Collaborative Research Center TRR 257

P H

Particle Physics Phenomenology after the Higgs Discovery

Research Training Group
Physics of the Heaviest
Particles at the LHC

RWTH AACHEN UNIVERSITY

Theory Summary

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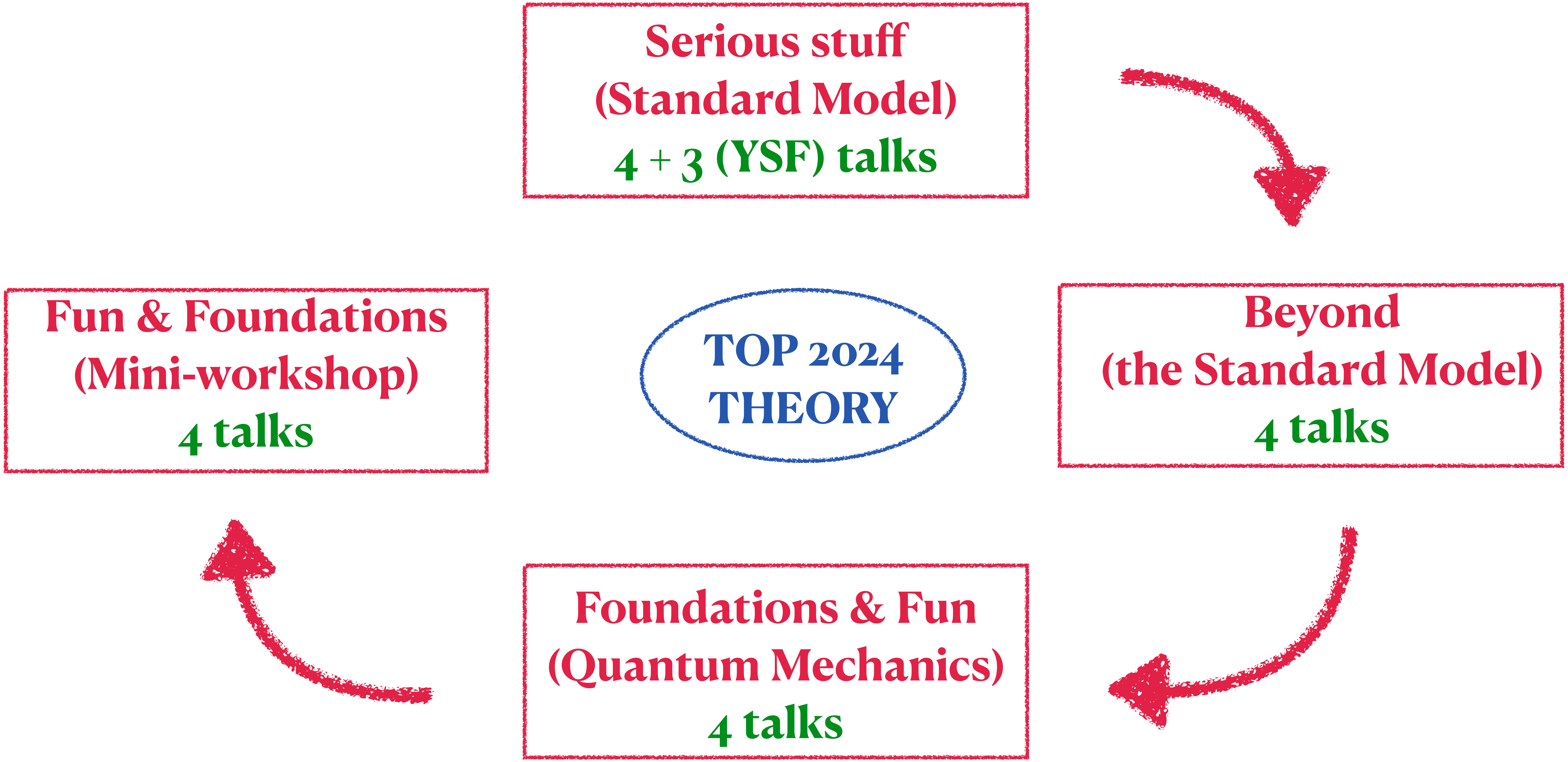
17th International Workshop on Top Quark Physics (TOP2024), 27th September 2024, Saint-Malo, Brittany, France



TOP 2024
THEORY

Serious stuff
(Standard Model)
4 + 3 (YSF) talks

Beyond
(the Standard Model)
4 talks

Foundations & Fun
(Quantum Mechanics)
4 talks

Fun & Foundations
(Mini-workshop)
4 talks

Serious stuff
(Standard Model)

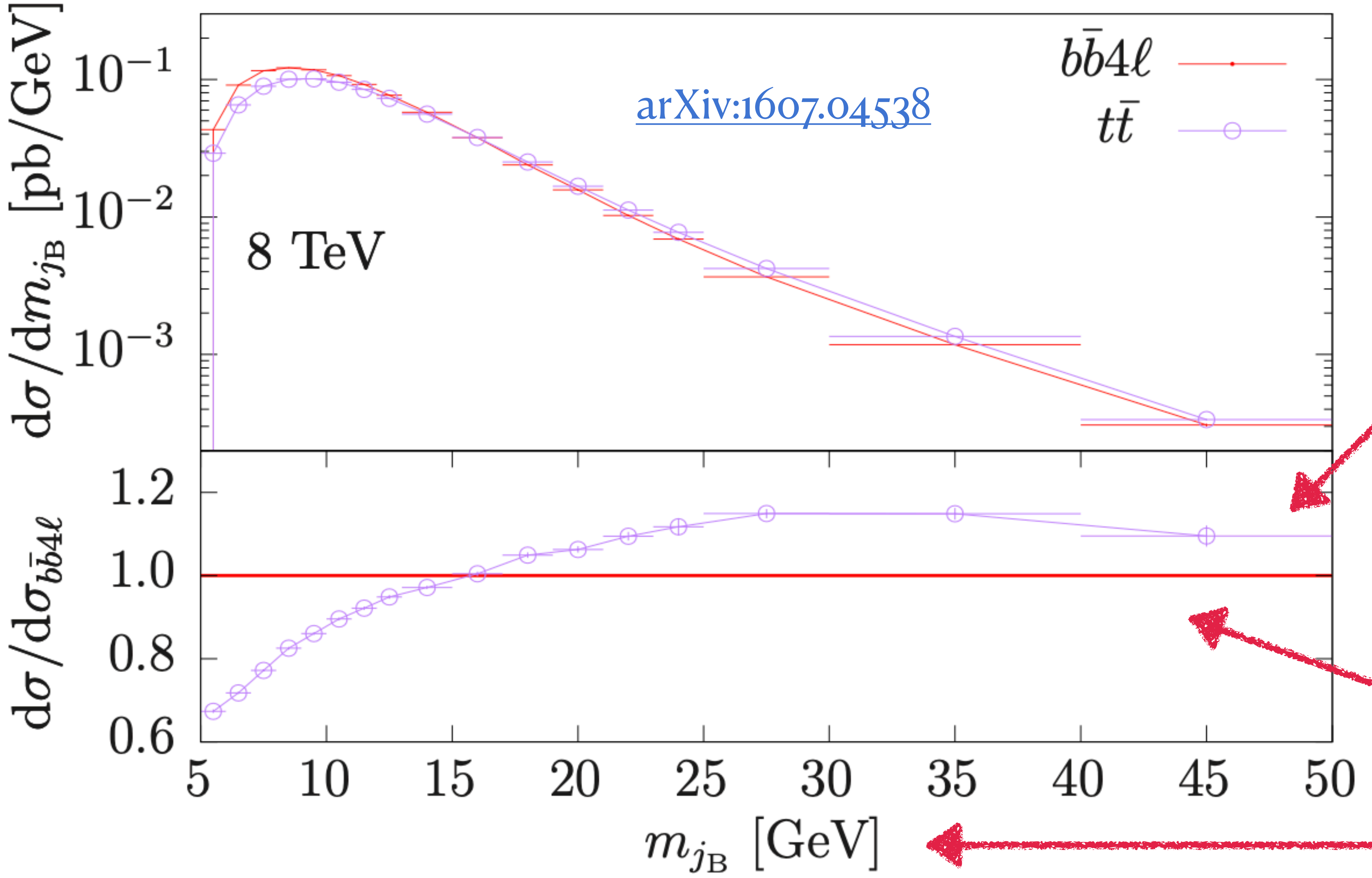
TOP 2024
THEORY

No joke: modelling of $t\bar{t} + tW$ (Tomas Jezo)

Precise simulation of top quark production and decay at LHC imperative!

Correspondingly we have: NLO QCD, NNLO QCD, NLO EW, NNLO QCD+NLO EW, analytic resummations, NLO QCD+PS and NNLO QCD+PS

Shower approximations for hardest emission in decay not good enough



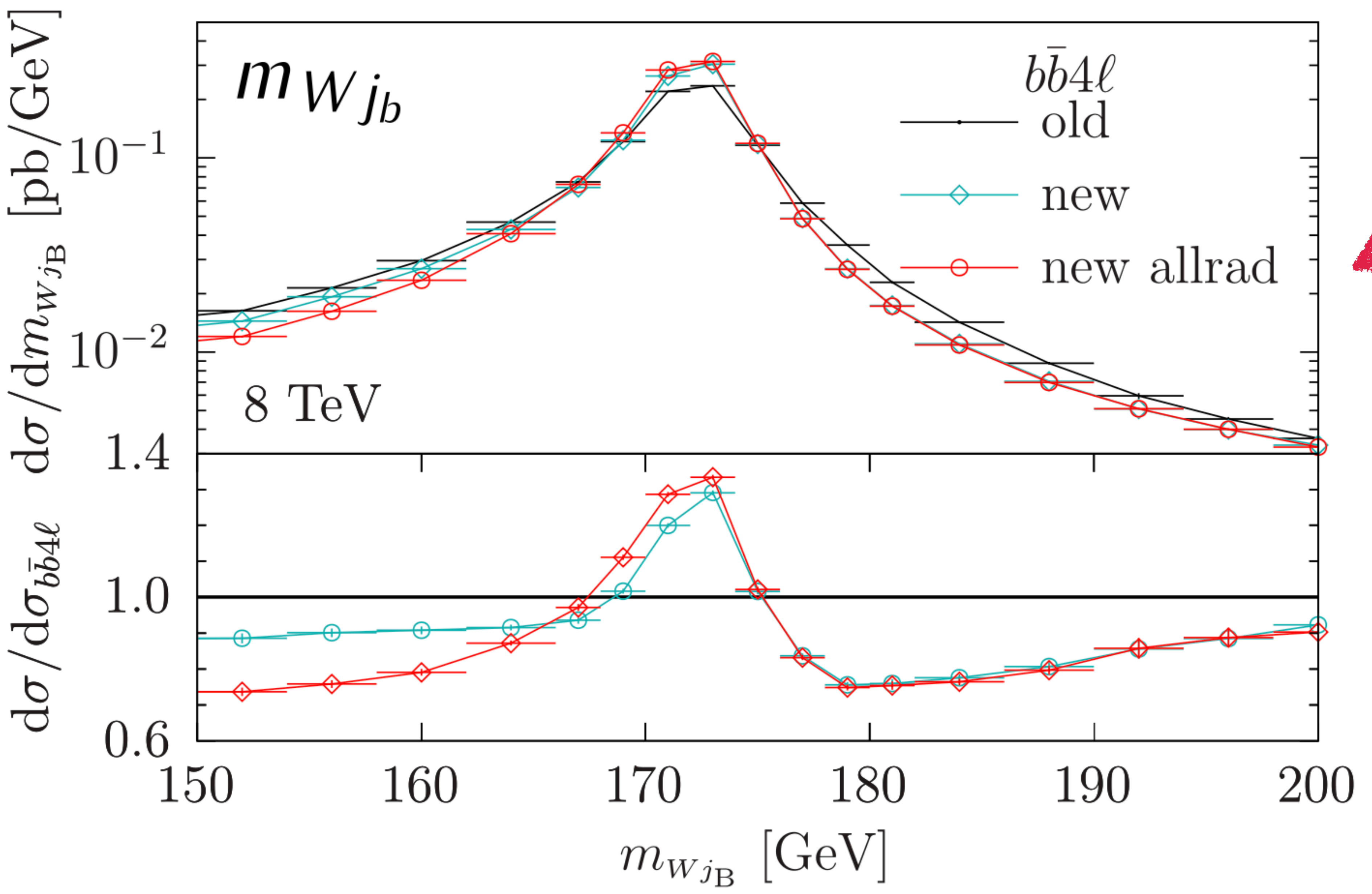
$pp \to t\bar{t}$ @ NLO QCD matched to Pythia with decays modelled by the shower

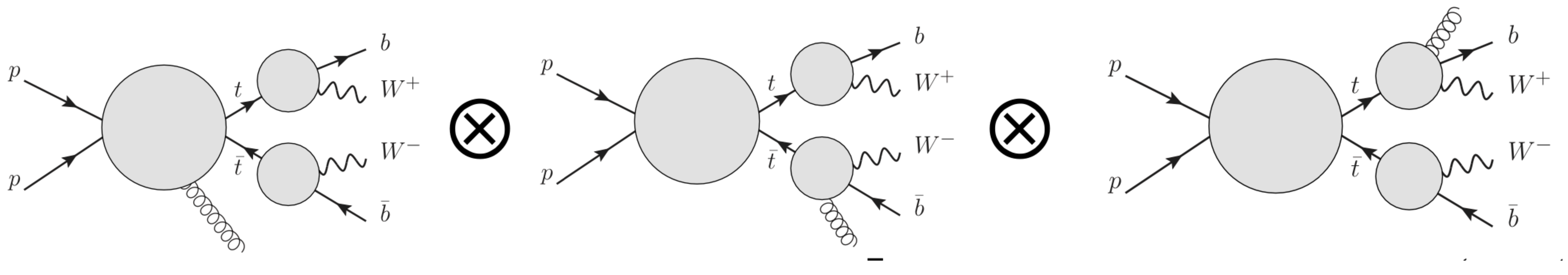
$pp \to l^+\nu_l l'^-\bar{\nu}_{l'} b\bar{b} + X$ @ NLO QCD with resonance aware PS matching

invariant mass of the b-jet

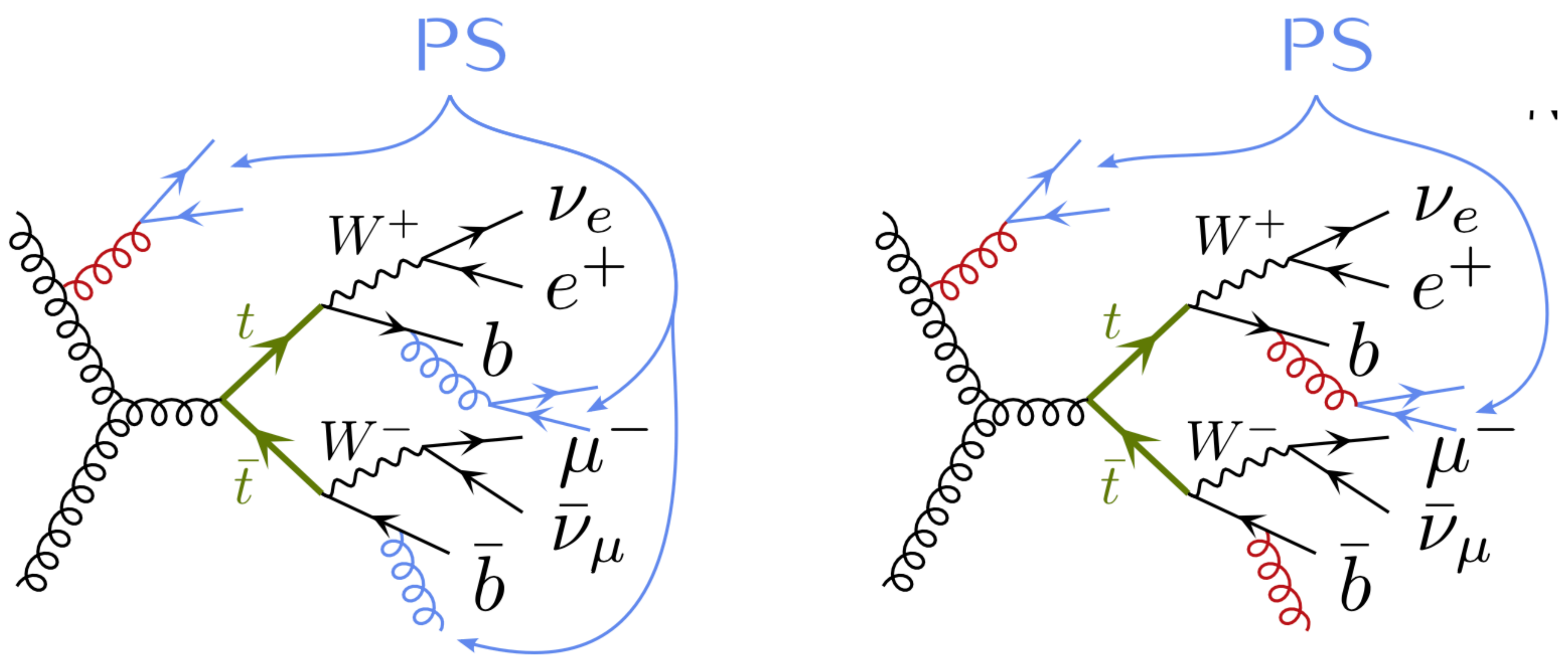
No joke: modelling of $t\bar{t} + tW$ (Tomas Jezo)

Do we need off-shell effects?



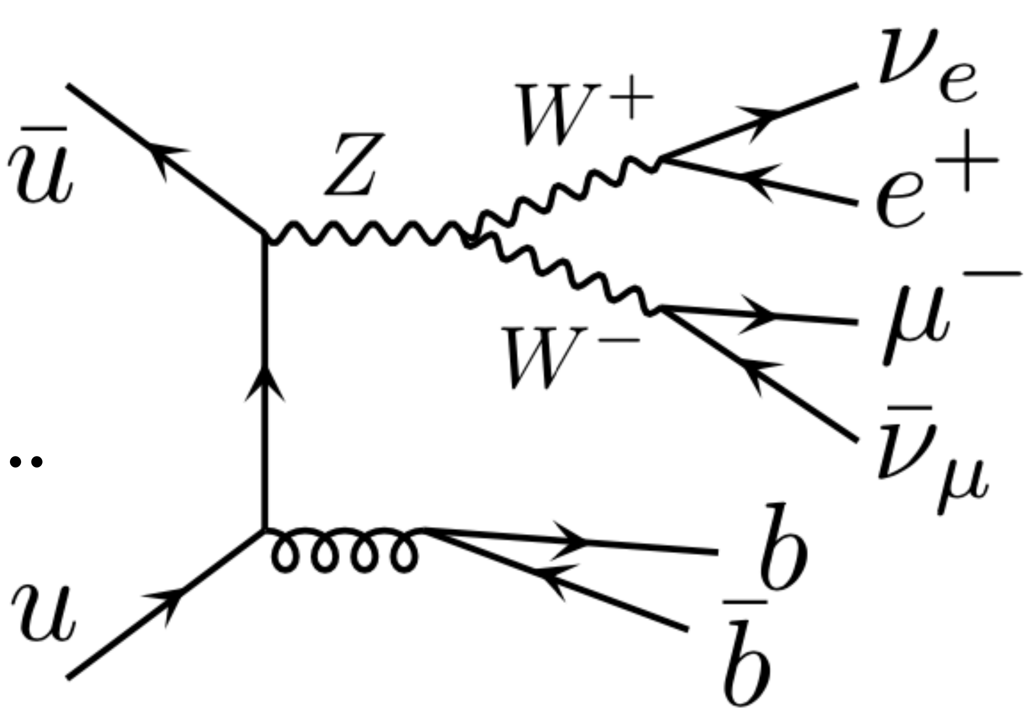


bb4l: $pp \to l^+\nu_l\ell^-\bar{\nu}_\ell b\bar{b}$ @ NLO+PS



...and double-resonant diagrams of course !

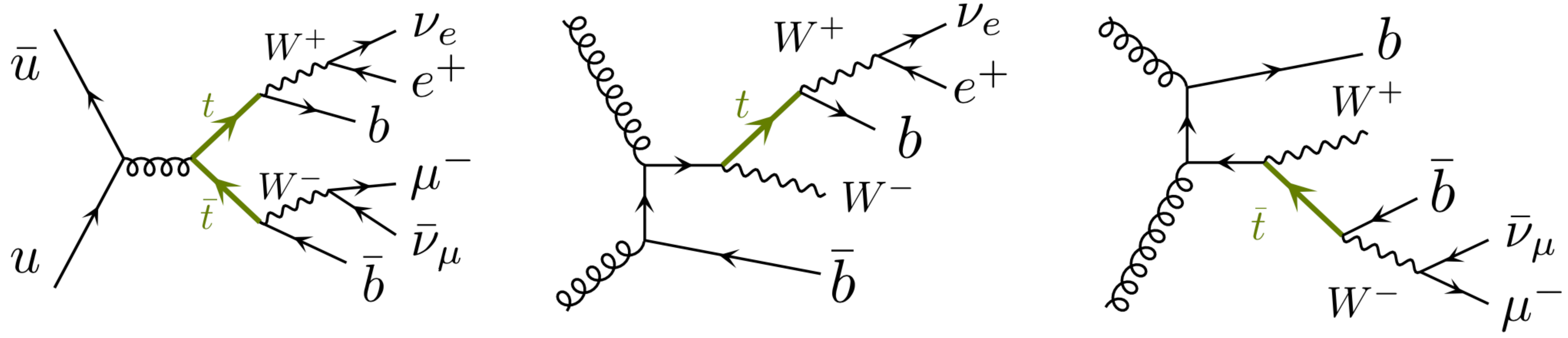
Special treatment of non-resonant diagrams...



No joke: modelling of $t\bar{t} + tW$ (Tomas Jezo)

Alternative approach: $bb4l - dl$

Don't care about non-resonant diagrams !

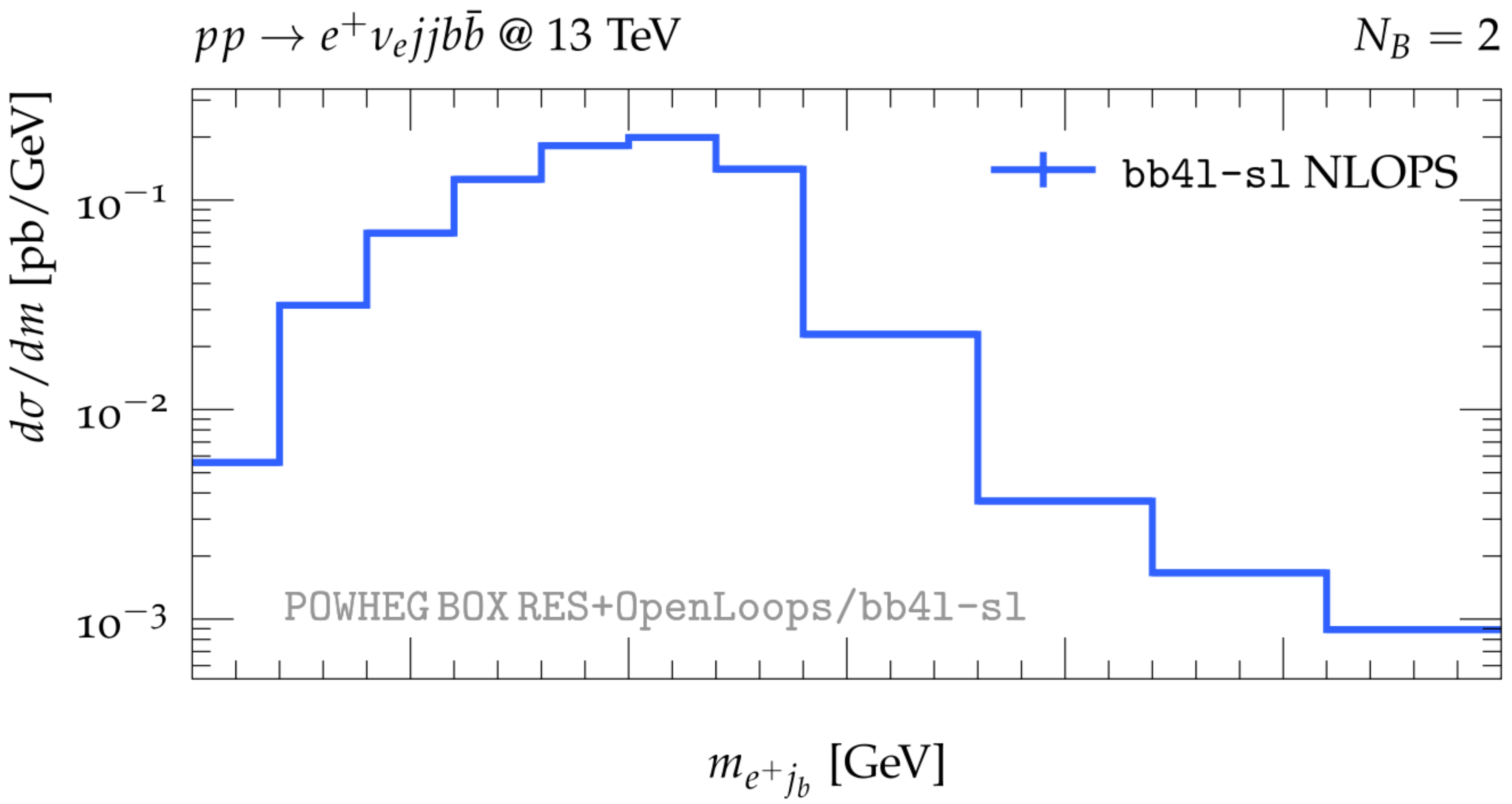


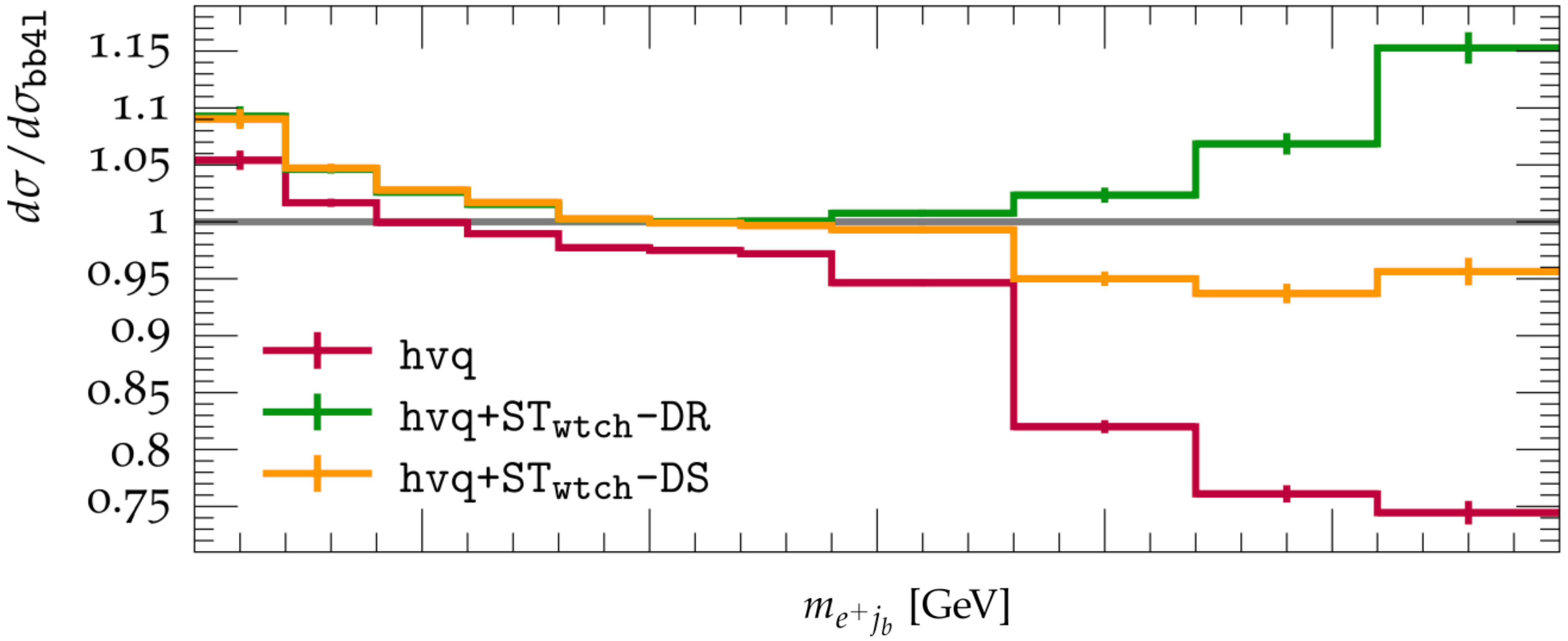
Different resonance history projector prescriptions agree extremely well, the worst agreement we found was in m_{jB} spectrum:

Semileptonic channel: `hvq` vs `bb4l-sl`

- `bb4l-sl`: $t\bar{t} + tW$, full–off-shell
- `hvq`: $t\bar{t}$, approx.–off-shell
- $\mathrm{ST_{wtch}}$-DS(DR): tW, approx.–off-shell

+`Pythia8.2`

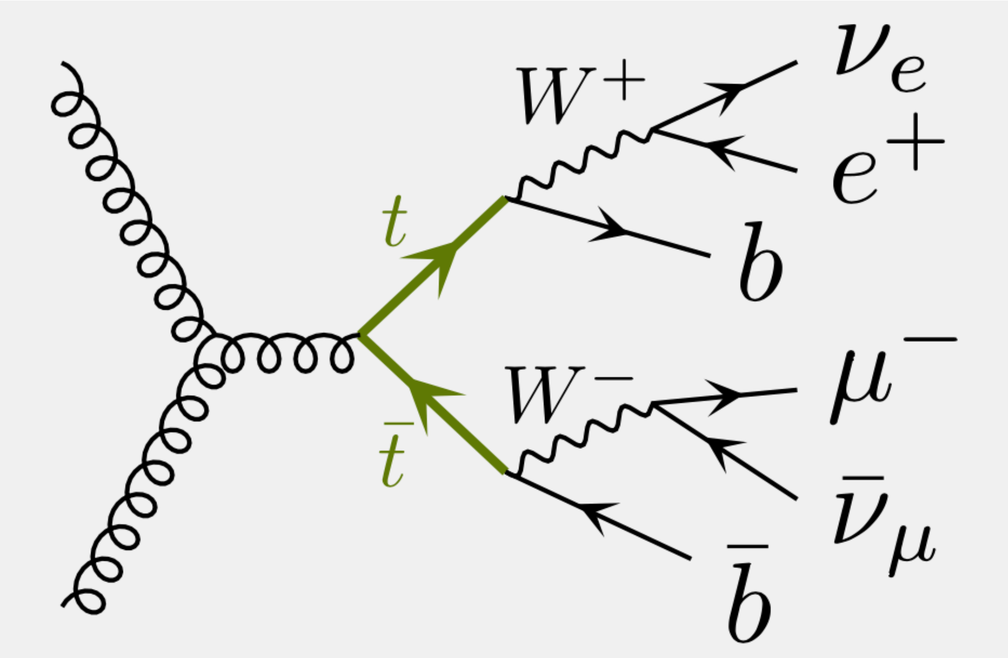




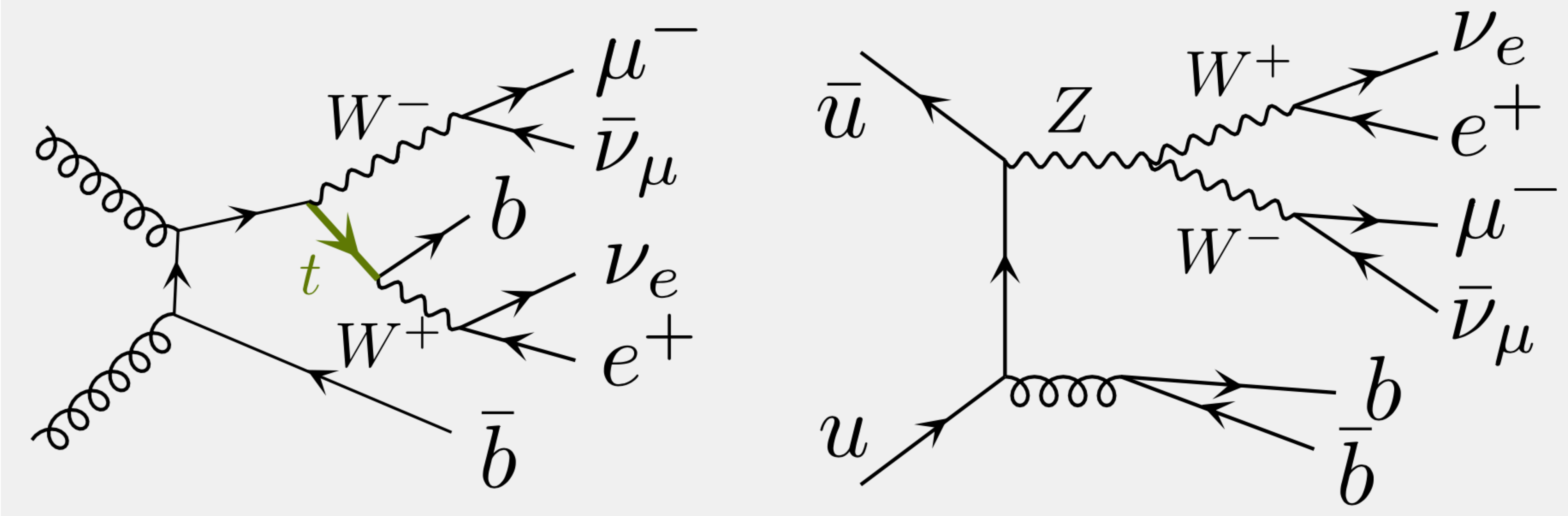
When do we get associated production in this formalism ?

