Physics at future hadron colliders

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pp @ 14 TeV, 3ab^{-1}

✓**Approved 2026-37**

HL-LHC PROJECT

pp @ 14 TeV, 3ab^{-1}

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FCC hh ee he

CDR (end ’18)

100km tunnel

- pp @ 100 TeV
- e^+e^- @ 91, 160, 240, 365 GeV
- e_{60GeV} p_{50TeV} @ 3.5 TeV

LHC tunnel: HE-LHC

- pp @ 27 TeV, 15ab^{-1}

pp @ 14 TeV, $3ab^{-1}$

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LHC tunnel: HE-LHC

- pp @ 27 TeV, $15ab^{-1}$

CDR (Summer ’18)

100km tunnel

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and e_{60GeV} p_{35TeV}

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- 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?
  - was the cosmological EW phase transition 1st order? Cross over? ??
  - could baryogenesis take place during the EW phase transition?

Higgs properties,

some sample studies

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

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

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

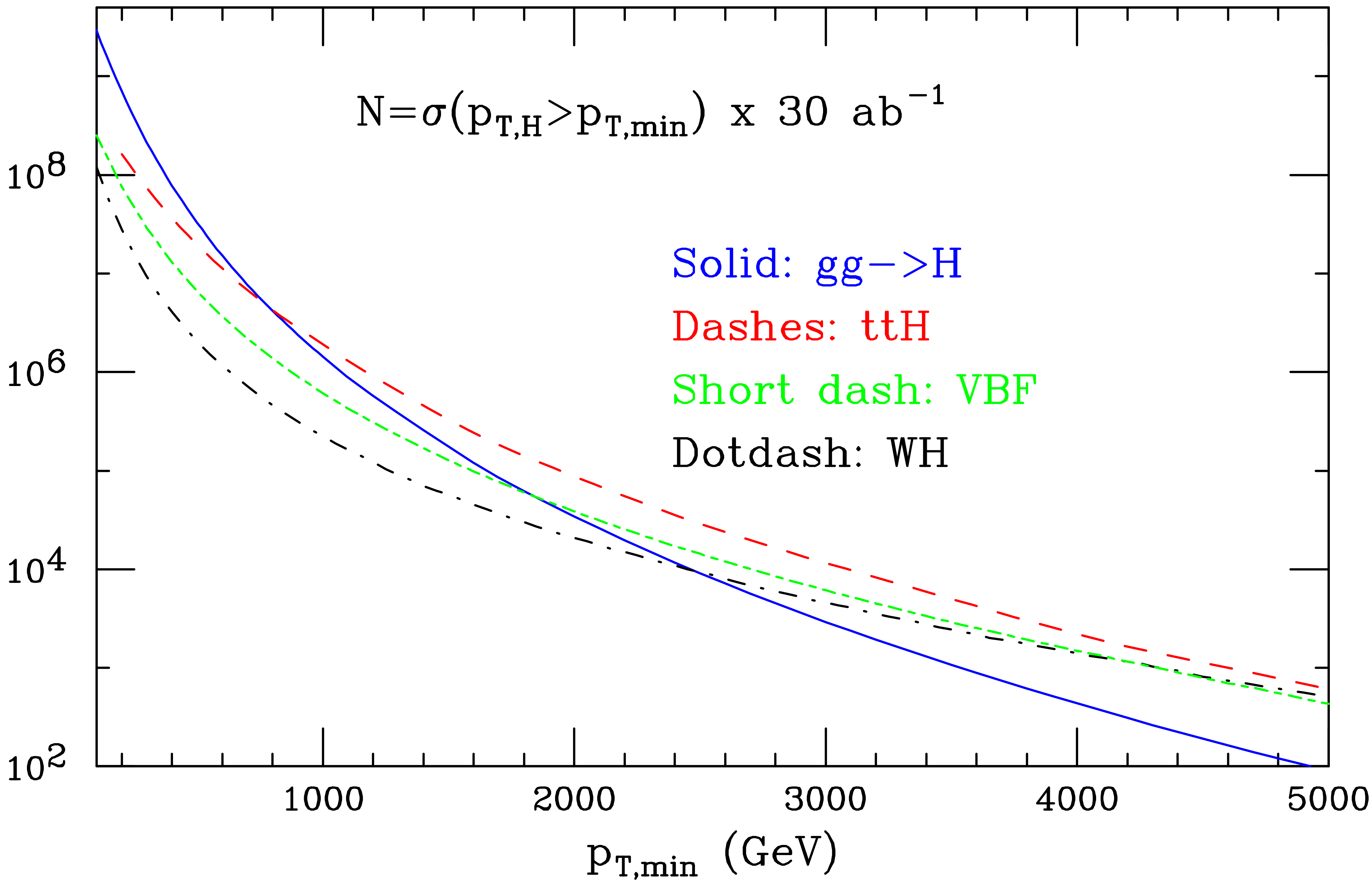
The uniqueness of
FCC-hh contributions to Higgs physics

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

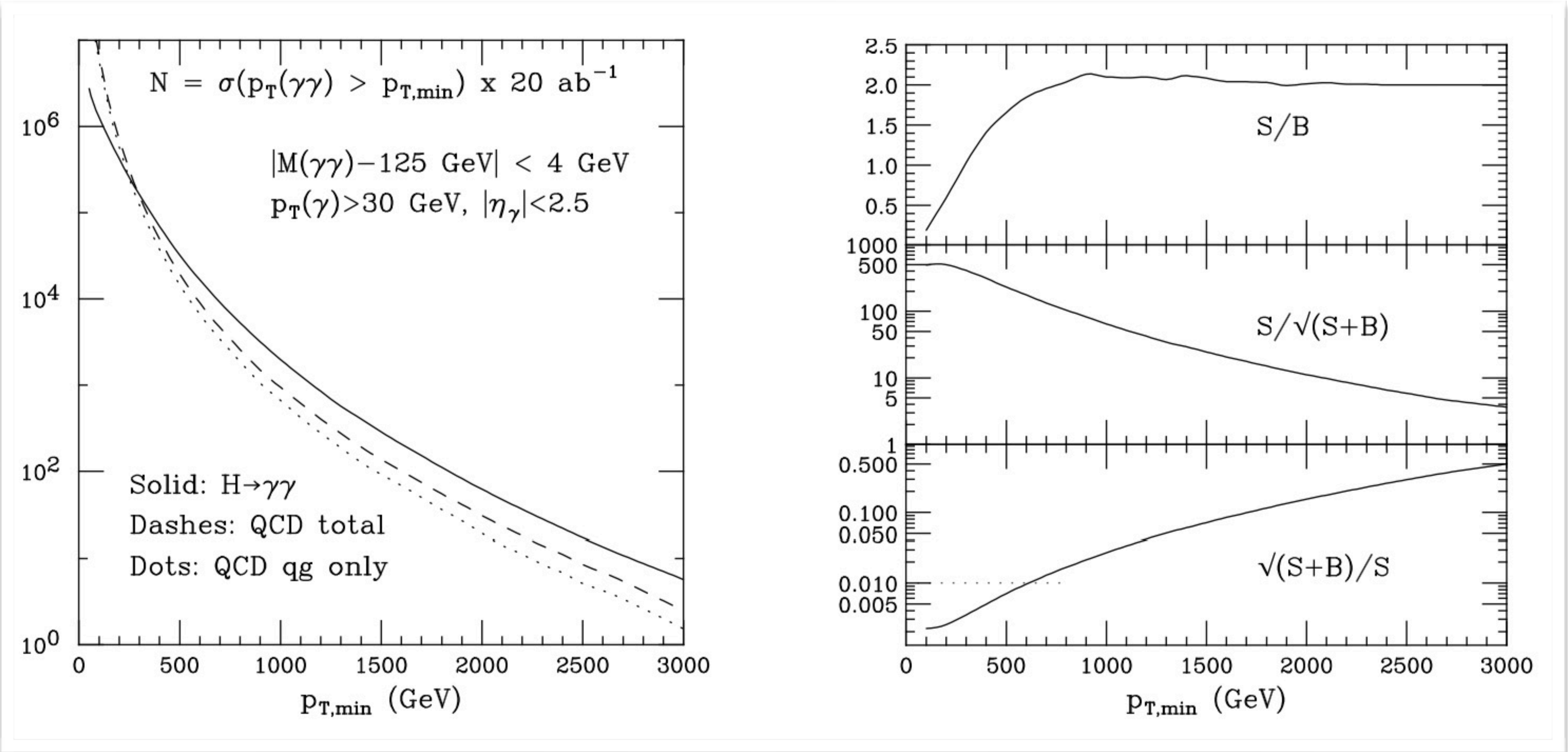
- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - …

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

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



- 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
- 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%

Delphes-based projections

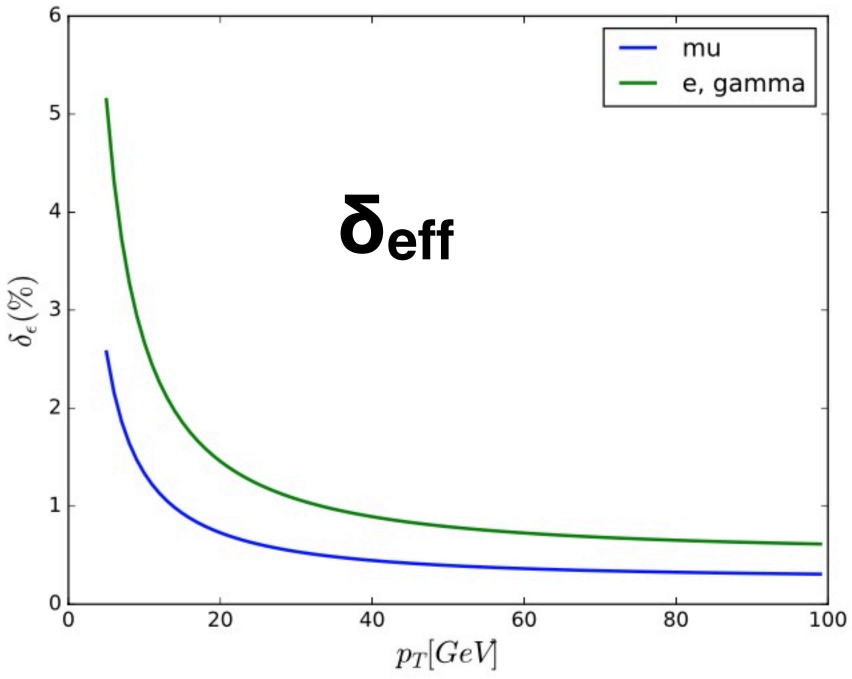
M.Selvaggi

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
- $\delta_{eff}{}^{(i)}$ (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:

- δ_{stat} → stat. only (I)
- δ_{stat} , δ_{eff} → stat. + eff. unc. (II)
- δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + eff. unc. + prod (III)

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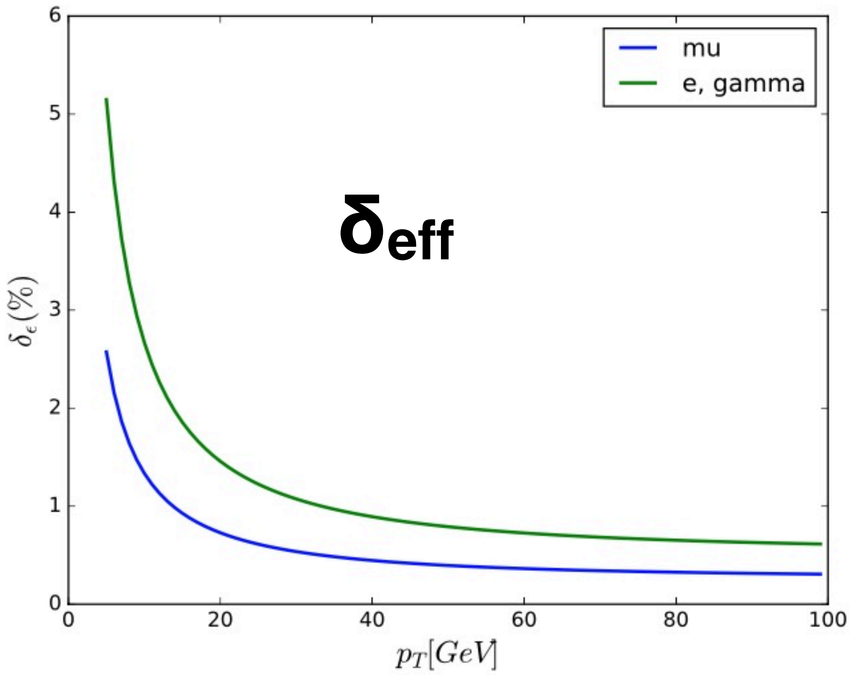

