# TOP-QUARKS AT 100 TEV

- based on work with Tao Han and Joshua Sayre -

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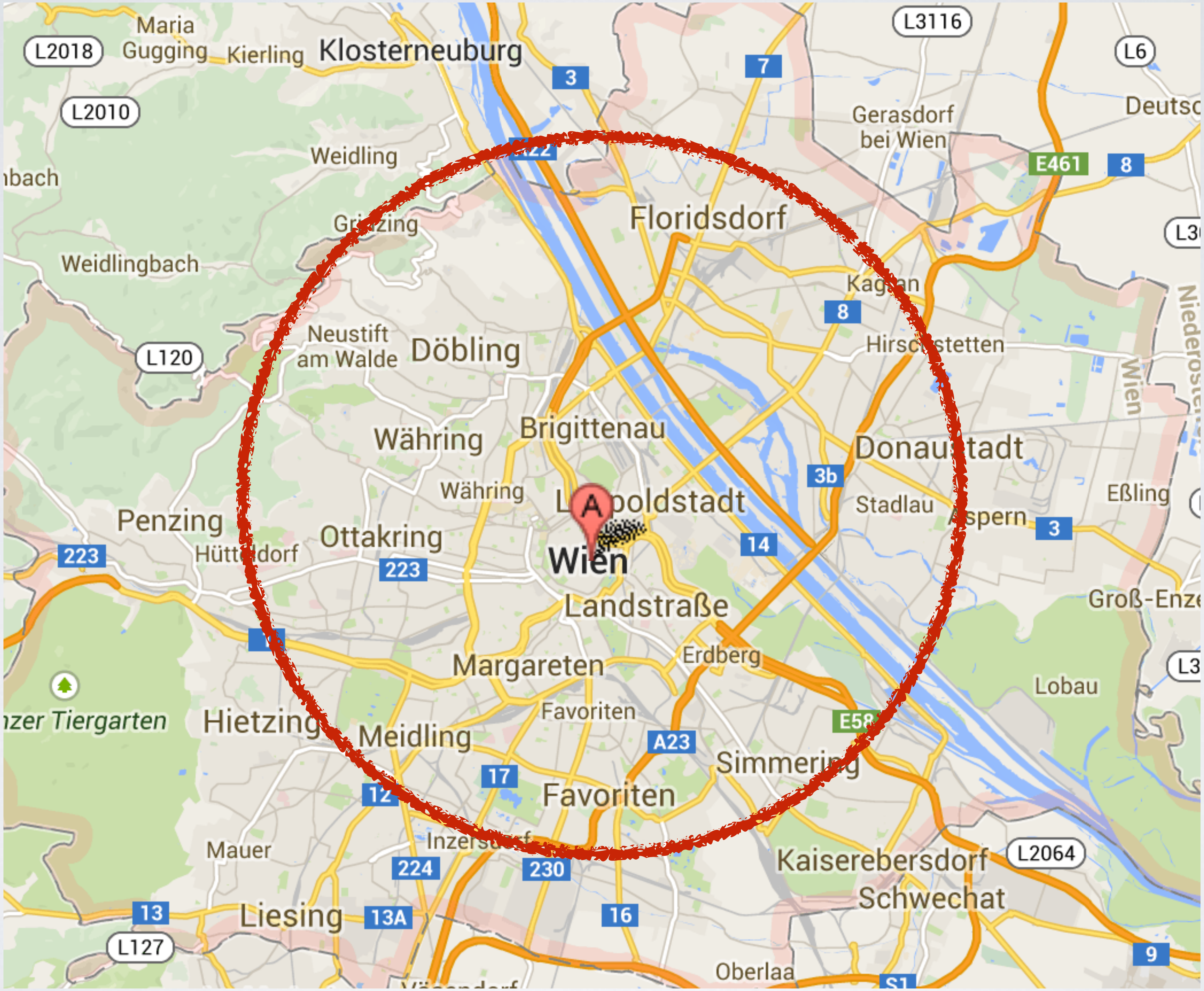
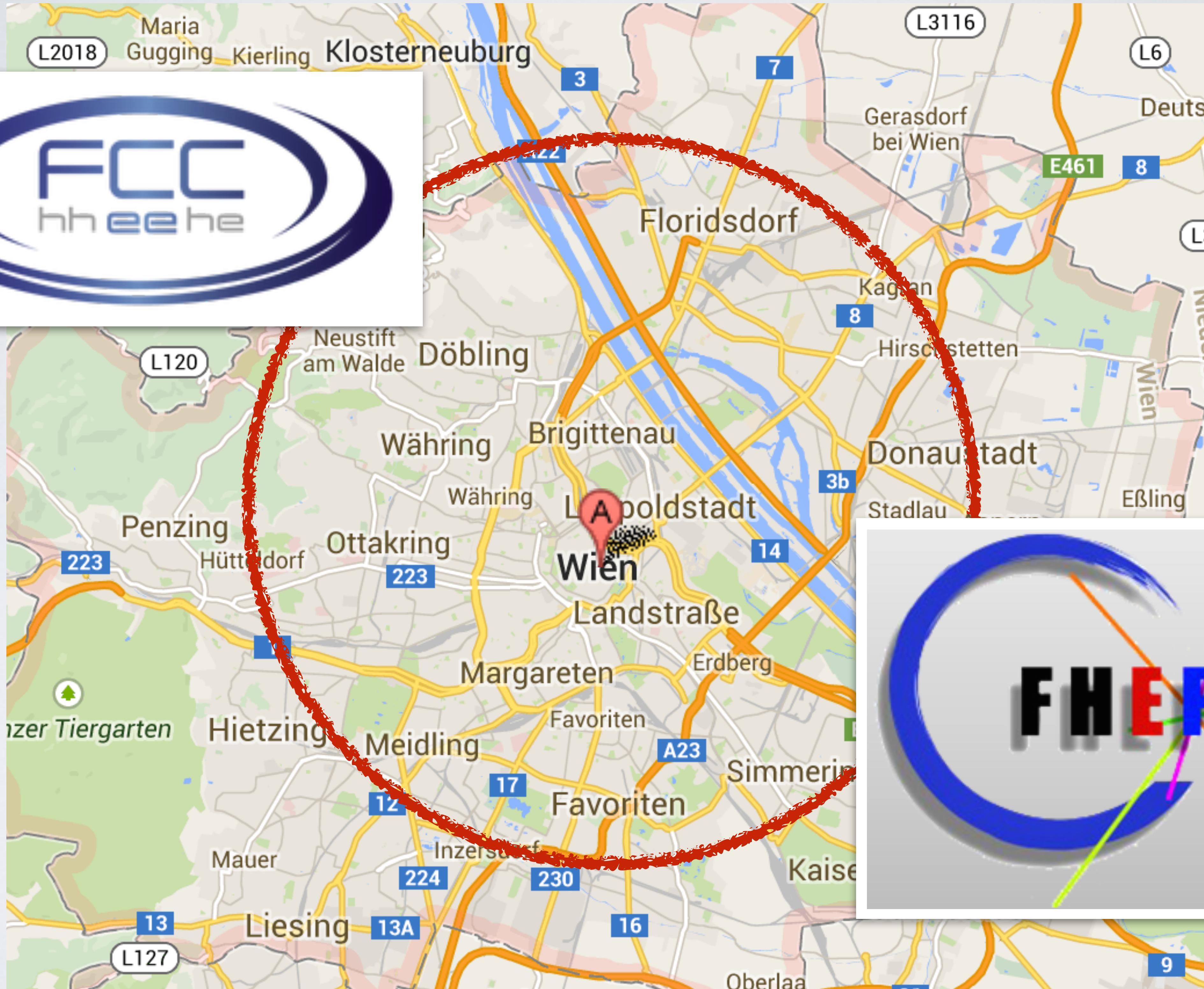
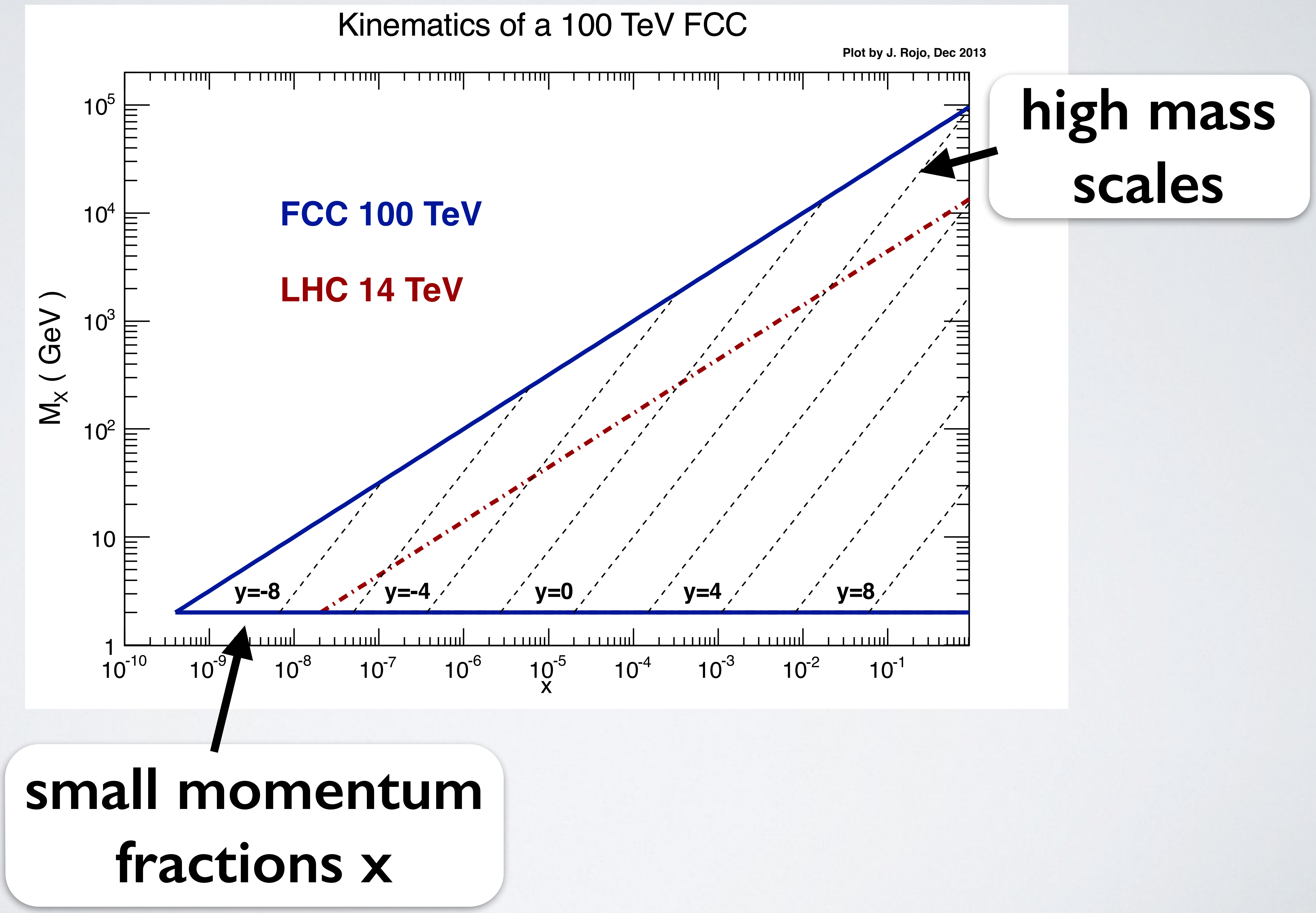
# A 100 TEV - 100 KM COLLIDER ?



