Theory Challenges in Collider and B-Physics at the LHC

“Effective Field Theory and LHC Processes” & “Theory Challenges in B-Physics at the LHC”

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A tale of many scales

- Collider processes characterized by many scales: s, s_{ij}, M_i, Λ_{QCD}, ...
- Large Sudakov logarithms arise, which need to be resummed (e.g. parton showers, mass effects, aspects of underlying event)
- Effective field theories provide modern, elegant approach to this problem based on scale separation (factorization theorems) and RG evolution (resummation)

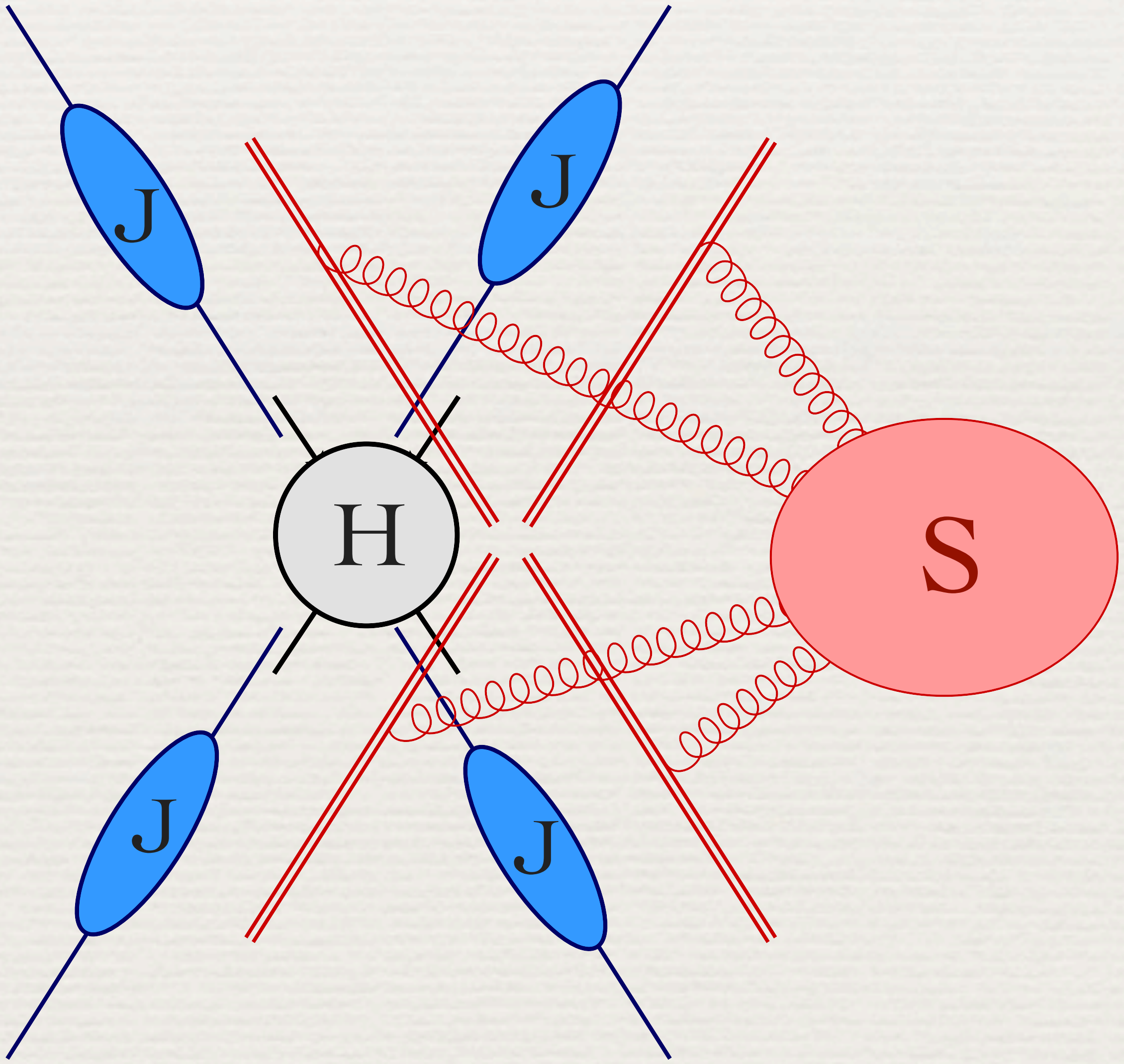
Soft-collinear factorization

Sen 1983; Kidonakis, Oderda, Sterman 1998

- Factorize cross section:

$$d\sigma \sim H(\{s_{ij}\},\mu) \prod_i J_i(M_i^2,\mu) \otimes S(\{\Lambda_{ij}^2\},\mu)$$

- Define components in terms of field theory objects in SCET
- Resum large Sudakov logarithms directly in momentum space using RG equations



Soft-collinear effective theory (SCET)

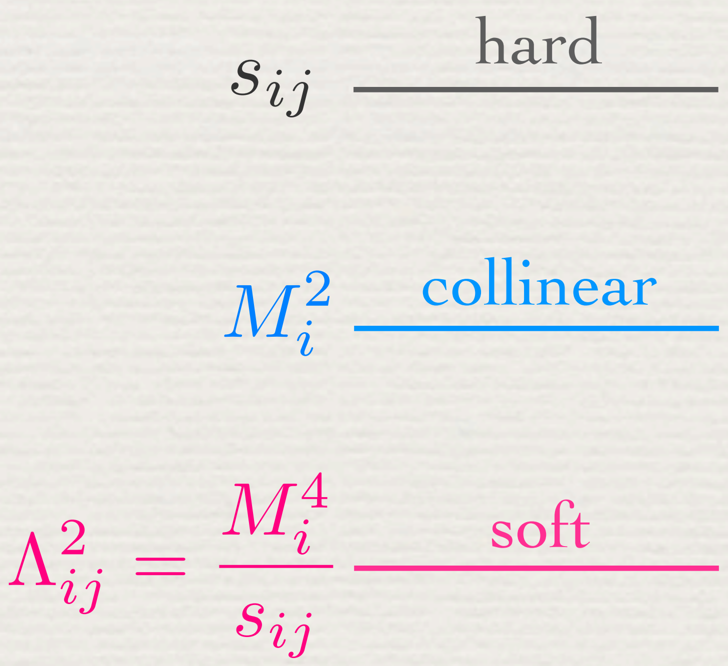
Bauer, Pirjol, Stewart et al. 2001 & 2002; Beneke et al. 2002; ...

- Two-step matching procedure:

SM $\xrightarrow{\text{integrate out hard fields}}$ SCET $\xrightarrow{\text{integrate out collinear fields}}$ soft Wilson lines

- Integrate out hard modes, describe collinear and soft modes by fields in SCET

- Integrate out collinear modes (if perturbative) and match onto a theory of Wilson lines



s_{ij} hard

M_i^2 collinear

$\Lambda_{ij}^2 = \frac{M_i^4}{s_{ij}}$ soft

NLO+NNLL resummation

in few cases (Drell-Yan, Higgs production) NNLO+N^{3}LL resummation

- Necessary ingredients:
    - **Hard functions:** from fixed-order results for on-shell amplitudes (but need amplitudes!)
    - **Jet functions:** from imaginary parts of two-point functions (depend on cuts, jet definitions)
    - **Soft functions:** from matrix elements of Wilson-line operators
    - **Anomalous dimensions:** known!
- Yields jet cross sections, not parton rates
- Goes beyond parton showers, which are accurate only at LL order even after matching

Anomalous dimension to two loops

- General result for arbitrary processes: Becher, MN 2009

$$\begin{aligned}\boldsymbol{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) &= \sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)\\ &\quad - \sum_{(I,J)} \frac{\boldsymbol{T}_I\cdot\boldsymbol{T}_J}{2}\,\gamma_{\rm cusp}(\beta_{IJ},\alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,j} \boldsymbol{T}_I\cdot\boldsymbol{T}_j\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{m_I\mu}{-s_{Ij}}\\ &\quad + \sum_{(I,J,K)} i f^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_K^c\,F_1(\beta_{IJ},\beta_{JK},\beta_{KI})\\ &\quad + \sum_{(I,J)}\sum_k i f^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_k^c\,f_2\Big(\beta_{IJ},\ln\frac{-\sigma_{Jk}\,v_J\cdot p_k}{-\sigma_{Ik}\,v_I\cdot p_k}\Big) + \mathcal{O}(\alpha_s^3)\,.\end{aligned}$$

massless partons

massive partons

new!

- Generalizes structure found for massless case
- Novel three-parton terms appear at two loops

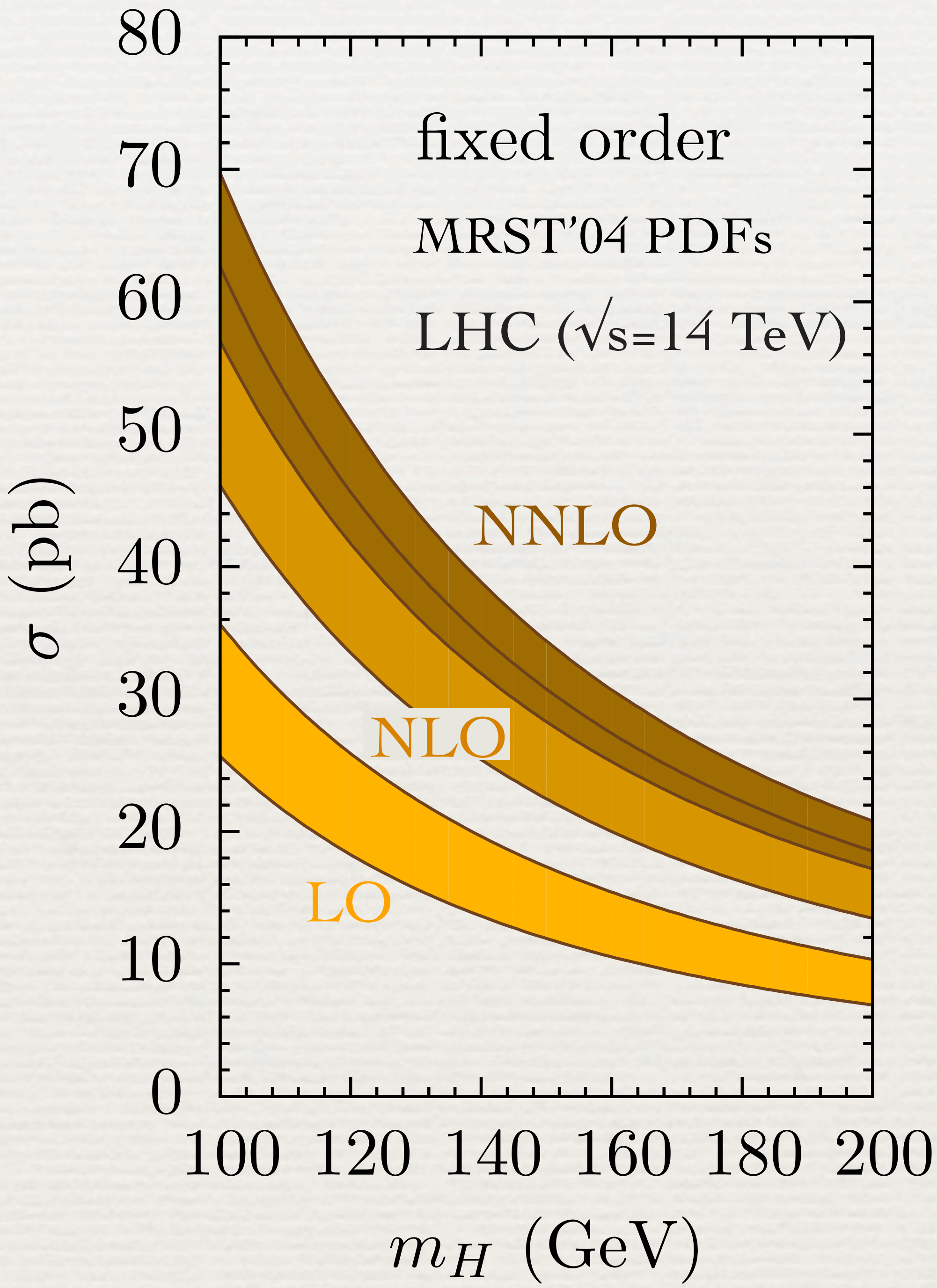
Mitov, Sterman, Sung 2009; Becher, MN 2009
Ferroglia, MN, Pecjak, Yang 2009

EFT-based predictions for Higgs production at Tevatron and LHC

Ahrens, Becher, MN, Yang 2008 & update for ICHEP 2010

http://projects.hepforge.org/rghiggs/

Large higher-order corrections



- Corrections are large:
  70% at NLO + 30% at NNLO [130% and 80% if PDFs and α_s are held fixed]
- Only gg channel contains leading singular terms, which give 90% of NLO and 94% of NNLO correction
- Contributions of qg and qq channels are small: -1% and -8% of the NLO correction

Harlander, Kilgore 2002; Anastasiou, Melnikov 2002
Ravindran, Smith, van Neerven 2003

Effective theory analysis

- Separate contributions associated with different scales, turning a multi-scale problems into a series of single-scale problems
- Evaluate each contribution at its natural scale, leading to improved perturbative behavior
- Use renormalization group to evolve contributions to a common factorization scale, thereby exponentiating (resumming) large corrections

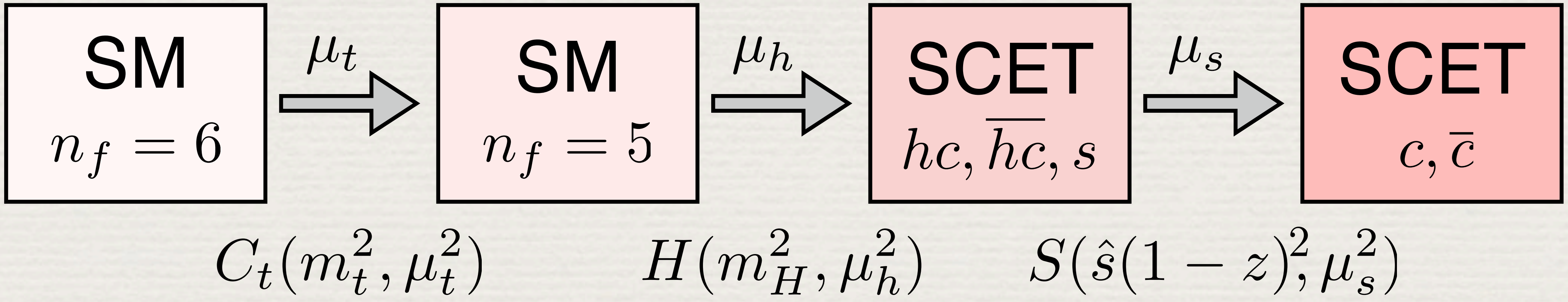
When this is done consistently, large K-factors should not arise, since no large perturbative corrections are left unexponentiated!

Scale hierarchy

- Will analyze the Higgs cross section assuming the scale hierarchy ($z = M_H^2/\hat{s}$)

$$2m_t \gg m_H \sim \sqrt{\hat{s}} \gg \sqrt{\hat{s}}(1-z) \gg \Lambda_{\rm QCD}$$

- Treating one scale at a time leads to a sequence of effective theories:



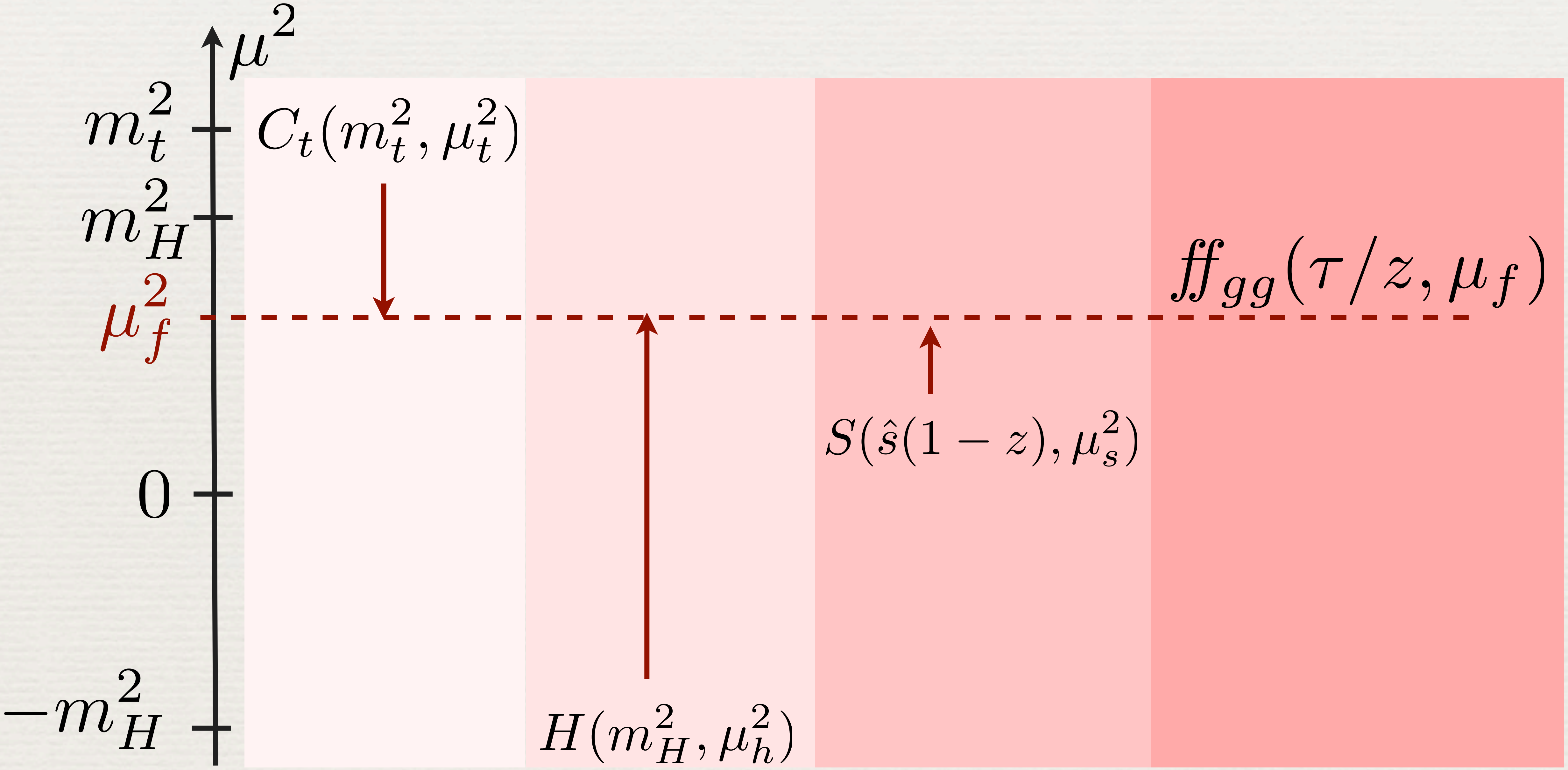
SM $n_f = 6$ $\xrightarrow{\mu_t}$ SM $n_f = 5$ $\xrightarrow{\mu_h}$ SCET $hc, \overline{hc}, s$ $\xrightarrow{\mu_s}$ SCET $c, \bar{c}$

$C_t(m_t^2, \mu_t^2)$ $H(m_H^2, \mu_h^2)$ $S(\hat{s}(1-z)^2, \mu_s^2)$

- Effects associated with each scale absorbed into matching coefficients

Scale hierarchy

- Evaluate each part at its characteristic scale and evolve to a common scale using RGEs:



RG evolution equations

- Top function:

$$\frac{d}{d\ln\mu}\,C_t(m_t^2,\mu^2) = \gamma^t(\alpha_s)\,C_t(m_t^2,\mu^2)$$

- Hard function $H(m_H^2,\mu^2) = \left|C_S(-m_H^2 - i\epsilon,\mu^2)\right|^2$:

$$\frac{d}{d\ln\mu}\,C_S(-m_H^2 - i\epsilon,\mu^2) = \left[\Gamma^A_{\text{cusp}}(\alpha_s)\,\boxed{\ln\frac{-m_H^2 - i\epsilon}{\mu^2}} + \gamma^S(\alpha_s)\right] C_S(-m_H^2 - i\epsilon,\mu^2)$$

Sudakov (cusp) logarithms

- Soft function:

$$\frac{dS(\omega^2,\mu^2)}{d\ln\mu} = -\left[2\Gamma_{\text{cusp}}(\alpha_s)\,\boxed{\ln\frac{\omega^2}{\mu^2}} + 2\gamma^W(\alpha_s)\right] S(\omega^2,\mu^2) - 4\Gamma_{\text{cusp}}(\alpha_s)\int_0^\omega d\omega'\,\frac{S(\omega'^2,\mu^2) - S(\omega^2,\mu^2)}{\omega - \omega'}$$

RG evolution equations

- Closed analytic solutions (Laplace transform):

Becher, MN 2006

$$C(z,m_t,m_H,\mu_f) = \left[C_t(m_t^2,\mu_t^2)\right]^2 \left|C_S(-m_H^2 - i\epsilon,\mu_h^2)\right|^2 U(m_H,\mu_t,\mu_h,\mu_s,\mu_f) \\ \times \frac{z^{-\eta}}{(1-z)^{1-2\eta}}\,\widetilde{s}_{\text{Higgs}}\left(\ln\frac{m_H^2(1-z)^2}{\mu_s^2 z} + \partial_\eta, \mu_s^2\right)\frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)}$$

with:

$$U(m_H,\mu_t,\mu_h,\mu_s,\mu_f) = \frac{\alpha_s^2(\mu_s^2)}{\alpha_s^2(\mu_f^2)}\left[\frac{\beta\big(\alpha_s(\mu_s^2)\big)/\alpha_s^2(\mu_s^2)}{\beta\big(\alpha_s(\mu_t^2)\big)/\alpha_s^2(\mu_t^2)}\right]^2 \left|\left(\frac{-m_H^2 - i\epsilon}{\mu_h^2}\right)^{-2a_\Gamma(\mu_h^2,\mu_s^2)}\right| \\ \times \left|\exp\left[4S(\mu_h^2,\mu_s^2) - 2a_{\gamma^S}(\mu_h^2,\mu_s^2) + 4a_{\gamma^B}(\mu_s^2,\mu_f^2)\right]\right| .$$

and:

$$\mu_t \approx m_t\,, \quad \mu_h^2 \approx -m_H^2\,, \quad \mu_s \text{ set dynamically}$$