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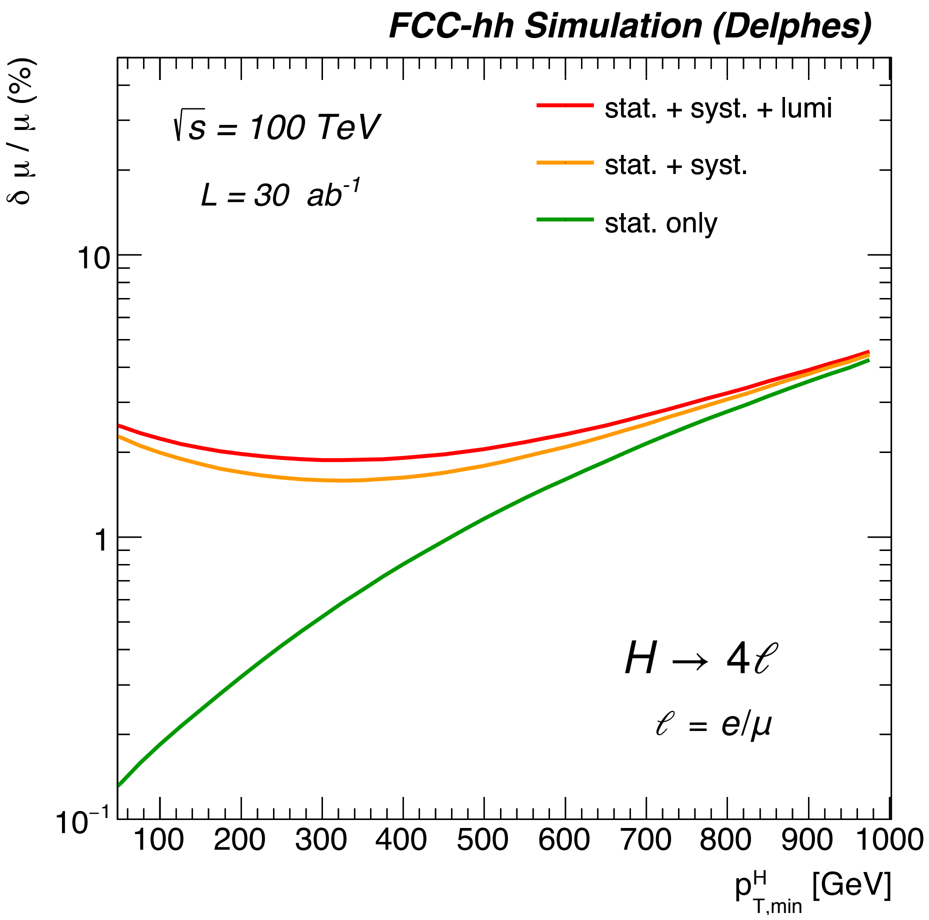
could be seen as syst in the normalization of production*lumi wrt standard candles such as pp→Z→ee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$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat. + syst. + lumi
stat. + syst.
stat. only
$H \rightarrow 4\ell$
ℓ = e/μ
δ μ / μ (%)
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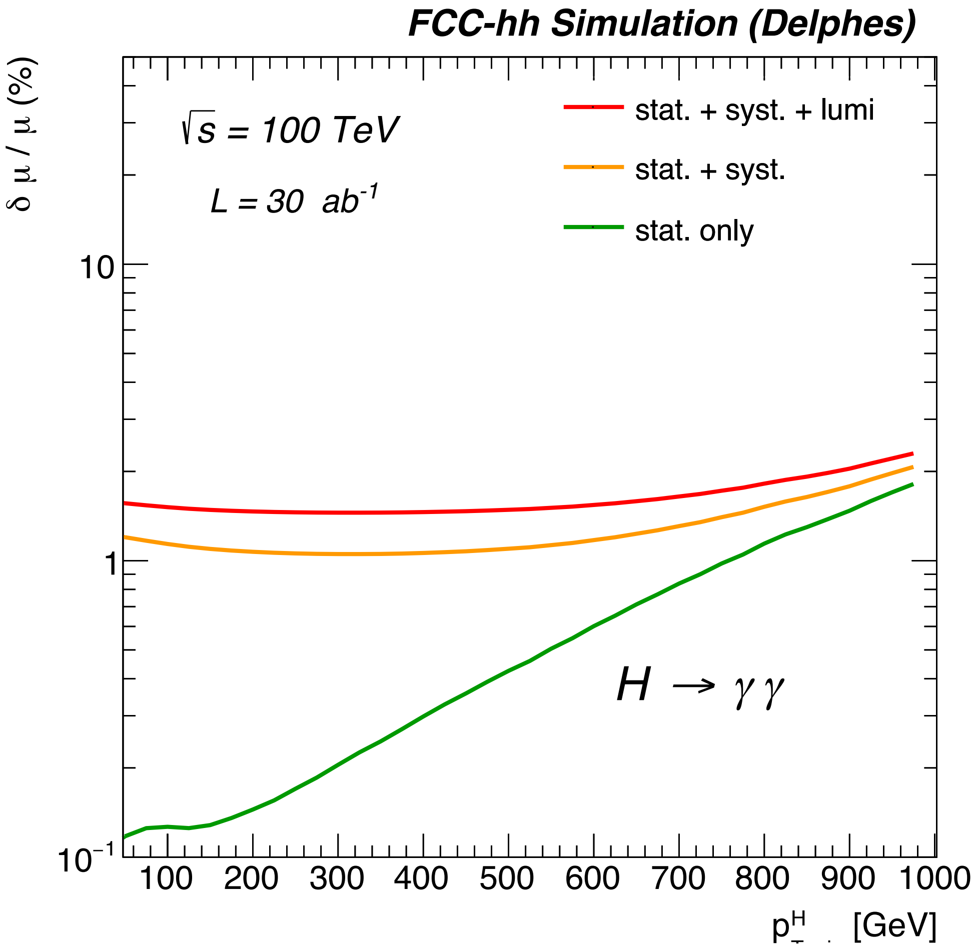
$p^{H}_{T,min}$ [GeV]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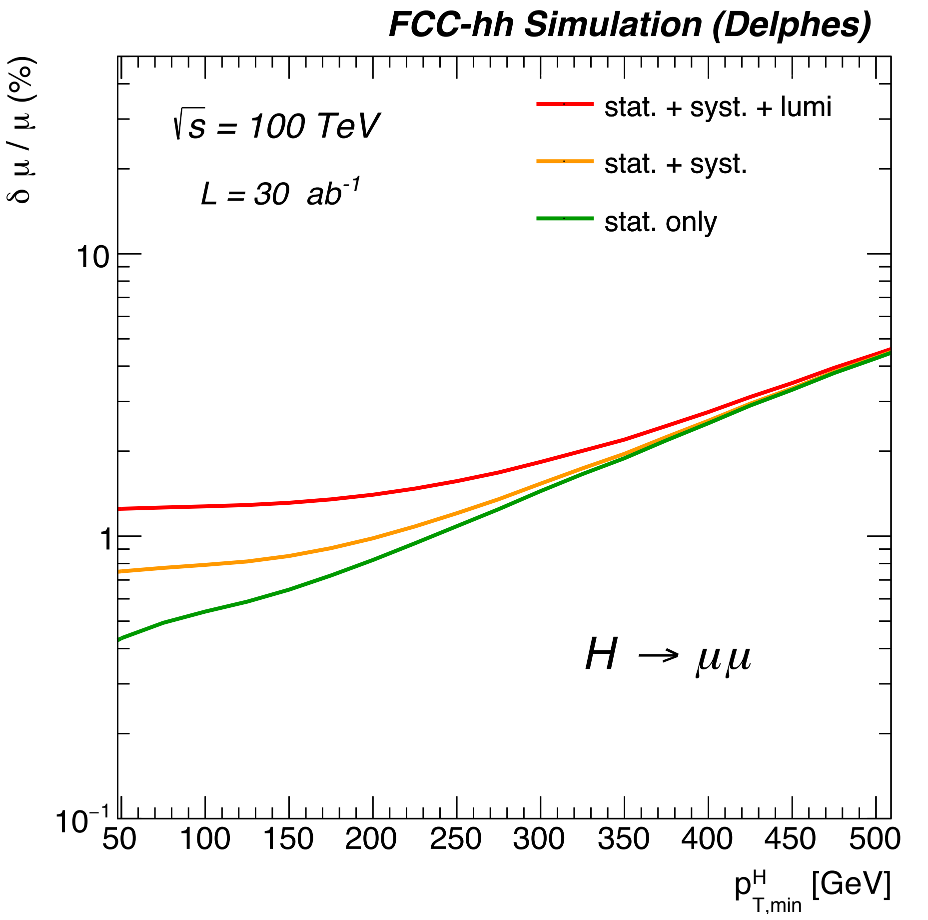
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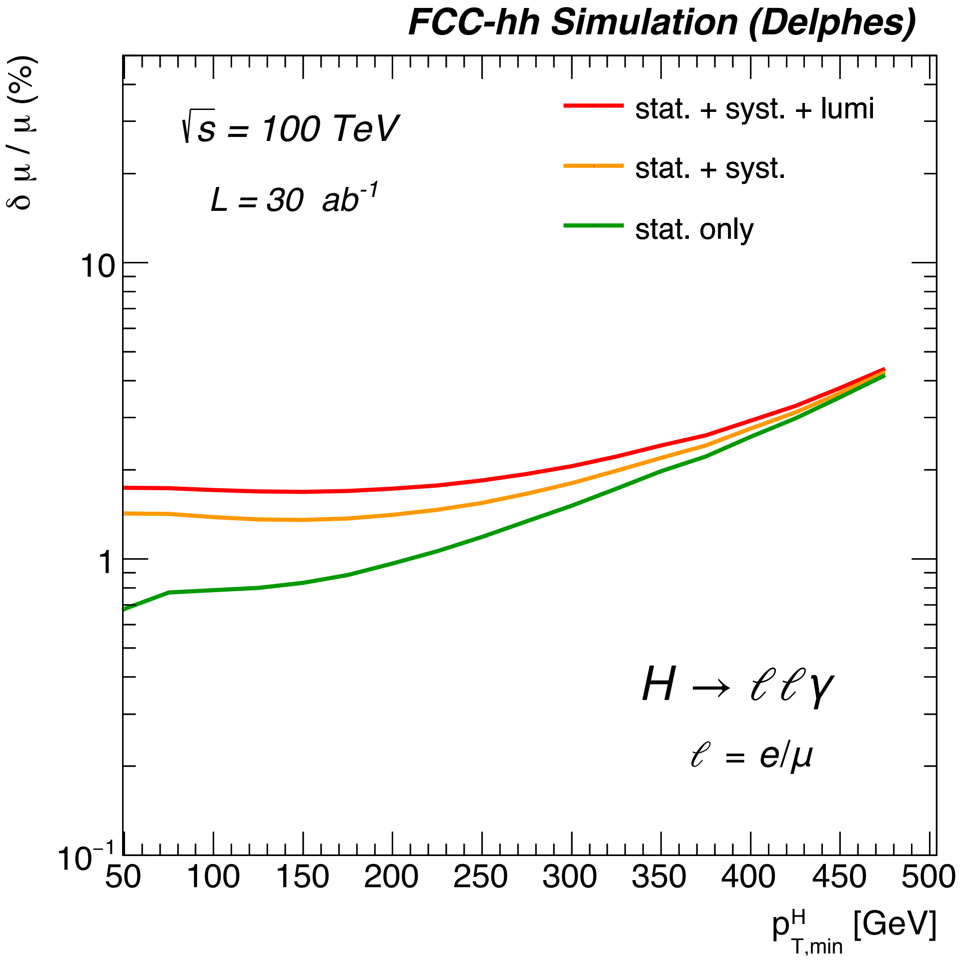
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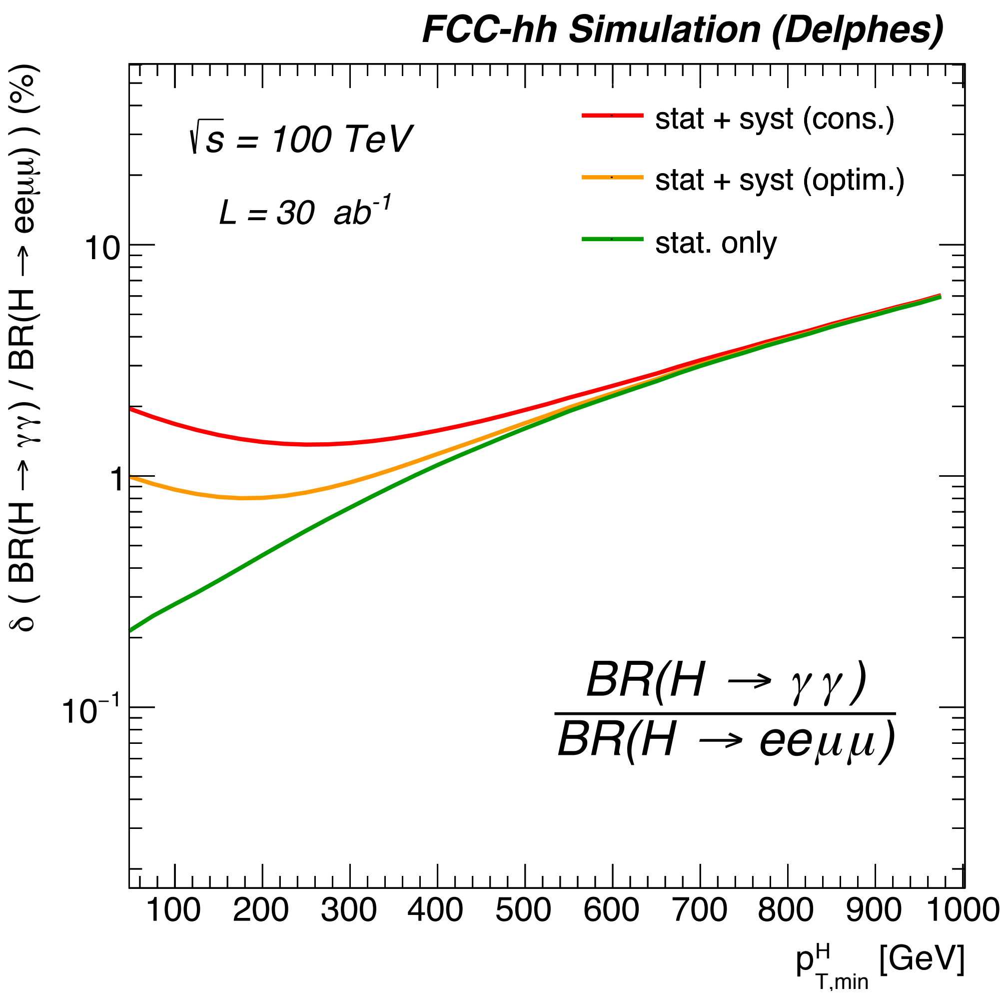
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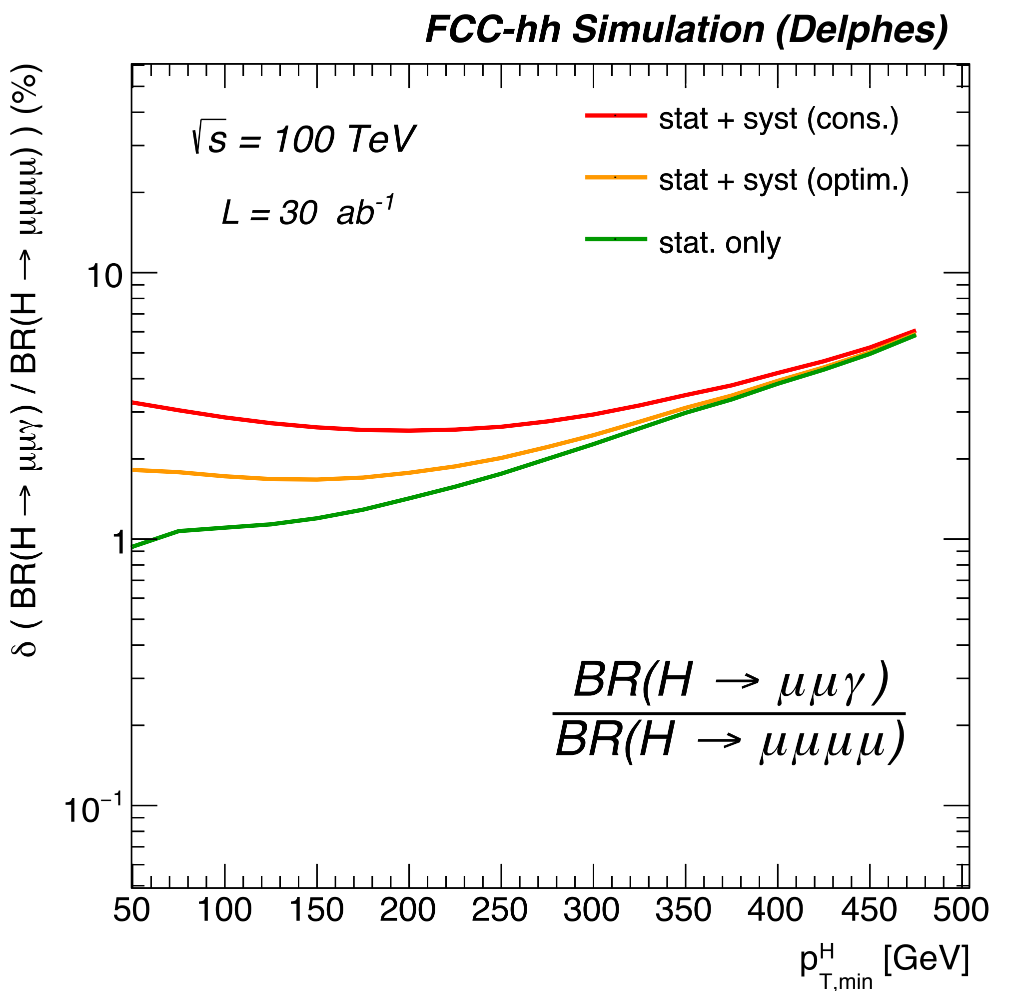
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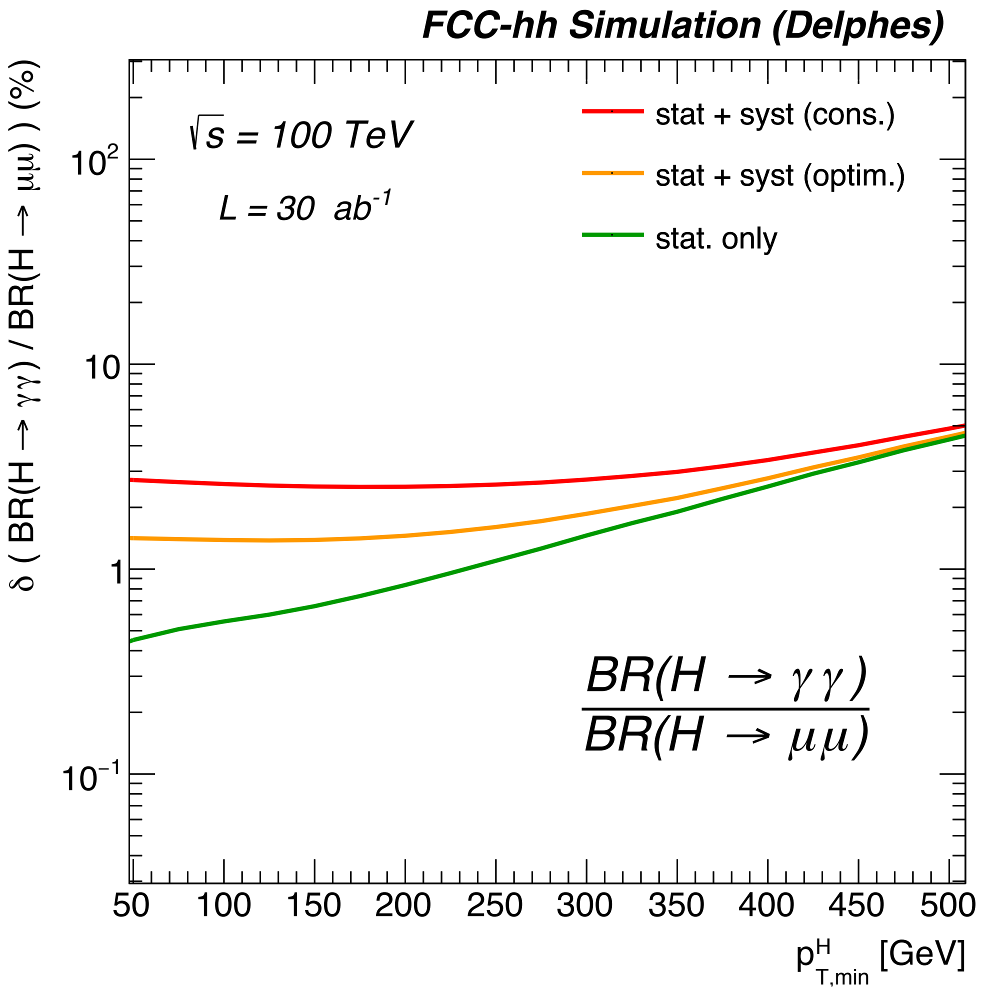
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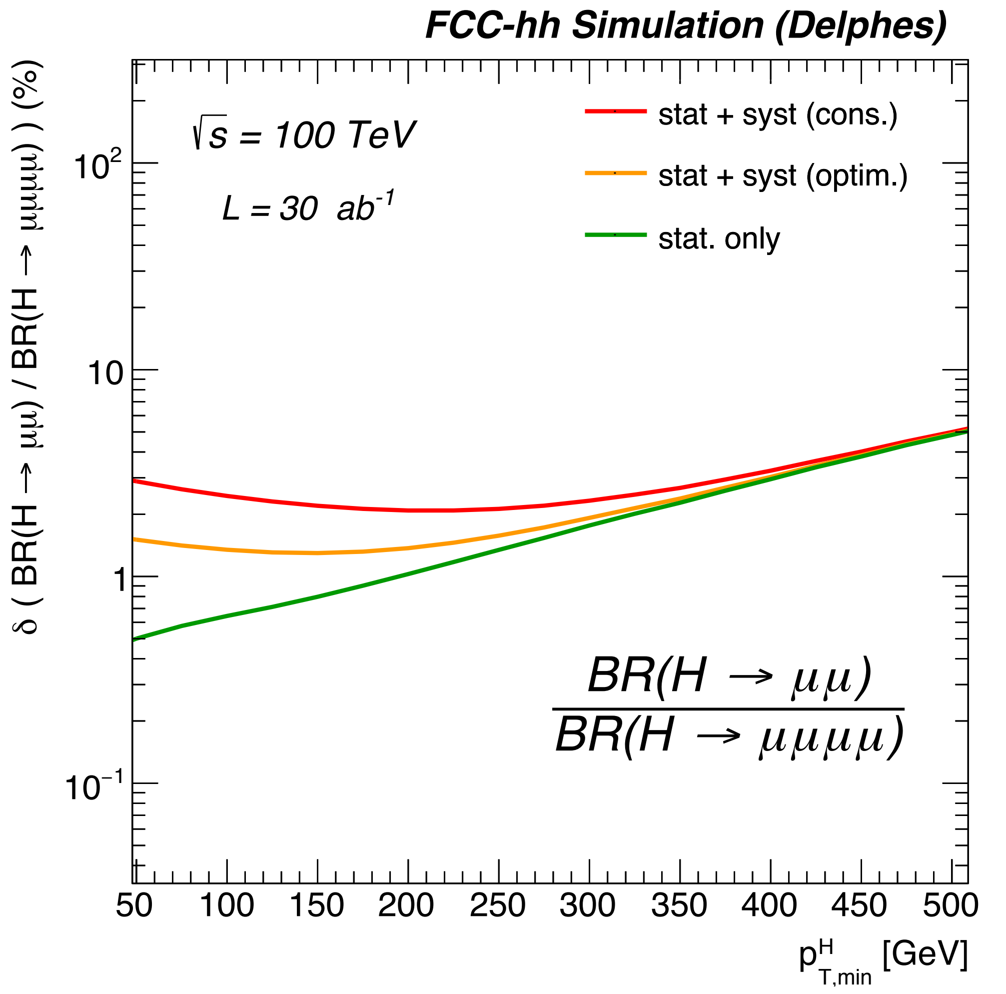
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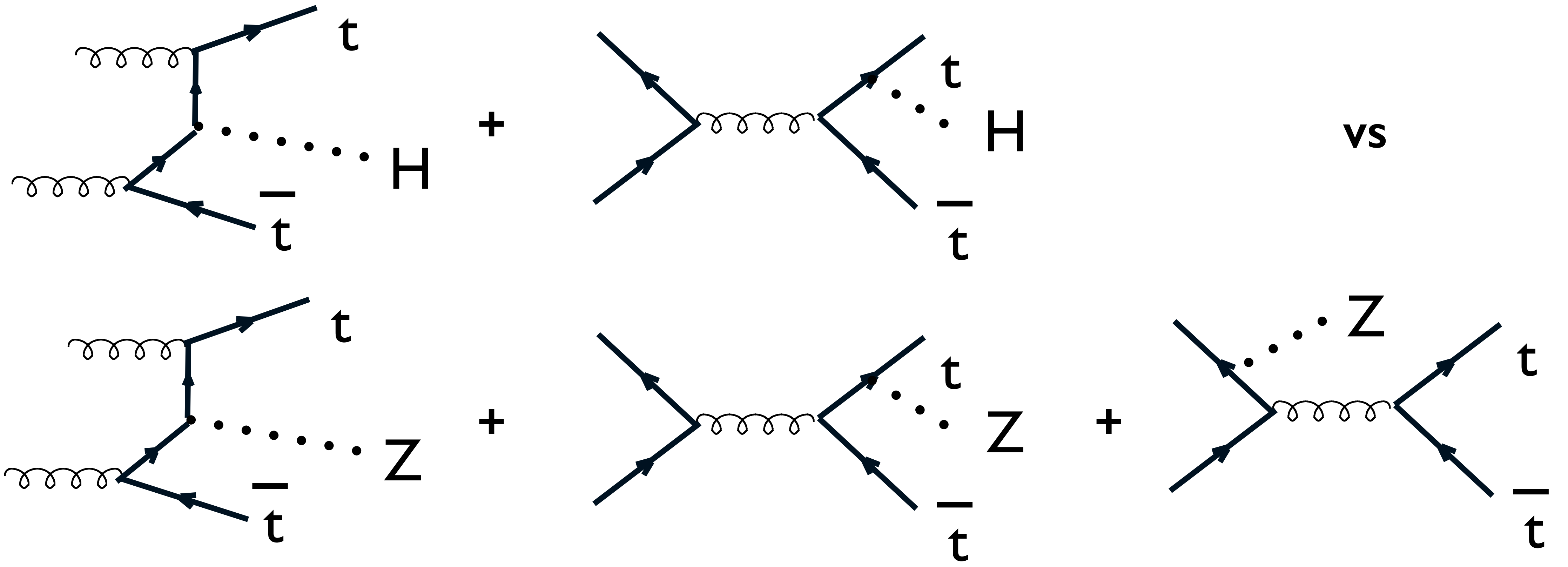
Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

arXiv:1507.08169



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

- Identical production dynamics:

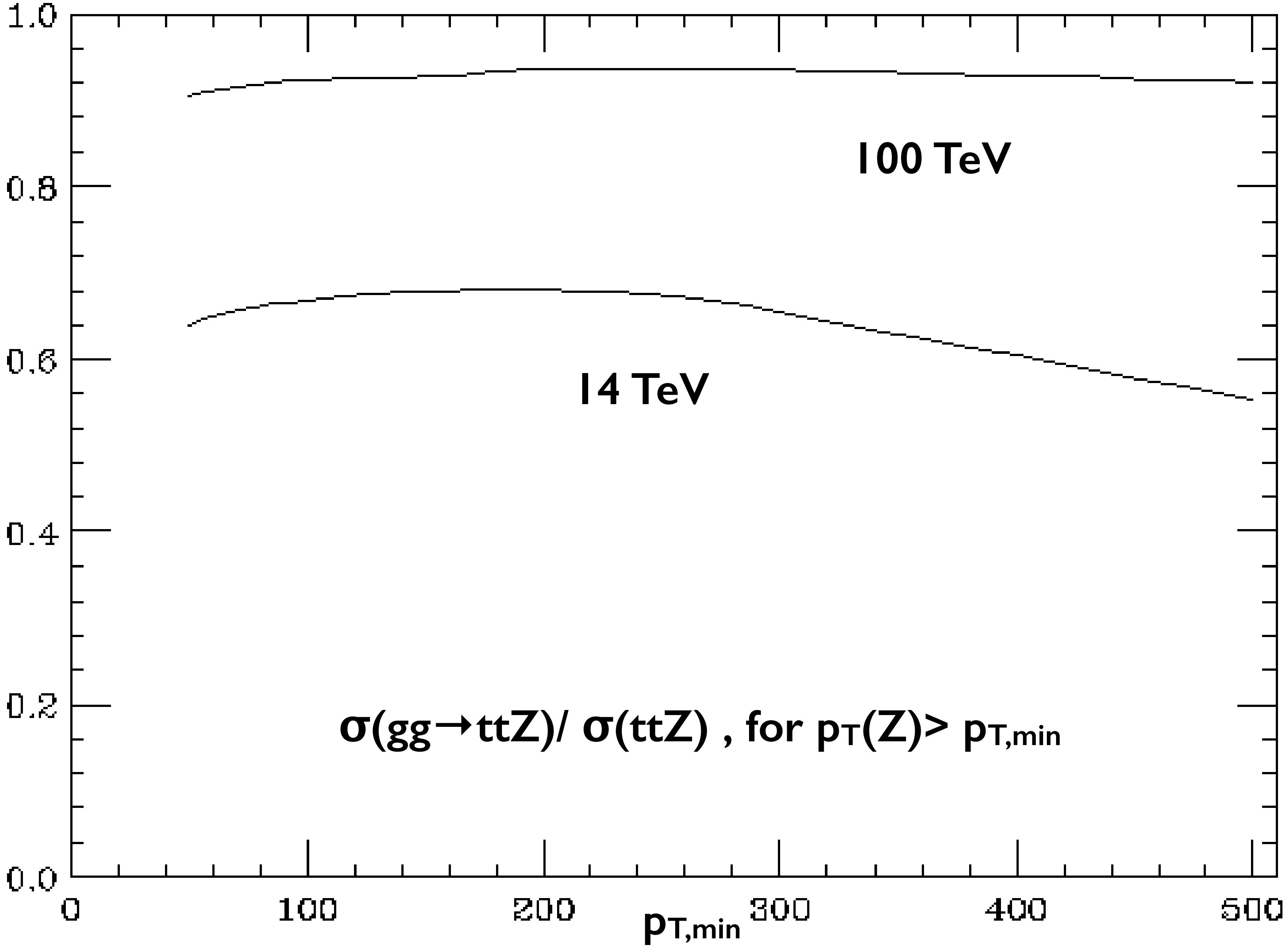
  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

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

  o correlated PDF systematics
  o correlated m_{top} systematics

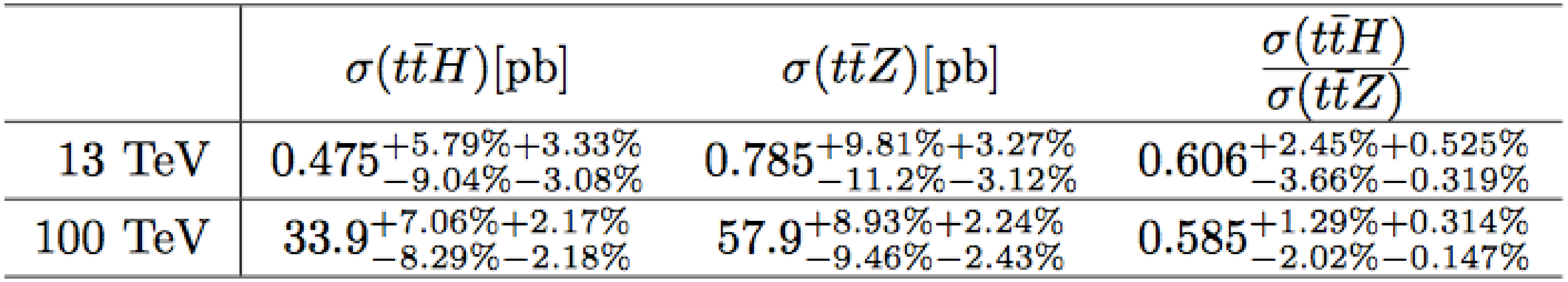
For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

