When is a top quark a parton?

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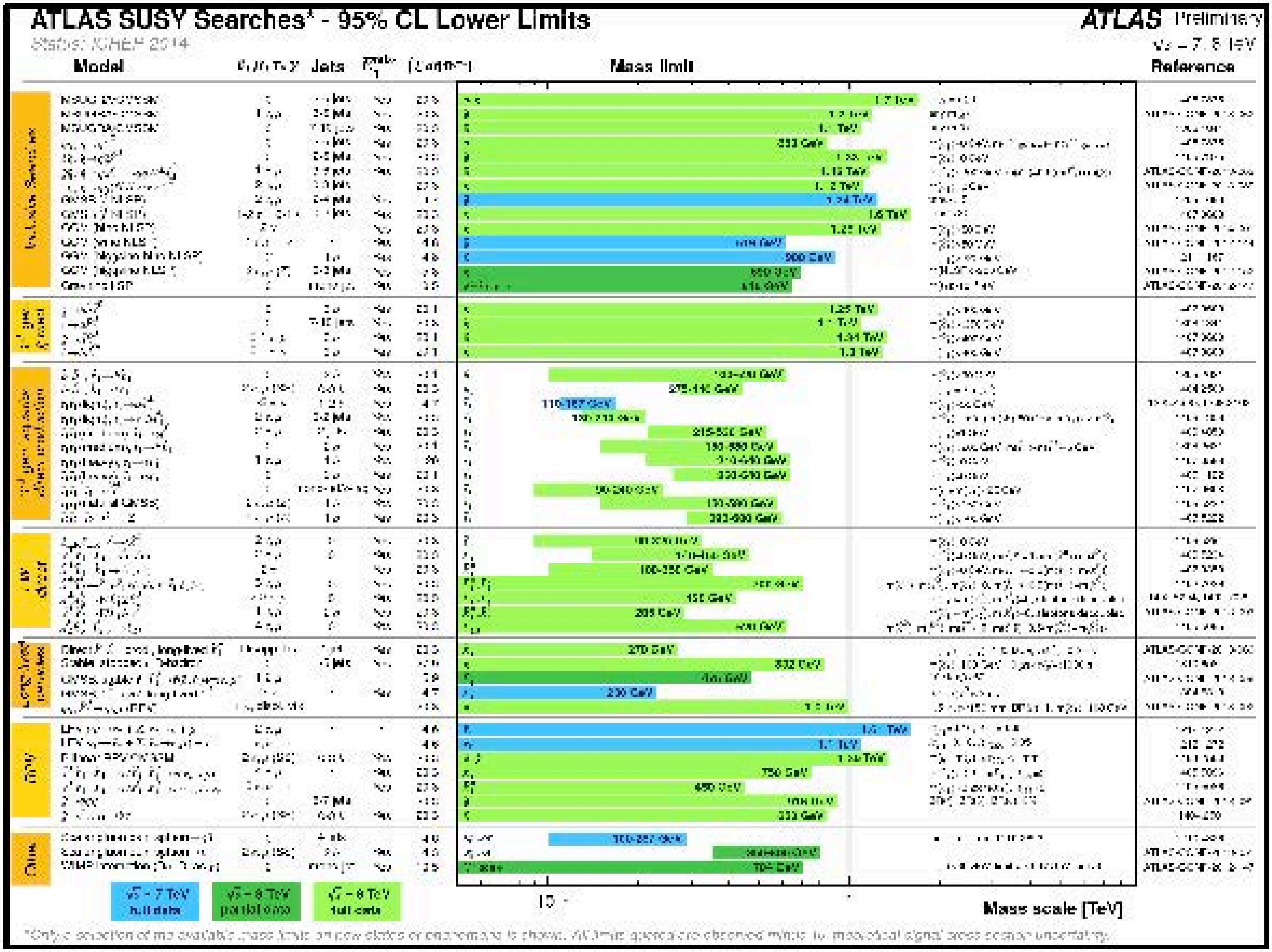
ANL/UIC

Kavli IPMU ACP Seminar
September 10, 2014

1405.6211
with Sally Dawson and Ian Low

After 8 TeV at the LHC, not much is around



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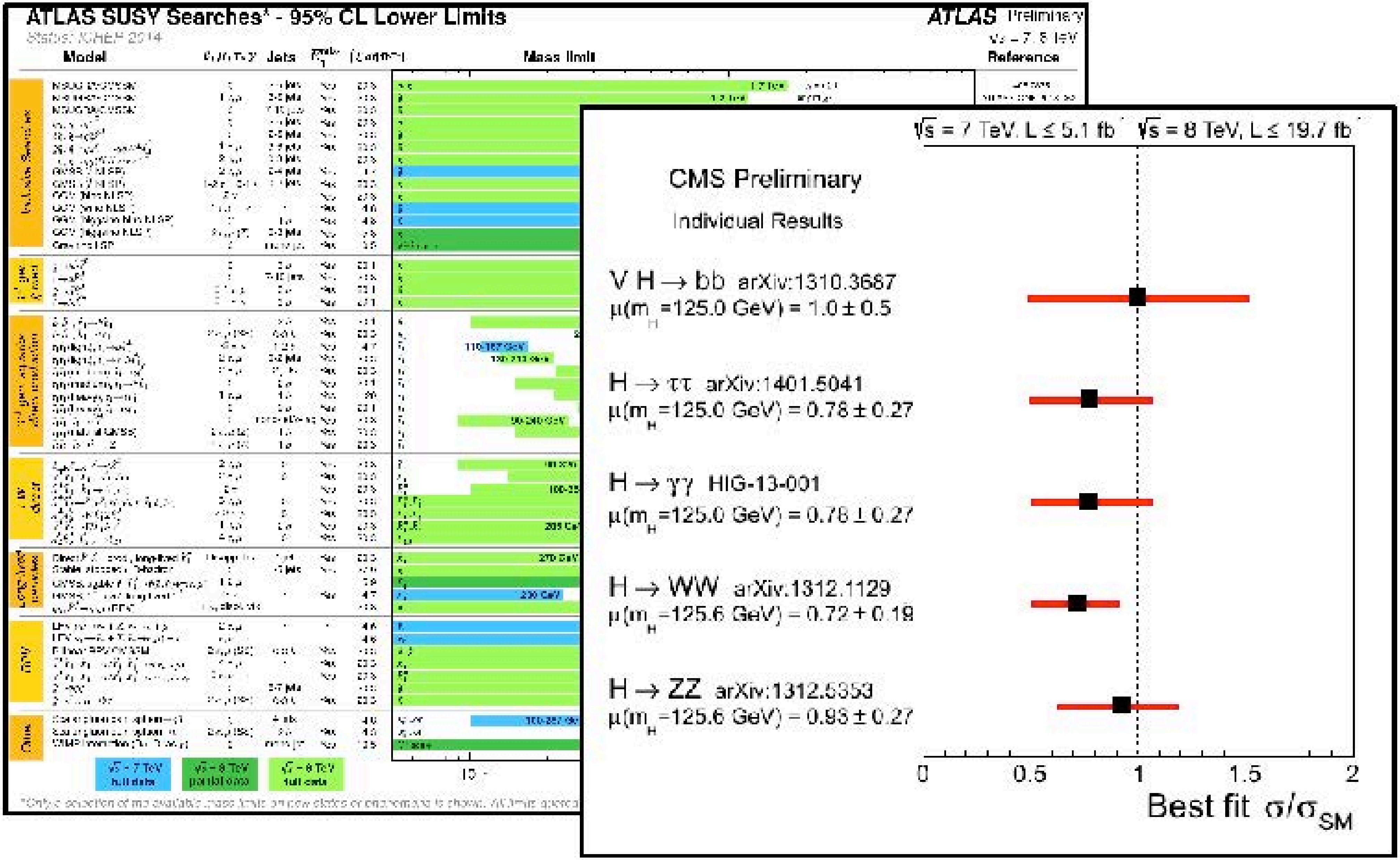

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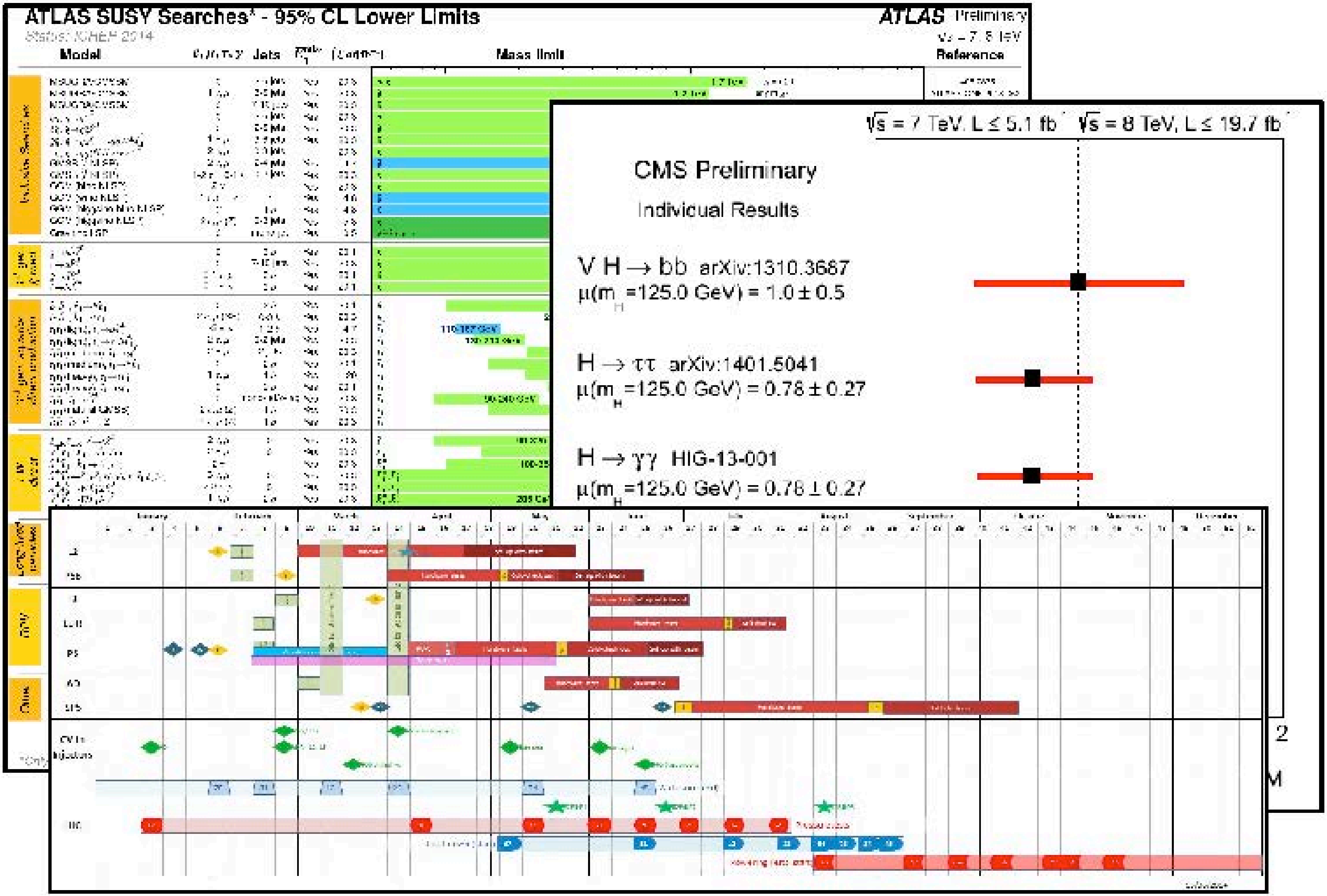
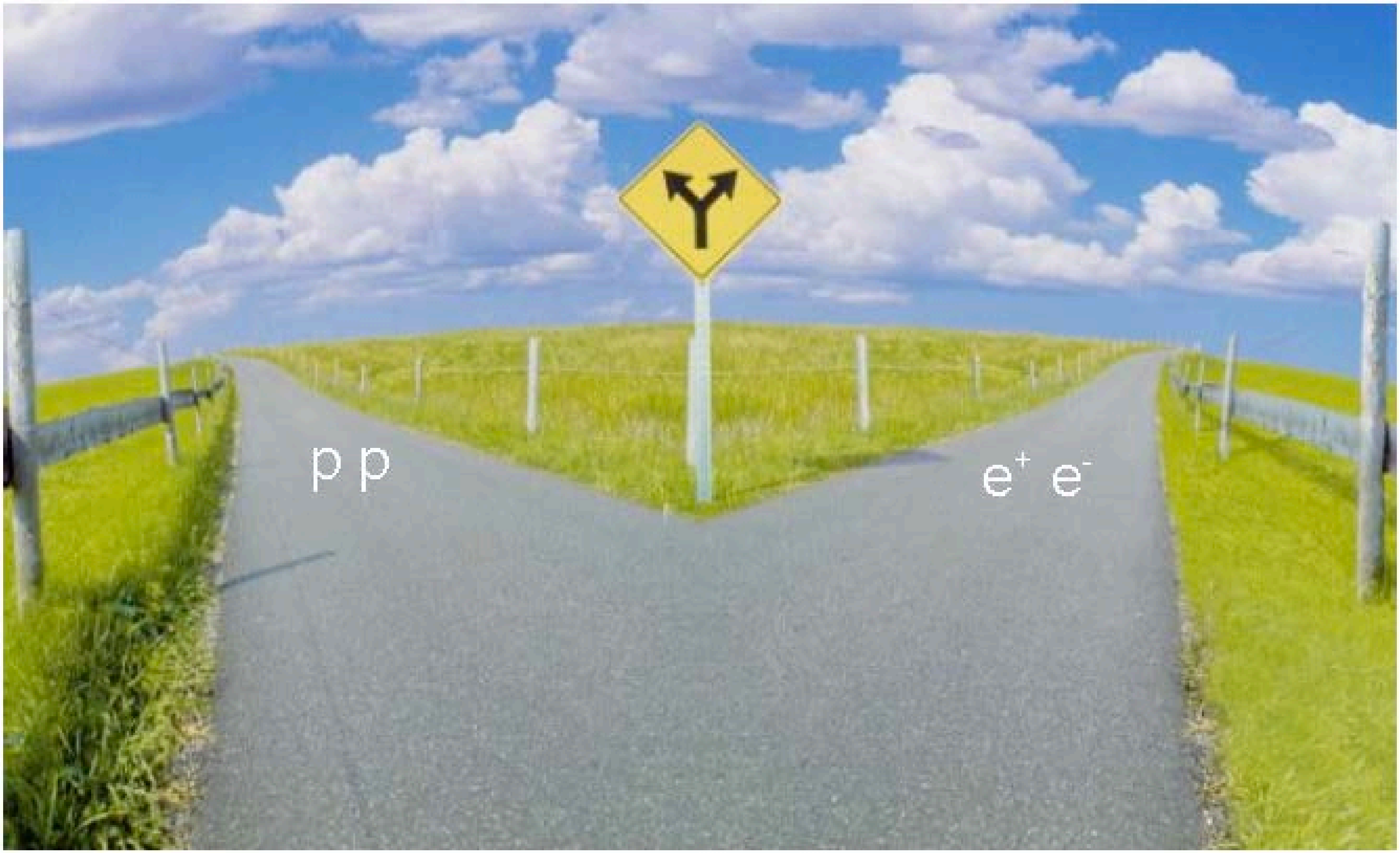