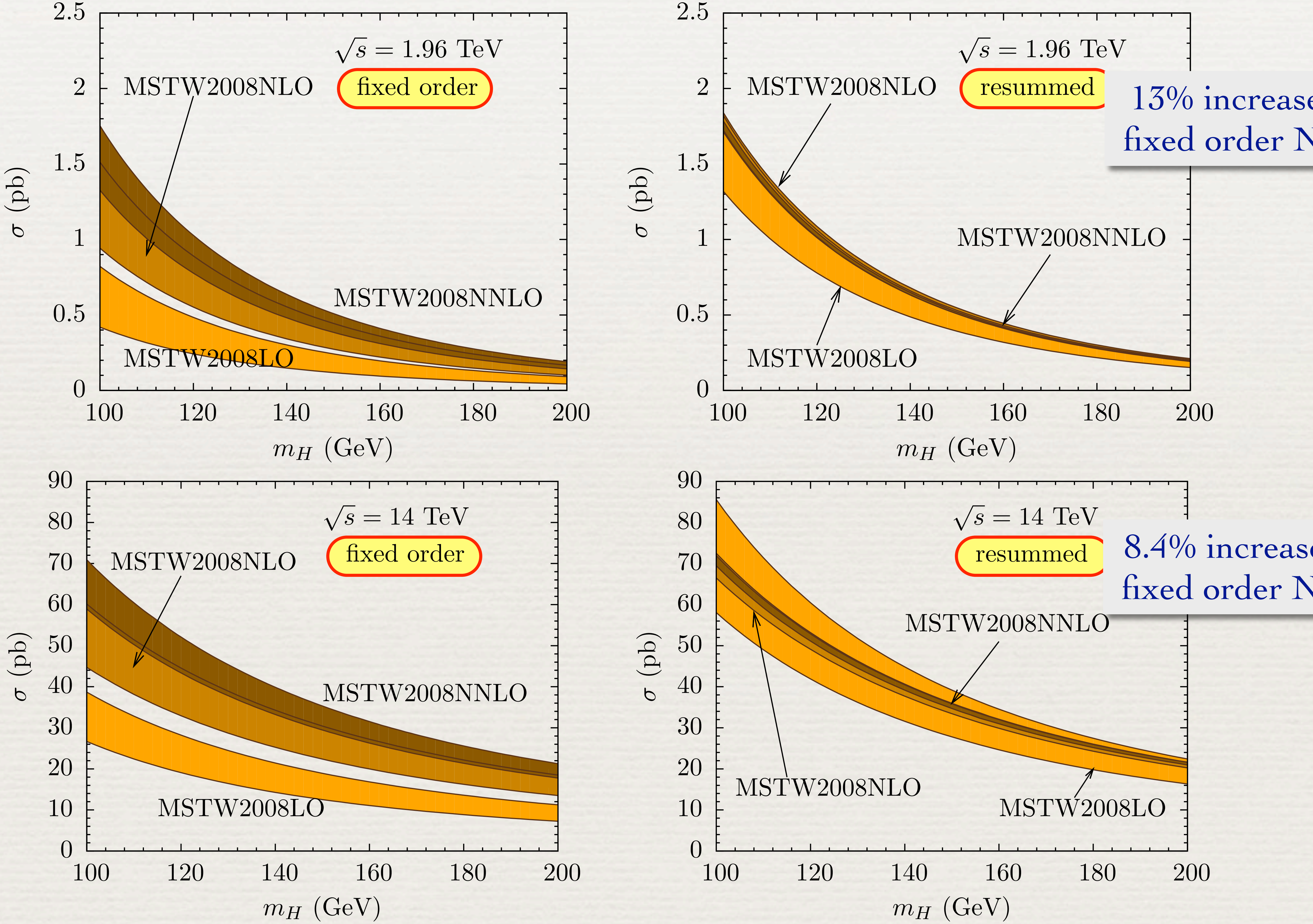
Advantages over standard approach

- Traditionally, threshold resummation is performed in Mellin-moment space

e.g.: Catani, de Florian, Grazzini, Nason 2003

- While equivalent at any order in α_s, our approach offers certain advantages:
  - Dependence on physical scales explicit
  - Large corrections $\sim(C_A \pi \alpha_s)^n$ from analytic continuation of gluon form factor resummed
  - No integrals over Landau pole of running coupling $\alpha_s(\mu^2)$, hence no regularization prescription
  - No need for numerical Mellin inversion
  - Trivial matching onto fixed-order results

Cross section predictions



13% increase over fixed order NNLO

8.4% increase over fixed order NNLO

Update for ICHEP 2010

- Consider lower LHC energies ($\sqrt{s}$=7, 10 TeV)
- Include electroweak radiative corrections, some of which were obtained after our paper

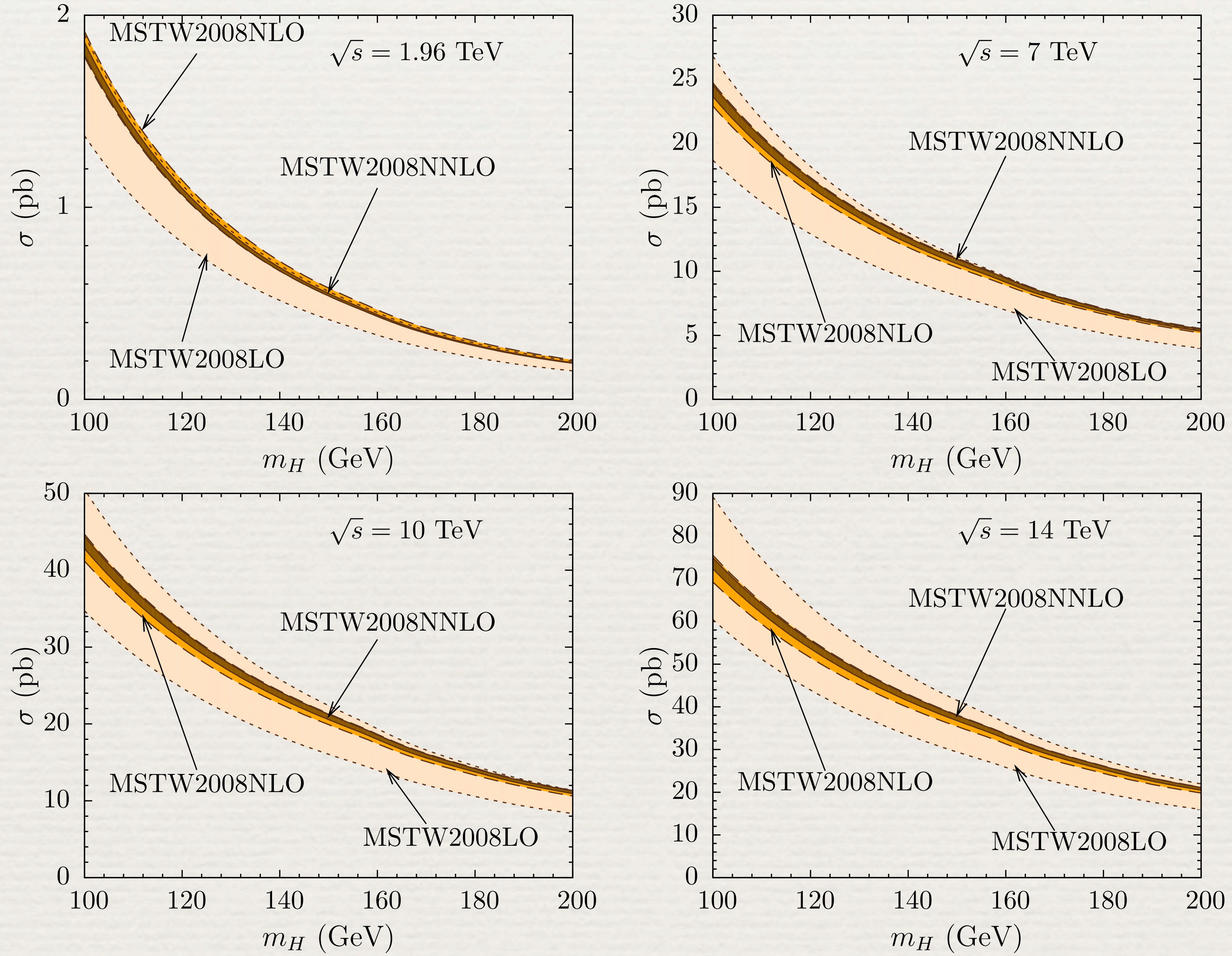
Actis, Passarino, Sturm, Uccirati 2008 & 2009
Anastasiou, Boughezal, Petriello 2009

- Include (as before) QCD corrections with NNNLL resummation (also large kinematical corrections specific for time-like processes) matched onto NNLO fixed-order results

Updated predictions

Ahrens, Becher, MN, Yang 2010 (arXiv:1008.3162)

- Cross section predictions after resummation, including perturbative uncertainties only:



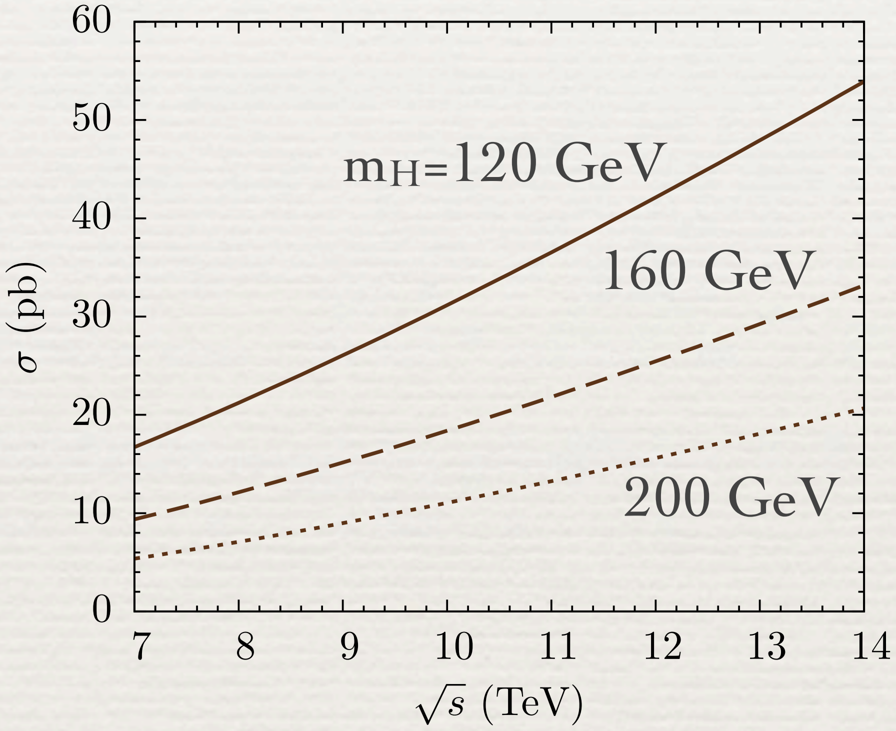
Updated predictions

Ahrens, Becher, MN, Yang 2010 (arXiv:1008.3162)

- State-of-the-art results (most complete to date) using MSTW2008NNLO PDFs:

m_H [GeV]	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
115	$1.215^{+0.031+0.141}_{-0.007-0.135}$	$18.19^{+0.53+1.46}_{-0.14-1.39}$	$33.7^{+1.0+2.6}_{-0.2-2.5}$	$57.9^{+1.6+4.4}_{-0.3-4.2}$
120	$1.073^{+0.026+0.126}_{-0.006-0.121}$	$16.73^{+0.48+1.34}_{-0.13-1.28}$	$31.2^{+0.9+2.4}_{-0.2-2.3}$	$54.0^{+1.5+4.1}_{-0.3-3.9}$
125	$0.950^{+0.022+0.113}_{-0.005-0.108}$	$15.43^{+0.44+1.23}_{-0.12-1.18}$	$29.0^{+0.8+2.2}_{-0.2-2.1}$	$50.4^{+1.4+3.8}_{-0.3-3.6}$
130	$0.844^{+0.019+0.102}_{-0.004-0.098}$	$14.27^{+0.40+1.14}_{-0.11-1.09}$	$27.0^{+0.7+2.1}_{-0.2-2.0}$	$47.2^{+1.3+3.5}_{-0.3-3.4}$
135	$0.753^{+0.016+0.093}_{-0.004-0.088}$	$13.23^{+0.36+1.06}_{-0.10-1.01}$	$25.2^{+0.7+1.9}_{-0.2-1.8}$	$44.3^{+1.2+3.3}_{-0.3-3.2}$
140	$0.672^{+0.014+0.084}_{-0.003-0.080}$	$12.29^{+0.33+0.98}_{-0.09-0.94}$	$23.5^{+0.6+1.8}_{-0.2-1.7}$	$41.6^{+1.1+3.1}_{-0.3-3.0}$
145	$0.602^{+0.012+0.076}_{-0.003-0.072}$	$11.44^{+0.31+0.91}_{-0.08-0.88}$	$22.1^{+0.6+1.7}_{-0.1-1.6}$	$39.2^{+1.0+2.9}_{-0.2-2.8}$
150	$0.541^{+0.010+0.070}_{-0.002-0.066}$	$10.67^{+0.28+0.85}_{-0.08-0.82}$	$20.7^{+0.5+1.6}_{-0.1-1.5}$	$37.0^{+1.0+2.7}_{-0.2-2.6}$
155	$0.486^{+0.009+0.064}_{-0.002-0.060}$	$9.95^{+0.26+0.80}_{-0.07-0.77}$	$19.4^{+0.5+1.5}_{-0.1-1.4}$	$34.9^{+0.9+2.6}_{-0.2-2.5}$
160	$0.433^{+0.008+0.058}_{-0.002-0.054}$	$9.21^{+0.24+0.74}_{-0.07-0.71}$	$18.1^{+0.5+1.4}_{-0.1-1.3}$	$32.7^{+0.8+2.4}_{-0.2-2.3}$
165	$0.385^{+0.006+0.052}_{-0.002-0.049}$	$8.50^{+0.22+0.68}_{-0.06-0.66}$	$16.8^{+0.4+1.3}_{-0.1-1.2}$	$30.5^{+0.8+2.2}_{-0.2-2.1}$
170	$0.345^{+0.005+0.047}_{-0.002-0.044}$	$7.89^{+0.20+0.63}_{-0.06-0.61}$	$15.7^{+0.4+1.2}_{-0.1-1.1}$	$28.6^{+0.7+2.1}_{-0.2-2.0}$
175	$0.310^{+0.005+0.043}_{-0.001-0.040}$	$7.36^{+0.18+0.59}_{-0.05-0.57}$	$14.7^{+0.4+1.1}_{-0.1-1.1}$	$27.0^{+0.7+1.9}_{-0.2-1.9}$
180	$0.280^{+0.004+0.040}_{-0.001-0.037}$	$6.88^{+0.17+0.56}_{-0.05-0.54}$	$13.8^{+0.3+1.0}_{-0.1-1.0}$	$25.5^{+0.6+1.8}_{-0.2-1.8}$
185	$0.252^{+0.003+0.036}_{-0.001-0.033}$	$6.42^{+0.15+0.52}_{-0.04-0.50}$	$13.0^{+0.3+1.0}_{-0.1-0.9}$	$24.0^{+0.6+1.7}_{-0.1-1.7}$
190	$0.228^{+0.003+0.033}_{-0.001-0.031}$	$6.02^{+0.14+0.49}_{-0.04-0.47}$	$12.2^{+0.3+0.9}_{-0.1-0.9}$	$22.7^{+0.5+1.6}_{-0.1-1.6}$
195	$0.207^{+0.002+0.031}_{-0.001-0.028}$	$5.67^{+0.13+0.46}_{-0.04-0.45}$	$11.6^{+0.3+0.9}_{-0.1-0.8}$	$21.6^{+0.5+1.6}_{-0.1-1.5}$
200	$0.189^{+0.002+0.028}_{-0.001-0.026}$	$5.35^{+0.12+0.44}_{-0.03-0.42}$	$11.0^{+0.3+0.8}_{-0.1-0.8}$	$20.6^{+0.5+1.5}_{-0.1-1.4}$

scale uncertainty ↗ ↖ PDF & α_s uncertainty



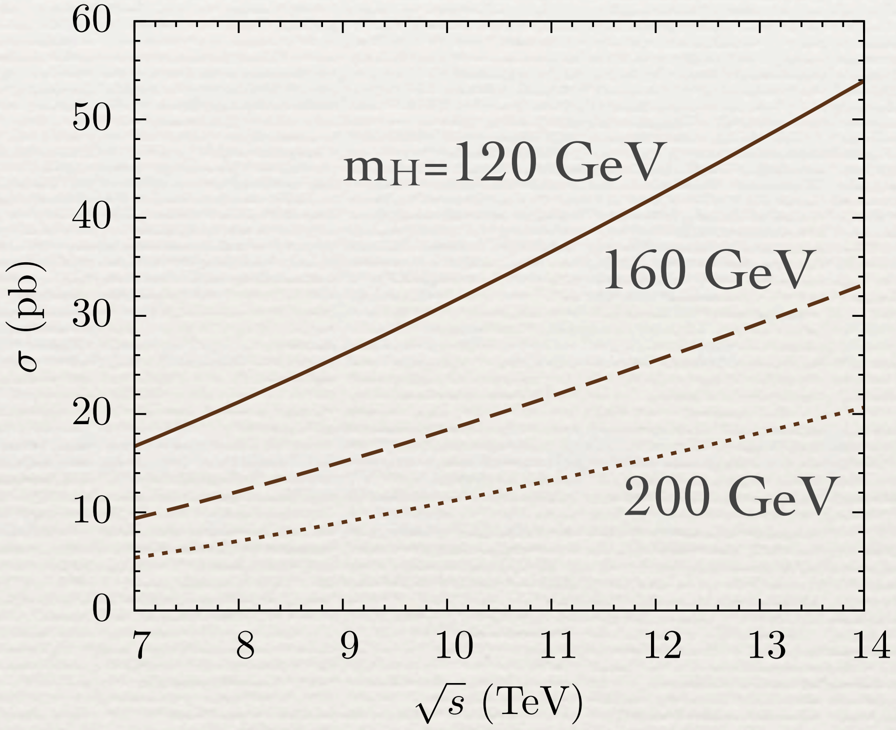
Updated predictions

Ahrens, Becher, MN, Yang 2010 (arXiv:1008.3162)

- State-of-the-art results (most complete to date) using CT10 PDFs:

m_H [GeV]	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
115	$1.215^{+0.031+0.105}_{-0.007-0.095}$	$18.34^{+0.54+0.95}_{-0.14-1.00}$	$34.1^{+1.0+1.8}_{-0.2-1.9}$	$58.8^{+1.7+3.1}_{-0.4-3.5}$
120	$1.073^{+0.026+0.096}_{-0.005-0.087}$	$16.86^{+0.49+0.87}_{-0.13-0.91}$	$31.5^{+0.9+1.6}_{-0.2-1.8}$	$54.7^{+1.6+2.9}_{-0.3-3.2}$
125	$0.950^{+0.022+0.088}_{-0.005-0.079}$	$15.54^{+0.45+0.80}_{-0.12-0.83}$	$29.3^{+0.8+1.5}_{-0.2-1.6}$	$51.1^{+1.4+2.6}_{-0.3-3.0}$
130	$0.845^{+0.019+0.081}_{-0.004-0.072}$	$14.36^{+0.41+0.74}_{-0.11-0.76}$	$27.2^{+0.8+1.4}_{-0.2-1.5}$	$47.8^{+1.3+2.5}_{-0.3-2.7}$
135	$0.753^{+0.016+0.075}_{-0.004-0.067}$	$13.31^{+0.37+0.68}_{-0.10-0.70}$	$25.4^{+0.7+1.3}_{-0.2-1.4}$	$44.8^{+1.2+2.3}_{-0.3-2.5}$
140	$0.673^{+0.014+0.069}_{-0.003-0.061}$	$12.35^{+0.34+0.63}_{-0.09-0.65}$	$23.7^{+0.7+1.2}_{-0.2-1.3}$	$42.1^{+1.1+2.1}_{-0.3-2.3}$
145	$0.604^{+0.012+0.064}_{-0.003-0.057}$	$11.50^{+0.31+0.59}_{-0.08-0.60}$	$22.2^{+0.6+1.1}_{-0.2-1.2}$	$39.7^{+1.1+2.0}_{-0.2-2.2}$
150	$0.542^{+0.010+0.059}_{-0.002-0.052}$	$10.71^{+0.29+0.55}_{-0.08-0.56}$	$20.9^{+0.6+1.0}_{-0.1-1.1}$	$37.4^{+1.0+1.9}_{-0.2-2.0}$
155	$0.487^{+0.009+0.055}_{-0.002-0.049}$	$9.99^{+0.26+0.51}_{-0.07-0.52}$	$19.6^{+0.5+1.0}_{-0.1-1.0}$	$35.2^{+0.9+1.7}_{-0.2-1.9}$
160	$0.435^{+0.008+0.050}_{-0.002-0.045}$	$9.24^{+0.24+0.48}_{-0.07-0.48}$	$18.2^{+0.5+0.9}_{-0.1-0.9}$	$33.0^{+0.9+1.6}_{-0.2-1.7}$
165	$0.387^{+0.007+0.046}_{-0.002-0.041}$	$8.52^{+0.22+0.44}_{-0.06-0.44}$	$16.9^{+0.4+0.8}_{-0.1-0.9}$	$30.7^{+0.8+1.5}_{-0.2-1.6}$
170	$0.347^{+0.006+0.043}_{-0.002-0.038}$	$7.91^{+0.20+0.41}_{-0.05-0.41}$	$15.8^{+0.4+0.8}_{-0.1-0.8}$	$28.8^{+0.7+1.4}_{-0.2-1.5}$
175	$0.313^{+0.005+0.039}_{-0.001-0.035}$	$7.38^{+0.19+0.38}_{-0.05-0.38}$	$14.8^{+0.4+0.7}_{-0.1-0.7}$	$27.2^{+0.7+1.3}_{-0.2-1.4}$
180	$0.282^{+0.004+0.037}_{-0.001-0.032}$	$6.89^{+0.17+0.36}_{-0.05-0.36}$	$13.9^{+0.3+0.7}_{-0.1-0.7}$	$25.7^{+0.6+1.2}_{-0.2-1.3}$
185	$0.254^{+0.004+0.034}_{-0.001-0.030}$	$6.43^{+0.16+0.34}_{-0.04-0.33}$	$13.1^{+0.3+0.6}_{-0.1-0.7}$	$24.2^{+0.6+1.1}_{-0.1-1.2}$
190	$0.230^{+0.003+0.032}_{-0.001-0.028}$	$6.02^{+0.15+0.32}_{-0.04-0.31}$	$12.3^{+0.3+0.6}_{-0.1-0.6}$	$22.9^{+0.6+1.1}_{-0.1-1.2}$
195	$0.210^{+0.003+0.030}_{-0.001-0.026}$	$5.67^{+0.14+0.30}_{-0.04-0.30}$	$11.6^{+0.3+0.6}_{-0.1-0.6}$	$21.8^{+0.5+1.0}_{-0.1-1.1}$
200	$0.191^{+0.002+0.028}_{-0.001-0.024}$	$5.35^{+0.13+0.29}_{-0.03-0.28}$	$11.1^{+0.3+0.5}_{-0.1-0.5}$	$20.8^{+0.5+1.0}_{-0.1-1.0}$

scale uncertainty ↗ ↖ PDF & α_s uncertainty



Updated predictions

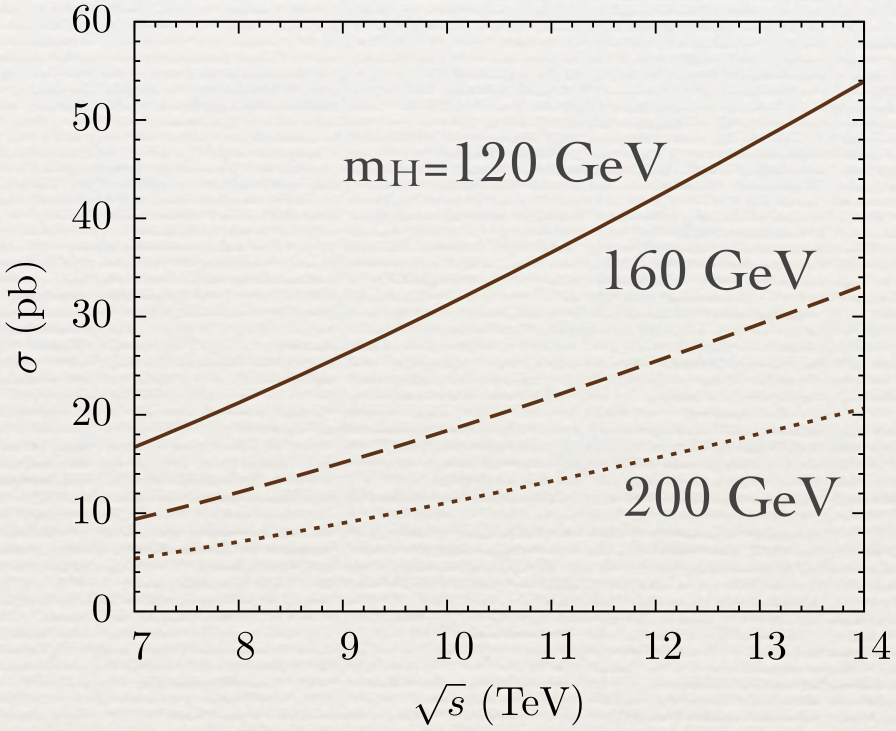
Ahrens, Becher, MN, Yang 2010 (arXiv:1008.3162)

