Physics at 100 TeV

Review of the FCC-hh physics potential

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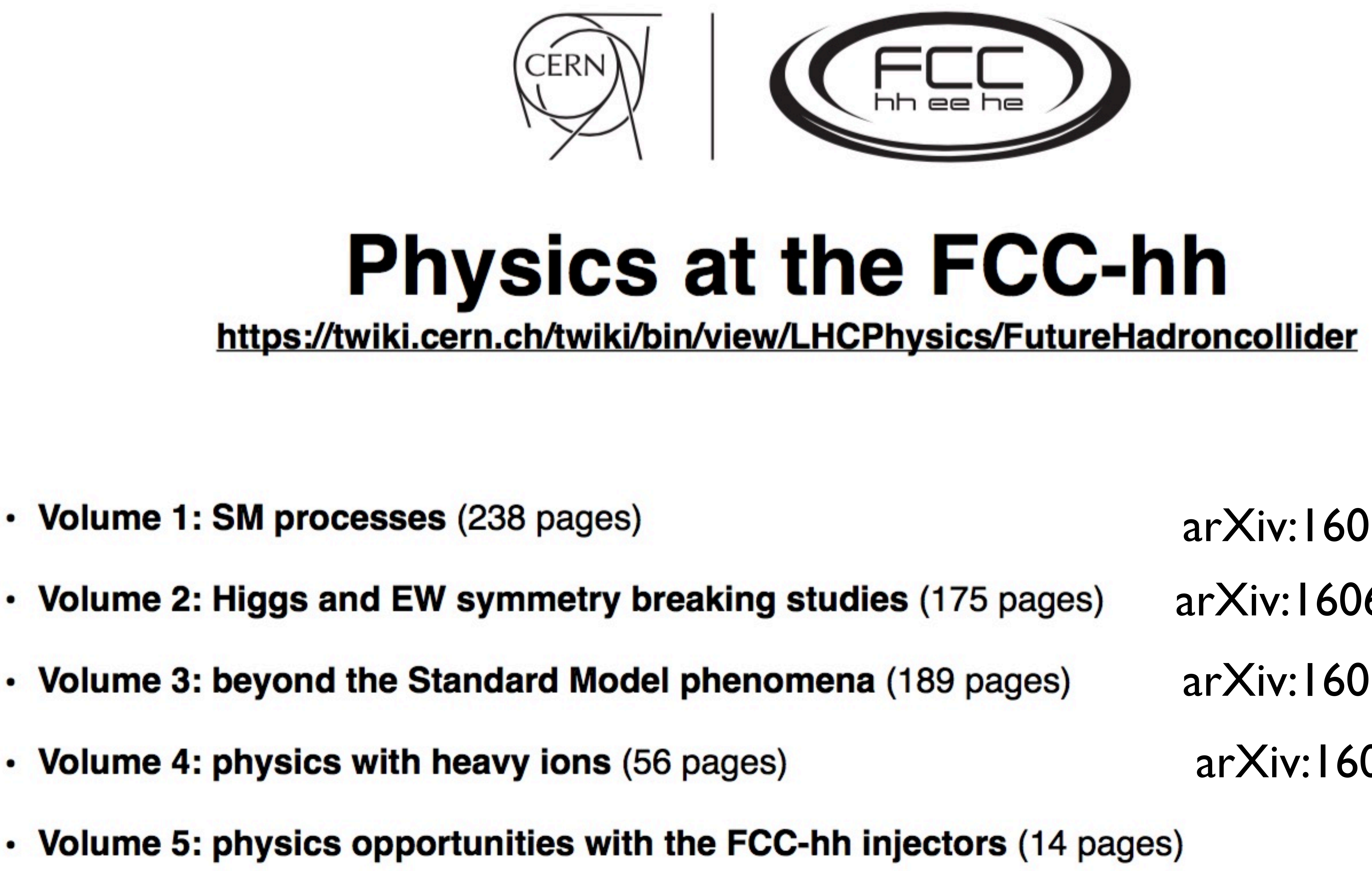
Outline

- The rationale and goals of the current efforts: the message for the CDR
- Higgs and EWSB physics
  - precision measurements (couplings and self-couplings)
  - EWSB beyond the SM
- BSM searches
  - high-mass reach
  - DM and other weakly-interacting BSM phenomena
- The role of HE-LHC



Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

in the slides, these refer to entries from the relevant volume

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831 <— Fig SM-xx
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408 <— Fig H-xx
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947 <— Fig BSM-xx
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

To appear anytime now as a bound volume of CERN Yellow Reports

- **FCC-hh events**: http://indico.cern.ch/category/5258/

The goals of the Report

- Document what, today, we can anticipate of the physics landscape at 100 TeV:
  - report cross sections, rates and theoretical uncertainties for relevant proc's, in the SM, Higgs and BSM sectors
  - expose aspects where 100 TeV goes beyond a mere extrapolation of the LHC potential
  - stimulate new ideas, starting from a few explicit examples of what 100 TeV and 20 ab^{-1} can deliver
  - Identify useful benchmarks to focus the detector design and the performance requirements
- The goal was not to define a "physics case", but to provide a first assessment, item by item, of the physics potential, and to outline prospects (for measurements and discoveries)

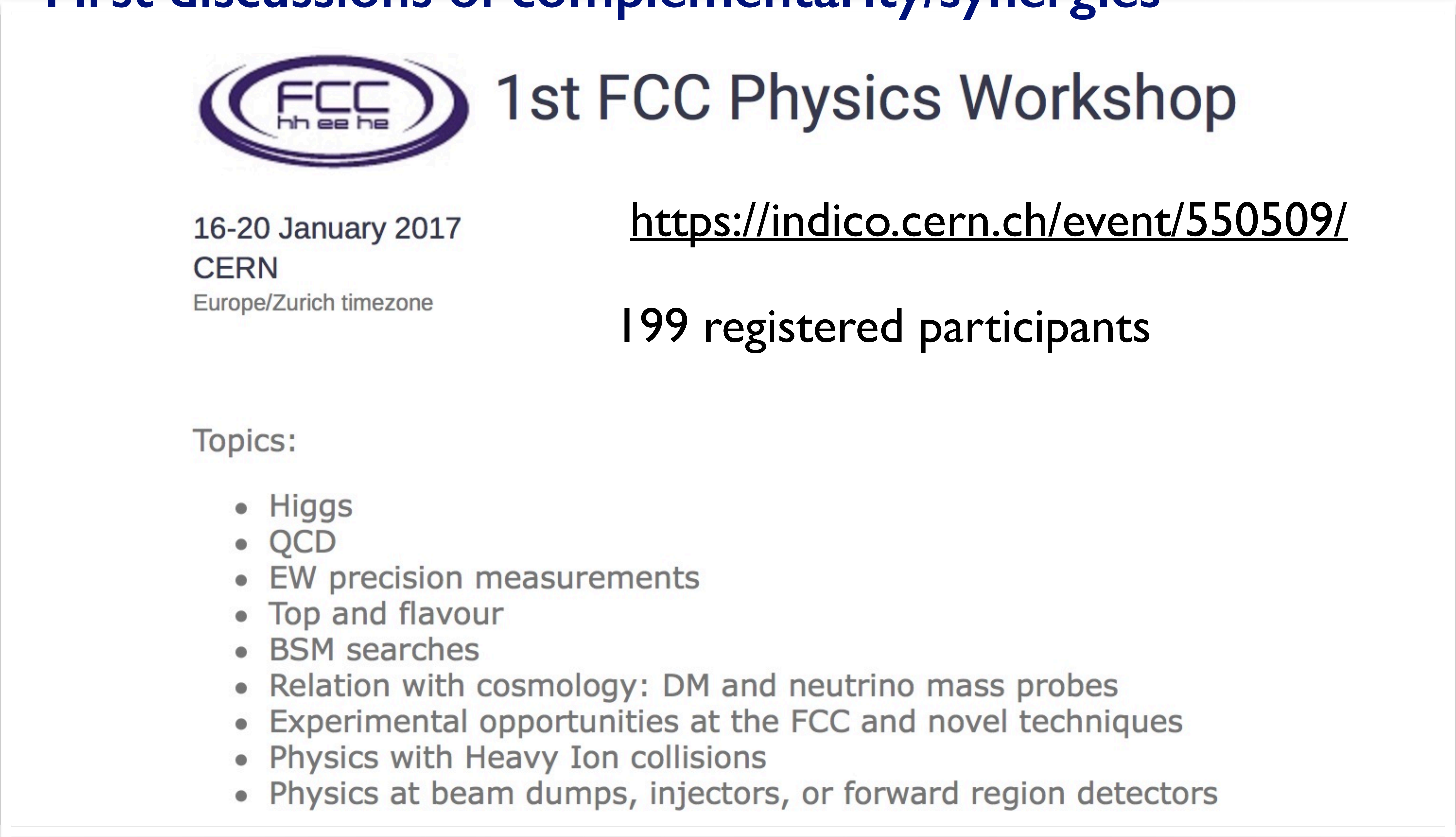
The goals of the Report

- With the firm belief that a FCC complex must appeal to more than the high-E physics progamme, sections of the Report focused on the additional opportunities offered by
  - heavy ion collisions
  - the exploitation of the injector chain (including the option of lower-E collisions in the last component of the injectors, eg the LHC)
- These components will not be discussed here, but should be considered as essential elements of the whole FCC project. They will further develop their own physics case as new results, open issues and ideas arise
- Flavour physics is another important component of a possible pp programme, which has not been studied as yet. Efforts are now focused on defining a programme for HL-LHC. Depending on the outcome of these studies, and on the development of the various flavour anomalies recorded by LHCb and flavour factories, dedicated efforts will be started (possibly post-CDR)

The next steps towards the CDR

- Consolidate the preliminary projections of the Report with dedicated detector simulation studies, including more realistic estimates of the experimental systematics
- Put the FCC-hh potential in the perspective of the global FCC physics programme:
  - Assess the complementarity and synergy with the deliverables of FCC-ee and FCC-eh
- FCC-hh has more work to do to be ready for this cross-facilities comparison, but preliminary results of this exercise will be documented in the 1st volume of the FCC CDR

First discussions of complementarity/synergies



1st FCC Physics Workshop

16-20 January 2017
CERN
Europe/Zurich timezone

Topics:

- Higgs
- QCD
- EW precision measurements
- Top and flavour
- BSM searches
- Relation with cosmology: DM and neutrino mass probes
- Experimental opportunities at the FCC and novel techniques
- Physics with Heavy Ion collisions
- Physics at beam dumps, injectors, or forward region detectors

https://indico.cern.ch/event/550509/

199 registered participants

… plus the session on Tue afternoon in Berlin

… to be continued at the 2nd FCC physics workshop, Jan 15-19 2018
https://indico.cern.ch/event/618254/

Current focus on FCC-hh physics: Detector studies

- **Detector design** group leader: Werner Riegler
  - Indico site of mtgs: http://indico.cern.ch/category/8920/
  - join the mailing list
- **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  - Indico site of mtgs: http://indico.cern.ch/category/6067/
  - join the mailing list
- Monthly mtgs of each group, if interested register to the mailing lists

=> see FCC-hh detector // sessions

The underlying rationale in building the physics case

- HEP has two priorities:
  - **explore the origin of known departures from the SM** (DM, neutrino masses, baryon asymmetry of the universe)
  - **explore the physics of electroweak symmetry breaking**:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)

The physics case of FCC project (ee, hh and eh) builds on the belief that these two directions are deeply intertwined

Key question for the future developments of HEP: Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios requires:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

The physics potential of any future HEP facility should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- ensure coverage of elusive signatures

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions

For the FCC, in particular:

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity
  - **tbd**: further clarification of the nature of new physics discovered at LHC or elsewhere

- Exploration potential:
  - mass reach enhanced by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
    - *statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC*
  - benefit from both direct (large Q^2) and indirect (precision) probes

- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

a remark

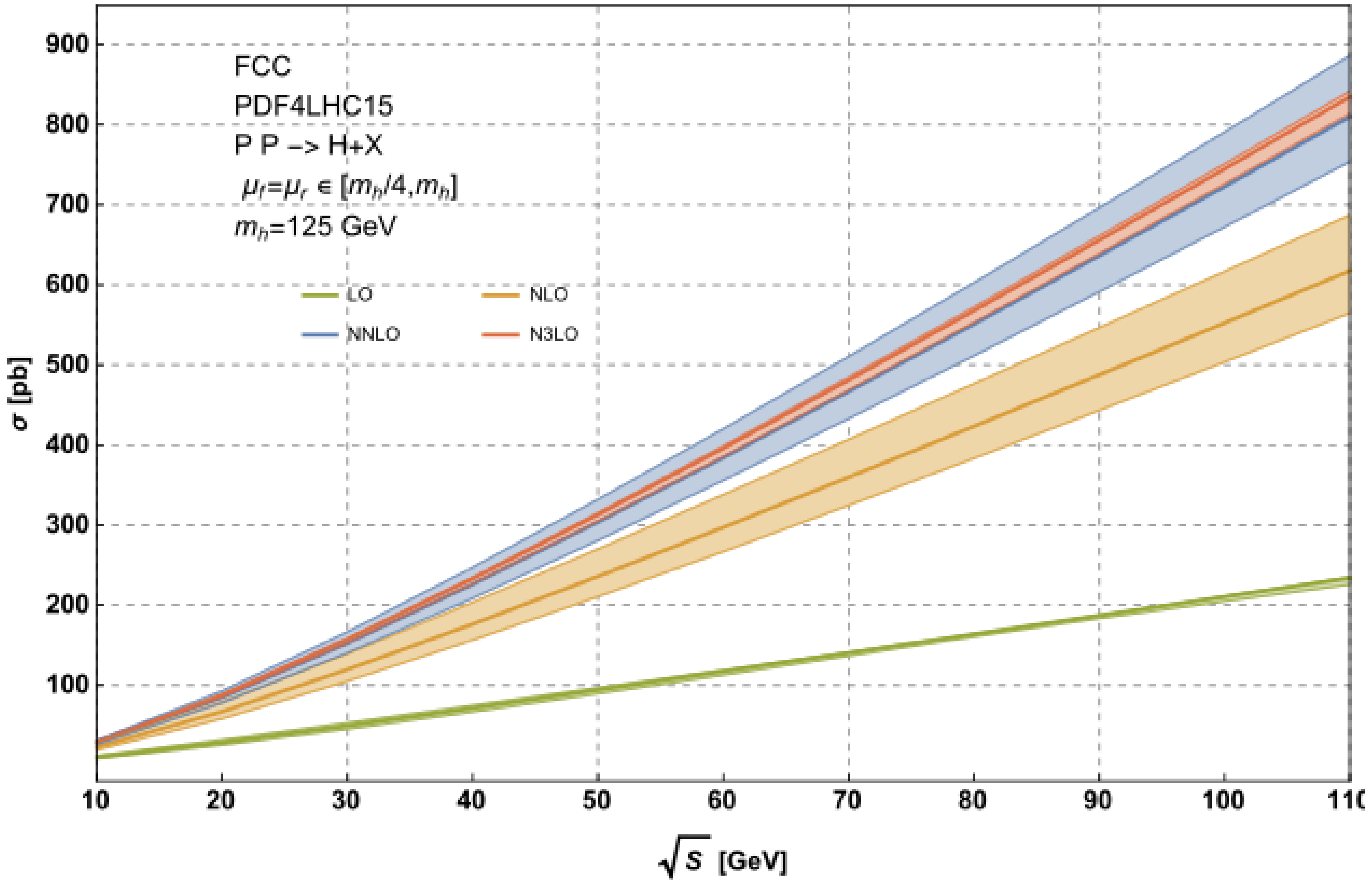
- The **FCC-hh** is part of the whole FCC, and it's the full exploitation of the FCC complex that guarantees the maximal outcome
- But the **FCC-hh** experiments are extremely versatile, and potentially capable, stand alone, to address a major part of the whole FCC programme
- As **FCC-hh**, we must explore every corner of its potential, from the discovery reach, to the precision frontier.
- The same should be (and is being) done by the FCC-ee studies….
- This puts the value of the individual projects in the right perspective, vis a vis possible future developments in HEP (eg discoveries at the LHC), in technology progress (eg time scale for 16T magnets), in the overall HEP landscape (eg approval of ILC, …), and in the political landscape (costs).
- And of course identifying areas where both ee and pp have independent sensitivity stimulates the assessment of synergy and complementarity ….

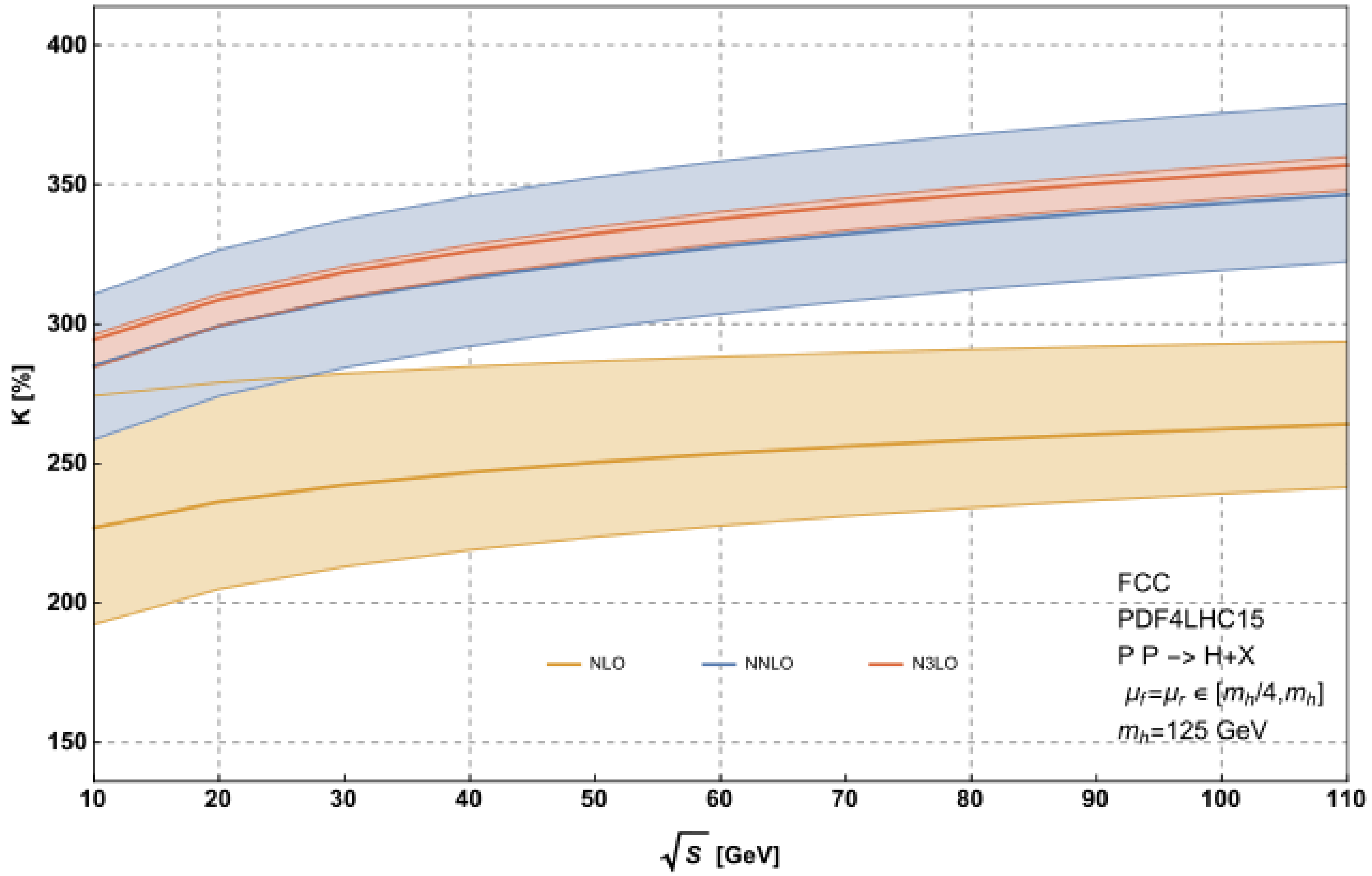
Status of SM calculations and tools reviewed in the SM volume

TH progress, an example

Figs H-1,2

Anastasiou et al, arXiv:1602.00695





δ_{PDF}	δ_{α_S}	δ_{scale}	$\delta_{\text{PDF-theo}}$	δ_{EW}	δ_{tbc}	$\delta_{\frac{1}{m_t}}$
$\pm 2.5\%$	$\pm 2.9\%$	$^{+0.8\%}_{-1.9\%}$	$\pm 2.5\%$	$\pm 1\%$	$\pm 0.8\%$	$\pm 1\%$

Table 3: Various sources of uncertainties of the inclusive gluon fusion Higgs production cross section at a 100 TeV proton-proton collider.

linear sum of all but PDF and α_S

$$\sigma = 802\ \text{pb}\ ^{+6.1\%}_{-7.2\%}(\delta_{\text{theo}})\,^{+2.5\%}_{-2.5\%}(\delta_{\text{PDF}})\,^{+2.9\%}_{-2.9\%}(\delta_{\alpha_s})$$

- **We've seen fantastic and unexpected progress in TH calculations since the start of the LHC.**

- **The most extreme kinematical regions covered by FCC-hh may pose new challenges, but HL-LHC will keep driving TH improvement efforts, and will allow crucial validation and tuning**

  - **It's impossible to predict how far this will go and what to expect by the time FCC-hh is running**

Ex: studies of EW corrections to DY in the multi-TeV mass region

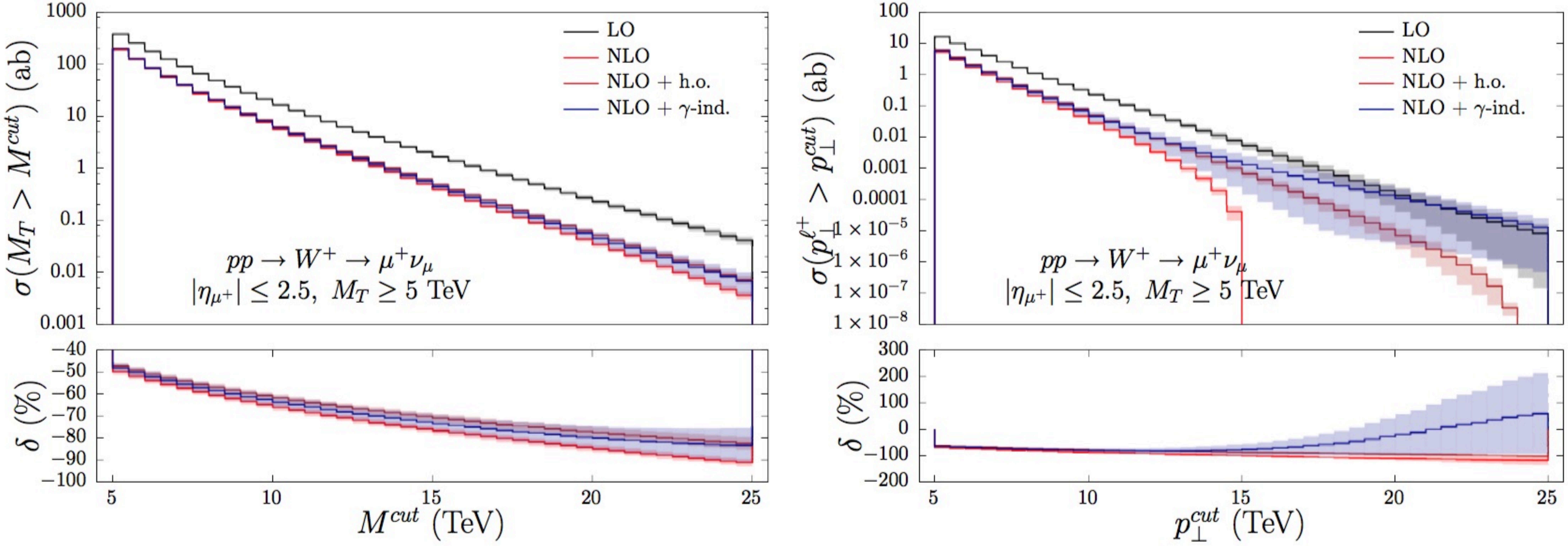
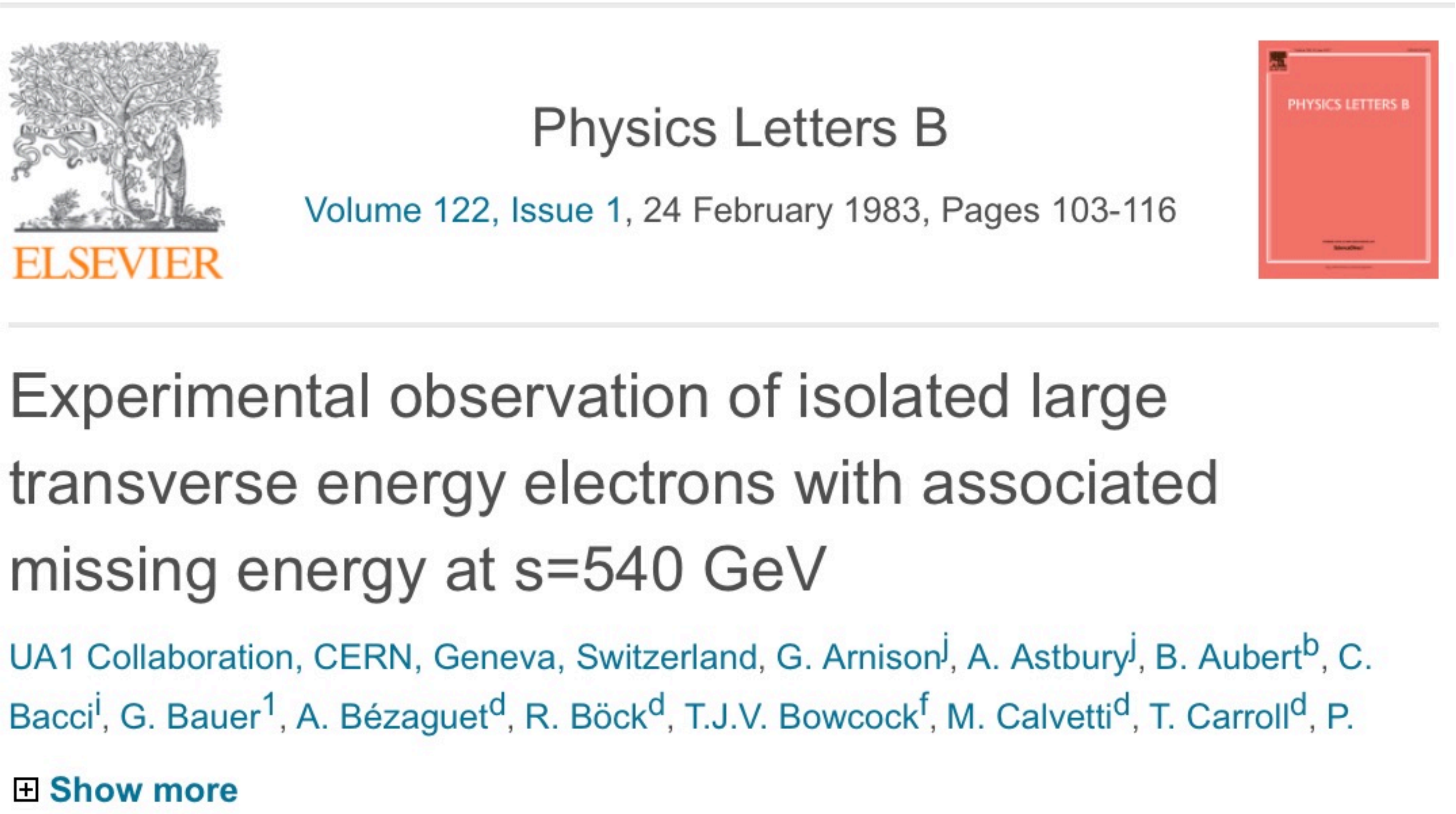


Fig SM-176

Higgs physics

1983



Physics Letters B

Volume 122, Issue 1, 24 February 1983, Pages 103-116

Experimental observation of isolated large transverse energy electrons with associated missing energy at s=540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland, G. Arnison[j], A. Astbury[j], B. Aubert[b], C. Bacci[i], G. Bauer[1], A. Bézaguet[d], R. Böck[d], T.J.V. Bowcock[f], M. Calvetti[d], T. Carroll[d], P.

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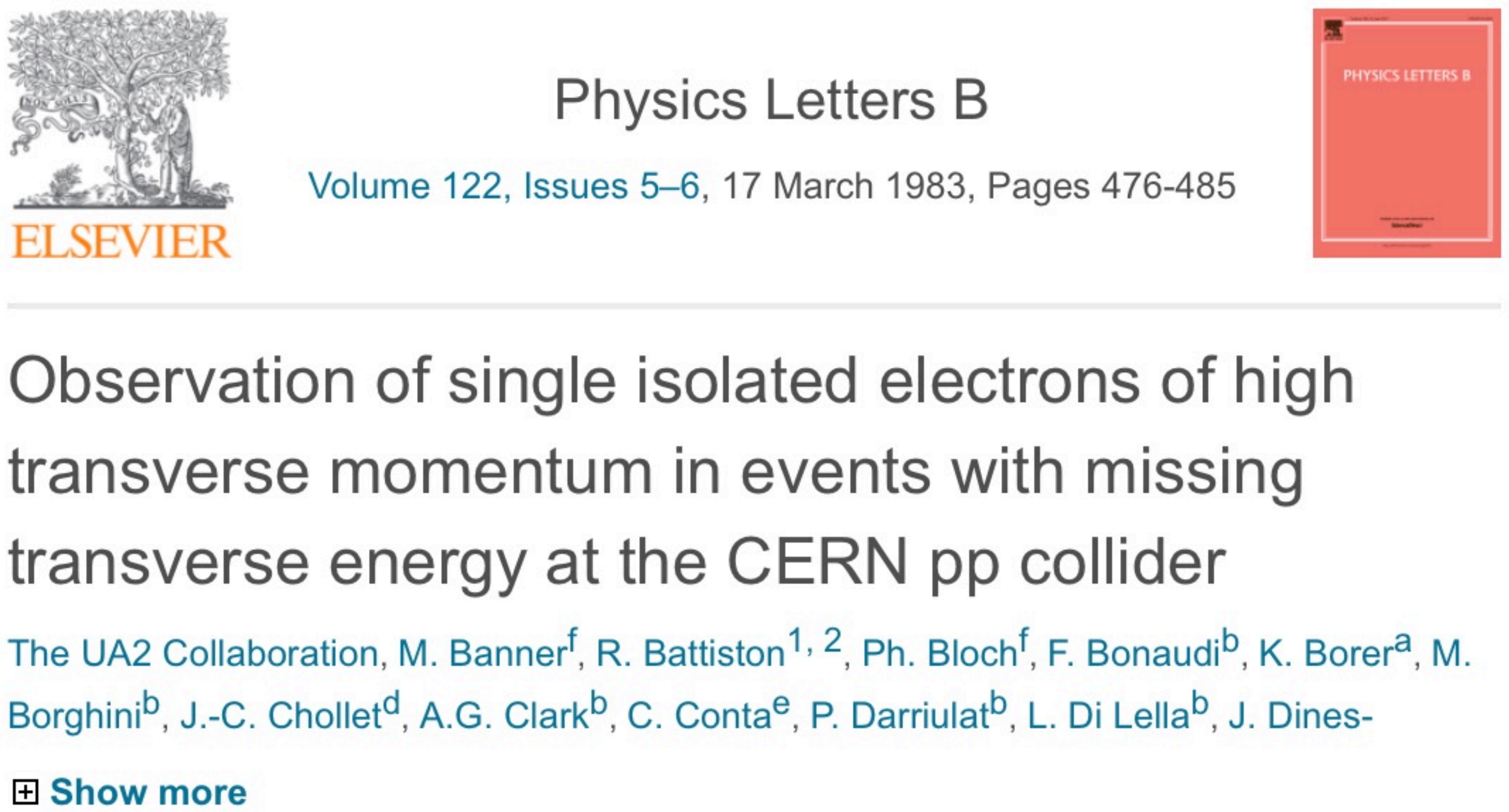

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Volume 122, Issues 5–6, 17 March 1983, Pages 476-485

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The UA2 Collaboration, M. Banner[f], R. Battiston[1, 2], Ph. Bloch[f], F. Bonaudi[b], K. Borer[a], M. Borghini[b], J.-C. Chollet[d], A.G. Clark[b], C. Conta[e], P. Darriulat[b], L. Di Lella[b], J. Dines-

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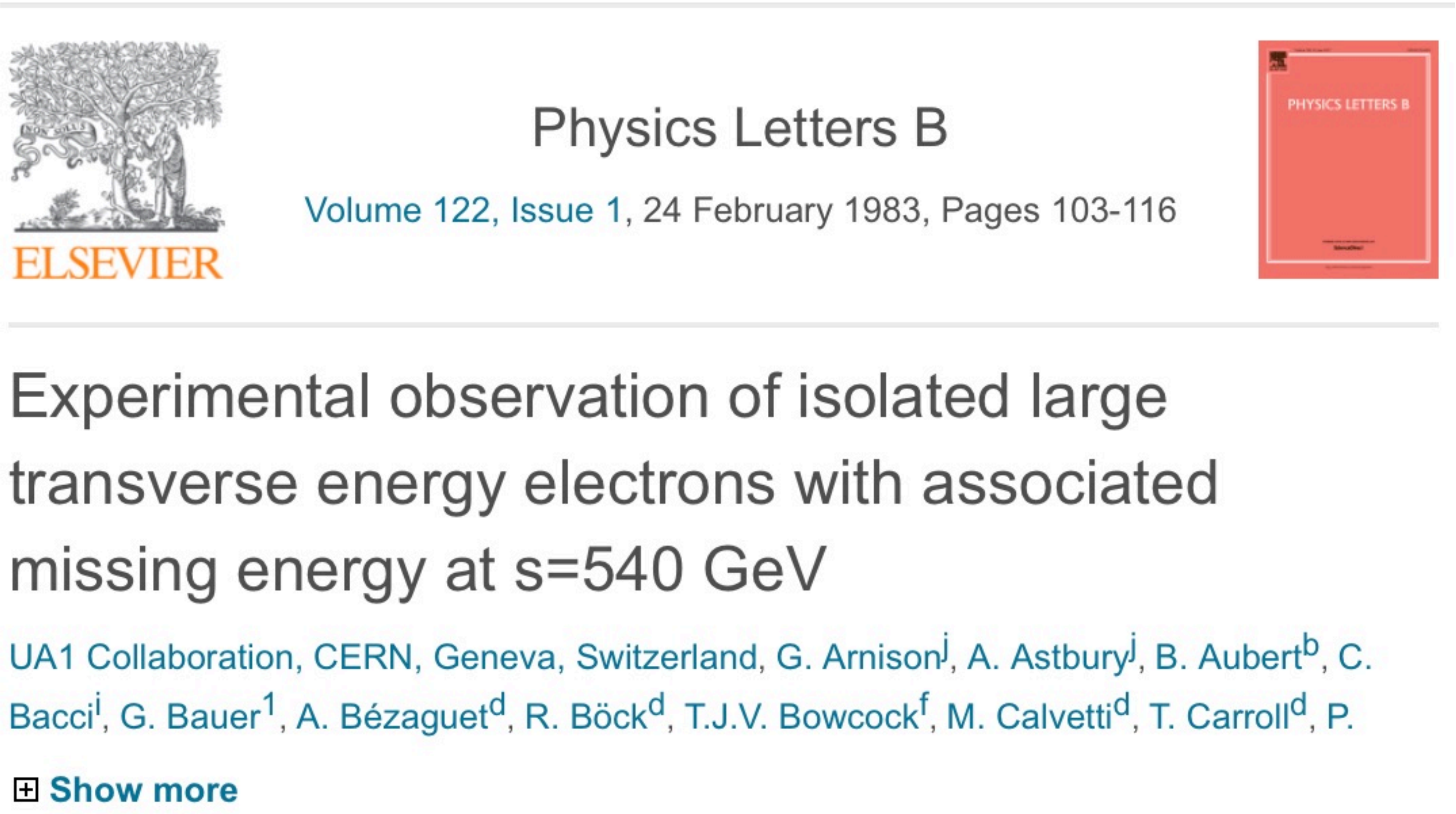
important things take time …

1983 → 2017



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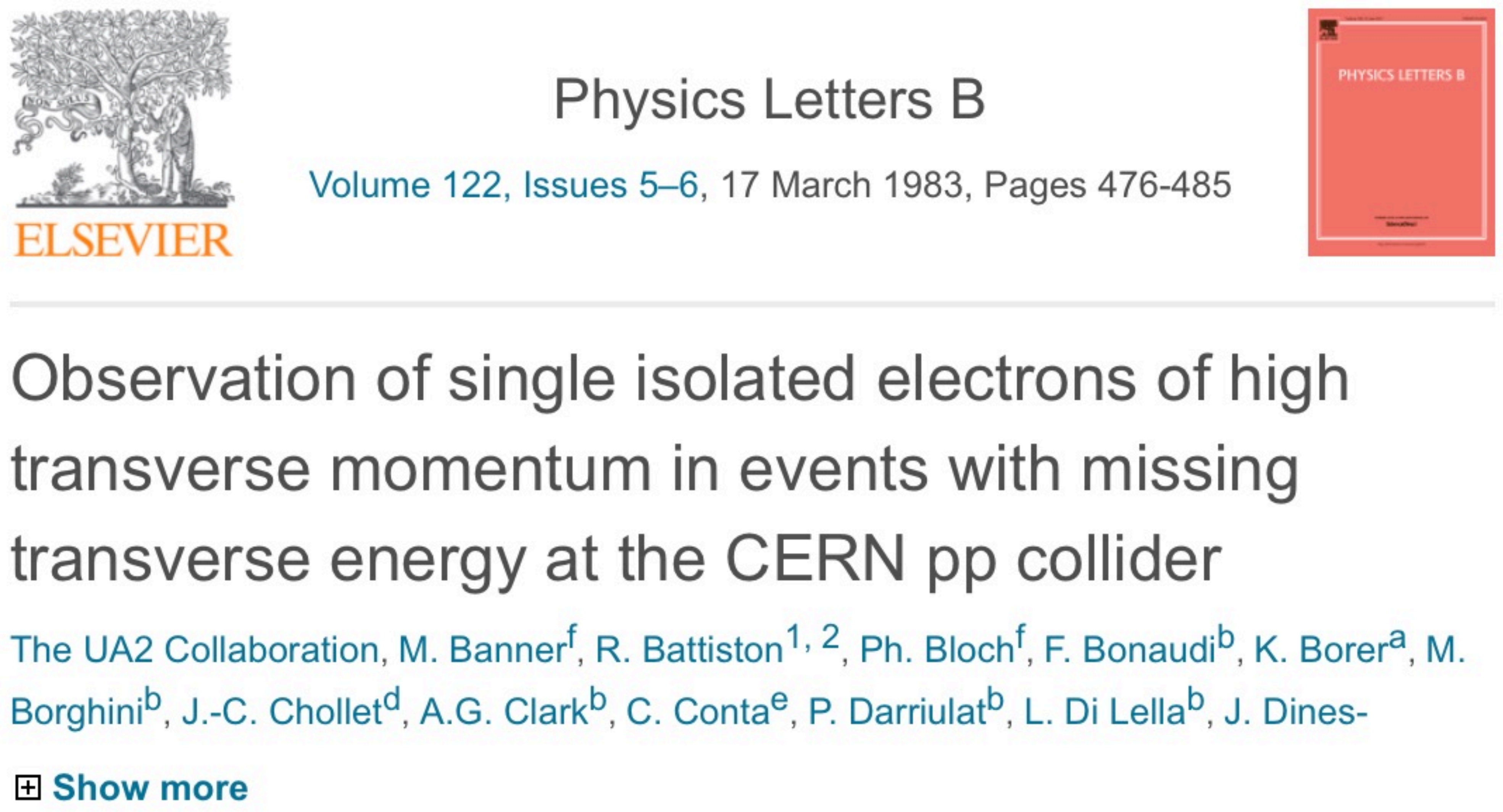