# FUTURE CIRCULAR COLLIDERS



# WHAT DO WE GAIN WITH 100 TEV ?



# FOUR GOOD REASONS TO BE EXCITED

1) We might find (predicted) new physics beyond LHC reach.

2) We might find something unexpected.

3) We will touch unexplored terrain.

4) We will explore the standard model in its unbroken phase.

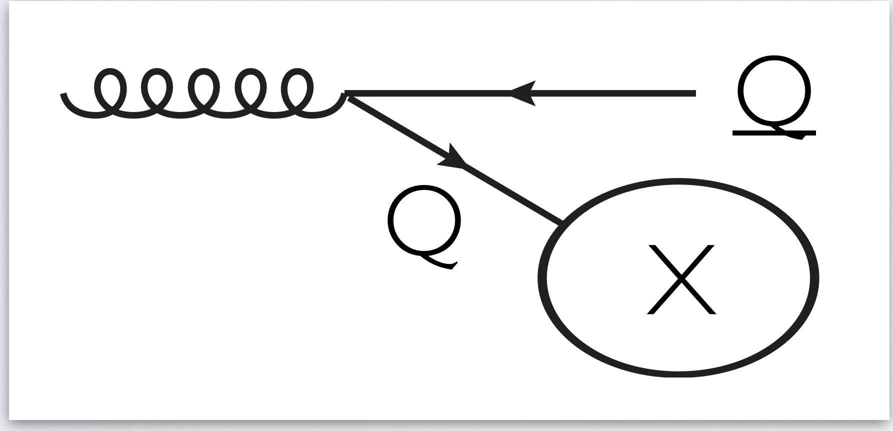
# HEAVY QUARKS AS PARTONS

Hadronic cross section for producing a heavy final state X:

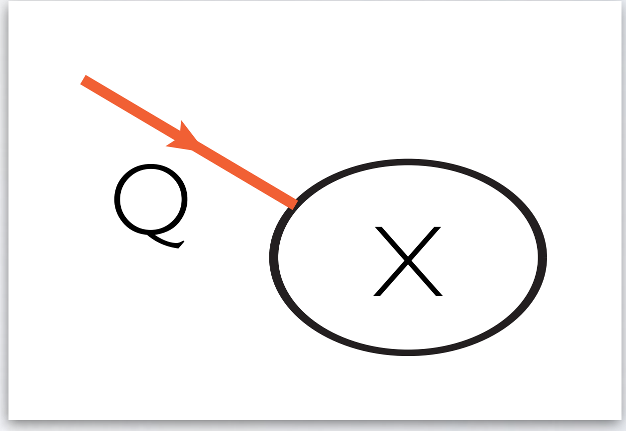
$$\sigma_{pp\to X}(S) = \sum_{p_{1,2}} \int dx_{1,2}\, f_{p_1}(x_1,\mu) f_{p_2}(x_2,\mu)\, \hat{\sigma}_{p_1 p_2 \to X}(\hat{s} = x_1 x_2 S)$$

Resummation of collinear enhancement:

- $f_Q^0(x,\mu) = \frac{\alpha_s}{2\pi} \log\left(\frac{\mu^2}{m_Q^2}\right) \int_x^1 \frac{dz}{z} P_{Qg}(z) f_g(x/z,\mu)$



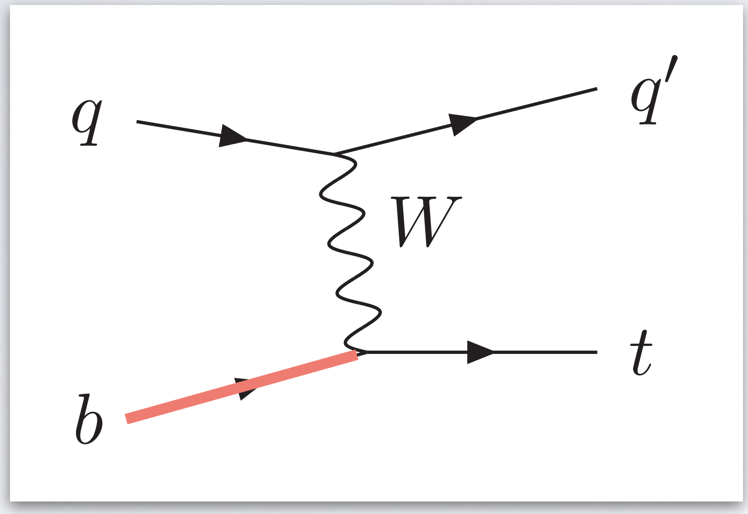

$m_X \gg m_Q$



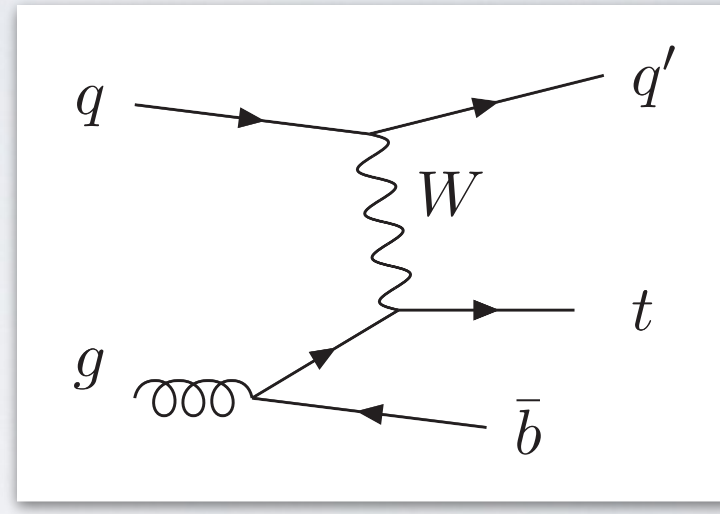

$$f_Q(x,\mu) = f_Q^0(x,\mu) + \mathcal{O}(\alpha_s^n \log^n(\mu^2/m_Q^2))$$

# EXAMPLE: SINGLE TOP PRODUCTION

5-flavor scheme




4-flavor scheme




Total cross section [pb]:

| Born | TeV $t\,(=\bar{t})$ (LO) NLO | LHC $t$ (LO) NLO | LHC $\bar{t}$ (LO) NLO |
|---|---|---|---|
| $2 \to 2$ | $(0.92)\ 1.00^{+0.03+0.10}_{-0.02-0.08}$ | $(153)\ 156^{+4+3}_{-4-4}$ | $(89)\ 93^{+3+2}_{-2-2}$ |
| $2 \to 3$ | $(0.68)\ 0.94^{+0.07+0.08}_{-0.11-0.07}$ | $(143)\ 146^{+4+3}_{-7-3}$ | $(81)\ 86^{+4+2}_{-3-2}$ |

← incl. resummation

[Campbell et al., 0903.0005]

5F and 4F schemes converge, if calculated to all orders.