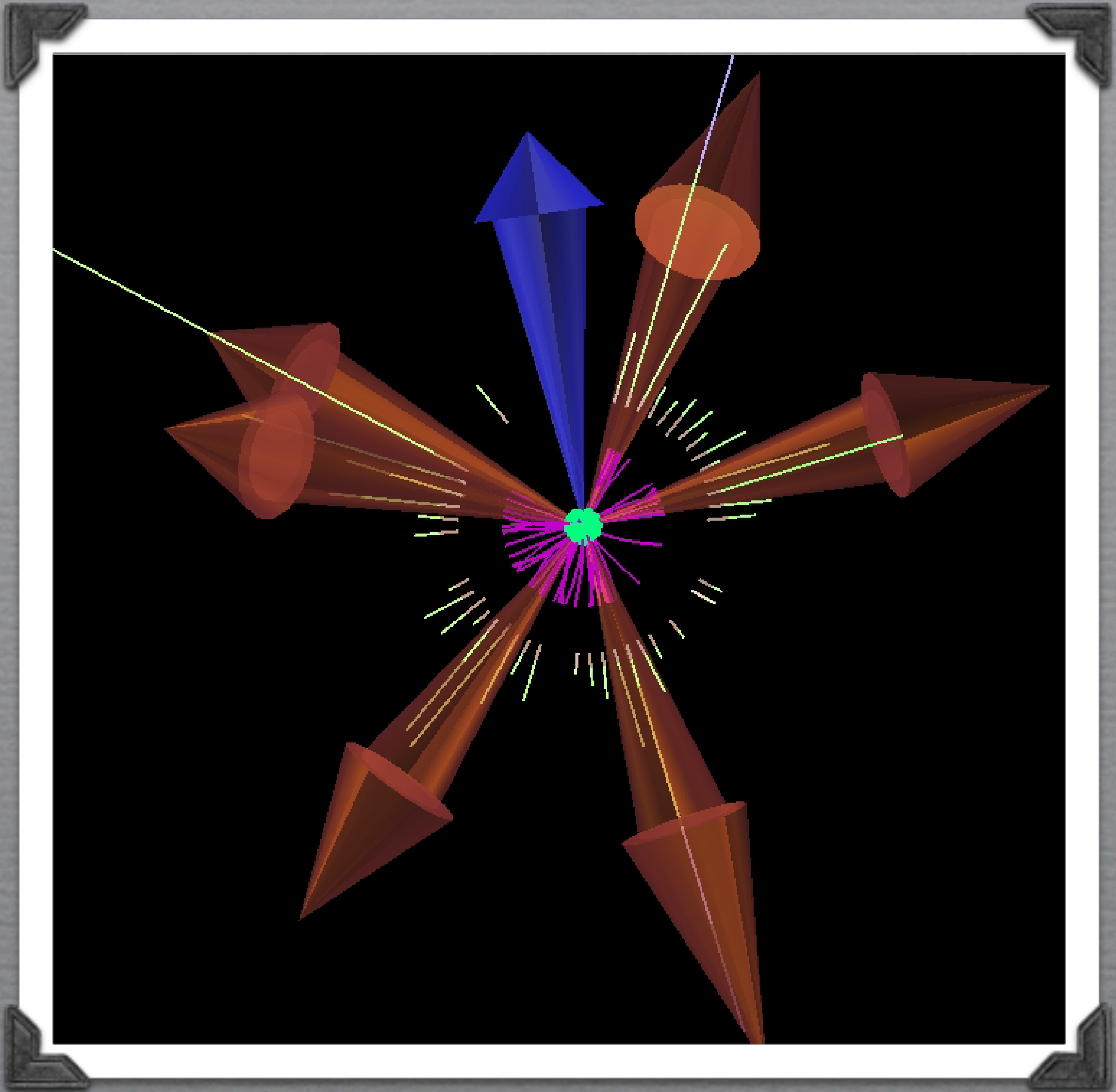
- State-of-the-art results (most complete to date) using NNPDF2.0 PDFs:

m_H [GeV]	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
115	$1.341^{+0.037+0.143}_{-0.018-0.143}$	$19.35^{+0.60+1.36}_{-0.29-1.36}$	$35.4^{+1.1+2.4}_{-0.5-2.4}$	$60.3^{+1.8+3.9}_{-0.7-3.9}$
120	$1.184^{+0.032+0.129}_{-0.016-0.129}$	$17.82^{+0.54+1.25}_{-0.29-1.25}$	$32.8^{+1.0+2.2}_{-0.5-2.2}$	$56.3^{+1.7+3.7}_{-0.7-3.7}$
125	$1.049^{+0.027+0.116}_{-0.014-0.116}$	$16.45^{+0.50+1.15}_{-0.28-1.15}$	$30.5^{+0.9+2.0}_{-0.5-2.0}$	$52.6^{+1.5+3.4}_{-0.8-3.4}$
130	$0.932^{+0.023+0.105}_{-0.013-0.105}$	$15.23^{+0.45+1.07}_{-0.28-1.07}$	$28.5^{+0.8+1.9}_{-0.5-1.9}$	$49.3^{+1.4+3.2}_{-0.8-3.2}$
135	$0.831^{+0.020+0.096}_{-0.011-0.096}$	$14.13^{+0.41+0.99}_{-0.27-0.99}$	$26.6^{+0.8+1.8}_{-0.5-1.8}$	$46.3^{+1.3+3.0}_{-0.8-3.0}$
140	$0.742^{+0.017+0.087}_{-0.010-0.087}$	$13.14^{+0.38+0.93}_{-0.26-0.93}$	$24.9^{+0.7+1.7}_{-0.5-1.7}$	$43.6^{+1.2+2.8}_{-0.8-2.8}$
145	$0.665^{+0.015+0.080}_{-0.009-0.080}$	$12.24^{+0.35+0.86}_{-0.25-0.86}$	$23.3^{+0.7+1.5}_{-0.5-1.5}$	$41.1^{+1.1+2.6}_{-0.8-2.6}$
150	$0.597^{+0.013+0.073}_{-0.008-0.073}$	$11.42^{+0.32+0.81}_{-0.24-0.81}$	$21.9^{+0.6+1.5}_{-0.4-1.5}$	$38.8^{+1.1+2.5}_{-0.7-2.5}$
155	$0.536^{+0.011+0.067}_{-0.007-0.067}$	$10.66^{+0.30+0.76}_{-0.23-0.76}$	$20.6^{+0.6+1.4}_{-0.4-1.4}$	$36.6^{+1.0+2.3}_{-0.7-2.3}$
160	$0.478^{+0.010+0.061}_{-0.006-0.061}$	$9.88^{+0.27+0.70}_{-0.22-0.70}$	$19.2^{+0.5+1.3}_{-0.4-1.3}$	$34.3^{+0.9+2.2}_{-0.7-2.2}$
165	$0.425^{+0.008+0.055}_{-0.005-0.055}$	$9.11^{+0.25+0.65}_{-0.21-0.65}$	$17.8^{+0.5+1.2}_{-0.4-1.2}$	$32.0^{+0.9+2.0}_{-0.7-2.0}$
170	$0.380^{+0.007+0.050}_{-0.005-0.050}$	$8.46^{+0.24+0.61}_{-0.19-0.61}$	$16.6^{+0.5+1.1}_{-0.4-1.1}$	$30.0^{+0.8+1.9}_{-0.6-1.9}$
175	$0.342^{+0.006+0.046}_{-0.004-0.046}$	$7.90^{+0.22+0.57}_{-0.18-0.57}$	$15.6^{+0.4+1.0}_{-0.4-1.0}$	$28.4^{+0.8+1.8}_{-0.6-1.8}$
180	$0.308^{+0.005+0.042}_{-0.003-0.042}$	$7.38^{+0.20+0.53}_{-0.17-0.53}$	$14.7^{+0.4+1.0}_{-0.3-1.0}$	$26.8^{+0.7+1.7}_{-0.6-1.7}$
185	$0.277^{+0.005+0.039}_{-0.003-0.039}$	$6.90^{+0.19+0.50}_{-0.16-0.50}$	$13.8^{+0.4+0.9}_{-0.3-0.9}$	$25.3^{+0.7+1.6}_{-0.6-1.6}$
190	$0.250^{+0.004+0.036}_{-0.002-0.036}$	$6.46^{+0.18+0.47}_{-0.15-0.47}$	$13.0^{+0.4+0.9}_{-0.3-0.9}$	$23.9^{+0.7+1.5}_{-0.5-1.5}$
195	$0.227^{+0.004+0.033}_{-0.002-0.033}$	$6.08^{+0.17+0.44}_{-0.14-0.44}$	$12.3^{+0.4+0.8}_{-0.3-0.8}$	$22.8^{+0.6+1.4}_{-0.5-1.4}$
200	$0.207^{+0.003+0.031}_{-0.002-0.031}$	$5.74^{+0.17+0.42}_{-0.13-0.42}$	$11.7^{+0.3+0.8}_{-0.3-0.8}$	$21.7^{+0.6+1.4}_{-0.5-1.4}$

scale uncertainty

PDF & α_s uncertainty



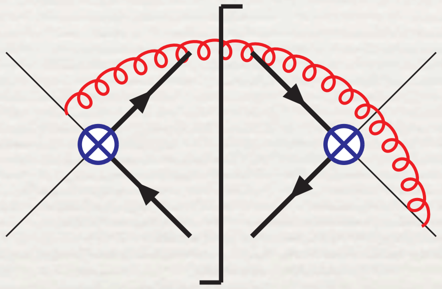


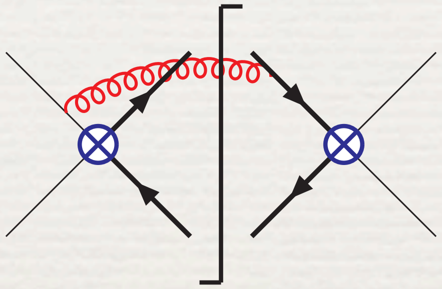
EFT-based predictions for top-pair production at Tevatron and LHC: First NNLL+NLO results for distributions

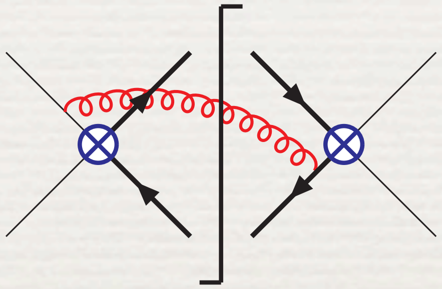
Ahrens, Ferroglia, MN, Pecjak, Yang 2009 & 2010

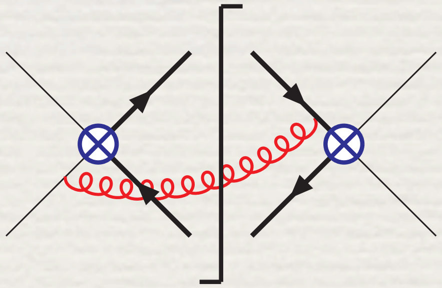
Top-pair production at NLO+NNLL

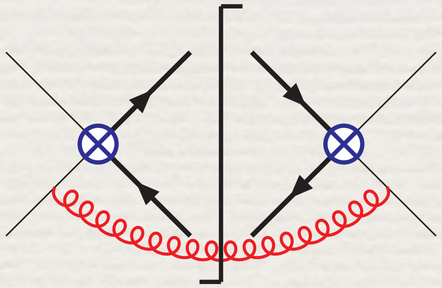
- Soft functions from time-like Wilson-line correlation function:

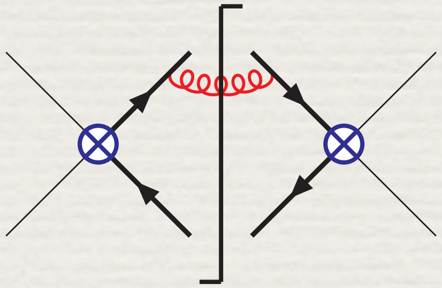

$\mathcal{I}_{12}$

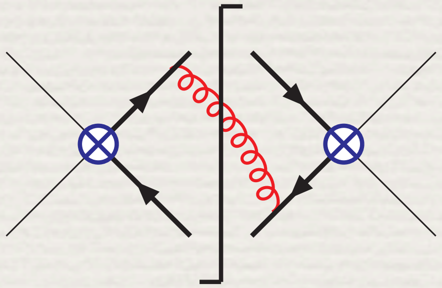

$\mathcal{I}_{13}$

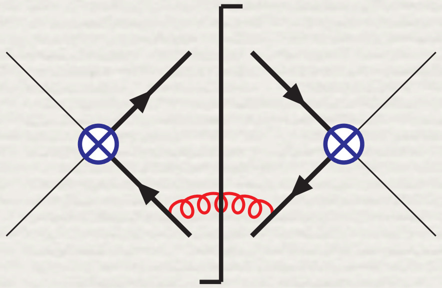

$\mathcal{I}_{14}$


$\mathcal{I}_{23}$


$\mathcal{I}_{24}$


$\mathcal{I}_{33}$


$\mathcal{I}_{34}$


$\mathcal{I}_{44}$

Top-pair production at NLO+NNLL

Ferroglia, MN, Pecjak, Yang 2009

- Anomalous-dimension matrices in s-channel singlet-octet basis for $q\bar{q}, gg \to t\bar{t}$ channels:

$$
\begin{aligned}
\boldsymbol{\Gamma}_{q\bar{q}} &= \left[C_F\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{-s}{\mu^2} + C_F\, \gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^q(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s)\, m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{C_F}{2N} \\ 1 & -\frac{1}{N} \end{pmatrix} + \frac{\alpha_s}{4\pi}\, g(\beta_{34}) \begin{pmatrix} 0 & \frac{C_F}{2} \\ -N & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3) \\[2ex]
\boldsymbol{\Gamma}_{gg} &= \left[N\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{-s}{\mu^2} + C_F\, \gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^g(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s)\, m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (55) \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{1}{2} & 0 \\ 1 & -\frac{N}{4} & \frac{N^2-4}{4N} \\ 0 & \frac{N}{4} & -\frac{N}{4} \end{pmatrix} + \frac{\alpha_s}{4\pi}\, g(\beta_{34}) \begin{pmatrix} 0 & \frac{N}{2} & 0 \\ -N & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3)\,.
\end{aligned}
$$

Top-pair production at NLO+NNLL

- Can use these results to predict leading singular terms near partonic threshold $z = M^2/\hat{s} \to 1$
- Obtain NNLO coefficients of distributions

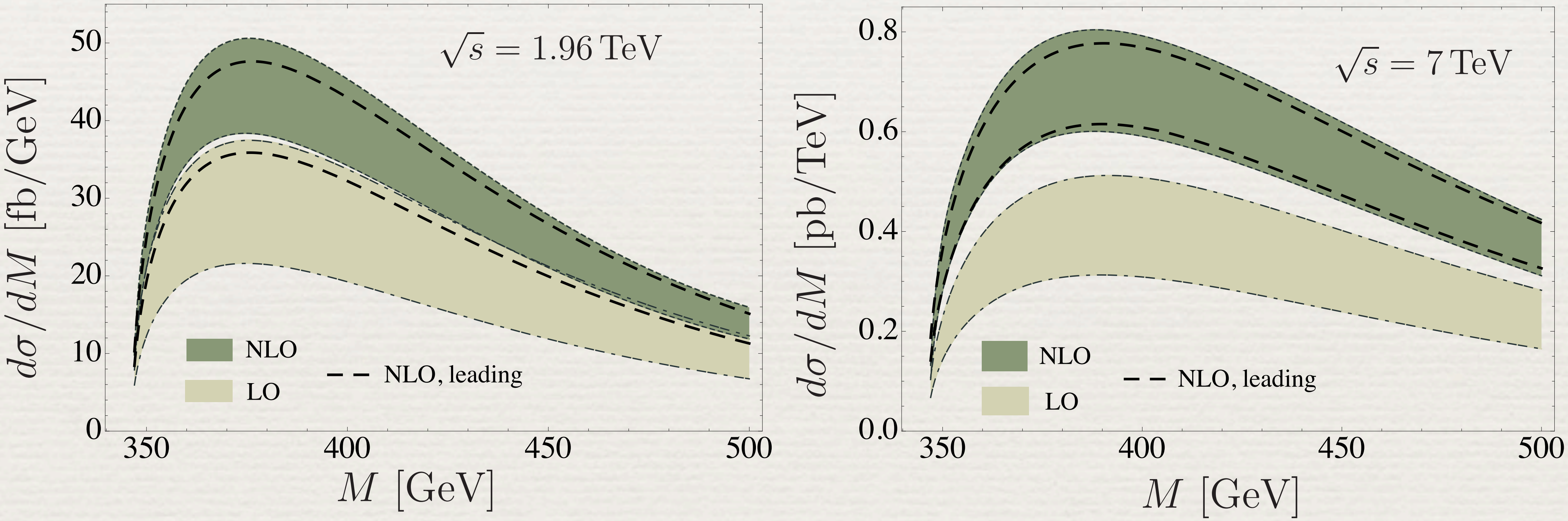
$$P'_n(z) = \left[\frac{1}{1-z}\ln^n\left(\frac{M^2(1-z)^2}{\mu^2 z}\right)\right]_+$$

  and (partially) of δ(1-z)

- Yields presently best estimate of NNLO terms
- Note: includes some subleading terms ~ ln(z) beyond distributions $P_n(z) = \left[\frac{\ln^n(1-z)}{1-z}\right]_+$

Dominance of threshold terms

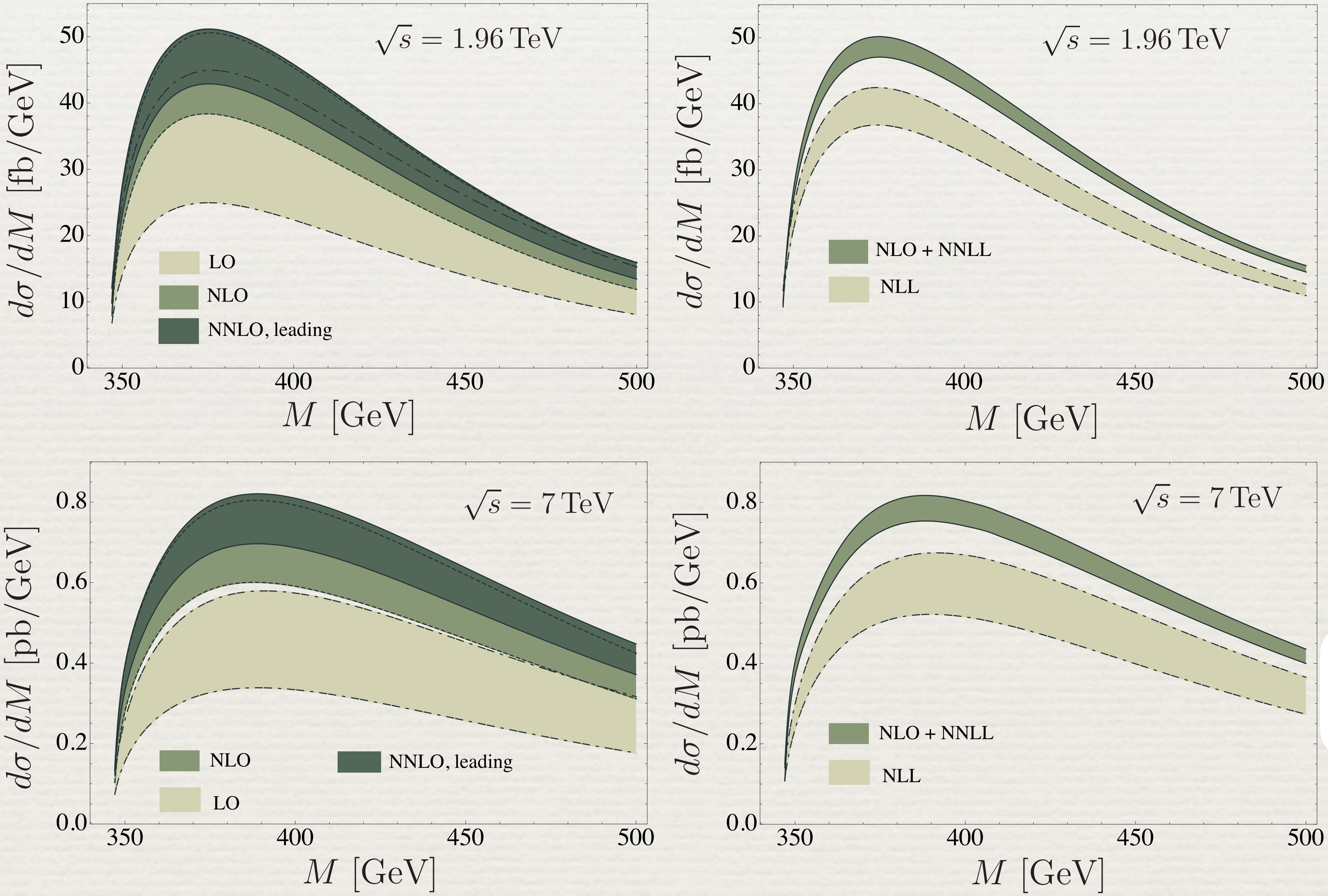
- Fixed-order results for invariant mass distribution at Tevatron and LHC:



- Leading singular terms near partonic threshold $z = M^2/\hat{s} \to 1$ give dominant contributions even at low and moderate M values

Invariant mass distributions

- Fixed-order vs. resummed PT (matched to NLO):



Tevatron

LHC

NNLO
(partial)

