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CERN, Jan 16-20 2017

The SM Higgs Chapter of the FCC-hh report: lessons and future work

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Higgs chapter of FCC physics report

arXiv:1606.09408

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Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

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Contents

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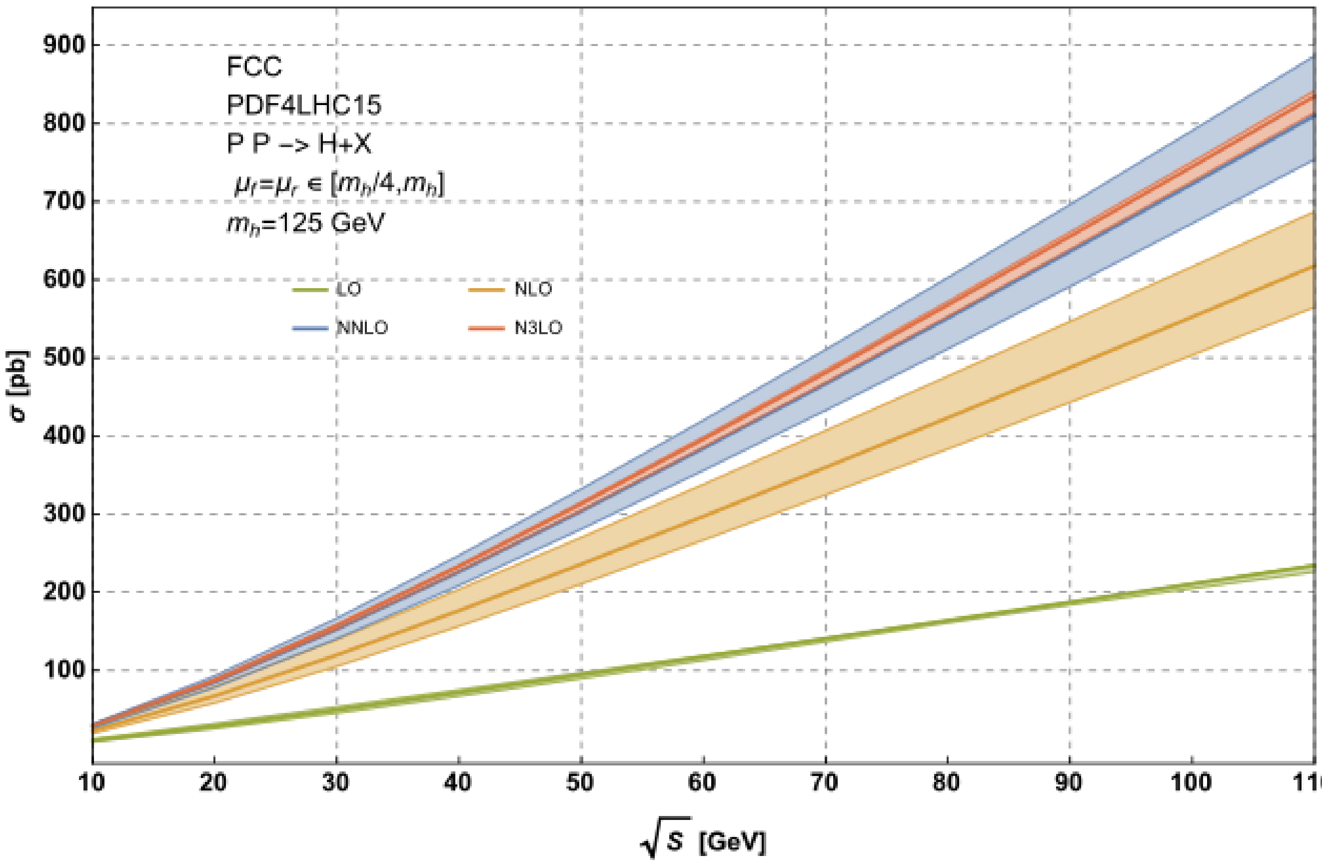
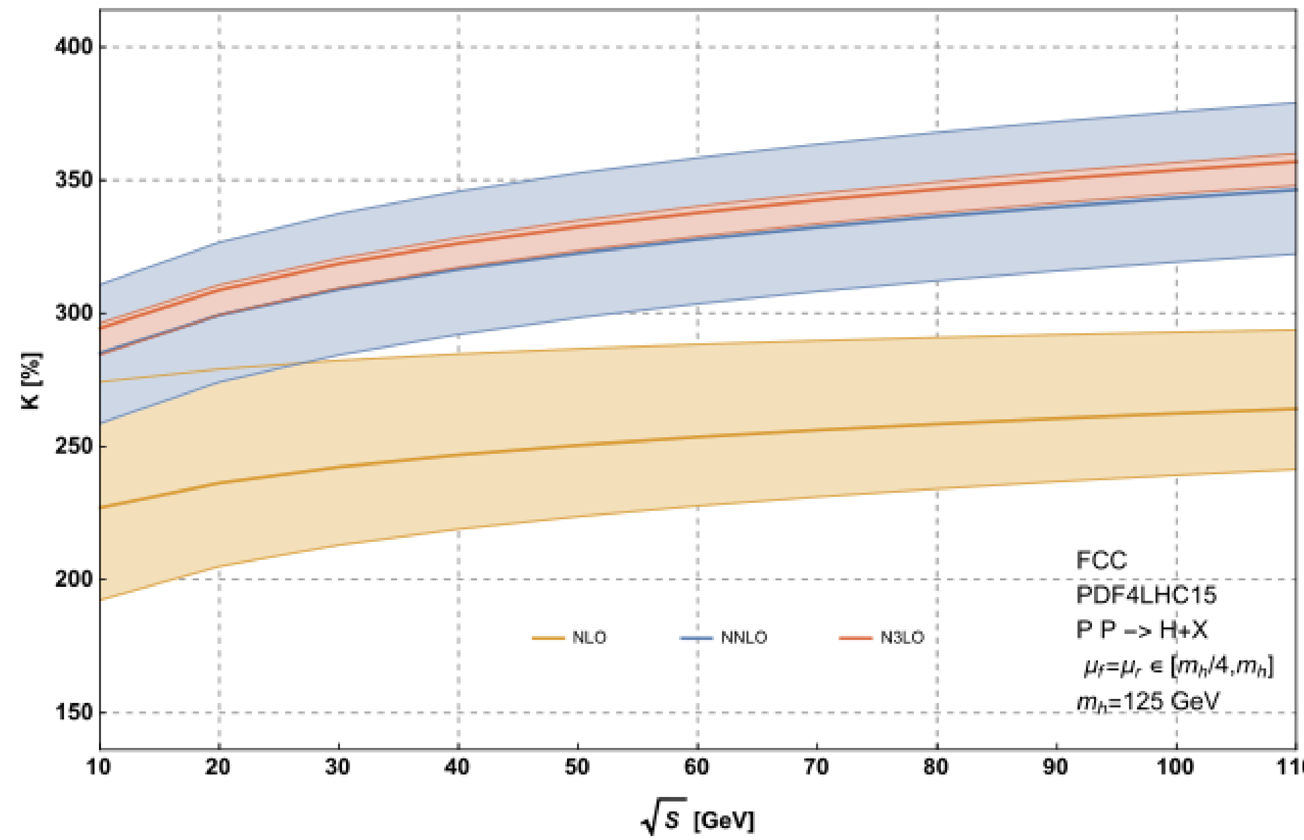
updates later

tomorrow morning session

TH progress: inclusive H@ NNNLO





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

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

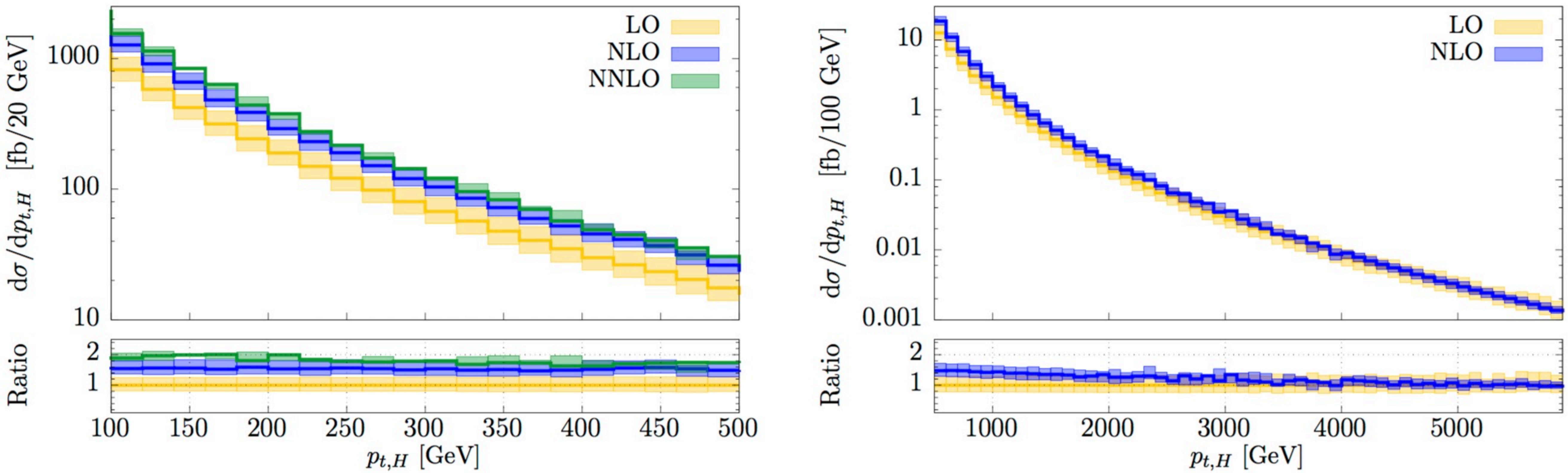
@100TeV:

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

Anastasiou et al, arXiv:1602.00695

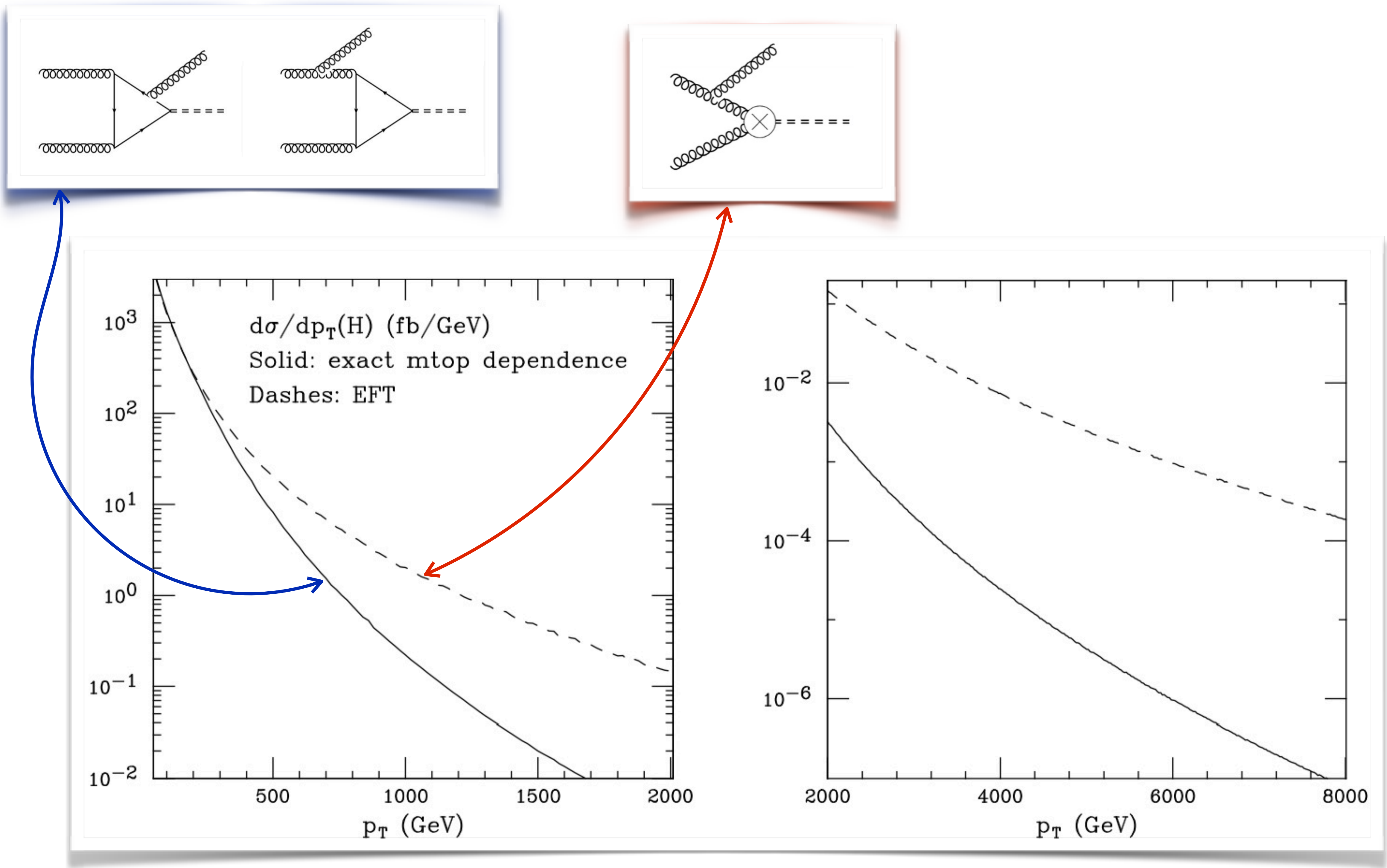
TH progress: high-p_T H @ NNLO

@100TeV:



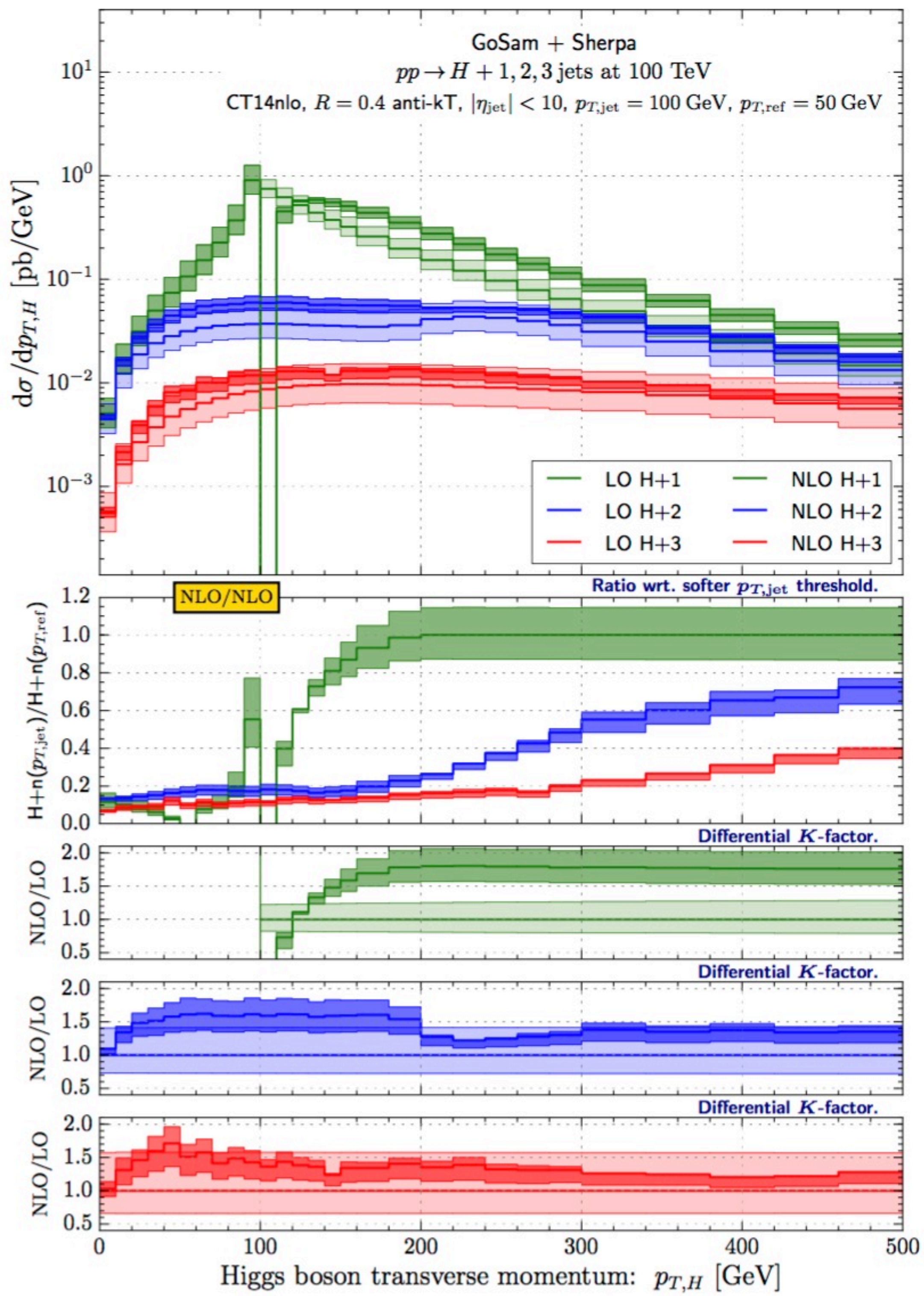
Boughezal, Caola, Melnikov, Petriello, Schulze Phys.Rev.Lett. 115 (2015)

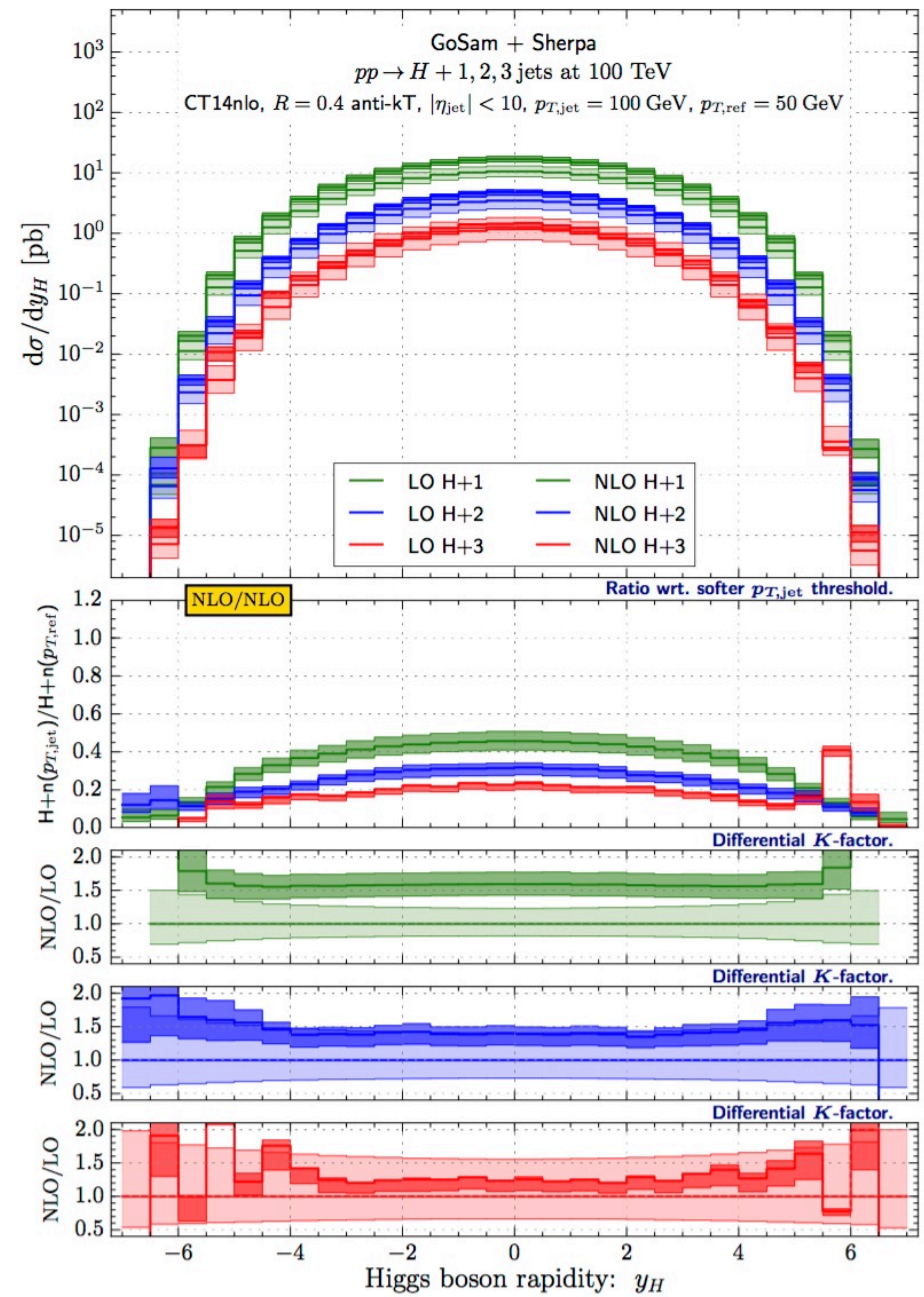
… but notice the huge sensitivity to the neglect of exact m_{top} effects in the matrix elements