Off-shell effects with AI (Mathias Kuschick)

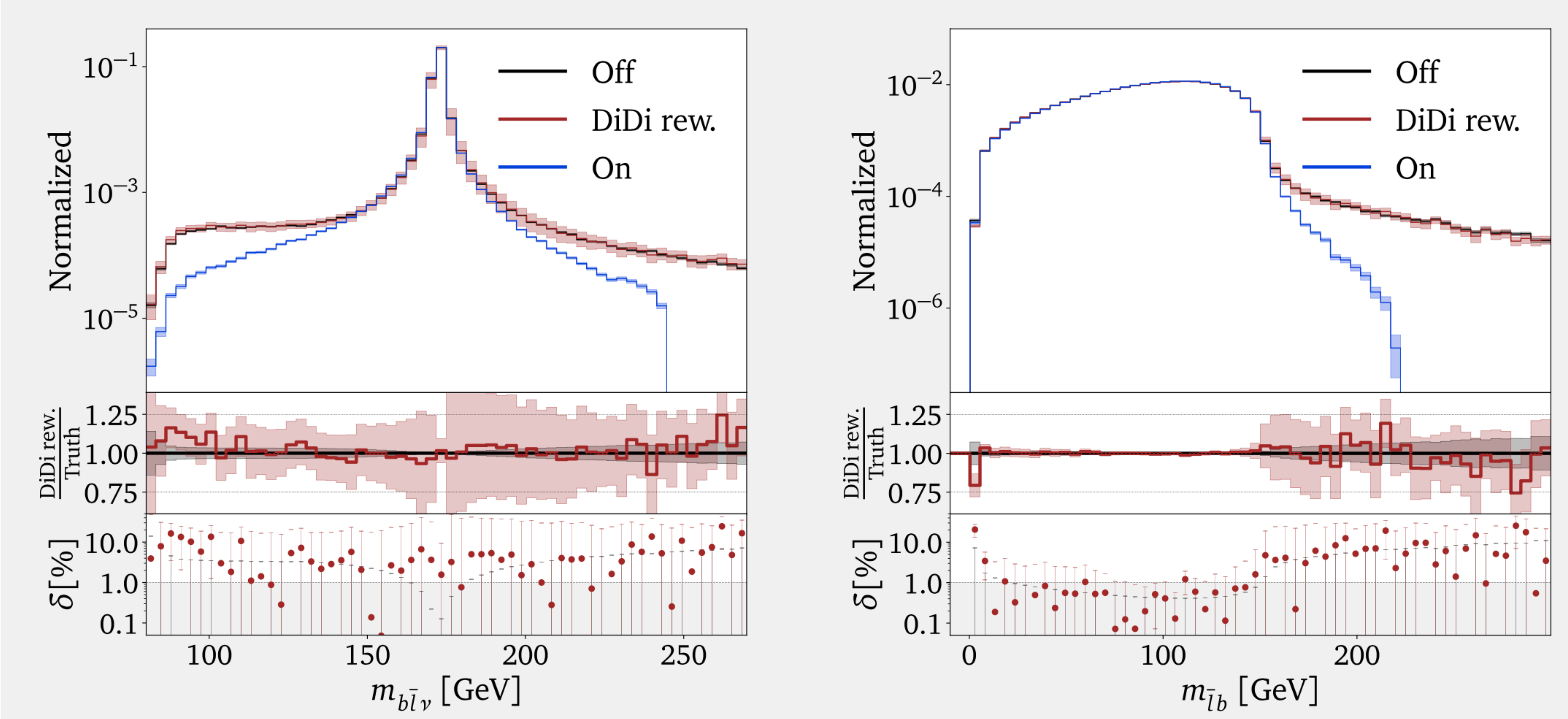
transformation of “on-shell” to off-shell events



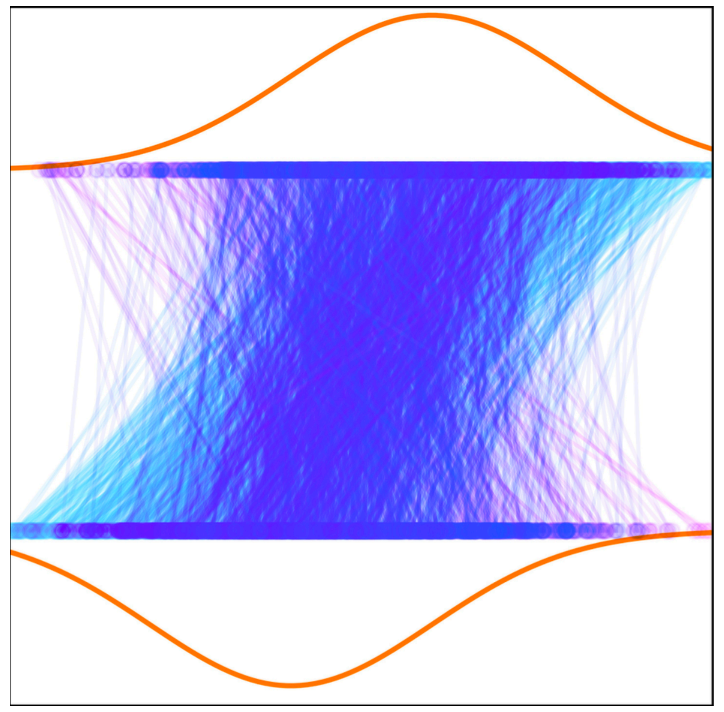
hvq & bb4l

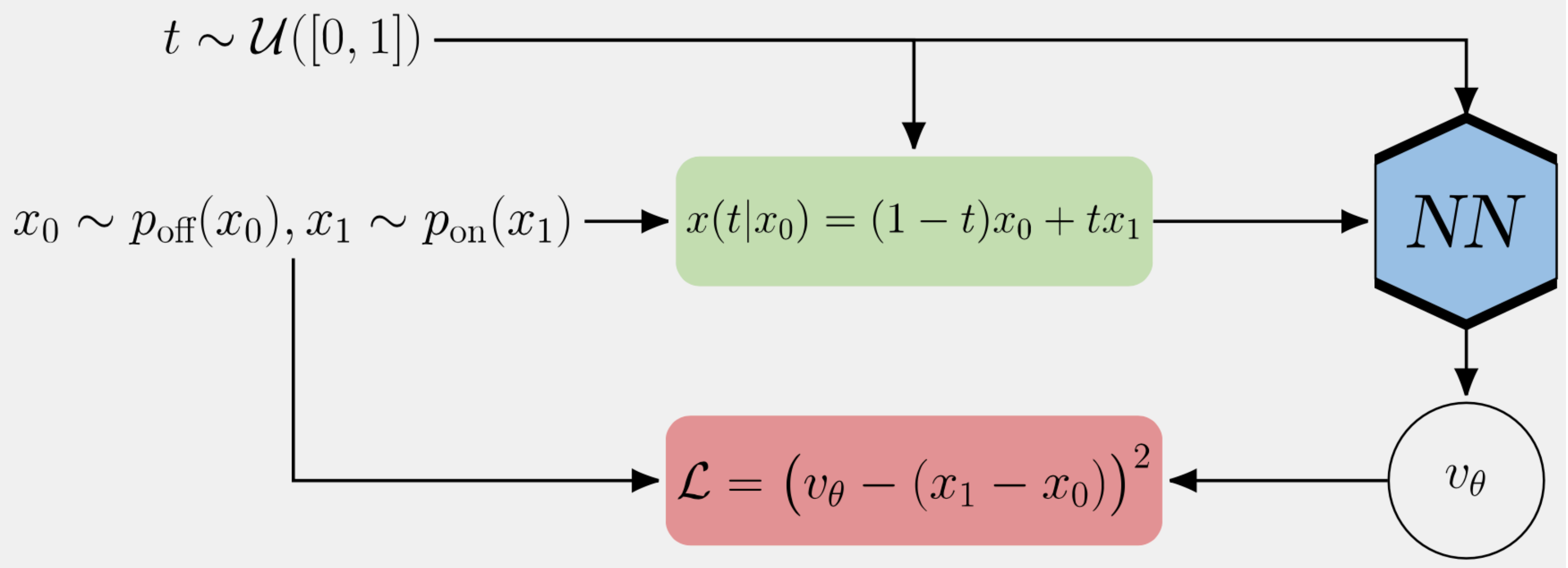


bb4l



Direct Diffusion network





$t \sim \mathcal{U}([0,1])$

$x_0 \sim p_{\text{off}}(x_0), x_1 \sim p_{\text{on}}(x_1)$

$x(t|x_0) = (1-t)x_0 + t x_1$

NN

v_θ

$\mathcal{L} = \left(v_\theta - (x_1 - x_0)\right)^2$

just 5 million training events !
goal is to improve efficiency
off-shell is very expensive at higher order

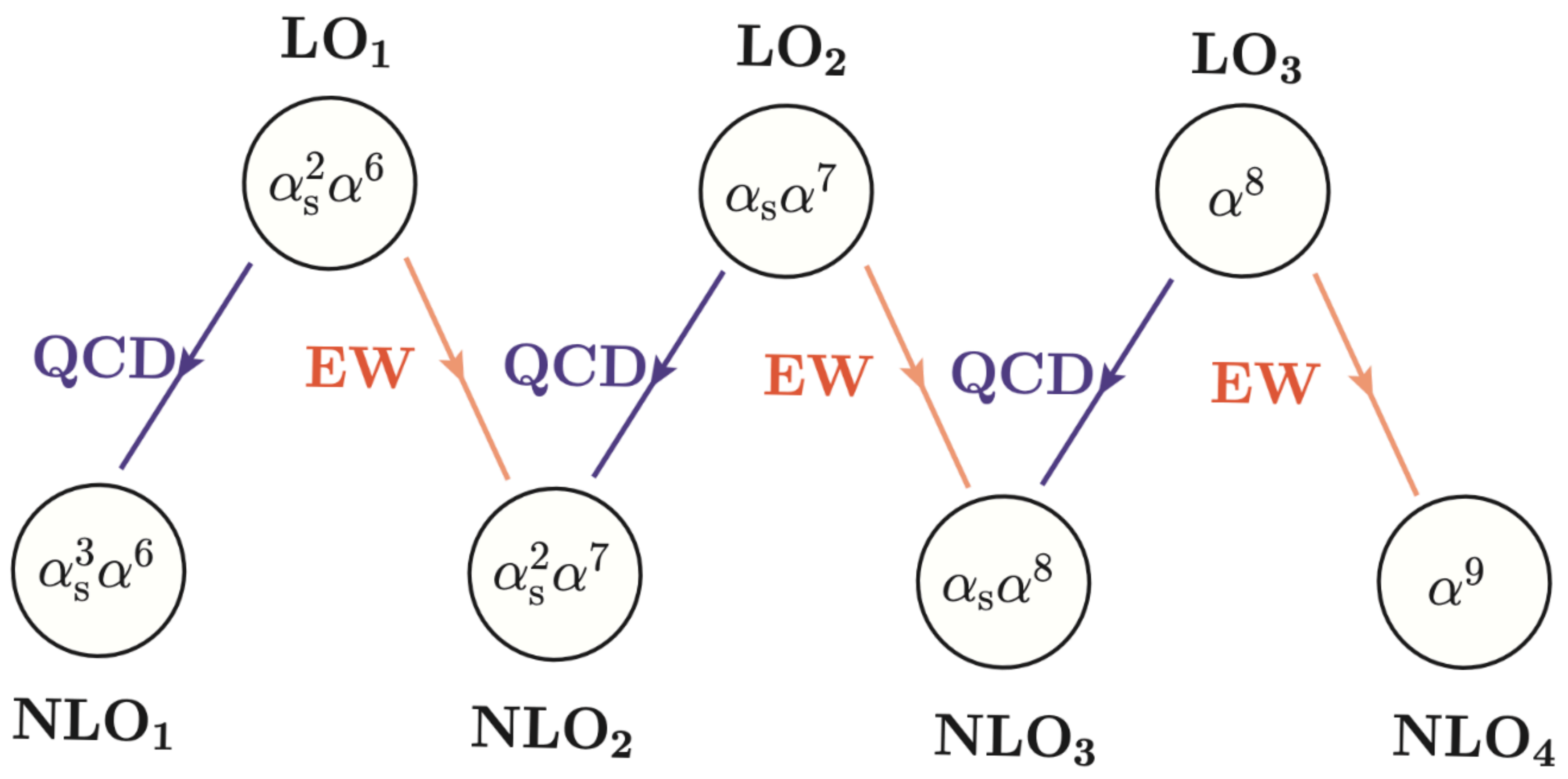
study at LO
what about NLO + PS ?

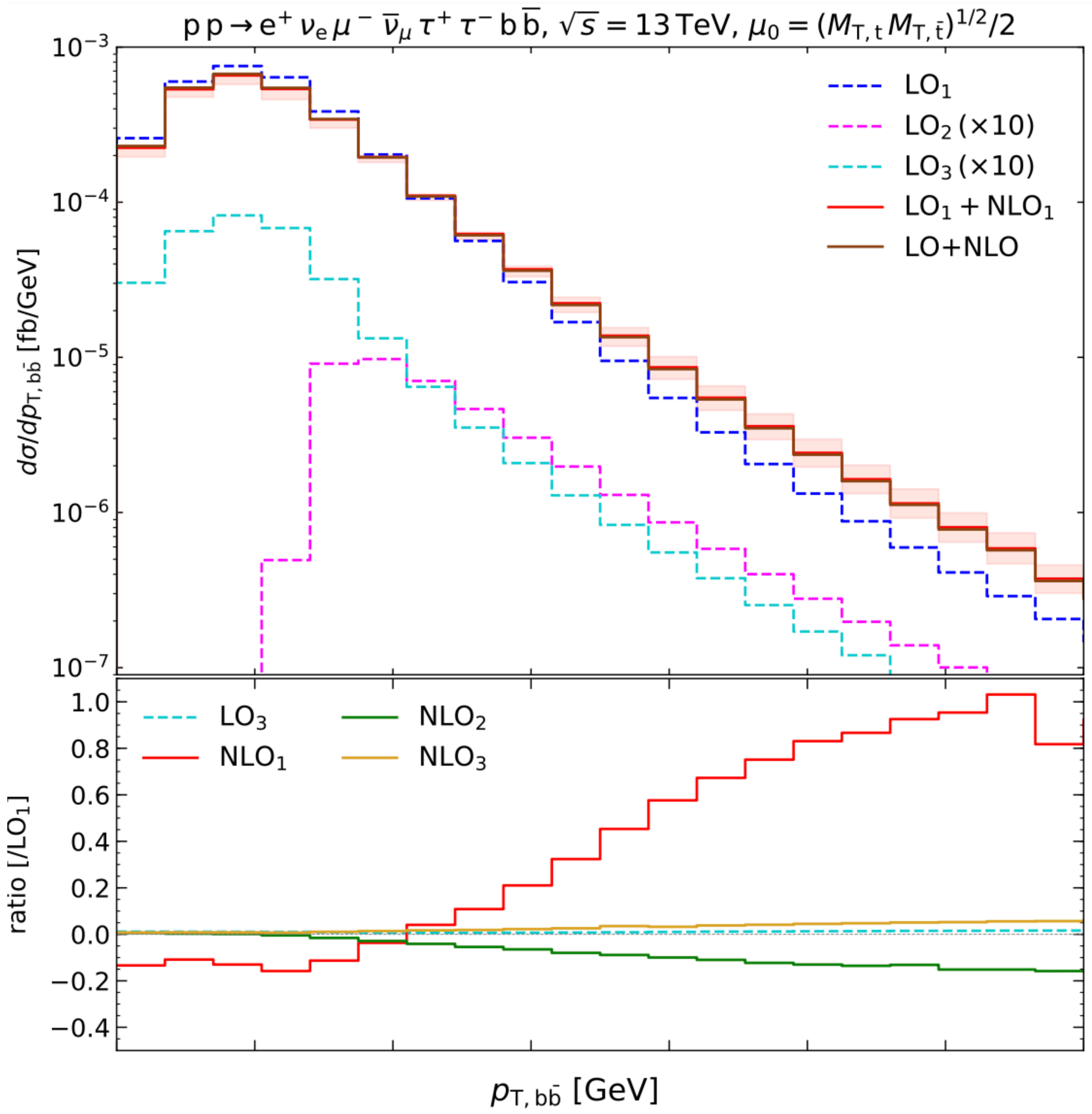
Off-shell effects in $t\bar{t} + Z$ (Daniele Lombardi)

NLO QCD and NLO EW corrections to fully off-shell $t\bar{t}Z$:

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$$

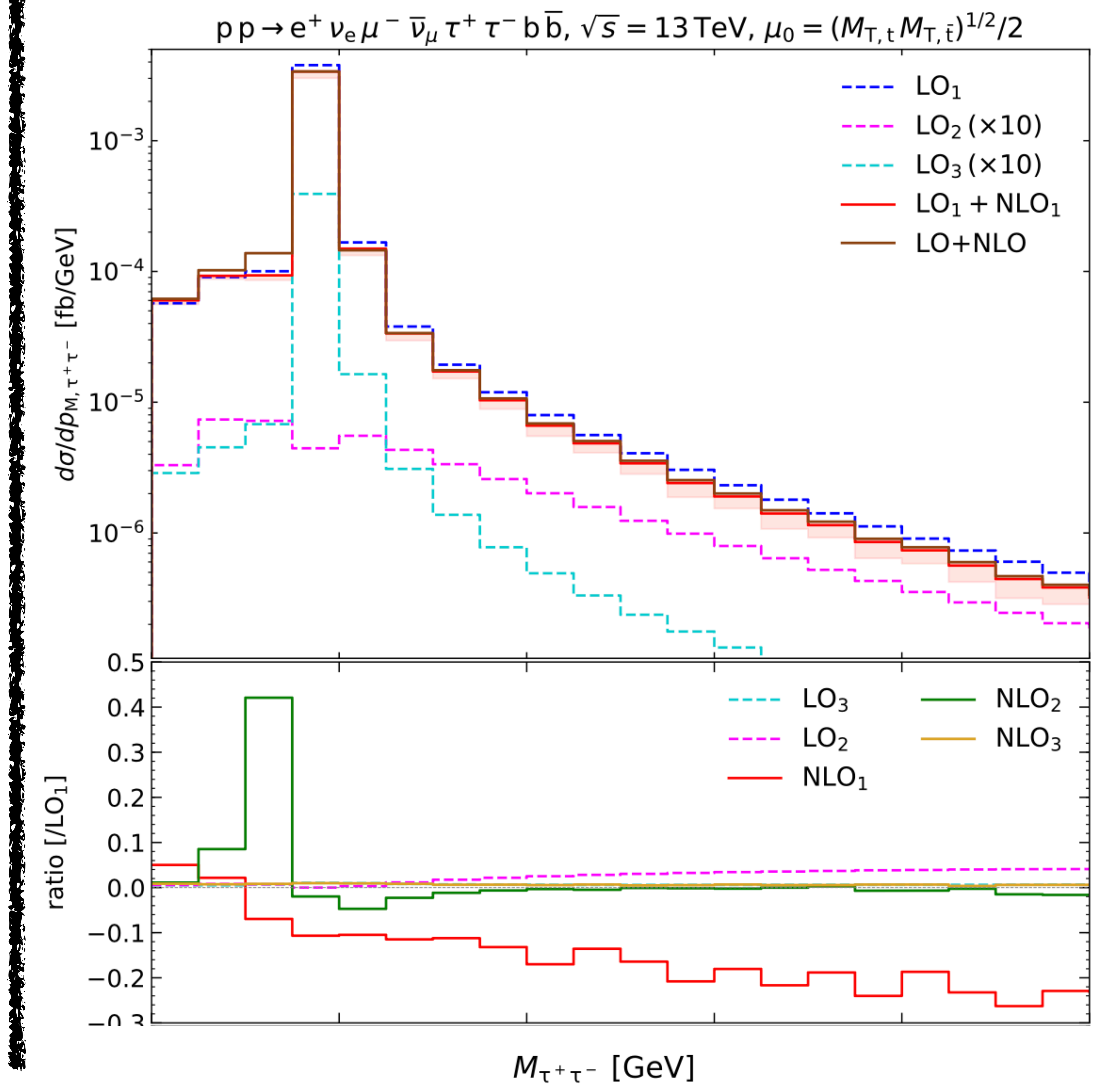
At the inclusive level, sub-leading LO and NLO terms amount to less than a percent correction





Large *NLO$_1$* corrections due to giant QCD K-factor.

Interplay between *NLO$_2$* corrections (EW Sudakov logarithms) and *NLO$_3$* ones (dominance of real gluon-induced contributions).



Negative *NLO$_1$* corrections in the far off-shell region.

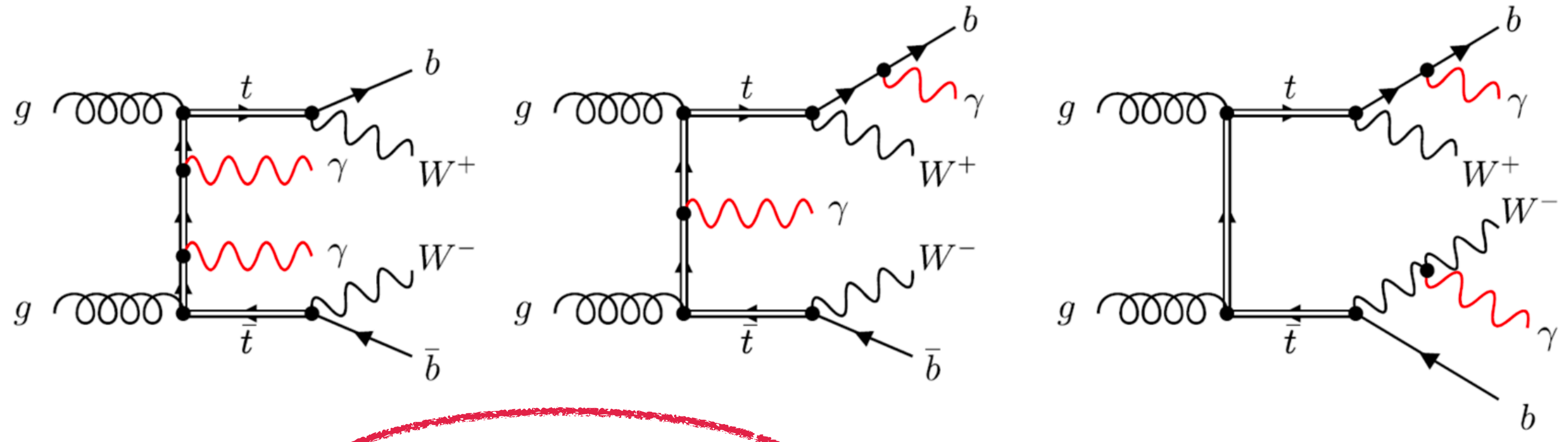
LO$_2$ is the largest sub-leading contribution in the off-shell region, due to the γg channel.

CPU killer: $t\bar{t}$+photon(s) (Daniel Stremmer)

$$d\sigma^{\text{LO}}_{\text{Full}} = \Gamma_t^{-2}\Big(\underbrace{d\sigma^{\text{LO}}_{t\bar{t}\gamma\gamma}\, d\Gamma^{\text{LO}}_{t\bar{t}}}_{\text{Prod.}} + \underbrace{d\sigma^{\text{LO}}_{t\bar{t}\gamma}\, d\Gamma^{\text{LO}}_{t\bar{t}\gamma}}_{\text{Mixed}} + \underbrace{d\sigma^{\text{LO}}_{t\bar{t}}\, d\Gamma^{\text{LO}}_{t\bar{t}\gamma\gamma}}_{\text{Decay}}\Big)$$

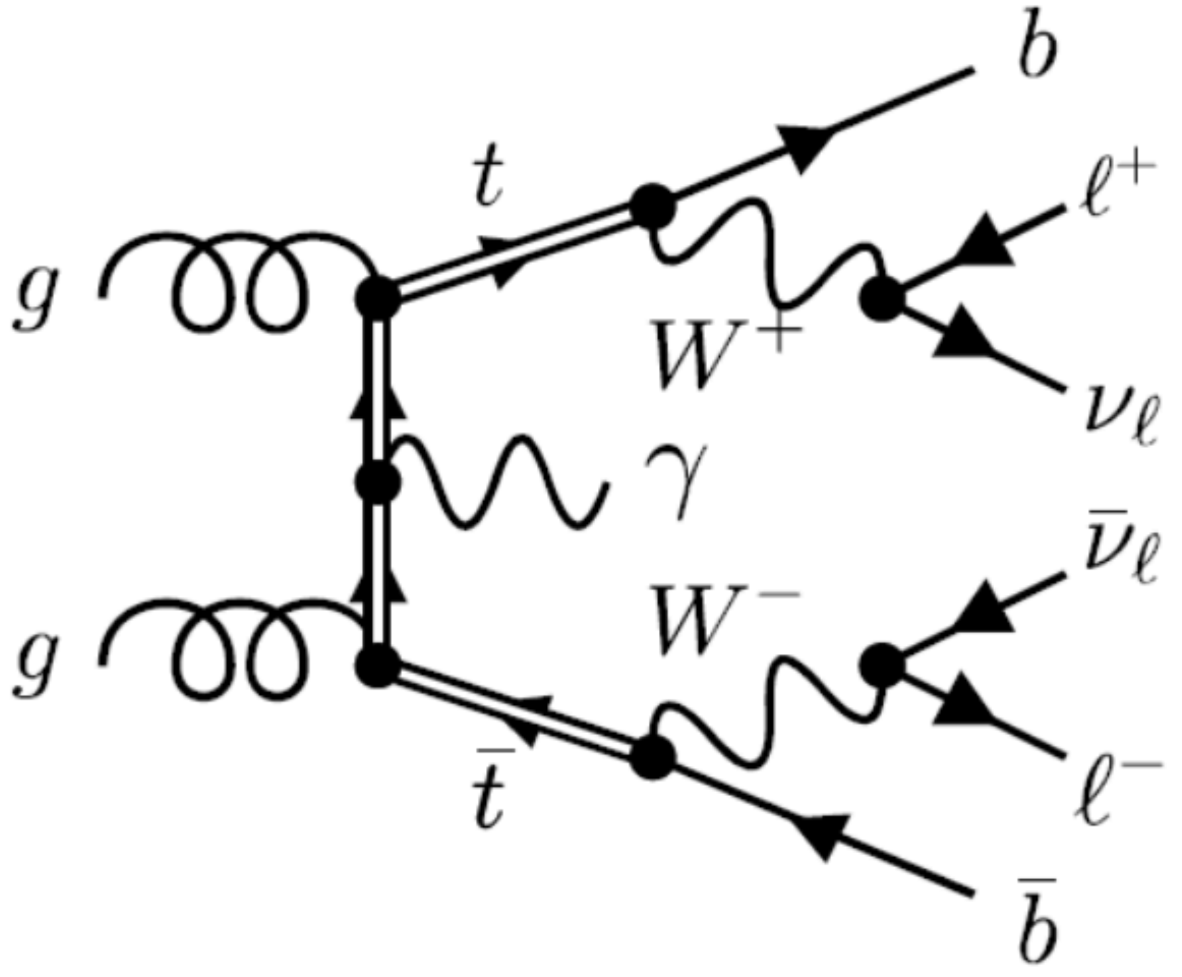
No observation of pp → $t\bar{t}\gamma\gamma$ yet

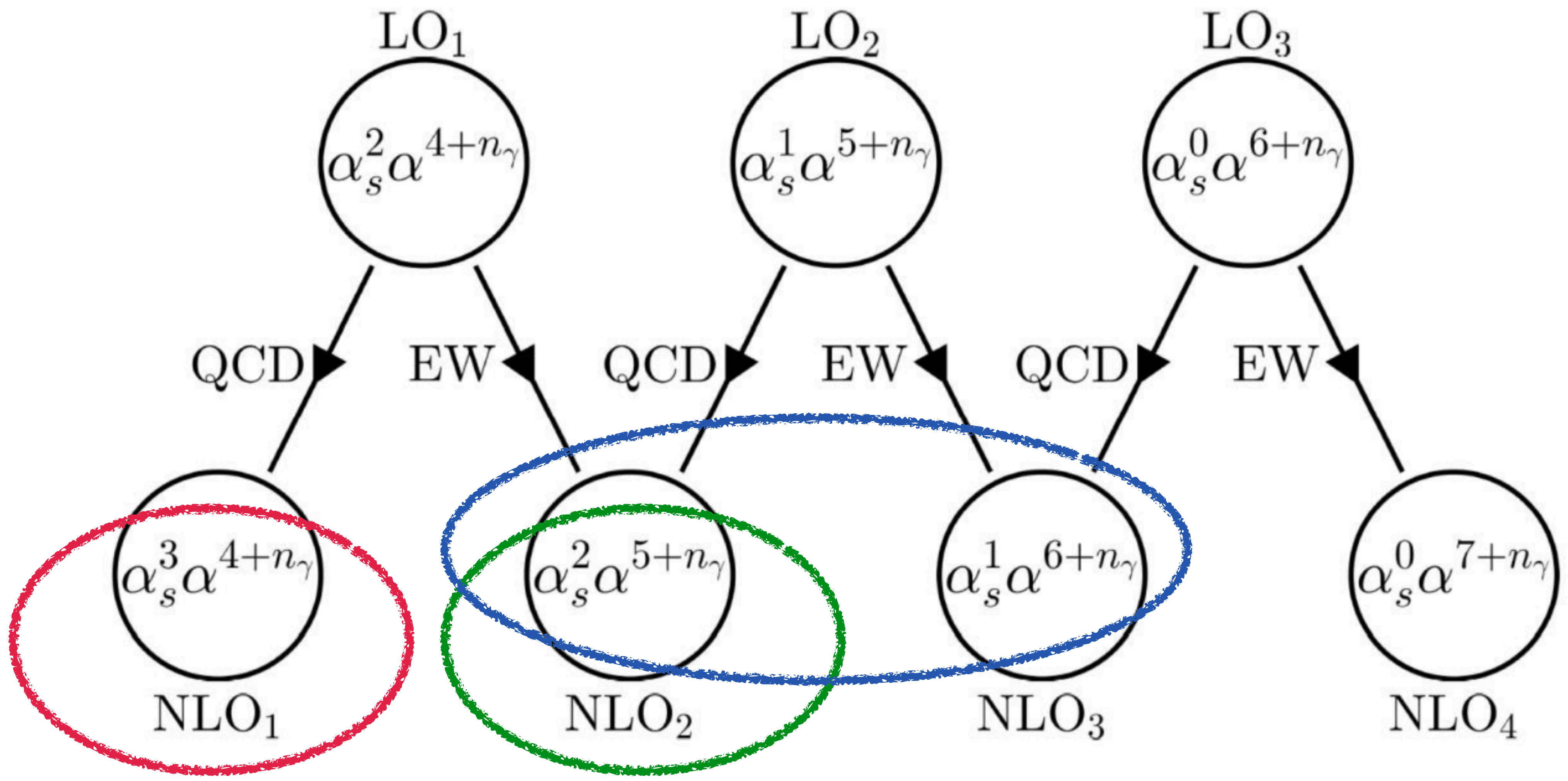
Full off-shell calculation is way too expensive !



Full = Prod. (40%) + Mixed (44%) + Decay (16%)

Complete NLO





inclusive

10% Sudakov tails

accidental cancellations

$t\bar{t}$+photon(s): goodbye Frixione (Daniel Stremmer)

Photon isolation in pp → $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ at $\sqrt{s} = 13.6$ TeV

Smooth-cone isolation ***Frixione '98***

- $E_{T,\mathrm{had}}(R) \leq \epsilon_\gamma \, E_{T,\gamma} \left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})} \right)^n \quad \text{for all } R \leq R_{\gamma j}$

Fixed-cone isolation

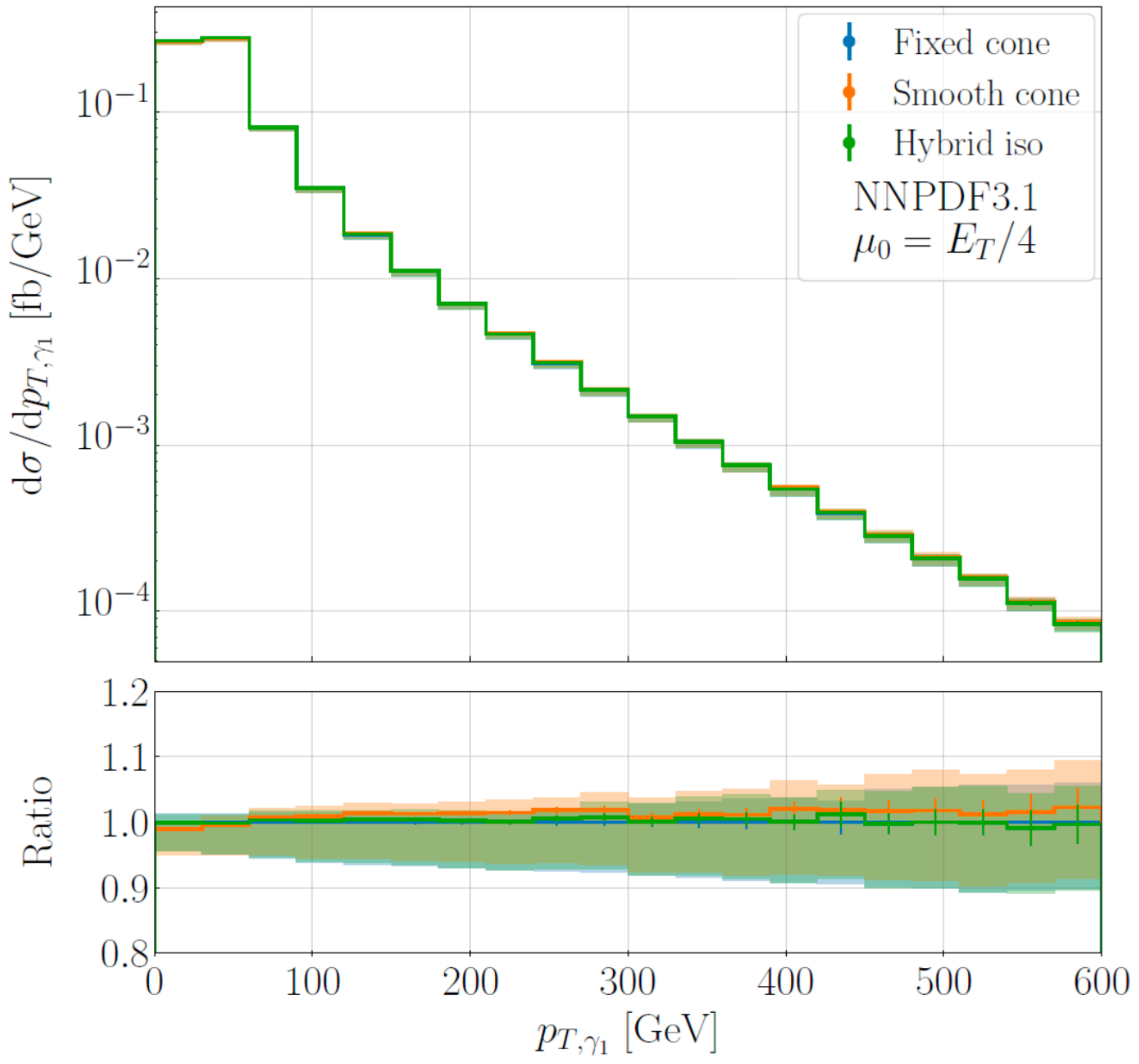
- $E_{T,\mathrm{had}}(R_{\gamma j}) \leq E_{T,\mathrm{max}}(E_{T,\gamma})$
- Collinear photon-quark configurations allowed
- $\mathrm{d}\hat{\sigma}^{\gamma+X,\mathrm{NLO}} = \mathrm{d}\hat{\sigma}_\gamma^{\mathrm{NLO}} + \sum_p \mathrm{d}\hat{\sigma}_p^{\mathrm{LO}} \otimes D_{p\to\gamma} - \frac{\alpha}{2\pi} \sum_p \mathrm{d}\hat{\sigma}_p^{\mathrm{LO}} \otimes \boldsymbol{\Gamma}^{(0)}_{p\to\gamma}$

Hybrid photon isolation

- First use smooth-cone isolation to remove fragmentation contribution and then the fixed-cone isolation

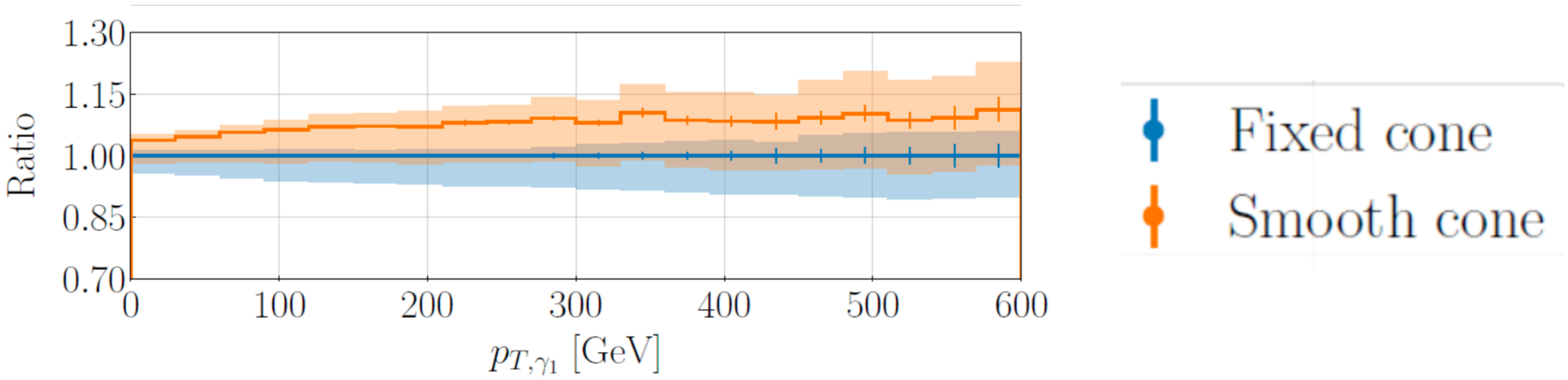
Fragmentation contribution negligible small with ~0.2%

Tuned !



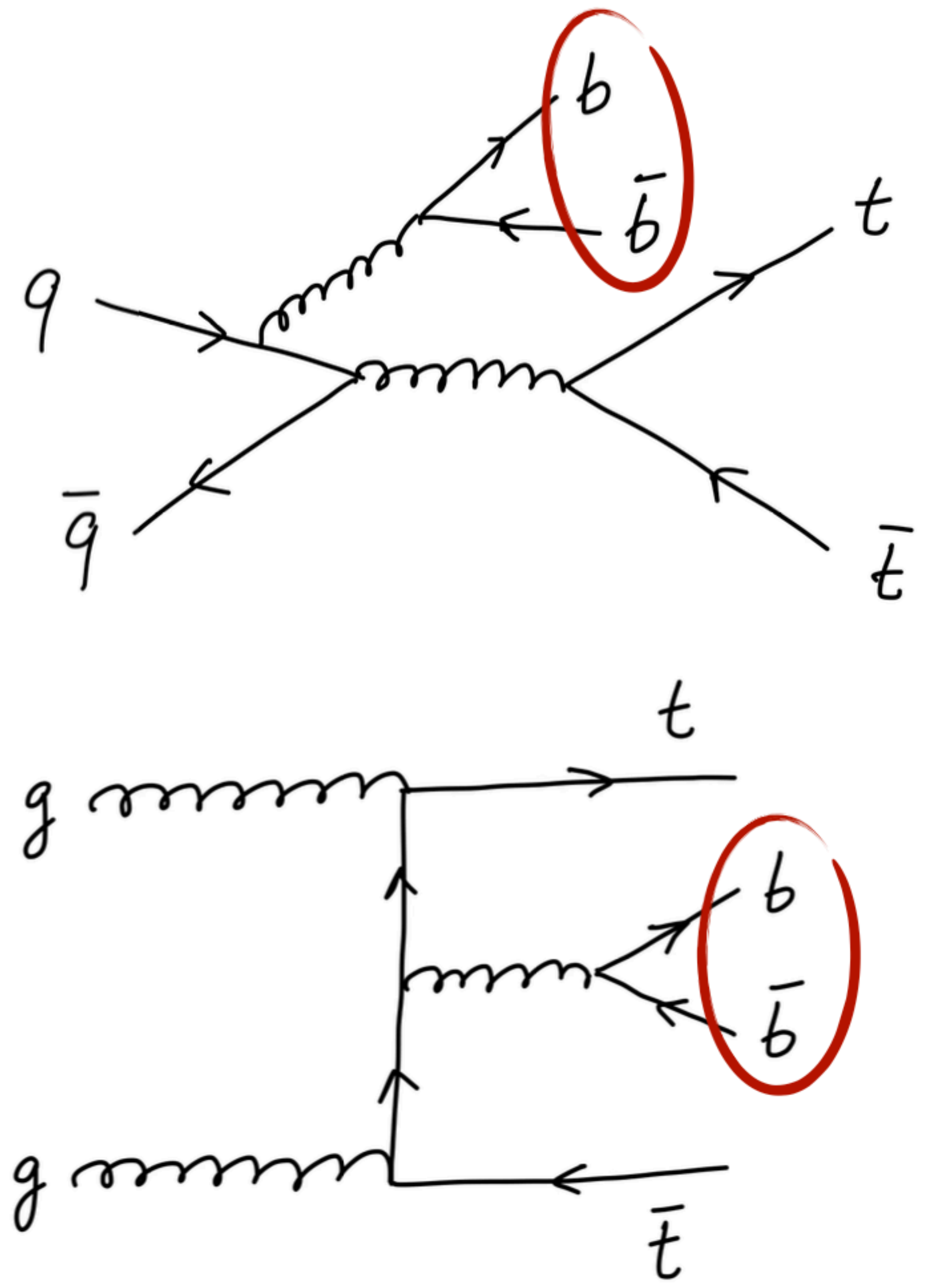
- Smooth cone isolation: $(R = 0.4, \epsilon_\gamma = 0.10, n = 0.5)$
- Hybrid photon isolation: $(R = 0.1, \epsilon_\gamma = 0.10, n = 2.0)$

Not tuned:

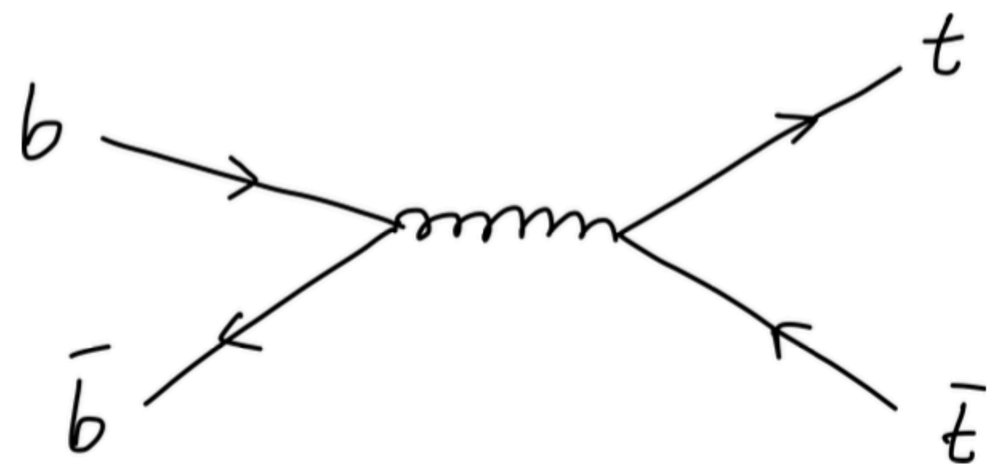


No need for Frixione so... compare with measurements !