NLO

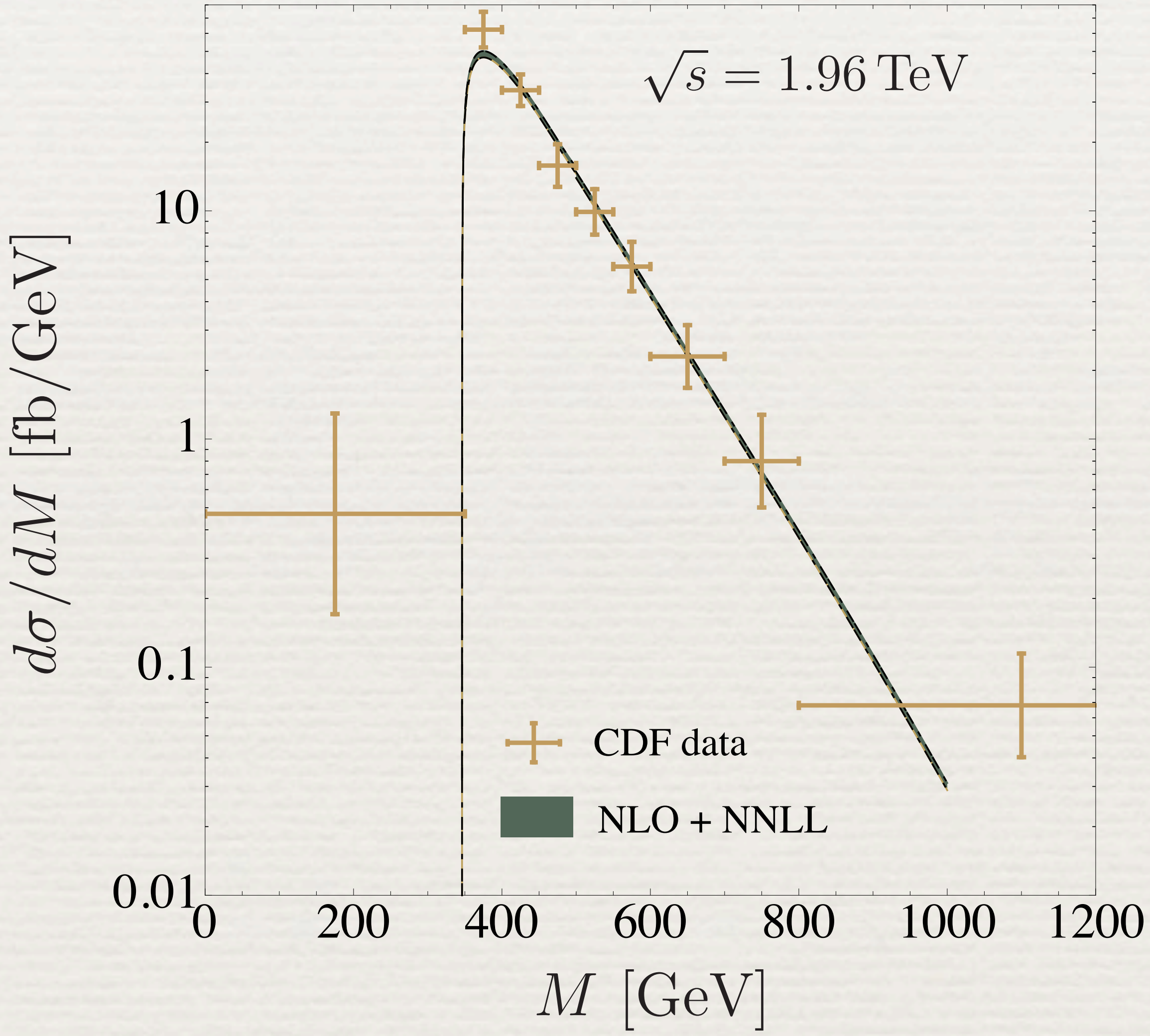
LO

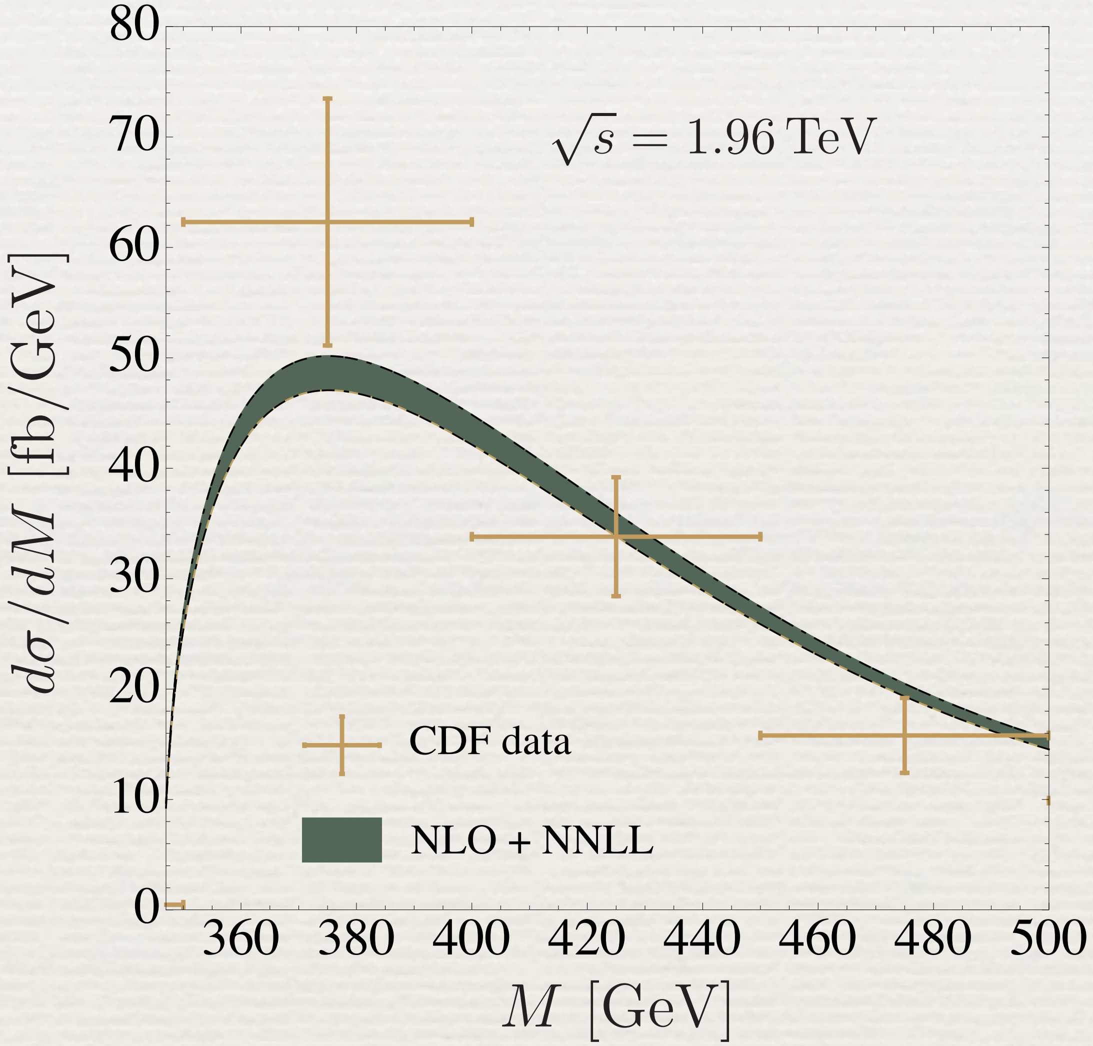
NNLL+NLO

NLL+LO

Comparison with CDF data

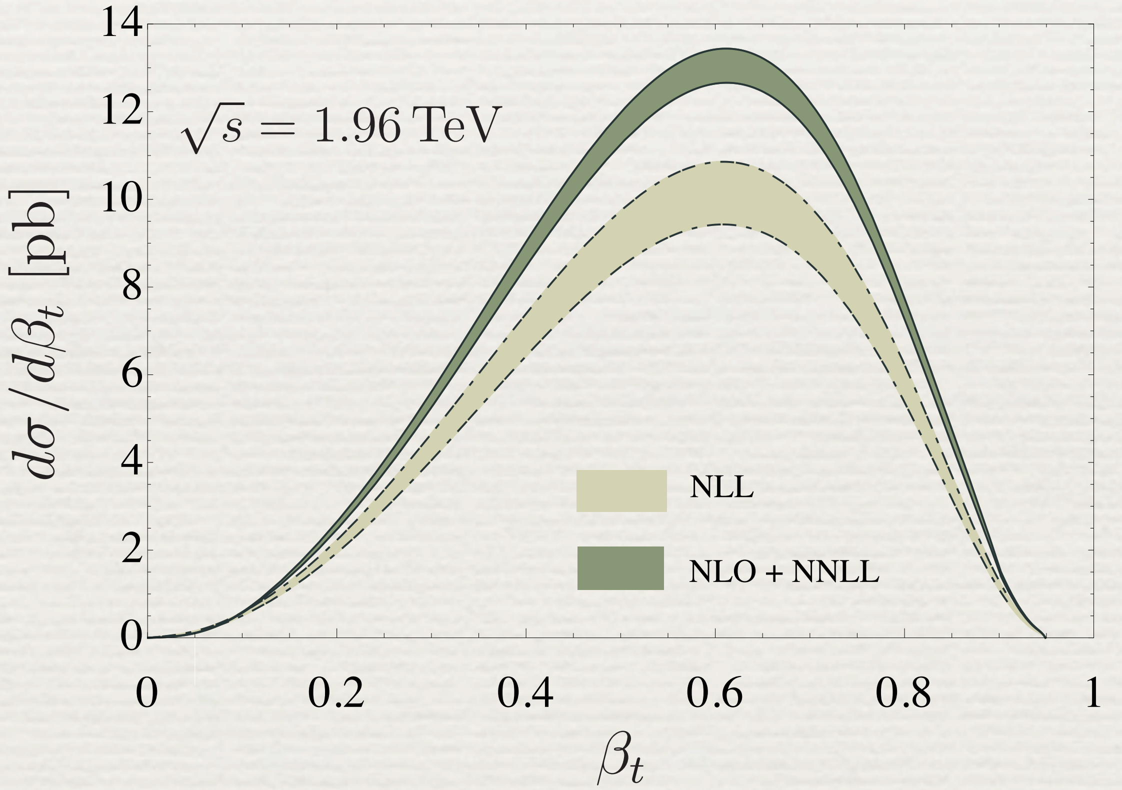
- Overlay (not a fit!) for m_t=173.1 GeV:

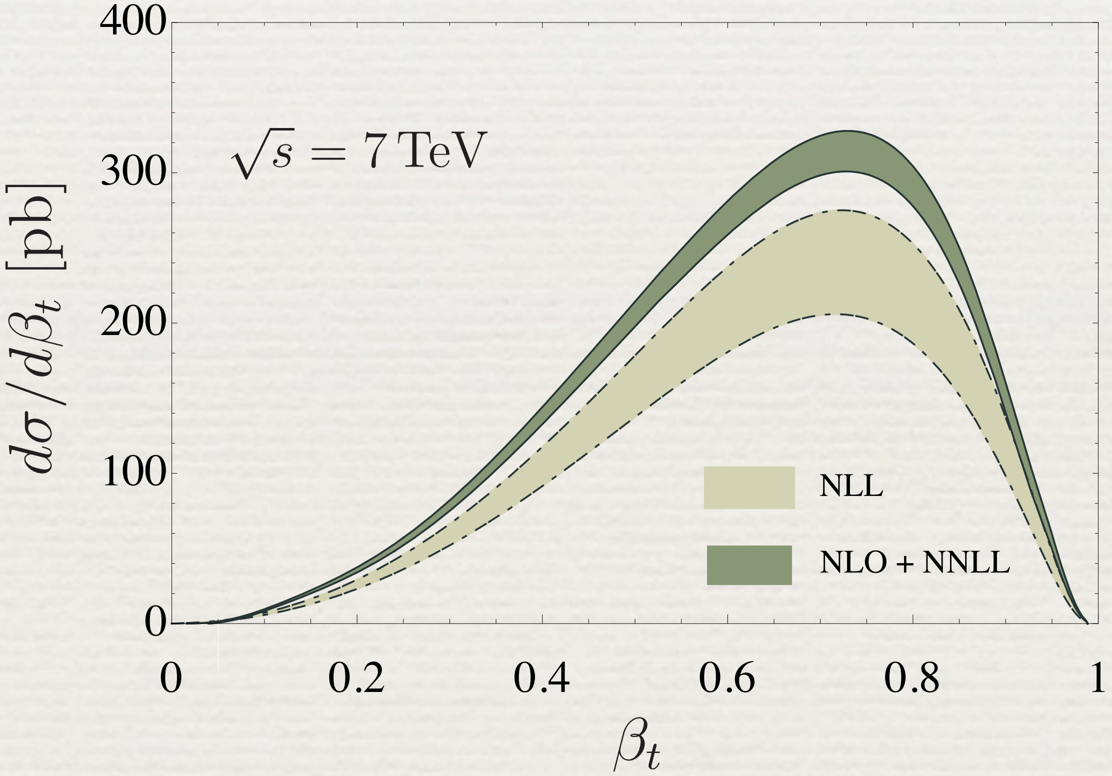




Velocity distribution

- Transform to relative 3-velocity of top quarks in $t\bar{t}$ rest frame: $\beta_t = \sqrt{1 - \frac{4m_t^2}{M^2}}$


Tevatron

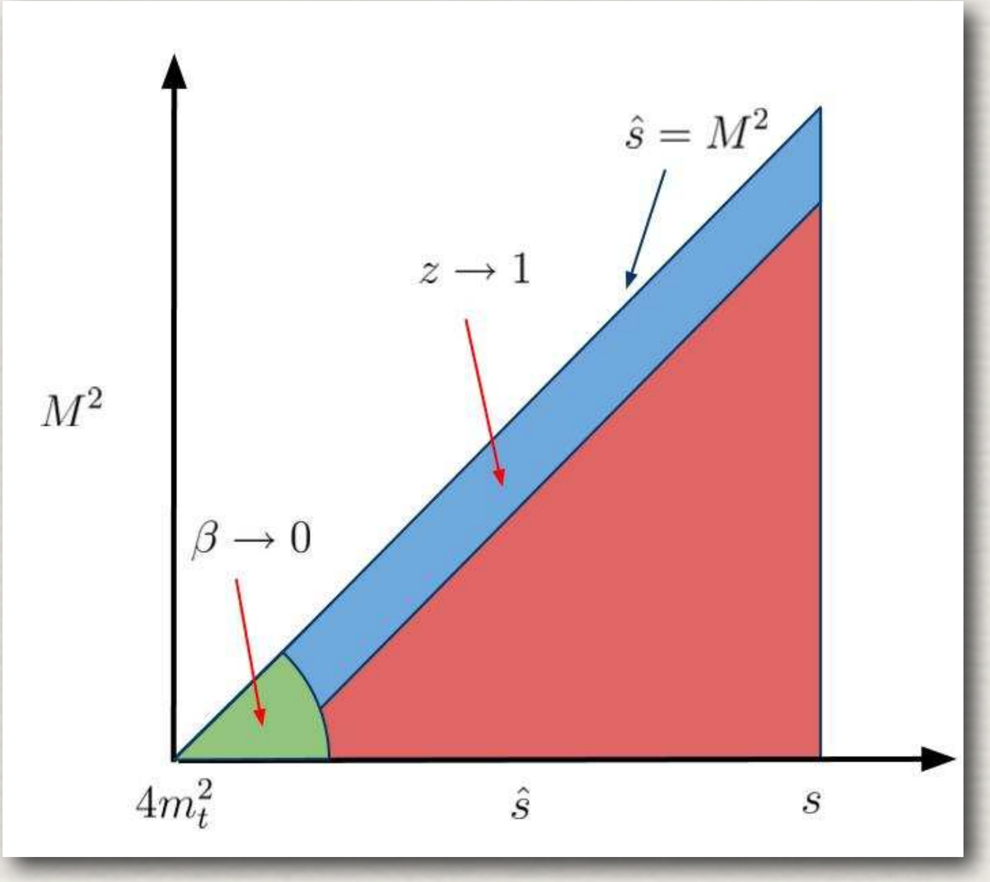

LHC

- Top quarks are relativistic, $\beta_t \sim 0.4$-0.9

Total cross section

- Usually, resummation is done around absolute threshold at $\hat{s}=4m_t^2$ (non-relativistic top quarks)
- Mixed Coulomb and soft gluon singularities arise for $\beta = \sqrt{1-4m_t^2/\hat{s}} \to 0$
- Obtain partial NNLO results based on small-β expansion

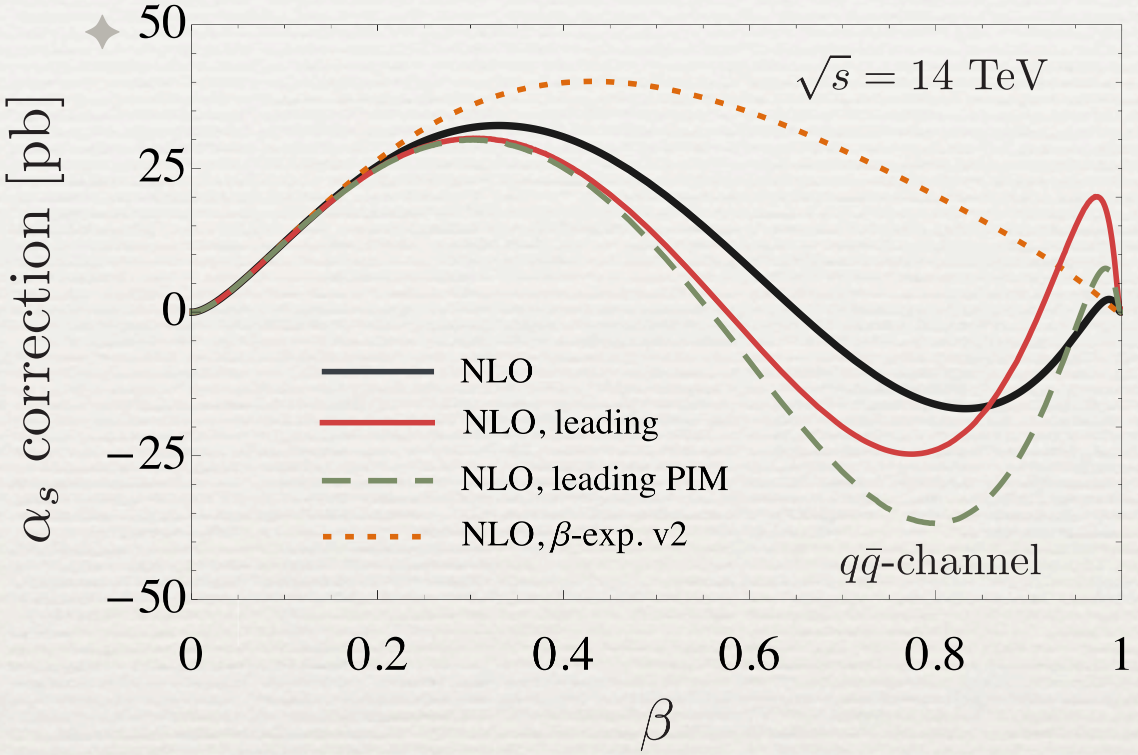
  Moch, Uwer 2008; Beneke et al. 2009
- In our approach, soft gluon effects are resummed also far above absolute threshold!

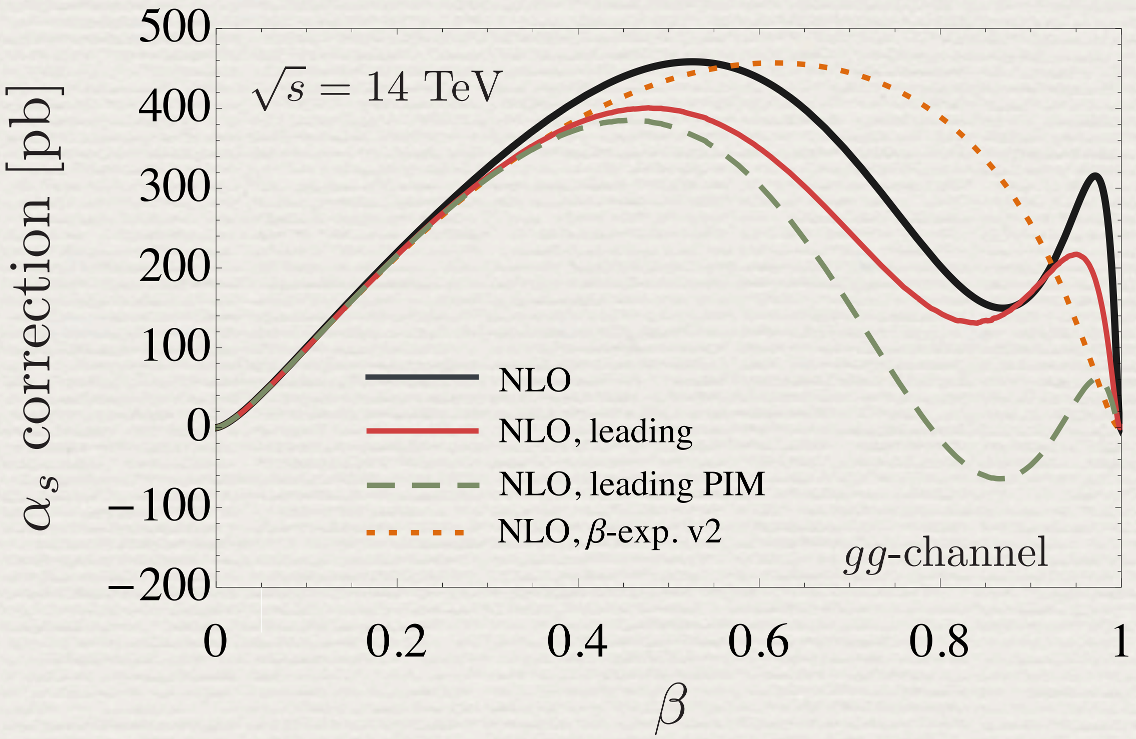


Total cross section

Comparison of different approximations to NLO corrections (including parton luminosities):

- our approximation lies much closer to NLO result than small-β approximation (Moch, Uwer)
- reproduces fine details of the curves
- improvement over traditional PIM curve (Kidonakis)





Total cross section

- Detailed predictions for total cross sections:

Cross section (pb)	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
σ_{LO}	$4.49^{+1.71+0.24}_{-1.15-0.19}$	84^{+29+4}_{-20-5}	217^{+70+10}_{-49-11}	$495^{+148+19}_{-107-24}$
σ_{NLL}	$5.07^{+0.37+0.28}_{-0.36-0.18}$	112^{+18+5}_{-14-5}	276^{+47+10}_{-37-11}	$598^{+108+19}_{-94\ -19}$
$\sigma_{\mathrm{NLO,\ leading}}$	$5.49^{+0.78+0.31}_{-0.78-0.20}$	134^{+16+7}_{-17-7}	341^{+34+14}_{-38-14}	761^{+64+25}_{-75-26}
σ_{NLO}	$5.79^{+0.79+0.33}_{-0.80-0.22}$	133^{+21+7}_{-19-7}	341^{+50+14}_{-46-15}	$761^{+105+26}_{-101-27}$
$\sigma_{\mathrm{NLO+NNLL}}$	$6.30^{+0.19+0.31}_{-0.19-0.23}$	149^{+7+8}_{-7-8}	373^{+17+16}_{-15-16}	821^{+40+24}_{-42-31}
$\sigma_{\mathrm{NNLO,\ approx}}$ (scheme A)	$6.14^{+0.49+0.31}_{-0.53-0.23}$	146^{+13+8}_{-12-8}	369^{+34+16}_{-30-16}	821^{+71+27}_{-65-29}
$\sigma_{\mathrm{NNLO,\ approx}}$ (scheme B)	$6.05^{+0.43+0.31}_{-0.50-0.23}$	139^{+9+7}_{-9-7}	349^{+23+15}_{-23-15}	773^{+47+25}_{-50-27}

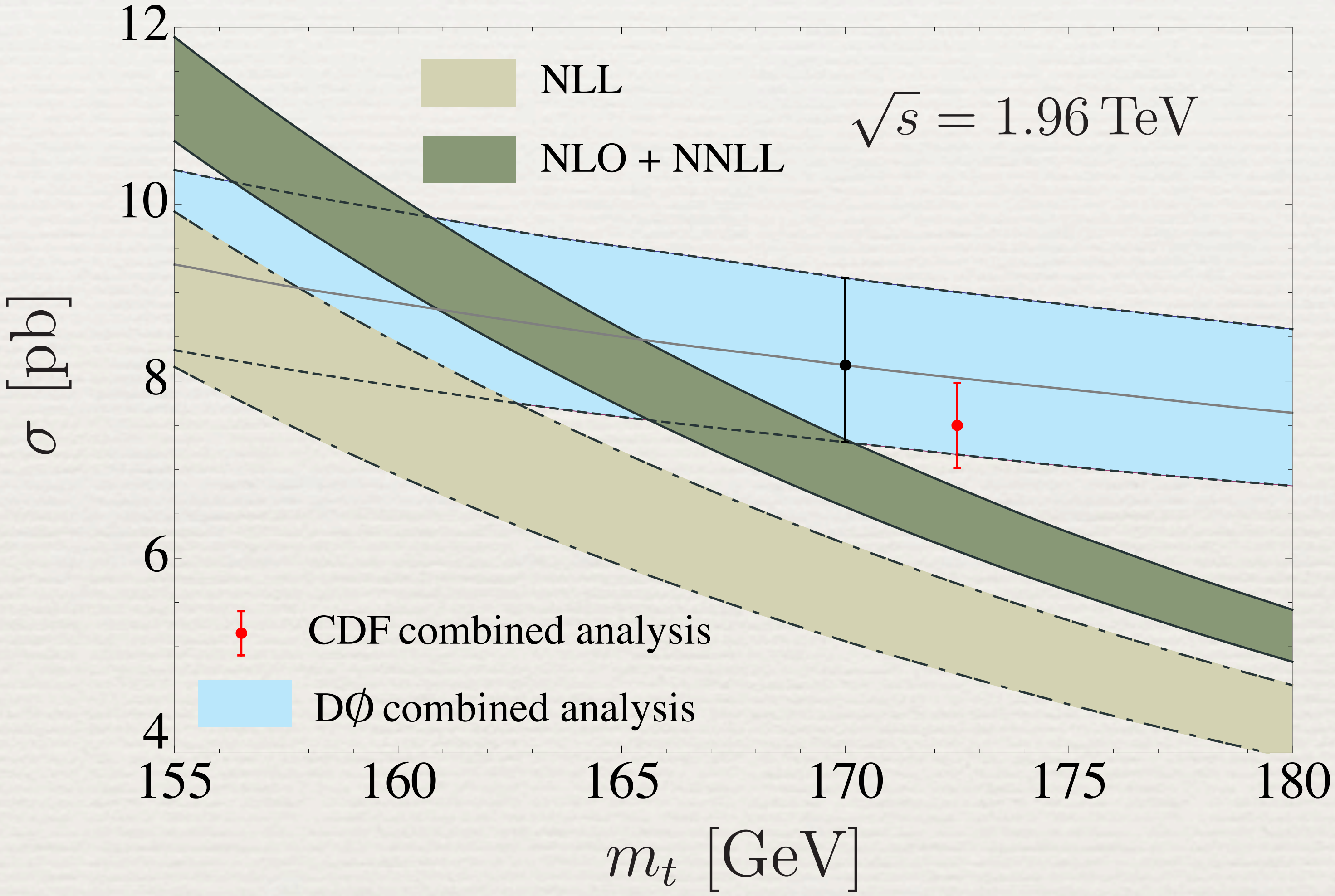
scale uncertainty

PDF uncertainty

- Singular terms dominate NLO corrections
- Resummation stabilizes scale dependence

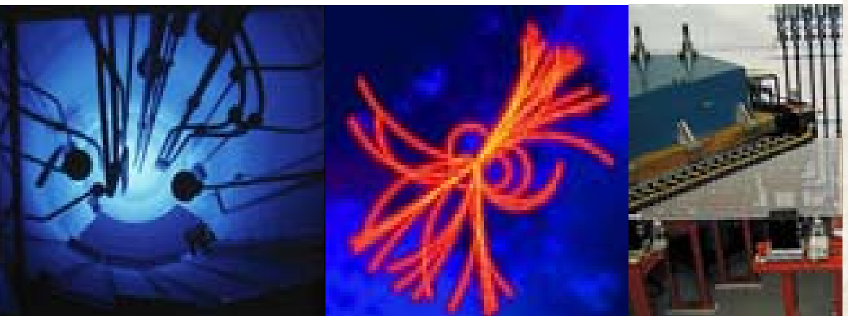
Total cross section

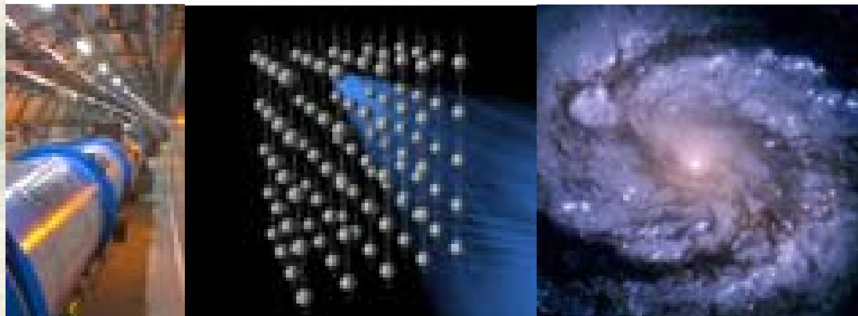
- Mass dependence (pole scheme):



- Extract $m_t = (163.0^{+7.2}_{-6.3})$ GeV, in fair agreement with world average m_t=(173.1±1.3) GeV

Flavor Structure beyond the Standard Model





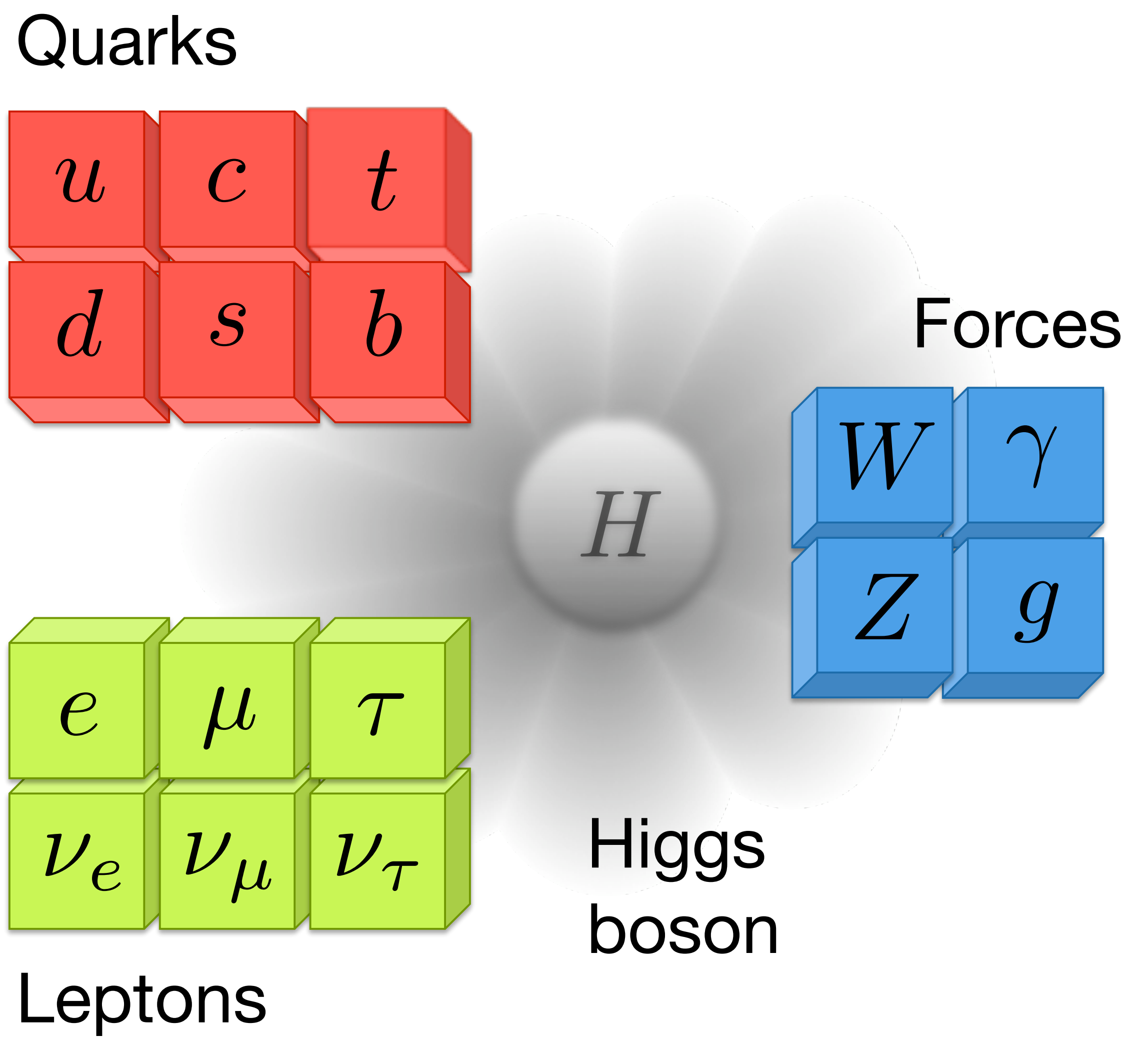
Standard Model and Beyond

Fundamental laws derived from few, basic guiding principles:

- Symmetries (gauge theories)
- Simplicity and beauty (few parameters)
- Naturalness (avoid fine-tuning)
- Anarchy (everything is allowed)

Standard Model of particle physics:

- works beautifully, explaining all experimental phenomena with great precision
- no compelling hints for deviations
- triumph of 20th century science



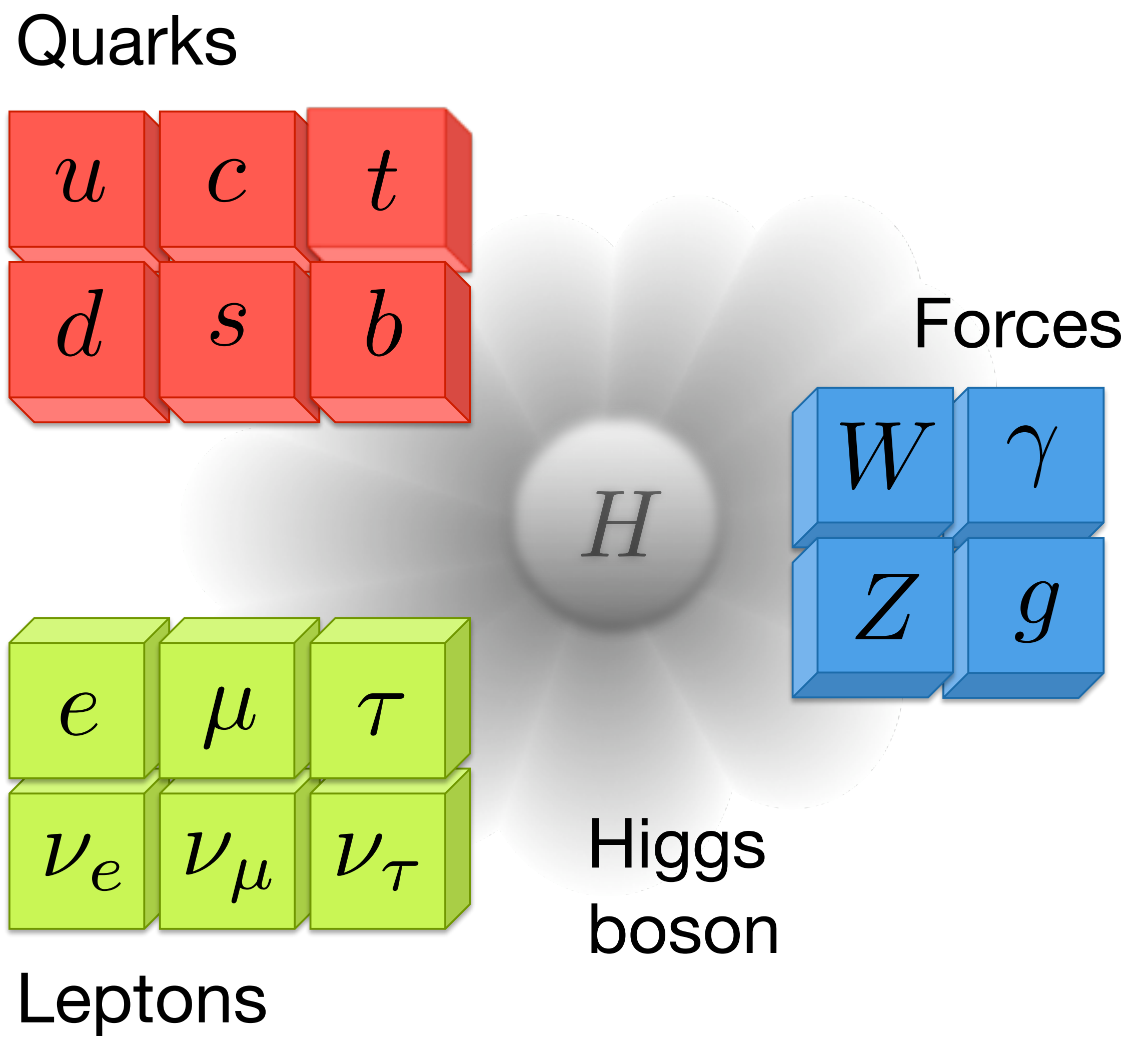
Standard Model and Beyond

Fundamental laws derived from few, basic guiding principles:

- Symmetries (gauge theories)
- Simplicity and beauty (few parameters)
- Naturalness (avoid fine-tuning)
- Anarchy (everything is allowed)

But many questions remain unanswered:

- Origin of generations and structure of Yukawa interactions?
- Matter-antimatter asymmetry?
- Unification of forces? Neutrino masses?
- Dark matter and dark energy?



Strong prejudice that there must be "New Physics"

Standard Model and Beyond: The Gordian Knot

What is the “New Physics” and how to find it ?

Standard Model and Beyond

4th generation

extended Higgs sectors

extended technicolor

left-right symmetry

leptoquarks

universal extra dimensions

large extra dimensions

warped extra dimensions

gauge-Higgs unification

Higgsless models

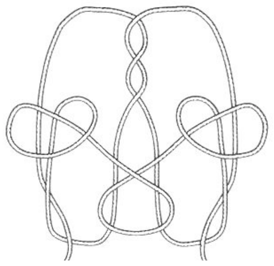
MSSM

CMSSM

NMSSM

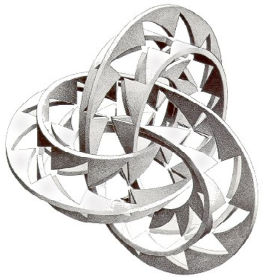
νMSSM

SUSY GUTs



unparticles

Little Higgs



hidden valleys

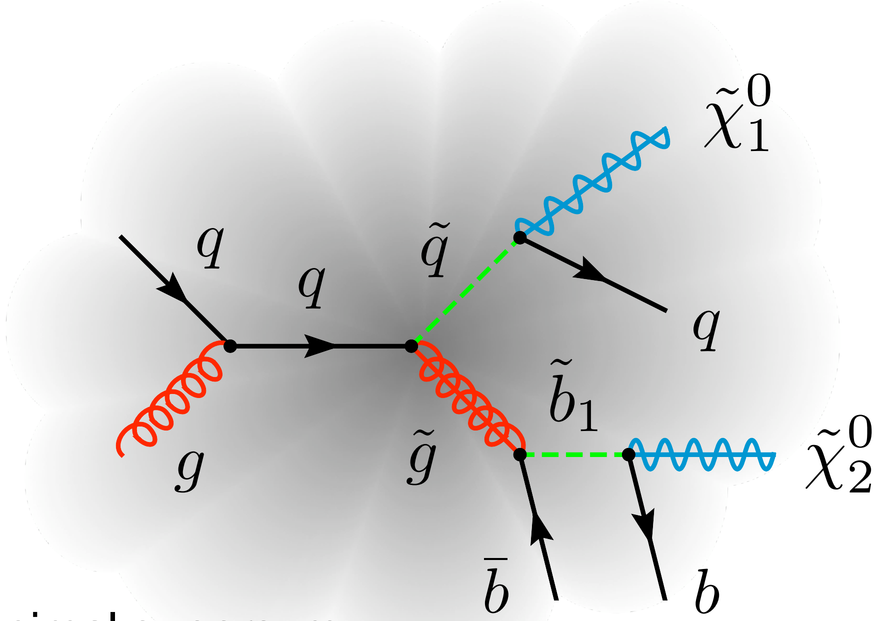
not yet thought of ...

Searches for New Physics: Energy Frontier

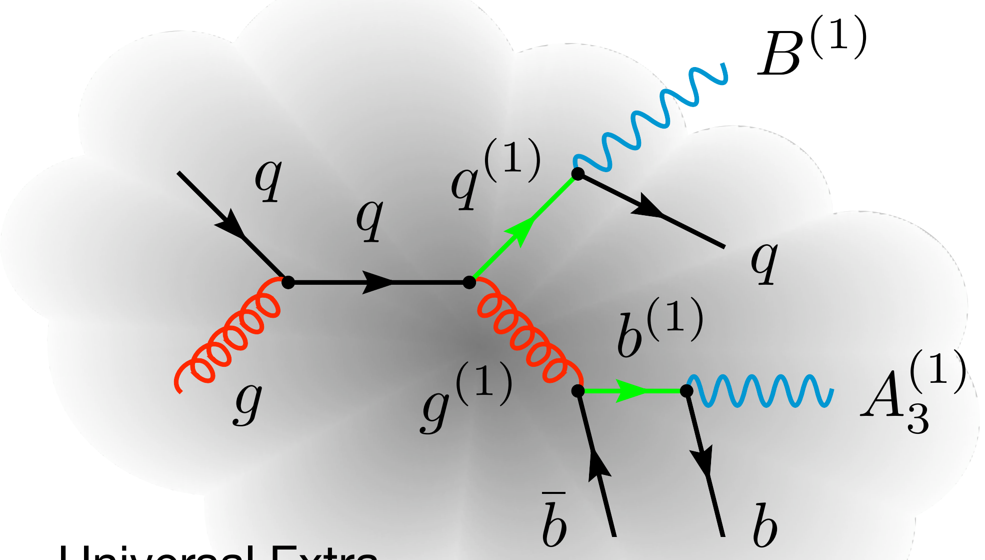
Production of new particles at high-energy colliders probes directly the structure of matter and its interactions:

- Charm at BNL, SLAC (1974)
- Bottom by E288 at FNAL (1977)
- W, Z bosons by UA1/2 at CERN (1983)
- Top by CDF, DØ at FNAL (1995)
- Higgs at FNAL (?), CERN (?), ...

However, quite different scenarios of New Physics can lead to very similar signatures and hence to experimental signals that are difficult to disentangle



Minimal supersymmetric SM (MSSM)



Universal Extra Dimensions (UED)

Searches for New Physics: Energy Frontier

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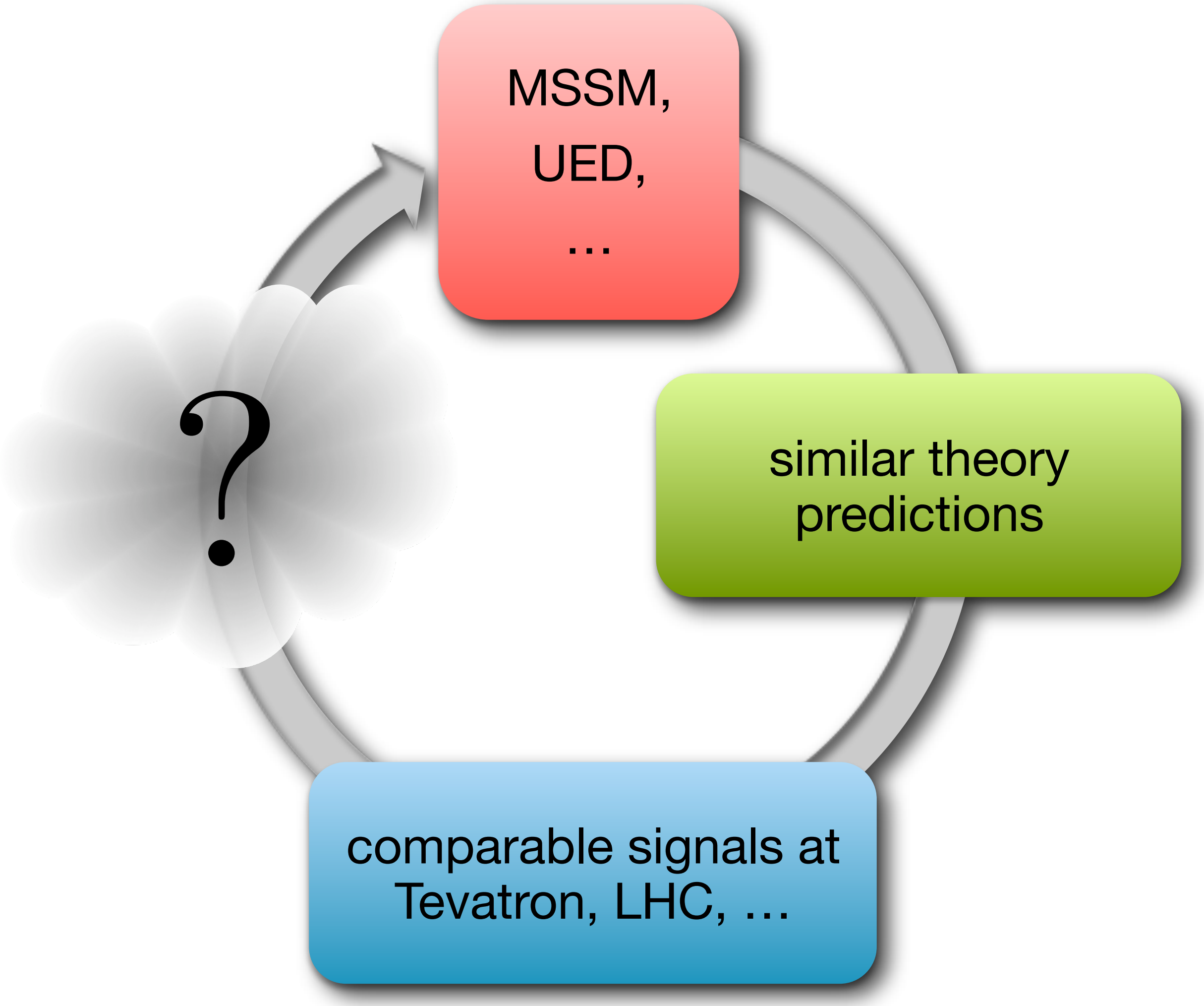

MSSM,
UED,
...

similar theory predictions

comparable signals at Tevatron, LHC, ...