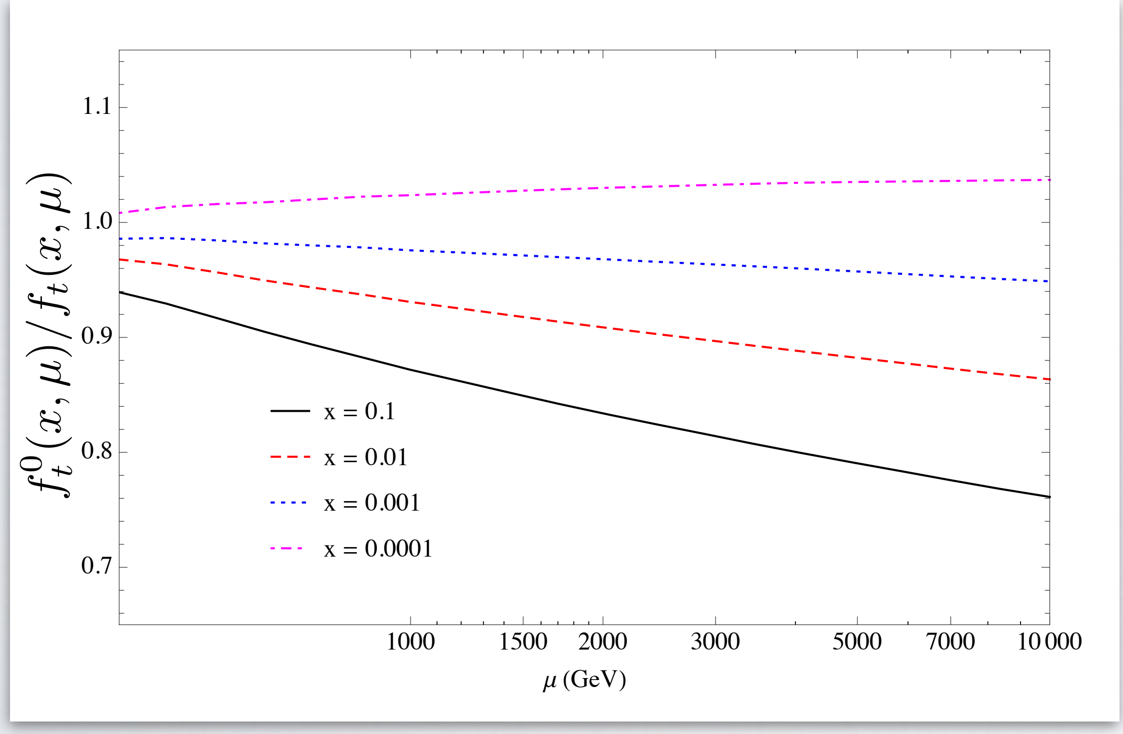
# IMPACT OF HEAVY-QUARK RESUMMATION

1) Asymptotic freedom of QCD mitigates collinear enhancemt.:

Electroweak single-top production: $\alpha_s(m_t)\log\left(\frac{m_t^2}{m_b^2}\right) \approx 0.84$

Top-initiated prod. of 10-TeV particle: $\alpha_s(m_X)\log\left(\frac{m_X^2}{m_t^2}\right) \approx 0.60$

2) Larger resummation effects at large Bjorken x:

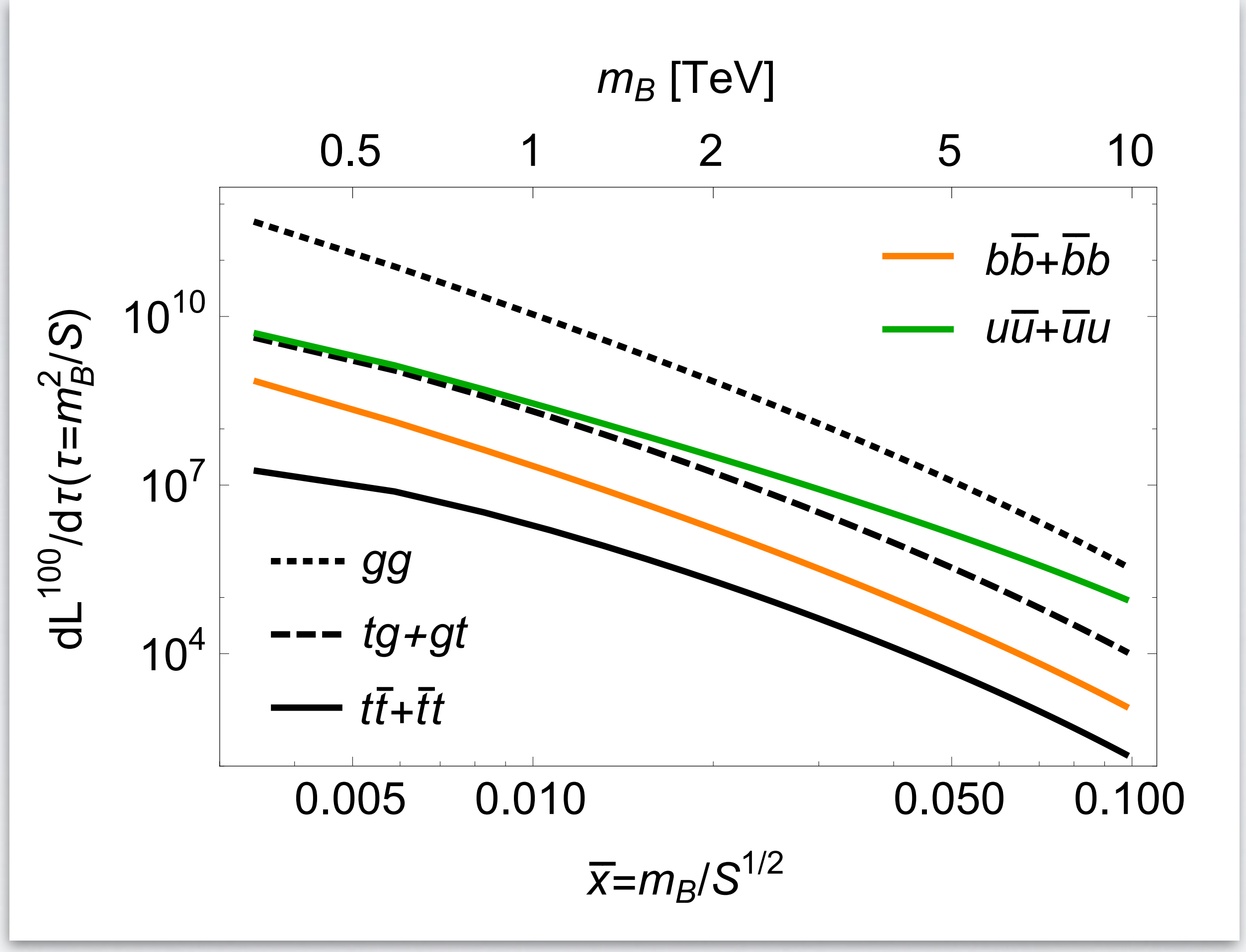



$$x = \frac{m_X}{\sqrt{S}} e^{-y}$$

[Dawson et al., 1405.6211]

# PARTON LUMINOSITIES AT 100 TEV

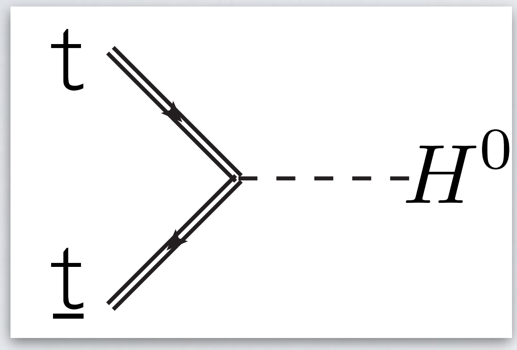
$$\frac{dL_{ij}}{d\tau}(\tau,\mu) = \int_\tau^1 \frac{dx}{x} f_i(x,\mu) f_j(\tau/x,\mu)$$

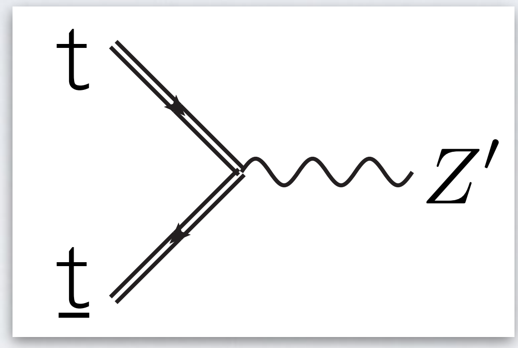



Top-quark luminosity suppressed,
but important in interactions with flavor hierarchy.

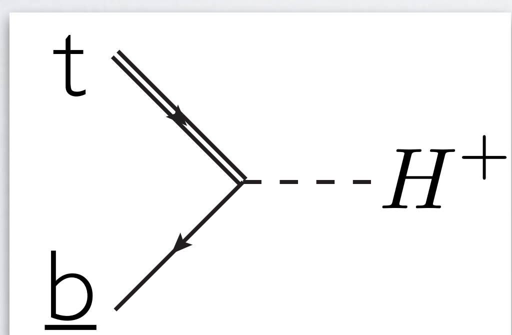
# NEW TERRAIN: TOP-QUARK INITIATED PROCESSES

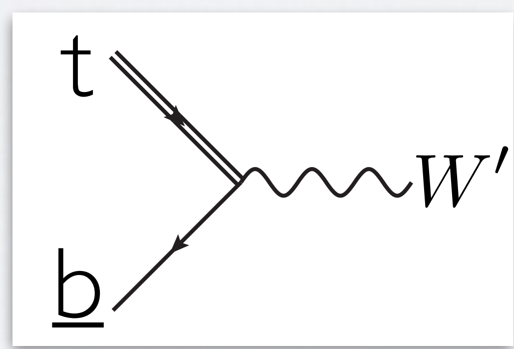
Neutral bosons: double collinear enhancement




Charged bosons: single collinear enhancement

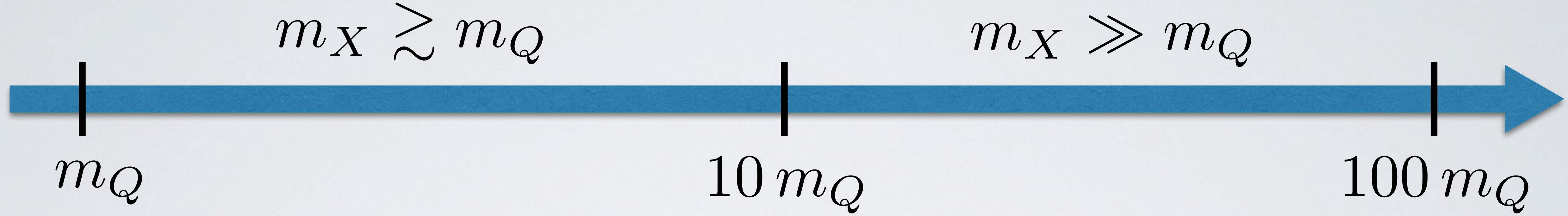



Bottom-quark may be treated as massless parton at 100 TeV.

