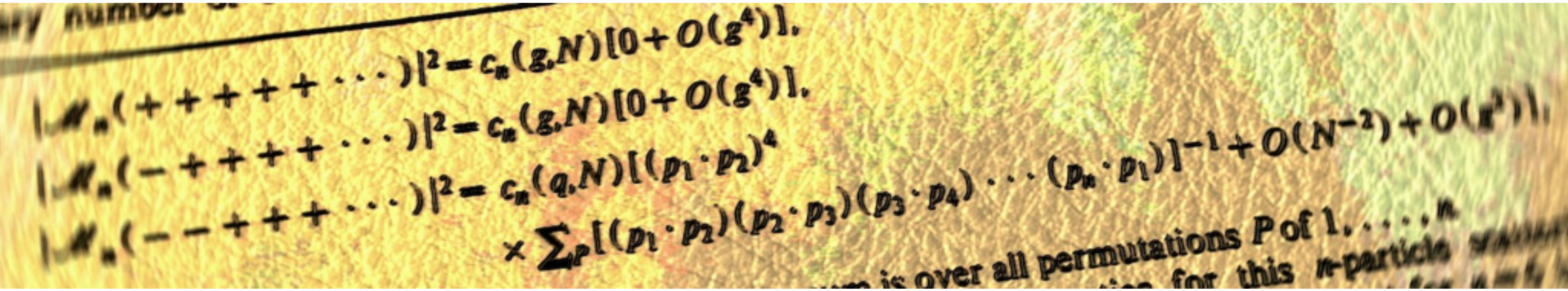

$$|\mathcal{M}_n(+++++\cdots)|^2 = c_n(g,N)[0+O(g^4)],$$
$$|\mathcal{M}_n(-++++\cdots)|^2 = c_n(g,N)[0+O(g^4)],$$
$$|\mathcal{M}_n(--+++\cdots)|^2 = c_n(g,N)[(p_1\cdot p_2)^4 \times \sum_P [(p_1\cdot p_2)(p_2\cdot p_3)(p_3\cdot p_4)\cdots(p_n\cdot p_1)]^{-1}+O(N^{-2})+O(g^2)],$$

is over all permutations P of $1,\ldots,n$ for this n-particle

MHV @ 30: Amplitudes and Modern Applications

Precision physics in hadronic collisions: challenges and future opportunities

FNAL Wine & Cheese,
March 18 2016

Michelangelo L. Mangano
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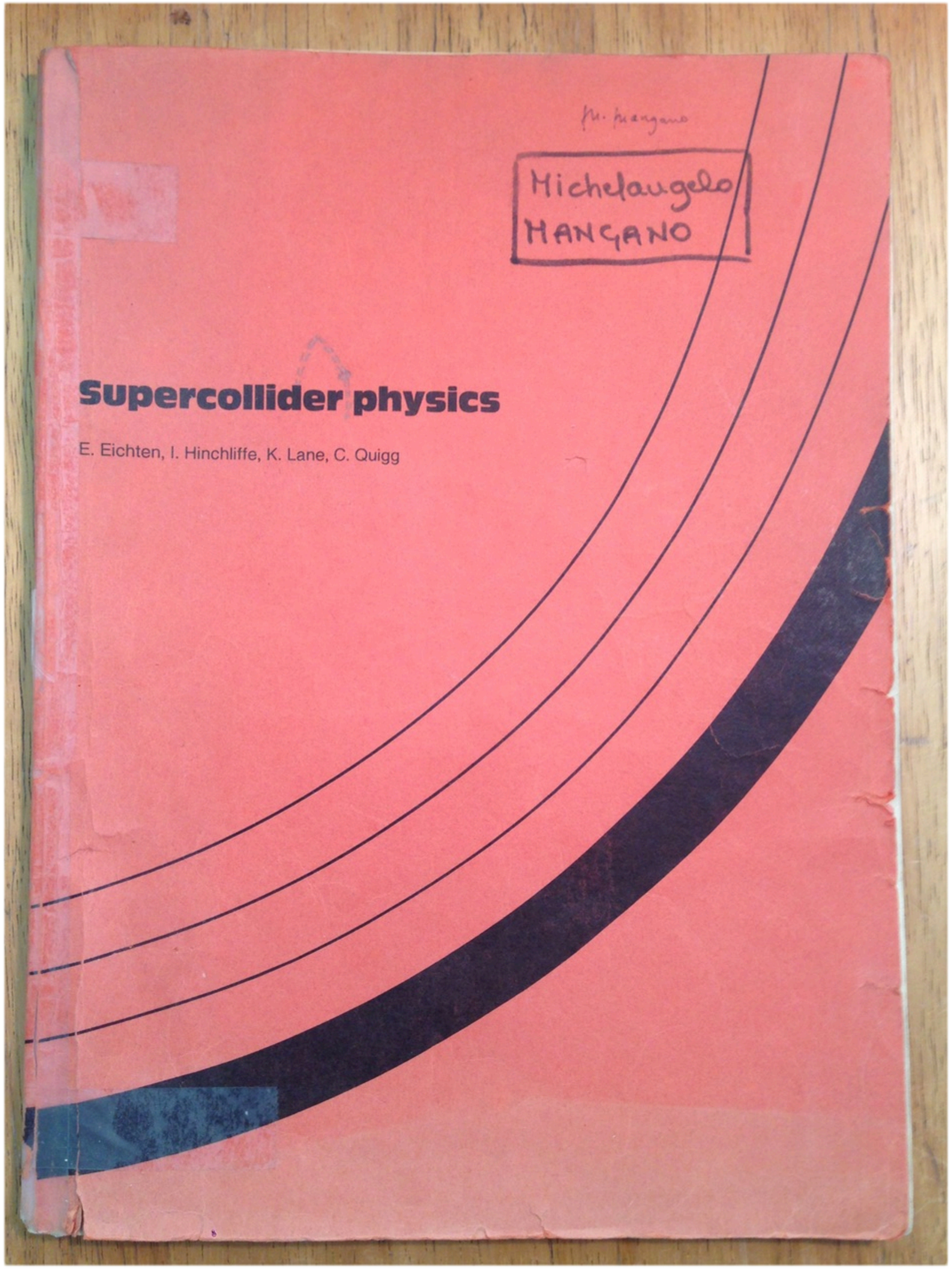
Theoretical Physics Department
CERN

Contents

- MHV@30: the context
- Highlights from the past and the present …
- … prospects for the future

Reviews of Modern Physics, Vol. 56, No. 4, October 1984



M. Mangano

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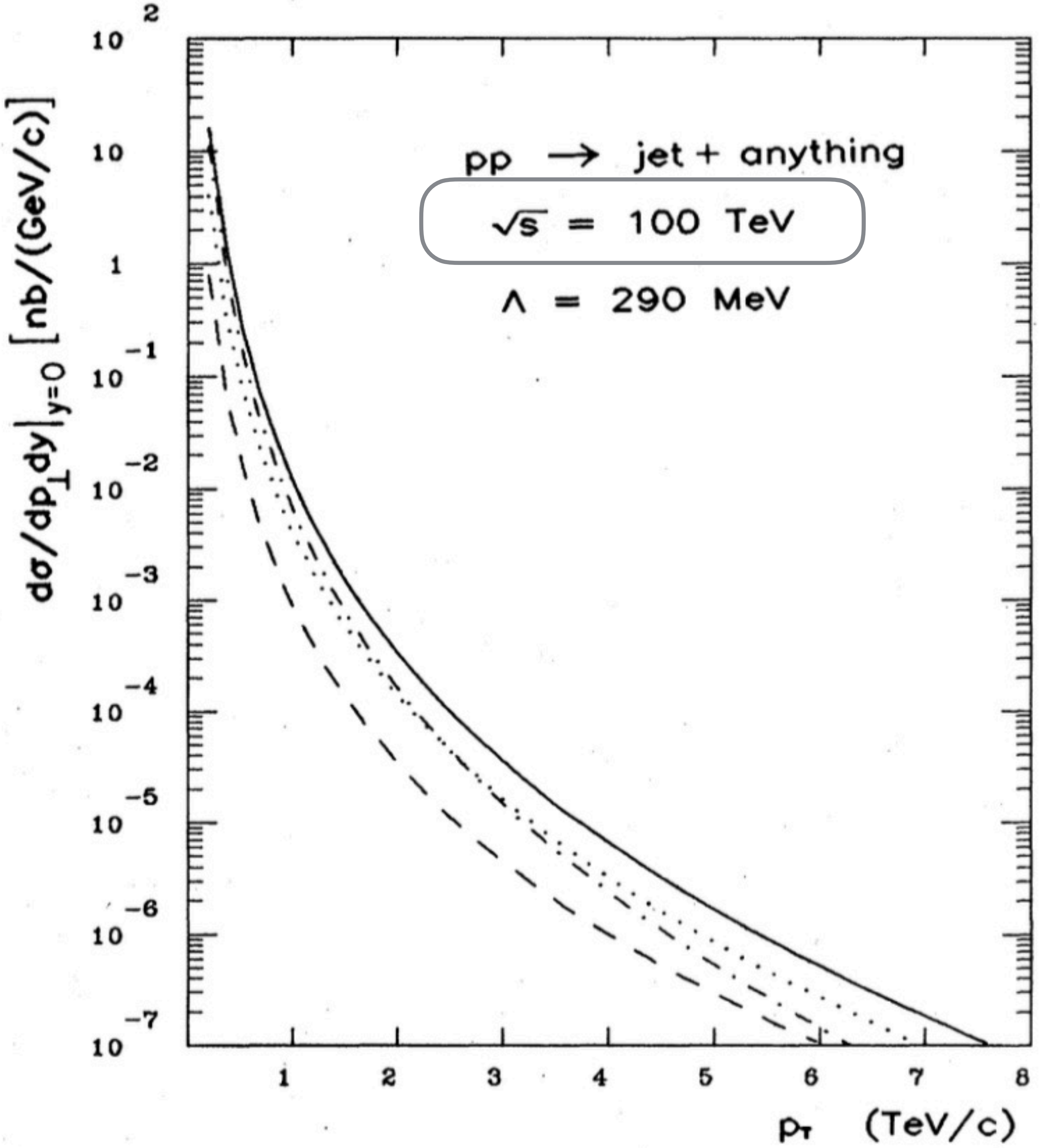
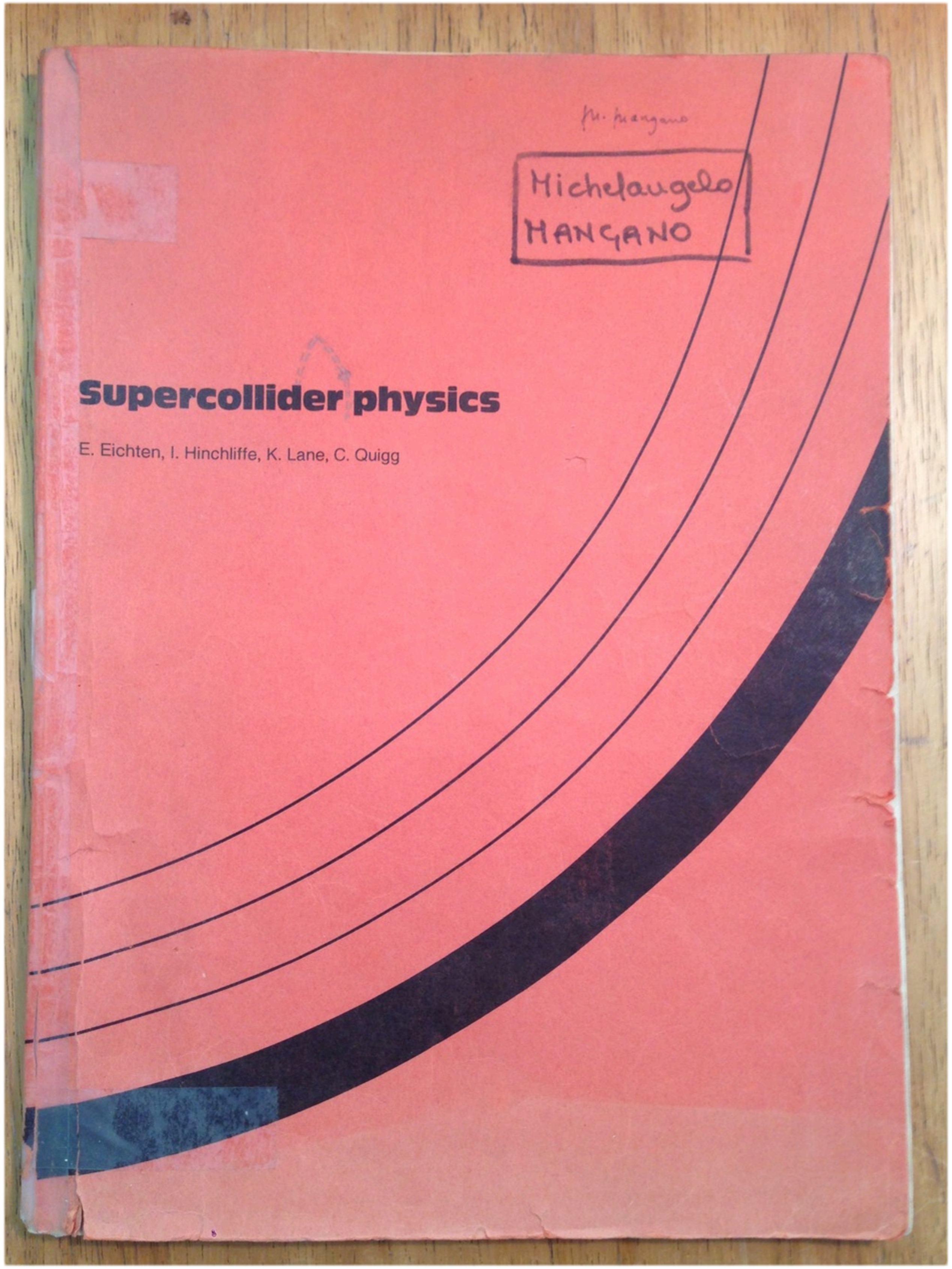
Supercollider physics

E. Eichten, I. Hinchliffe, K. Lane, C. Quigg



Reviews of Modern Physics, Vol. 56, No. 4, October 1984



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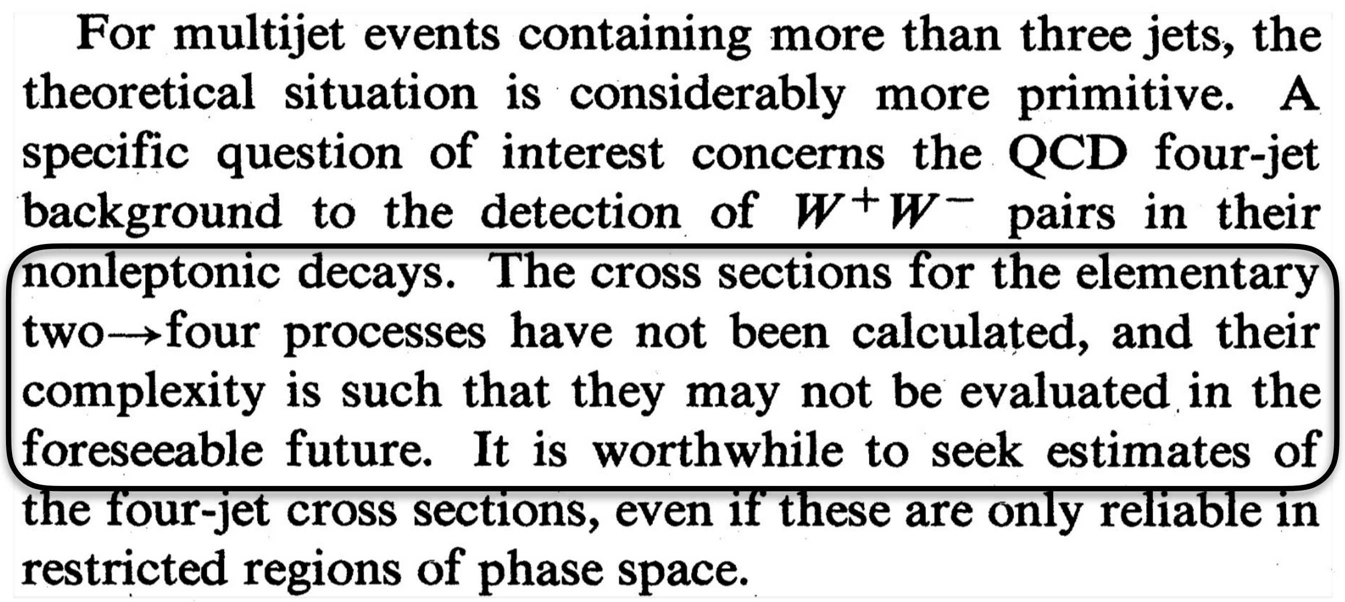


For multijet events containing more than three jets, the theoretical situation is considerably more primitive. A specific question of interest concerns the QCD four-jet background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Those calculations actually became available in the following 12 months (see Z.Kunszt opening talk on Wed), thanks to new ideas (e.g. SUSY relations), which surpassed the potential improvements due to the availability of more powerful computers.

But each technology eventually saturates, and further progress required even more radical conceptual ***quantum leaps*** *….*

MHV@30

- The MHV@30 Symposium being held this week celebrates the trigger of one such **quantum leaps**, namely the proposal, by Parke and Taylor, of an incredibly simple formula to express, exactly at tree-level, the subset of non-zero Maximally Helicity-Violating* contributions to the multi-gluon production cross section in hadronic collisions:

$$|\mathcal{M}_n^{PT}(g_1^- g_2^- \to g_3^+ g_4^+ \dots g_n^+)|^2 = |\mathcal{M}_n^{PT}(g_1^+ g_2^- \to g_3^+ g_4^+ \dots g_n^+)|^2 = 0$$

$$|\mathcal{M}_n^{PT}(g_1^+ g_2^+ \to g_3^+ g_4^+ \dots g_n^+)|^2 = c_n(g,N) \times \sum_{P(2,3,\dots,n)} \frac{(p_1 \cdot p_2)^4}{(p_1 \cdot p_2)(p_2 \cdot p_3) \cdots (p_n \cdot p_1)}$$

$$c_n(g,N) = g^{2n-4} N^{n-2} (N^2 - 1)$$

* $|\sum_{i \in final} (hel)_i - \sum_{i \in initial} (hel)_i| > 0$

Why are they PT amplitudes interesting?

- They admit extraordinarily simple analytic expressions ∀ n
- For n=4,5, all non-zero amps are MHV ⇒ complete result
- For n≥6, they can be used to approximate the non-MHV amps

Maxwell approximate amps^2

C.J. Maxwell, Phys. Lett. B192 (1987) 190

$$(p_a + p_b)^2 = \min_{i,j}(p_i + p_j)^2 \Rightarrow p_X = p_a + p_b$$

$$|\mathcal{M}_n|^2 = |\mathcal{M}_n^{PT}|^2 \times F(R,z)\frac{|\mathcal{M}_{n-1}|^2}{|\mathcal{M}_{n-1}^{PT}|^2}$$

e.g if a,b final state: $F(R,z) = \frac{(1+R)\left[z^4 + (1-z)^4 + 1\right]}{z^4 + (1-z)^4 + R}$ *1 < F(R,z) < 2*

$$R = \sum_{i,j\neq a,b}(p_i p_j)^4 / \sum_{i\neq a,b}(p_i p_X)^4$$

Iterate till n–1=5, where PT is exact.

OK to ~10% for gg→4, 5 jets

Why are the PT amplitudes interesting?

- They admit extraordinarily simple analytic expressions ∀ n
- For n=4,5, all non-zero amps are MHV ⇒ complete result
- For n≥6, they can be used to approximate the non-MHV amps

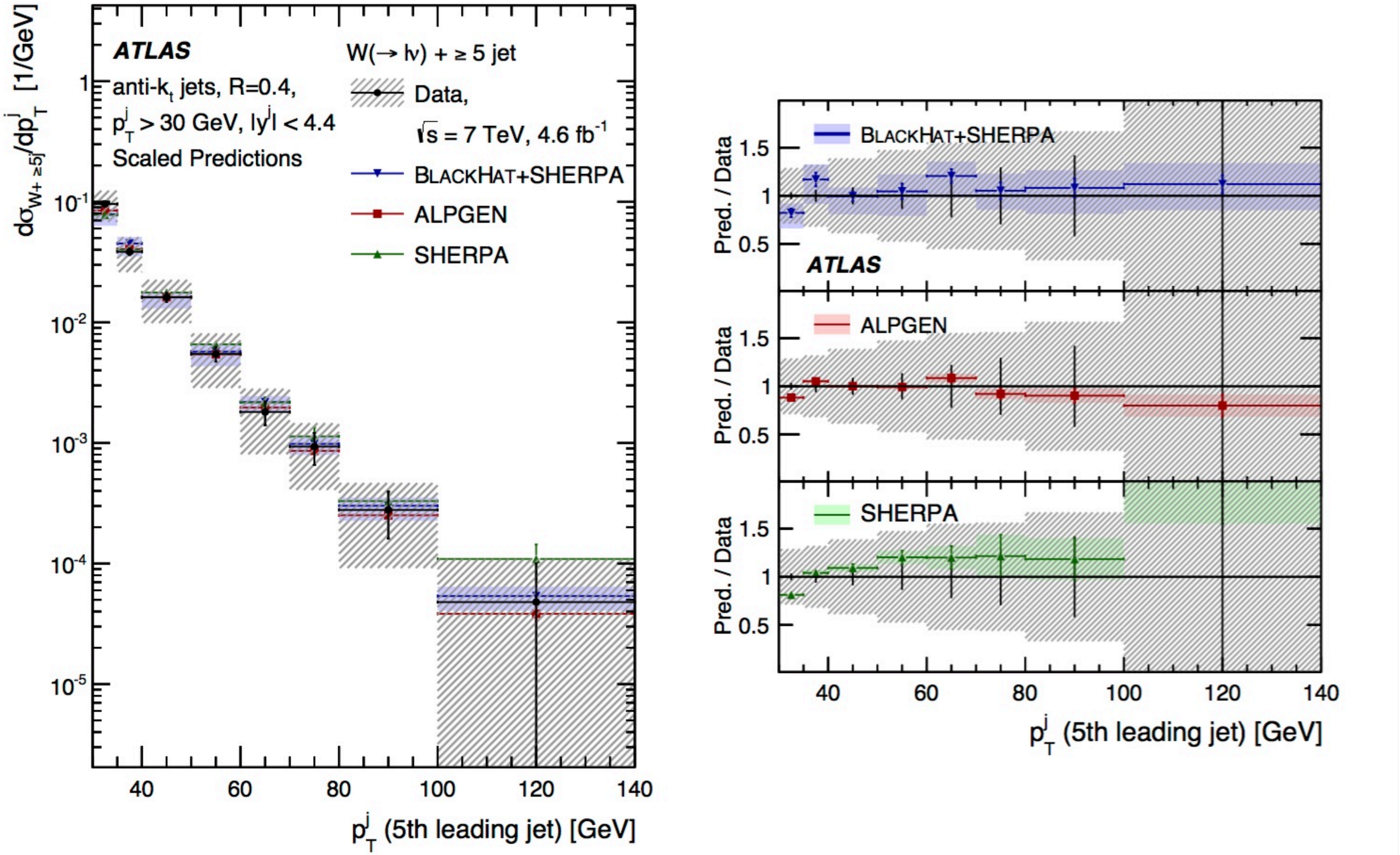
➡ they quickly became very useful for phenomenological applications in the study of multi-jet production at the Tevatron *(Vecbos, Njets — Berends, Giele, Kleiss, Kuijf)*

➡ the theoretical frameworks identified to reproduce them explicitly led soon to exact results for non-MHV, and within few years for the first results at the loop level *(Bern, Dixon, Kosower)*

➡ they triggered work to understand the deep origin of their simplicity, branching off into totally unexpected and still mysterious directions *(see Nima's Wed colloquim)*

- Directly or indirectly, the work done to understand and extend the structure of MHV amps led to the development of theoretical tools that, in the recent years, have allowed calculations of otherwise insurmountable complexity, opening the way to precision calculations for high-energy colliders:
    - NLO and NNLO results for important multiparton processes:

