$t\bar{t}$ experimental talk

more like introduction to non-experts
focusing on experimental aspects

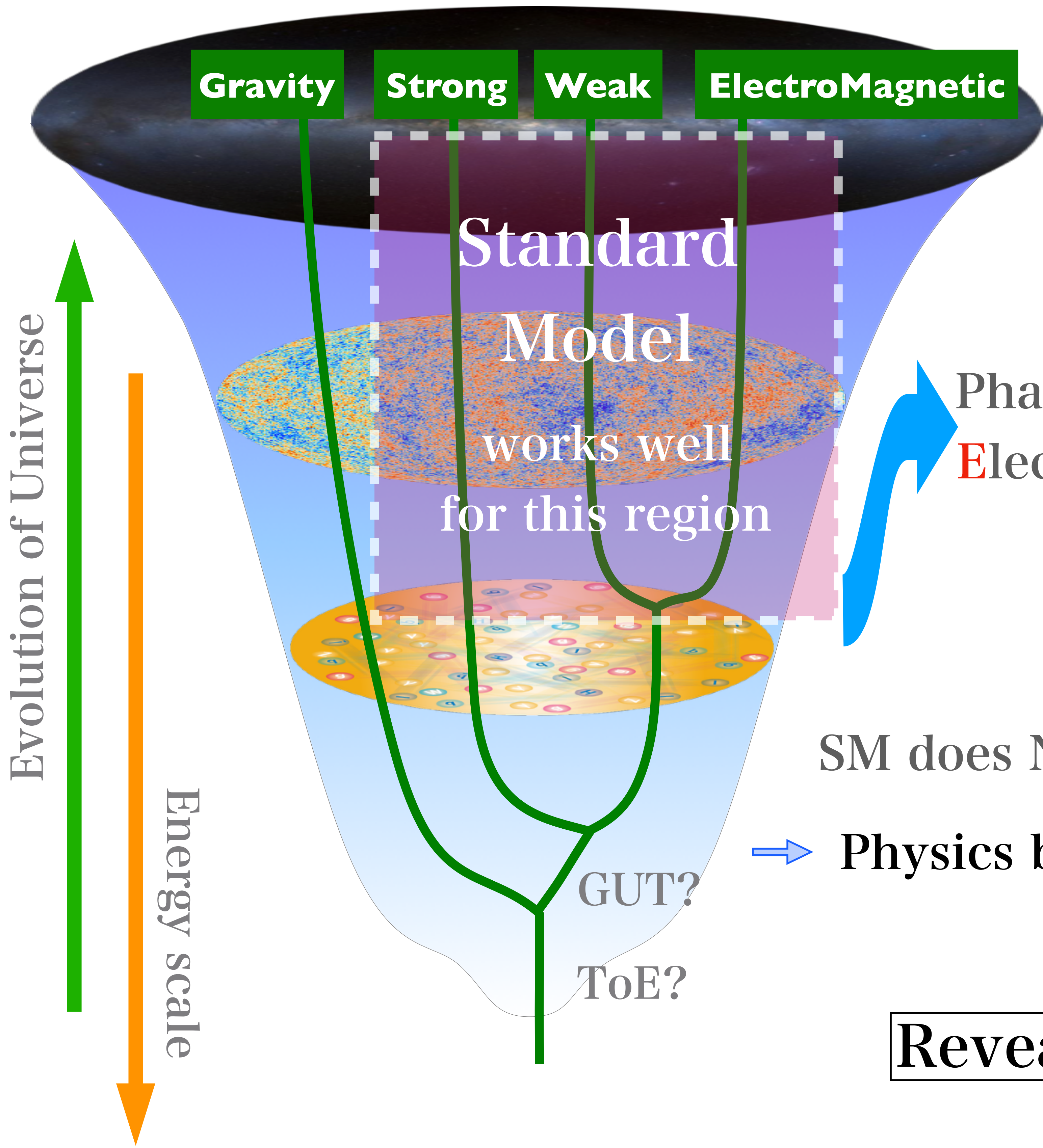
All results in this presentation comes from several collaborations
but RY is responsible for this presentation

Ryo Yonamine

TOHOKU UNIVERSITY

Introduction

Where we are : Standard Model



Phase transition of vacuum

Electroweak Symmetry Breaking

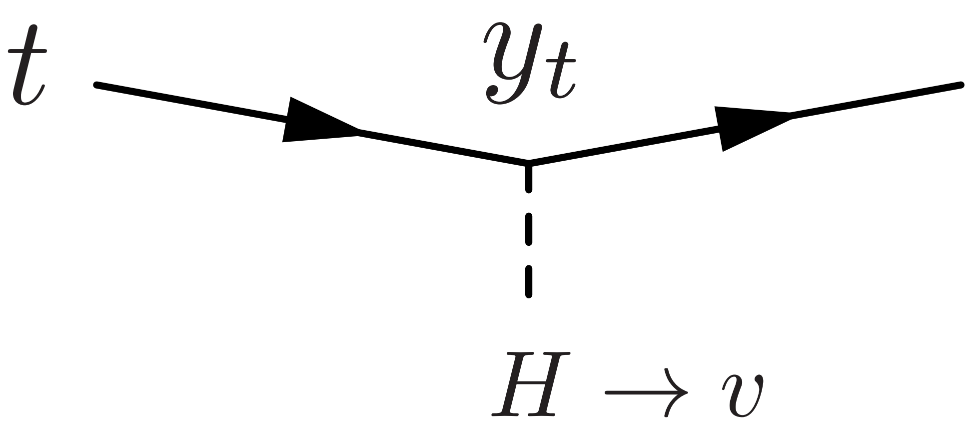
SM does NOT explain why it happened

⇨ **Physics beyond the SM (BSM) will do !**

Revealing EWSB —> BSM

EWSB : Mass generation mechanism

EWSB —> <H> ≠ 0



$$\boxed{\Delta L = -\frac{y_t}{\sqrt{2}} H\bar{t}t \to -m_t\bar{t}t}$$

Heaviest particle should maximally be involved in EWSB

⇨ **Target : top quark**

Examples :
- EWSB and top quark mass can be generated in Composite Higgs models,
- Top Yukawa coupling dynamically can cause EWSB in SUSY theories.

https://arxiv.org/pdf/hep-ph/9807349.pdf

Top quark can be a good probe for EWSB

What makes top quark special (attractive)?

$\boxed{\text{Its large mass!}}$

(heavy enough to decay into b + W)

1. **Heaviest particle (~173GeV) in SM.**

   Why so heavy compared to the other fermions?

2. **Top quark mass affects theoretical predictions.**

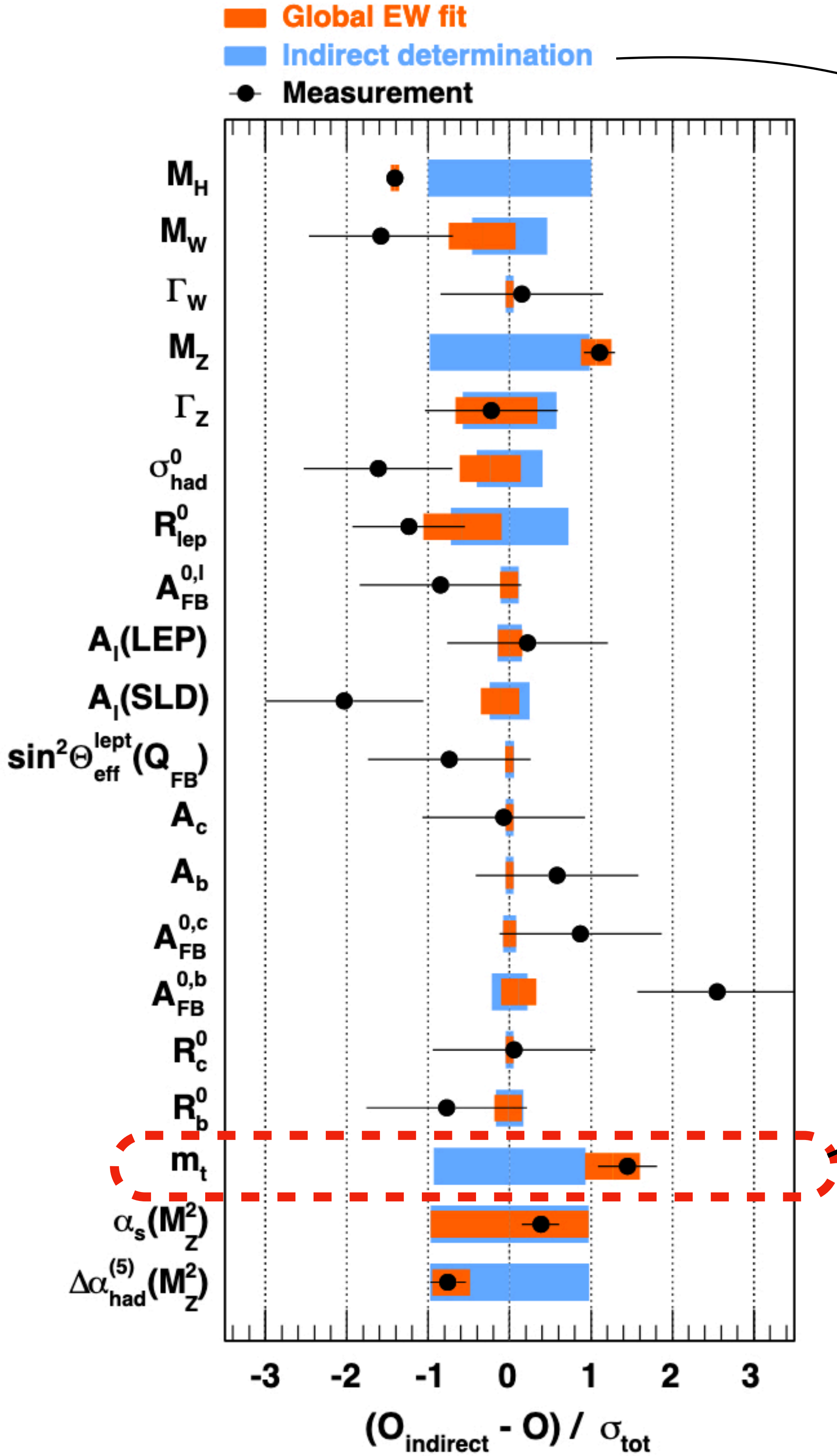
   Large loop contributions to many precision measurements
   e.g. EW fit, vacuum stability, BSM predictions etc. (see next 2 pages)

3. **Top quark decays before hadronization.**

   Allows precise comparisons between measurements and theoretical predictions
   (Large width of top quark acts as an infrared cutoff which allows to use pQCD).

Why top mass ? : Input parameter for EW fit

https://arxiv.org/pdf/1407.3792.pdf



Indirect determination

Fit results w/o corresponding exp. input

Global EW fit results :

Difference from indirect determination in units of total uncertainty

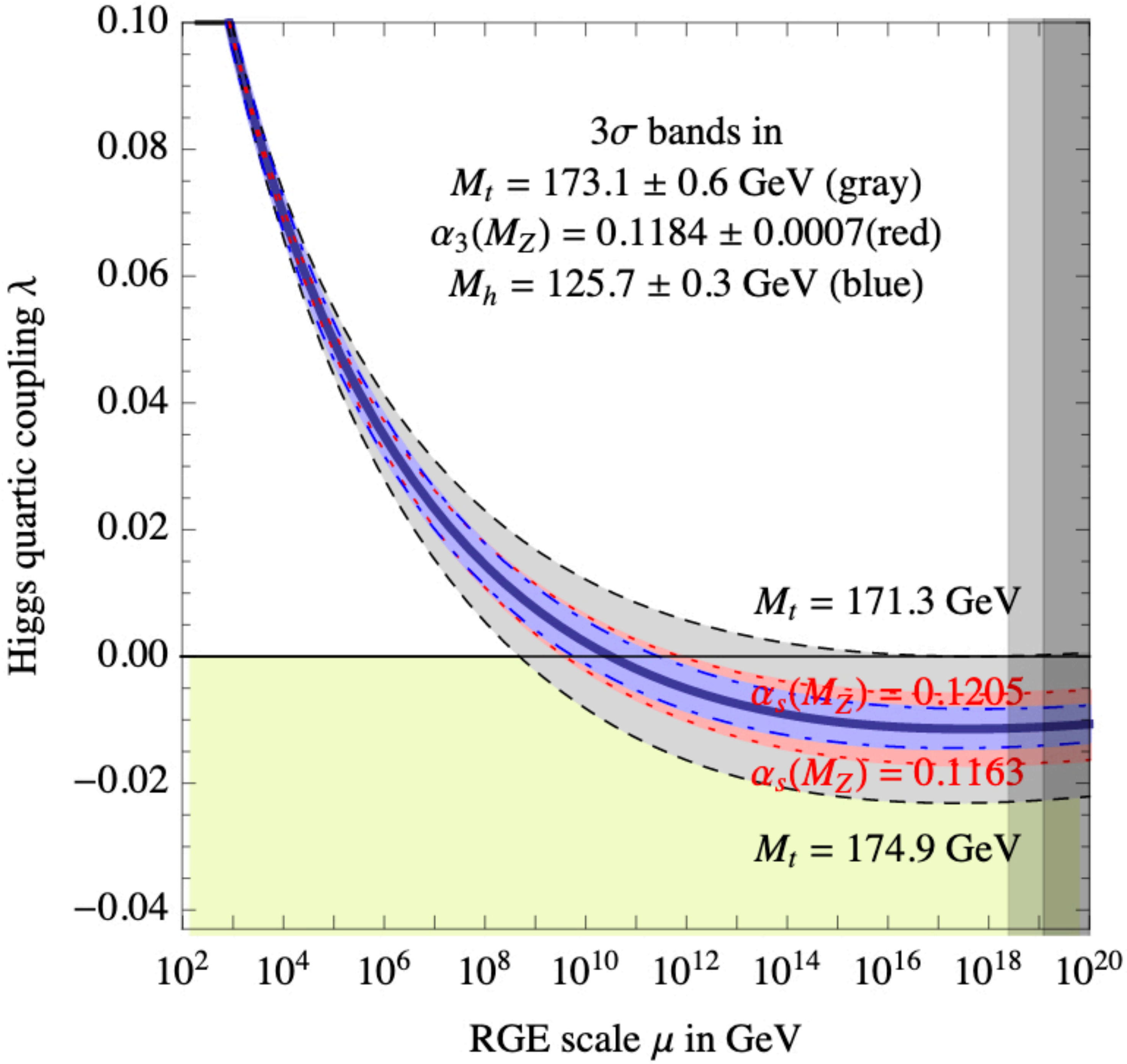
$(\sigma_{tot}^2 = \sigma_{meas}^2 + \sigma_{indirect}^2)$

