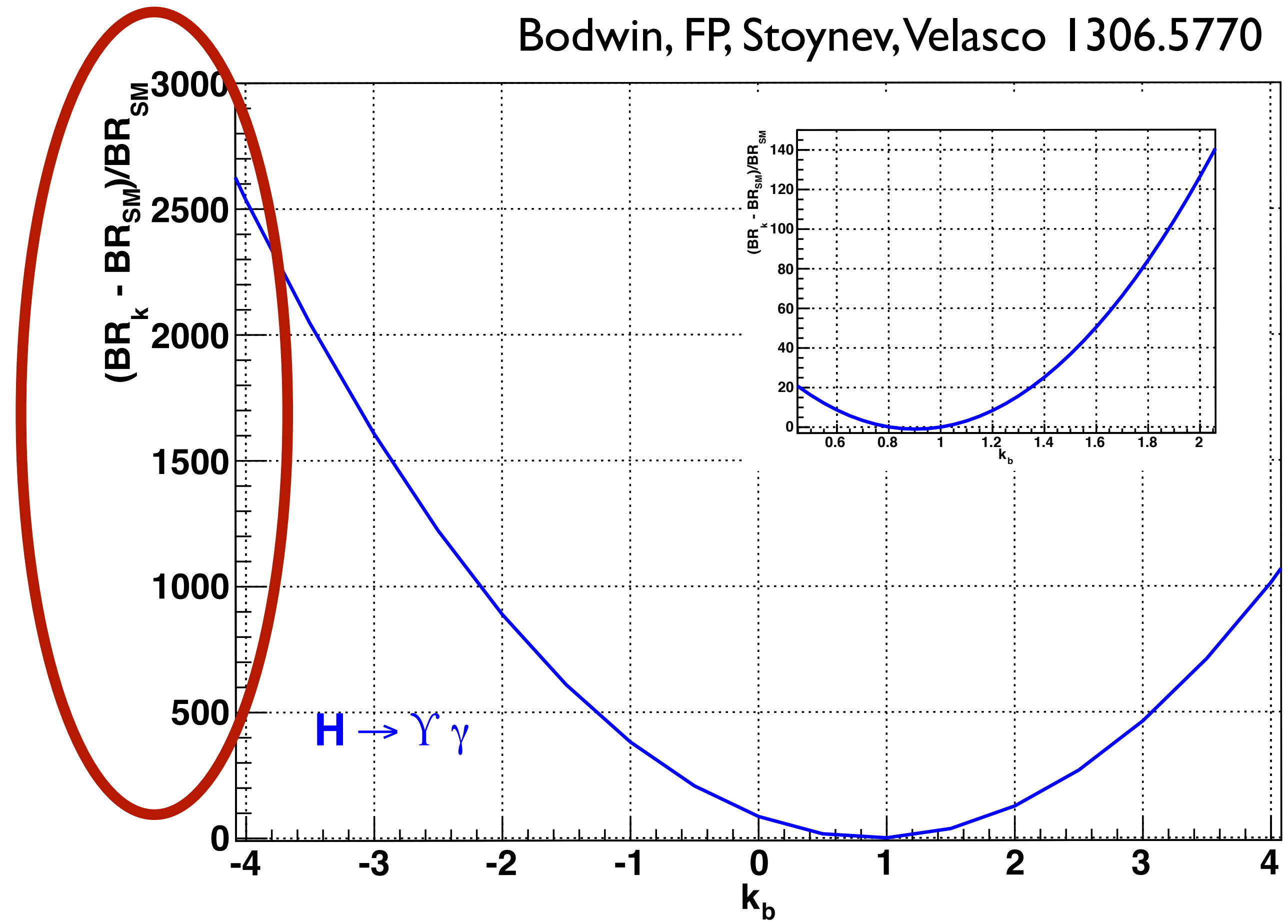
- Enhanced charm couplings can appear in composite Higgs and 2HDMs