TH progress: H+multijets @ NLO

@100TeV:





Greiner, Hoeche, Luisoni, Schonherr, Winter arXiv:1608.01195

Message

- Theoretical progress proceeds at astounding pace, thanks to the current and future needs of the LHC
- As we approach the few-% level in systematics, several relevant effects appear:
    - finite m_{top} corrections
    - higher-order EW corrections
    - PDF
- While these will require the development of new techniques, input from data (eg for PDFs, validation of HO calculations, …), and a lot of sweat and blood, it is reasonable to assume that the TH systematics will have reached by the start of FCC-pp the level of
    - % for absolute rates
    - sub-% (per mille?) for shapes and ratios (eg ttH/ttZ vs pt(H,Z))

Remarks

- Being optimistic in the assumptions about TH syst's when exploring the potential of FCC to perform precise Higgs measurements, will expose much more clearly the value of theoretical progress, and will be a very strong motivation and incentive to work hard on this progress!
- This will also set higher standards for the detector performance

SM Higgs rates at 100 TeV

	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

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

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

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

- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

Higgs as a BSM probe: precision vs dynamic reach

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

reiterating this morning's message from Adam, Francesco and Josh

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

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For H decays, or inclusive production, $\mu \sim O(v, m_H)$

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

$\Rightarrow$ **precision** probes large Λ

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

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

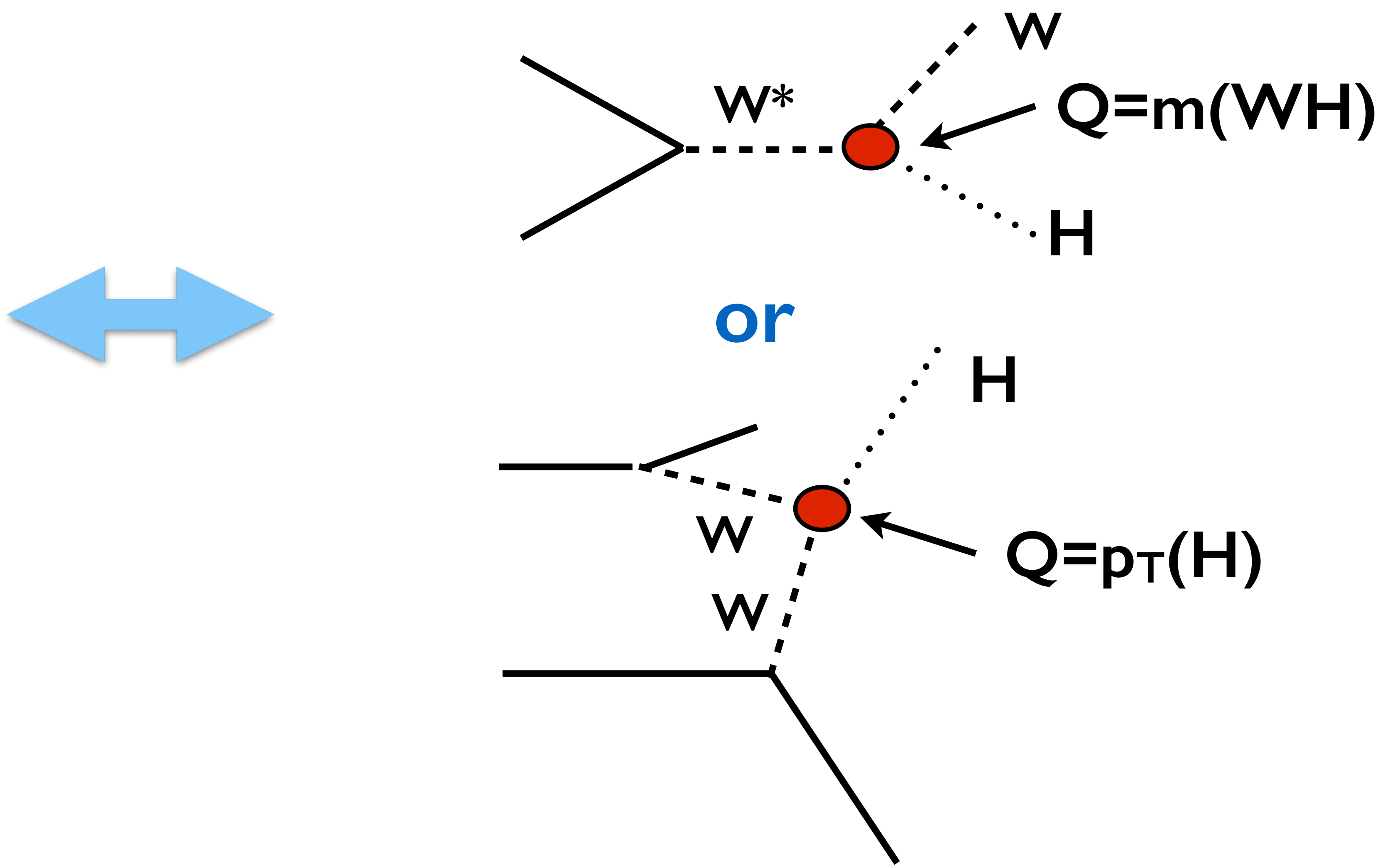
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