top mass

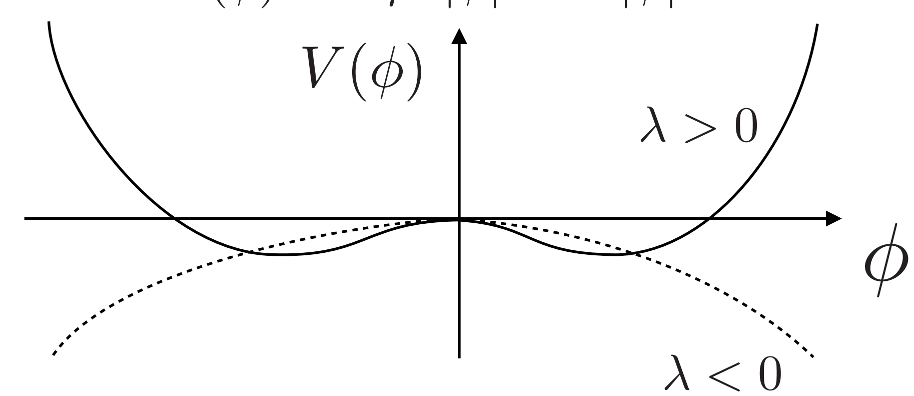
Precise measurement of top mass validates SM

Why top mass (+ α_s) ? : Vacuum stability

https://arxiv.org/pdf/1205.6497.pdf



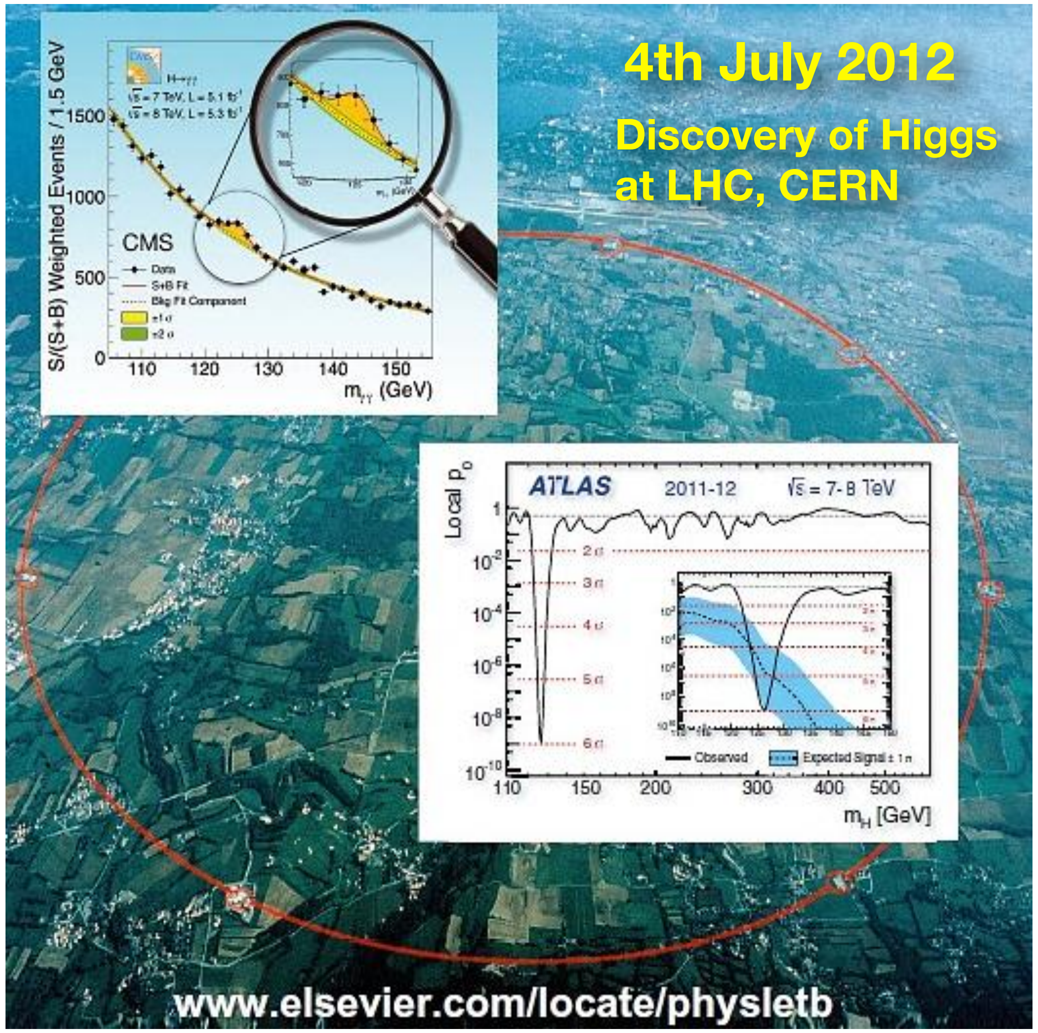
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

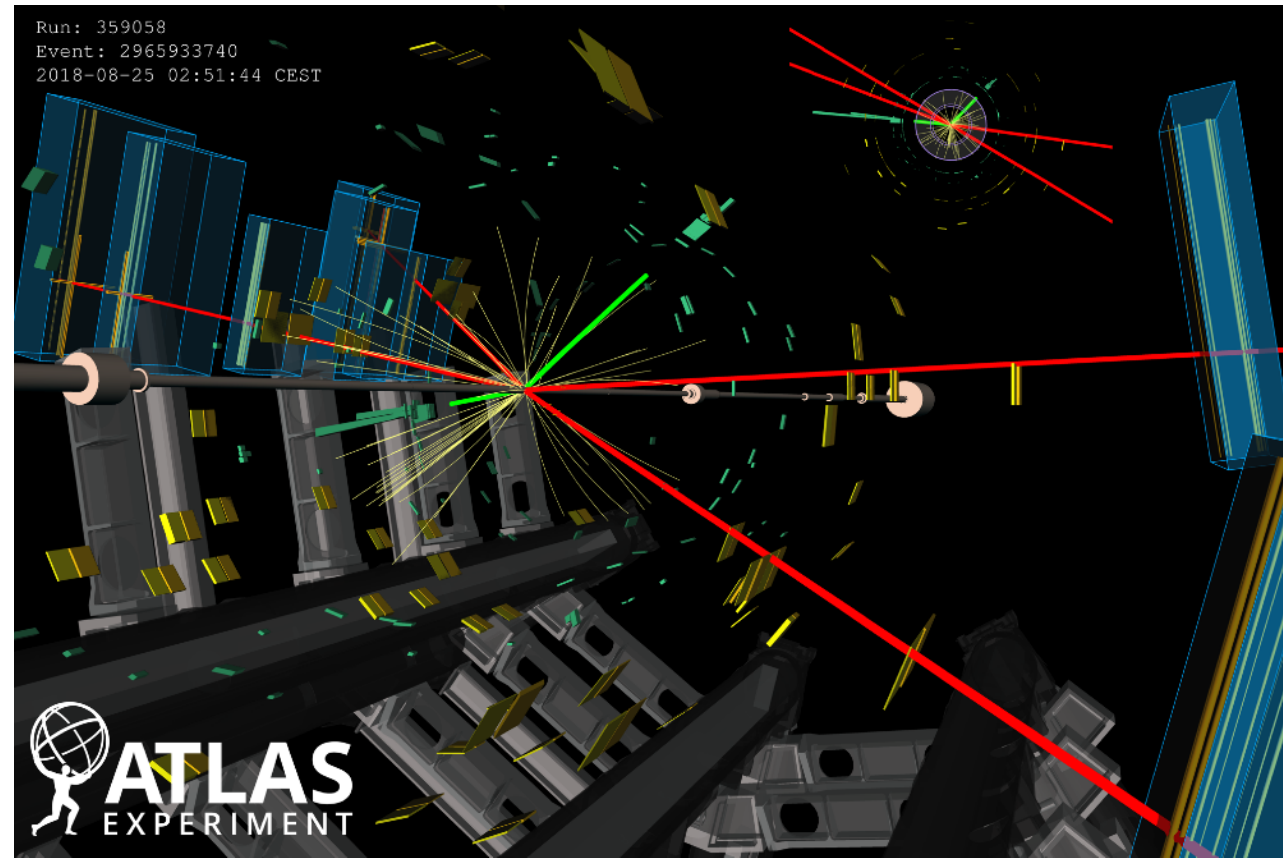


Evolution of λ :
depends on M_t and α_s
BSM should appear before $\lambda<0$!

Top mass and α_s probes BSM

Importance of precision measurements





Historical discovery :

Higgs, Yukawa couplings of 3rd generation fermions

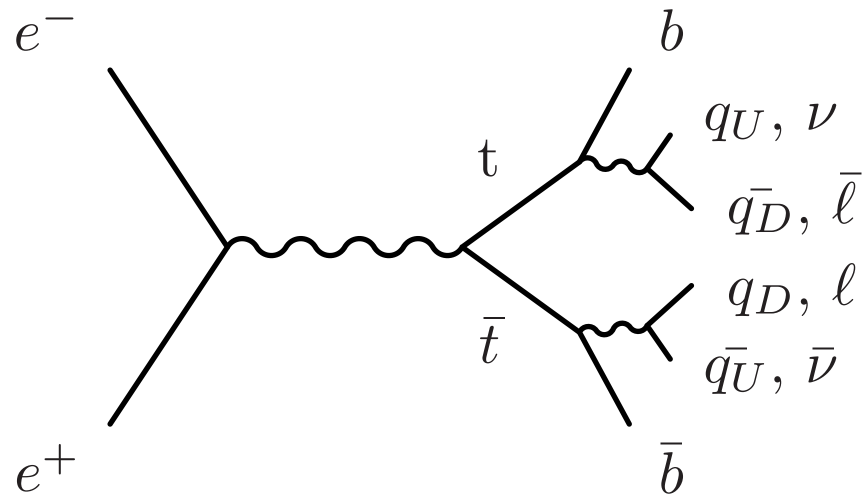
… and many validations of SM processes !

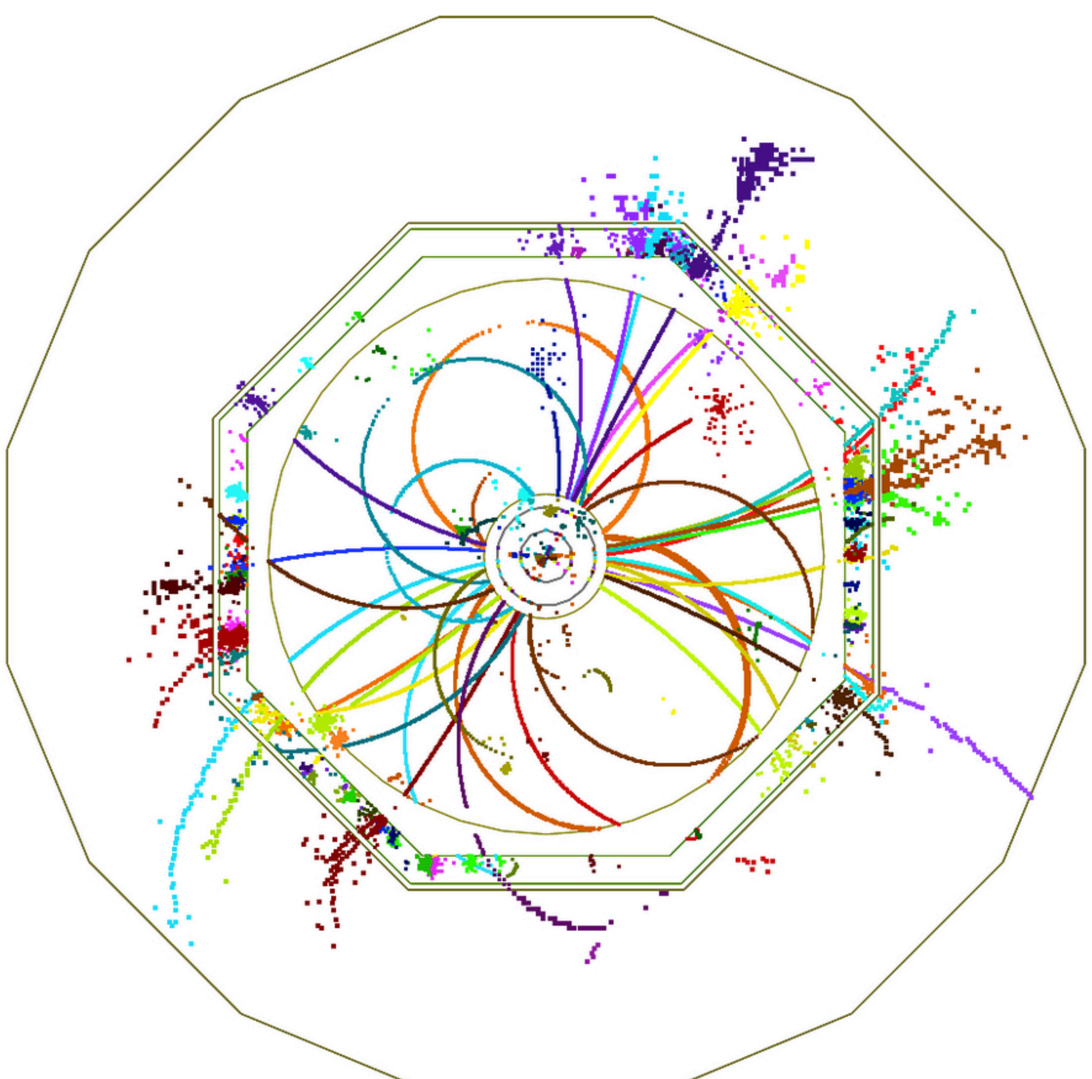
No new colored particles reported yet

$\boxed{\text{BSM energy is likely very high = Deviation from SM is likely very small!}}$

Reconstruction aspects

Top event signature and reconstruction





tt (6q), 500GeV, ILD

Event signature:

- 2 b-jets + 2 isolated leptons
- 2 b-jets + 2 q-jets + 1 isolated lepton
- 2 b-jets + 4 q-jets

Typical reconstruction procedure :

1. Find isolated leptons (0, 1, 2)
2. Overlay removal
3. Jet clustering (2, 4, 6 jets)
4. b-tagging (2 b-jets)
5. Kinematic constraints (e.g. m_W, $\cos\theta_{bW}$)

Typical efficiency of t $\bar{t}$ event selection :

50~80% (depends on purity)

Assignment of 6 fermions to t / $\bar{t}$ is more challenging!