W+multijets at LHC



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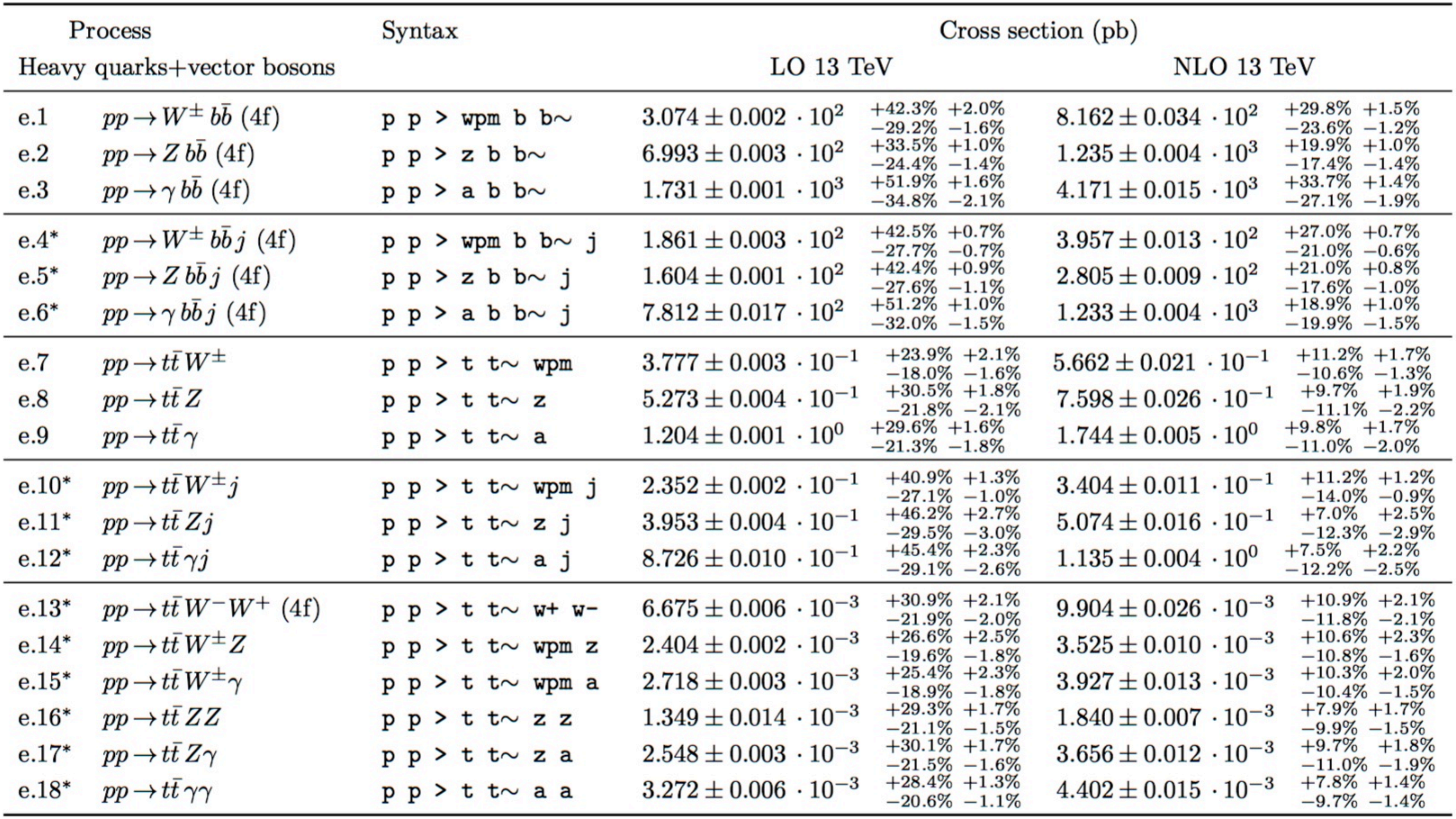
  - NLO and NNLO results for important multiparton processes
  - tools for the totally automatic evaluation of arbitrary NLO cross sections, and their merging with realistic parton-shower and hadronization codes …

Fully automatic NLO cross sections

MadGraph5_aMC@NLO, Alwall et al, arXiv:1405.0301

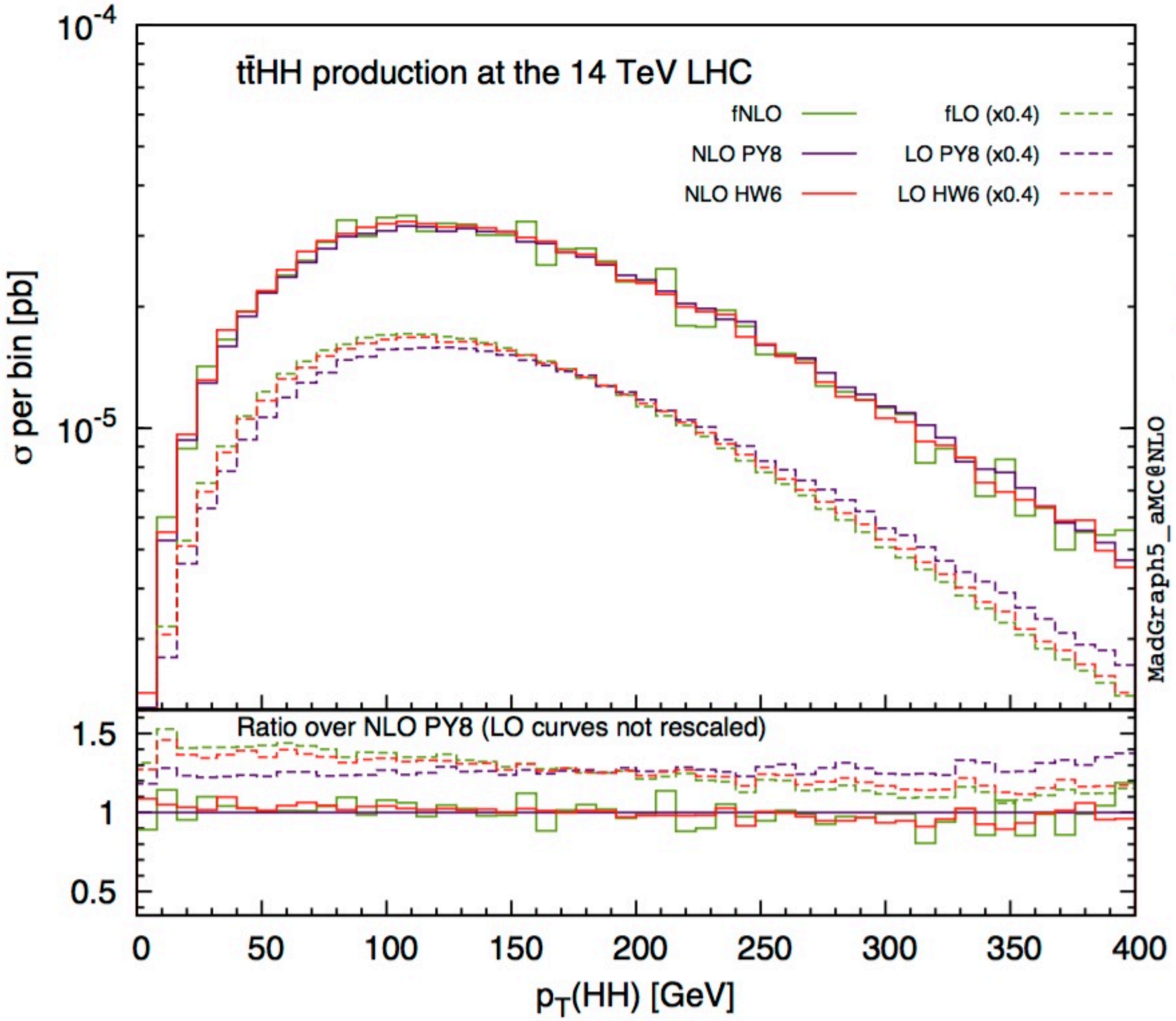
gone are the days when the calculation of a single process at 1-loop meant years of work ….

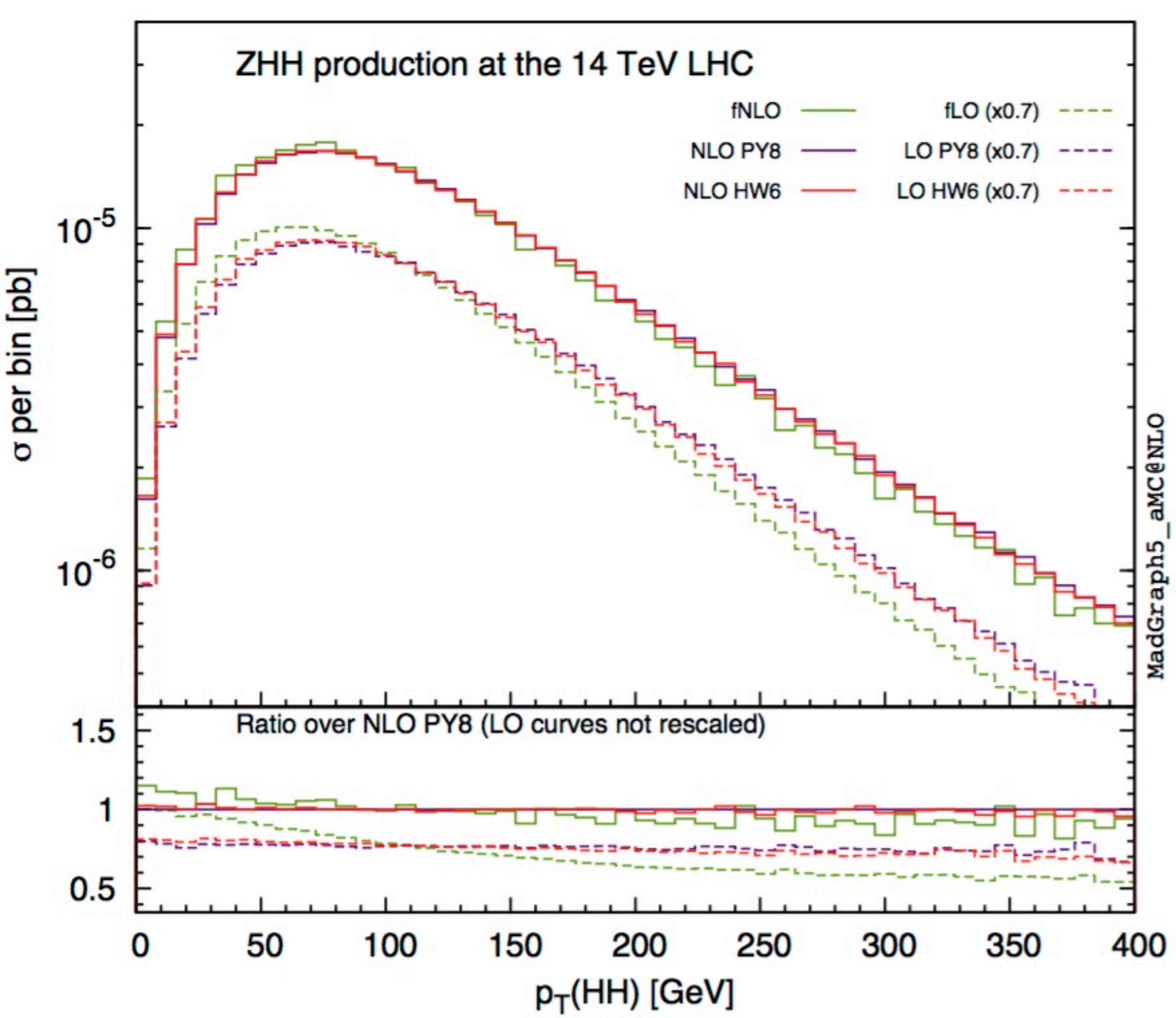


Process		Syntax	Cross section (pb)			
Heavy quarks+vector bosons			LO 13 TeV		NLO 13 TeV	
e.1	$pp \to W^\pm b\bar{b}$ (4f)	`p p > wpm b b~`	$3.074 \pm 0.002 \cdot 10^{2}$	${}^{+42.3\%}_{-29.2\%}$ ${}^{+2.0\%}_{-1.6\%}$	$8.162 \pm 0.034 \cdot 10^{2}$	${}^{+29.8\%}_{-23.6\%}$ ${}^{+1.5\%}_{-1.2\%}$
e.2	$pp \to Z b\bar{b}$ (4f)	`p p > z b b~`	$6.993 \pm 0.003 \cdot 10^{2}$	${}^{+33.5\%}_{-24.4\%}$ ${}^{+1.0\%}_{-1.4\%}$	$1.235 \pm 0.004 \cdot 10^{3}$	${}^{+19.9\%}_{-17.4\%}$ ${}^{+1.0\%}_{-1.4\%}$
e.3	$pp \to \gamma b\bar{b}$ (4f)	`p p > a b b~`	$1.731 \pm 0.001 \cdot 10^{3}$	${}^{+51.9\%}_{-34.8\%}$ ${}^{+1.6\%}_{-2.1\%}$	$4.171 \pm 0.015 \cdot 10^{3}$	${}^{+33.7\%}_{-27.1\%}$ ${}^{+1.4\%}_{-1.9\%}$
e.4*	$pp \to W^\pm b\bar{b}j$ (4f)	`p p > wpm b b~ j`	$1.861 \pm 0.003 \cdot 10^{2}$	${}^{+42.5\%}_{-27.7\%}$ ${}^{+0.7\%}_{-0.7\%}$	$3.957 \pm 0.013 \cdot 10^{2}$	${}^{+27.0\%}_{-21.0\%}$ ${}^{+0.7\%}_{-0.6\%}$
e.5*	$pp \to Z b\bar{b}j$ (4f)	`p p > z b b~ j`	$1.604 \pm 0.001 \cdot 10^{2}$	${}^{+42.4\%}_{-27.6\%}$ ${}^{+0.9\%}_{-1.1\%}$	$2.805 \pm 0.009 \cdot 10^{2}$	${}^{+21.0\%}_{-17.6\%}$ ${}^{+0.8\%}_{-1.0\%}$
e.6*	$pp \to \gamma b\bar{b}j$ (4f)	`p p > a b b~ j`	$7.812 \pm 0.017 \cdot 10^{2}$	${}^{+51.2\%}_{-32.0\%}$ ${}^{+1.0\%}_{-1.5\%}$	$1.233 \pm 0.004 \cdot 10^{3}$	${}^{+18.9\%}_{-19.9\%}$ ${}^{+1.0\%}_{-1.5\%}$
e.7	$pp \to t\bar{t}W^\pm$	`p p > t t~ wpm`	$3.777 \pm 0.003 \cdot 10^{-1}$	${}^{+23.9\%}_{-18.0\%}$ ${}^{+2.1\%}_{-1.6\%}$	$5.662 \pm 0.021 \cdot 10^{-1}$	${}^{+11.2\%}_{-10.6\%}$ ${}^{+1.7\%}_{-1.3\%}$
e.8	$pp \to t\bar{t}Z$	`p p > t t~ z`	$5.273 \pm 0.004 \cdot 10^{-1}$	${}^{+30.5\%}_{-21.8\%}$ ${}^{+1.8\%}_{-2.1\%}$	$7.598 \pm 0.026 \cdot 10^{-1}$	${}^{+9.7\%}_{-11.1\%}$ ${}^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t}\gamma$	`p p > t t~ a`	$1.204 \pm 0.001 \cdot 10^{0}$	${}^{+29.6\%}_{-21.3\%}$ ${}^{+1.6\%}_{-1.8\%}$	$1.744 \pm 0.005 \cdot 10^{0}$	${}^{+9.8\%}_{-11.0\%}$ ${}^{+1.7\%}_{-2.0\%}$
e.10*	$pp \to t\bar{t}W^\pm j$	`p p > t t~ wpm j`	$2.352 \pm 0.002 \cdot 10^{-1}$	${}^{+40.9\%}_{-27.1\%}$ ${}^{+1.3\%}_{-1.0\%}$	$3.404 \pm 0.011 \cdot 10^{-1}$	${}^{+11.2\%}_{-14.0\%}$ ${}^{+1.2\%}_{-0.9\%}$
e.11*	$pp \to t\bar{t}Zj$	`p p > t t~ z j`	$3.953 \pm 0.004 \cdot 10^{-1}$	${}^{+46.2\%}_{-29.5\%}$ ${}^{+2.7\%}_{-3.0\%}$	$5.074 \pm 0.016 \cdot 10^{-1}$	${}^{+7.0\%}_{-12.3\%}$ ${}^{+2.5\%}_{-2.9\%}$
e.12*	$pp \to t\bar{t}\gamma j$	`p p > t t~ a j`	$8.726 \pm 0.010 \cdot 10^{-1}$	${}^{+45.4\%}_{-29.1\%}$ ${}^{+2.3\%}_{-2.6\%}$	$1.135 \pm 0.004 \cdot 10^{0}$	${}^{+7.5\%}_{-12.2\%}$ ${}^{+2.2\%}_{-2.5\%}$
e.13*	$pp \to t\bar{t}W^-W^+$ (4f)	`p p > t t~ w+ w-`	$6.675 \pm 0.006 \cdot 10^{-3}$	${}^{+30.9\%}_{-21.9\%}$ ${}^{+2.1\%}_{-2.0\%}$	$9.904 \pm 0.026 \cdot 10^{-3}$	${}^{+10.9\%}_{-11.8\%}$ ${}^{+2.1\%}_{-2.1\%}$
e.14*	$pp \to t\bar{t}W^\pm Z$	`p p > t t~ wpm z`	$2.404 \pm 0.002 \cdot 10^{-3}$	${}^{+26.6\%}_{-19.6\%}$ ${}^{+2.5\%}_{-1.8\%}$	$3.525 \pm 0.010 \cdot 10^{-3}$	${}^{+10.6\%}_{-10.8\%}$ ${}^{+2.3\%}_{-1.6\%}$
e.15*	$pp \to t\bar{t}W^\pm\gamma$	`p p > t t~ wpm a`	$2.718 \pm 0.003 \cdot 10^{-3}$	${}^{+25.4\%}_{-18.9\%}$ ${}^{+2.3\%}_{-1.8\%}$	$3.927 \pm 0.013 \cdot 10^{-3}$	${}^{+10.3\%}_{-10.4\%}$ ${}^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t}ZZ$	`p p > t t~ z z`	$1.349 \pm 0.014 \cdot 10^{-3}$	${}^{+29.3\%}_{-21.1\%}$ ${}^{+1.7\%}_{-1.5\%}$	$1.840 \pm 0.007 \cdot 10^{-3}$	${}^{+7.9\%}_{-9.9\%}$ ${}^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t}Z\gamma$	`p p > t t~ z a`	$2.548 \pm 0.003 \cdot 10^{-3}$	${}^{+30.1\%}_{-21.5\%}$ ${}^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3}$	${}^{+9.7\%}_{-11.0\%}$ ${}^{+1.8\%}_{-1.9\%}$
e.18*	$pp \to t\bar{t}\gamma\gamma$	`p p > t t~ a a`	$3.272 \pm 0.006 \cdot 10^{-3}$	${}^{+28.4\%}_{-20.6\%}$ ${}^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	${}^{+7.8\%}_{-9.7\%}$ ${}^{+1.4\%}_{-1.4\%}$

*** ⇒ new result**

**automatic merging with a shower MC, hadronization …
ready for use by the experiments !!**





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    - NLO and NNLO results for important multiparton processes
    - tools for the totally automatic evaluation of arbitrary NLO cross sections, and their merging with realistic parton-shower and hadronization codes
- This work also opened a new branch of theoretical physics, which has brought together phenomenologists and (string-) field theorists in a community counting now hundred(s?) of experts

Go to day

Wednesday, March 16, 2016

09:00 - 10:30 Session 1

09:00 **From discovery of the gluon jet to the NNLO precision for multi-jet production** *40'*
Speaker: Zoltan Kunszt
Material: **Slides**

09:45 **From Maximal Helicity to Maximal Jets** *40'*
Speaker: David Kosower
Material: **Slides**

10:30 - 11:00 Coffee

11:00 - 12:30 Session 2

11:00 **Twistors and Amplitudes** *40'*
Speaker: Andrew Hodges
Material: **Slides**

11:45 **MHV Amplitudes from 0 to 5 loops** *40'*
Speaker: Lance Dixon
Material: **Slides**

12:30 - 14:00 Lunch

14:00 - 15:30 Session 3

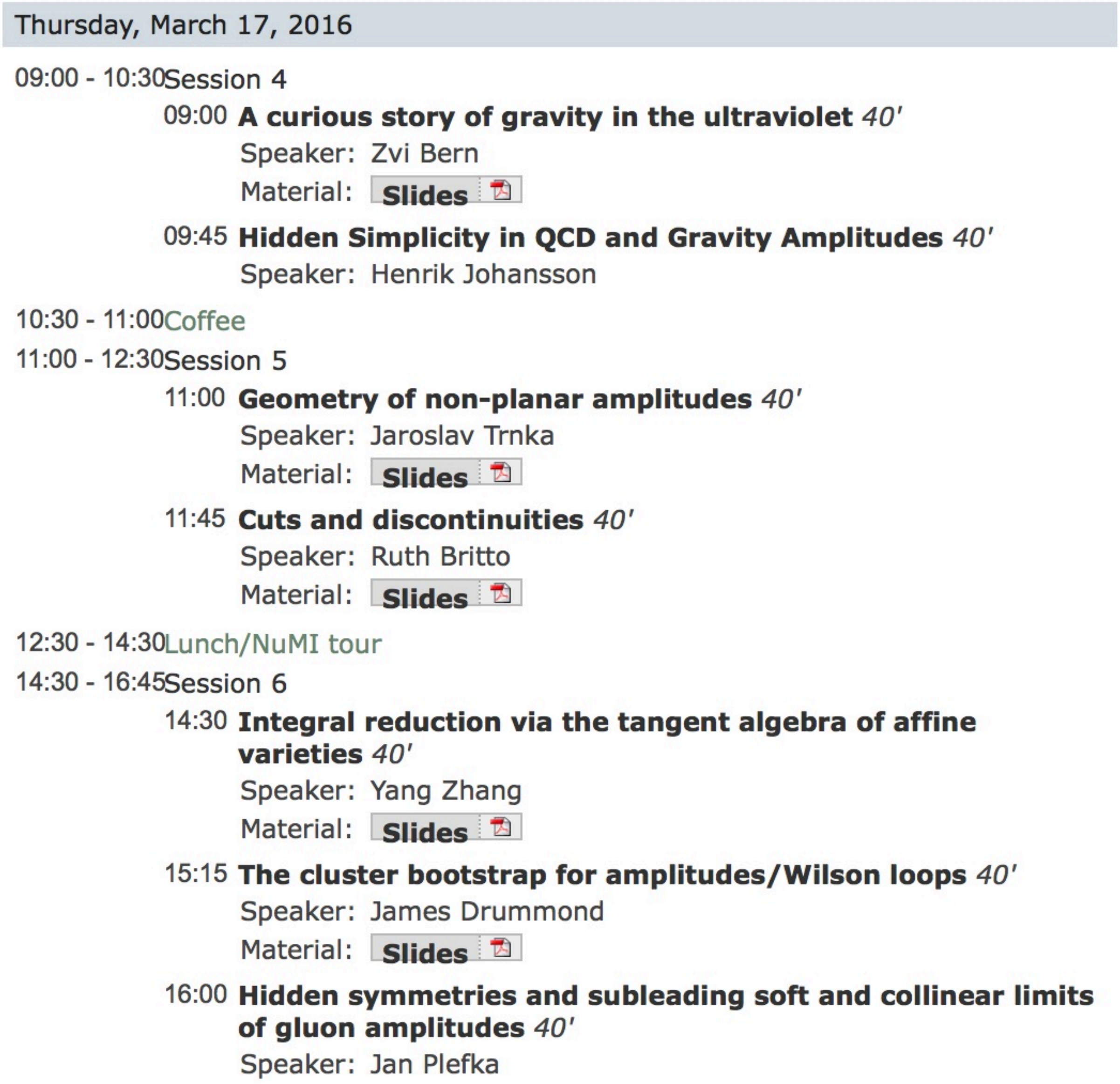
14:00 **Analytic result for a two-loop five-particle amplitude in QCD** *40'*
Speaker: Johannes Henn
Material: **Link to paper**

14:45 **Scattering Forms as Binary Code** *40'*
Speaker: Nima Arkani-Hamed

15:30 - 16:00 Coffee

16:00 - 17:00 Colloquium

16:00 **From the Parke-Taylor Amplitude to Deeper Origins for Space-time and Quantum Mechanics** *1h0'*
Speaker: Nima Arkani-Hamed



Thursday, March 17, 2016

09:00 - 10:30 Session 4

09:00 **A curious story of gravity in the ultraviolet** *40'*
Speaker: Zvi Bern
Material: **Slides**

09:45 **Hidden Simplicity in QCD and Gravity Amplitudes** *40'*
Speaker: Henrik Johansson

10:30 - 11:00 Coffee

11:00 - 12:30 Session 5

11:00 **Geometry of non-planar amplitudes** *40'*
Speaker: Jaroslav Trnka
Material: **Slides**

11:45 **Cuts and discontinuities** *40'*
Speaker: Ruth Britto
Material: **Slides**

