EP-TH Faculty meeting on
"Measurement of Higgs properties: sensitivity of present and future facilities"
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Higgs physics at hadronic circular colliders beyond HL-LHC

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See also R.Contino et al, Physics at 100 TeV Yellow Report,
http://arxiv.org/abs/arXiv:1606.09408

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

Goal: 30 (15) ab^{-1} during the 100 (27) TeV collider lifetime

SM Higgs: event rates at 100 TeV

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

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

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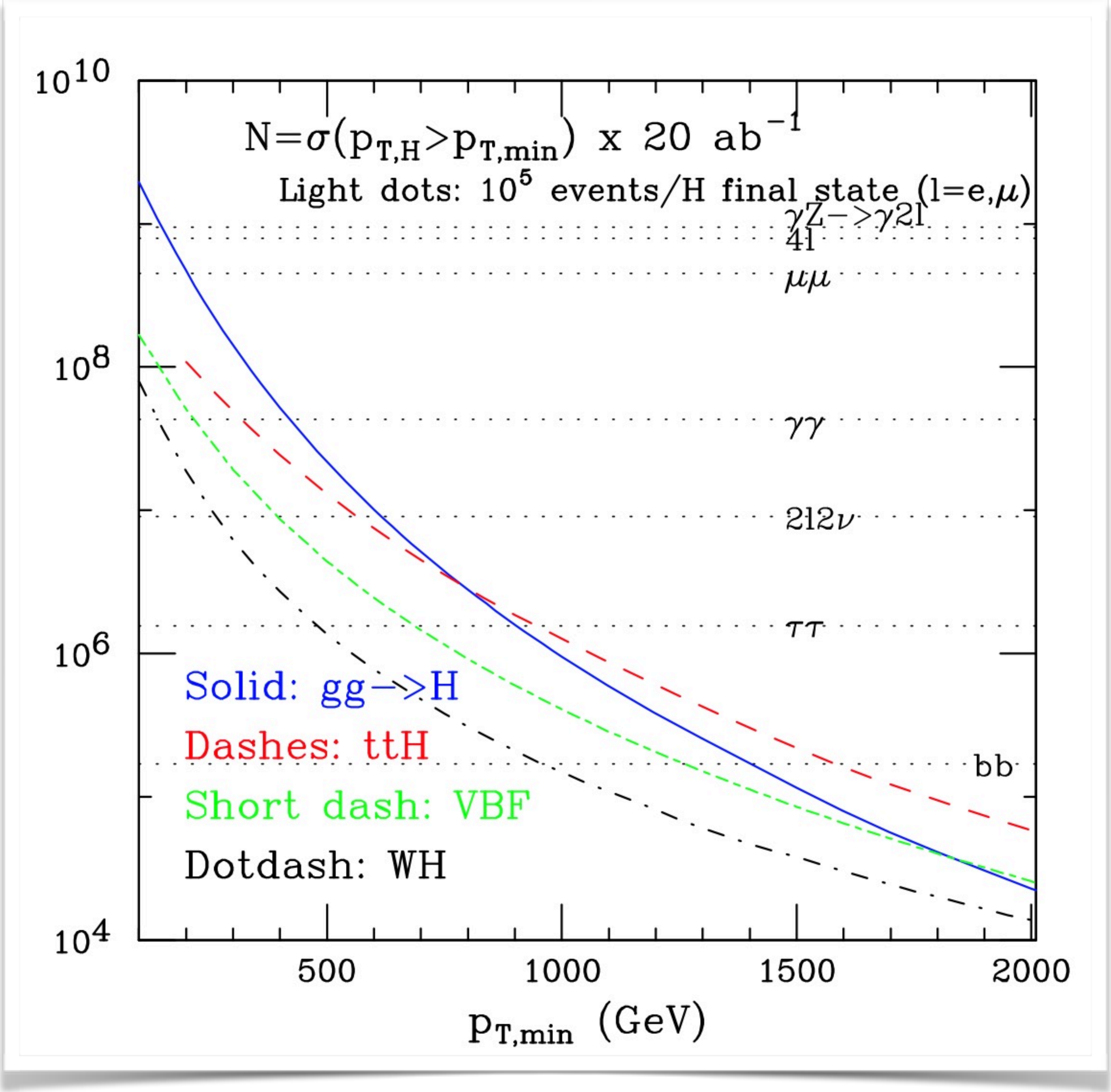
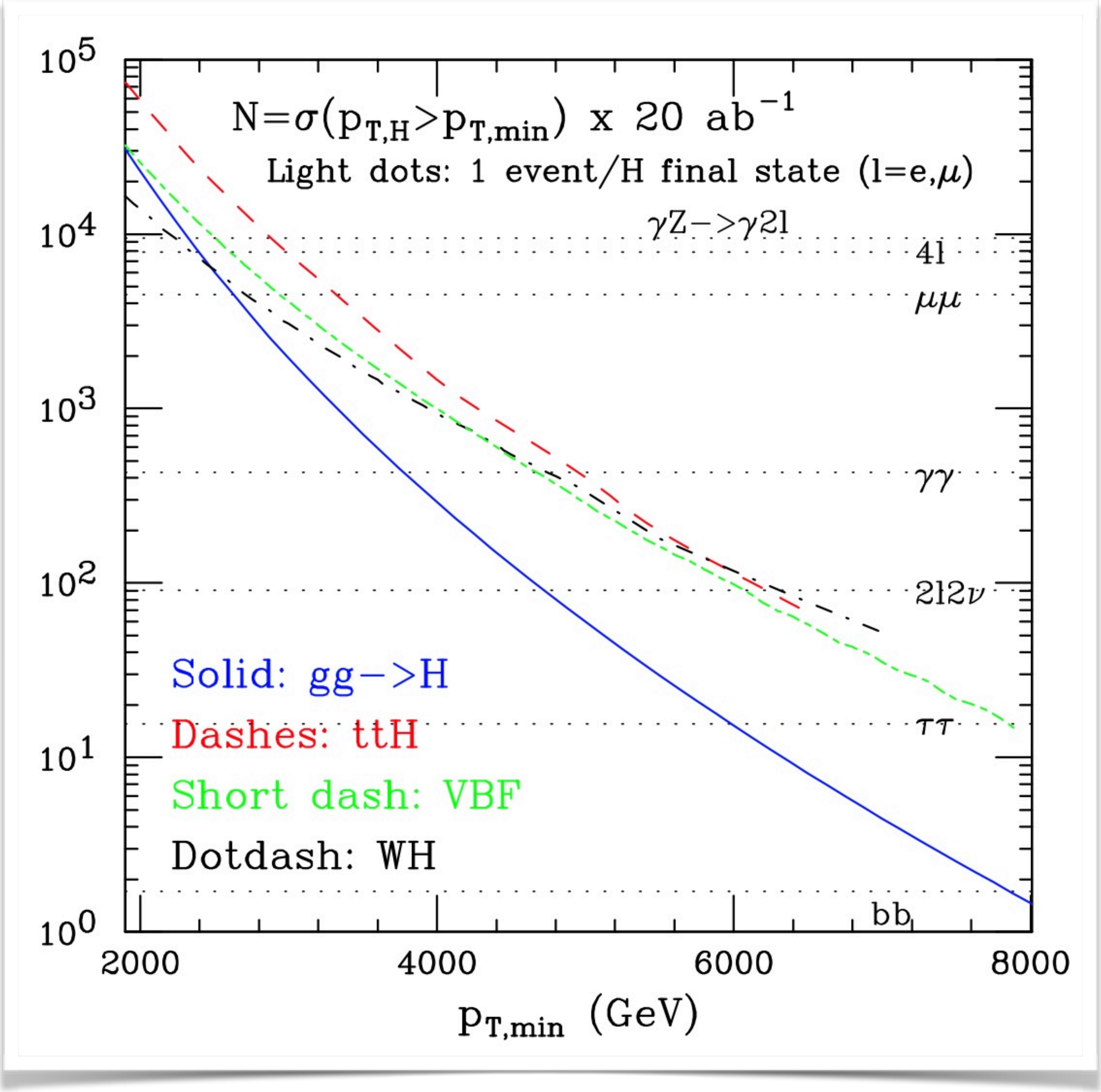
H at large p_T



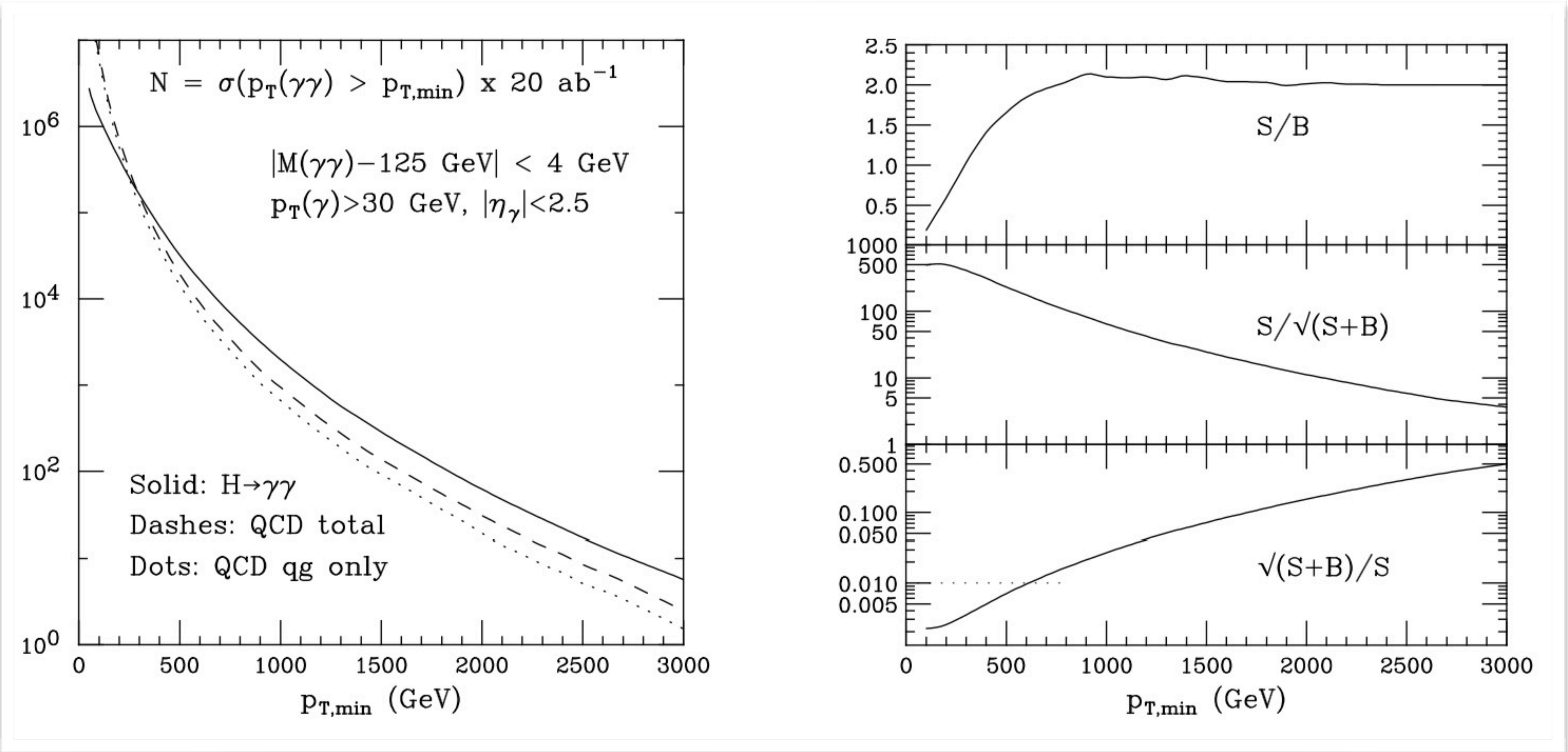
- Hierarchy of production channels changes at large p_T(H):
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