?

LHC inverse problem

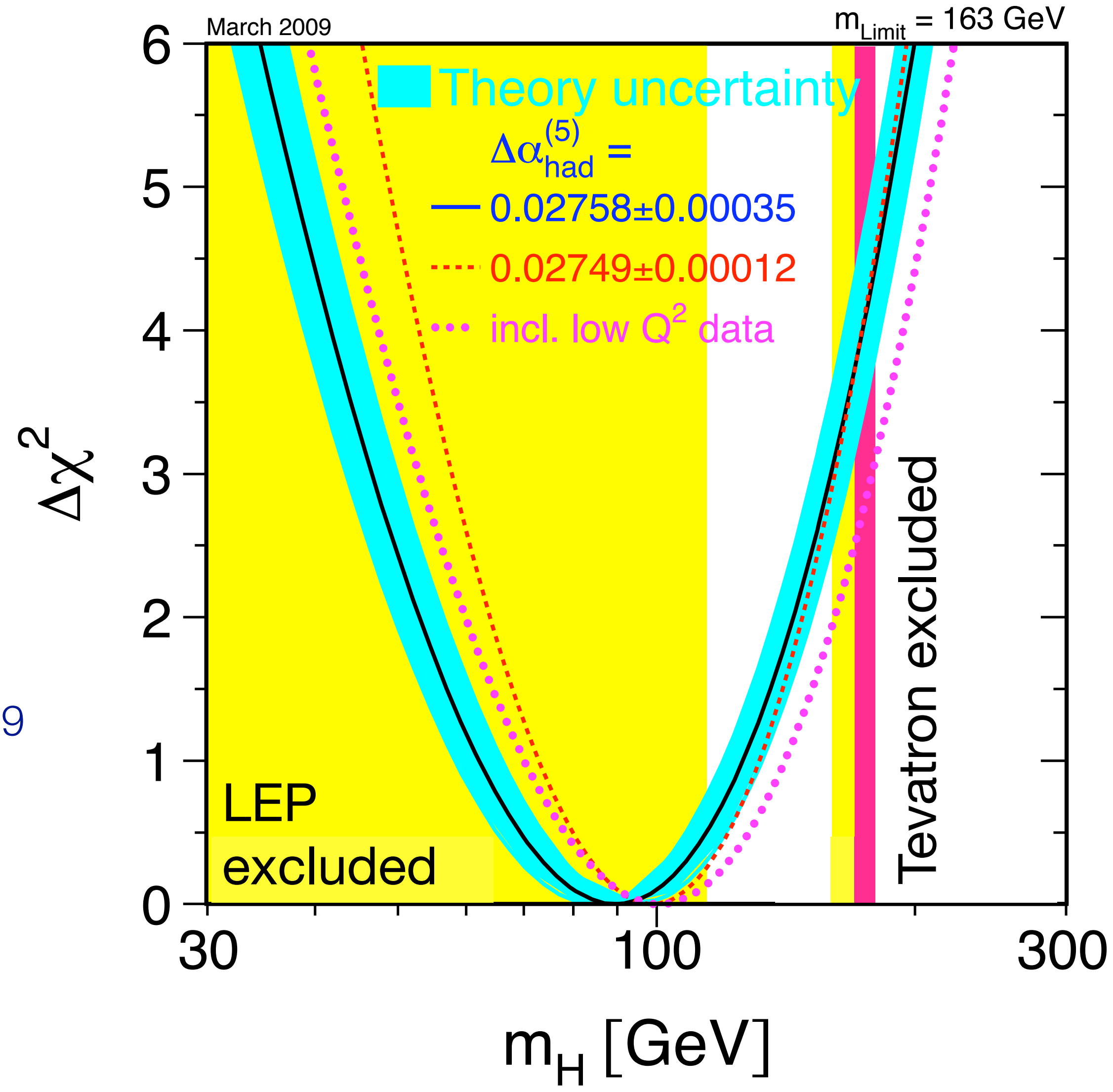
Searches for New Physics: Intensity Frontier

Low-energy experiments at high luminosity study effects resulting from virtual particle exchange:

- Charm mass from K–$\overline{K}$ mixing
- Top mass from B–$\overline{B}$ mixing, precision measurements at Z pole
- Higgs mass from electroweak precision observables
- hints for New Physics in $(g\text{-}2)_\mu$:
  $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (290 \pm 90) \cdot 10^{-11}$
  Jegerlehner, Nyffeler 2009

Offers indirect insights into the structure of matter and its interactions at quantum level

Indirect constraints on the Higgs mass:



Searches for New Physics: Intensity Frontier

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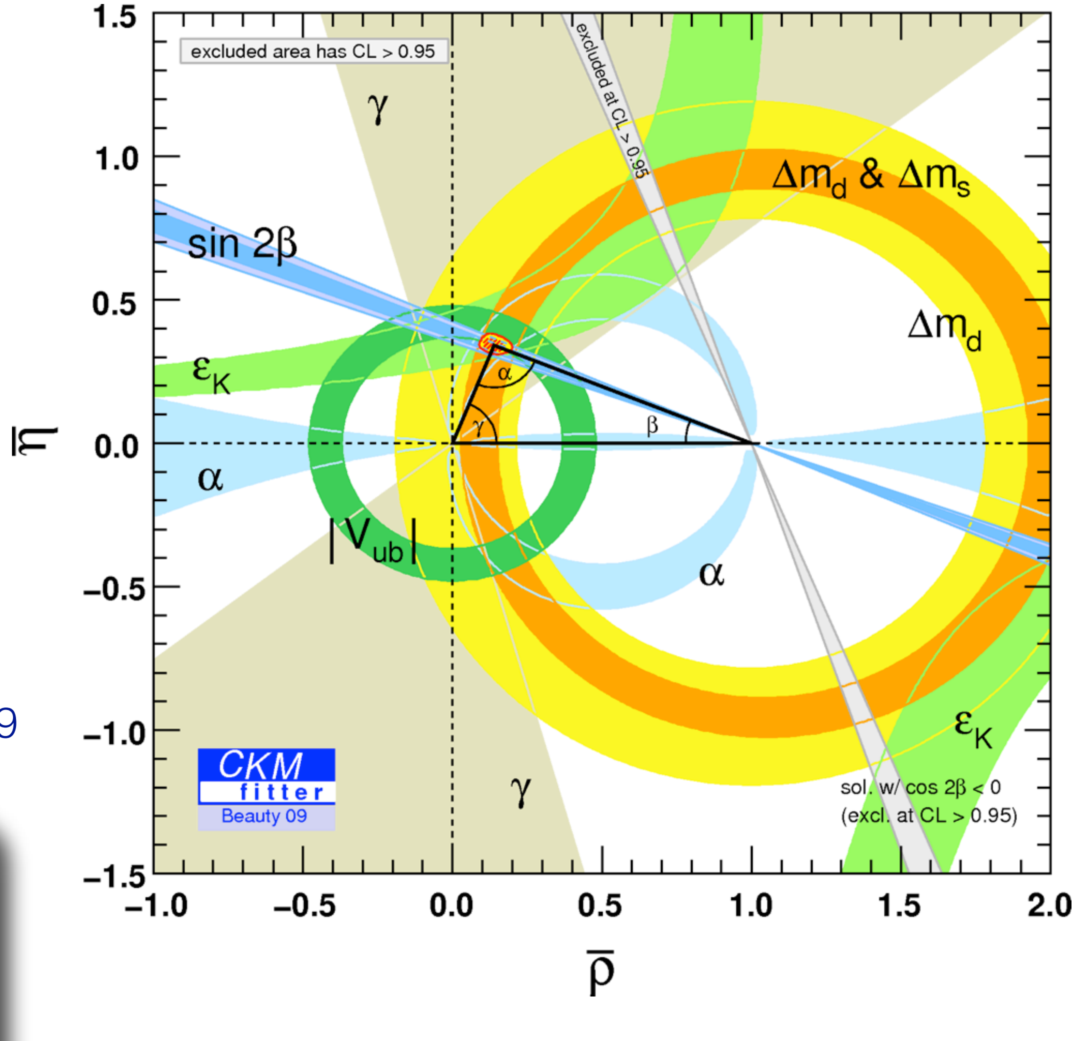
  Jegerlehner, Nyffeler 2009

Provides sensitivity to energy regimes and probes aspects of couplings not accessible to direct searches, paving the way for discoveries or constraints of New Physics

Global analysis of the unitarity triangle:

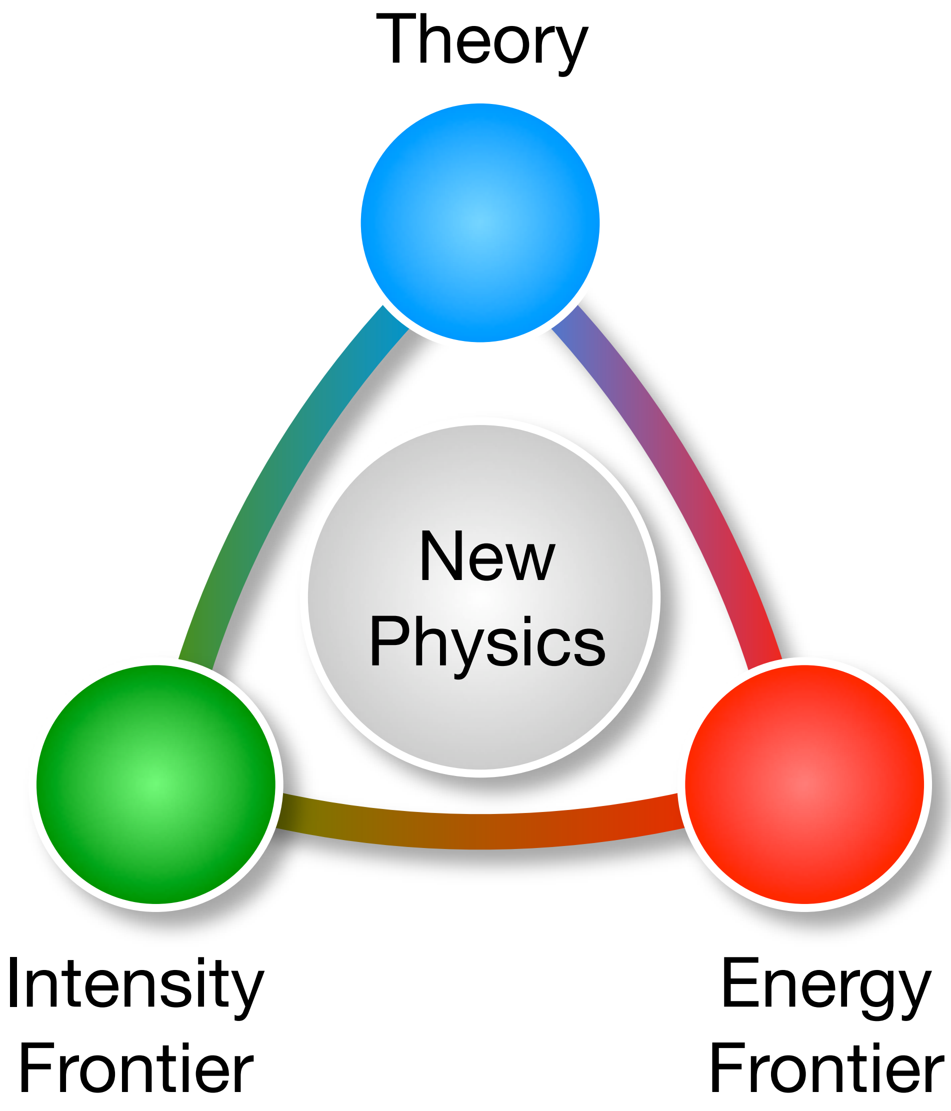


Searches for New Physics: Interplay

Complementarity and synergy:

Answering the open questions of elementary particle physics requires a joint effort:

- **Theory:** precision calculations in the SM, studies of New Physics, model-building, ...
- **High-energy experiments:** Tevatron, LHC, ILC (?), CLIC (?), Muon Collider (?), ...
- **Low-energy experiments:** BaBar, Belle, Super-*B*, NA62, J-PARC, Project X, neutrino physics, EDMs, $(g-2)_\mu$, ...



Theory

New Physics

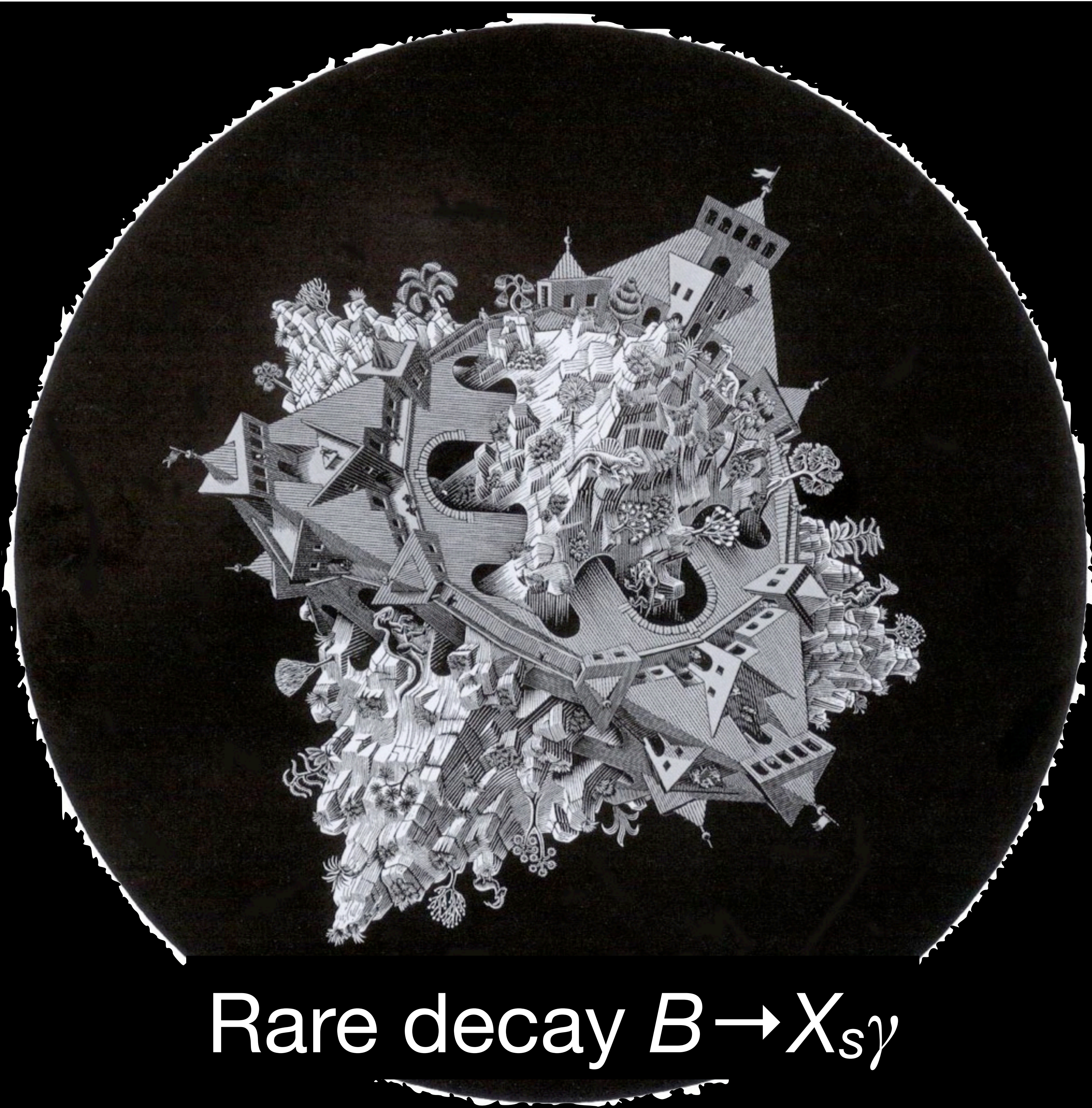
Intensity Frontier

Energy Frontier

Quark flavor physics is a crucial component in this program, which provides surgical probes of subtle corrections to fundamental interactions

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Complementarity of High Energy and Precision



Rare decay $B \to X_s \gamma$

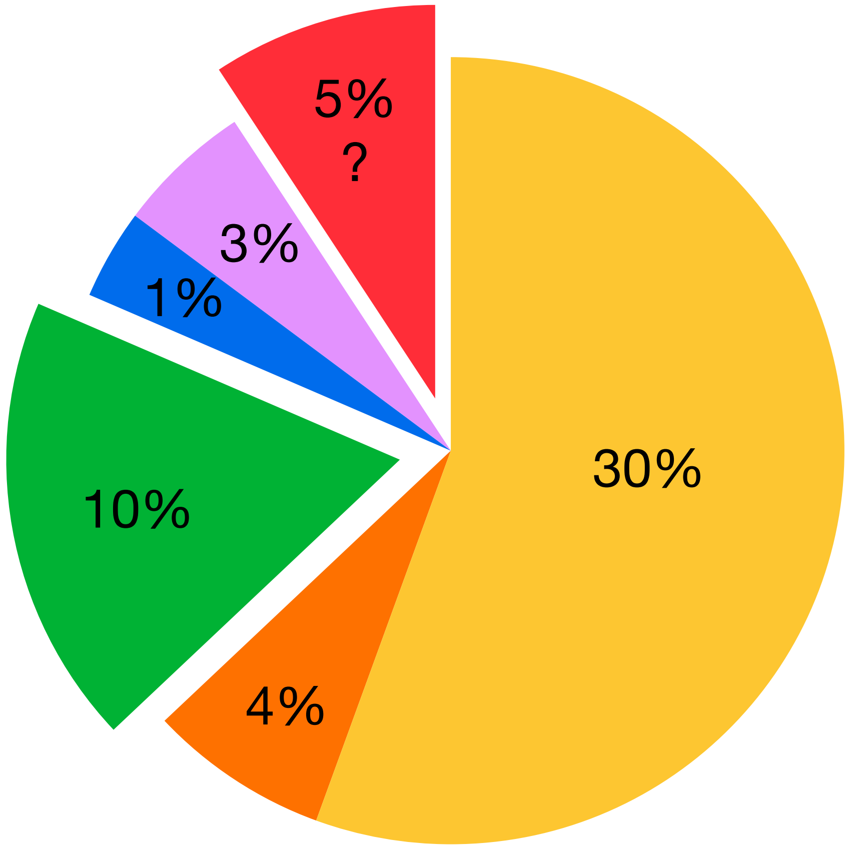
Probing FCNCs in $B\to X_s\gamma$ Decay

$$\mathcal{B}(B\to X_s\gamma)^{E_\gamma>1.6\ \text{GeV}}_{\text{SM}} = \mathcal{B}(B\to X_c e\bar{\nu})_{\text{exp}}\left[\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu})}\right]_{\text{LO}}$$

$$\times\left\{1+\mathcal{O}(\alpha_s)+\mathcal{O}(\alpha)+\mathcal{O}(\alpha_s^2)+\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{m_b^2}\right)+\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{m_c^2}\right)+\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)\right\}$$

Misiak *et al.* 2006; Becher, Neubert 2006

Lee, Neubert, Paz 2006



● NLO QCD

● NLO EW

● NNLO QCD

perturbative

● LO QCD + local $1/m_b^2$

● LO QCD + local $1/m_c^2$

● non-local (!) $1/m_b$

non-perturbative

relative size of corrections compared to leading-order (LO) branching ratio

Probing FCNCs in $B\to X_s\gamma$ Decay

$$\mathcal{B}(B\to X_s\gamma)^{E_\gamma>1.6\ \text{GeV}}_{\text{SM}} = \mathcal{B}(B\to X_c e\bar{\nu})_{\text{exp}}\left[\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu})}\right]_{\text{LO}}$$

$$\times\left\{1+\mathcal{O}(\alpha_s)+\mathcal{O}(\alpha)+\mathcal{O}(\alpha_s^2)+\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{m_b^2}\right)+\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{m_c^2}\right)+\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)\right\}$$

