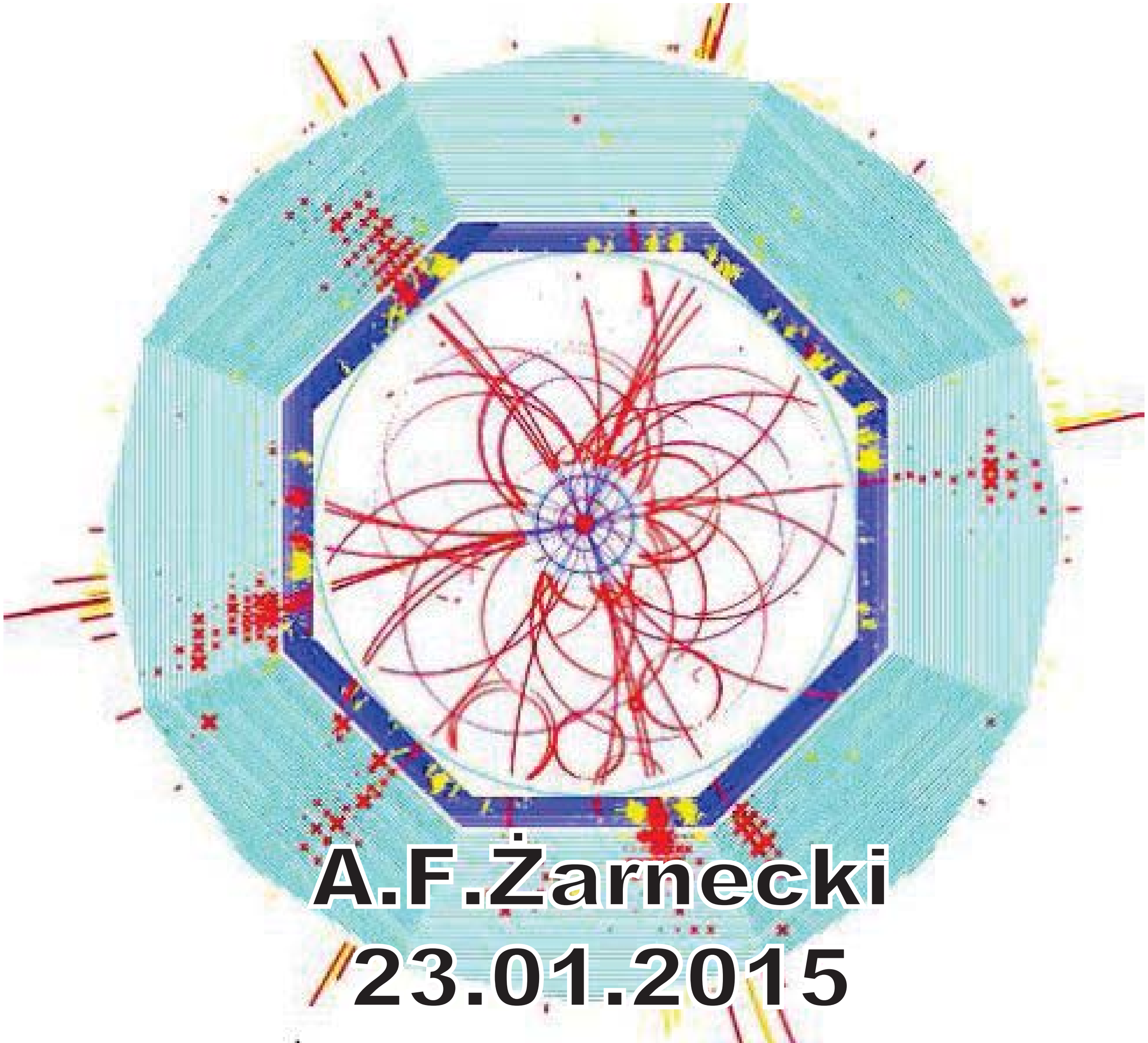
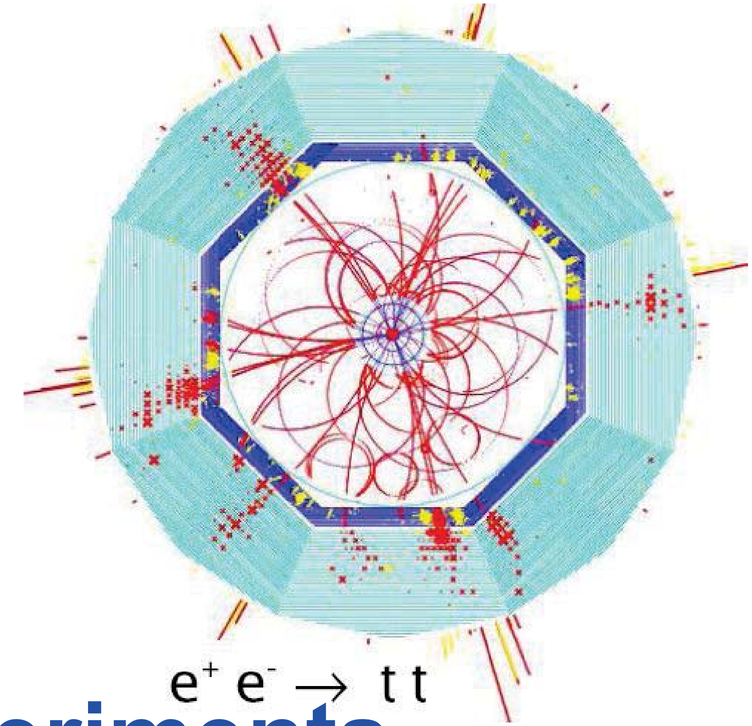
Top physics at future e^+e^- colliders