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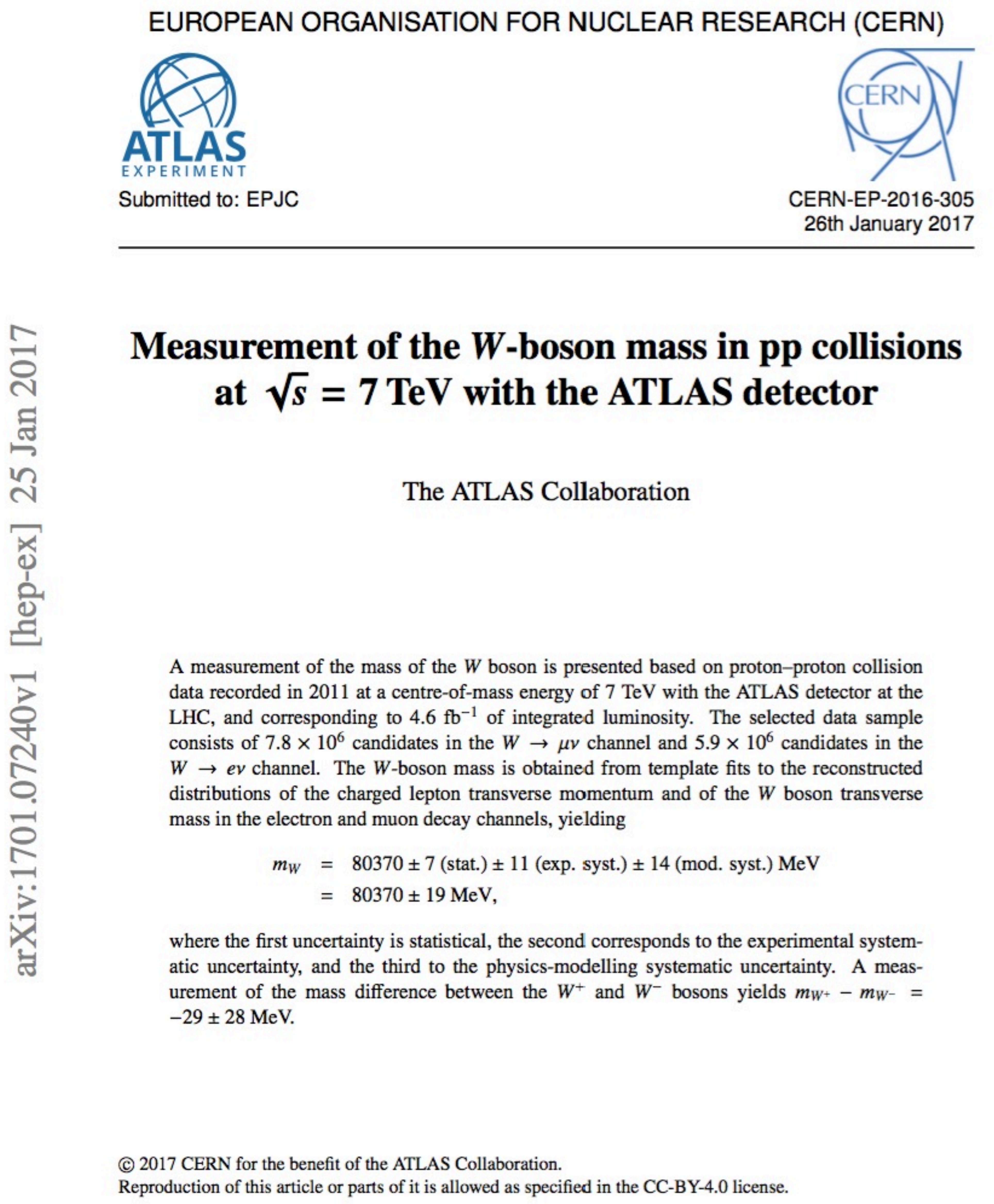


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: EPJC

CERN-EP-2016-305
26th January 2017

Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

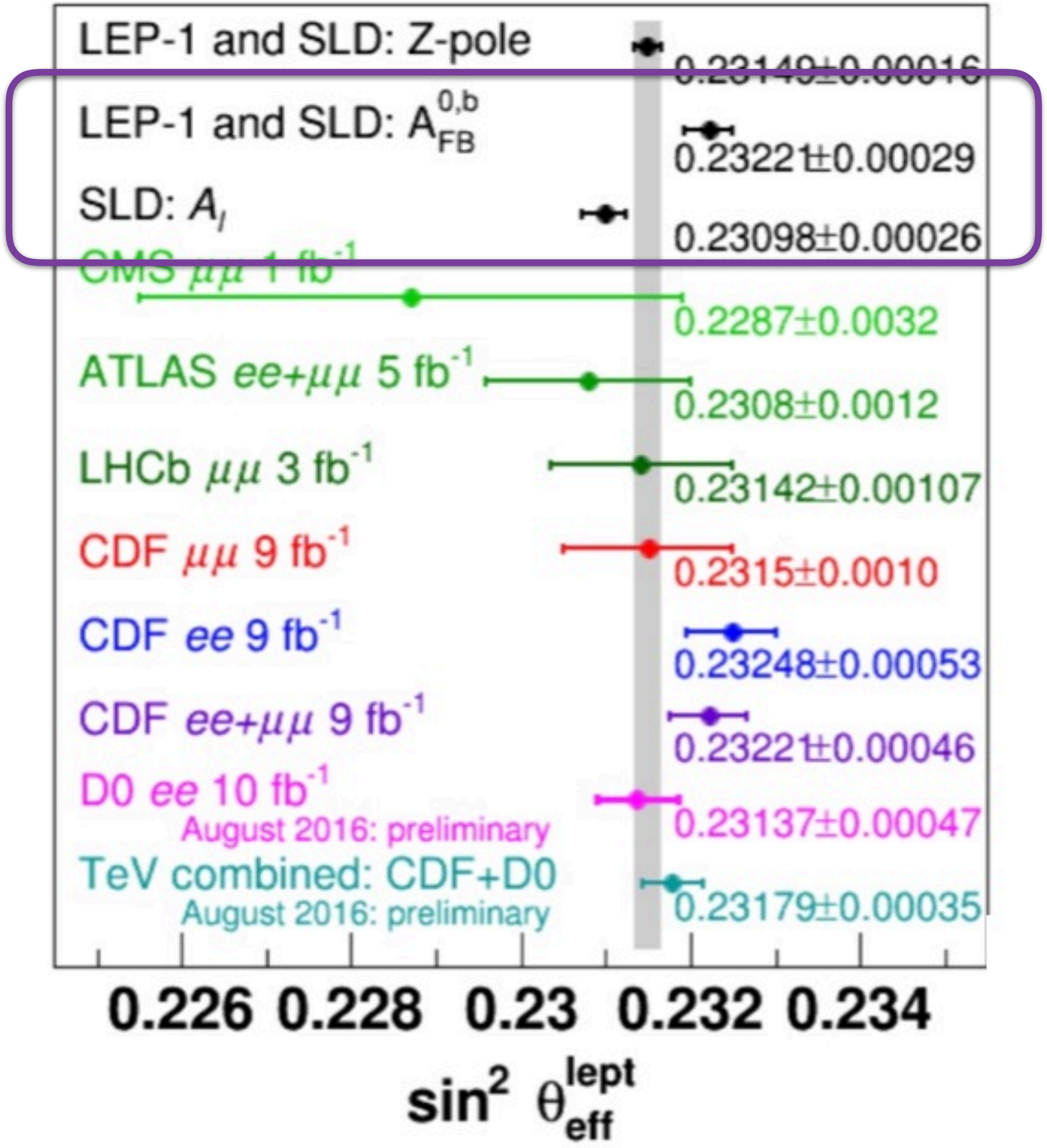
The ATLAS Collaboration

A measurement of the mass of the W boson is presented based on proton–proton collision data recorded in 2011 at a centre-of-mass energy of 7 TeV with the ATLAS detector at the LHC, and corresponding to 4.6 fb^{-1} of integrated luminosity. The selected data sample consists of 7.8×10^6 candidates in the $W \to \mu\nu$ channel and 5.9×10^6 candidates in the $W \to e\nu$ channel. The W-boson mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass in the electron and muon decay channels, yielding

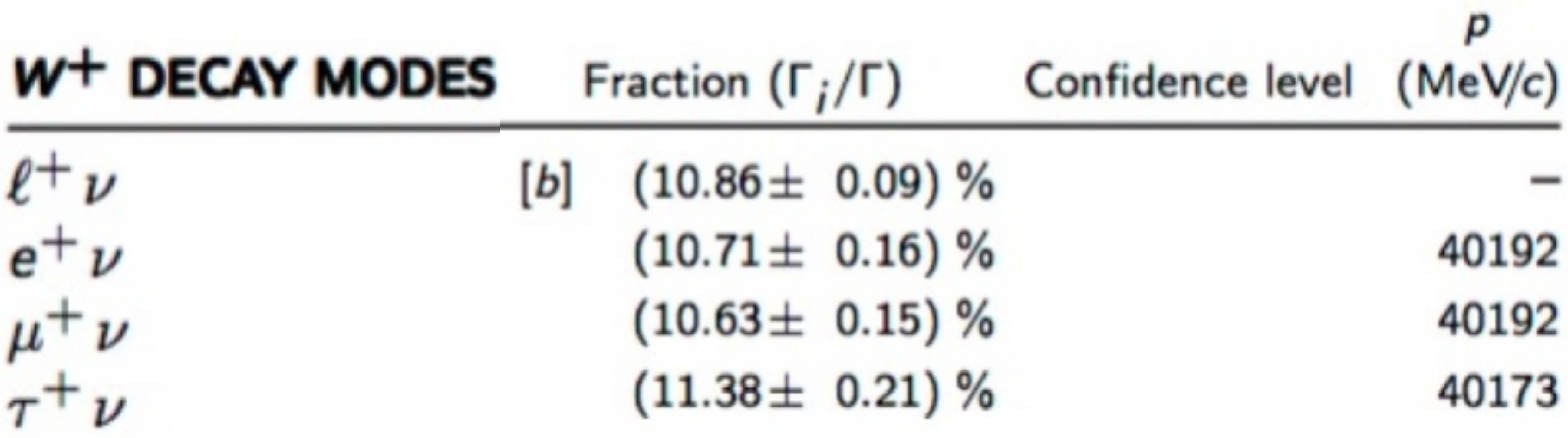
$$\begin{aligned} m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

where the first uncertainty is statistical, the second corresponds to the experimental systematic uncertainty, and the third to the physics-modelling systematic uncertainty. A measurement of the mass difference between the W^+ and W^- bosons yields $m_{W^+} - m_{W^-} = -29 \pm 28$ MeV.

34 years, and still open issues ….



PDG entries dominated by LEP2 data

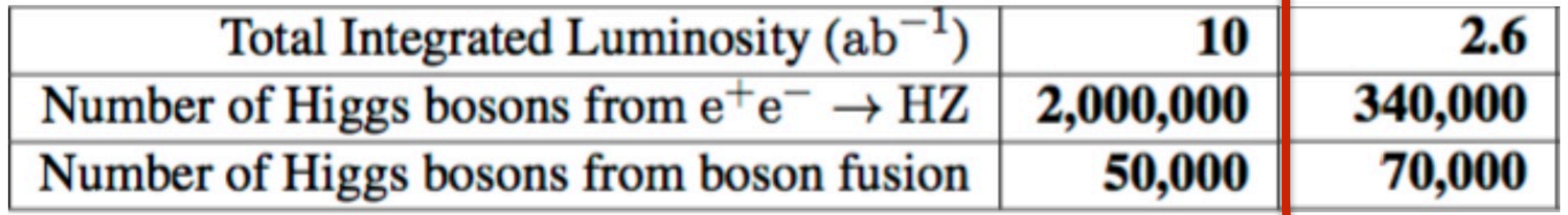


W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	$(10.86\pm\ 0.09)$ %		–
$e^+\nu$		$(10.71\pm\ 0.16)$ %		40192
$\mu^+\nu$		$(10.63\pm\ 0.15)$ %		40192
$\tau^+\nu$		$(11.38\pm\ 0.21)$ %		40173

BR(τ) / BR(e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ

That we like it or not, to anticipate 40 years of work to pin down the structure of the Higgs sector should not be seen as an outrageous prospect!

Higgs couplings @ FCC-ee



	240 GeV	350 GeV
Total Integrated Luminosity (ab^{-1})	10	2.6
Number of Higgs bosons from $e^+e^- \to HZ$	2,000,000	340,000
Number of Higgs bosons from boson fusion	50,000	70,000

the value of tt runs goes beyond top physics….

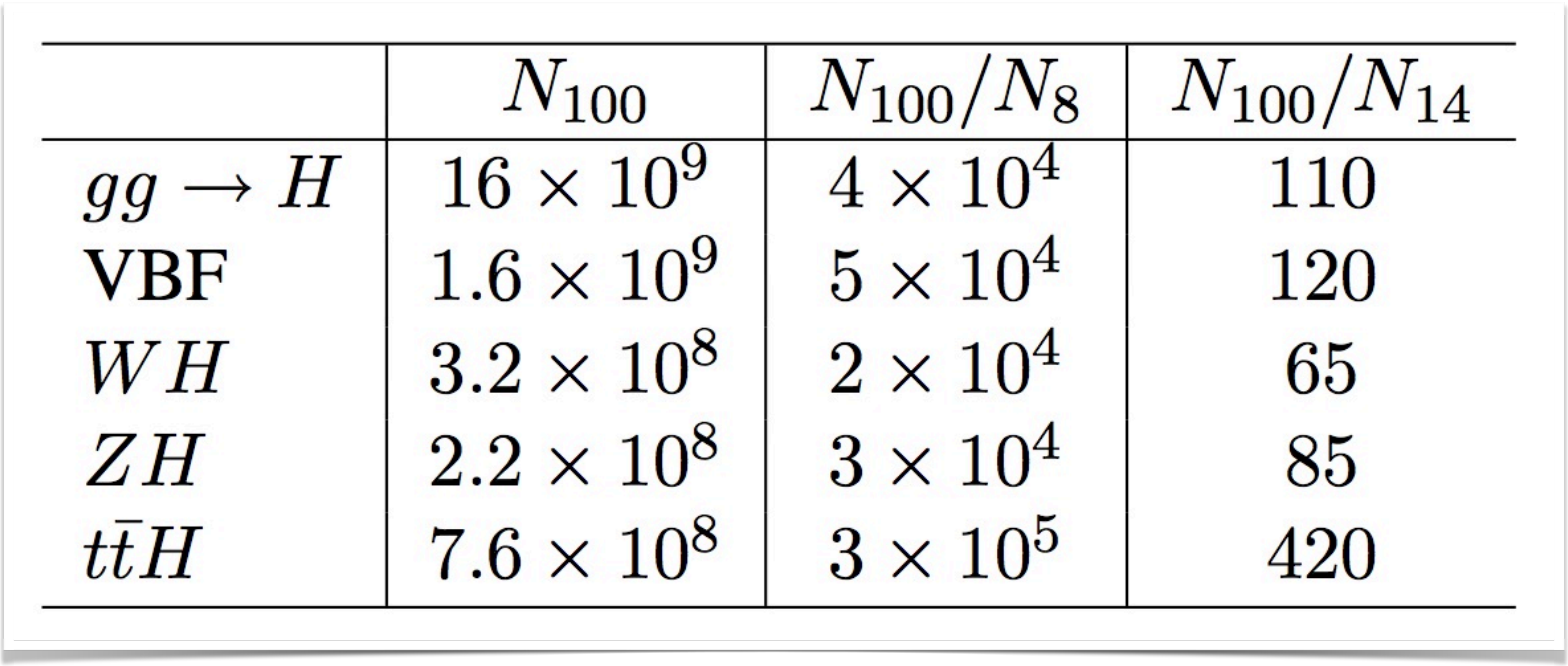
sub-% precision

g_{HXY}	240	240+350 (4IP)	240+350 (2IP)
ZZ	0.16%	0.15%	0.18%
WW	0.85%	0.19%	0.23%
bb	0.88%	0.42%	0.52%
cc	1.0%	0.71%	0.87%
gg	1.1%	0.80%	0.98%
ττ	0.94%	0.54%	0.66%
μμ	6.4%	6.2%	7.6%
γγ	1.7%	1.5%	1.8%
Zγ			
tt		~13% from loop effects at tt threshold	
HH	~30%	from loop effects at ZH production	
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR_{inv}	< 0.48%	< 0.45%	< 0.55%
Γ_{tot}		1%	

(SM: 0.12%)

SM Higgs rates at 100 TeV

Tab H-20



	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

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

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

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

Remarks

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- 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.

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- 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.

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- 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, μ~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. δO=1% ⇒ Λ ~ 2.5 TeV

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

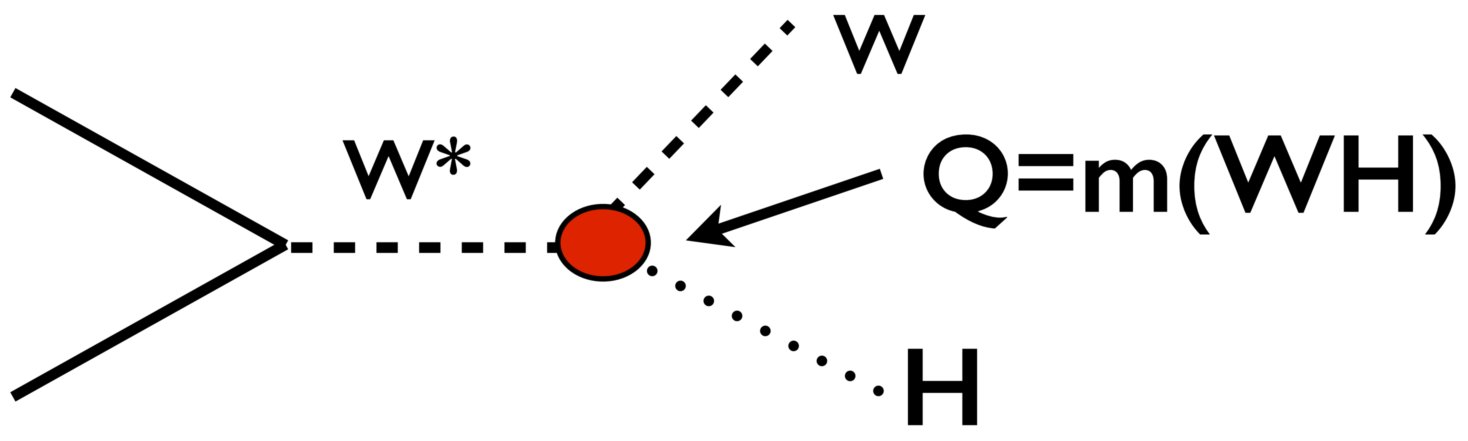
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

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

e.g. $\delta O = 15\%$ at $Q = 1$ TeV $\Rightarrow \Lambda \sim 2.5$ TeV

Examples

$\delta BR(H \to WW^*)$ ⟷



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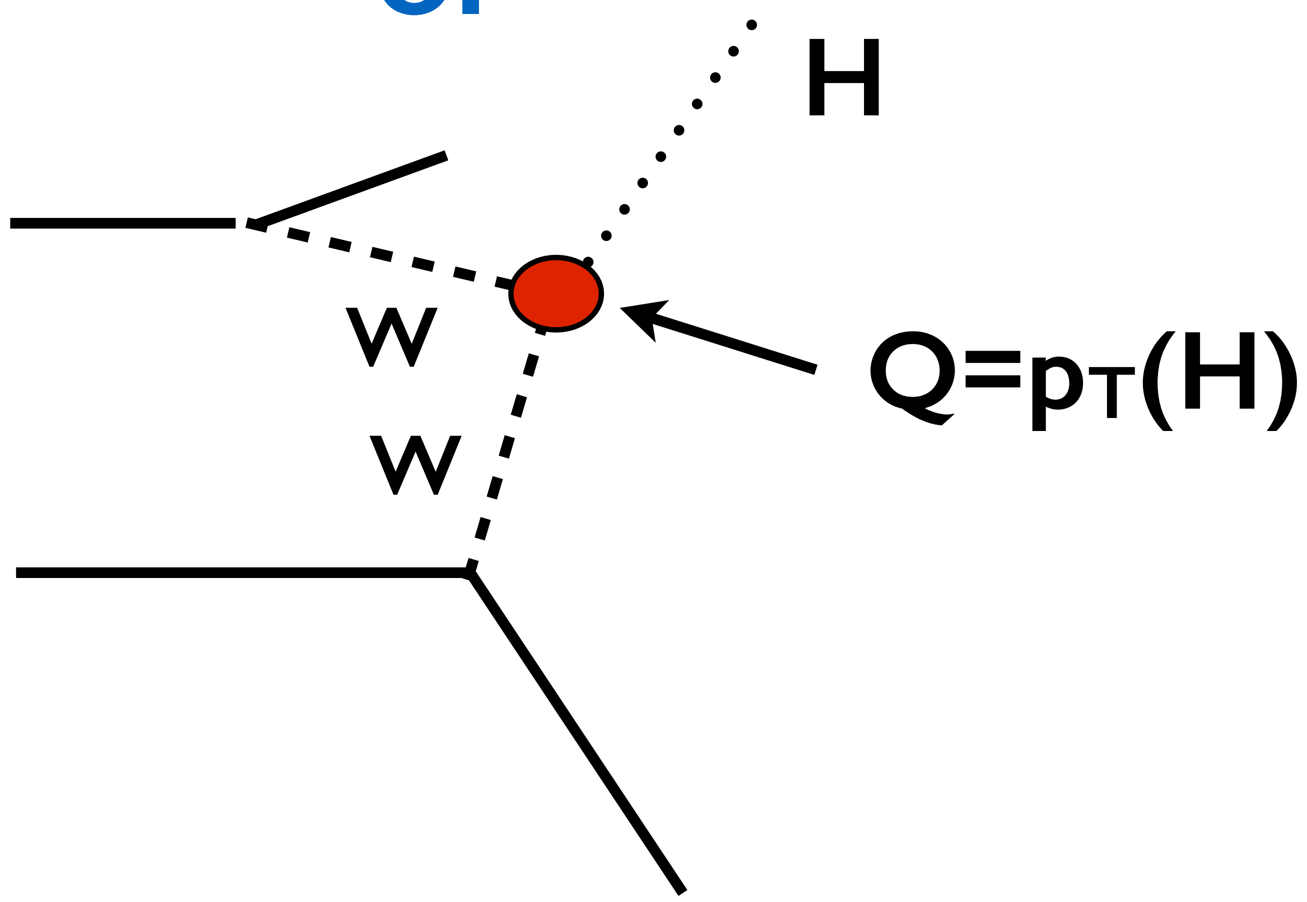
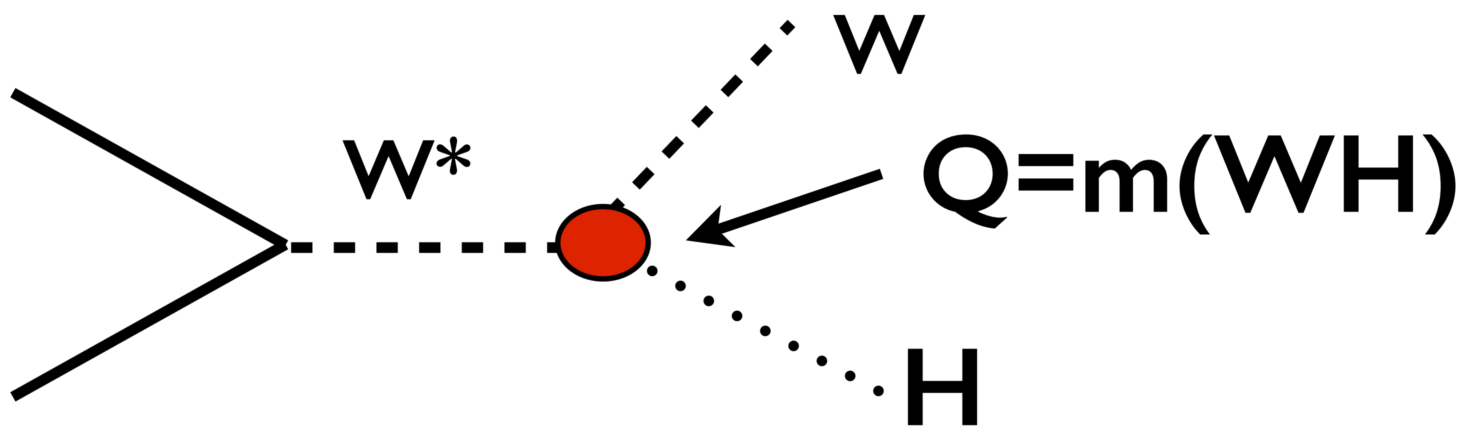


Examples

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



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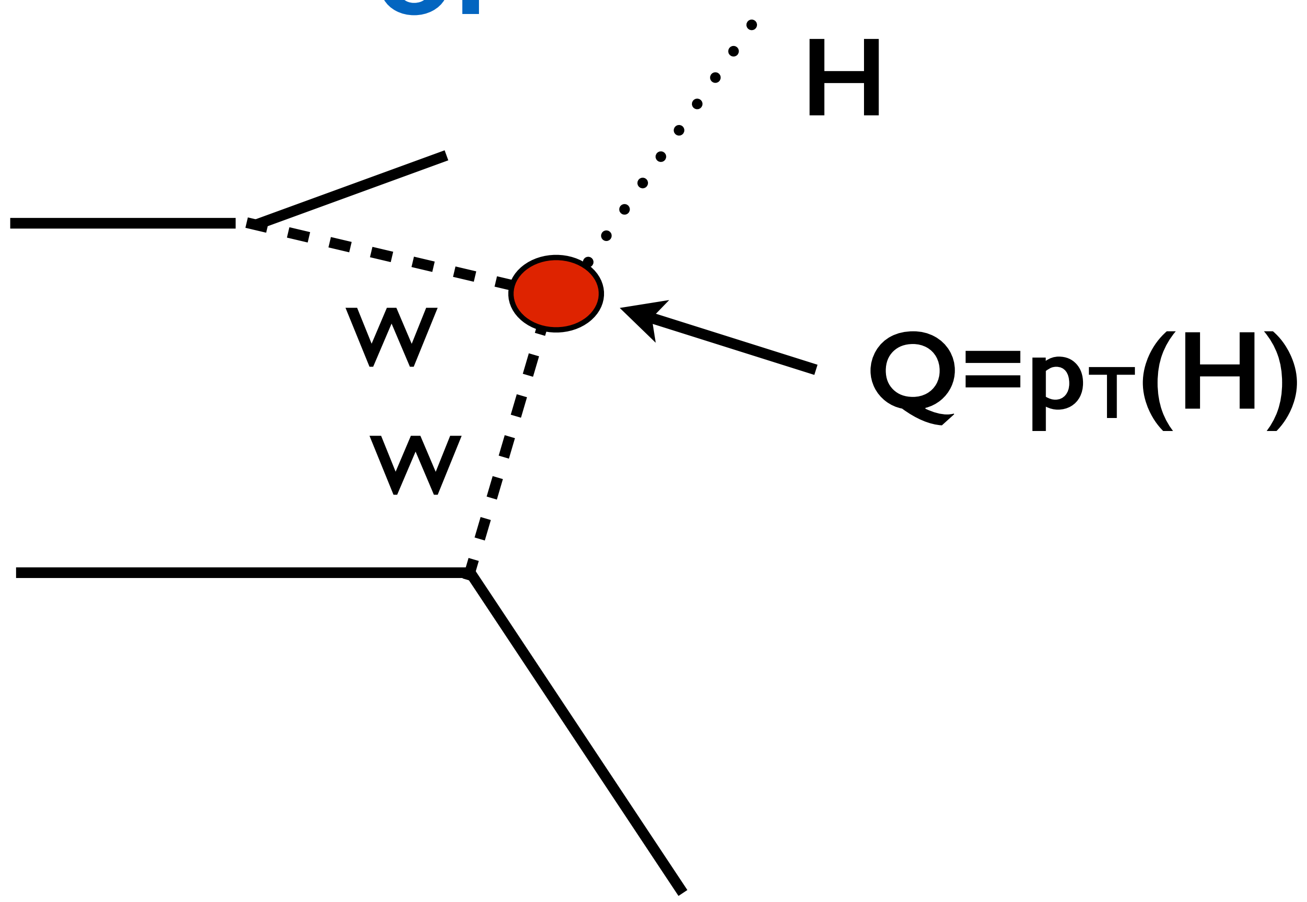
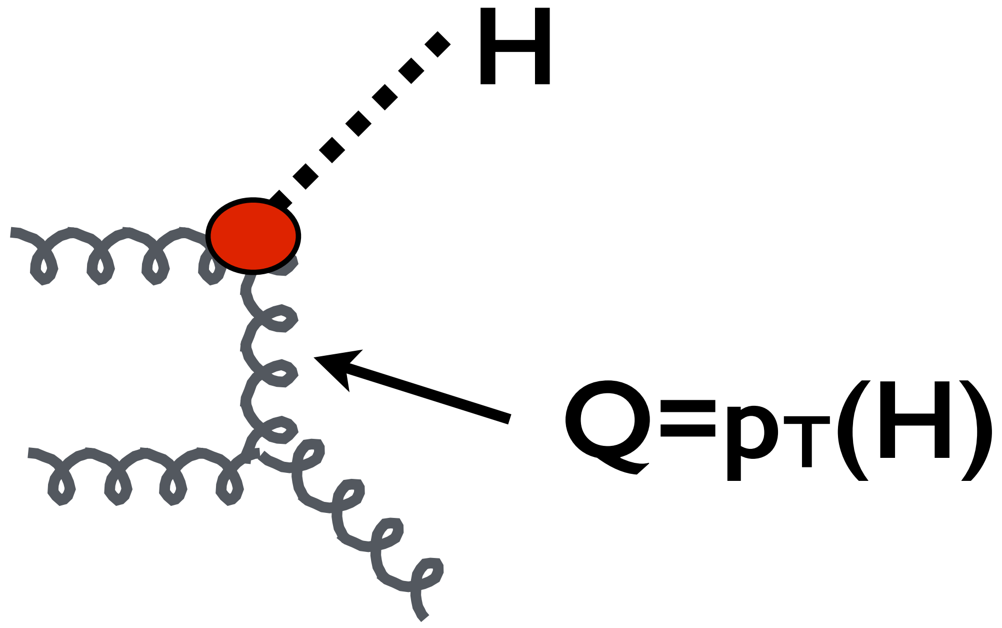


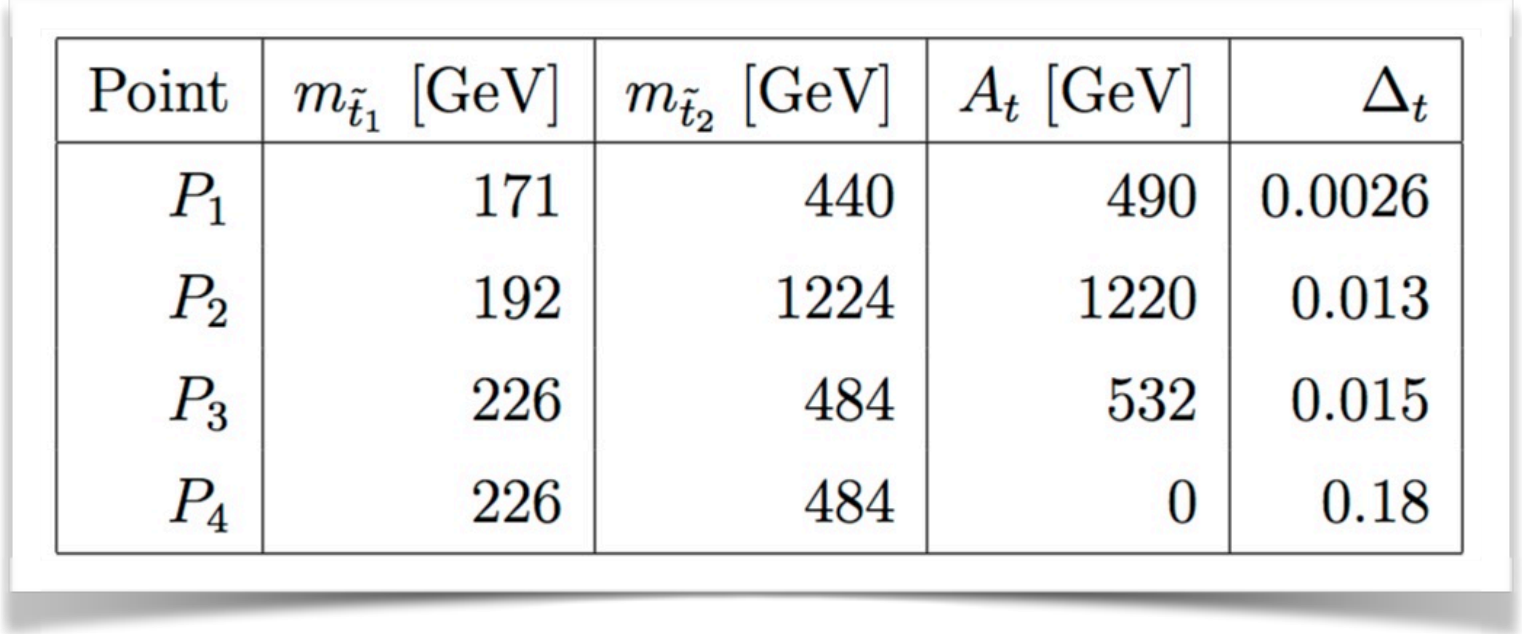
$\delta BR(H \to gg)$



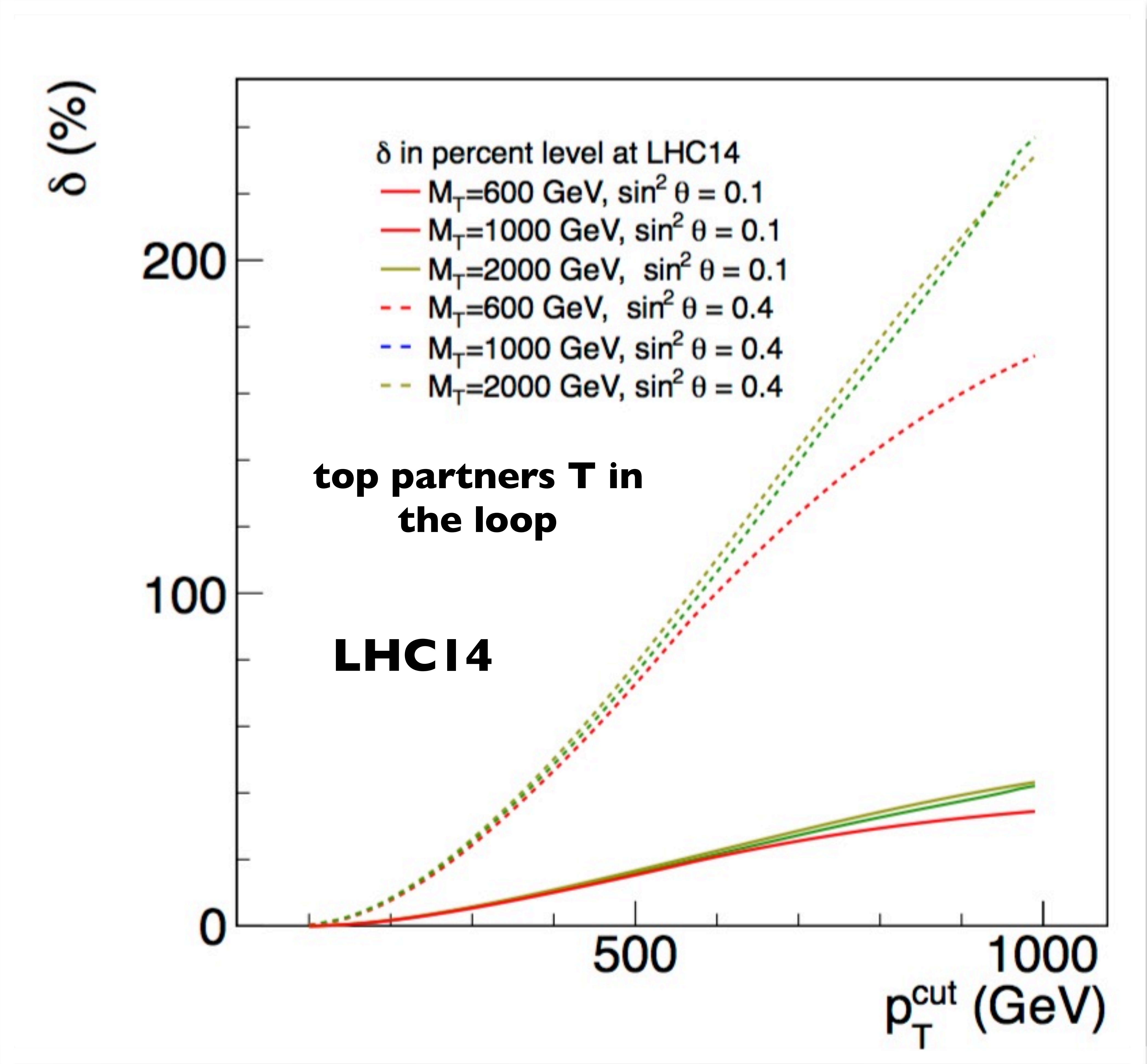
Examples

(See also
Azatov and Paul arXiv:1309.5273v3)

Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\mathrm{GeV}$, $M_2 = 1000\,\mathrm{GeV}$, $\mu = 200\,\mathrm{GeV}$ 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.