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 $m_Z<m_H$

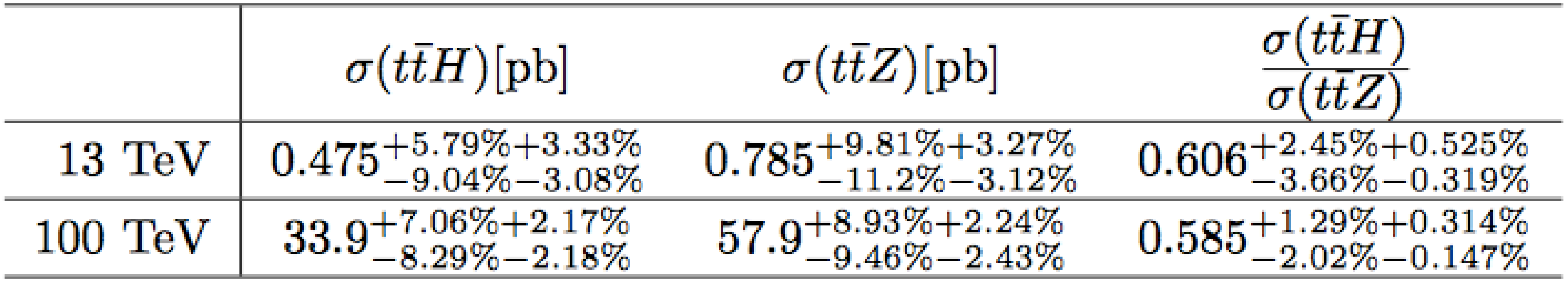
Cross section ratio stability



	$\sigma(t\bar{t}H)$[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

Cross section ratio stability



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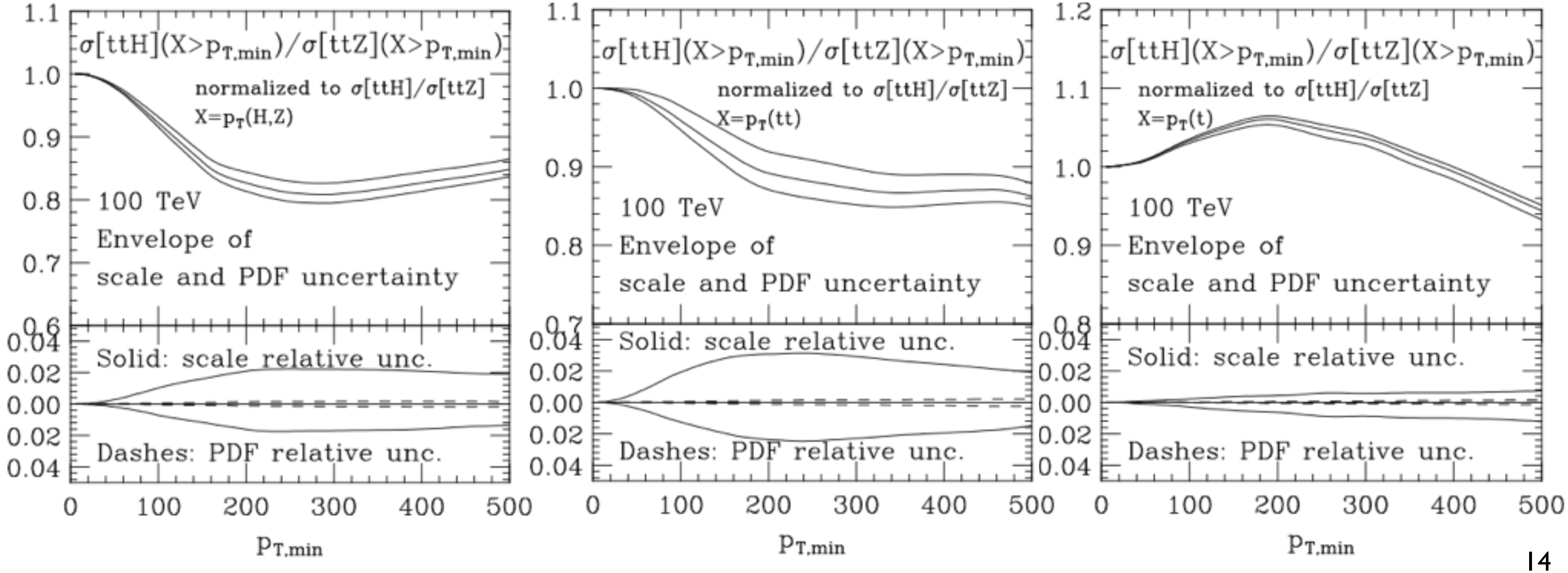
↑ scale ↑ PDF

Production kinematics ratio stability



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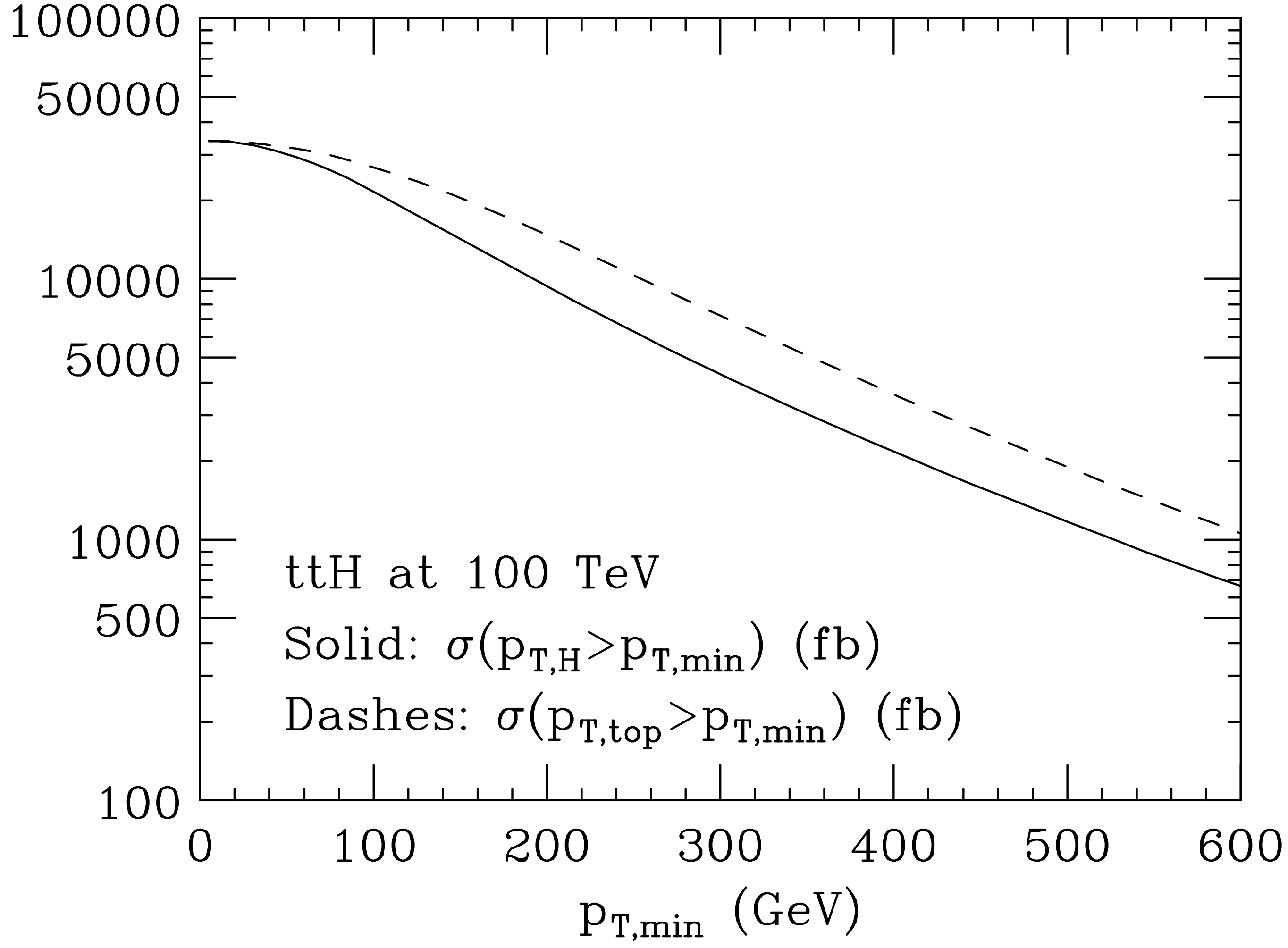
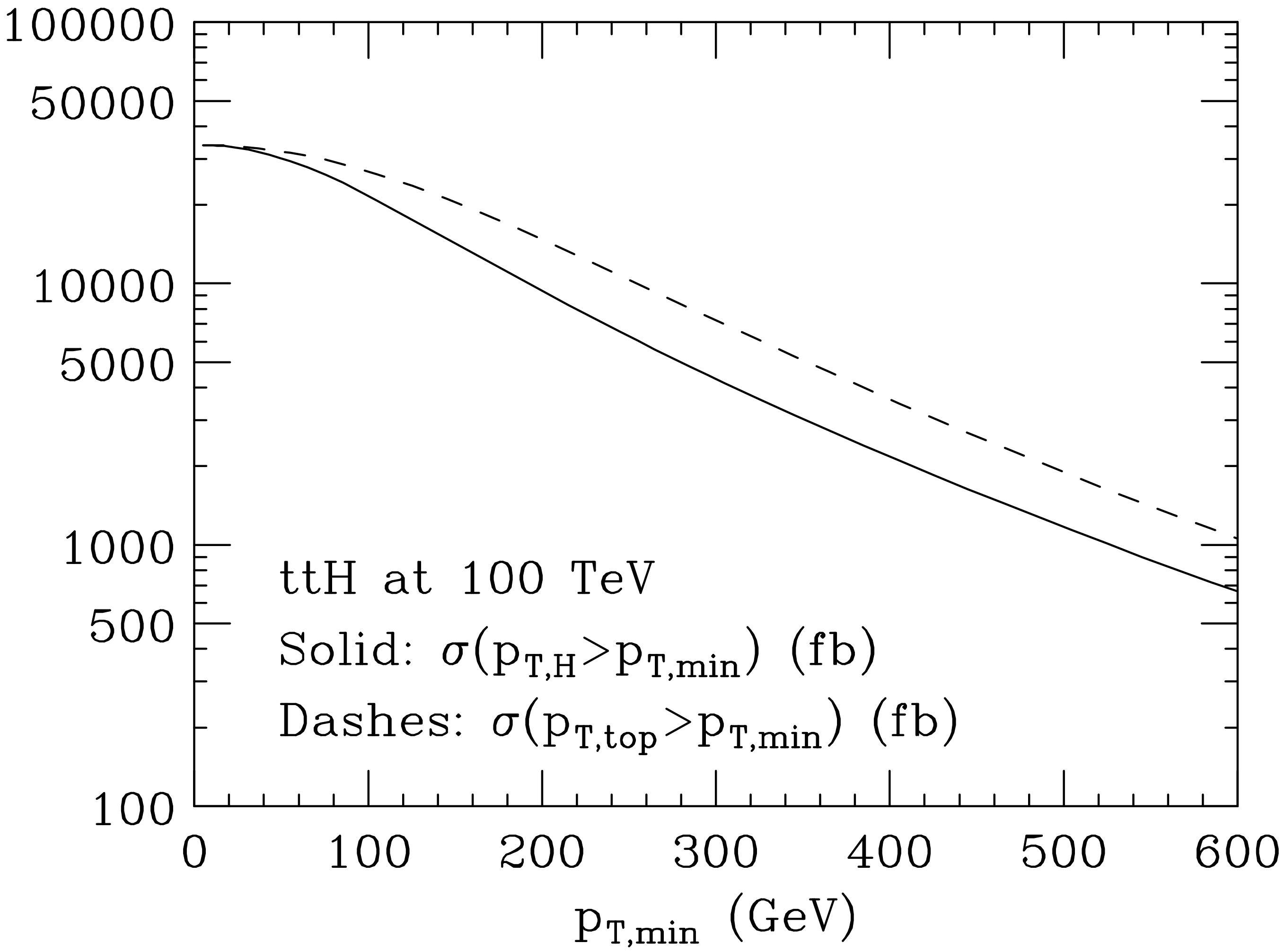


$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

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

⇒ huge rates, exploit boosted topologies arXiv:1507.08169



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

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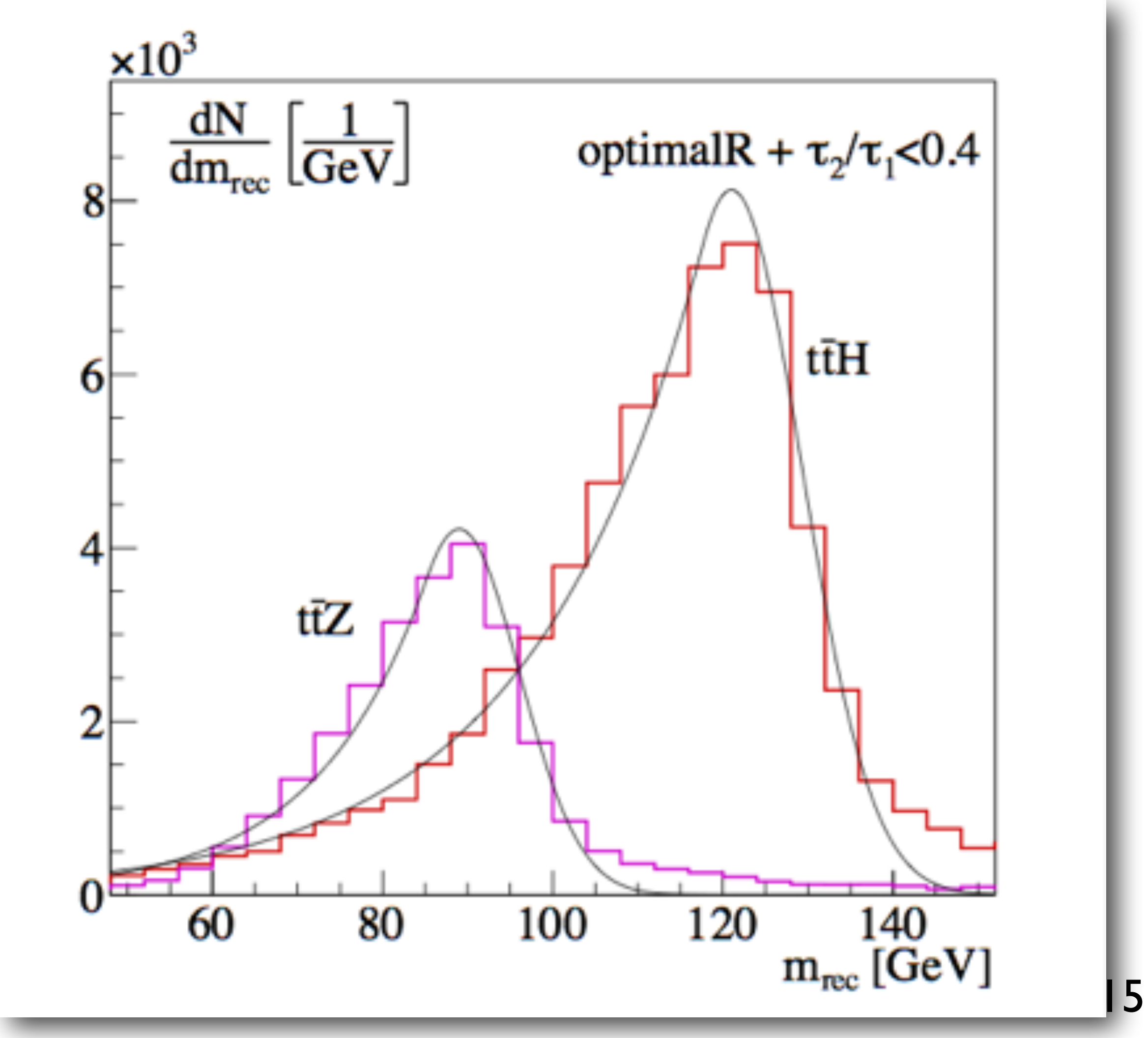
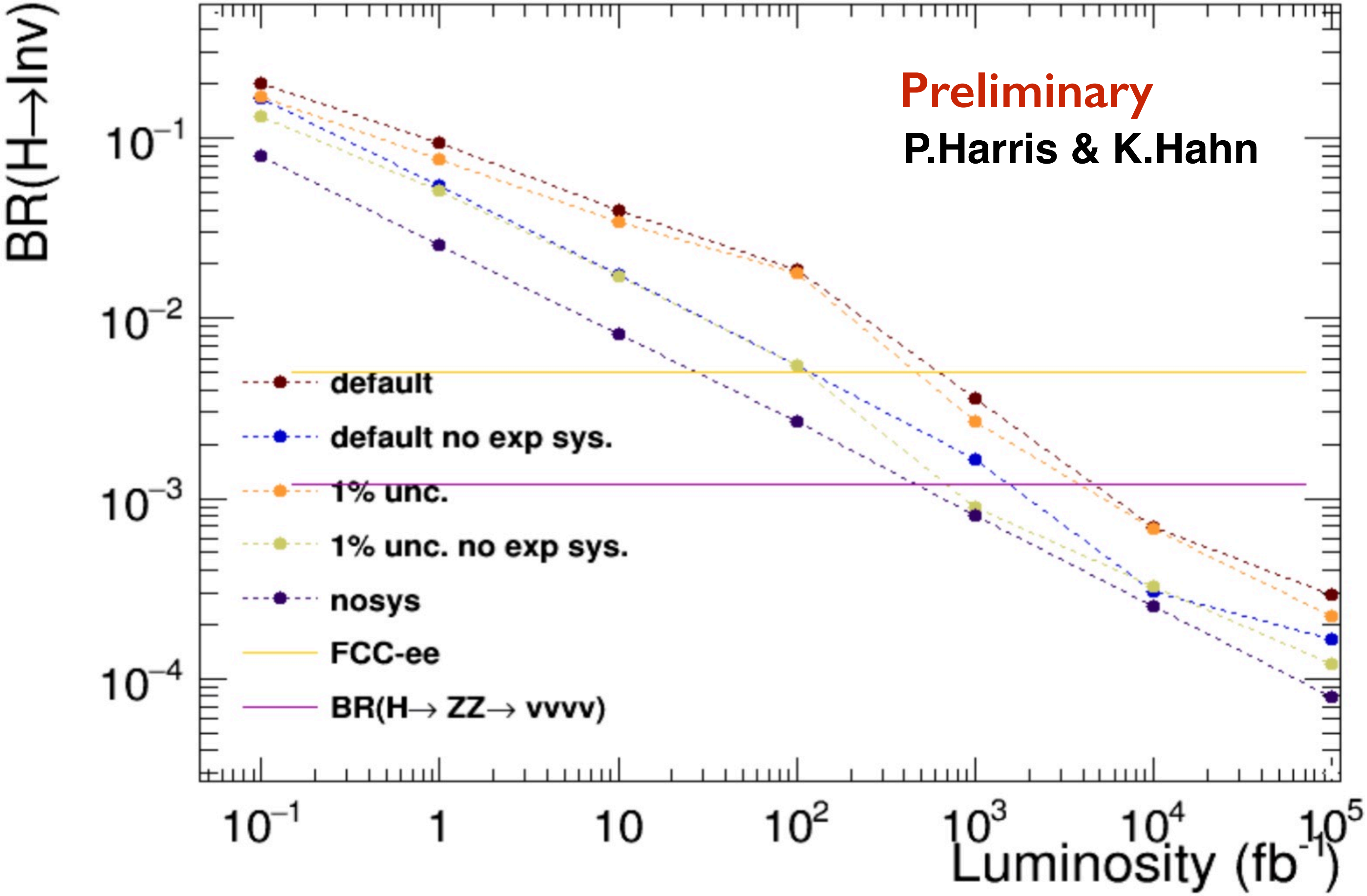


BR(H→inv) in H+X production at large $p_T(H)$

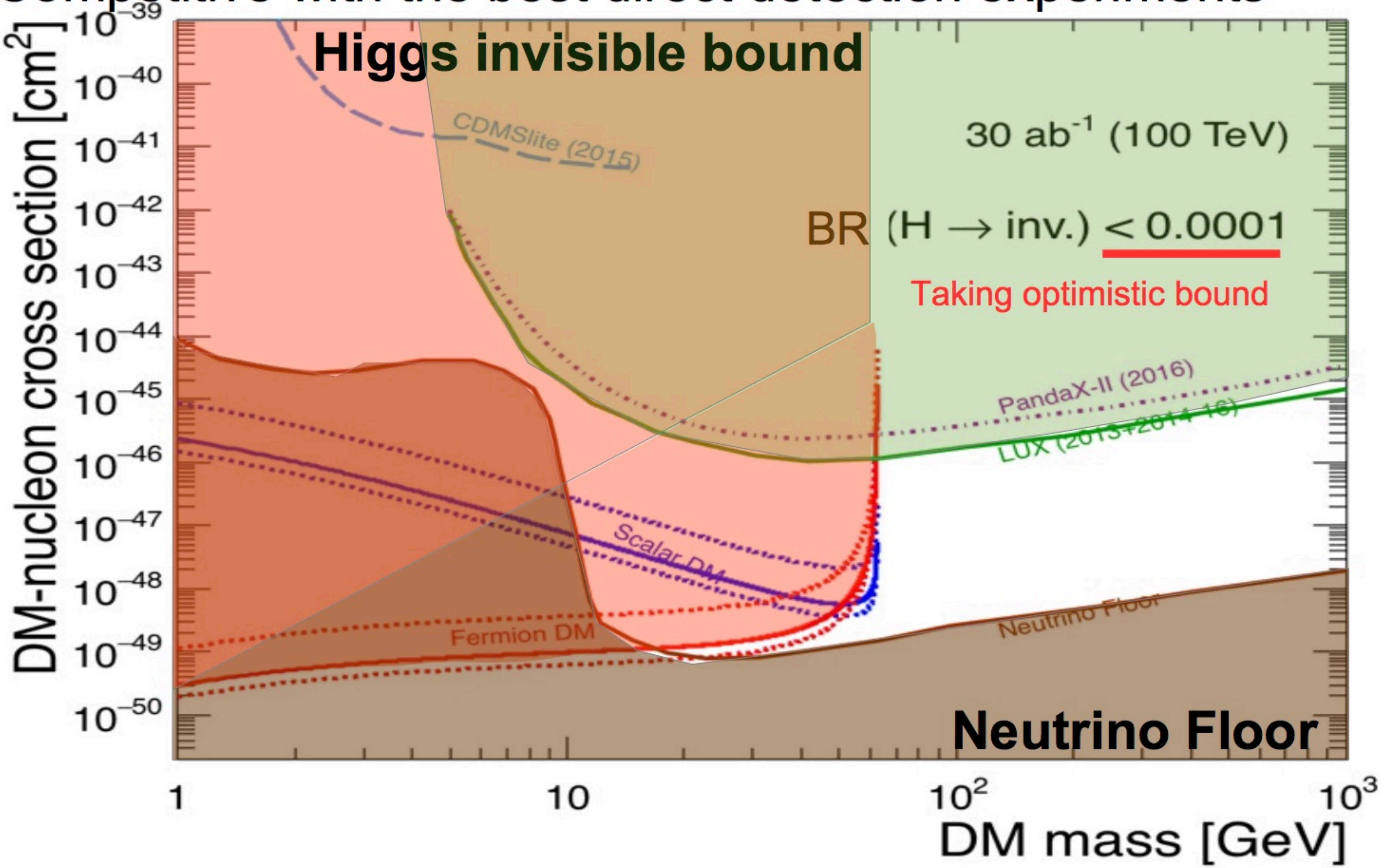
Constrain bg pt spectrum from Z→νν to the % level using
NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