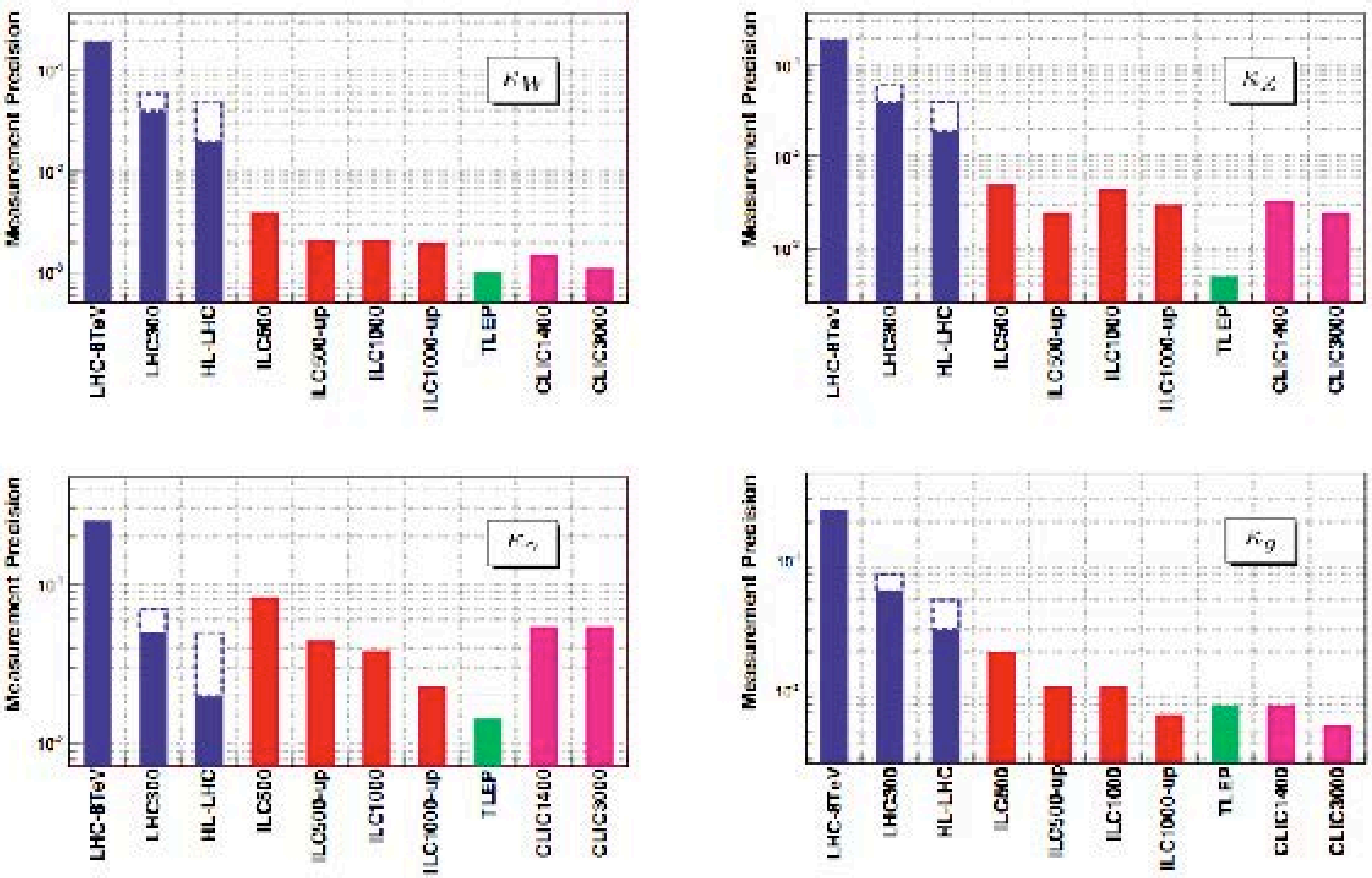
Where to go next?

- Two main paths possible for future colliders



Where to go next?

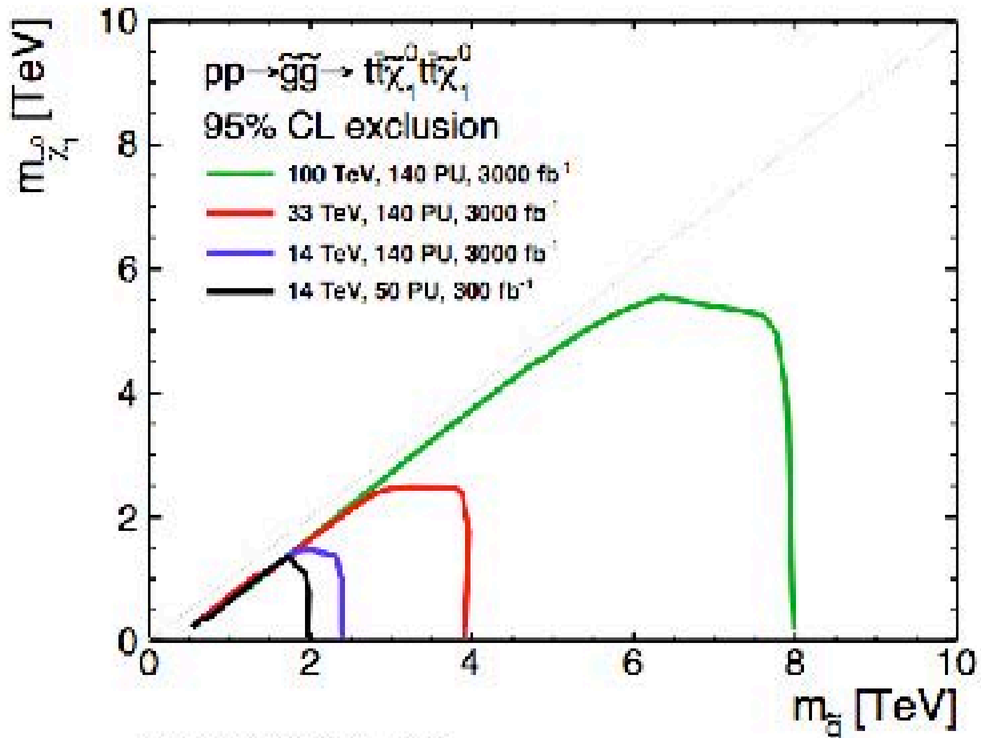
- A linear collider can do some things particularly well, e.g. measure Higgs couplings



Snowmass Higgs WG report
1310.8361

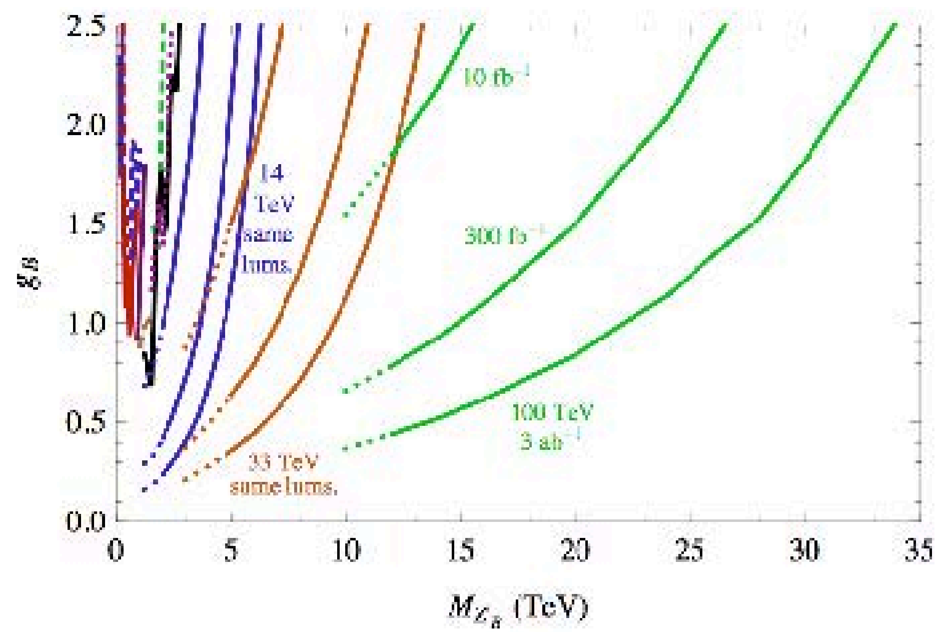
Where to go next?

- Many studies, however, are best served by going to higher energies



T. Cohen et al.
1310.0077

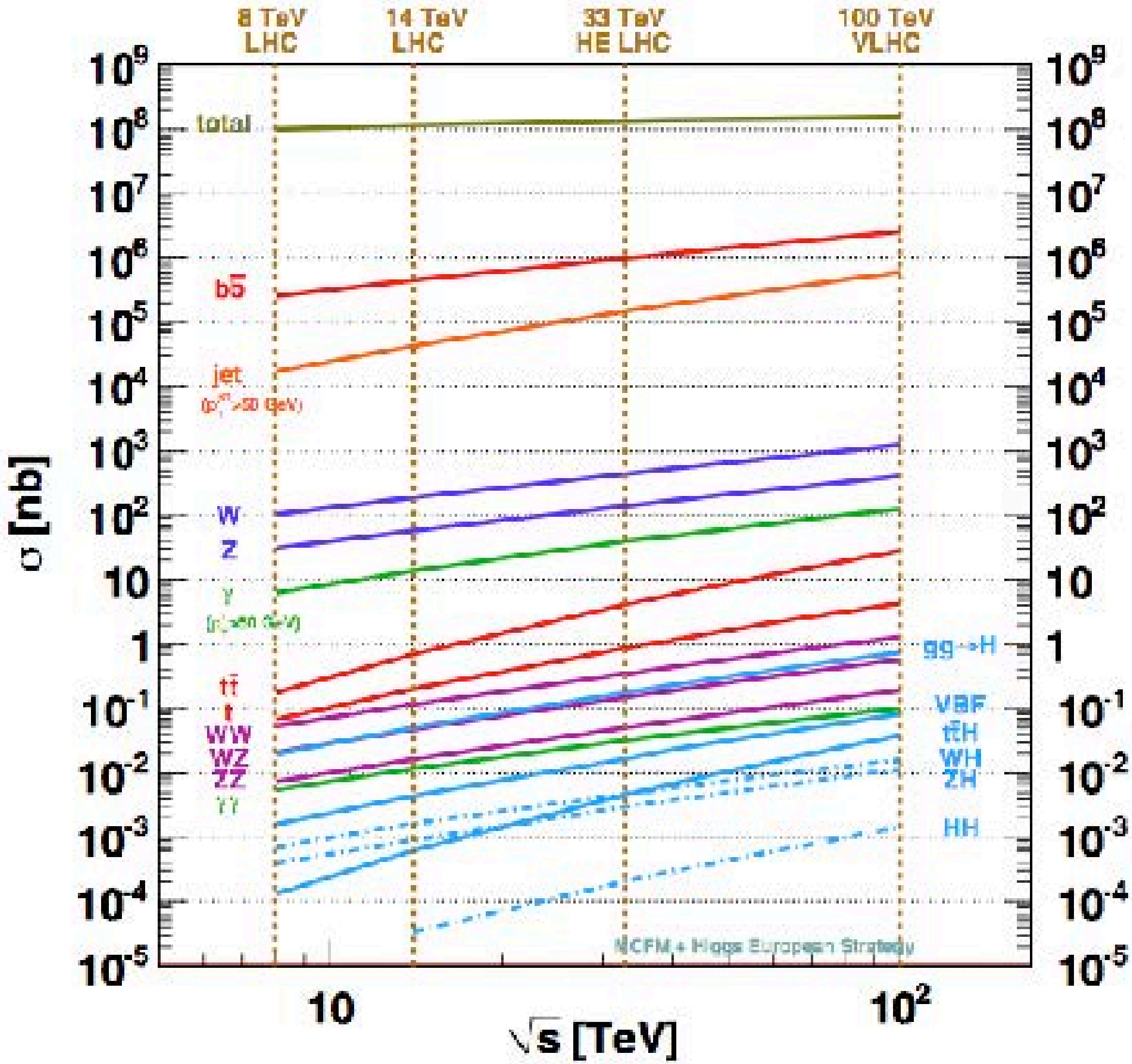
Searches for heavy BSM particles are the most obvious example



F. Yu
1308.1077

Where to go next?