A.F.Żarnecki

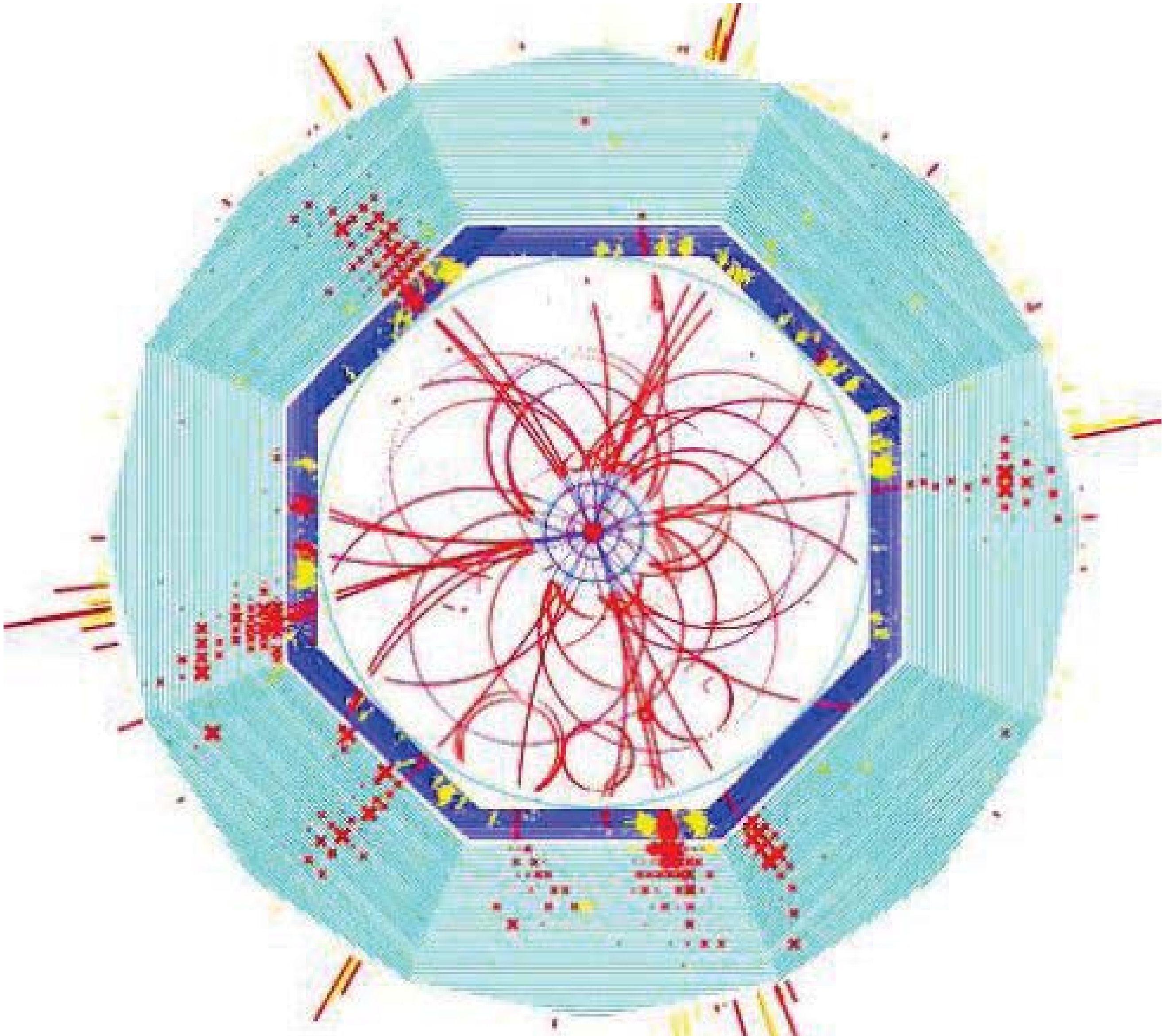
23.01.2015

Outline


$e^+ e^- \rightarrow t\,t$

- Introduction
- Motivation
- Future colliders and experiments
- Prospects for precise measurements
  - threshold scan and top mass
  - Yukawa coupling
  - EW couplings