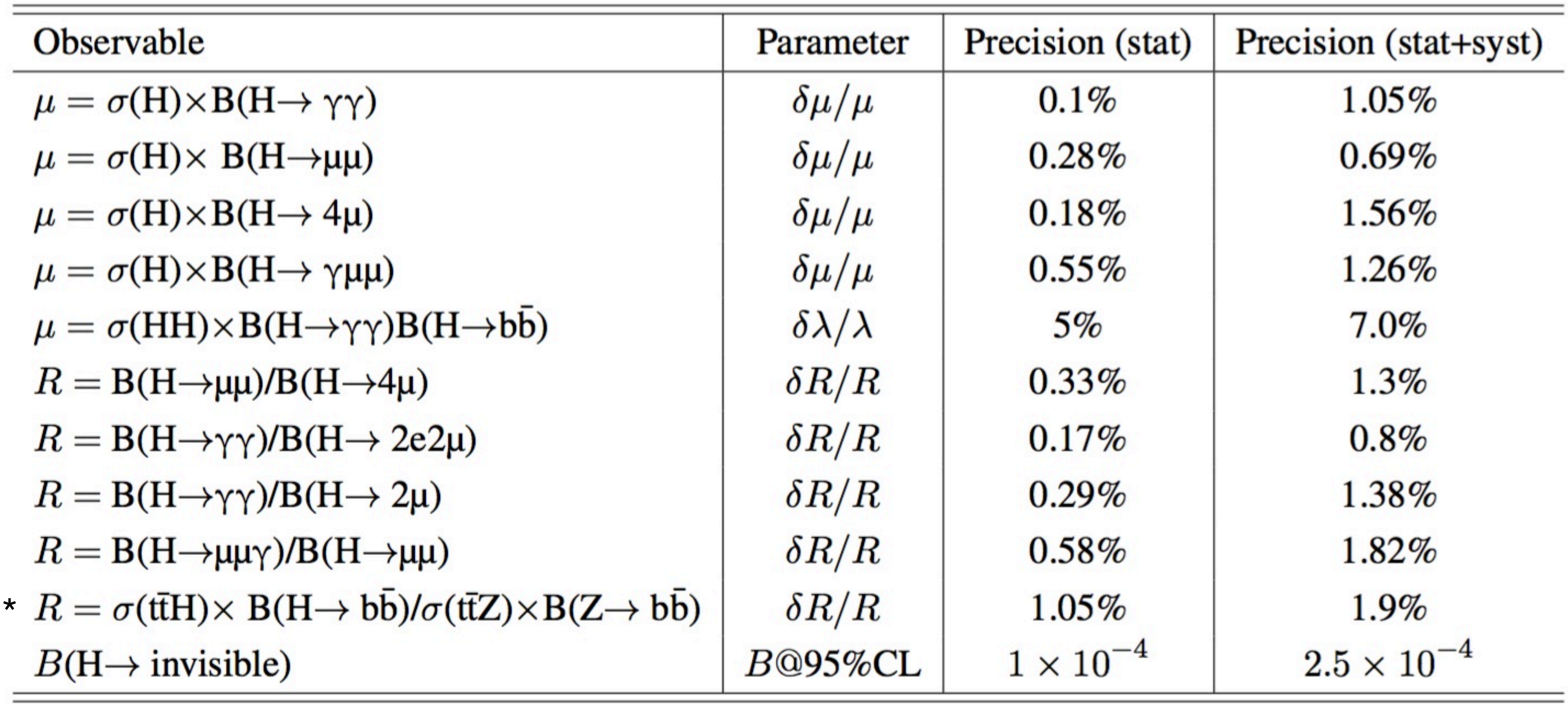
SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

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}



	Observable	Parameter	Precision (stat)	Precision (stat+syst)
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.05%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta\mu/\mu$	0.28%	0.69%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.56%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.26%
	$\mu = \sigma(\mathrm{HH})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)\mathrm{B}(\mathrm{H}\to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
*	$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
*	$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
*	$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
*	$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.82%
**	$R = \sigma(t\bar{t}\mathrm{H})\times\mathrm{B}(\mathrm{H}\to b\bar{b})/\sigma(t\bar{t}\mathrm{Z})\times\mathrm{B}(\mathrm{Z}\to b\bar{b})$	$\delta R/R$	1.05%	1.9%
	$B(\mathrm{H}\to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

* Measurements of ratios of BRs, combined with the absolute measurement of the HZZ coupling at FCC-ee, will yield absolute coupling measurements in FCC-hh

** Will use results from FCC-ee: BR(H->bb), ttZ EW coupling

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

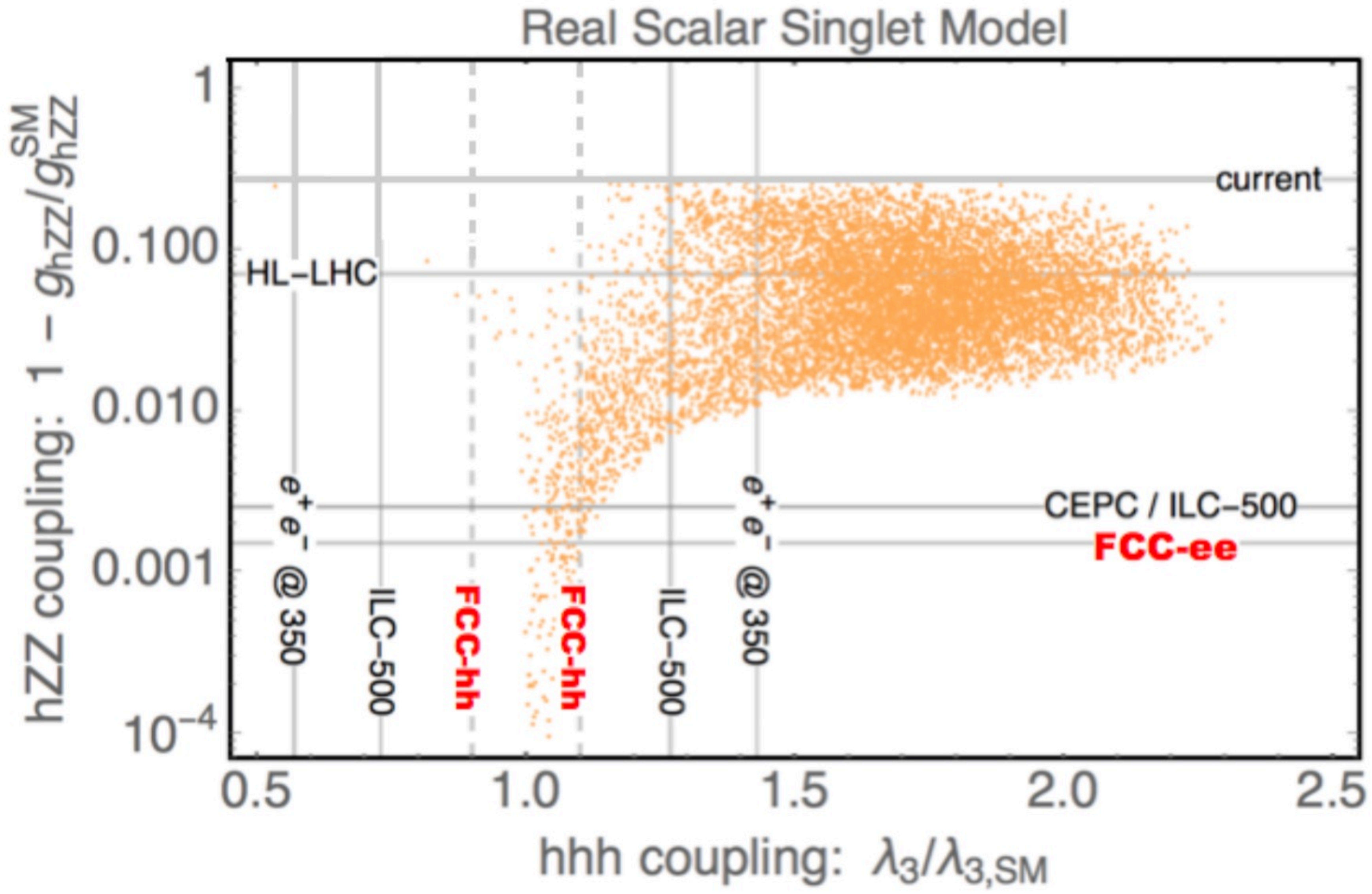
BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

H selfcoupling measurements: constraints on models with 1st order phase transition



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

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

$$\boxed{L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots}$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

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. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\, \langle f | L | i \rangle \,|^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots \right]$$

For H decays, or inclusive production, μ~O(v,m_H)

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

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e.g. δO=1% ⇒ Λ ~ 2.5 TeV

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. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

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Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

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

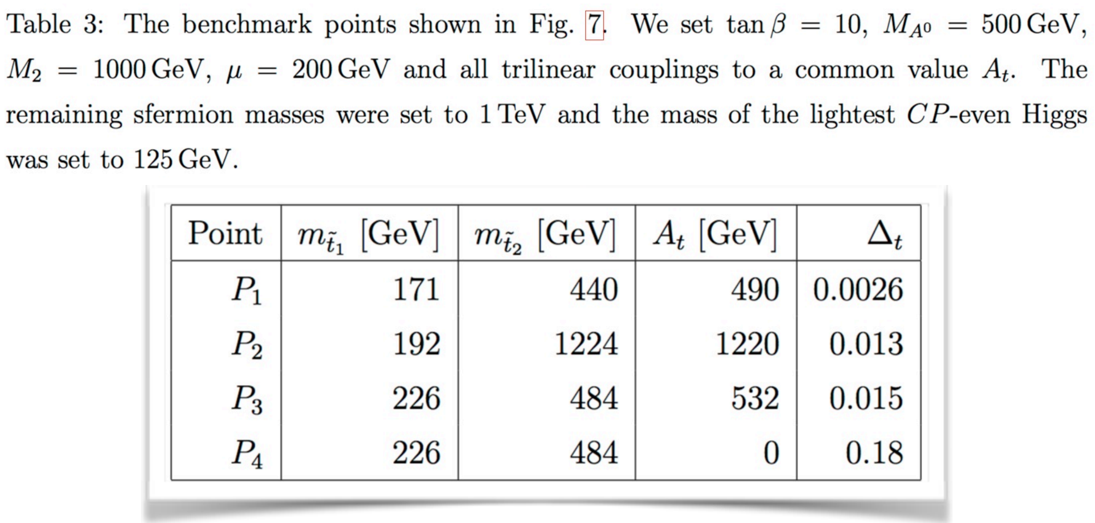
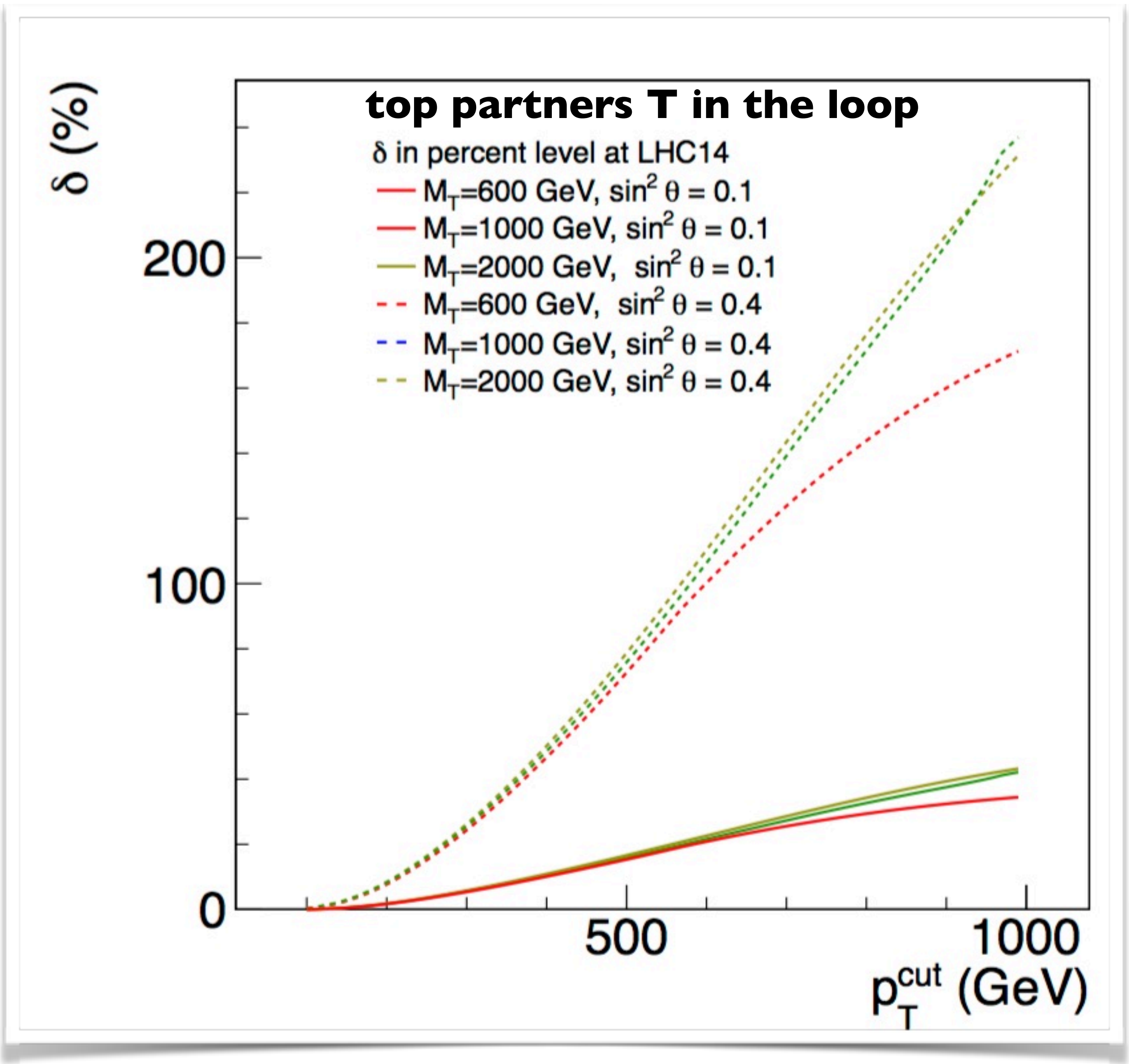


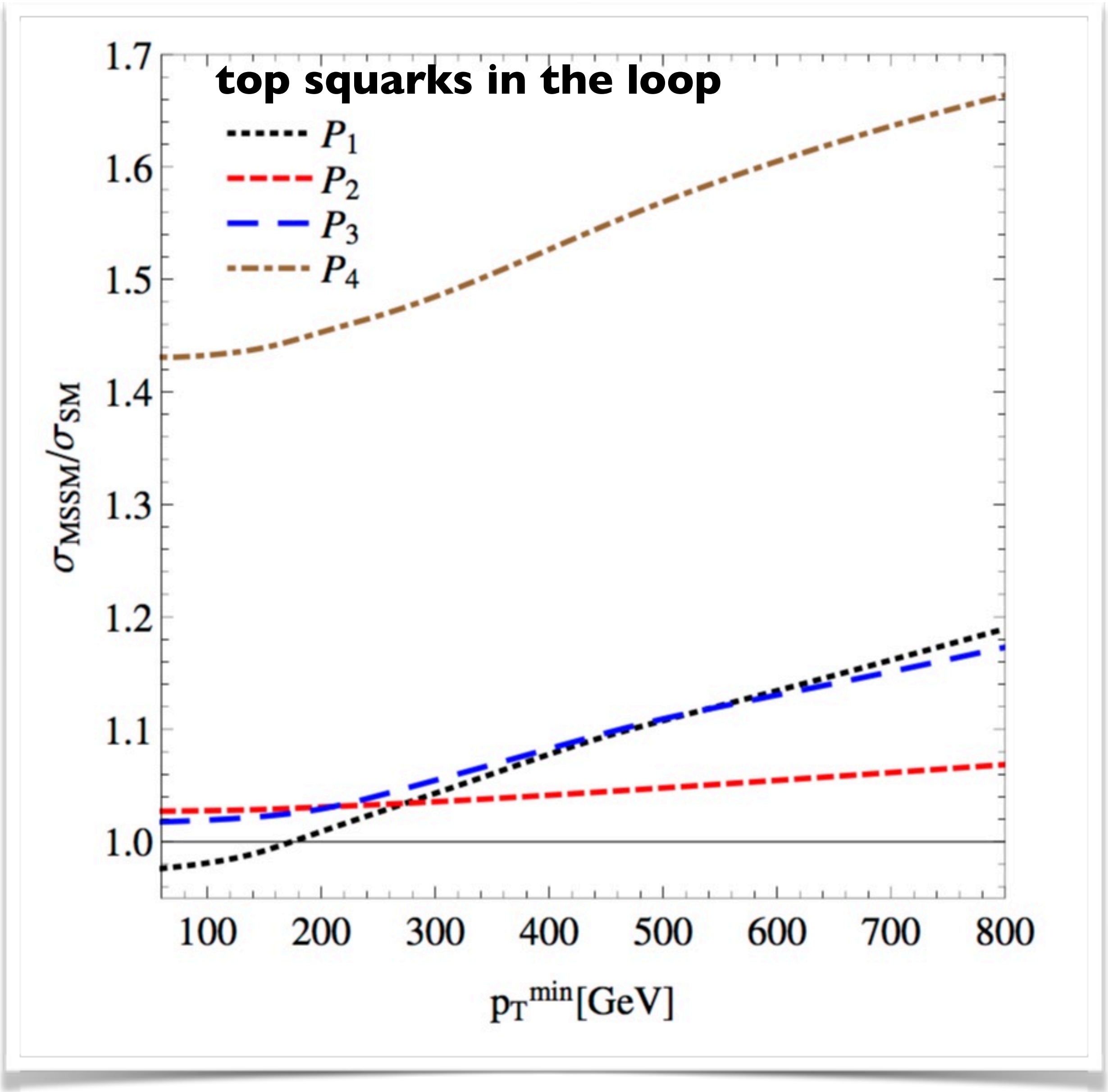
Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\text{GeV}$, $M_2 = 1000\,\text{GeV}$, $\mu = 200\,\text{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was set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

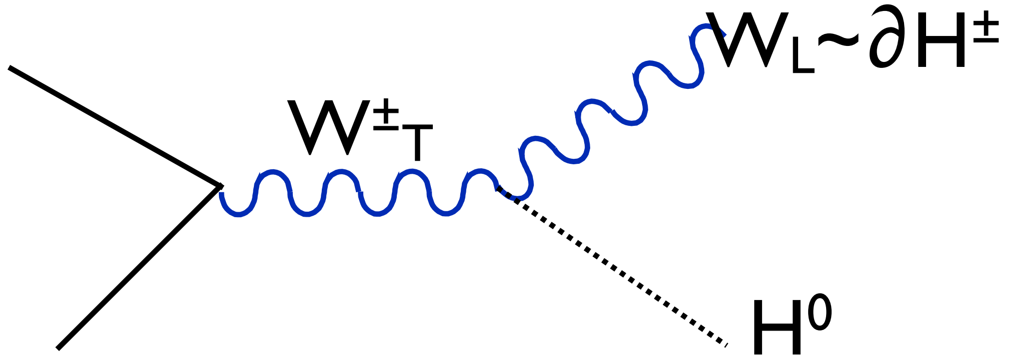


Banfi Martin Sanz, arXiv:1308.4771



Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

VH prodution at large m(VH)