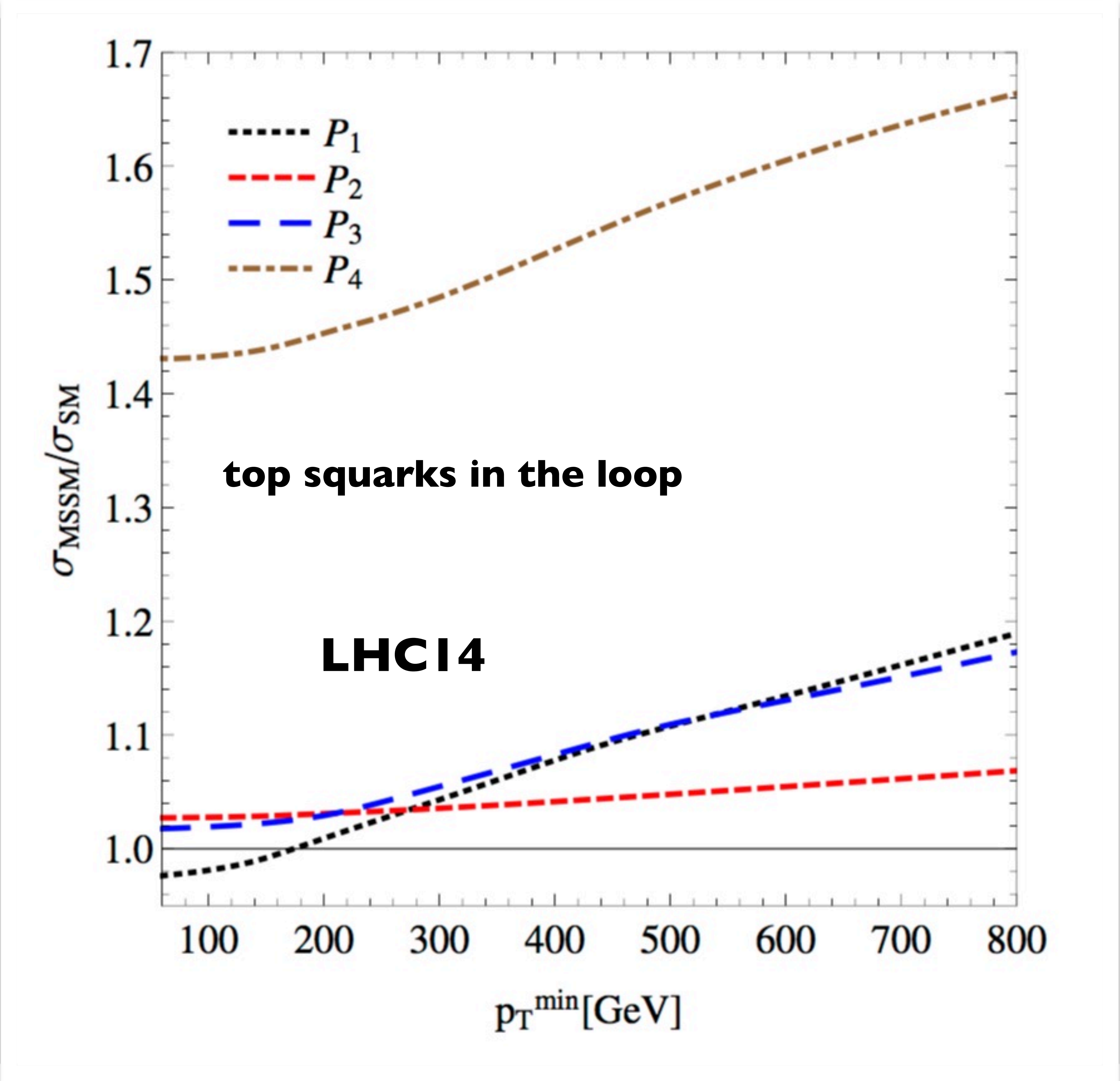
Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18



top partners T in the loop

LHC14

Banfi Martin Sanz, arXiv:1308.4771



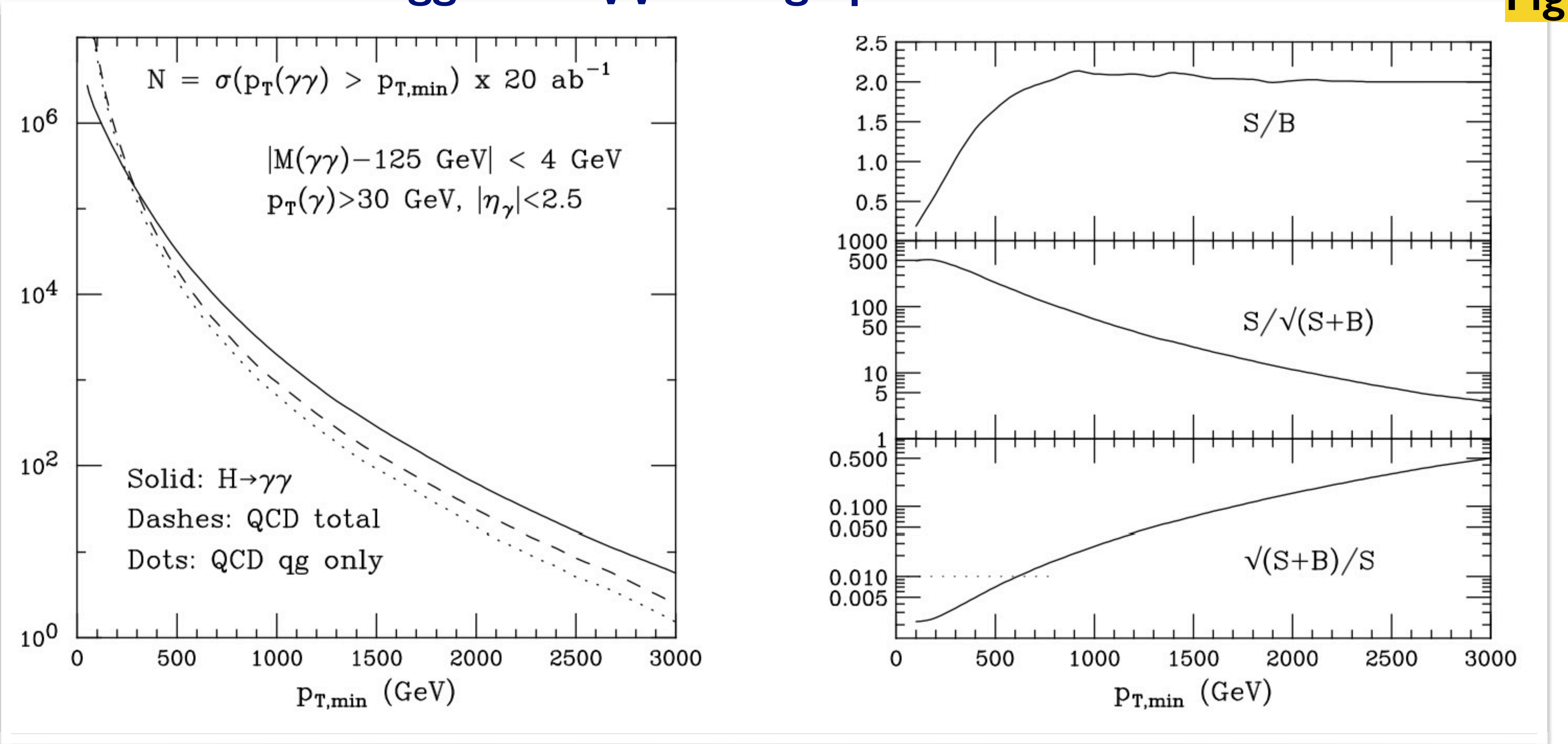
top squarks in the loop

LHC14

Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

gg→H→γγ at large p_T at 100 TeV

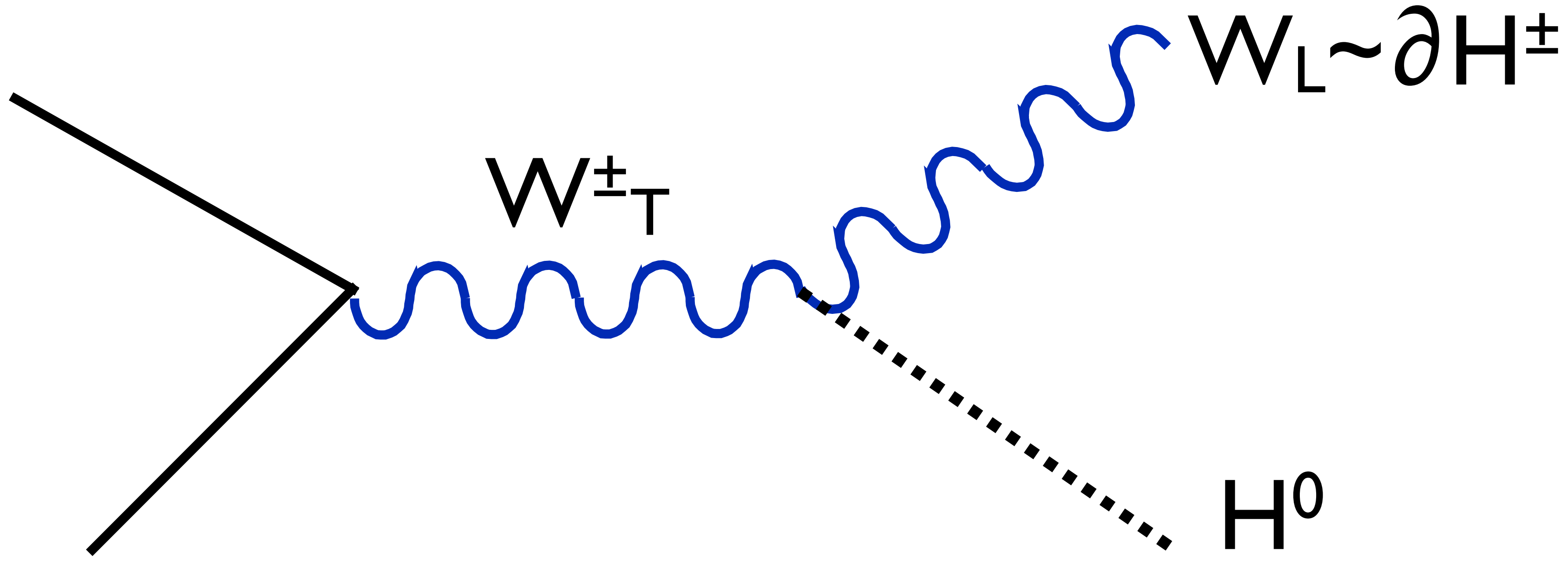
Fig H-45



- At 1 TeV, statistical sensitivity (accounting for bg) well below 10% !!
- What is a best BSM probe: BR(γγ) or shape of $p_T(H)$?
  - answer likely BSM-model dependent
    - ==> synergy/complementarity !!

VH prodution at large m(VH)

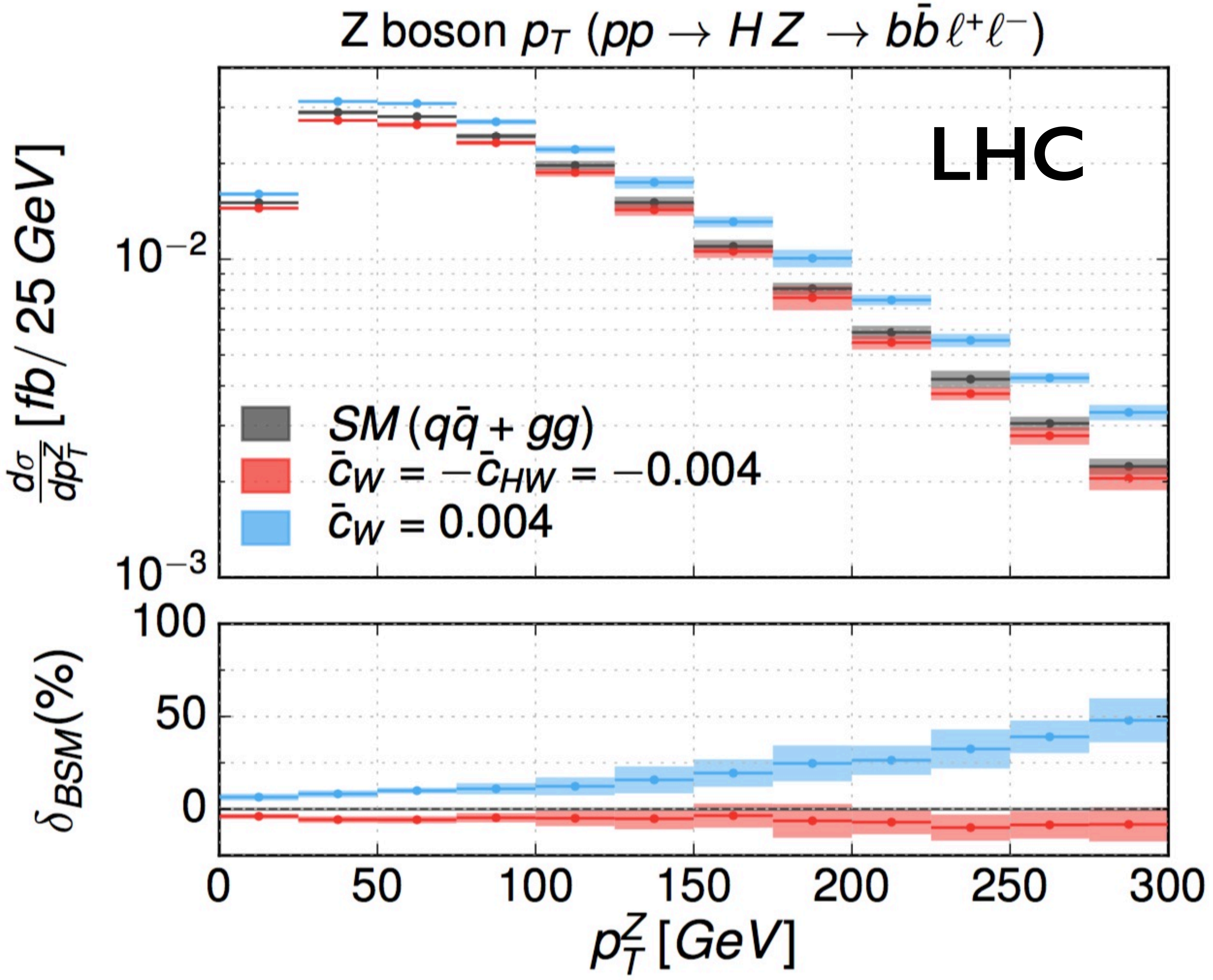
See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320



In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

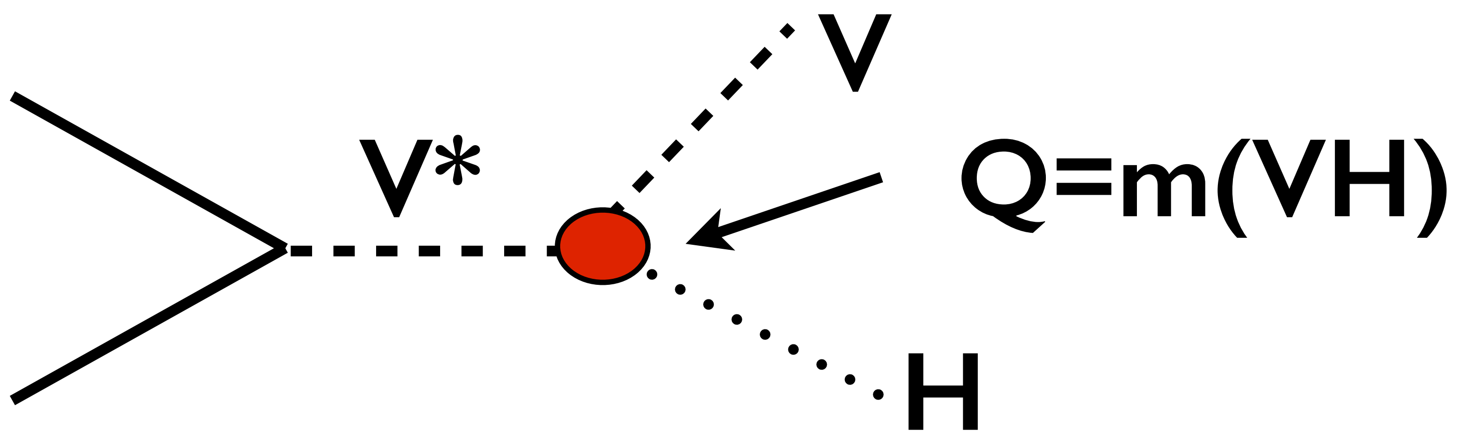


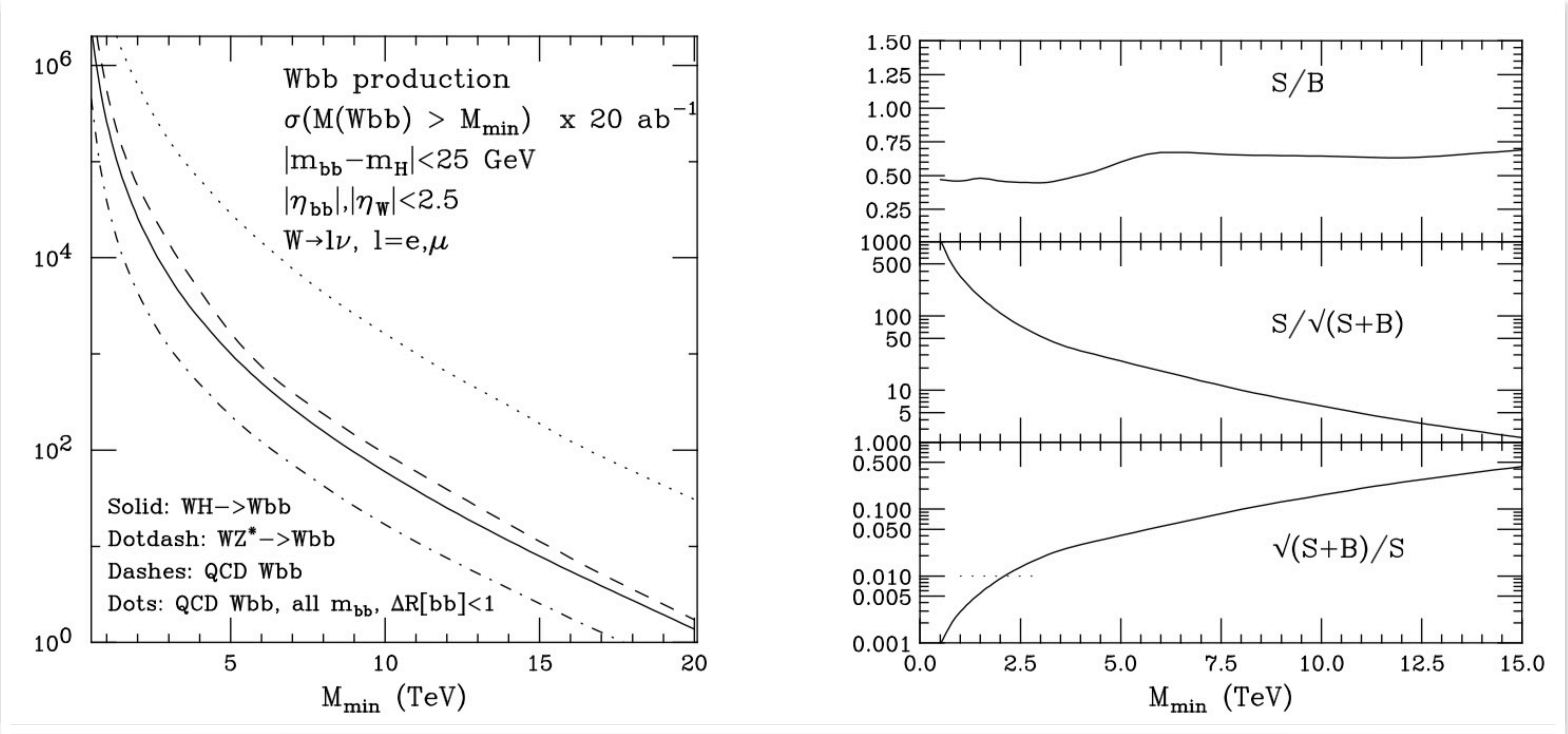
Mimasu, Sanz, Williams, arXiv:1512.02572v

WH→Wbb at large M_{WH}

100 TeV

Fig H-49



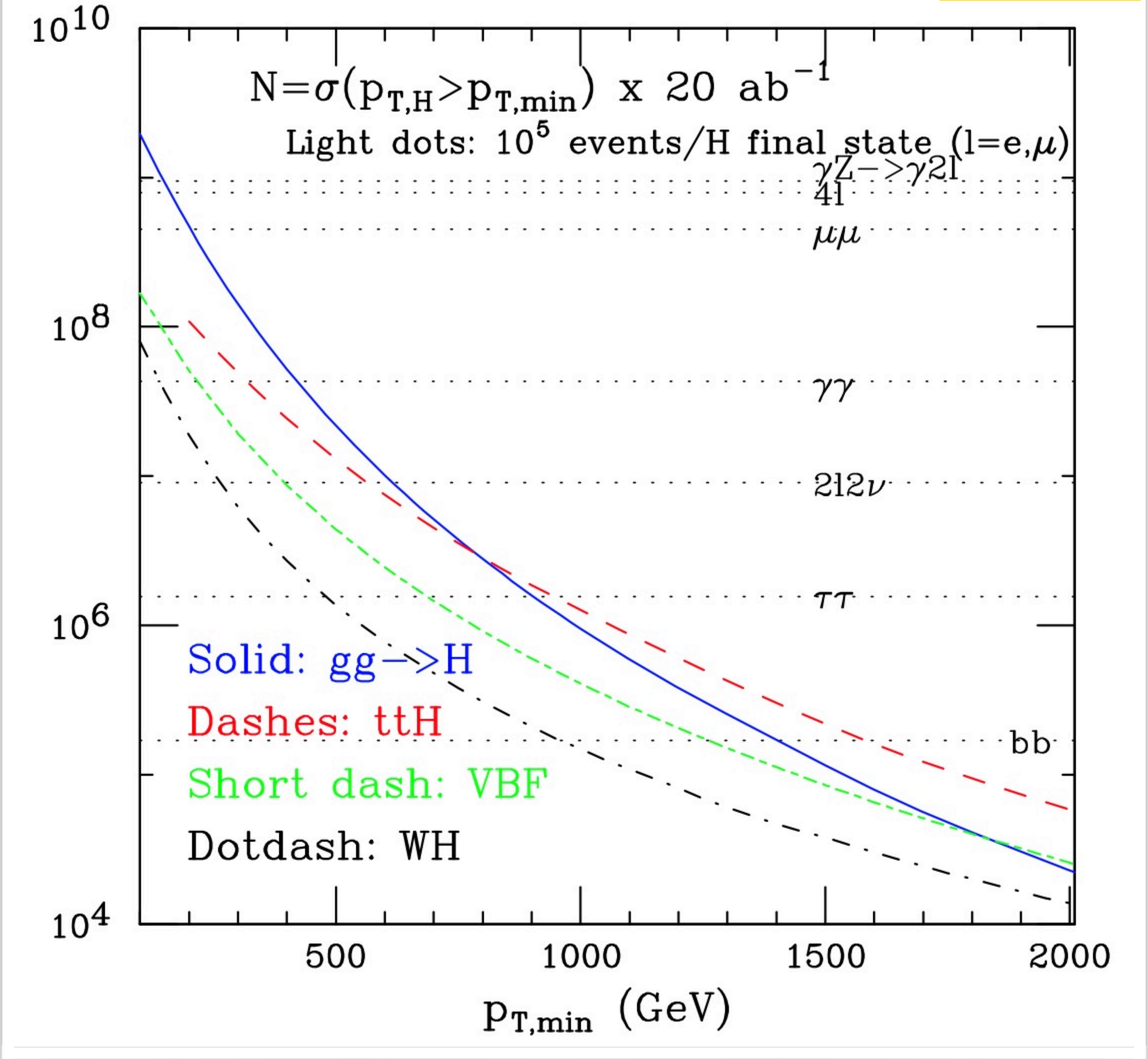


H at large p_T

Lesson: Hierarchy of production channels changes at large p_T(H):

- σ(ttH) > σ(gg→H) above 800 GeV
- σ(VBF) > σ(gg→H) above 1800 GeV

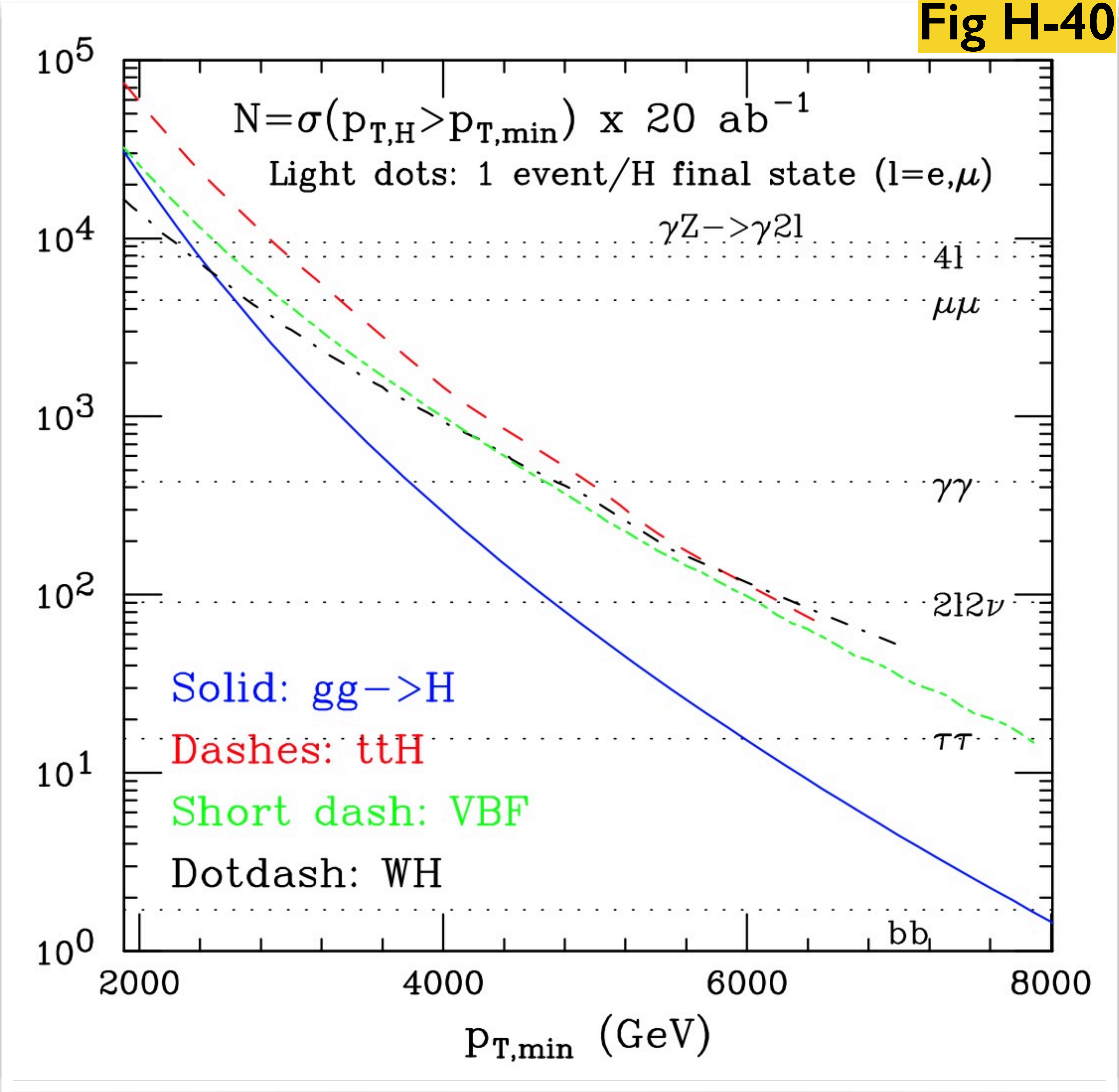
Fig H-40



H at large p_T

Statistics in potentially visible final states out to several TeV

Fig H-40

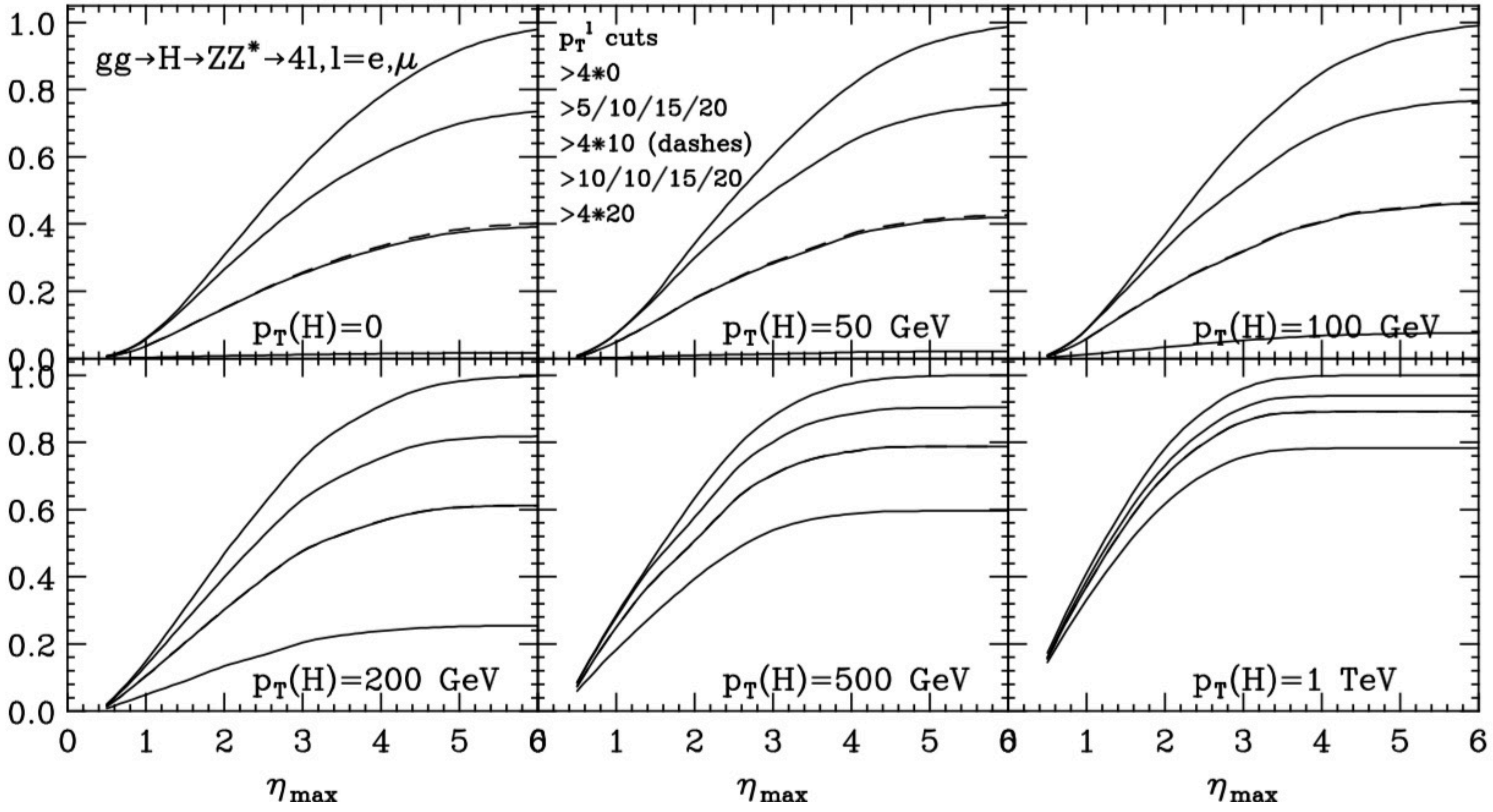


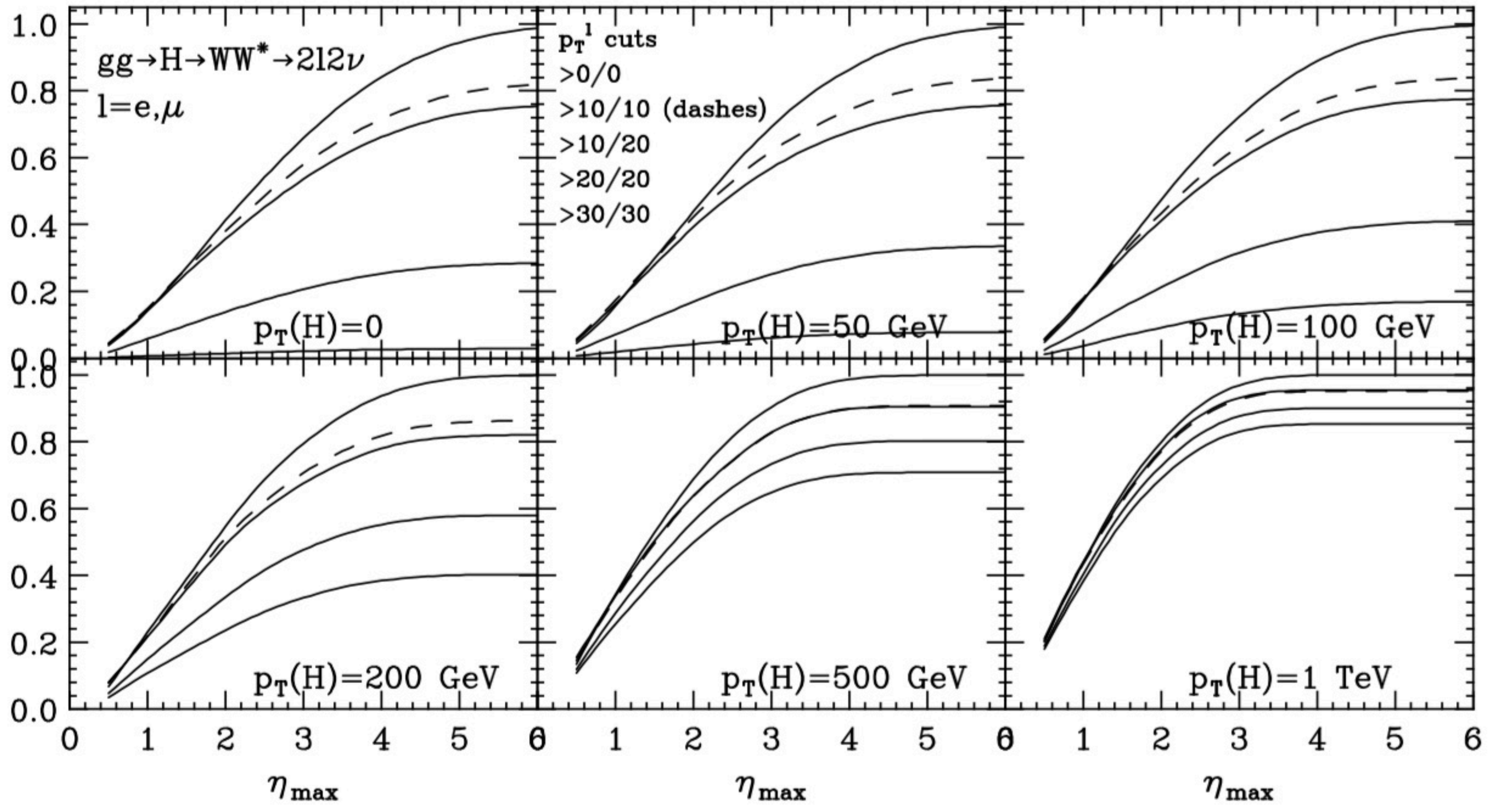
Opportunities for % - level measurements at intermediate p_T (100-500 GeV)

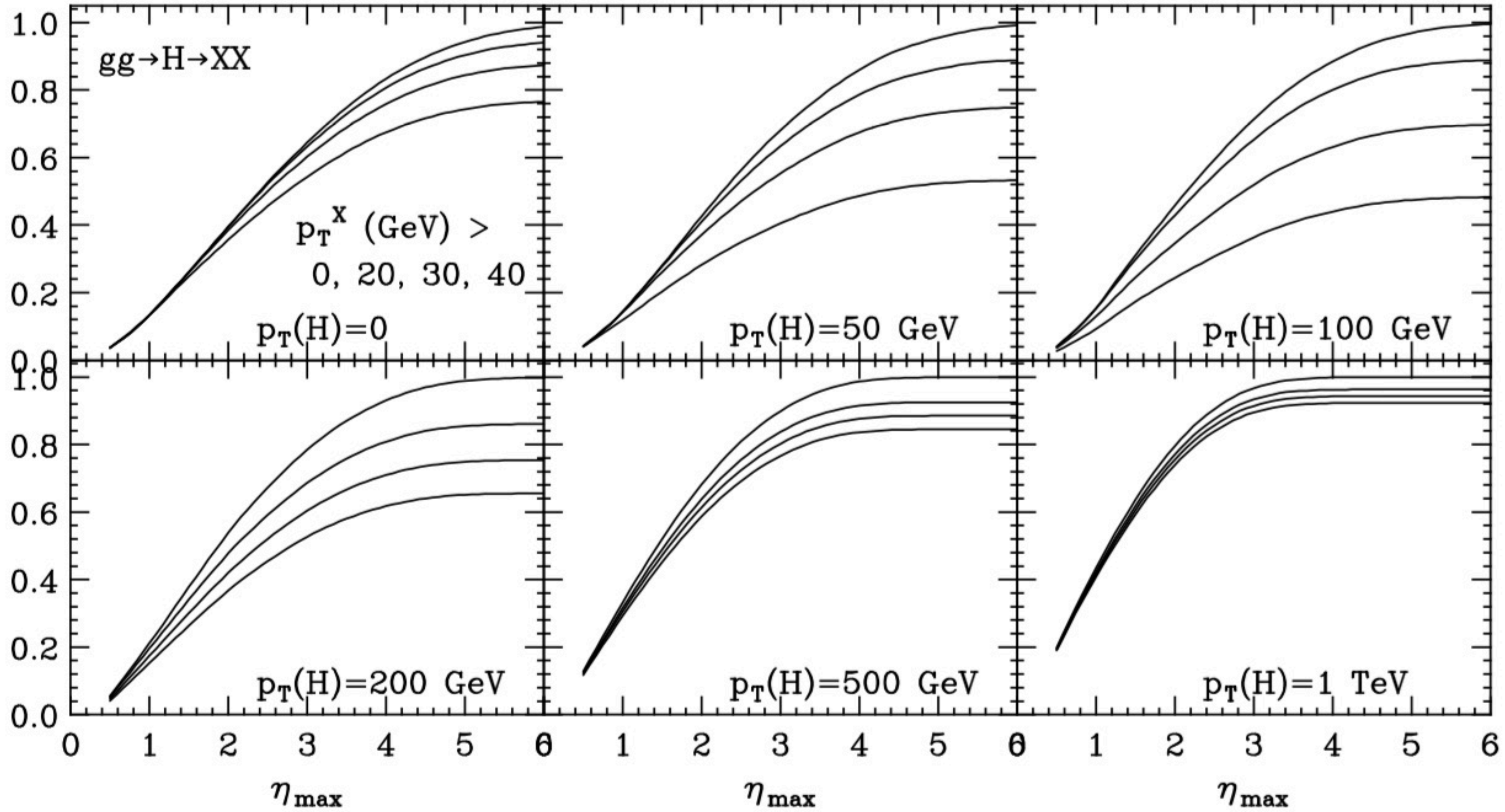
see M.Selvaggi in the FCC-hh physics/detector // session
Thursday for more recent Delphes-based studies

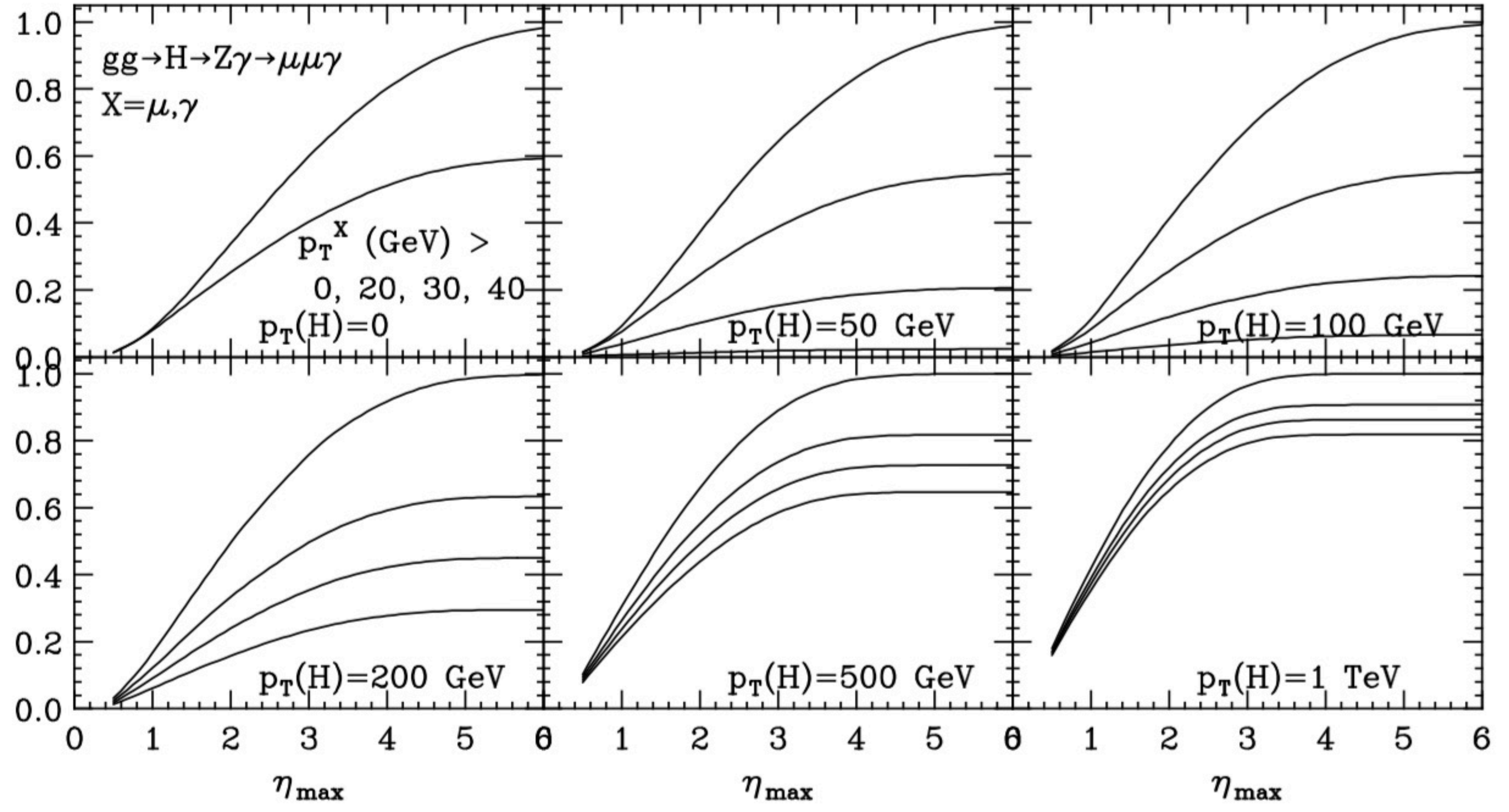
Acceptance studies vs pt(H)