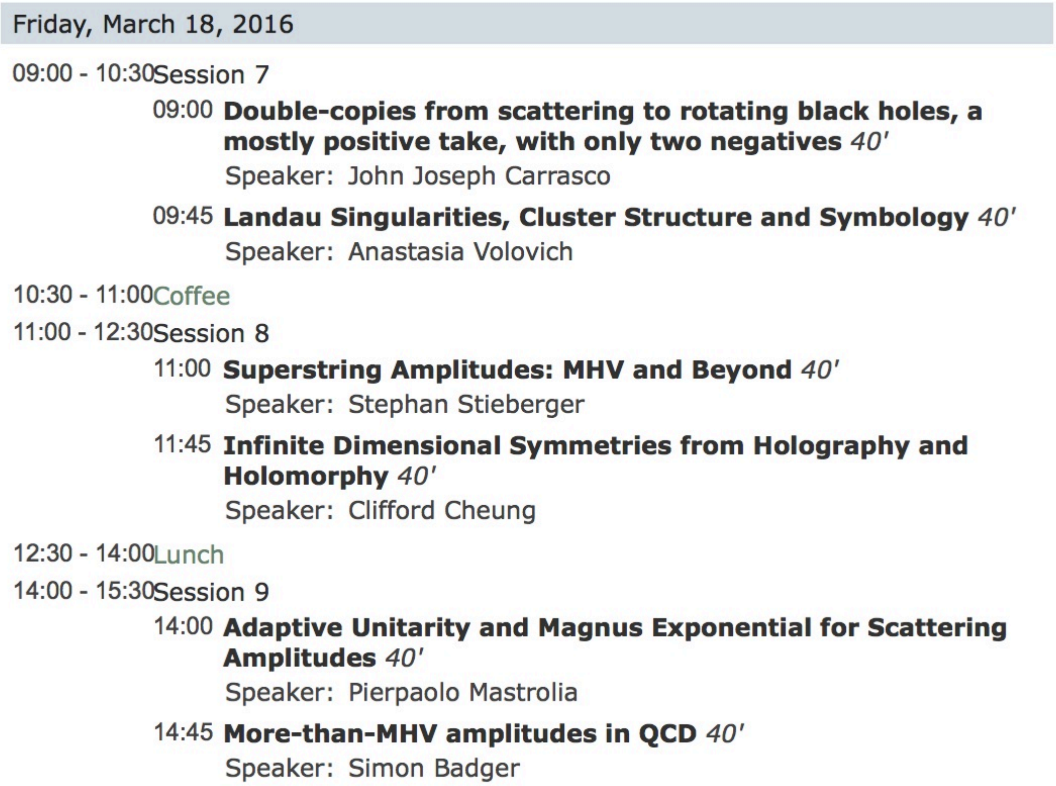
12:30 - 14:30 Lunch/NuMI tour

14:30 - 16:45 Session 6

14:30 **Integral reduction via the tangent algebra of affine varieties** *40'*
Speaker: Yang Zhang
Material: **Slides**

15:15 **The cluster bootstrap for amplitudes/Wilson loops** *40'*
Speaker: James Drummond
Material: **Slides**

16:00 **Hidden symmetries and subleading soft and collinear limits of gluon amplitudes** *40'*
Speaker: Jan Plefka



Friday, March 18, 2016

09:00 - 10:30 Session 7

09:00 **Double-copies from scattering to rotating black holes, a mostly positive take, with only two negatives** *40'*
Speaker: John Joseph Carrasco

09:45 **Landau Singularities, Cluster Structure and Symbology** *40'*
Speaker: Anastasia Volovich

10:30 - 11:00 Coffee

11:00 - 12:30 Session 8

11:00 **Superstring Amplitudes: MHV and Beyond** *40'*
Speaker: Stephan Stieberger

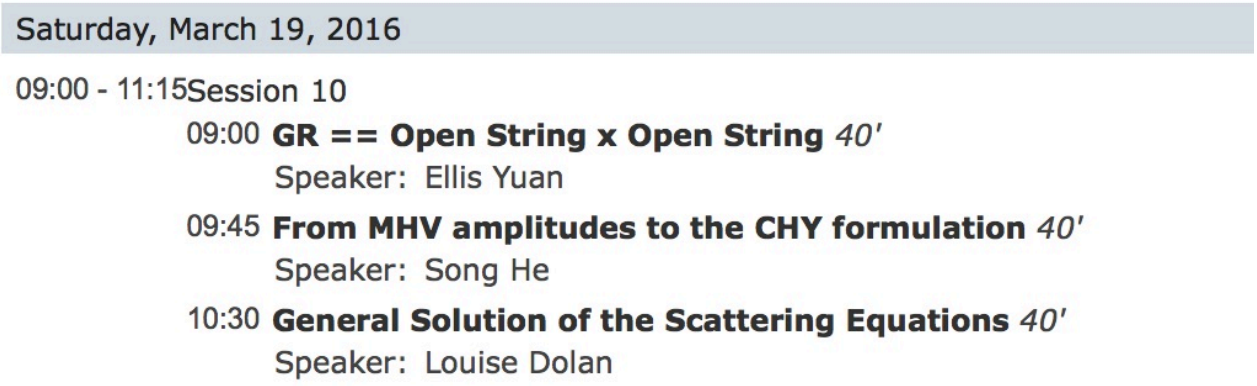
11:45 **Infinite Dimensional Symmetries from Holography and Holomorphy** *40'*
Speaker: Clifford Cheung

12:30 - 14:00 Lunch

14:00 - 15:30 Session 9

14:00 **Adaptive Unitarity and Magnus Exponential for Scattering Amplitudes** *40'*
Speaker: Pierpaolo Mastrolia

14:45 **More-than-MHV amplitudes in QCD** *40'*
Speaker: Simon Badger



Saturday, March 19, 2016

09:00 - 11:15 Session 10

09:00 **GR == Open String x Open String** *40'*
Speaker: Ellis Yuan

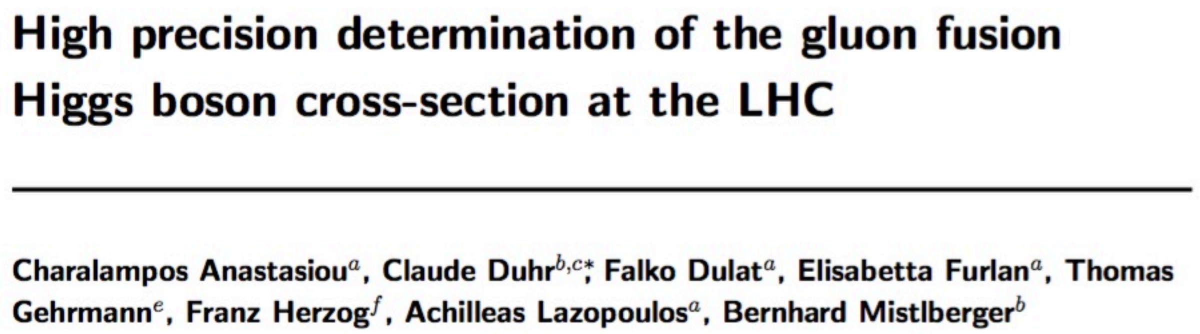
09:45 **From MHV amplitudes to the CHY formulation** *40'*
Speaker: Song He

10:30 **General Solution of the Scattering Equations** *40'*
Speaker: Louise Dolan

This talk is an overview of the status and prospects of the exploitation of these precision calculations at the LHC and beyond

Why we need multi-loop calculations to achieve precision?

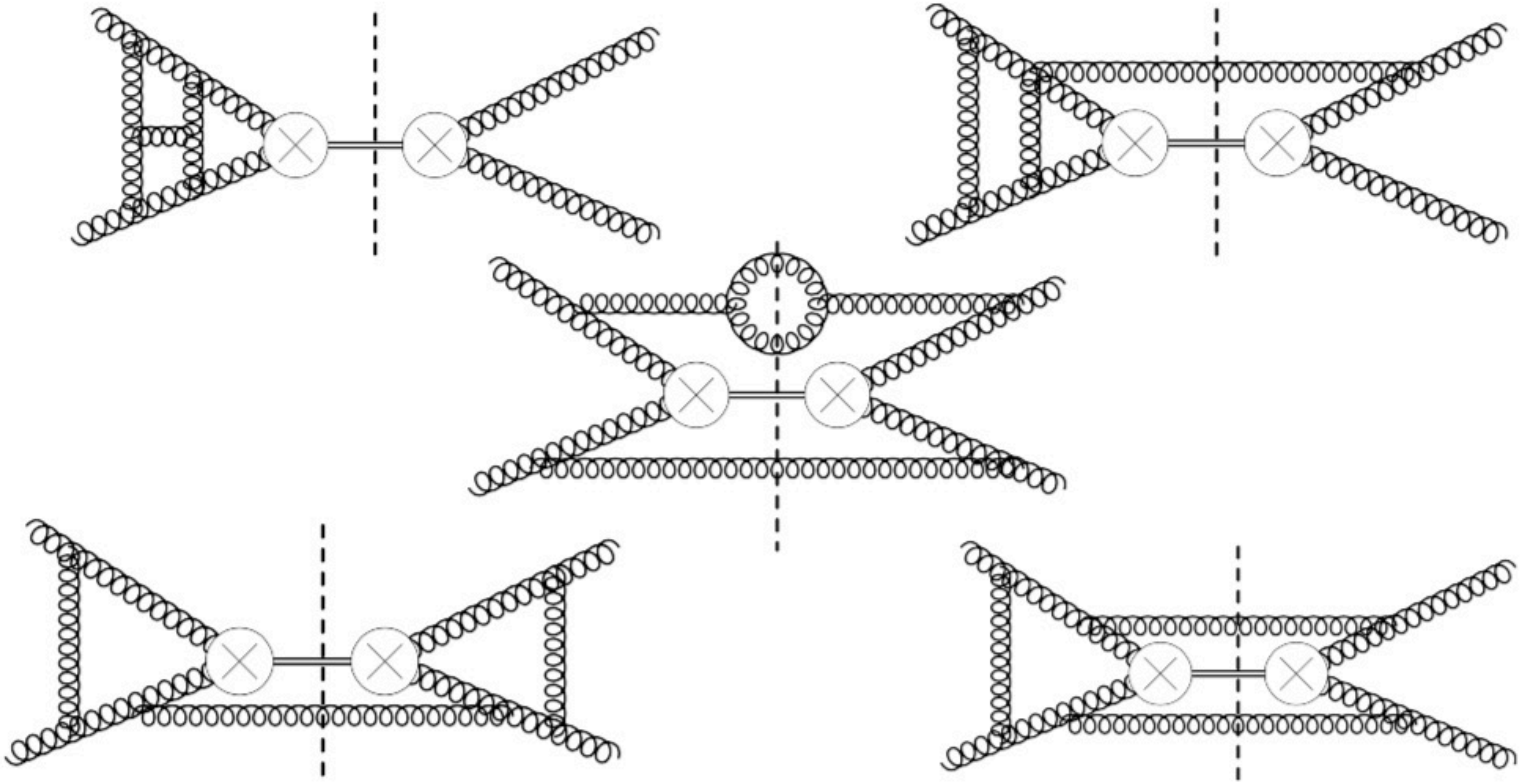
Example: pp→Higgs, via gg fusion

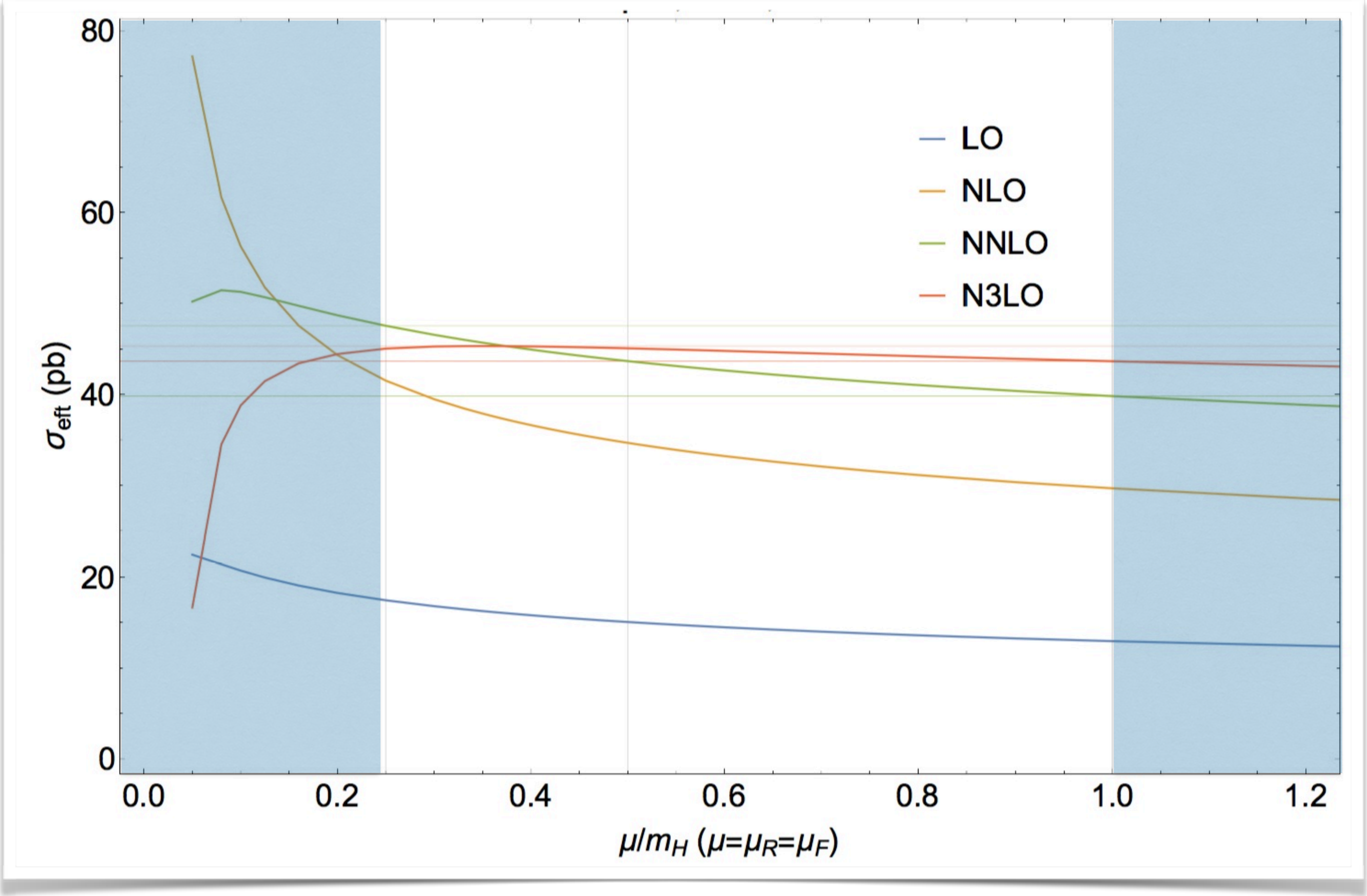


High precision determination of the gluon fusion Higgs boson cross-section at the LHC

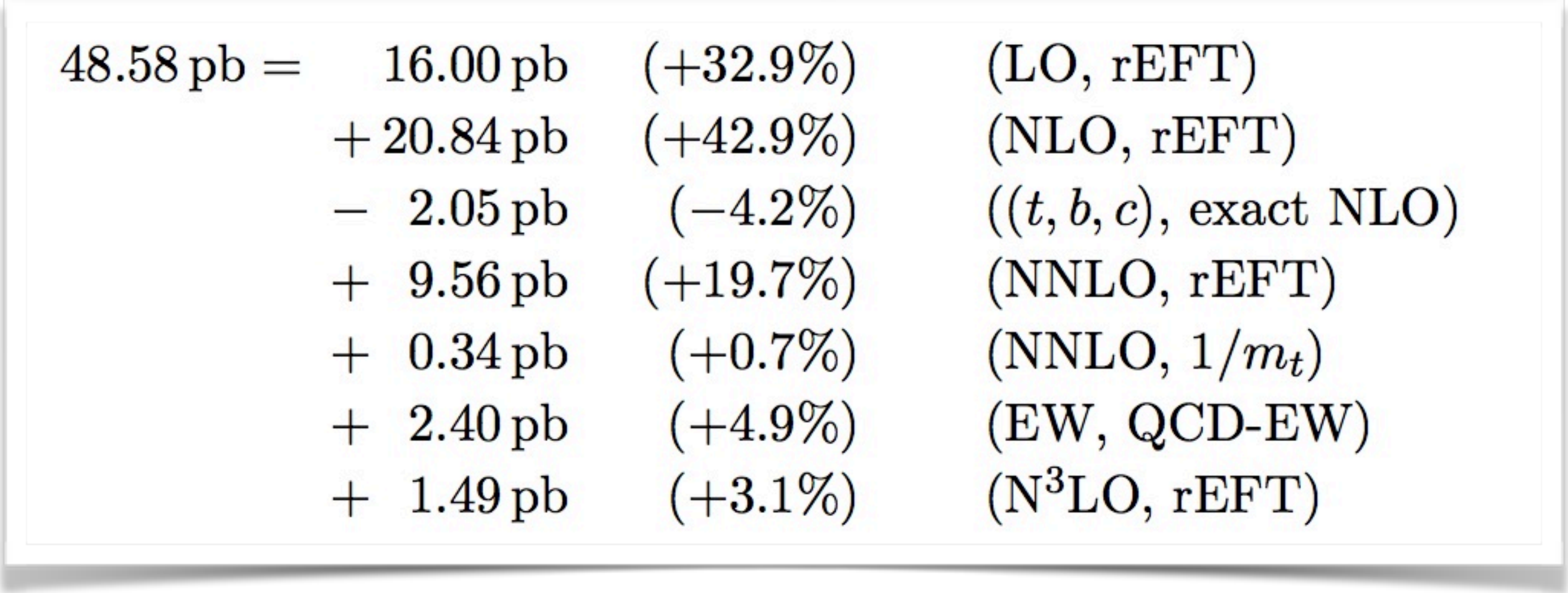
Charalampos Anastasiou[a], Claude Duhr[b,c]*, Falko Dulat[a], Elisabetta Furlan[a], Thomas Gehrmann[e], Franz Herzog[f], Achilleas Lazopoulos[a], Bernhard Mistlberger[b]

arXiv:1602.00695





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



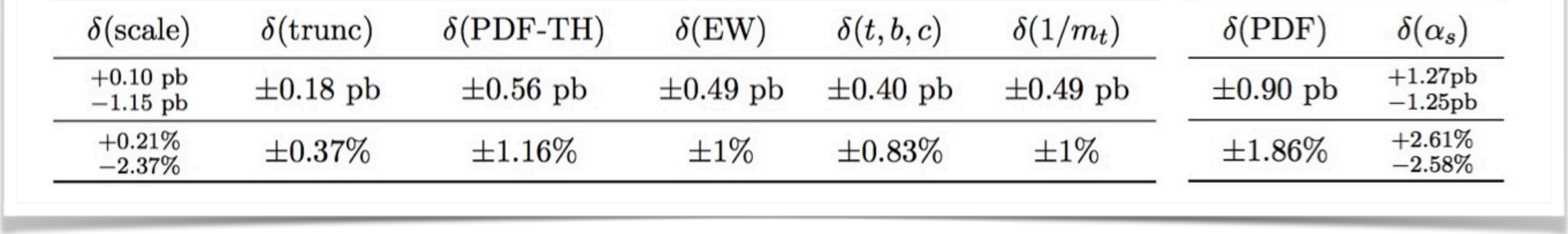
$$
\begin{aligned}
48.58\,\text{pb} = {} & \,16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
& +20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
& -2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c),\ \text{exact NLO}) \\
& +9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
& +0.34\,\text{pb}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

Lack of NNNLO in PDF evolution

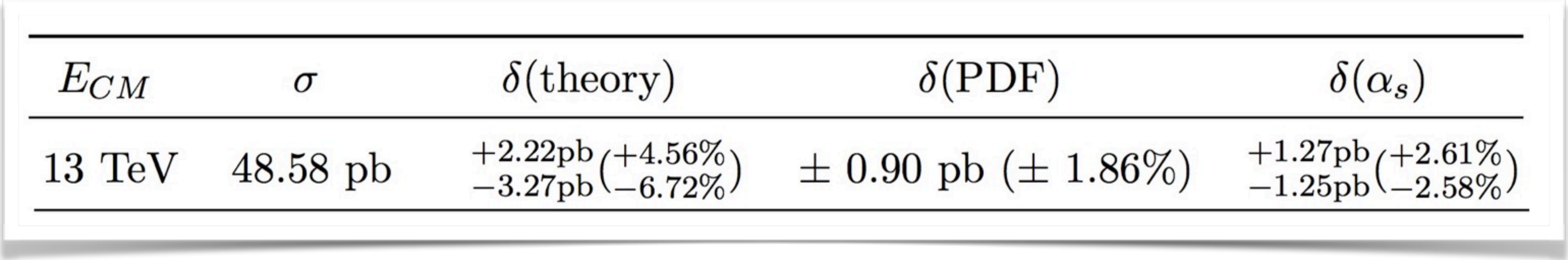
Higher-order EW and mt corrections

PDF fits syst's

αs Ssyst's



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



E_{CM}	σ	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
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%)	$^{+1.27\text{pb}}_{-1.25\text{pb}}\left(^{+2.61\%}_{-2.58\%}\right)$

The roles of theory in precision physics at HE hadron colliders

- Allow improving
  - the knowledge of the fundamental parameters of the SM (α_S, $\sin^2\theta_W$, m_{top}, $m_{W,Z,H}$, CKM)
  - the knowledge of the proton structure (PDFs)
  - the understanding, and ability to model, the SM dynamics

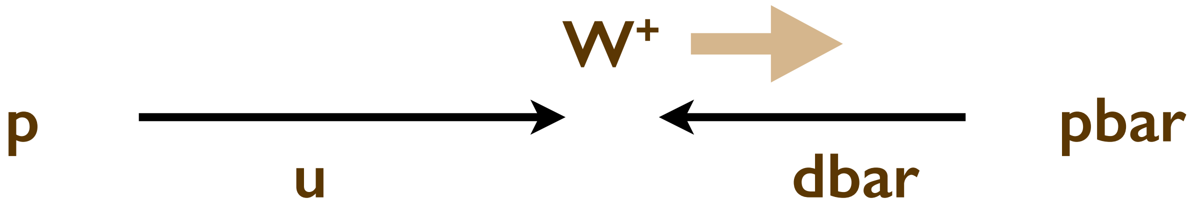
All of the above is the necessary premise to the second role of precise theoretical predictions:

- *Support* and *enhance* the search (and discovery!) of new physics
  - … and the determination of its properties, when found!