- Even for processes involving SM particles only, high energy proton colliders can have something to say

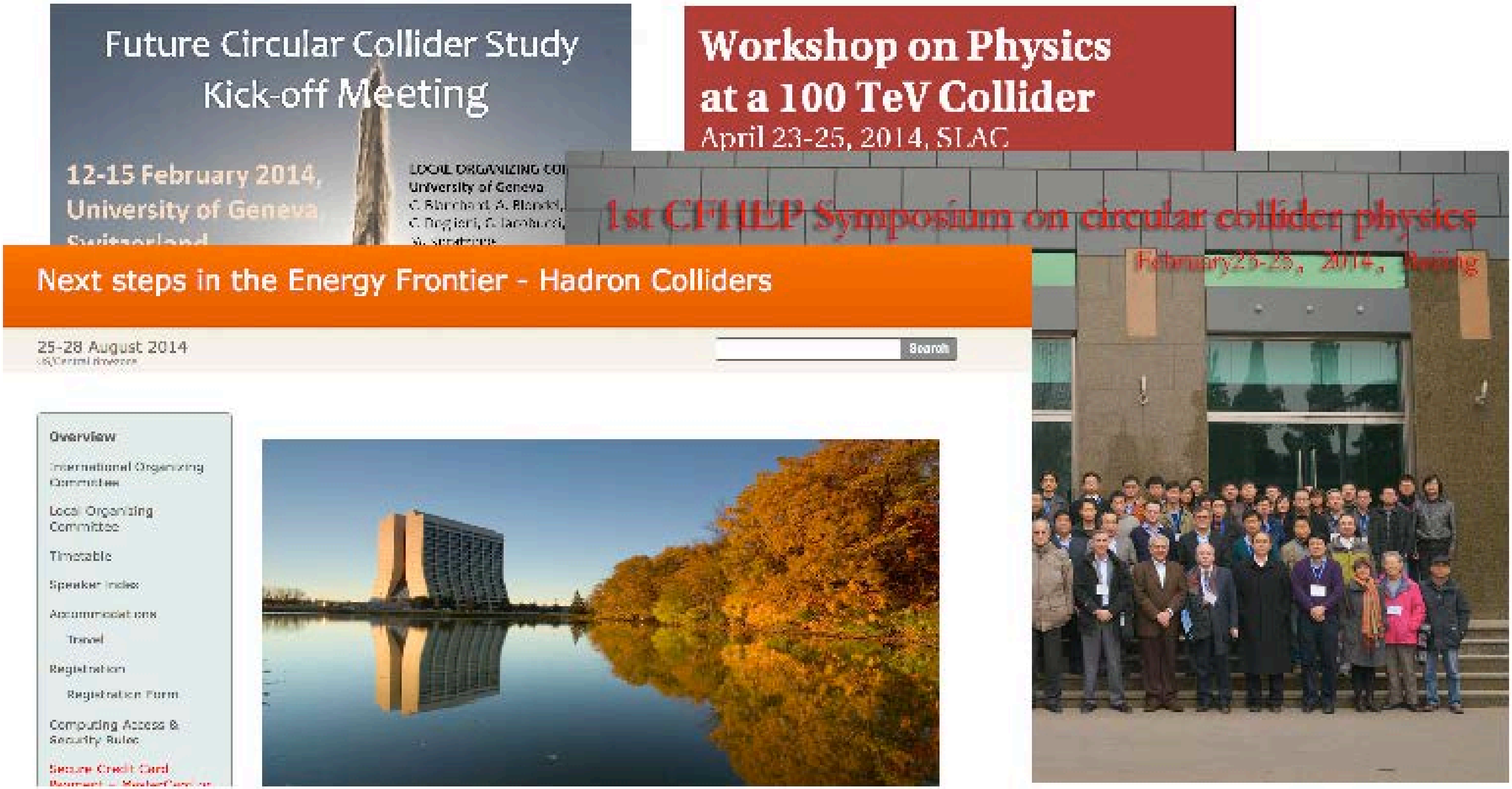


Cross sections for processes involving t and H increase substantially at high energies

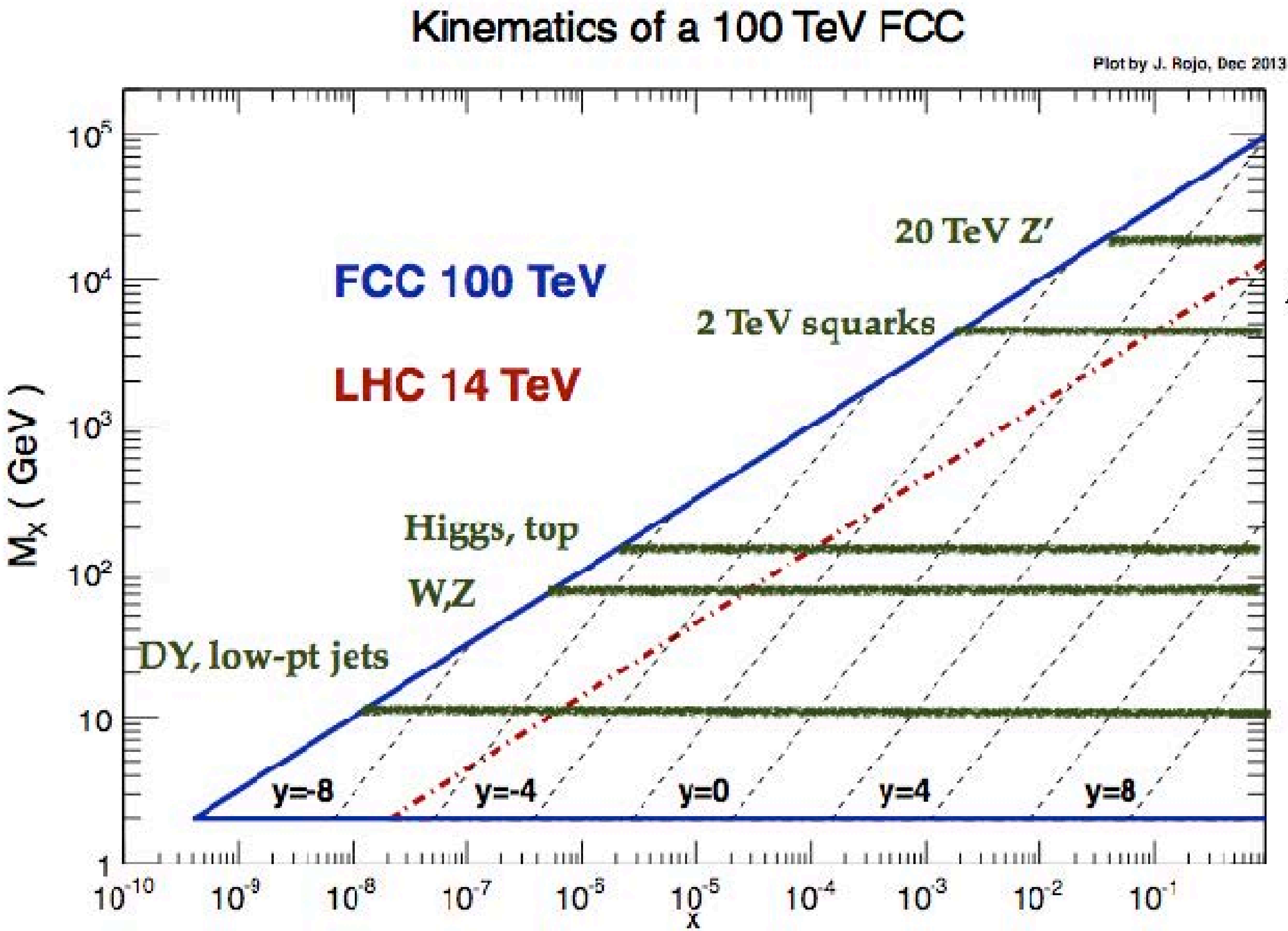
Snowmass QCD WG report 1310.5189

Where to go next?

- Recently, there has been renewed interest in future high energy proton colliders, centered around the prospect of a 100 TeV machine



A 100 TeV pp collider



$x = M_X e^y / \sqrt{s}$

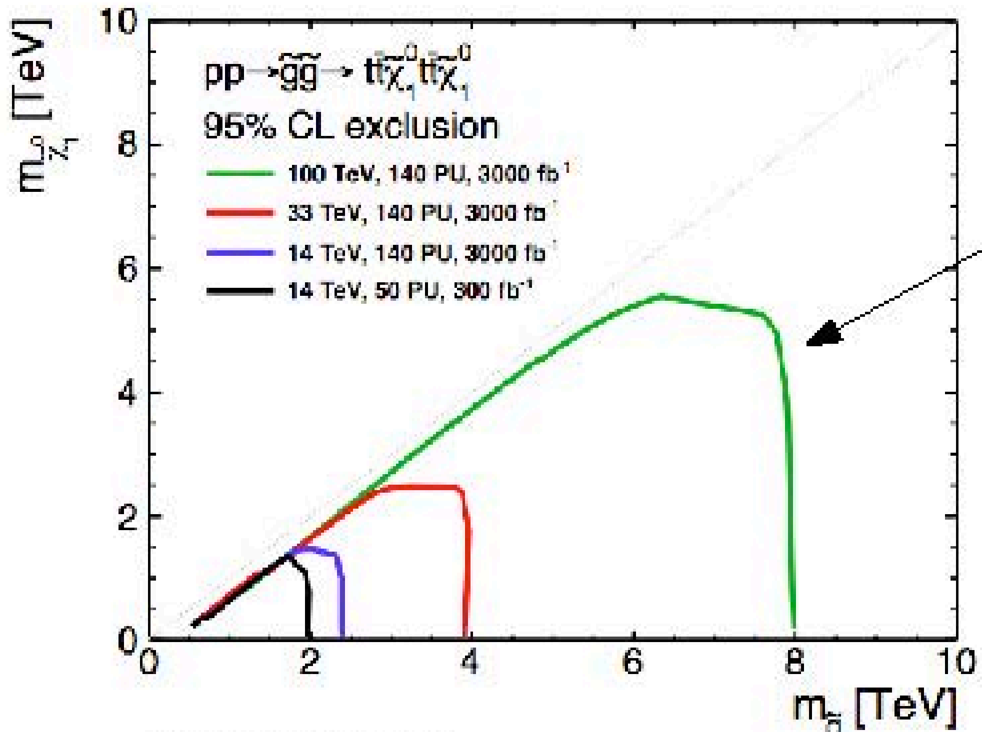
New reach at both high *and* low scales

A 100 TeV pp collider

- Work is clearly needed to investigate the power of a future collider
- BSM particle reach, Higgs couplings, rare SM processes are in principle all feasible studies; of course, the results depend on (and influence!) machine considerations
  - Calorimeter resolution?
  - How much luminosity is needed to attain real gains in physics?
  - Trigger, pileup considerations

A 100 TeV pp collider

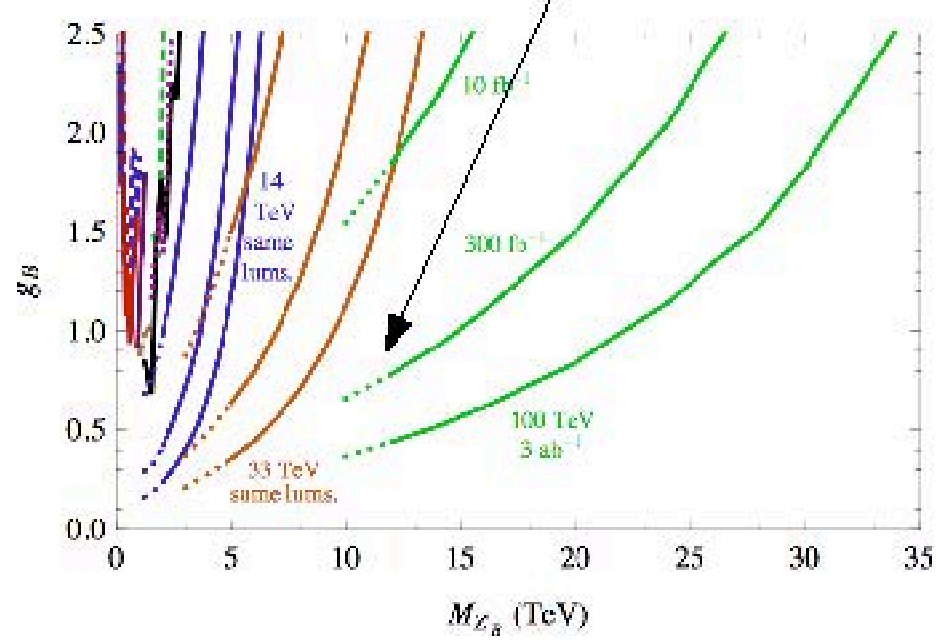
- Work is clearly needed to investigate the power of a future collider



T. Cohen et al.
1310.0077

pileup reduces lepton efficiencies due to isolation requirements

lower reach depends on multijet trigger thresholds



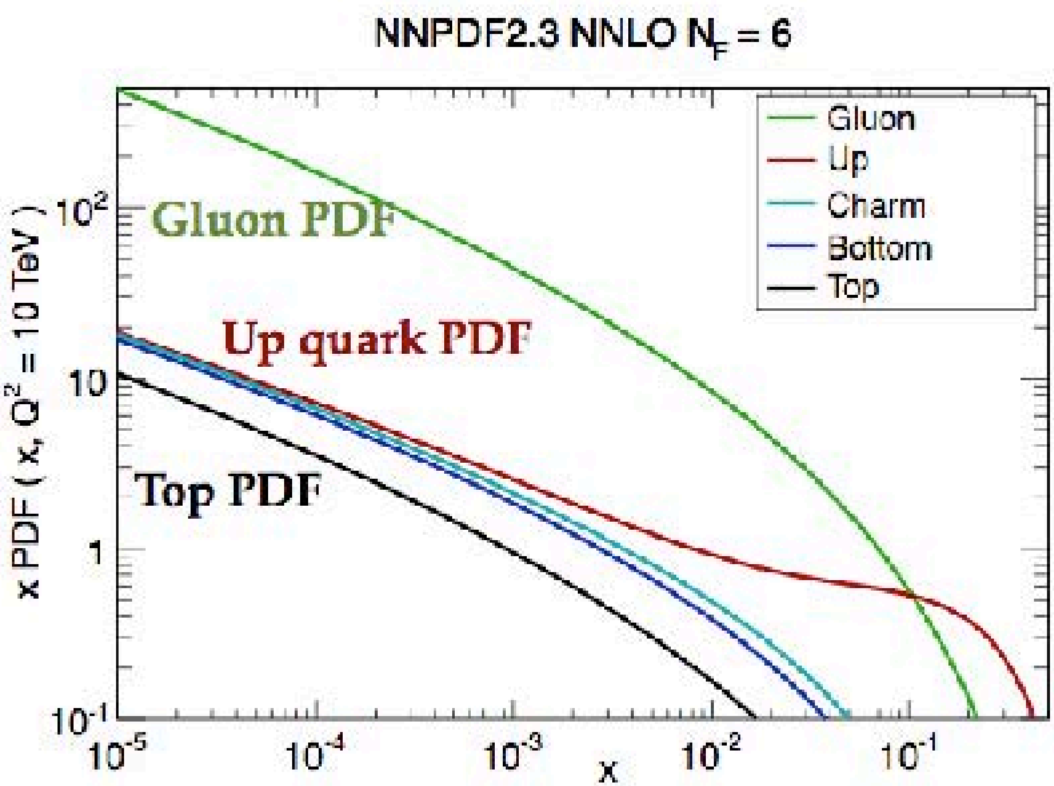
F. Yu
1308.1077

A 100 TeV pp collider

- There are also *qualitatively* new effects at high energies ~ 100 TeV
- As an example, electroweak radiation in jets is expected to become more important Manohar et al., 1409.1918
- Exotic signatures possible, e.g. W radiation from neutrinos Hook and Katz, 1407.2607
- Additionally, essentially all SM particles can now be routinely produced with high boost
- Motivates further development of jet substructure techniques Larkoski and Thaler, 1406.7011

A 100 TeV pp collider

- At 100 TeV, even "heavy" quarks have masses below scales of new processes
- Do we need to consider a top PDF?
- Most PDF sets only include five flavors

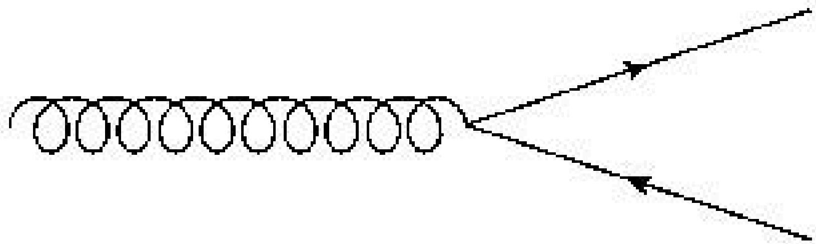


If included, top PDF is non-trivial in size at high scales

J. Rojo, Future Circular Collider Study Kickoff Meeting

Heavy quark PDFs

- Arise from gluon splitting at scales above quark mass



- Should be able to approximate heavy quark PDF

$$\tilde{f}_Q(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log \frac{\mu^2}{m_Q^2} \int_x^1 \frac{dz}{z} P_{qg}(z) f_g(\frac{x}{z},\mu)$$