Key : Jet clustering and b-tagging

Jet Clustering

Reconstructing multi jet events will be the key for many analyses

Fundamental difficulty :

# of quarks in final state ≠ # of jets (there can be hard gluons emitted)

Lesson learned :

- Improving jet-clustering ≒ better paring (mini-jets into colour-singlets)
- Non negligible beam background at high energies even for e+e- colliders

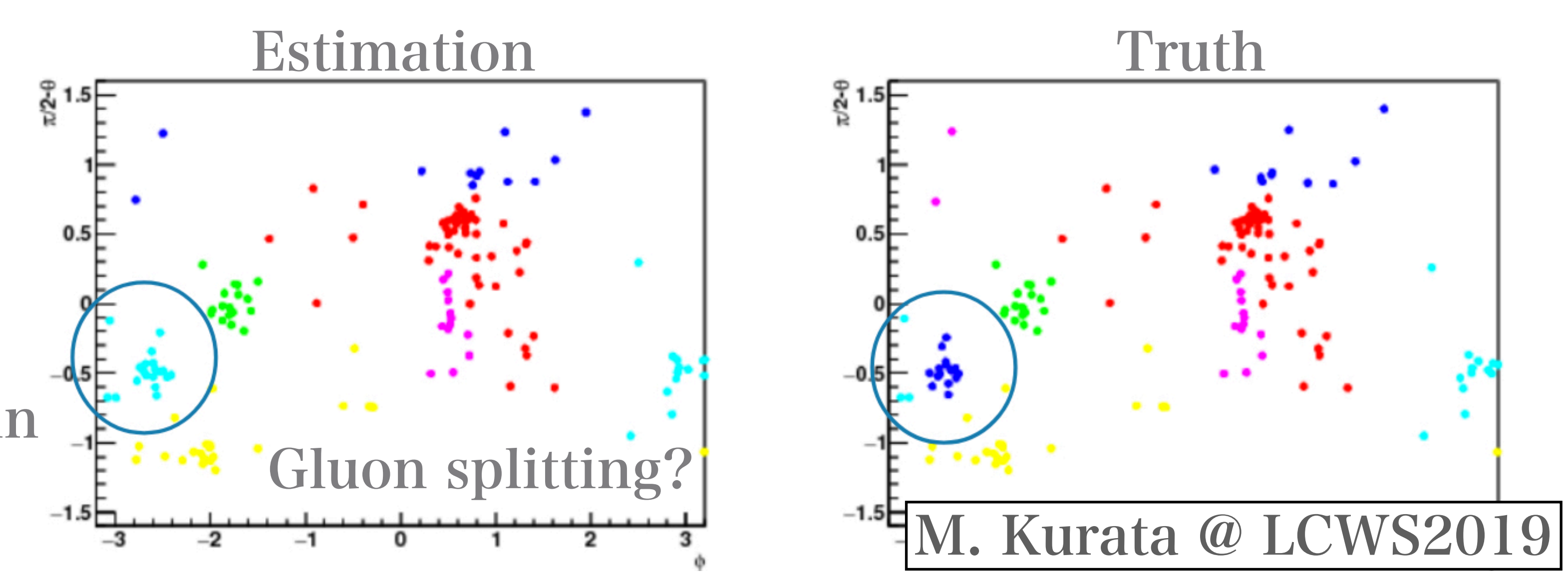
https://agenda.linearcollider.org/event/7760/contributions/40910/attachments/32767/49845/JetRec_ILD2018.pdf

https://agenda.linearcollider.org/event/8217/contributions/44662/

Pei-Zhu Lai @ LCWS2019, CEPC2019

An interesting study with deep learning technique

Same colors indicate same origin



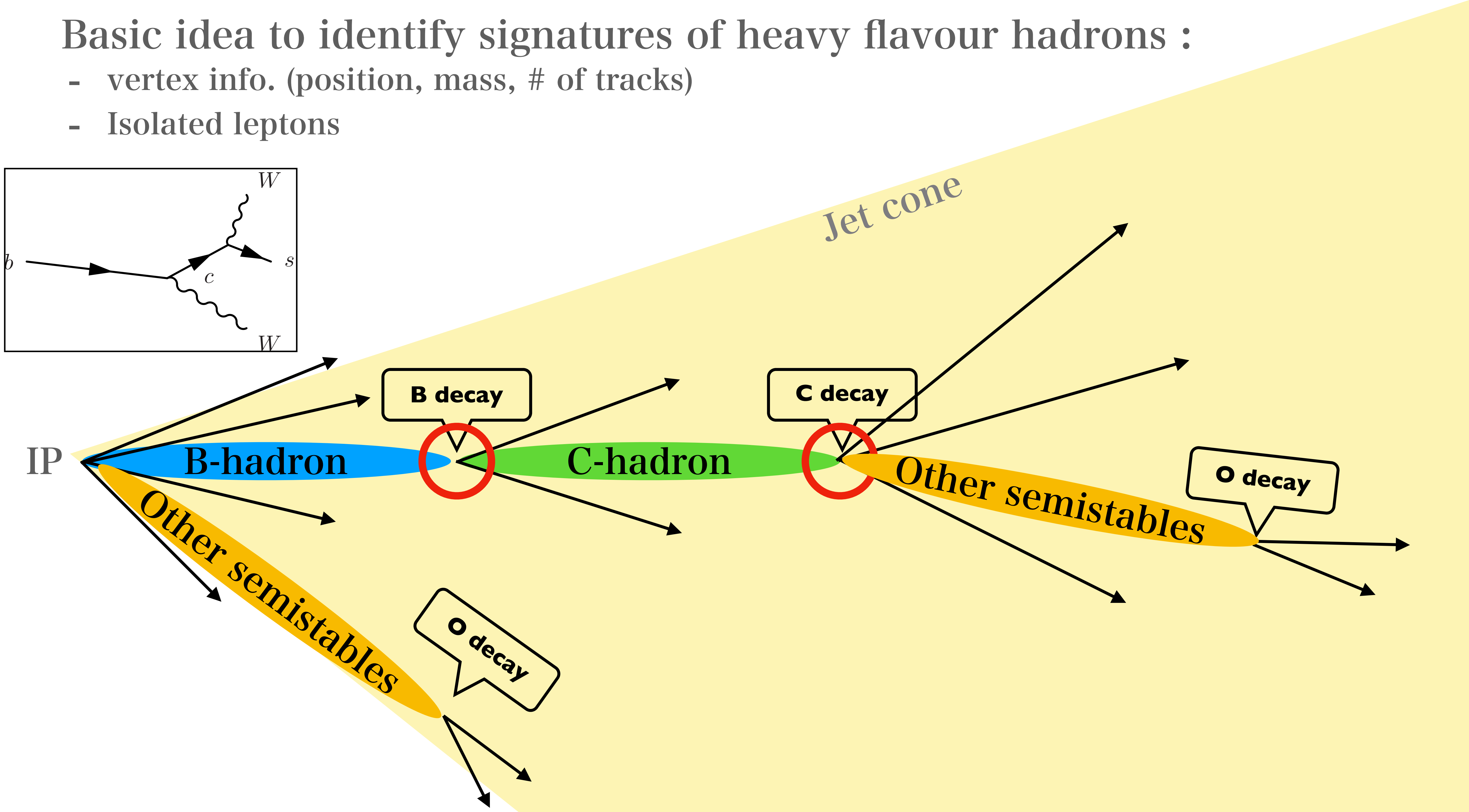
https://agenda.linearcollider.org/event/8217/contributions/44665/

Keep improving for best physics performance!

Flavor tagging : b-tagging, c-tagging

Basic idea to identify signatures of heavy flavour hadrons :

- vertex info. (position, mass, # of tracks)
- Isolated leptons



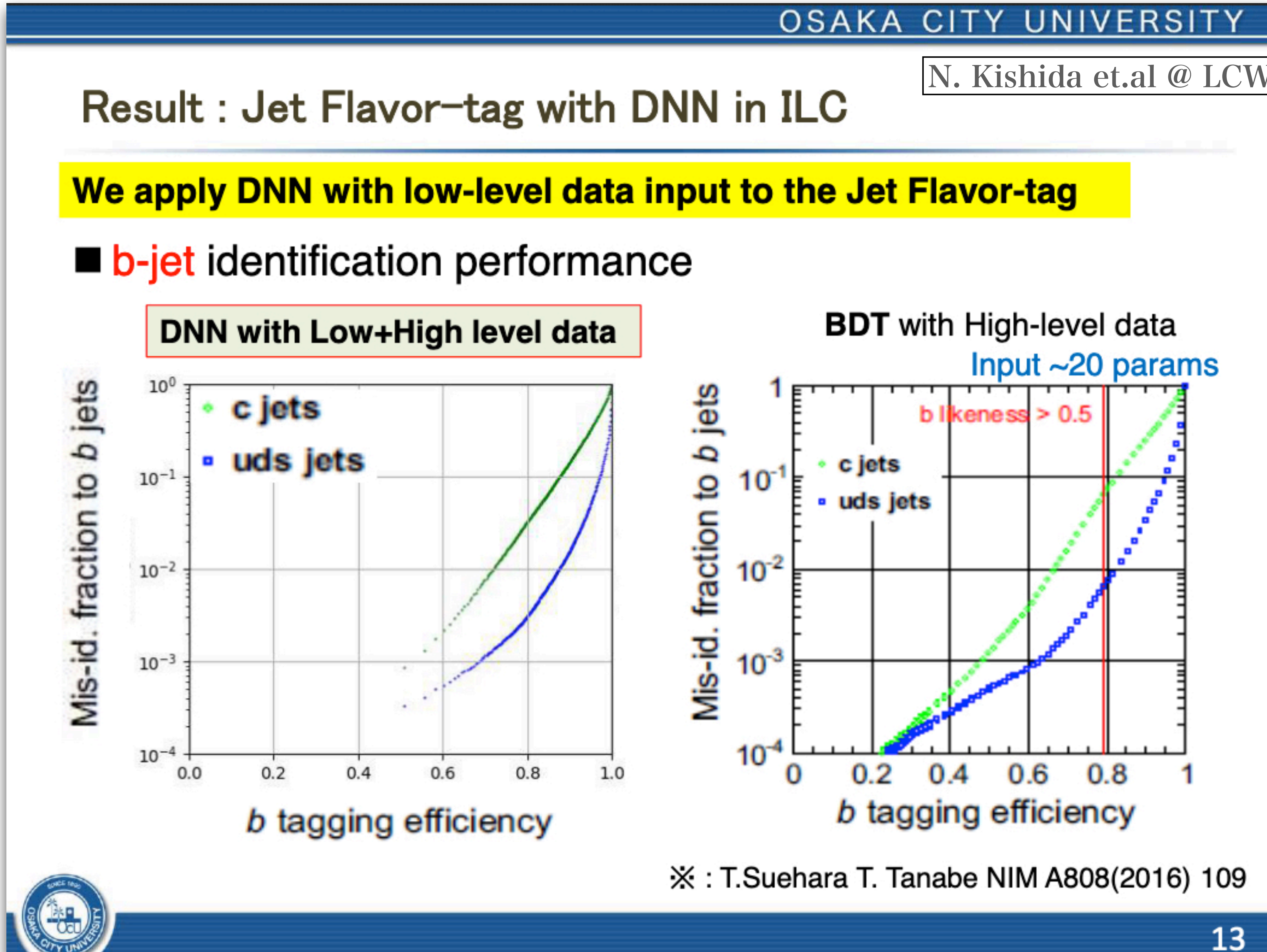
Splitting secondary vertex tracks (e.g. by jet mis-clustering) would easily lose the signatures, especially in “jetty” environment.