Some examples of recent progress

(focused on measurements relying on dynamics
— production rates and distributions —
neglecting topics like m_{top}, m_W, CKM, etc)

Lepton charge asymmetry in W decays

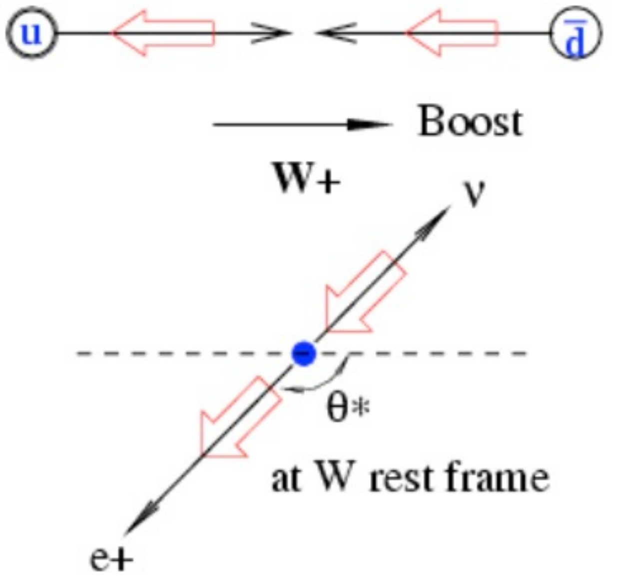

W^+

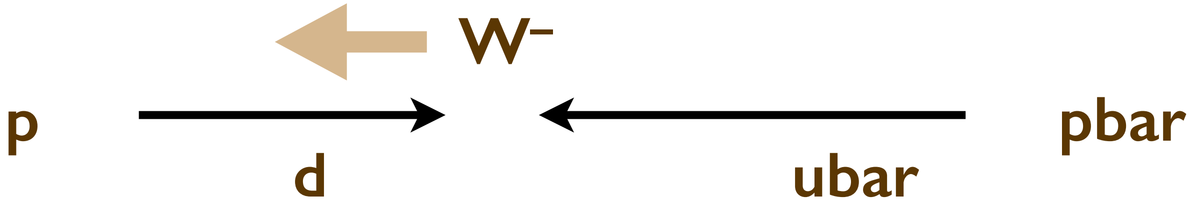
p

u

dbar

pbar



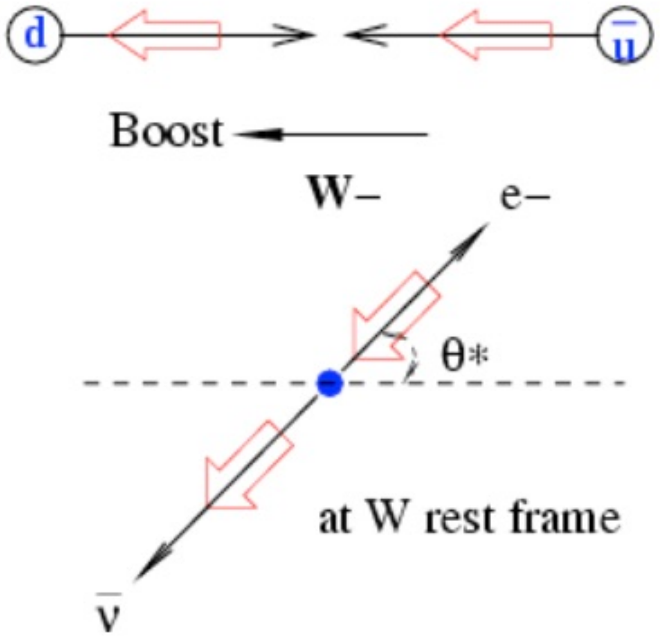

W^-

p

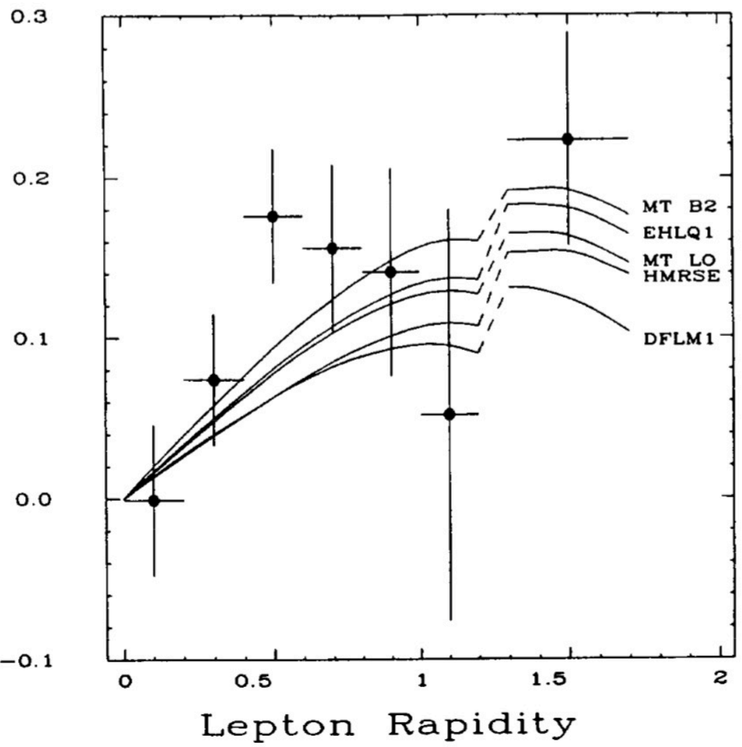
d

ubar

pbar



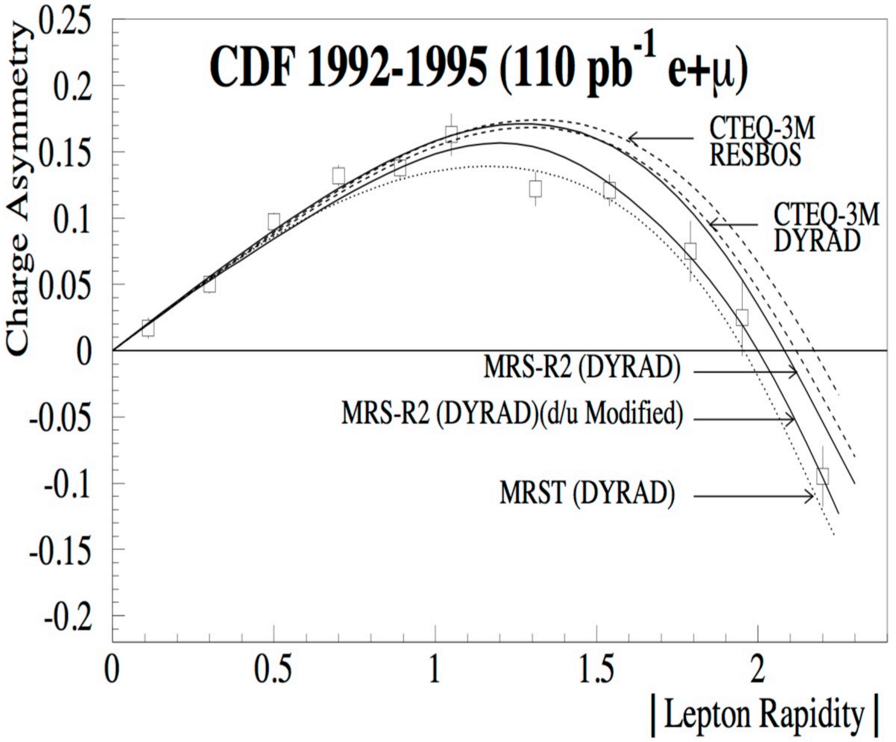
Lepton charge asymmetry in W decays



CDF (1992)

TH: **LO** QCD

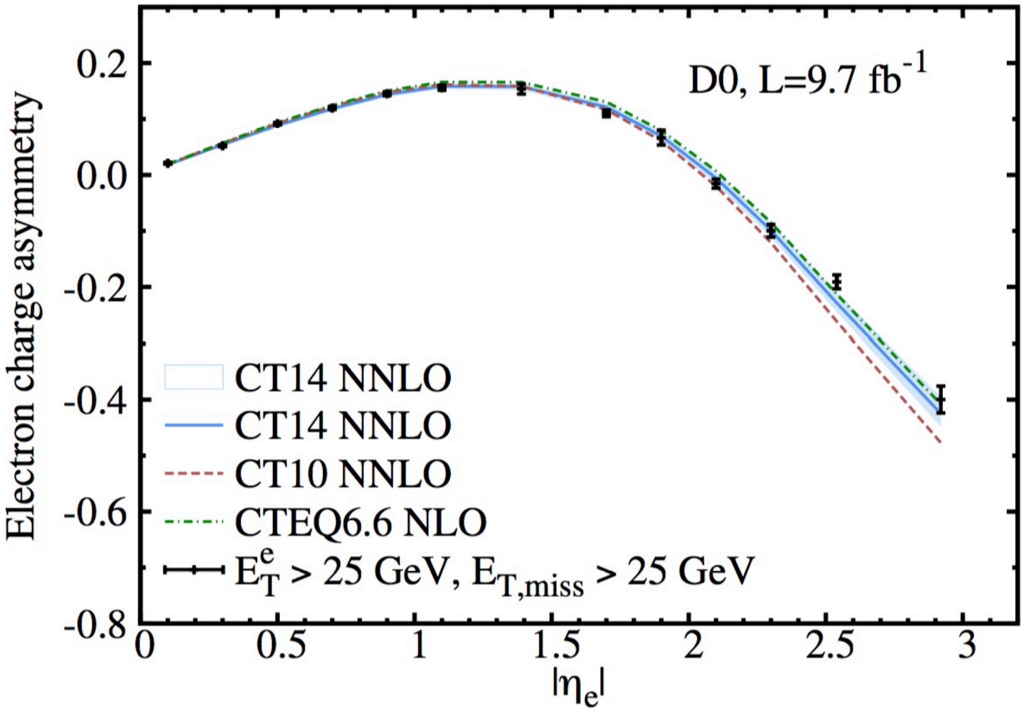
" …. Recently, a more complete NLO calculation has been made with cuts designed to simulate our experimental cuts …"



CDF (1998)

TH: **NLO** QCD

DYRAD, Giele, Glover, Kosower, Nucl. Phys. B403, 633 (1993)



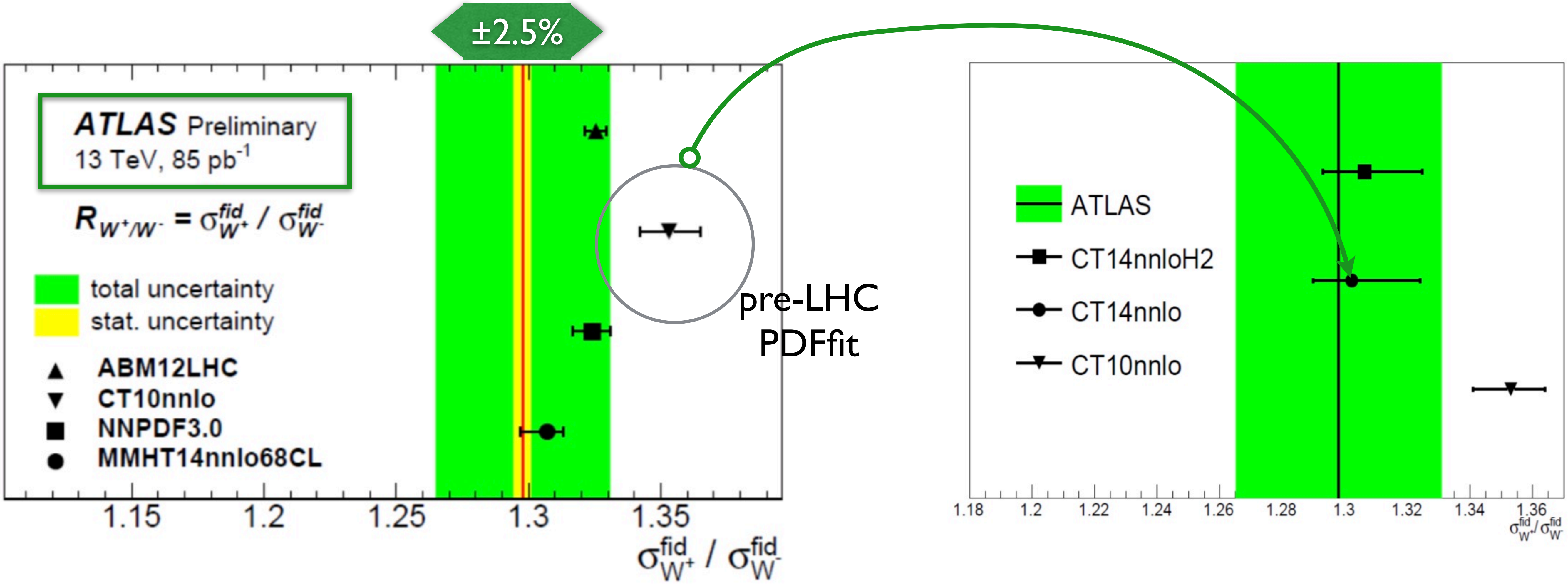
D0 (2015)

TH: **NNLO** QCD, differential distributions (Anastasiou, Dixon, Melnikov, Petriello, 2003)

NNLO QCD + NLO EW, event generator FEWZ, Li, Petriello, arXiv:1208.5967

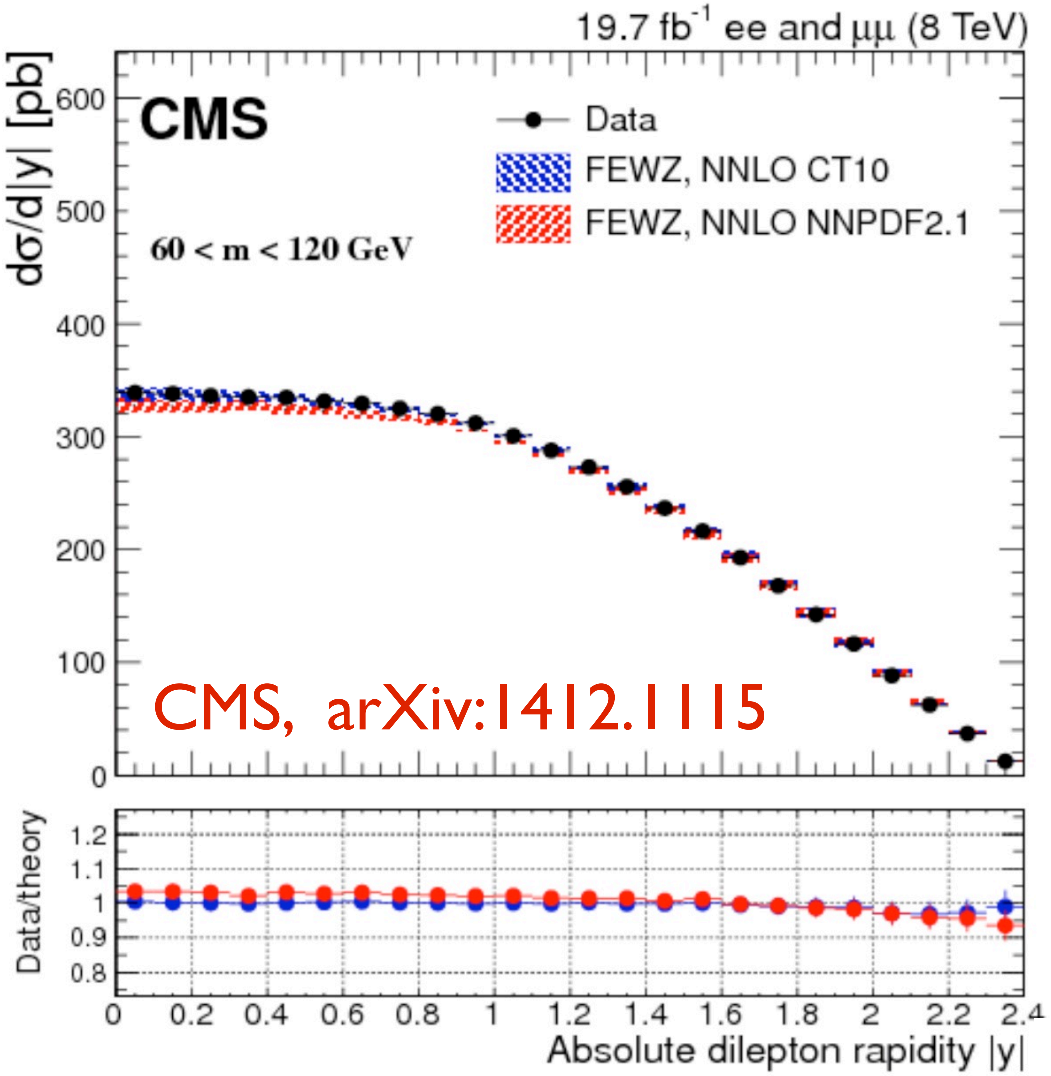
CTEQ-TEA arXiv: 1506.07443

inclusion of LHC run 1 and
Tevatron run 2 W asym data



±2.5%

pre-LHC
PDFfit



CMS, arXiv:1412.1115

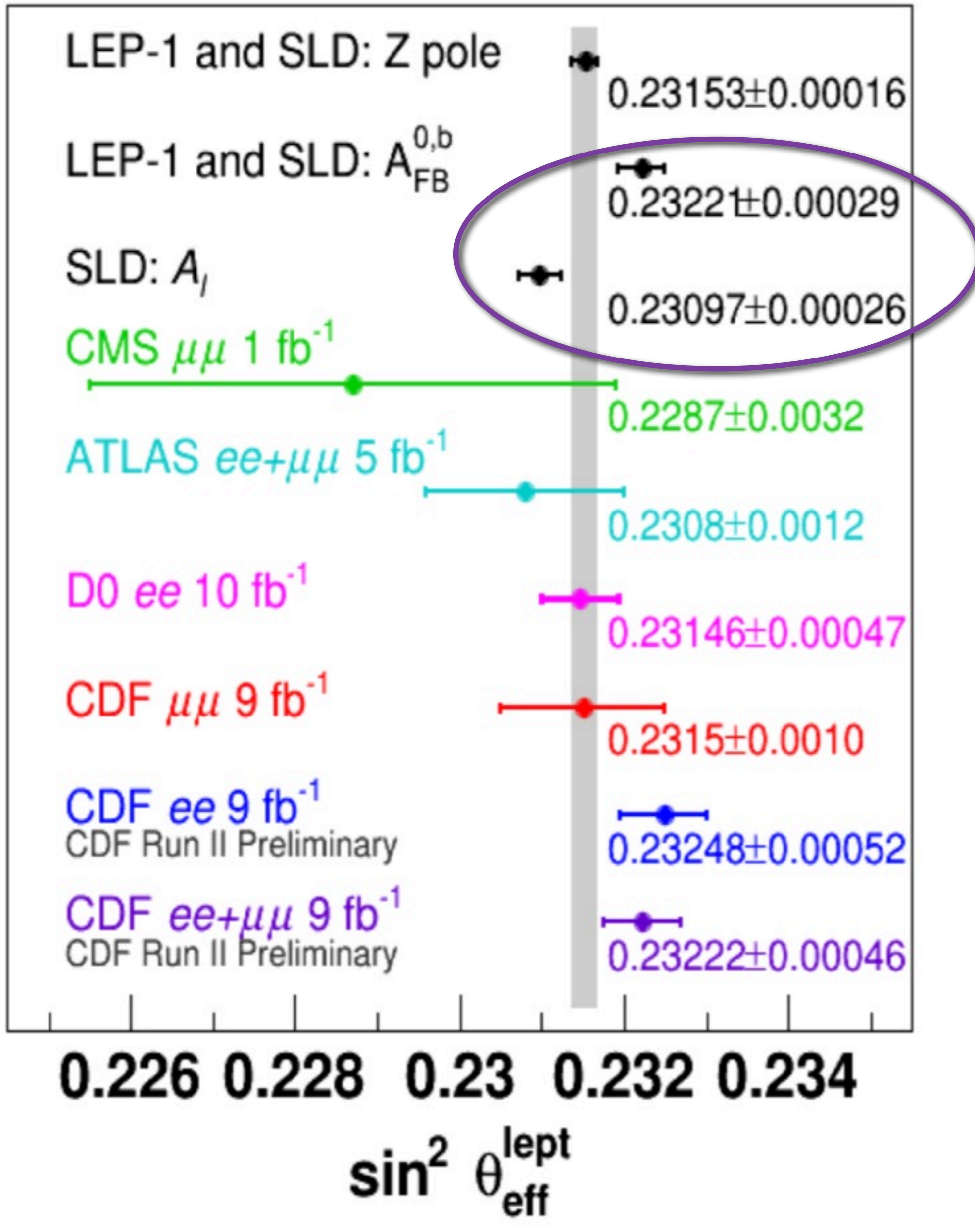
⇒ opens prospects for a precise

measurement of sinθ_W from FB lepton asymmetry in Z^0 decays at large y

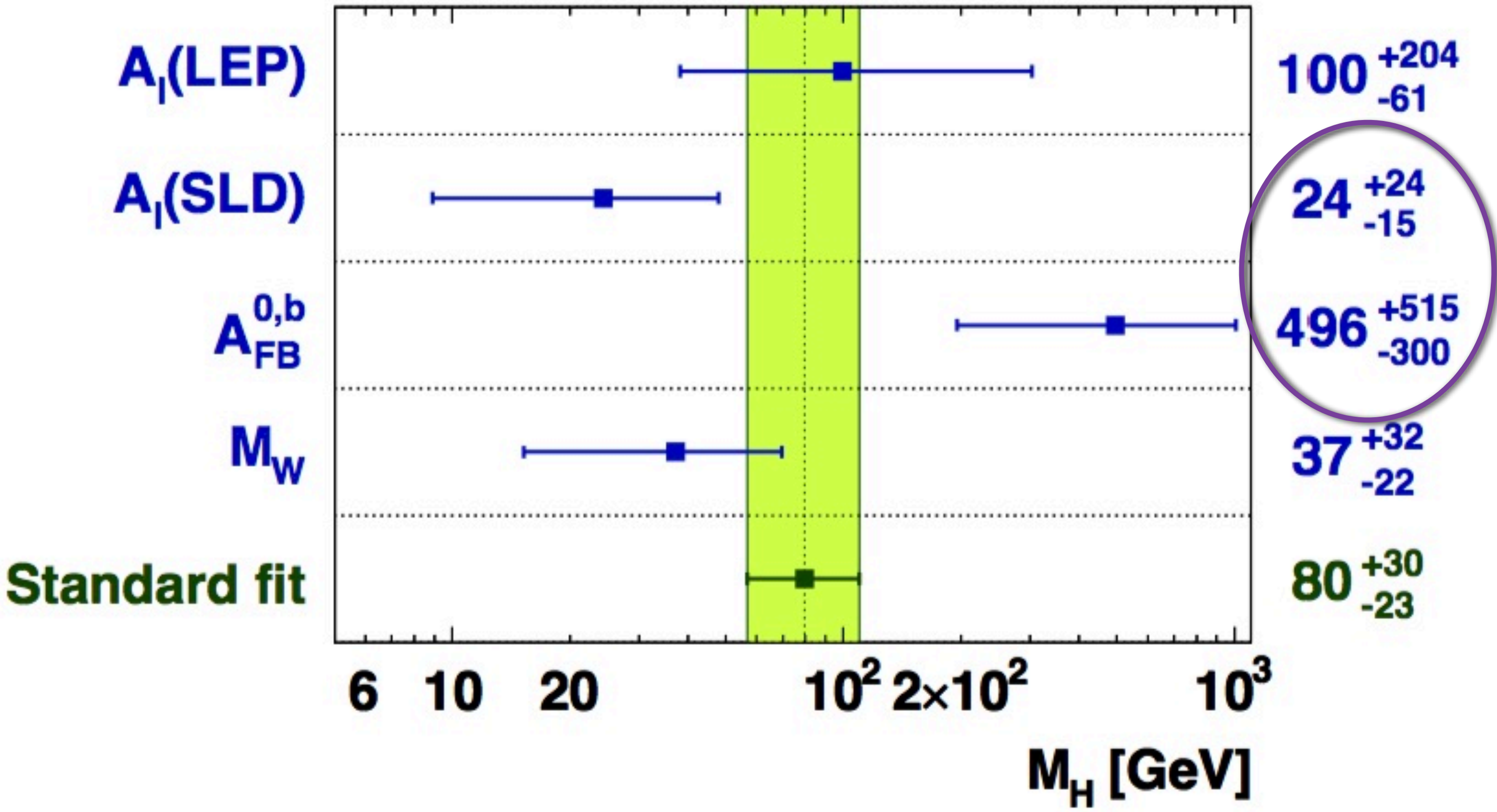
CMS like detector Energy data sample	20 fb^{-1} 8 TeV current	≈ 200 fb^{-1} 13-14 TeV future
Number of reconstructed events	8.2M $\mu^+\mu^-$ 6.8M e^+e^-	≈ 120M $\mu^+\mu^-$
$\Delta\sin^2\theta_W$ CT10 PDF error	± 0.00090	± 0.00090
$\Delta\sin^2\theta_W$ NNPDF3.0 NNLO error	± 0.00050	± 0.00050
$\Delta\sin^2\theta_W$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