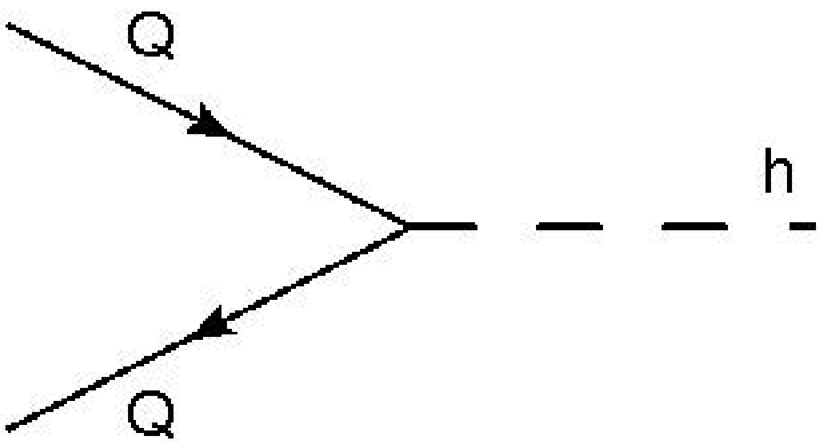
splitting function

gluon PDF

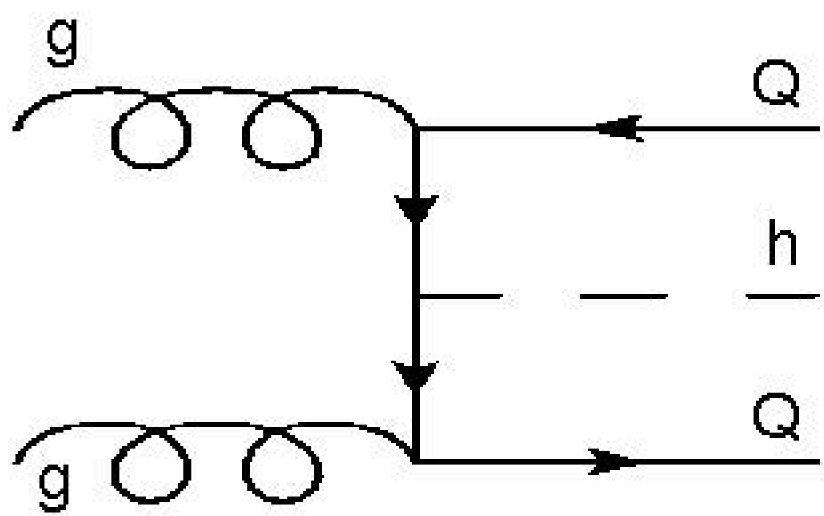
$$P_{qg}(z) = \frac{1}{2}\left(z^2 + (1-z)^2\right)$$

Heavy quark PDFs

- If we could calculate to infinite order, it wouldn't matter whether we used a heavy quark PDF or not
- As an example, consider h + X production in the PDF schemes with and without the heavy quark



Massless scheme
NF = N

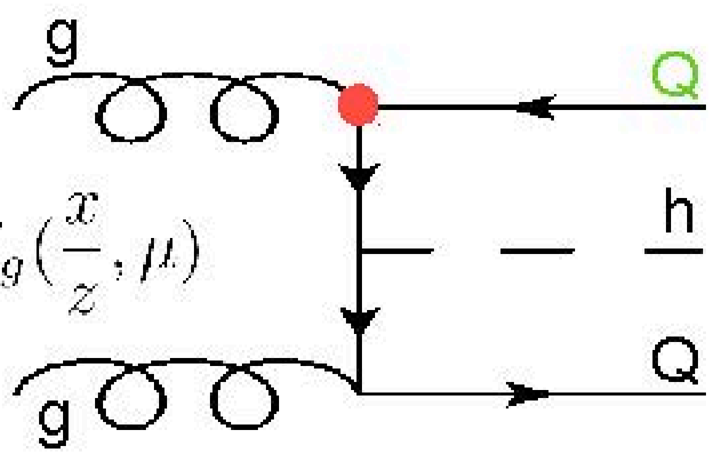


Massive scheme
NF = N - 1

Heavy quark PDFs

- In the scheme without a heavy quark PDF, the leading diagram for h + X production has a collinear divergence
- When we integrate over the phase space for Q, we pick up a factor $\log(m_h / m_Q)$, as the quark mass regulates this divergence
- At large m_h, this is just the approximate heavy quark distribution

$$\tilde{f}_Q(x,\mu) = \frac{\alpha_s(\mu)}{2\pi}\log\frac{\mu^2}{m_Q^2}\int_x^1 \frac{dz}{z} P_{qg}(z) f_g(\frac{x}{z},\mu)$$



Heavy quark PDFs

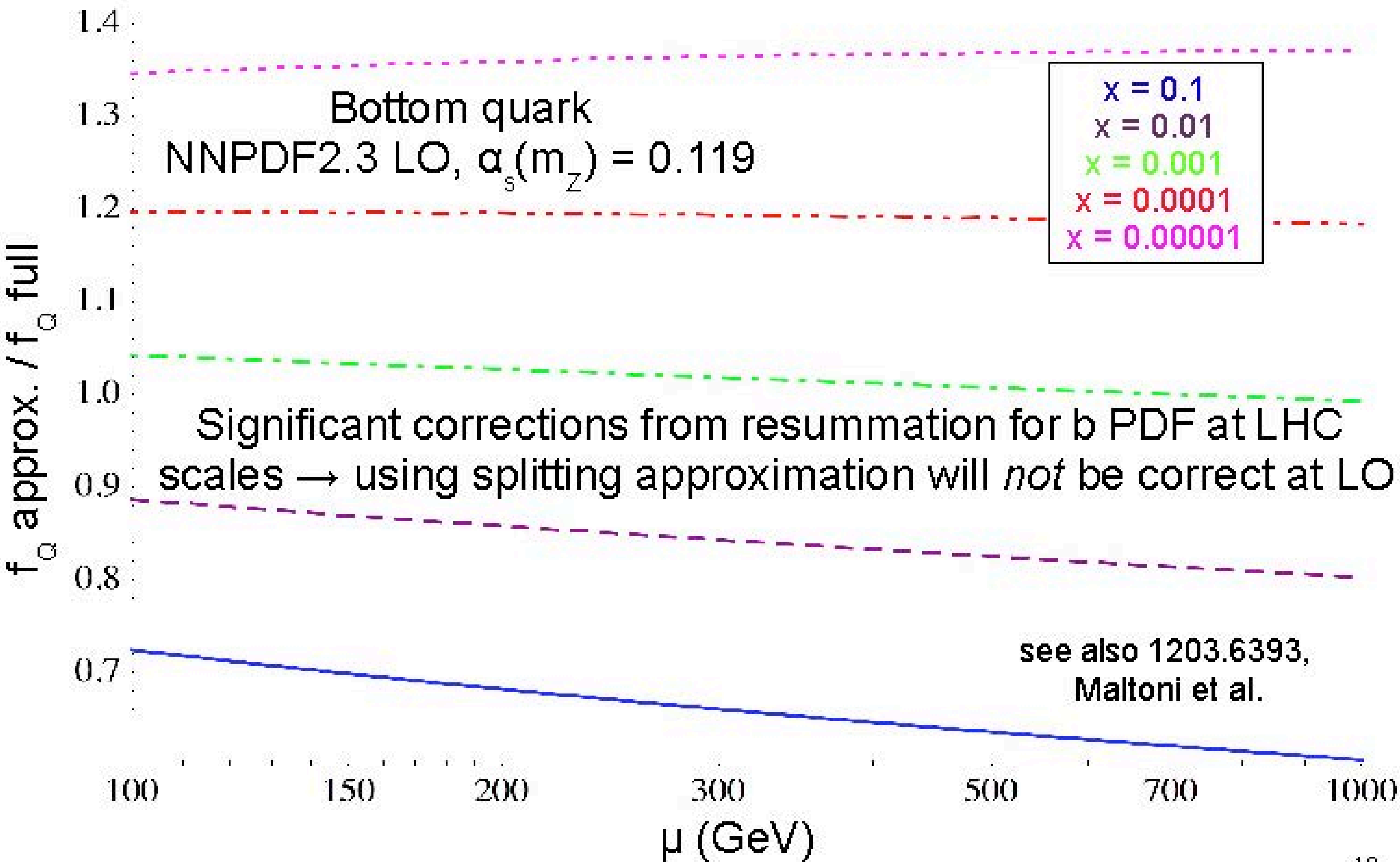
- To get the full heavy quark PDF at leading order, we would have to numerically solve the LO DGLAP equations

$$\frac{d}{d\log\mu^2} f_Q(x,\mu) = \frac{\alpha_s(\mu)}{2\pi}\int_x^1 \frac{dz}{z}\Big(P_{qq}(z) f_Q(\frac{x}{z};\mu) + P_{qg}(z) f_g(\frac{x}{z};\mu)\Big)$$

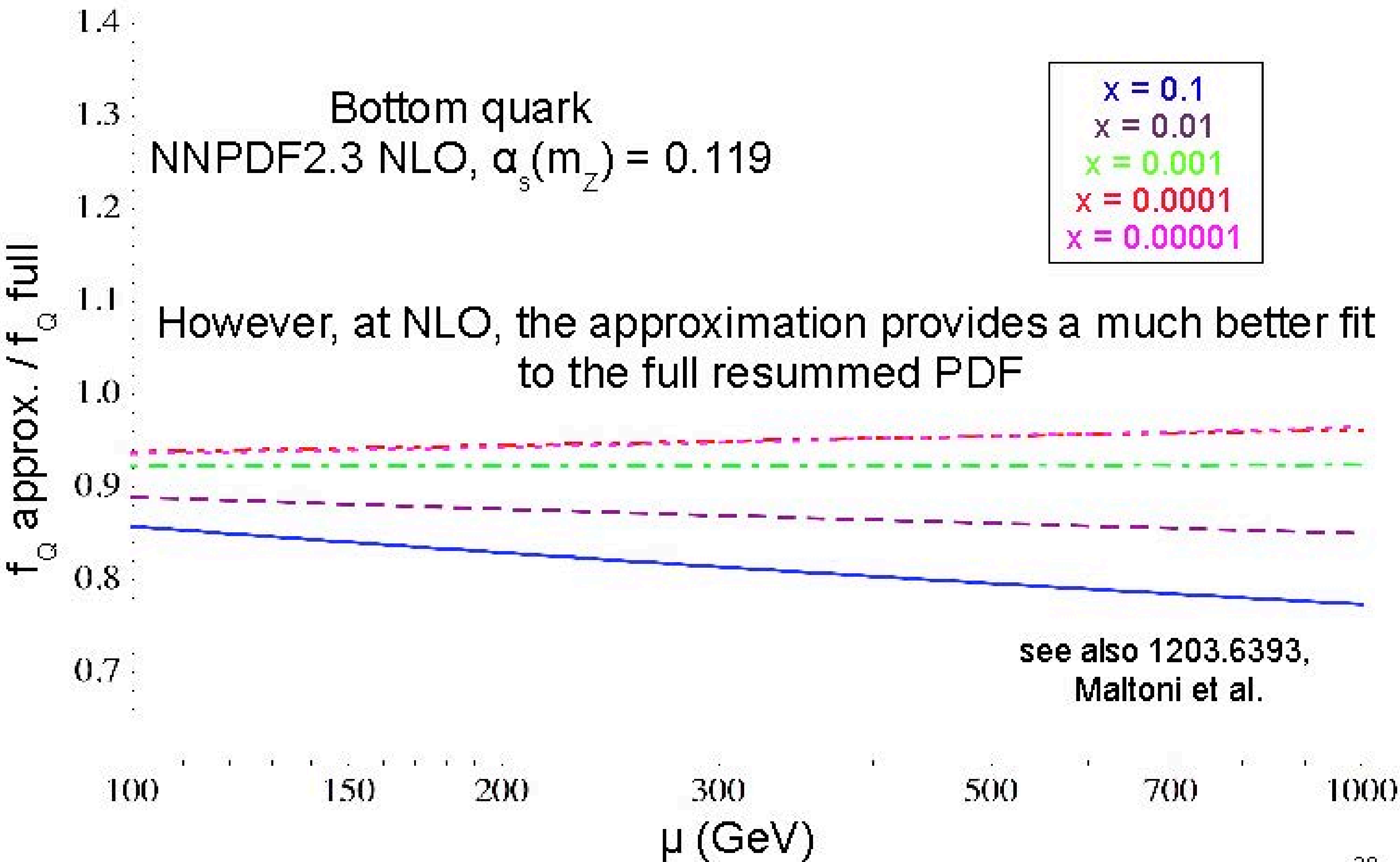
$$f_Q(x, m_Q) = 0$$

- Physically, the difference between our approximation and the full LO heavy quark PDF is the resummation of the logarithms corresponding to multiple parton splittings that are strongly ordered
- How important is this resummation?

Heavy quark PDFs

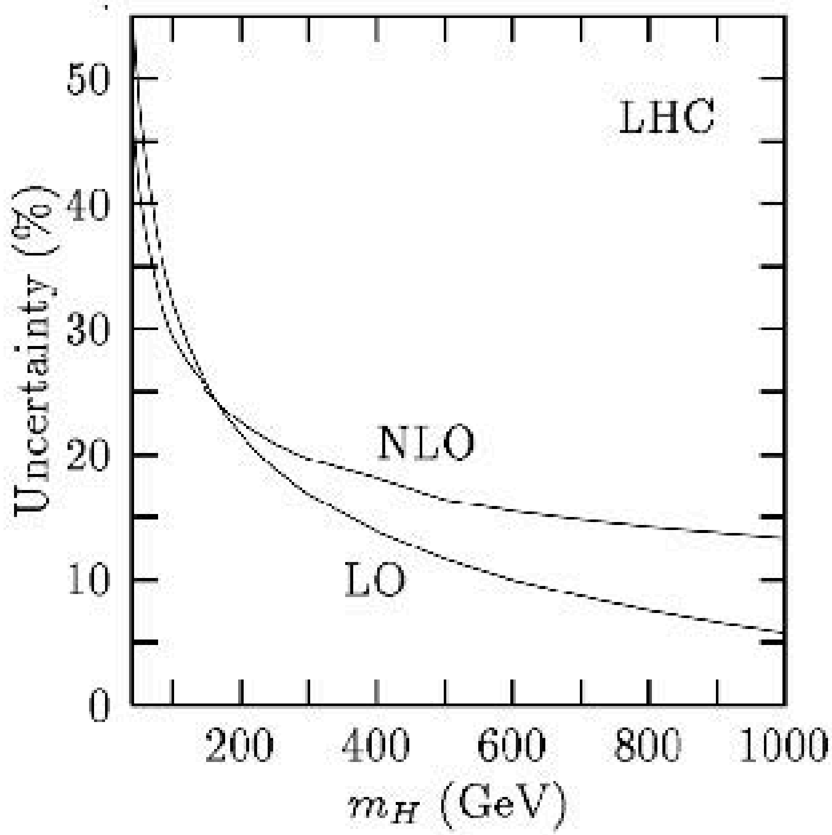


Heavy quark PDFs



Heavy quark PDFs

- So, for inclusive Higgs production in association with bottom quarks, the 4- and 5-flavor number schemes should give similar predictions at NLO for the LHC
- Scale uncertainties are sizable at NLO, unfortunately....