H at large p_T



- Statistics in potentially visible final states out to several TeV

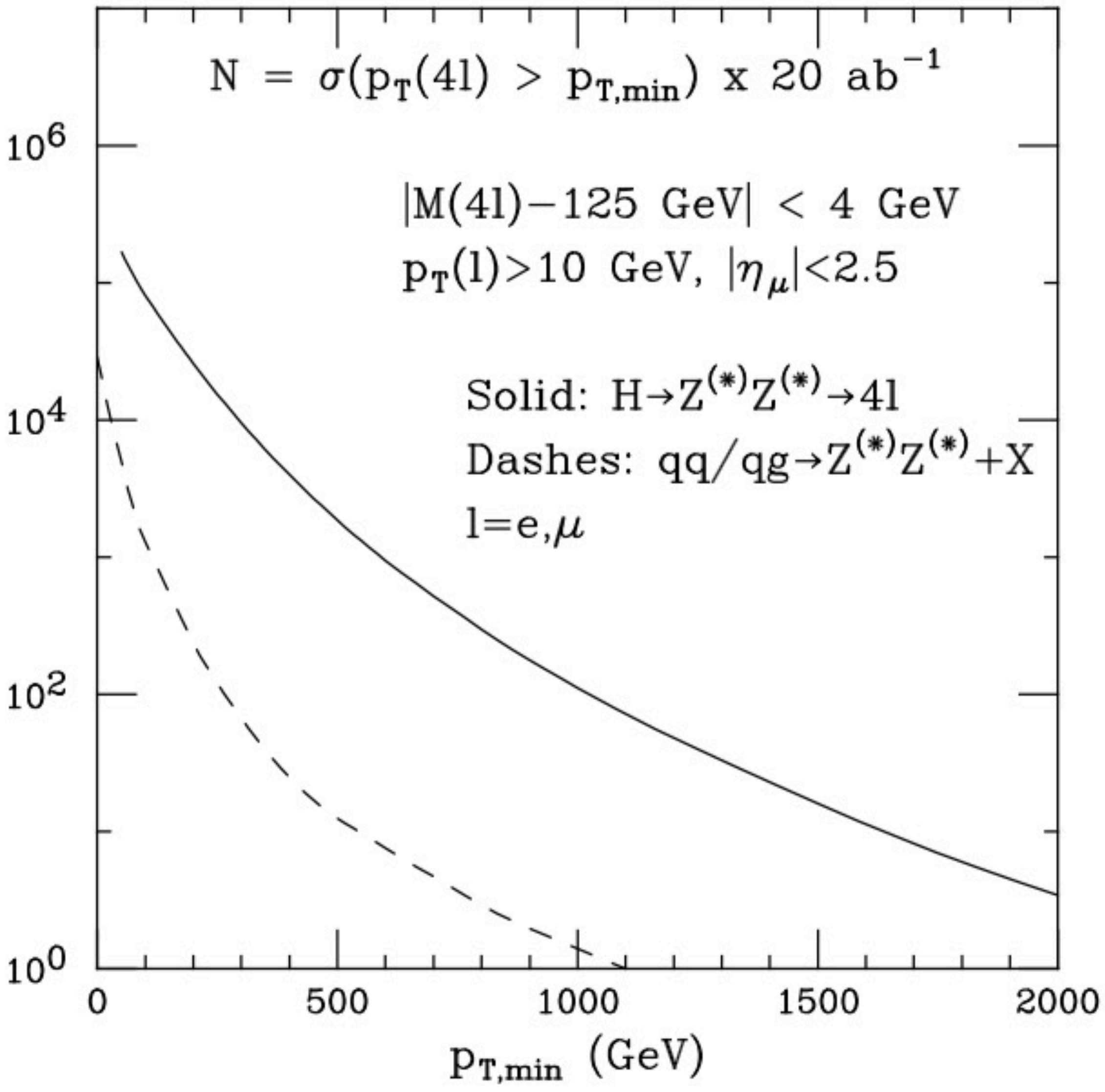
gg→H→γγ at large p_T

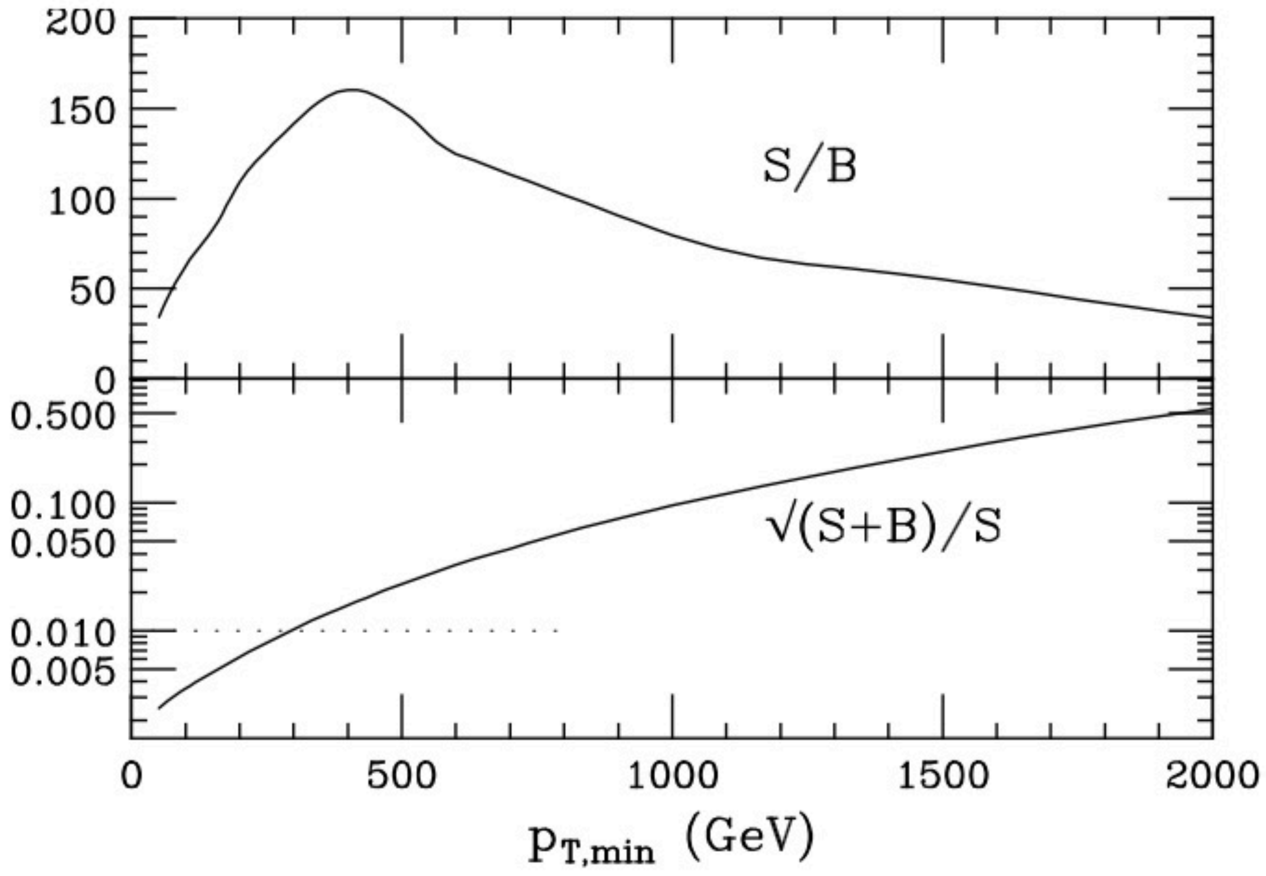


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

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

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

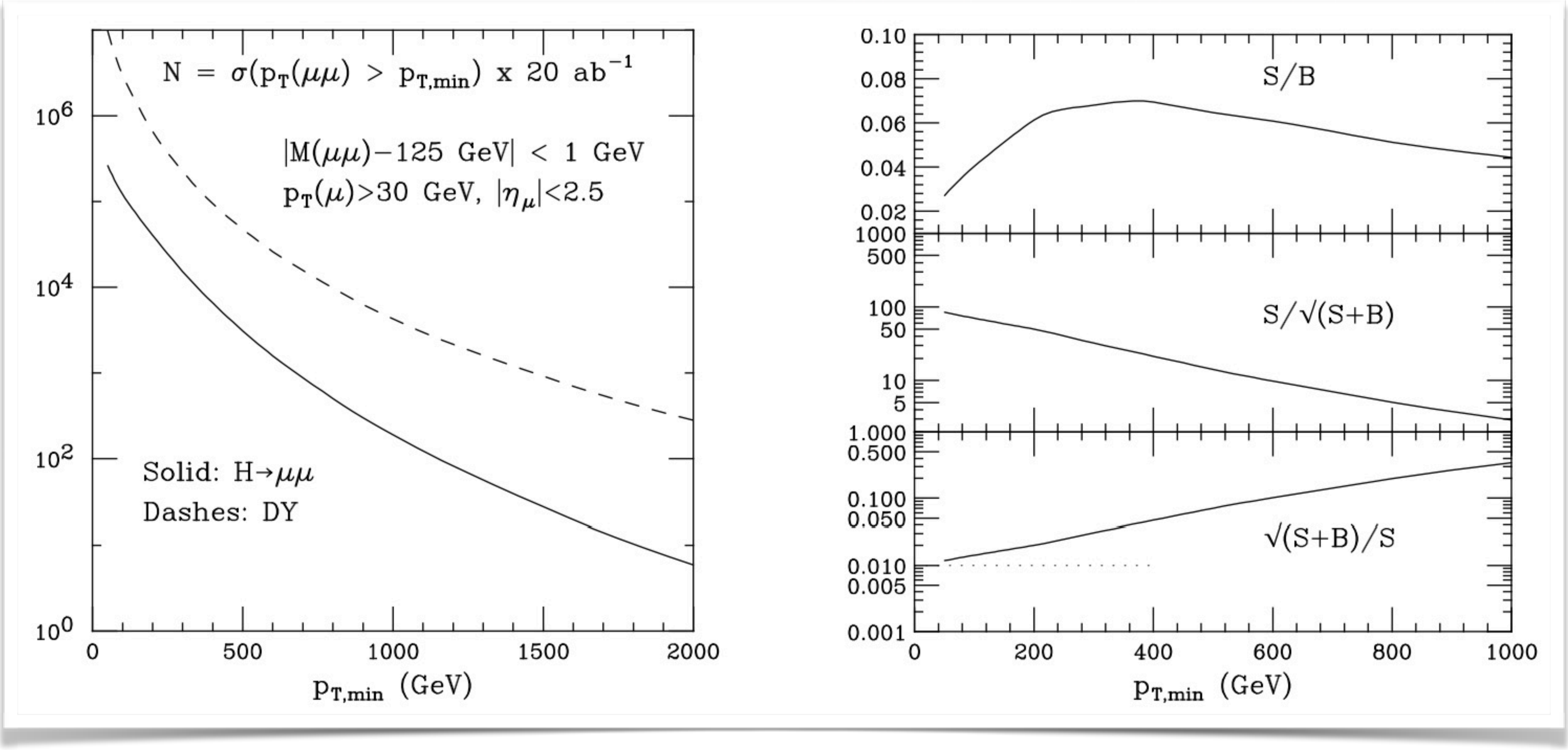




- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

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

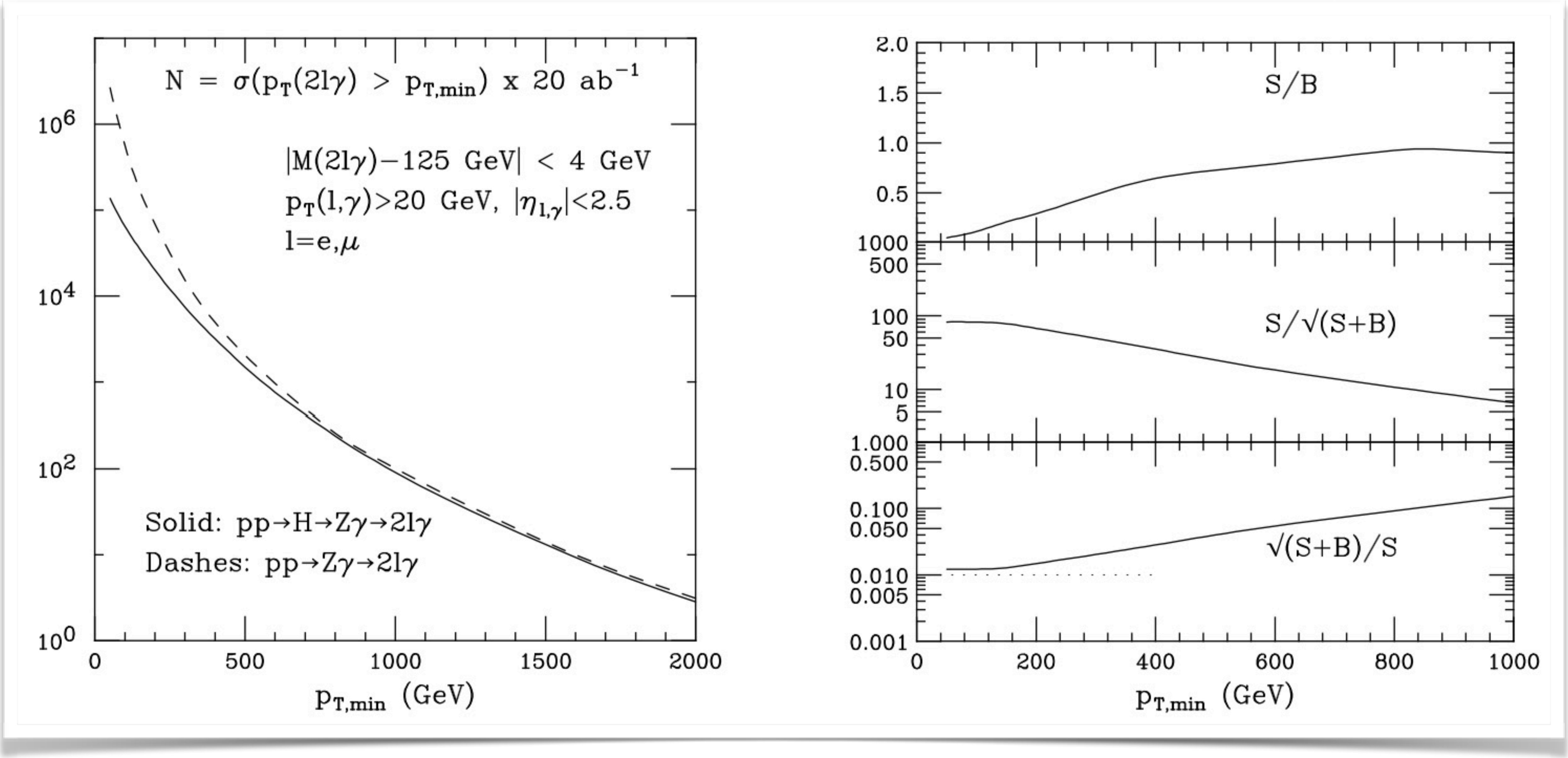
gg→H→μμ at large p_T



- Stat reach ~1% at p_T~100 GeV

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

gg→H→Zγ→ℓℓγ at large p_T



- S/B → 1 at large p_T
- Stat reach ~1% at pT~100 GeV

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

Delphes-based projections

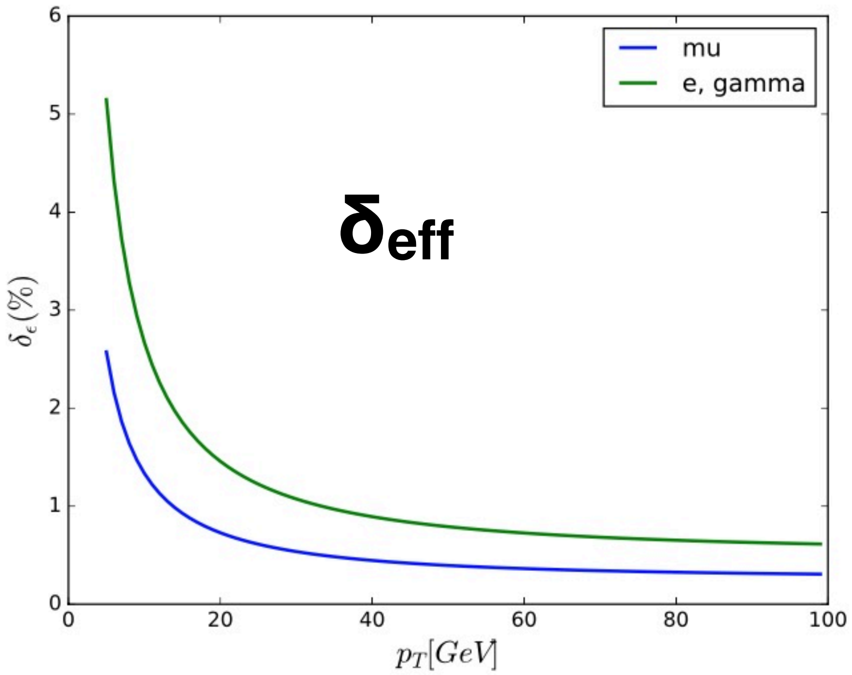
M.Selvaggi

All **signal and background samples** have been generated via the following chain (using the FCCSW): http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php

- **MG5aMC@NLO + Pythia8**
  - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for N$^{2/3}$LO corrections
  - full list of signal prod. modes simulated (ggH with finite m_{top})
- **Delphes-3.4.2** with baseline FCC-hh detector

Consider the following categories of uncertainties:

- δ_{stat} = statistical
- δ_{prod} = production + luminosity systematics
- δ_{eff} $^{(i)}$ (p_T) = object reconstruction (trigger+isolation +identification) systematics
- δ_B = 0, background (assume to have ∞ statistics from control regions)



Assume (un-)correlated uncertainties for (different) same final state objects

Following scenarios are considered:

- δstat → stat. only (I)
- δstat , δeff → stat. + eff. unc. (II)
- δstat , δeff , δprod = 1% → stat. + eff. unc. + prod (III)

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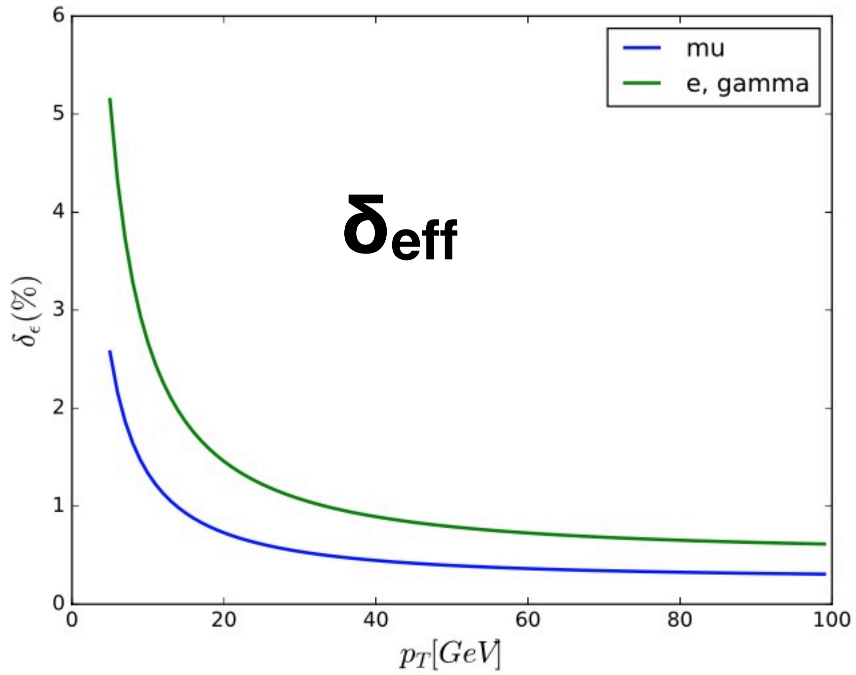

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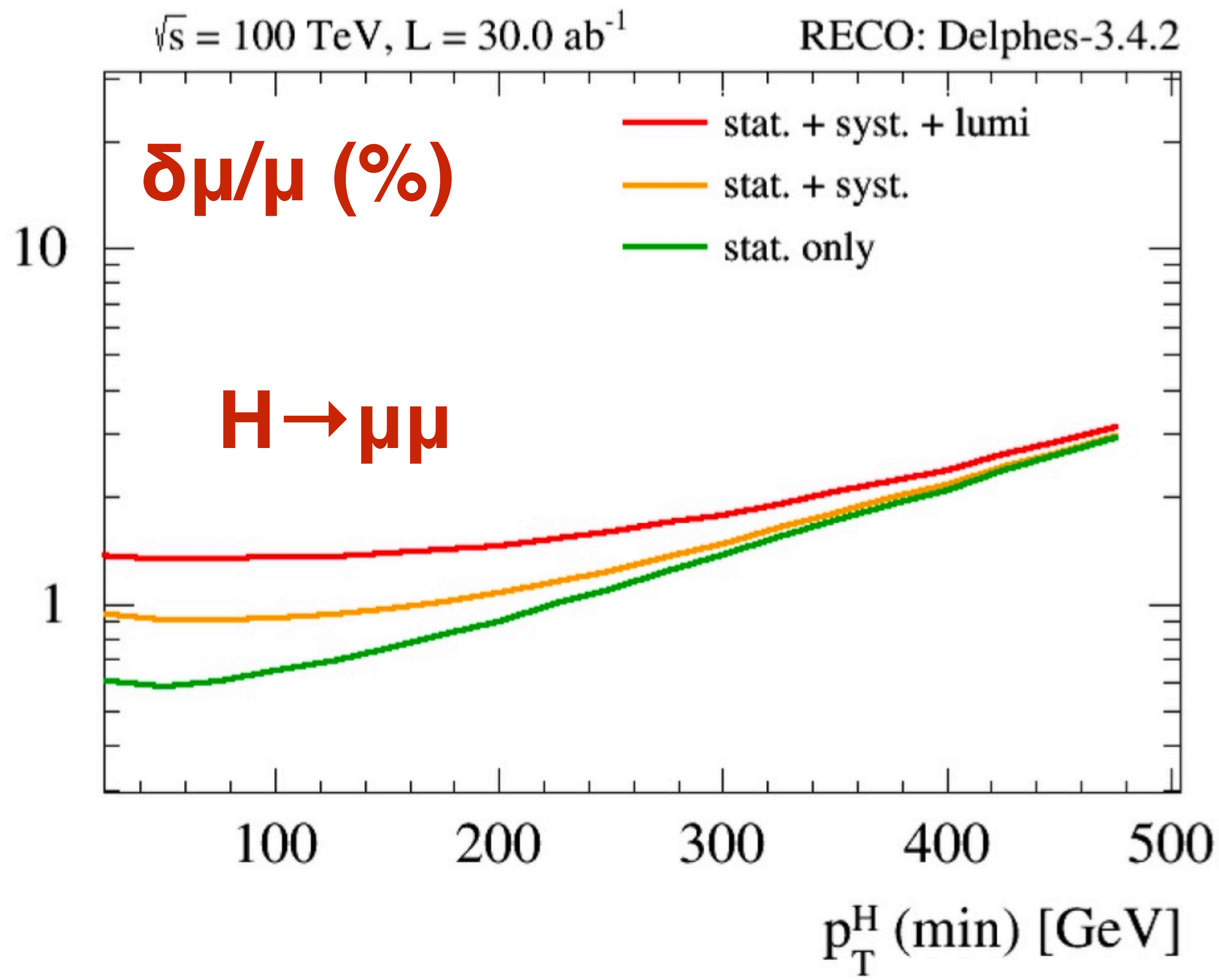
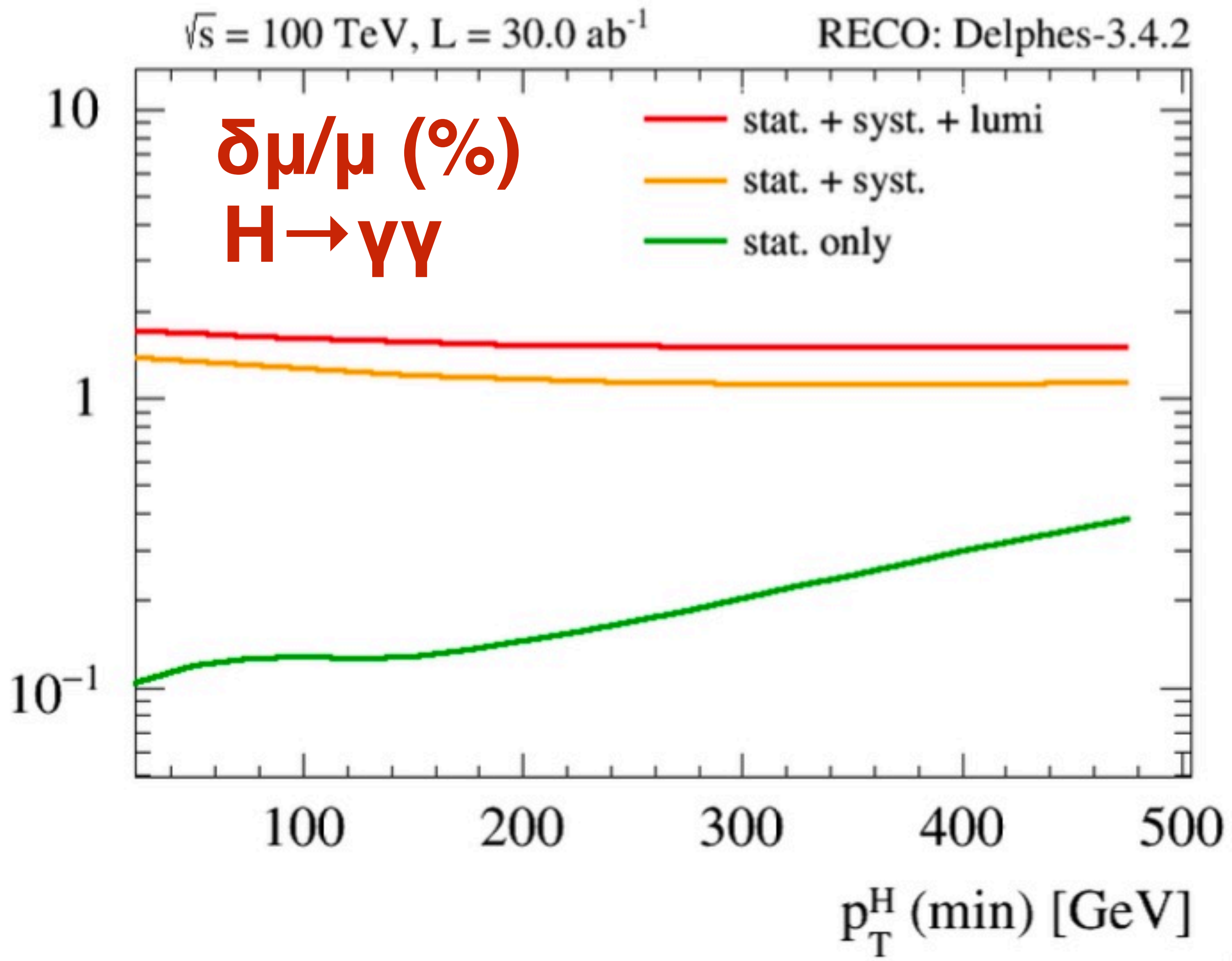
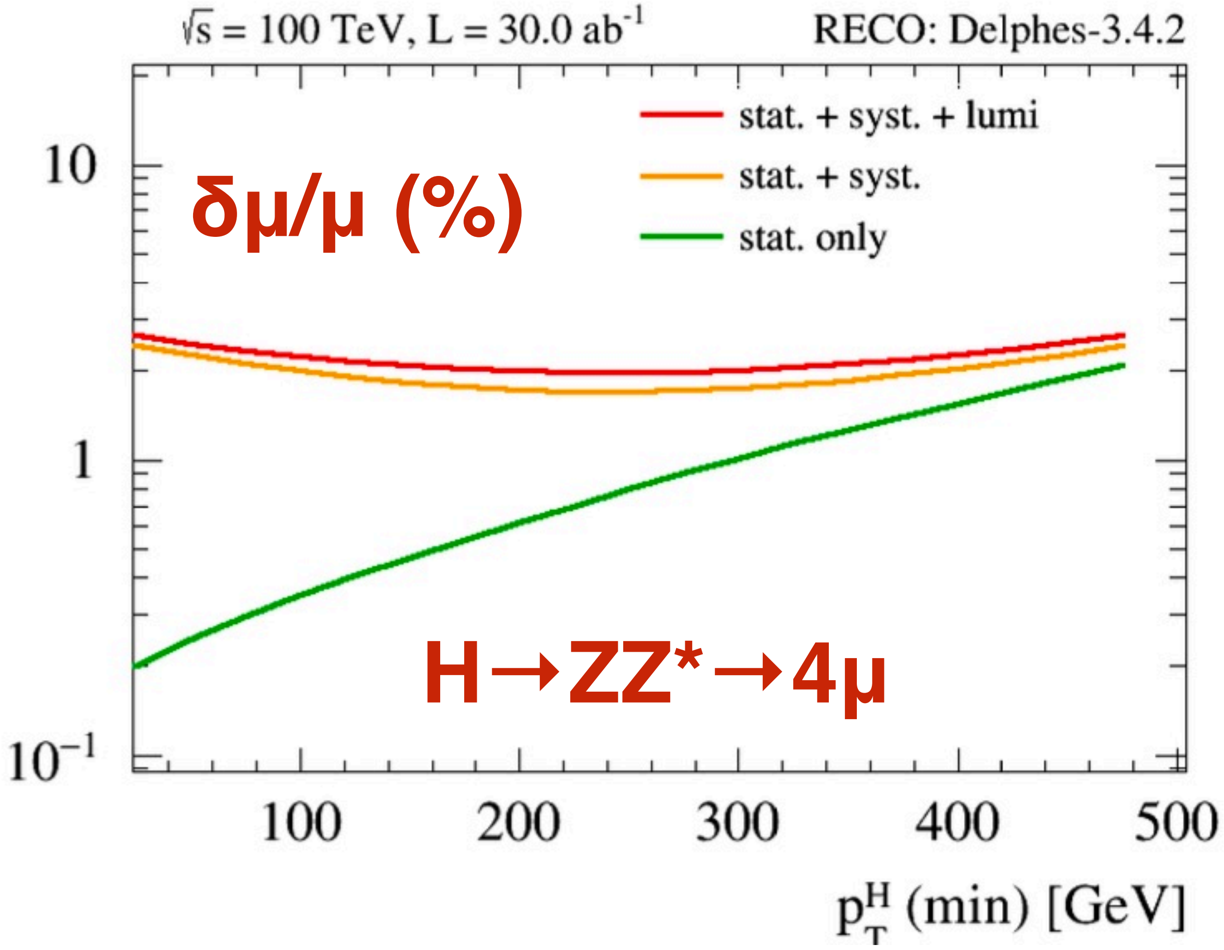
could be seen as syst in the normalization of production*lumi wrt standard candles such as pp→Z→ee