Bodek, Han, Khukhunaishvili, Sakumoto, arXiv:1507.02470

LHC projection:
±0.00018

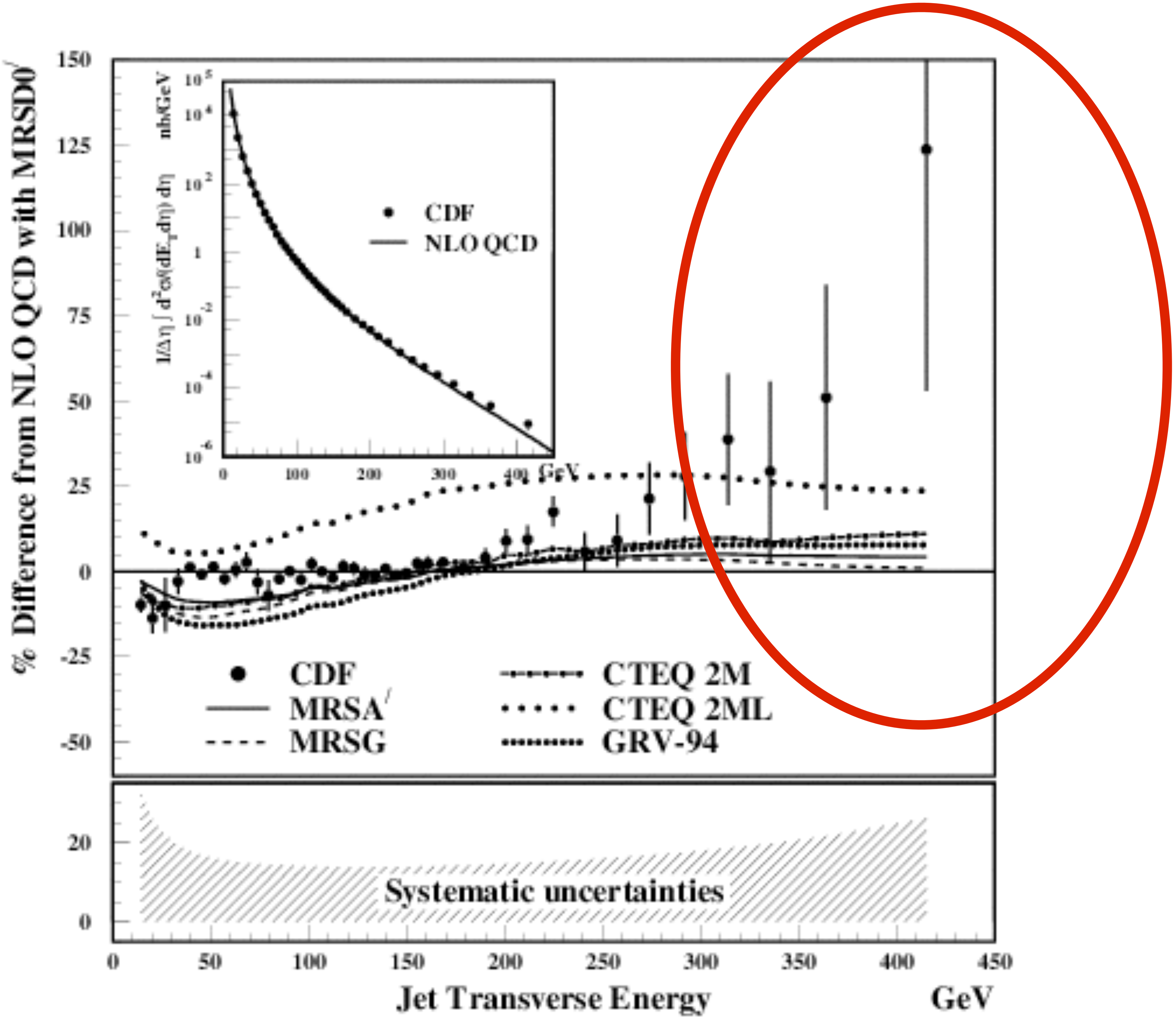


Gfitter, arXiv:0811.0009

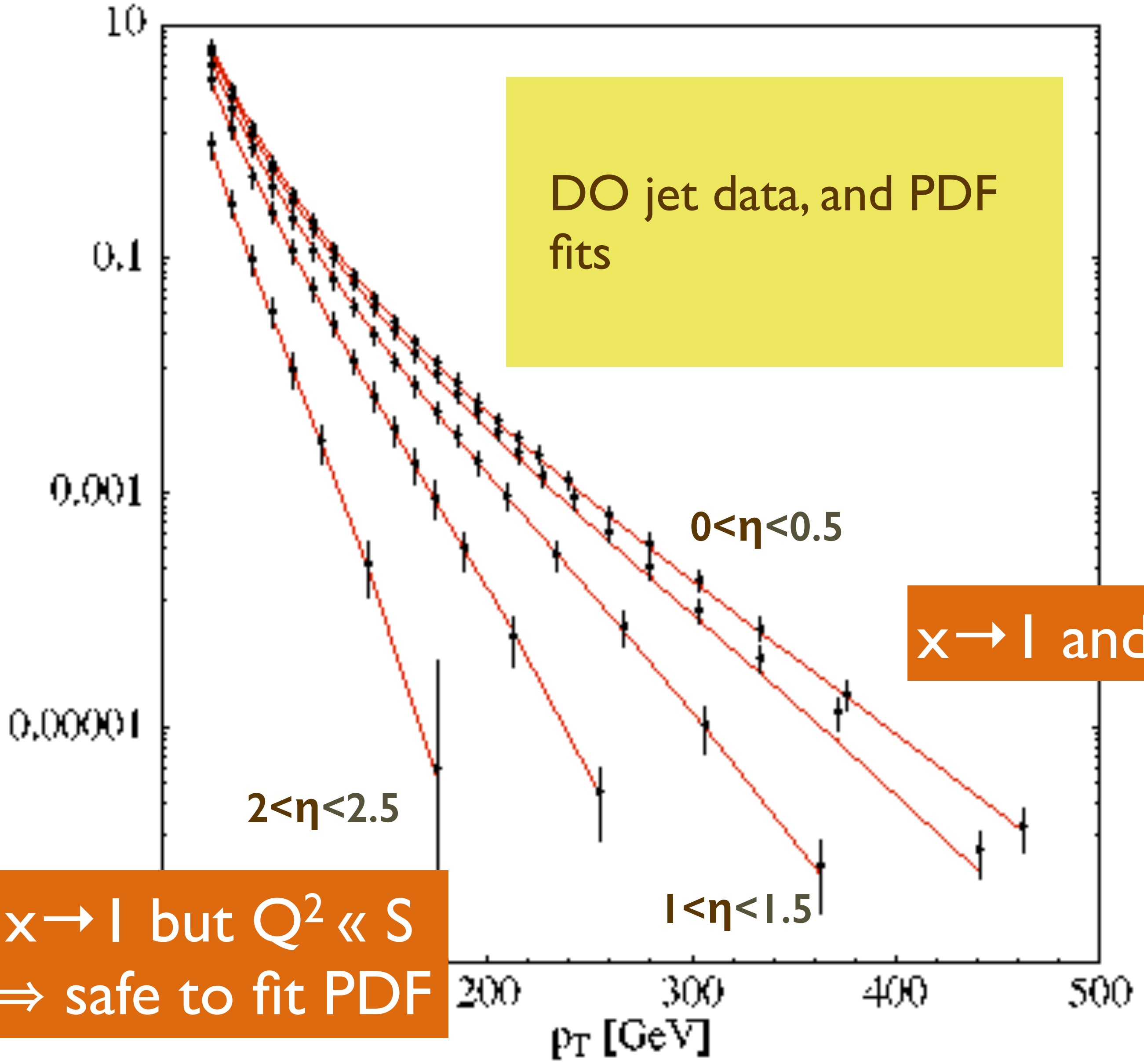


Does the use of data to fit PDFs tune away possible new physics?

Example, at the Tevatron, ~1995



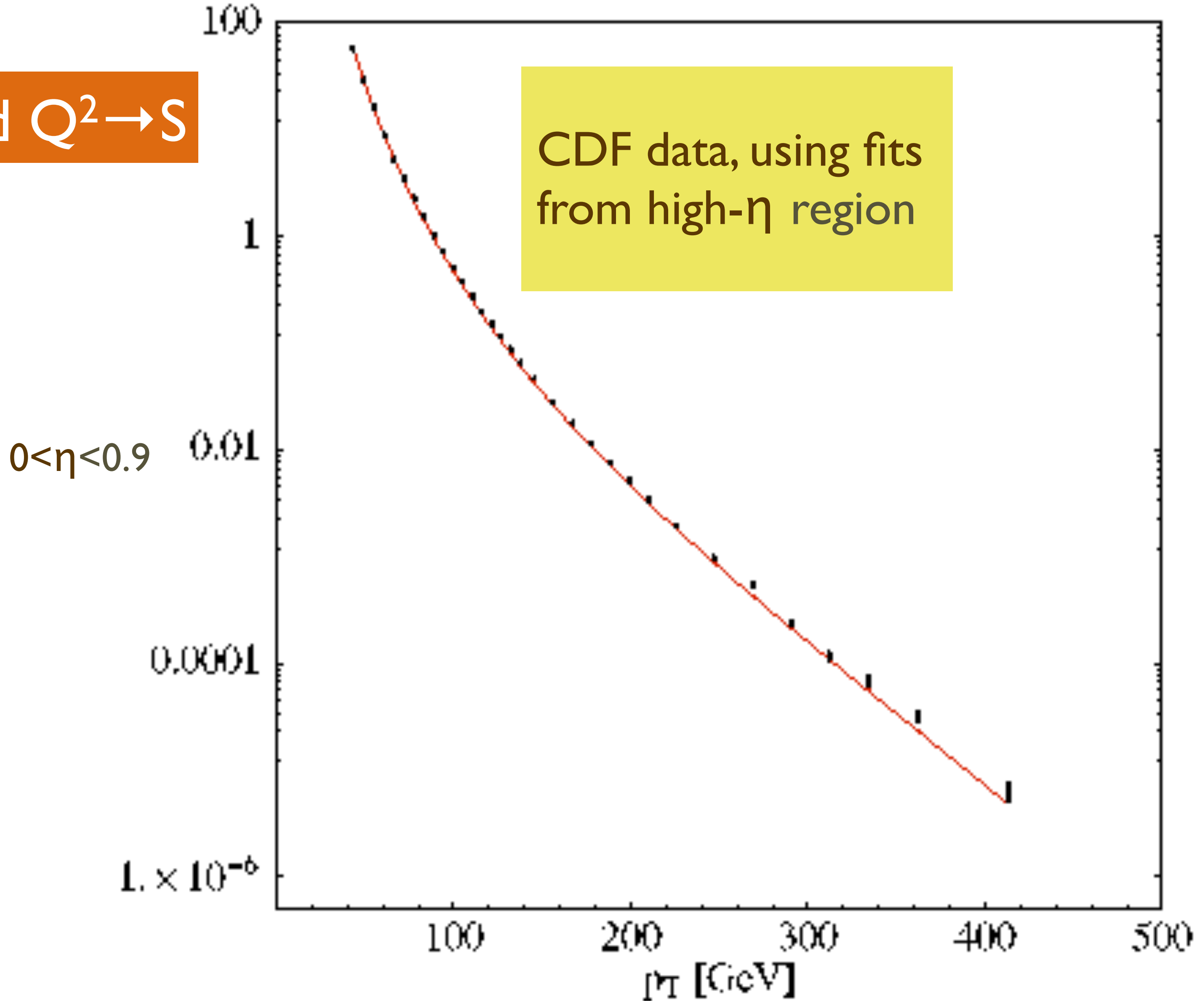
Follow-up analyses, **spectra vs eta**, PDF refitting, ...



DO jet data, and PDF fits

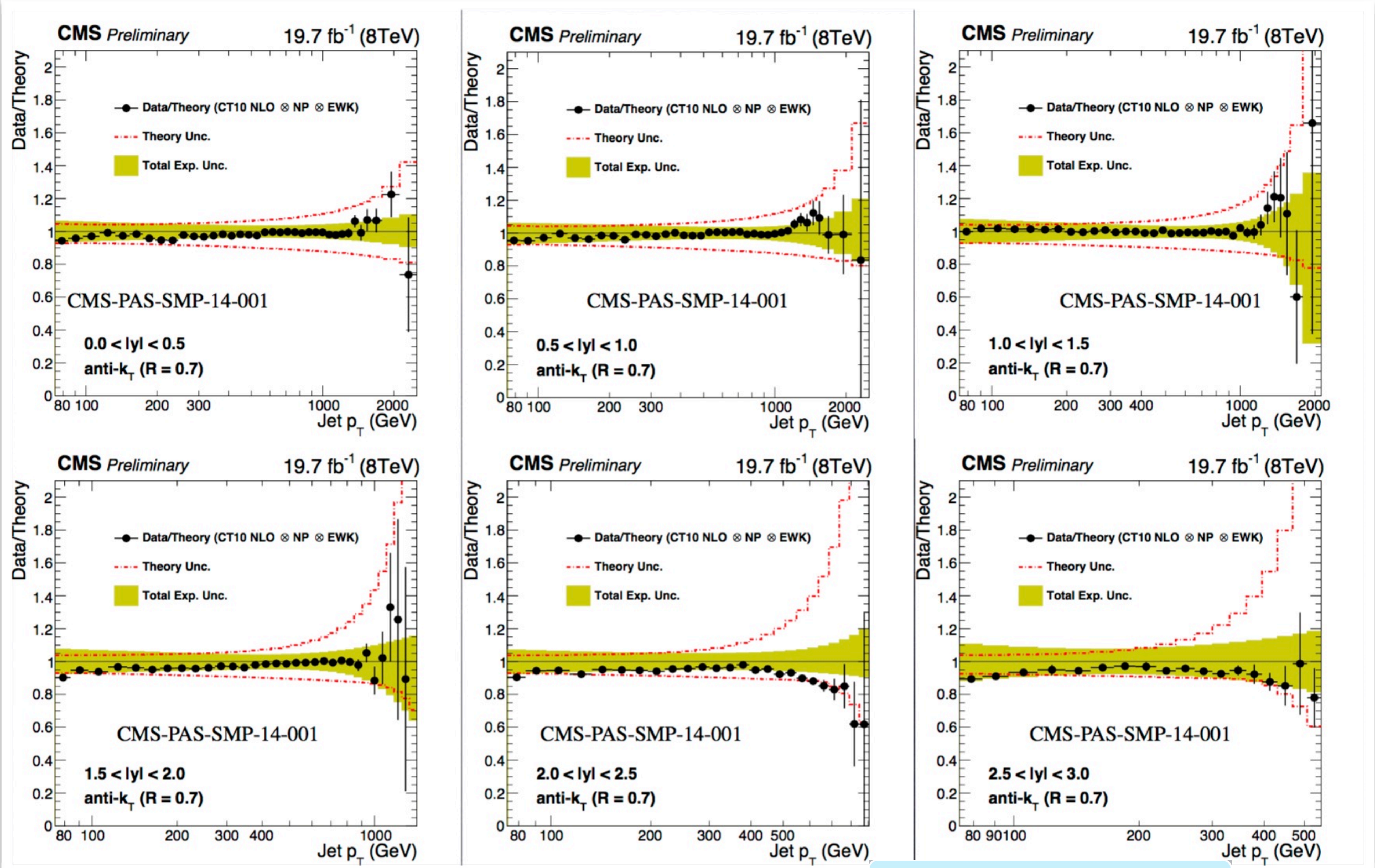
x→1 and Q^2→S

x→1 but Q^2 « S
⇒ safe to fit PDF



CDF data, using fits from high-η region

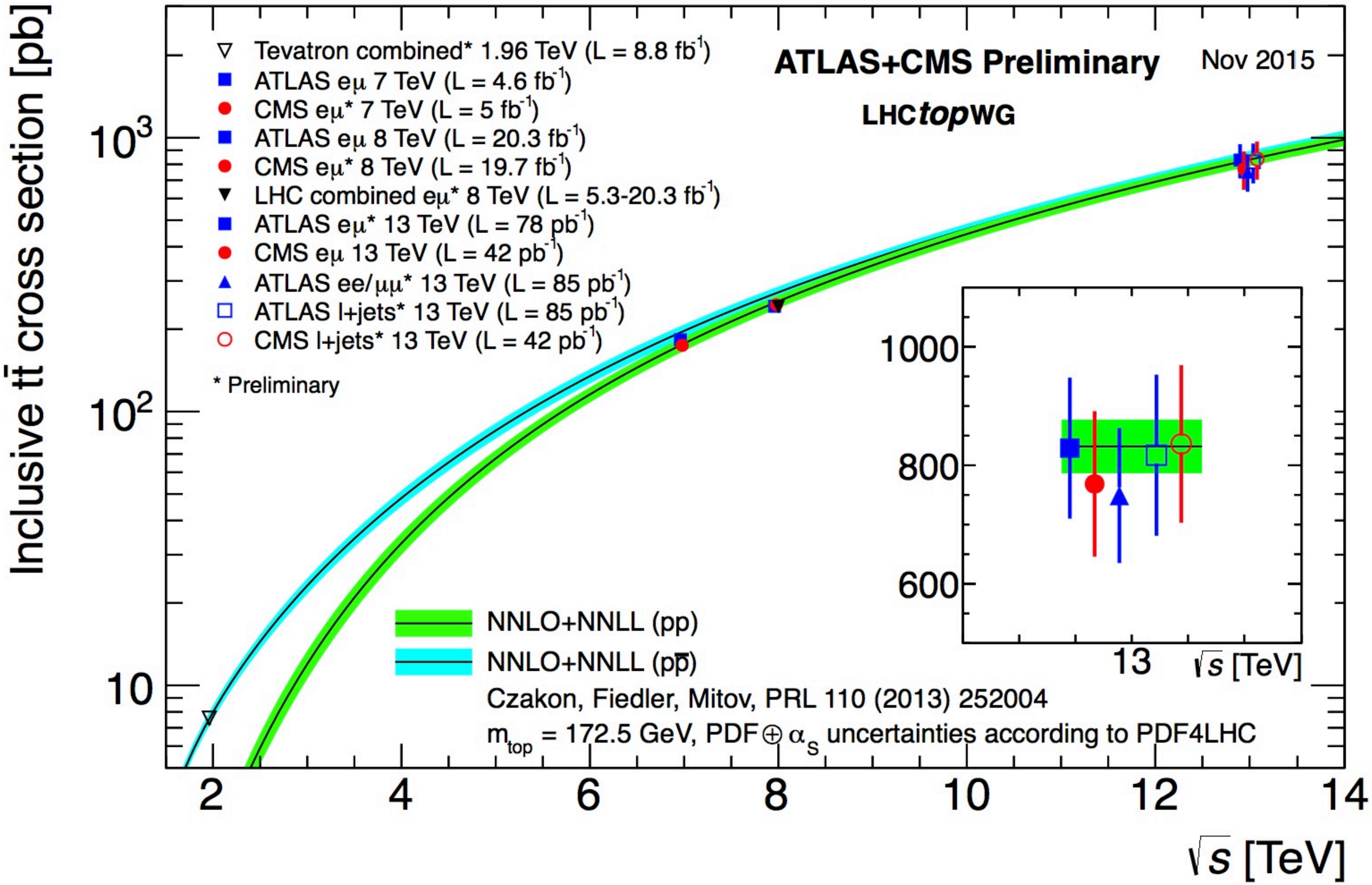
Jets at LHC, data vs TH

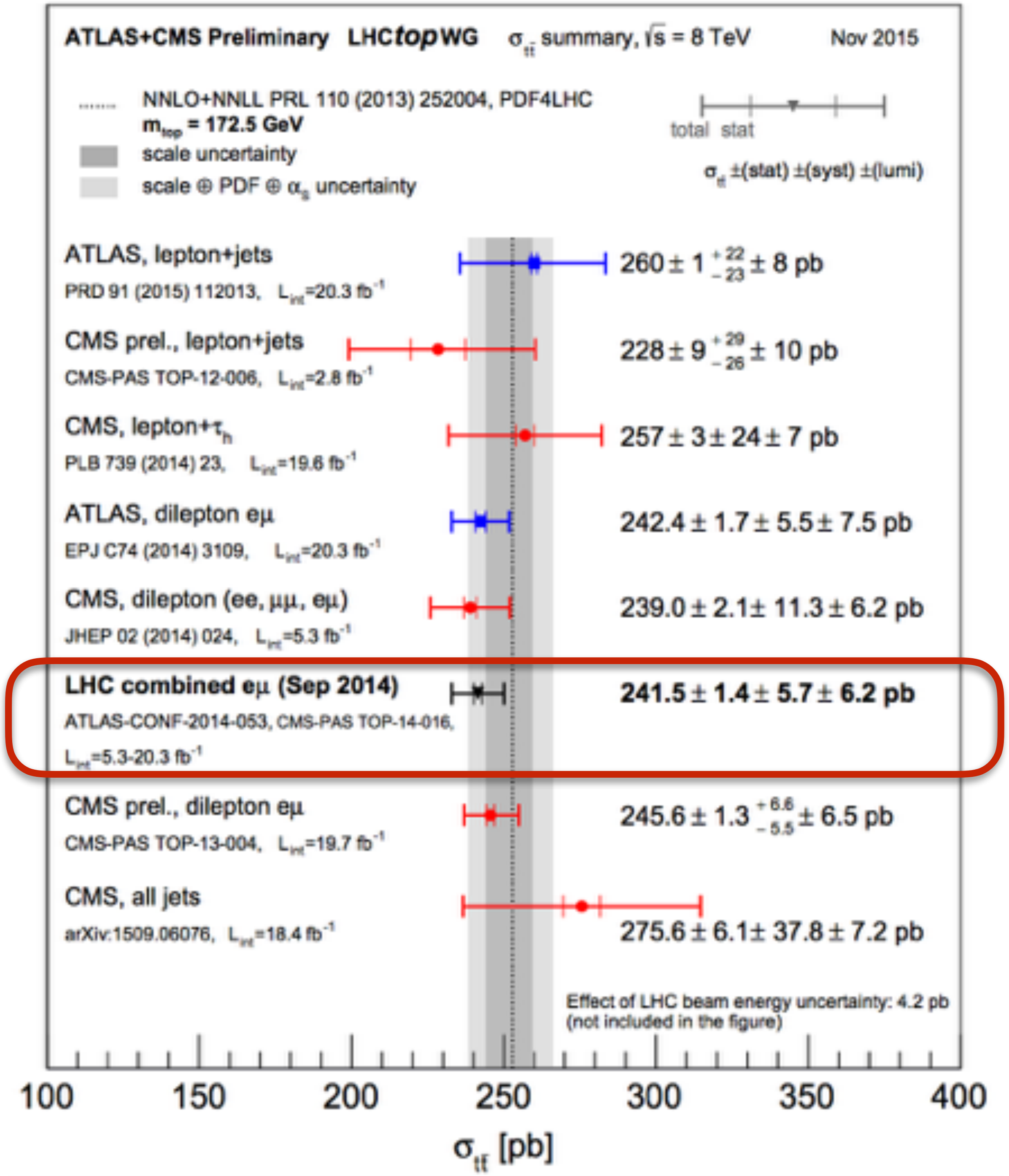


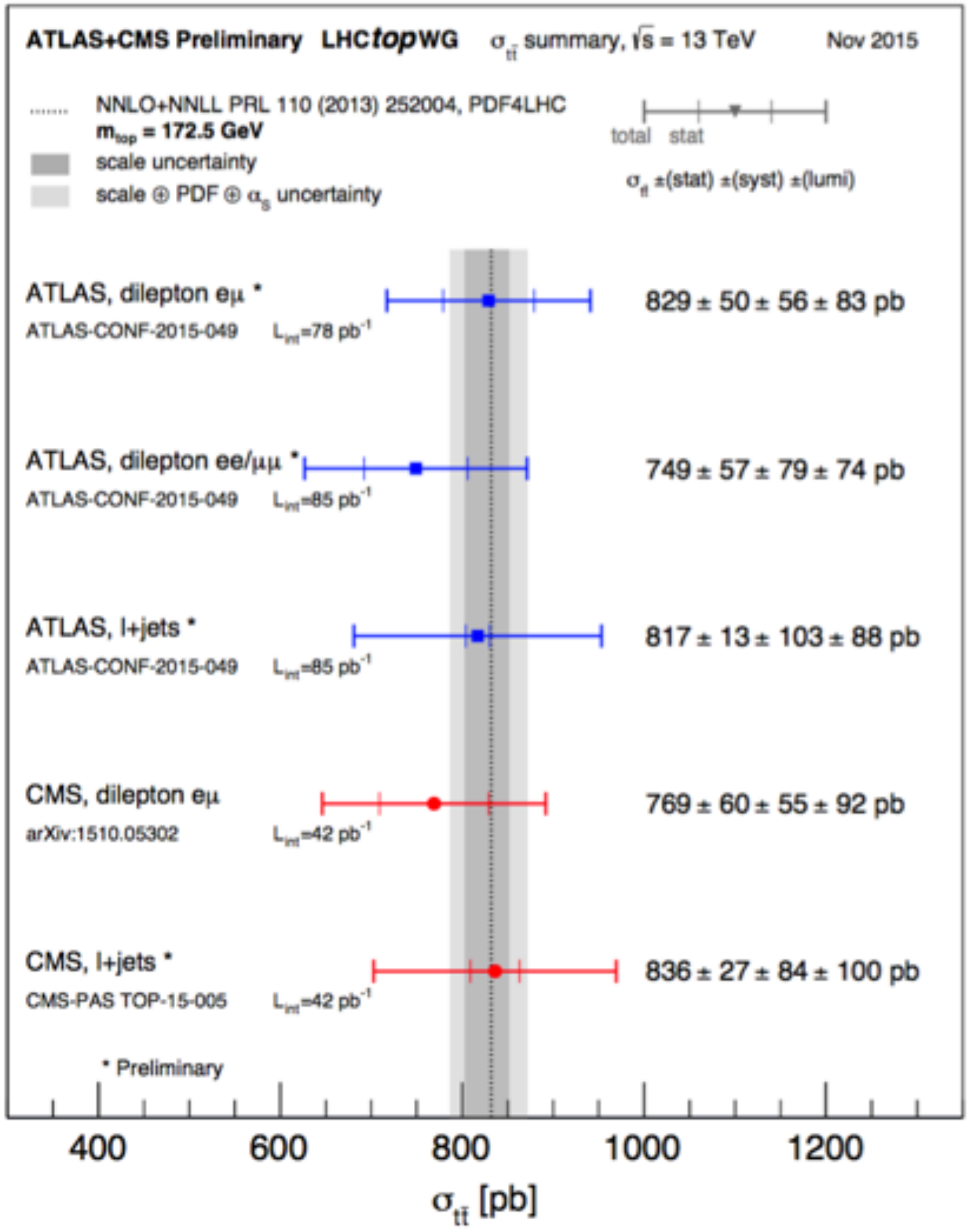
Dominant uncertainties:
Data: Jet Energy Scale (1-4% central |y| ; 6-45% outer |y|)
Luminosity 2.6%