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

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

Examples

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



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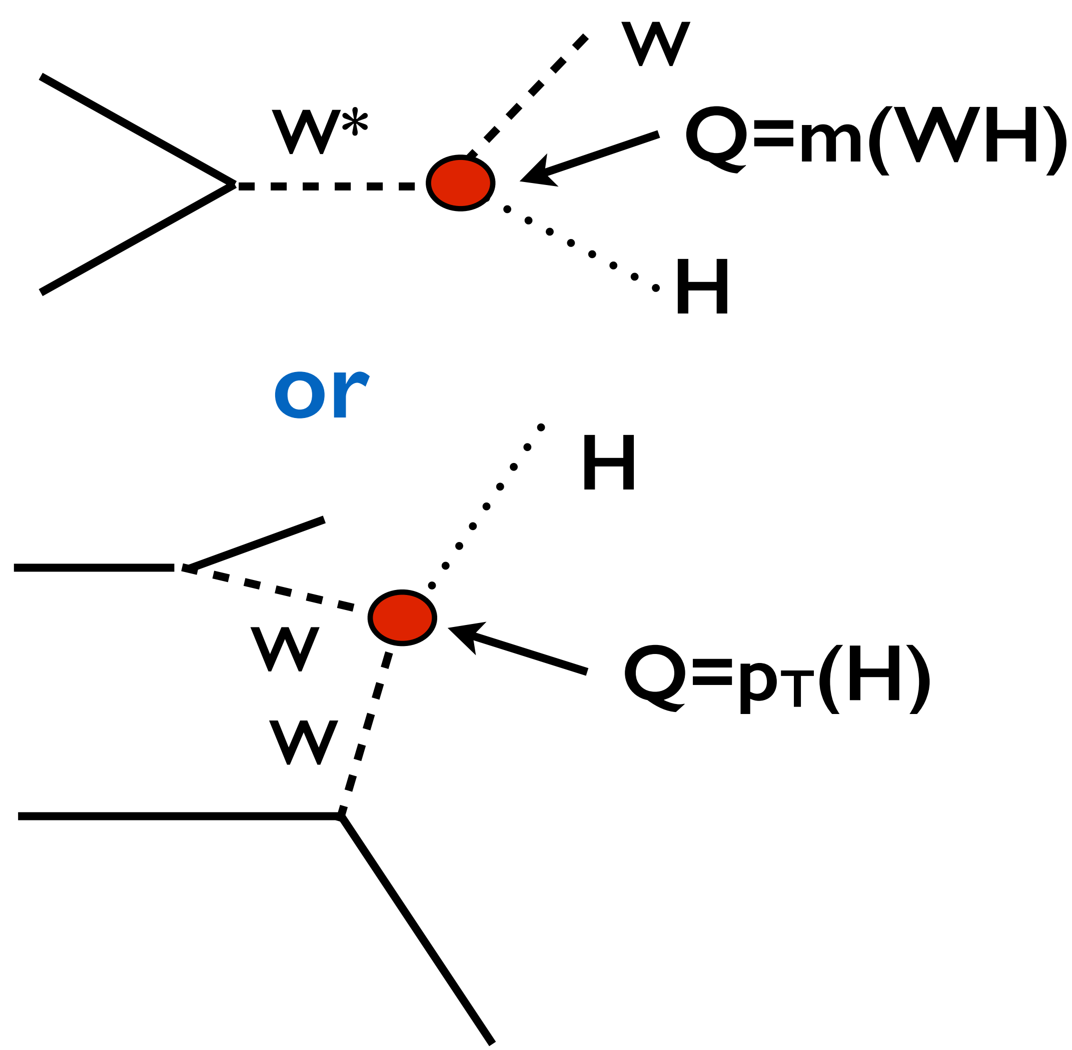
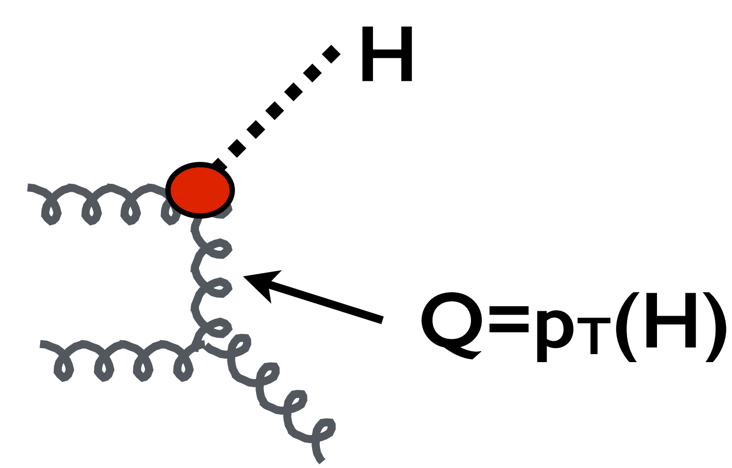
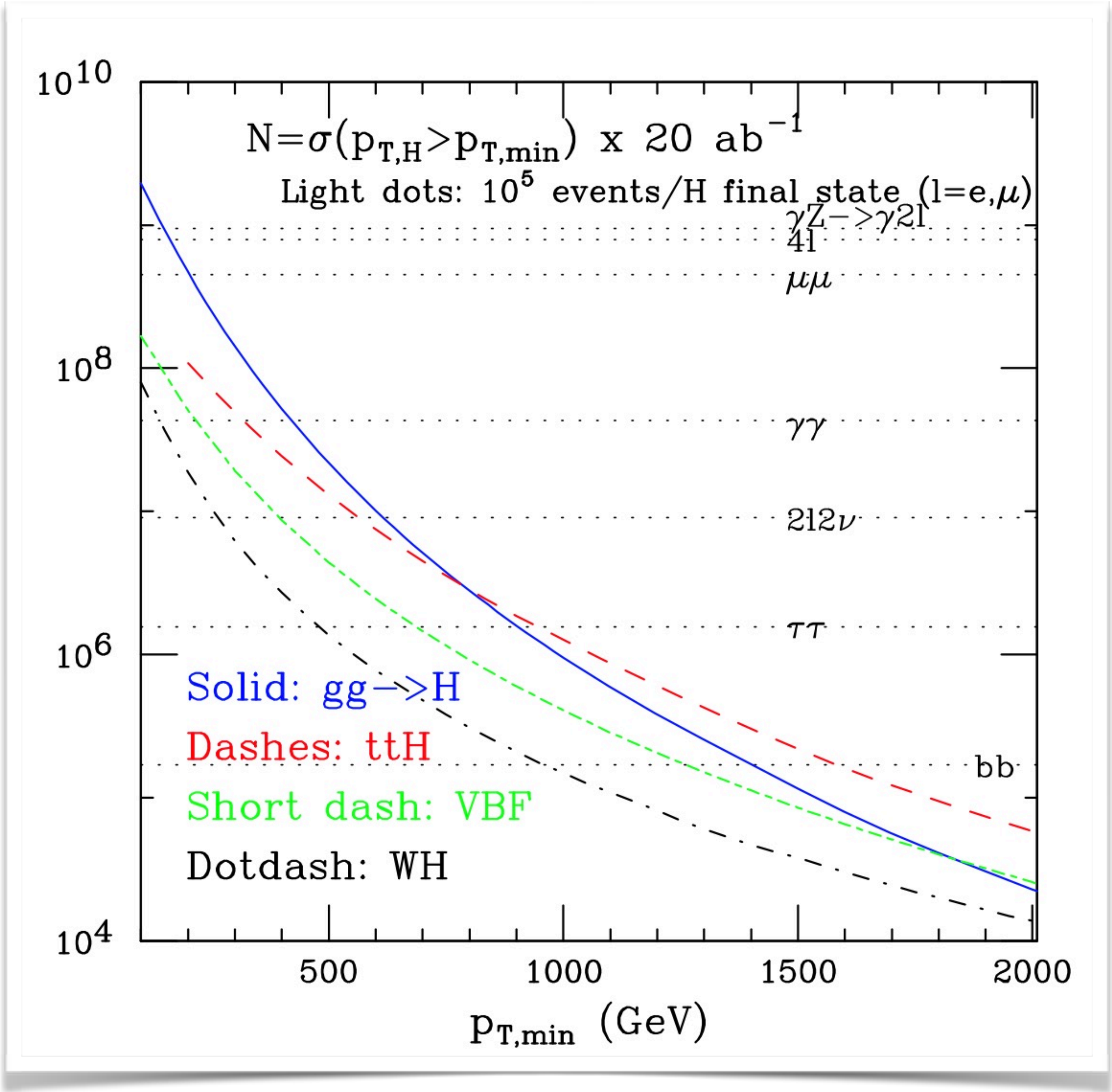