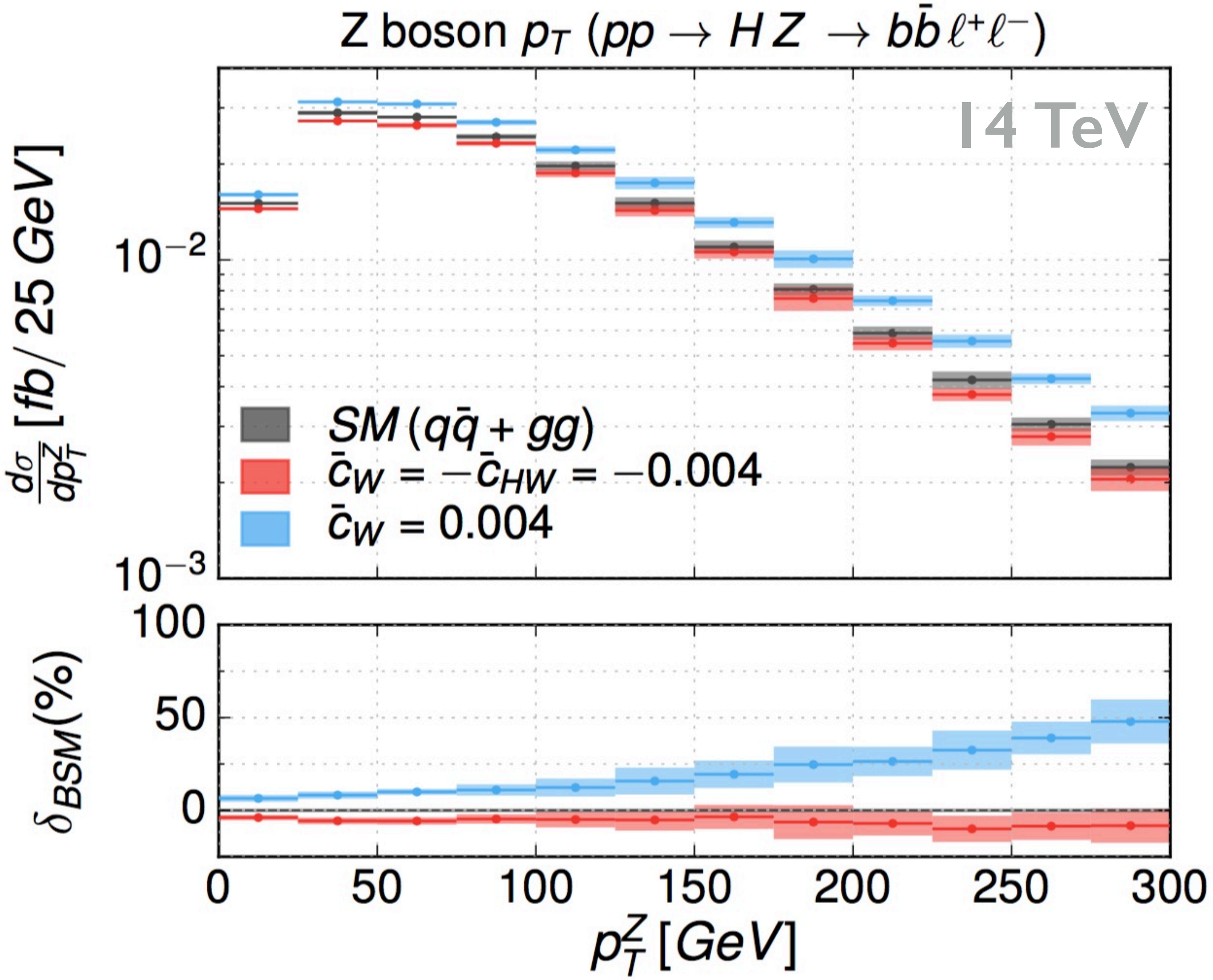


See e.g.
Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320

In presence of a higher-dim op such as:

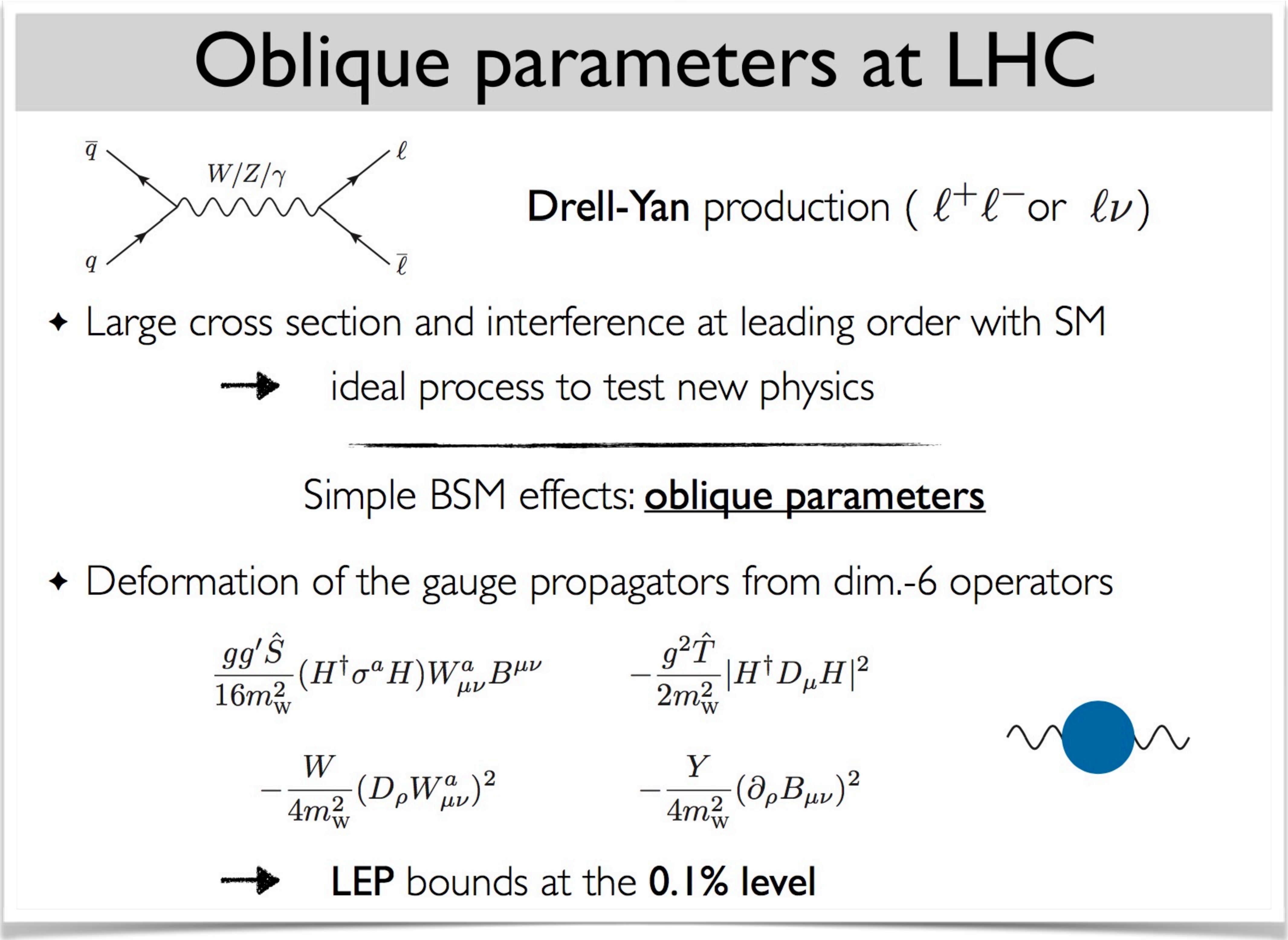
$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

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



Mimasu, Sanz, Williams, arXiv:1512.02572v

Example of indirect sensitivity from high-Q^2 EW observables



Oblique parameters at LHC

Drell-Yan production ($\ell^+\ell^-$or $\ell\nu$)

- Large cross section and interference at leading order with SM

→ ideal process to test new physics

Simple BSM effects: **oblique parameters**

- Deformation of the gauge propagators from dim.-6 operators

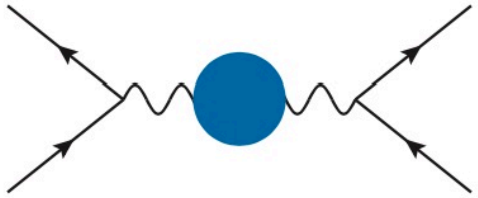
$$\frac{gg'\hat{S}}{16m_{\rm W}^2}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \qquad -\frac{g^2\hat{T}}{2m_{\rm W}^2}|H^\dagger D_\mu H|^2$$

$$-\frac{W}{4m_{\rm W}^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{Y}{4m_{\rm W}^2}(\partial_\rho B_{\mu\nu})^2$$

→ **LEP** bounds at the **0.1% level**

Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer arXiv:1609.08157

Oblique parameters at LHC



Drell-Yan production ($\ell^+\ell^-$or $\ell\nu$)

Simple BSM effects: **oblique parameters**

$$P_{\rm N} = \begin{bmatrix} \frac{1}{q^2} - \frac{t_{\rm W}^2 W + Y}{m_{\rm Z}^2} & \frac{t_{\rm W}((Y+\hat{T})c_{\rm W}^2 + s_{\rm W}^2 W - \hat{S})}{(c_{\rm W}^2 - s_{\rm W}^2)(q^2 - m_{\rm Z}^2)} + \frac{t_{\rm W}(Y-W)}{m_{\rm Z}^2} \\ \star & \frac{1+\hat{T}-W-t_{\rm W}^2 Y}{q^2-m_{\rm Z}^2} - \frac{t_{\rm W}^2 Y + W}{m_{\rm Z}^2} \end{bmatrix}$$

$$P_{\rm C} = \frac{1+((\hat{T}-W-t_{\rm W}^2 Y) - 2t_{\rm W}^2(\hat{S}-W-Y))/(1-t_{\rm W}^2)}{q^2-m_{\rm W}^2} - \frac{W}{m_{\rm W}^2}$$

- $\hat{S}$ and $\hat{T}$: only affect pole residues (i.e. total cross-section)
  LHC measurements (% from syst.) **not competitive**
- W and Y: induce constant terms
  quadratically enhanced at high energy

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2\times10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times10^4$	$[-19,3]$	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
Y $\times10^4$	$[-17,4]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	$\sim$ ±0.5	$\sim$ ±0.15

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
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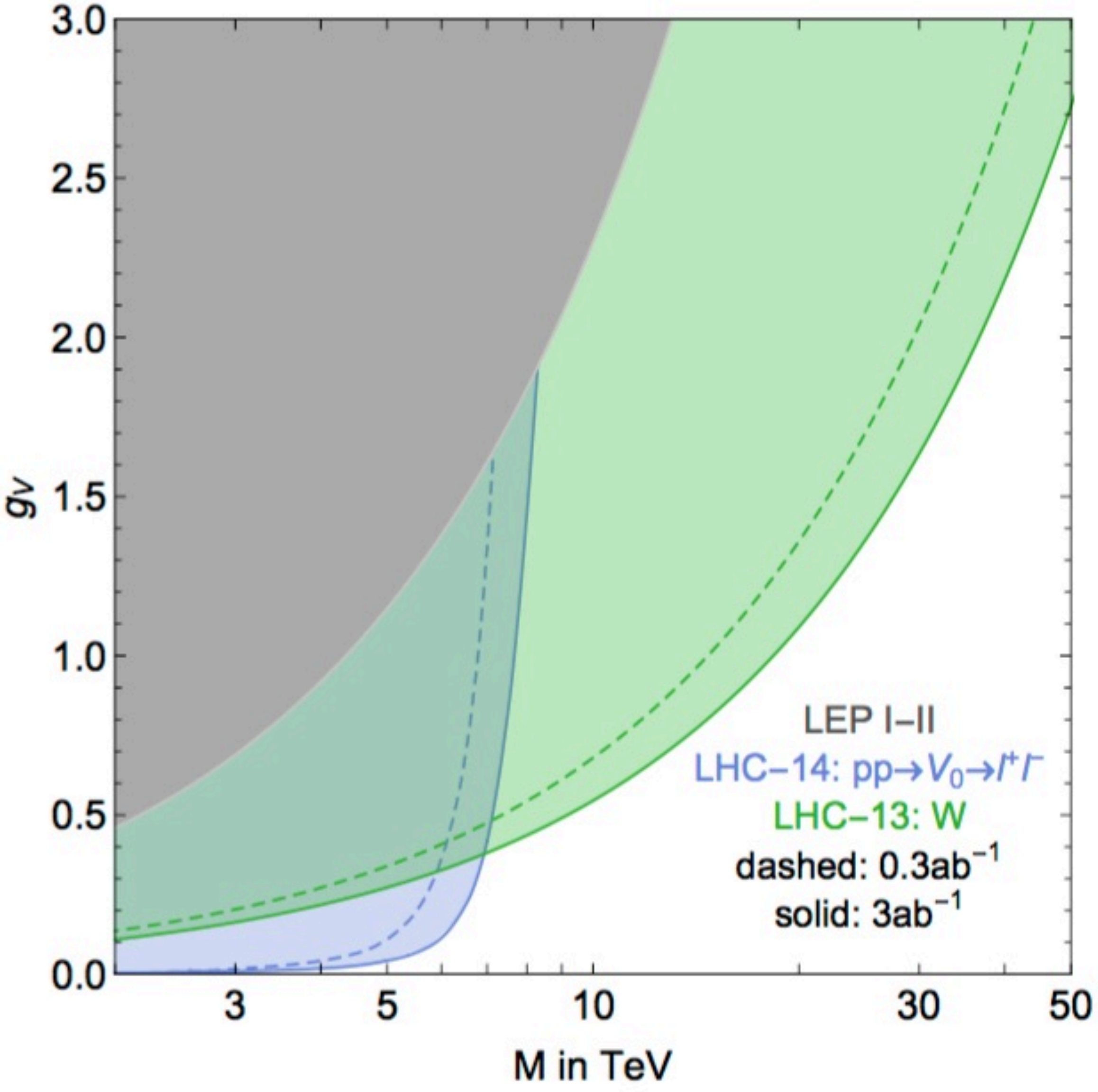
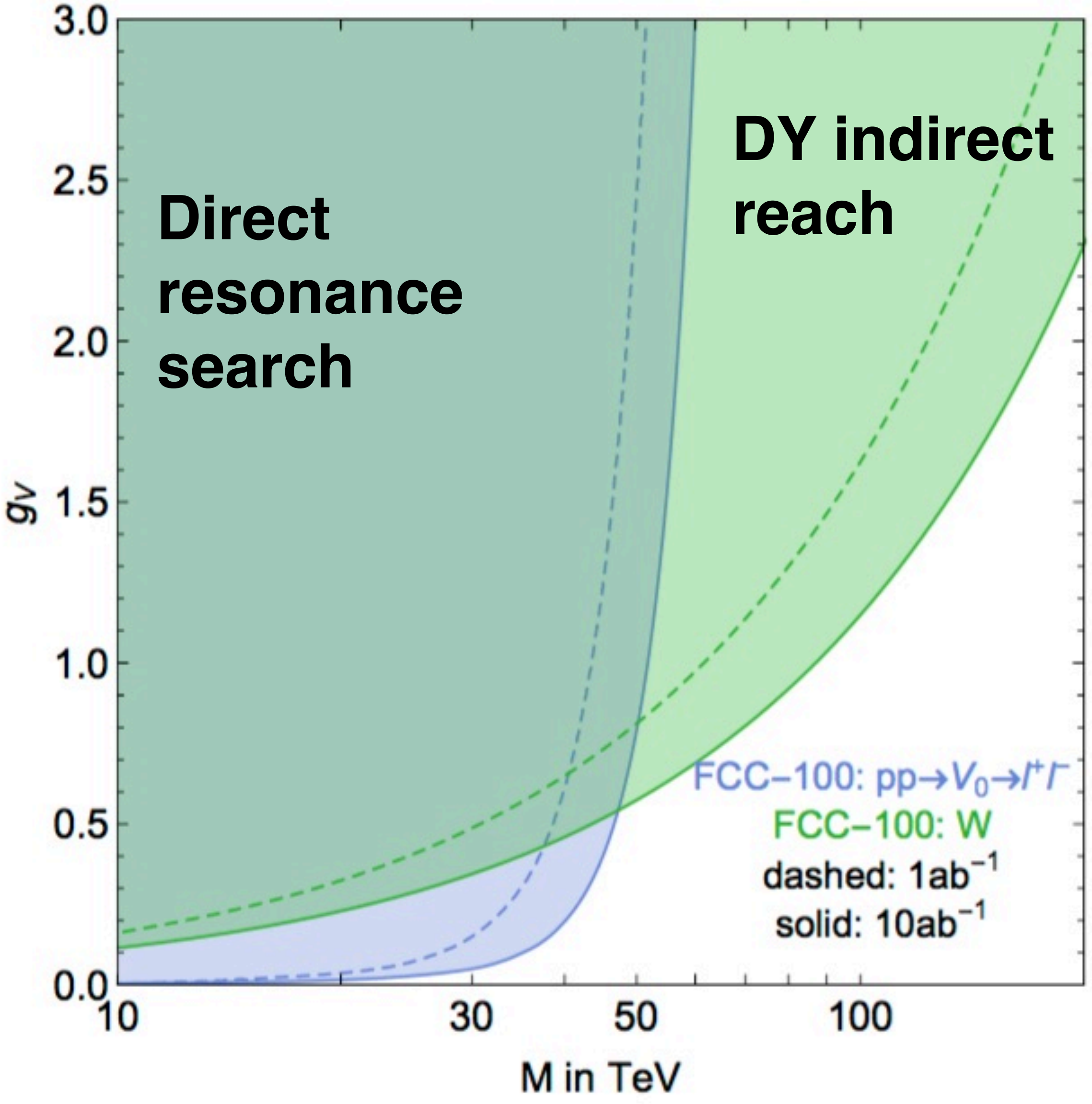
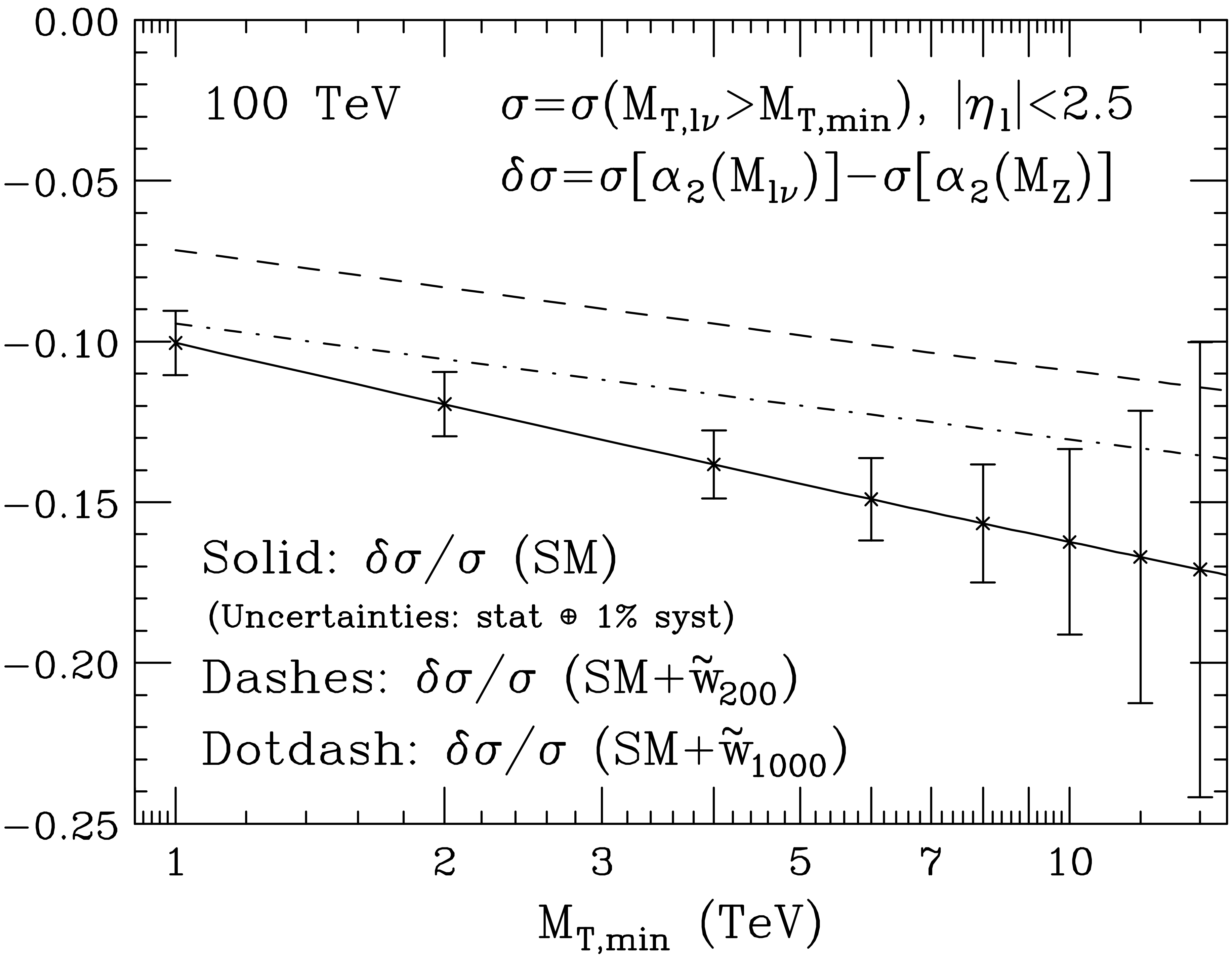




Direct resonance search

DY indirect reach

DY at large mass, the running of α_W



$\tilde{w}$: SU(2) triplet of Majorana fermions (eg SUSY partners of W/Z)

Examples: direct discovery reach

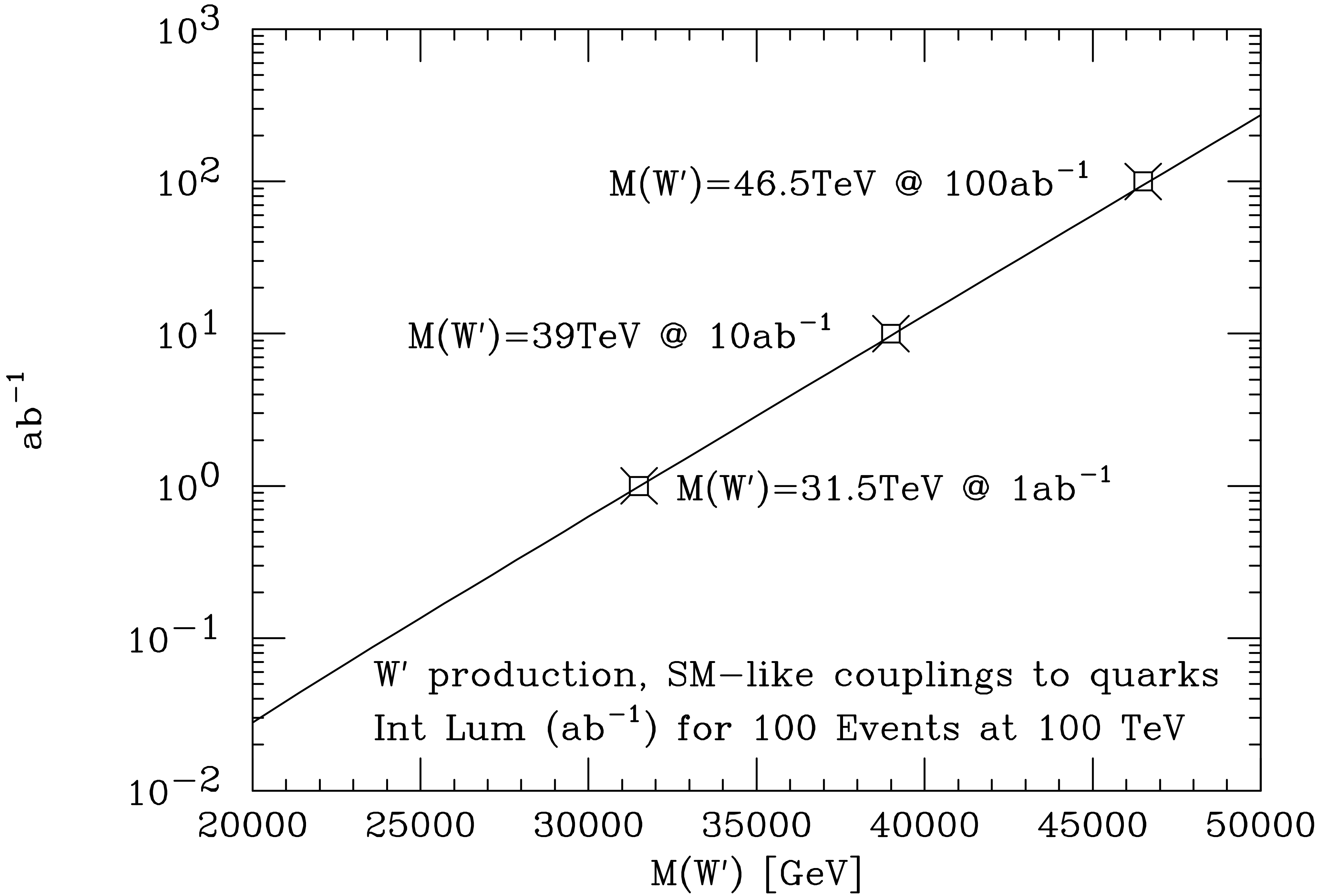
To first approximation, the discovery reach at the highest masses is driven by the energy increase wrt the LHC.