Theory: Scale (5-10% central |y|, up to 40% outer |y|)
PDF(10-50% central |y|, up to 100% outer |y|)

Top quark production





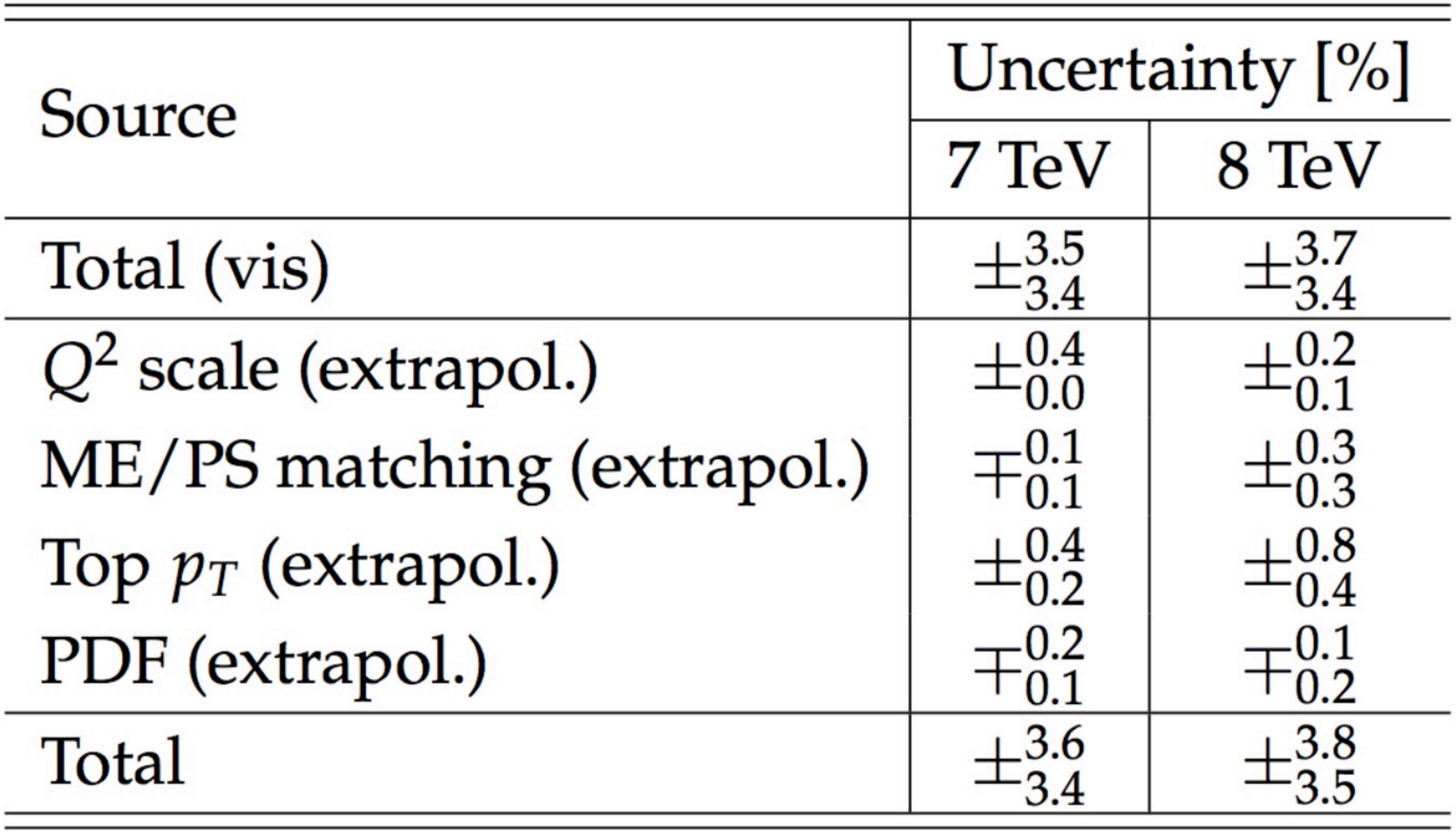


(pb)	σ(172.5 GeV)	δ_{scale}	$\delta_{PDF+\alpha s}$	δ_{mtop}
8 TeV	253	+6 –9	± 12	± 7.5
13 TeV	832	+20 –29	± 35	± 23

Czakon, Fiedler, Mitov,
arXiv:1303.6254

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

Uncertainties in the modeling of the extrapolation from fiducial to total cross sections have fallen below the percent level!



Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (vis)	$\pm^{3.5}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\pm^{0.4}_{0.0}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\mp^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.4}_{0.2}$	$\pm^{0.8}_{0.4}$
PDF (extrapol.)	$\mp^{0.2}_{0.1}$	$\mp^{0.1}_{0.2}$
Total	$\pm^{3.6}_{3.4}$	$\pm^{3.8}_{3.5}$

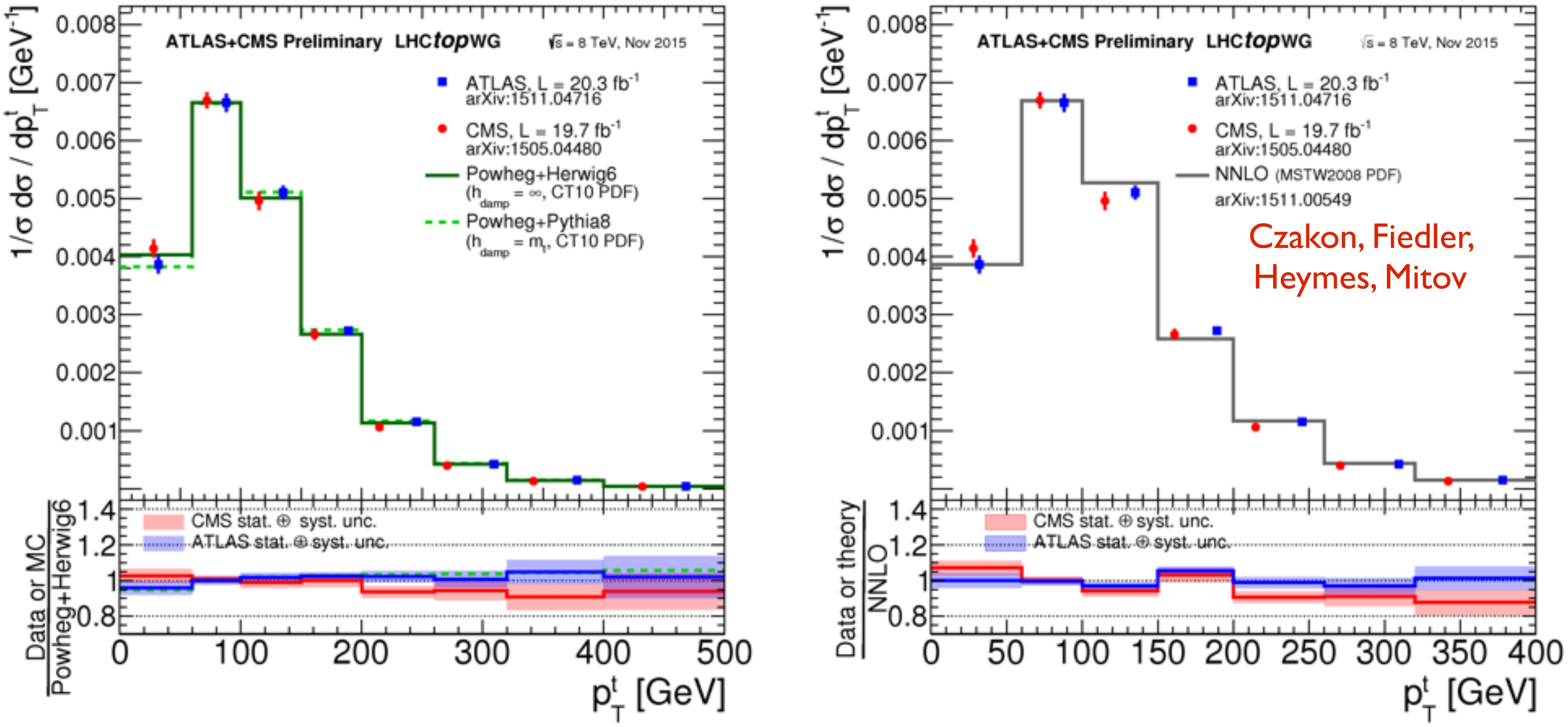
CMS-PAS-TOP-13-004

~11%

cfr CDF 1998 Dilepton cross section:

“ …. (0.74 ± 0.08)% of all $t\bar{t}$ decays pass the above dilepton selection criteria. The uncertainty is dominated by the differences between the event generators ….“

Top quark differential distributions

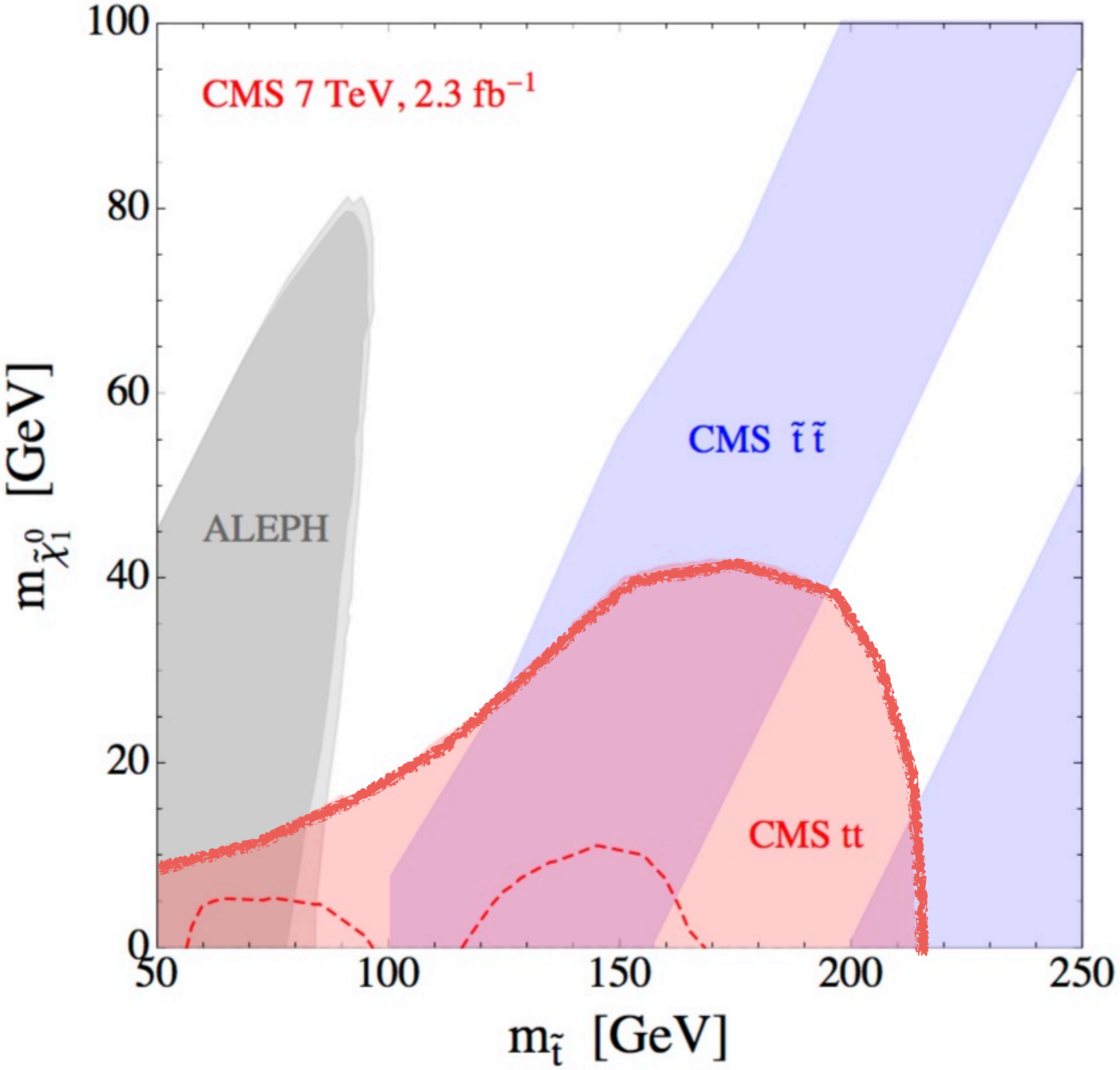


Czakon, Fiedler, Heymes, Mitov

- Precision of data and TH at the few-% level
- Still room for progress (e.g. improving ATLAS vs CMS compatibility)

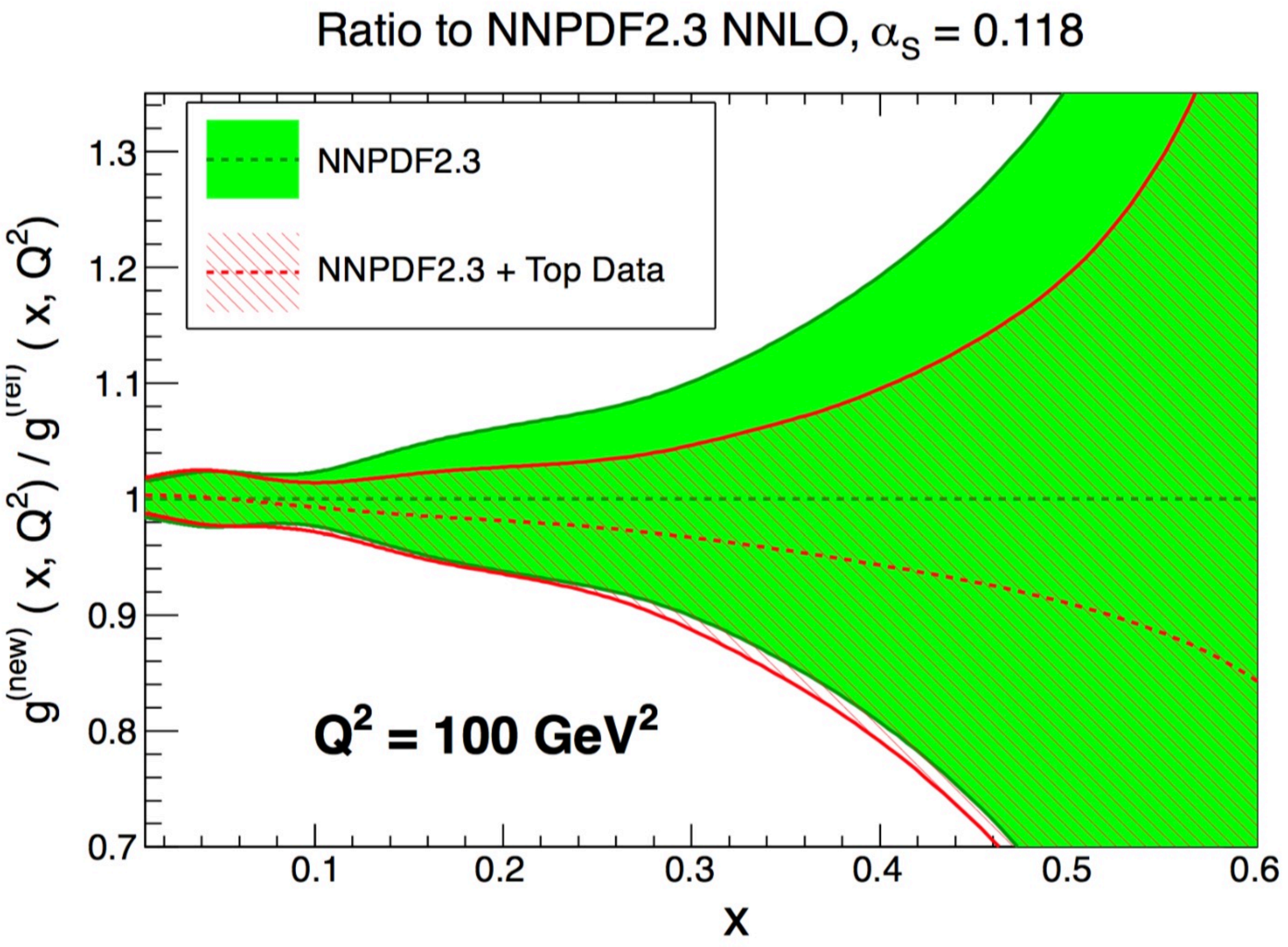
Some applications

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



Czakon, Papucci Mitov Rudermann Weiler, arXiv:1407.1043

Improved determination of gluon density



Czakon, et al arXiv:1407.1043

remarks

- Are we ever going to claim a discovery because of a TH vs data discrepancy in some cross-section or distribution?
- It never happened in the history of the SM (except perhaps for the gluon?), and I doubt it will happen in the future ….
- …. but discrepancies can raise flags, and trigger dedicated studies
- In absence of an established BSM scenario, providing the lamppost under which to search for the new physics, robust predictions and reliable data vs TH comparisons can be critical to highlight the possible presence of new phenomena

Prospects for MHV@60 …

or

… precision physics at a 100 TeV pp collider

remarks

- We don’t plan to build a 100 TeV collider with the primary goal of doing precision physics
- But we must guarantee that precision physics can be made there, since it will play a crucial role in the exploration of new physics to be done at 100 TeV
- I’ll give here some examples of the opportunities for precision measurements in the Higgs sector

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
gg→H	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	70
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
gg→HH	28 M		280

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

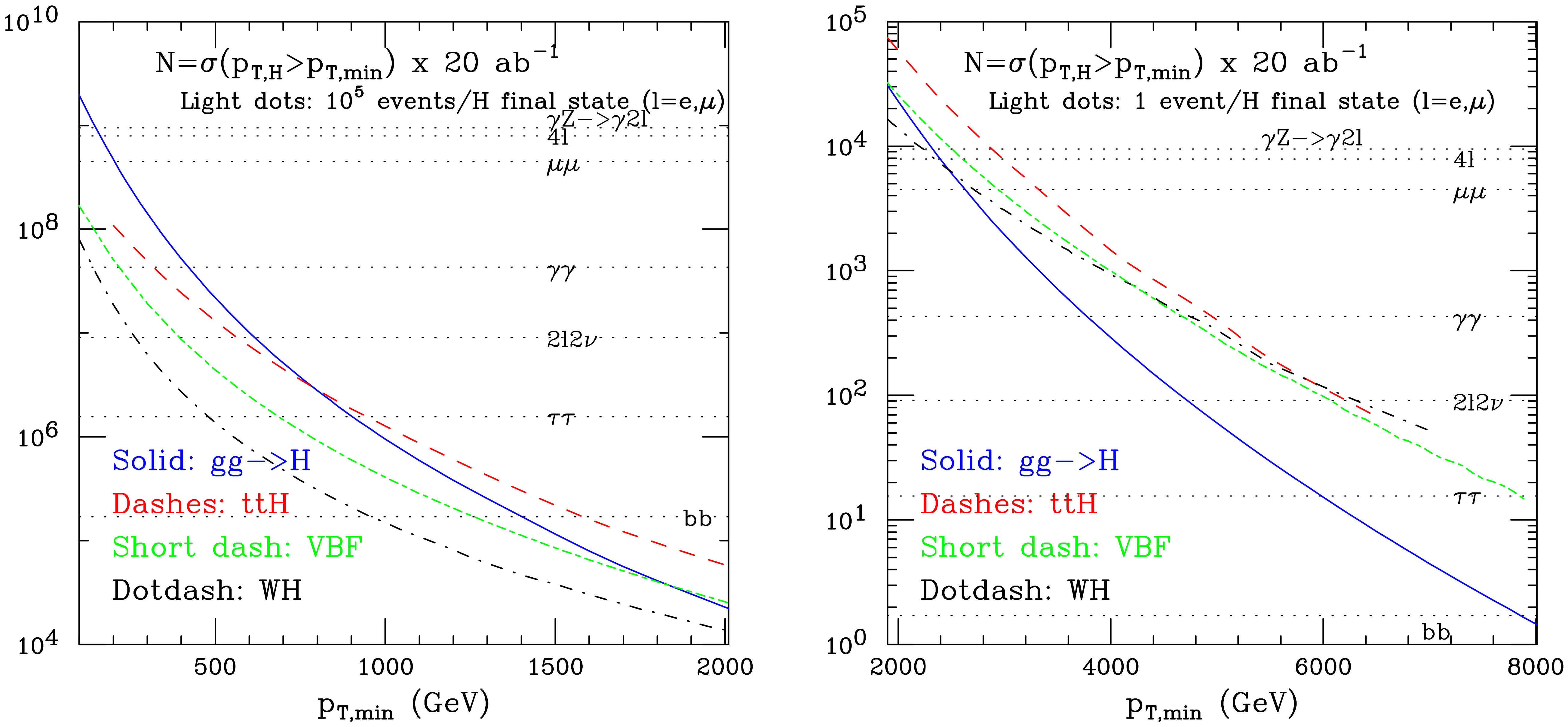
Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

How can be possibly exploit this immense statistics ??

What are the theoretical precision demands posed by this challenge?