$\delta BR(H \to gg)$



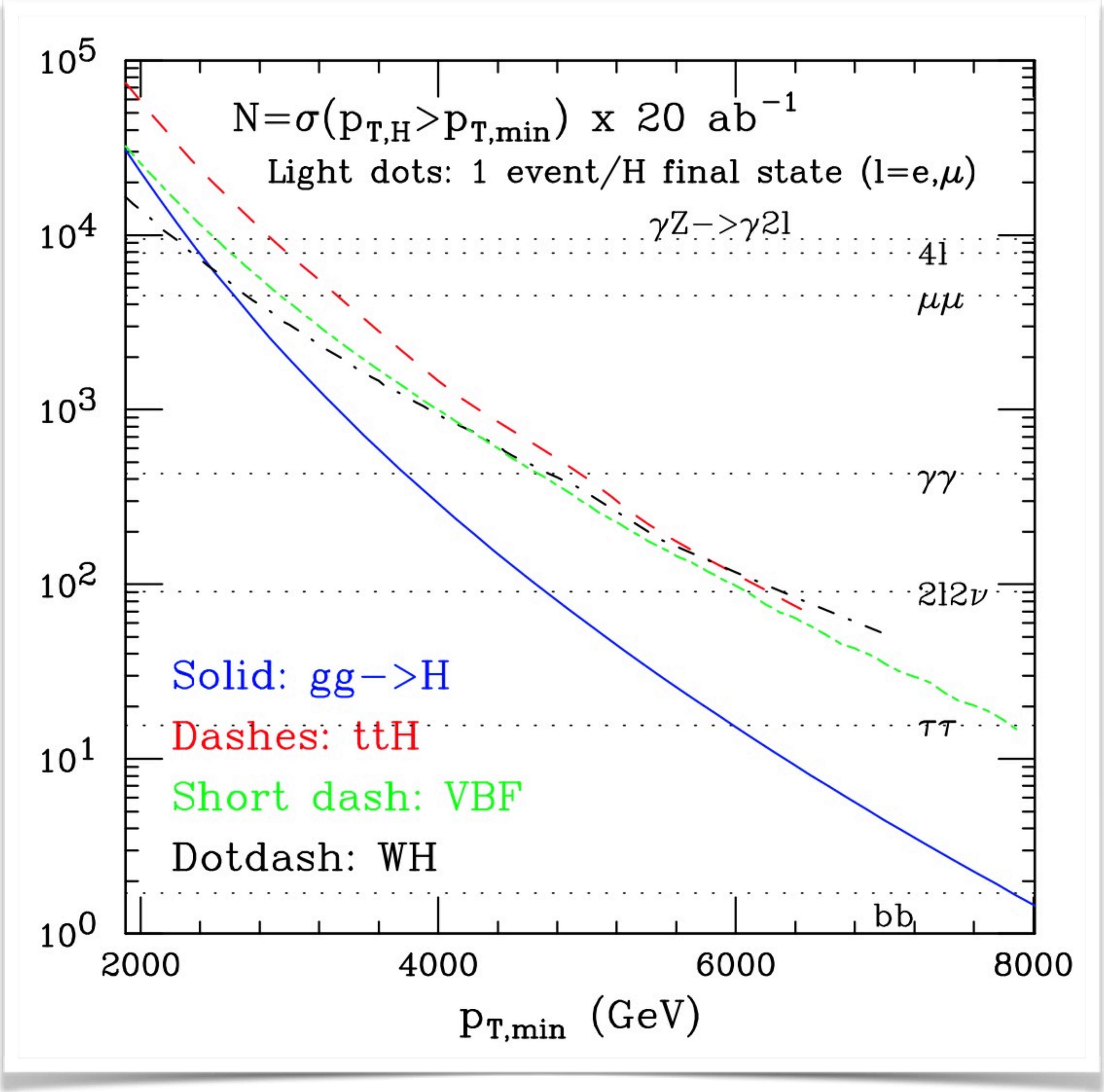
H at large p_T



Lesson: 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

H at large p_T



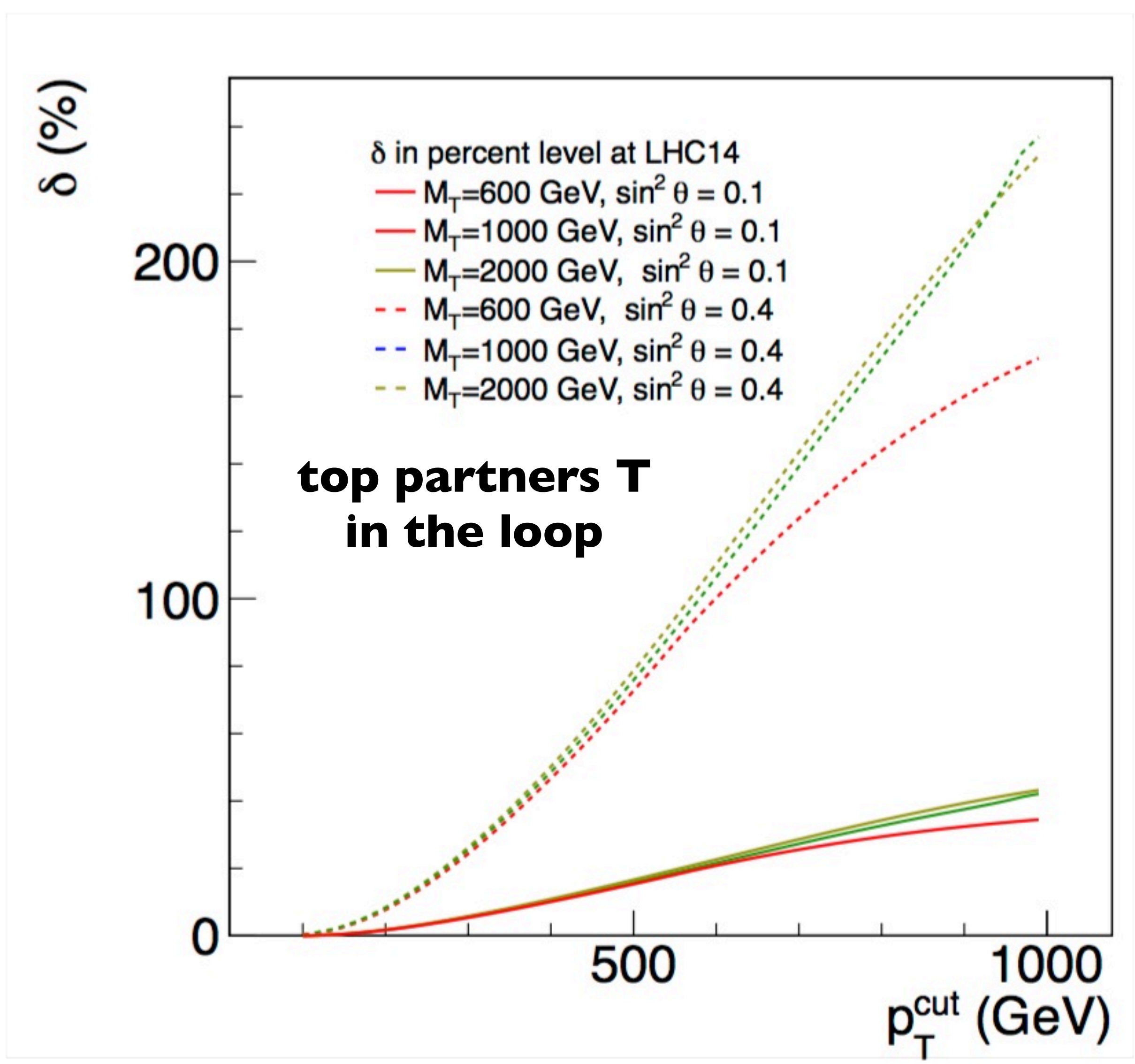
- Statistics in potentially visible final states out to several TeV

Examples of LHC sensitivity of the pt(H) spectrum to new physics in the loop

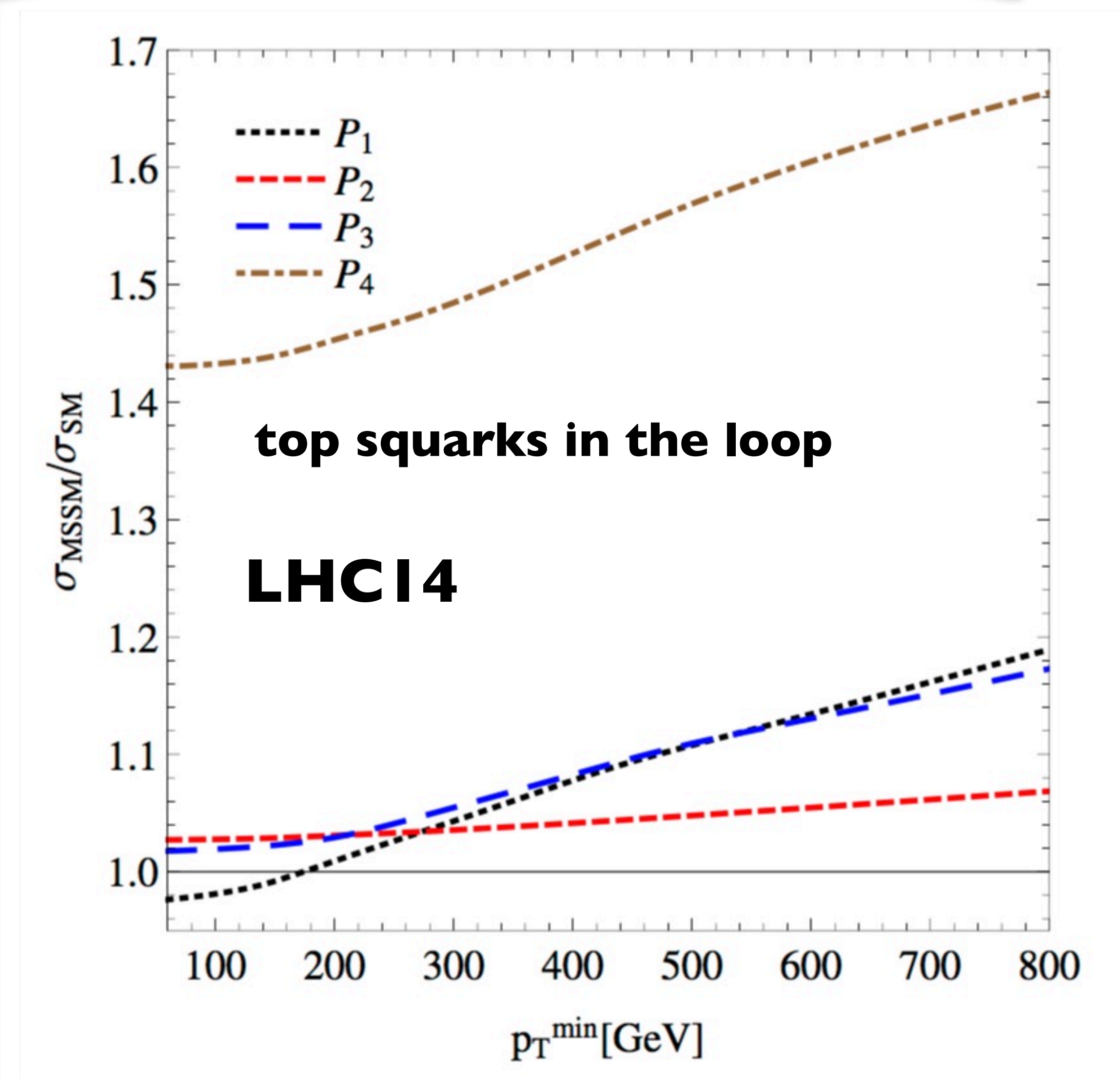
(See also
Azatov and Paul arXiv:1309.5273v3)

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



Banfi Martin Sanz, arXiv:1308.4771



Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

Open questions, for future work, TH

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- Analyses likely based on shape (e.g. $\sigma(p_T>2\text{ TeV})/\sigma(p_T>1\text{ TeV})$), to reduce dependence on absolute production rate, BRs, lumi, etc:
  - ultimate TH systematics?
    - EW corrections at large pt
    - m_{top}

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  - ultimate TH systematics?
    - EW corrections at large pt
    - m_{top}
- Bottom line question:
  - *How to high-pt measurements complement precise BR measurements in probing EFT couplings?*

Open questions, for future work, EXP

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- What are the most robust decay channels to explore the highest p_T range?
  - $H \to bb$:
    - b-tagging, mass resolution (H vs Z), H-tagging as color singlet vs QCD continuum bg's, … ?
  - $H \to WW$, leptonic, semileptonic and fully hadronic
  - $H \to \tau\tau$ hadronic ?

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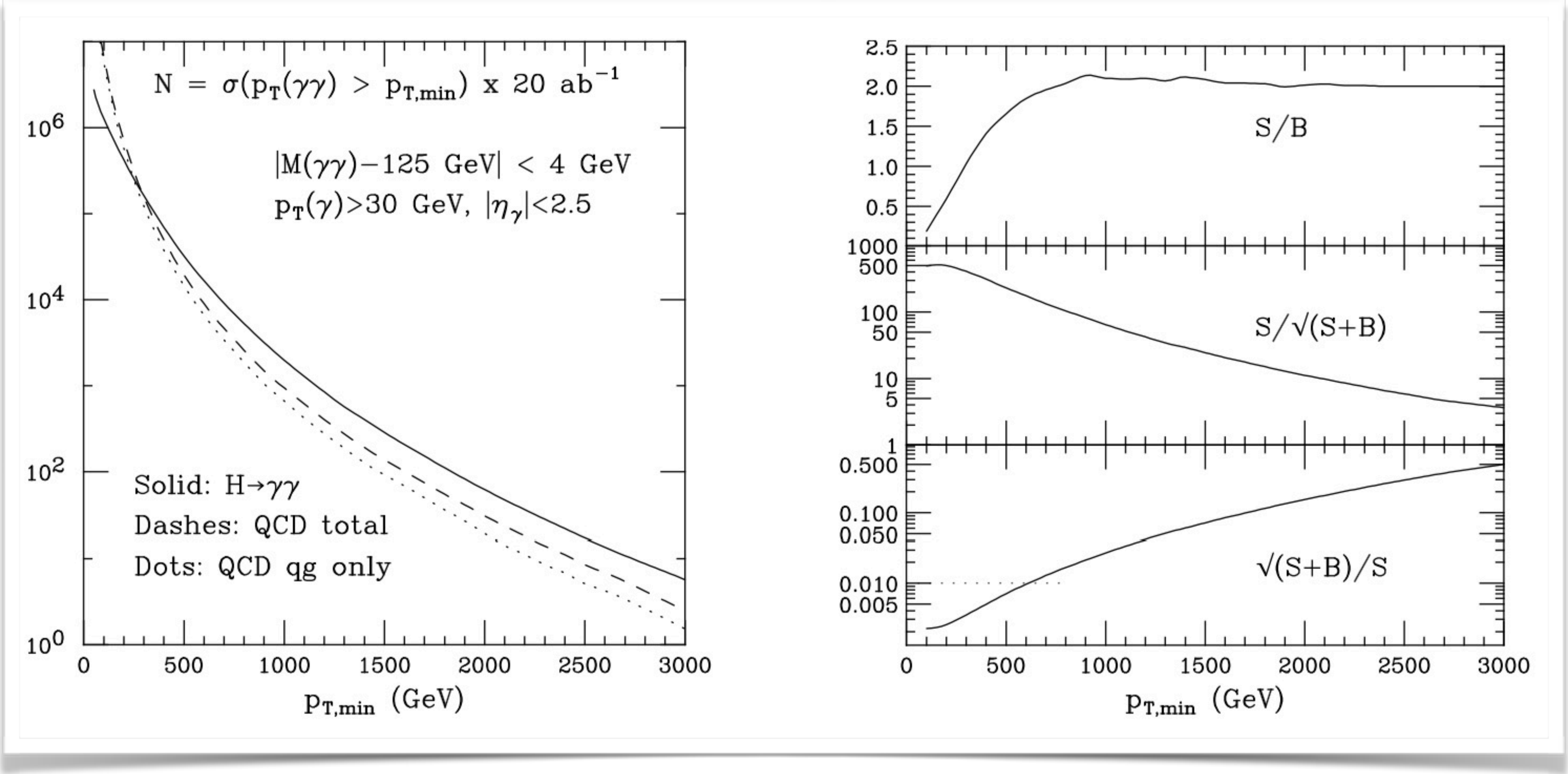
- Define efficient and high-purity cuts to separate different production modes: will play crucial role in reducing bgs and optimize interpretation

- H@large p_T has probably little impact on detector issues like eta acceptance, pt threshold. Forward jets?