Introduction

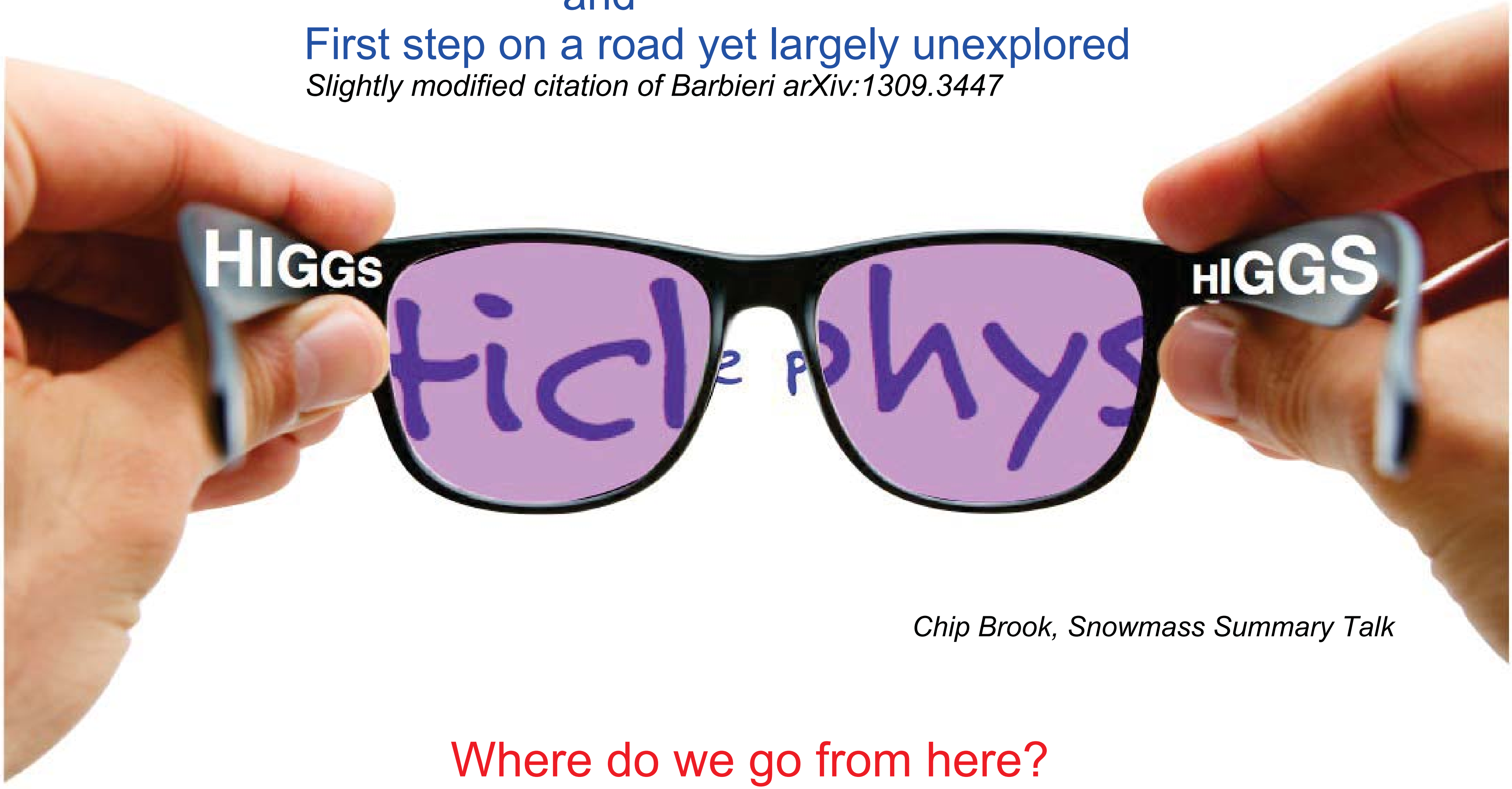


$e^+ e^- \rightarrow t t$

2012: New view on Particle Physics ...

Coronation of the Standard Model
and
First step on a road yet largely unexplored

Slightly modified citation of Barbieri arXiv:1309.3447



Chip Brook, Snowmass Summary Talk

Where do we go from here?

Peeping through the Higgs window!

P5 likes Particle Astrophysics

Five science drivers:

- Higgs boson
- Neutrino mass
- Dark matter
- Cosmic acceleration
- Explore the unknown