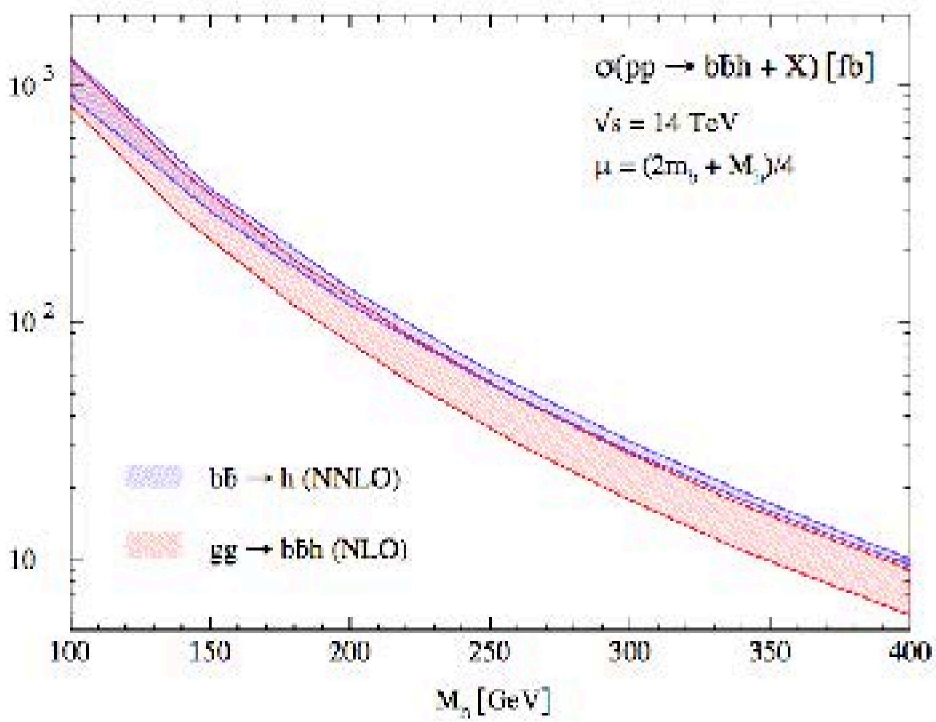


Scale uncertainty of NLO inclusive Higgs production in association with bottom quarks, calculated in 5-flavor number scheme

Dicus et al., hep-ph/9811492

Heavy quark PDFs

- After going to NNLO, different schemes agree quite well, with smaller scale uncertainties

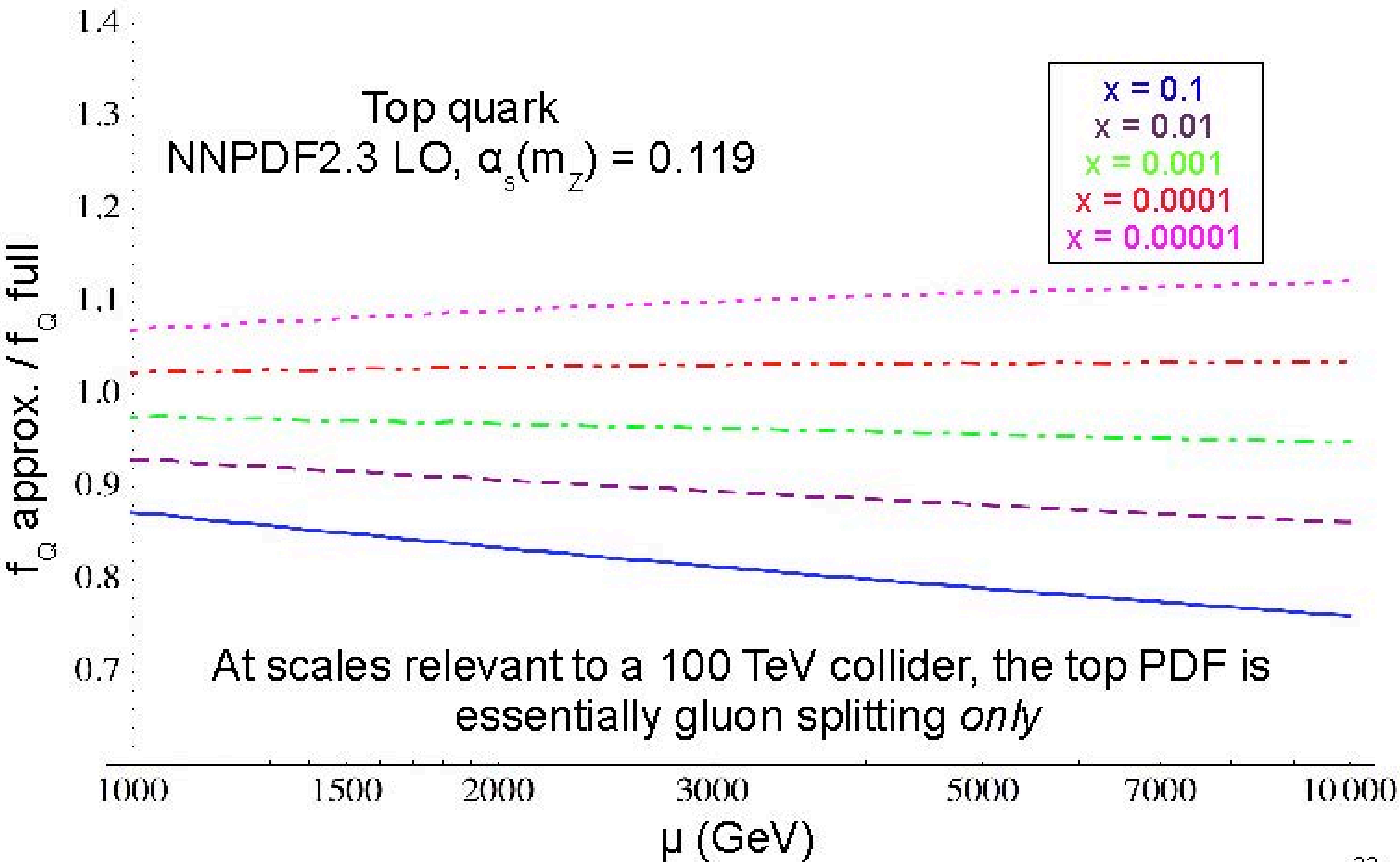


Inclusive Higgs production in association with bottom quarks, 4FNS vs. 5FNS

Campbell et al., hep-ph/0405302

- Much more has been said about the role of heavy quark PDFs in b-initiated Higgs processes at the LHC

Heavy quark PDFs



Heavy quark PDFs

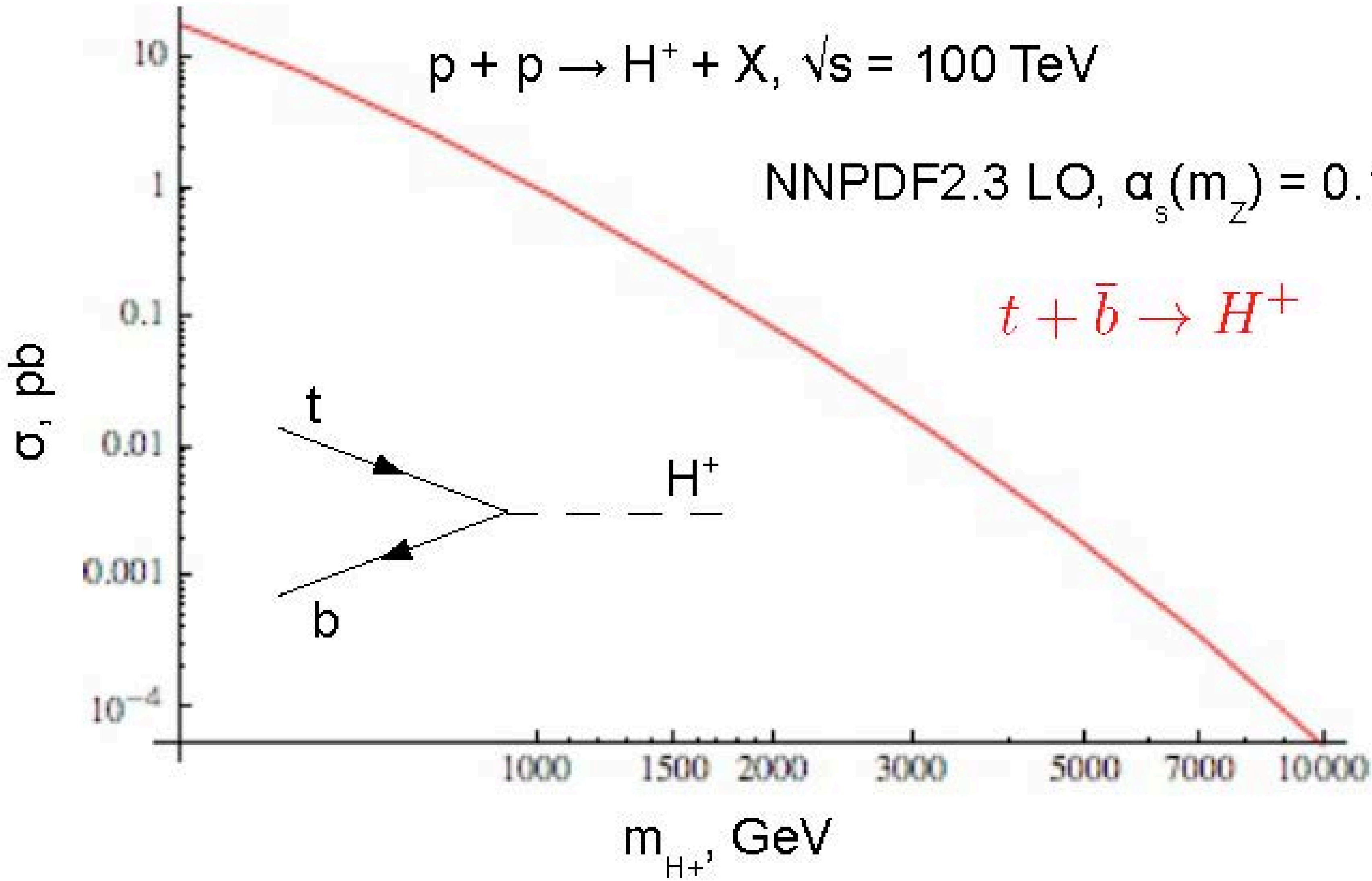
- The approximate top PDF at 100 TeV works better than the approximate bottom PDF at the LHC
- The difference can be attributed to the fact that $\alpha_s(\mu) \log(\mu / m_Q)$ is smaller in the former case
- So we should expect that in general, the 5- and 6-flavor schemes give similar results at a 100 TeV collider for processes involving top quarks
- Only at very high scales, when the log gets large, should there be any appreciable difference between the schemes

Charged Higgs production

- We can now apply our PDF studies to a sample process at 100 TeV
- Charged Higgses are generic in models with additional Higgs multiplets, with significant couplings to heavy quarks
- To what extent must we calculate H^+ production using a top PDF? Barnett, Haber and Soper, Nucl. Phys. B306 (1988) 697
  Olness and Tung, Nucl. Phys. B308 (1988) 813
- We will outline the computation of the cross section in the NF = 6 scheme, including the top PDF
- Assume MSSM-type couplings with tan β = 5 for numerics, but this is just an overall factor

Charged Higgs production

- Leading diagram is $t + \bar{b} \to H^+$



Charged Higgs production

- Can organize terms in charged Higgs production cross section according to powers of strong coupling and large logs; first term in 6FNS gives leading log
- The different flavor number schemes sum these terms differently, but of course the final results would be identical if we could work to infinite order

Powers of strong coupling →

Fewer logs ↓

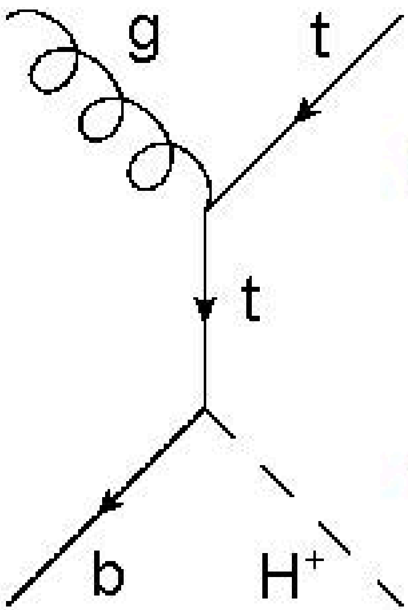
$\alpha_s \log \frac{m_H}{m_t}$	$\alpha_s^2 \log^2 \frac{m_H}{m_t}$	$\alpha_s^3 \log^3 \frac{m_H}{m_t}$	$\ldots$
α_s	$\alpha_s^2 \log \frac{m_H}{m_t}$	$\alpha_s^3 \log^2 \frac{m_H}{m_t}$	$\ldots$
	α_s^2	$\alpha_s^3 \log \frac{m_H}{m_t}$	$\ldots$
		$\ldots$	$\ldots$

$t + \bar{b} \to H^+$

Charged Higgs production

- In 6FNS, next we have $g+\bar{b}\rightarrow\bar{t}+H^+$

  (note this is the leading diagram for NF = 5)
- In the limit $m_t \rightarrow 0$, this process has a divergence, but it's regulated by the top mass
- Adding it to the previous process would be double-counting the collinear gluon splitting



$\alpha_s \log \frac{m_H}{m_t}$	$\alpha_s^2 \log^2 \frac{m_H}{m_t}$	$\alpha_s^3 \log^3 \frac{m_H}{m_t}$	$\dots$
α_s	$\alpha_s^2 \log \frac{m_H}{m_t}$	$\alpha_s^3 \log^2 \frac{m_H}{m_t}$	$\dots$
	α_s^2	$\alpha_s^3 \log \frac{m_H}{m_t}$	$\dots$
		$\dots$	$\dots$