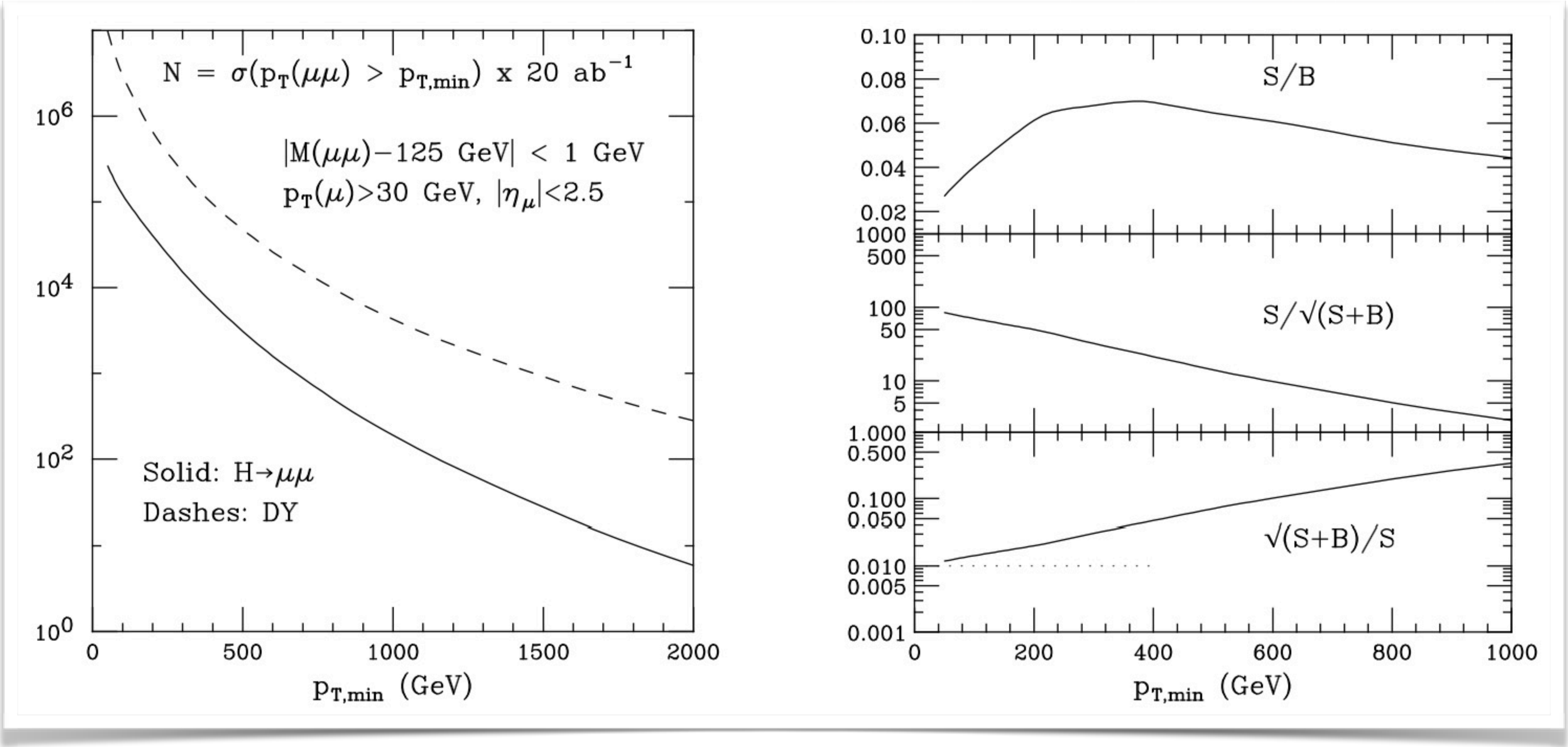
Rare decays at high-p_T:
a clean environment for %-level BR measurements?

gg→H→γγ at large p_T



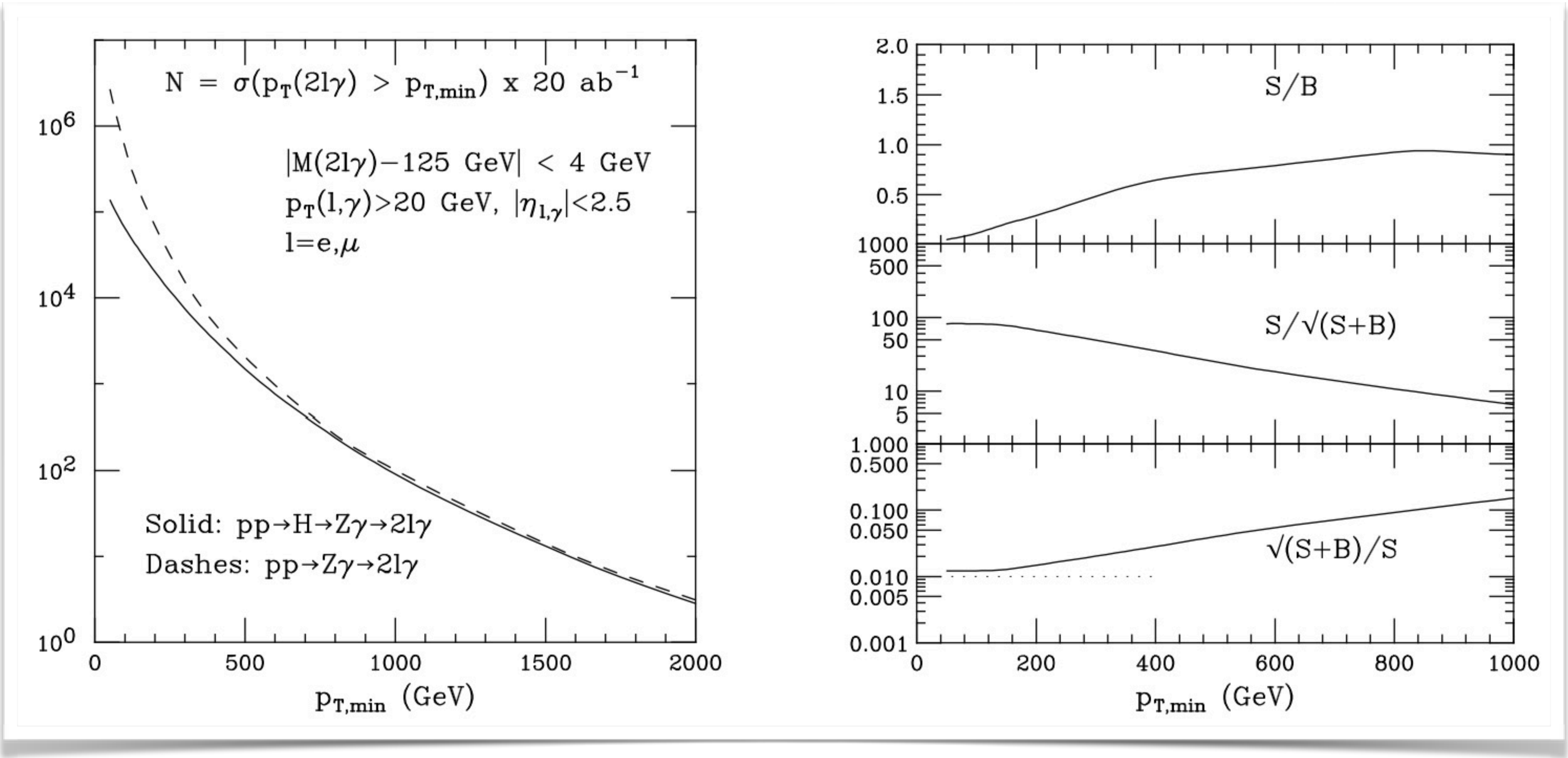
- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Exptl mass resolution at large pt(H)?