Particle Astrophysics experiments address all but the first

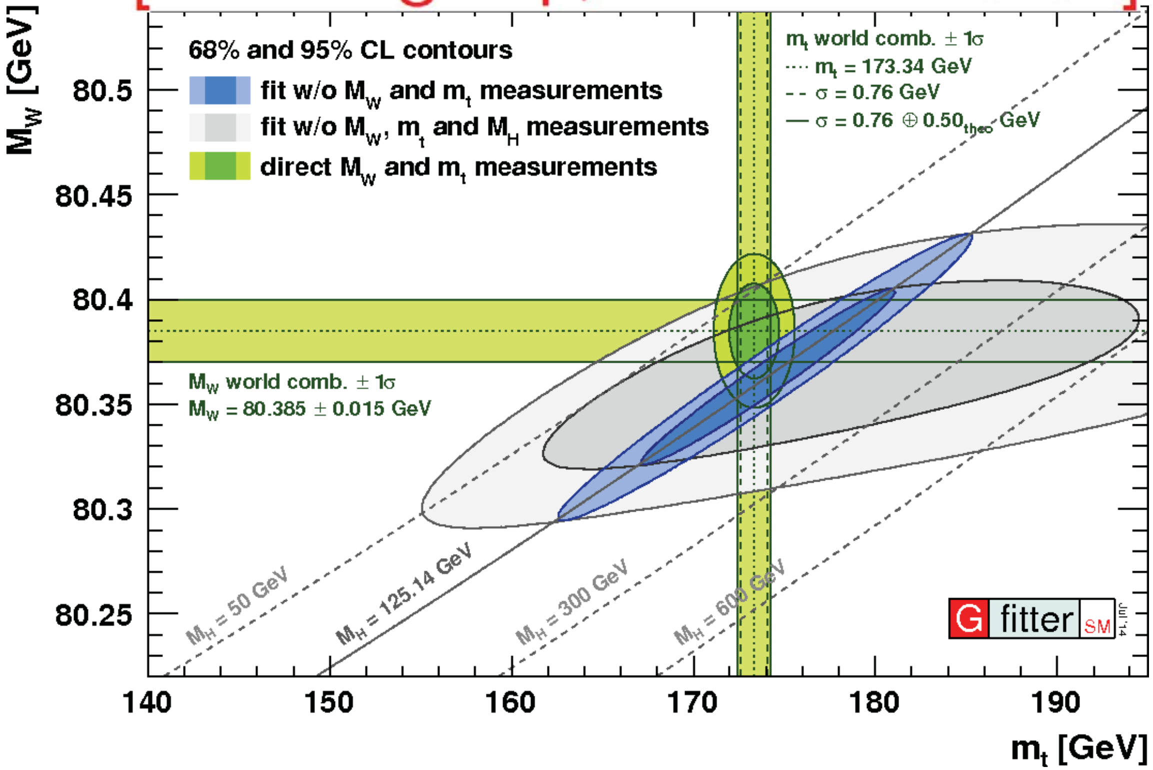
Many experiments address more than one

Report supports expanded dark matter program, new cosmic surveys, and a new multi-agency program in CMB