So for $\sqrt{S}$=100 TeV we expect the reach to extend by factors ~5-7 the reach at LHC, for the same BSM particles/parameters

New gauge bosons discovery reach

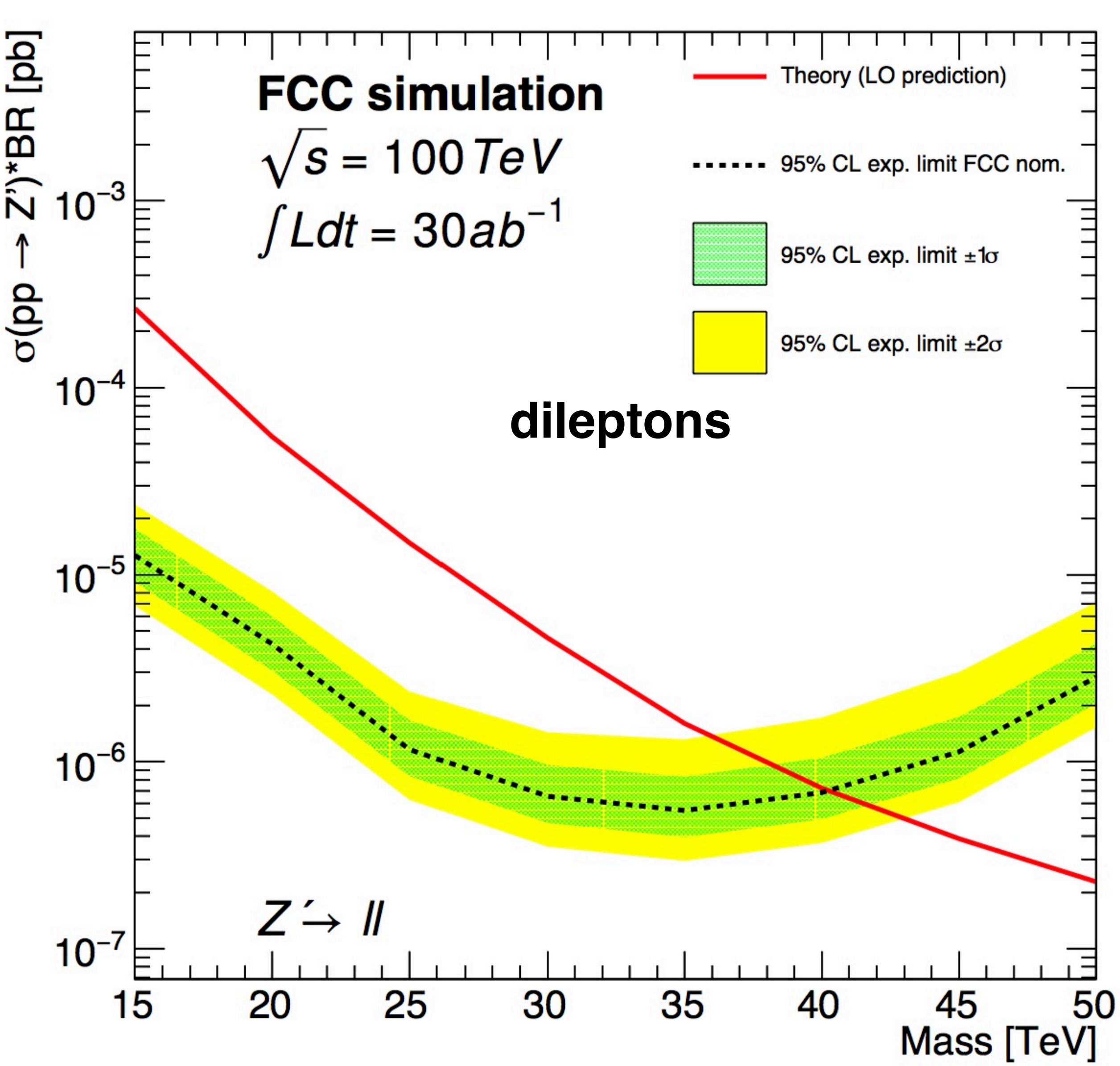
Example: **W’ with SM-like couplings**

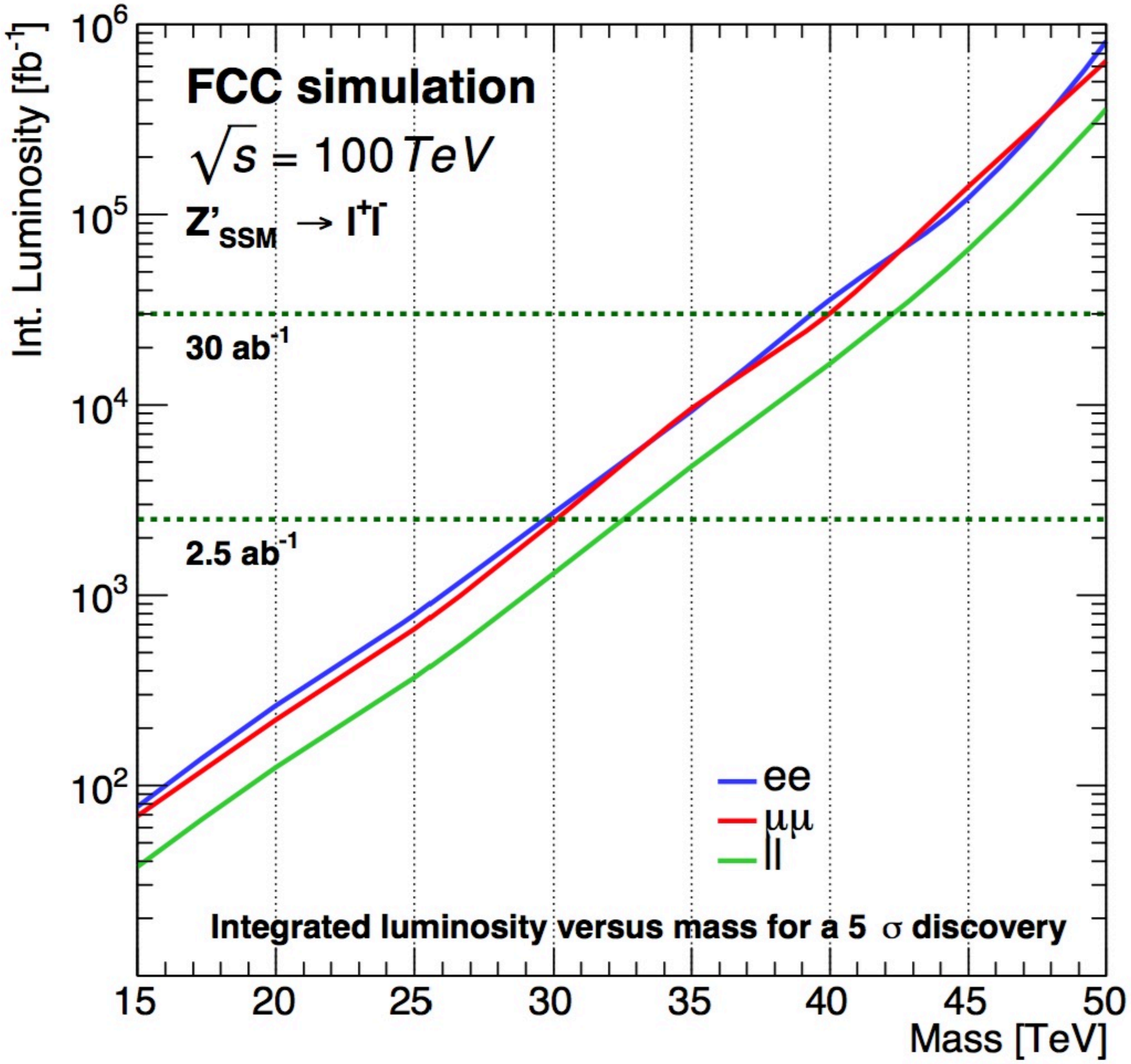
NB For SM-like Z’, $\sigma_{Z'}$ BR_{lept} ~ 0.1 x $\sigma_{W'}$ BR_{lept} , ⇒ rescale lum by ~ 10



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

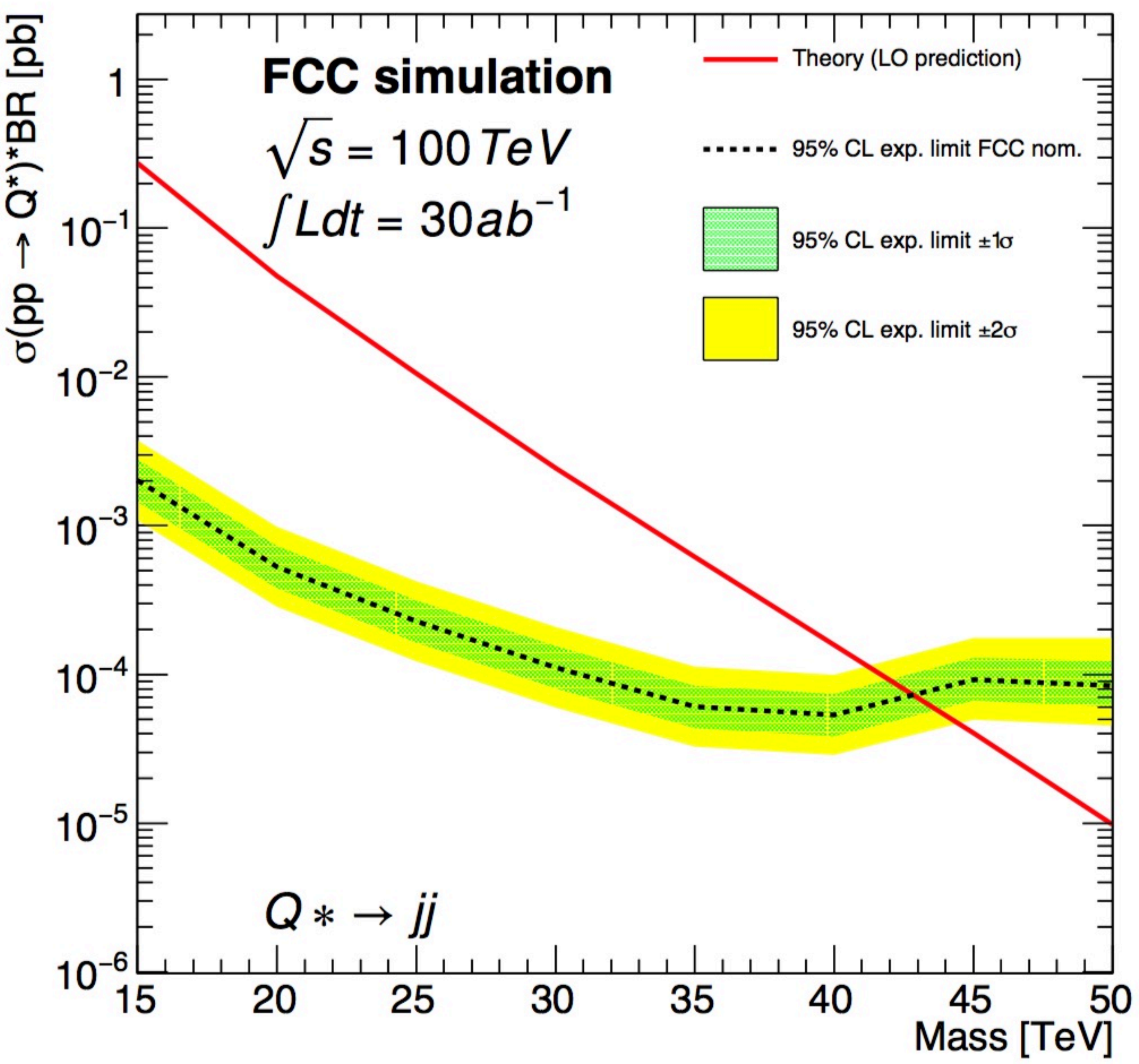
Resonances: SSM Z' to dileptons

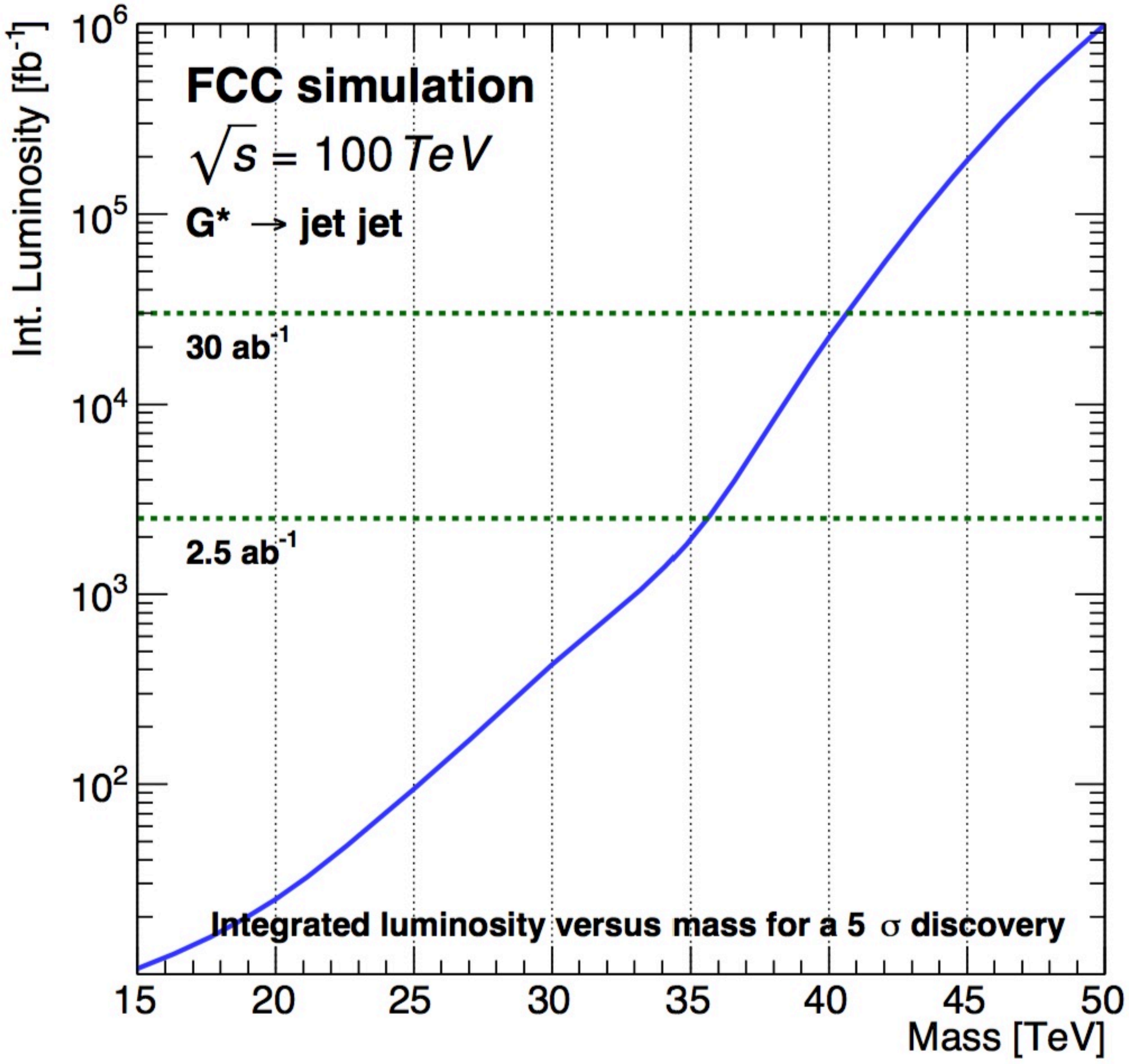




C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

Resonances: colored resonances to dijets





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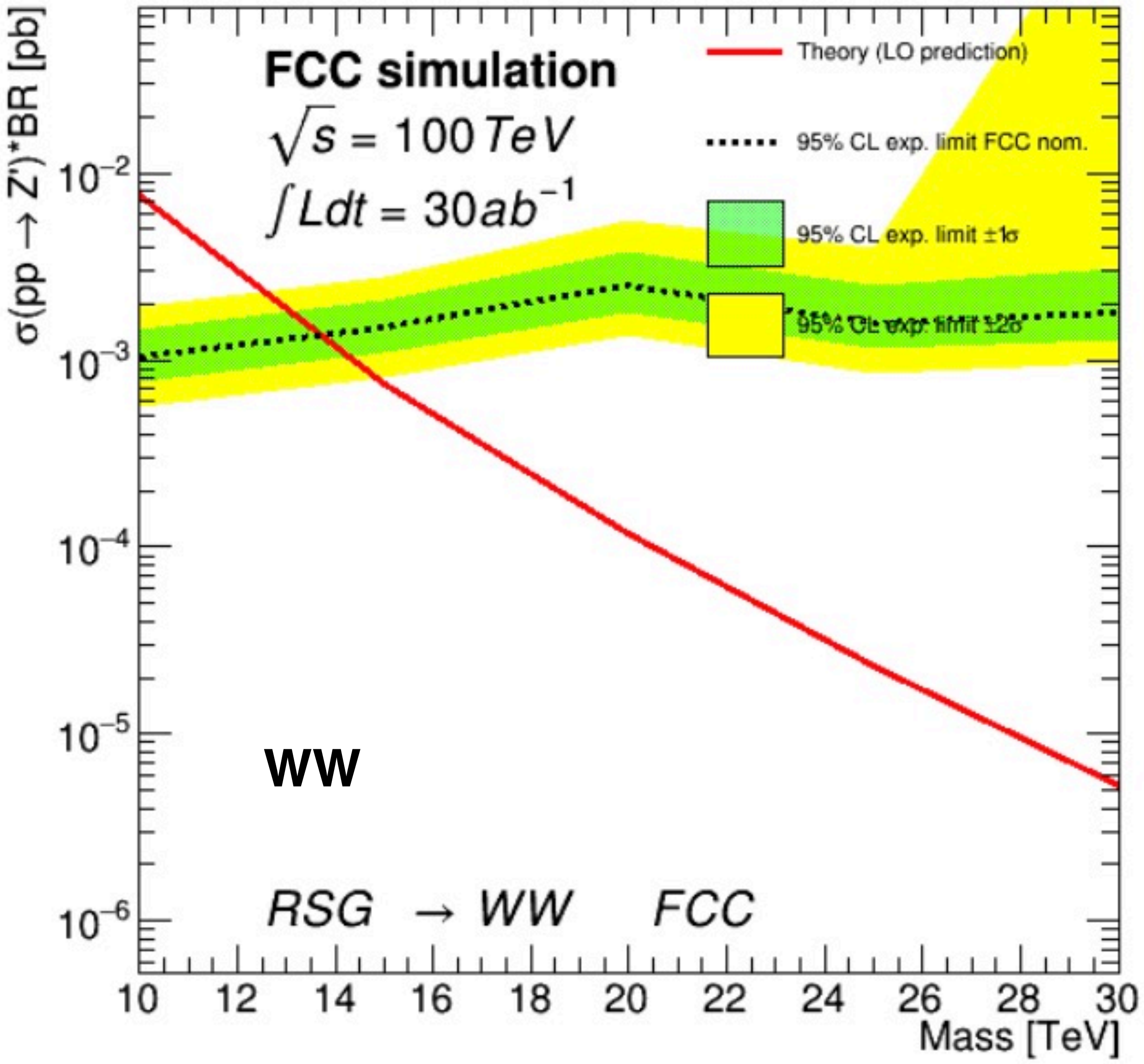
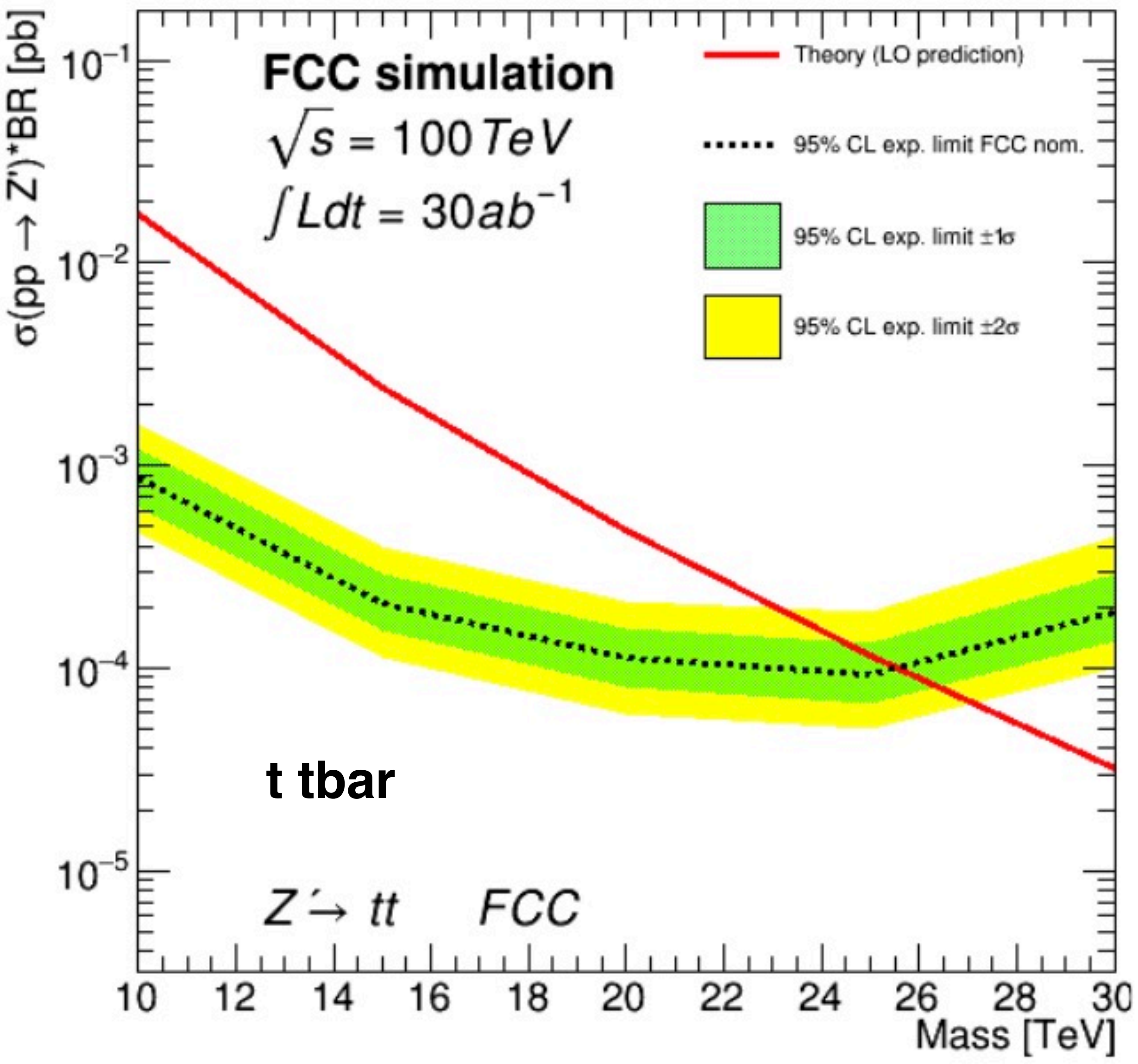
More on resonances