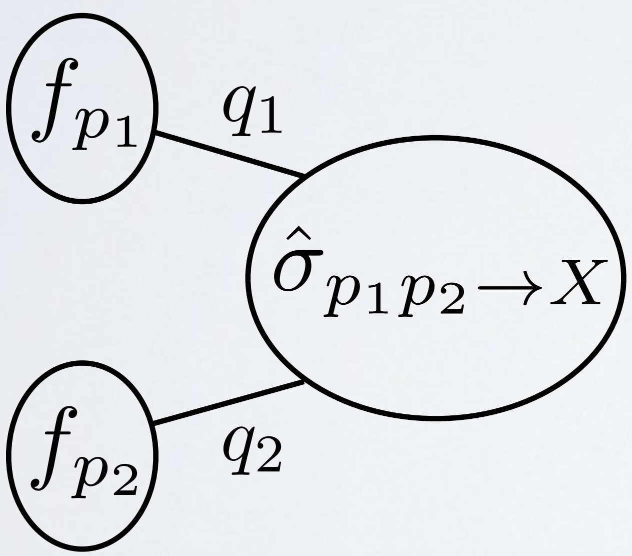
Top mass effects determine behavior close to threshold.
Resummation procedure is universal.

# FACTORIZATION WITH HEAVY PARTONS




Q massive — Q (essentially) massless

Factorization: initial partons on-shell and collinear w/ beam line



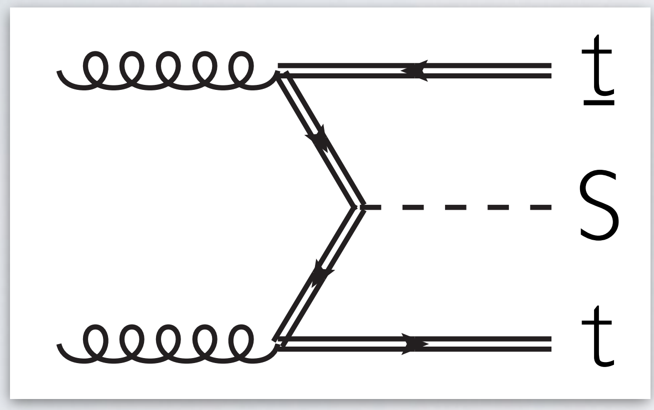

$q_i^2 = m_Q^2$ Q massive (ACOT)

$q_i^2 = 0$ Q massless

$$\sigma_{pp \to X} = \sum_{p_{1,2}} \int dx_{1,2} f_{p_1}(x_1) f_{p_2}(x_2) \hat{\sigma}_{p_1 p_2 \to X}(m_Q, m_X) + \mathcal{O}\Big(\frac{\Lambda^2}{m_X^2}\Big)$$

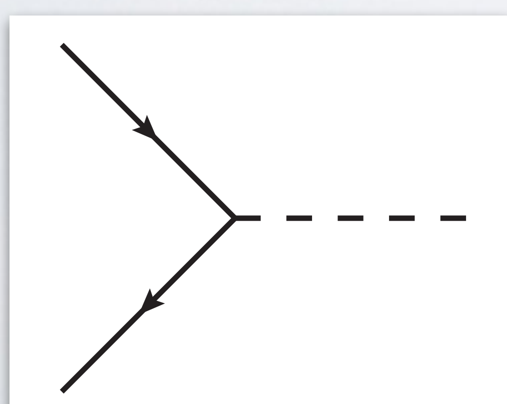
# EXAMPLE: TOP-INITIATED SCALAR PRODUCTION

5-flavor scheme: top-quarks are massive




$$\alpha_s^2 \log^2\left(\frac{m_S^2}{m_t^2}\right) + \mathcal{O}\left(\alpha_s^3 \log^3\left(\frac{m_S^2}{m_t^2}\right)\right)$$

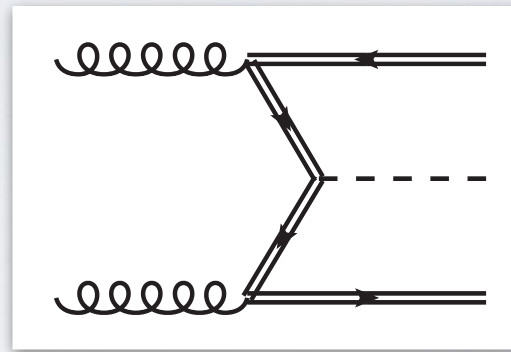
6-flavor scheme: top-quarks are (massless) partons

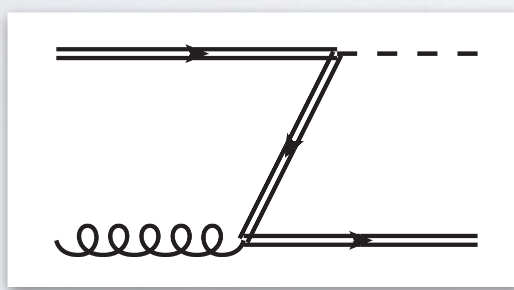
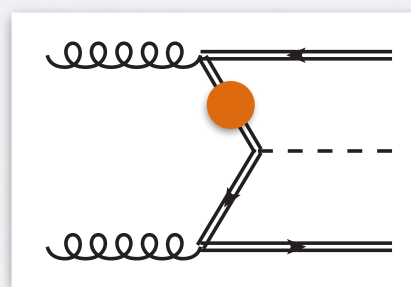


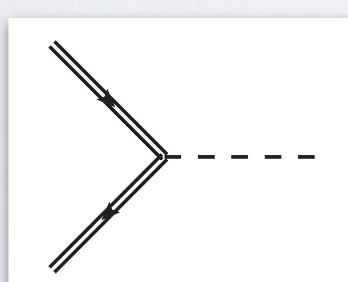
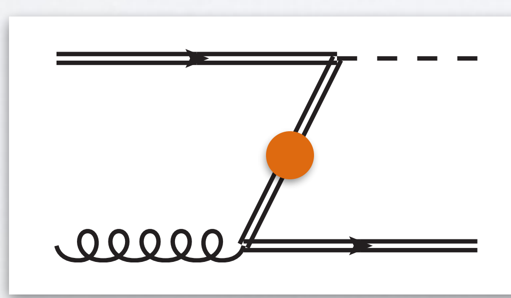
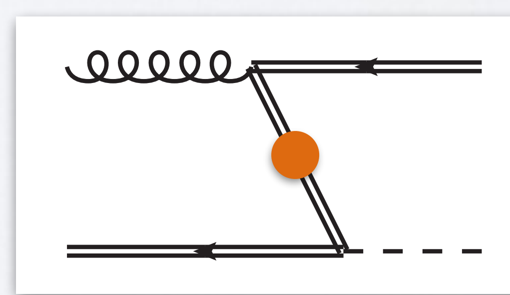
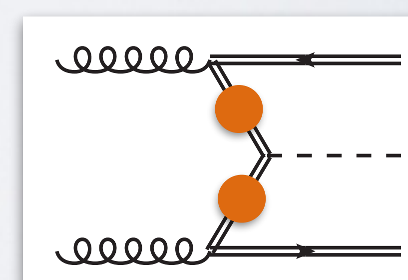
$$\alpha_s^{2n} \log^{2n}\left(\frac{m_S^2}{m_t^2}\right) + \mathcal{O}\left(\alpha_s^{2n+1} \log^{2n}\left(\frac{m_S^2}{m_t^2}\right)\right)$$

# ACOT SCHEME: MASSIVE TOP-QUARKS

Initial top-quarks are on-shell, all internal tops are massive.