Misiak *et al.* 2006; Becher, Neubert 2006

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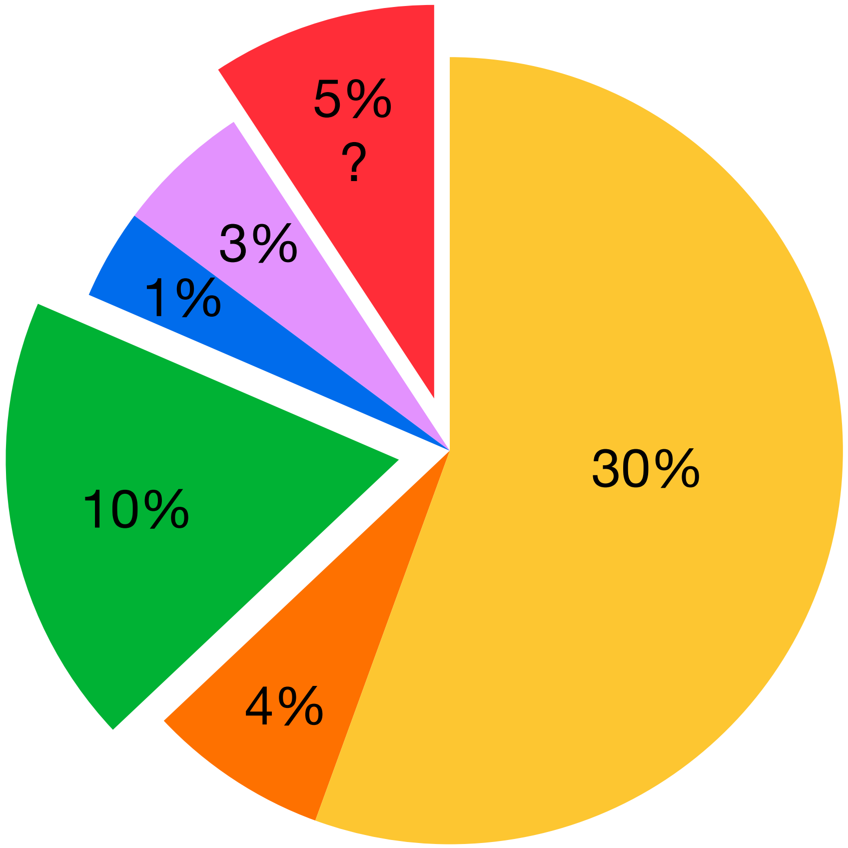


relative size of corrections compared to leading-order (LO) branching ratio

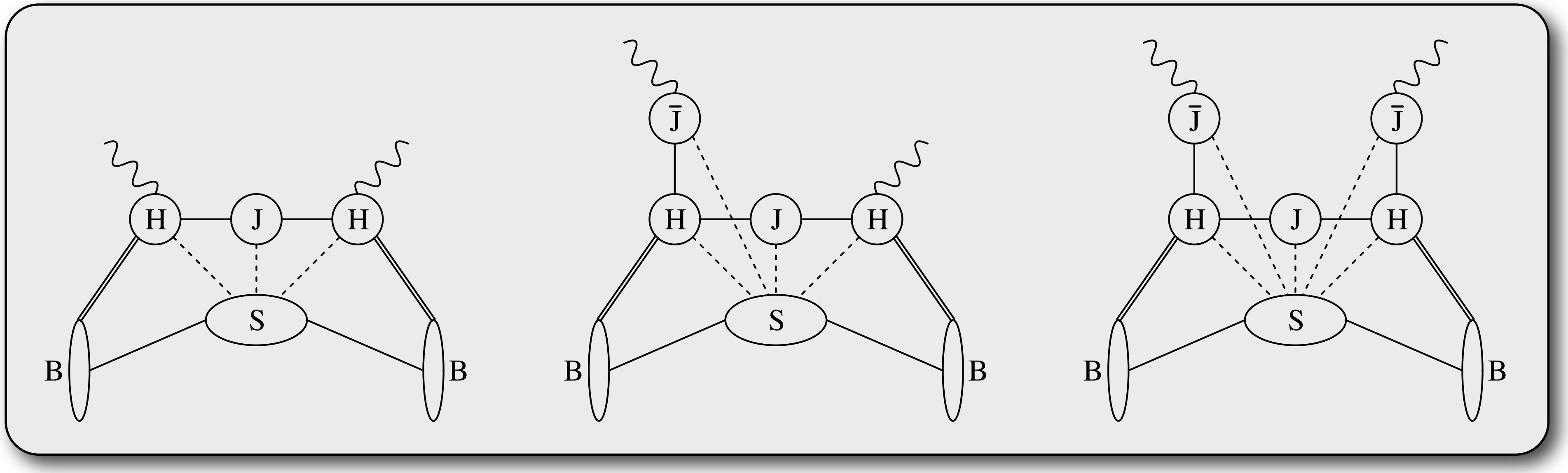
NNLO perturbative calculation (technically difficult) and systematic estimate of **non-local power corrections** (conceptually difficult) are required in order to obtain an uncertainty of 5%

$$\mathcal{B}(B\to X_s\gamma)^{E_\gamma>1.6\,\text{GeV}}_{\text{NNLO}} = (3.15\pm0.23)\times10^{-4}$$

$$\mathcal{B}(B\to X_s\gamma)^{E_\gamma>1.6\,\text{GeV}}_{\text{exp}} = (3.52\pm0.23\pm0.09)\times10^{-4}$$

Probing FCNCs in $B \to X_s \gamma$ Decay

Systematic analysis of non-local Λ_{QCD}/m_b corrections based on novel factorization theorem derived using soft-collinear effective theory:



Examples of relevant non-local soft matrix elements:

Benzke, Lee, Neubert, Paz 2010

$$g_{17}(\omega,\omega_1,\mu) = \int \frac{dr}{2\pi}\, e^{-i\omega_1 r} \int \frac{dt}{2\pi}\, e^{-i\omega t}$$

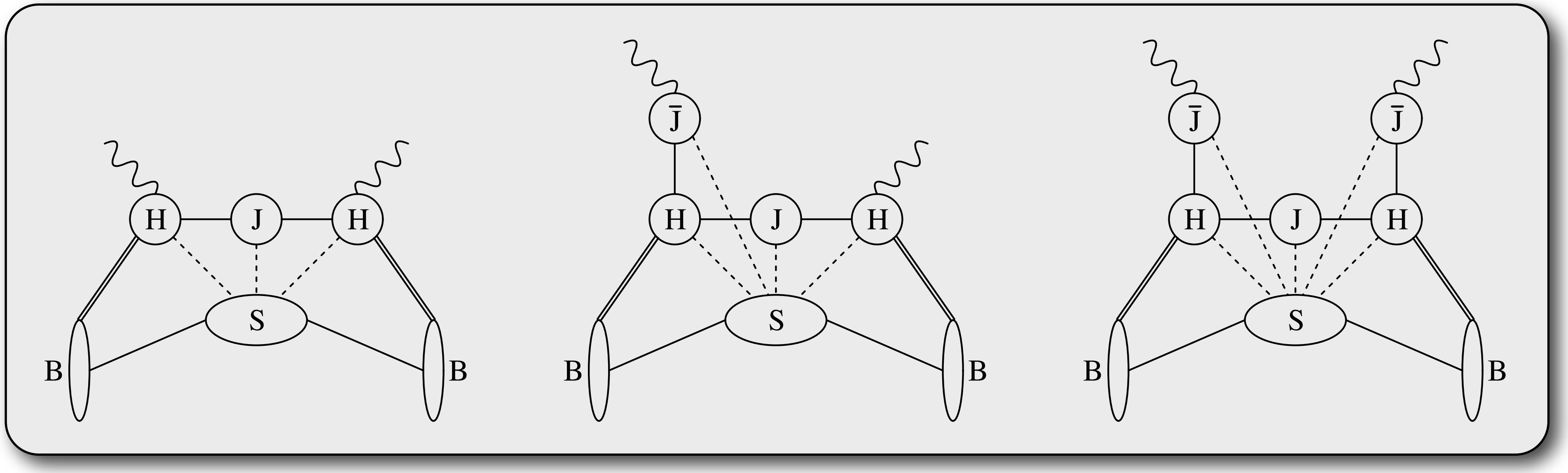
$$\times \frac{\langle \bar{B} | \big(\bar{h} S_n\big)(tn)\, \not{\bar{n}}(1+\gamma_5)\big(S_n^\dagger S_{\bar{n}}\big)(0)\, i\gamma_\alpha^\perp \bar{n}_\beta\, \big(S_{\bar{n}}^\dagger\, g G_s^{\alpha\beta} S_{\bar{n}}\big)(r\bar{n})\, \big(S_{\bar{n}}^\dagger h\big)(0) | \bar{B} \rangle}{2M_B}$$

$$g_{78}^{(5)}(\omega,\omega_1,\omega_2,\mu) = \int \frac{dr}{2\pi}\, e^{-i\omega_1 r} \int \frac{du}{2\pi}\, e^{i\omega_2 u} \int \frac{dt}{2\pi}\, e^{-i\omega t}$$

$$\times \frac{\langle \bar{B} | \big(\bar{h} S_n\big)(tn) \big(S_n^\dagger S_{\bar{n}}\big)(0)\, T^A\, \not{\bar{n}}(1+\gamma_5)\, \big(S_{\bar{n}}^\dagger h\big)(0)\, \mathbf{T} \sum_q e_q\, \big(\bar{q} S_{\bar{n}}\big)(r\bar{n})\, \not{\bar{n}}\gamma_5\, T^A \big(S_{\bar{n}}^\dagger q\big)(u\bar{n}) | \bar{B} \rangle}{2M_B}$$

Probing FCNCs in $B \to X_s\gamma$ Decay

Systematic analysis of non-local Λ_{QCD}/m_b corrections based on novel factorization theorem derived using soft-collinear effective theory:



Corrections to short-distance calculation of decay rate:

Benzke, Lee, Neubert, Paz 2010

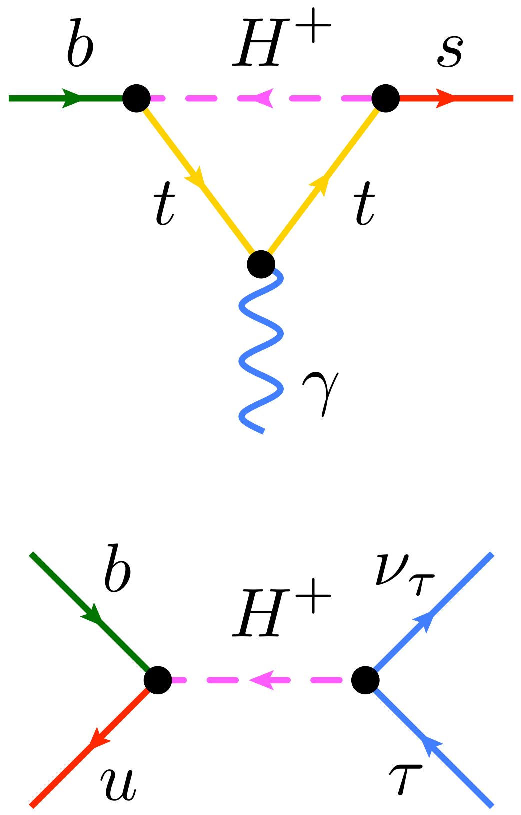
$$\mathcal{F}_E(\Delta) = \frac{C_1(\mu)}{C_{7\gamma}(\mu)} \frac{\Lambda_{17}(m_c^2/m_b, \mu)}{m_b} + \frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)} 4\pi\alpha_s(\mu) \frac{\Lambda_{78}^{\text{spec}}(\mu)}{m_b}$$
$$+ \left(\frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)}\right)^2 \left[4\pi\alpha_s(\mu) \frac{\Lambda_{88}(\Delta, \mu)}{m_b} - \frac{C_F\alpha_s(\mu)}{9\pi} \frac{\Delta}{m_b} \ln\frac{\Delta}{m_s}\right] + \ldots$$

Our estimate:

$$-5.1\% < \mathcal{F}_E(\Delta) < +4.2\%$$

Irreducible theoretical uncertainty!

Impact on New Physics: Type-II 2HDM

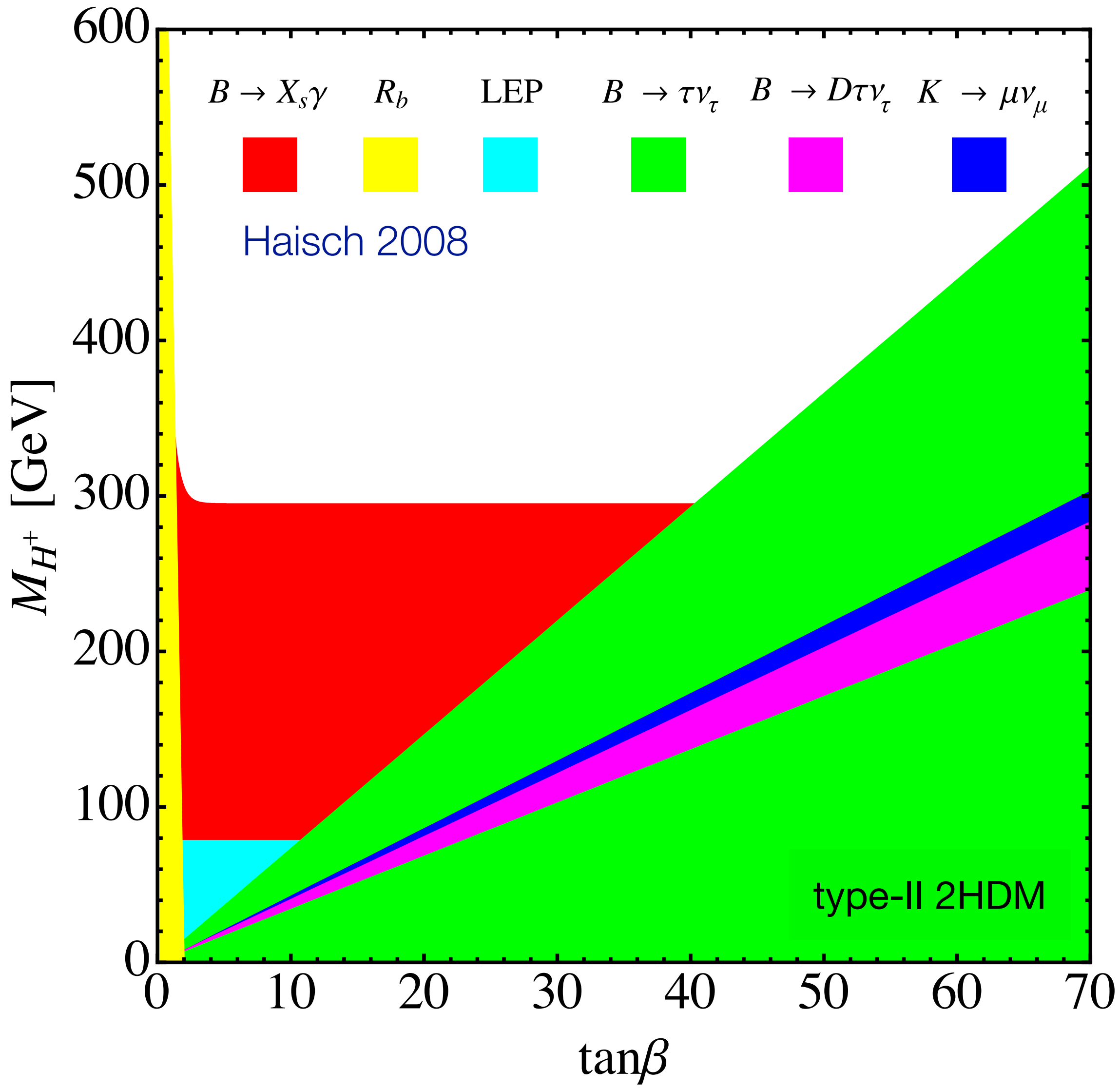


2HDM diagrams

$$\frac{m_t^2}{M_{H^+}^2}\ln\frac{m_t^2}{M_{H^+}^2}$$

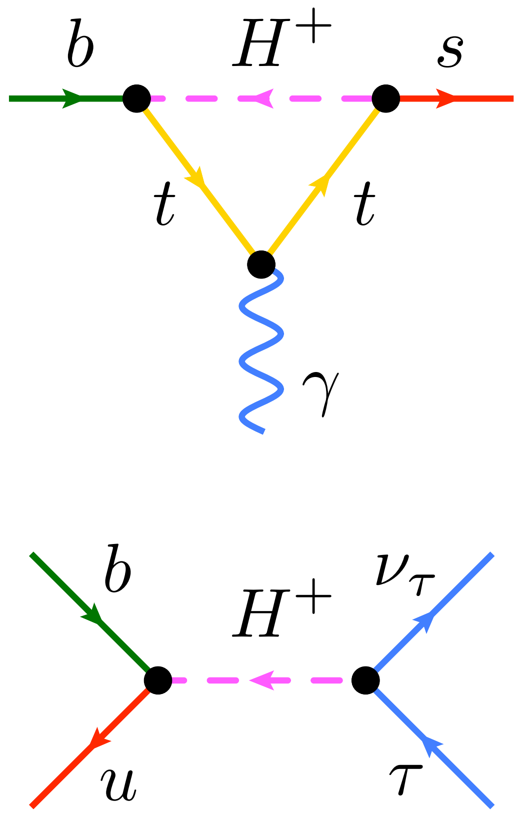
$$\tan^2\beta\,\frac{m_B^2}{M_{H^+}^2}$$

M_{H^+} dependence of amplitude



Flavor physics, in particular $B \to X_s\gamma$ and $B \to \tau\nu$, yield constraints much stronger than those derived from LEP data

Impact on New Physics: Type-II 2HDM



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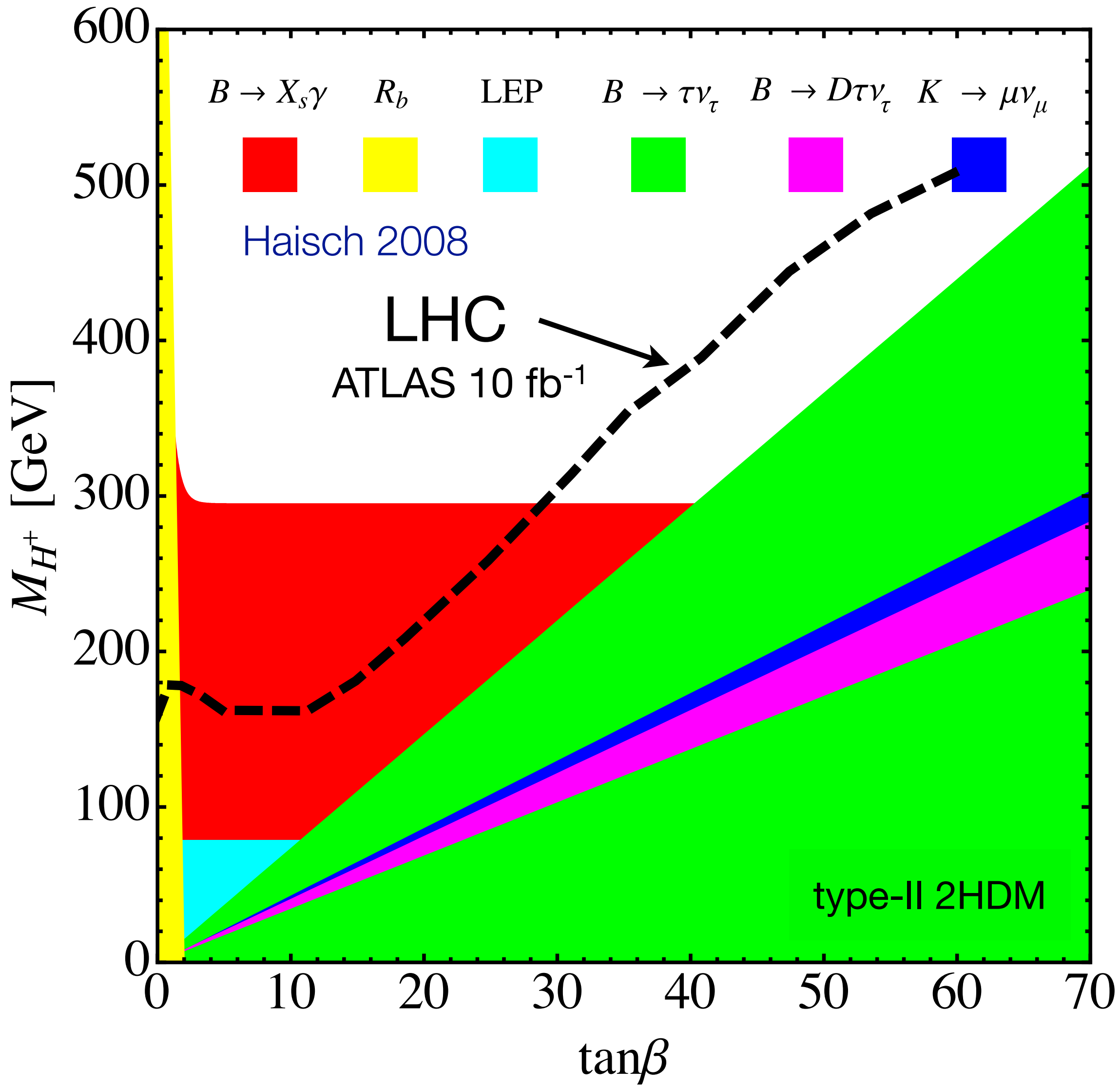
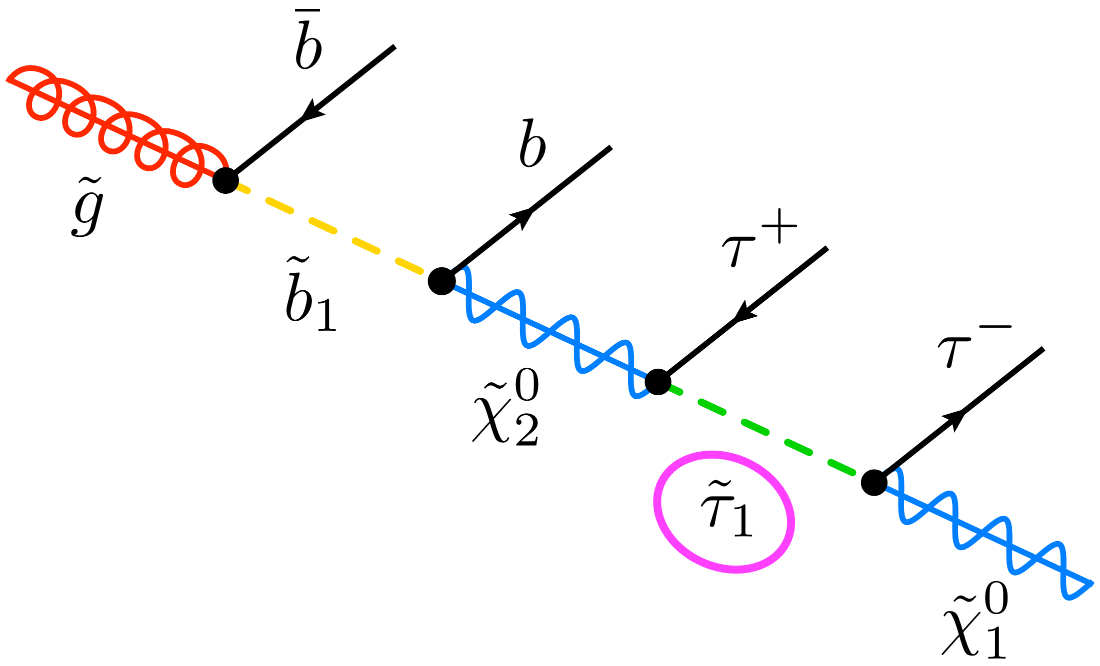
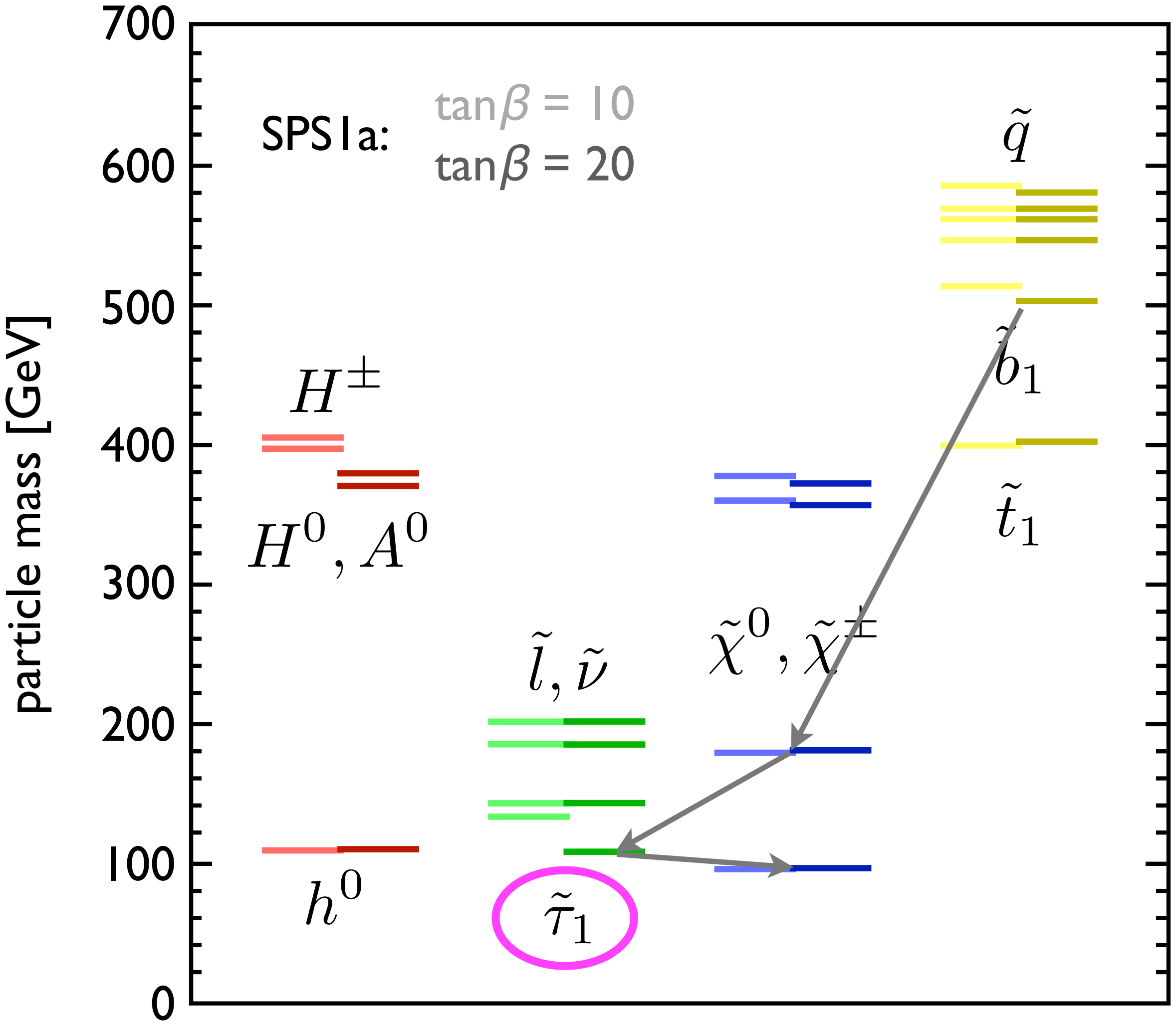