Production rates vs $p_T(H)$



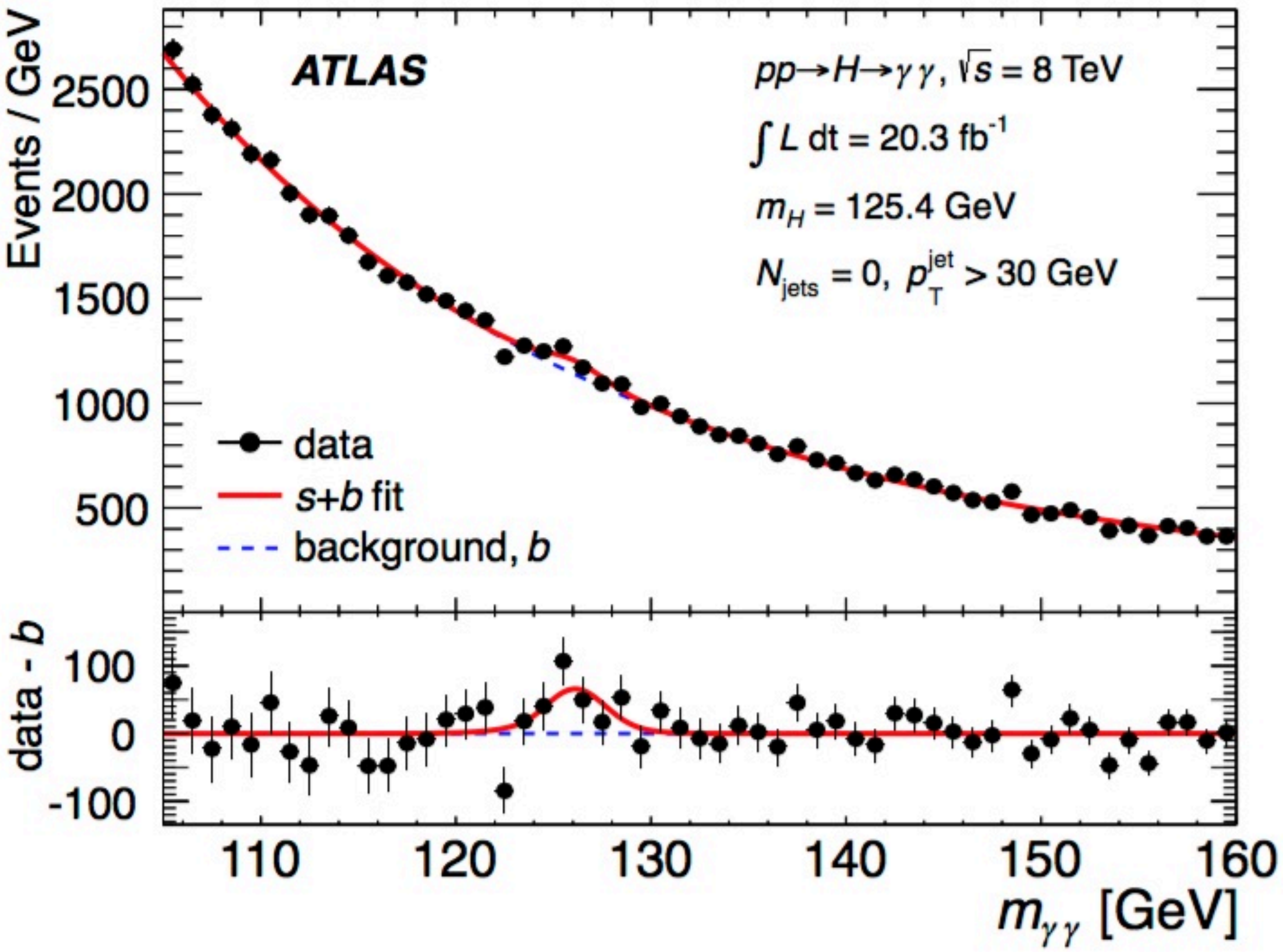
- Huge rates out to several TeV
- Hierarchy of production processes varies at large p_T: ttH > VBF ~ WH >> gg
- Plenty of room to re-balance statistical, systematical and theoretical uncertainties by selecting suitable kinematical cuts, in a context of sub-percent statistical precision

Example, $H\rightarrow\gamma\gamma$ (fiducial, all channels)

8 TeV reference results from ATLAS, arXiv:1407.4222

Fiducial cross section for $|\eta_\gamma| < 2.37$,
$p_{T\gamma}^{max} / m_{\gamma\gamma} > 0.35$
$p_{T\gamma}^{min} / m_{\gamma\gamma} > 0.25$

S=570 ± 130 events, B~16000 events
$(| m_{\gamma\gamma} - 125 | < 4 \text{ GeV})$



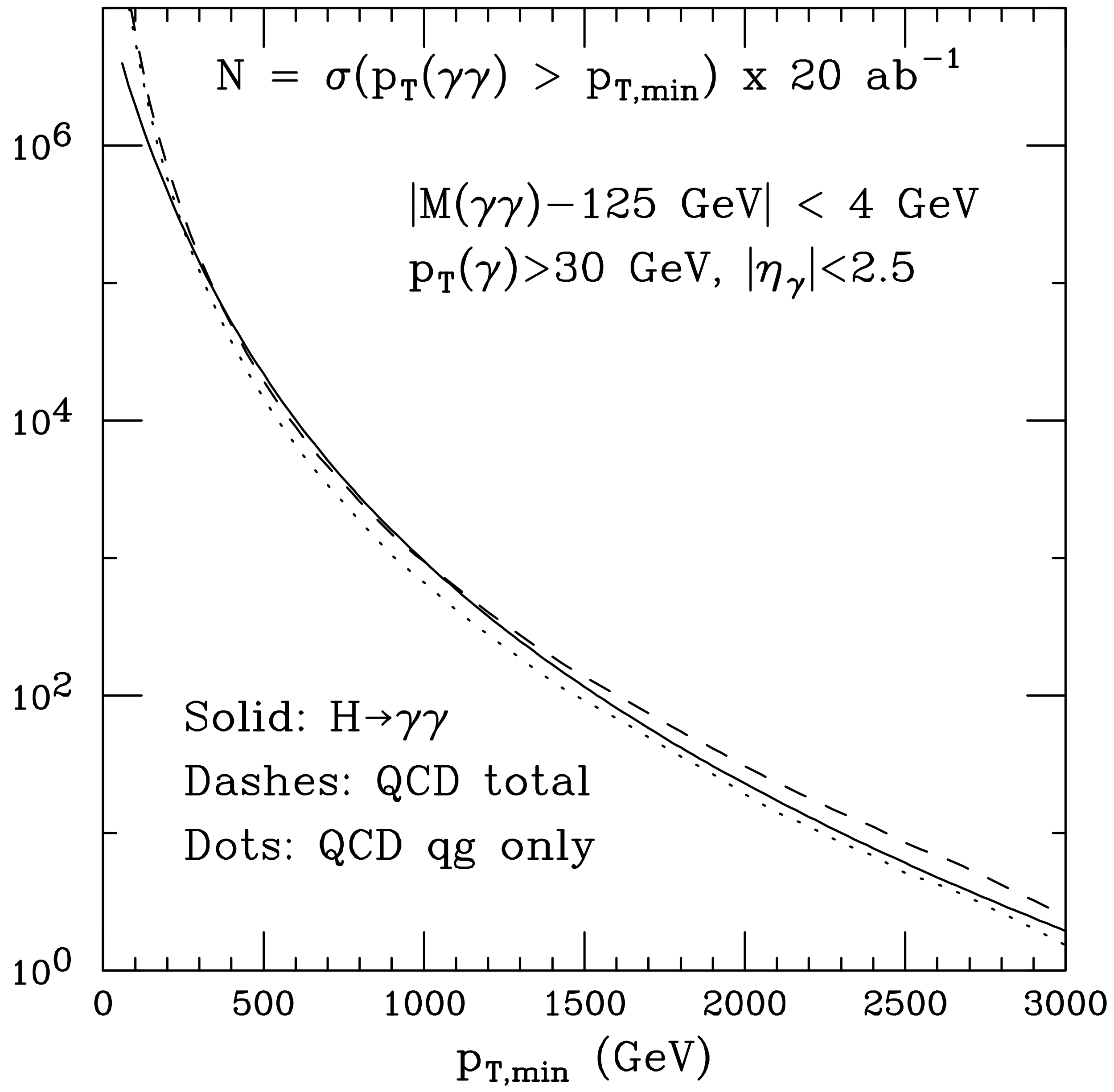
Measure $\sigma_{FIDUCIAL}(pp\rightarrow H\rightarrow\gamma\gamma) = 43.2 \pm 9.4\ (stat.) +3.2\ (syst.) \pm 1.2\ (lumi)\ fb$

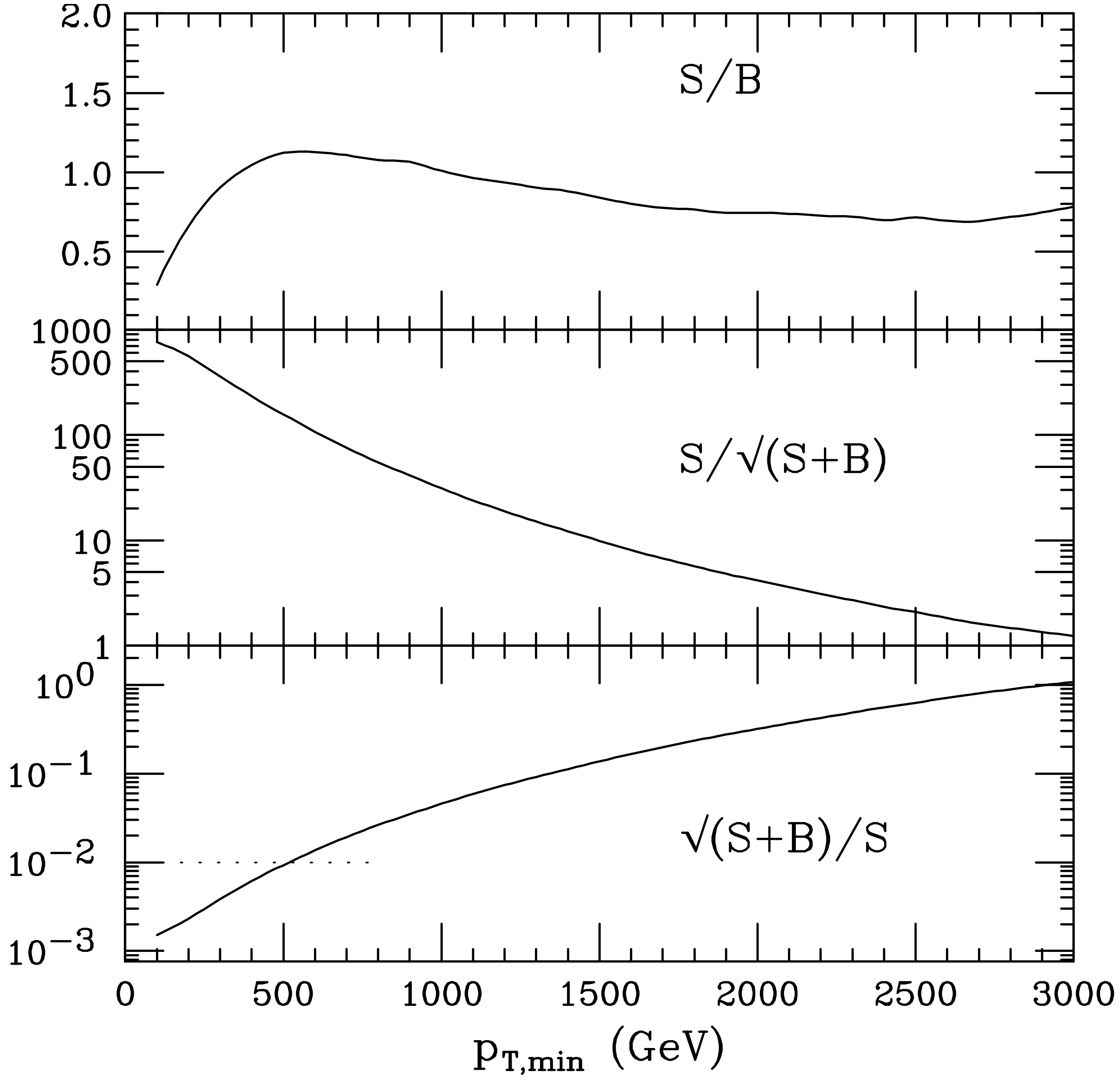
$\delta\ (\sigma\cdot B) / (\sigma\cdot B) \sim 22\%\ (stat.) + 7\%\ (syst.) \pm 3\%\ (lumi)$

Extrapolate to 14 TeV 3000 fb^{-1} $(N_{14}/N_8 \sim 400)$

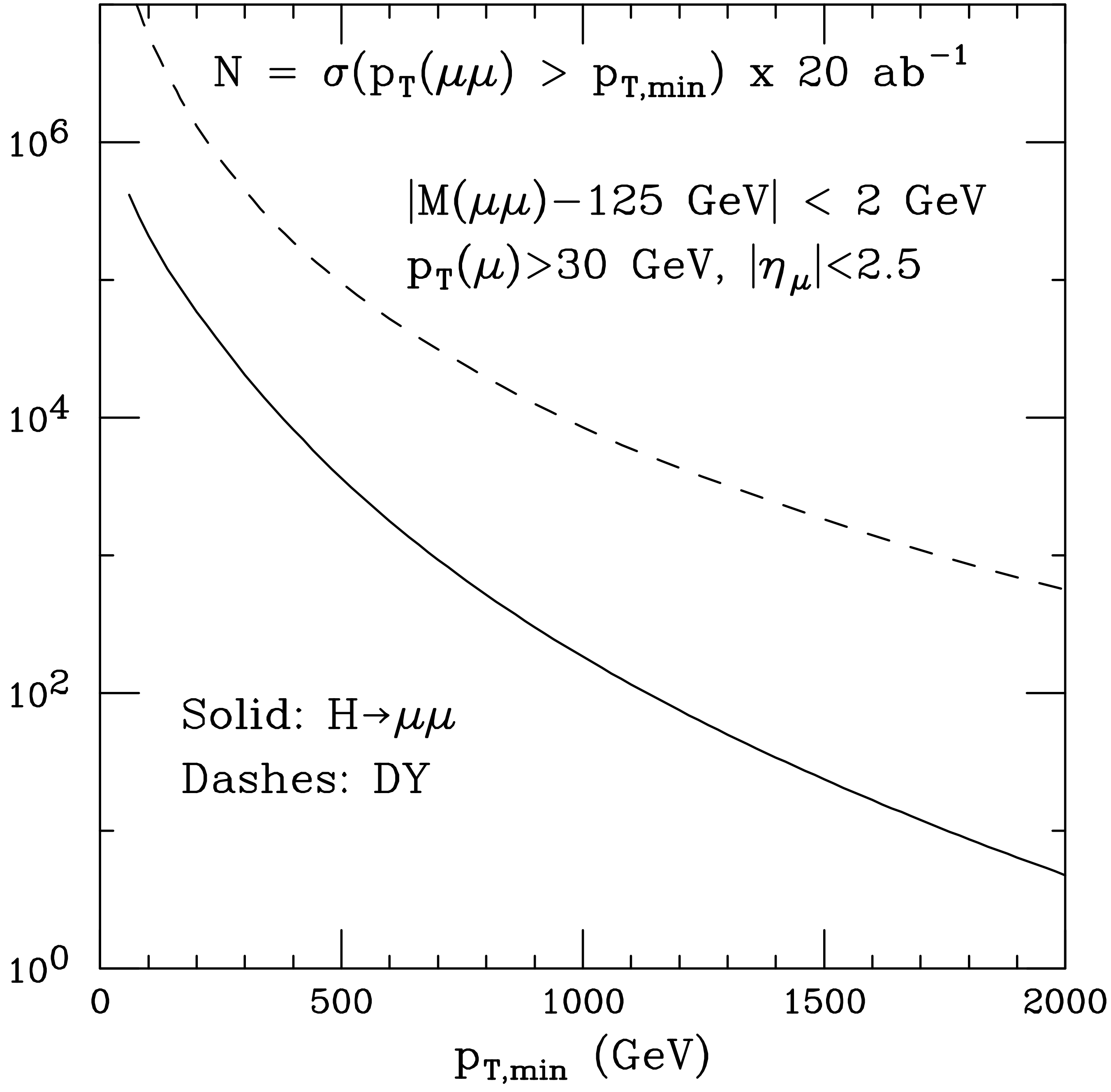
$\delta\ (\sigma\cdot B) / (\sigma\cdot B) \sim 1\ \%\ (stat.) + X_{14}\ \%\ (syst.) \pm 3\%\ (lumi)$

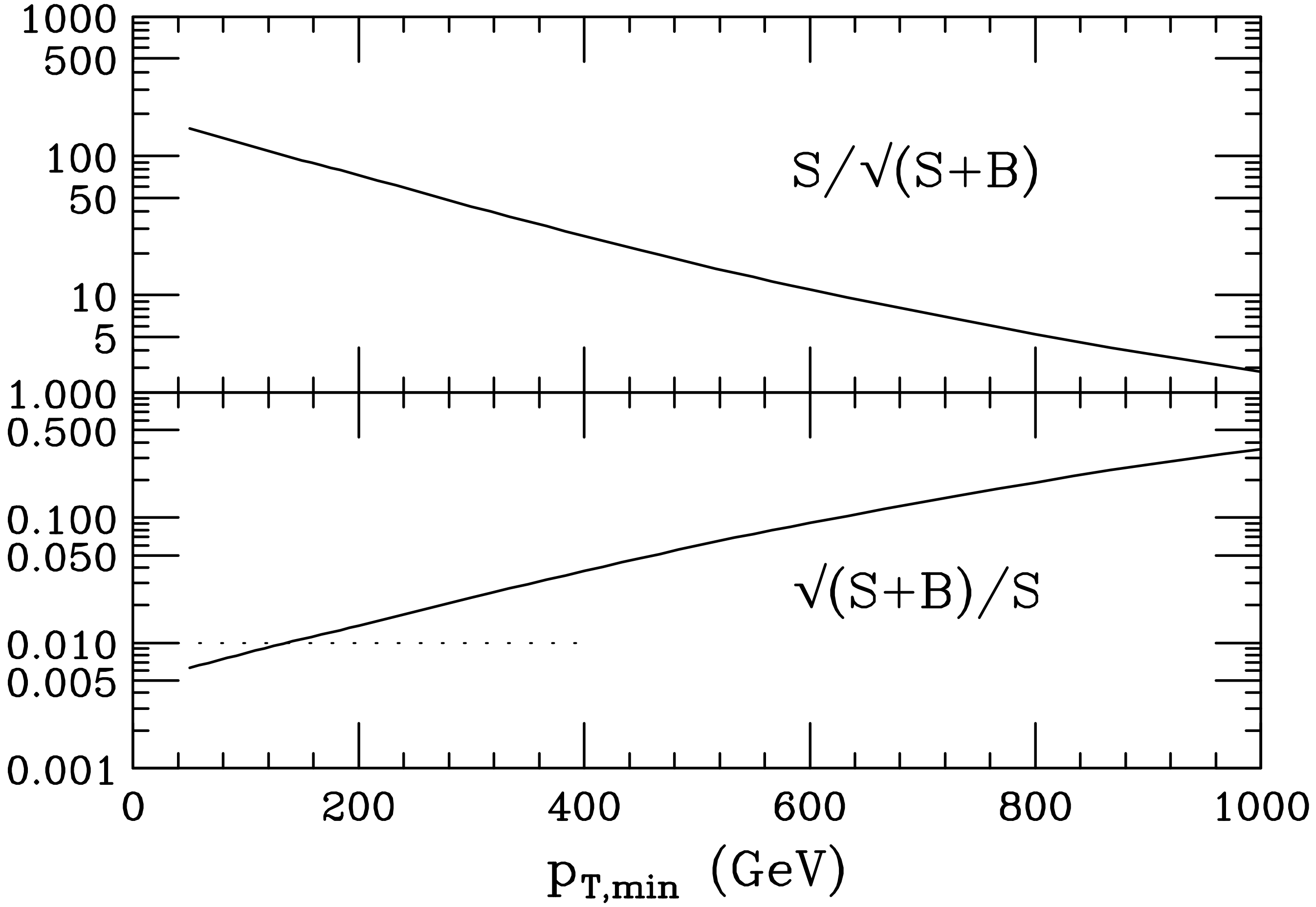
H→γγ at 100 TeV





$H \to \mu\mu$ at 100 TeV

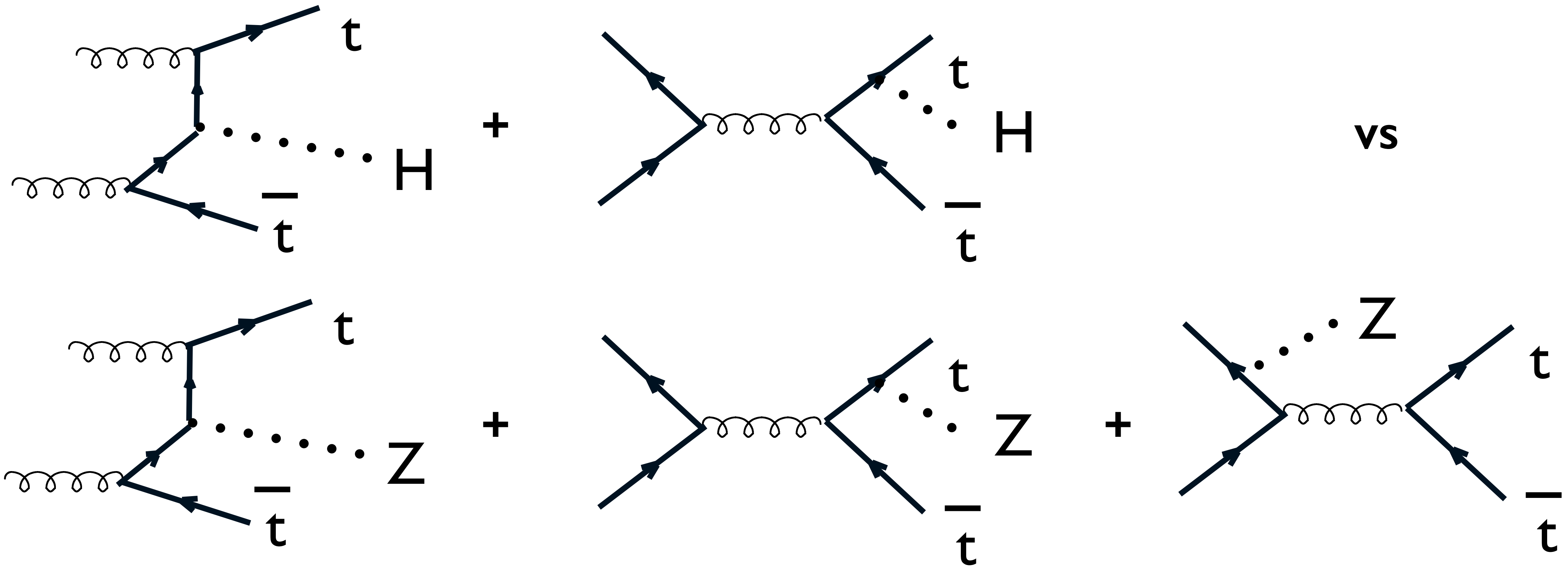




- Ratio of $H \to \mu\mu / H \to \gamma\gamma$ in the range $p_T \sim 100$-200 GeV gives $BR(\mu\mu)/BR(\gamma\gamma)$ with % precision $\Rightarrow \delta y_\mu / y_\mu \sim 0.5\%$
- Similar results for $H \to Z\gamma$

Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:

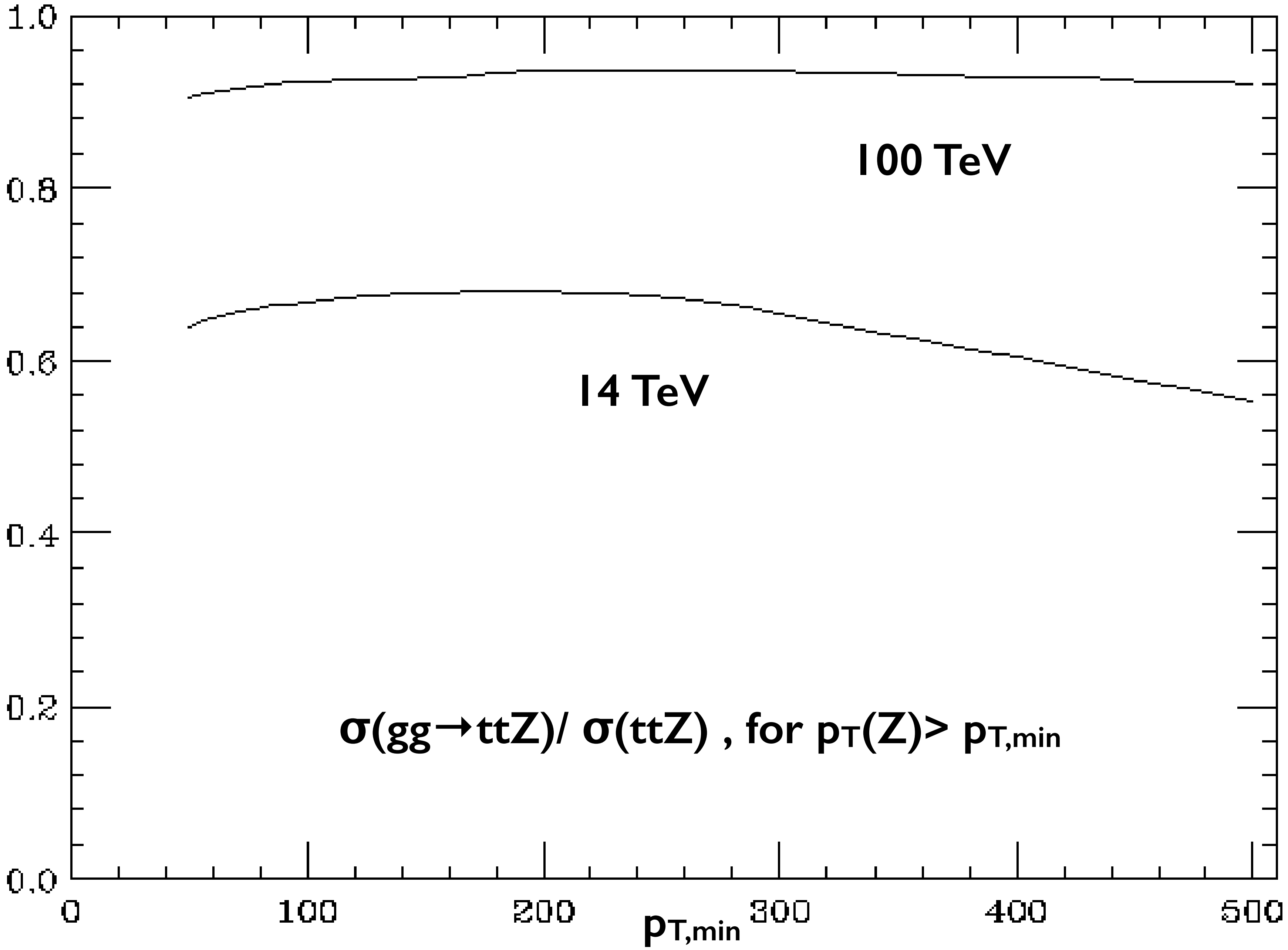
  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- $m_Z \sim m_H$ ⇒ almost identical kinematic boundaries:

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

At 100 TeV, gg→tt X is indeed dominant ....