Figs H-41/44



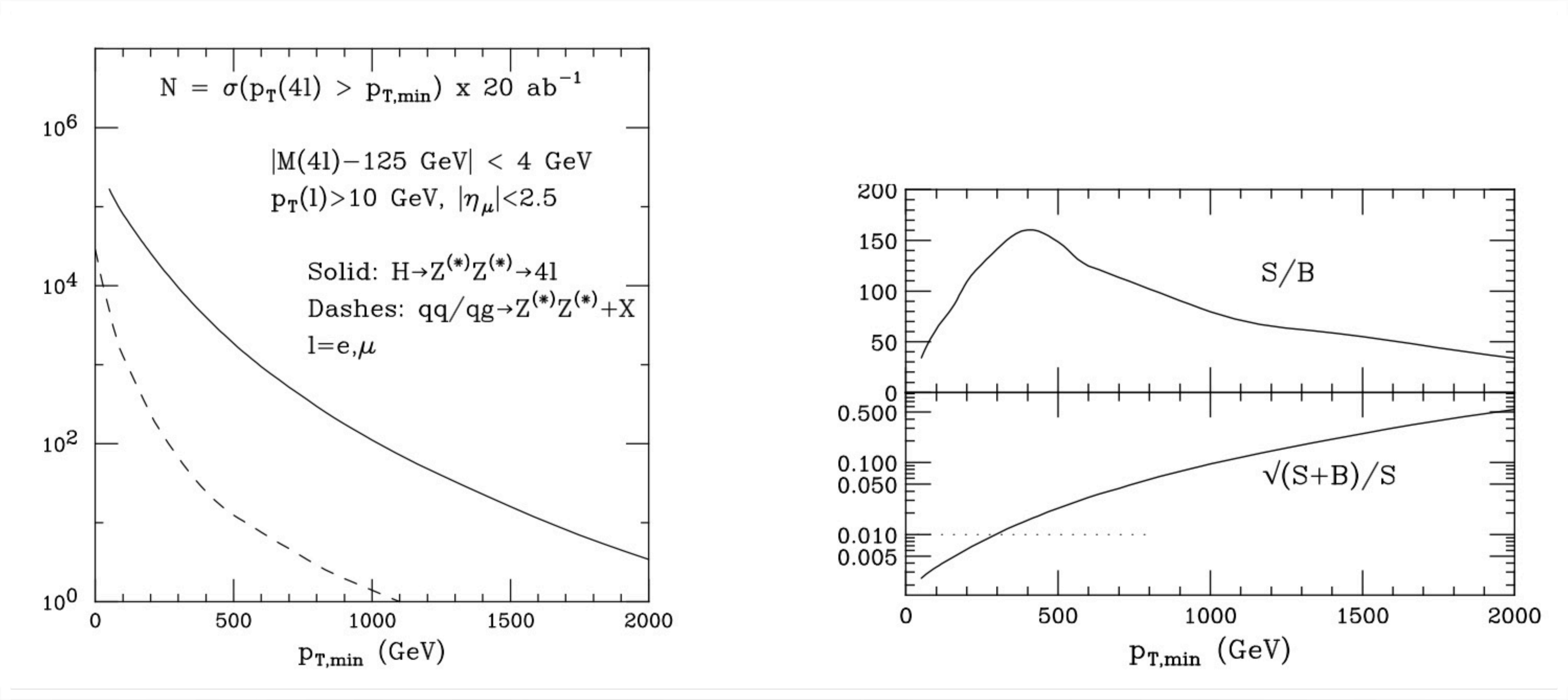






$gg \to H \to ZZ^* \to 4l$ at large p_T

Fig H-47

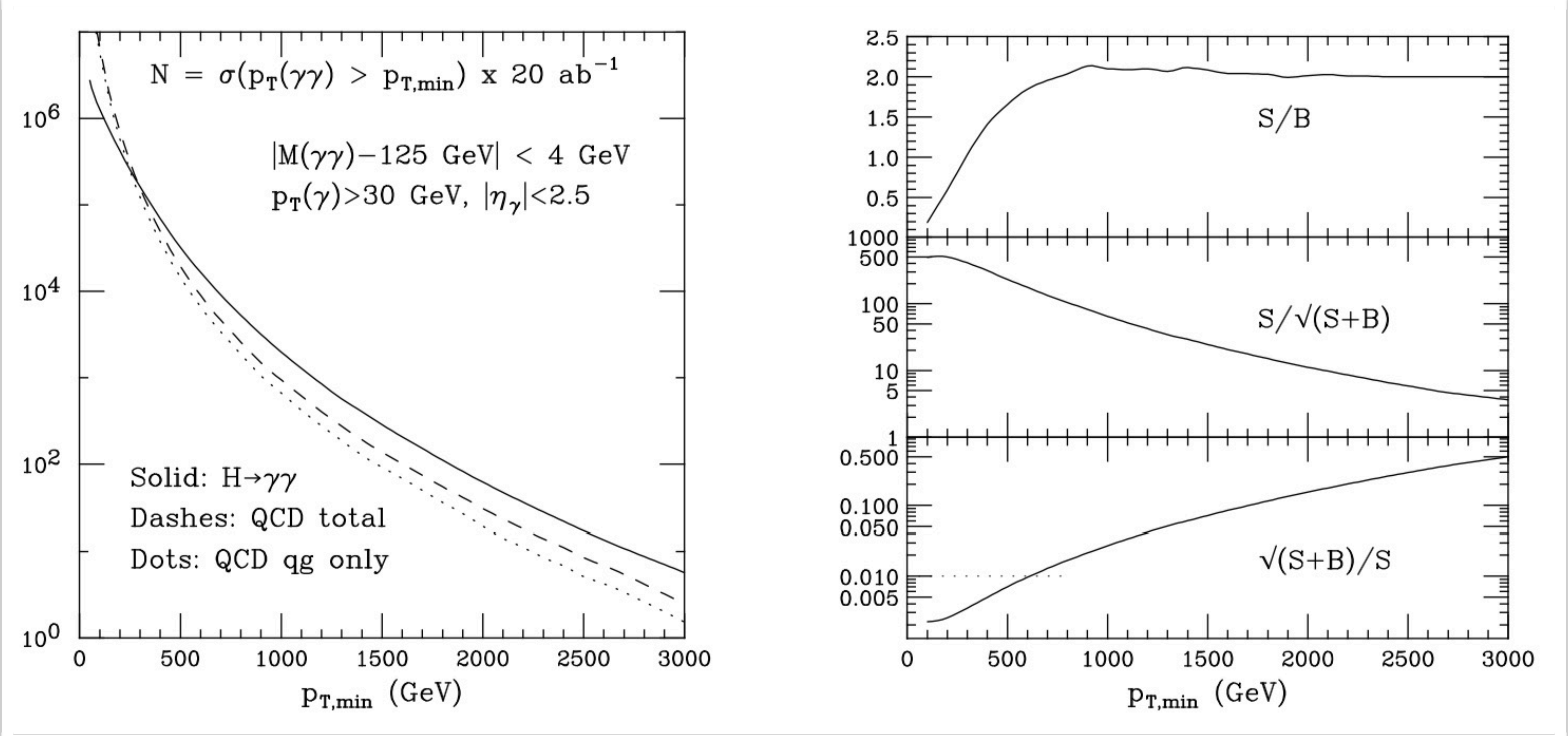


- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%

$gg \to H \to \gamma\gamma$ at large p_T

Fig H-45

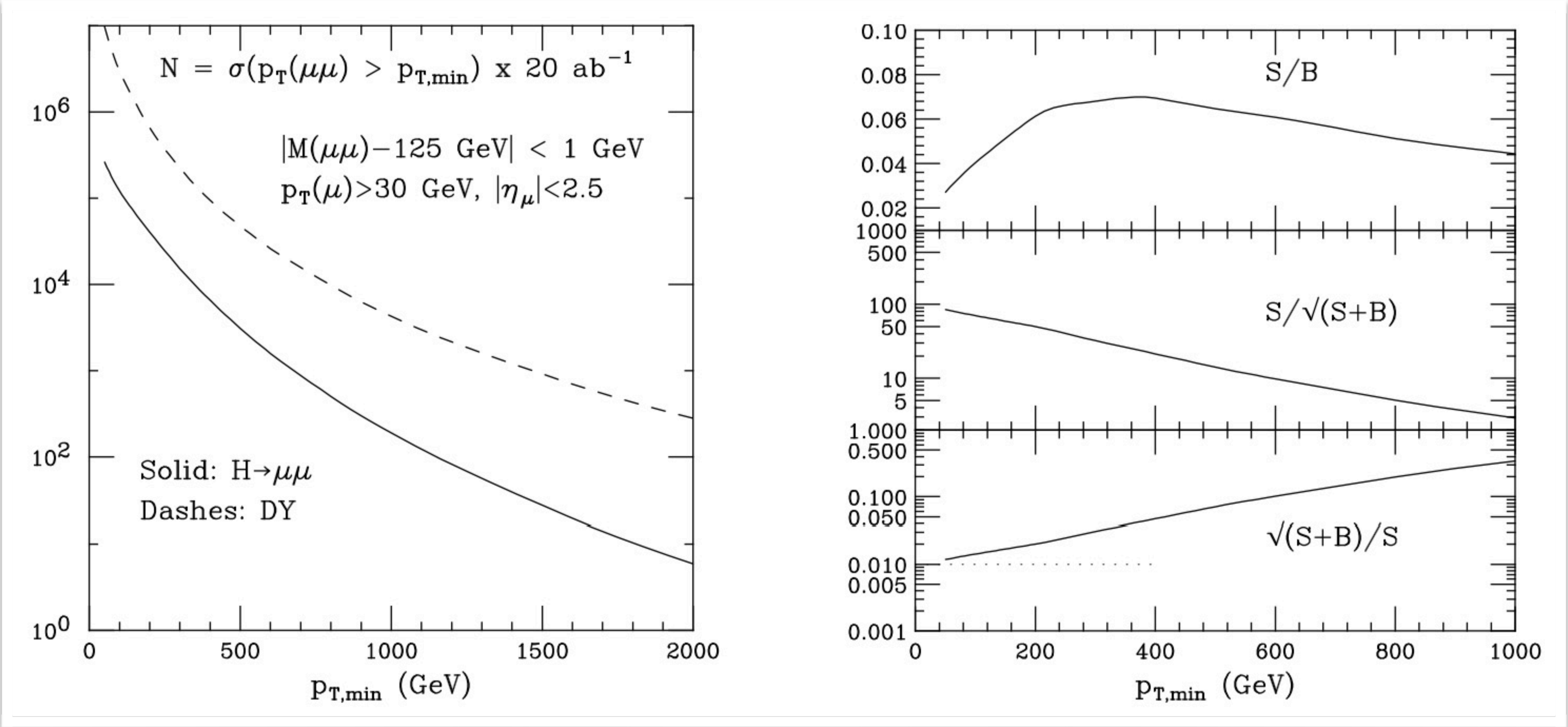


- At LHC, S/B in the $H\to\gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)
- Exptl mass resolution at large pt(H)?
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

gg→H→μμ at large p_T

Fig H-46

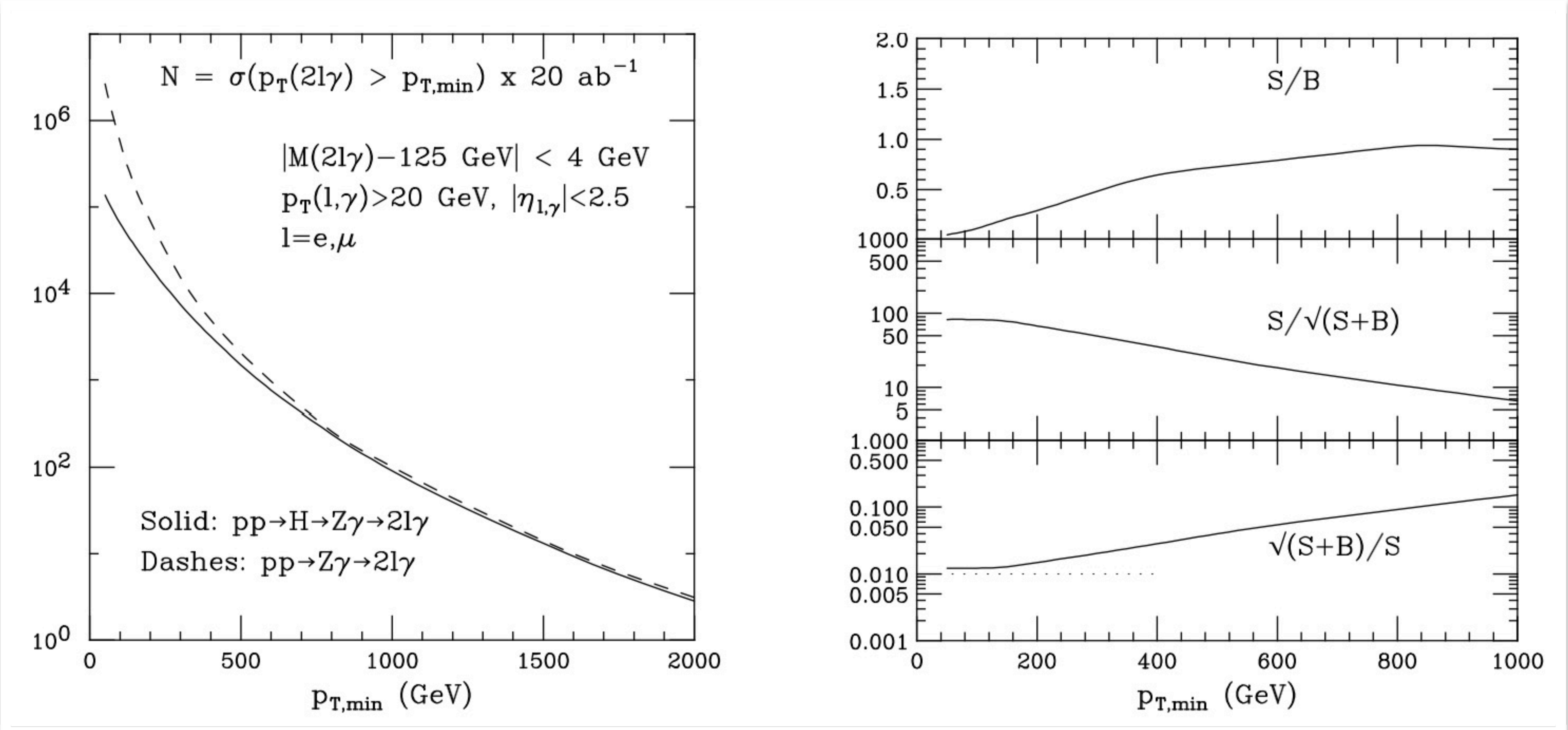


- Stat reach ~1% at p_T~100 GeV
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
500	10%

$gg \to H \to Z\gamma \to \ell\ell\gamma$ at large p_T

Fig H-48



- S/B → 1 at large p_T
- Stat reach ~1% at pT~100 GeV
- Exptl systematics on BR(Zγ)/BR(γγ)?

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
900	10%

Using **BR(H→ZZ*) from FCC-ee** (known at ~0.3% from δg_{HZZ}~0.15%), production ratios σ(H→XY)/σ(H→ZZ*) for $p_T>100$ GeV return the following stat precision on the **absolute value** of rare BRs

	γγ	Zγ	μμ
δ BR	**~0.5%**	**~1%**	**~1%**

One should not underestimate, however, the value of FCC-hh standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

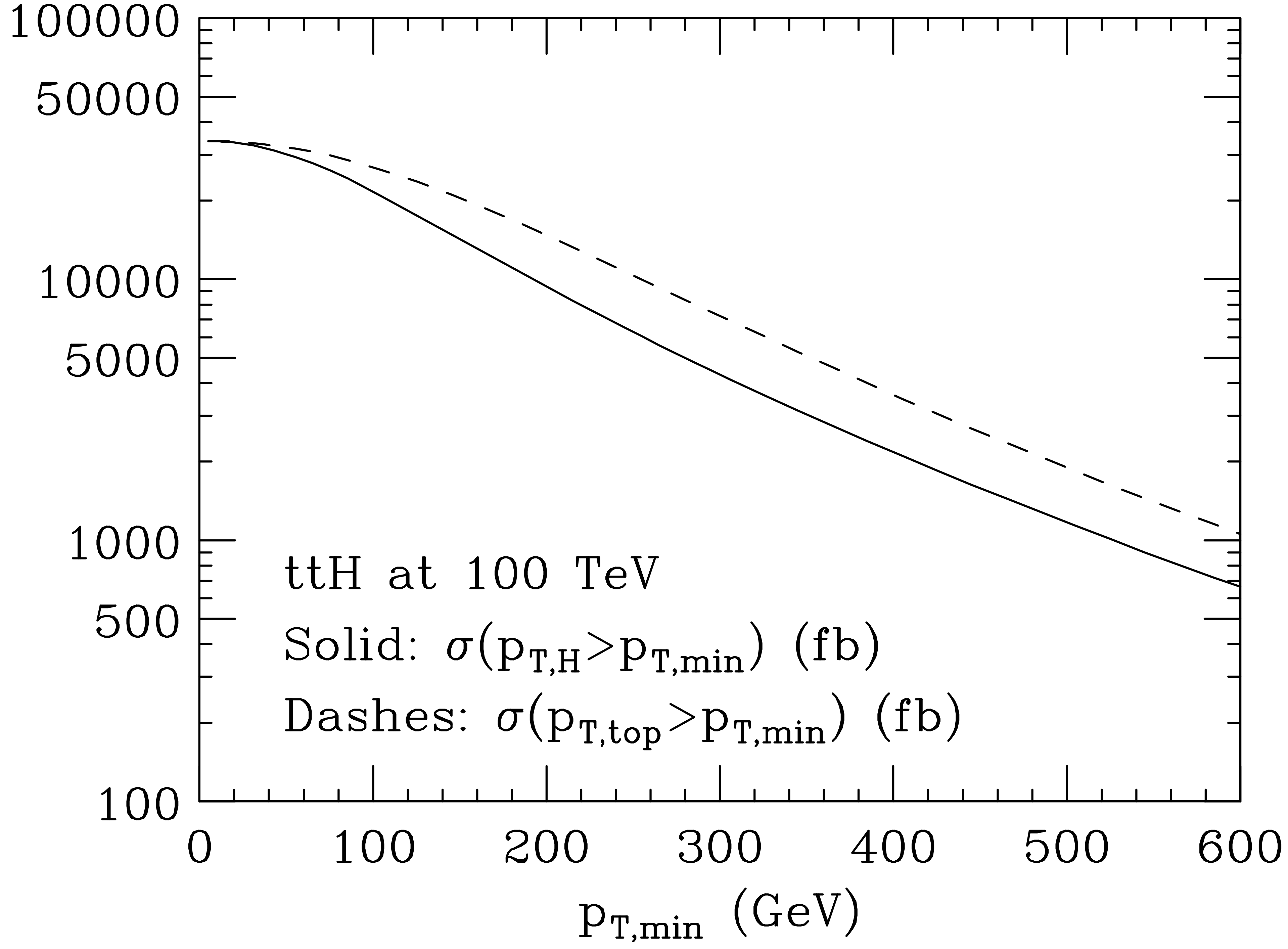
2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

Top Yukawa from ttH/ttZ

arXiv:1507.08169



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

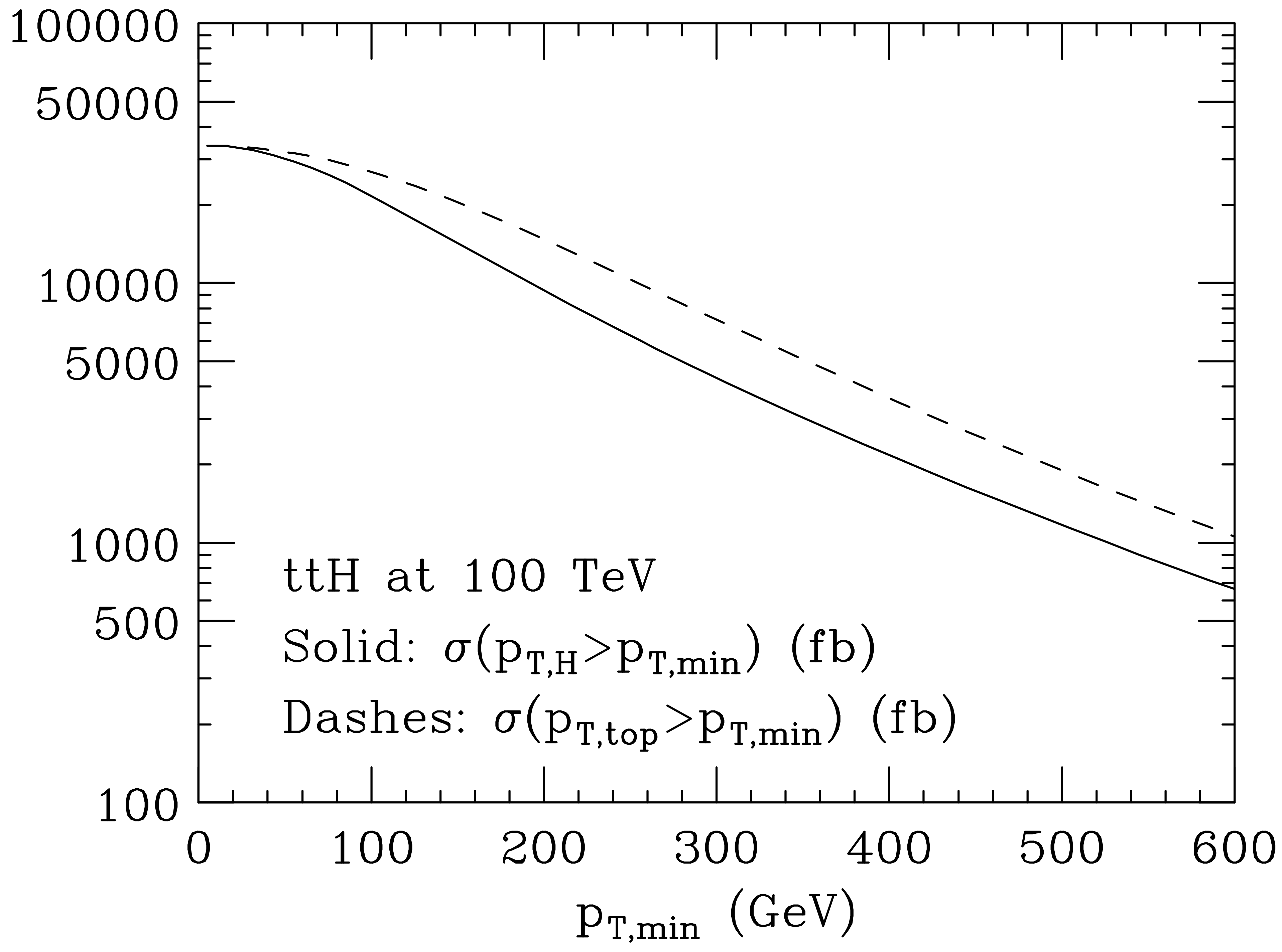
Events/20ab^{-1} , with tt→$\ell\nu$+jets

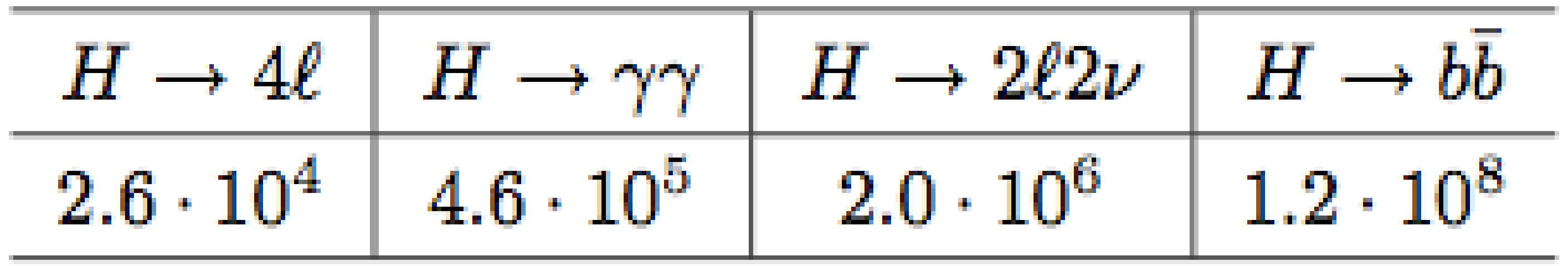
⇒ huge rates, exploit

boosted topologies

Top Yukawa from ttH/ttZ

arXiv:1507.08169





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

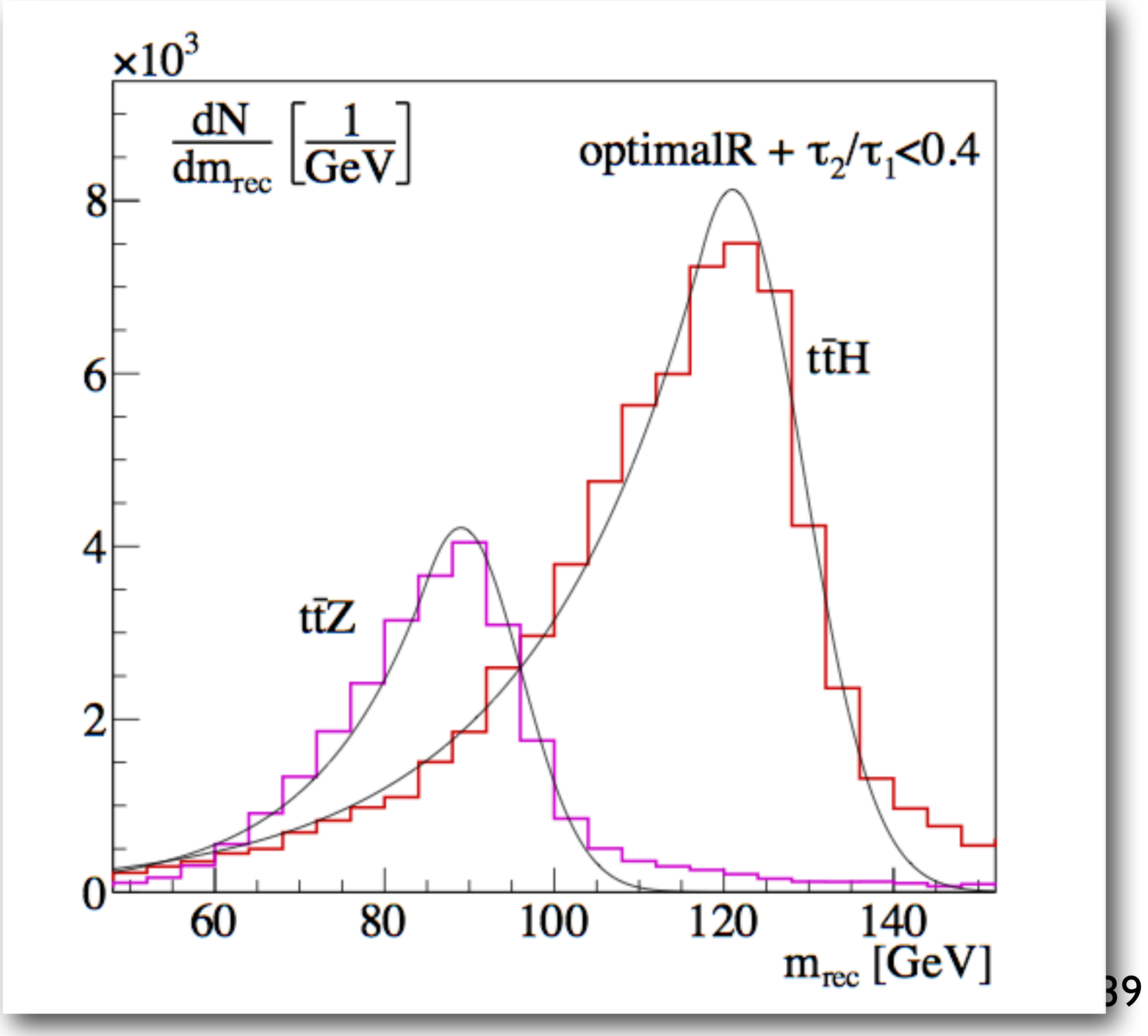
Events/20ab^{-1} , with tt→ℓν+jets

⇒ huge rates, exploit boosted topologies

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

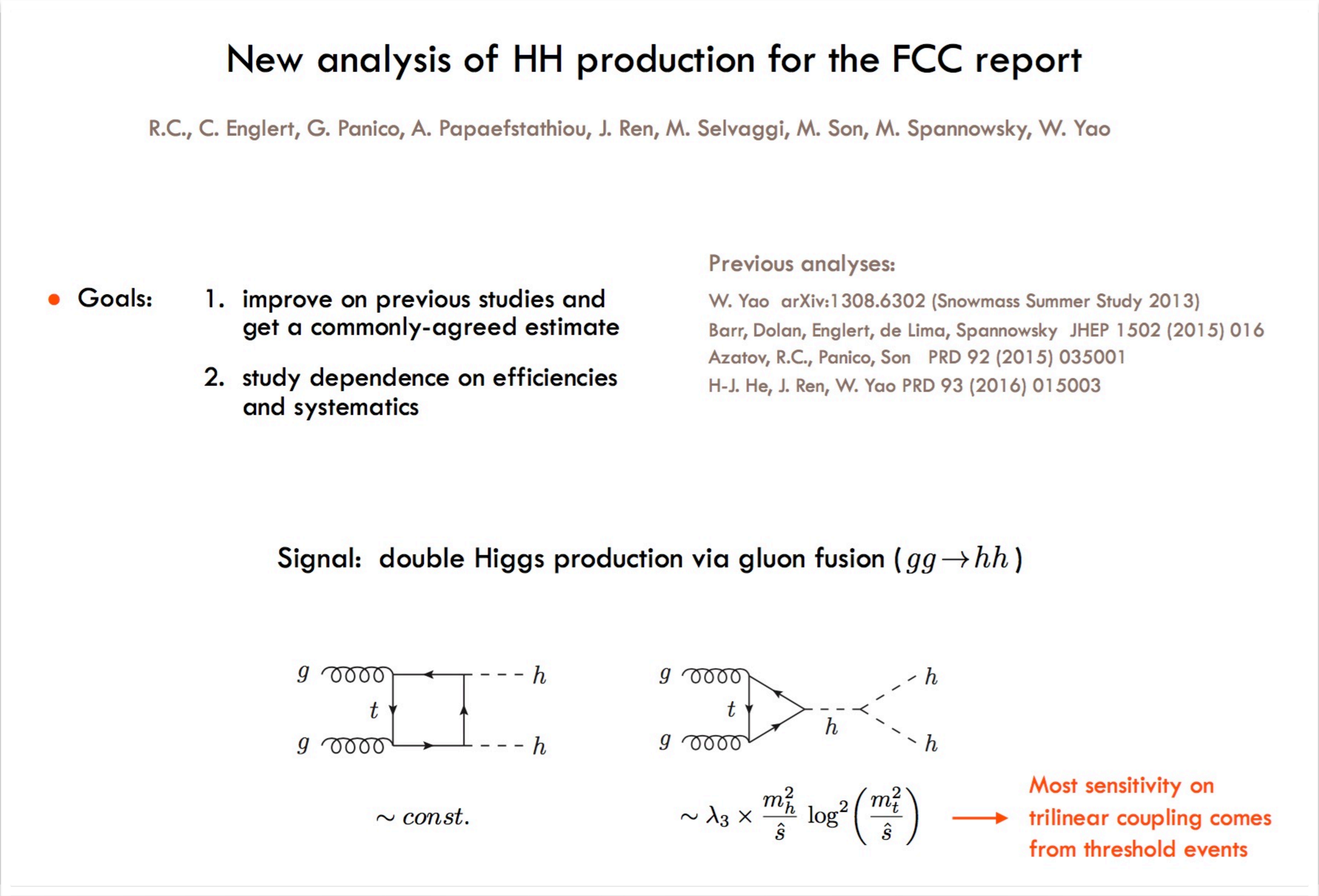
- δy_t (stat + syst $_{TH}$) ~ 1%

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



remarks

- These examples prove that TH uncertainties do not need to be a limiting factor for very precise measurements, once statistics are large and allow for new and diverse measurements
- Needless to say, careful work on the exptl systematics (eg absolute and relative detection efficiencies for the individual final states, pileup, etc) must be done to consolidate these naive estimates
- The role of the the highest p_T Higgs production (multi-TeV) in probing higher-dim op's of the EFT must still be studied. Can they compete with, or outplay, the BSM sensitivity of BR and coupling measurements?



New analysis of HH production for the FCC report

R.C., C. Englert, G. Panico, A. Papaefstathiou, J. Ren, M. Selvaggi, M. Son, M. Spannowsky, W. Yao

- **Goals:**
  1. improve on previous studies and get a commonly-agreed estimate
  2. study dependence on efficiencies and systematics

Previous analyses:

W. Yao arXiv:1308.6302 (Snowmass Summer Study 2013)
Barr, Dolan, Englert, de Lima, Spannowsky JHEP 1502 (2015) 016
Azatov, R.C., Panico, Son PRD 92 (2015) 035001
H-J. He, J. Ren, W. Yao PRD 93 (2016) 015003

Signal: double Higgs production via gluon fusion ($gg \to hh$)

$\sim const.$

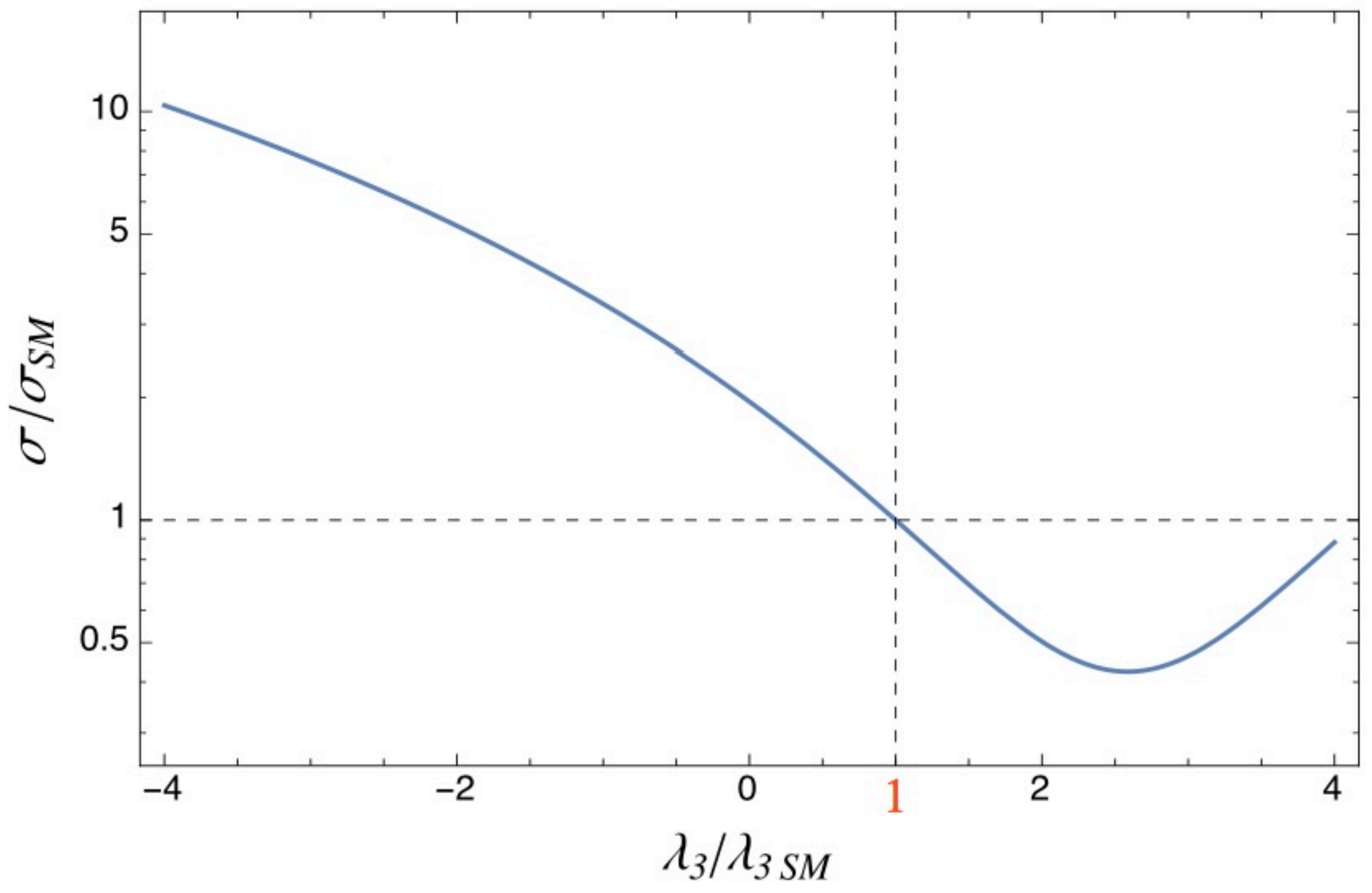
$\sim \lambda_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$ → Most sensitivity on trilinear coupling comes from threshold events

Slides from R.Contino Higgs chapter overview at Rome’s FCC-week, April 2016

	Signal cross section [fb] at NNLO+NNLL *
14 TeV	$45.05^{+4.4\%}_{-6.0\%} \pm 3.0\% \pm 10\%$
100 TeV	$1749^{+5.1\%}_{-6.6\%} \pm 2.7\% \pm 10\%$

$\sim 40\times$ increase

Theoretical uncertainties: scale, PDFs $+\alpha_s$, infinite m_t approx.