—> LCFIPlus searches secondary vertices first, then construct jets keeping the vertex structures.

https://arxiv.org/pdf/1506.08371.pdf

Flavour tagging with DNN

N. Kishida et.al @ LCWS2019

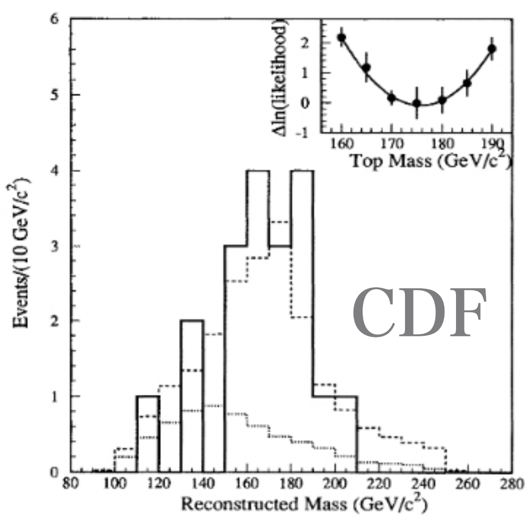


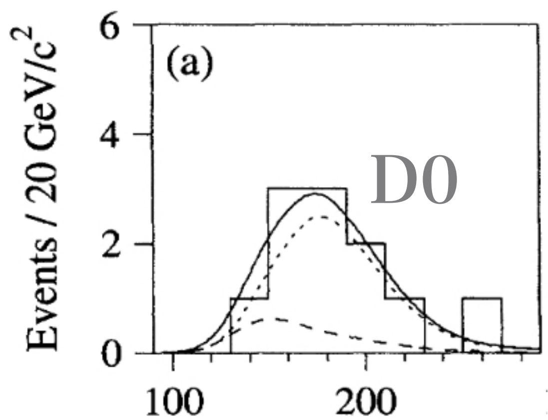
https://agenda.linearcollider.org/event/8217/contributions/44677/

Front runners of Top factories

Top factories : Hadron colliders

- Tevatron at Fermilab



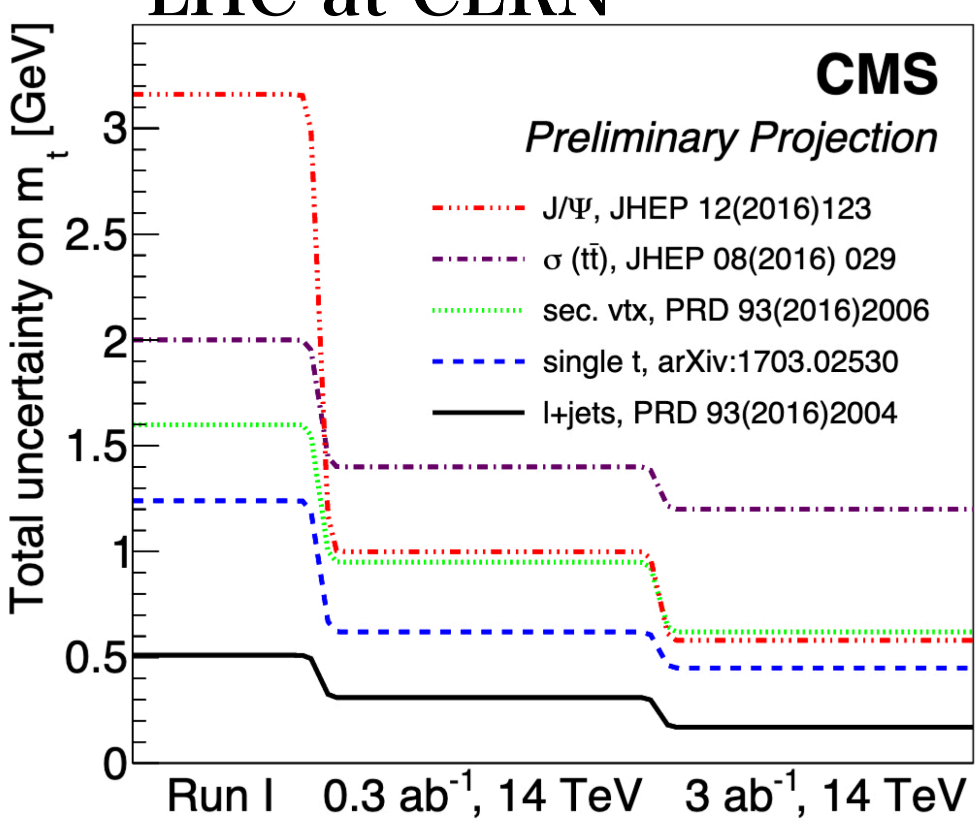


$p\bar{p}$ TeV collider ($\sqrt{s}$~2 TeV)

- Discovery of top quark
- Discovery of single top production
- Measurement of the properties
- Established analyses base etc.

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.74.2626
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.74.2632

- LHC at CERN



https://arxiv.org/pdf/1902.04070.pdf

pp TeV collider ($\sqrt{s}$~14 TeV)

- Discovery of Higgs boson
- Discovery of Yukawa couplings of 3rd generation fermions
- Precise top mass measurements
- Validating SM with many processes in details etc.

Providing precise measurements of top-strong and EW charged current interactions

A lot of measurements validate SM!

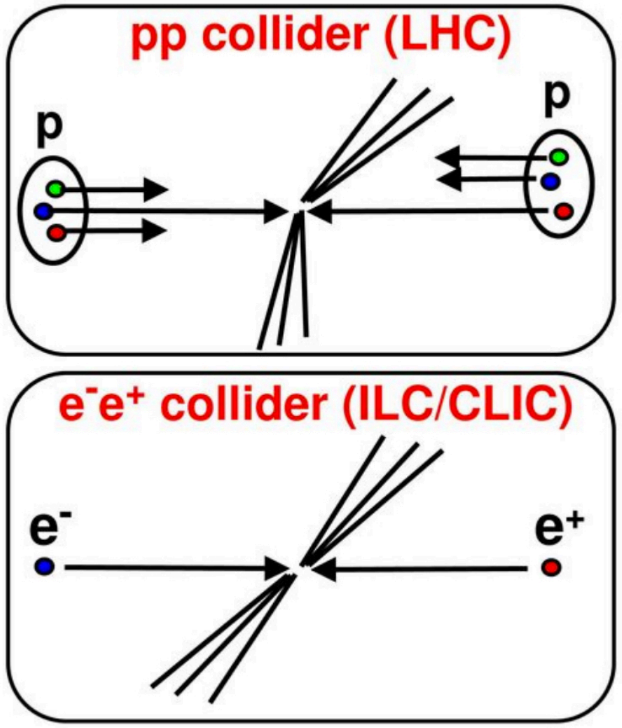
Future e+e- colliders

can also produce top quarks (e.g. e+e- --> tt)

Why e+e- colliders for top?

1. The shape of $t\bar{t}$ threshold cross section is strongly dependent on top mass
   - Center-of-mass energy : adjustable!
   - Theoretically preferable (see next page)

⇒ Scanning t t bound state cross sections around its threshold (~350 GeV) (see page 19, 20)

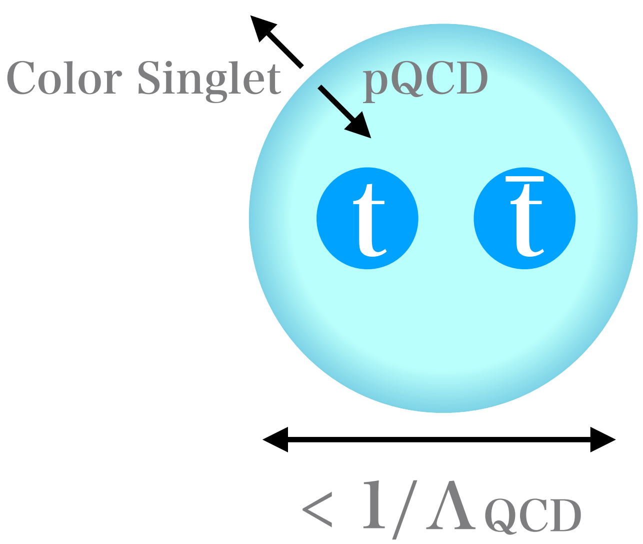


2. Possible to produce top pairs via Z/γ with low QCD background
   Electroweak neutral current interactions of top quark are to be precisely investigated (see page 19, 20)

∗Single top production at e+e- collider :
Single and pair production will be comparable at $\sqrt{s}$~3 TeV (CLIC)

$t\bar{t}$ bound state characteristic

1s bound state



- Top quark decays into bW before hadronization

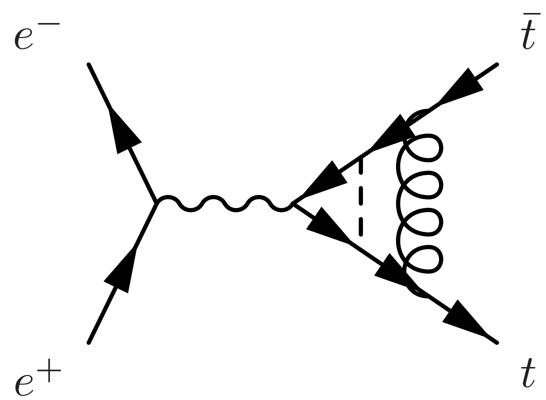
→ $t\bar{t}$ bound state cross section can be calculated by perturbative QCD

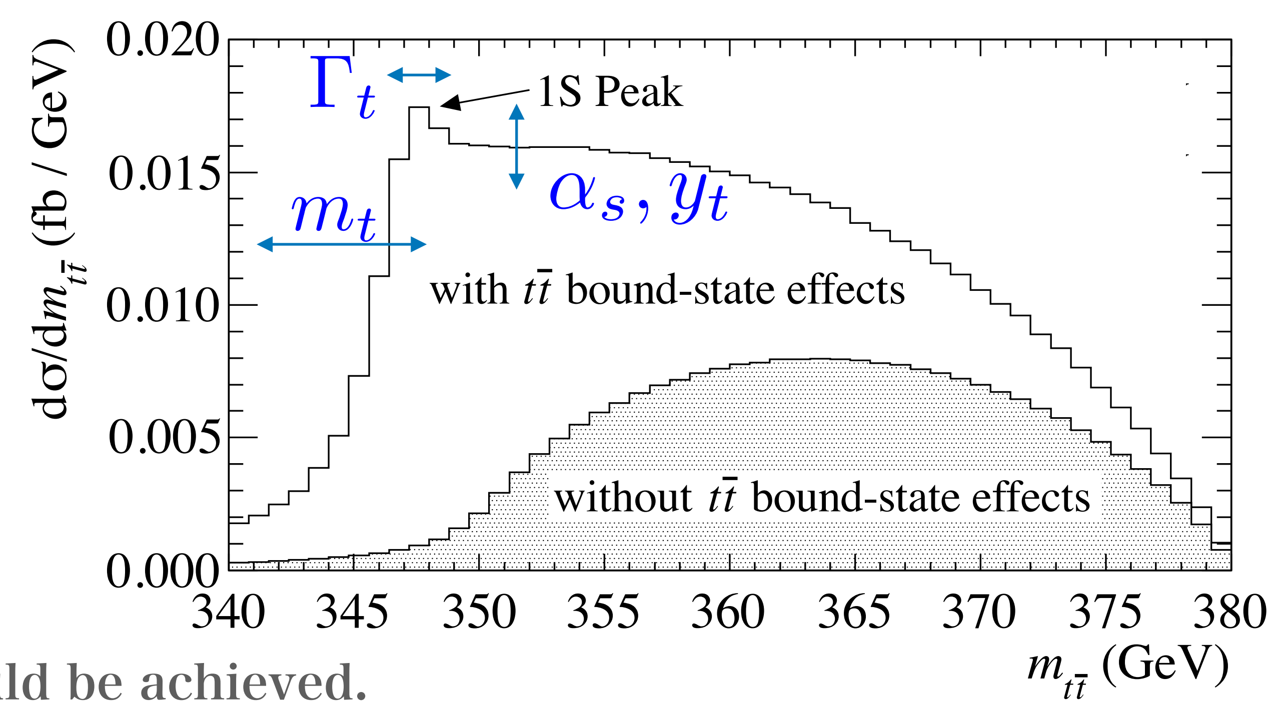
Ideal laboratory to measure top mass!