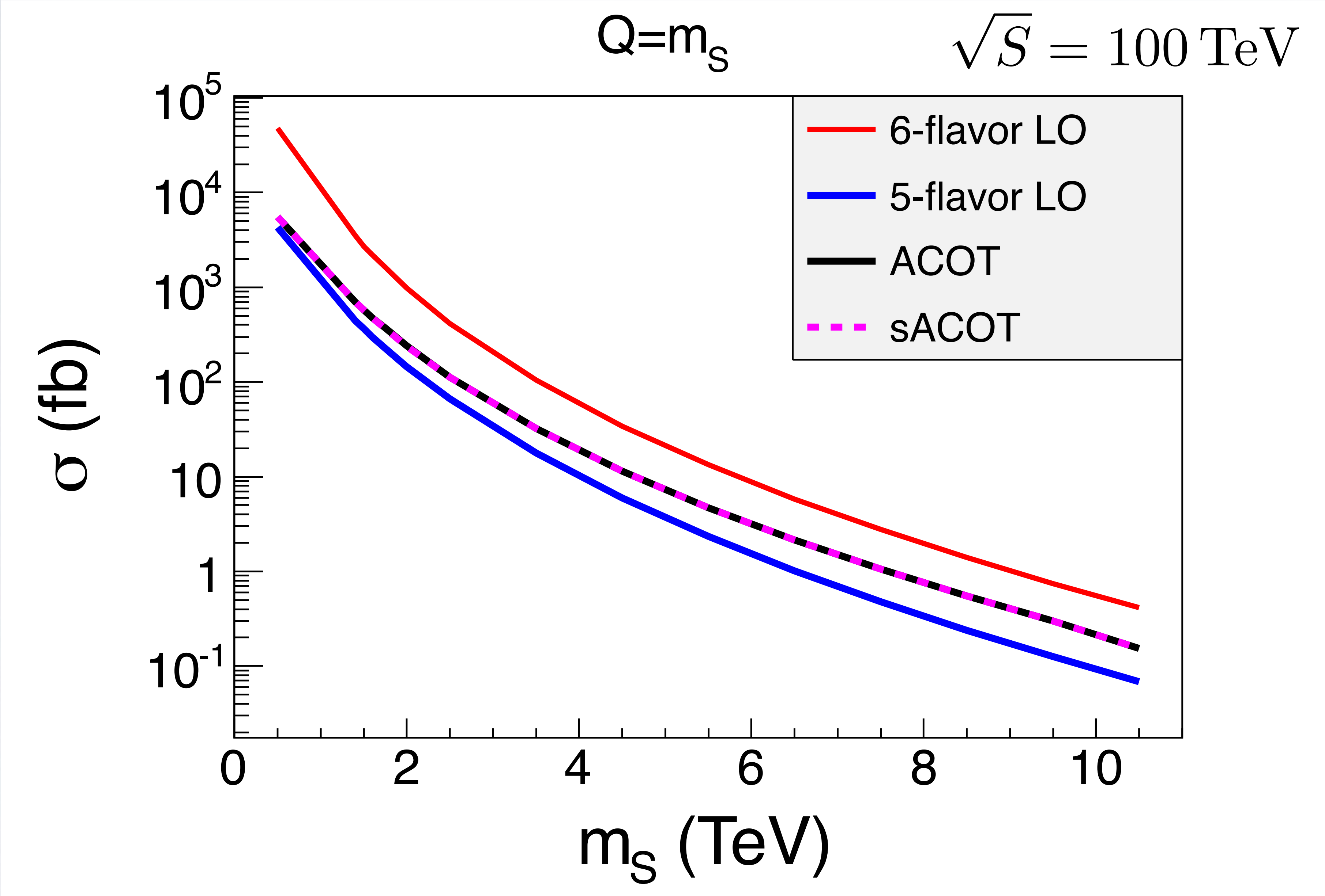
$m_S \gtrsim m_t : \ \sigma_{pp\to S} =$ 

**+**  **-**  **+** $(t \to g, g \to \bar{t})$

**+**  **-**  **-**  **+** 

$+(t \leftrightarrow \bar{t})$

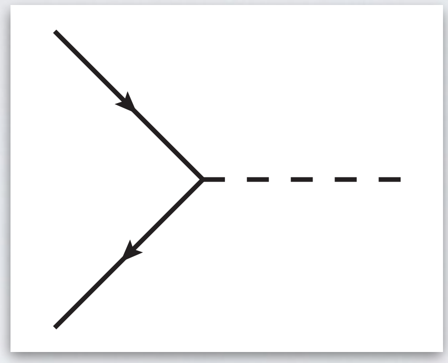
# SCALAR PRODUCTION IN ACOT SCHEME




ACOT scheme applicable for all scales above top mass.

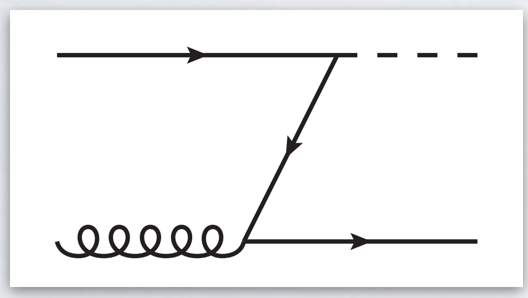
# HIGH-ENERGY LIMIT: MASSLESS TOP-QUARKS

$m_S \gg m_t : \ \sigma_{pp\to S} =$



$\mathcal{O}(\alpha_s^{2n} L^{2n})$

+



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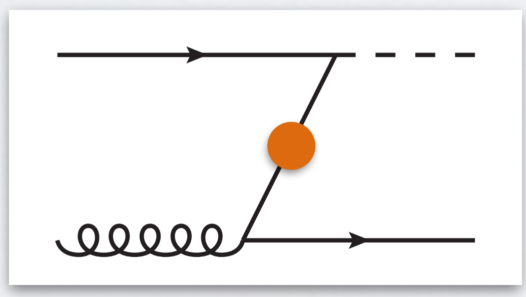
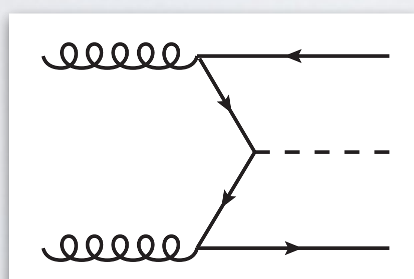


$+ \ (t \to g, g \to \bar{t})$ $\qquad \mathcal{O}(\alpha_s \alpha_s^n L^n)$

+



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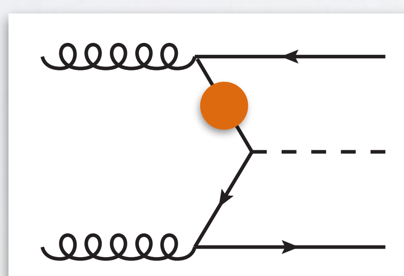

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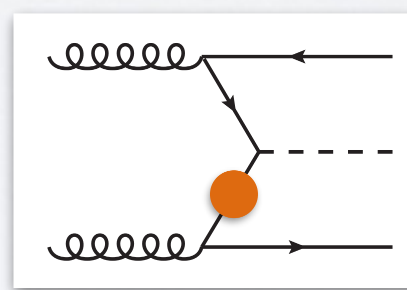

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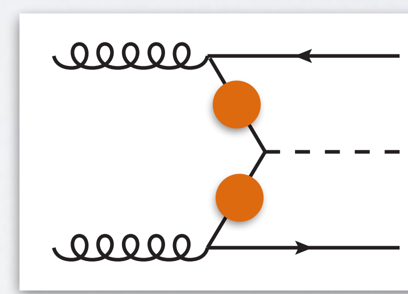


$\mathcal{O}(\alpha_s^2)$

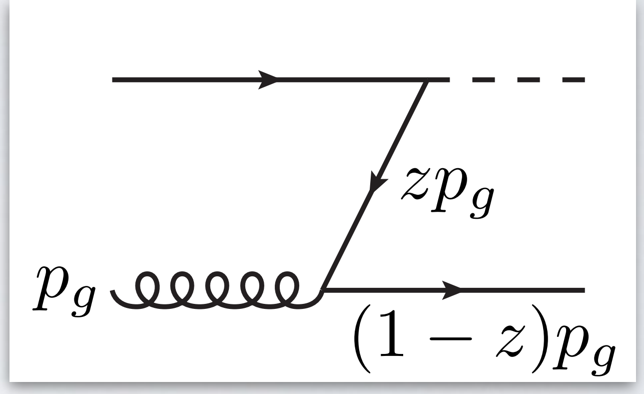
$$+(t \leftrightarrow \bar{t}) + \mathcal{O}\left(\frac{m_t^2}{m_S^2}\right)$$

Collinear singularities must be regularized and subtracted.