$t\bar{t} + b\bar{b}$ with massless b-quarks (Tetiana Moskalets)



	4FS	5FS
***b*-quarks in the matrix element**	massive	massless
***b*-quarks included in the PDF?**	no	yes
renormalisation scheme	on-shell	$\overline{\text{MS}}$
final state	exclusively $t\bar{t}b\bar{b}$	inclusive $t\bar{t}$ + jets



- $gg \to t\bar{t}b\bar{b}(g)$
- $gb \to t\bar{t}bg(\to b\bar{b})$
- $bb \to t\bar{t}q\bar{q}(g)$

…

5FS calculation of $t\bar{t}b\bar{b}$ at NLO yields the most accurate prediction for this process to date
- no large logarithms appearing in the matrix element calculation
- no complications when matching to a parton shower

Parton shower radiation can produce additional b-quarks
- Jets generated by the shower can be harder than the matrix-element-level bottom quarks
- We need only the subleading -quarks to come from the parton shower, but not the leading ones
- Not fully understood how the parton shower radiation should be constrained

But generating $t\bar{t}$ + 0,1,2 jets @ NLO accuracy requires substantional computing resources

	$gg \to t\bar{t}$	$gg \to t\bar{t}gg$	$gg \to t\bar{t}ggg$
`madevent`	13G	470G	11T
`matrix1`	3.1G (23%)	450G (96%)	11T (>99%)
↳ ext	450M (3.4%)	3.3G (<1%)	7.3G (<1%)
↳ int	1.9G (14%)	160G (35%)	2T (19%)
↳ amp	530M (4.0%)	210G (44%)	5.5T (51%)

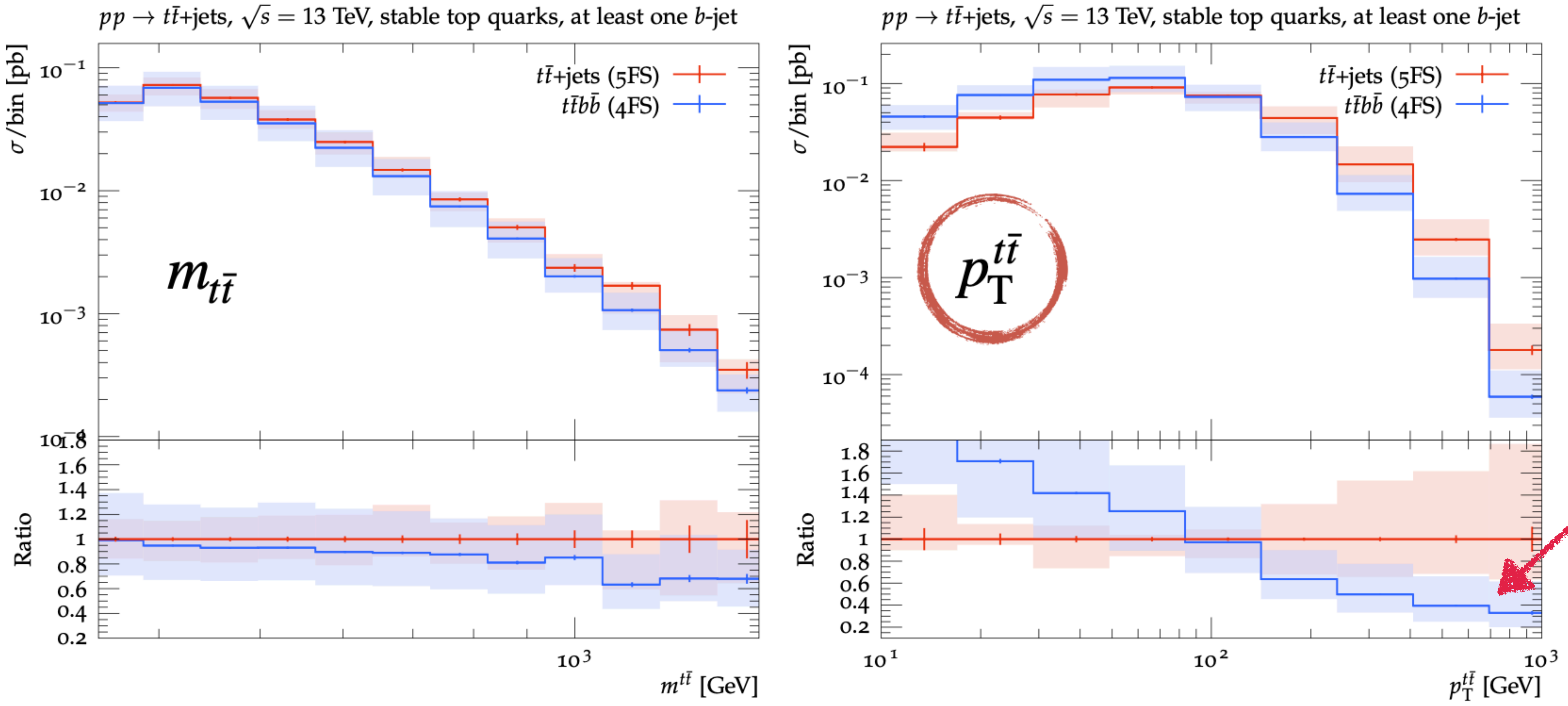
Selection efficiency of $t\bar{t}b\bar{b}$ is low

newly implemented feature MadGraph5_aMC@NLO

$t\bar{t} + b\bar{b}$ with massless b-quarks (Tetiana Moskalets)

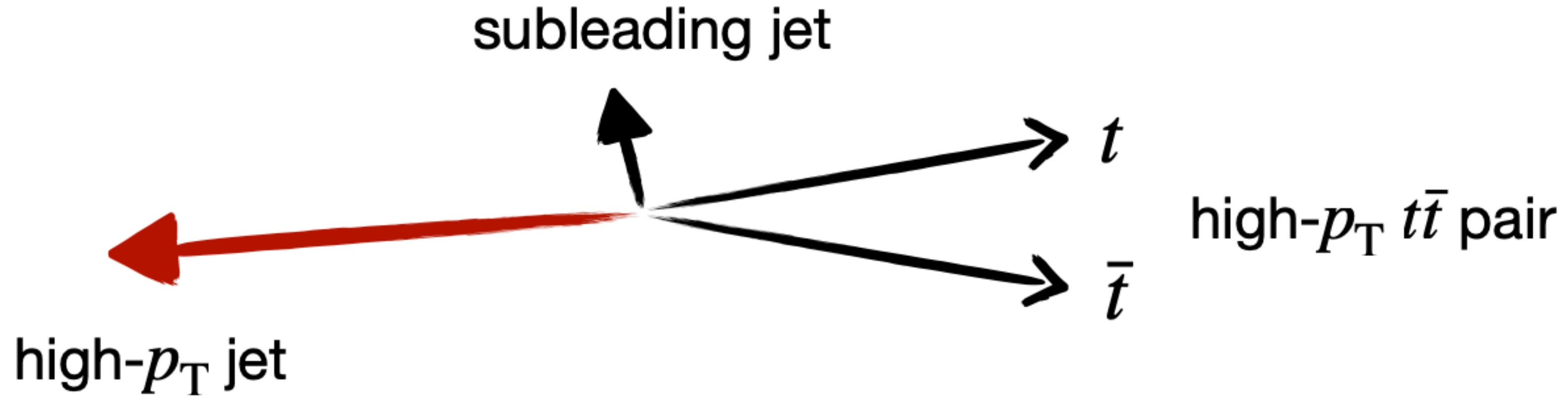
For most of the variables, 4FS and 5FS predictions are compatible within the uncertainty bands

5FS uncertainty is more reliable than the 4FS one, since the 4FS matching uncertainty is expected to be significant but is not included



the band should actually be wider

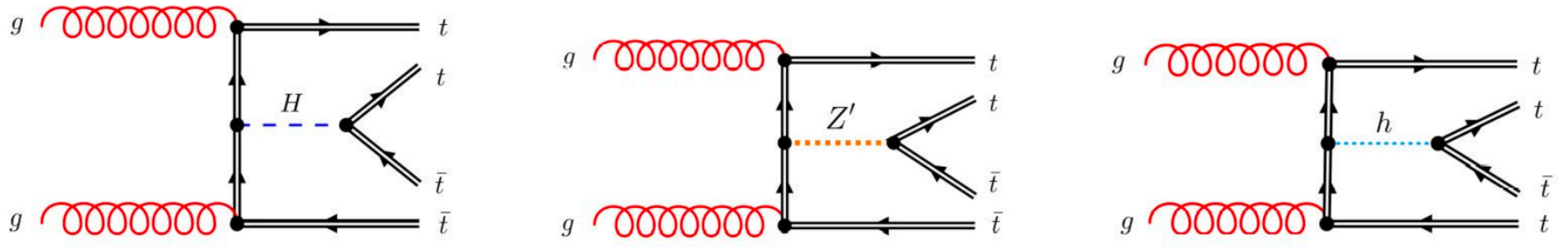
At large $p_T^{t\bar{t}}$, it is kinematically most-likely that the $t\bar{t}$ pair recoils agains a single hard jet

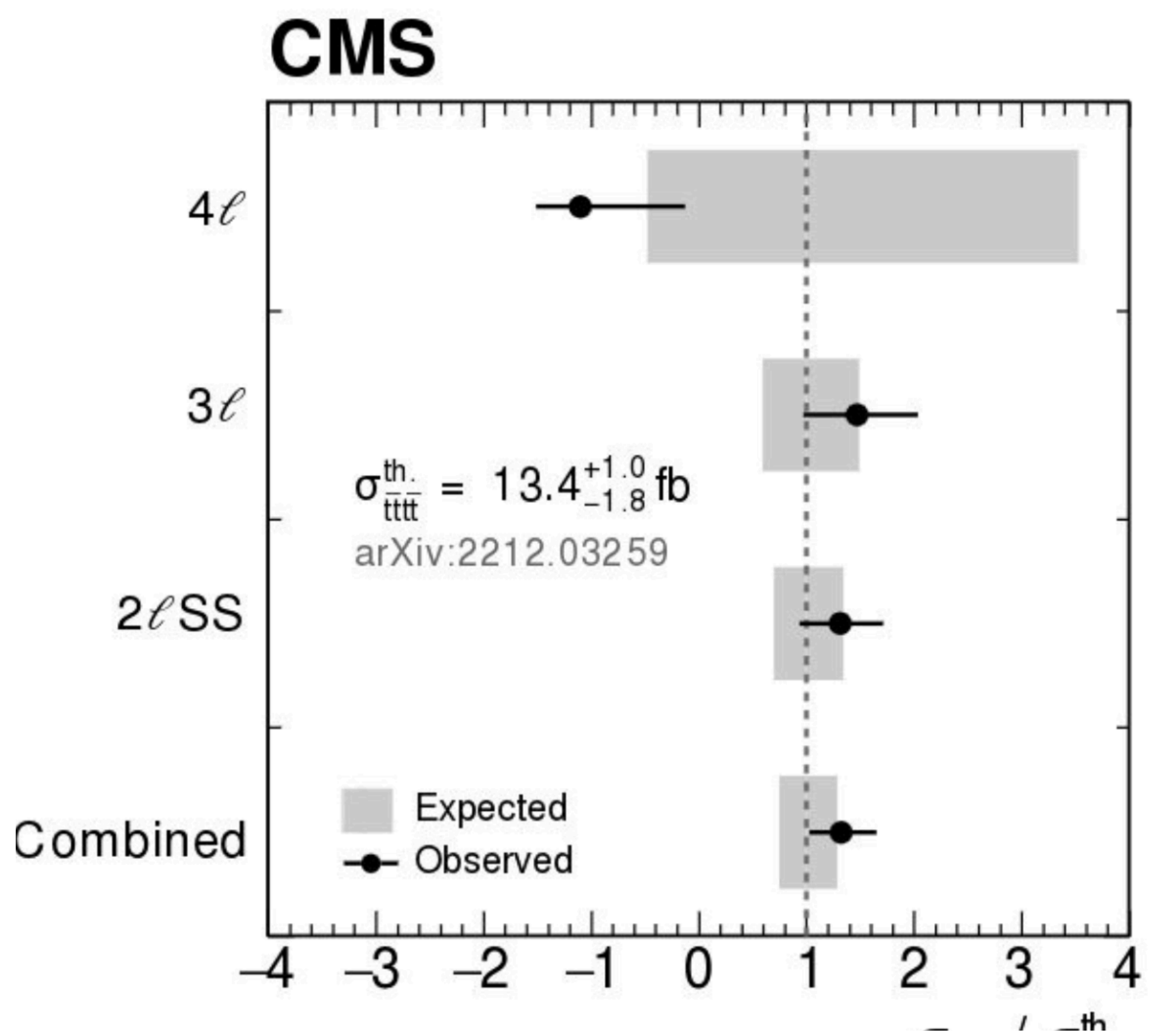


- ➡ The reason for the large 5FS–4FS difference in the $p_T^{t\bar{t}}$ spectrum at large momenta is
  - The correlation between $p_T^{t\bar{t}}$ and $p_T^{\text{light jet, hardest}}$
  - Expected 5FS–4FS difference between the fraction of events with the hardest jet being light-flavoured

$(t\bar{t})^2$ with decays (Nikolaos Dimitrakopoulos)

- Direct way to measure the top Yukawa coupling complementary to ttH production
- Very sensitive to many New Physics models





Highly accurate SM calculations are essential alongside BSM modeling

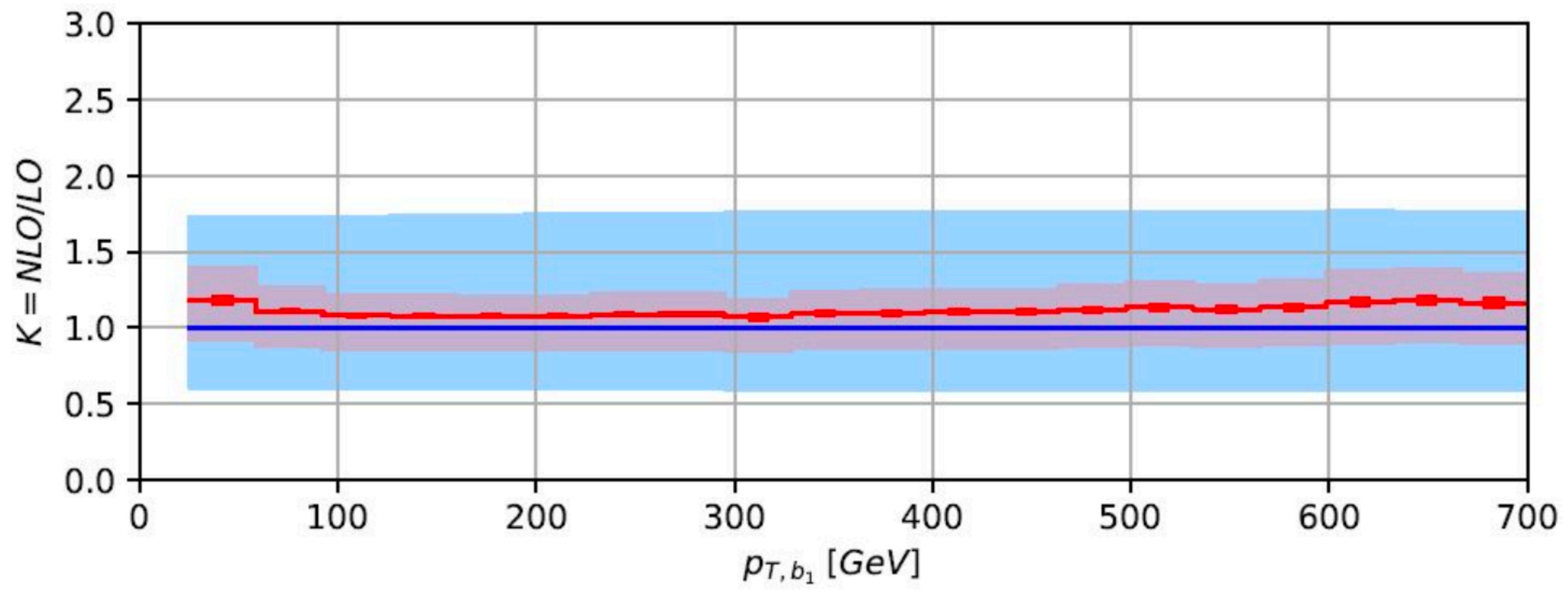
4 lepton decay channel

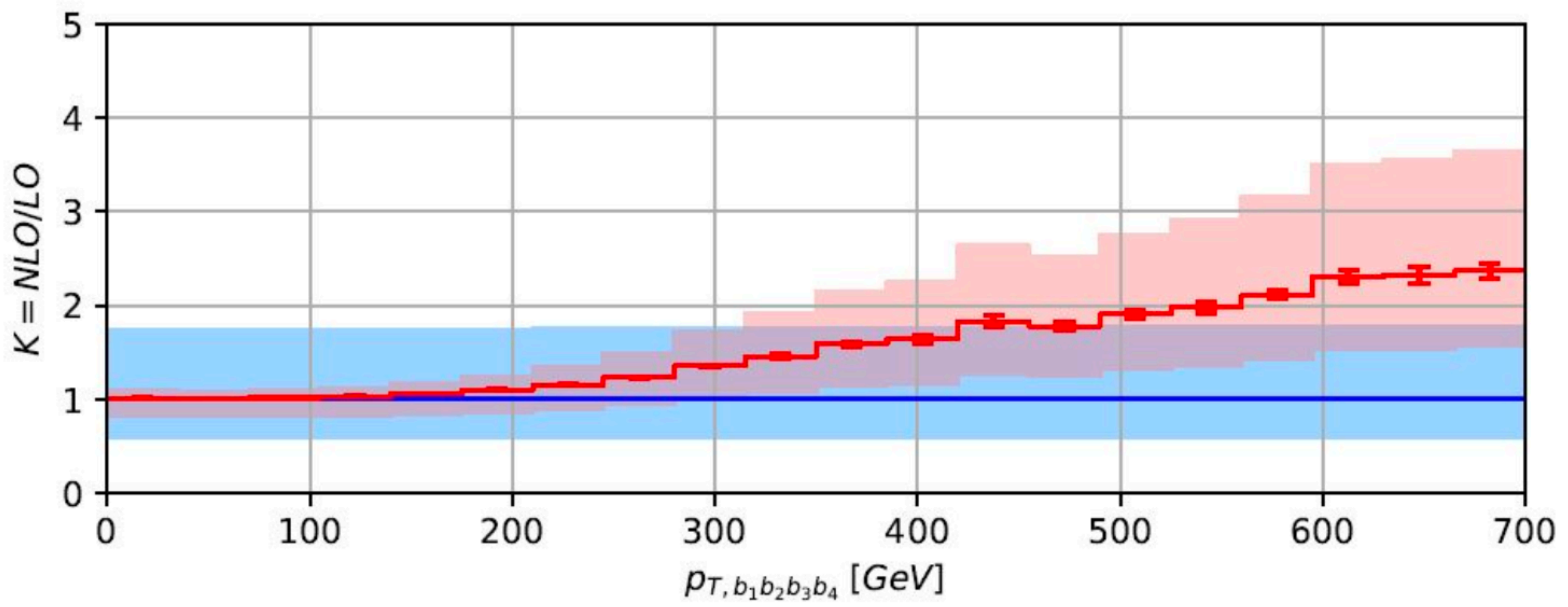
studied in the Narrow Width Approximation due to computational cost !

$$d\sigma = d\sigma_{tt\bar{t}\bar{t}} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}$$

$$d\sigma_{tt\bar{t}\bar{t}} = d\sigma^{(0)}_{tt\bar{t}\bar{t}} + \alpha_s d\sigma^{(1)}_{tt\bar{t}\bar{t}} + \mathcal{O}(\alpha_s^2)$$

$$d\Gamma_t = d\Gamma_t^{(0)} + \alpha_s d\Gamma_t^{(1)} + \mathcal{O}(\alpha_s^2)$$



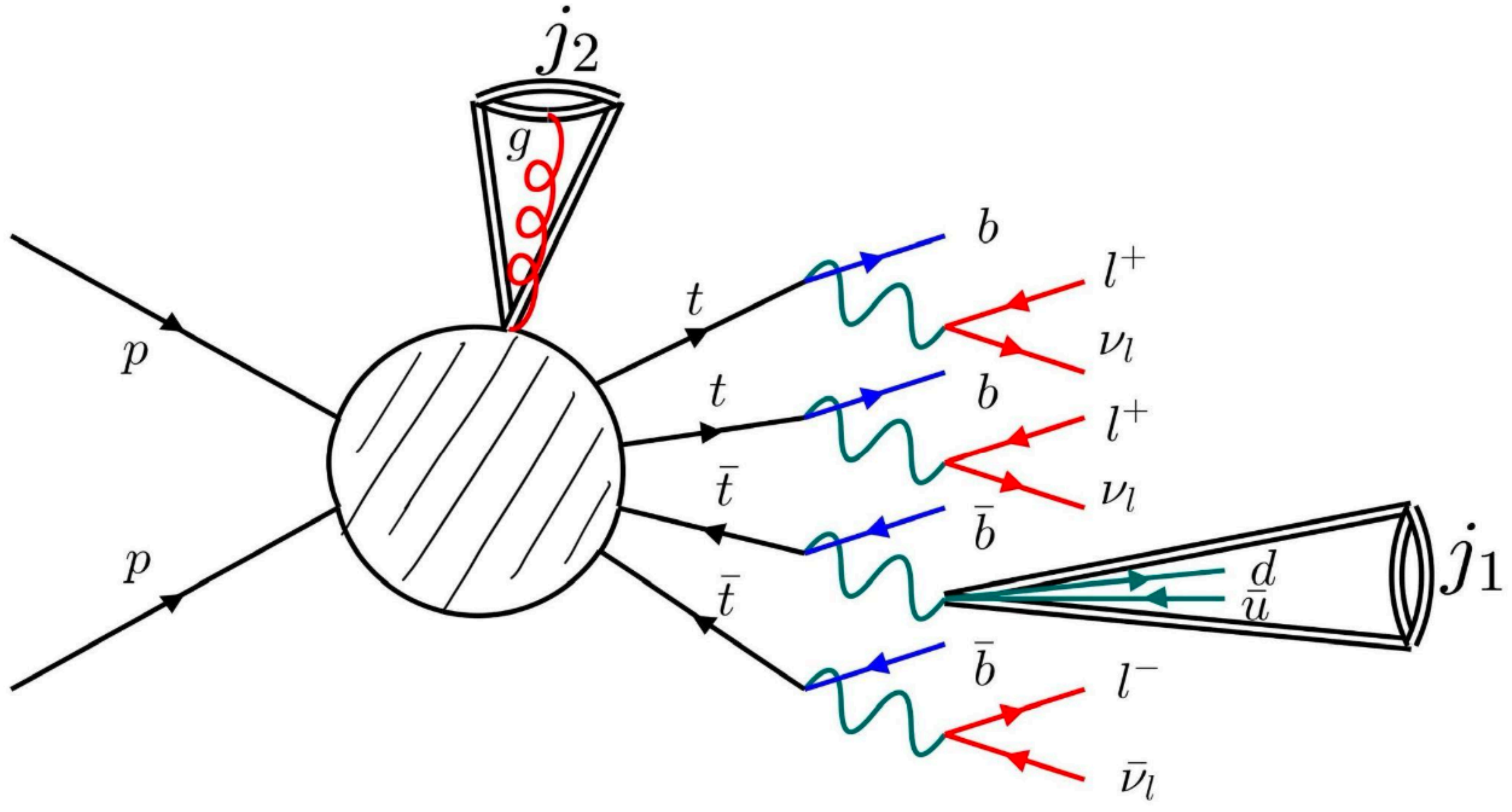


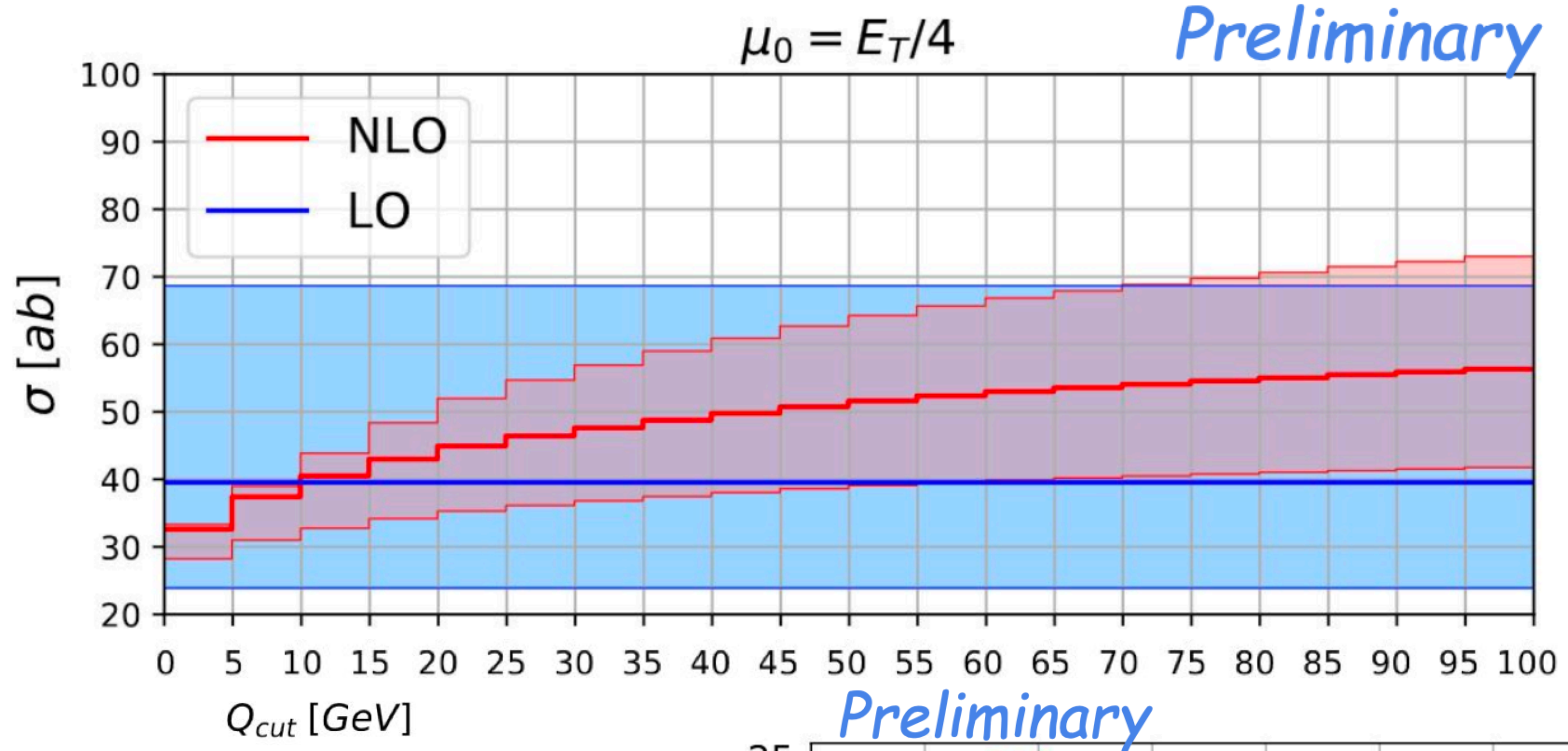
- QCD corrections at the level of 10%-12%
- Impact of QCD corrections at the decays at the level of 8%-9%

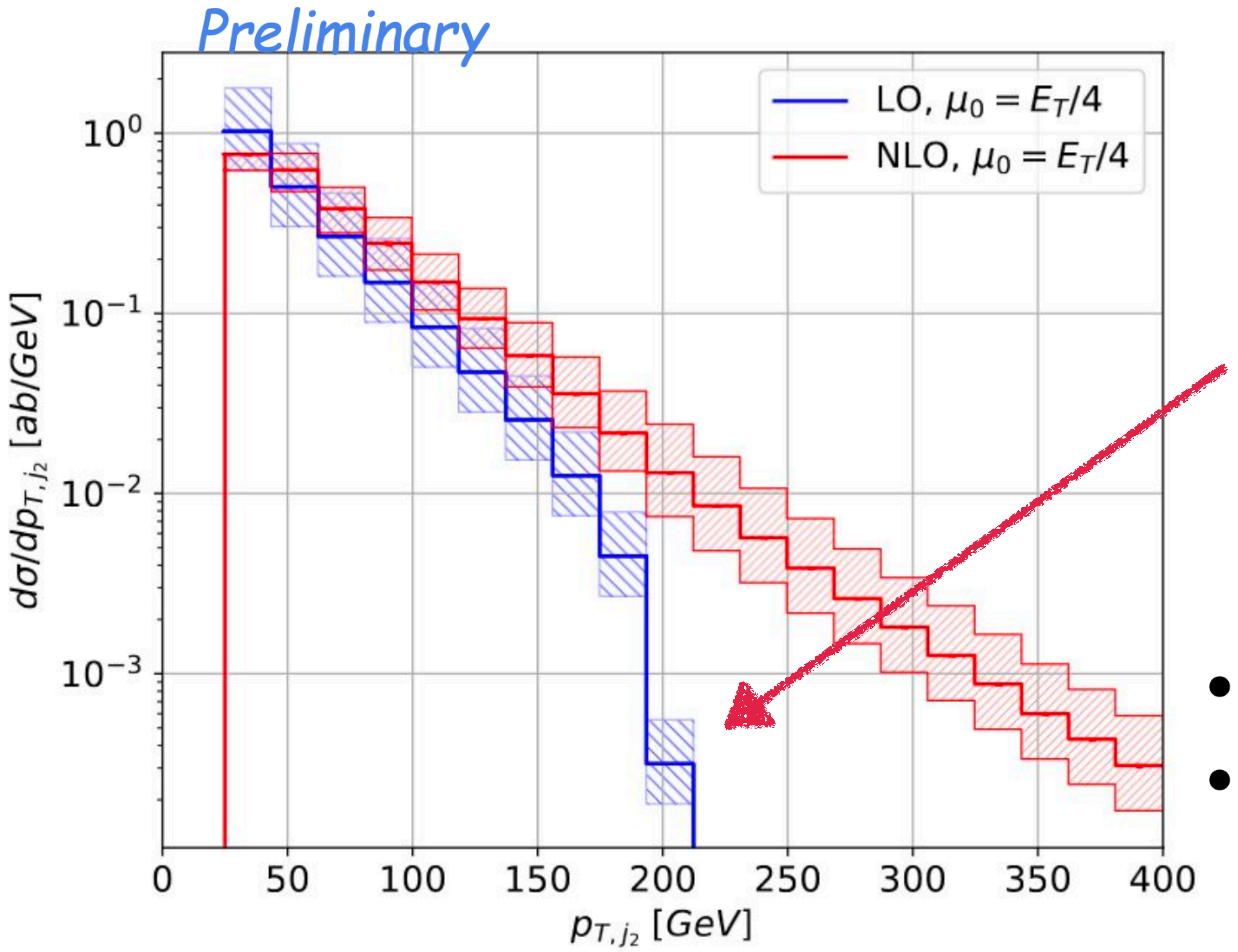
$(t\bar{t})^2$ with decays (Nikolaos Dimitrakopoulos)

3 lepton channel - Qcut dependence

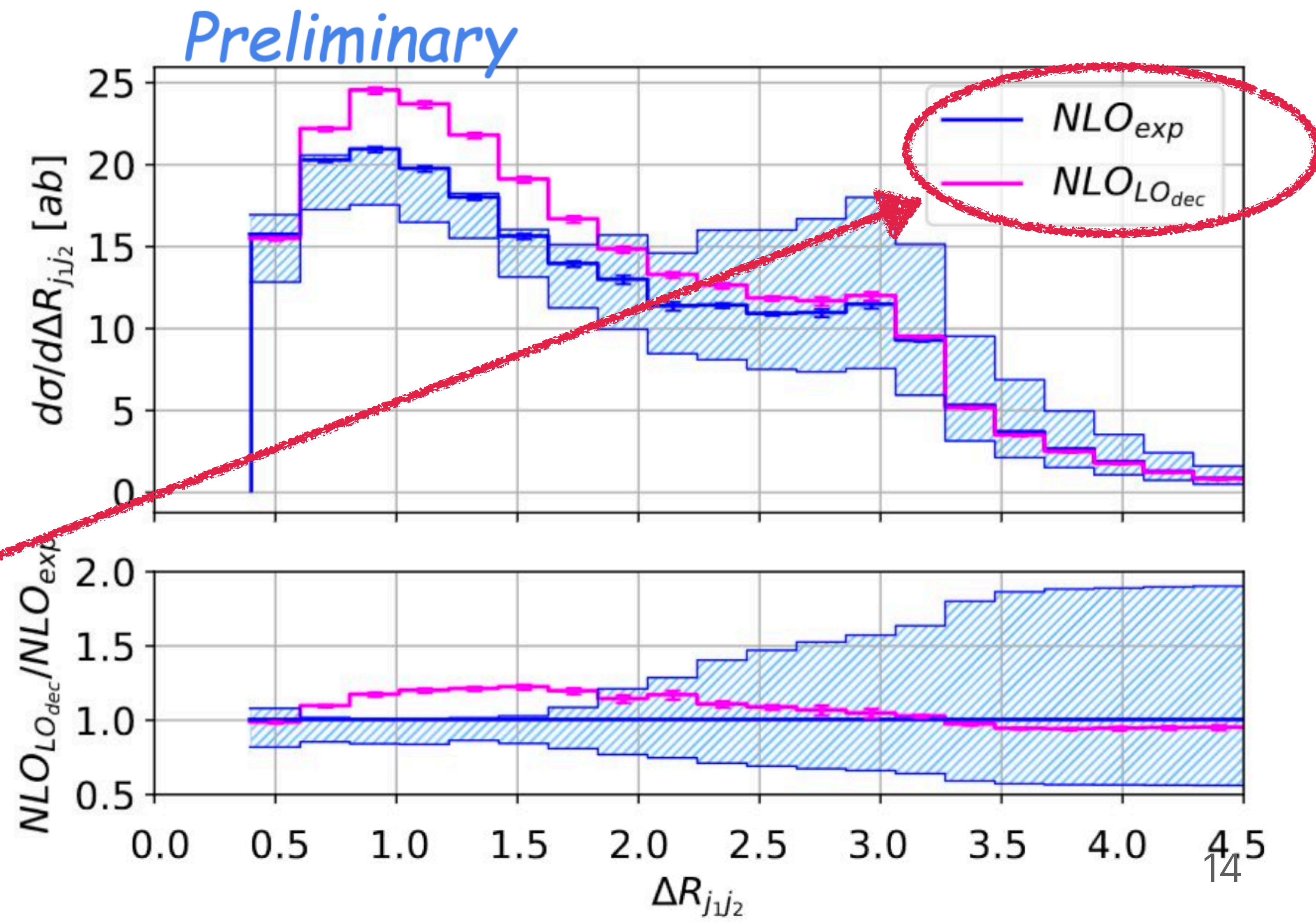
$$|M_{jj} - m_W| < Q_{cut}$$







$$(p_{T,j_2})_{max} \approx \frac{m_W}{(\Delta R_{j_1 j_2})_{min}} \approx 201 \text{ GeV}$$