(PS/1S mass)

- $t\bar{t}$ bound state correction enhances threshold cross section —> QCD test, α_s

Non relativistic QCD correction
+ Higgs boson exchange contribution





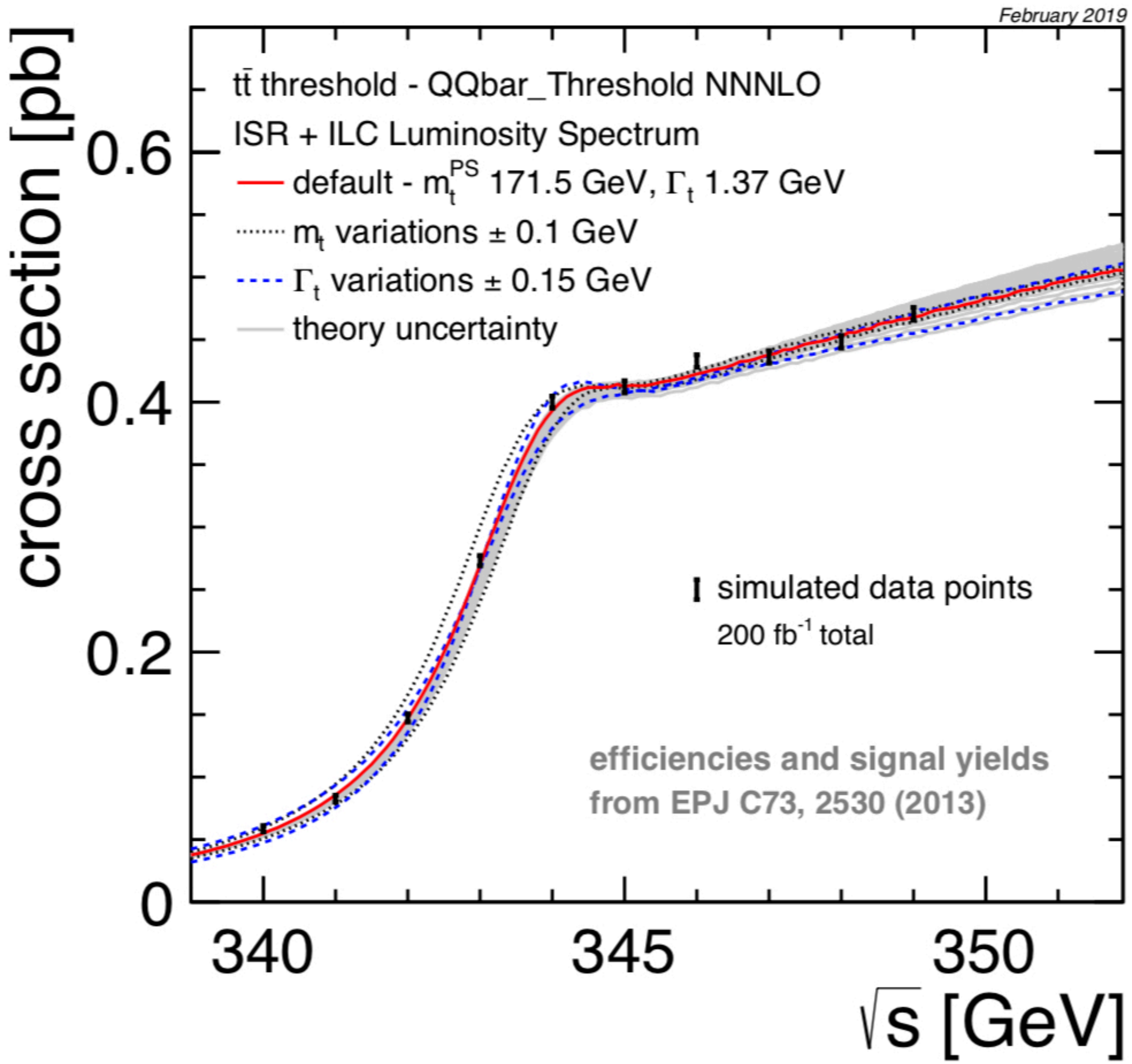
Ideally 4% level Yukawa coupling measurement could be achieved.

Currently it would be 20% due to QCD calculation (N^3LO order + NNLL resummation)

Several top quark properties can be extracted by scanning tt bound state cross section

Extraction of top mass (1)

https://arxiv.org/pdf/1903.01629.pdf



Precise theoretical understanding of the shape of the $t\bar{t}$ threshold

—>

Scanning the cross section at several energy point will be a good test

Total uncertainty on $\overline{\text{MS}}$ mass
~ 50 MeV

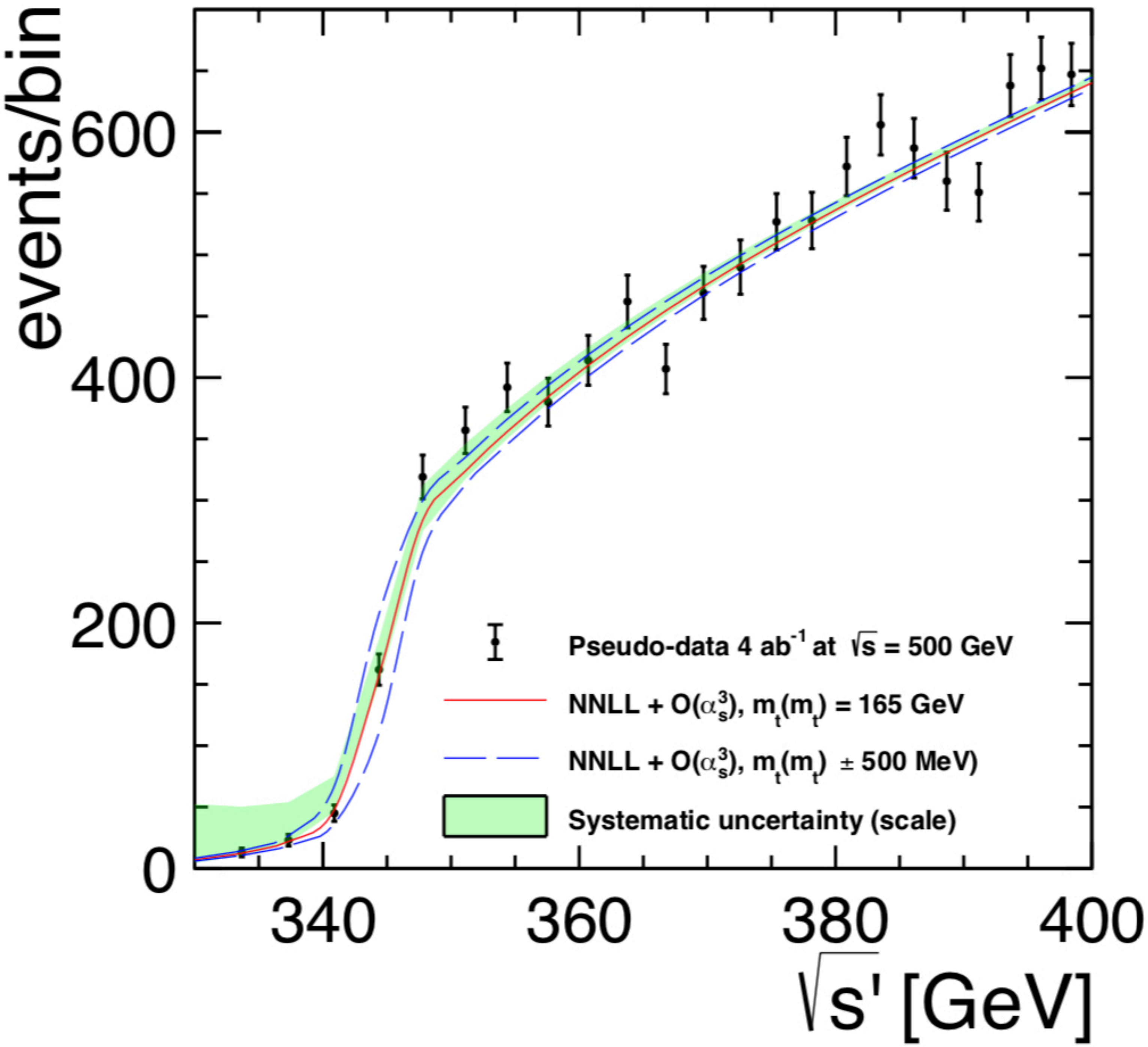
Understanding relation between MS mass and jet invariant mass would help LHC analyses.

See also Kacper Nowak @ LCWS2019 https://agenda.linearcollider.org/event/8217/contributions/44657/

Marcel Vos et. al @ LCWS2019 https://agenda.linearcollider.org/event/8217/contributions/44591/

Extraction of top mass (2)

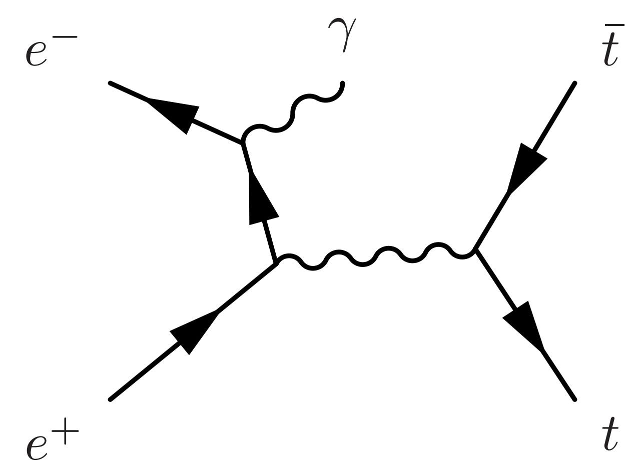
https://agenda.linearcollider.org/event/8217/contributions/44591/



center-of-mass energy of tt system

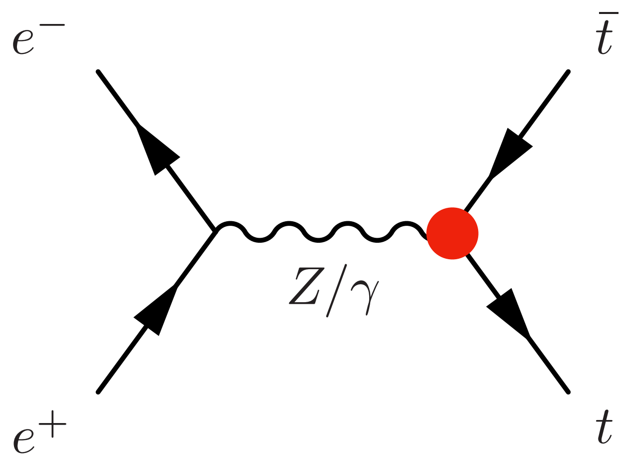
Even above t $\bar{t}$ threshold, ISR emission allows us to perform threshold scan

Radiative events



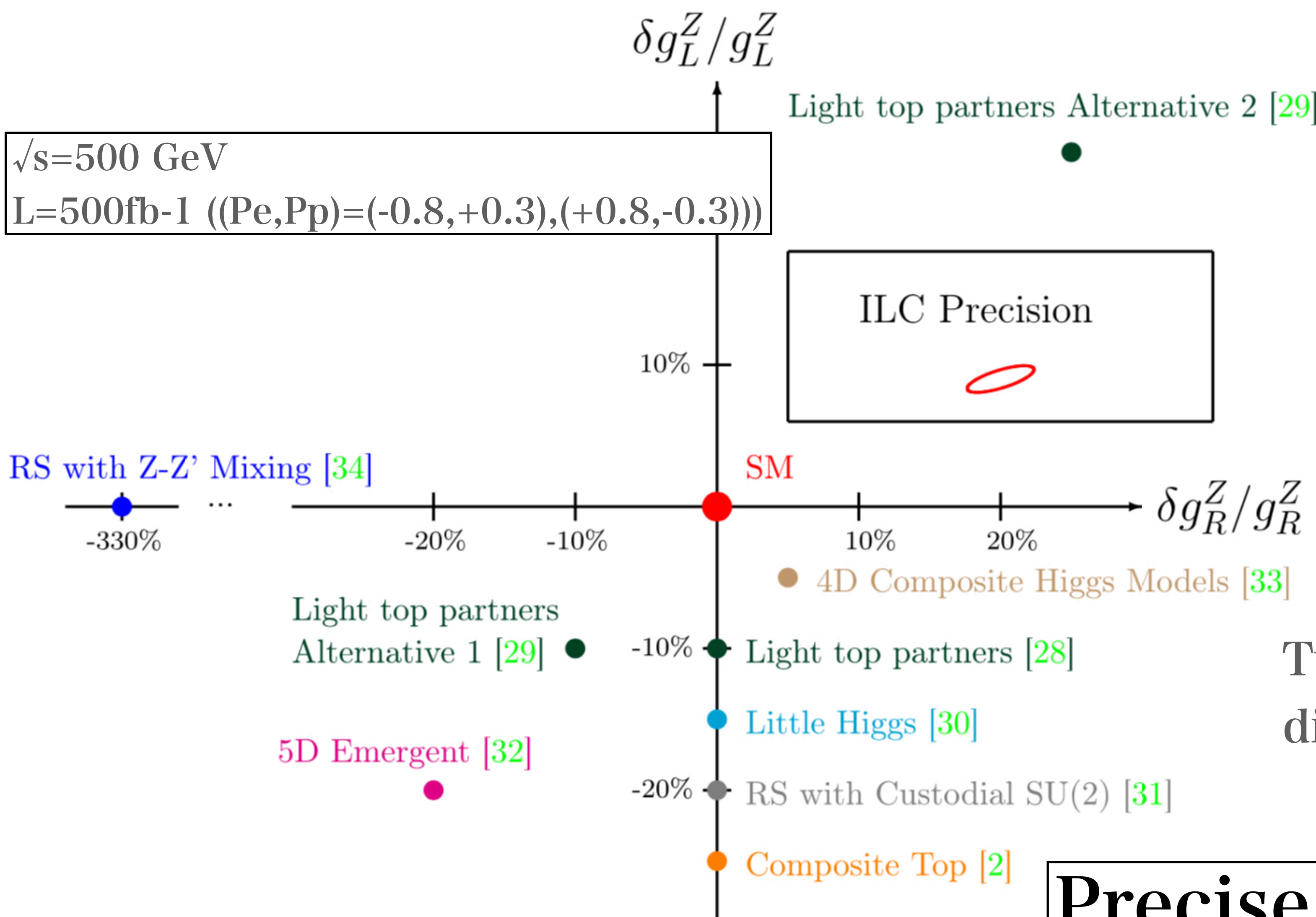
Total uncertainty on $\overline{\text{MS}}$ mass below 200 MeV

Anomalous EW couplings



Form factors in a general expression for ttZ/γ vertices

$$\mathcal{L}_{\rm int} = \sum_{v=\gamma,Z} g^v \left[V_l^v \bar t \gamma^l (F_{1V}^v + F_{1A}^v \gamma_5) t + \frac{i}{2m_t} \partial_\nu V_l \bar t \sigma^{l\nu} (F_{2V}^v + F_{2A}^v \gamma_5) t \right]$$



Why √s=500 here?
t $\bar{\text{t}}$ cross section is high
(ZHH, t $\bar{\text{t}}$ H measurements)

Two beam polarizations allow to disentangle Z/γ form factors.