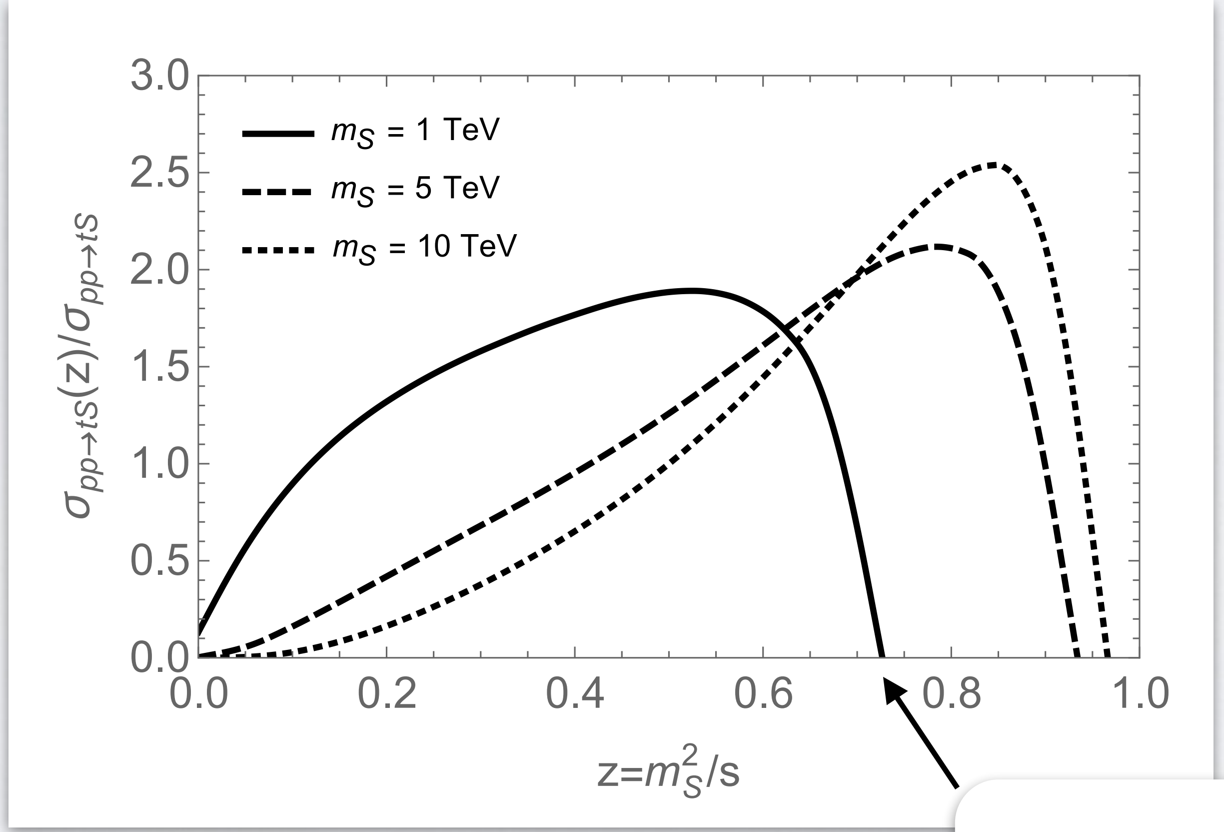
# PROBLEM WITH MASSLESS LIMIT

Cross section enhanced for large momentum transfer z:

$$\overline{\sigma}_{tg\to tS}(z) \sim \log\left(\frac{m_S^2}{\mu^2}\frac{(1-z)^2}{z}\right)$$

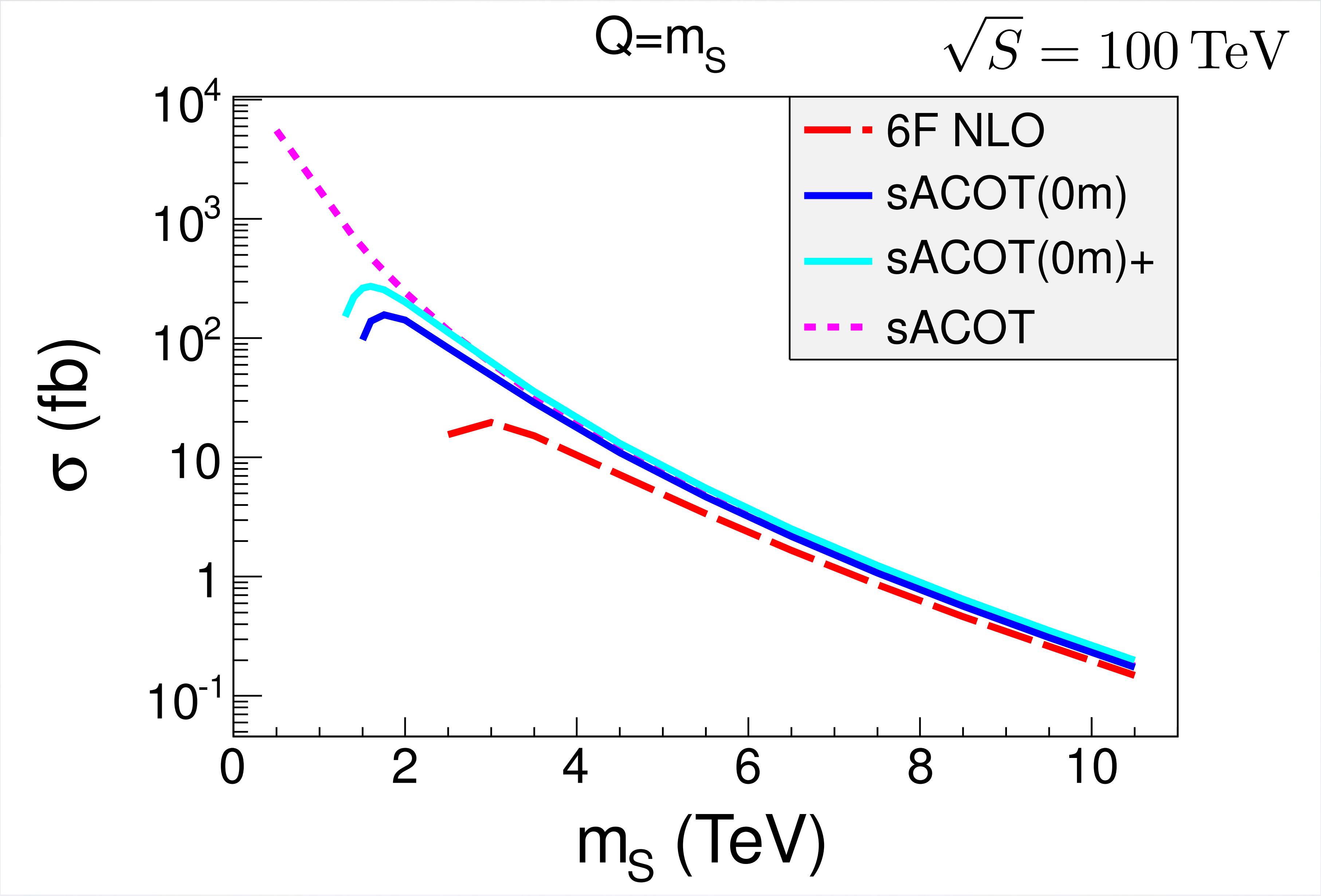



[Maltoni et al., 1203.6393]




$$z_{\max} = \frac{m_S^2}{(m_S+m_t)^2} < 1$$

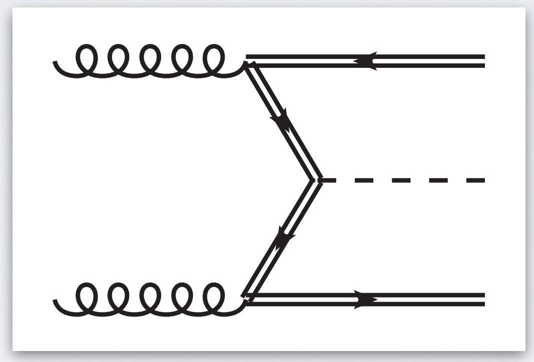
# SCALAR PRODUCTION IN MASSLESS LIMIT

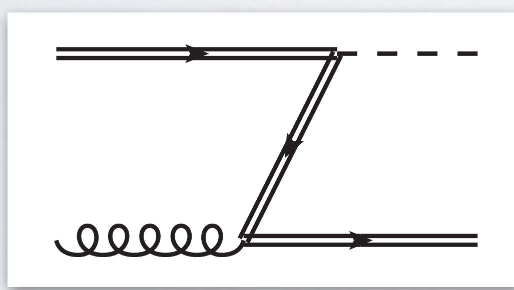
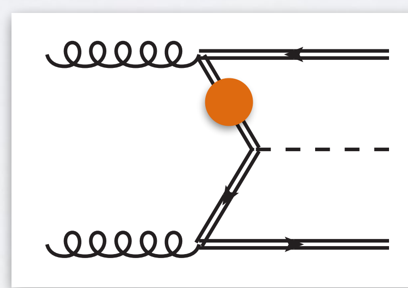


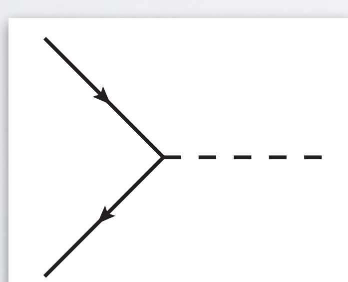
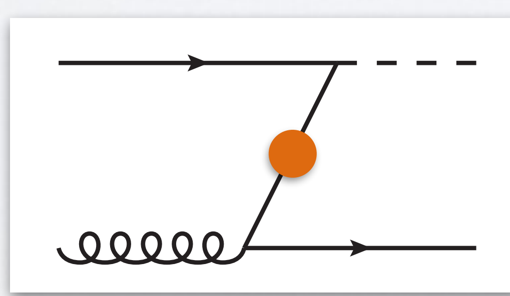
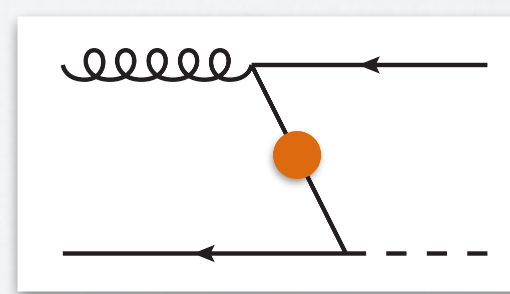
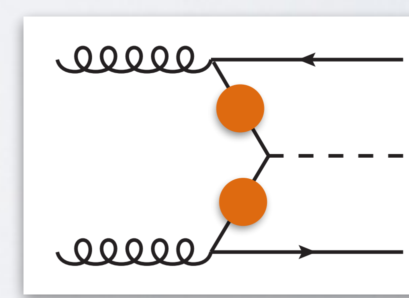

Massless limit fails for scales not far above top threshold.