Delaunay, Golling, Perez, Soreq 1310.7029

Rare Higgs decays and Hcc, Hbb couplings

Bodwin, FP, Stoynev, Velasco 1306.5770

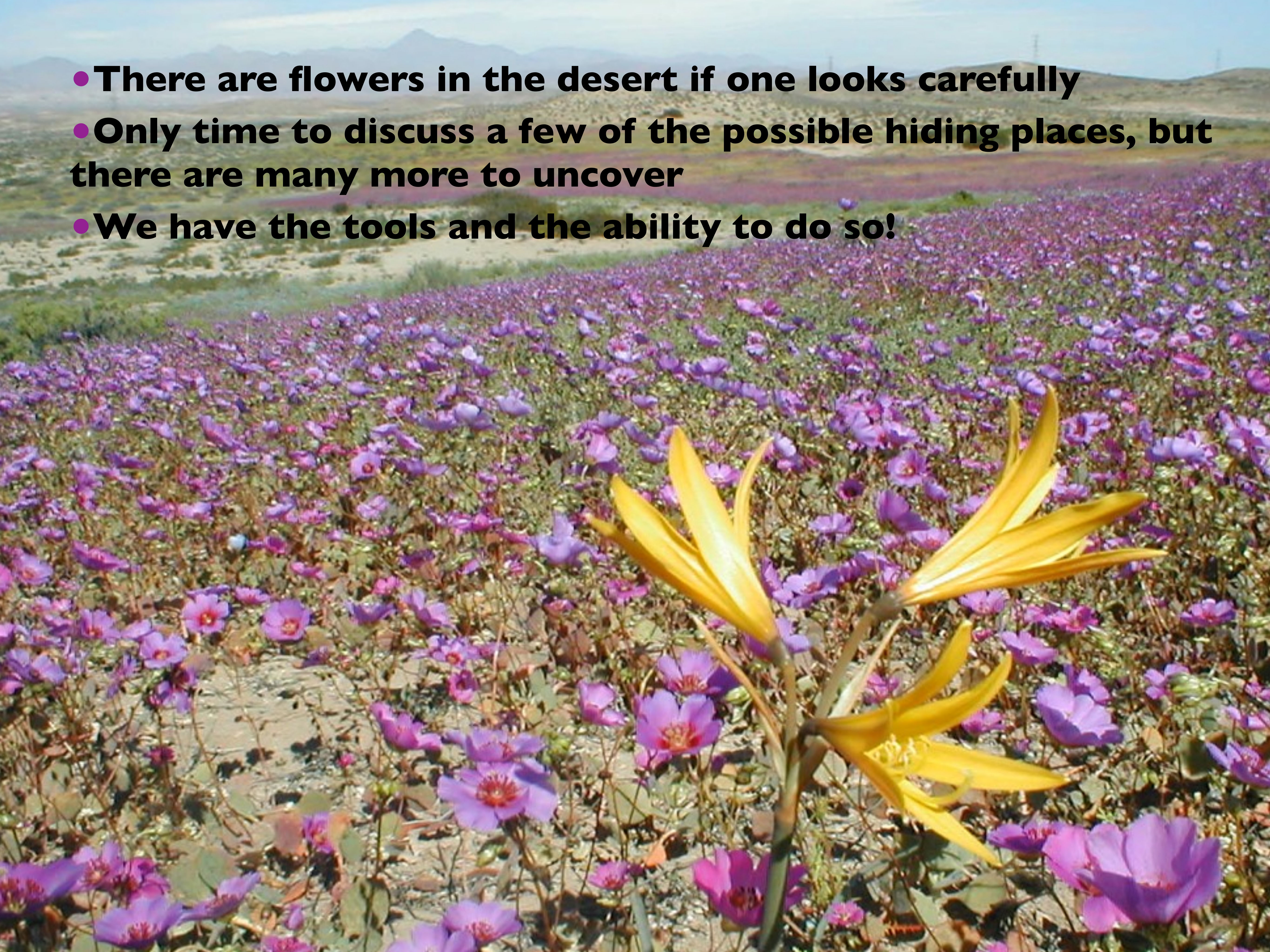




$$\mathrm{BR_{SM}}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6},$$
$$\mathrm{BR_{SM}}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}.$$

Note the scale on this axis; almost complete cancellation between production mechanisms in the SM. Extraordinary sensitivity to BSM deviations!

- Careful study of experimental capabilities indicates that J/Ψ in the SM is accessible, but need the luminosity upgrade for ab^{-1}!



- **There are flowers in the desert if one looks carefully**
- **Only time to discuss a few of the possible hiding places, but there are many more to uncover**
- **We have the tools and the ability to do so!**