μ = σ x BR

1% level within reach for rates,

sub-% for couplings (~sqrt(μ))

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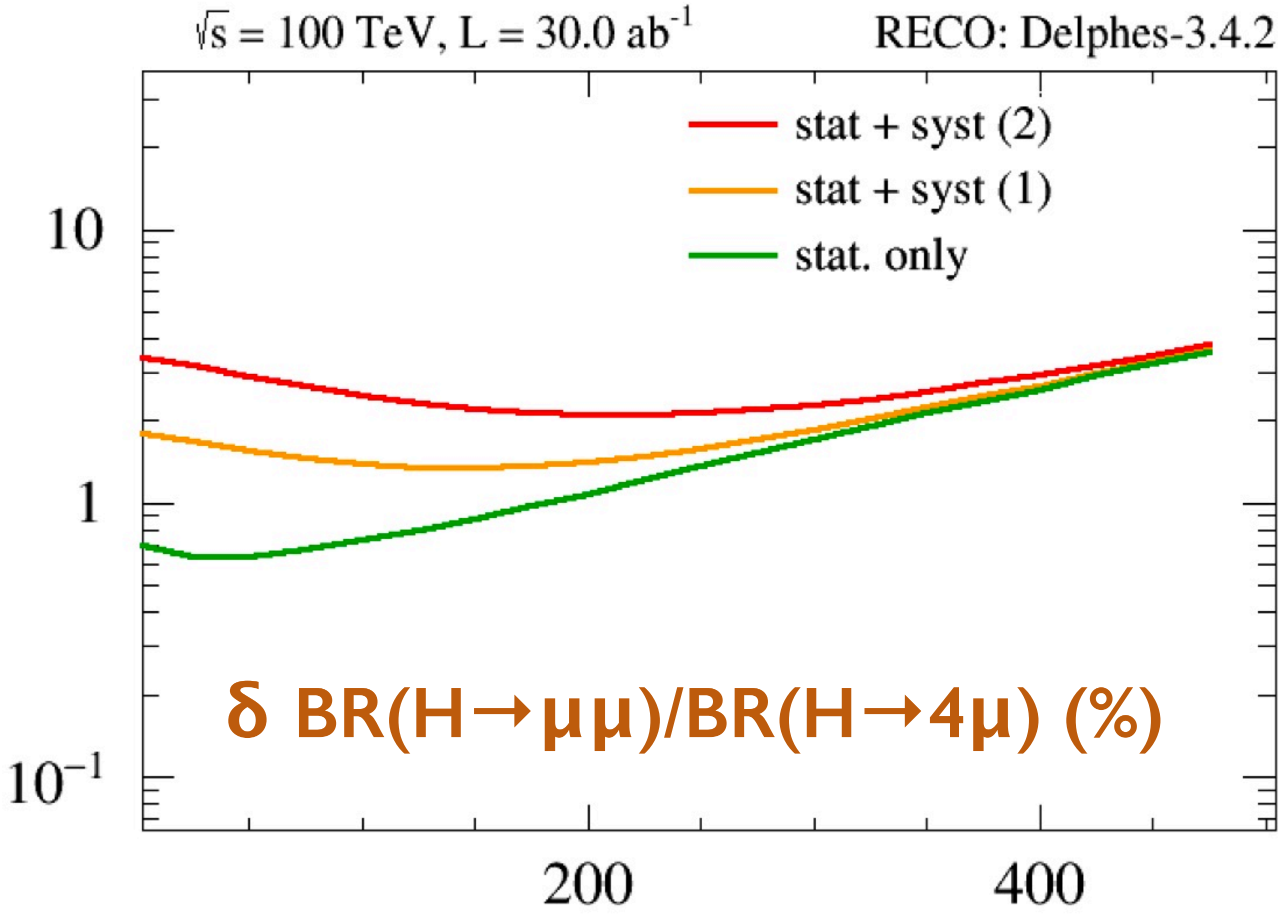

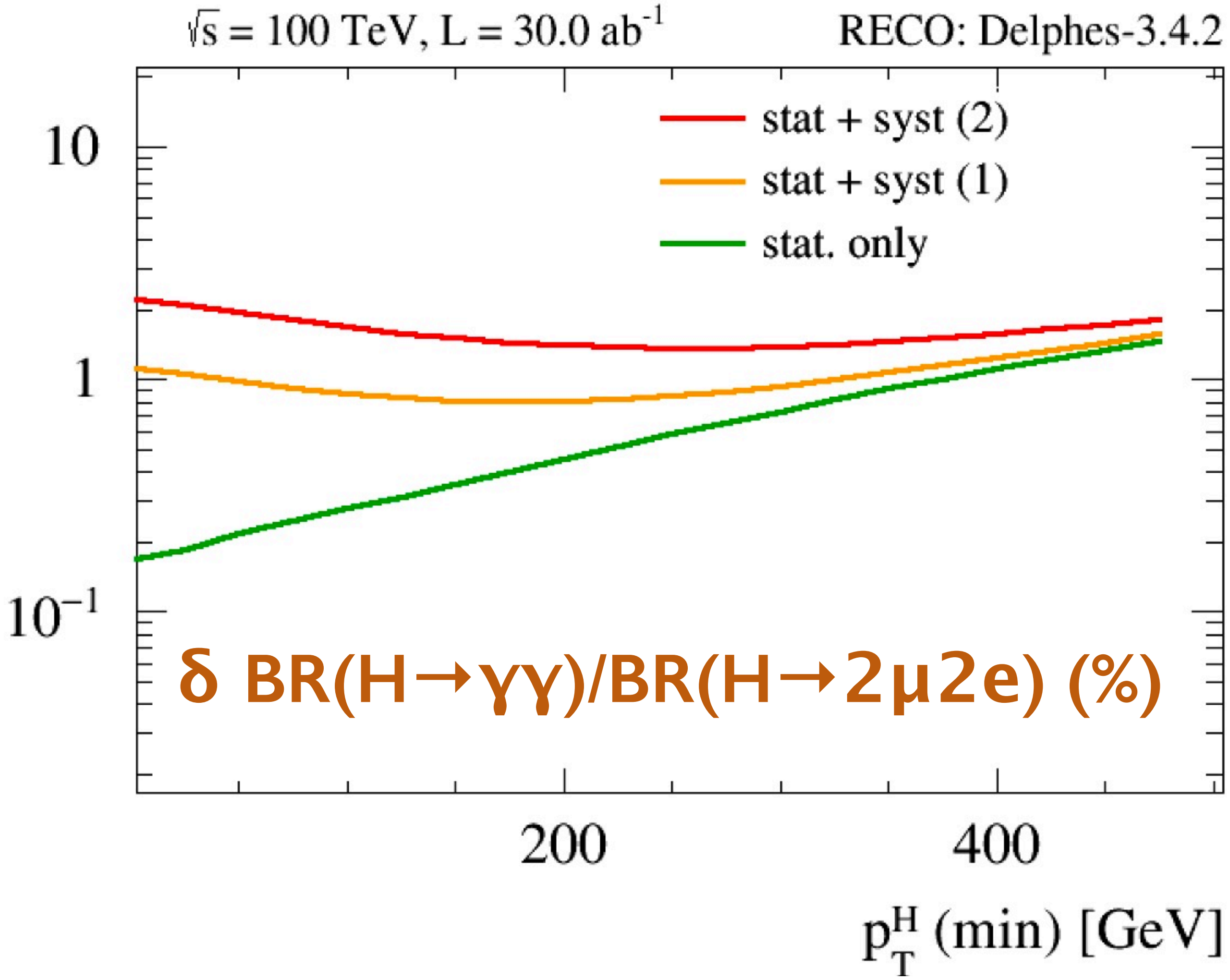

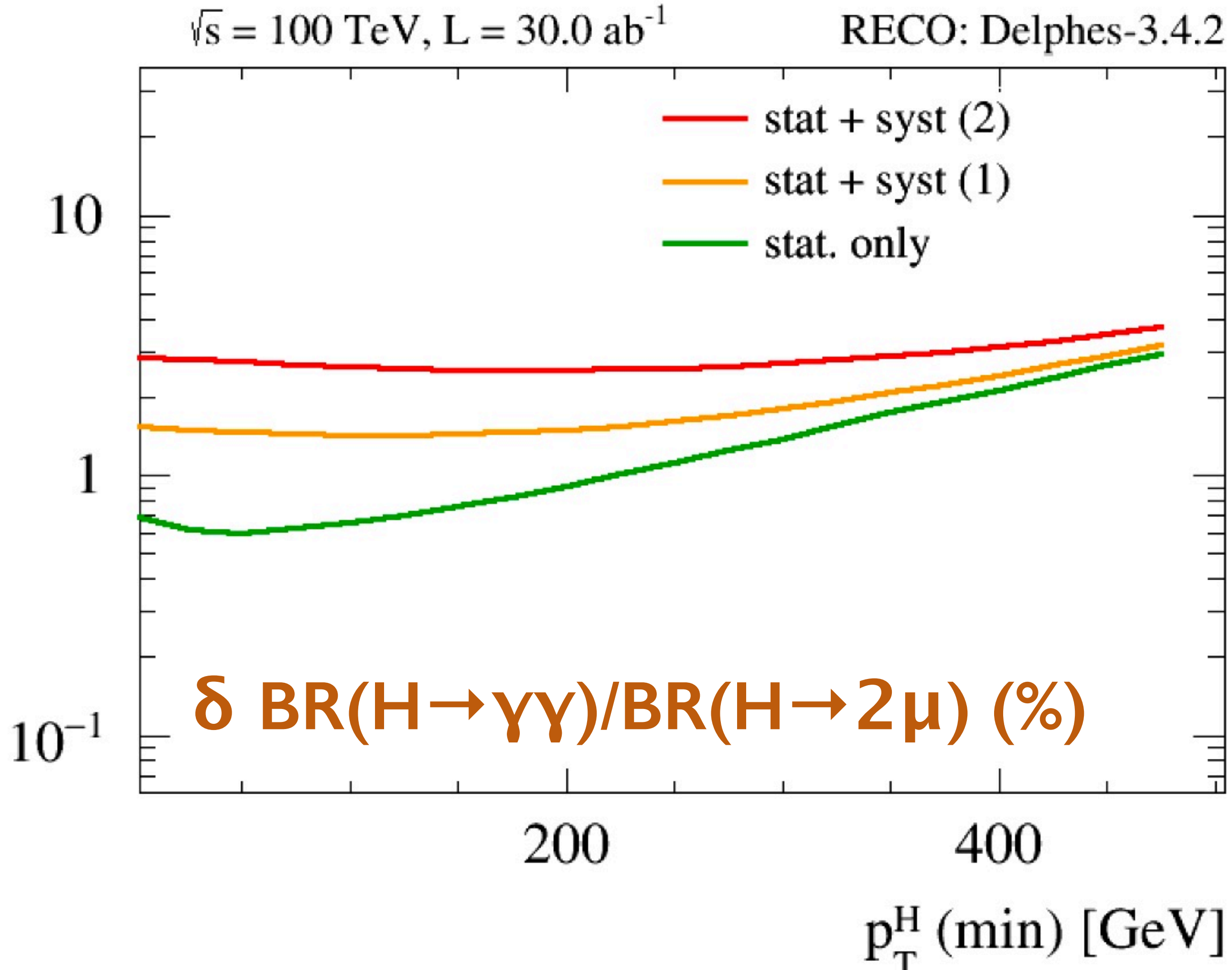

Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings

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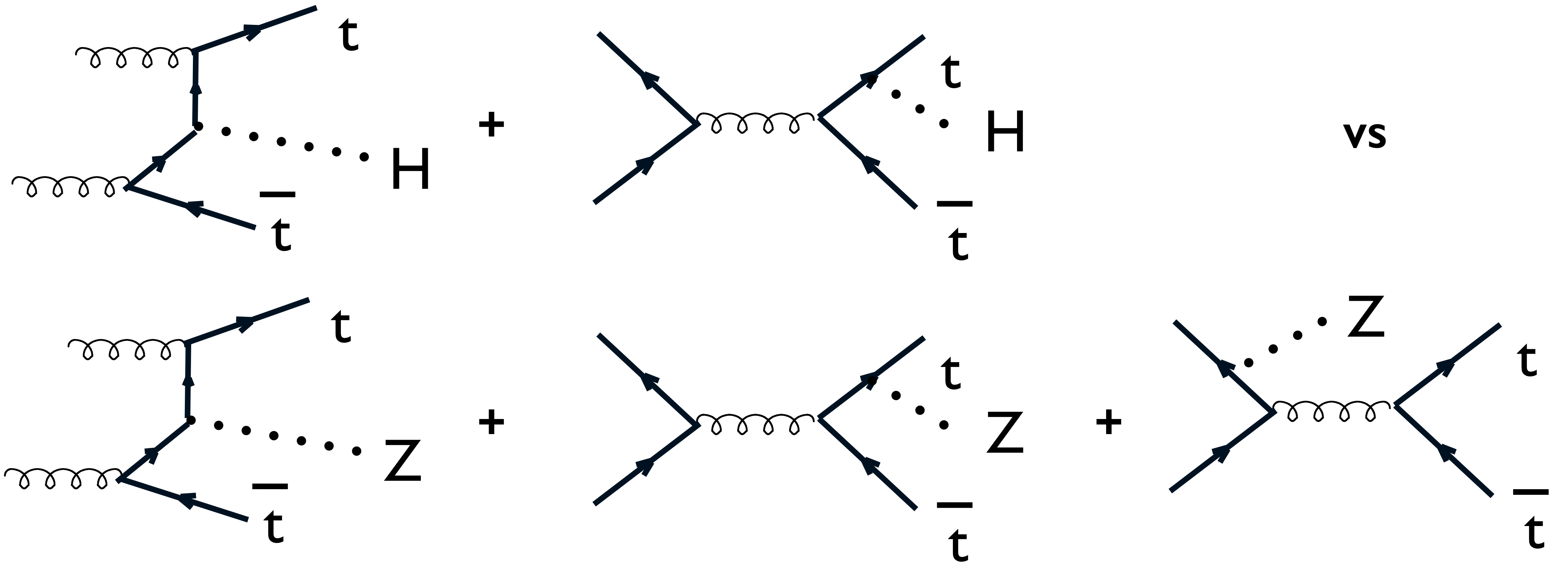
Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

arXiv:1507.08169



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

- Identical production dynamics:

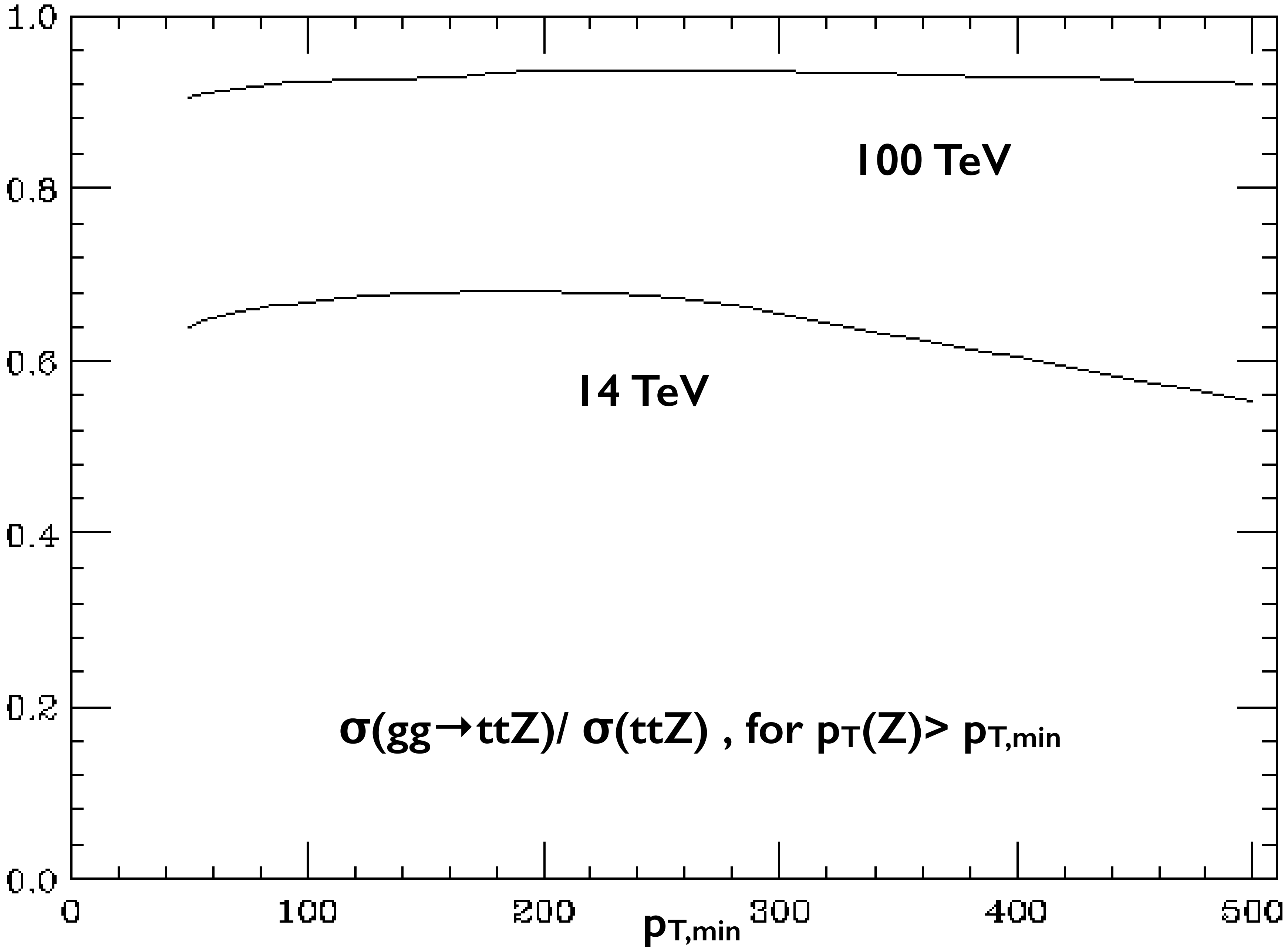
  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

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

  o correlated PDF systematics
  o correlated m_{top} systematics

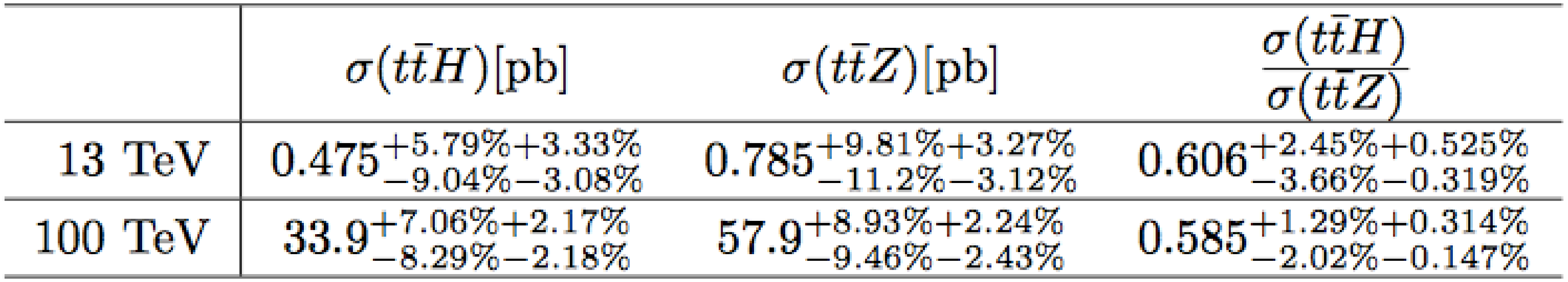
For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

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



	$\sigma(t\bar{t}H)[\mathrm{pb}]$	$\sigma(t\bar{t}Z)[\mathrm{pb}]$	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
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