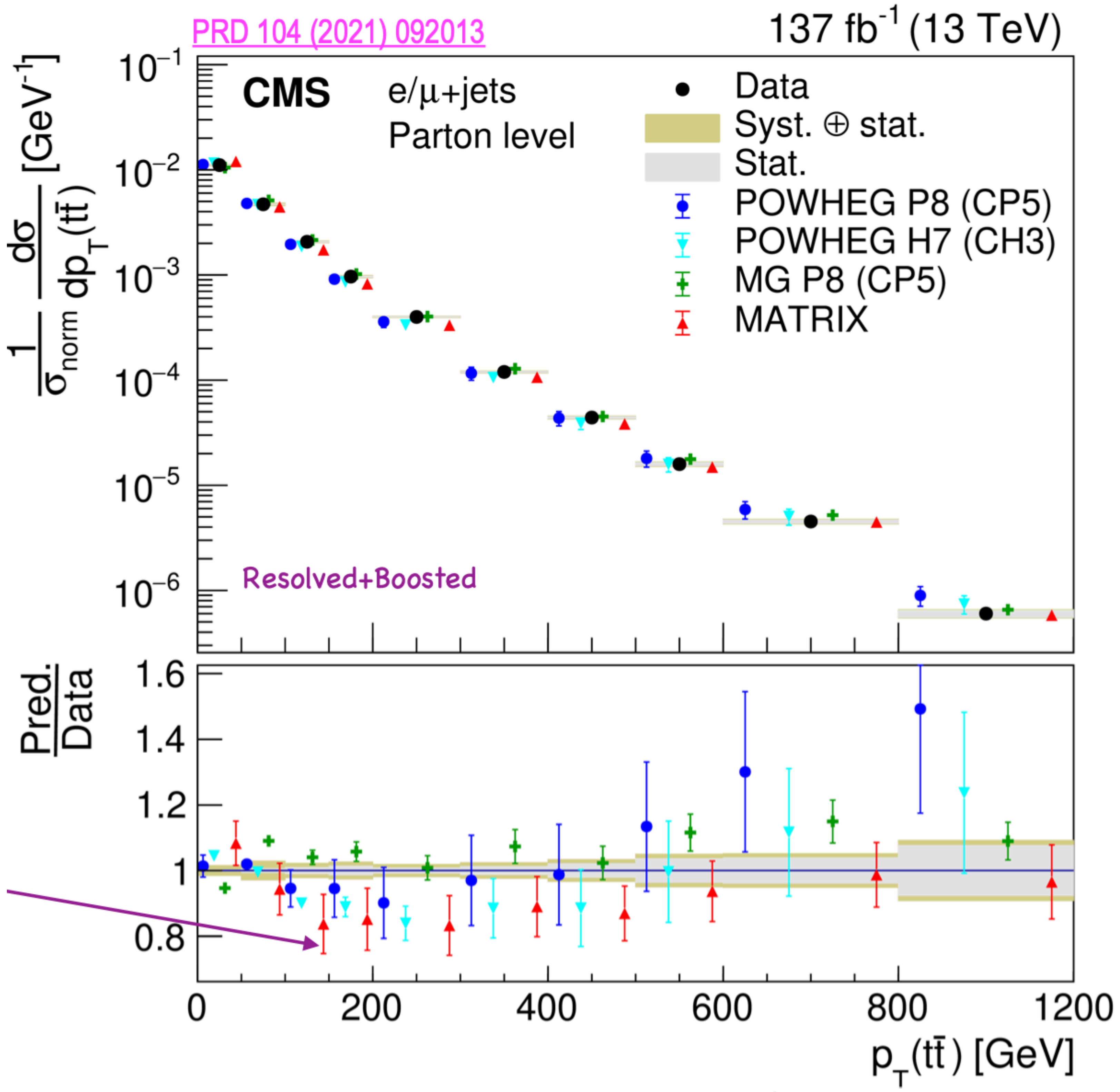


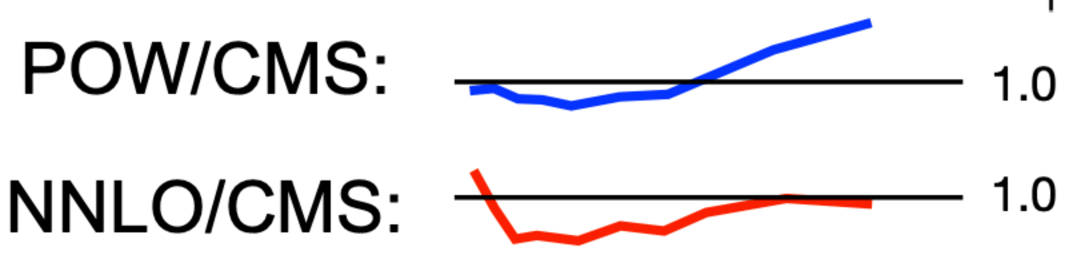
- Differences up to 22% near $\Delta R_{j_1 j_2}$ = 1
- Differences at the level of 10%-12% for $\Delta\phi_{l_1 l_2}$

Two-loop QCD corrections to $pp \to t\bar{t}j$ (Colomba Brancaccio)

From Olaf Behnke's talk

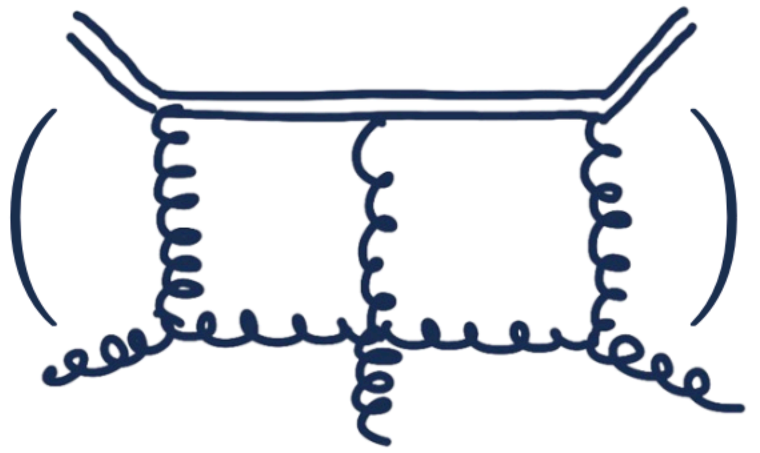
$p_T(t\bar{t})$





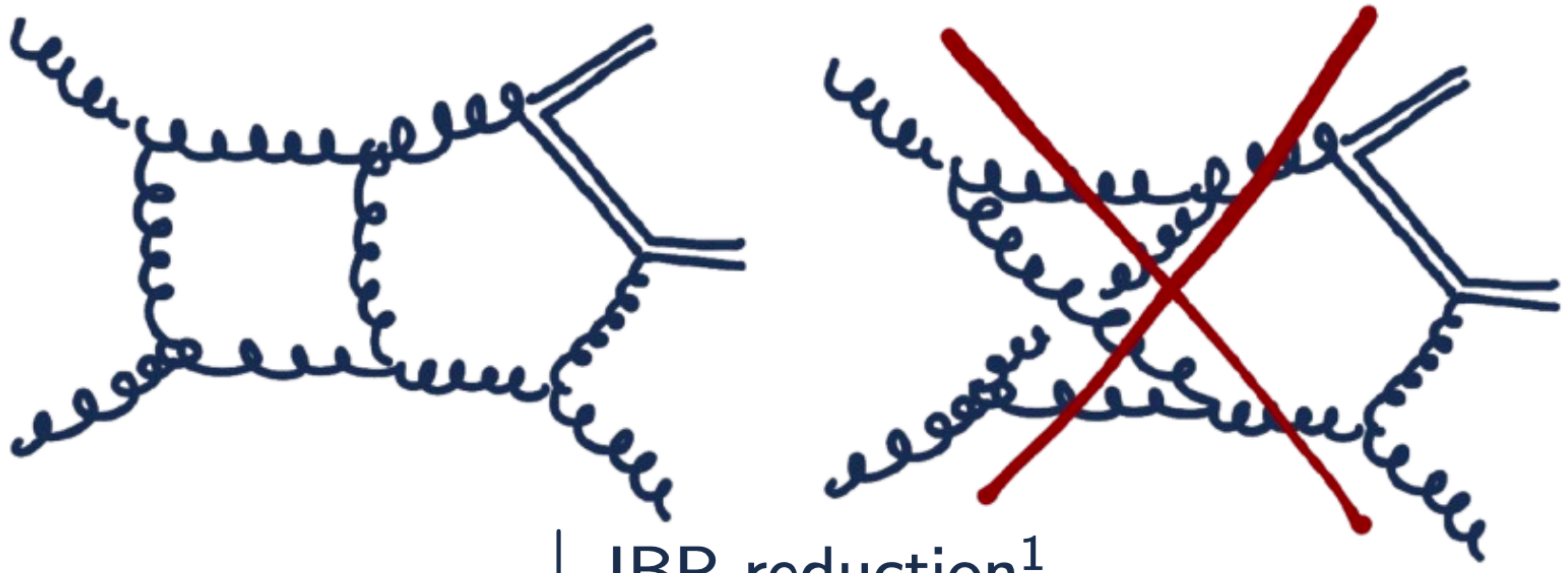
⇒ Both NNLO and POW exhibit some wiggles around the data

⇒ Need NNNLO



$$A^{2L}(\epsilon) = \sum_i \Big(\quad \Big)_i$$

↓ colour decomposition



↓ IBP reduction^1

...

Phase-Space	$A_{\text{LC}}^{2\text{L},+++++,n_t n_{\bar{t}}}$ [GeV^{-2}]
point #1	$19.028262 - 3.1078961\,i$
point #2	$0.07061470 - 0.00649655\,i$
point #3	$-29.219122 - 27.542150\,i$
point #4	$-0.97280521 + 0.86357506\,i$
point #5	$-0.40407926 - 0.53165671\,i$

Preliminary

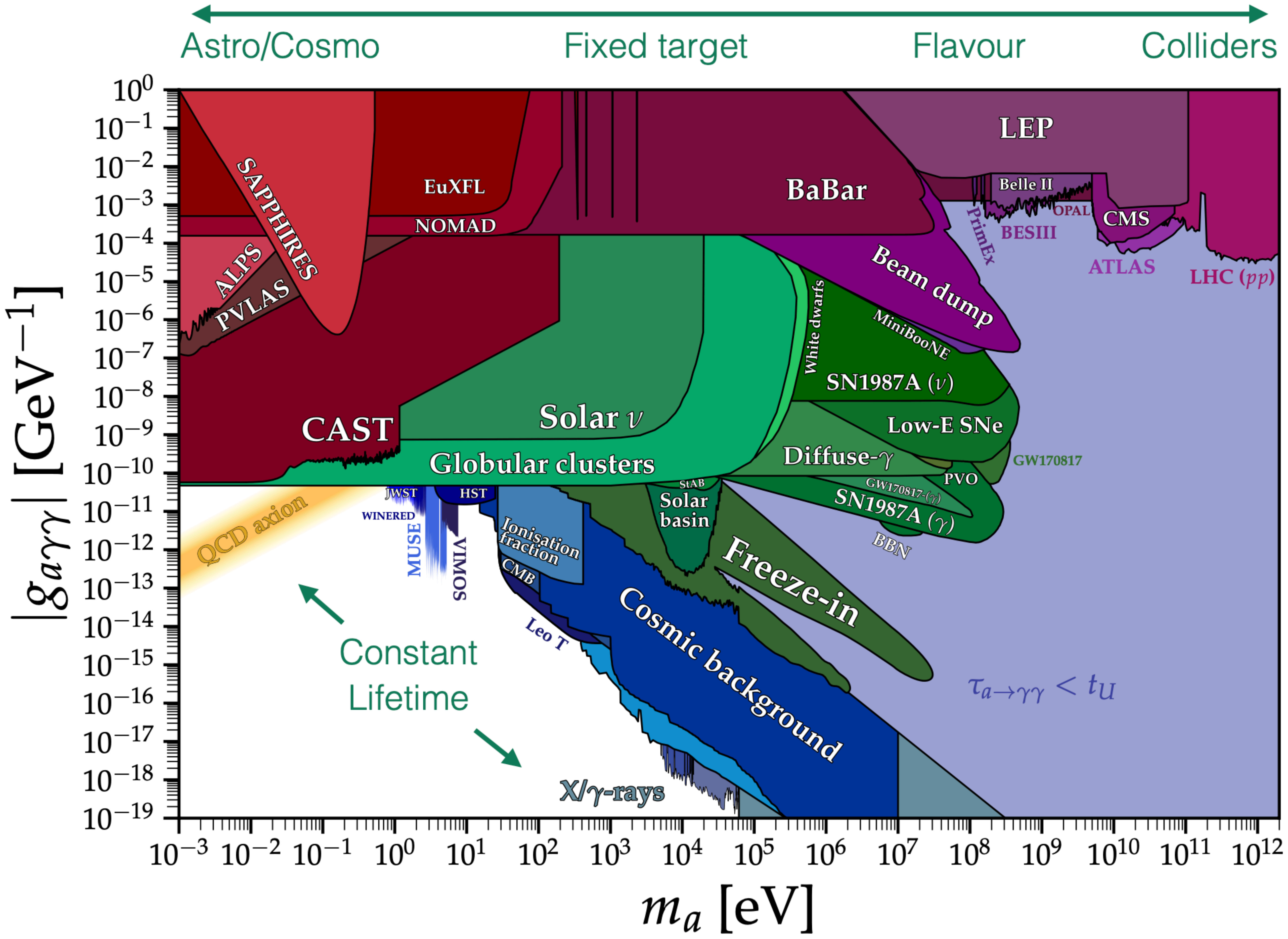
TOP 2024
THEORY

Beyond
(the Standard Model)

Axion-impostors but top friends (Ken Mimasu)

Axions: originally motivated by strong CP problem

$$\mathscr{L} \supset \frac{a}{f_a} G^{\mu\nu}_A \tilde{G}^A_{\mu\nu} \quad \Rightarrow \quad m_a f_a = \text{ constant}$$



ALPs: model of light, singlet pseudoscalar, a

- Generic, independent interactions

$\{m_a, f_a\}$ independent

- SM singlet

⇒ *Interactions described by EFT starting at dimension-5, $O(1/f_a)$*

- Pseudo Nambu-Goldstone boson

⇒ *light particle with shift-symmetric interactions*

$$a(x) \to a(x) + c \quad \Rightarrow \quad \mathscr{L} = \mathscr{L}\left[\partial^\mu a(x)\right]$$

explicit shift symmetry

$$\mathscr{L}^{(5)}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\partial^\mu a}{f_a} \sum_f \bar{\psi}_f \mathbf{c}_f \gamma_\mu \psi_f + c_H \frac{\partial^\mu a}{f_a} H^\dagger i \overleftrightarrow{D}_\mu H$$

shift symmetry breaking

$$+ c_{GG} \frac{\alpha_S}{4\pi} \frac{a}{f_a} G^{\mu\nu}_A \tilde{G}^A_{\mu\nu} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f_a} W^{\mu\nu}_I \tilde{W}^I_{\mu\nu} + c_{BB} \frac{\alpha_Y}{4\pi} \frac{a}{f_a} B^{\mu\nu}_I \tilde{B}_{\mu\nu}$$

Anomaly induced, 'hidden' shift symmetry

Top philic ALP

Top-philic ALP ≠ top-philic pseudo scalar!

$$\mathscr{L}^{(5)}_{top} = c_t \frac{\partial^\mu a}{f_a} \bar{t}_R \gamma_\mu t_R , \quad c_t = [\mathbf{c}_u]_{33}$$

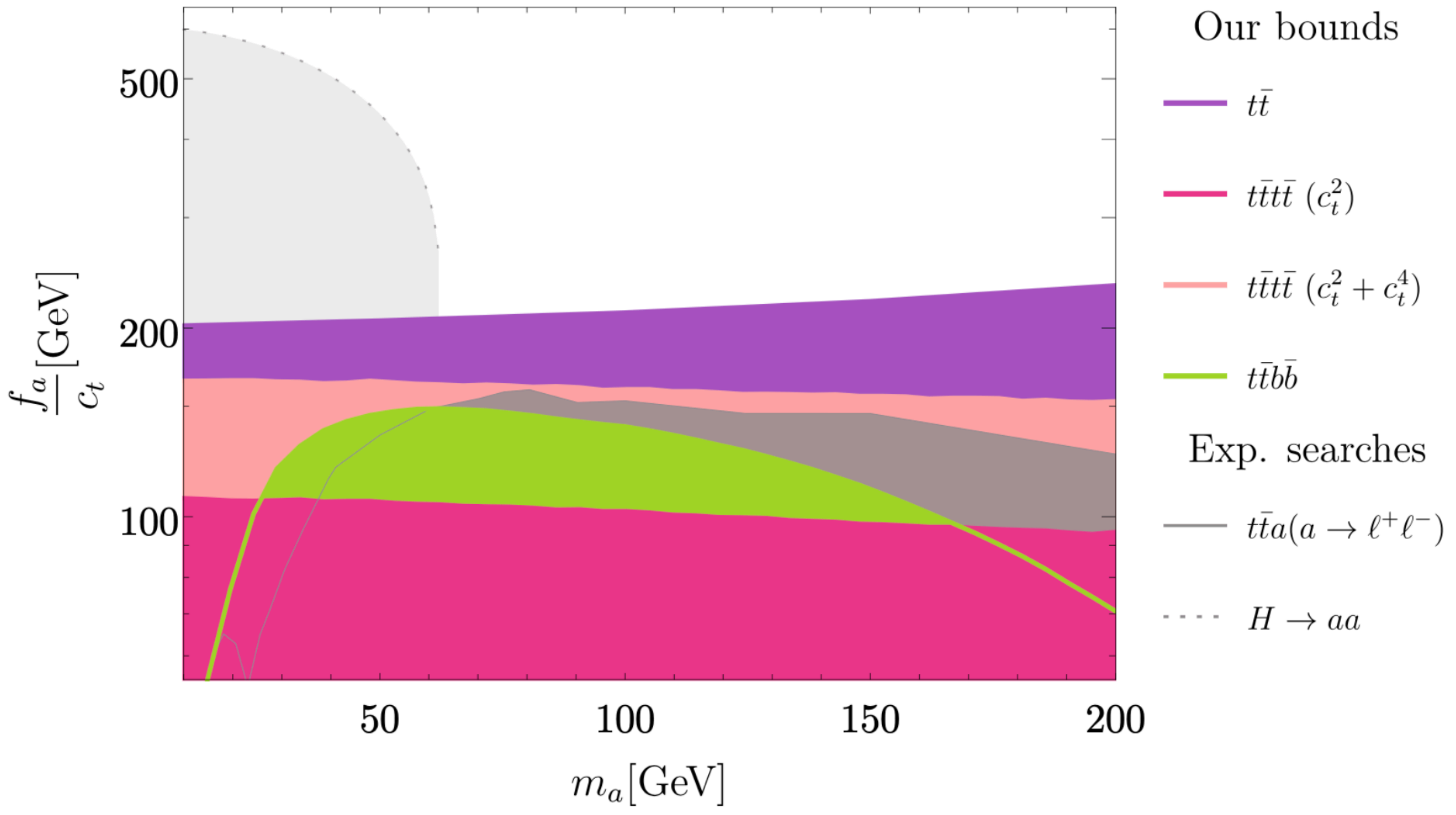
Axion-impostors but top friends (Ken Mimasu)

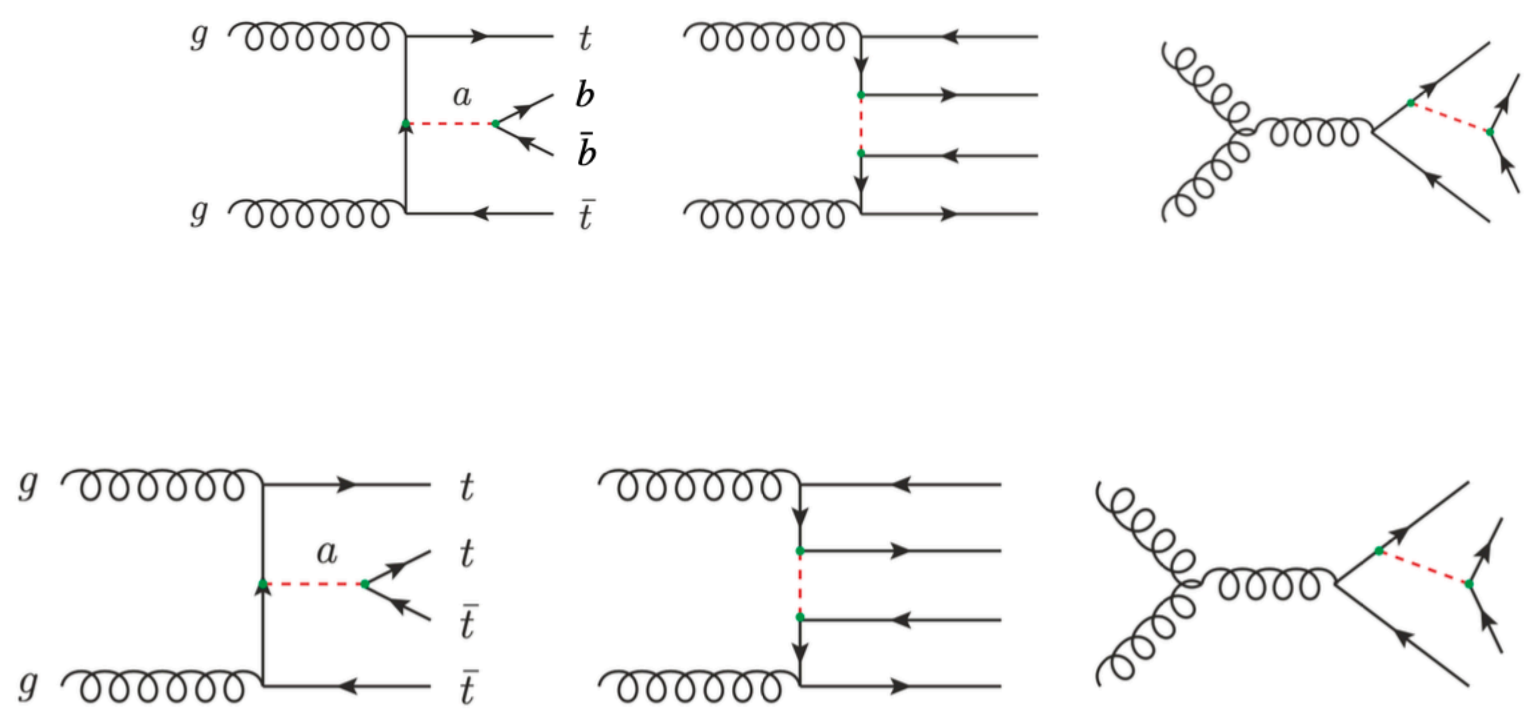
Elusive mass window $10 \lesssim m_a \lesssim 200\,\mathrm{GeV}$

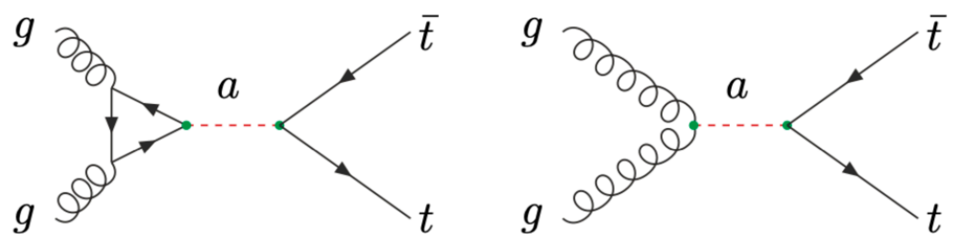
Strong bounds from astro/flavour below $m_a \sim$ few GeV

Larger m_a means shift symmetry breaking effects $\propto m_a^2$

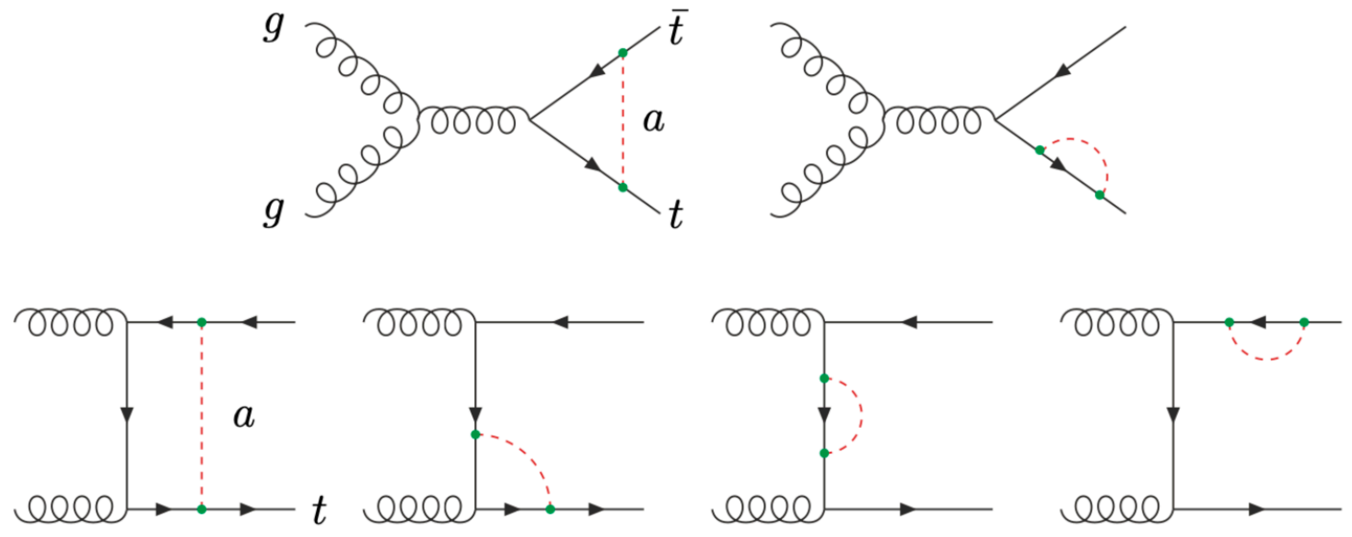
$m_a > 2m_t$, on-shell top decays $\Rightarrow t\bar{t}$ resonance searches



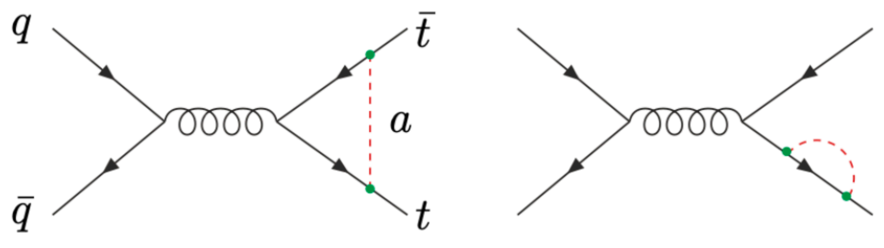




(a)



(b)



(c)

What next?

Dedicated resonance searches

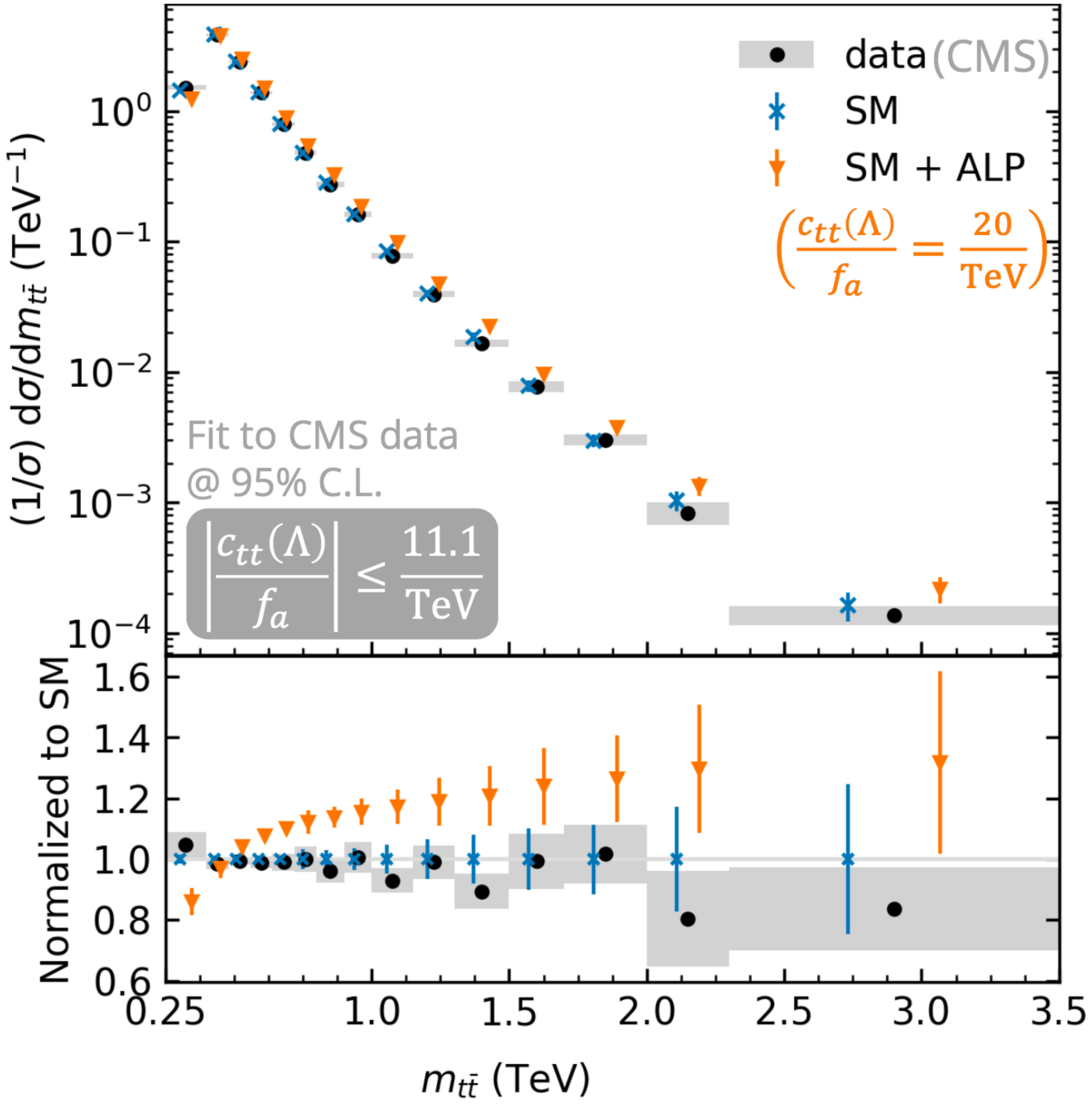
- $m_a > 90\,\mathrm{GeV},\ a \to Z\gamma$
- $m_a > 160\,\mathrm{GeV},\ a \to W^+W^-$

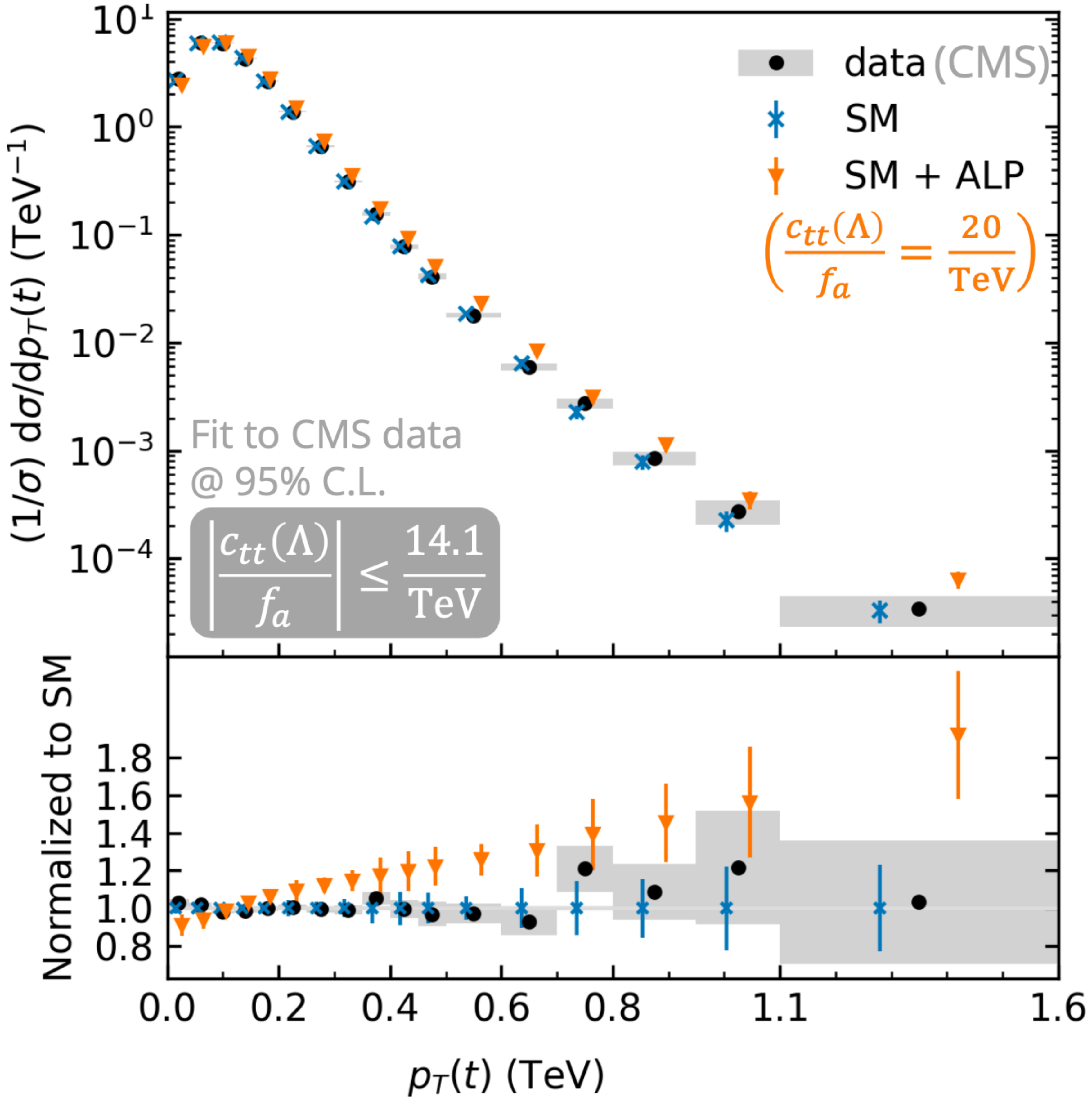
How strong is this friendship? (Anh Vu Phan)

Anh asks Ken: why do you stop at 200 GeV and not $2m_t$?