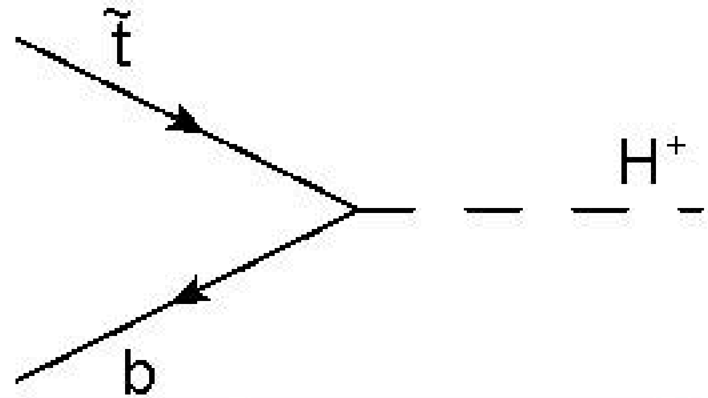
$g+\bar{b}\rightarrow\bar{t}+H^+$

Charged Higgs production

- To avoid double-counting, need to perform subtraction
- Use approximate top PDF

$$\tilde{f}_Q(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log \frac{\mu^2}{m_Q^2} \int_x^1 \frac{dz}{z} P_{qg}(z) f_g(\frac{x}{z}, \mu)$$

Subtract from sum of previous two processes

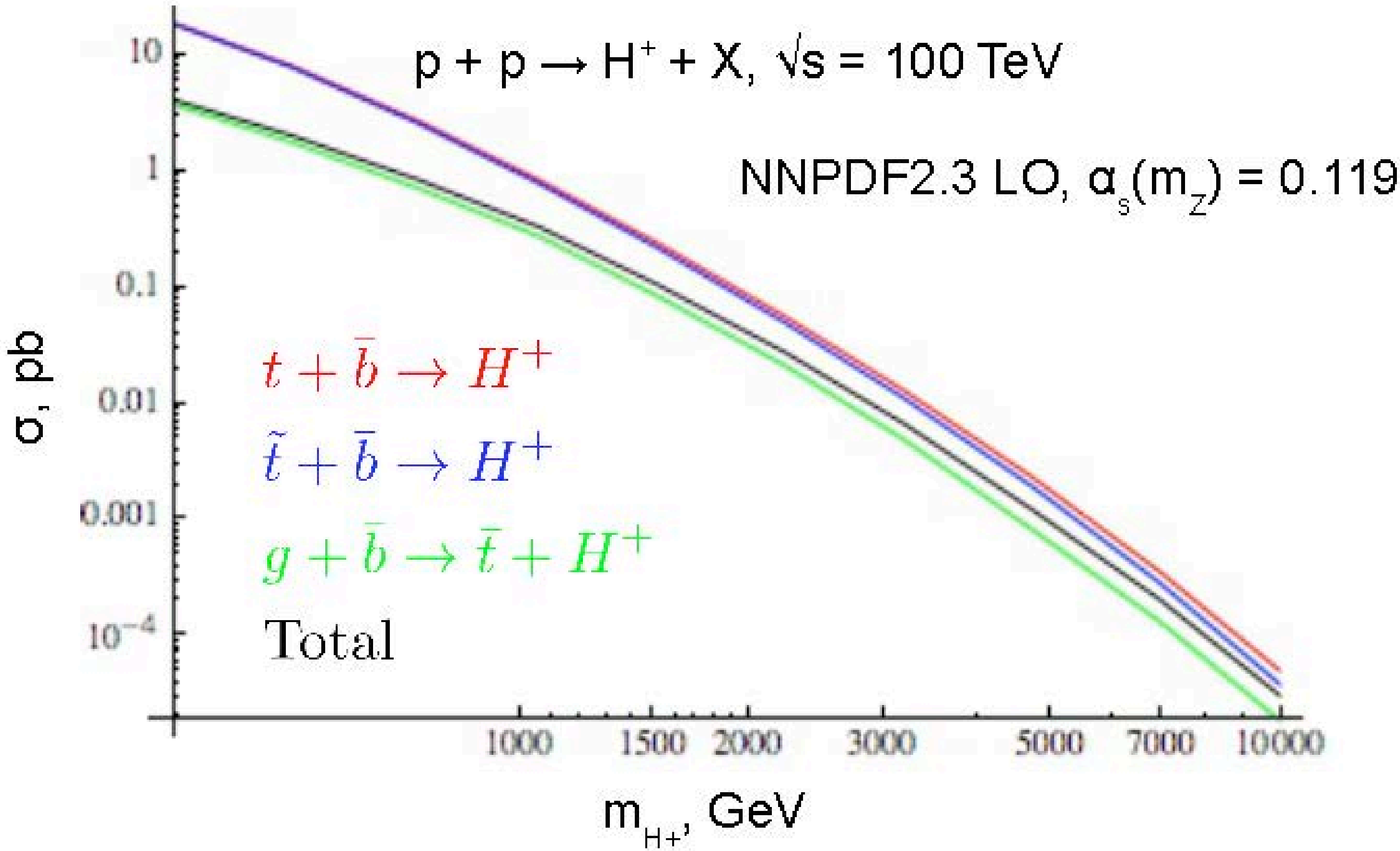


$\alpha_s \log \frac{m_H}{m_t}$	$\alpha_s^2 \log^2 \frac{m_H}{m_t}$	$\alpha_s^3 \log^3 \frac{m_H}{m_t}$	$\cdots$
α_s	$\alpha_s^2 \log \frac{m_H}{m_t}$	$\alpha_s^3 \log^2 \frac{m_H}{m_t}$	$\cdots$
	α_s^2	$\alpha_s^3 \log \frac{m_H}{m_t}$	$\cdots$
		$\cdots$	$\cdots$

$\tilde{t} + \bar{b} \rightarrow H^+$

Charged Higgs production

- Subtraction term matches leading log well up to high scales, indicating negligible resummation effects



Charged Higgs production

- As expected, the full top PDF is well approximated by single gluon splitting, and the difference between full LL and gluon splitting is only significant at large scales
- This indicates that the effect of resumming large logs coming from the top phase space is small
- In fact, phase space suppression yields a log even smaller than the ratio of scales we would roughly estimate

$$\log \frac{\mu^2}{m_t^2} \leftarrow \mu^2 = m_{H+}^2 \frac{(1-z)^2}{z}, z = m_{H+}^2/\hat{s}$$

- This phase space suppression is generic for processes involving heavy quarks

Charged Higgs production

- The cross section is now complete up to terms of order α_s^2 (log m_H / m_t) and higher
- Full NLL requires a few more components

(so far: leading order plus leading log)

$\alpha_s \log \frac{m_H}{m_t}$	$\alpha_s^2 \log^2 \frac{m_H}{m_t}$	$\alpha_s^3 \log^3 \frac{m_H}{m_t}$	$\ldots$
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Charged Higgs production

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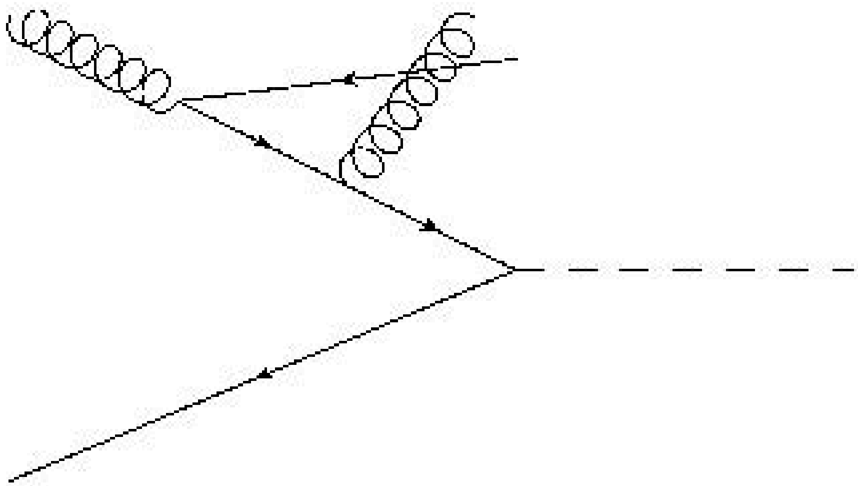
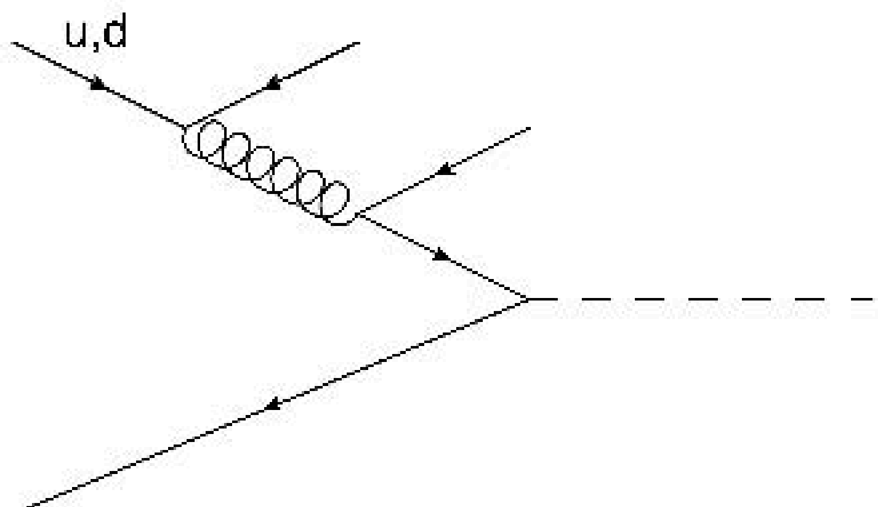
  - NLO PDFs rather than LO PDFs



out of order splittings

splittings from light quarks



Charged Higgs production

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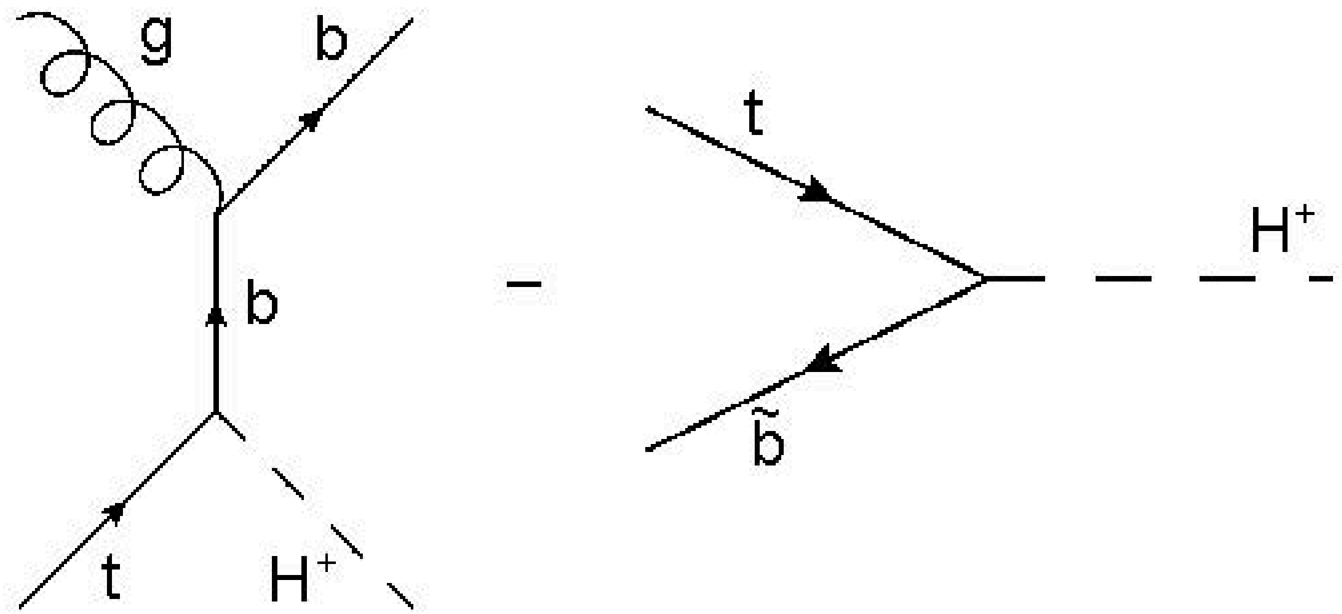
  - The log-suppressed process $g + t \to b + H^+$ with the appropriate subtraction term



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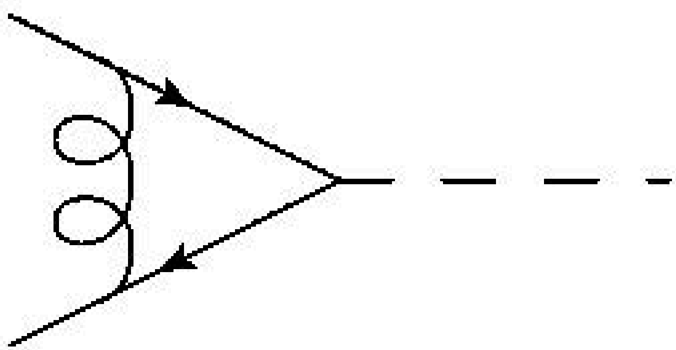
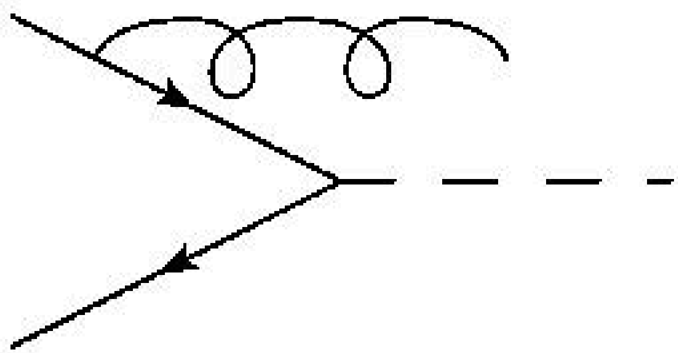
  - The log-suppressed process $g + t \to b + H^+$ with the appropriate subtraction term
  - The virtual and real corrections to $t + \bar{b} \to H^+$