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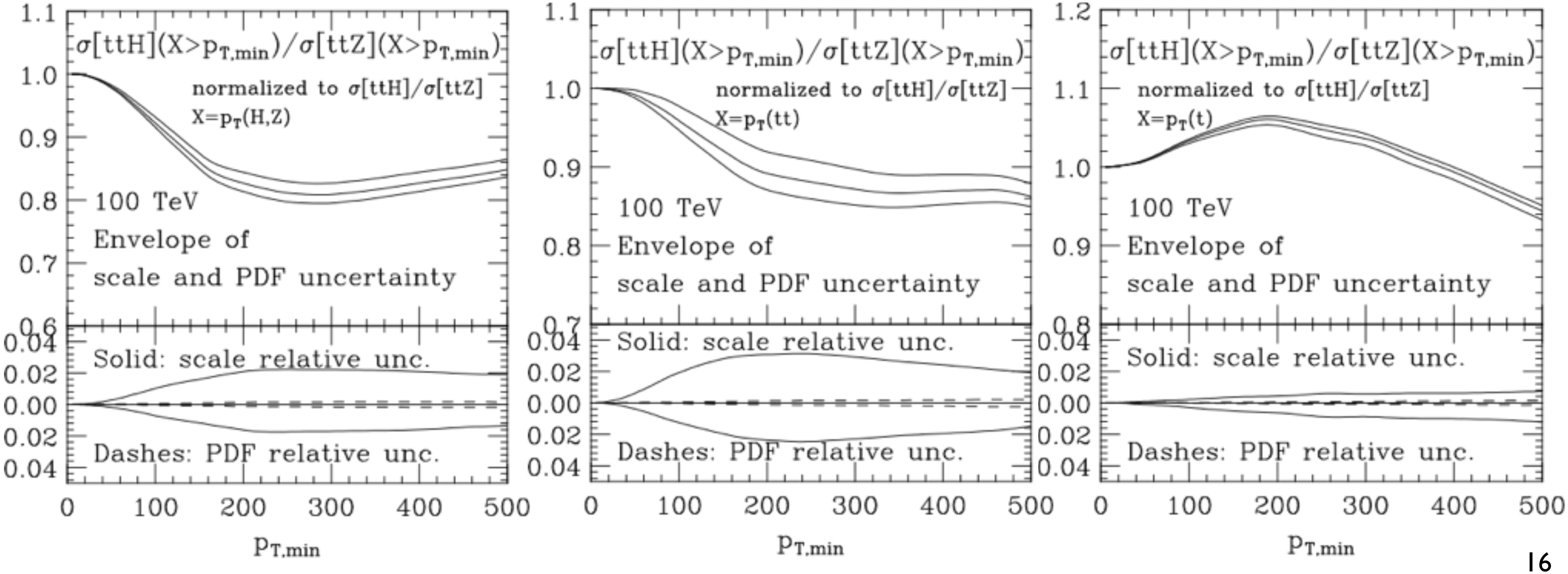
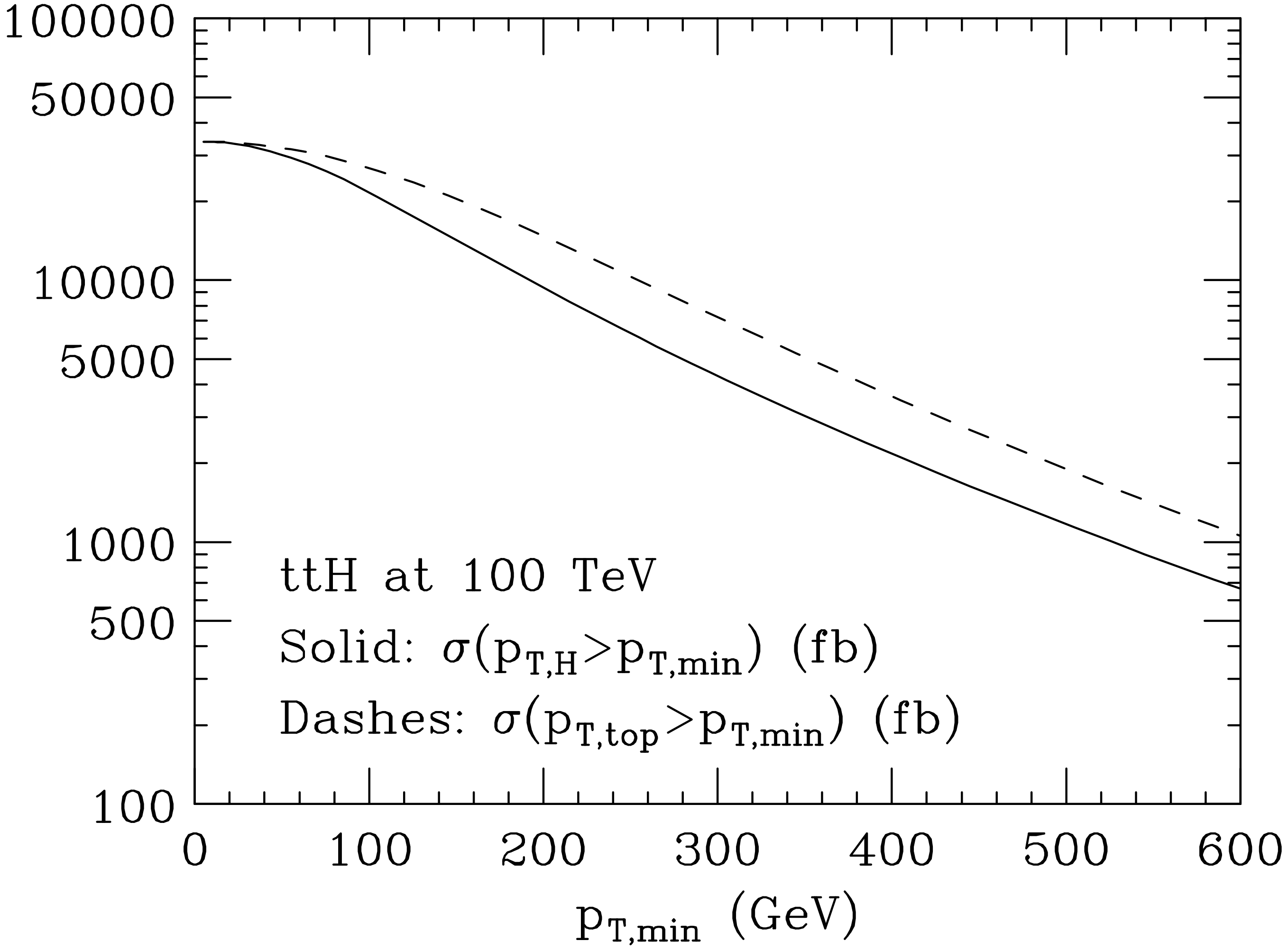
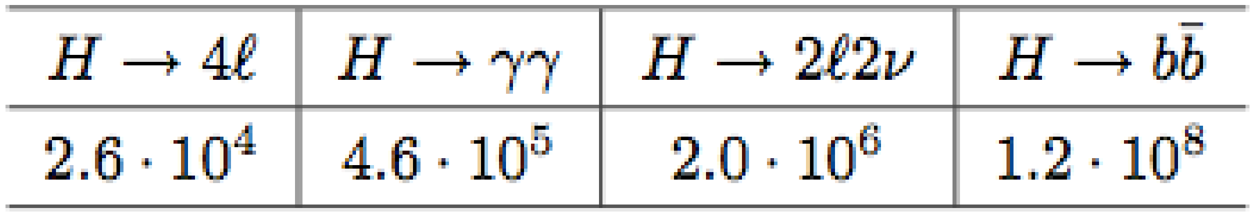
scale PDF

Production kinematics ratio stability



arXiv:1507.08169

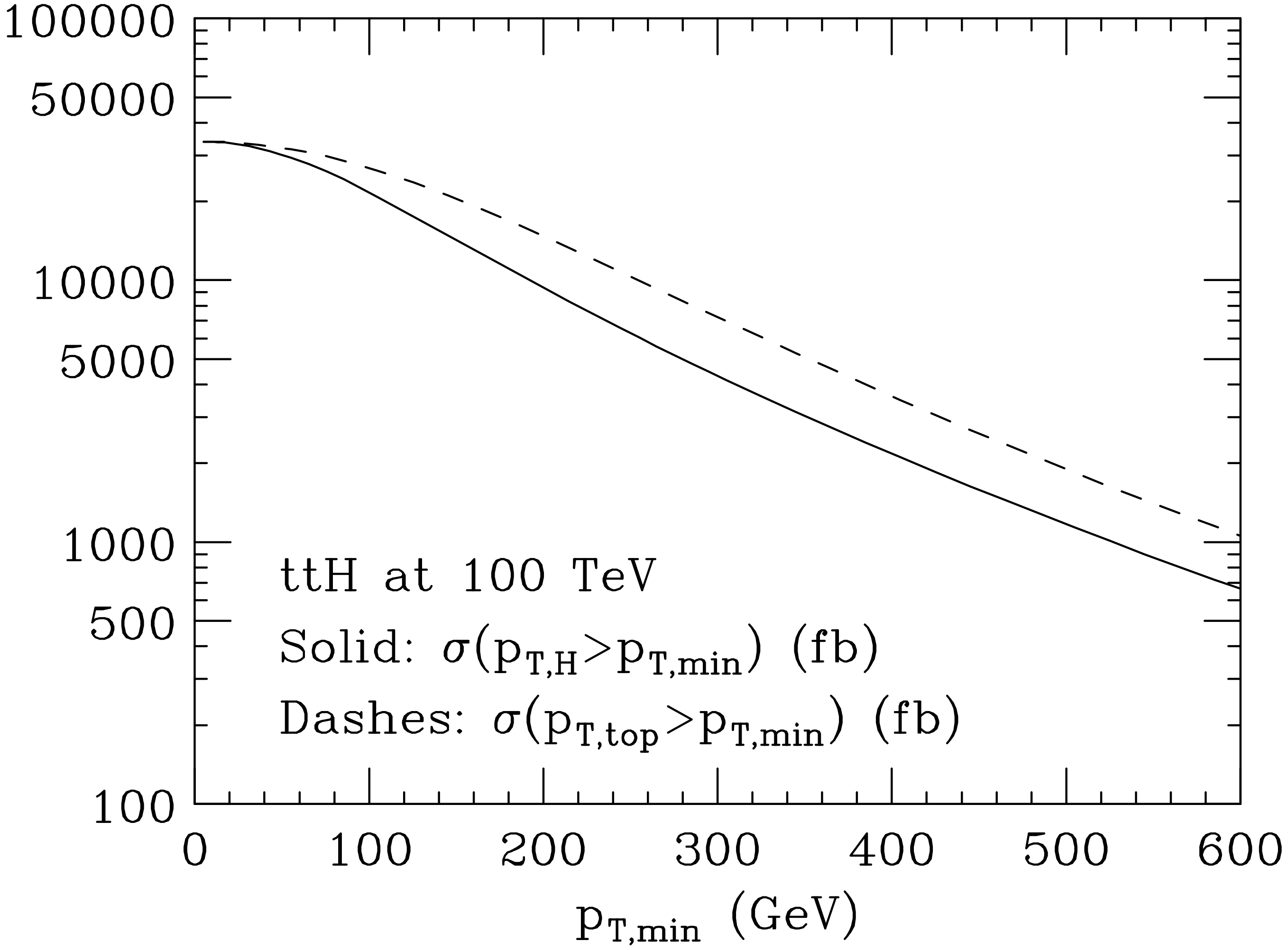




$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

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

⇒ huge rates, exploit boosted topologies arXiv:1507.08169



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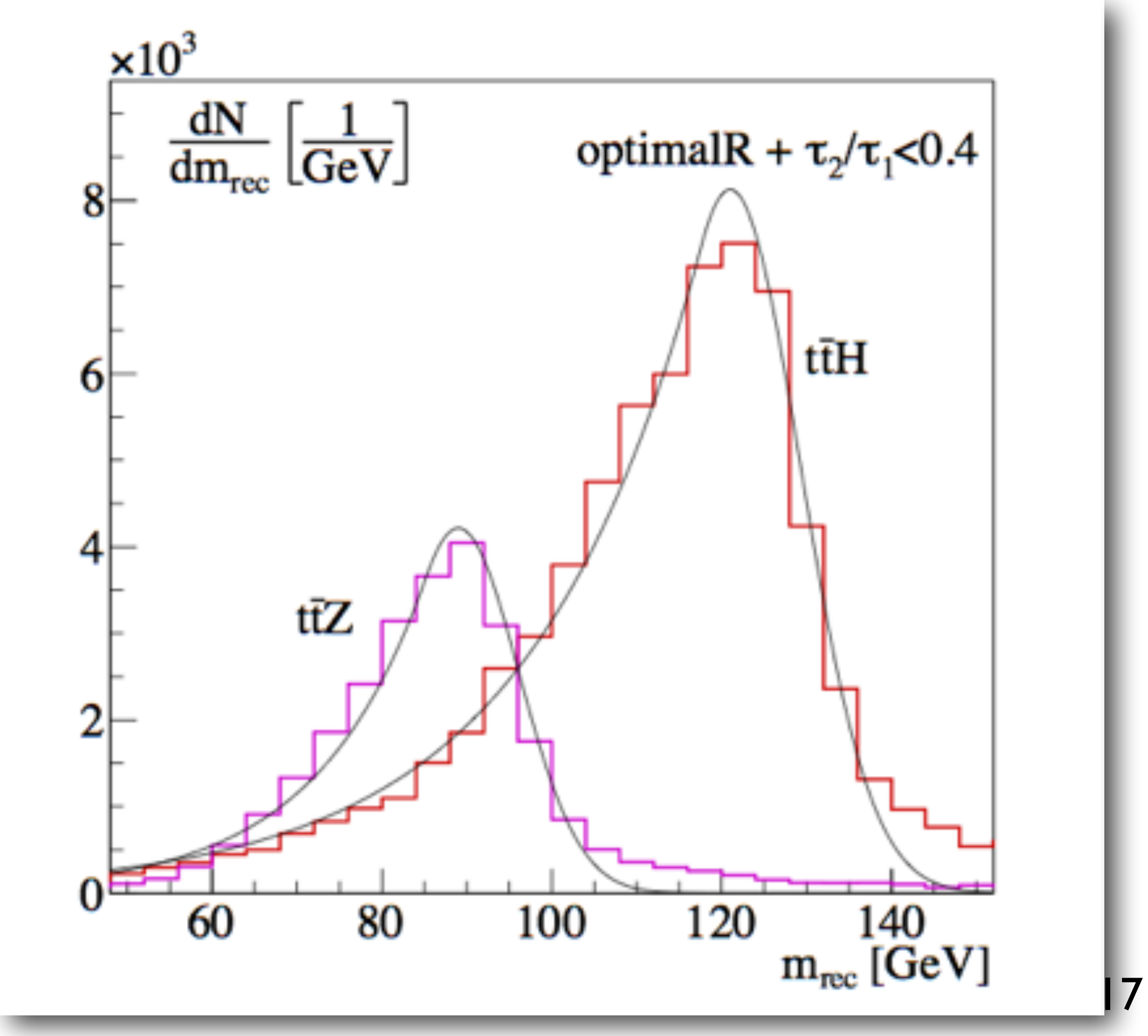
Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

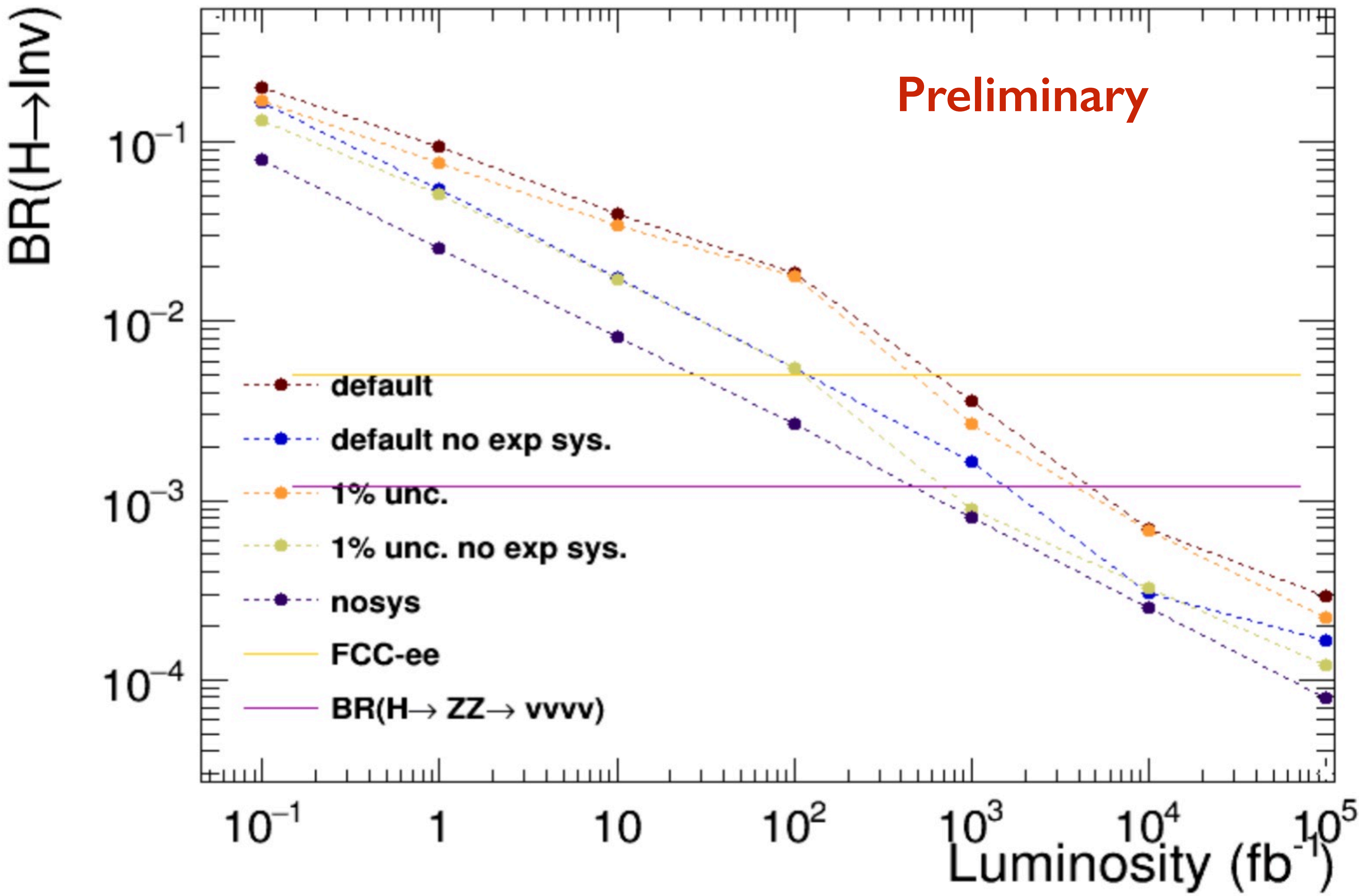
- δy_t (stat + syst $_{TH}$) ~ 1%

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



BR(H→inv) in H+X production at large $p_T(H)$

Constrain bg pt spectrum from Z→νν to the % level using
NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