Ken gives up: I could have gone further…

Some difference in setup and data in Ken's analysis leads to slightly different bounds





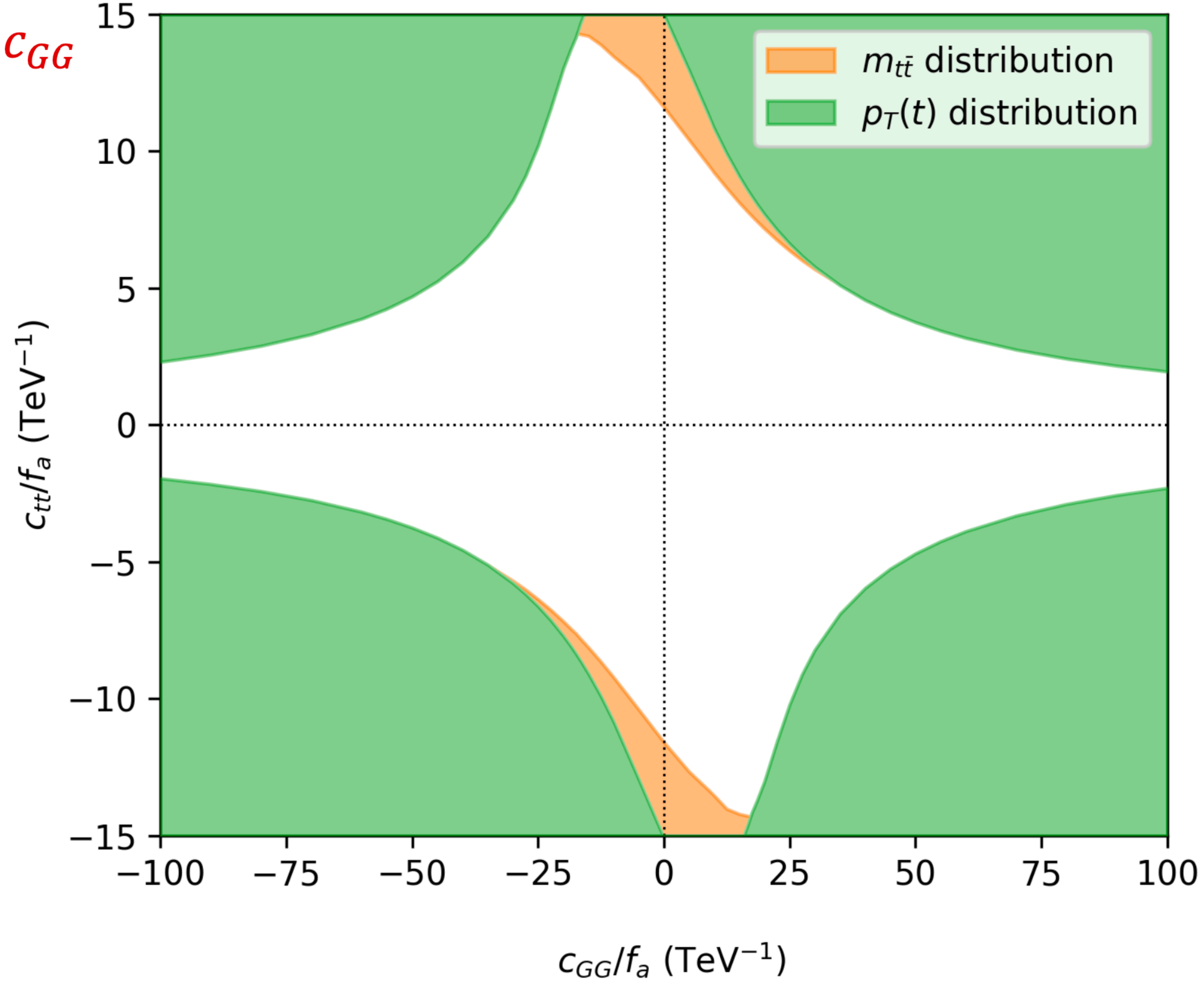
$c_{GG}(\Lambda) = 0\,; m_a = 10\ \mathrm{GeV}$

How strong is this friendship? (Anh Vu Phan)

BOUNDS ON c_{tt} AND c_{GG}

***AVP**, Westhoff (2023) [2312.00872]*

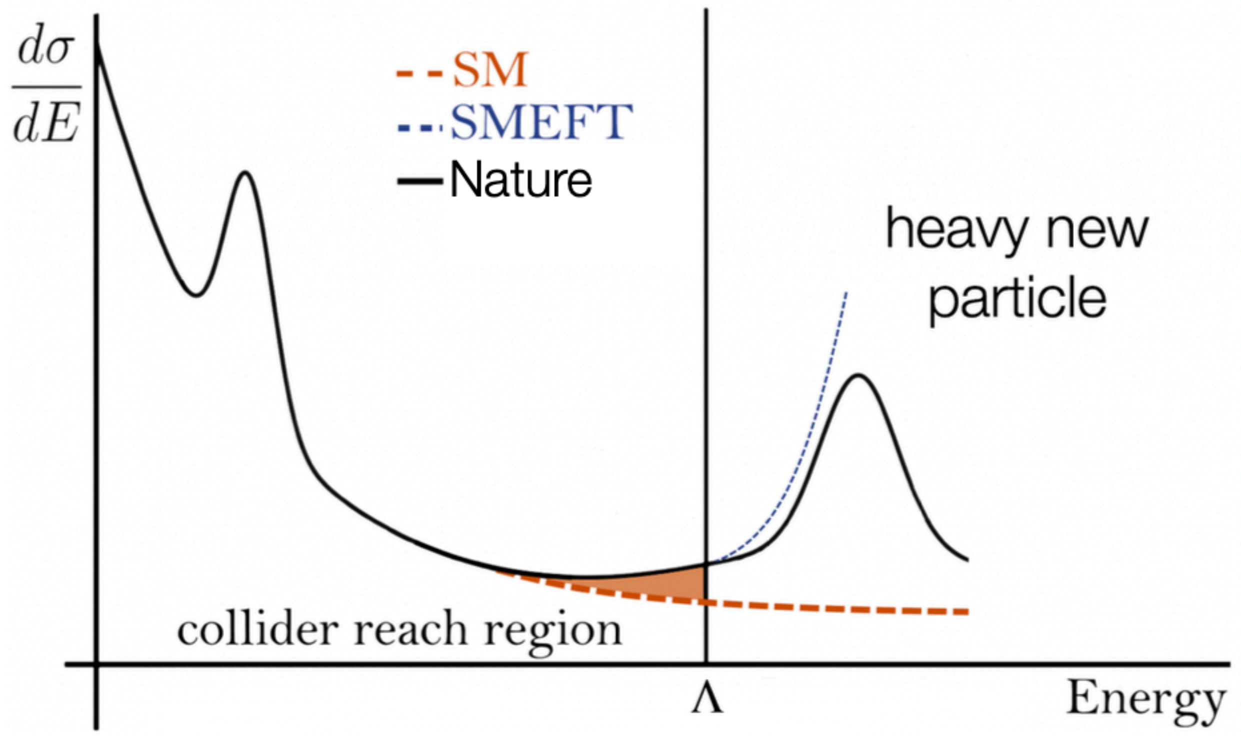
$m_a = 10$ GeV,
c_{GG}, c_{tt} vary

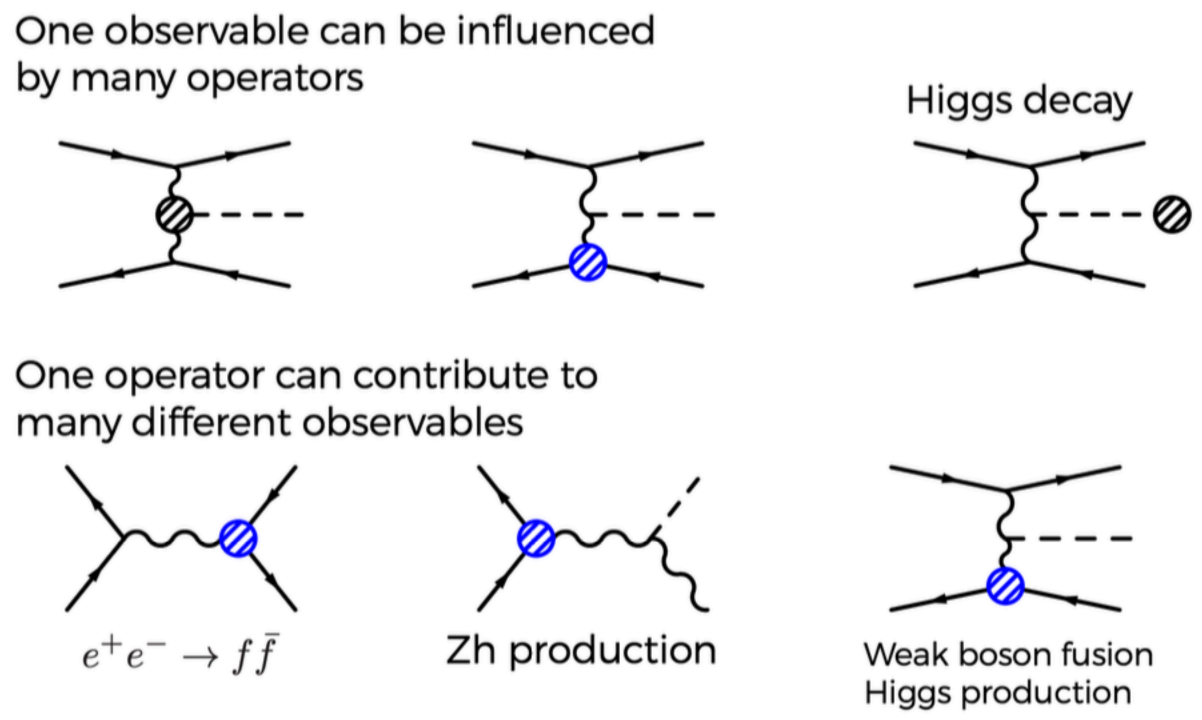


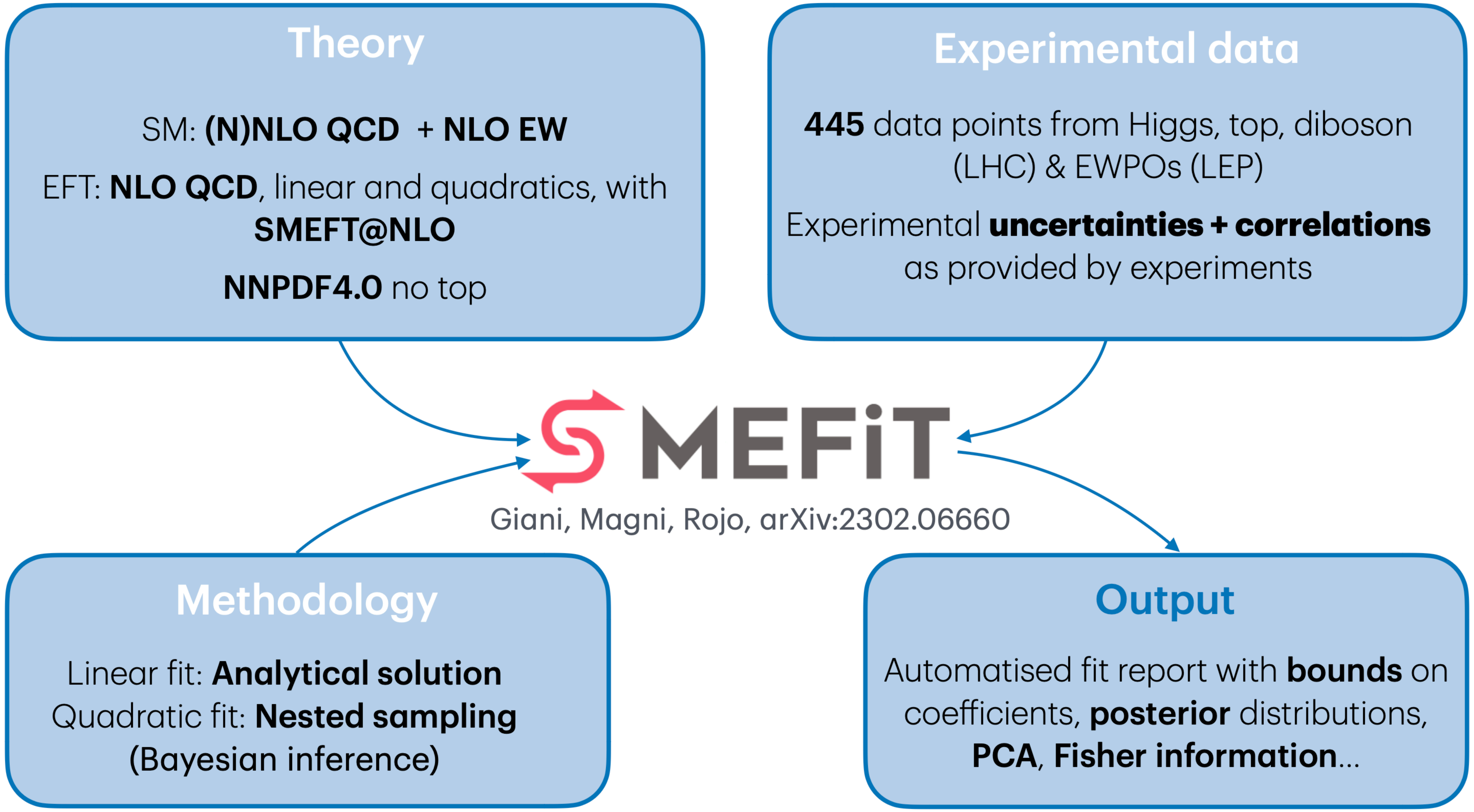
SMEFT: not just LHC (Eugenia Celada)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

$$\sigma = |\mathcal{M}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\left(\sum c^{(6)}\, 2{\rm Re}[\mathcal{M}_{\rm SM}^{*}\mathcal{M}_{\rm EFT}^{(6)}]\right) + \frac{1}{\Lambda^4}\left(\sum c^{(6)} \mathcal{M}_{\rm EFT}^{(6)}\right)^2$$







Theory

SM: **(N)NLO QCD + NLO EW**

EFT: **NLO QCD**, linear and quadratics, with **SMEFT@NLO**

NNPDF4.0 no top

Experimental data

445 data points from Higgs, top, diboson (LHC) & EWPOs (LEP)

Experimental **uncertainties + correlations** as provided by experiments

Giani, Magni, Rojo, arXiv:2302.06660

Methodology

Linear fit: **Analytical solution**
Quadratic fit: **Nested sampling**
(Bayesian inference)

Output

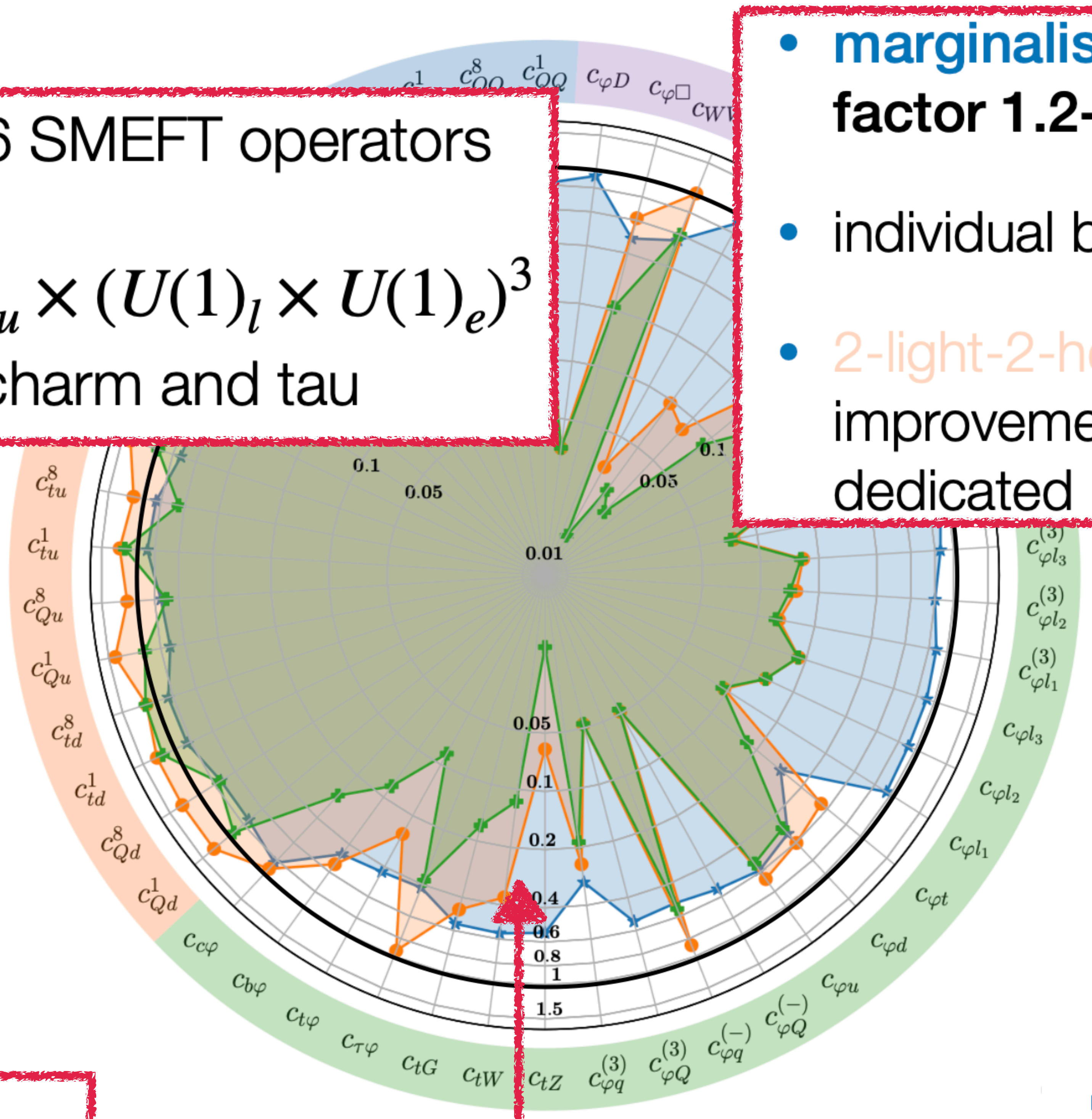
Automatised fit report with **bounds** on coefficients, **posterior** distributions, **PCA**, **Fisher information**...

SMEFiT3.0 in the biggest global SMEFT analysis to date: 50 Wilson coefficients and 445 datapoints

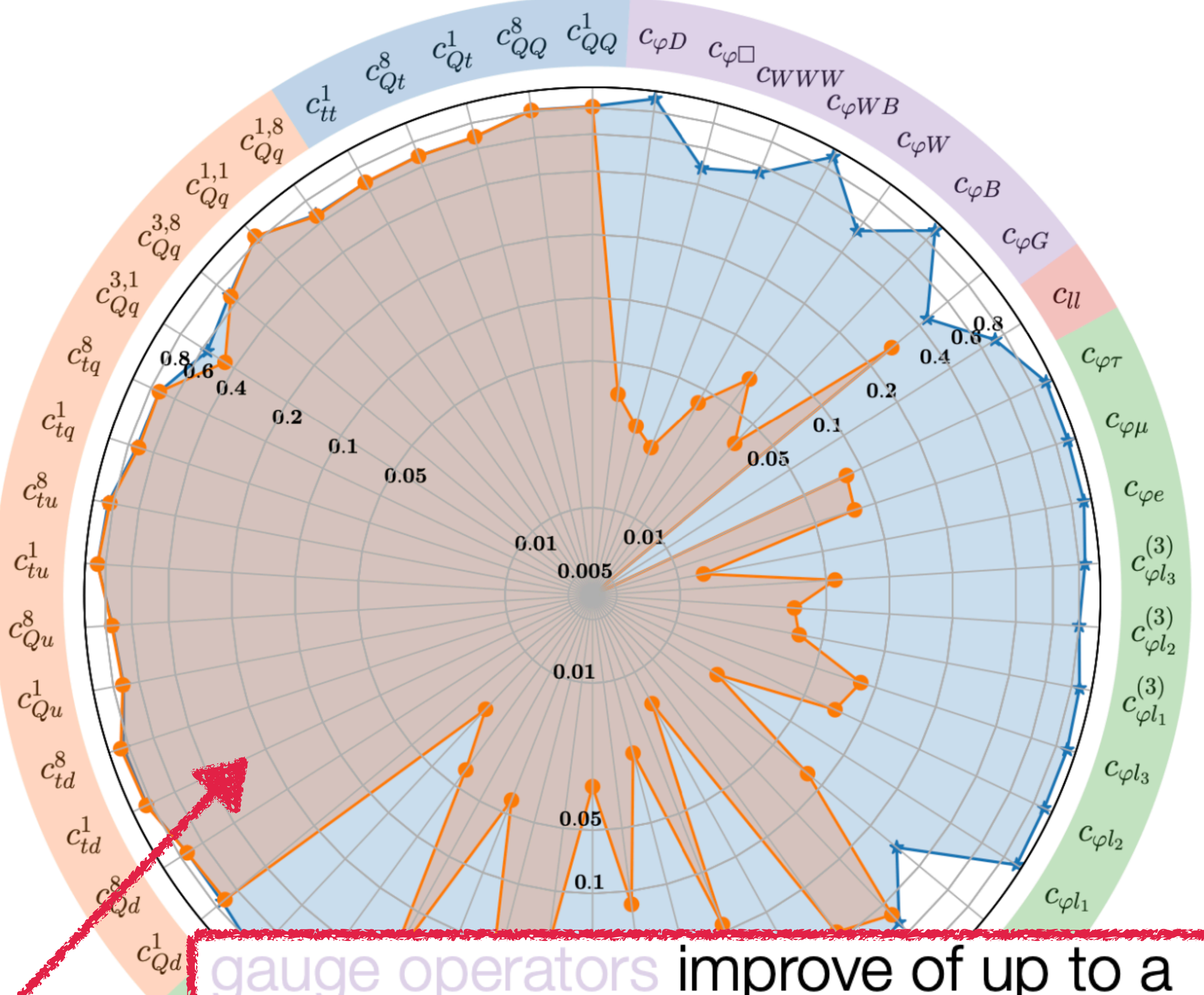
SMEFT: not just LHC (Eugenia Celada)

- Warsaw basis of dim-6 SMEFT operators
- Flavour symmetry:
  $U(2)_q \times U(3)_d \times U(2)_u \times (U(1)_l \times U(1)_e)^3$
  + Yukawa of bottom, charm and tau

Simultaneous fit of 50 Wilson coefficients



- **marginalised bounds improve by a factor 1.2-3**
- individual bounds are overly optimistic
- 2-light-2-heavy improved by 30% (further improvement of a factor 2 expected with a dedicated binning)



gauge operators improve of up to a factor 30

2-fermion operators improve of up to a factor 50

Large correlations in the linear fit are lifted in the quadratic fit

Many improvements are still underway (colliders, running)

Implemented in SMEFiT3.0

SMEFT from low energy (Antonio Rodriguez Sanchez)

Starting point

- BSM exists. Hopefully found in the next scale jump...
- Plausible scenario: new physics mainly couples to the top quark
- Assume that mostly top quark operators are induced at the TeV

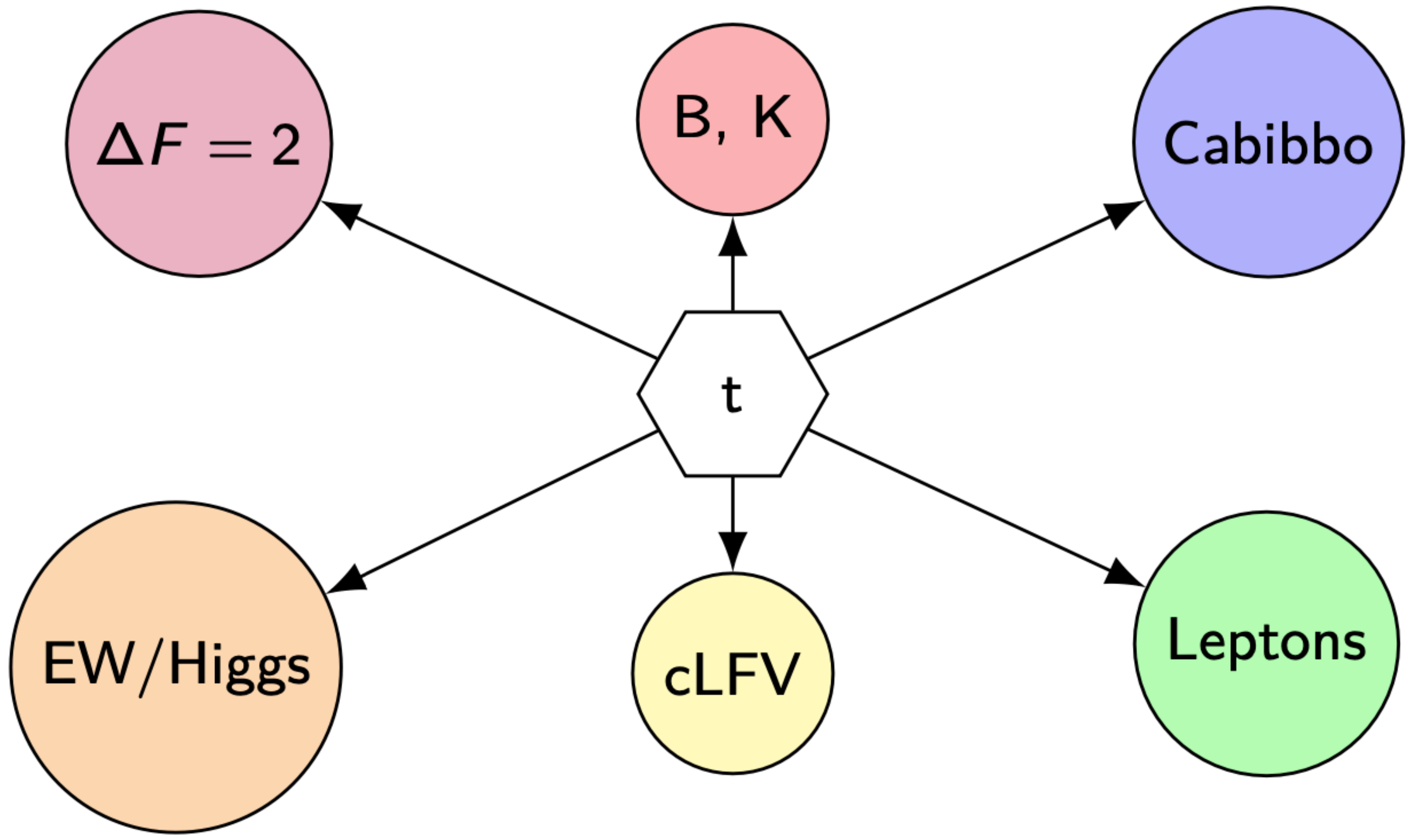
Semi-leptonic	
$\mathcal{O}_{lq}^{(1),\alpha\beta}$	$(\bar{l}^\alpha\gamma_\mu l^\beta)(\bar{q}^3\gamma^\mu q^3)$
$\mathcal{O}_{lq}^{(3),\alpha\beta}$	$(\bar{l}^\alpha\gamma_\mu\tau^a l^\beta)(\bar{q}^3\gamma^\mu\tau^a q^3)$
$\mathcal{O}_{lu}^{\alpha\beta}$	$(\bar{l}^\alpha\gamma^\mu l^\beta)(\bar{u}^3\gamma_\mu u^3)$
$\mathcal{O}_{qe}^{\alpha\beta}$	$(\bar{q}^3\gamma^\mu q^3)(\bar{e}^\alpha\gamma_\mu e^\beta)$
$\mathcal{O}_{eu}^{\alpha\beta}$	$(\bar{e}^\alpha\gamma^\mu e^\beta)(\bar{u}^3\gamma_\mu u^3)$
$\mathcal{O}_{lequ}^{(1),\alpha\beta}$	$(\bar{l}^\alpha e^\beta)\epsilon(\bar{q}^3 u^3)$
$\mathcal{O}_{lequ}^{(3),\alpha\beta}$	$(\bar{l}^\alpha\sigma_{\mu\nu}e^\beta)\epsilon(\bar{q}^3\sigma^{\mu\nu}u^3)$

Dipoles	
$\mathcal{O}_{uG}$	$(\bar{q}^3\sigma^{\mu\nu}T^A u^3)\tilde{H}G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{q}^3\sigma^{\mu\nu}u^3)\tau^a\tilde{H}W^a_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{q}^3\sigma^{\mu\nu}u^3)\tilde{H}B_{\mu\nu}$

Four quarks	
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}^3\gamma^\mu q^3)(\bar{q}^3\gamma_\mu q^3)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}^3\gamma^\mu\tau^a q^3)(\bar{q}^3\gamma_\mu\tau^a q^3)$
$\mathcal{O}_{uu}$	$(\bar{u}^3\gamma^\mu u^3)(\bar{u}^3\gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}^3\gamma^\mu q^3)(\bar{u}^3\gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}^3\gamma^\mu T^A q^3)(\bar{u}^3\gamma_\mu T^A u^3)$

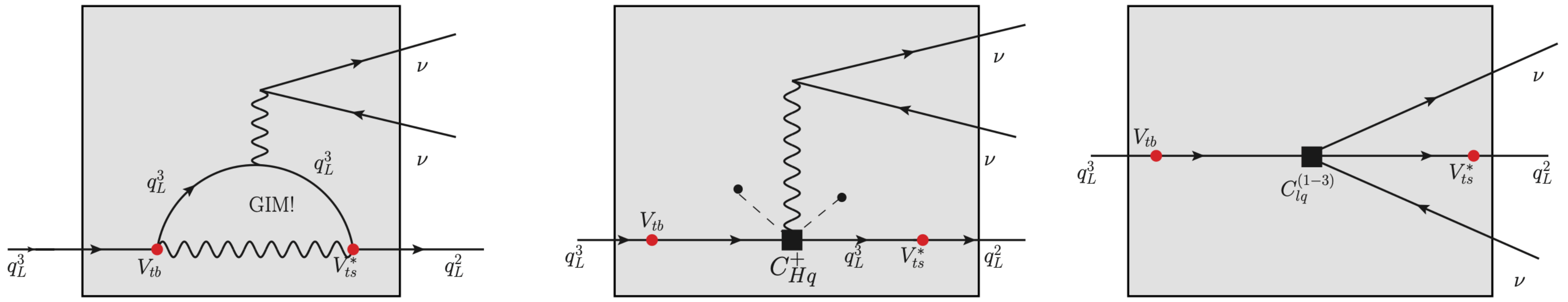
Higgs-Top	
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overset{\leftrightarrow}{D}_\mu H)(\bar{q}^3\gamma^\mu q^3)$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overset{\leftrightarrow}{D}{}^a_\mu H)(\bar{q}^3\gamma^\mu\tau^a q^3)$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overset{\leftrightarrow}{D}_\mu H)(\bar{u}^3\gamma^\mu u^3)$
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}^3 u^3\tilde{H})$

flavor rotation or radiative corrections



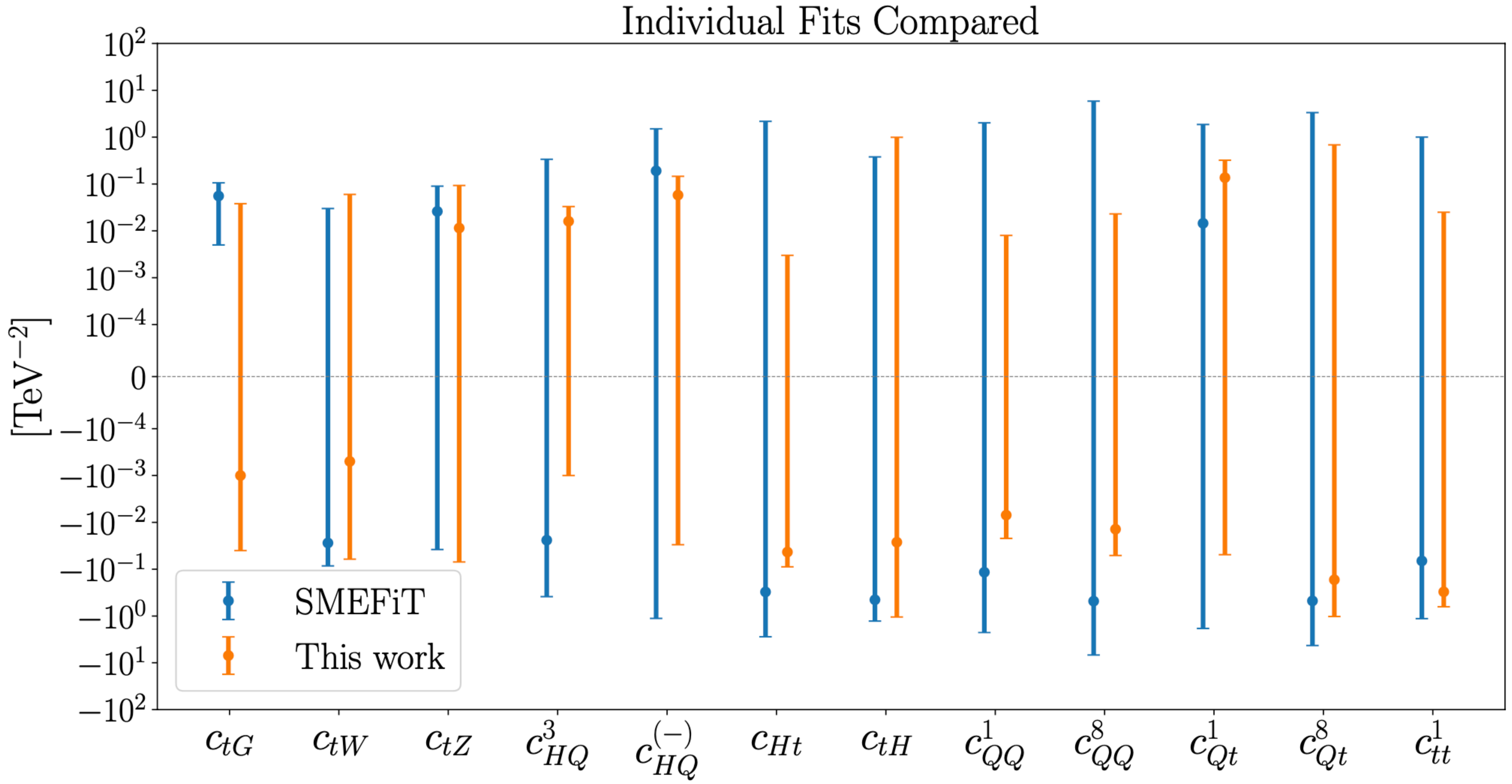
one example of many

$R^\nu_{K^{(*)}}$, $K \to \pi\nu\bar{\nu}$



SMEFT from low energy (Antonio Rodriguez Sanchez)

- Direct searches of top interactions: a BSM signal most likely points out to BSM in top operators. Weaker bounds
- Indirect searches of top operators: a BSM signal may be BSM in top operators. Stronger bounds.



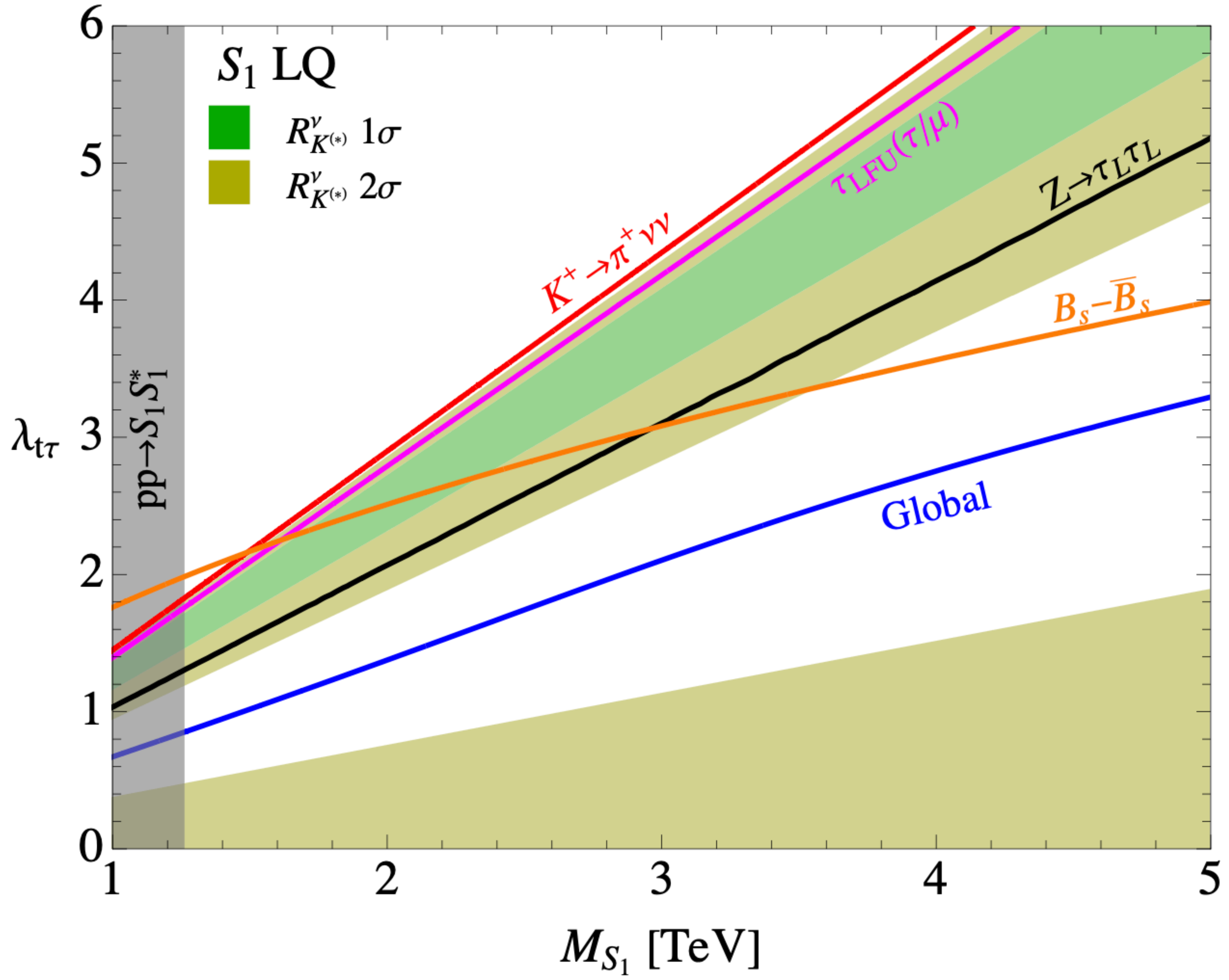
One parameter fits: comparison with direct bounds

Two parameter fits also performed in the study

Applications to UV models

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{+1/3}$

$$\mathcal{L} \supset \lambda_{t\tau}\, \bar{q}_3^c\, i\sigma_2 l_3\, S_1 + \text{h.c.}$$



Baryon Number Violation

Channel	Limit [10^{30} years]
$p \to \pi^0 e^+$	2.4×10^4

TOP 2024
THEORY

Foundations & Fun (Quantum Mechanics)

Entanglement ? (J.A. Aguilar Saavedra's Backup)

For closed quantum systems in a pure state

Subsystems A and B separable when:

$$|\psi\rangle = |a\rangle_A \otimes |b\rangle_B$$

Classical non-separable, i.e. entangled state:

$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$

But top-quarks are not in a pure state at the LHC → correct description through the density operator

separable:

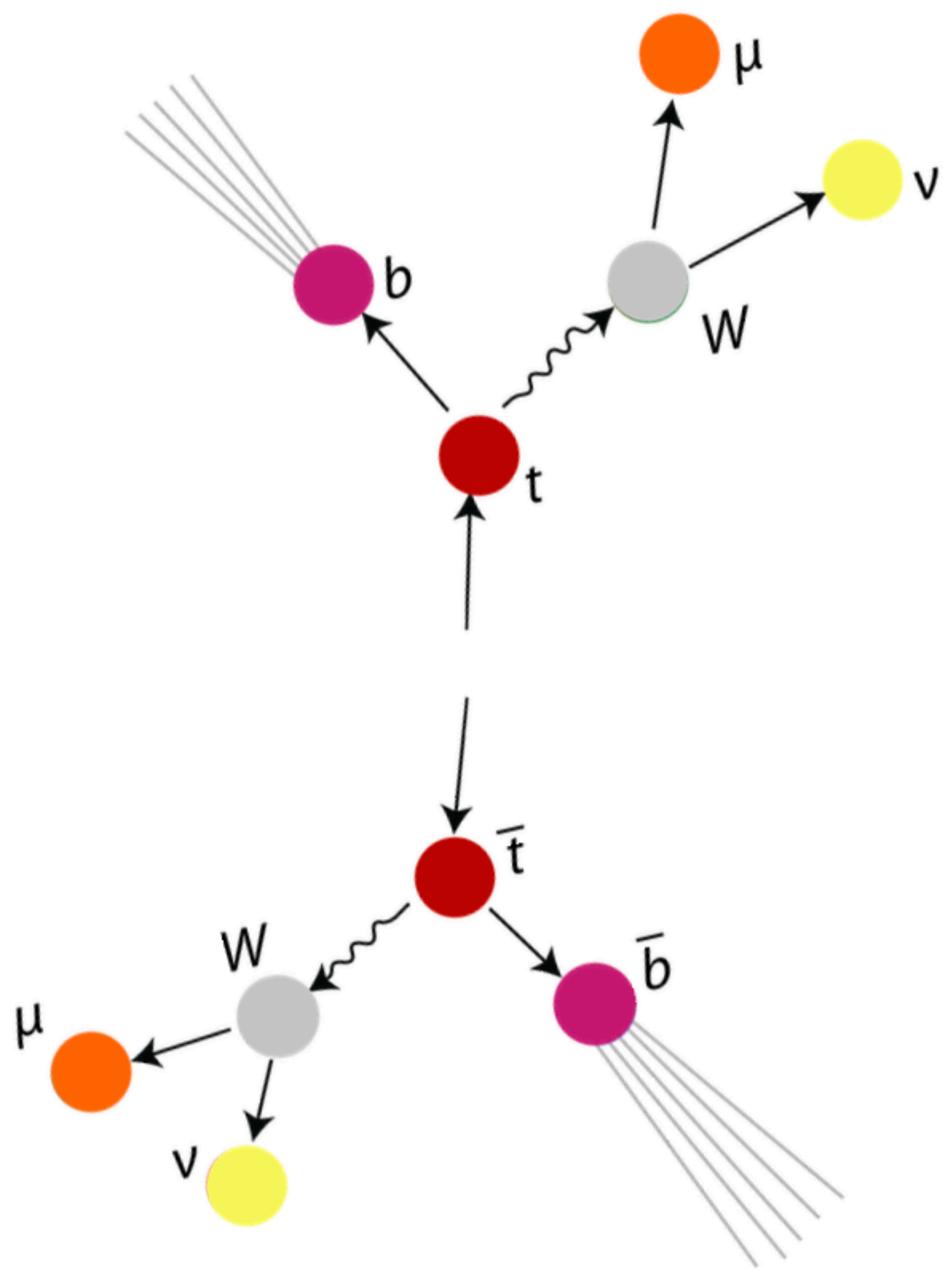
$$\rho_{\text{sep}} = \sum_n p_n \rho_n^A \otimes \rho_n^B$$

otherwise entangled

Bell's/Clauser-Horne-Shimony-Holt (CHSH) inequality

$$\boxed{\left|E(\hat{\boldsymbol{a}},\hat{\boldsymbol{b}}) - E(\hat{\boldsymbol{a}},\hat{\boldsymbol{b}}') + E(\hat{\boldsymbol{a}}',\hat{\boldsymbol{b}}) + E(\hat{\boldsymbol{a}}',\hat{\boldsymbol{b}}')\right| \leqslant 2,}$$

Entanglement and SMEFT (Eleni Vryonidou)



Spin density matrix:

$$\boxed{\rho = \frac{1}{4}\Big(\mathbb{1}\otimes\mathbb{1} + \sum_{i=1}^{3} B_i\,\sigma_i \otimes \mathbb{1} + \sum_{i=j}^{3} \bar{B}_j\,\mathbb{1}\otimes\sigma_j + \sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij}\,\sigma_i\otimes\sigma_j\Big)}$$

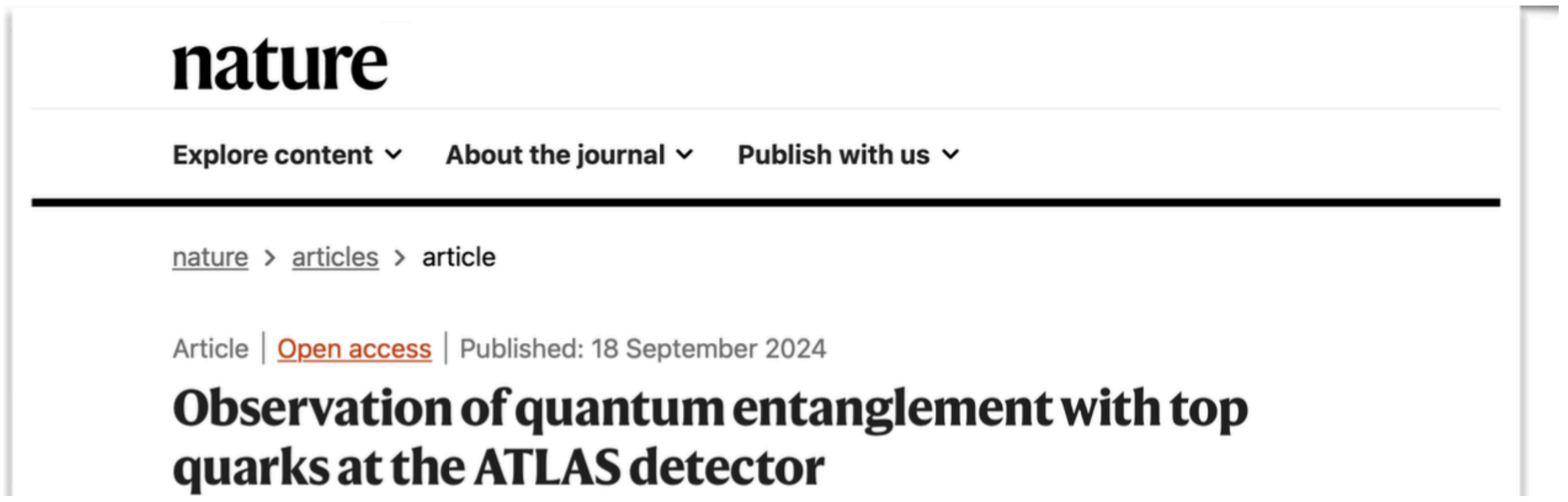
Entanglement markers

$$D^{(1)} = 1/3(+C_{kk} + C_{rr} + C_{nn}),$$
$$D^{(k)} = 1/3(+C_{kk} - C_{rr} - C_{nn}),$$
$$D^{(r)} = 1/3(-C_{kk} + C_{rr} - C_{nn}),$$
$$D^{(n)} = 1/3(-C_{kk} - C_{rr} + C_{nn}).$$
$$D_{\min} \equiv \min\{D^{(1)}, D^{(k)}, D^{(r)}, D^{(n)}\}$$

Necessary and sufficient condition for entanglement

$$C = \frac{1}{2}\max\left(0, -1 - 3D_{\min}\right) > 0$$

Quantum entanglement is fun… can you get an article on spin correlations like that ?



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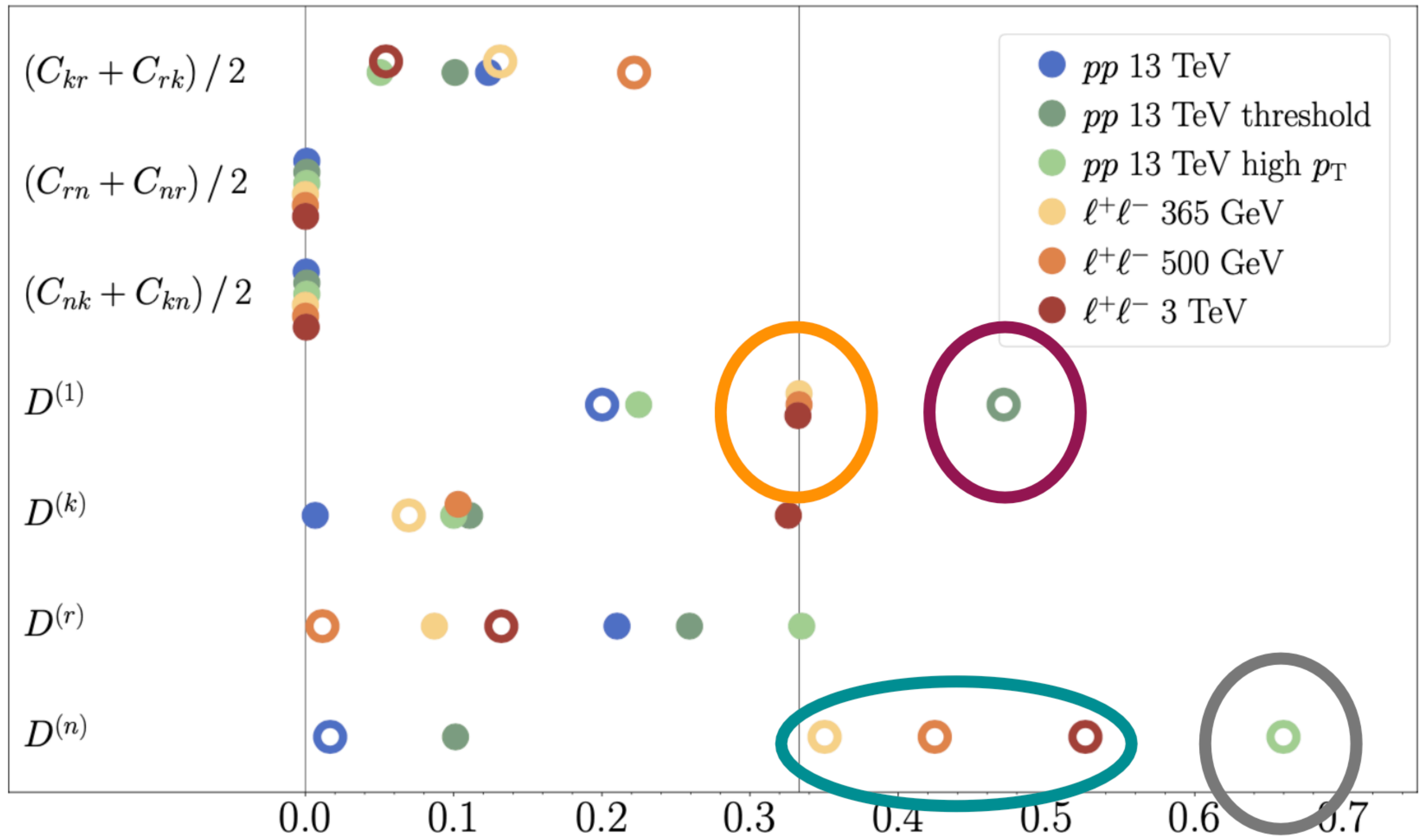
Observation of quantum entanglement with top quarks at the ATLAS detector

There is nothing more than the full spin density matrix !

Eleni: we are just trying to keep spin correlations alive

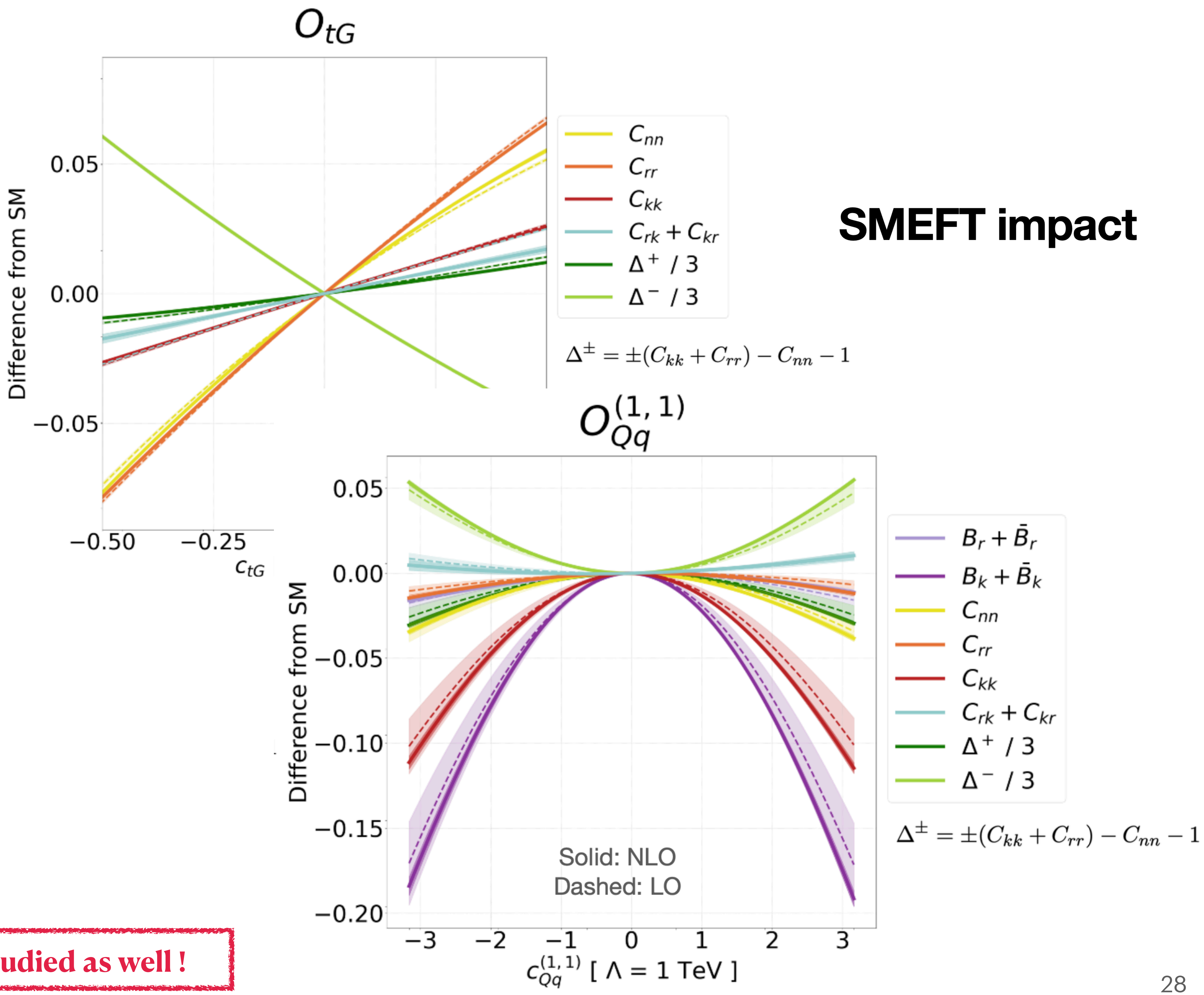
Entanglement and SMEFT (Eleni Vryonidou)

Lepton vs pp collisions



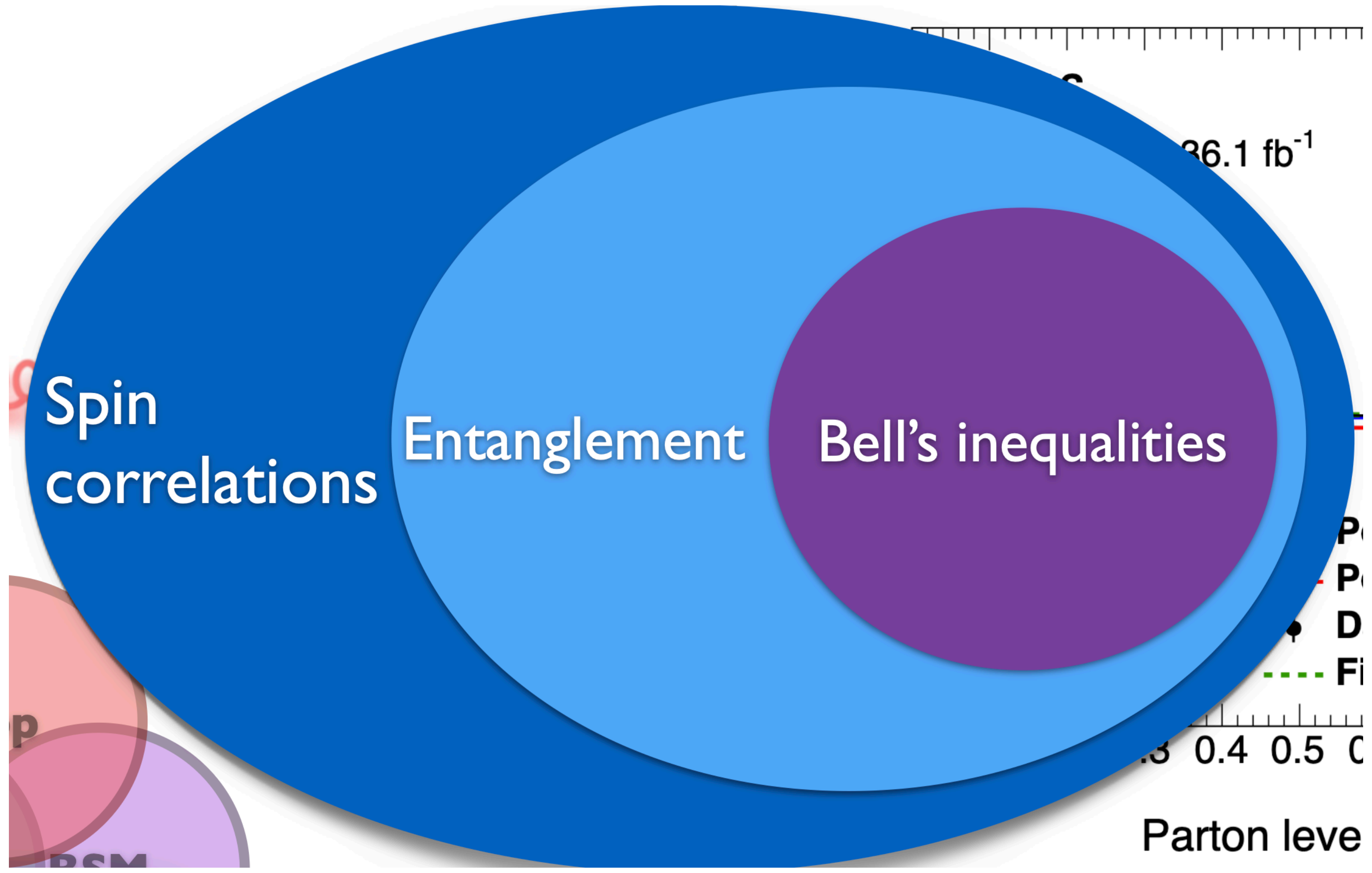
- Spin Triplet state $D^{(1)} = +1/3$
- Entanglement through $D^{(n)}$ for lepton colliders
- Entanglement through $D^{(1)}$ for LHC at threshold
- Entanglement through $D^{(n)}$ for LHC at high transverse momentum

SMEFT impact



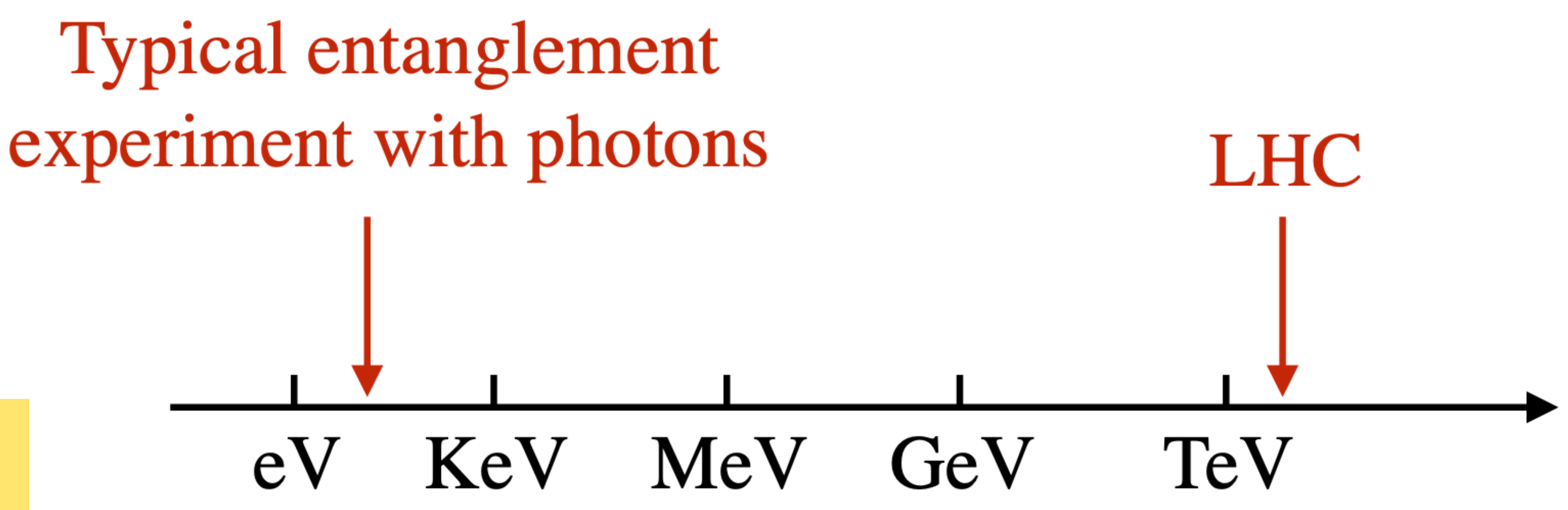
Other models studied as well !

How to access spin densities ? (Dorival Gonçalves)



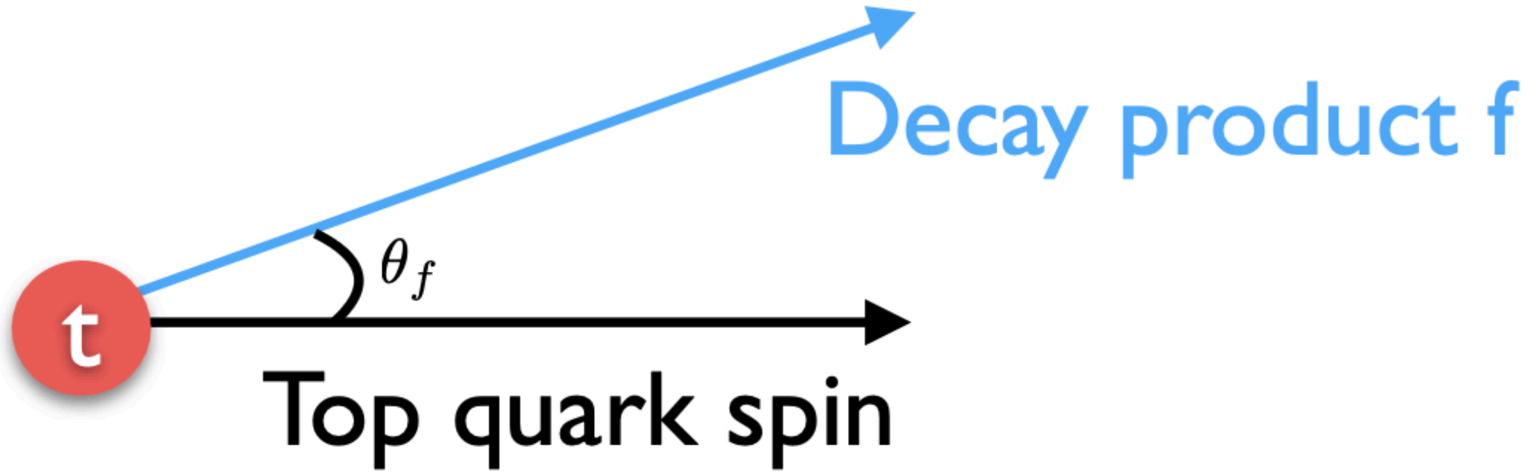
LHC can provide a unique environment to study entanglement and violation of Bell's inequalities at the highest energy available to date

forget optimal observables but make it more exciting



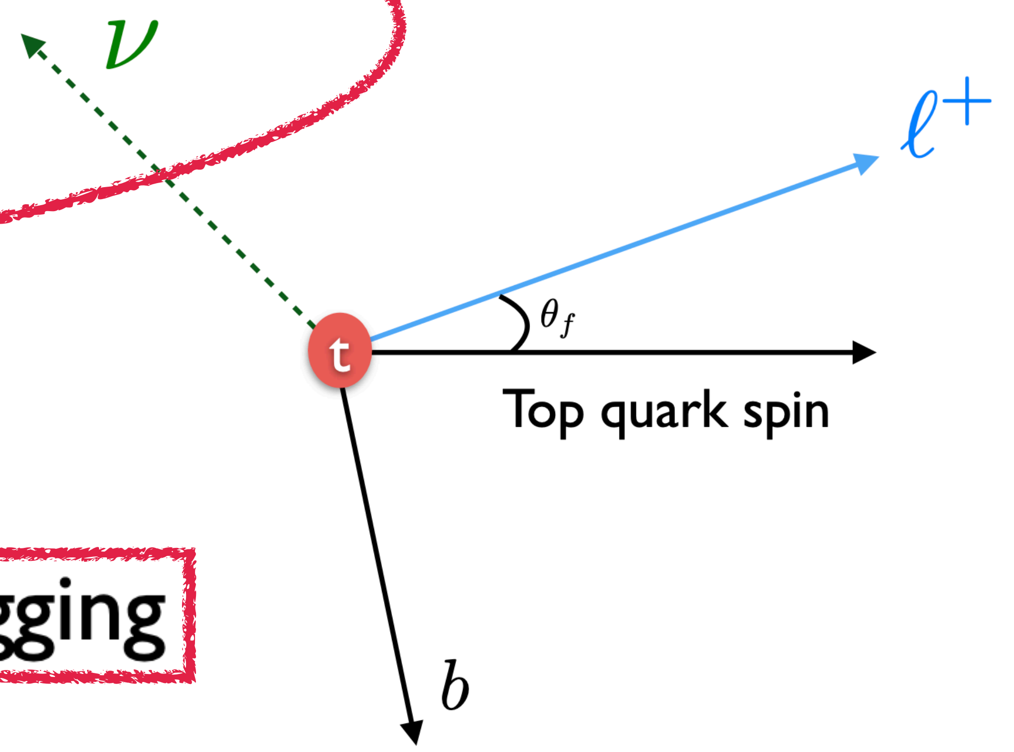
Spin density matrix:

$$\rho = \frac{1}{4}\Big(\mathbb{1}\otimes\mathbb{1} + \sum_{i=1}^{3} B_i\,\sigma_i\otimes\mathbb{1} + \sum_{i=j}^{3}\bar{B}_j\,\mathbb{1}\otimes\sigma_j + \sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij}\,\sigma_i\otimes\sigma_j\Big)$$



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1+\beta_f\cos\theta_f\right)$$

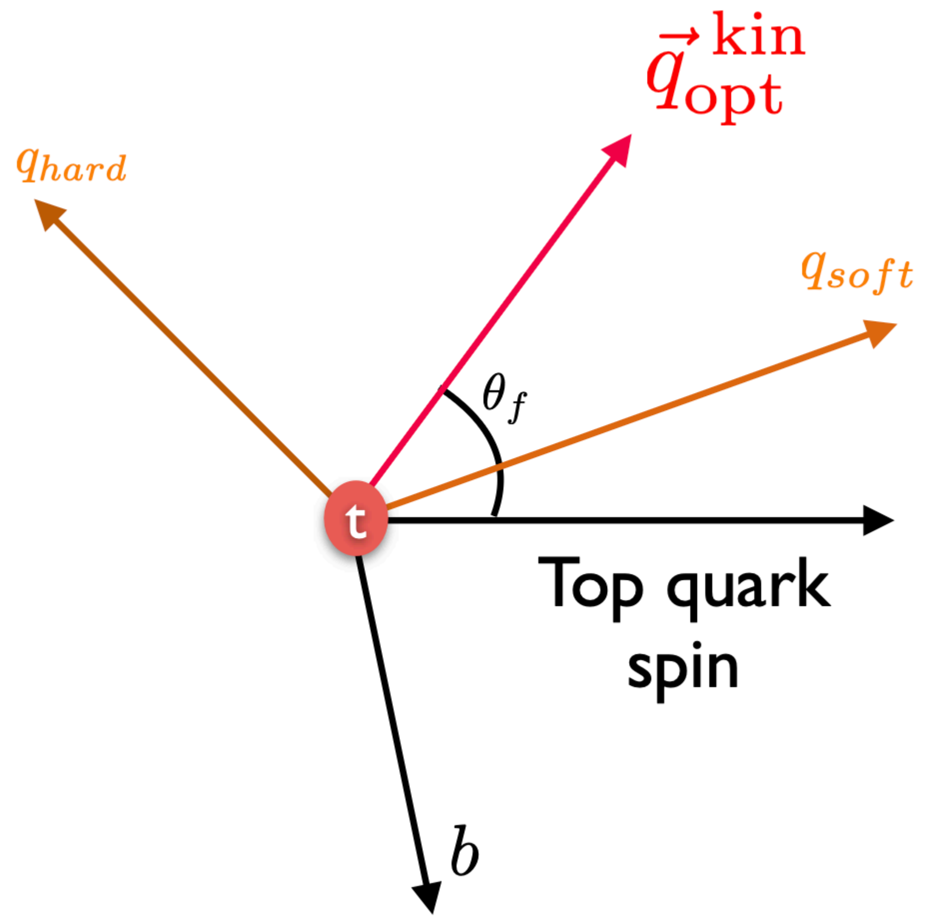
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
β_f	1	-0.4	-0.3



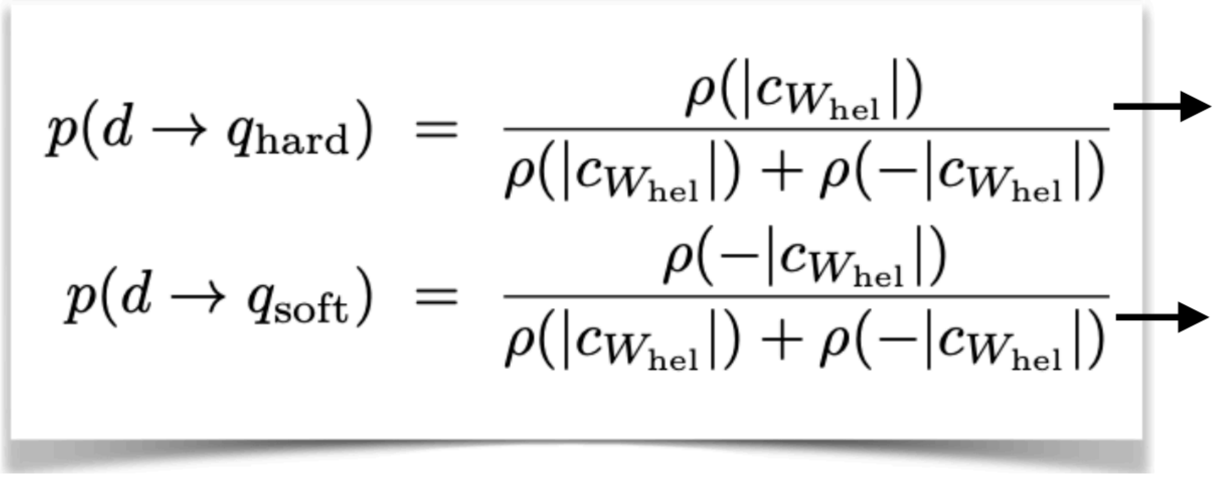
great !
but what to do for semi-leptonic events
we do not just see down type quarks

Down-type Jet flavor tagging

How to access spin densities ? (Dorival Gonçalves)



$$\vec{q}^{\,\rm kin}_{\rm opt} = p(d \to q_{\rm hard}|c_W)\,\hat{q}_{\rm hard} + p(d \to q_{\rm soft}|c_W)\,\hat{q}_{\rm soft}$$



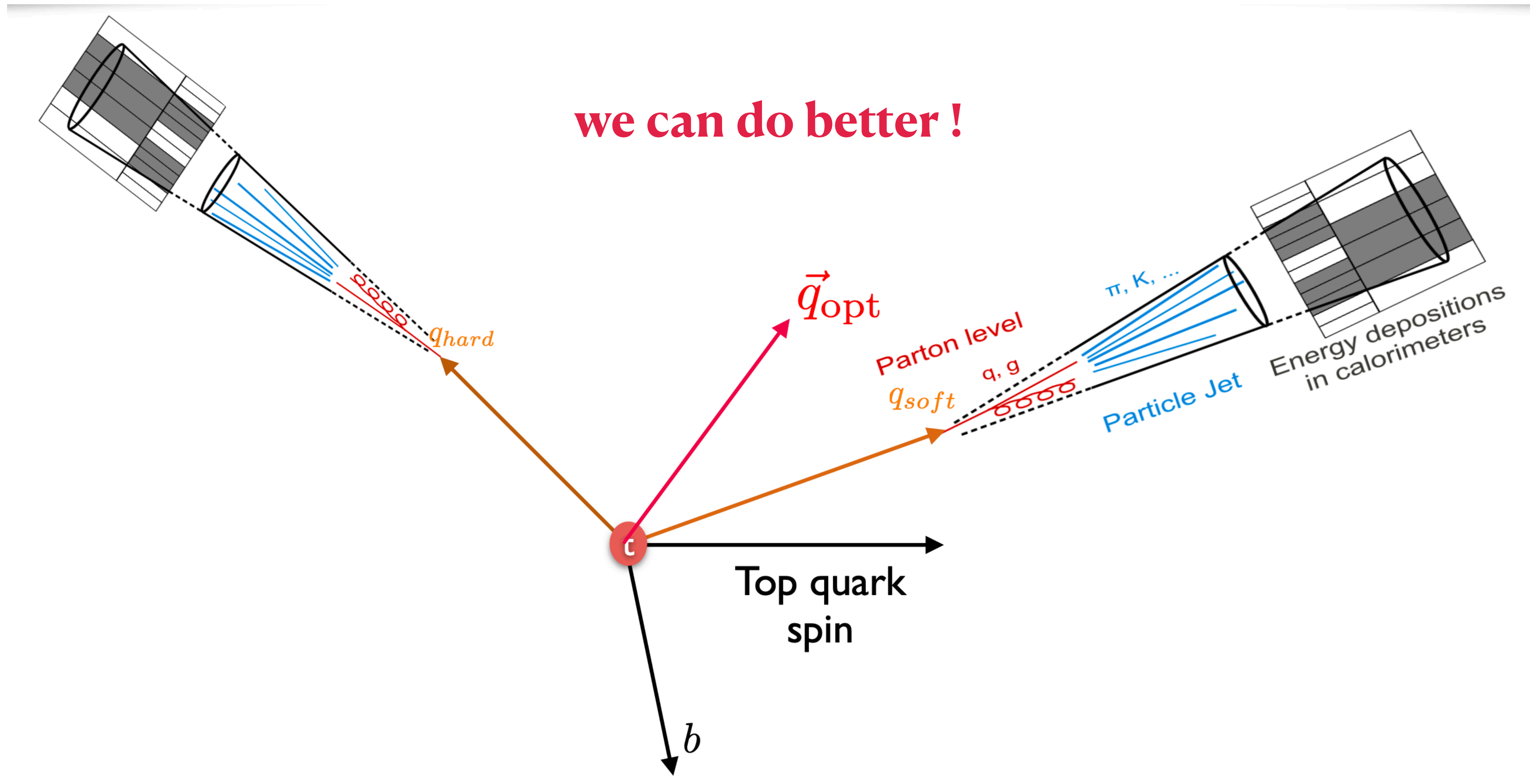
$$p(d \to q_{\rm hard}) = \frac{\rho(|c_{W_{\rm hel}}|)}{\rho(|c_{W_{\rm hel}}|) + \rho(-|c_{W_{\rm hel}}|)} \to$$

quark emitted in forward direction in W rest frame will be harder and more separated from b-quark in top rest frame

$$p(d \to q_{\rm soft}) = \frac{\rho(-|c_{W_{\rm hel}}|)}{\rho(|c_{W_{\rm hel}}|) + \rho(-|c_{W_{\rm hel}}|)} \to$$

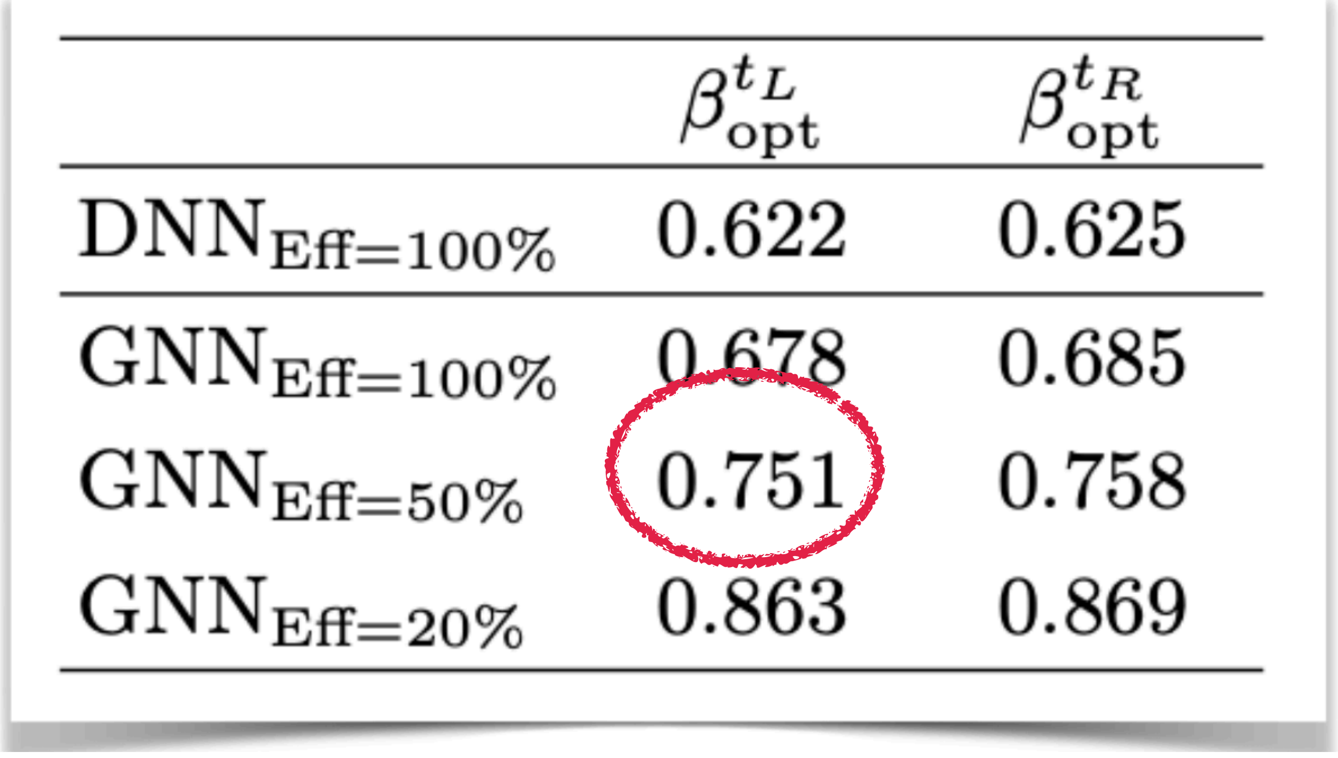
quark emitted in backward direction in W rest frame will be softer and more aligned with b-quark in top rest frame

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + 0.64\cos\theta_f)$$



we can do better !