# S-ACOT: MASSLESS INITIAL TOP-QUARKS

Top-quarks massless in processes with **two** incoming tops.

$m_S > m_t : \ \sigma_{pp \to S} =$ 

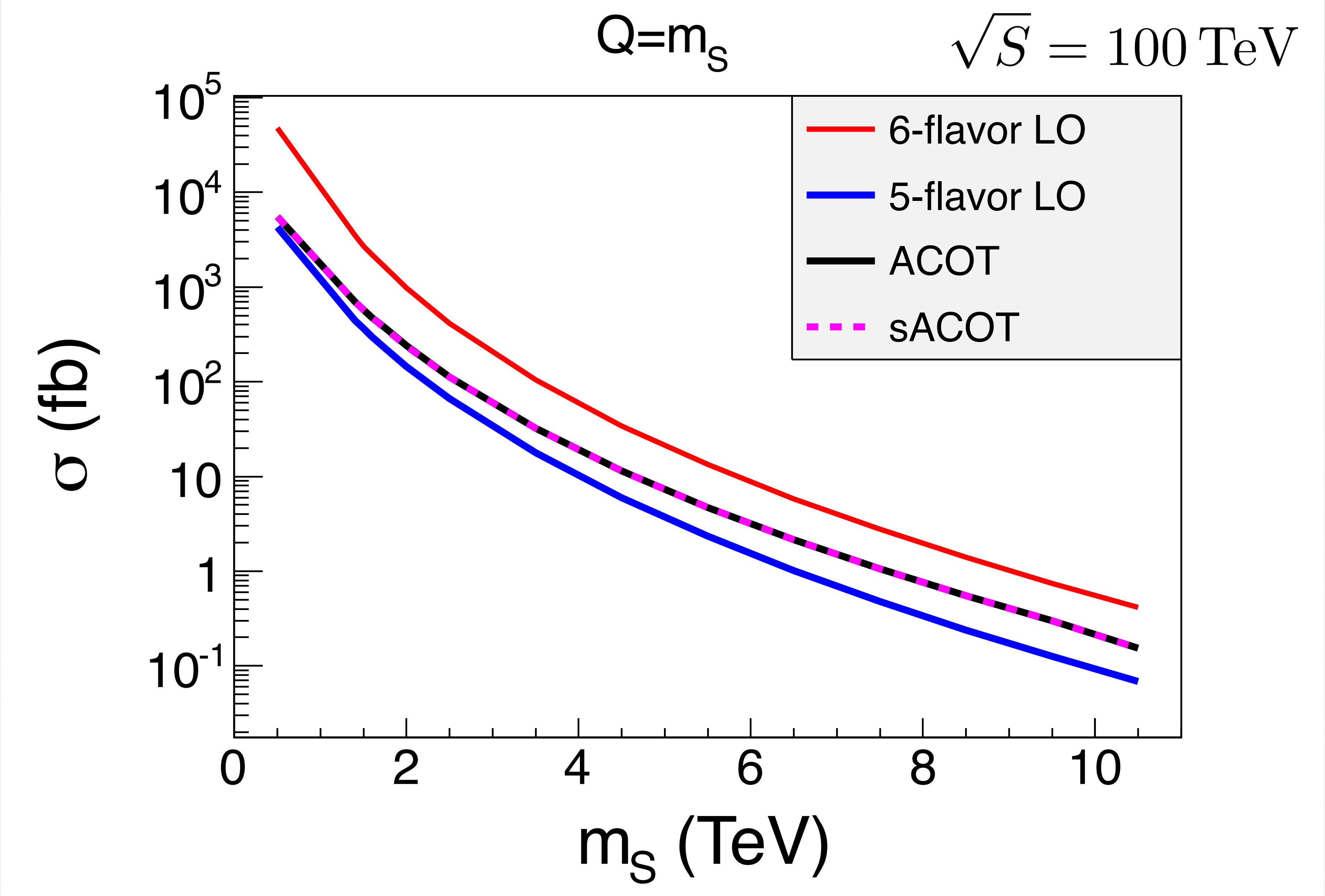
**+**  **-**  **+** $(t \to g, g \to \bar{t})$

**+**  **-**  **-**  **+** 

$+(t \leftrightarrow \bar{t})$

[cf. s-ACOT in DIS: Collins, hep-ph/9806259]

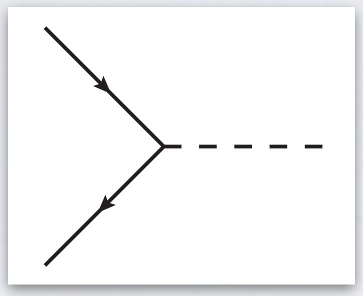
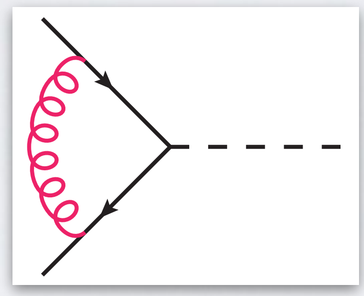
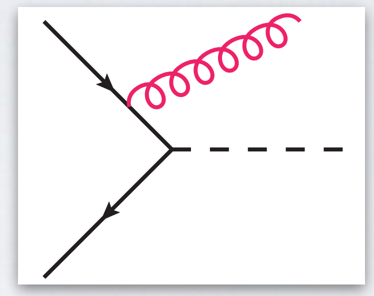
# SCALAR PRODUCTION IN S-ACOT SCHEME




Applicable at all scales; higher-order calculation simplifies.

# TOP-INITIATED PROCESSES BEYOND LO QCD

$m_S \gg m_t$ : NLO corrections to sub-process $t\bar{t} \to S$

$\sigma^{\mathrm{NLO}}_{pp\to S} =$  **+**  **+**  **+** $\mathcal{O}(\alpha_s \alpha_s^n L^n)$

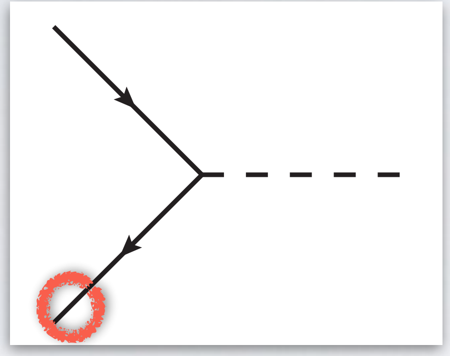
$m_S \gtrsim m_t$ : NLO corrections to all sub-processes

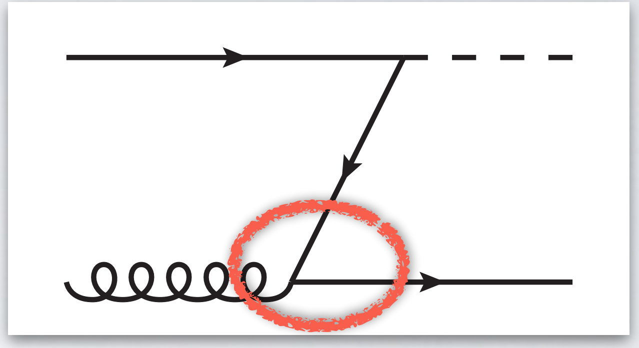
$$\sigma^{\mathrm{NLO}}_{pp\to S} = \sigma^{\mathrm{NLO}}_{gg\to t\bar{t}S} + \sigma^{\mathrm{NLO}}_{tg\to tS} + \sigma^{\mathrm{NLO}}_{t\bar{t}\to S} + \mathcal{O}(\alpha_s^4 L^2)$$

| |
|---|
| Top-mass treatment in s-ACOT applicable to all orders. |

# EFFECTIVE FACTORIZATION SCALE

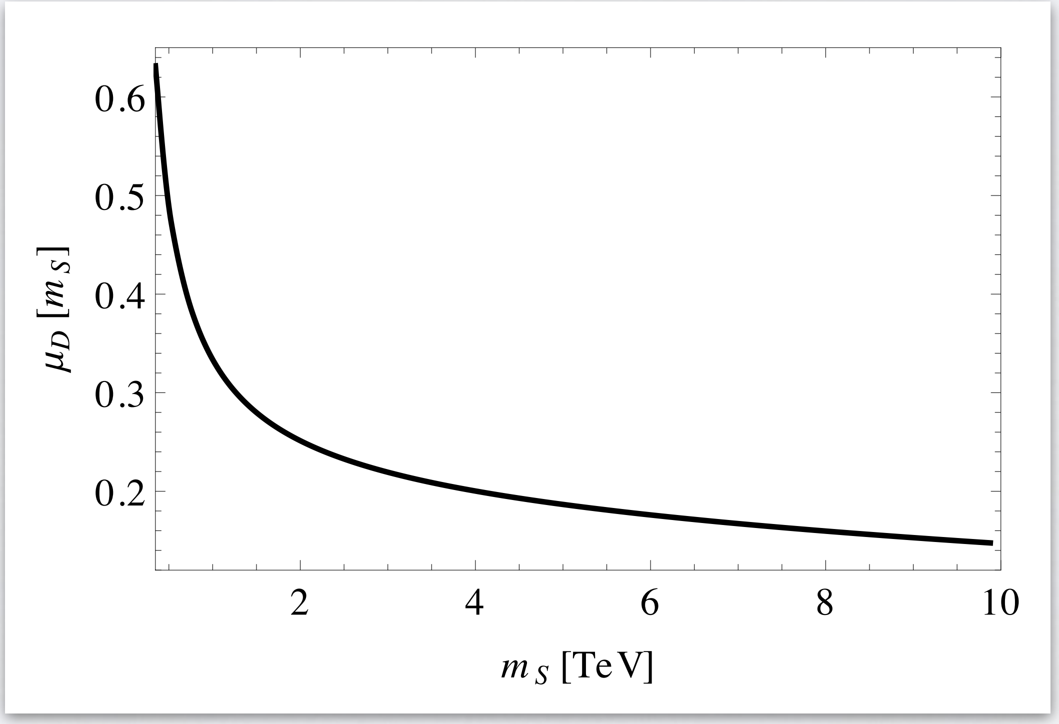
Match scale in 6-flavor scheme with collinear region:



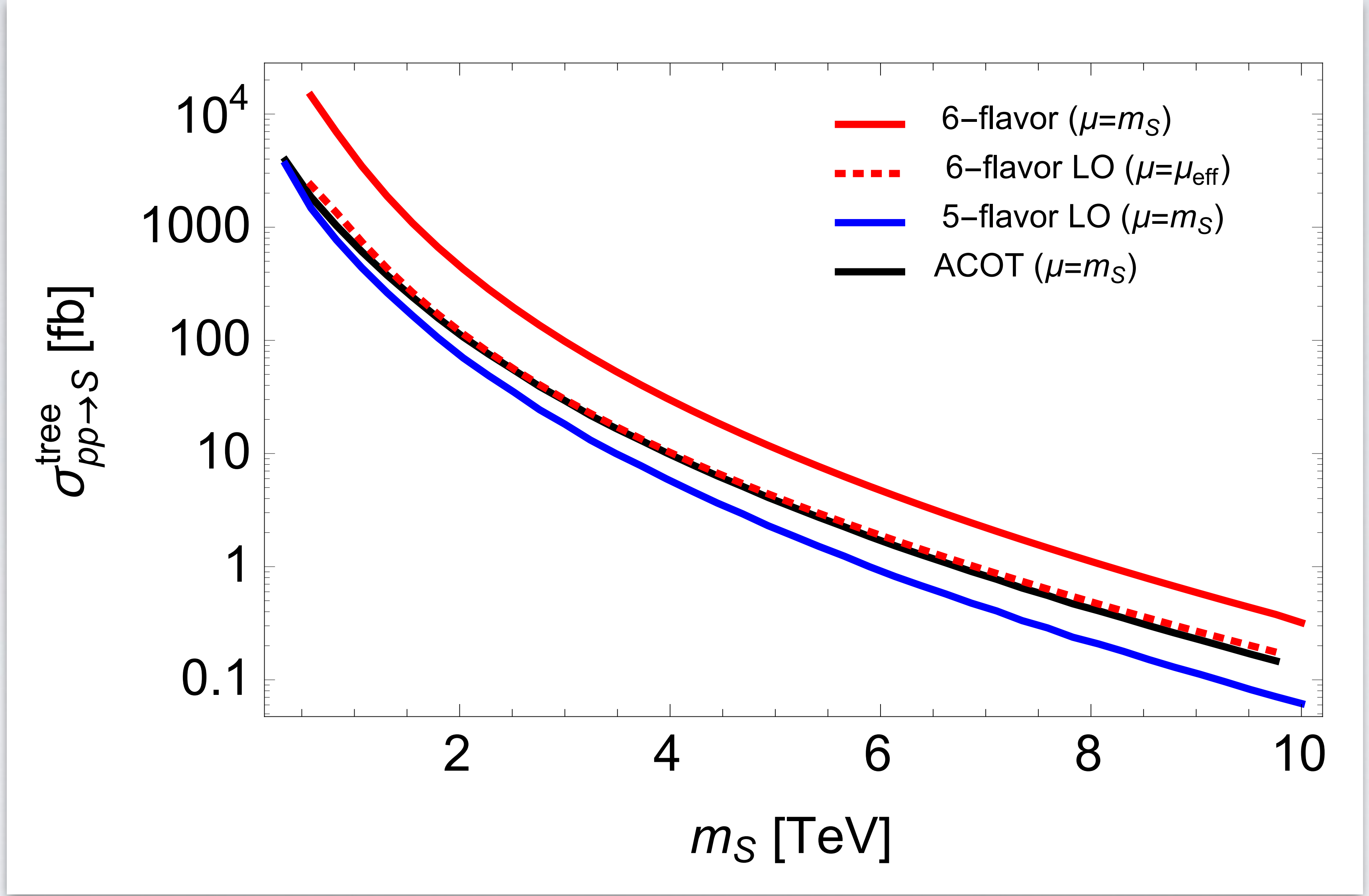


$$\log\left(\frac{\mu^2}{m_t^2}\right)\int_x^1 \frac{dz}{z} P_{tg}(z) f_g\left(\frac{x}{z}, m_S\right)$$

$$\int_x^1 \frac{dz}{z} P_{tg}(z) \log\left(\frac{m_S^2}{m_t^2}\frac{(1-z)^2}{z}\right) f_g\left(\frac{x}{z}, m_S\right)$$

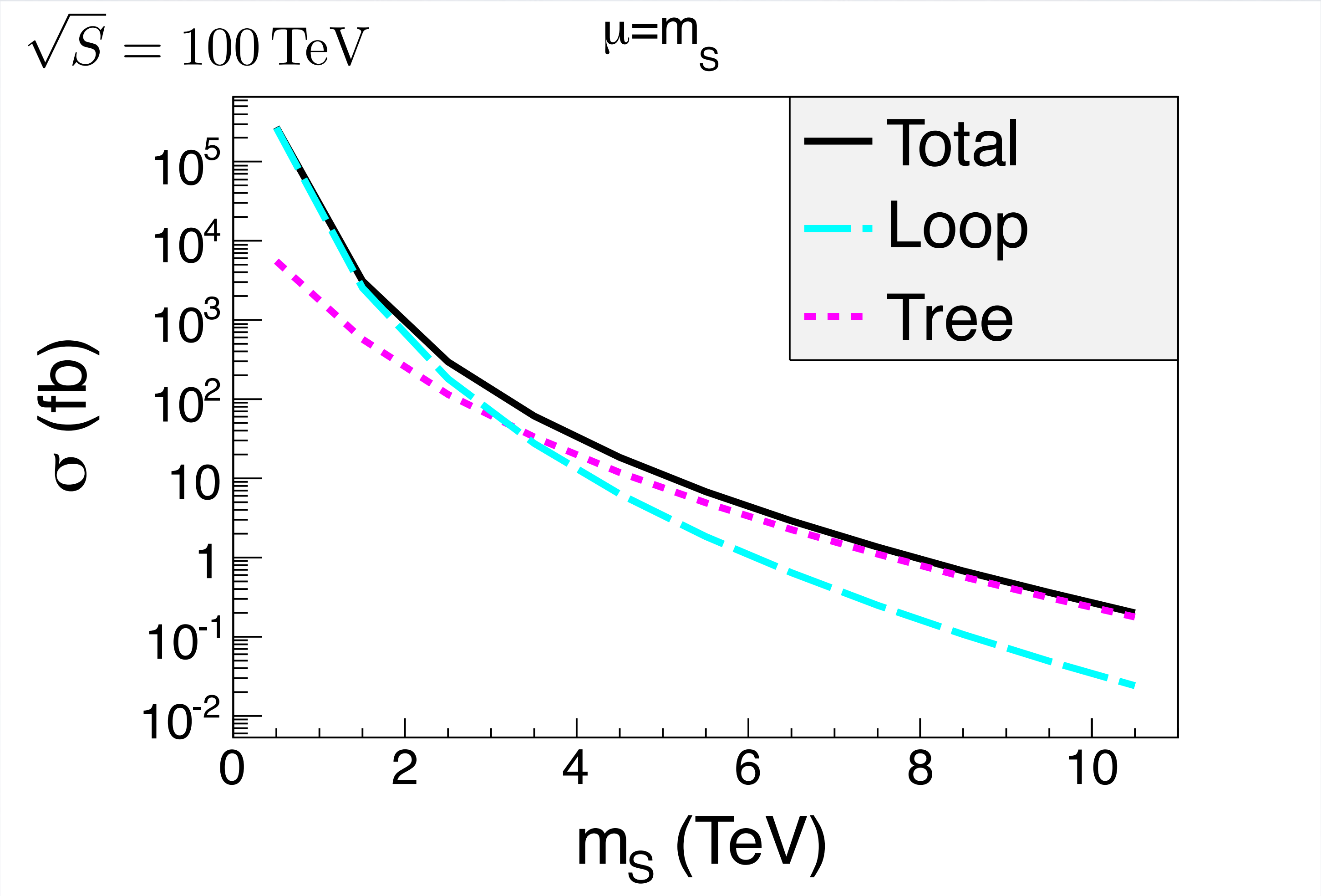


# MATCHING SCHEMES




6-flavor scheme with effective scale matches ACOT.

# INCLUDING GLUON-GLUON FUSION




Tree-level processes dominate at high scales, where resummation is important.

# TAKE HOME

- At high energies, top-quarks may be treated as partons.

- Collinear resummation is important at large Bjorken x.

- The factorization scheme s-ACOT is applicable at all scales above the top-quark threshold.

- Quark masses can be neglected in graphs with two incoming heavy quarks only.

- Including resummation effects greatly reduces the strong scale dependence of the 6-flavor scheme at tree level.