Probing the Standard Model

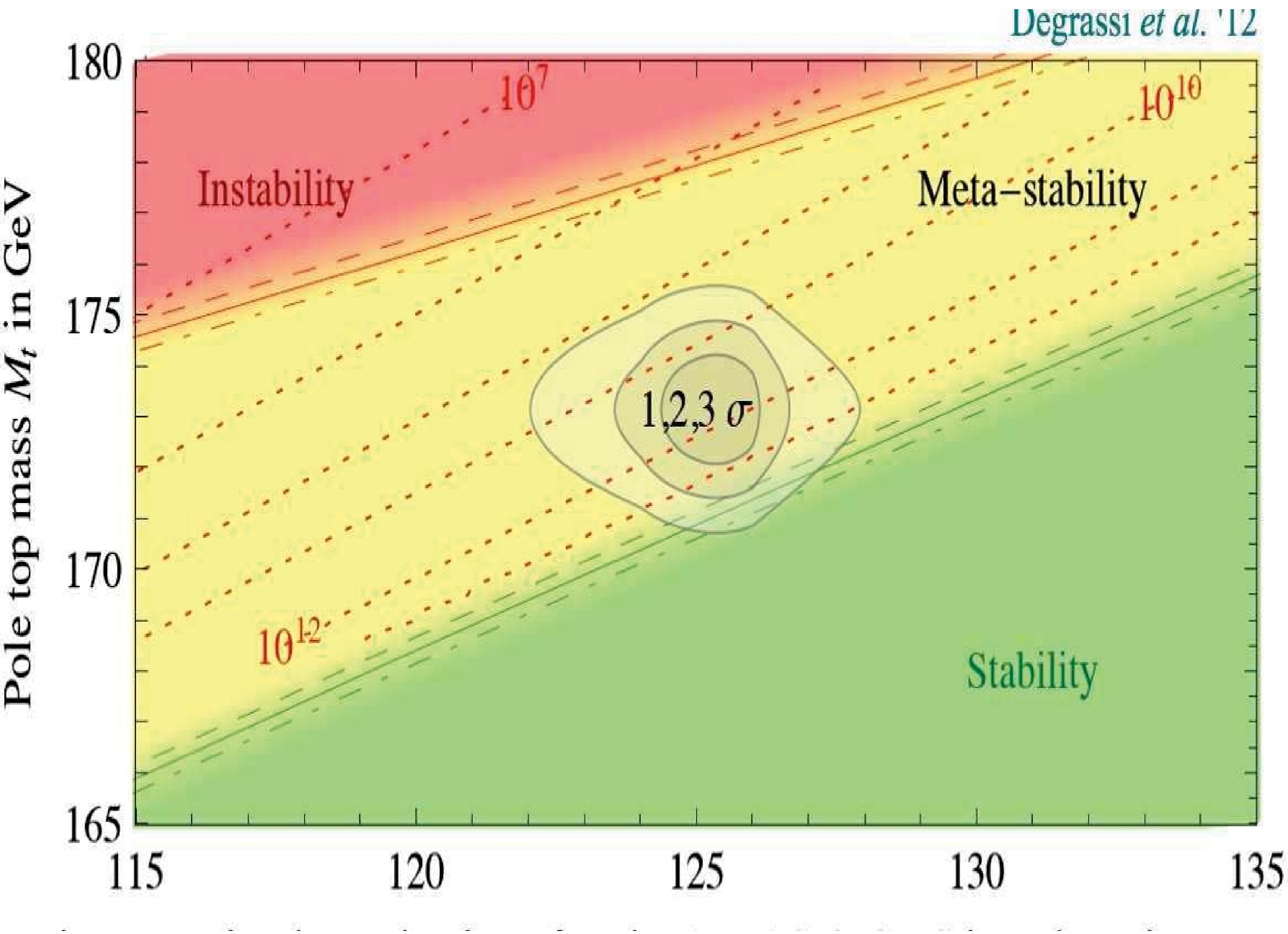
- SM is self-consistent model accounting all particle physics phenomena at energy of current accelerators
  - with m_H all parameters of SM are known