Hadronic Top Quark Polarimetry with ParticleNet



	$\beta^{t_L}_{\rm opt}$	$\beta^{t_R}_{\rm opt}$
$\mathrm{DNN}_{\mathrm{Eff}=100\%}$	0.622	0.625
$\mathrm{GNN}_{\mathrm{Eff}=100\%}$	0.678	0.685
$\mathrm{GNN}_{\mathrm{Eff}=50\%}$	0.751	0.758
$\mathrm{GNN}_{\mathrm{Eff}=20\%}$	0.863	0.869

$$\vec{q}_{\rm opt} = p(d \to q_{\rm hard}|c_W, \{\mathcal{O}\})\,\hat{q}_{\rm hard} + p(d \to q_{\rm soft}|c_W, \{\mathcal{O}\})\,\hat{q}_{\rm soft}$$

More than just entanglement (Chris White)

Which quantities from Quantum Information / Computing could be useful for collider physics?

The Gottesman-Knill theorem

For every quantum computer containing stabiliser states only, there is a classical computer that is just as efficient! 😅

- Stabiliser states include certain maximally entangled states.
- Something other than entanglement is needed for efficient quantum computers!

- The “something else” has been called *magic* in the literature…
- …and basically means “non-stabiliserness” of a quantum state.

- The magic is additive, **vanishes** for stabiliser states, and is crucial for making fault-tolerant quantum computers.

More than just entanglement (Chris White)

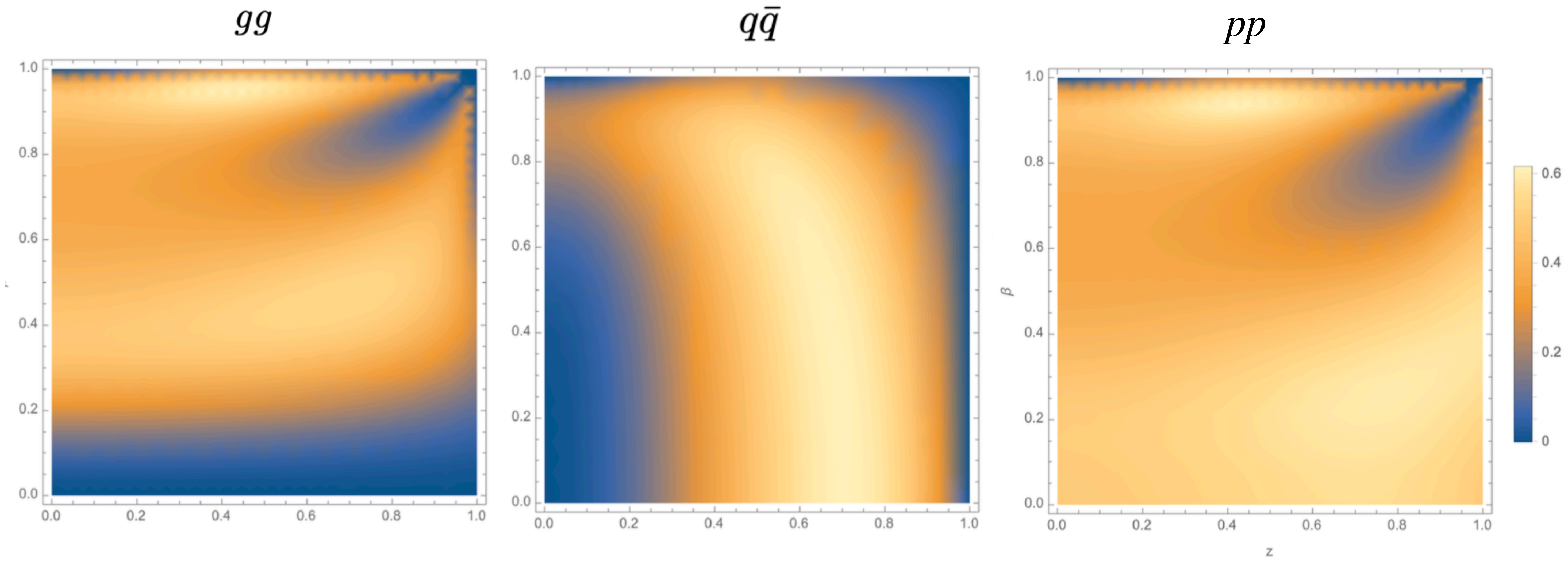
$$\rho^I \sim \tilde{A}^I I_4 + \sum_i \left(\tilde{B}_i^{I+} \sigma_i \otimes I_2 + \tilde{B}_i^{I-} I_2 \otimes \sigma_i + \sum_{i,j} \tilde{C}_{ij}^I \sigma_i \otimes \sigma_j \right)$$

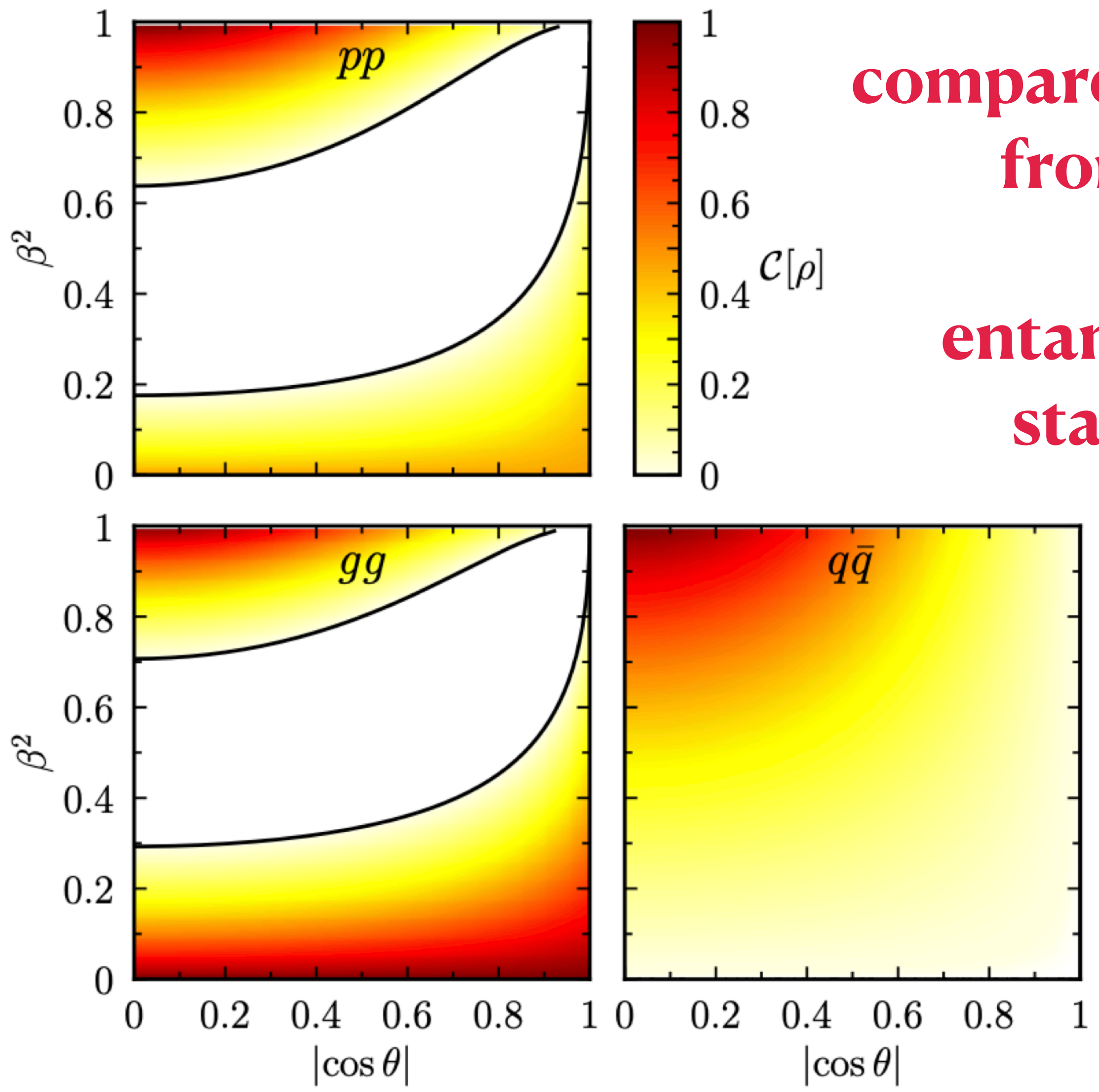
LO in the SM

$$\tilde{B}_i^{I+} = \tilde{B}_i^{I-} = \tilde{C}_{nr}^I = \tilde{C}_{nk}^I = 0, \quad \tilde{C}_{ij}^I = \tilde{C}_{ji}^I$$

One definition of Magic for top quarks yields:

$$\tilde{M}_2(\rho^I) = -\log_2 \left(\frac{(\tilde{A}^I)^4 + (\tilde{C}_{nn}^I)^4 + (\tilde{C}_{kk}^I)^4 + (\tilde{C}_{rr}^I)^4 + 2(\tilde{C}_{rk}^I)^4}{(\tilde{A}^I)^2[(\tilde{A}^I)^2 + (\tilde{C}_{nn}^I)^2 + (\tilde{C}_{kk}^I)^2 + (\tilde{C}_{rr}^I)^2 + 2(\tilde{C}_{rk}^I)^2]} \right)$$





compare to entanglement from Eleni's talk

entangled states are stabiliser states

- Might it provide useful insights into how to make magic in other systems?
- Can one use magic as a useful observable for new physics?
- Or strengthen the dialogue between Quantum Computing / Collider Physics?

Entanglement with one top (Juan Aguilar Saavedra)

The top doesn't just spin,
it also orbits!

full density operator ρ$_{LWb}$ describes the top decay

$$(\rho_{LWb})^{s_1' s_2'; l' m'}_{s_1 s_2; lm} = (\rho_t)_{MM'} A_{M s_1 s_2; lm} A^*_{M' s_1' s_2'; l' m'}$$

$$\mathcal{H}_L \otimes \mathcal{H}_{S_1} \otimes \mathcal{H}_{S_2}$$

W

b

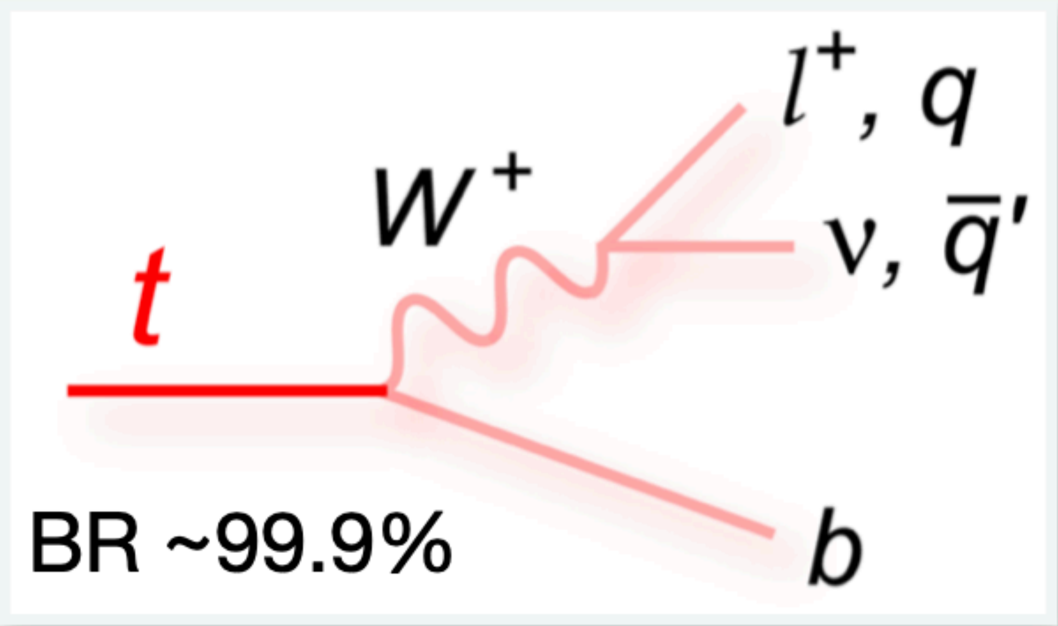
Angular momentum of the final state

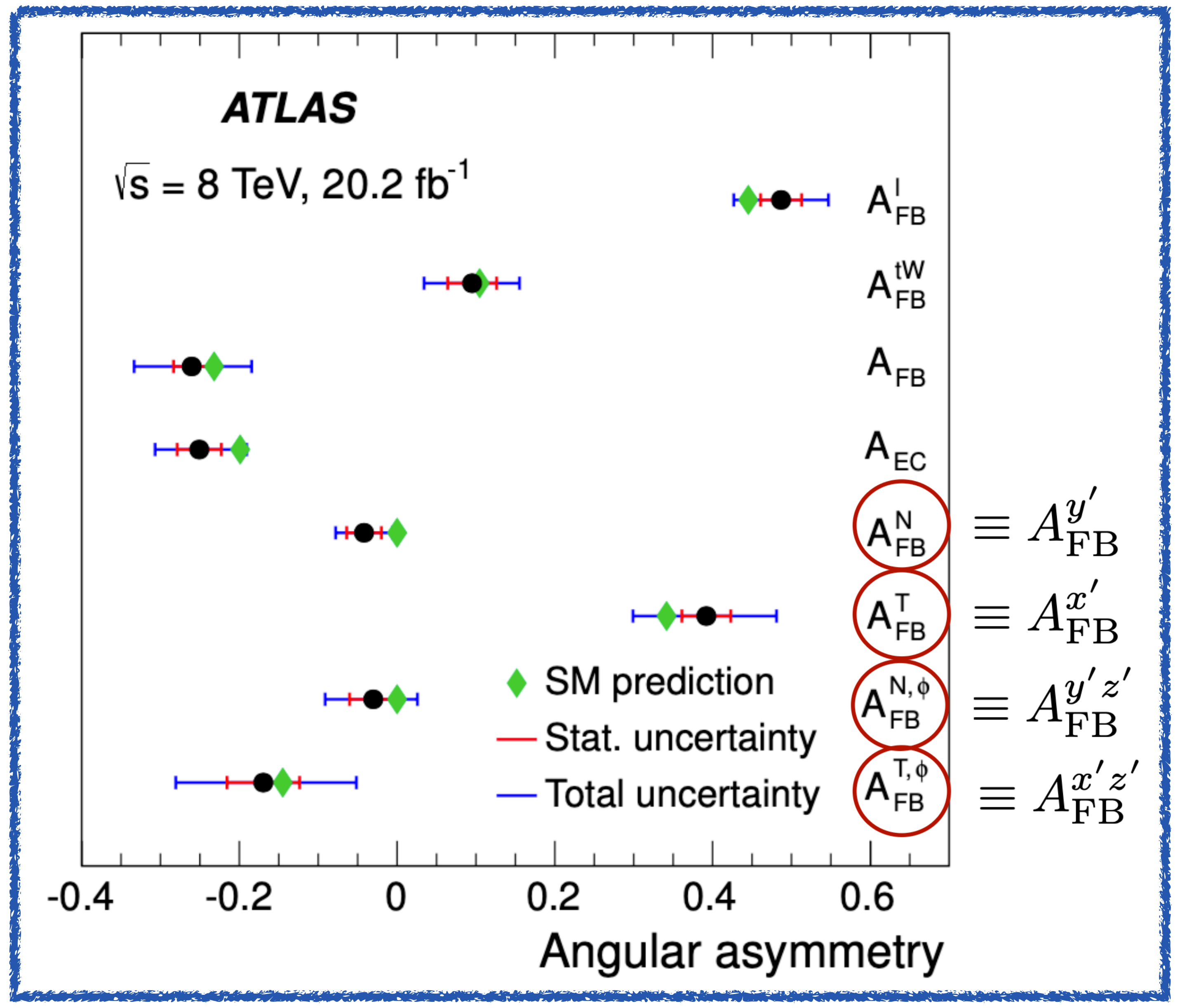
You only need to measure these

W helicity fractions

$(\theta^*_\ell, \phi^*_\ell)$ of ℓ in W rest frame

(θ, ϕ) of W in t rest frame





Entanglement with one top (Juan Aguilar Saavedra)

Bipartite and tripartite entanglement

Tripartite entanglement is genuine if the state is entangled under any bipartition of $\mathcal{H}_L \otimes \mathcal{H}_{S_1} \otimes \mathcal{H}_{S_2}$

N > 0 ⇒ entanglement

A	B	N(ρ)
$\mathcal{H}_L$	$\mathcal{H}_W \otimes \mathcal{H}_b$	1.65
$\mathcal{H}_W$	$\mathcal{H}_L \otimes \mathcal{H}_b$	0.80
$\mathcal{H}_b$	$\mathcal{H}_L \otimes \mathcal{H}_W$	0.50

marginalise

A	B	N(ρ)
$\mathcal{H}_L$	$\mathcal{H}_W$	0.62
$\mathcal{H}_L$	$\mathcal{H}_b$	0.40
$\mathcal{H}_W$	$\mathcal{H}_b$	0.01

Entanglement significance including systematics

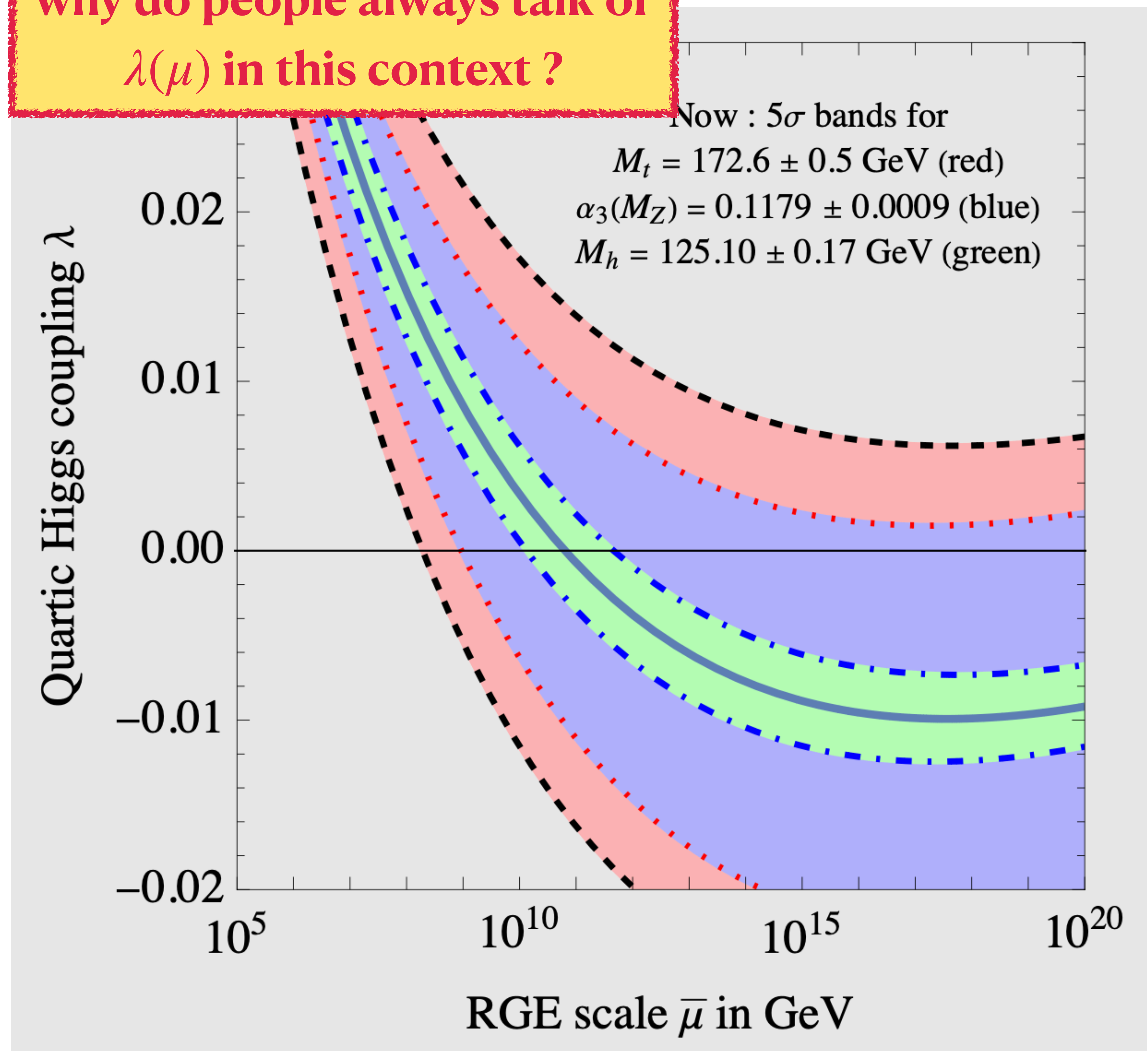
	Run 2
L-(*Wb*)	15σ
W-(L*b*)	18σ
b-(L*W*)	12σ
L-*W*	8.7σ
L-*b*	3.2σ

Fun & Foundations
(Mini-workshop)

TOP 2024
THEORY

Vacuum Stability: what are we talking about? (Tom Steudtner)

why do people always talk of $\lambda(\mu)$ in this context ?



From Roberto's talk

$$V_{\text{eff}}(h,\,\mu) = \tfrac{1}{4}\lambda(\mu)h^4 + \mathcal{O}(\alpha^2) = \tfrac{1}{4}\lambda_{\text{eff}}(h)e^{4\bar{\Gamma}(h,h_0)}h^4$$

$$\rightarrow \text{stability:}\;\; \lambda_{\text{eff}} > 0$$

$$\lambda_{\text{eff}}(h) = \lambda_{\text{eff}}(h_0) + \int_{h_0}^{h}\frac{\mathrm{d}h'}{h'}\sum_i \bar{\beta}_i \frac{\partial}{\partial\bar{\alpha}_i(h')}\lambda_{\text{eff}}(h')$$

negligible by scale choice

$$\begin{aligned}\lambda_{\text{eff}}(h_0) = \lambda(\mu_{\text{ref}})\\ &+4\lambda^2\left(\ln\frac{2\lambda h_0^2}{\mu_{\text{ref}}^2}-\frac{3}{2}\right)+\frac{3}{8}g_2^4\left(\ln\frac{g_2^2h_0^2}{4\mu_{\text{ref}}^2}-\frac{5}{6}\right)\\ &+\frac{3}{16}(g_1^2+g_2^2)^2\left(\ln\frac{(g_1^2+g_2^2)h_0^2}{4\mu_{\text{ref}}^2}-\frac{5}{6}\right)-\sum_f N_f y_f^4\left(\ln\frac{y_f^2h_0^2}{2\mu_{\text{ref}}^2}-\frac{3}{2}\right)\\ &+\dots\end{aligned}$$

Running couplings and field normalisation

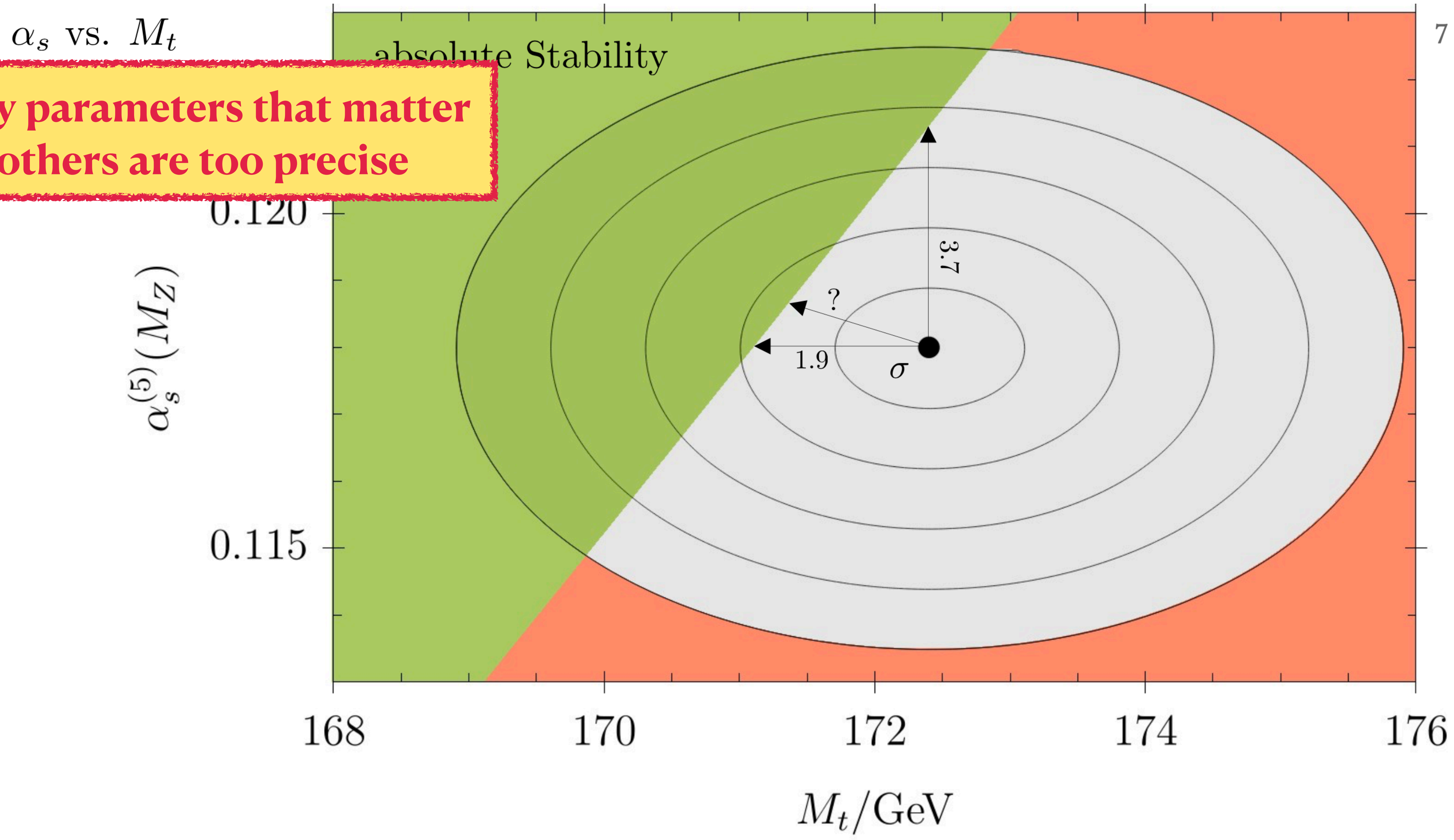
$$\bar{\alpha}_i(h_0) = \alpha_i(\mu_{\text{ref}})$$

$$\bar{\beta}_i(\bar{\alpha}) \equiv \frac{\partial\bar{\alpha}_i(h)}{\partial\ln h} = \frac{\beta_i(\bar{\alpha})}{1+\gamma(\bar{\alpha})}$$

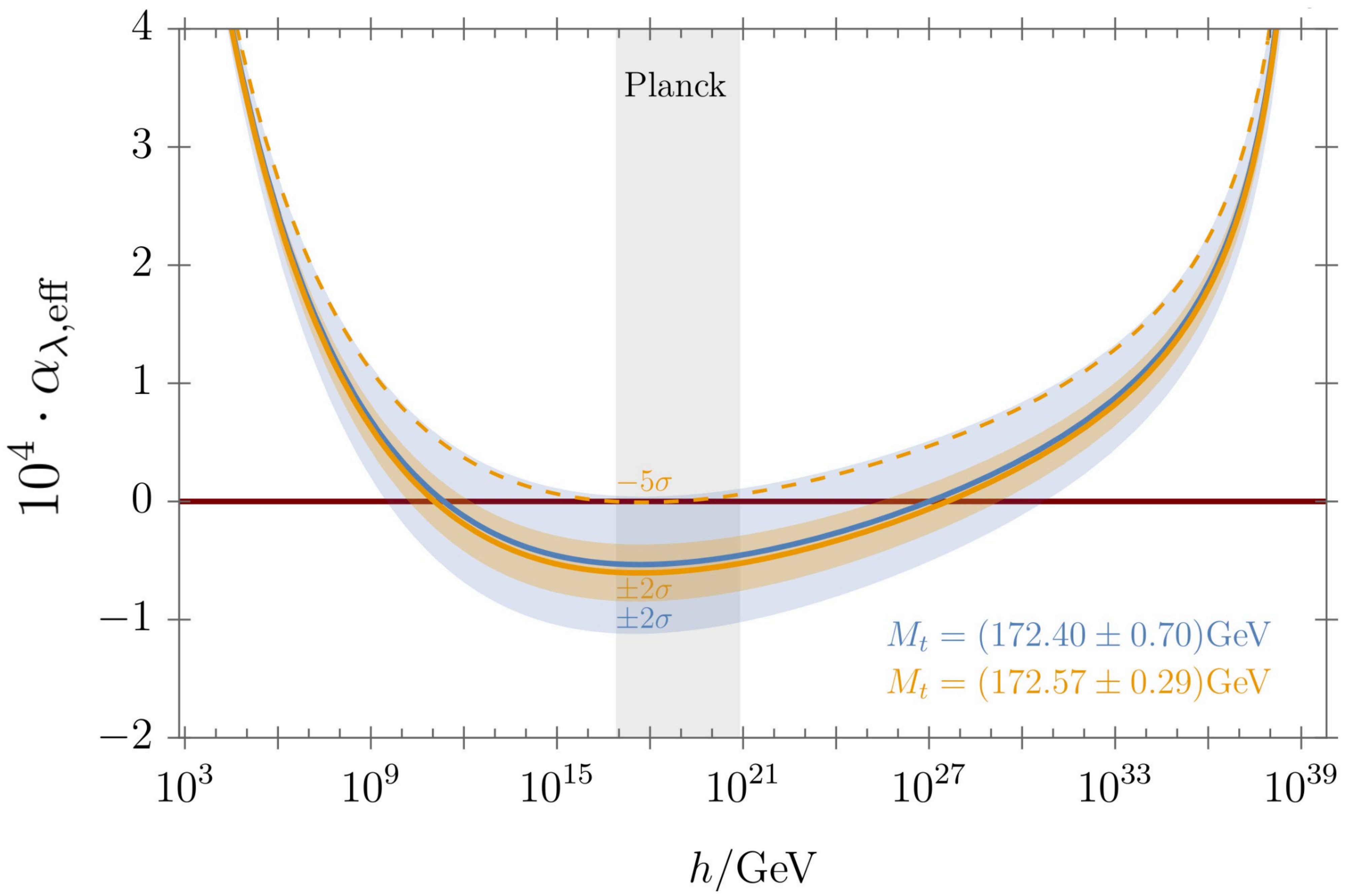
$$\bar{\Gamma}(h,h_0) = \int_{h_0}^{h}\frac{\mathrm{d}h'}{h'}\frac{\gamma(\bar{\alpha})}{1+\gamma(\bar{\alpha})}$$

field anomalous dimension

Vacuum Stability: what are we talking about? (Tom Steudtner)



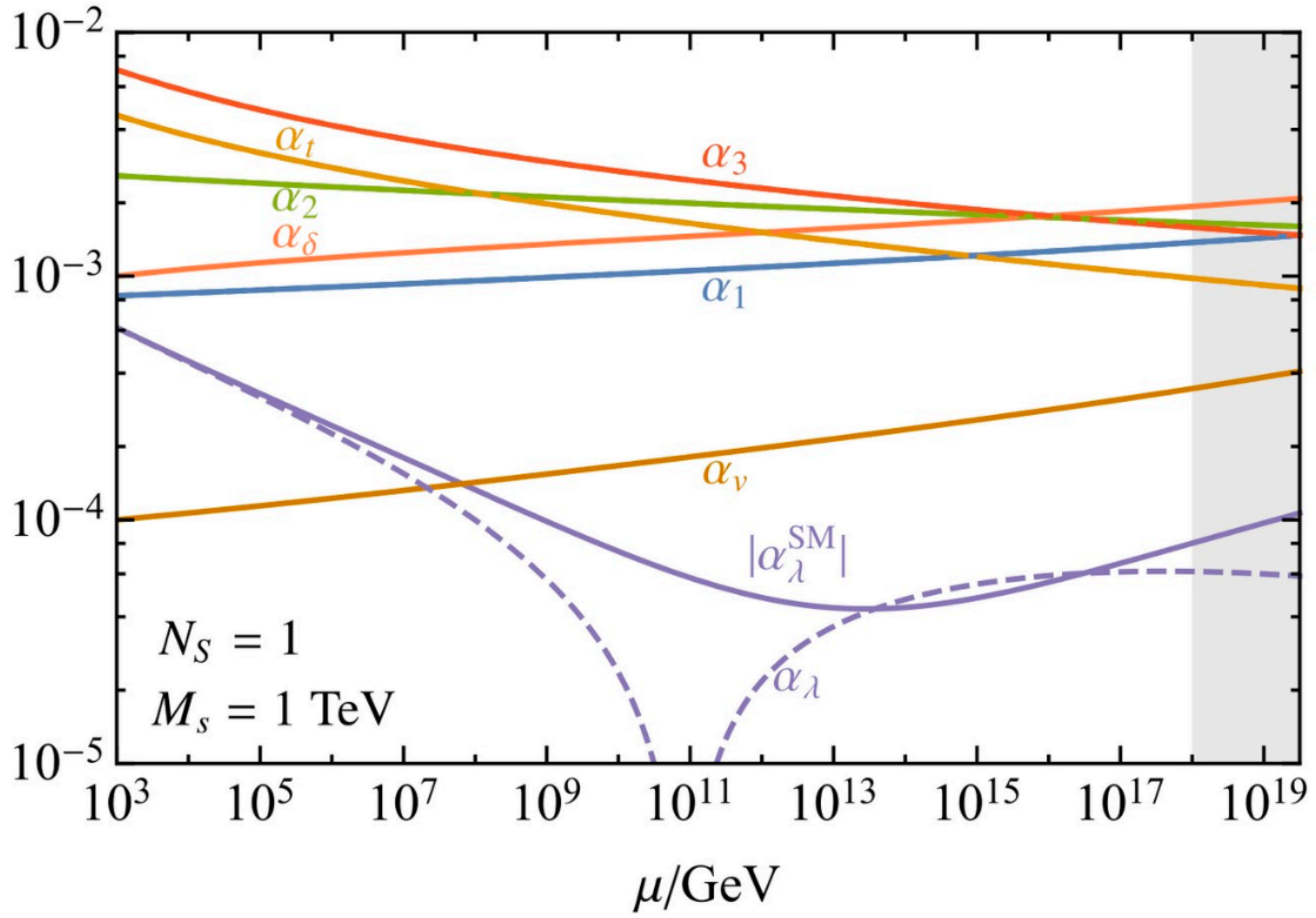
only parameters that matter others are too precise



Stability via BSM?