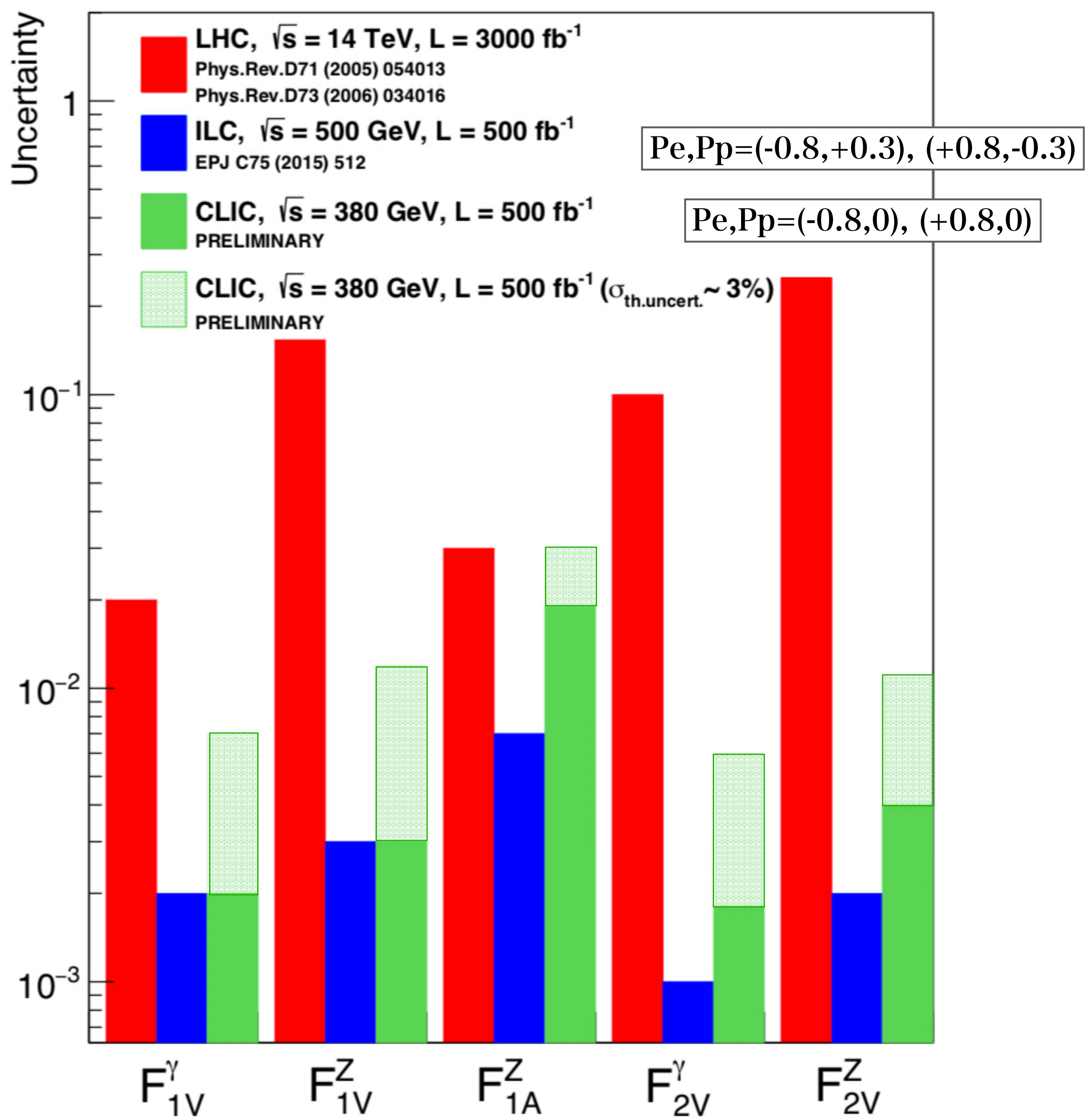
Precise EW coupling probes BSM

https://doi.org/10.1140/epjc/s10052-015-3746-5

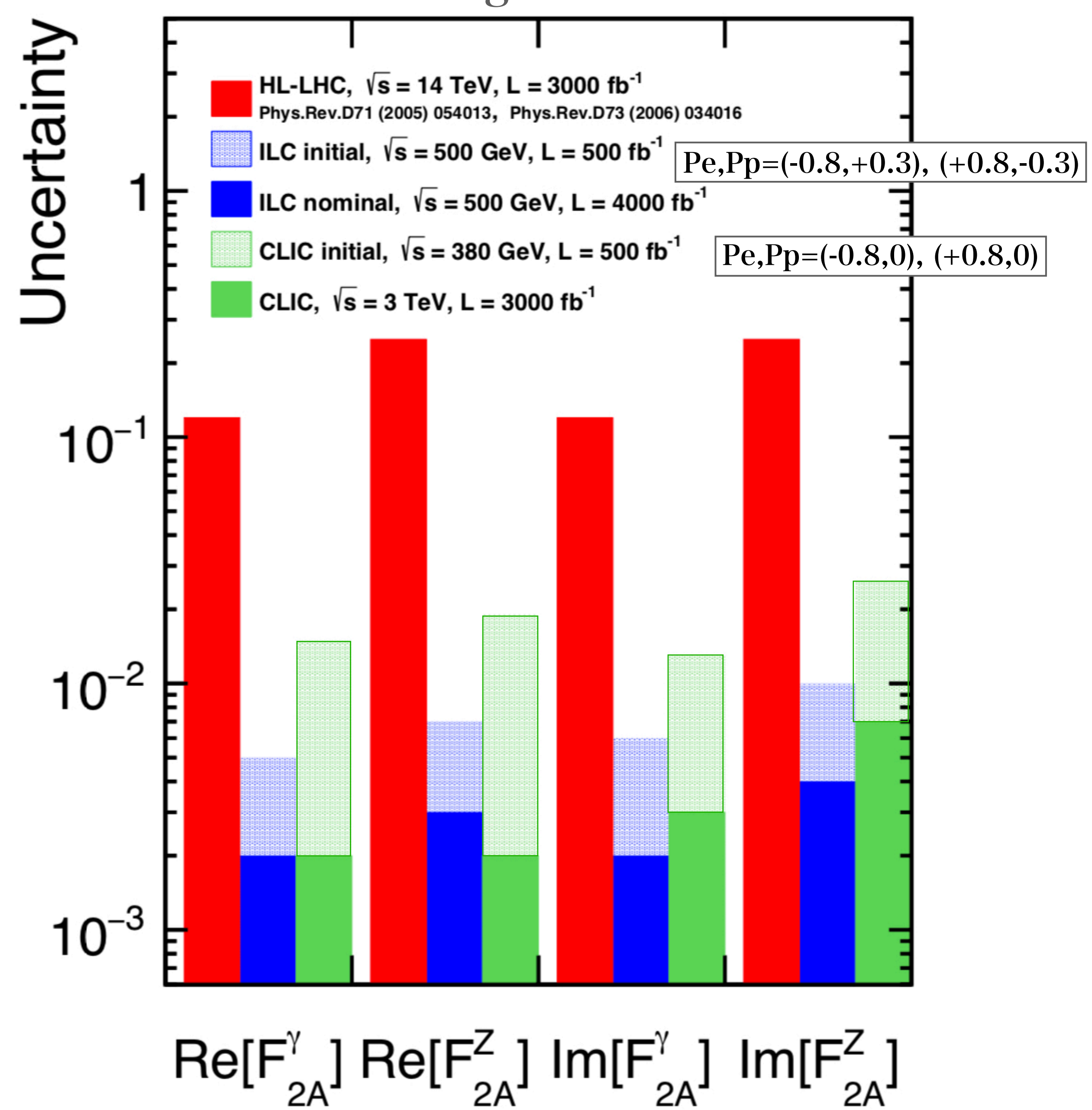
Prospects for top EW coupling

https://arxiv.org/pdf/1903.01629.pdf
https://arxiv.org/pdf/1710.06737.pdf

Statistical uncertainty on
CP conserving form factors



Statistical uncertainty on
CP violating form factors



e^+e^- top factories will elucidate top quark properties!

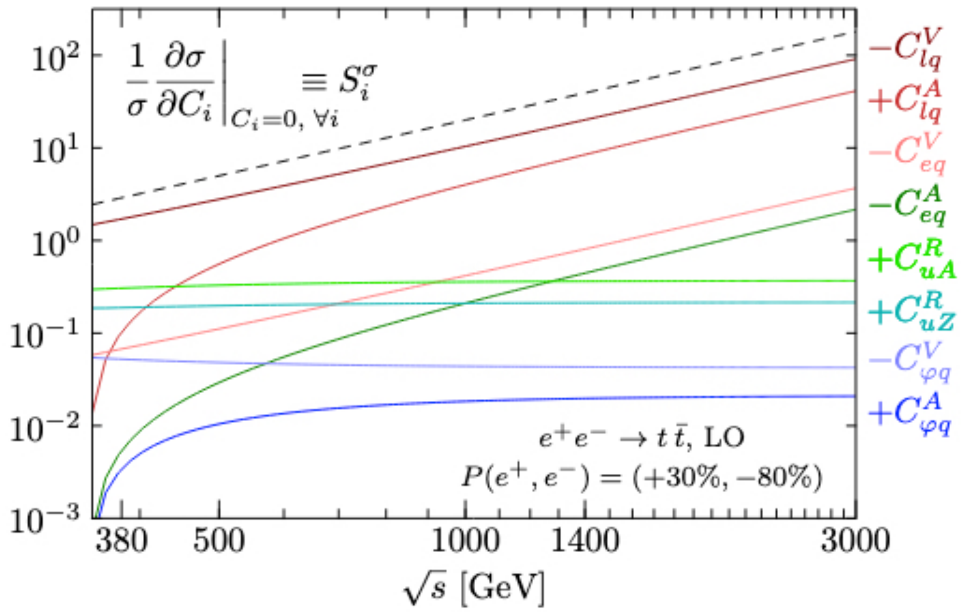
Top quark Effective Field Theory

To generalize anomalous coupling description :

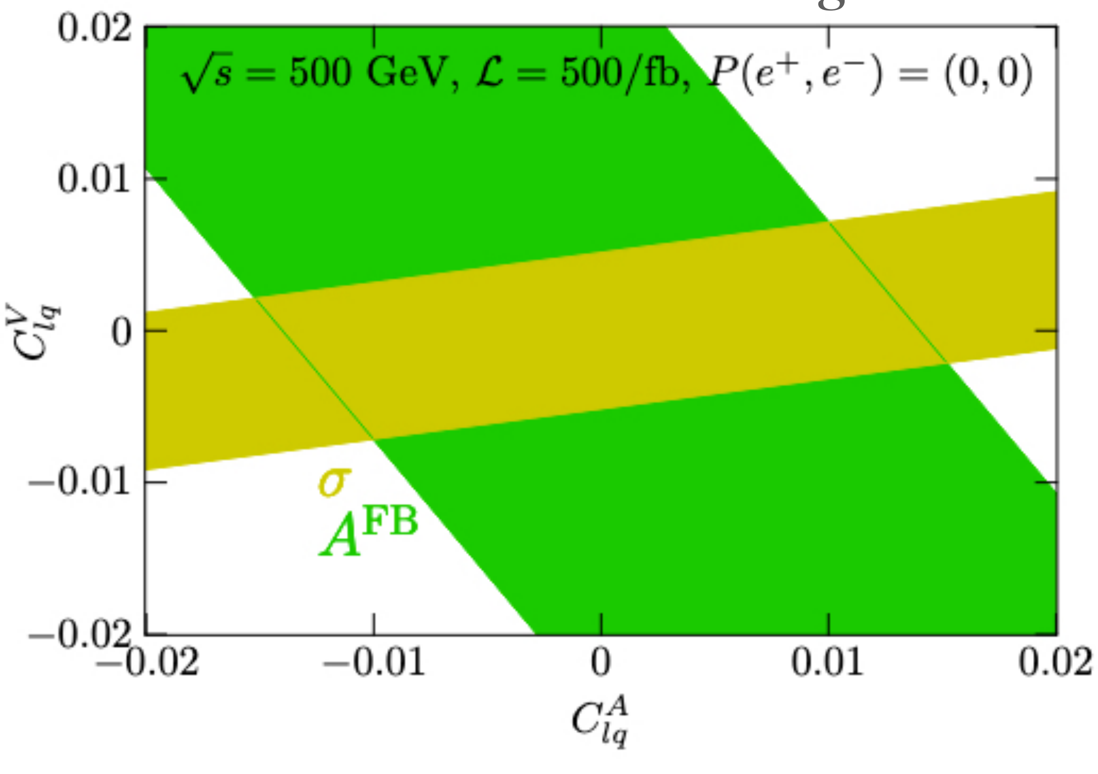
https://arxiv.org/pdf/1807.02121.pdf

Parameterize deviations from SM in $t\,\bar{t}$ production using dimension-six effective operators