	# Higgs pairs to bbγγ
LHC: 14TeV 300fb^{-1}	36
HL-LHC: 14TeV 3ab^{-1}	360
FCC: 100TeV 20ab^{-1}	92 x 10^3

← percent precision physics

Backgrounds:

- $b\bar{b}\gamma\gamma$
- $t\bar{t}h(\gamma\gamma)$
- $b\bar{b}h(\gamma\gamma)$
- $jj\gamma\gamma$ (two fake b-jets)
- $b\bar{b}j\gamma$ (one fake photon)

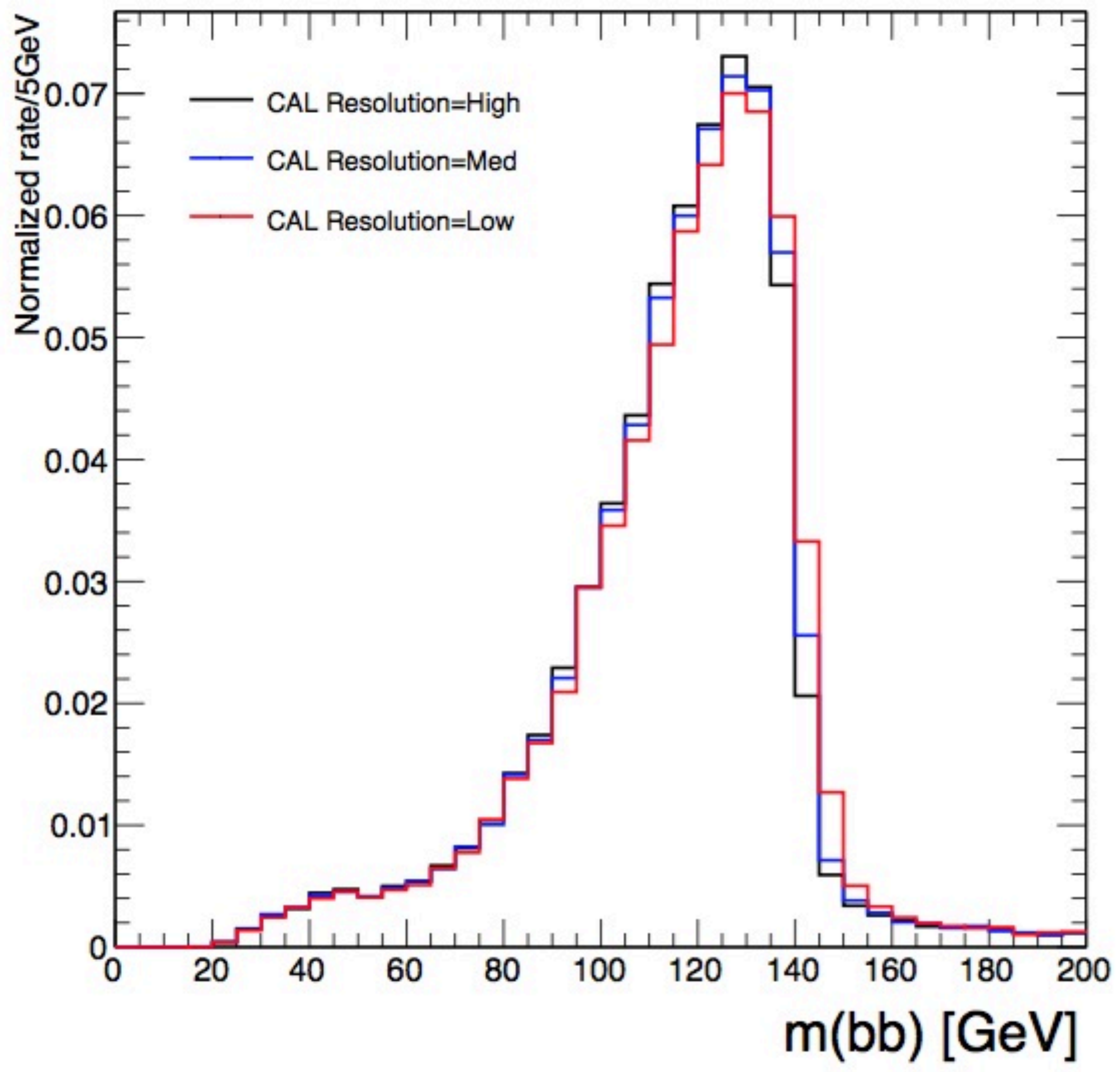
* Results of the recent full-m$_{top}$ NLO calculation (Borowka et al, arXiv: 1604.06447) not included here (as yet….)

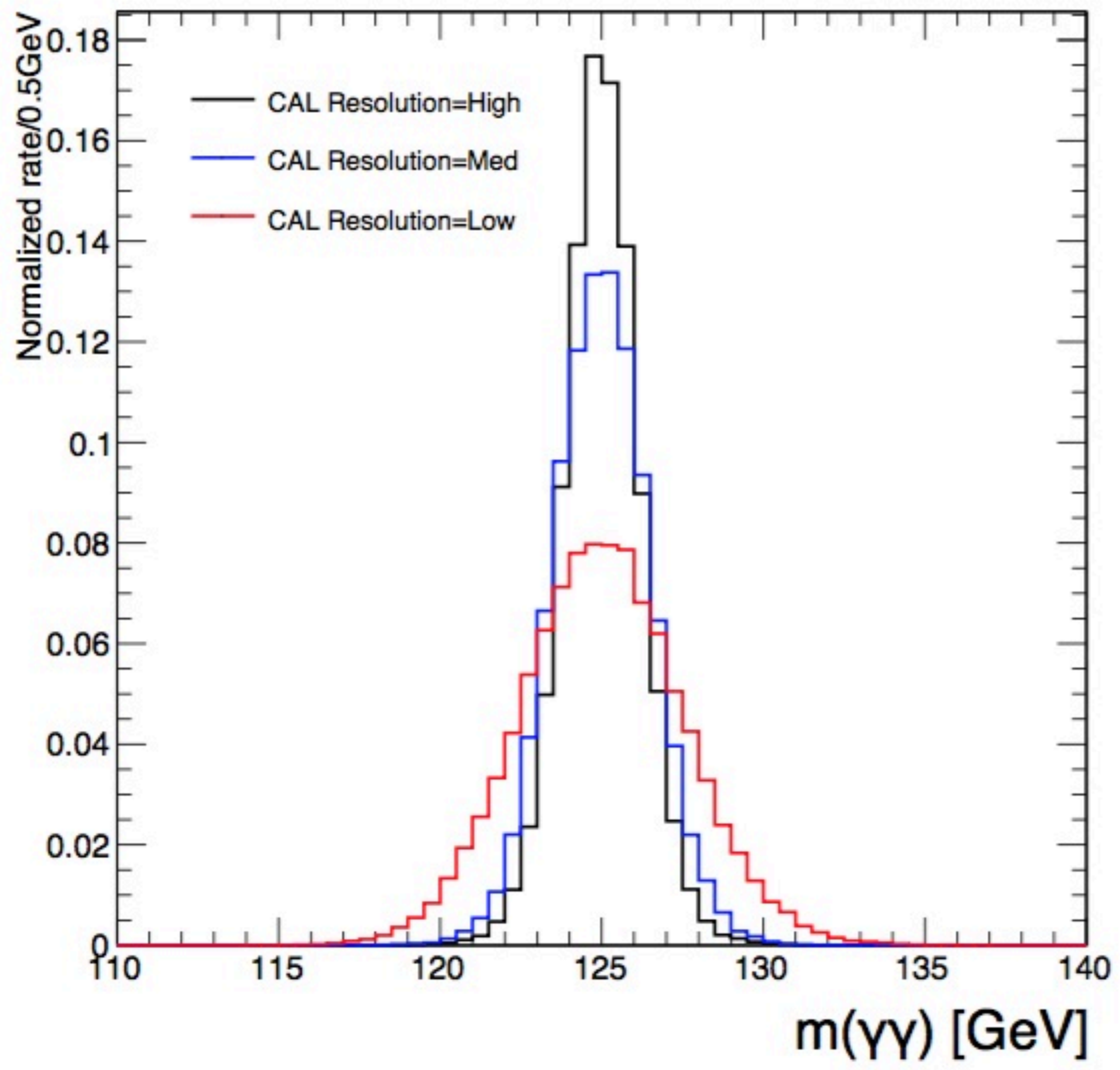
Montecarlo Simulation: MadGraph5_aMC@NLO ⟶ Pythia 6 ⟶ Delphes (FCC card)

Three benchmark scenarios for ECAL and HCAL resolution:

$$\Delta E = \sqrt{a^2E^2 + b^2E}$$

	ECAL				HCAL			
	$\lvert\eta\rvert \le 4$		$4 < \lvert\eta\rvert \le 6$		$\lvert\eta\rvert \le 4$		$4 < \lvert\eta\rvert \le 6$	
	a	b	a	b	a	b	a	b
low	0.02	0.2	0.01	0.1	0.05	1.0	0.05	1.0
medium	0.01	0.1	0.01	0.1	0.03	0.5	0.05	1.0
high	0.007	0.06	0.01	0.1	0.01	0.3	0.03	0.5





High
$\Delta m(\gamma\gamma) = 1.5\,\mathrm{GeV}$

Med
$\Delta m(\gamma\gamma) = 2.0\,\mathrm{GeV}$

Low
$\Delta m(\gamma\gamma) = 3.0\,\mathrm{GeV}$

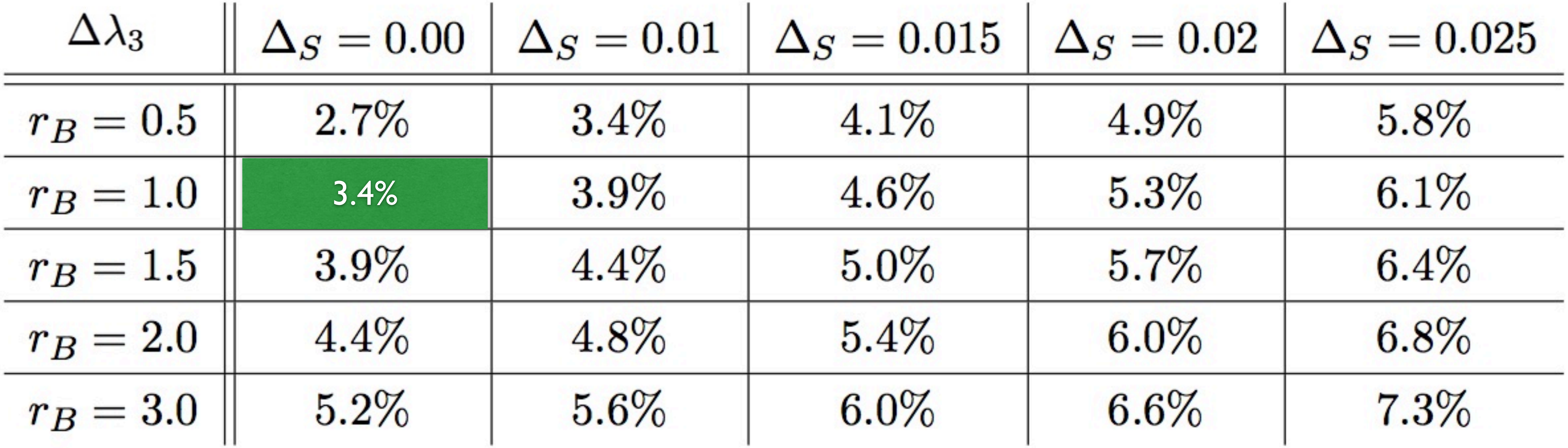
Fig H-63

- overall rescaling of background rate $n_B \to r_B \times n_B$

using "medium" calorimeter resolution

- uncertainty on signal rate $\Delta_S = \dfrac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$

For $\Delta_S \gtrsim 2.5\%$ the precision on λ_3 is dominated by the theory error on the signal: $\Delta\lambda_3 \simeq 2\Delta_S$

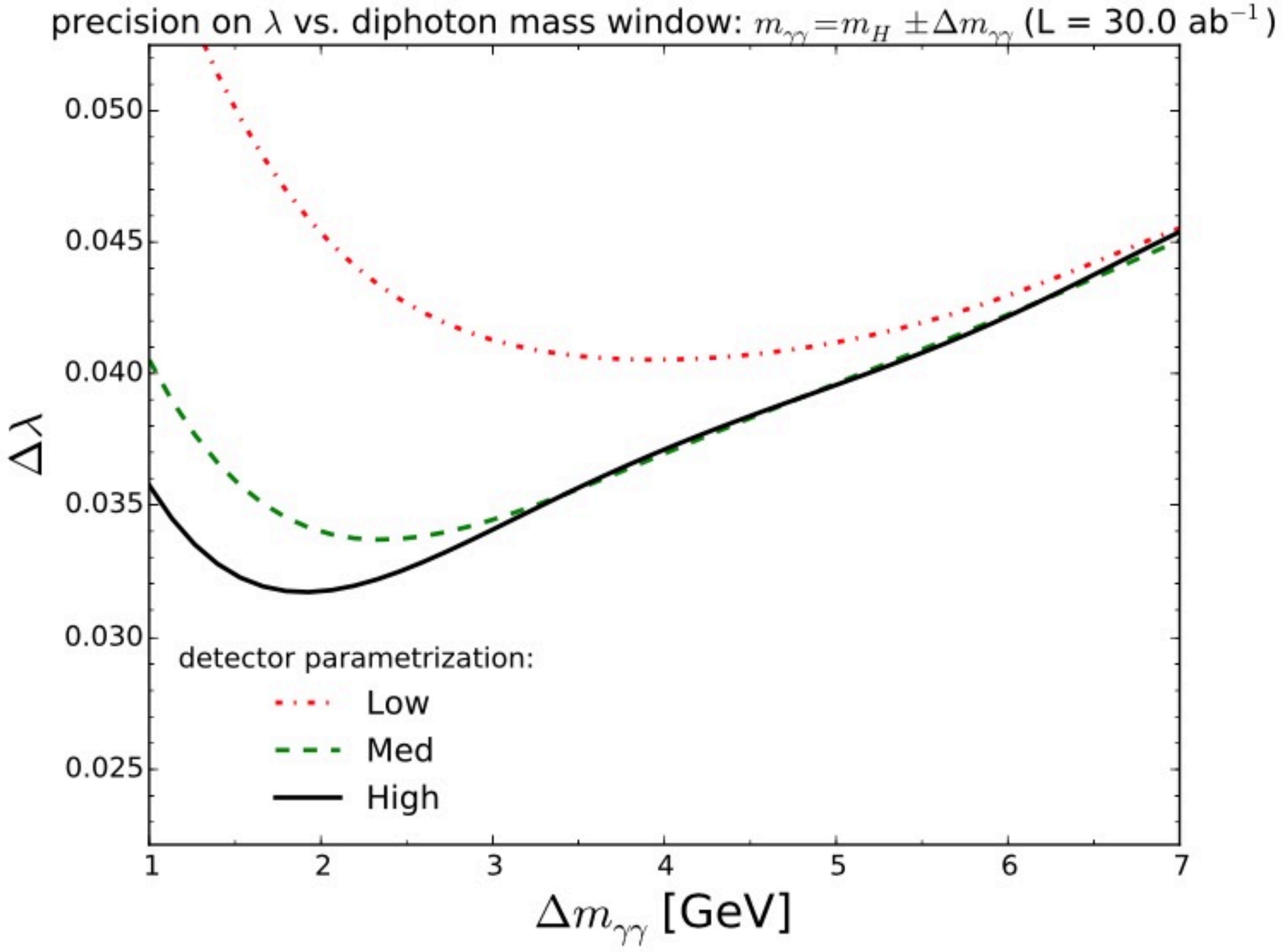


$\Delta\lambda_3$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

Tab H-30

Results updated/confirmed with improved analysis by M.Selvaggi, https://indico.cern.ch/event/613195/

impact of detector performance, 1


precision on λ vs. diphoton mass window: $m_{\gamma\gamma}=m_H \pm\Delta m_{\gamma\gamma}$ (L = 30.0 ab^{-1})

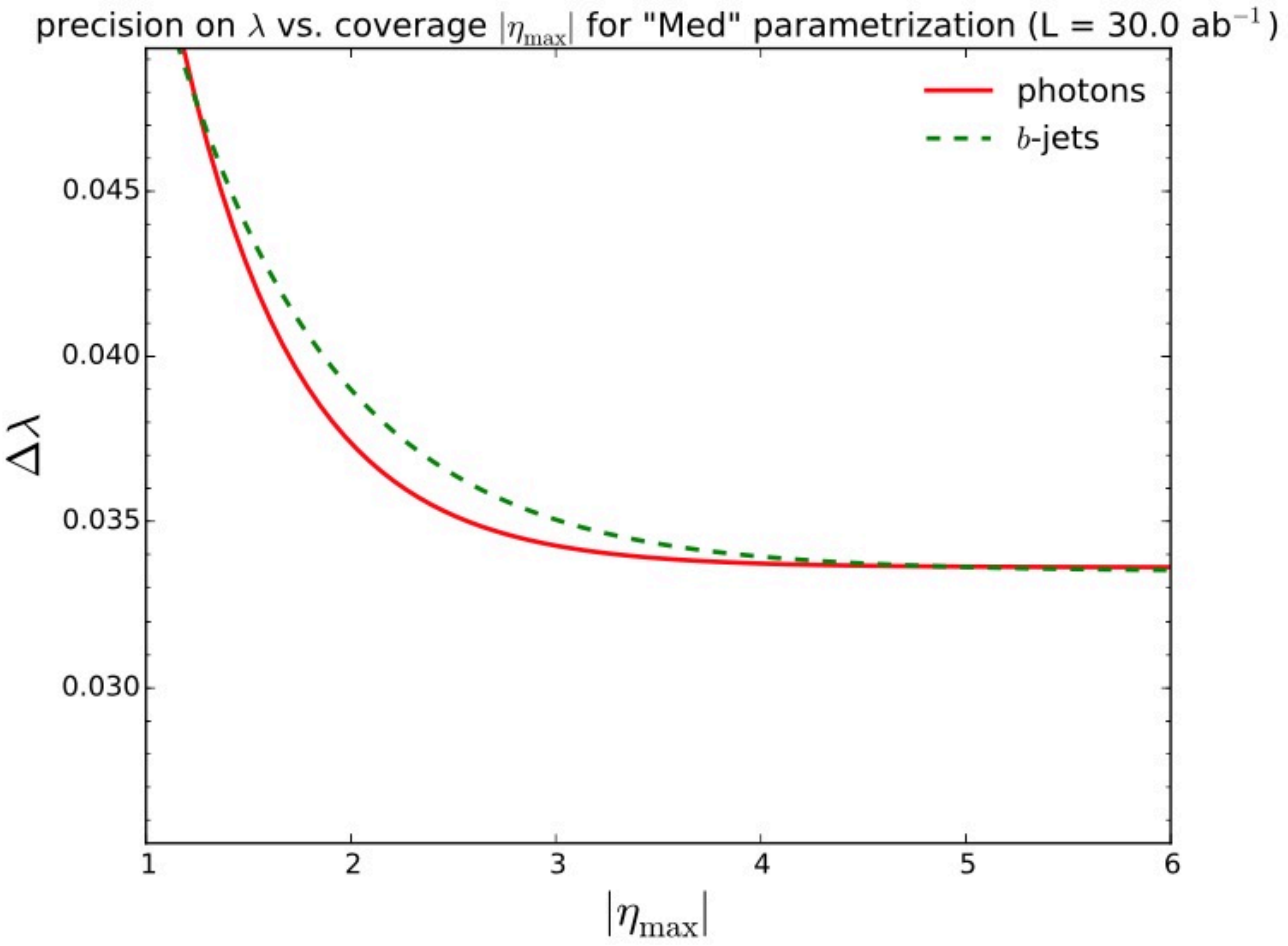

precision on λ vs. coverage $|\eta_{\max}|$ for "Med" parametrization (L = 30.0 ab^{-1})

Fig H-65

impact of detector performance, 2

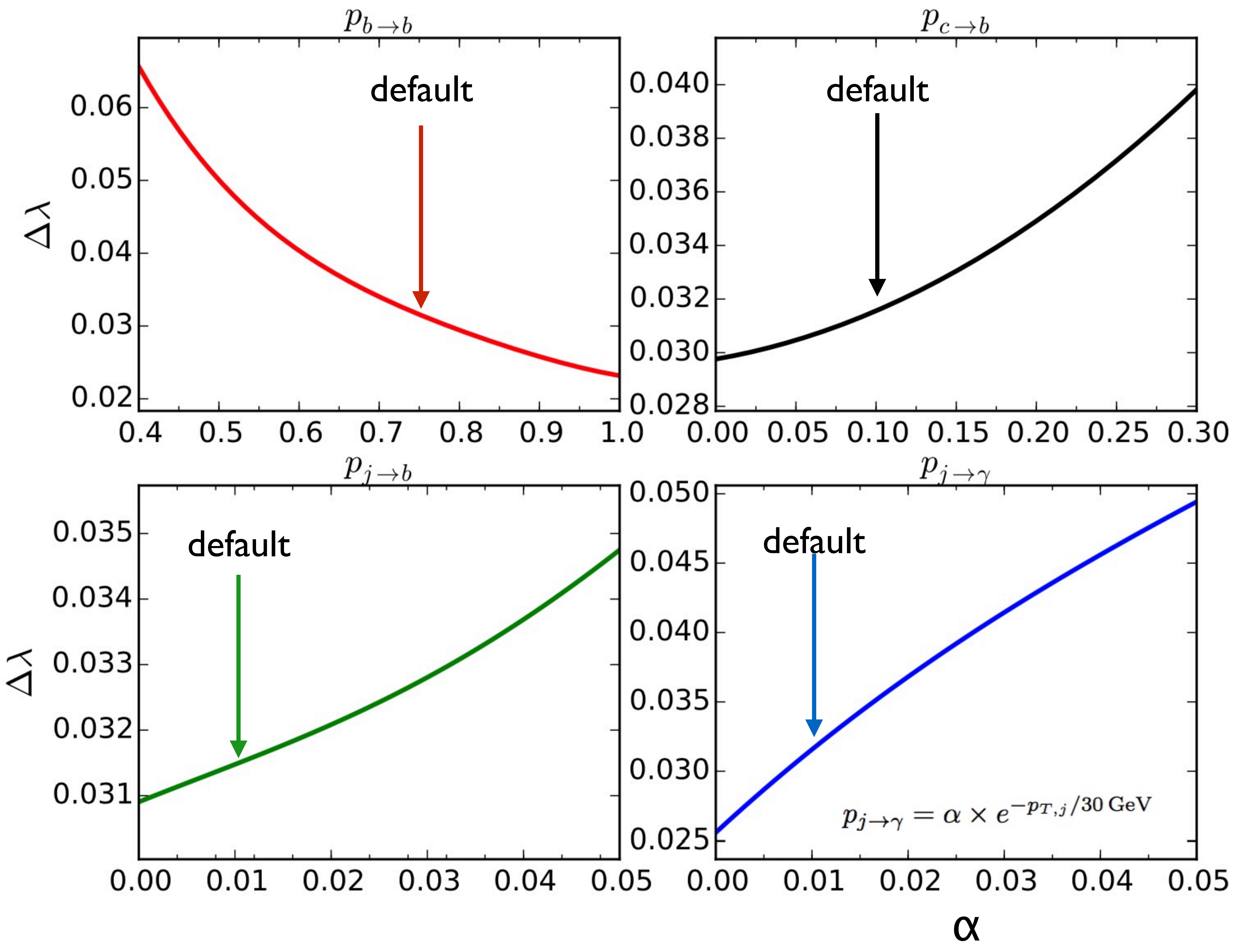
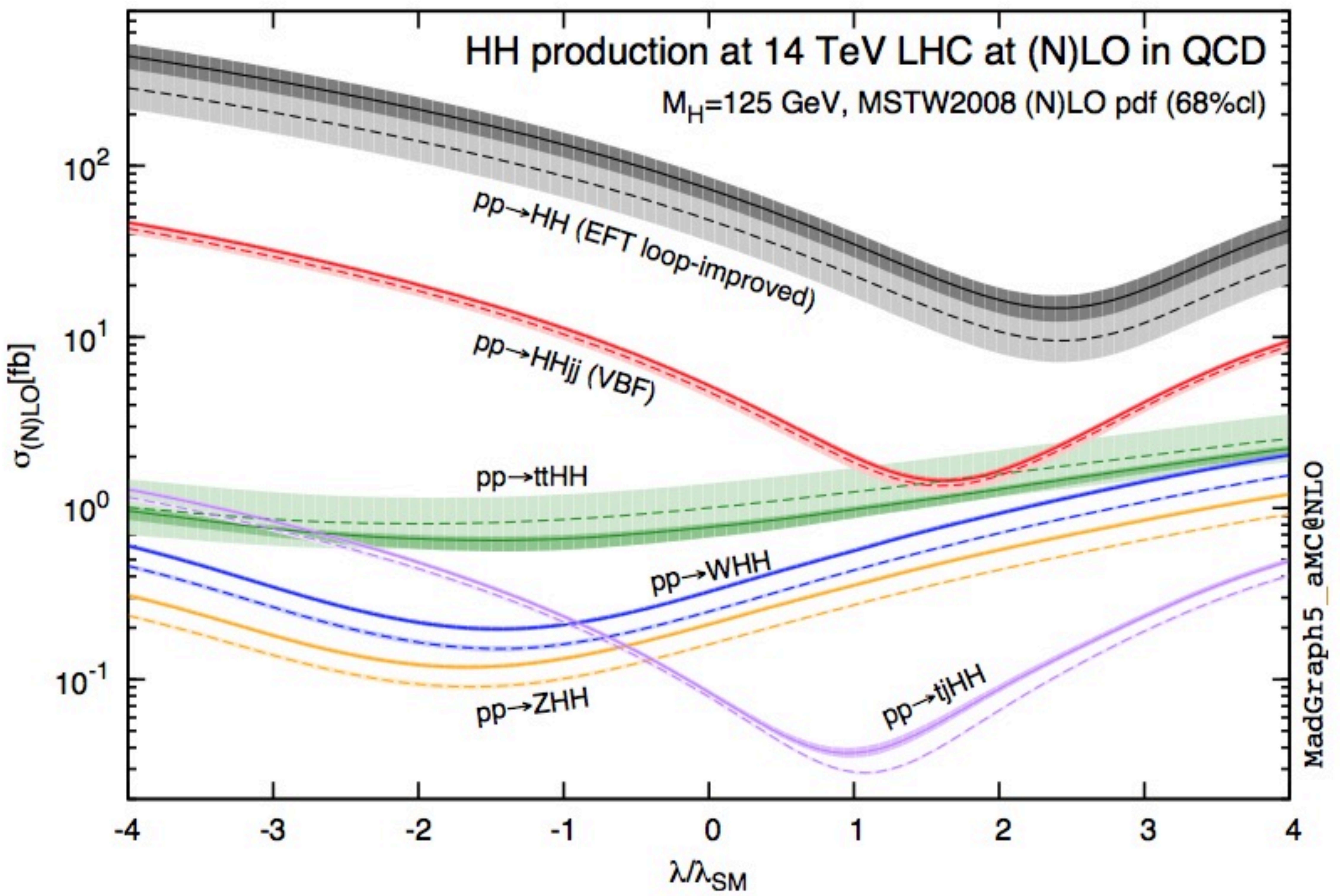
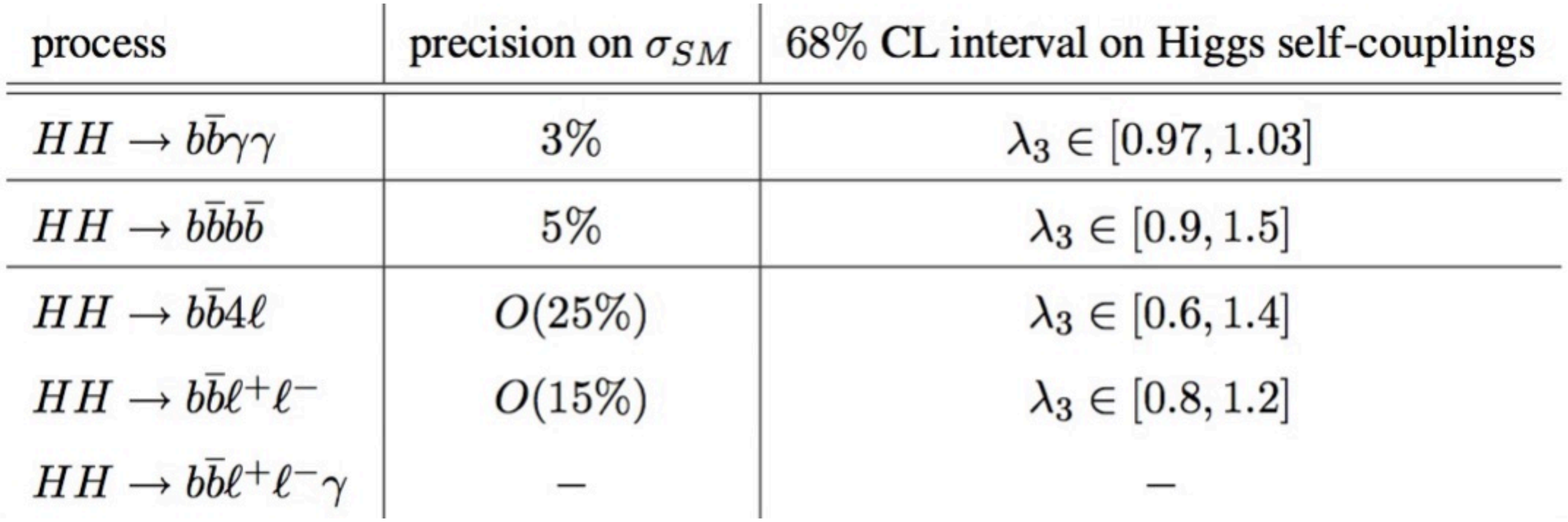


Fig H-66

other channels, first assessments ….



λ dependence at 14 and 100 TeV are similar

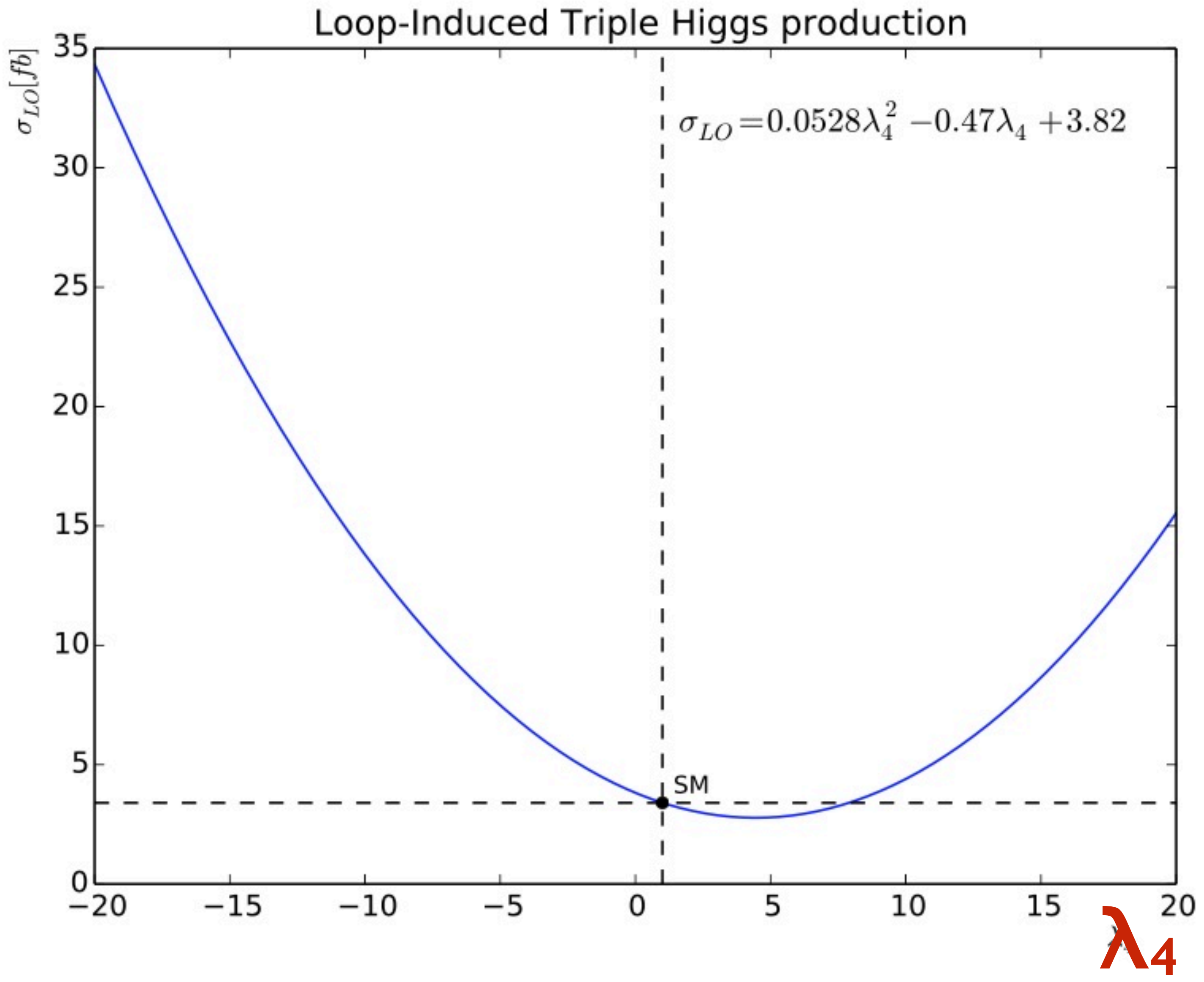


process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–

Sec H-5.2.3,5.2.4

See B.DiMicco HH status review, Thu // session

Quartic Higgs selfcoupling



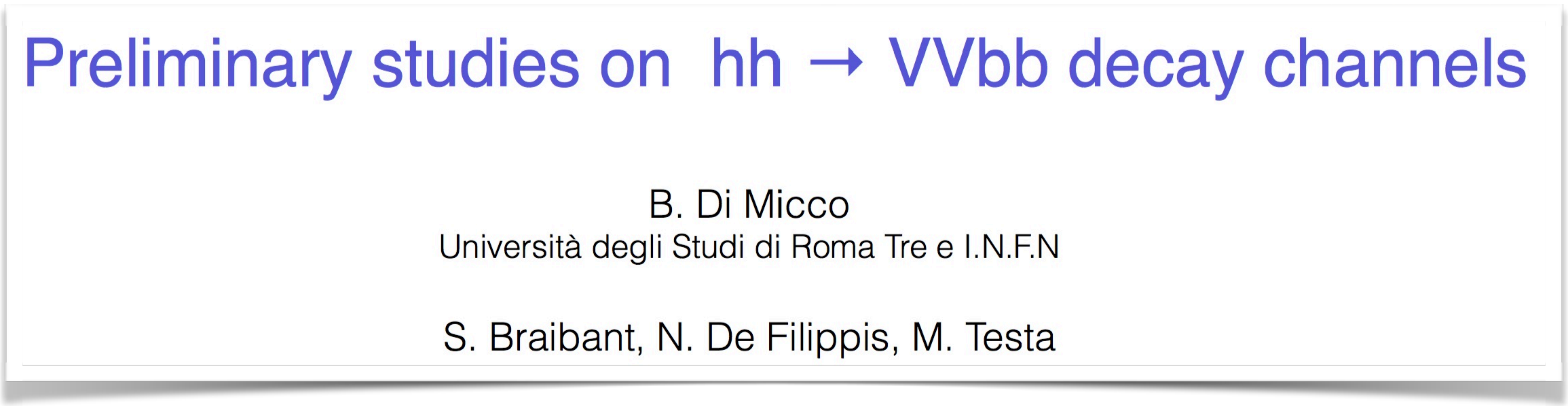
observable	selection cut
$p_{T,b_{\{1,2,3,4\}}}$	$> \{80, 50, 40, 40\}$ GeV
$\lvert\eta_b\rvert$	< 3.0
$m_{bb}^{\text{close},1}$	$\in [100, 160]$ GeV
$m_{bb}^{\text{close},2}$	$\in [90, 170]$ GeV
$\Delta R_{bb}^{\text{close},1}$	$\in [0.2, 1.6]$
$\Delta R_{bb}^{\text{close},2}$	no cut
$p_{T,\gamma_{\{1,2\}}}$	$> \{70, 40\}$ GeV
$\lvert\eta_\gamma\rvert$	< 3.5
$\Delta R_{\gamma\gamma}$	$\in [0.2, 4.0]$
$m_{\gamma\gamma}$	$\in [124, 126]$ GeV

process	σ_{LO} (fb)	$\sigma_{\text{NLO}} \times \text{BR} \times \mathcal{P}_{\text{tag}}$ (ab)	$\epsilon_{\text{analysis}}$	$N_{30\ \text{ab}^{-1}}^{\text{cuts}}$
$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, SM	2.89	5.4	0.06	9.7
$b\bar{b}b\bar{b}\gamma\gamma$	1.28	1050	2.6×10^{-4}	8.2
hZZ, (NLO) $(ZZ \to (b\bar{b})(b\bar{b}))$	0.817	0.8	0.002	$\ll 1$
hhZ, (NLO)$(Z \to (b\bar{b}))$	0.754	0.8	0.007	$\ll 1$
hZ, (NLO) $(Z \to (b\bar{b}))$	8.02×10^3	1130	$\mathcal{O}(10^{-5})$	$\ll 1$
$b\bar{b}b\bar{b}\gamma$ + jets	2.95×10^3	2420	$\mathcal{O}(10^{-5})$	$\mathcal{O}(1)$
$b\bar{b}b\bar{b}$ + jets	5.45×10^3	4460	$\mathcal{O}(10^{-6})$	$\ll 1$
$b\bar{b}\gamma\gamma$ + jets	98.7	4.0	$\mathcal{O}(10^{-5})$	$\ll 1$
hh + jets, SM	275	593	7×10^{-4}	12.4

Sec H-5.3.4

=> λ_4 in [– 4 , 16] at 95%CL

Further ongoing studies for HH discussed at the Wshop

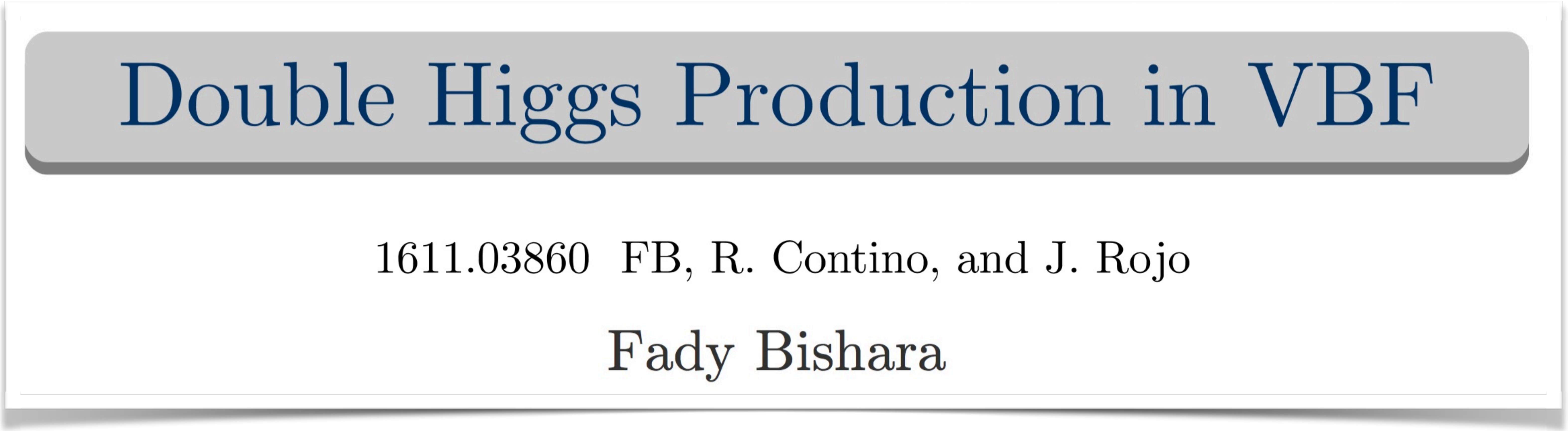


Preliminary studies on hh → VVbb decay channels

B. Di Micco
Università degli Studi di Roma Tre e I.N.F.N

S. Braibant, N. De Filippis, M. Testa

see Biagio's talk Thu morning



Double Higgs Production in VBF

1611.03860 FB, R. Contino, and J. Rojo

Fady Bishara

[Grinstein and Trott: [0704.1505]
[Contino, Grojean, Moretti, Piccinini, Rattazzi: 1002.1011]

$$\boxed{\Sigma = e^{i\sigma^a \pi^a / v}}$$

F.Bishara

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

$$+ \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \boxed{\Sigma^\dagger} D^\mu \Sigma\right)\left[1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \ldots\right] - m_i\, \bar{\psi}_{Li}\, \Sigma \left(1 + c\frac{h}{v} + \ldots\right)\psi_{Ri}$$