- » Gauge Portal – adding new charged fermions
- » Yukawa Portal – sizable new Yukawa interactions
- » Scalar Portal

$$V_{H,S} = \lambda\,(H^\dagger H)^2 + \delta\,(H^\dagger H)(S^T S) + \upsilon\,(S^T S)^2$$

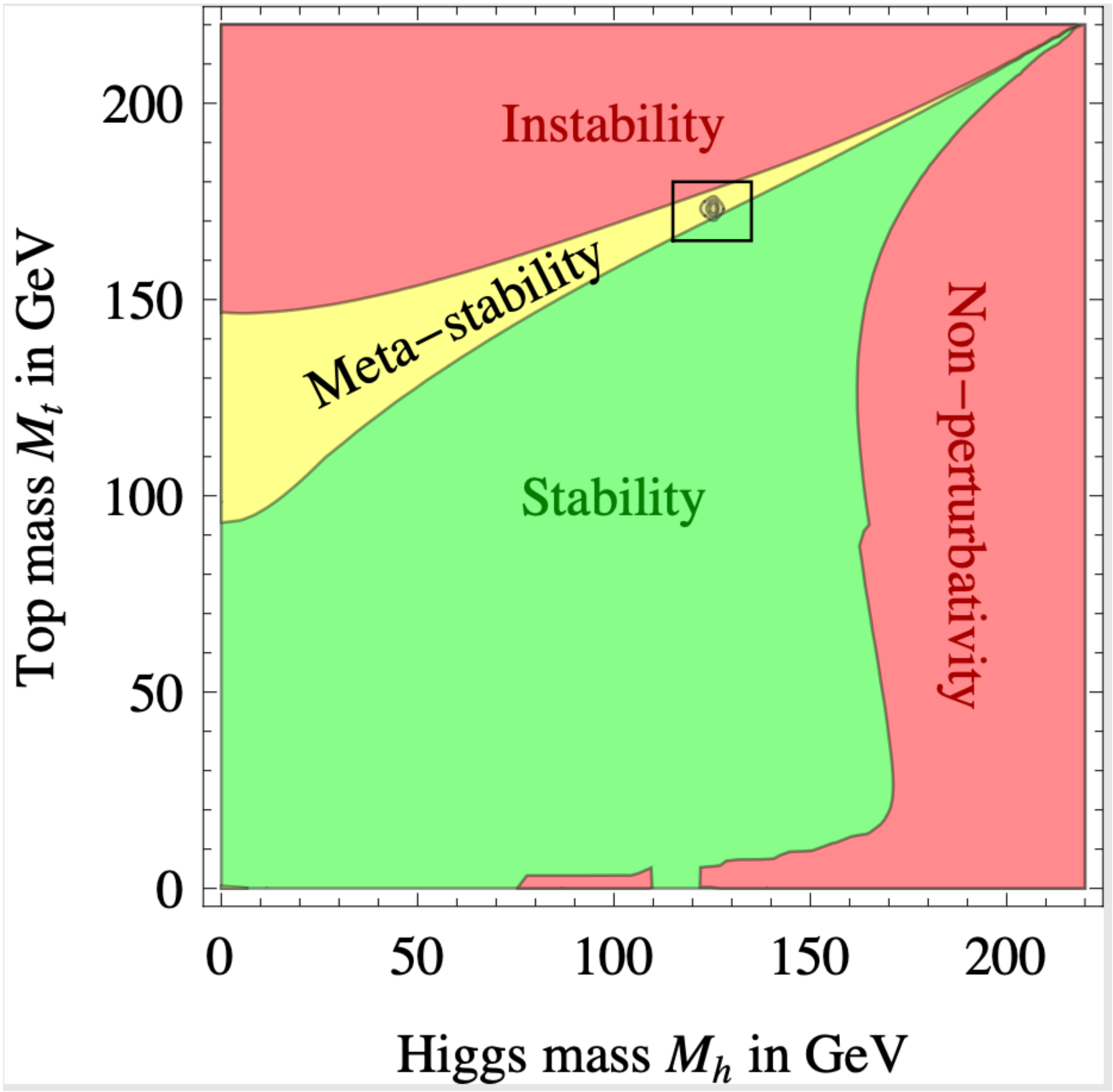


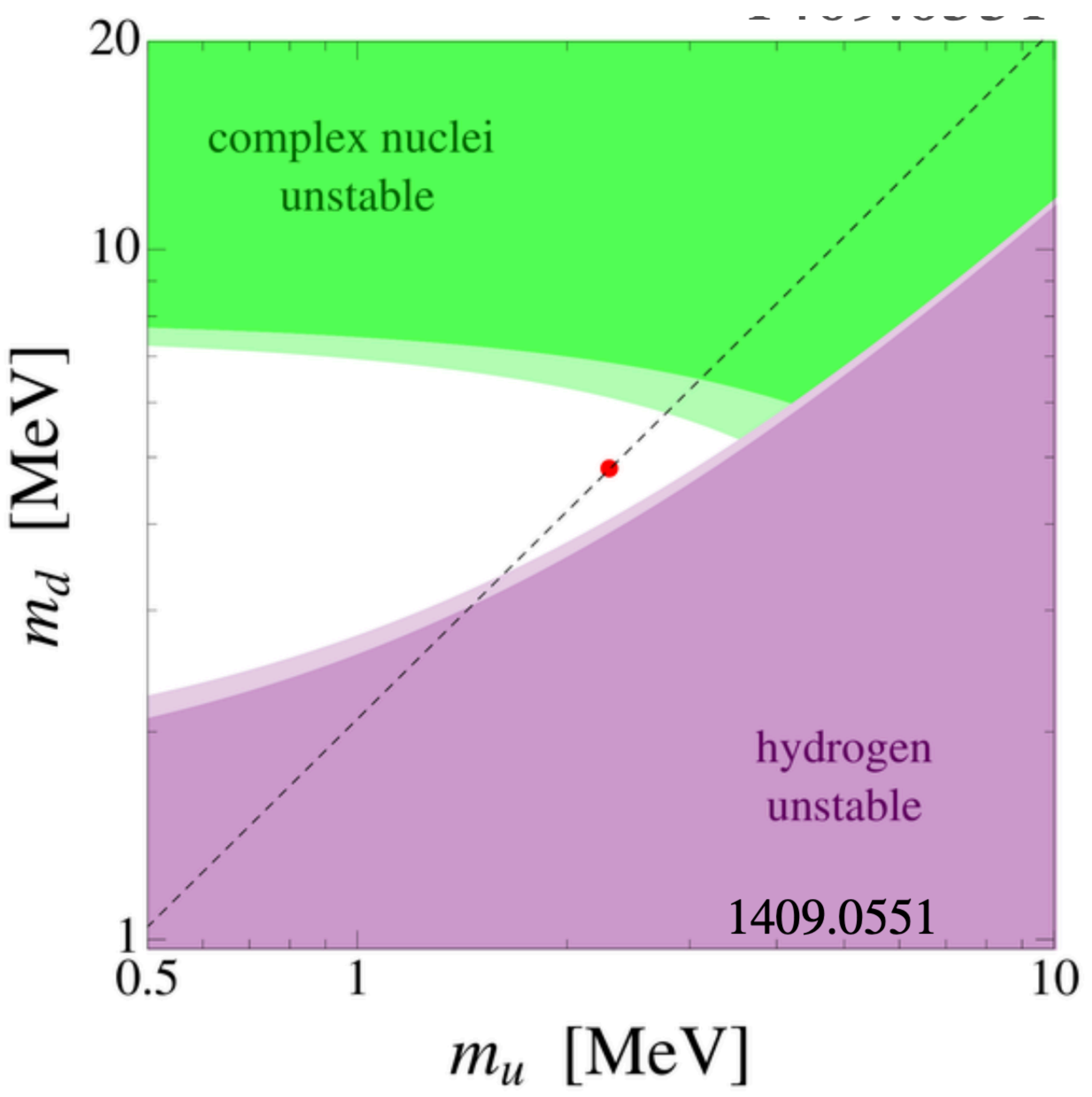
Can we argue for a collider ? (Roberto Franceschini)

A very useful reference for outreach and talking to your family and children

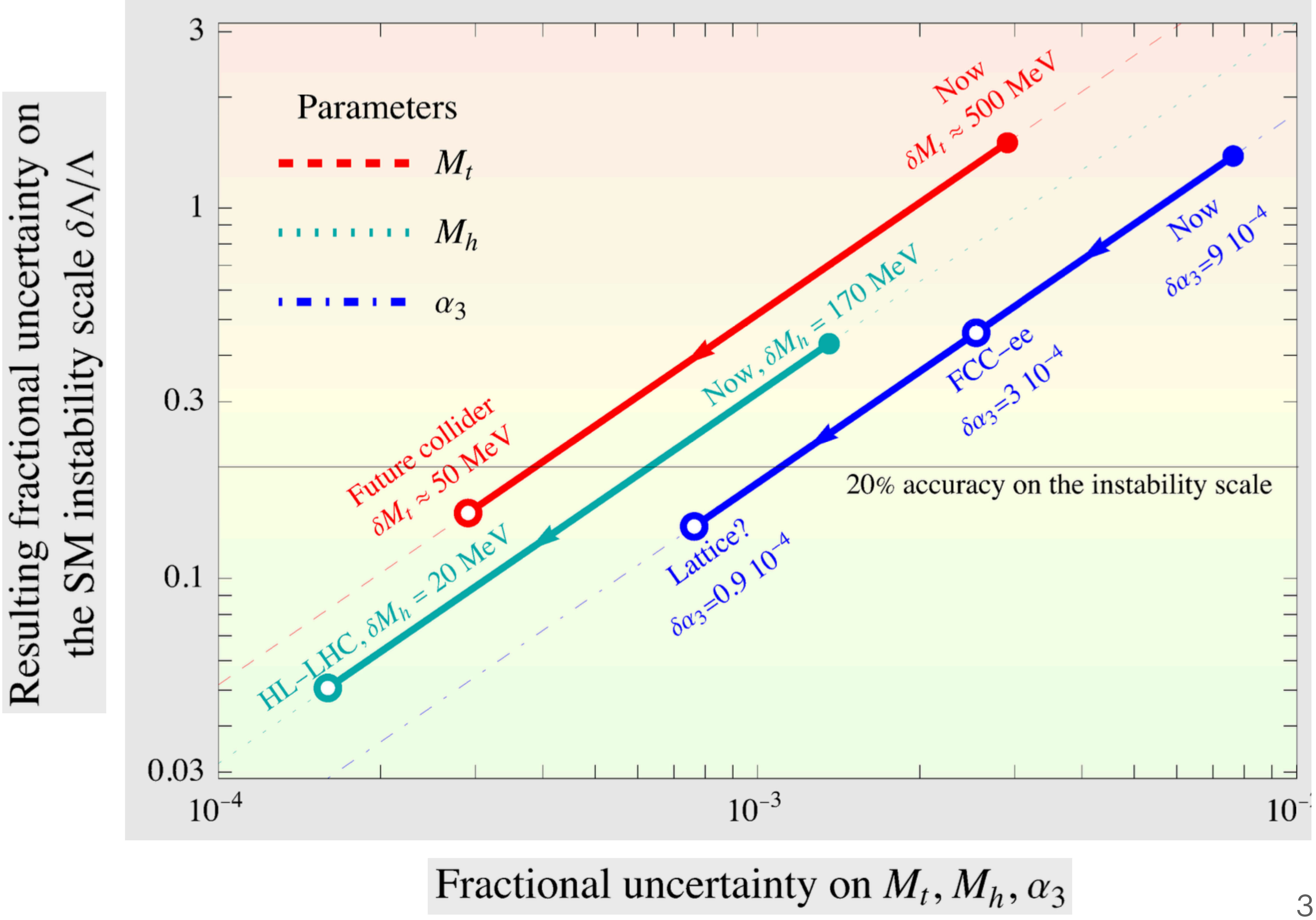
Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

Disenchanting the fine-tuning of Universe stability

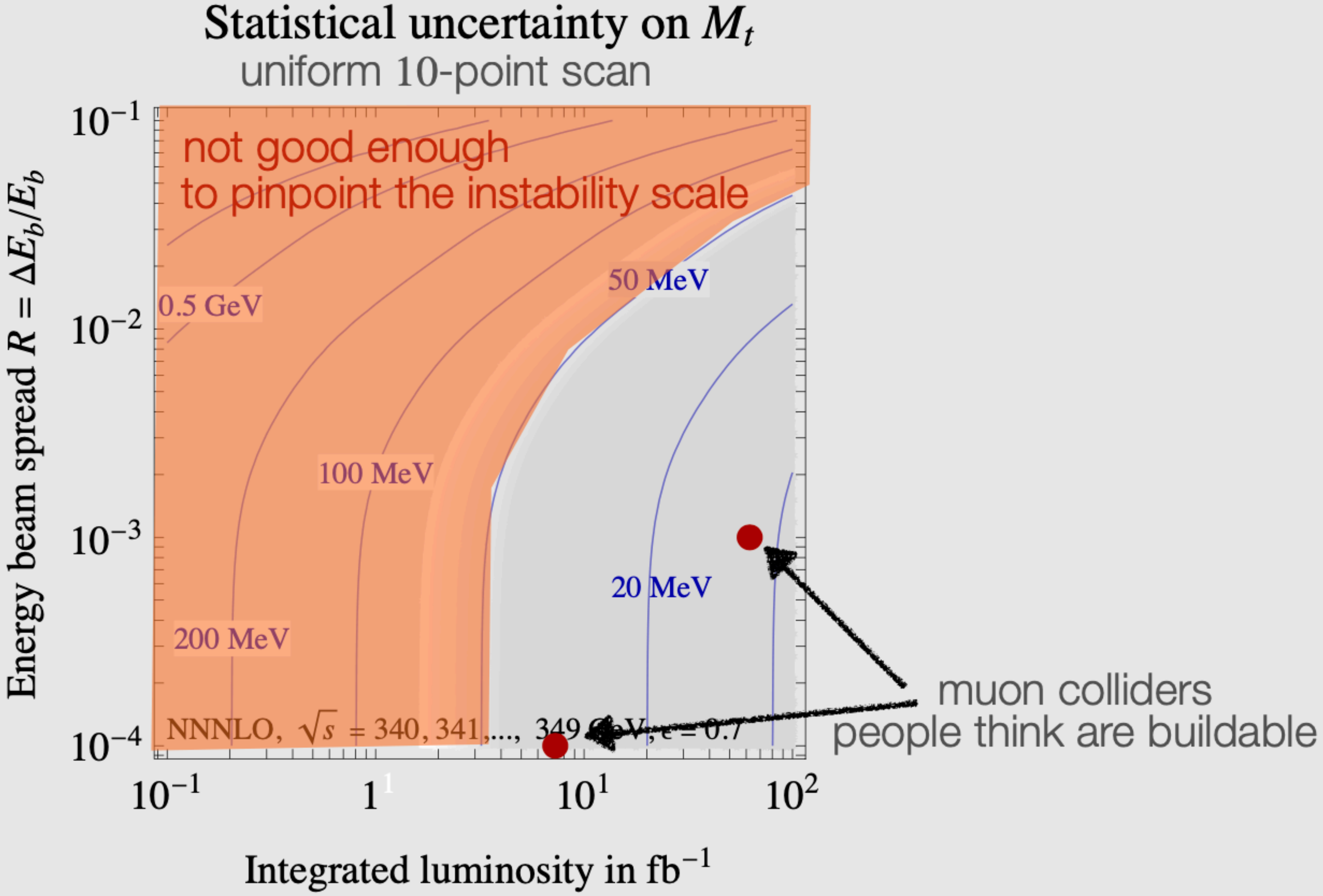




Can we guess the scale of new physics ?

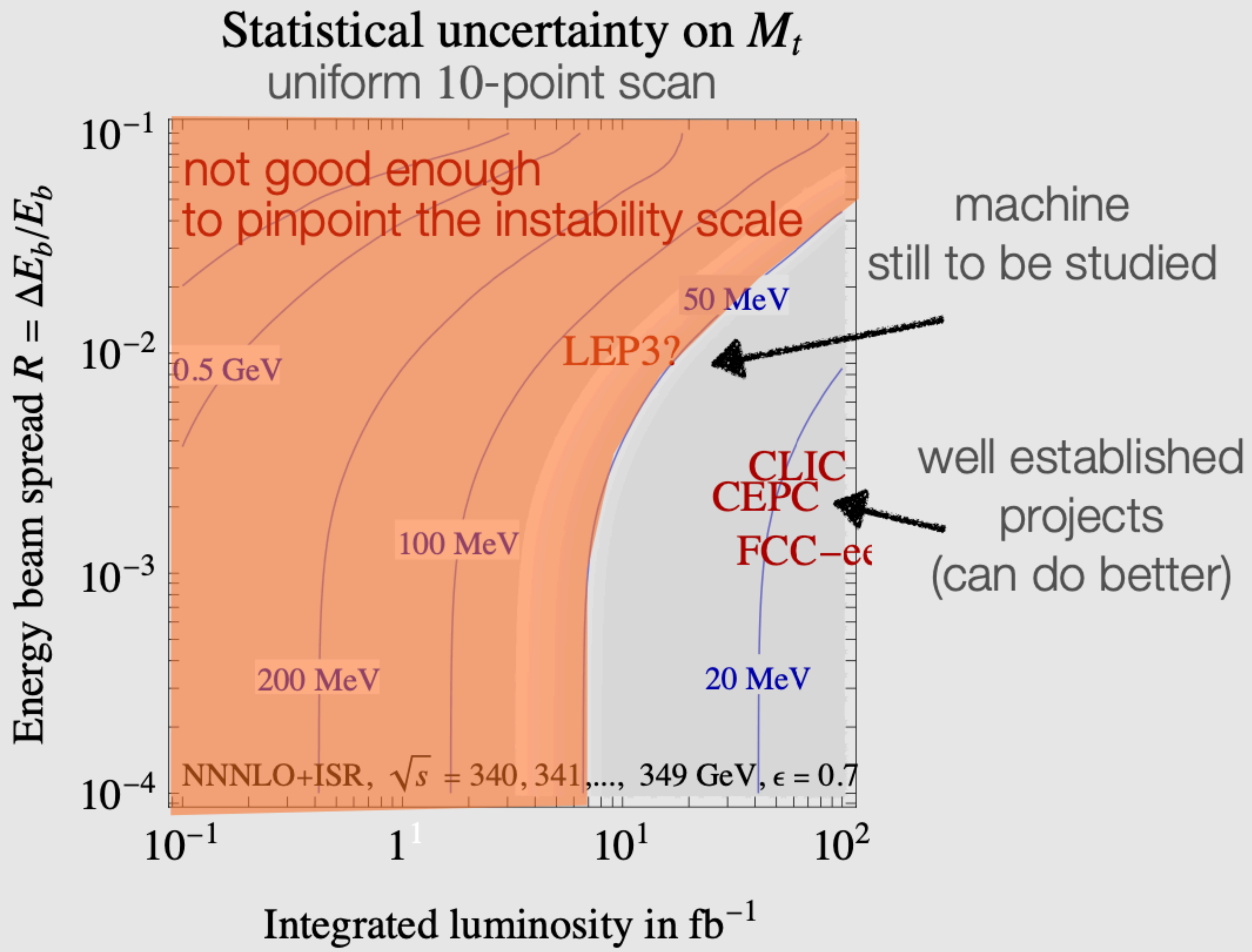


Can we argue for a collider ? (Roberto Franceschini)



muon colliders
people think are buildable

a muon collider with 10-100 fb^{-1} and BES 10^{-3}-10^{-4}
hits the target perfectly



machine
still to be studied

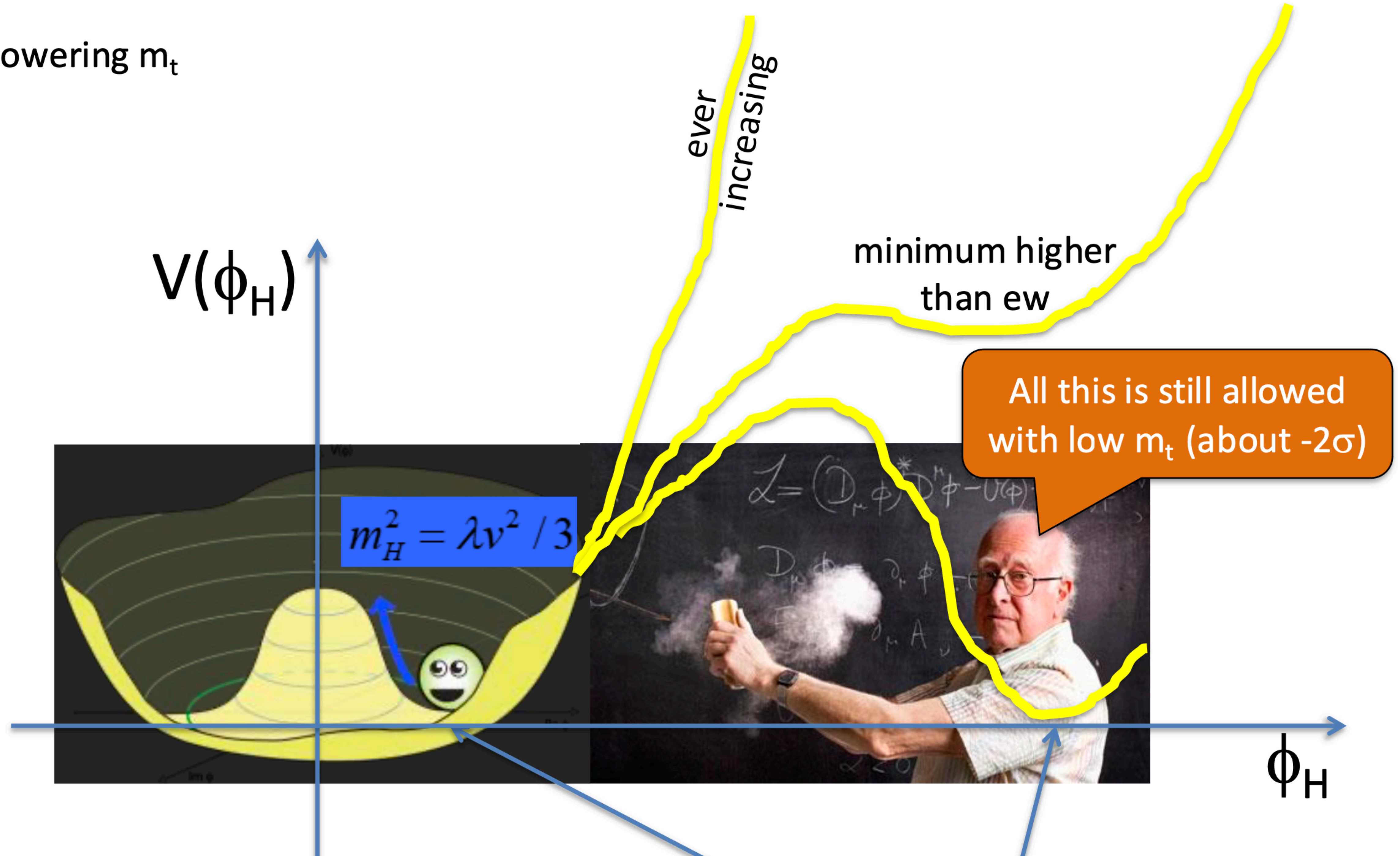
well established
projects
(can do better)

all e^+e^- projects on the table
exceed by far the target

LEP3 is borderline (and uncertain)

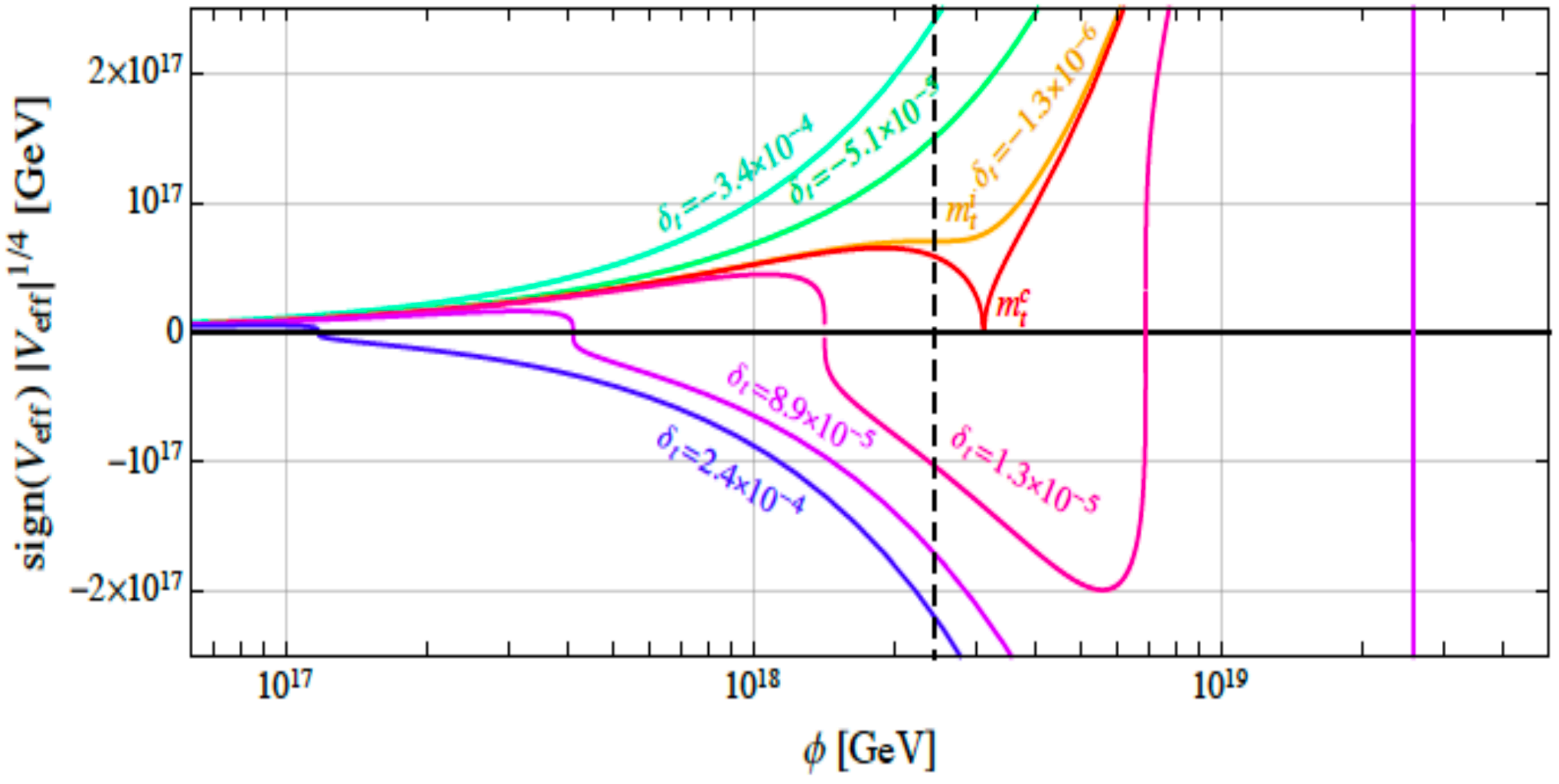
Electroweak metastability and Higgs inflation (Isabella Masina)

… Lowering m_t



All this is still allowed with low m_t (about -2σ)

critical configuration: minimum degenerate with ew



$$m_t = m_t^c\,(1+\delta_t)$$

m_t^c ←→ 2 deg vacua

Can we have inflation with just the Higgs possibly with non-minimal coupling to gravity ???

ξ=non-minimal coupling of Higgs with gravity

$$1 + \frac{\xi\phi^2}{M_P^2}$$

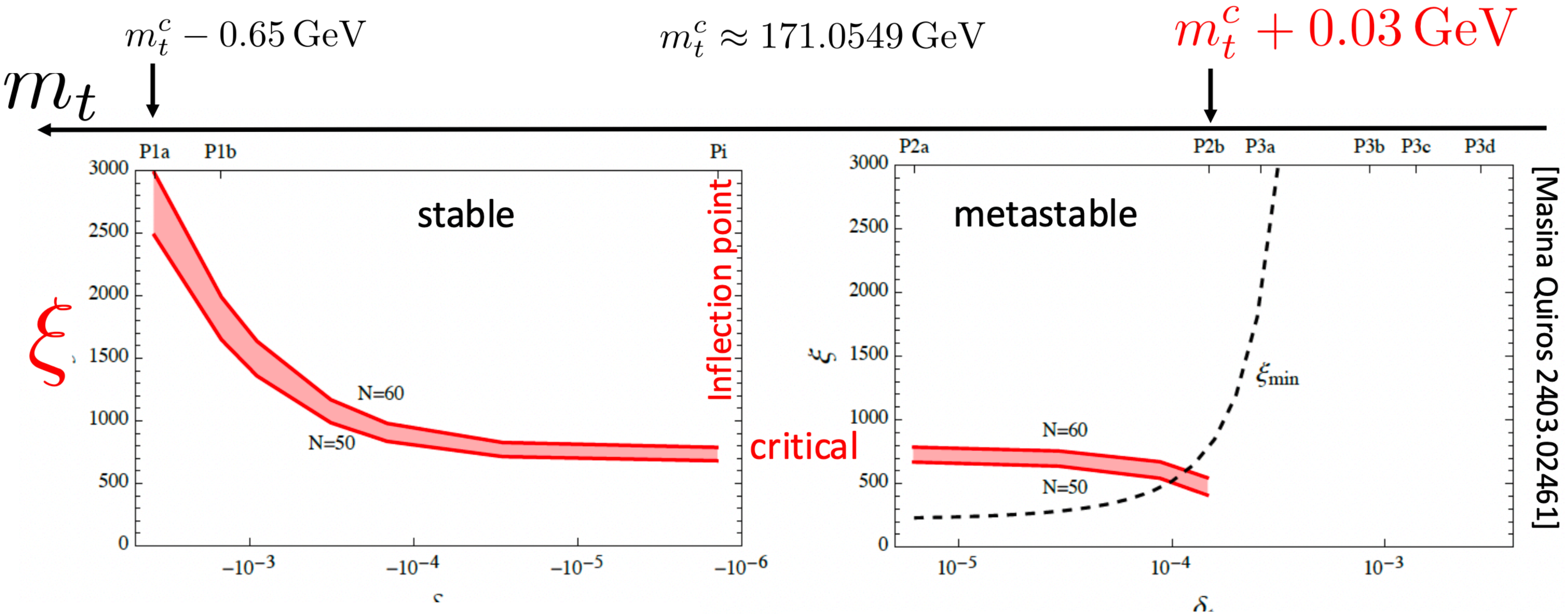
SM Higgs potential

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}f(\phi)R + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)\right)$$

Electroweak metastability and Higgs inflation (Isabella Masina)

Name of the game:
get ξ as small as possible
so that it appears natural

RESULTS for central m_H and α_3



[Masina Quiros 2403.02461]

1) Intriguing *coincidence* for the values of m_t , m_H and α_3 suggests Higgs potential might be close to *criticality*

2) Need BSM for inflation: conservative possibility is a non-minimal coupling with gravity, so called *Higgs-inflation*

3) Higgs-inflation works even (better) for *slightly metastable* configurations:

→ up to mt = m_t^c + 0.03 GeV

→ with smaller value of ξ , down to 550

Higgs potential criticality beyond the Standard Model (Thomas Steingasser)

Near-criticality in the SM

Higgs Potential: $V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$

V_0 : close to transition "dS"↔"AdS"

m_{eff}^2 : close to transition "SSB"↔"no SSB"

λ_{eff} : close to transition "v_{EW} stable"↔"v_{EW} unstable"

"Critical values"

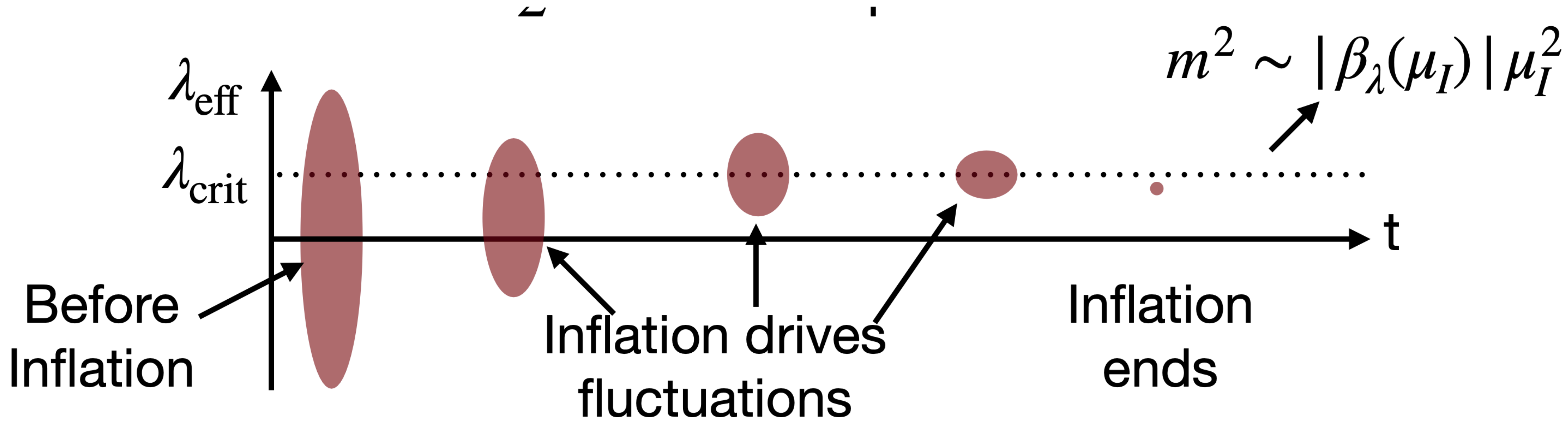
"**Quantum** phase transitions"

How to avoid pure fine tuning ???

Self-organized localisation

New scalar

$$V_{\text{eff}}(\phi, \sigma) = V_0 - \frac{1}{2}m_{\text{eff}}^2(\sigma)\phi^2 + \frac{1}{4}\lambda_{\text{eff}}(\sigma)\phi^4 + \ldots$$

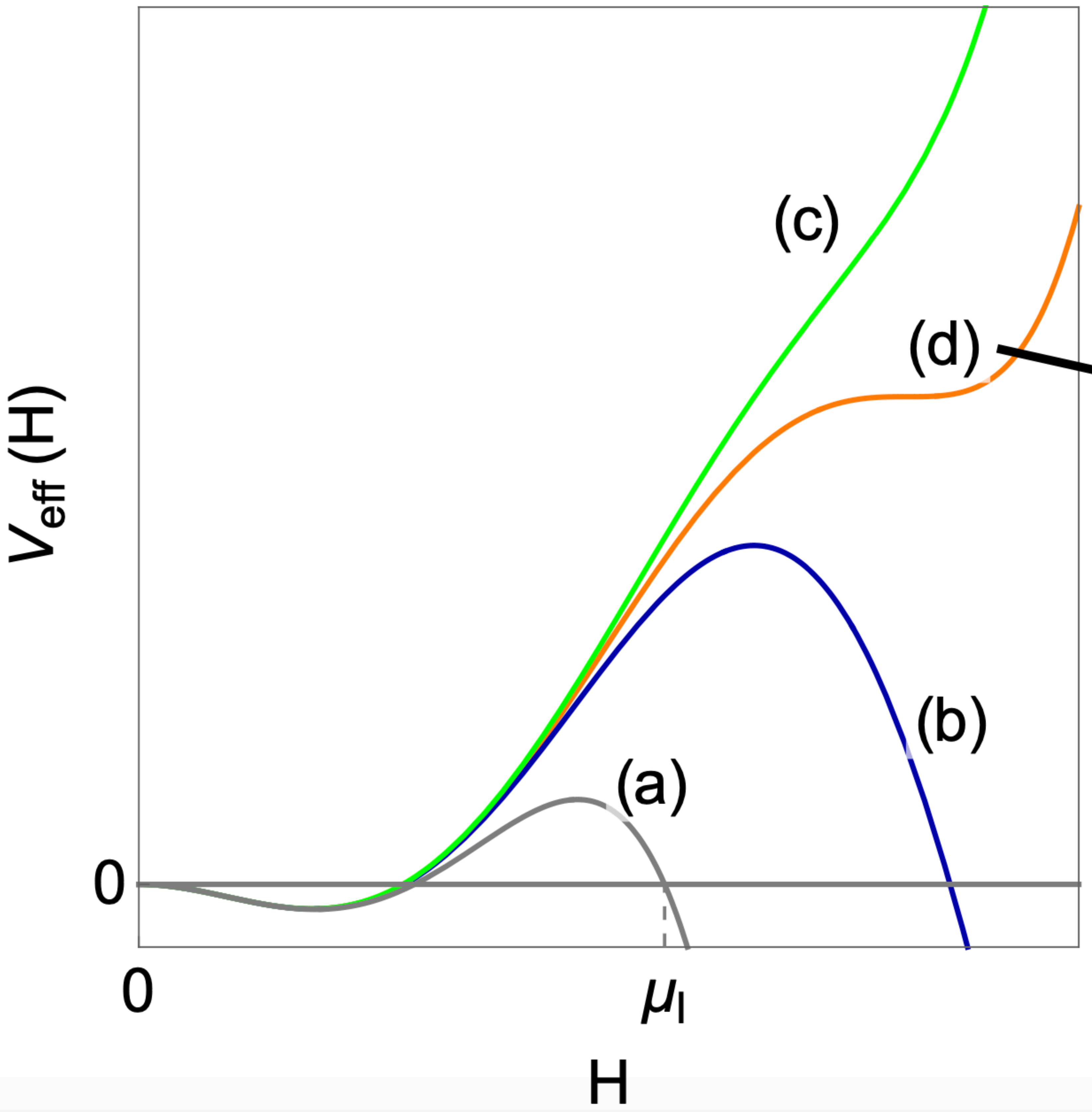


Landscape statistics

Higgs potential criticality beyond the Standard Model (Thomas Steingasser)

Critical BSM physics - toy model

$$V_{\text{eff}}(\phi) \to V_{\text{eff}}(\phi) + \frac{C_6}{\Lambda_{\text{UV}}^2}\phi^6 + \dots$$



$$\left(\frac{C_6}{\Lambda_{\text{UV}}^2}\right)_{\text{crit.}} = (12\sqrt{e})^{-1} \cdot \frac{|\beta_\lambda(\mu_I)|}{\mu_I^2}$$

Running of λ: $\beta_\lambda = (4\pi)^{-2}\left[24\lambda^2 - 6y_t^4 + \dots\right]$

RHN: $\beta_\lambda \to \beta_\lambda - 2\text{Tr}(Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu)/(4\pi)^2$

$\beta_{y_t} \to \beta_{y_t} + 2\text{Tr}(Y_\nu^\dagger Y_\nu)/(4\pi)^2$

EWPD + RHN: $\mu_I \gtrsim \mathcal{O}(\text{TeV})$

Possible applications:
- **Higgs mass from metastability**
- **Right-handed neutrino coupling bounds**
- **....**


That's all Folks!