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



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

gg→H→Zγ→ℓℓγ at large p_T



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

Questions

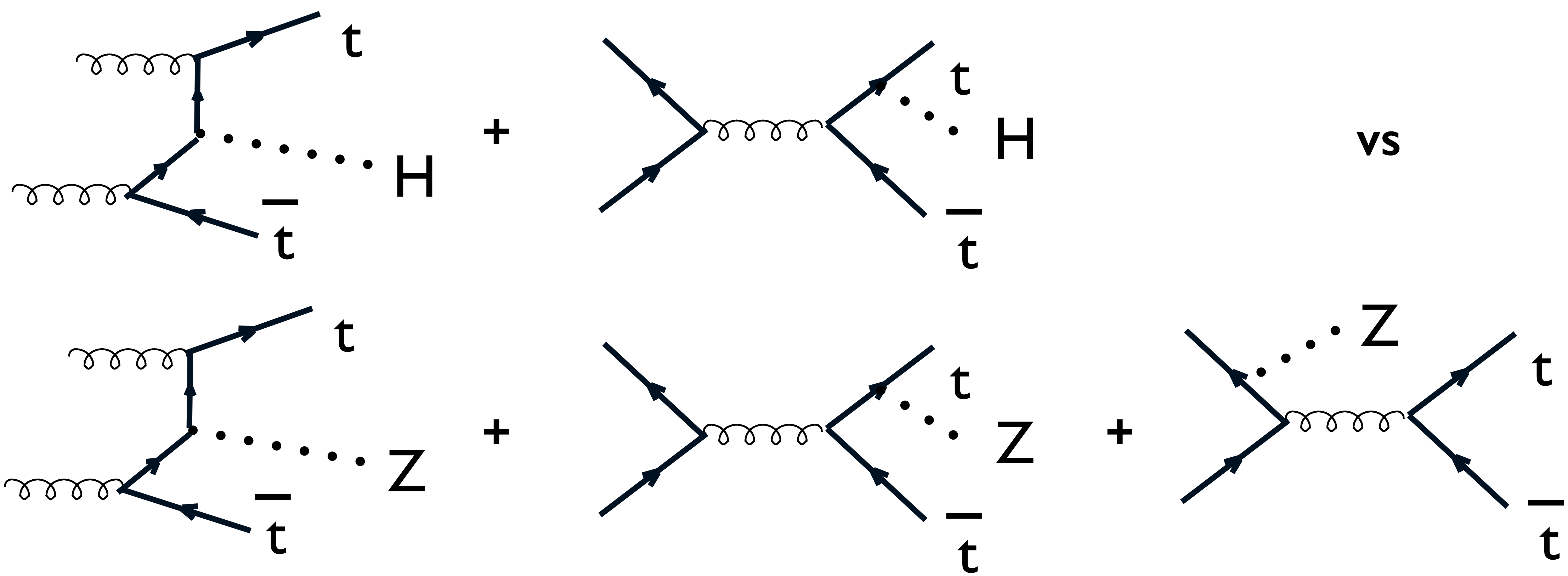
- Statistics and TH systematics allow for %-level measurement of very rare decay modes ($Z\gamma$, $\mu\mu$) (absolute, if $B(\gamma\gamma)$ or $B(ZZ^*)$ known from e^+e^-, or relative w.r.t. $B(\gamma\gamma)$ using pp-only data)
  - What are the exptl systematics?
  - What is the impact of these BR ratio measurements on constraining EFT param's?
  - Comparison of studies done at large-pT (cleaner/small statistics) vs inclusive studies (more bg but larger stats)

- Much larger statistics and p_T reach for modes like WW and $\tau\tau$. Needs dedicated studies to check potential precision (e.g. study of bgs, systematics from corrections to common fiducial regions, impact of neutrinos, …)

Precise BRs from ratios of different processes

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

MLM, Plehn, Reimitz, Schell, Shao *arXiv:1507.08169*



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

- Identical production dynamics:

o correlated QCD corrections, correlated scale dependence

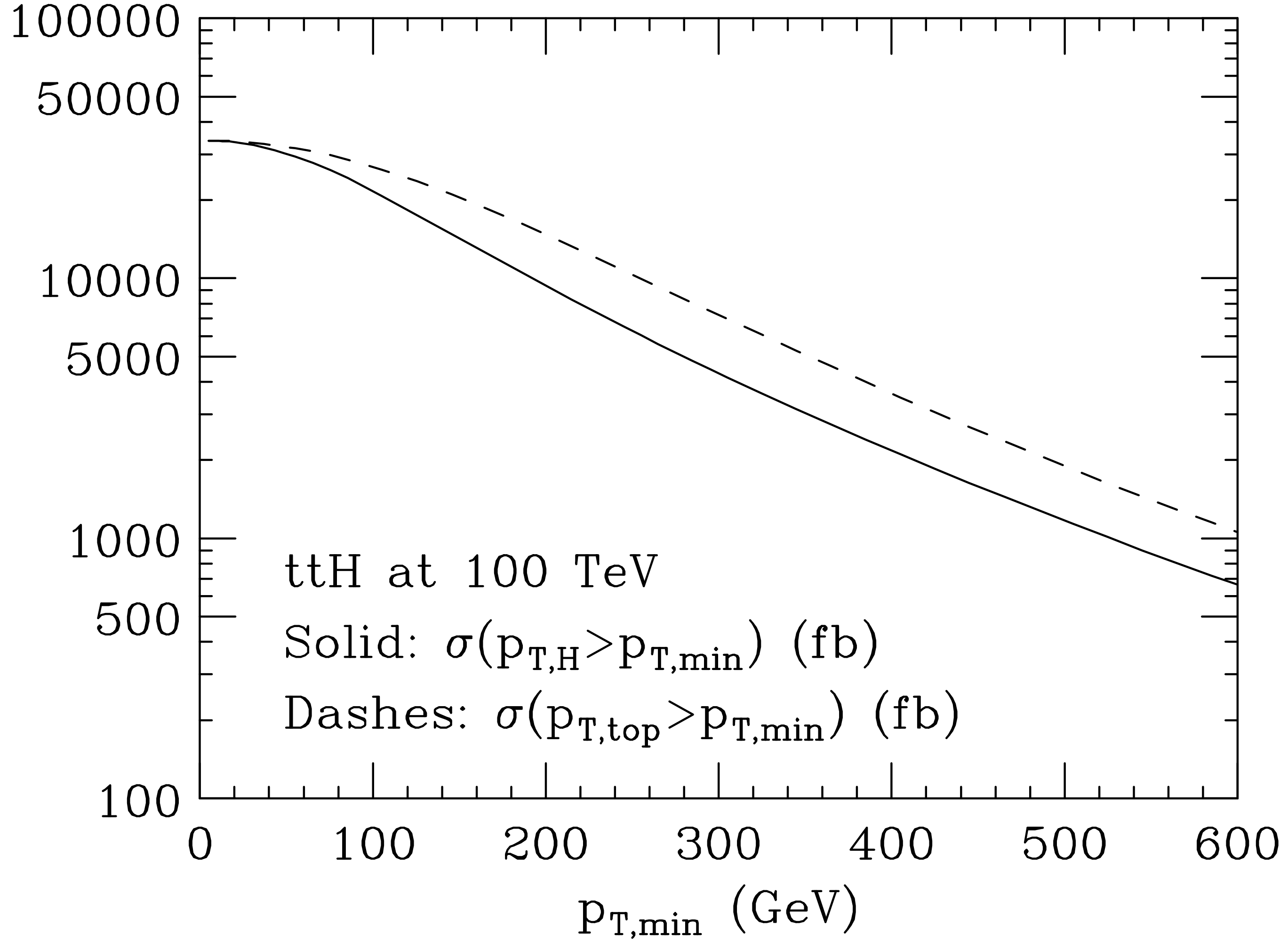
o correlated α_S systematics

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

o correlated PDF systematics

o correlated m_{top} systematics

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



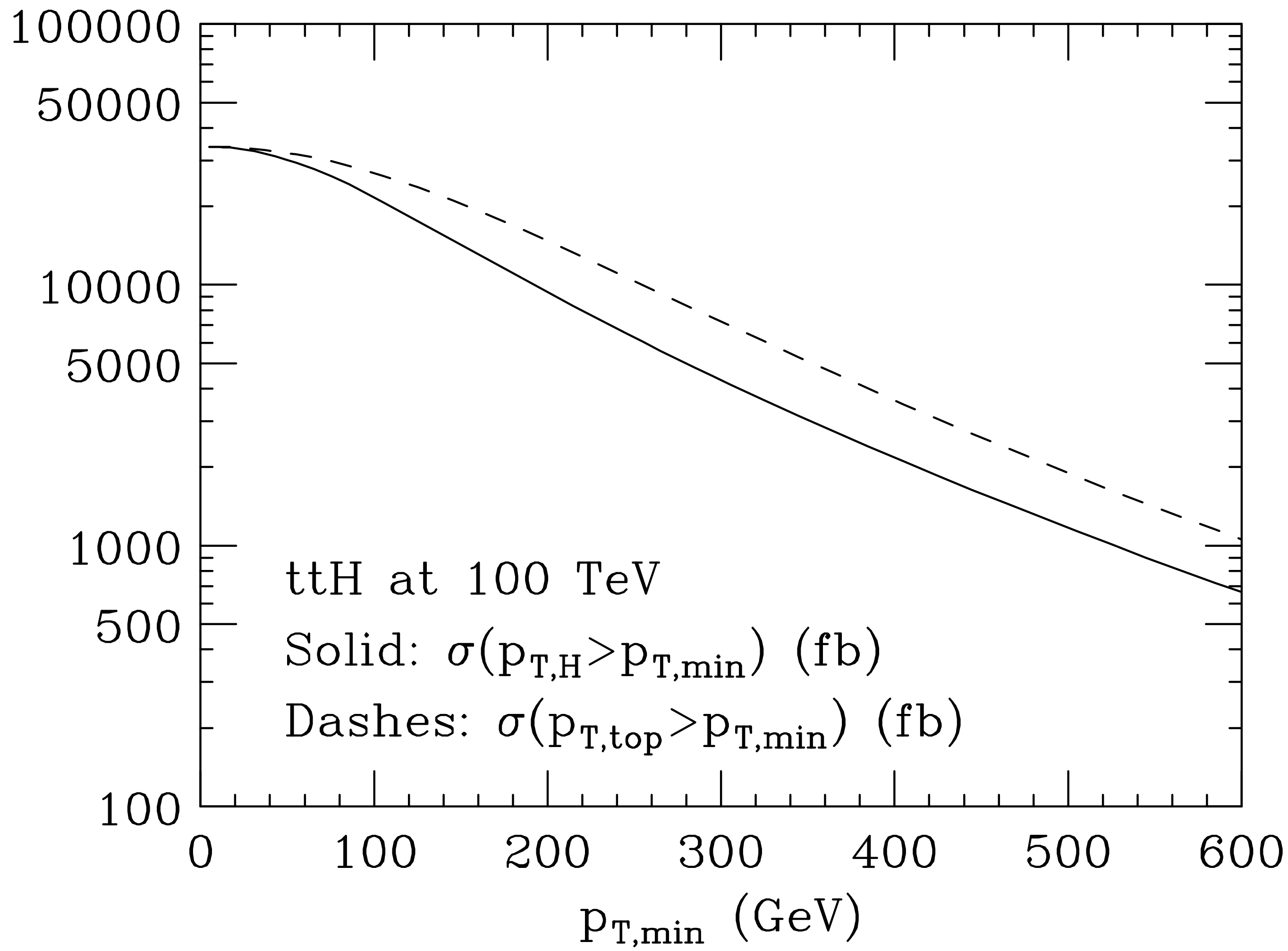
$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