Sensitivity of σtt to operators



68% C.L. allowed region



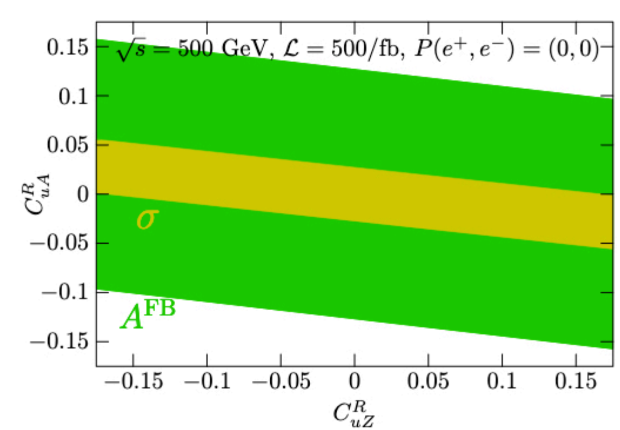
Observables (measurements)
(e.g. σtt, AFB, top polarization, CP-odd observables)

⇩

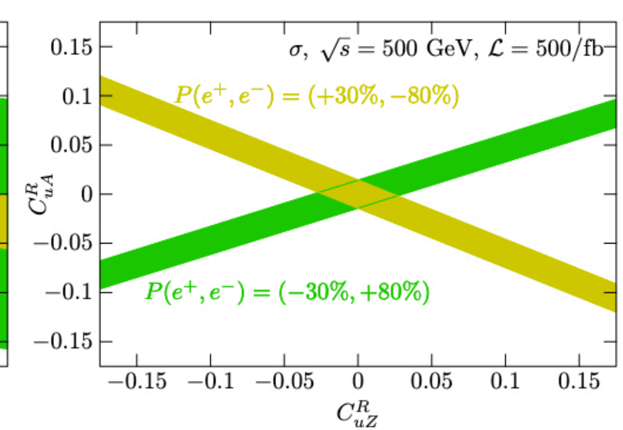
Constrain operator coefficients
—> Robust BSM probes

＊For some coefficients,
beam polarization gives tight constraint

w/o beam pol

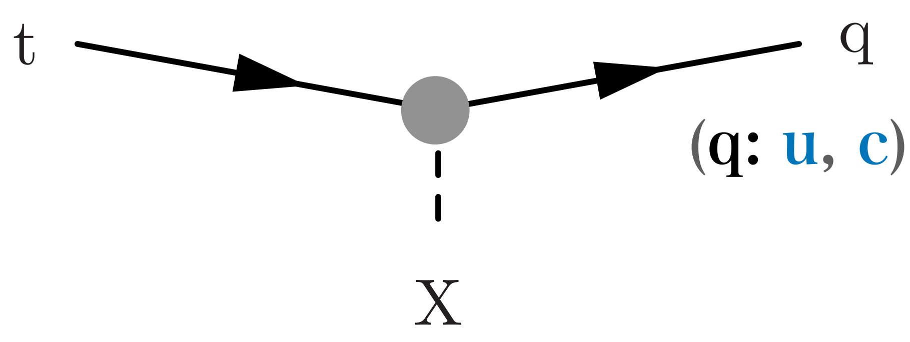


w/ beam pol



Flavour-Changing Neutral Current

Forbidden at tree level, highly suppressed at loop level (GIM mechanism) in SM

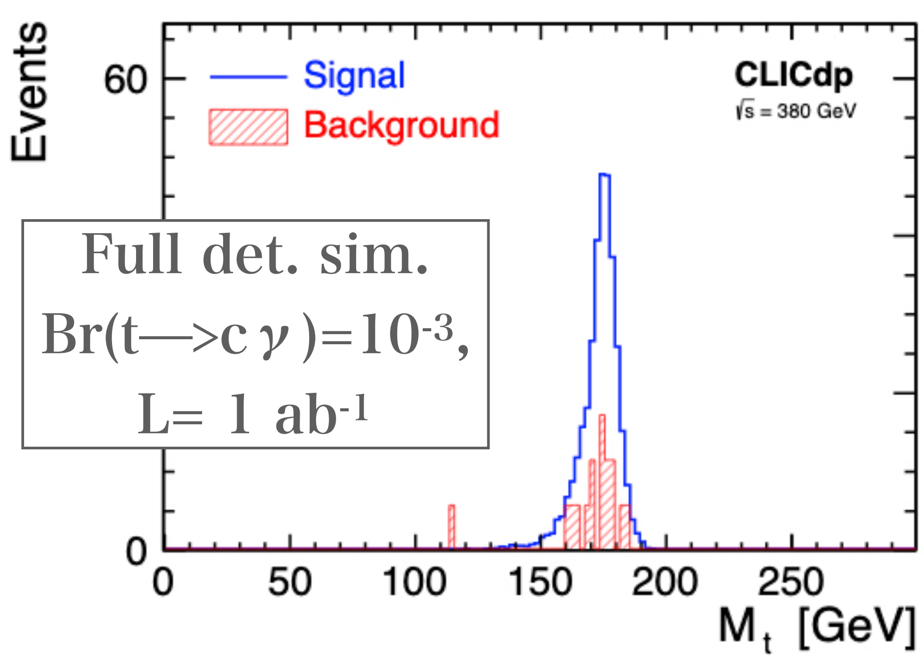


(X: g, γ ,Z, H, DM)

Several BSM scenarios predict contributions to FCNC processes

- Tree level FCNC couplings
- Loop level contributions of new particles/properties

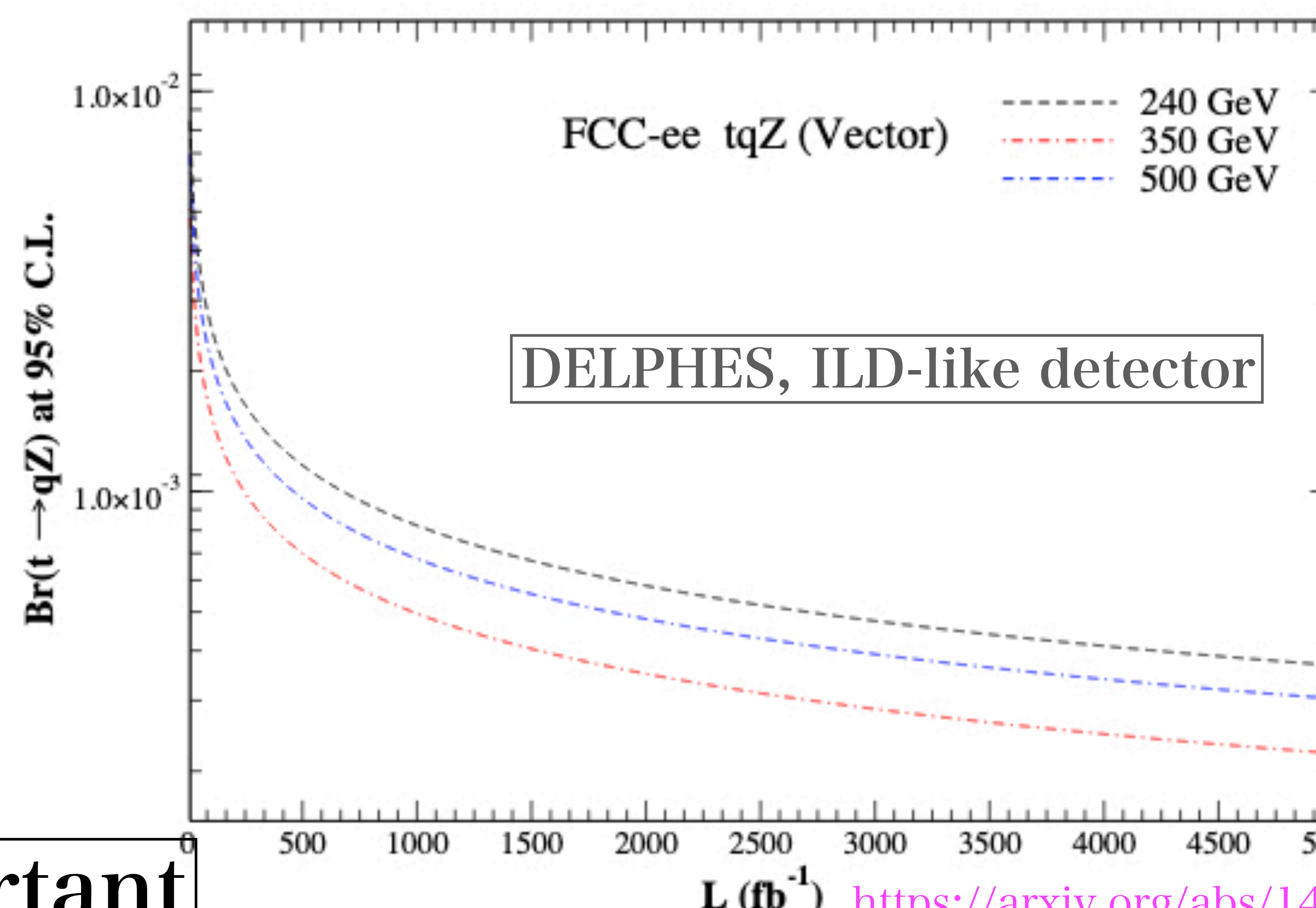
Reconstructed mass after signal selection



Full det. sim.
Br(t—>c γ)=10^{-3},
L= 1 ab^{-1}

https://arxiv.org/pdf/1807.02441.pdf

Single top production e+e- —> t c



DELPHES, ILD-like detector

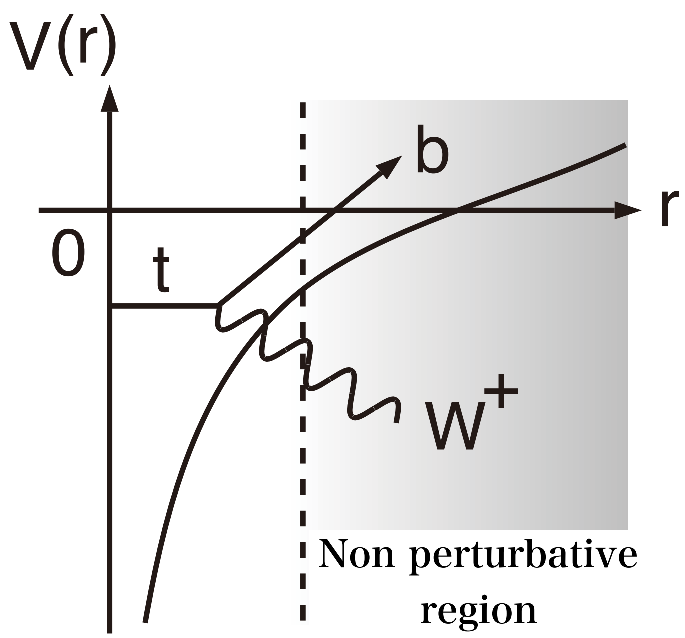
https://arxiv.org/abs/1408.2090

Charm tagging is also important

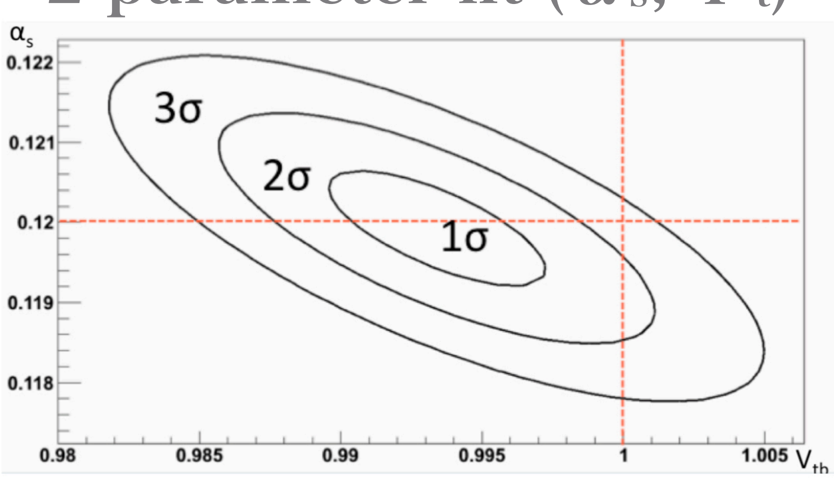
See also https://arxiv.org/pdf/1906.04573.pdf (CEPC)