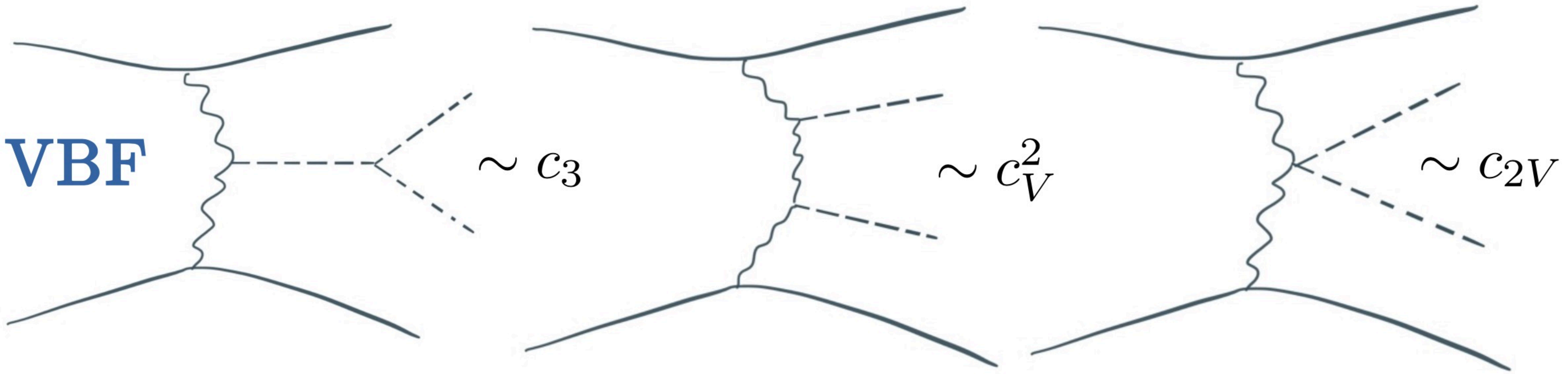
$$V(h) = \frac{1}{2}m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + c_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

e.g. in minimal SO(5)/SO(4) models $\quad c_V = \sqrt{1-\xi}\,, \qquad c_{2V} = 1 - 2\xi$

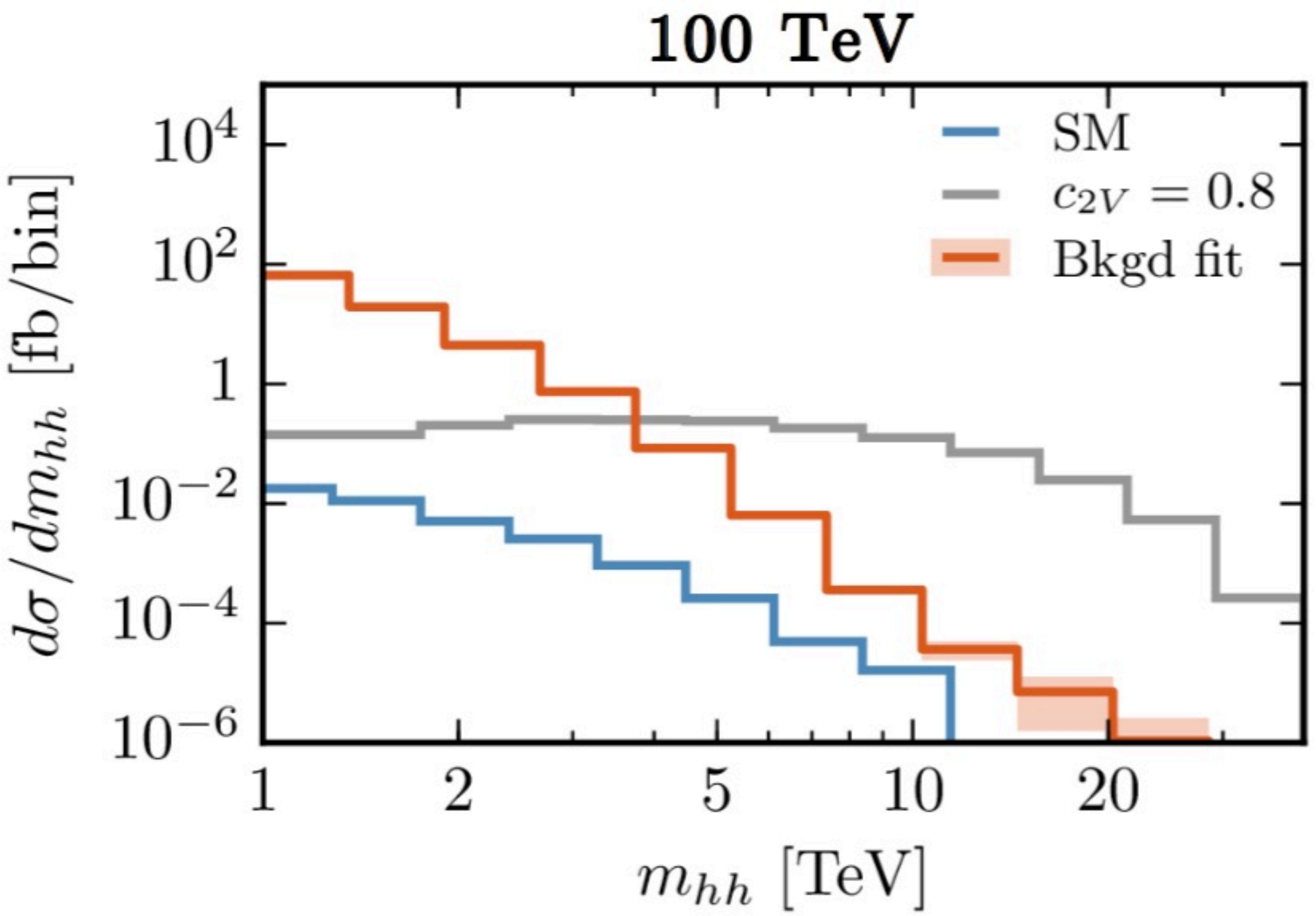
$$\xi = v^2/f^2$$

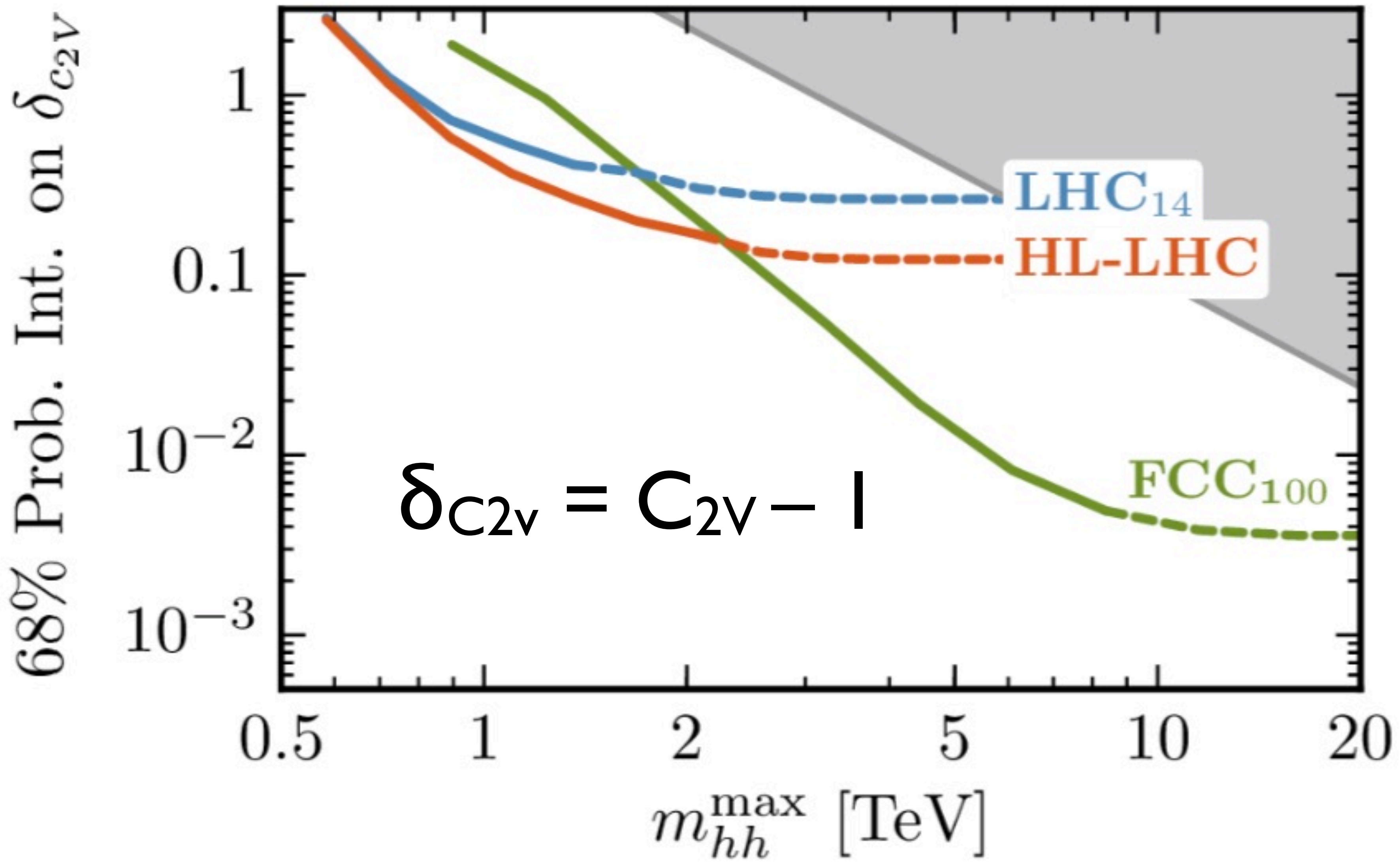
Agashe et al. [hep-ph/0412089]
Contino et al. [hep-ph/0612048]

$$\begin{cases} c = \sqrt{1-\xi} & \text{for } \mathbf{4} \text{ of SO(5)} \\ c = \dfrac{1-2\xi}{\sqrt{1-\xi}} & \text{for } \mathbf{5} \text{ of SO(5)} \end{cases}$$

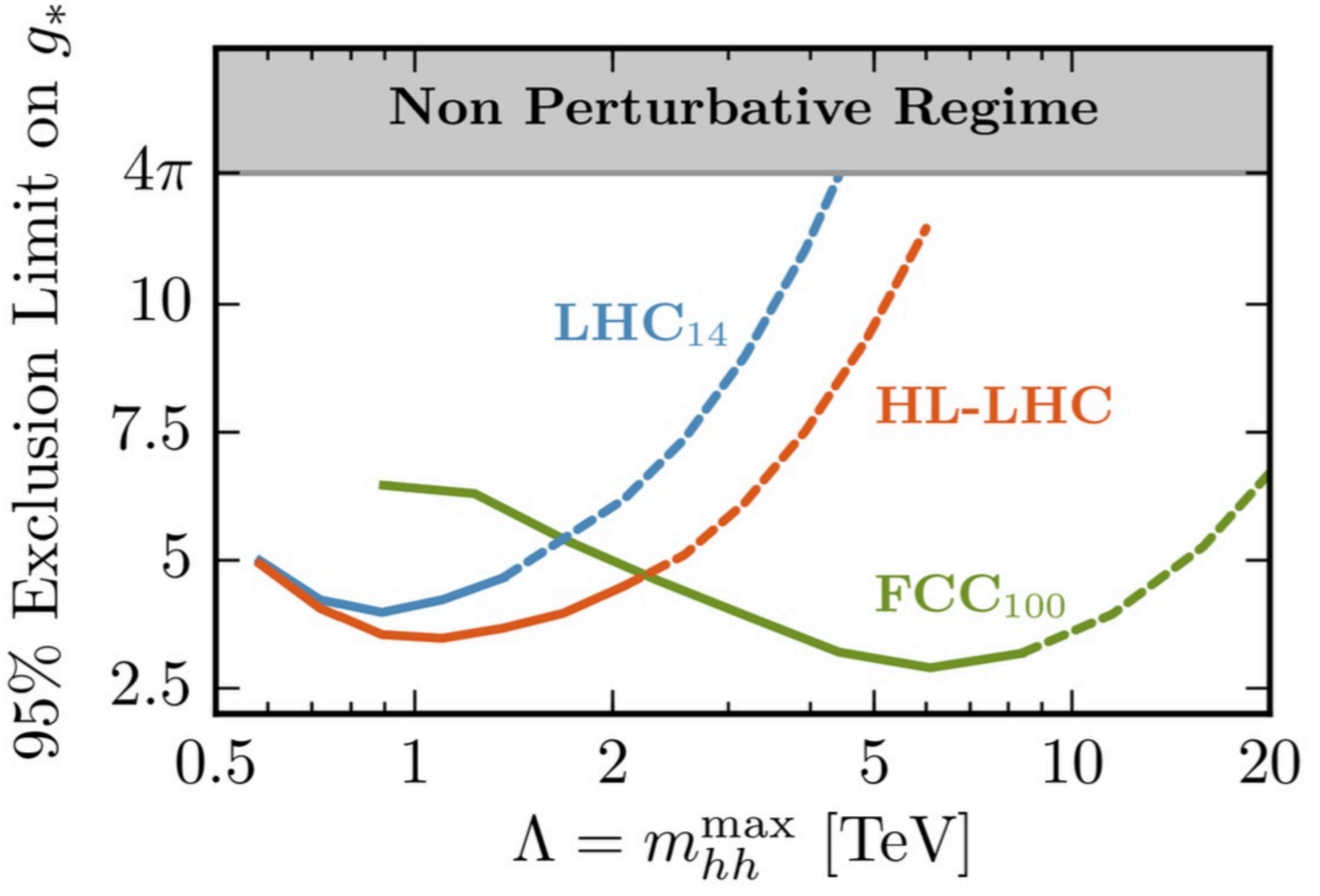


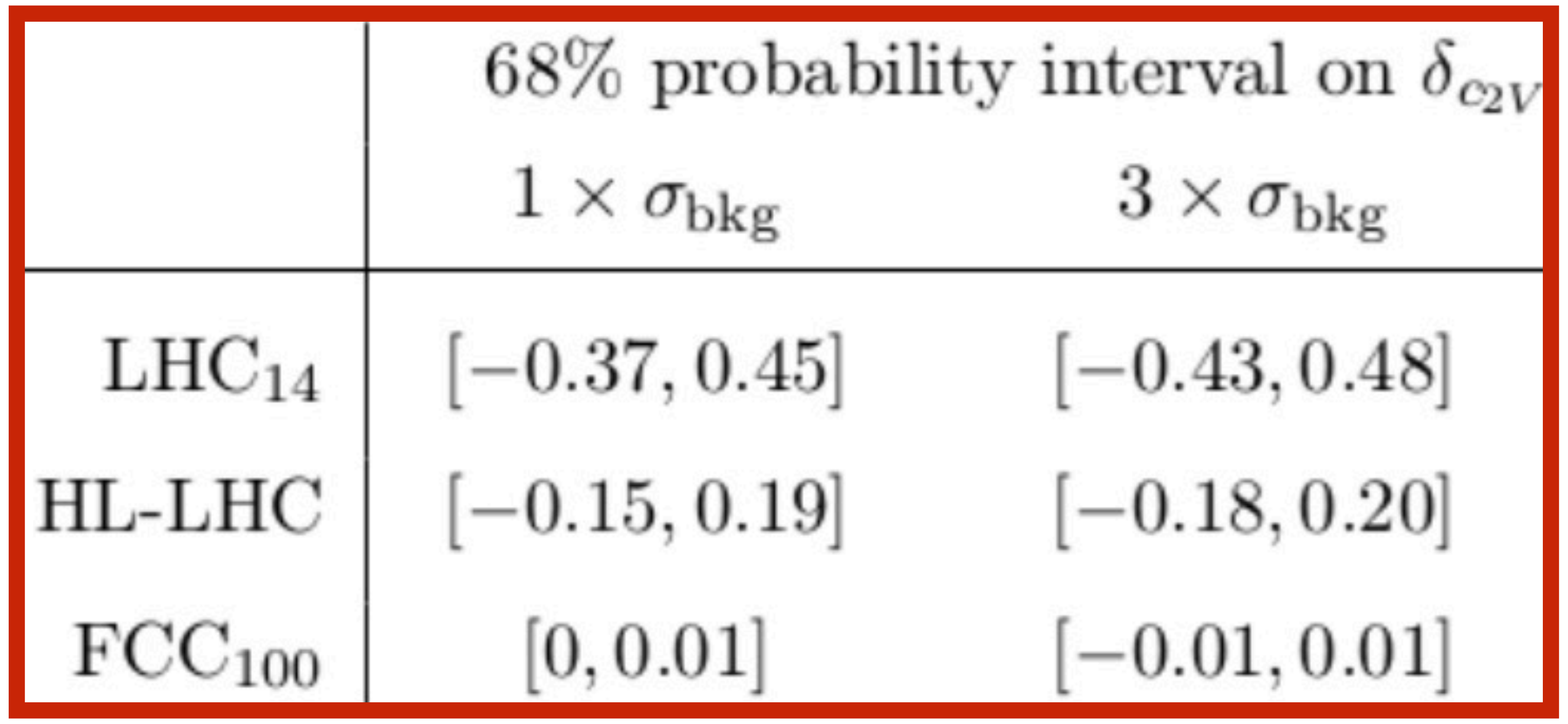
$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$





$\delta_{C2v} = C_{2V} - 1$





	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC$_{14}$	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC$_{100}$	$[0, 0.01]$	$[-0.01, 0.01]$

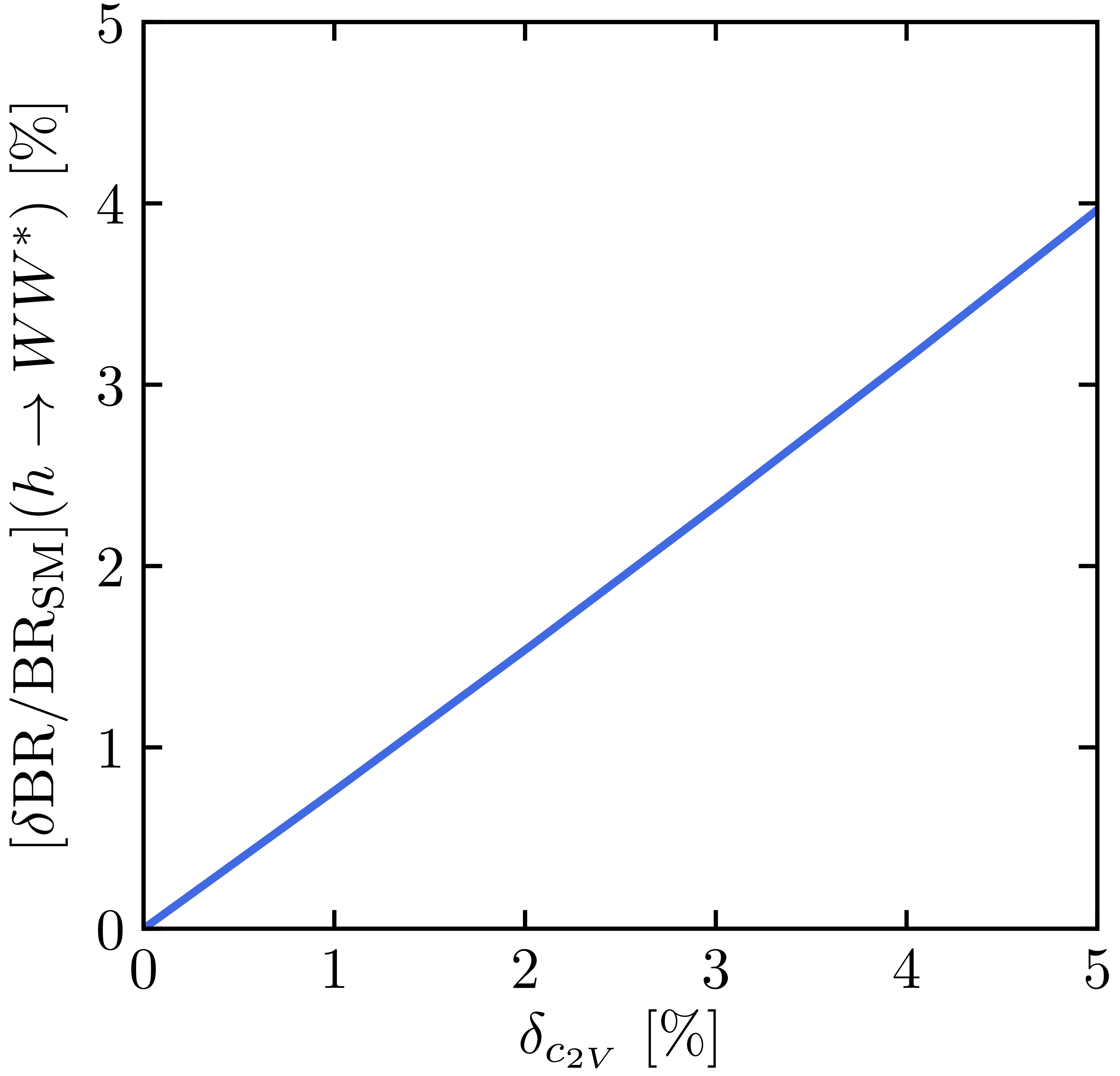
$\delta_{c_{2V}} \approx g_*^2 v^2/\Lambda^2$

See, e.g., [Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]

NB model-by-model, correlations exist between BR deviations and δ_{c2V}

E.g. in the SO(5)/SO(4) models shown before, and for the embedding in the fundamentl rep of SO(5) (**5**) with the fermion couplings modified by

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

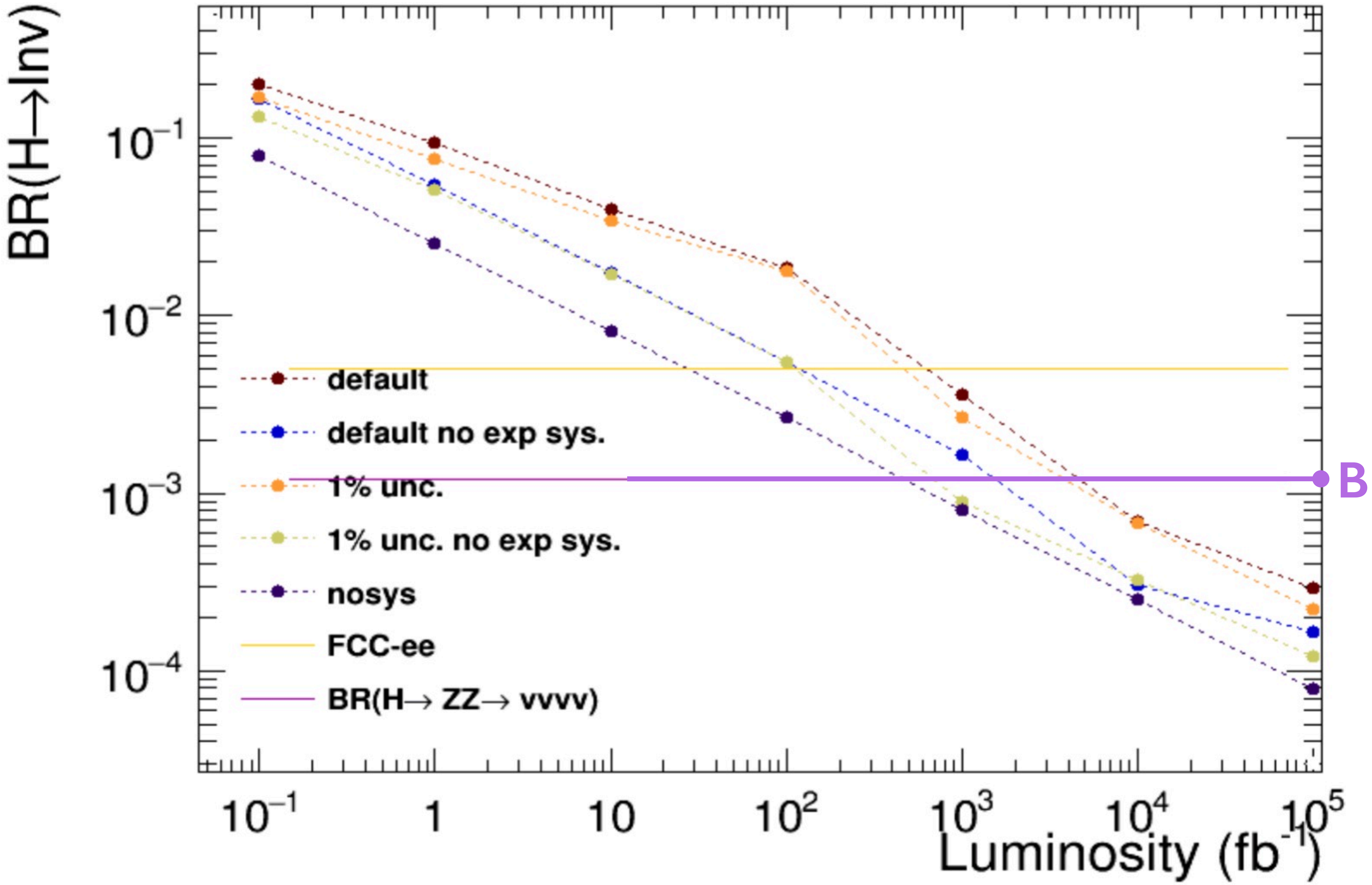


=> 1% sensitivity to δ_{c2V} is equivalent to < 1% sensitivity in BR(H->WW*)

BSM Higgs

Higgs to invisible

Constrain bg pt spectrum from $Z\to\nu\nu$ to the % level using NNLO QCD/EW* to relate to measured $Z\to ee$, W and γ spectra



$BR^{SM}(H\to4\nu)$

P.Harris at FCC wshop, updated at Feb 21 Physics WG mtg

* arXiv:1705.04664

SM sensitivity with $1ab^{-1}$, can reach few x 10^{-4} with $30ab^{-1}$

Minimal stealthy model for a strong EW phase transition:

the "nightmare scenario"

Curtin, Meade, Yu, arXiv:1409.0005

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \boxed{\frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4}$$

Unmixed SM+Singlet.

No exotic H decay, no H-S mixing, no EWPO, …

Two regions with strong EWPT

Only Higgs Portal signatures:

h*→SS direct production

Higgs cubic coupling

σ(Zh) deviation (> 0.6% @ TLEP)

⇒ Appearance of first "no-lose" arguments for classes of compelling scenarios of new physics

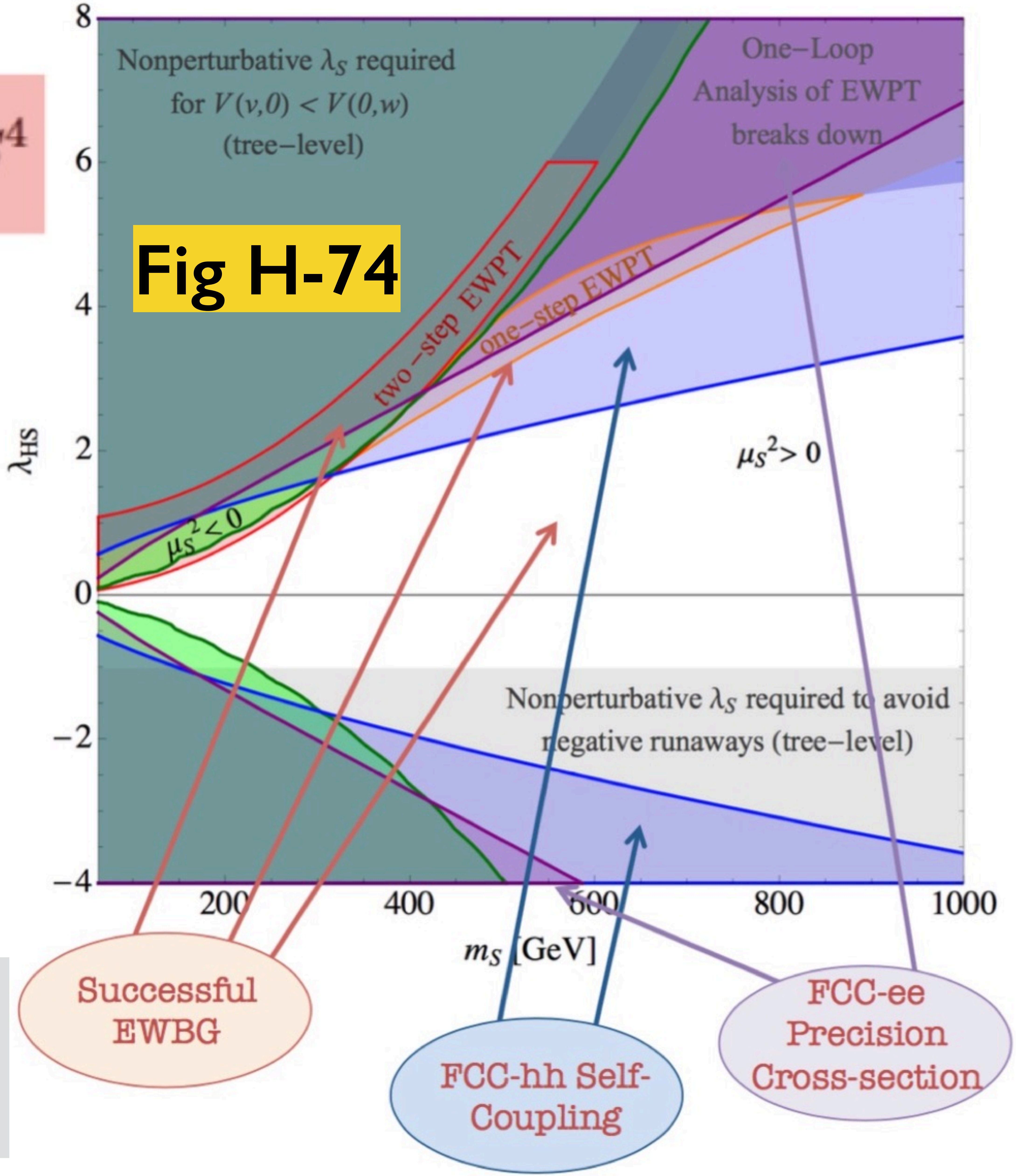
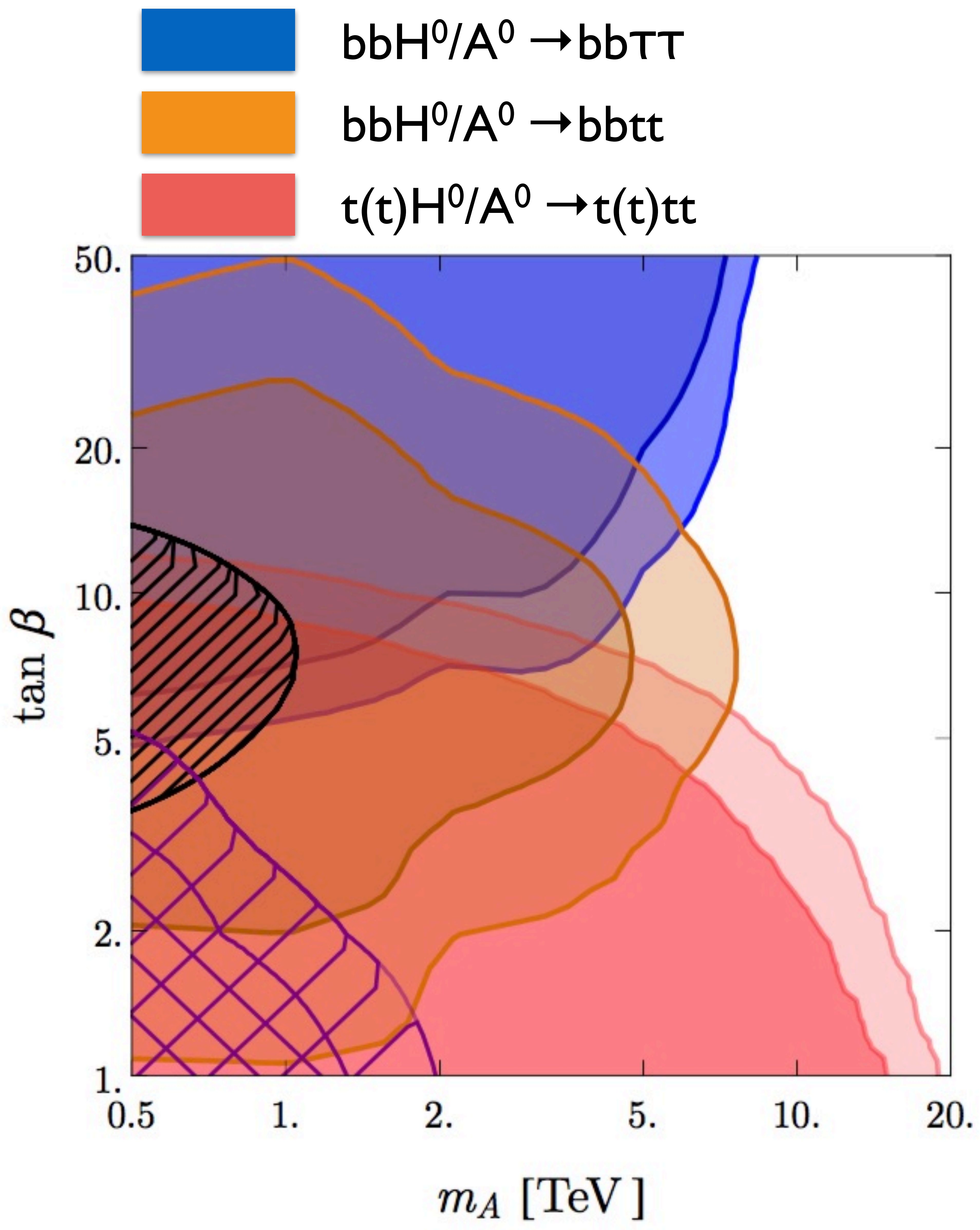
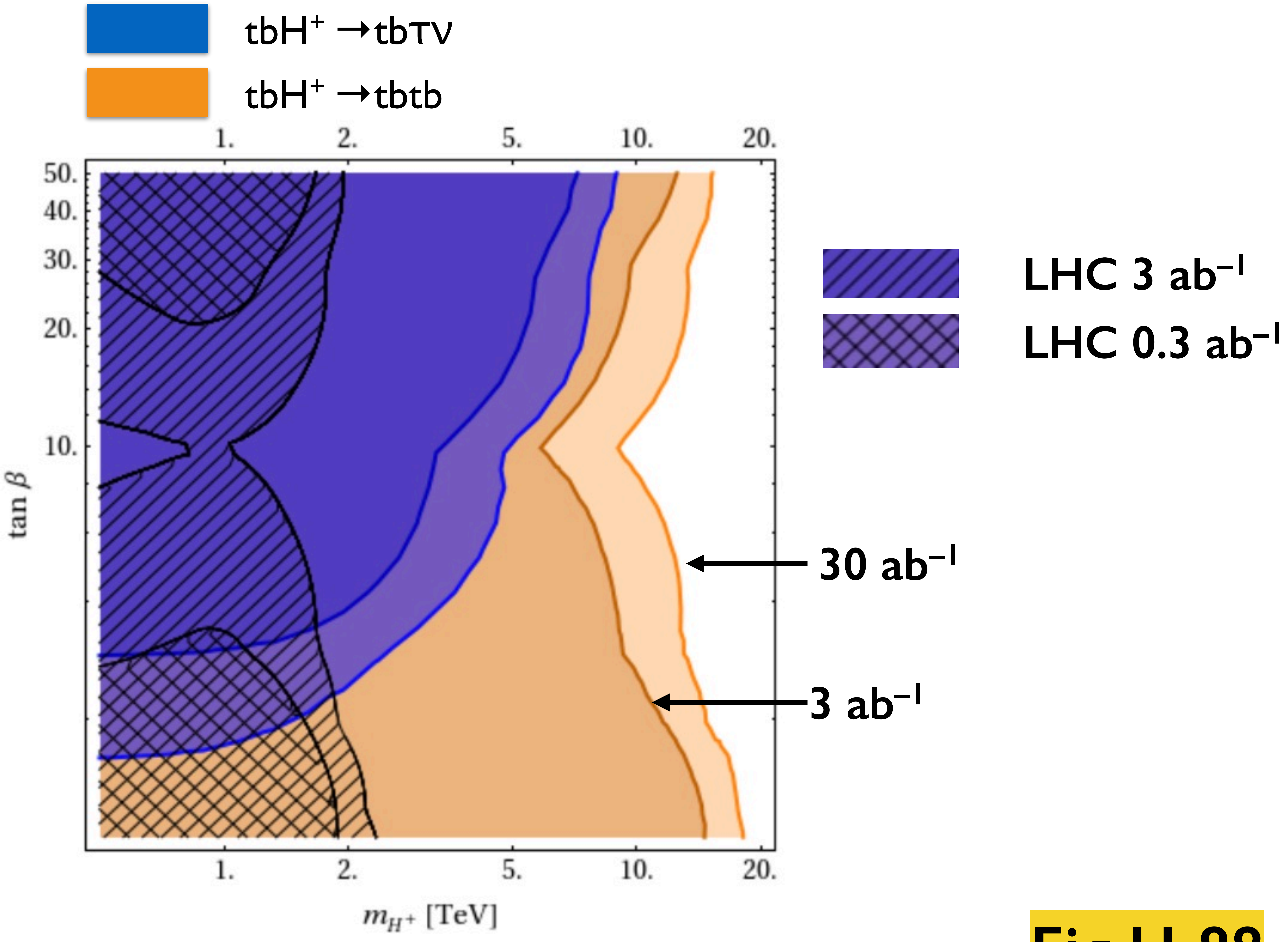


Fig H-74

MSSM Higgs @ 100 TeV



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, and H. Zhang, arXiv:1605.08744



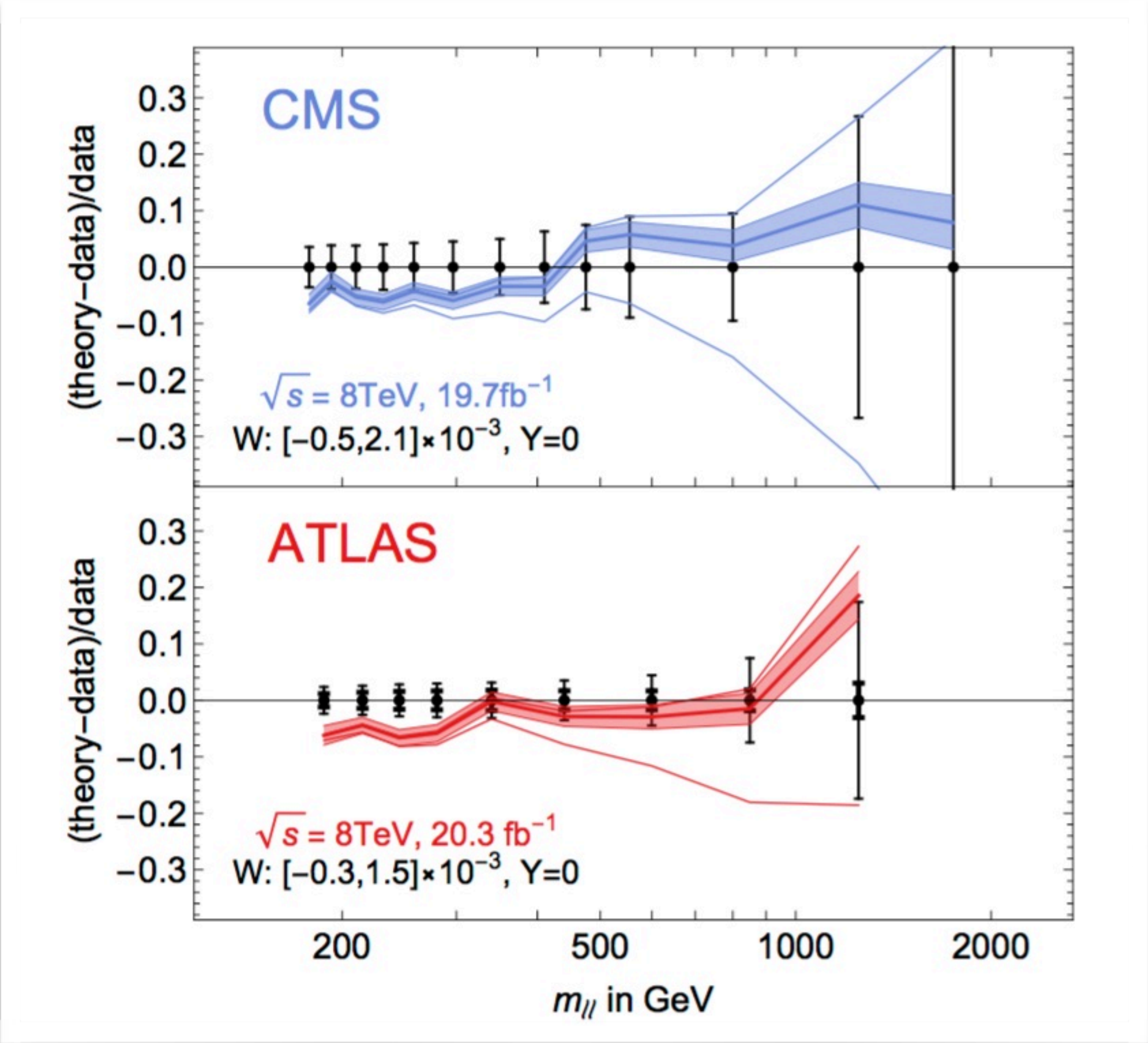
J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