Existing constraints in $\tan\beta$-M_{H^+} plane from flavor physics are comparable and complementary to the expected 95% CL exclusion limits from LHC, derived using $gg,gb \to t(b)H^+$ followed by $H^+ \to \tau\nu_\tau, tb$

Impact on New Physics: MSSM

A gluino cascade decay chain that can be used to reconstruct mass of lightest stau at LHC

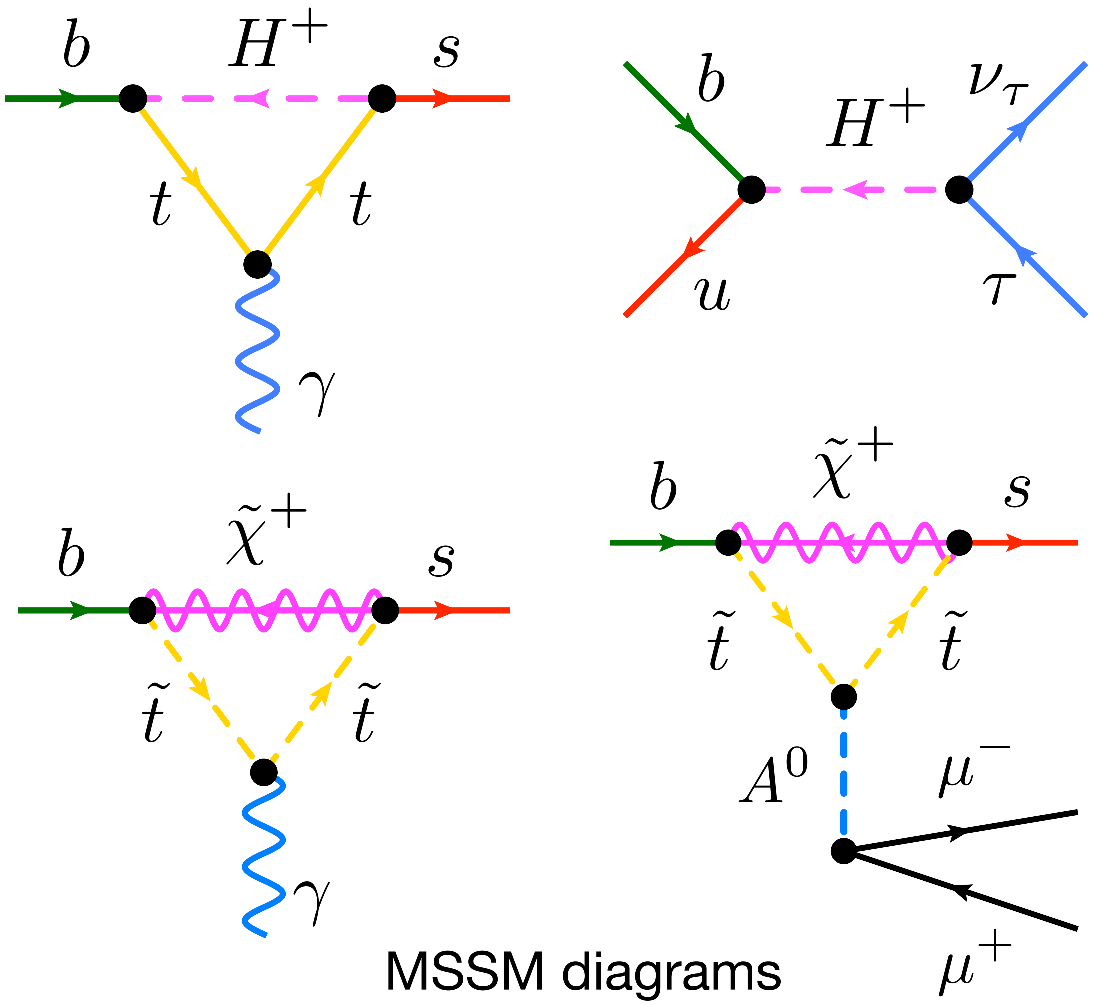




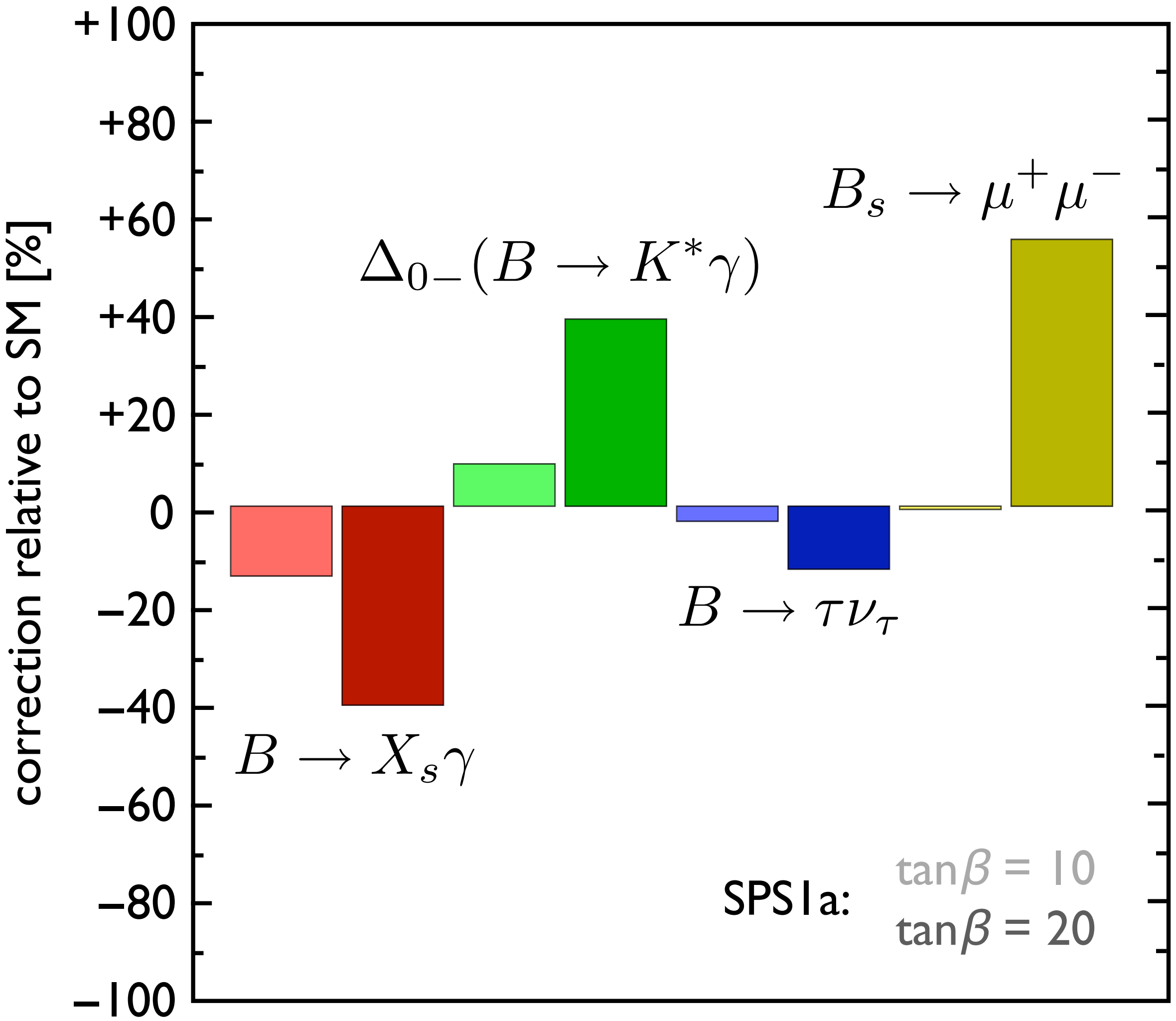
Knowing masses of gluino ($\tilde{g}$), sbottom ($\tilde{b}_1$), and neutralinos ($\tilde{\chi}^0_{1,2}$), the mass of the lightest stau ($\tilde{\tau}_1$) can be measured with precision of only 20% at LHC

LHC sensitivity to tanβ is thus typically not very large, since sparticle spectrum does not change significantly with tanβ

Impact on New Physics: MSSM



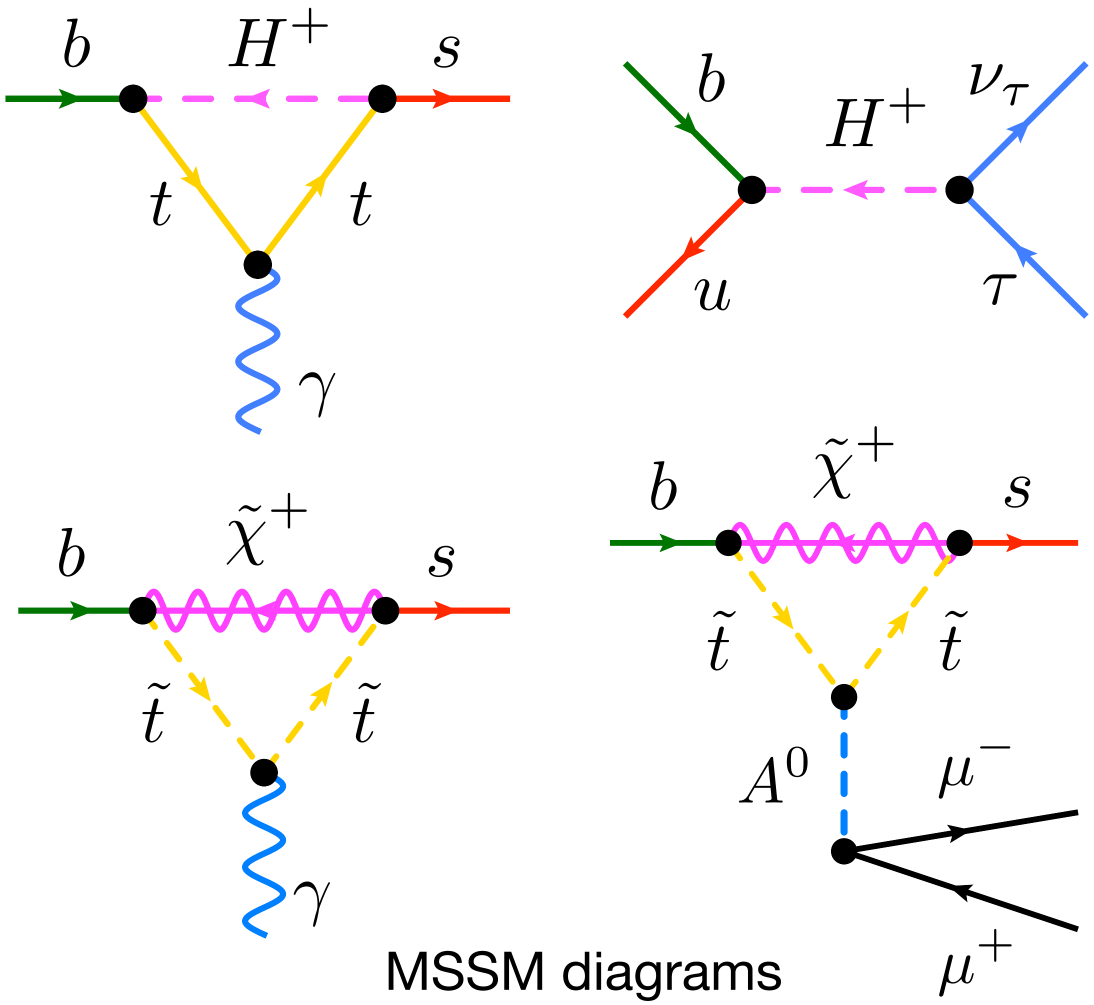
MSSM diagrams



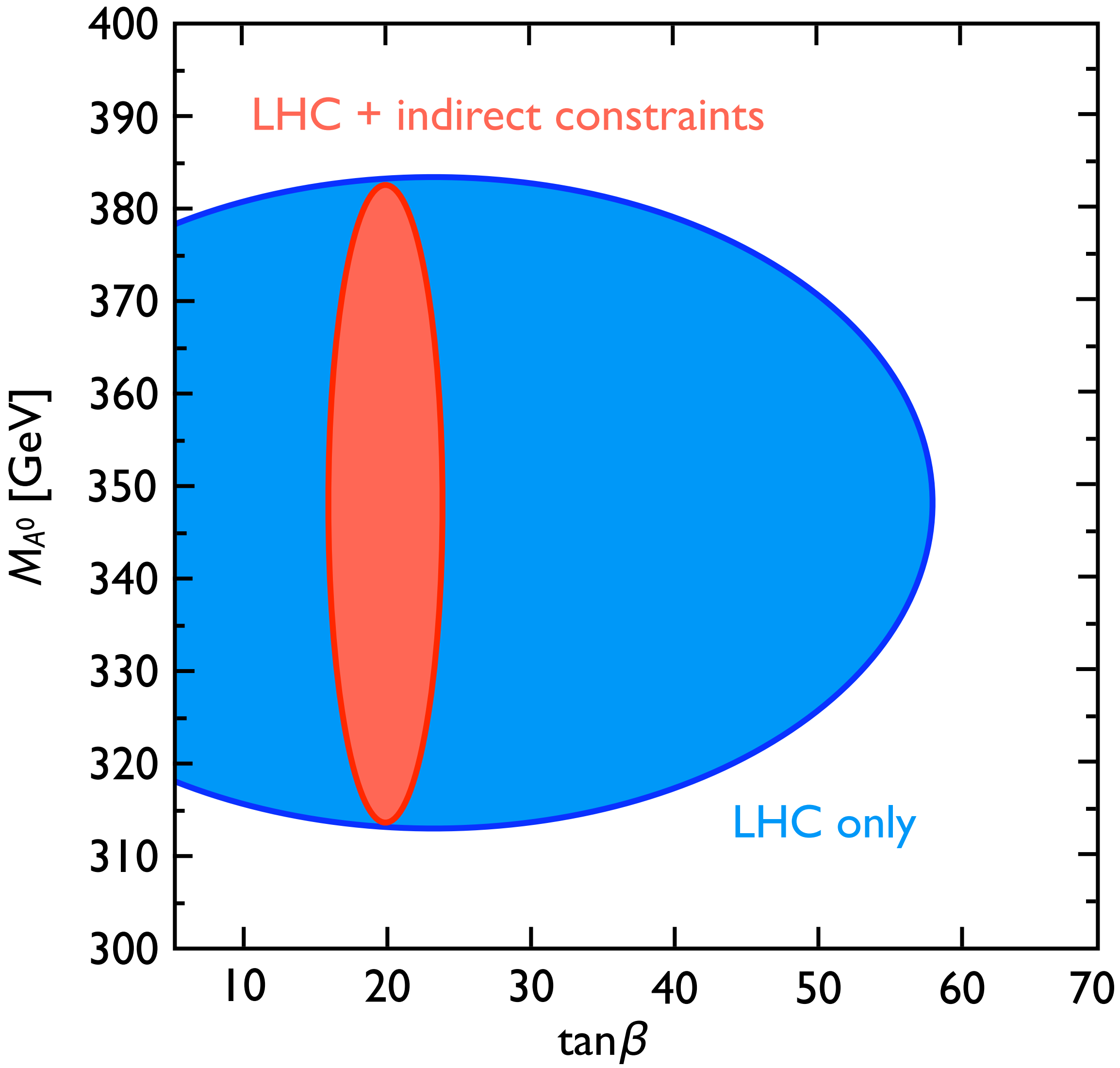
Branching ratios of $B \to X_s\gamma$, $B \to \tau\nu_\tau$, $B_s \to \mu^+\mu^-$, and isospin asymmetry of $B \to K^*\gamma$, depend quite sensitively on tanβ

By measuring correlated shifts in these observables, it might be possible to determine tanβ with 10% accuracy, by far exceeding LHC sensitivity

Impact on New Physics: MSSM



MSSM diagrams



Branching ratios of $B \to X_s\gamma$, $B \to \tau\nu_\tau$, $B_s \to \mu^+\mu^-$, and isospin asymmetry of $B \to K^*\gamma$, depend quite sensitively on exact value of tanβ

By measuring correlated shifts in these observables, it might be possible to determine tanβ with 10% accuracy, by far exceeding LHC sensitivity

Puzzles in the Flavor Sector: **Facts or Fiction?**

$\sin 2\beta$ from tree vs. loop processes

$|V_{cb}|$ and $|V_{ub}|$ exclusive vs. inclusive

$|V_{ub}|$ vs. $\sin 2\beta$ and ε_K

$\Delta A_{CP}(B\to\pi K)$ puzzle

CP violation in B_s mixing

enhanced $B\to\tau\nu$ rate

A_{FB} asymmetry in $B\to K^* l^+ l^-$

not yet measured ...

Several observables don't look quite right ... ($\sim 2\sigma$ effects)

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Perhaps, one of these hints will solidify and point us the way beyond the SM!

CP violation in B_s mixing

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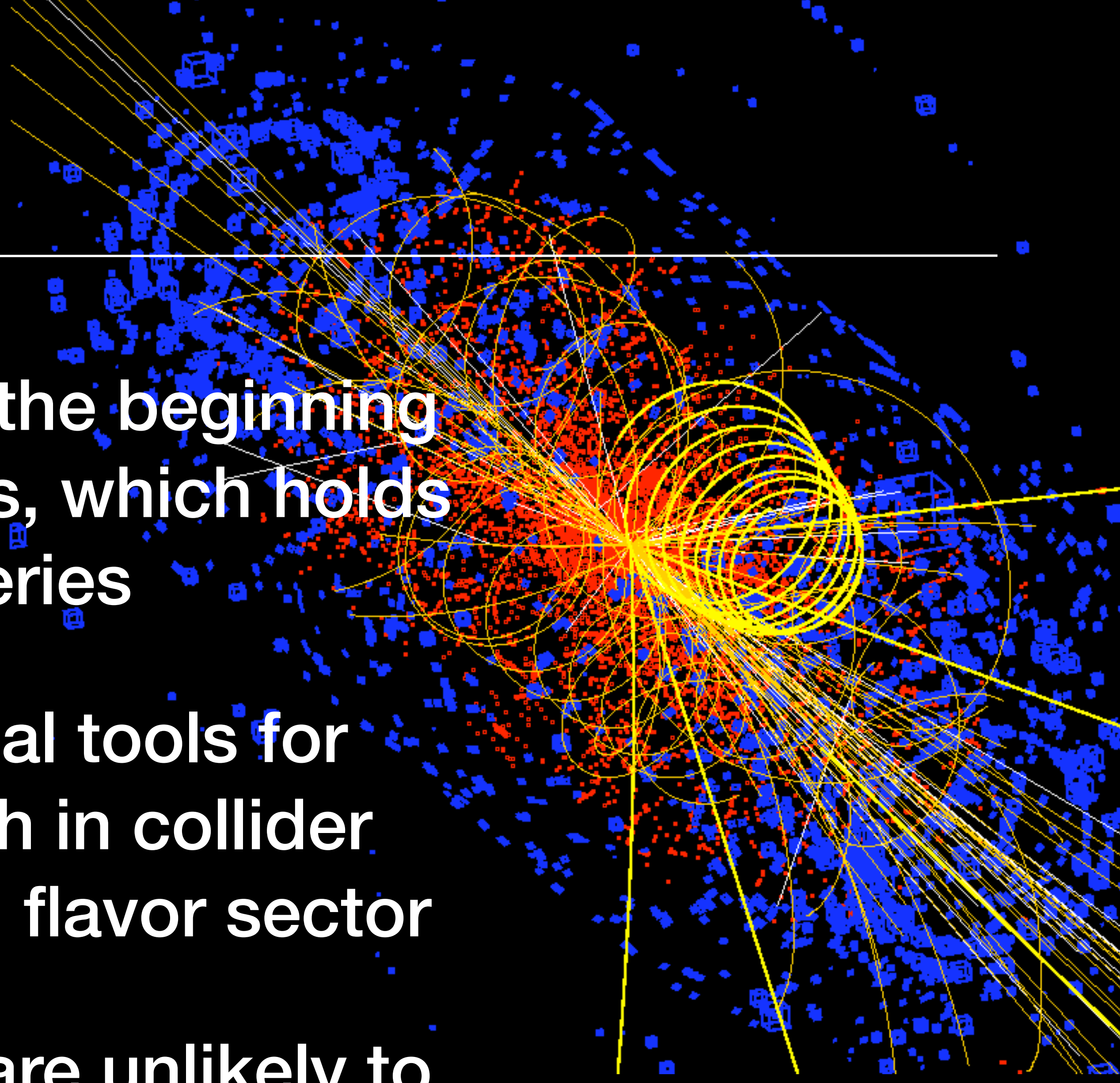
Summary and Outlook



The first collisions at the LHC mark the beginning of a fantastic era for particle physics, which holds promise of ground-breaking discoveries

Effective field theories provide crucial tools for precision analyses of LHC data, both in collider physics (high-energy frontier) and in flavor sector

ATLAS and CMS discoveries alone are unlikely to provide a complete understanding of the observed phenomena

Flavor physics (more generally, low-energy precision physics) will play a key role in unravelling what lies beyond the Standard Model, providing access to energy scales and couplings unaccessible at the energy frontier