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

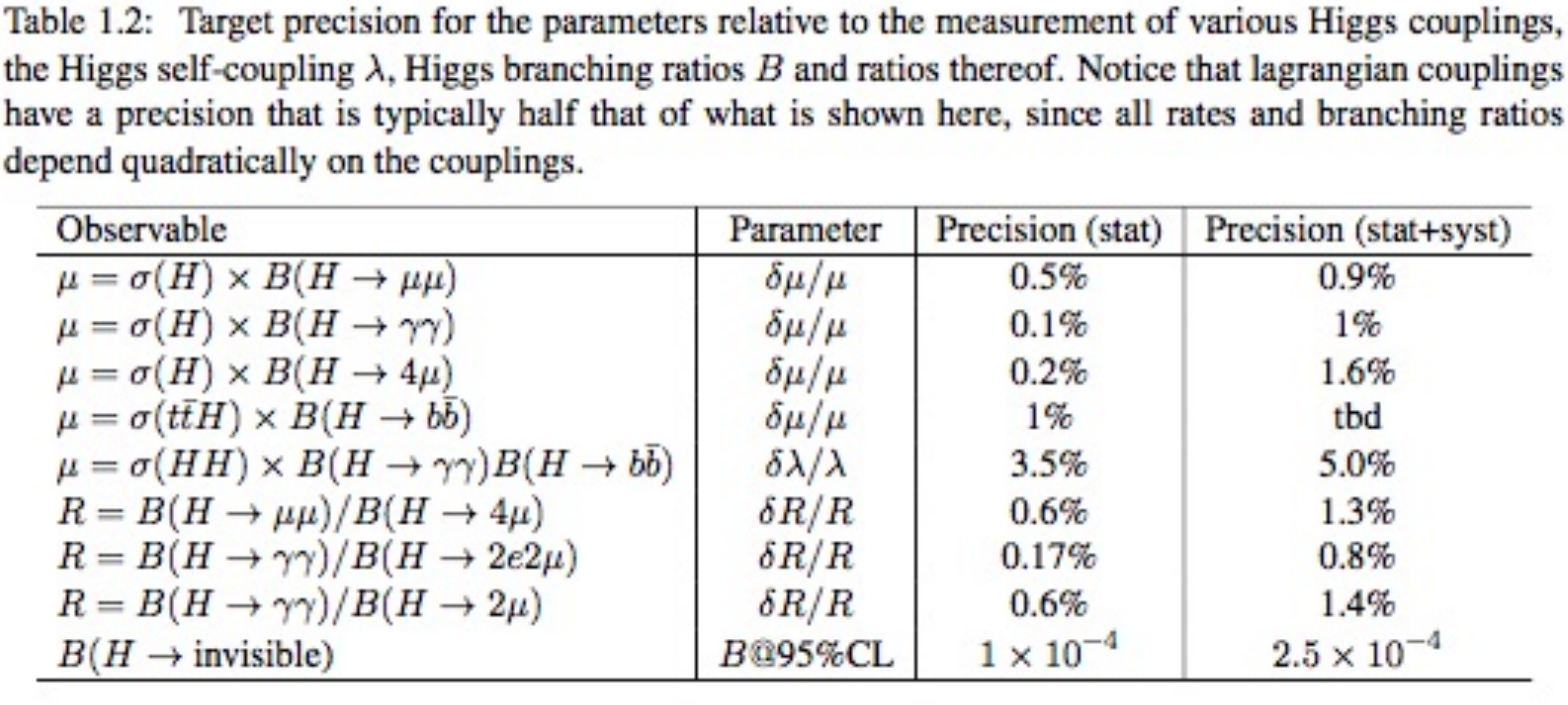
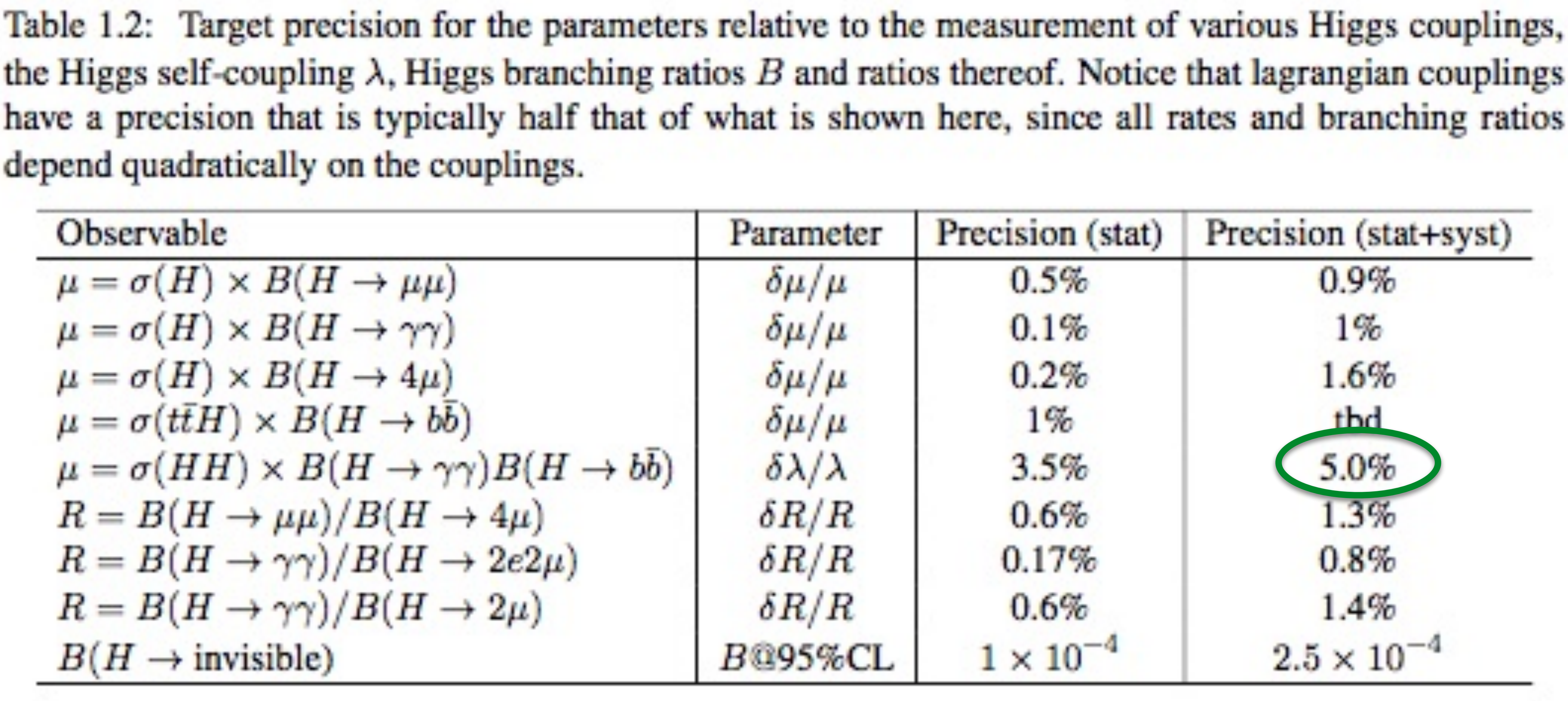


Table 1.2: Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling λ, Higgs branching ratios B and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.5%	0.9%
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.6%	1.4%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Study for $B(H \to Z\gamma)$ in progress

first probe of the Higgs potential beyond the 2-point function



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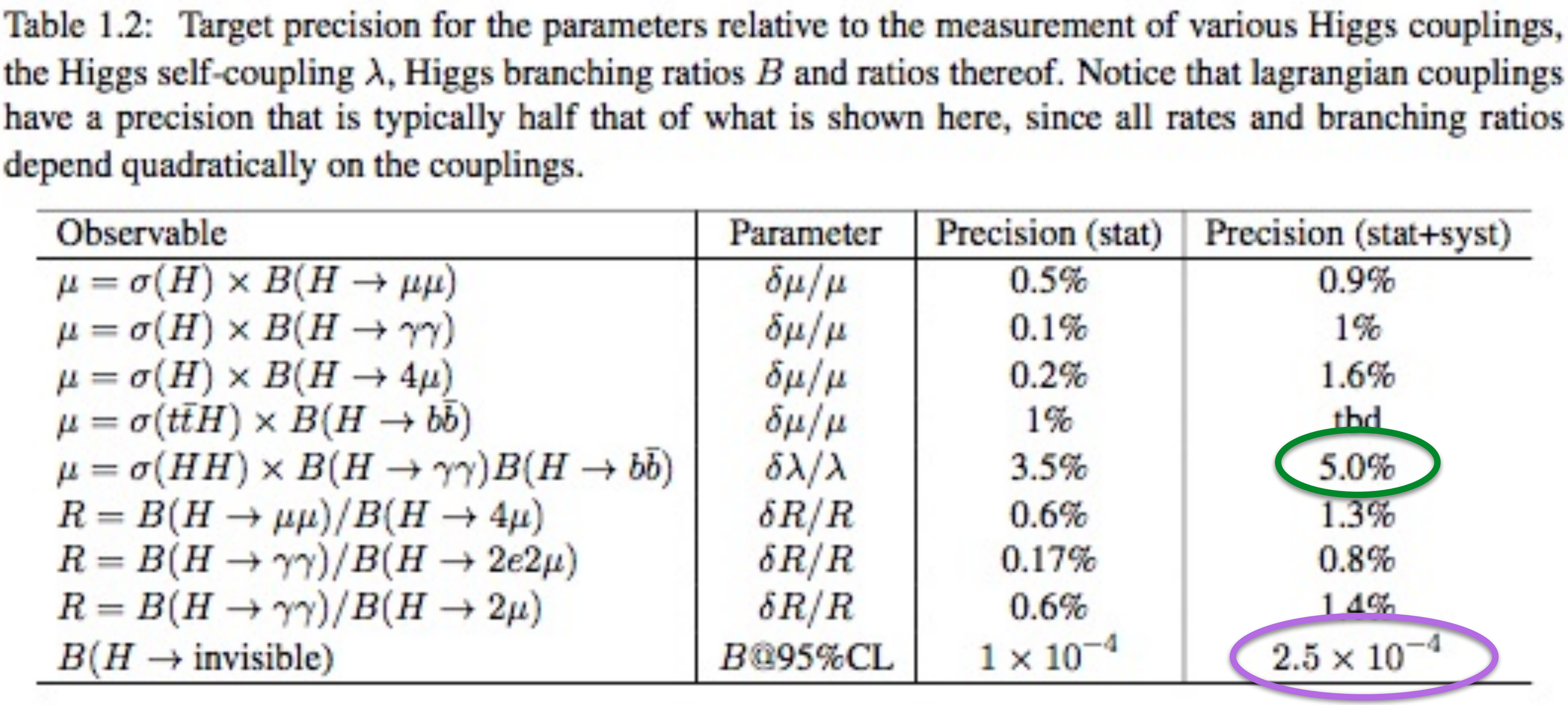
Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.5%	0.9%
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.6%	1.4%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Study for B(H→Zγ) in progress

first probe of the Higgs potential beyond the 2-point function



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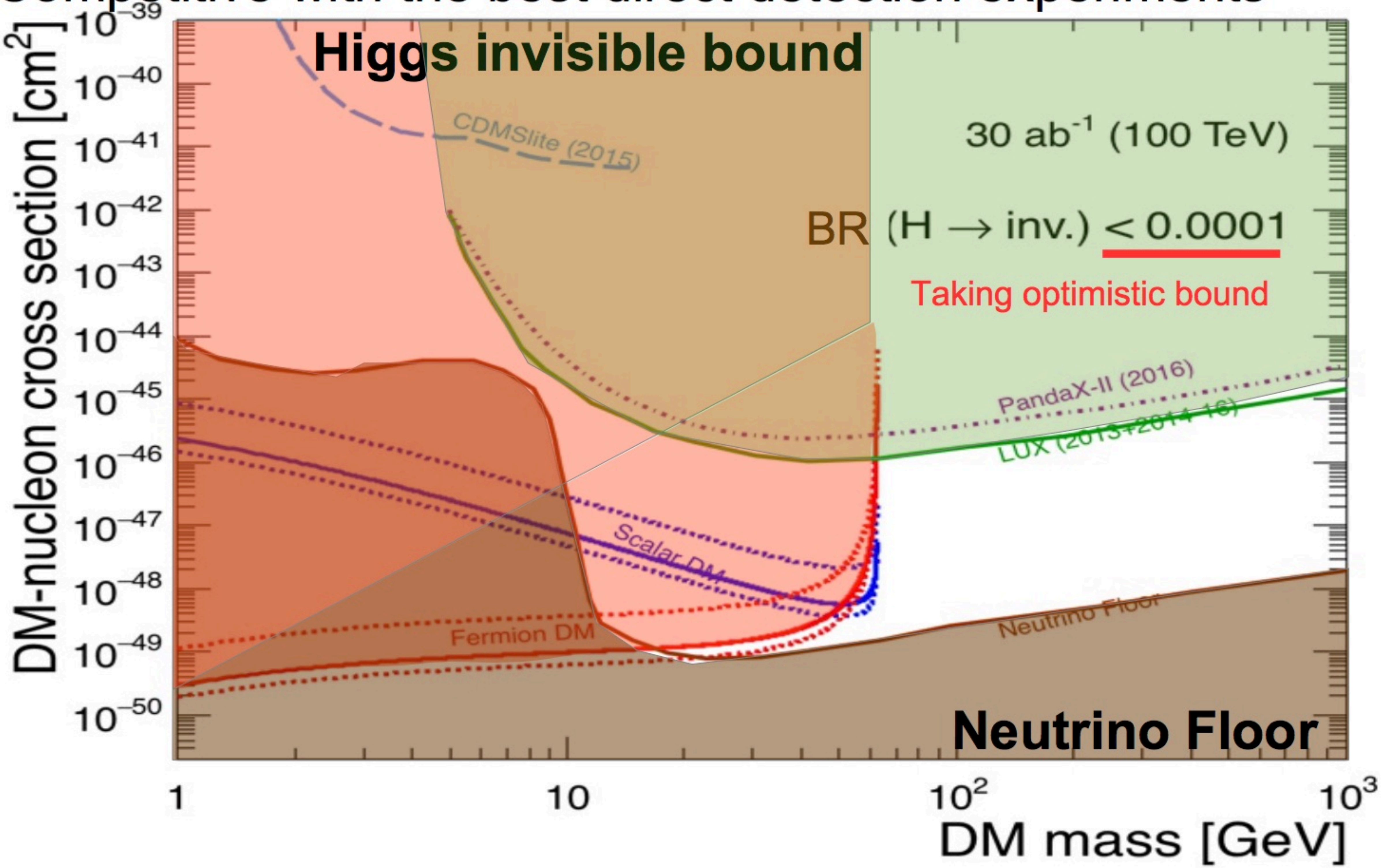
Study for B(H→Zγ) in progress

sensitive to possible Higgs-to-DM decays

Impact on DM bounds

Competitive with the best direct detection experiments



Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

One should not underestimate 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

BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

High-Q^2 aspects

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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, $\mu \sim O(v, m_H)$

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

⇒ **precision** probes large Λ

e.g. $\delta O = 1\%$ ⇒ Λ ~ 2.5 TeV

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For H production off-shell or with large momentum transfer Q, μ~O(Q)

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

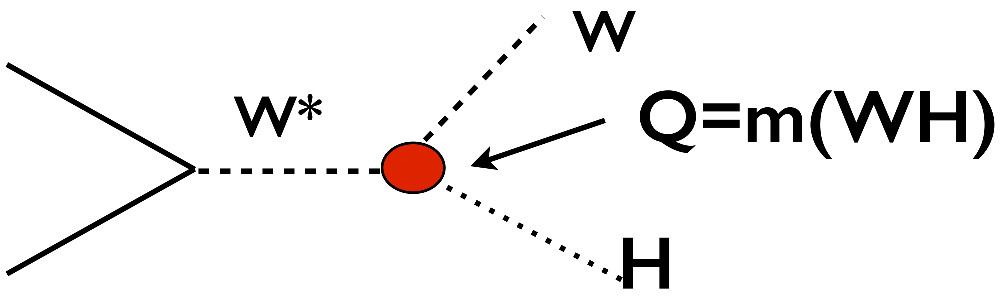
⇒ **kinematic reach** probes large

Λ even if precision is low

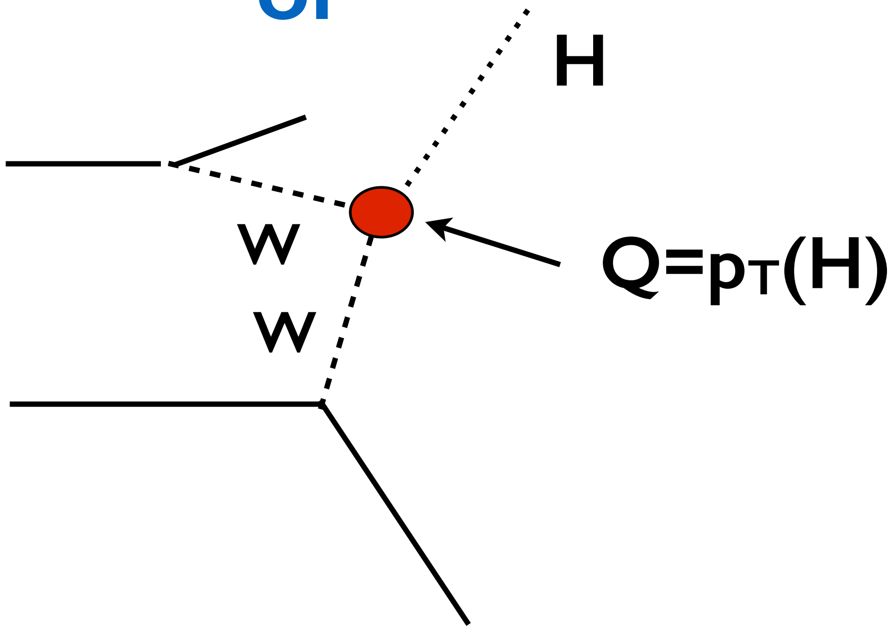
e.g. δ*O*=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Examples

$\delta BR(H \to WW^*)$ ⟷

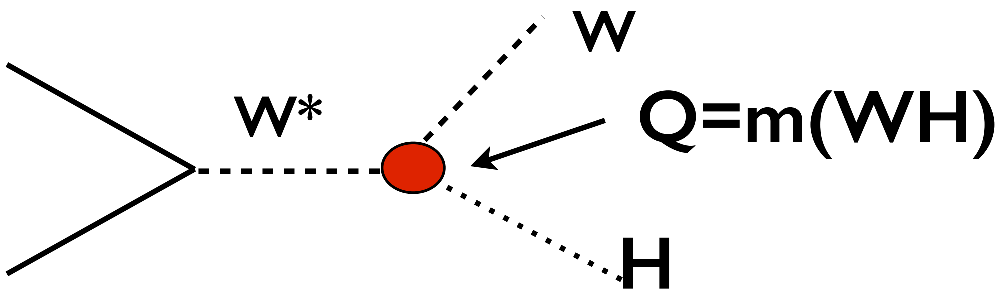


or

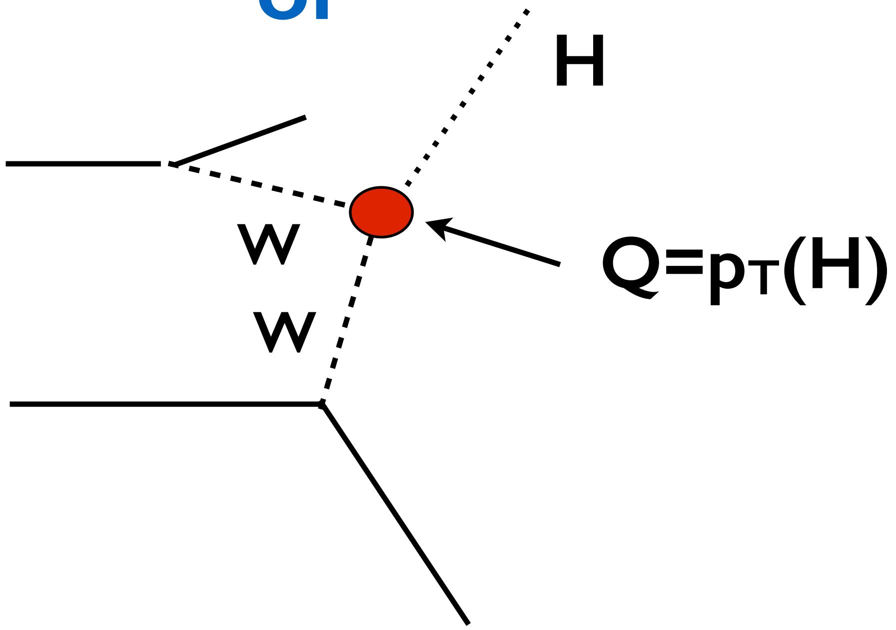


Examples

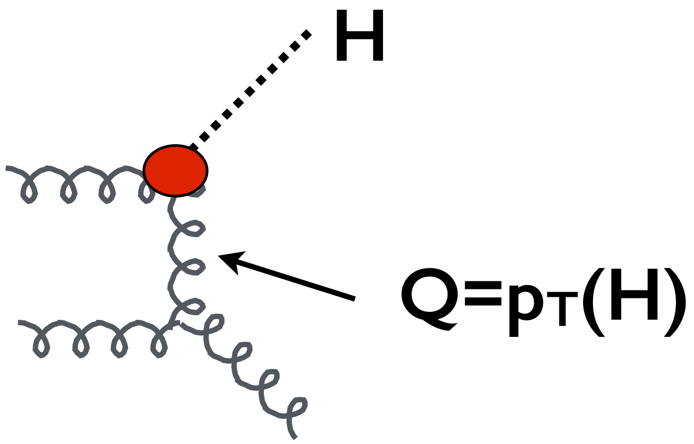
$\delta BR(H\to WW^*)$



or



$\delta BR(H\to gg)$



Examples of deviations of the Higgs p_T spectrum from SM, in presence of new particles in the ggH loop