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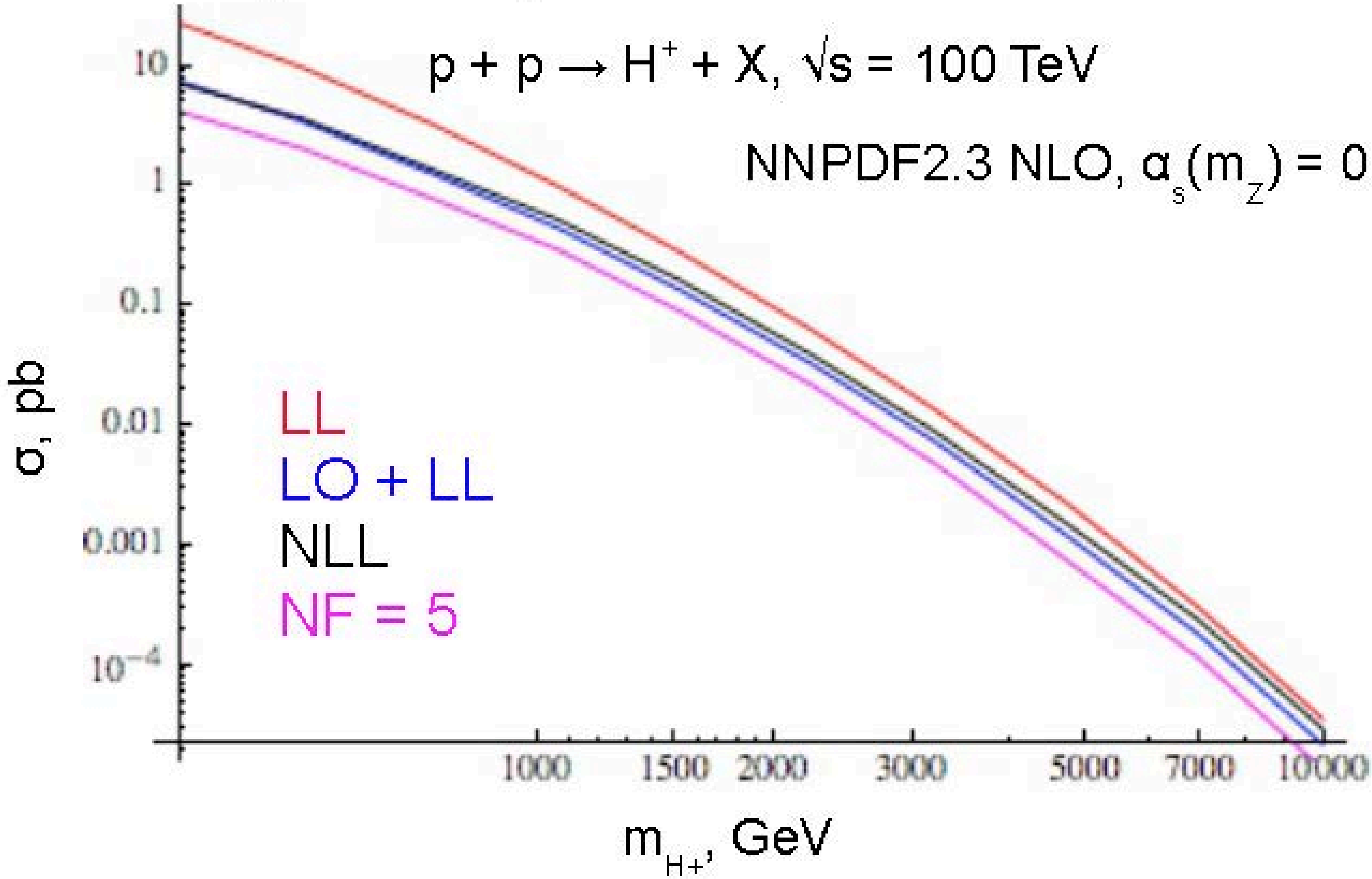
$\alpha_s \log \frac{m_H}{m_t}$	$\alpha_s^2 \log^2 \frac{m_H}{m_t}$	$\alpha_s^3 \log^3 \frac{m_H}{m_t}$	$\ldots$
α_s	$\alpha_s^2 \log \frac{m_H}{m_t}$	$\alpha_s^3 \log^2 \frac{m_H}{m_t}$	$\ldots$
	α_s^2	$\alpha_s^3 \log \frac{m_H}{m_t}$	$\ldots$
		$\ldots$	$\ldots$

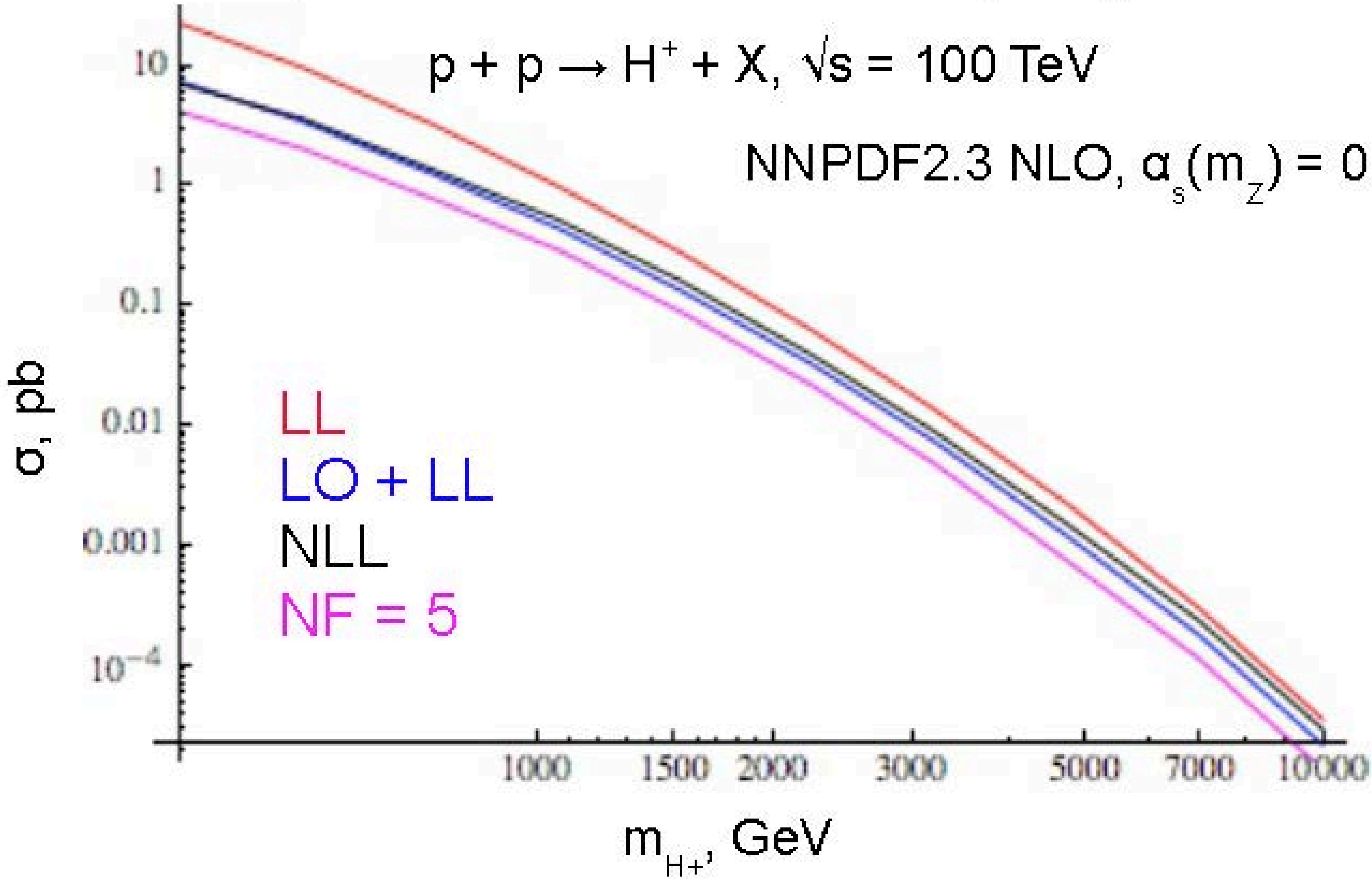
Charged Higgs production

- Going from LO + LL to full NLL doesn't change much, indicating that the perturbation series is under control



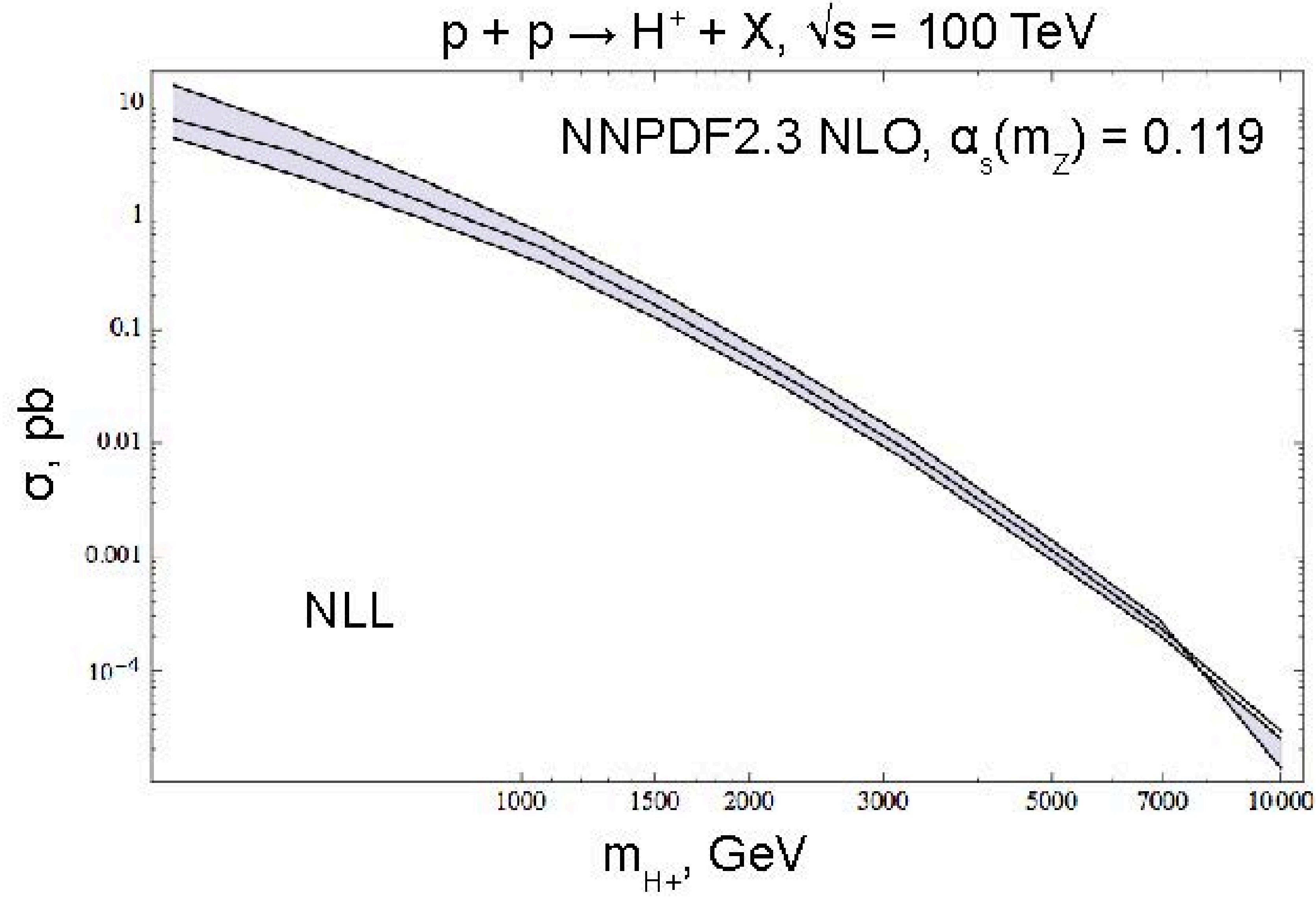
Charged Higgs production

- Total cross section is well approximated by the NF = 5 scheme up to factors of a few at very large H^+ mass



Charged Higgs production

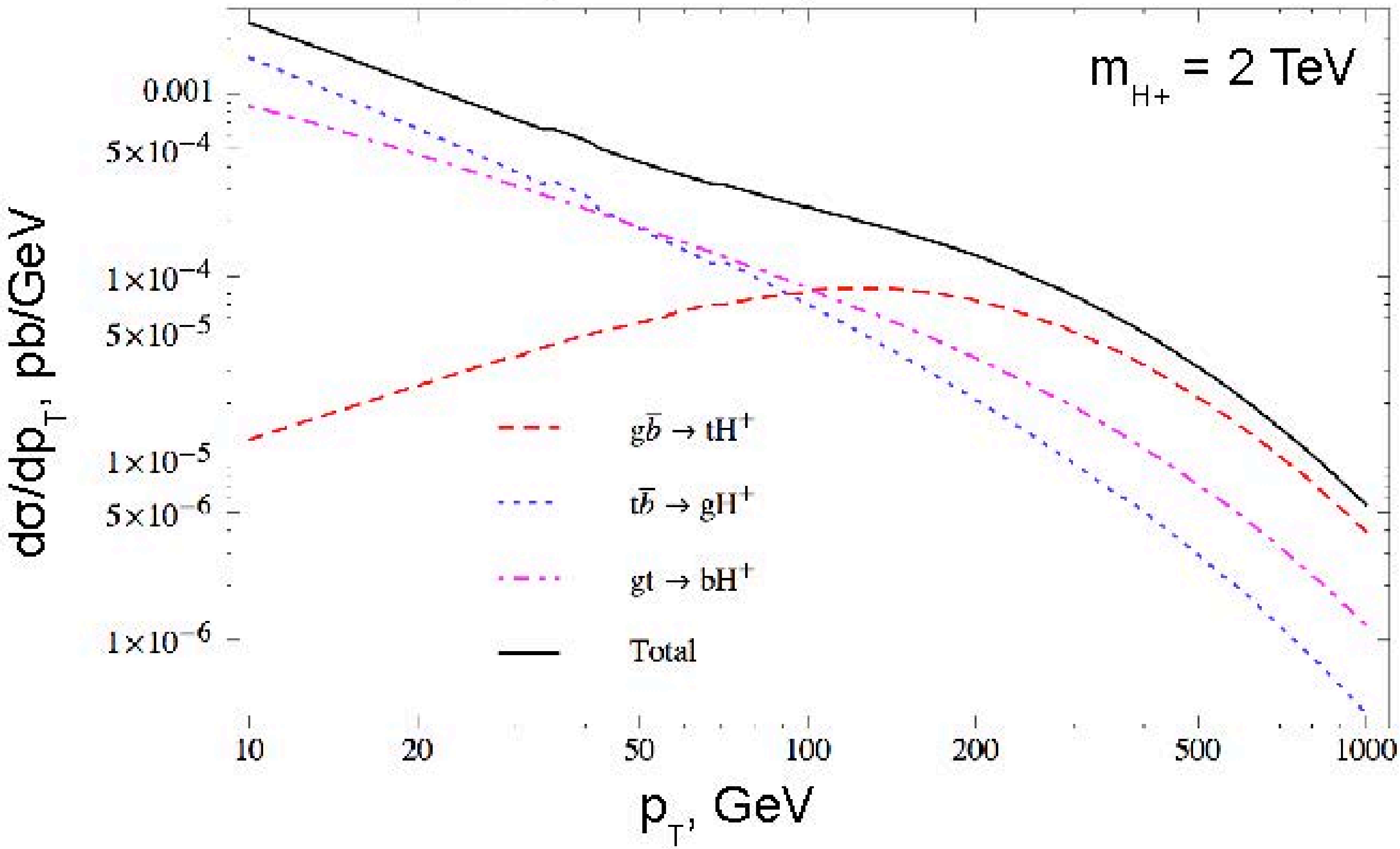
- At high charged Higgs mass, differences between schemes is small compared to scale uncertainty