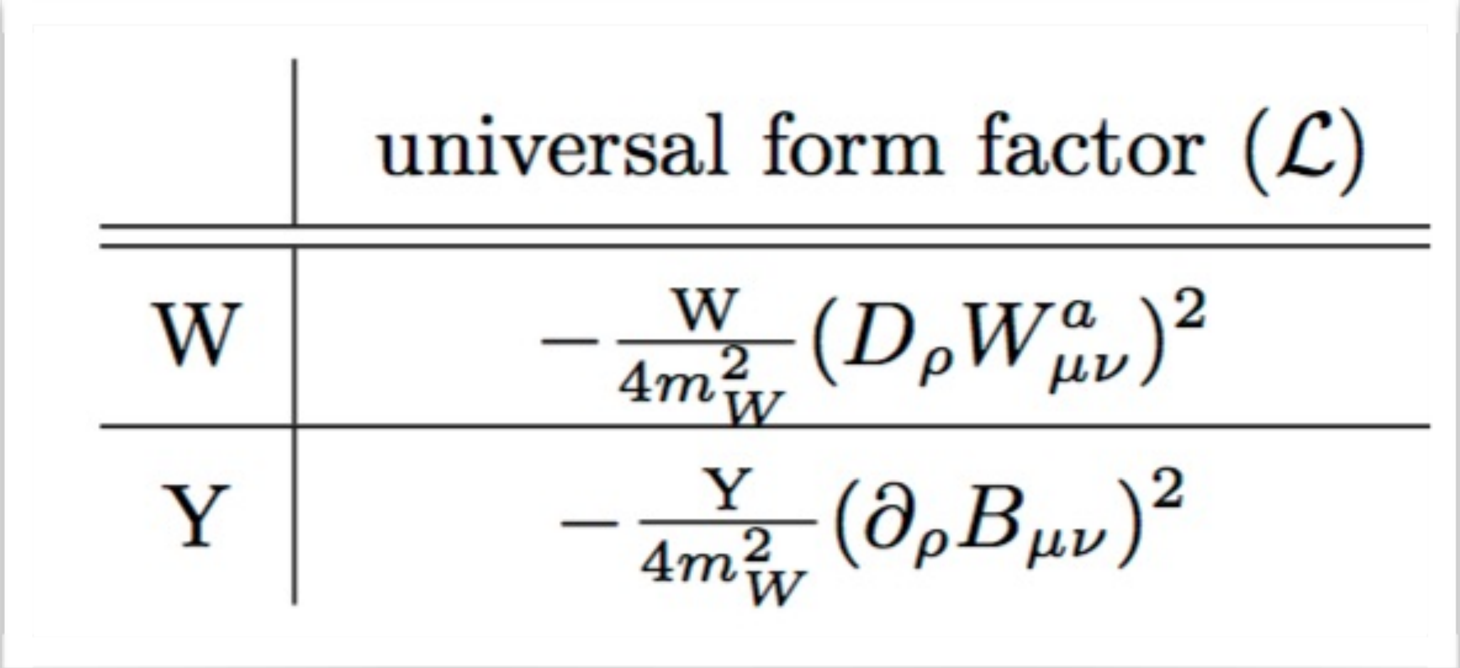
Fig H-88

Precision EW observables at 100 TeV

Probes of dim-6 op's with high-mass DY @ 100 TeV

Trade extreme precision for dynamical range, in pursuit of high-scale sensitivity

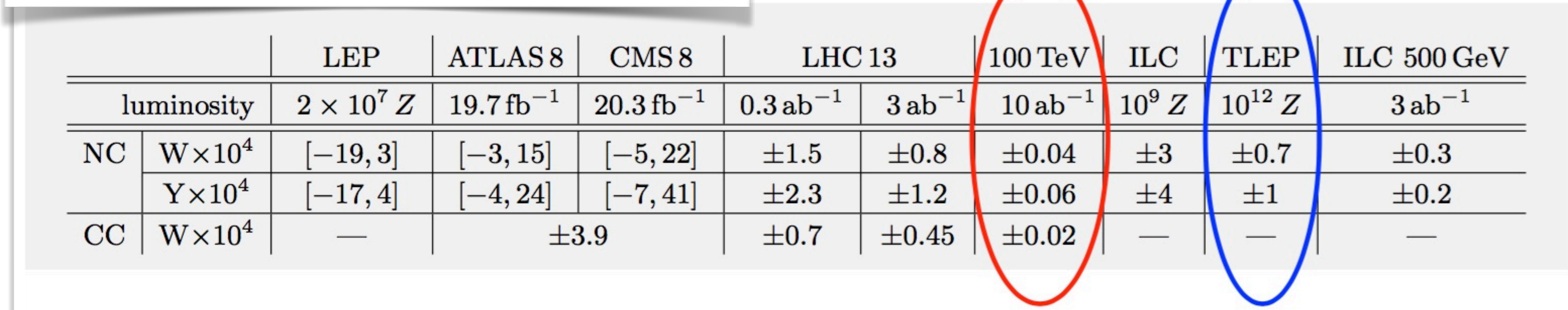




	universal form factor ($\mathcal{L}$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

M.Farina et al, arXiv:1609.08157

Josh Ruderman at the Wshop



		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		2×10^7 Z	19.7 fb^{-1}	20.3 fb^{-1}	0.3 ab^{-1}	3 ab^{-1}	10 ab^{-1}	10^9 Z	10^{12} Z	3 ab^{-1}
NC	W$\times10^4$	[−19, 3]	[−3, 15]	[−5, 22]	±1.5	±0.8	±0.04	±3	±0.7	±0.3
	Y$\times10^4$	[−17, 4]	[−4, 24]	[−7, 41]	±2.3	±1.2	±0.06	±4	±1	±0.2
CC	W$\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—

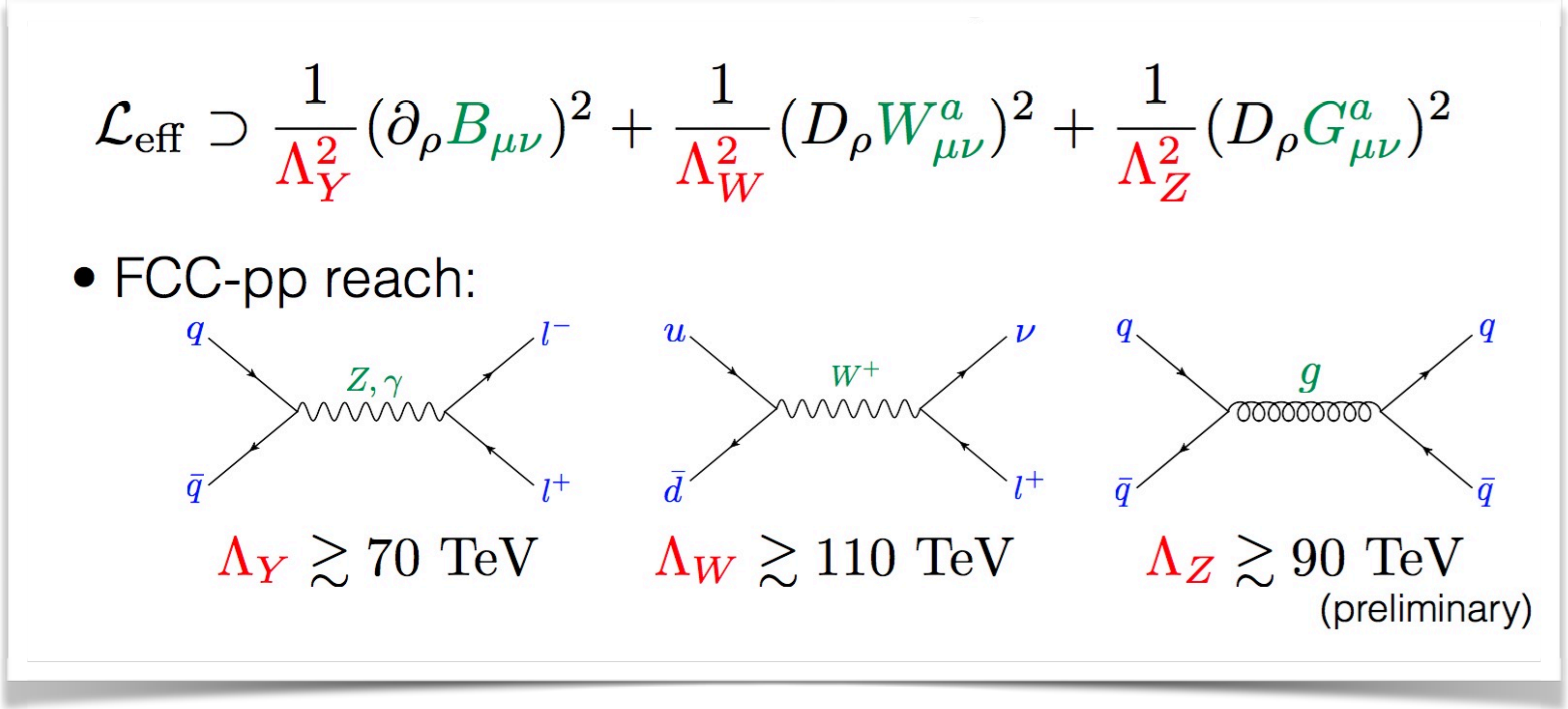
FCC-pp

FCC-ee

assumed syst's at 100 TeV:

- neutral: $\delta_{\rm cor} = \delta_{\rm unc} = 2\%$
- charged: $\delta_{\rm cor} = \delta_{\rm unc} = 5\%$

Josh Ruderman at the Wshop



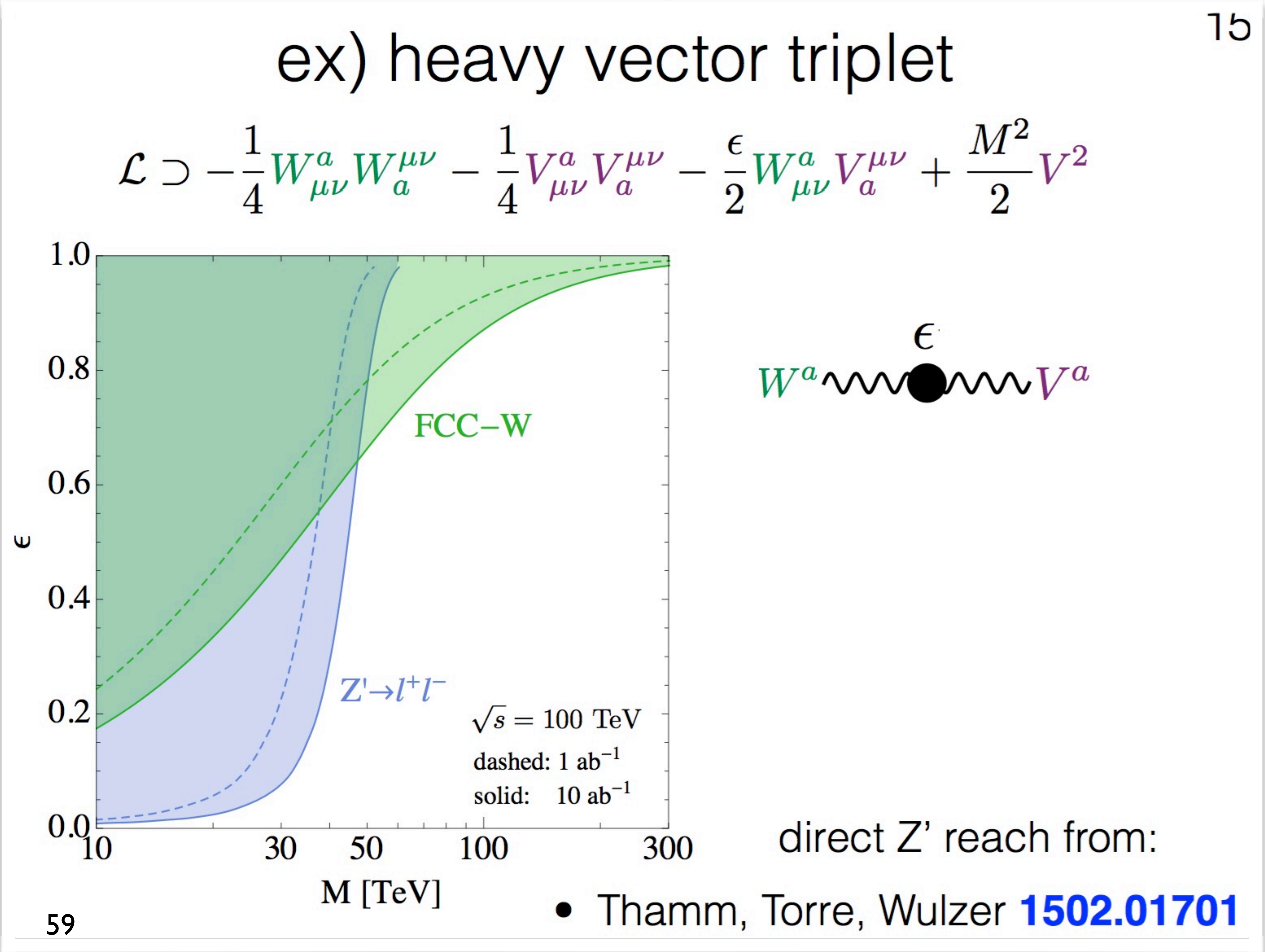
$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda_Y^2}(\partial_\rho B_{\mu\nu})^2 + \frac{1}{\Lambda_W^2}(D_\rho W^a_{\mu\nu})^2 + \frac{1}{\Lambda_Z^2}(D_\rho G^a_{\mu\nu})^2$$

- FCC-pp reach:

$\Lambda_Y \gtrsim 70$ TeV $\Lambda_W \gtrsim 110$ TeV $\Lambda_Z \gtrsim 90$ TeV

(preliminary)

complementarity of direct and indirect searches



ex) heavy vector triplet

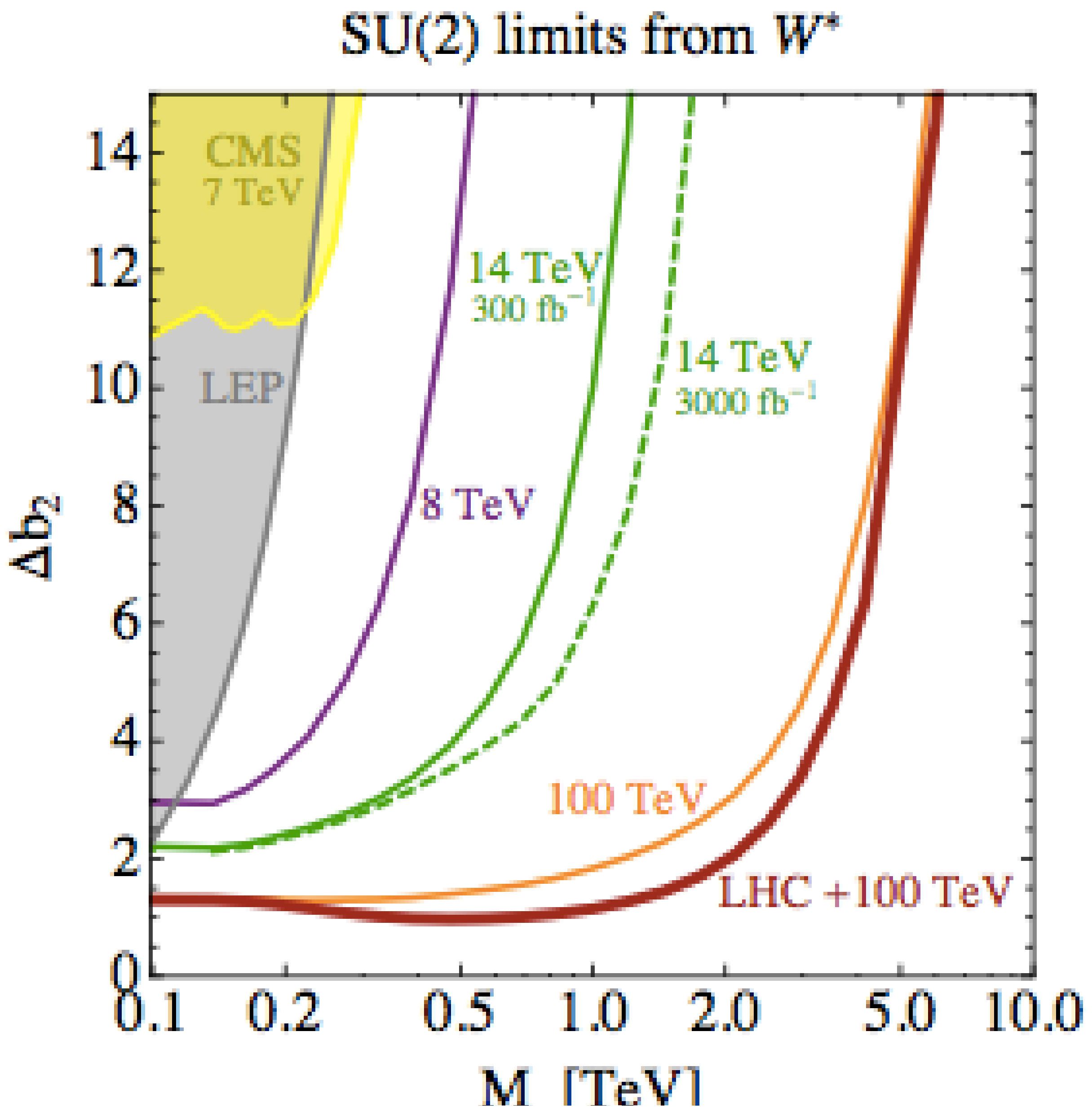
$$\mathcal{L} \supset -\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} - \frac{1}{4}V^a_{\mu\nu}V_a^{\mu\nu} - \frac{\epsilon}{2}W^a_{\mu\nu}V_a^{\mu\nu} + \frac{M^2}{2}V^2$$

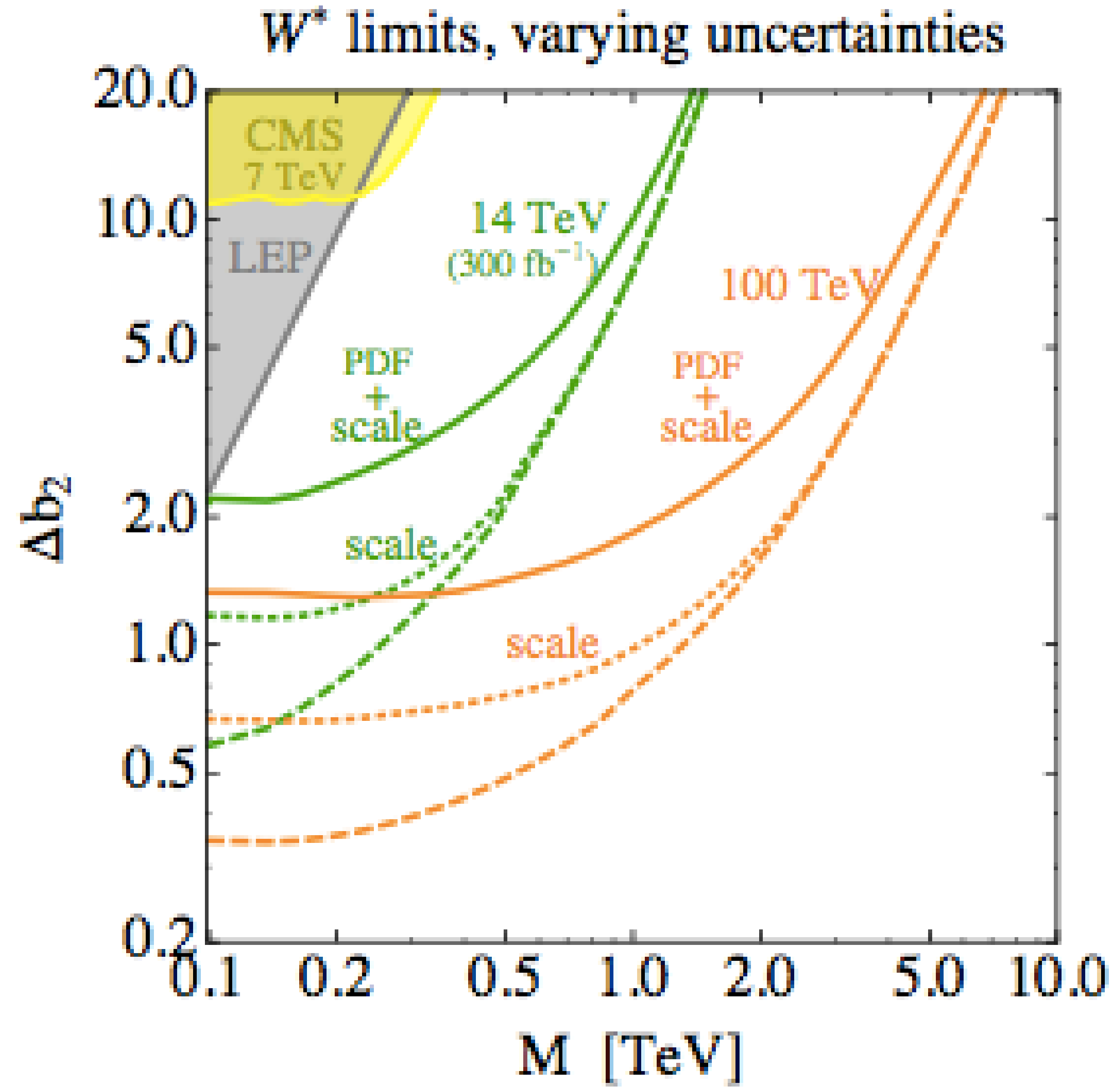
direct Z' reach from:

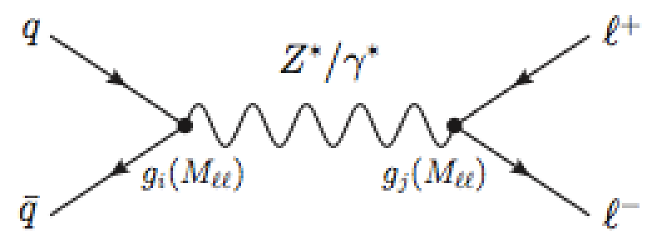
- Thamm, Torre, Wulzer **1502.01701**

Running Electroweak Couplings at 100 TeV

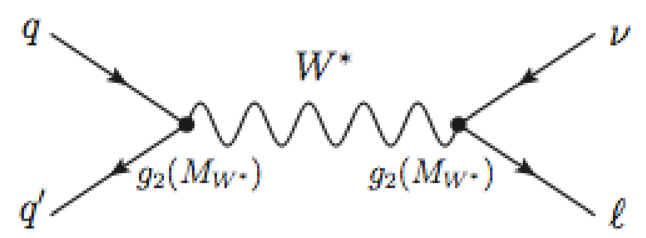
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*



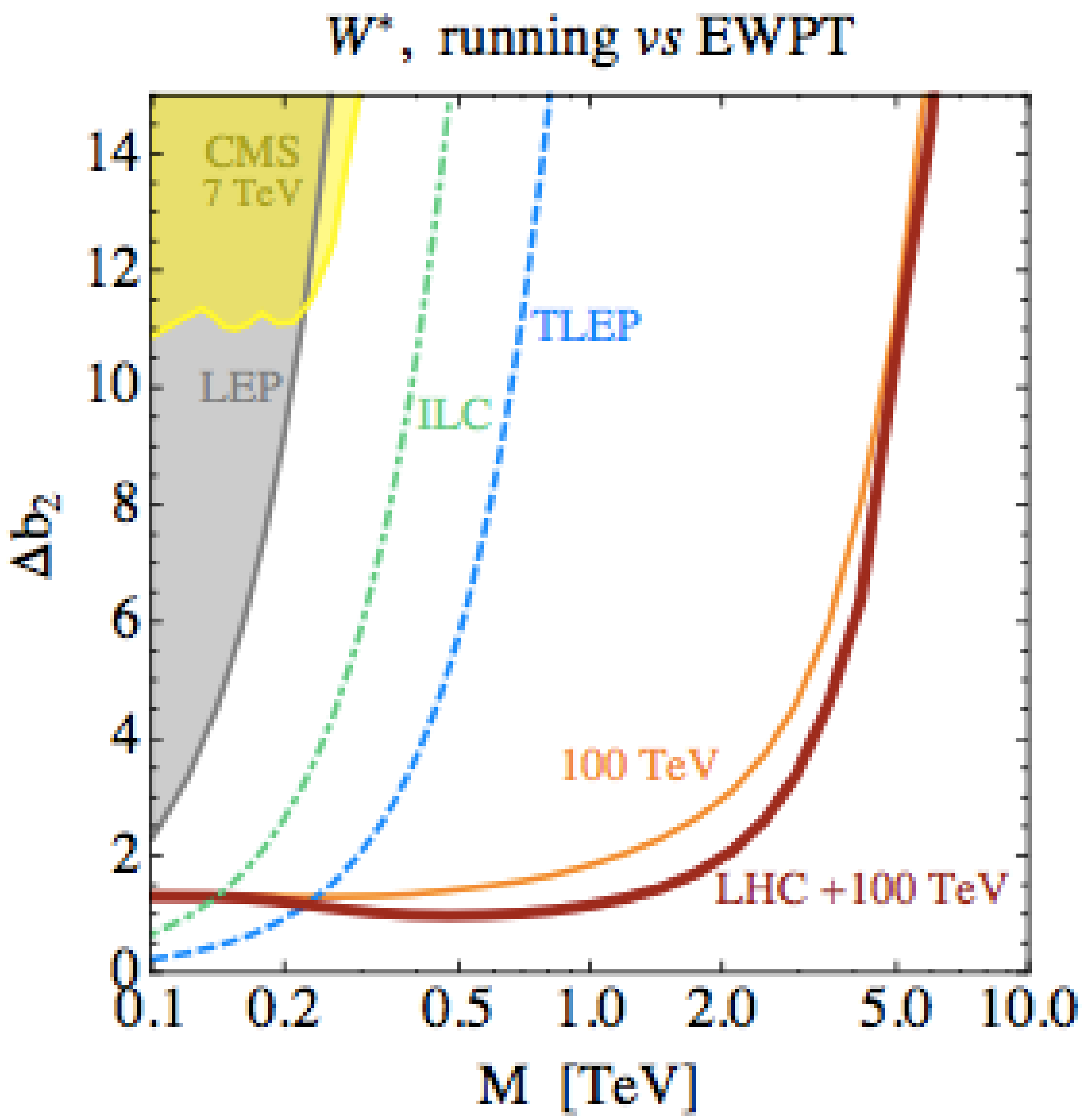


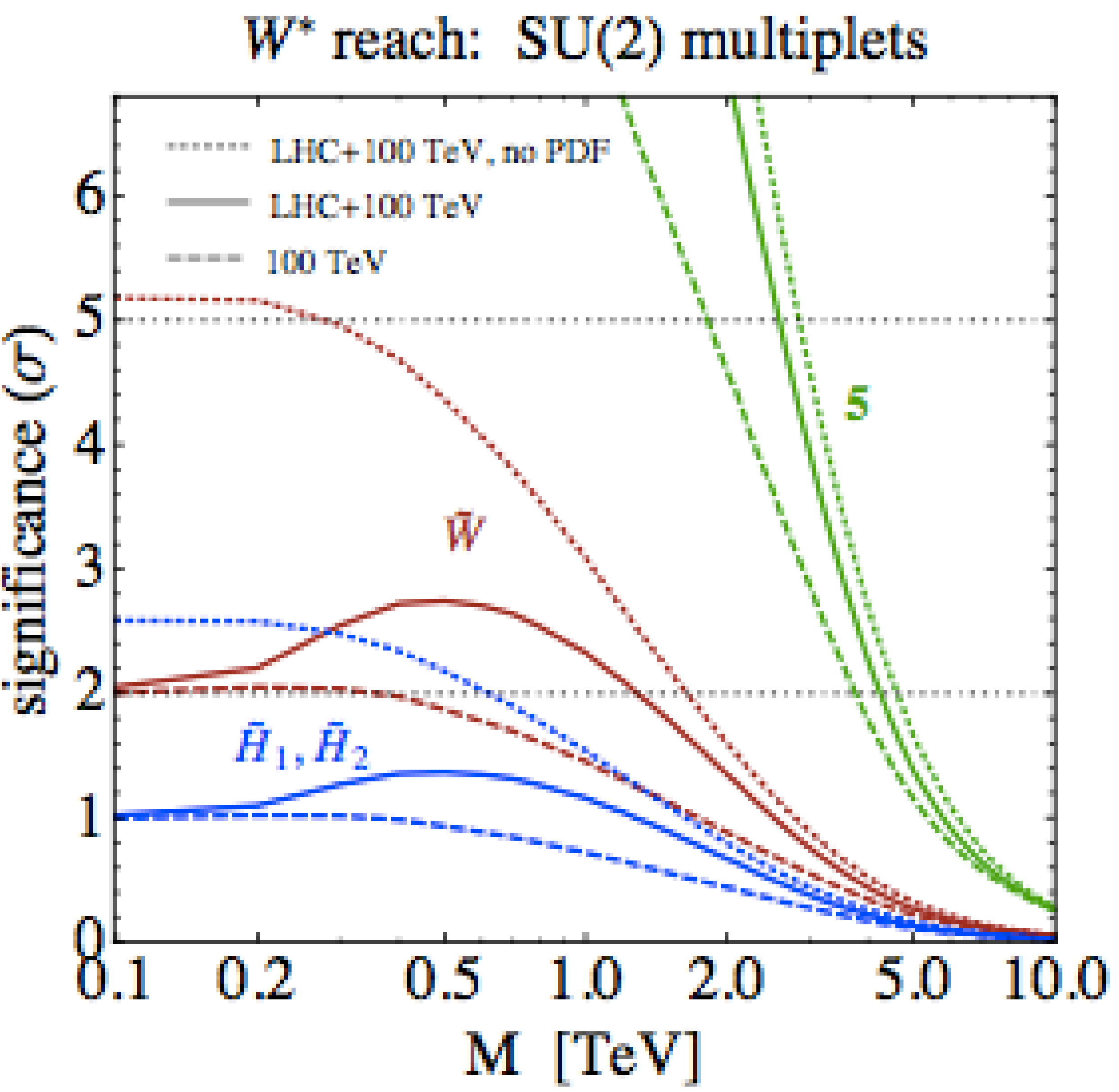


$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$



$$\frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q)$$





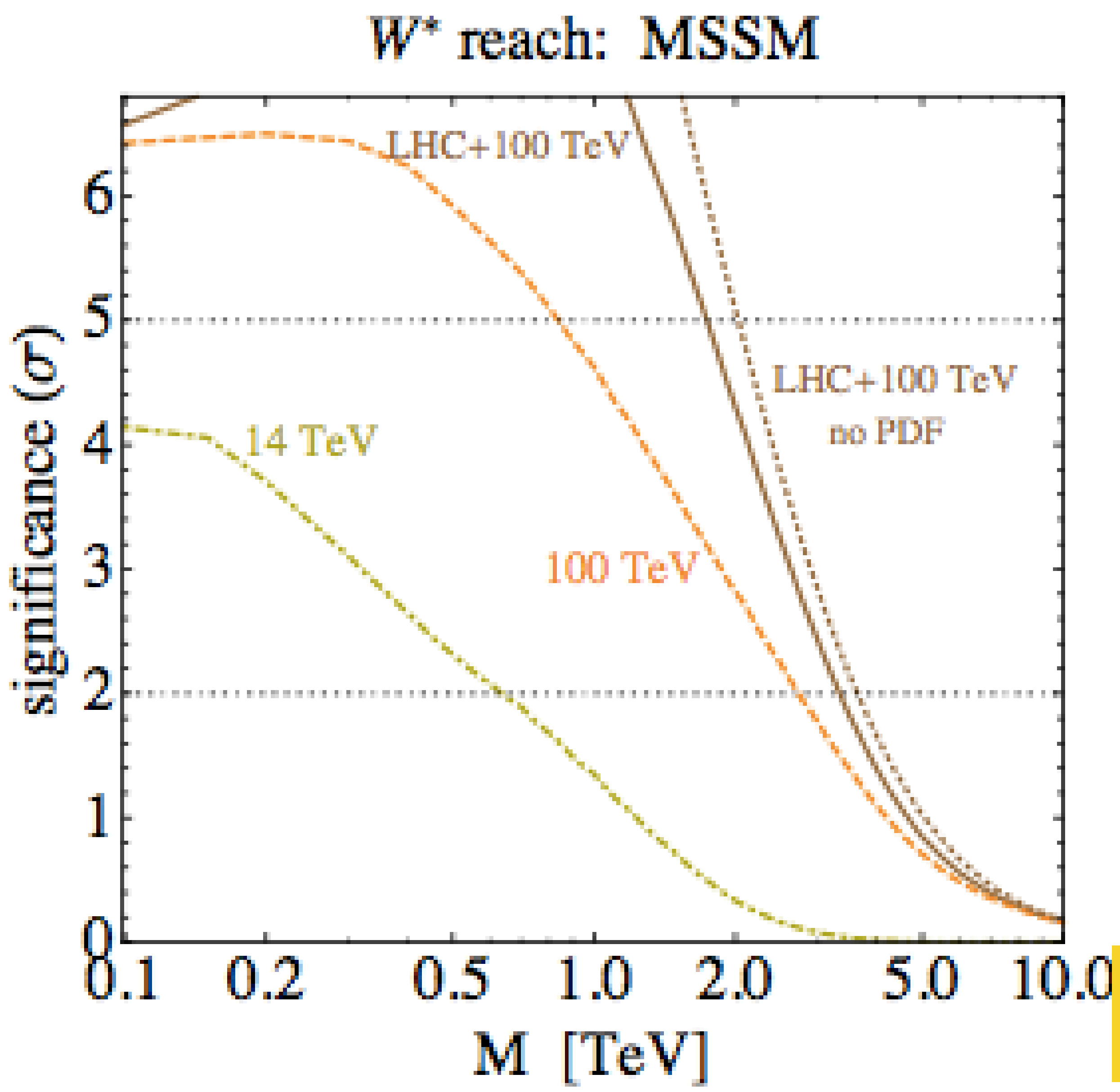
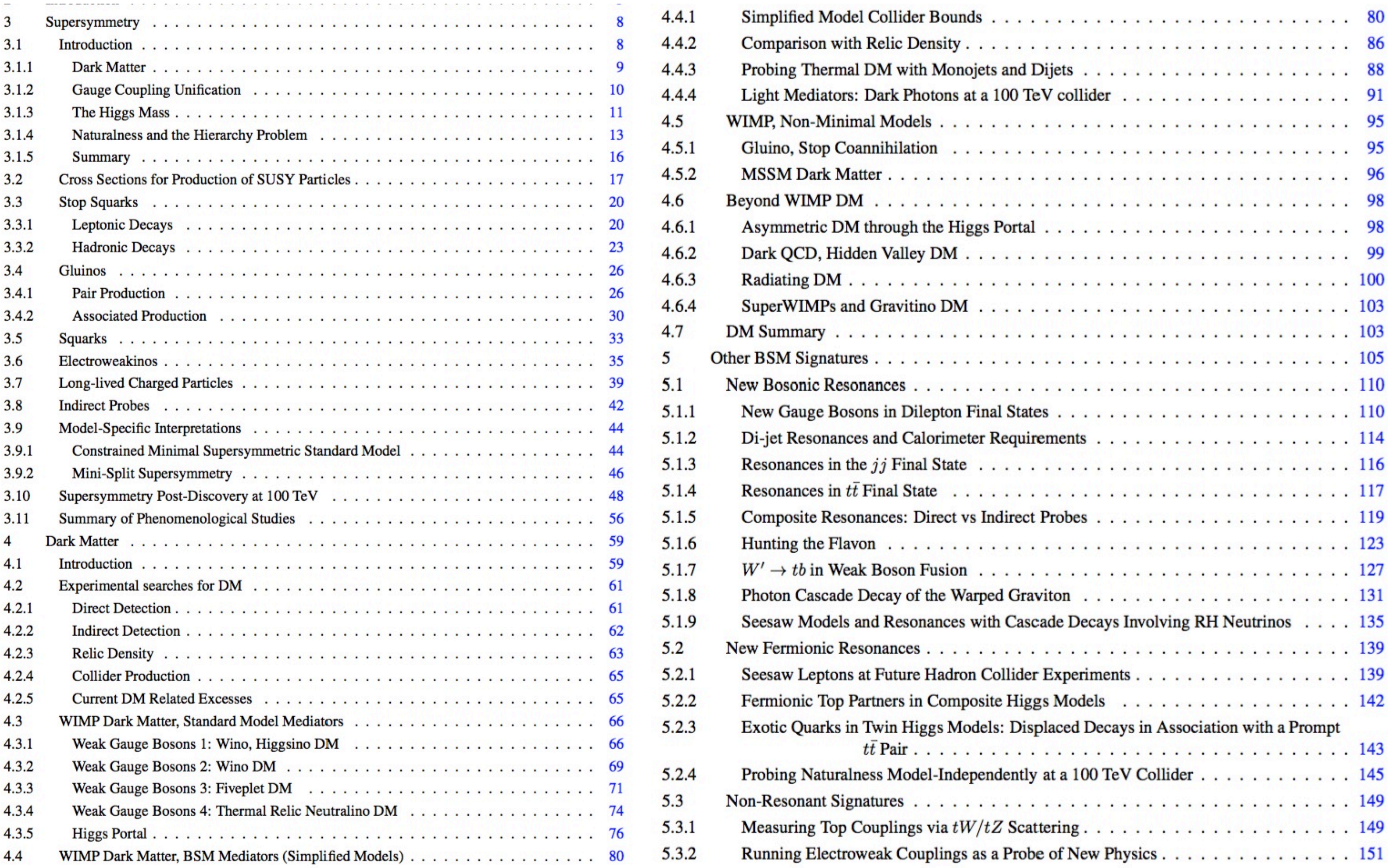