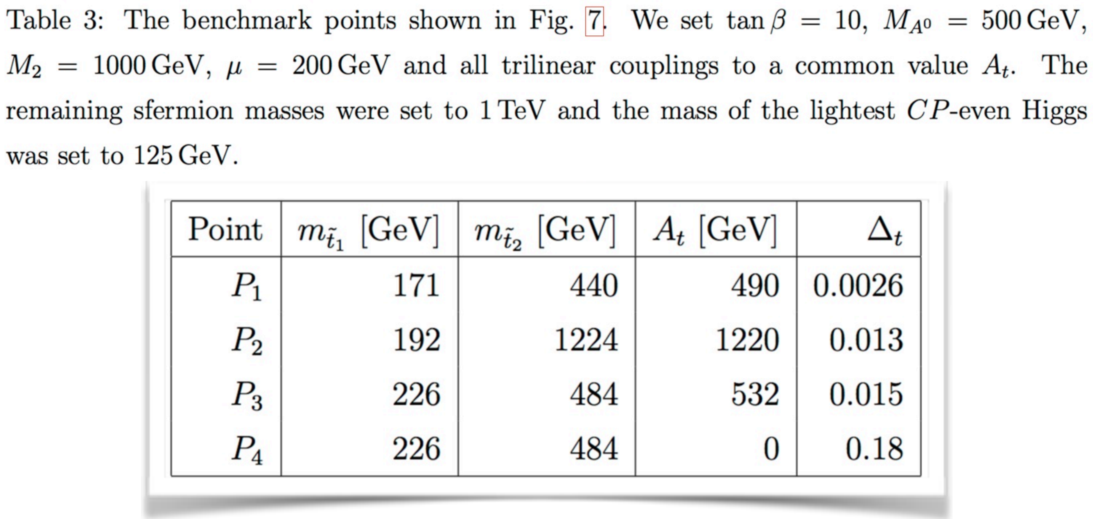
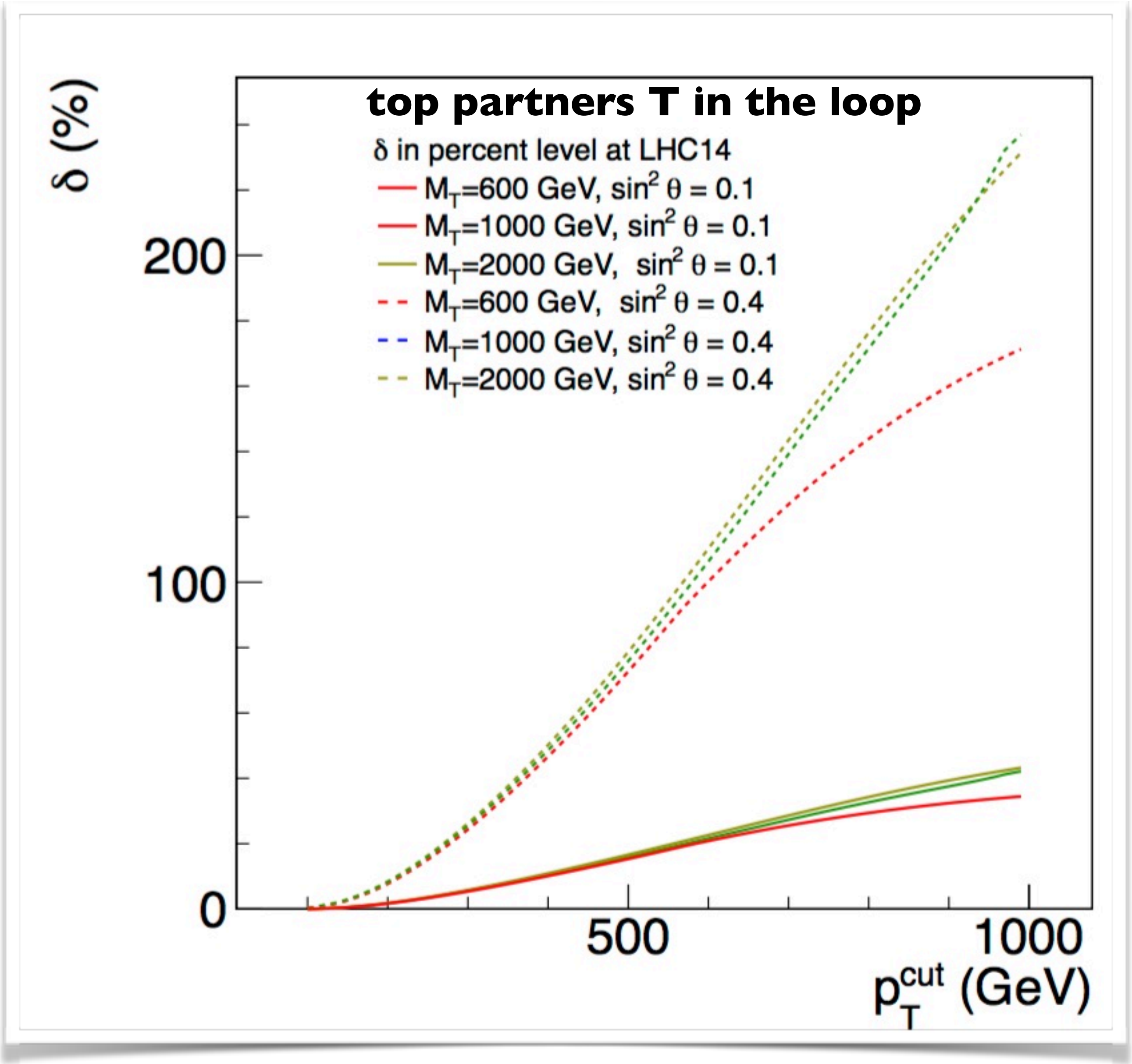


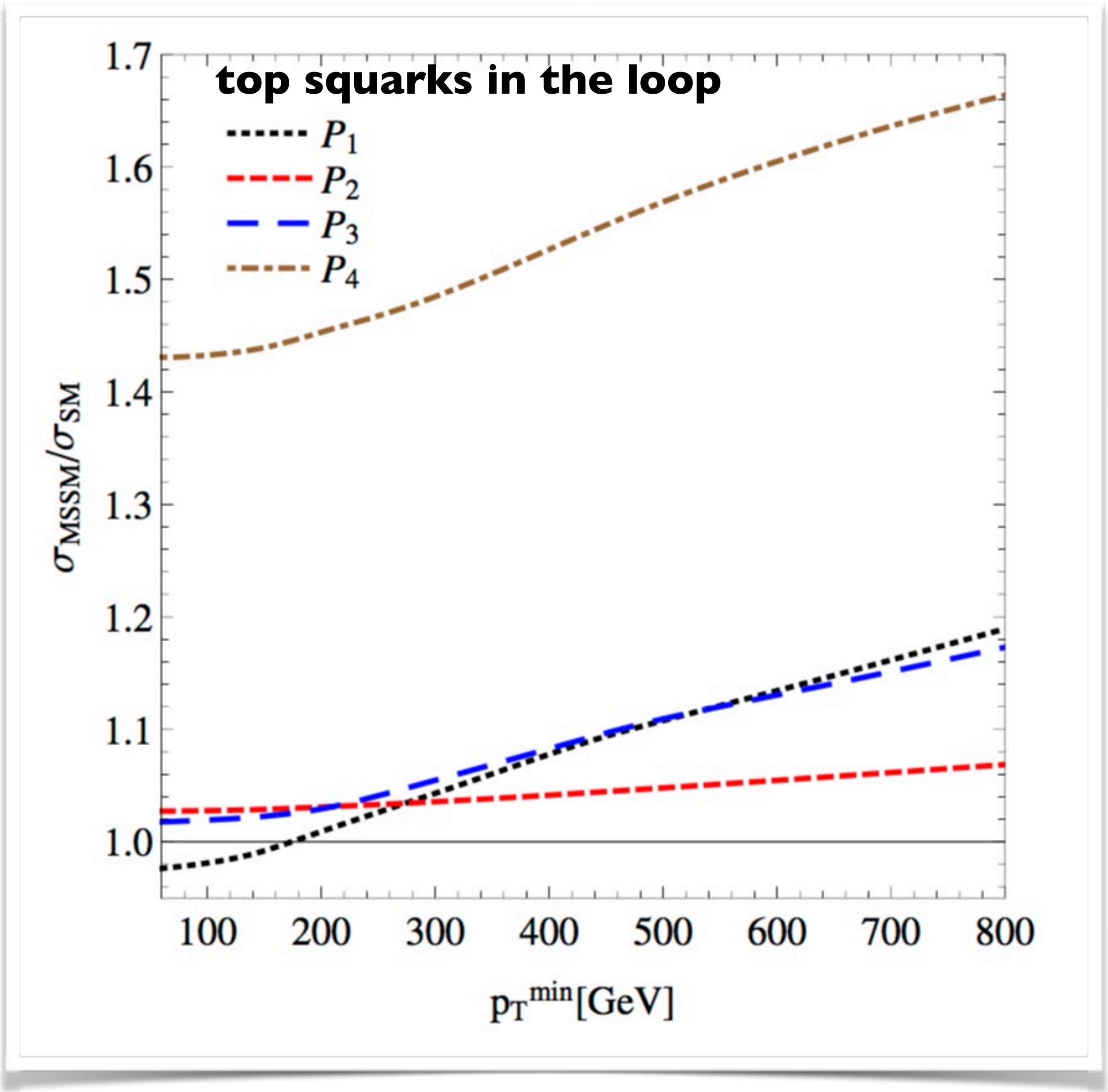
Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\mathrm{GeV}$, $M_2 = 1000\,\mathrm{GeV}$, $\mu = 200\,\mathrm{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was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

(See also
Azatov and Paul arXiv:1309.5273v3)

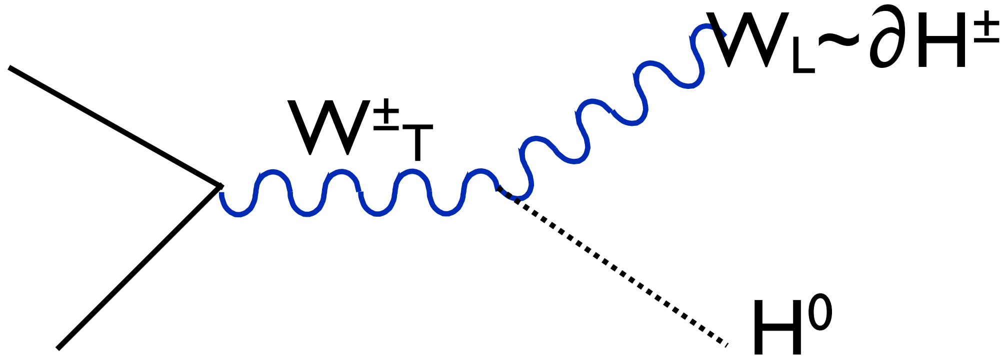


Banfi Martin Sanz, arXiv:1308.4771



Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

VH prodution at large m(VH)



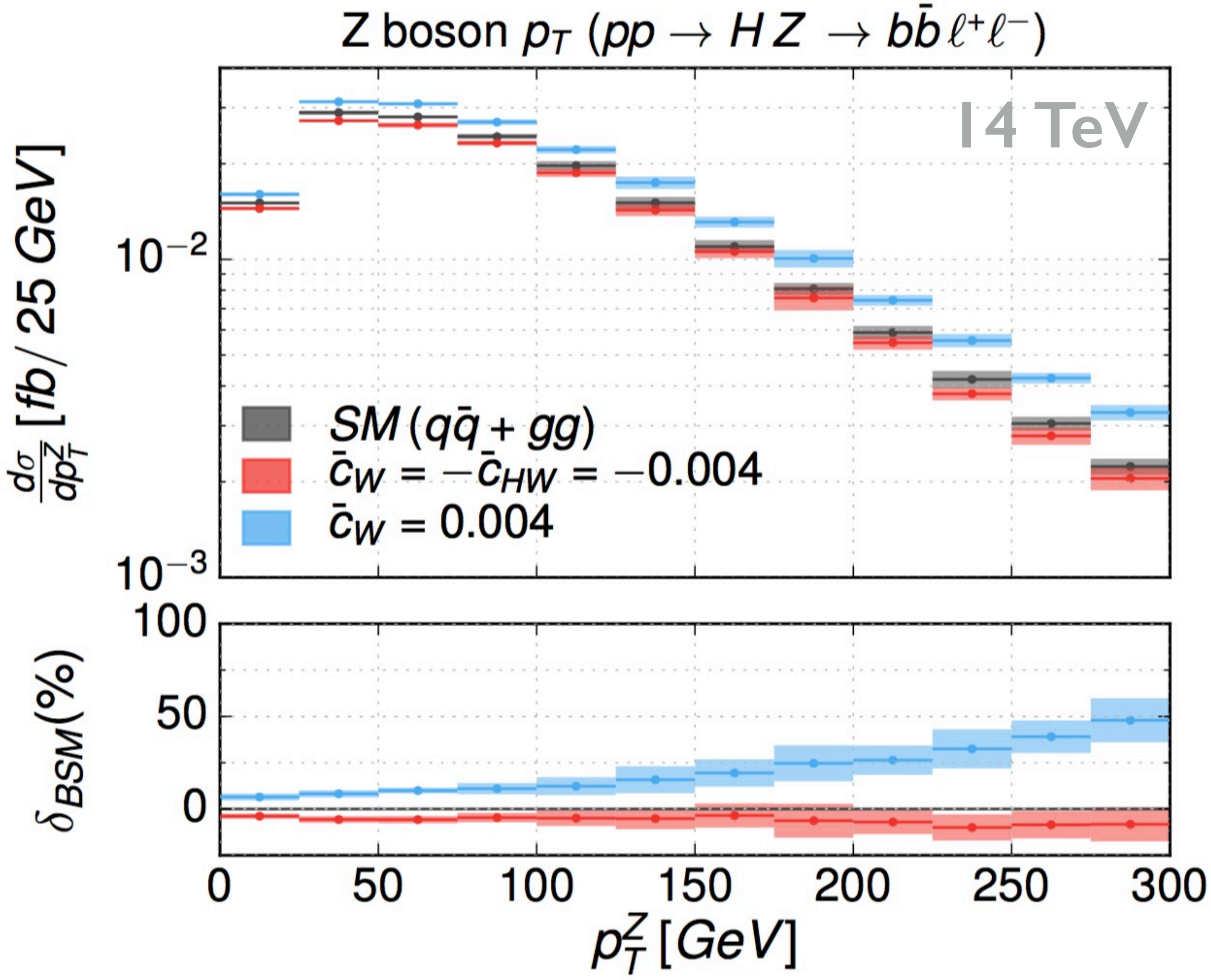
See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320

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

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Of particular interest will be the exploration of the complementarity between the information gained from precise BR measurements at FCC-ee and high-Q^2 measurements at FCC-hh (eg ability to pin down origin of deviations by testing complementary dim-6 operators)

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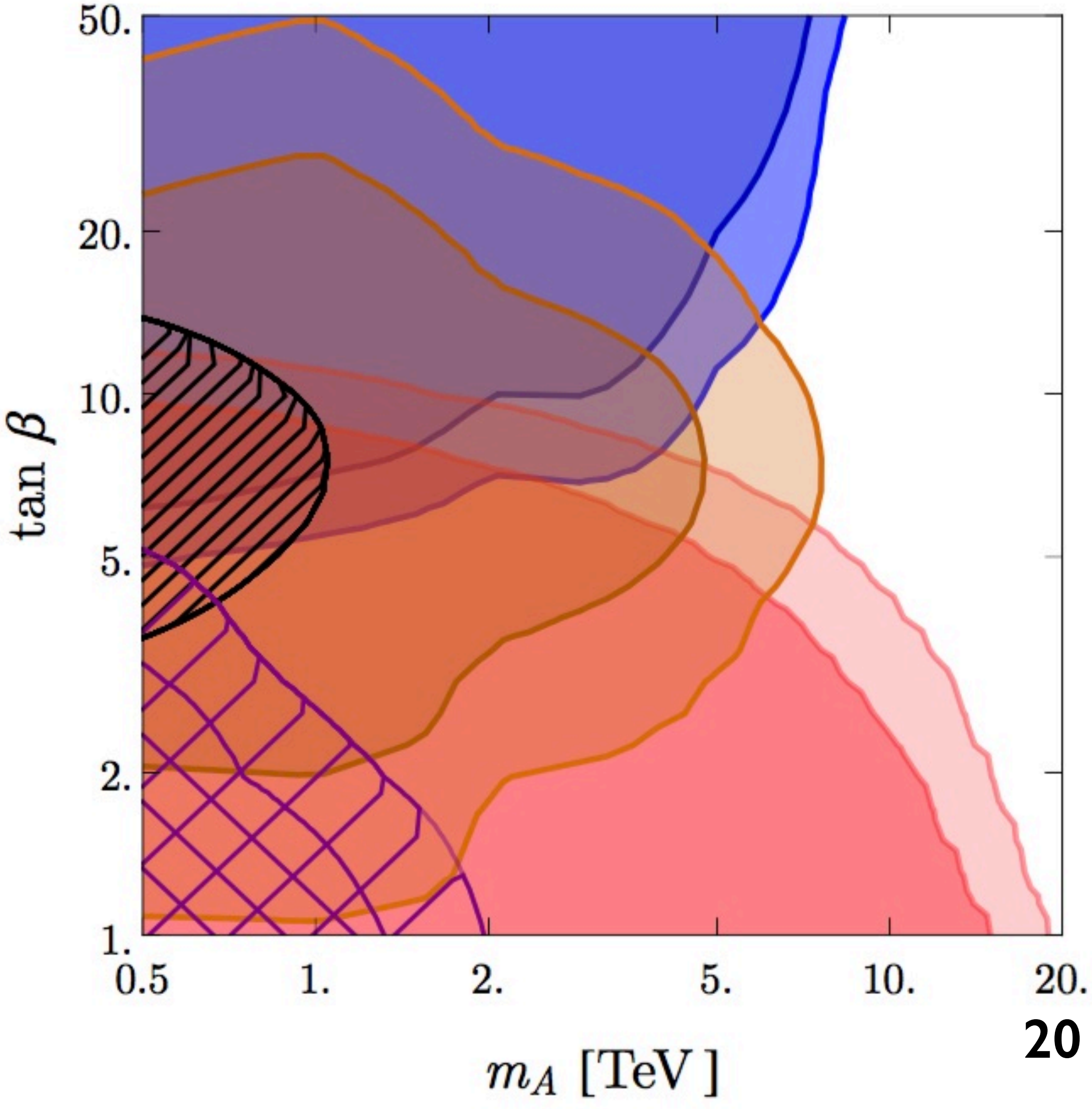
Further work to be done includes estimating the precision targets for the total width, eg using off-shell production

MSSM Higgs @ 100 TeV

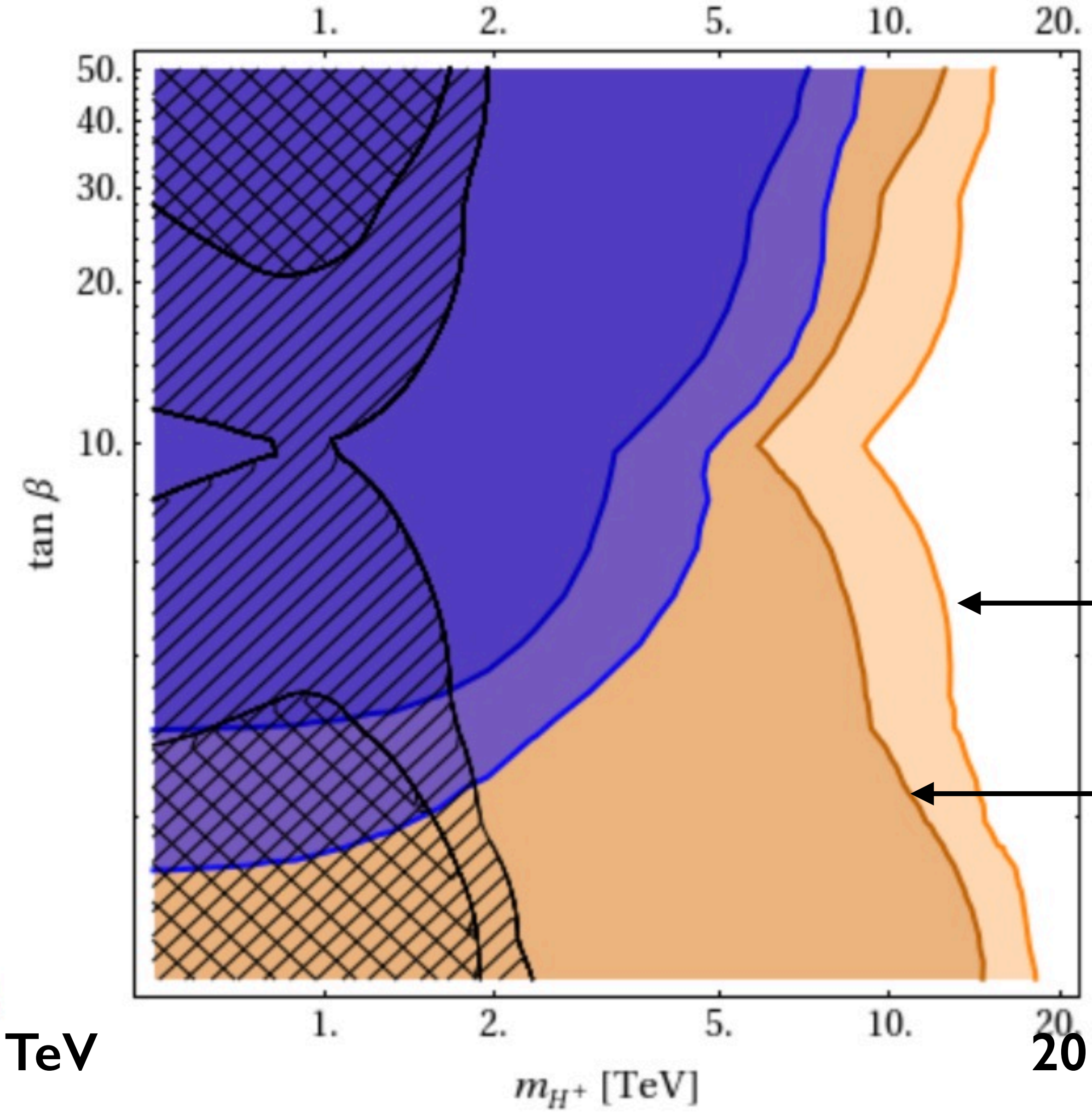
🟦 $bbH^0/A^0 \to bb\tau\tau$
🟧 $bbH^0/A^0 \to bbtt$
🟥 $t(t)H^0/A^0 \to t(t)tt$