C. Helsens & M. Selvaggi + Summer students
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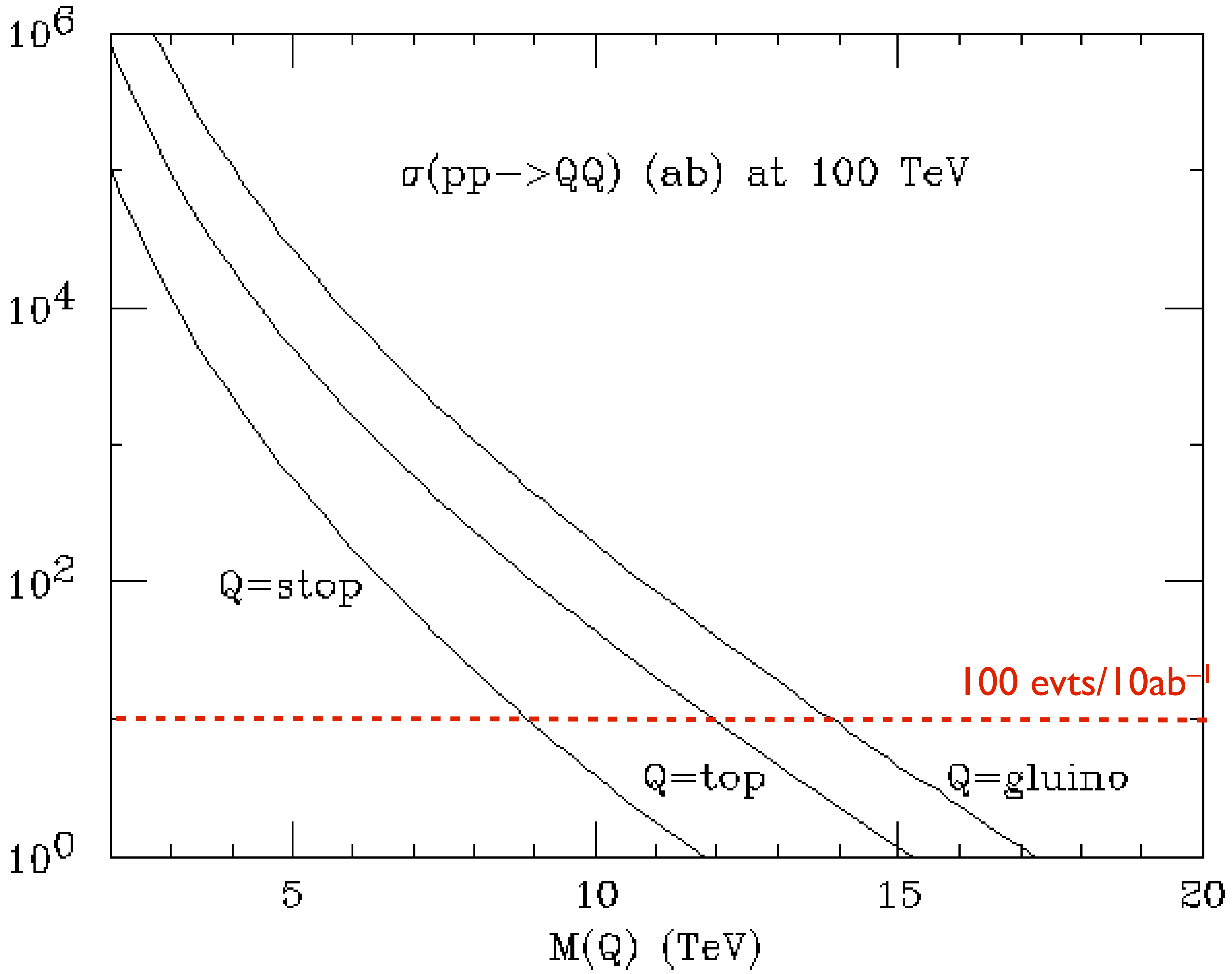
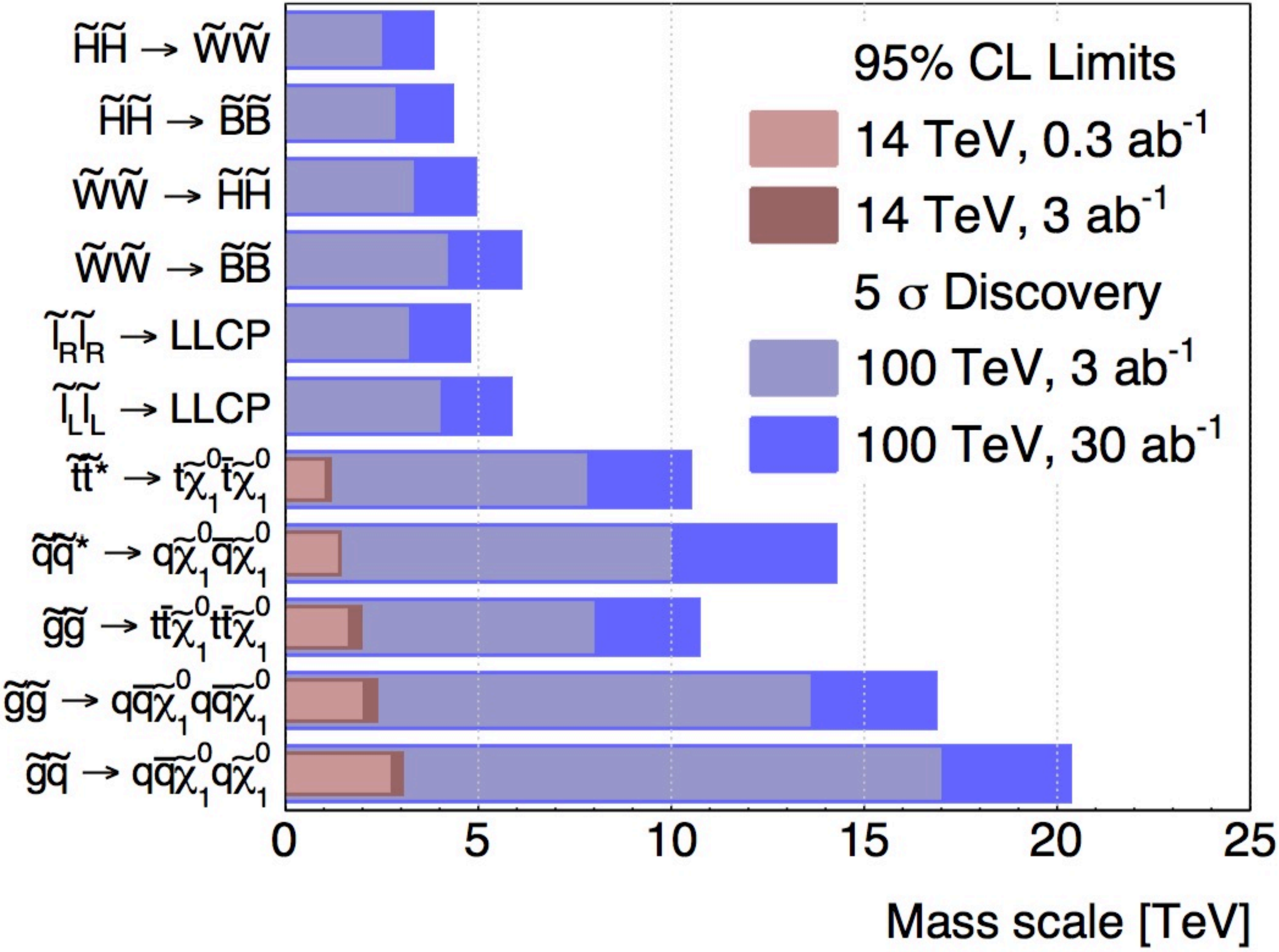
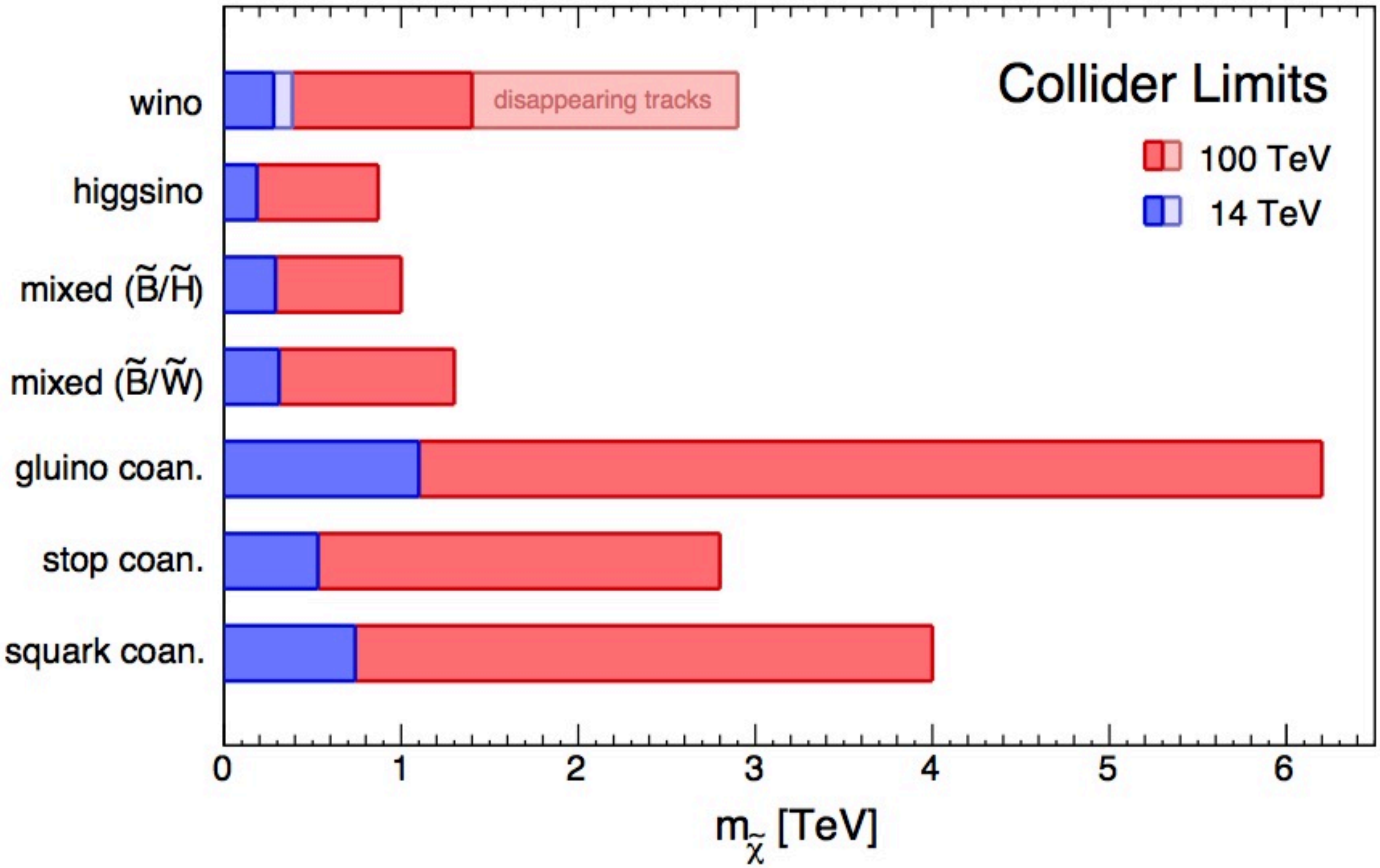
Discovery reach for pair production of strongly-interacting particles



SUSY reach at 100 TeV



DM reach at 100 TeV

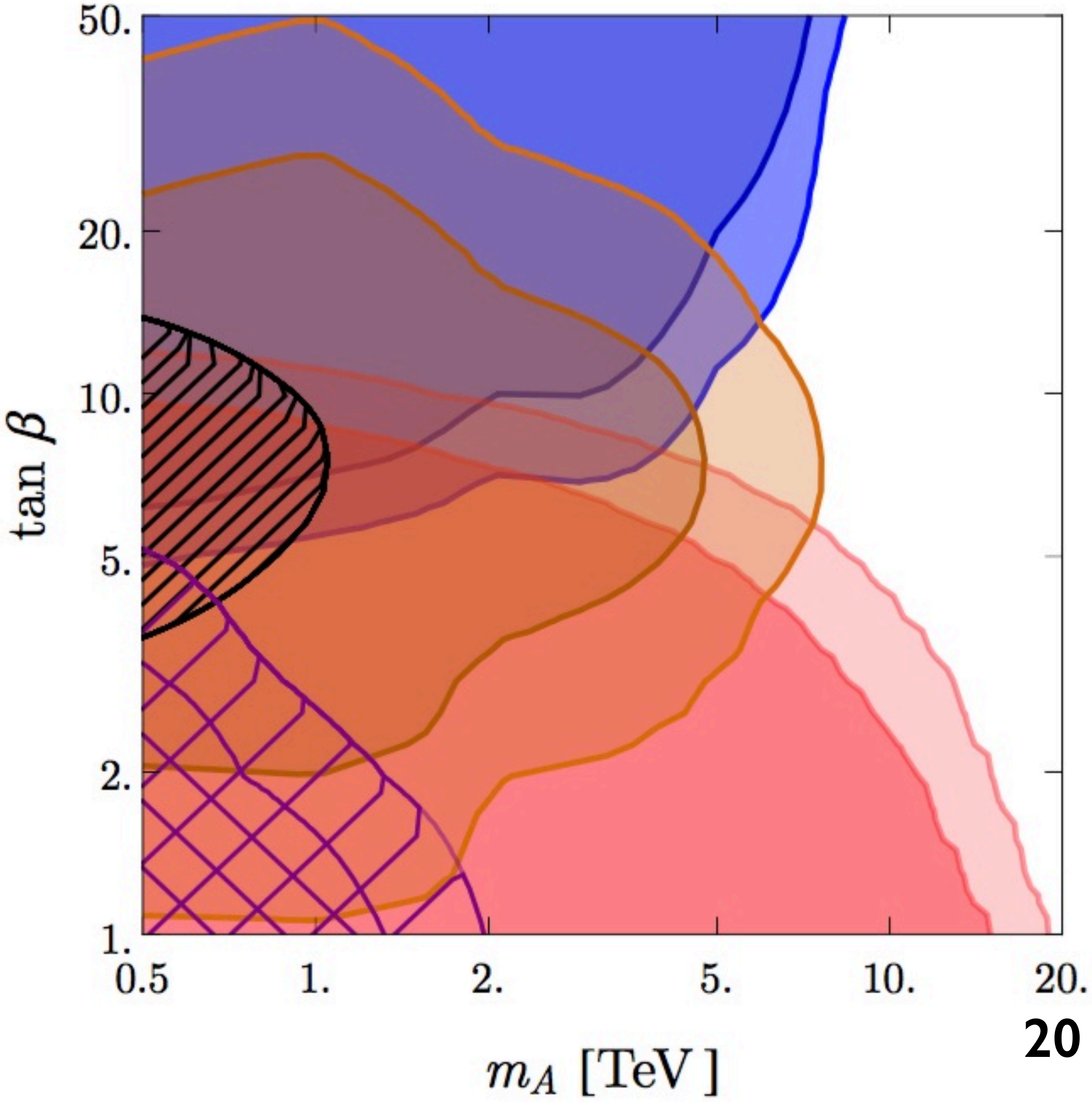


$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\left(\frac{g^2}{0.3}\right)$$

possibility to find (or rule out) thermal WIMP DM candidates

MSSM Higgs @ 100 TeV

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

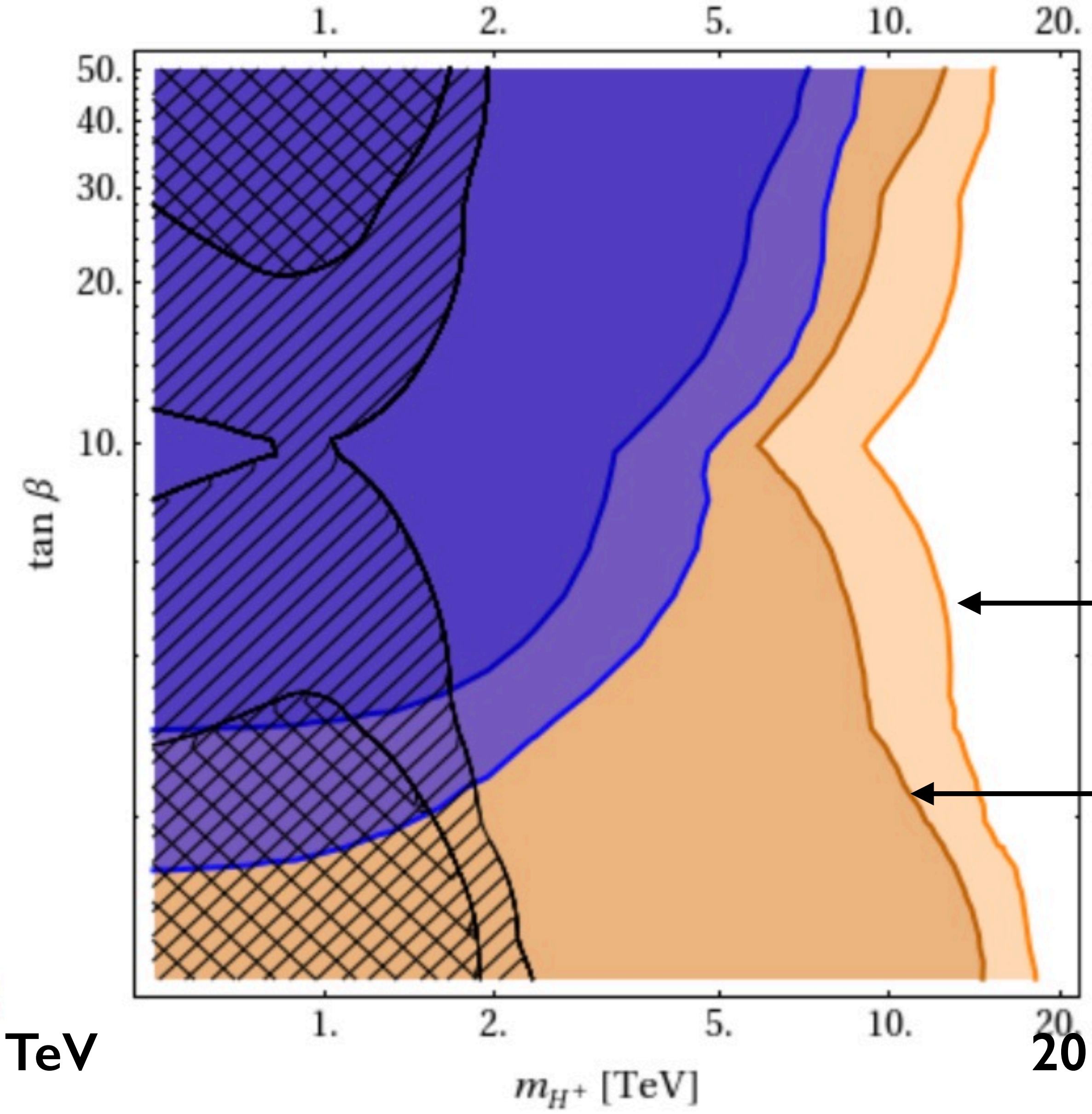


20 TeV

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

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

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



30 ab^{-1}

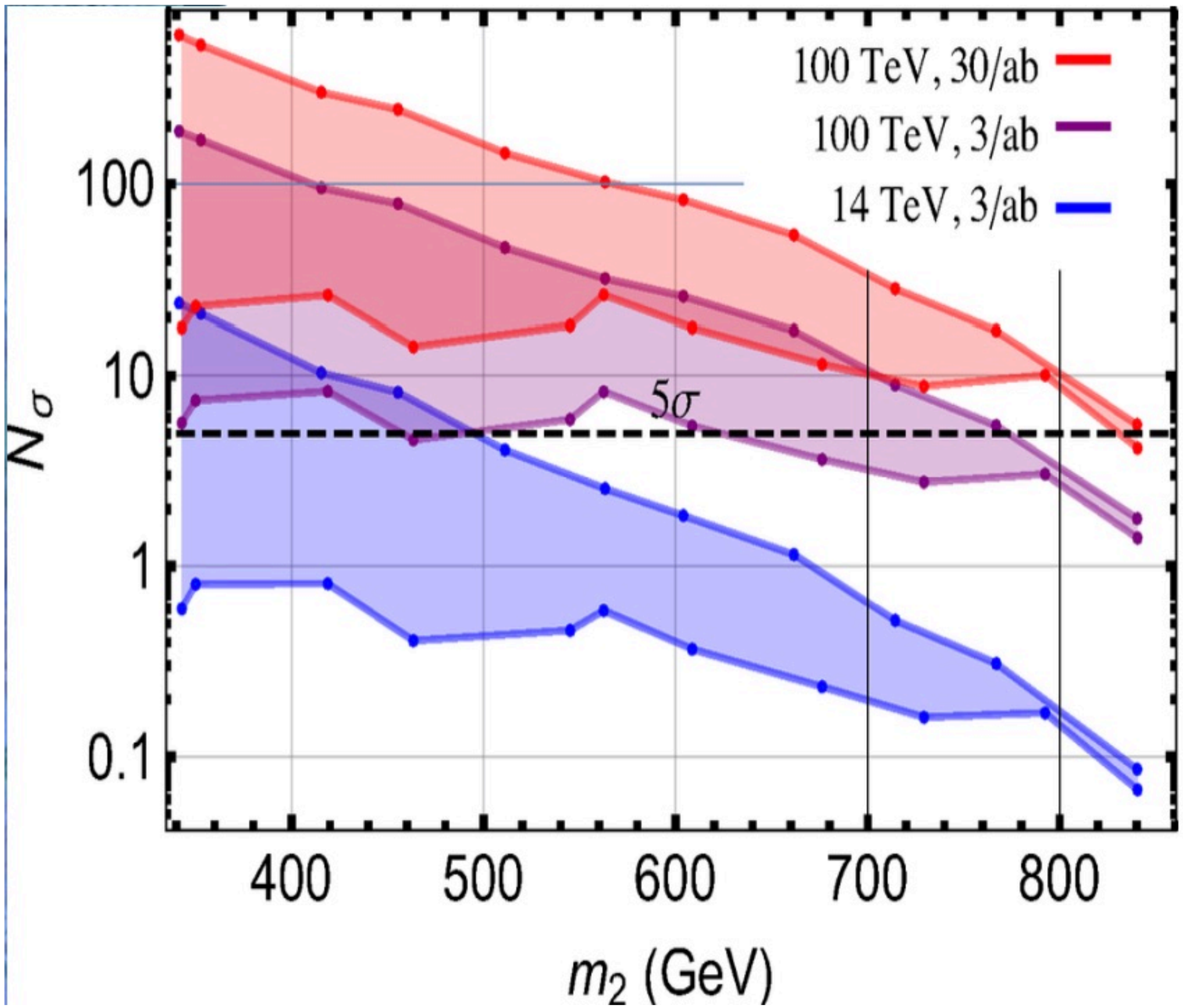
3 ab^{-1}

20 TeV

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

Direct search for 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

100 TeV ?

100 TeV ?

200 TeV ?

100 TeV ?

200 TeV ?

27 TeV in the LHC tunnel, replacing current magnets with those developed for FCC ?

=> High-Energy LHC (HE-LHC)

HE-LHC physics potential: domains to be evaluated

(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing firm evidence for the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly **(e.g. the flavour anomalies under discussion nowadays)** or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).