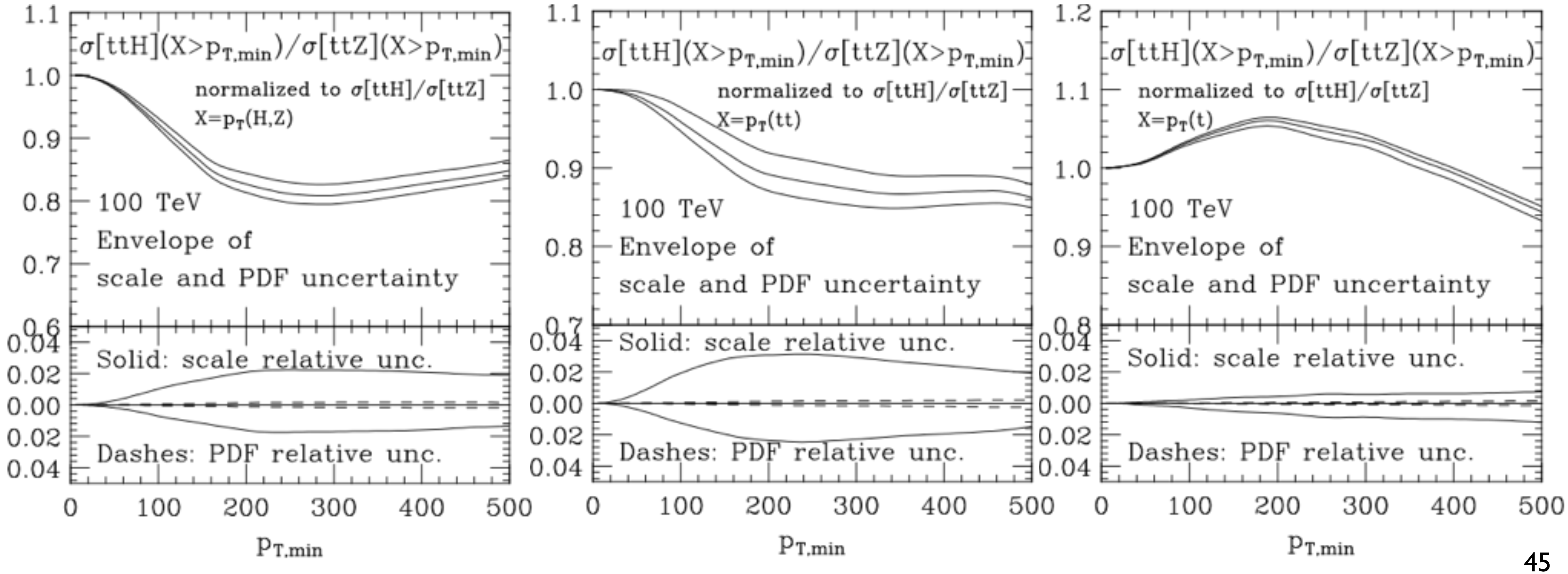
NB: At lower p_T values, gg fraction is slightly larger for ttZ than for ttH, since $m_Z < m_H$

Cross section ratio stability

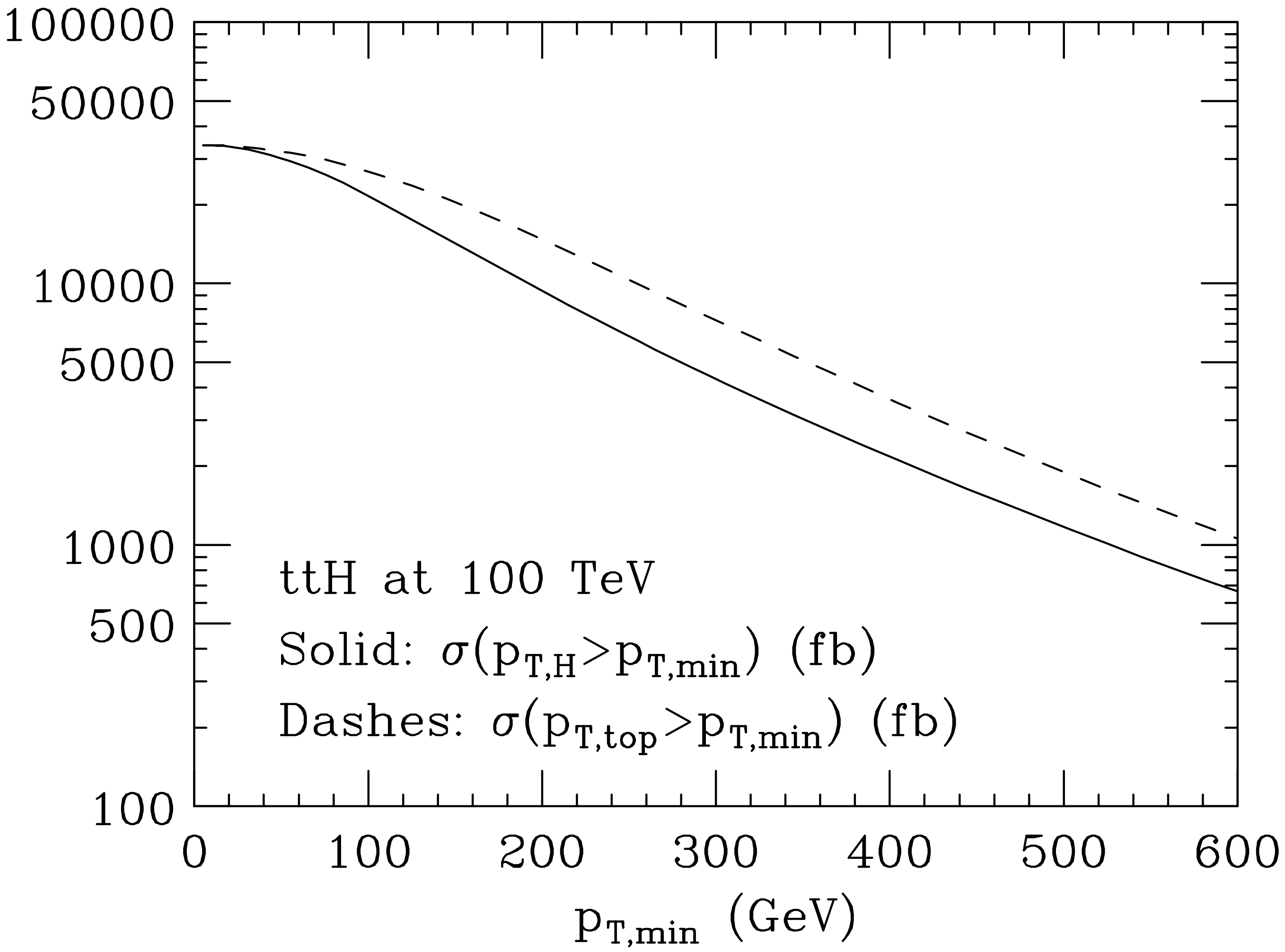
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

↑ scale ↑ PDF

Production kinematics ratio stability



arXiv:1507.08169



$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

Events/20ab^{-1}, with tt→$\ell\nu$+jets

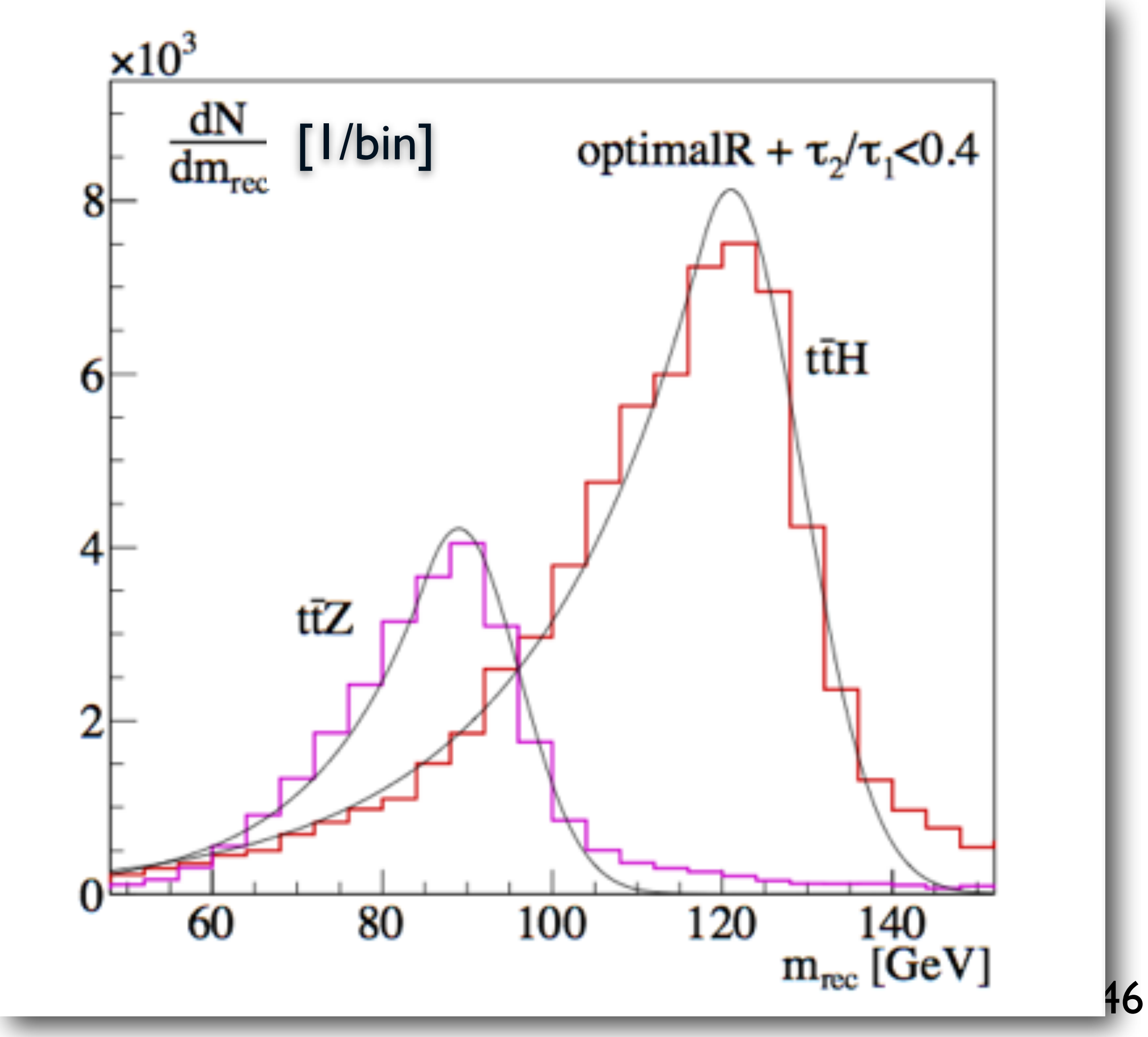
⇒ huge rates, exploit

boosted topologies

Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

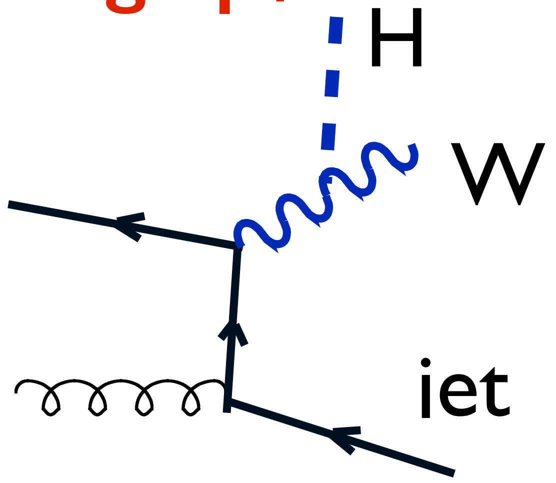
- **δy_t (stat + syst $_{TH}$) ~ 1%**

- great potential to reduce to similar levels $\delta_{\text{exp syst}}$
- consider other decay modes, e.g. 2l2nu



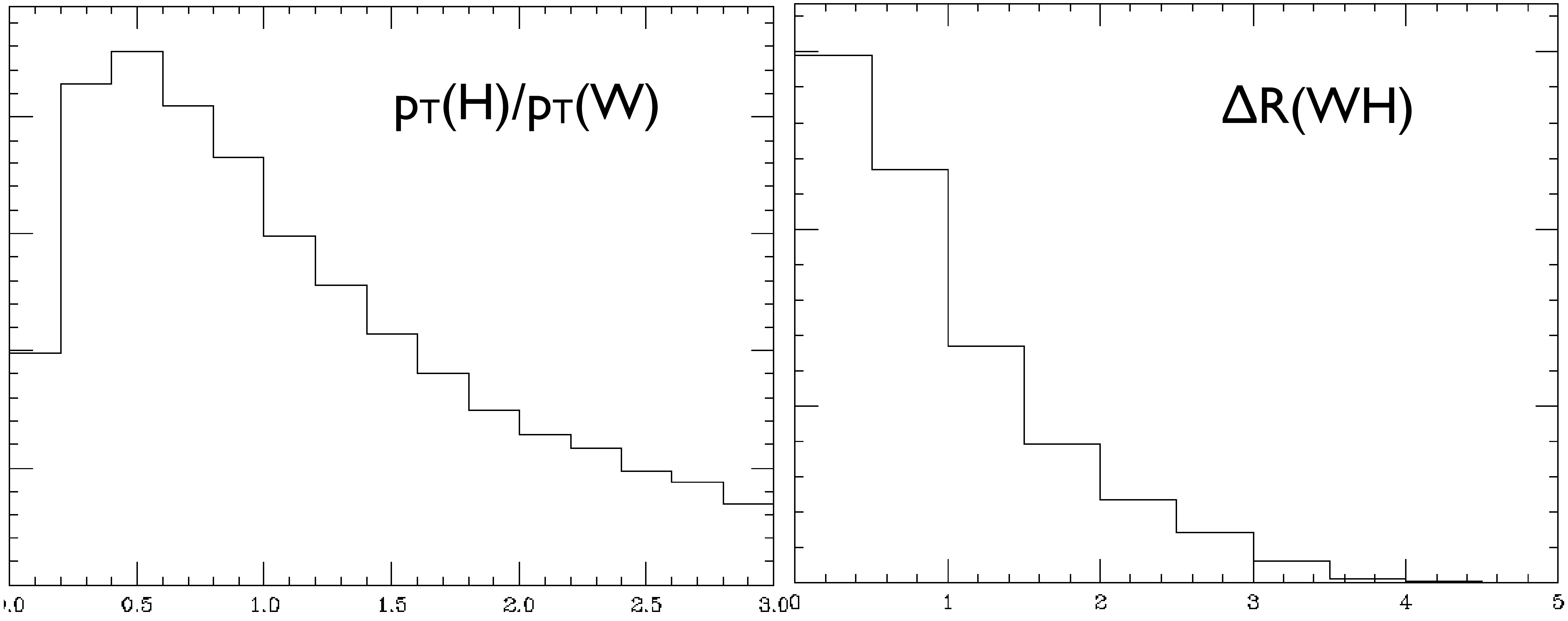
Ex.(WH→e ν bb)+jet production at large p_T^{jet}

- Dominant contribution from the following diagram topologies:



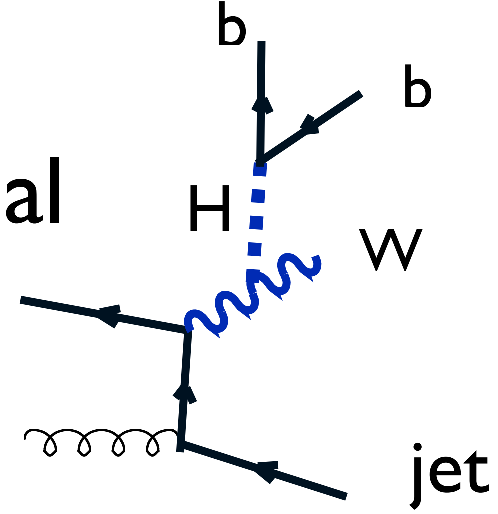
- Production in this kinematics tends to have small m(HW), and the WH system recoiling against the jet

E.g for events with p_T(jet) > 1 TeV



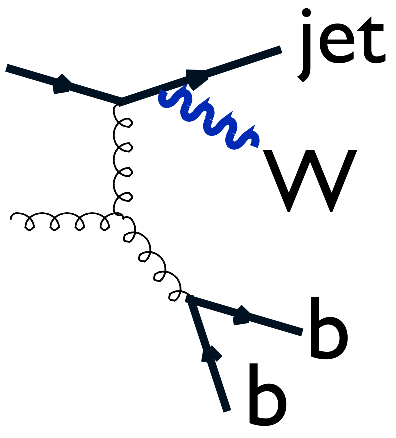
Ex.(WH→e ν bb)+jet production at large p_T^{jet}

Signal

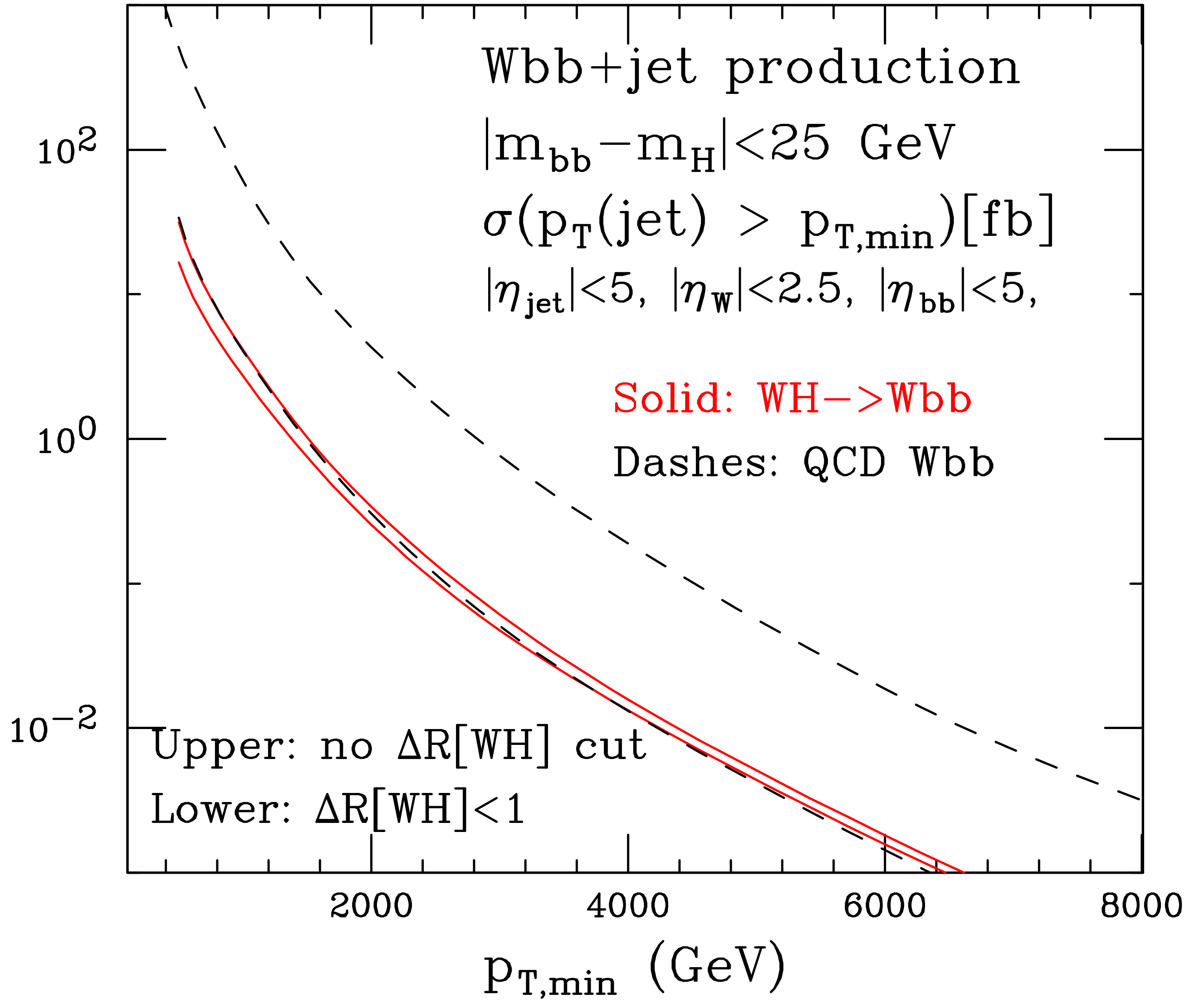


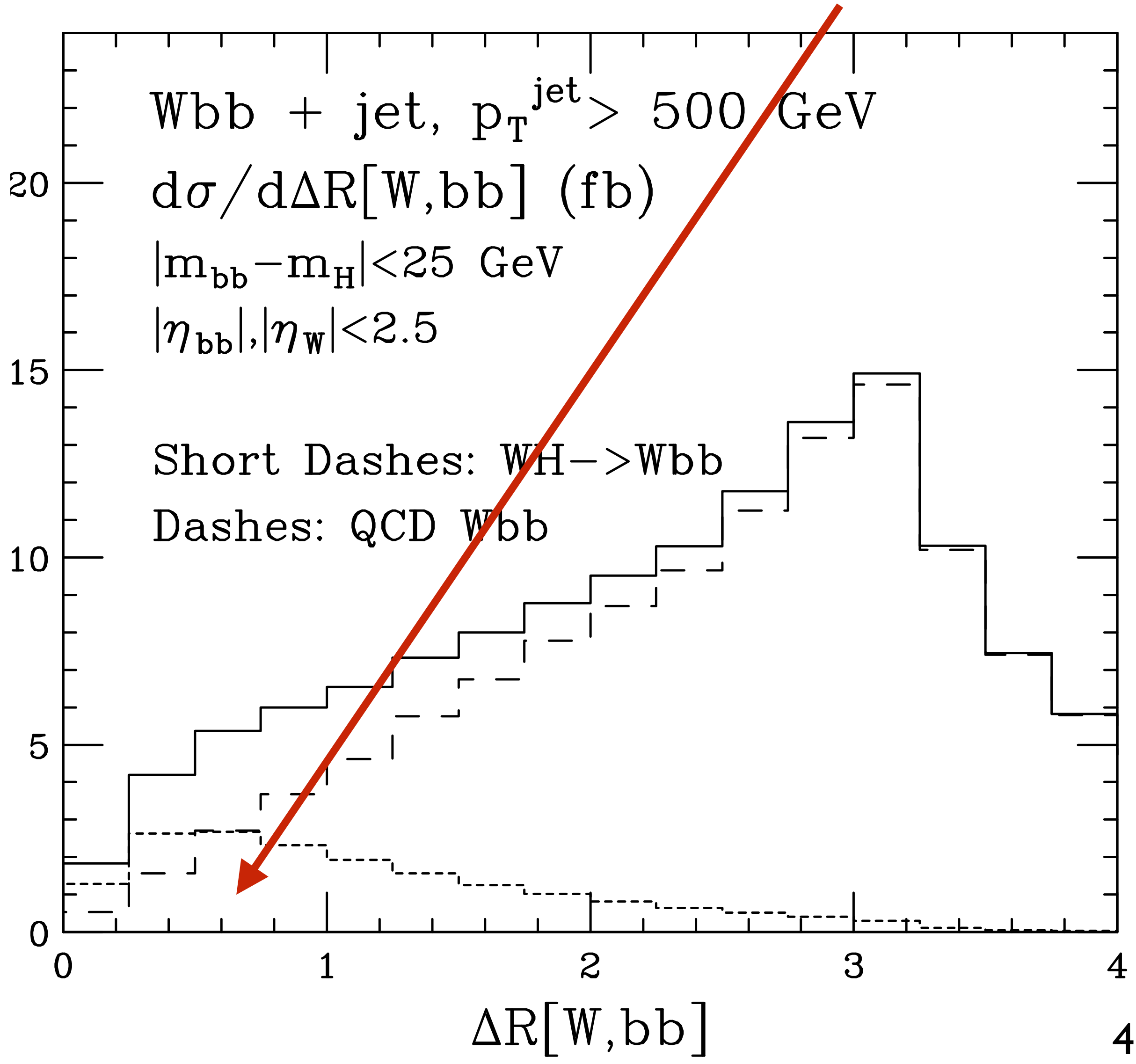
Background

100< m(bb) < 150 GeV



~10^5 signal events in $20ab^{-1}$





Final remarks

- Precision measurements remain, even at a time of discoveries, an essential tool of progress
- In the past 30 years, accelerator, experimental and theoretical technologies have evolved hand in hand, making it possible to best capitalize on the respective progress
- As the LHC starts its long path towards 3000 fb^{-1} @ maximum energy, theory should get ready to match the expected precision

- Physics at a 100 TeV collider is not just a plain extrapolation of physics at the LHC, it's a different ball game. There are many opportunities, exploiting the large statistics and the novel kinematical regimes
- The ability to do precision Higgs physics at a future hadron collider is mandatory
  - H as a probe of EW dynamics at the multi-TeV scale
  - H as a signal of, or background to, possible new physics
- The requirements of a precision-physics programme with the Higgs, provides a concrete playground to stimulate and assess theoretical progress in precision physics