20 TeV

🟦 $tbH^+ \to tb\tau\nu$
🟧 $tbH^+ \to tbtb$

▨ **LHC 3 ab^{-1}**
▩ **LHC 0.3 ab^{-1}**



30 ab^{-1}

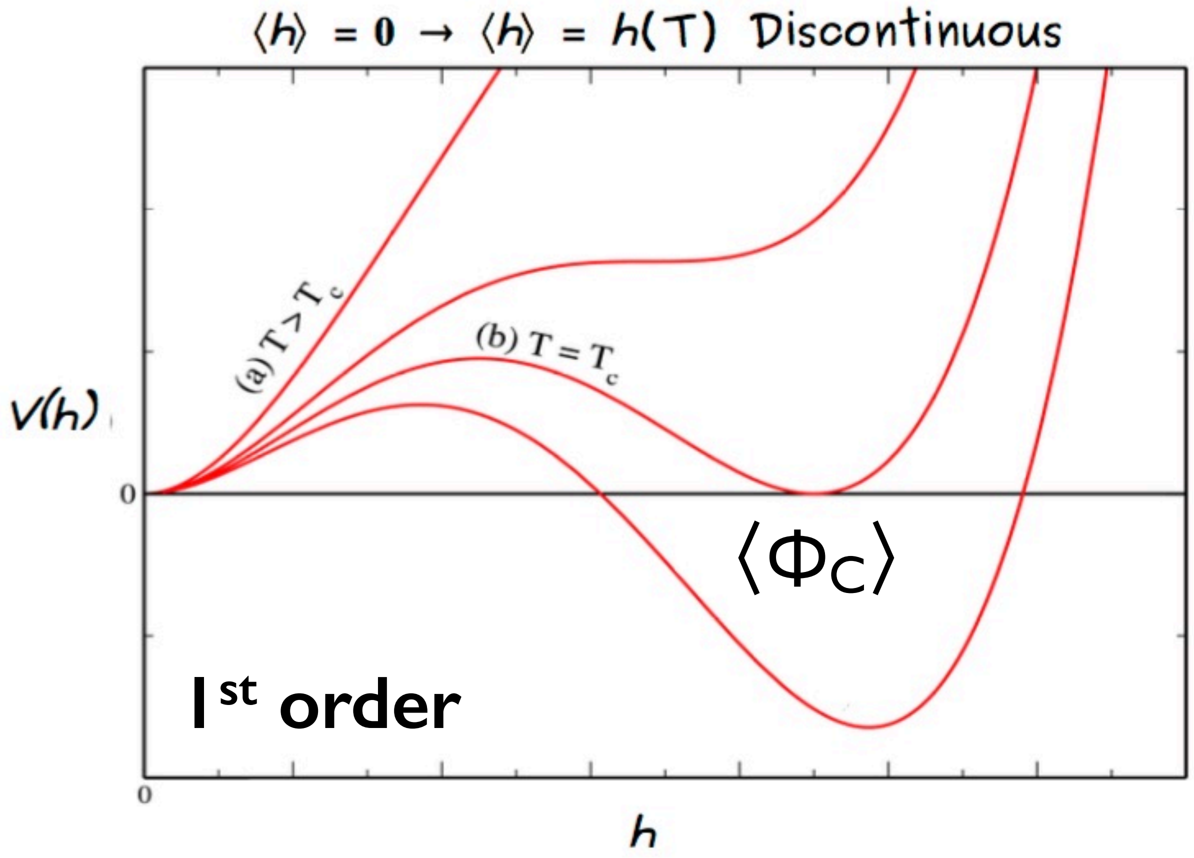
3 ab^{-1}

20 TeV

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

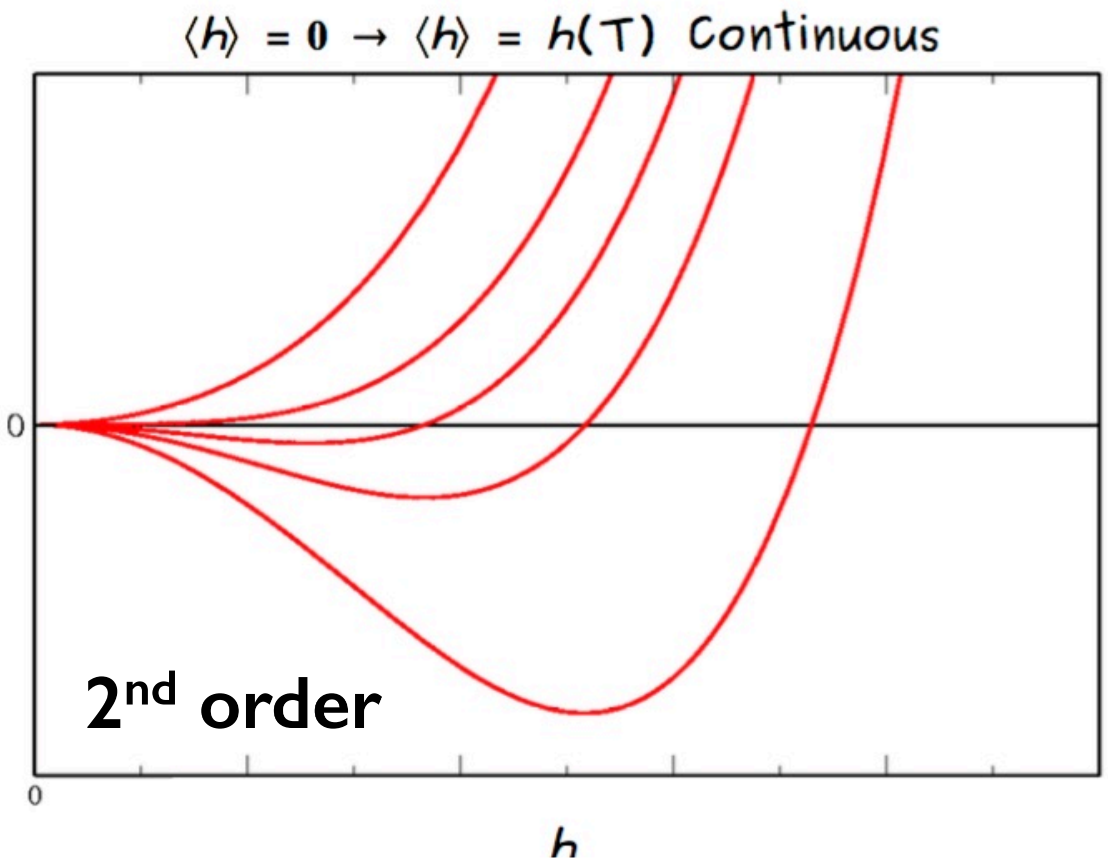
J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