Fig BSM-112-113

BSM



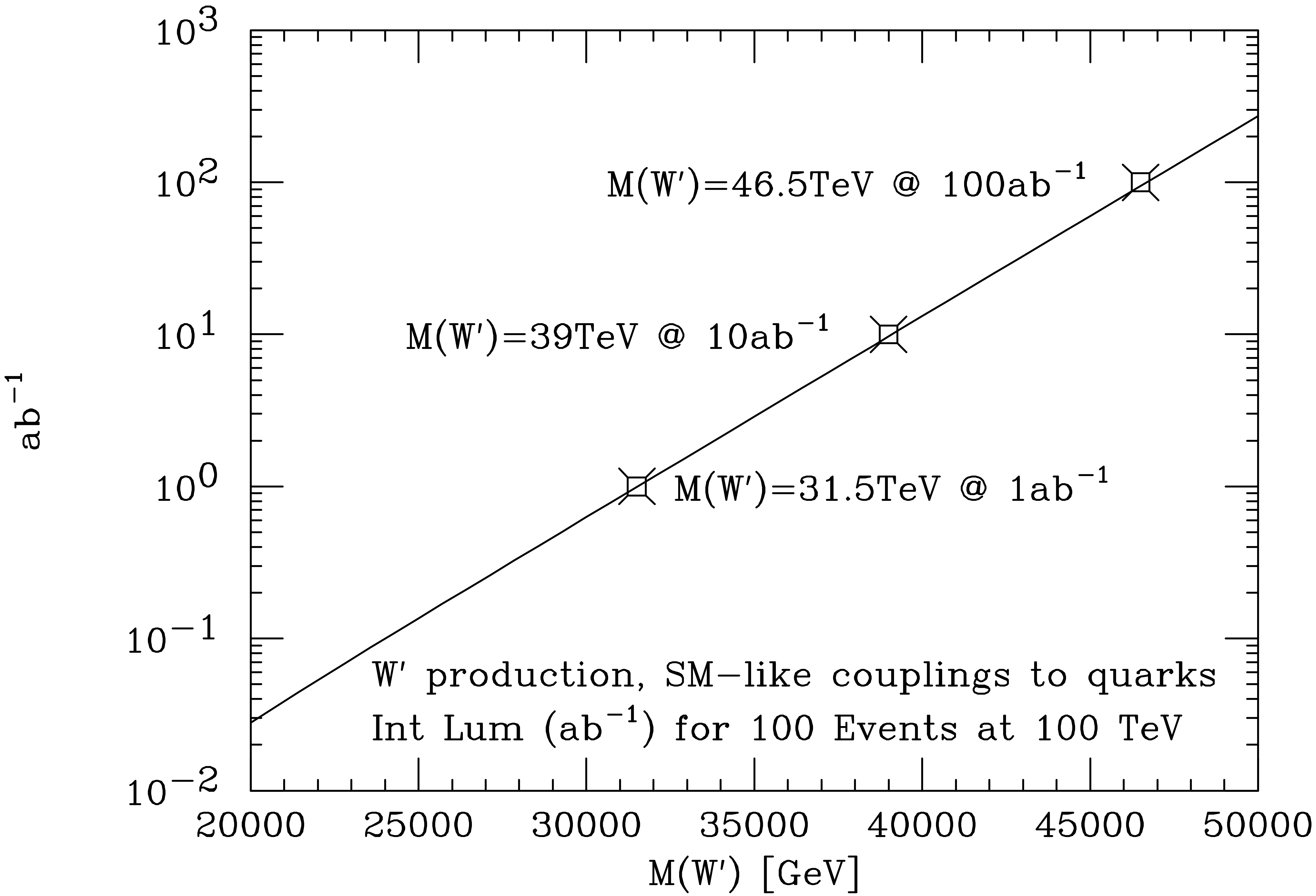
Direct discovery potential at the highest masses

at high mass, the mass reach of LHC searches for BSM phenomena like Z’, W’, SUSY, LQs, top partners, etc.etc. scales trivially by ~5-7, depending on total luminosity …

New gauge bosons discovery reach

Example: **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}$ BR$_{lept}$ ~ 0.1 x $\sigma_{W'}$ BR$_{lept}$, ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951

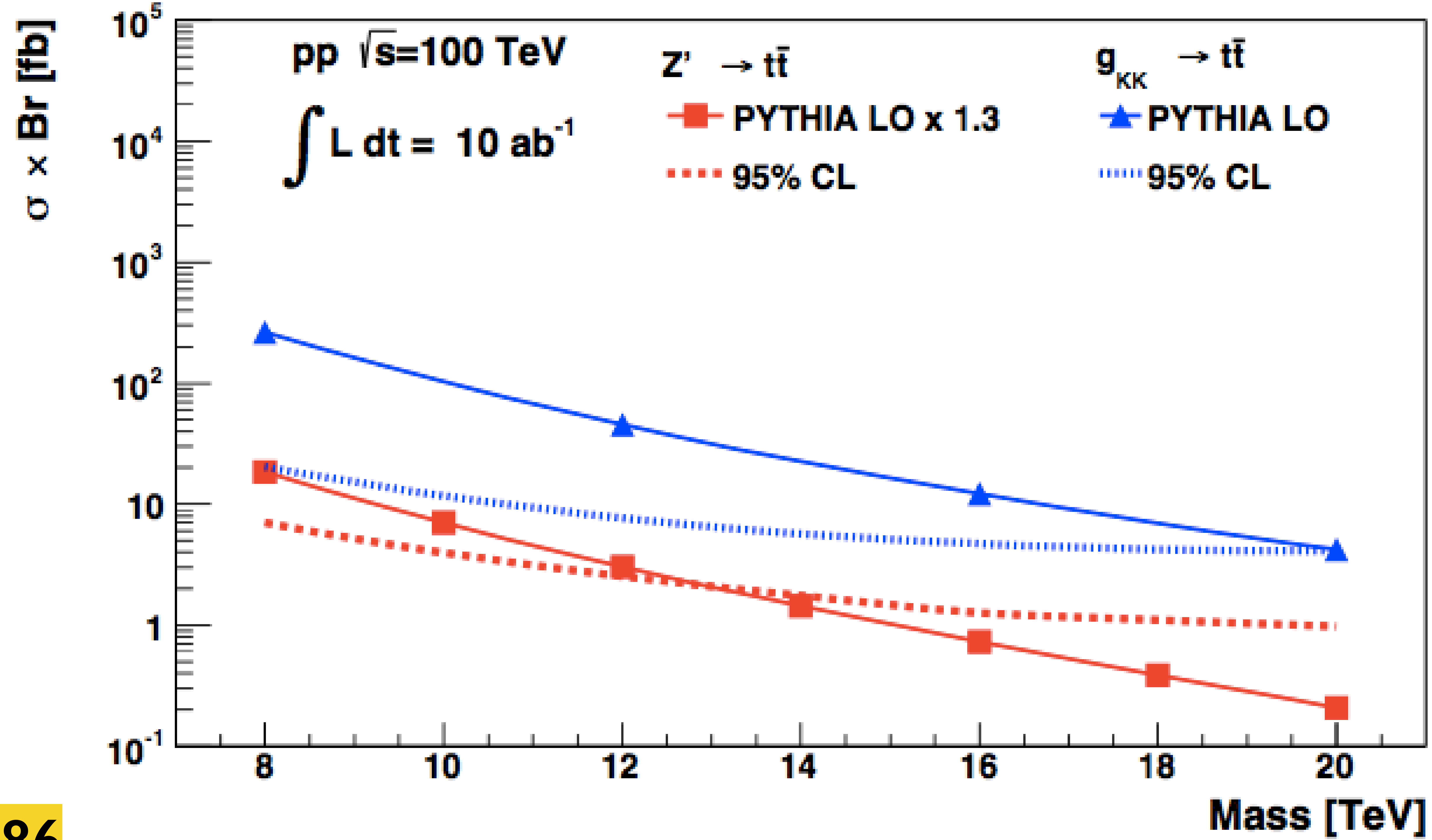
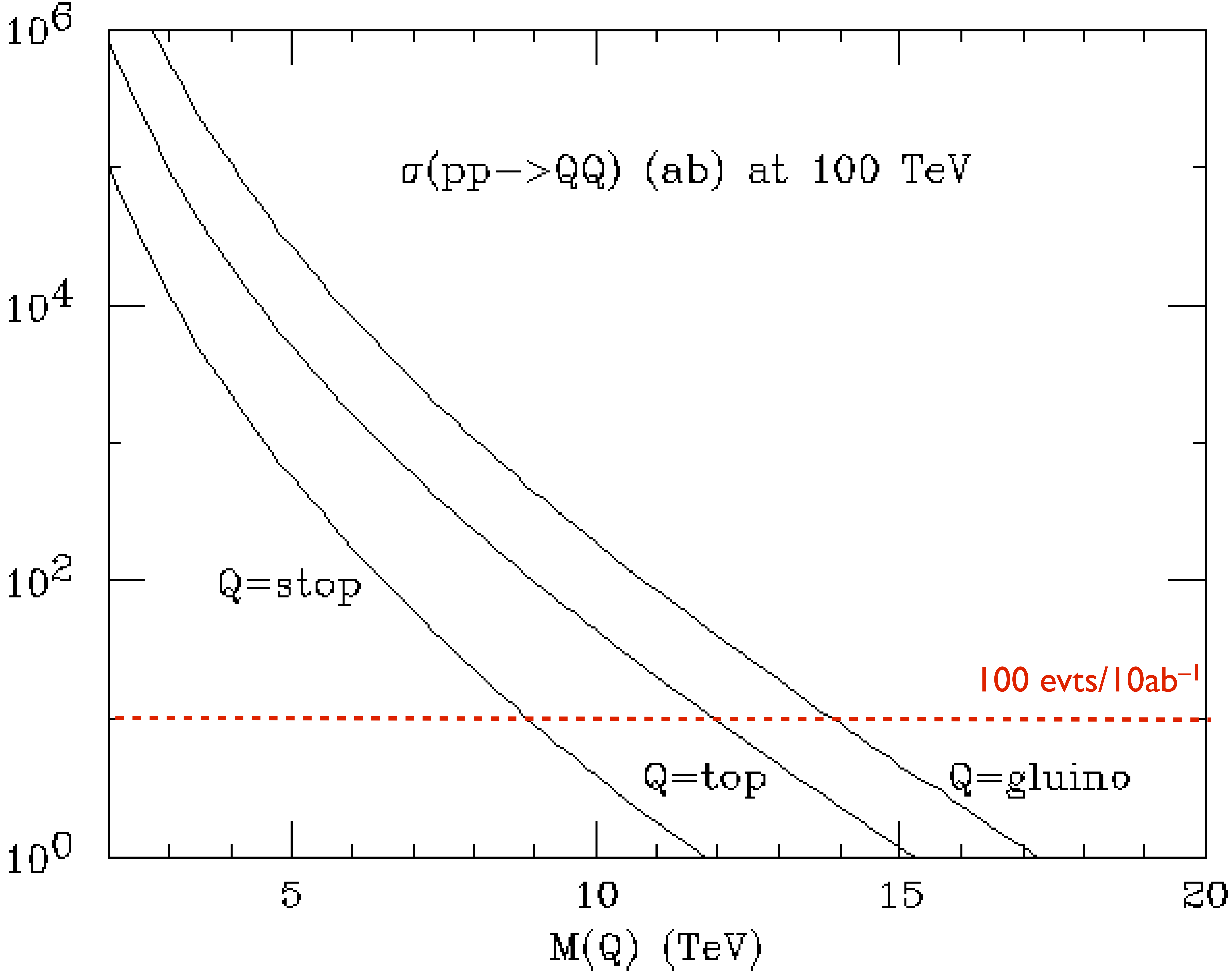


Fig BSM-86

Discovery reach for pair production of strongly-interacting particles



SUSY and DM reach at 100 TeV

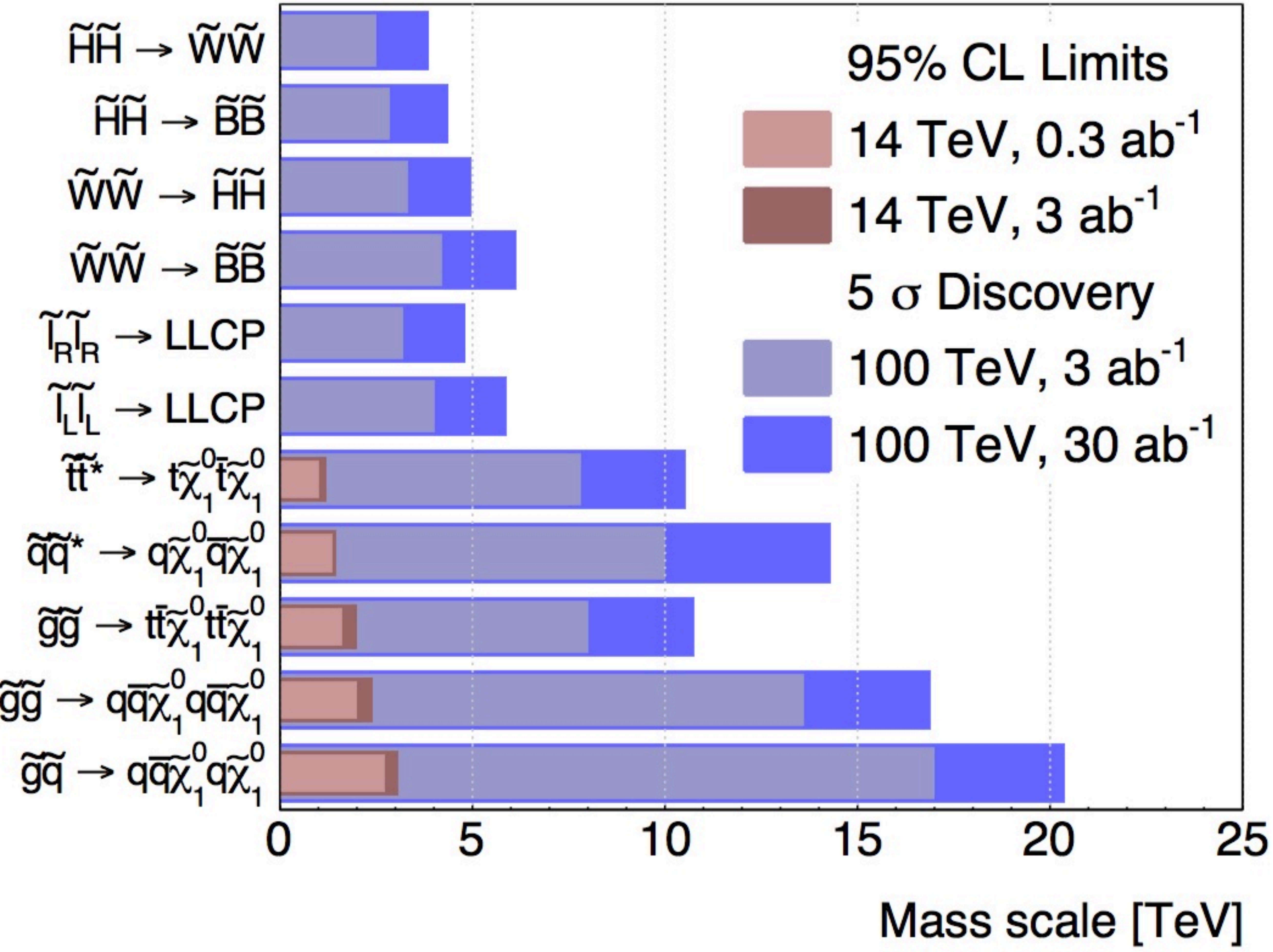


Fig BSM-38

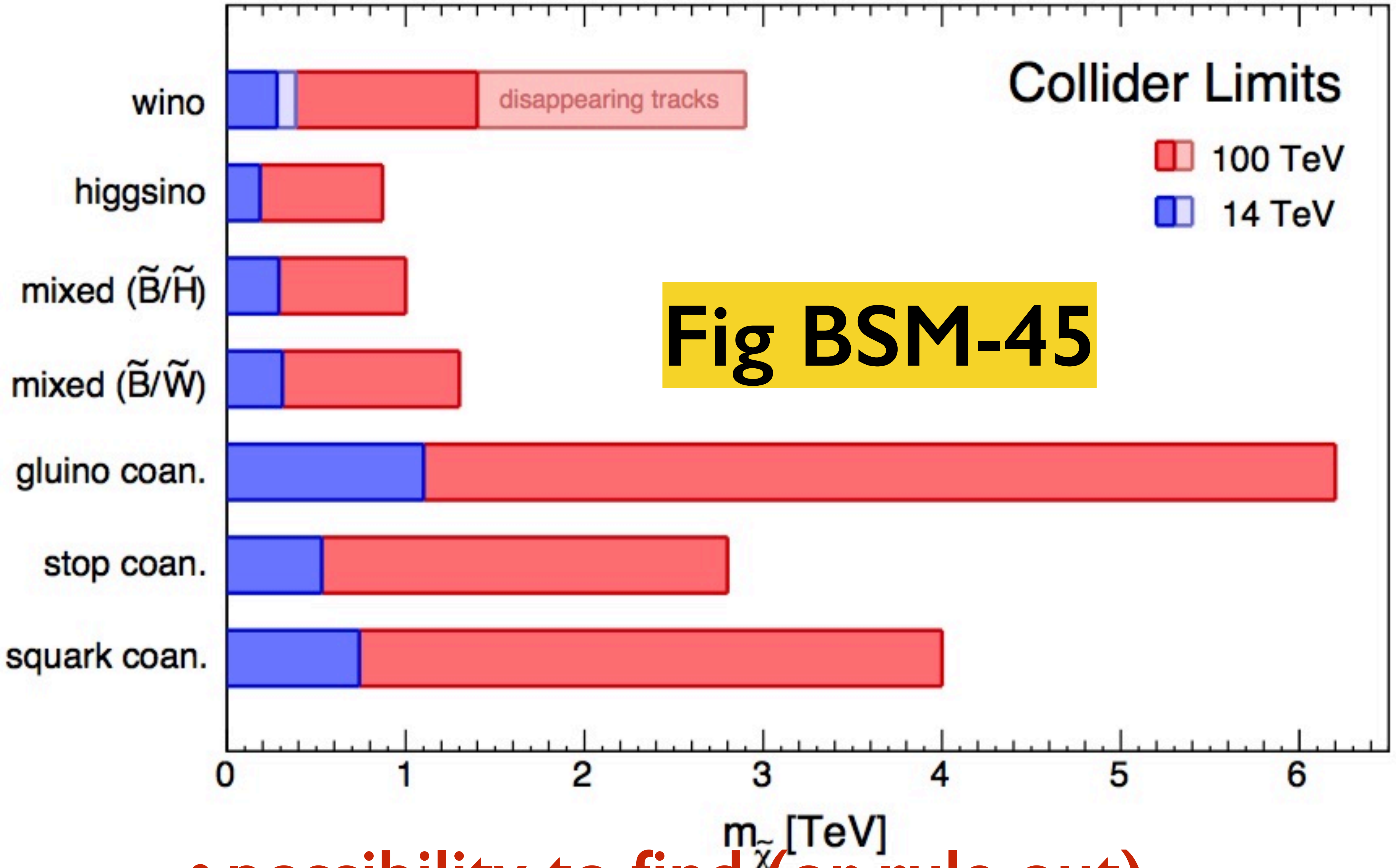
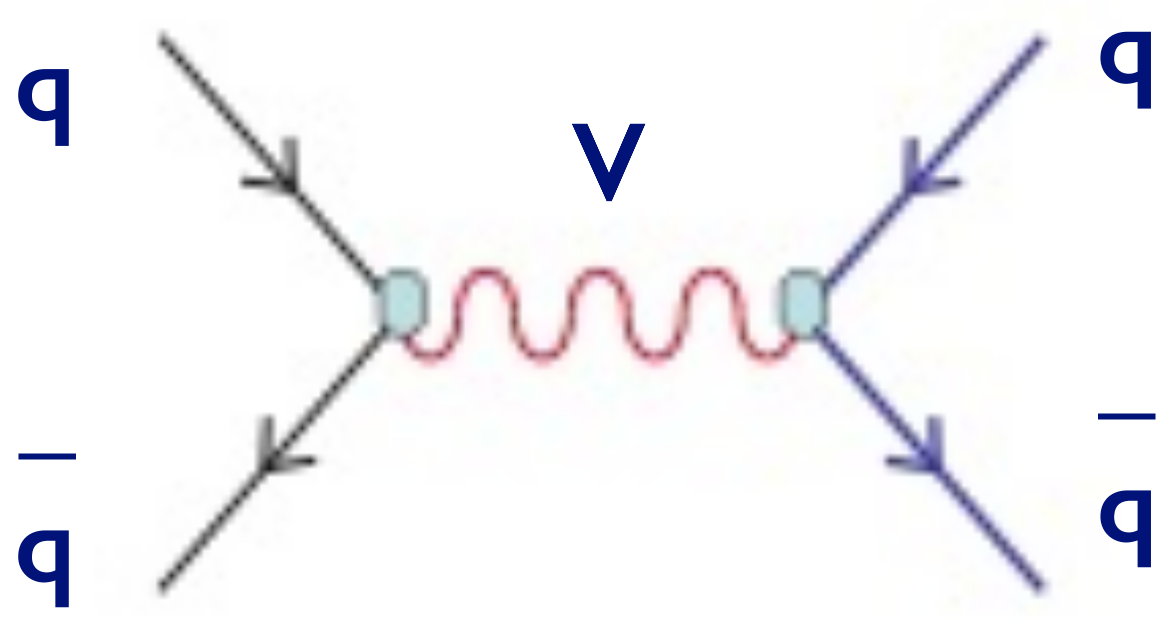


Fig BSM-45

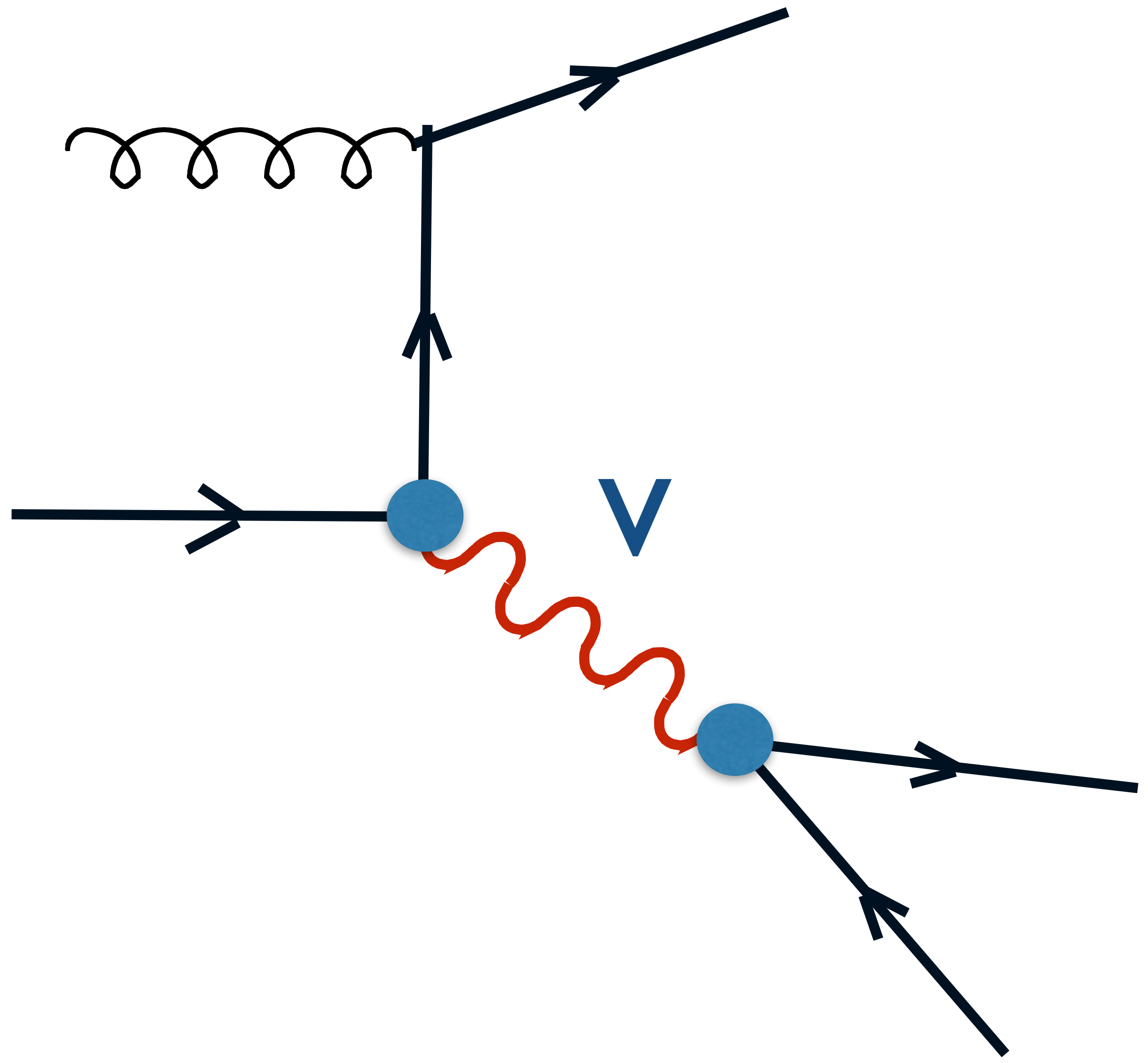
- possibility to find (or rule out) thermal WIMP DM candidates
- see P.Harris DM review in FCC-hh detector/physics // session, Thu afternoon

Larger statistics, giving access to more extreme kinematical regions, allow to exploit new powerful analysis tools, and gain sensitivity to otherwise elusive signatures

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

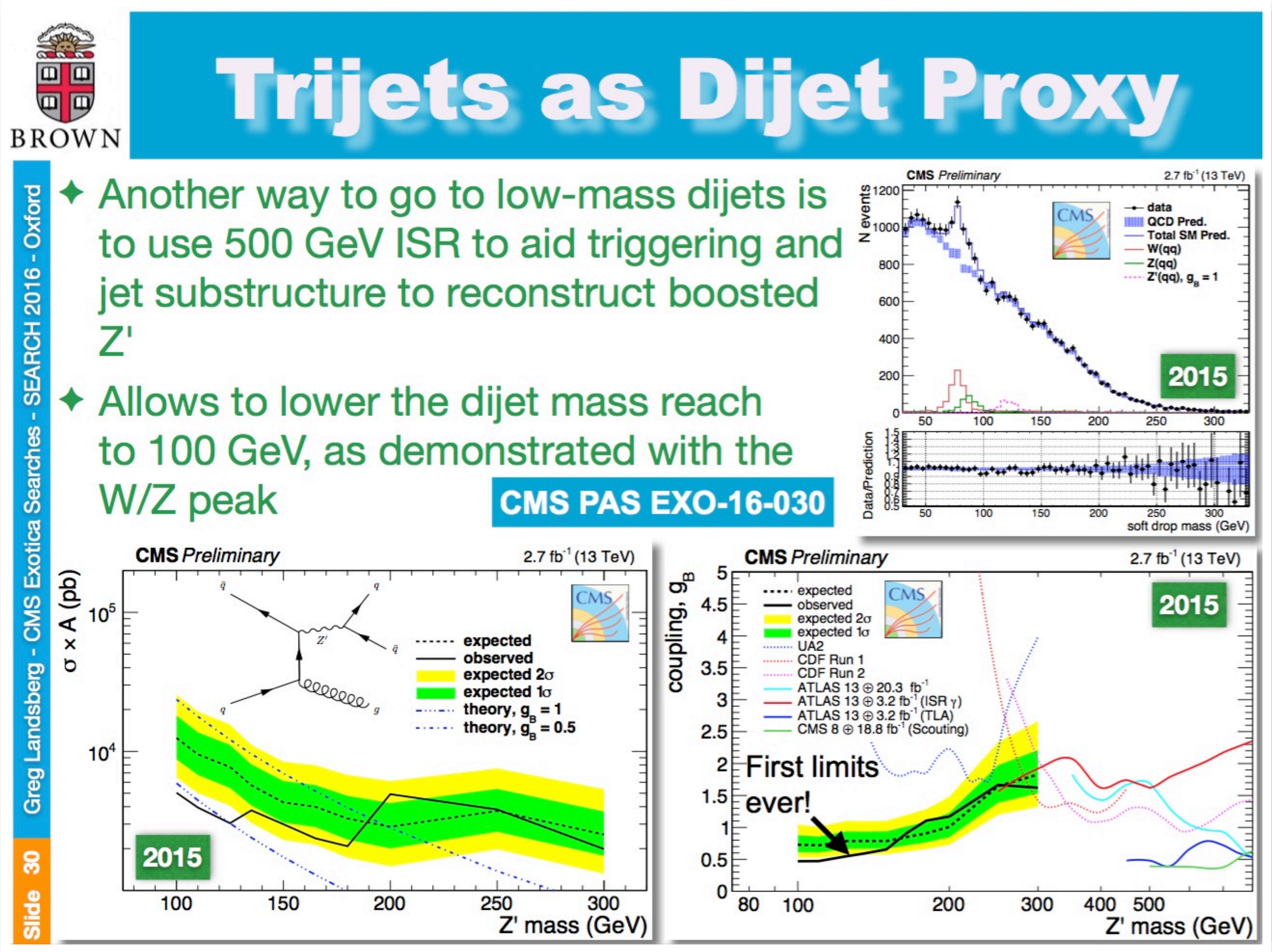


search impossible at masses below few hundred GeV, due to large gg→gg bg's and trigger thresholds



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%



Trijets as Dijet Proxy

- Another way to go to low-mass dijets is to use 500 GeV ISR to aid triggering and jet substructure to reconstruct boosted Z'
- Allows to lower the dijet mass reach to 100 GeV, as demonstrated with the W/Z peak

CMS PAS EXO-16-030

These techniques will be extremely powerful at 100 TeV. Only partly explored so far ….

If no discoveries are made at the LHC, the simplest versions of low-energy supersymmetry would be ruled out. […] the era of natural supersymmetry would come to an end. However, in such an instance it would be incorrect to conclude that the naturalness principle is misguided. Excluding new dynamics at the weak scale would mean ruling out our favoured solutions to the naturalness problem, but not the problem itself, and knowing how nature deals with Higgs naturalness will remain a standing issue. **This reframing of the naturalness question would imply the loss of the logical connection between Higgs naturalness and new phenomena at the TeV scale. If this connection is lost, what would be so special about the energy scale explored by a 100 TeV collider and why should we expect new phenomena in that range?**

Speculations have been made about logical schemes that deal with Higgs naturalness without dynamics at the weak scale, such as the anthropic principle or cosmological relaxation. Intriguingly, even within these very different schemes, motivations for supersymmetry emerge, although at a scale different than the weak scale and also for different reasons. In the context of unnatural setups, **considerations about dark matter, gauge coupling unification, or the Higgs mass, or the limited cutoff that can be achieved in cosmological relaxation scenarios call for supersymmetry with a certain preference for the O(10’s)TeV range**.

Speculations about the role of supersymmetry in ‘unnatural’ theories suggest that a future physics program should not be regarded as an extension of LHC searches, but rather as conceptually different. If the LHC is the machine of the naturalness era, future colliders would become the machine of the post-naturalness era. An era in which we are forced to change the focus of our basic questions about particle physics, in which we contemplate partly unnatural theories or theories where naturalness is realised in unconventional ways, and in which supersymmetry may enter in a new guise.

100 TeV ?

200 TeV ?

28 TeV ?

HE-LHC

HE-LHC

- Technological dimension. Eg
  - does the FCC-hh need a demonstrator?

HE-LHC

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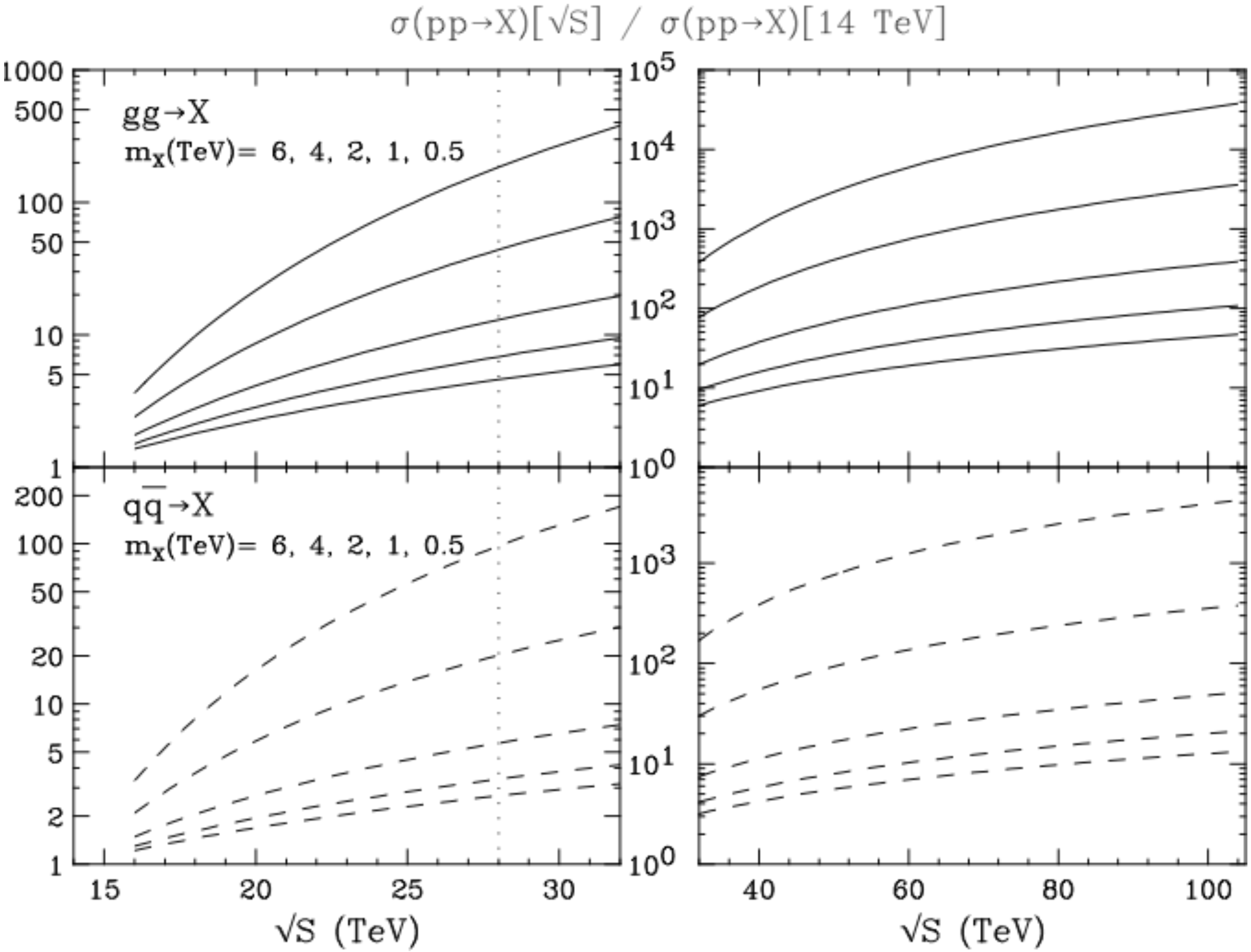
  - does the FCC-hh need a demonstrator?
- Political dimension. Eg
  - acceptable cost ?
  - keep community active during a possibly long wait for the FCC
  - …

HE-LHC

not for this discussion

- ~~Technological dimension. Eg~~
  - ~~does the FCC-hh need a demonstrator?~~
- ~~Political dimension. Eg~~
  - ~~acceptable cost ?~~
  - ~~keep community active during a possibly long wait for the FCC~~
  - ~~…~~
- Physics dimension
  - some first considerations to follow …

Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



Possible questions/options

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- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:

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- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?

Possible questions/options

- If $m_X \sim 6$ TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?

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  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *28 TeV would be insufficient ....*)

Possible questions/options

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  - .... and the answers may depend on whether we expect partners of X at masses ≳ $2m_X$ (⇒ *28 TeV would be insufficient* ....)

- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:

Possible questions/options

- If $m_X \sim 6$ TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ (⇒ *28 TeV would be insufficient ....*)

- If $m_X \sim 0.5$ TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?

Possible questions/options

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  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
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- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?

Possible questions/options

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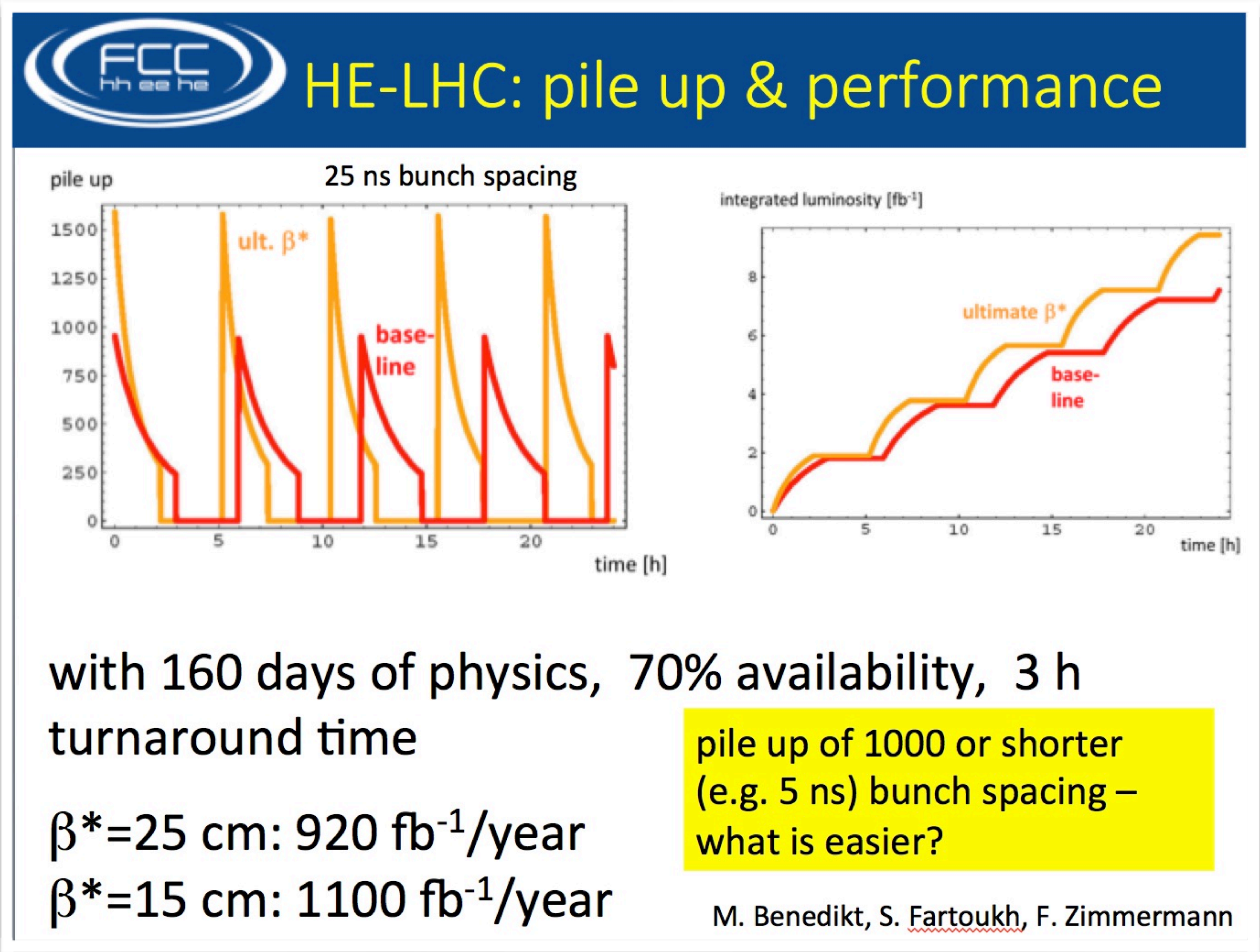
- etc.etc.

HE-LHC (27 TeV), prelim performance estimates



HE-LHC: pile up & performance

with 160 days of physics, 70% availability, 3 h turnaround time

β^*=25 cm: 920 fb^{-1}/year

β^*=15 cm: 1100 fb^{-1}/year

pile up of 1000 or shorter (e.g. 5 ns) bunch spacing – what is easier?

M. Benedikt, S. Fartoukh, F. Zimmermann

=> O(15 ab^{-1}) over 15-20 years

Systematics studies* of the full physics potential at O(28) TeV, with O(15 ab^{-1}), need to be carried out

* except for straightfwd mass-reach extrapolations from LHC

E.g. HH at 28 TeV (back of the envelope)

σ_{HH}(28 TeV)/σ_{HH}(14 TeV) ~ 4 ;   Lum(28)~ 4 Lum(14 TeV)

=> N_{HH}(28) ~ 16 N_{HH}(14)

=> $\delta\lambda_{HHH}$ (28) ~ $\delta\lambda_{HHH}$ (HL-LHC) / 4 ~ 10%

Expect to carry out an overall evaluation of the physics potential during 2018 (likely in the context of the HL-LHC Physics workshop)

Final remarks

- FCC-hh physics studies today focus on exploring possible scenarios, assessing the physics potential, defining benchmarks for the accelerator and detector design and performance, in order to better inform the discussions that will take place when the time for decisions comes...
- The interplay of the three colliders (ee, eh and hh) is crucial to the full exploitation of the FCC physics potential
- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there must take account of the fuller picture, to reflect the future data (and the impact they will have on the theoretical thinking) from the LHC, as well as other current and future experiments in areas ranging from flavour physics to searches for dark matter, axions, ALPs, ….