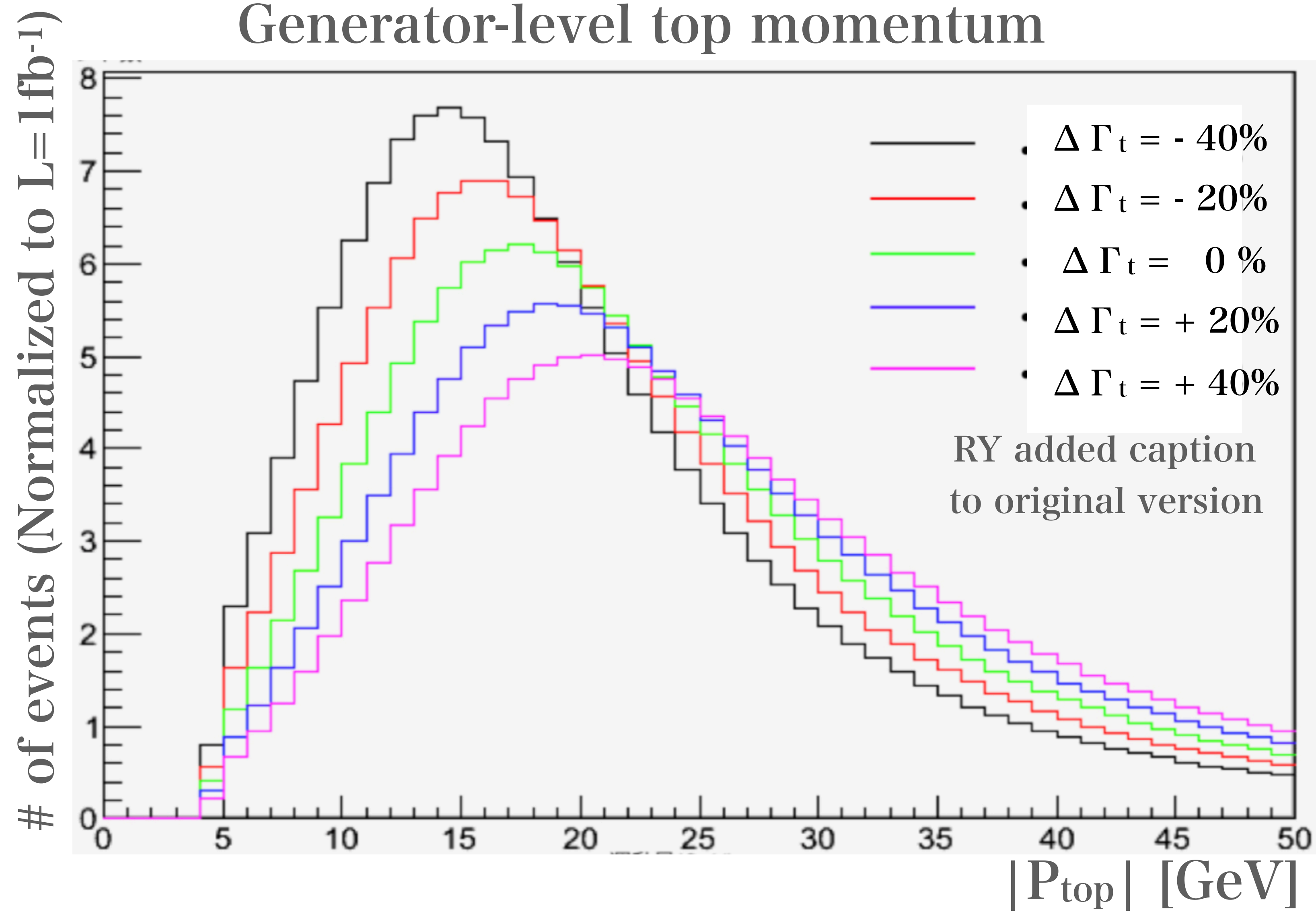
Top decay width from momentum

Y. Eda @ Tohoku U.



2 parameter fit (α_s, Γ_t)





- $\sqrt{s}$: optimized for a m_t ($\sqrt{s}$=347 GeV for m_t = 174 GeV)
- α_s also changes P_{top} distribution

Basic concept has been confirmed with toy MC data.
Probably templates used in study were to be generated depending not only on |P| but also polar angle that was missing. —> Future work

Matrix element method for fully leptonic mode

Y. Sato @ Tohoku U.
collaboration with LAL

See also https://arxiv.org/pdf/1503.04247.pdf

Optimal variable (ω) for form factors F

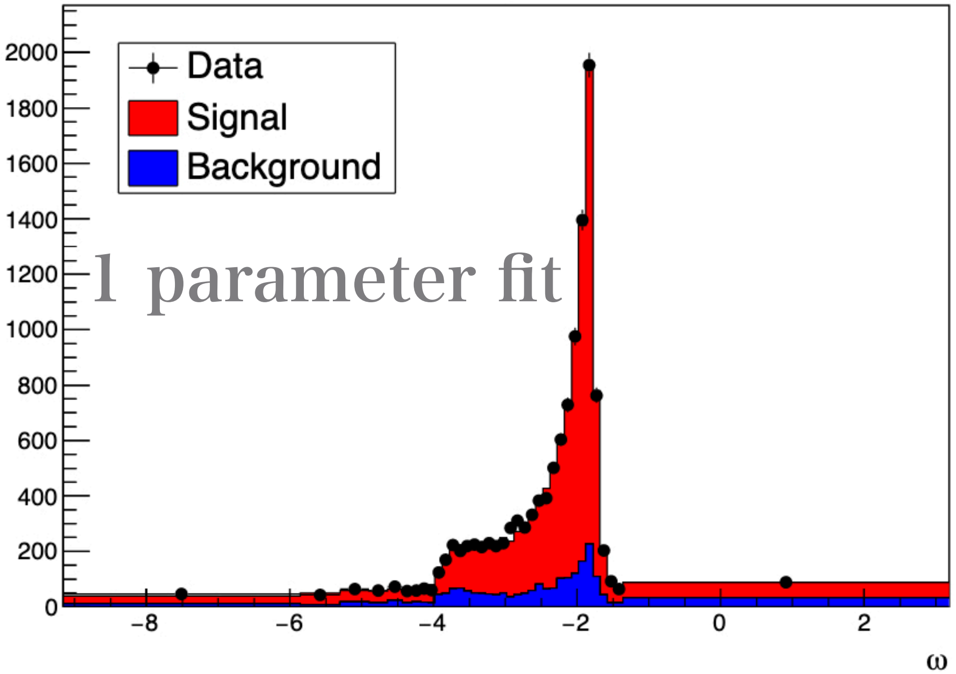
$$\omega_i(\boldsymbol{\Phi}) := \frac{1}{|M(\boldsymbol{\Phi};\boldsymbol{F}_{\mathrm{SM}})|^2} \cdot \left.\frac{\partial |M(\boldsymbol{\Phi};\boldsymbol{F})|^2}{\partial F_i}\right|_{\boldsymbol{F}=\boldsymbol{F}_{\mathrm{SM}}}$$

$$\begin{aligned}\boldsymbol{F} &= (F_1,F_2,F_3,F_4,F_5,F_6,F_7,F_8,F_9,F_{10}) \\ &:= (F_{1V}^{\gamma},F_{1V}^{Z},F_{1A}^{\gamma},F_{1A}^{Z},F_{2V}^{\gamma},F_{2V}^{Z},\mathrm{Re}F_{2A}^{\gamma},\mathrm{Re}F_{2A}^{Z},\mathrm{Im}F_{2A}^{\gamma},\mathrm{Im}F_{2A}^{Z})\end{aligned}$$

$$\boxed{\boldsymbol{\Phi} := (\cos\theta_t,\cos\theta_{W^+},\phi_{W^+},\cos\theta_{W^-},\phi_{W^-},\cos\theta_{l^+},\phi_{l^+},\cos\theta_{l^-},\phi_{l^-})}$$

$\Rightarrow$ Measurement variables

(W—>qq case is more challenging because of necessity of identification of W^+/W^-)



Obtain F_i by fitting with templates of ω (n^{sim}) :

$$\chi^2(F_i) = \sum_{ibin=1}^{nbin} \left(\frac{n_{ibin}^{Test} - n_{ibin}^{sim}(F_i)}{\sqrt{n_{ibin}^{Test}}} \right)^2$$

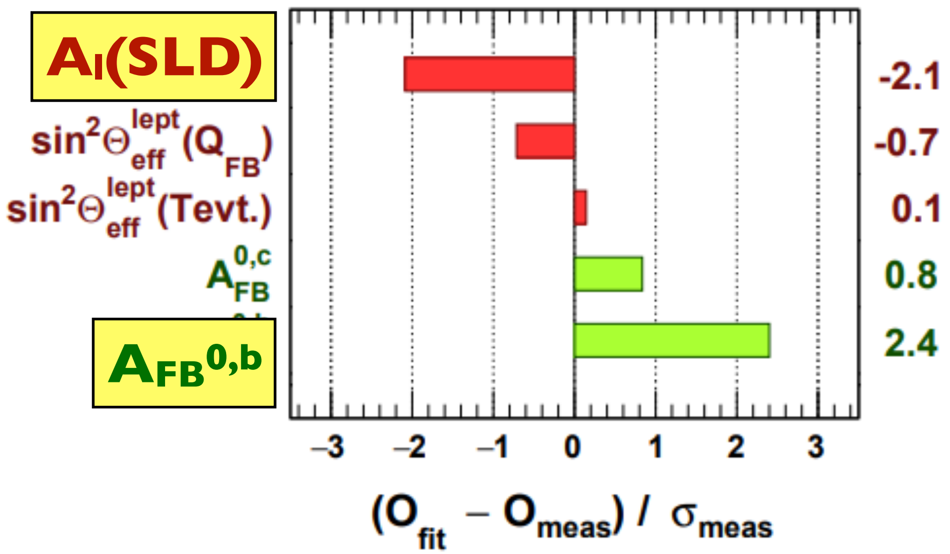
10~40% better performance to method by σ_{tt} and A_{FB} has been confirmed.

Multi parameter fit/Hadronic mode —> Future study

Extra : bbar production (σ_{bb}, A_{FB})

- b_L quark is the same SU(2)×U(1) partner of top quark
- b_R quark is not well constrained by earlier experiments

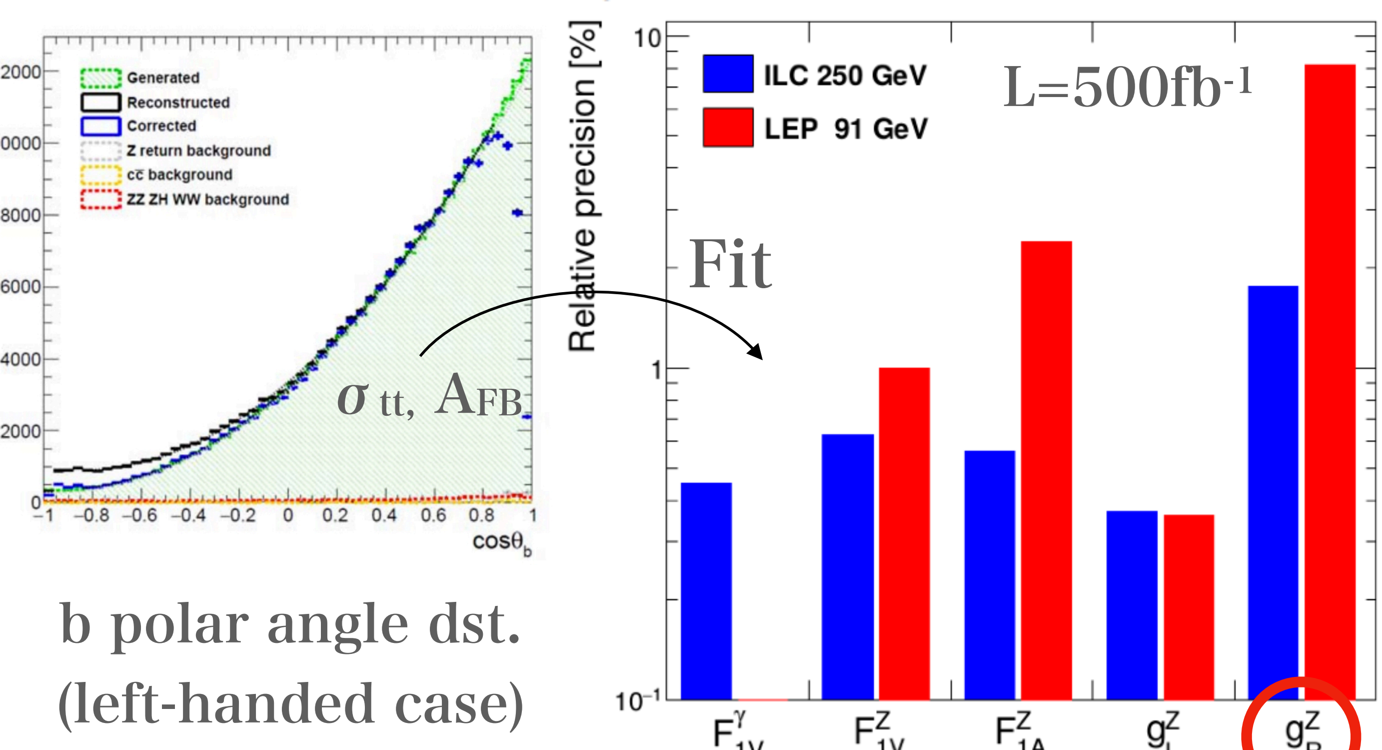
Global EW fit https://arxiv.org/pdf/1803.01853.pdf



3 σ discrepancy between $\sin^2\theta_w$ from A^b_{FB} at LEP and one from A_l at SLC

BSM models can explain LEP anomaly on $\sin^2\theta_w$
→ https://arxiv.org/pdf/hep-ph/0610173.pdf

Precise measurement of A^b_{FB} itself is interesting, but is also important to constrain other parameters



b polar angle dst.
(left-handed case)

Identifying b-quark is crucial
(vertex charge / Kaon charge)

~5 times better precision

Keys : - higher luminosity
- beam polarization

Applicable for other fermion pairs

https://arxiv.org/ftp/arxiv/papers/1709/1709.04289.pdf
Recent updates :
https://indico.cern.ch/event/577856/contributions/3420337/

Summary

- Top quark plays a key role to unravel EWSB
- Jet Clustering and Flavour tagging are crucial for top physics
- What are to be done at future e+e- colliders :
  - $t\bar{t}$ threshold scan —> m_t, Γ_t, α_s, y_t
  - Searches anomalous coupling, especially with neutral current :
    - FCNC processes
    - anomalous ttZ/γ coupling
  - and bottom quark (and other fermion) pairs, too

and should be more!

Mass scheme

$\overline{\mathrm{MS}}$ mass

Theoretically preferable at high energies :
Frequently used in precision calculation

Poor convergence at tt threshold region

Pole mass

Defined as pole of quark propagators
Numerically close to generator mass parameter

PS mass

Stable at tt threshold region
Can rigorously be converted to $\overline{\mathrm{MS}}$ mass with high precision

Compactly summerized in https://arxiv.org/pdf/1807.02441.pdf

Boosted top tagging

https://arxiv.org/pdf/1807.02441.pdf

Small separation between individual top decay products

Top tagger algorithm --> searching substructures