The nature of the EW phase transition



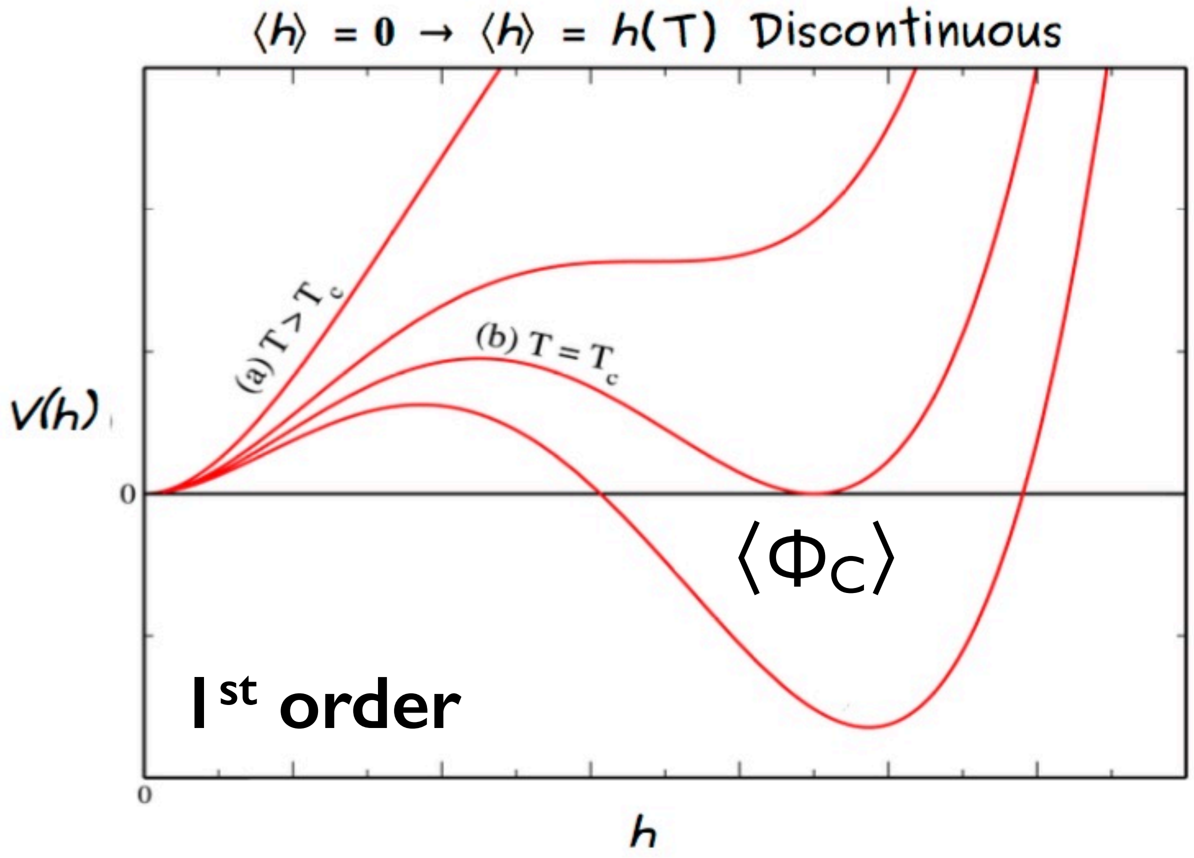
$\langle \Phi_C \rangle$

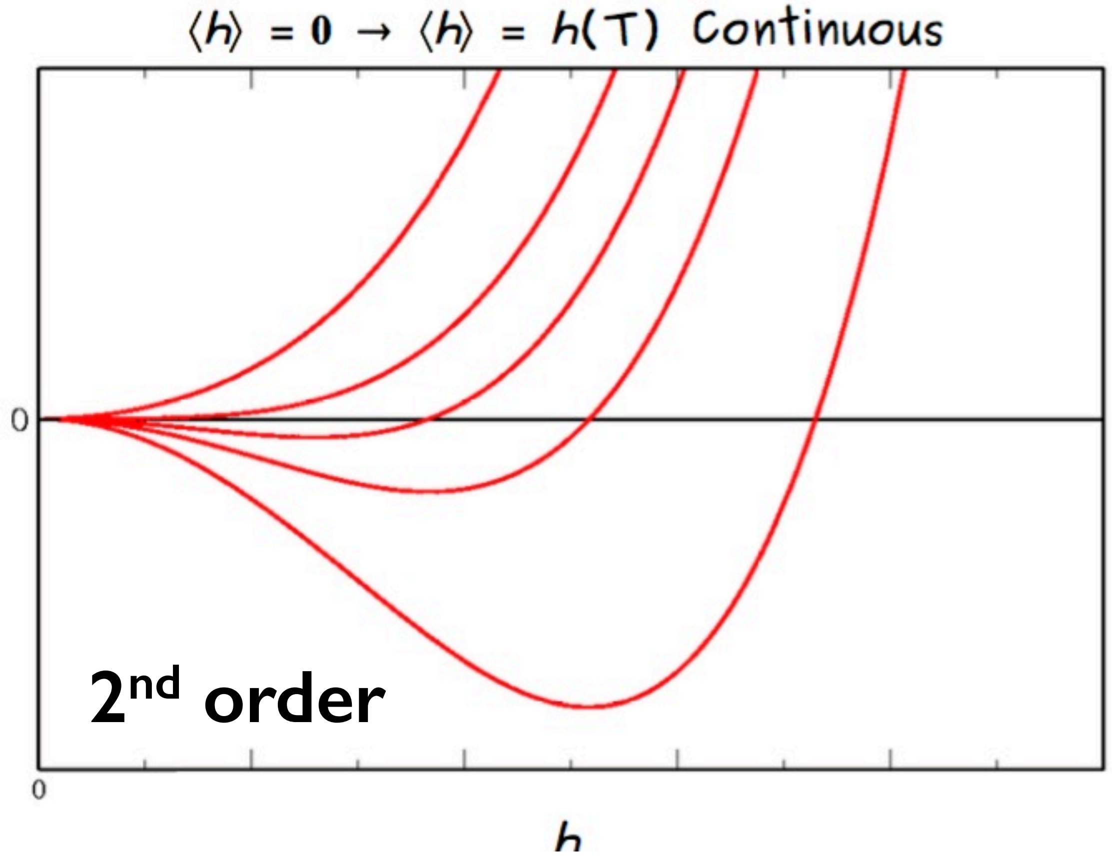
1st order



2nd order

The nature of the EW phase transition

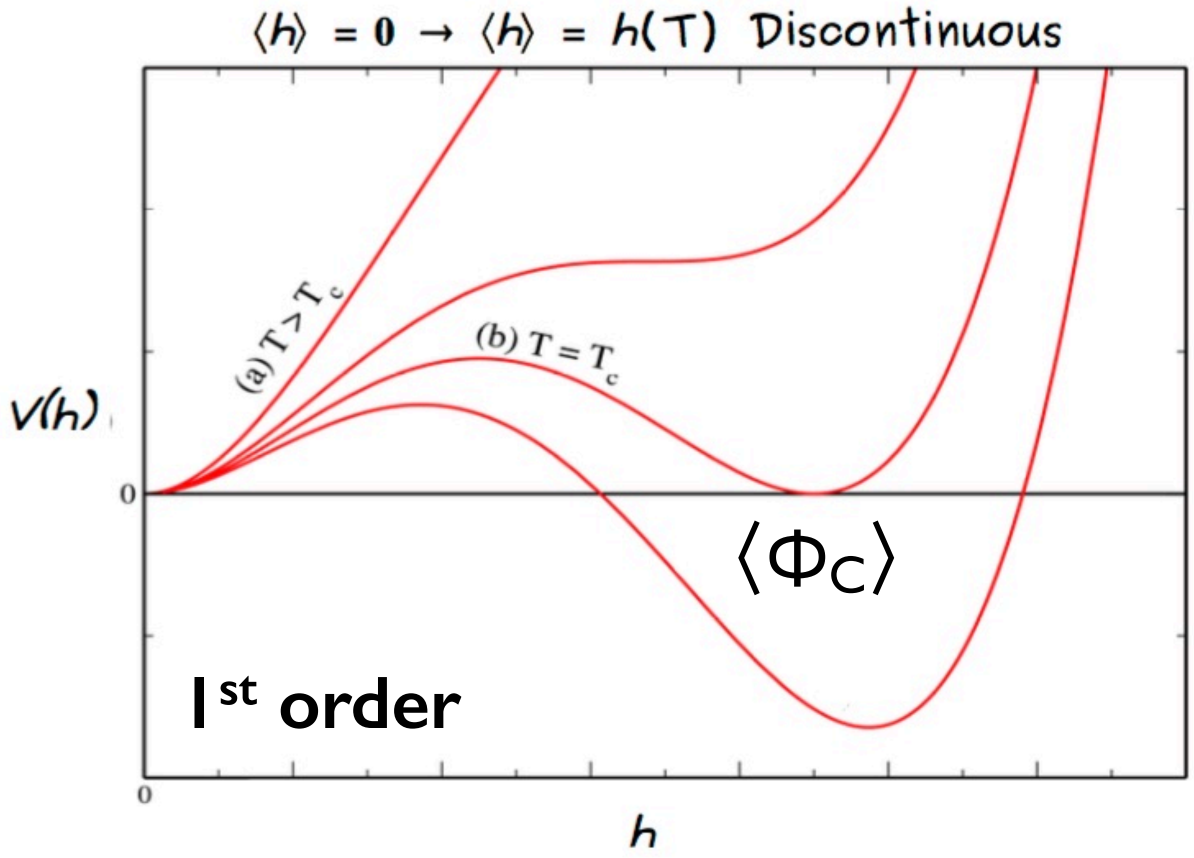


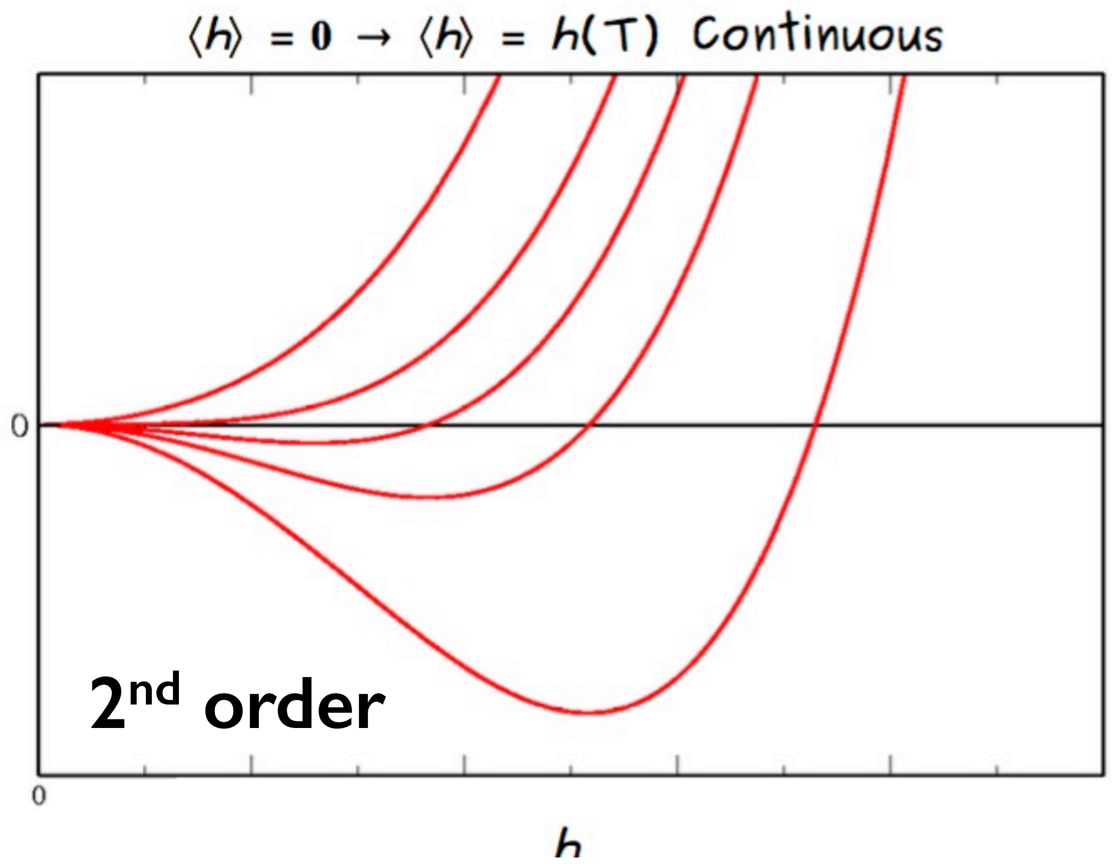


Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

The nature of the EW phase transition





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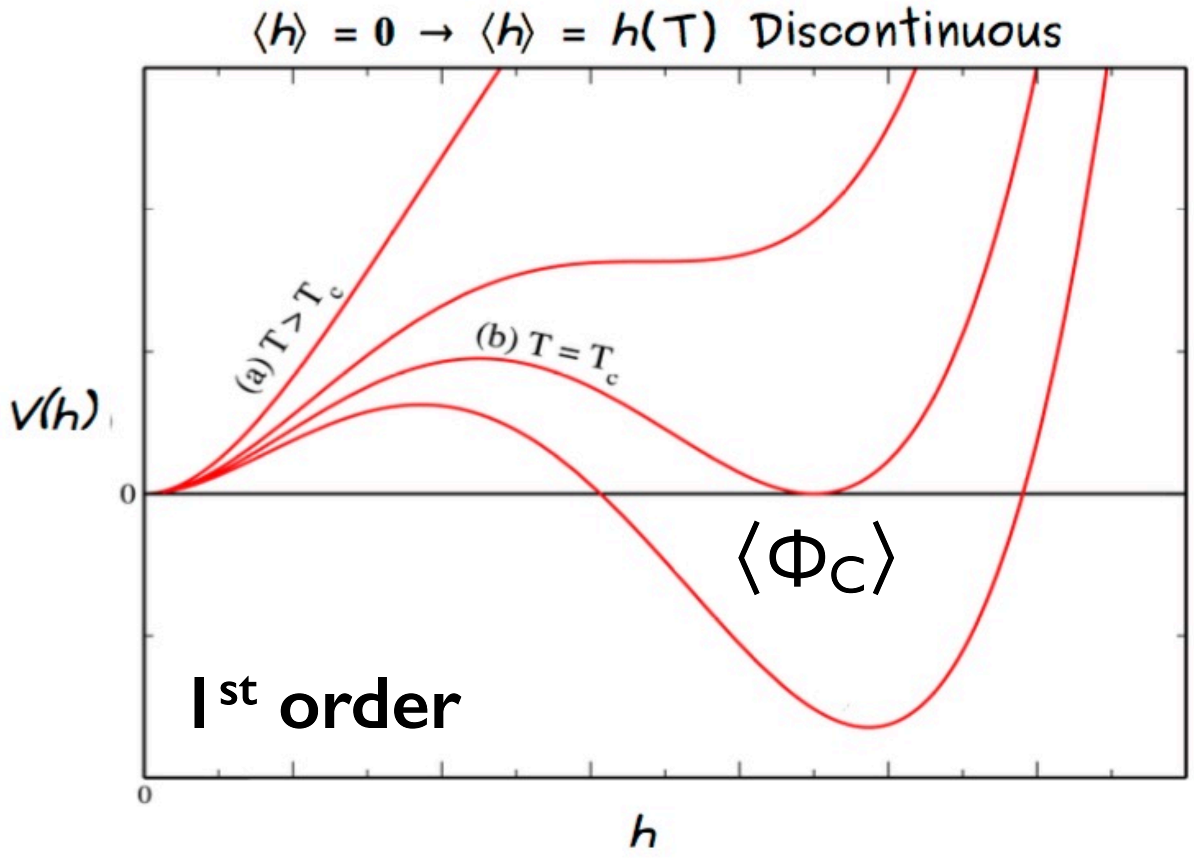
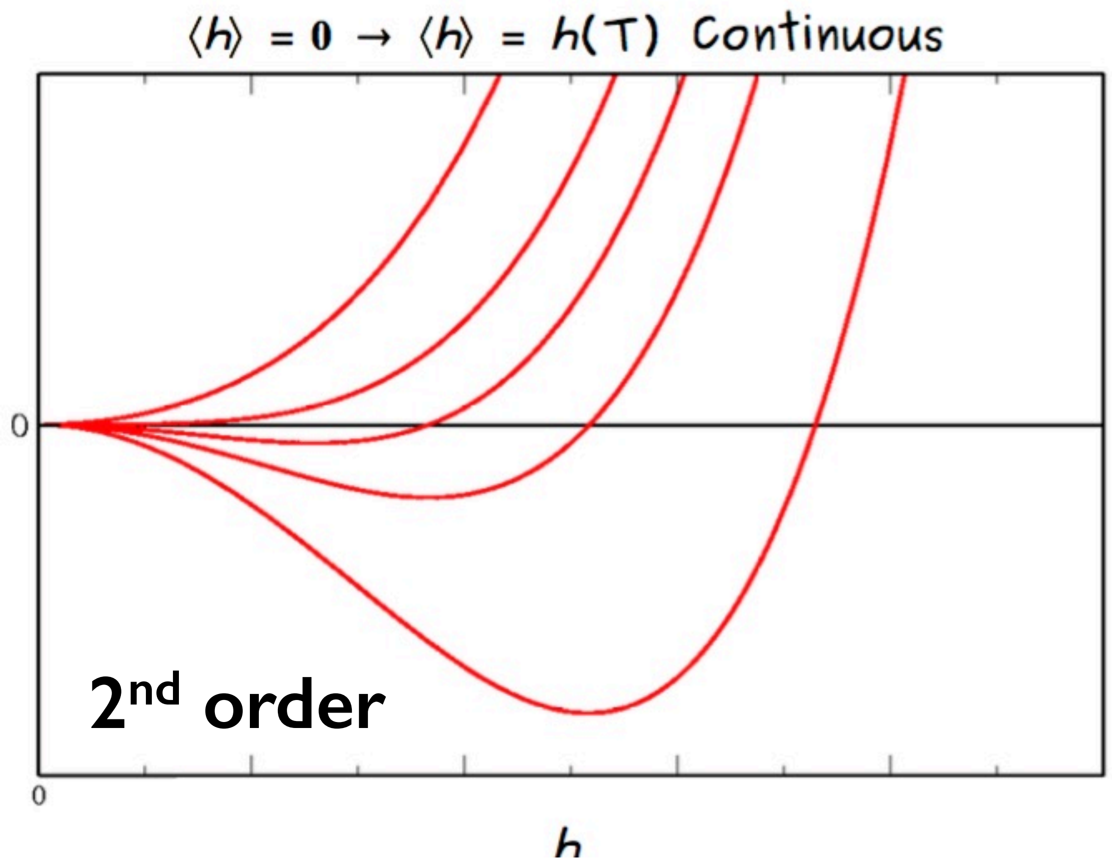
Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

The nature of the EW phase transition


$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous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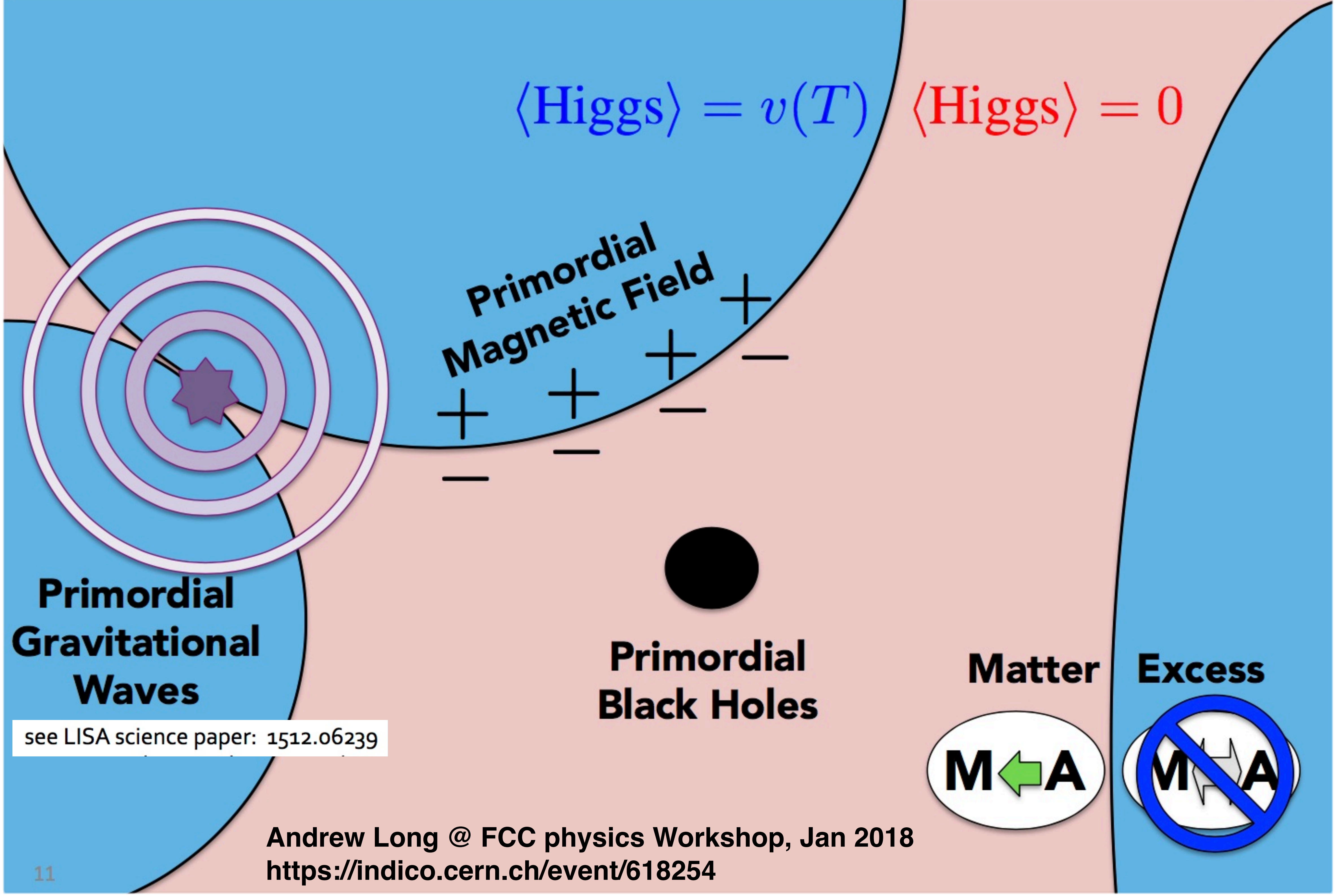
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

1st Order EWPT has profound implications for cosmology



$\langle \text{Higgs} \rangle = v(T)$ $\langle \text{Higgs} \rangle = 0$

Primordial Magnetic Field

Primordial Gravitational Waves

see LISA science paper: 1512.06239

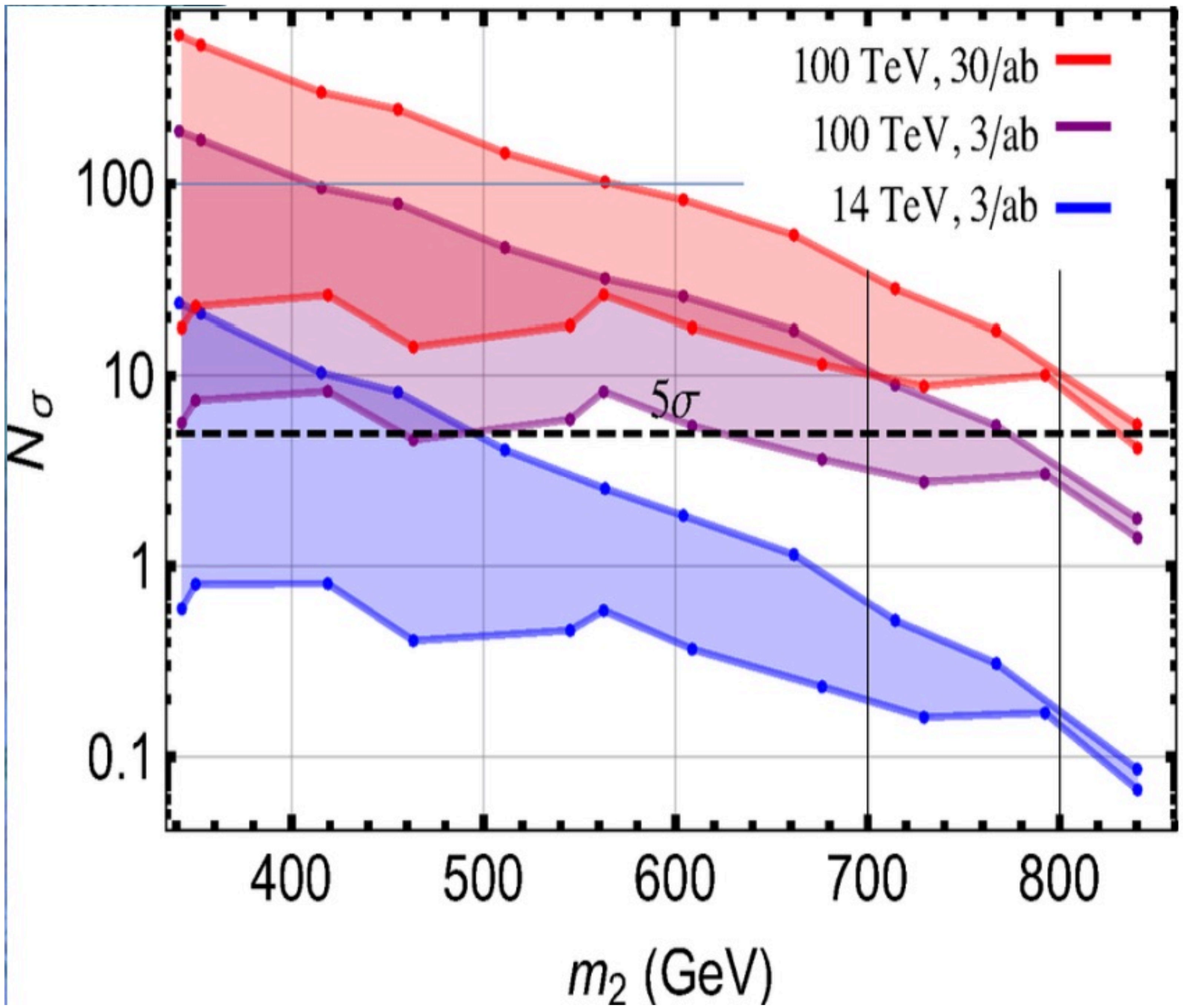
Primordial Black Holes

Matter Excess

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

What will FCC tells us about the existence of extra Higgs bosons enabling a 1st order EWPT?

$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$



Kotwal, No, Ramsey-Musolf, Winslow, arXiv:1605.06123

Minimal stealthy model for a strong EW phase transition: *the most challenging scenario for discovery*

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

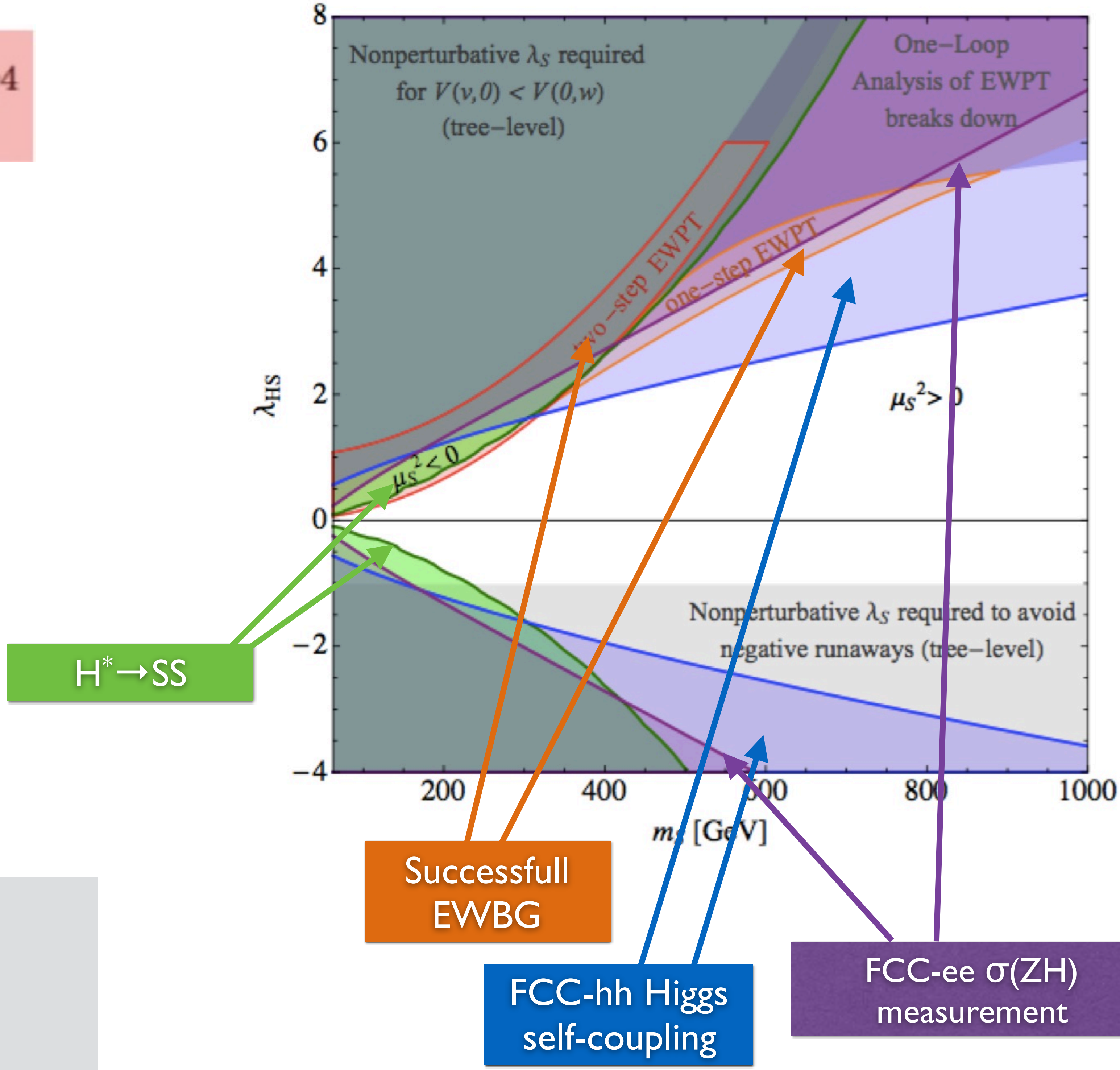
Unmixed SM+Singlet.
No exotic H decay, no H-S mixing, no EWPO, …

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

Curtin, Meade, Yu, arXiv:1409.0005



H*→SS

Successfull EWBG

FCC-hh Higgs self-coupling

FCC-ee σ(ZH) measurement

Higgs physics at HE-LHC (27 TeV, 15 ab^{-1})

Primary goals in the Higgs sector:

(a) sensitivity to the Higgs self-coupling

(b) reduce to the few percent level all major Higgs couplings

(c) improve the sensitivity to possible invisible Higgs decays

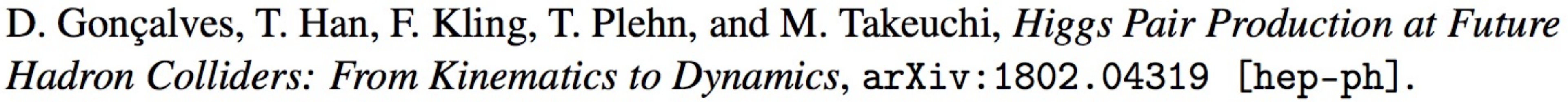
(d) measure the charm Yukawa coupling

	gg→H	WH	ZH	ttH	HH
N_{27}	2.2×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

$N_{27} = \sigma(27\text{ TeV}) * 15\ ab^{-1}$

$N_{14} = \sigma(14\text{ TeV}) * 3\ ab^{-1}$

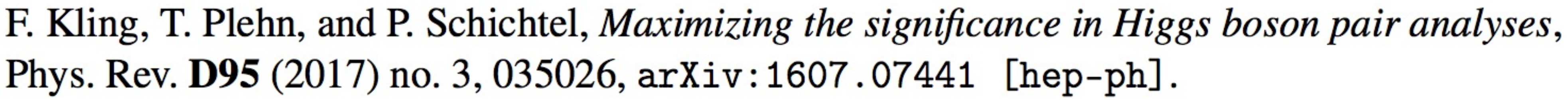
- First results on Higgs selfcouplings measurement:



D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, `arXiv:1802.04319 [hep-ph]`.

$\lambda/\lambda_{SM} = 1 \pm 0.3$ at 95%CL (1±0.15 at 68%CL)

(compare to $-0.2 < \lambda/\lambda_{SM} < 2.6$ at HL-LHC)



F. Kling, T. Plehn, and P. Schichtel, *Maximizing the significance in Higgs boson pair analyses*, Phys. Rev. **D95** (2017) no. 3, 035026, `arXiv:1607.07441 [hep-ph]`.

- For couplings like Hγγ, HZγ, Hμμ, Htt, … , plan to repeat studies presented at 100 TeV

Final remarks

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- Most precise extraction of absolute BRs, couplings and width from FCC-hh data will require FCC-ee input. But there is immense sensitivity to BSM deviations in the broad spectrum of FCC-hh Higgs measurements (BR ratios, p_T spectra, high-Q^2, direct searches, …)
- 27 TeV: 30% precision on the self-coupling starts touching an interesting region. However, while a real assessment is still pending, the limited increase in rate and kinematical/Q^2 reach wrt LHC, point to a possibly minor "Higgs case" for HE-LHC, in absence of other, yet unknown, physics drivers.