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

⇒ huge rates, exploit

boosted topologies

MLM, Plehn, Reimitz, Schell, Shao arXiv:1507.08169



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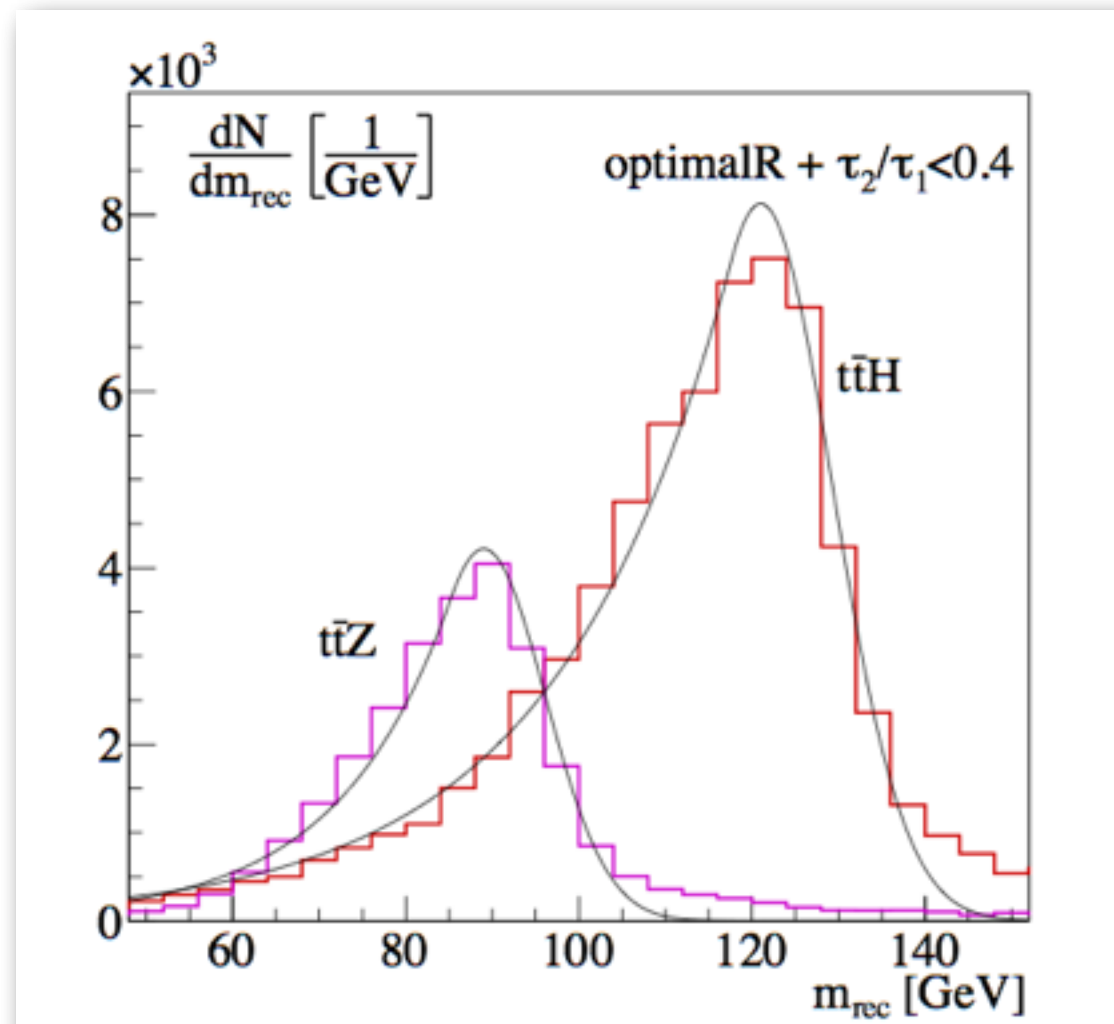
Events/20ab^{-1} , with tt→$\ell\nu$+jets

⇒ huge rates, exploit boosted topologies

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

- δy_t (stat + syst $_{TH}$) ~ 1%

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



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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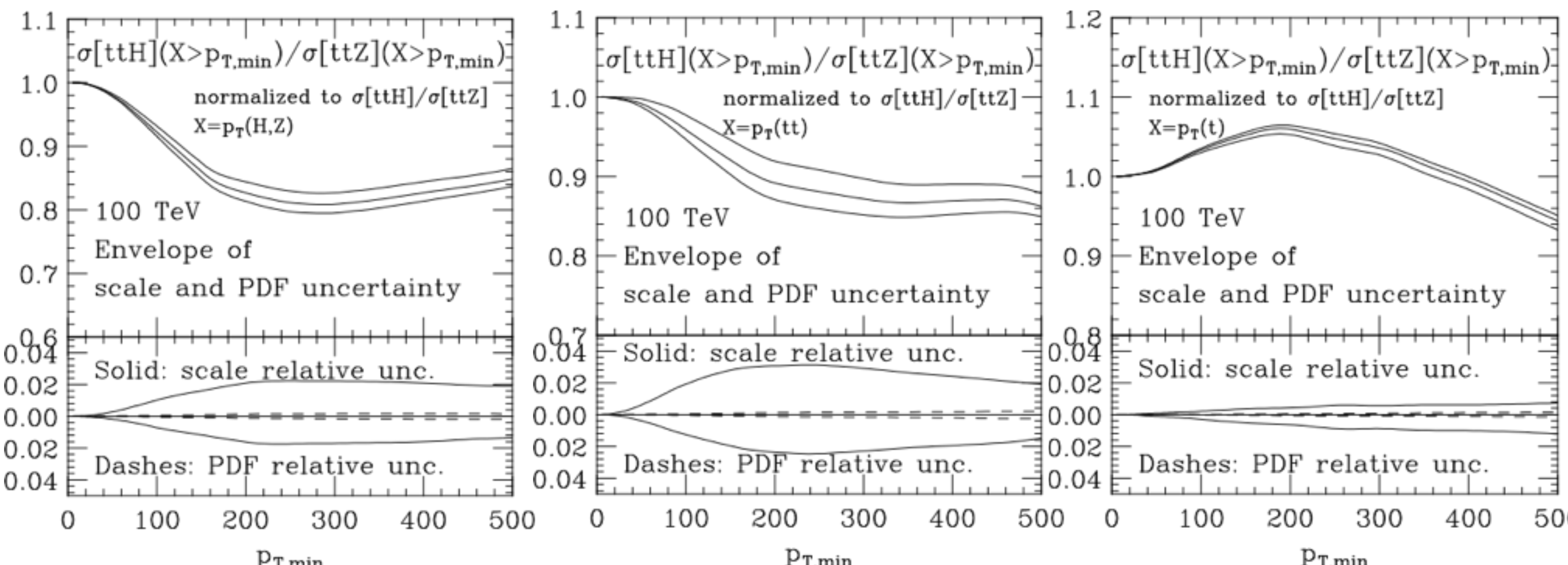
↑ scale ↑ PDF

Production kinematics ratio stability



Ex: BR($H \to inv$) in H+X production at large $p_T(H)$

Irreducible bg: Z+X, with $Z \to \nu\nu$

Can be extracted from $Z \to ee$, with a syst unc driven by the ee stat precision*:

$(\delta N/N)_{Z\to\nu\nu} \sim \{ BR(Z\to ee)\, N[ZX] \}^{-1/2}$

The limit to the precision of BR($H \to inv$) is then

$$\delta_{stat} BR(H\to inv) \sim \frac{N(Z+X) * BR(Z\to\nu\nu)}{N(H+X)} \times (\delta N/N)_{Z\to\nu\nu}$$

* *one needs to define ptZ in such a way as to avoid exptl syst in correlating $Z\to\nu\nu$ and $\to ee$. E.g. defining $p_T Z = p_T$(had recoil)*

In Higgs+jet production:

$\sigma(p_{T,H} > 1 \text{ TeV}) \sim 0.1 \times \sigma(p_{tZ} > 1 \text{ TeV}, Z \to \nu\nu)$

with $\sigma(p_{T,H} > 1 \text{ TeV}) \sim 50$ fb $\sim$ 1M evts in 20ab^{-1}

=> δ_{stat} BR($H \to$ inv) $\sim 10\ (\delta N/N)_{Z \to \nu\nu} \sim 1\%$

In ttH production:

$\sigma(p_{T,H} > 1 \text{ TeV}) \sim 2.5 \times \sigma(p_{tZ} > 1 \text{ TeV}, Z \to \nu\nu)$

with similar rate as H+jet, $\sigma(p_{T,H} > 1 \text{ TeV}) \sim 50$ fb $\sim$ 1M evts in 20ab^{-1}

=> δ_{stat} BR($H \to$ inv) $\sim 0.4\ (\delta N/N)_{Z \to \nu\nu} \sim 0.2\%$

Message: better S/B and comparable event rate makes ttH a better channel to explore invisible Higgs decays

Conclusions

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- There are many opportunities, exploiting the large statistics and the novel kinematical regimes
- With the exception of ttH and HH, where some more complete analyses has been made, there is still no reliable quantitative study of the actual precision potential of a 100 TeV pp collider at 20 ab^{-1}.
- In most cases there is potential to target 1% precision, at least for what concerns δ_{stat} and δ_{TH} …. but we still have no clue as to whether δ_{exp} is 1%, 10% or 100% !!

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- It is clear from the previous slides that Higgs physics at 100 TeV is a ballgame different from the LHC.
- There are many opportunities, exploiting the large statistics and the novel kinematical regimes
- With the exception of ttH and HH, where some more complete analyses has been made, there is still no reliable quantitative study of the actual precision potential of a 100 TeV pp collider at 20 ab^{-1}.
- In most cases there is potential to target 1% precision, at least for what concerns δ_{stat} and δ_{TH} …. but we still have no clue as to whether δ_{exp} is 1%, 10% or 100% !!
- Plenty of room for creative explorative work towards the CDR!