Charged Higgs production

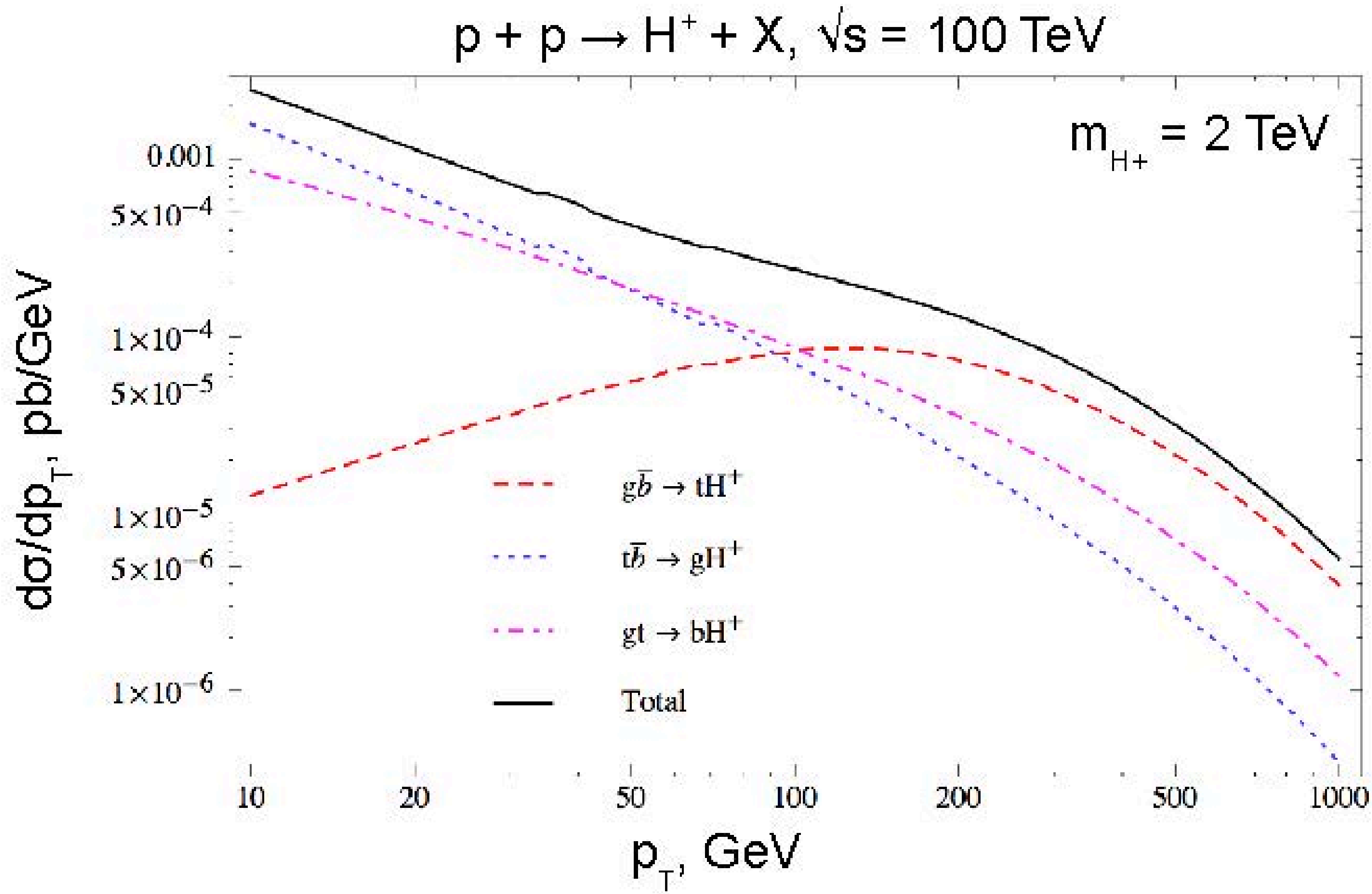
- Higgs p_T spectrum dominated by gluon emission at low p_T, which doesn't exist at LO in NF = 5 scheme

$p + p \rightarrow H^+ + X$, $\sqrt{s} = 100$ TeV



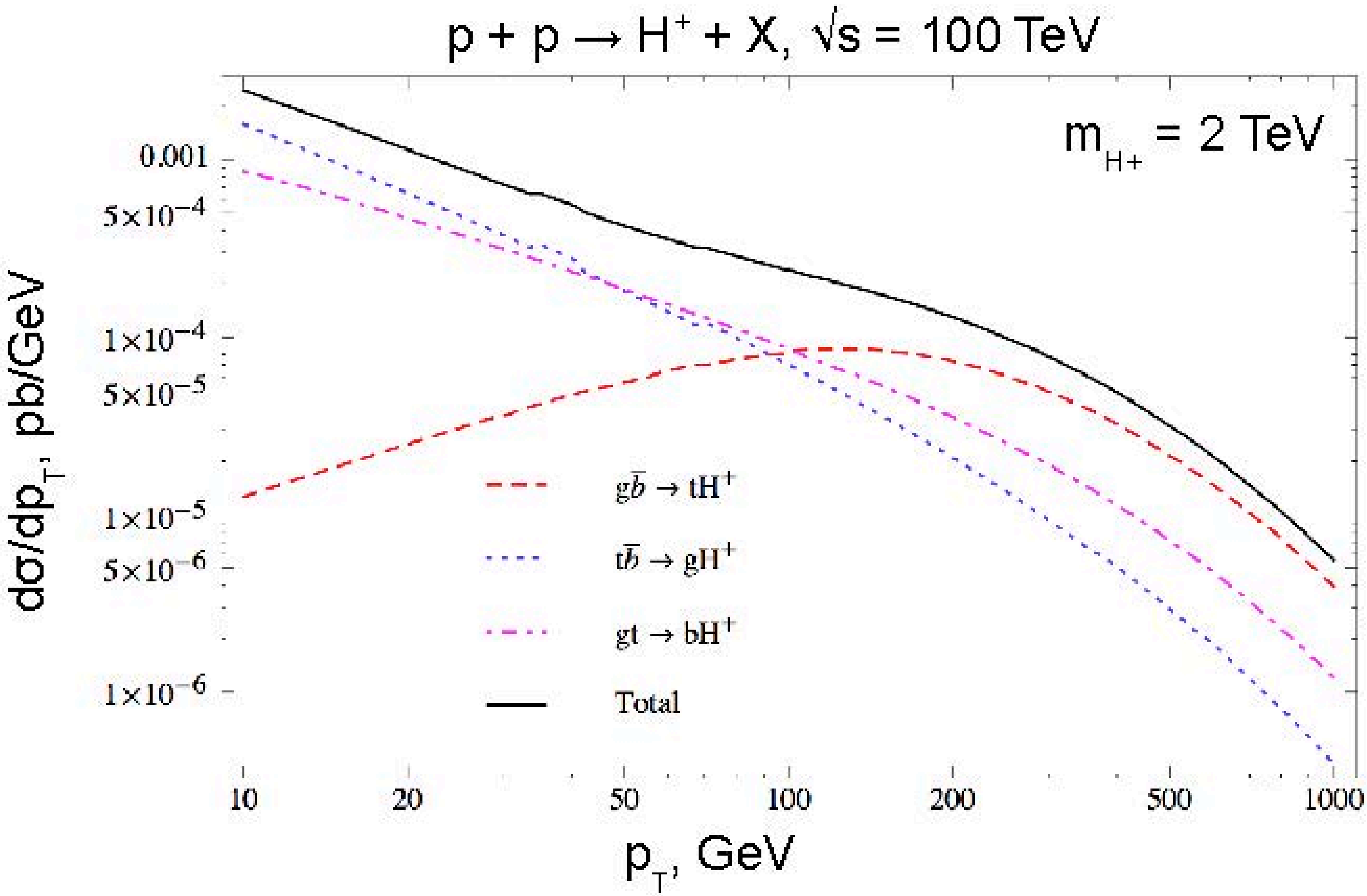
Charged Higgs production

- For production of charged Higgs plus X, turnover is roughly at $p_T \sim m_X$; this is more important than before!



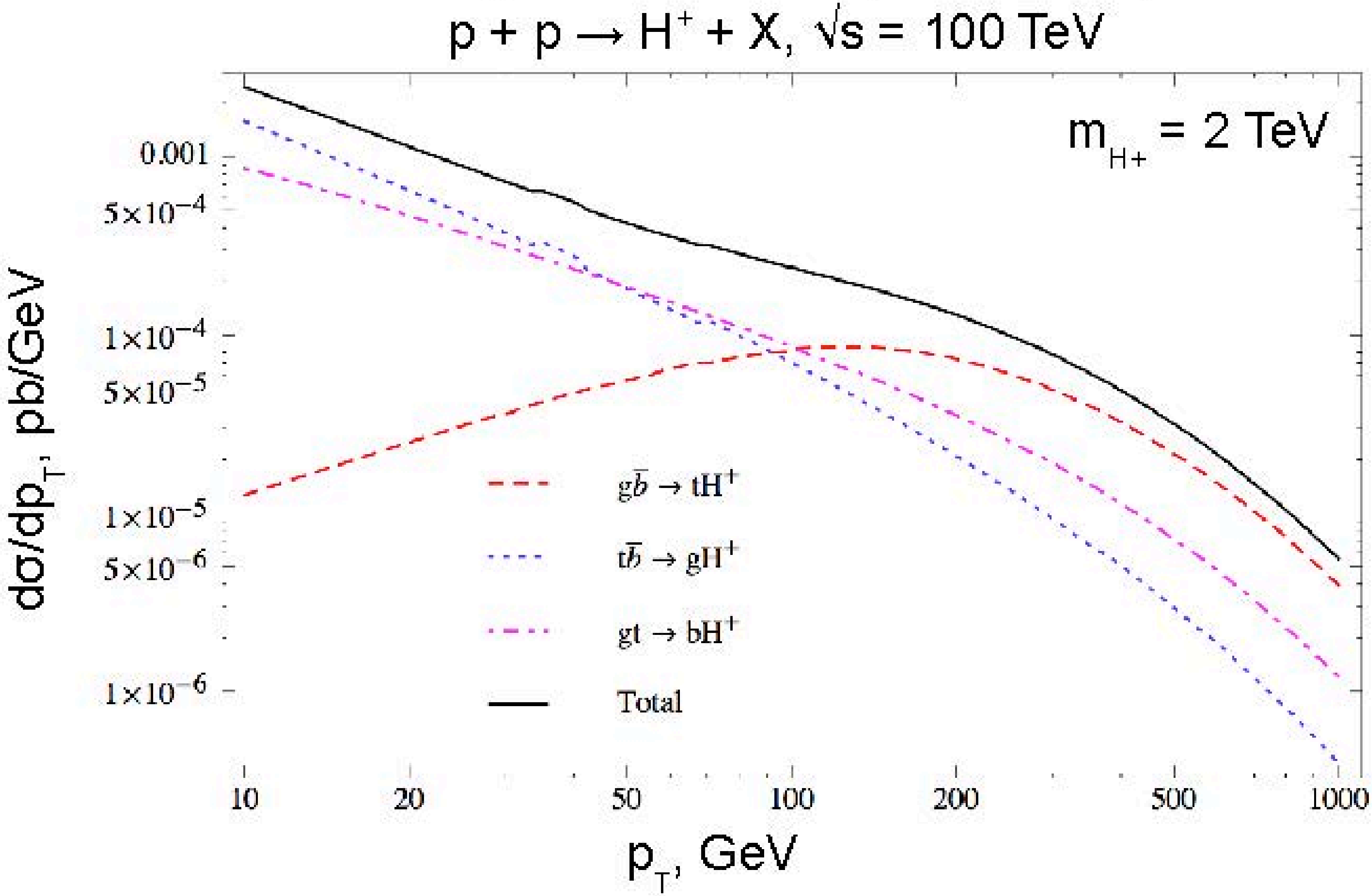
Charged Higgs production

- At low Higgs p_T, need to do 5FNS NLO calculation to compare with 6FNS NLL (stay tuned)



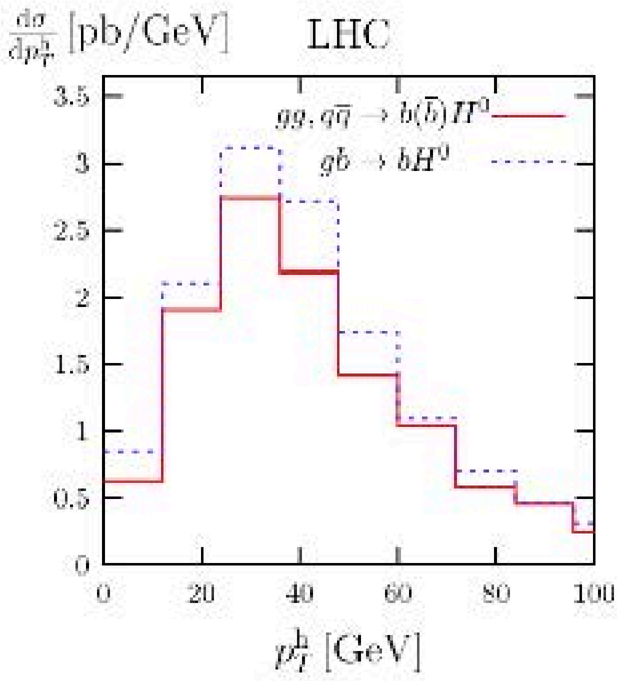
Charged Higgs production

- Mass effects at low p_T only included to LO in this calculation, using the S-ACOT (FONLL-A) scheme



Charged Higgs production

- For bottom quarks at the LHC, "low p_T" roughly corresponds to transverse momentum below the bottom mass, so this issue isn't as crucial
- Nevertheless, similar analogous studies suggest that we can do much better in predicting the charged Higgs p_T distribution in the 5FNS by going to NLO



p_T distribution for Higgs production in association with at least one b quark NLO 4FNS vs. 5FNS

Dawson et al., hep-ph/0508293

Summary

- Because of α_s running and the heavy top mass, the gain from using a top PDF at a future pp collider is less than that from using a bottom PDF at the LHC
- At very high scales, effect of resummed logs contained in top PDF can change calculated cross sections by a factor of a few, which would seemingly translate into only slight changes in search reach
- However, kinematic distributions such as the p_T spectrum need more care, with effects that are *more* important for the top quark than for the bottom quark
- For these, going to NLO in the 5FNS is probably needed

Backup

Mass effects

- Point of using a heavy quark PDF is to make predictions at scales >> the heavy quark mass
- At scales ~ the quark mass, finite mass effects enter
- S-ACOT: take heavy quark to be massless
- FONLL-A: LO massive quark function at low Q, NLO massless function at high Q (used by NNPDF2.3 NLO) *equivalent to S-ACOT*
- FONLL-B: NLO massive quark function at low Q, NLO massless function at high Q
- FONLL-C: NLO massive quark function at low Q, NNLO massless function at high Q