(1) extension of mass reach for discovery: generic results

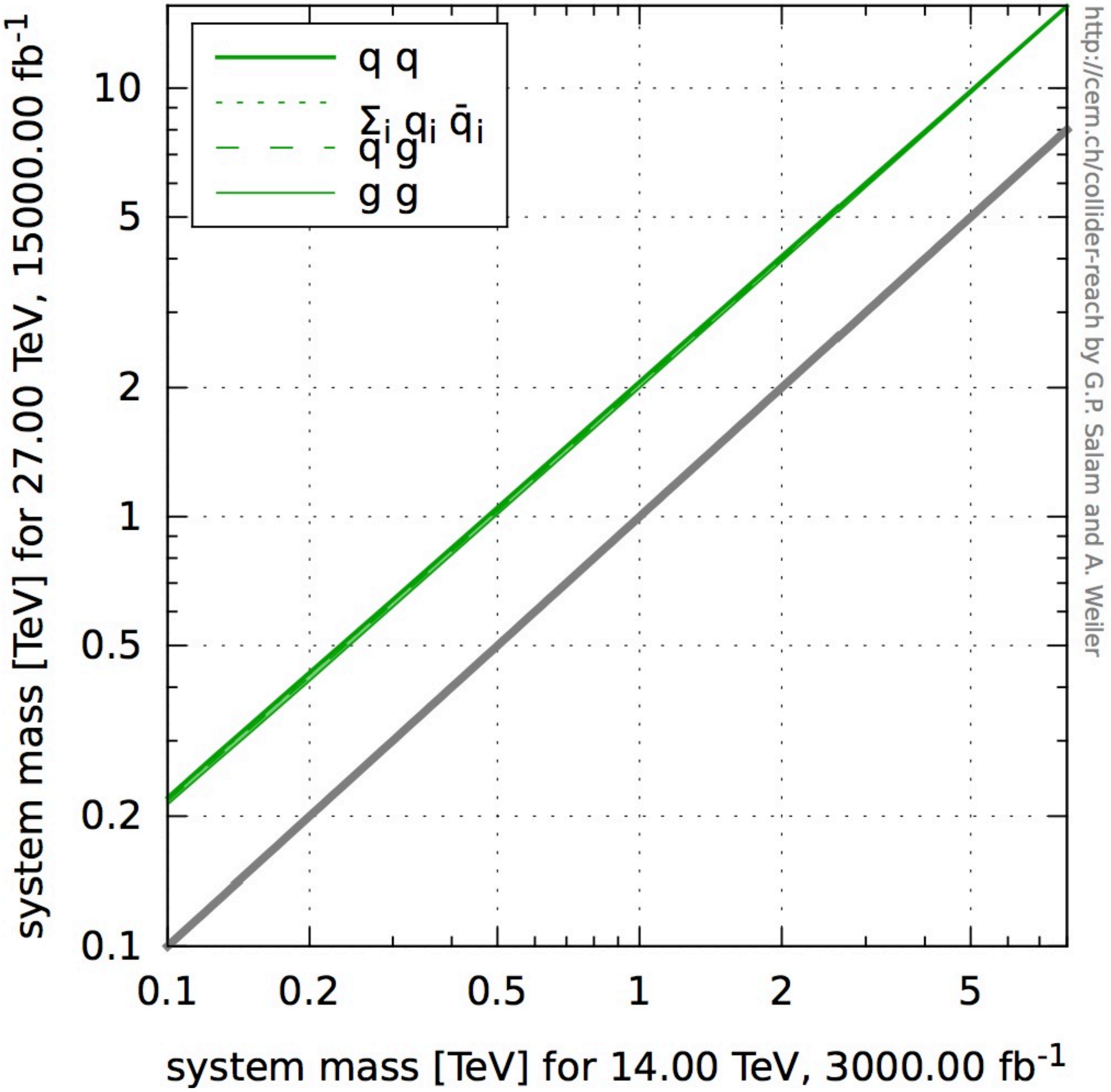


Figure 1.1: Estimate of the system mass (e.g. $m_{Z'}$ or $2m_{\tilde{g}}$) that can be probed in searches for new particles at HE-LHC, given an established system mass reach at HL-LHC.

G. Salam and A. Weiler, *Collider Reach*, `http://collider-reach.web.cern.ch/`.

(1) extension of mass reach for discovery: “natural” supersymmetry examples

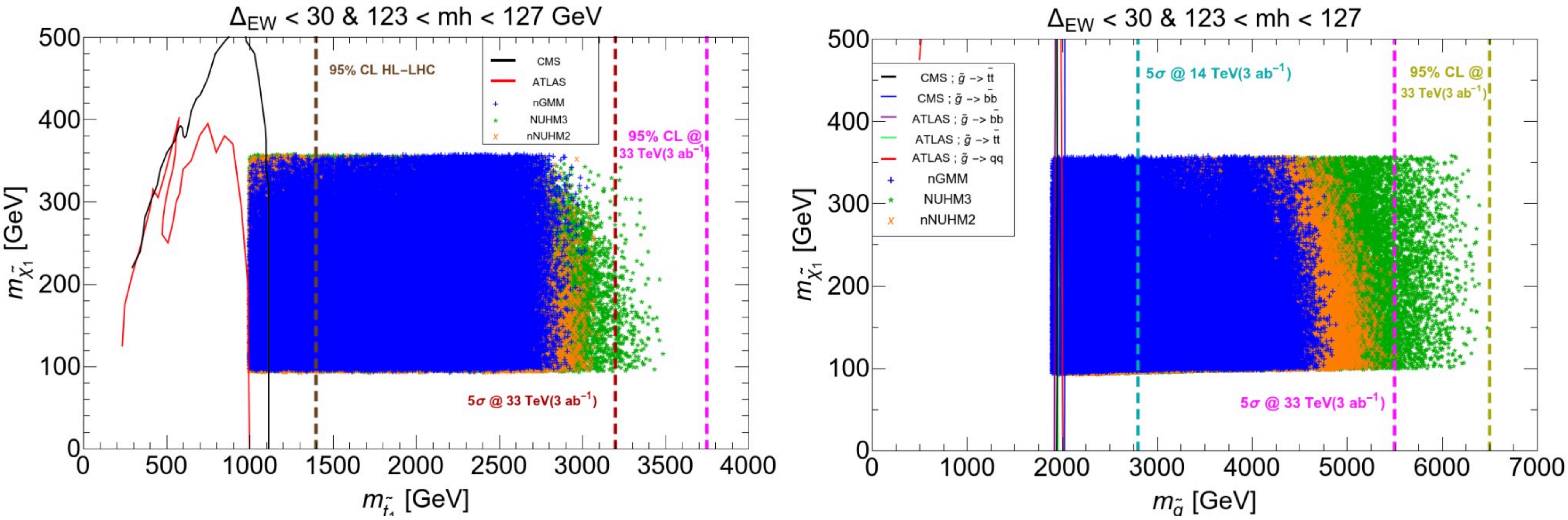


Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.

H. Baer, *talk at the Fermilab Workshop on HL-HE/LHC Physics, April 2-4 2018*, `https://indico.fnal.gov/event/16151/session/4/contribution/46/`.

For recent 27 TeV projections of DM WIMP searches:

T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, `arXiv:1805.00015 [hep-ph]`.

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the 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

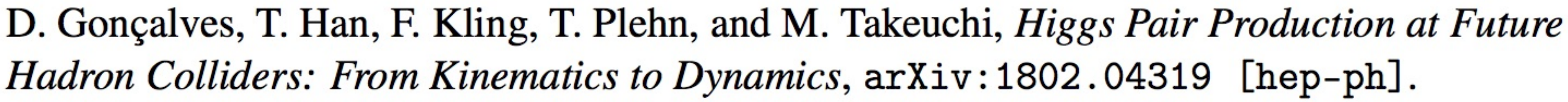
	gg→H	WH	ZH	ttH	HH
N_{27}	2.2×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

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

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

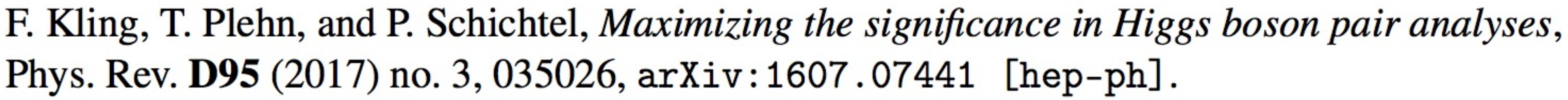
(II+III) precision measurements and EWSB probes: Higgs observables

- 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]`.

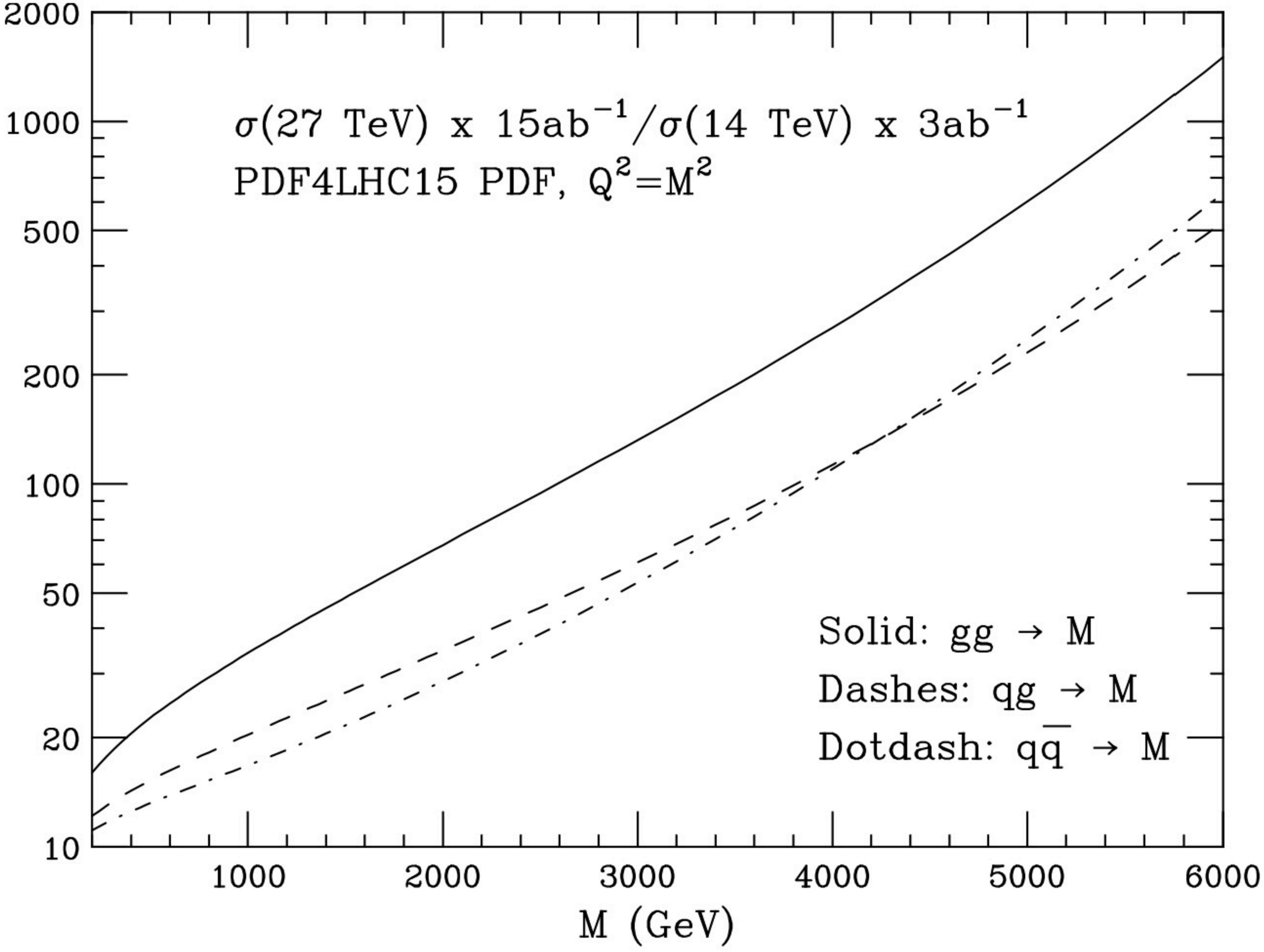
$\lambda/\lambda_{SM} = 1 \pm 0.3$ at 95%CL (1±0.15 at 68%CL)

(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

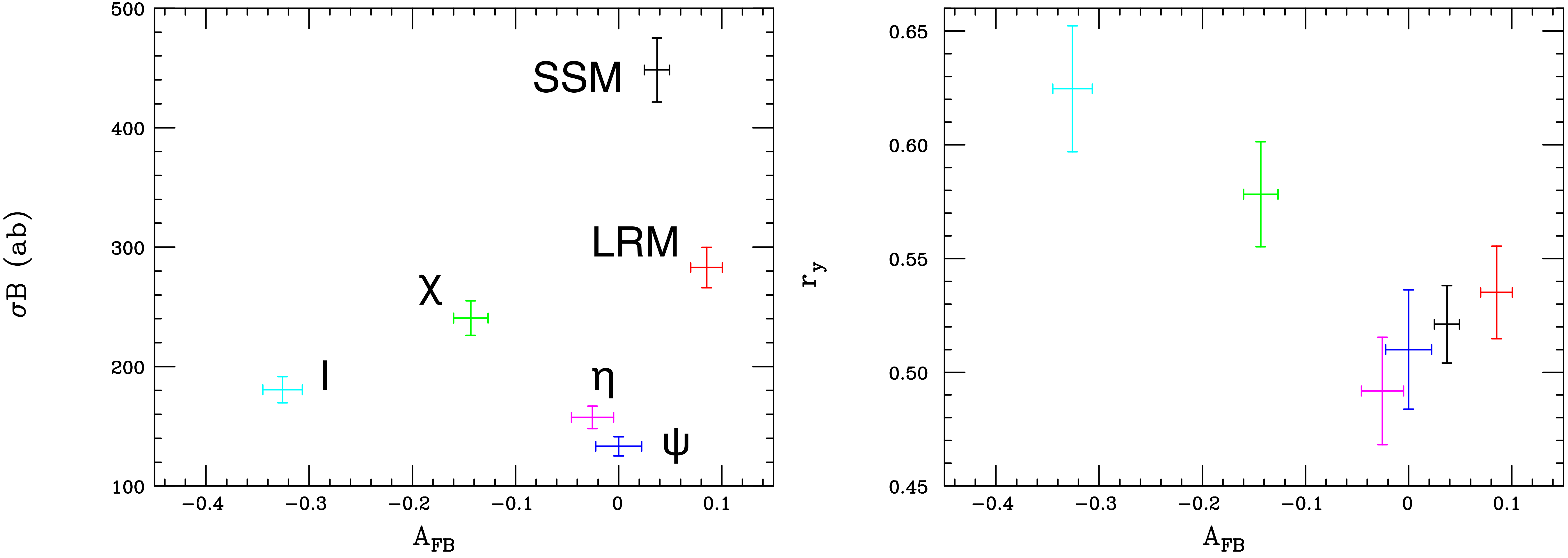
(IV) Exploration at 27 TeV of LHC discoveries: generic results



(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

C.Helsens, T.Rizzo, in progress

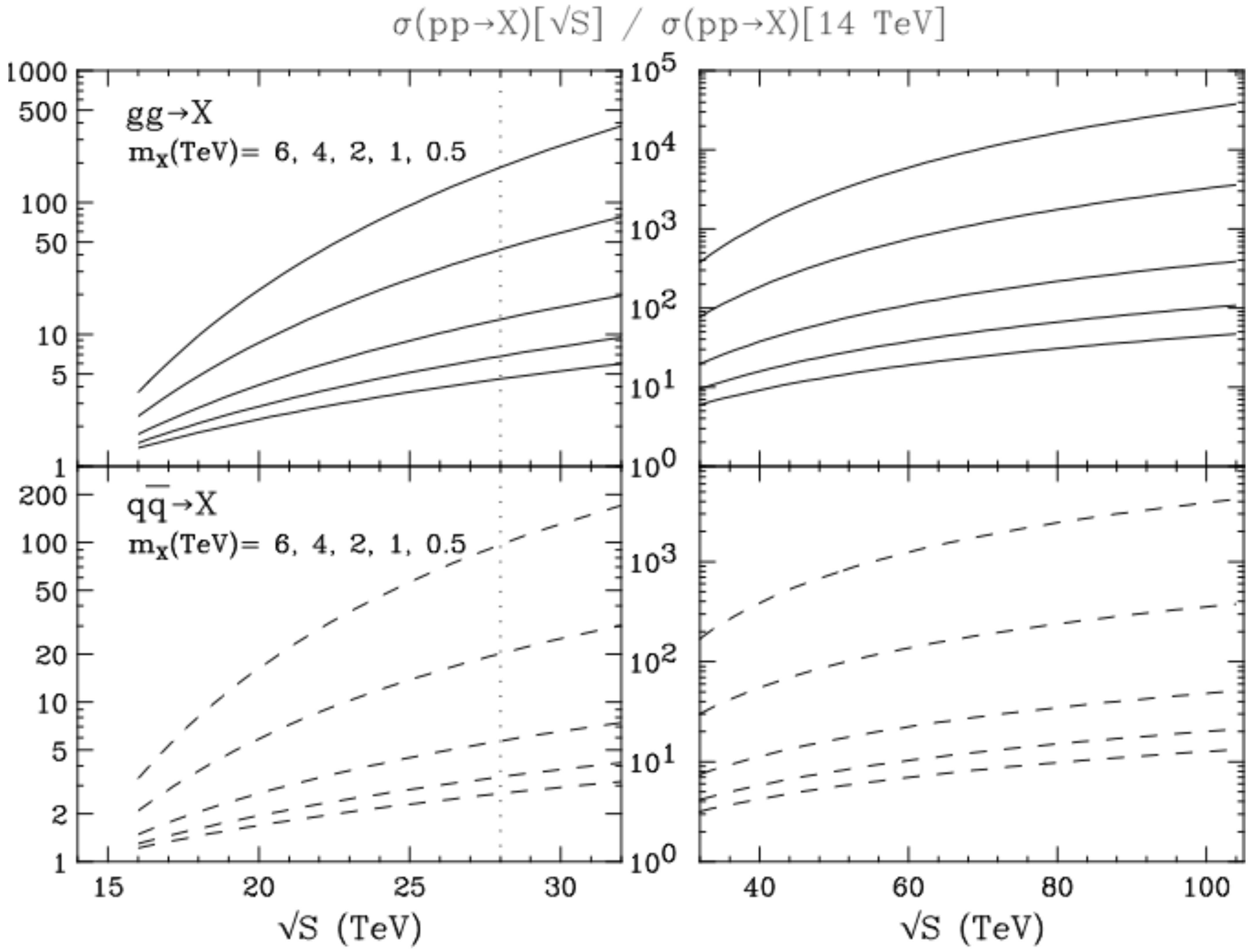
NB: uncertainty bars reflect very conservative syst assumptions



Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, `arXiv:1403.5465 [hep-ph]`.

27 or 100? √S evolution of LHC discovery scenarios



Possible questions/options

- If $m_X \sim 6$ TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 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 $\gtrsim 2m_X$ ($\Rightarrow$ *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?
  - Do we build CLIC?

- etc.etc.

Final remarks

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  - extends to the few-TeV region the sensitivity to WIMPS, in most cases closing the WIMP window
  - via H→invis it probes a huge range of Higgs-portal models

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