[GFitter group, arXiv:1407.3792]

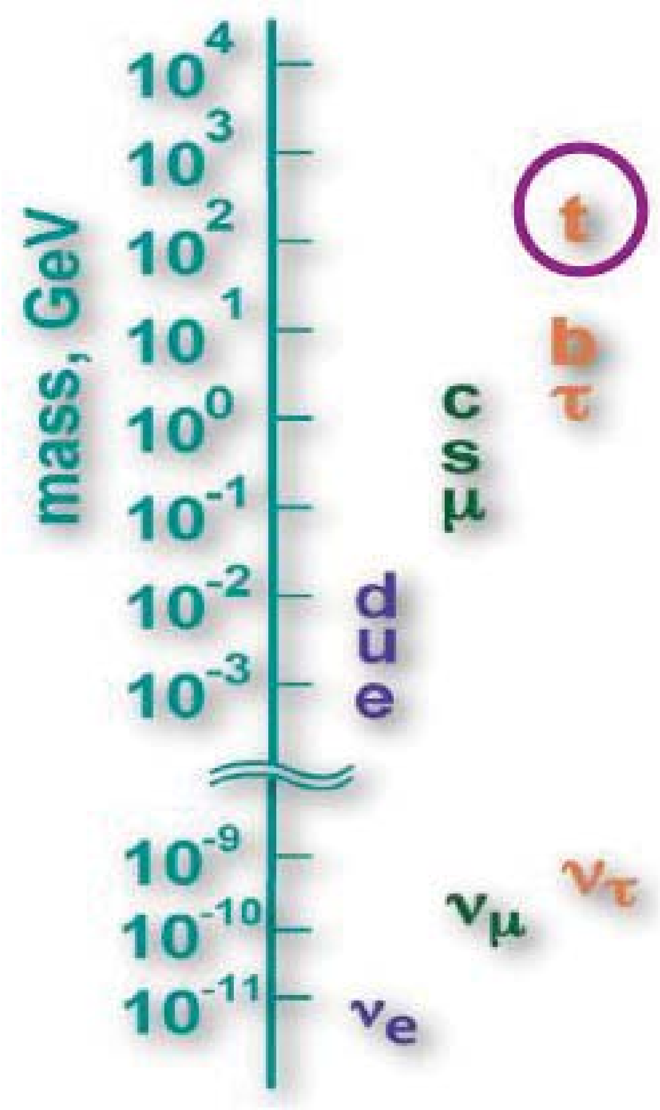


m_W = 80385 ± 15 MeV
m_t = 173.34 ± 0.76 GeV
m_H = 125.36 ± 0.41 GeV
Current p-value for (data|SM)=0.2
Need to improve m_W, m_t and m_H

Precision tests of further consistency of the SM are mandatory


Degrassi et al. '12
Pole top mass M_t in GeV
180
175
170
165
115
120
125
130
135
Instability
Meta–stability
Stability
10^7
10^{10}
10^{12}
1,2,3 σ

Top Quark and Flavor Hierarchy



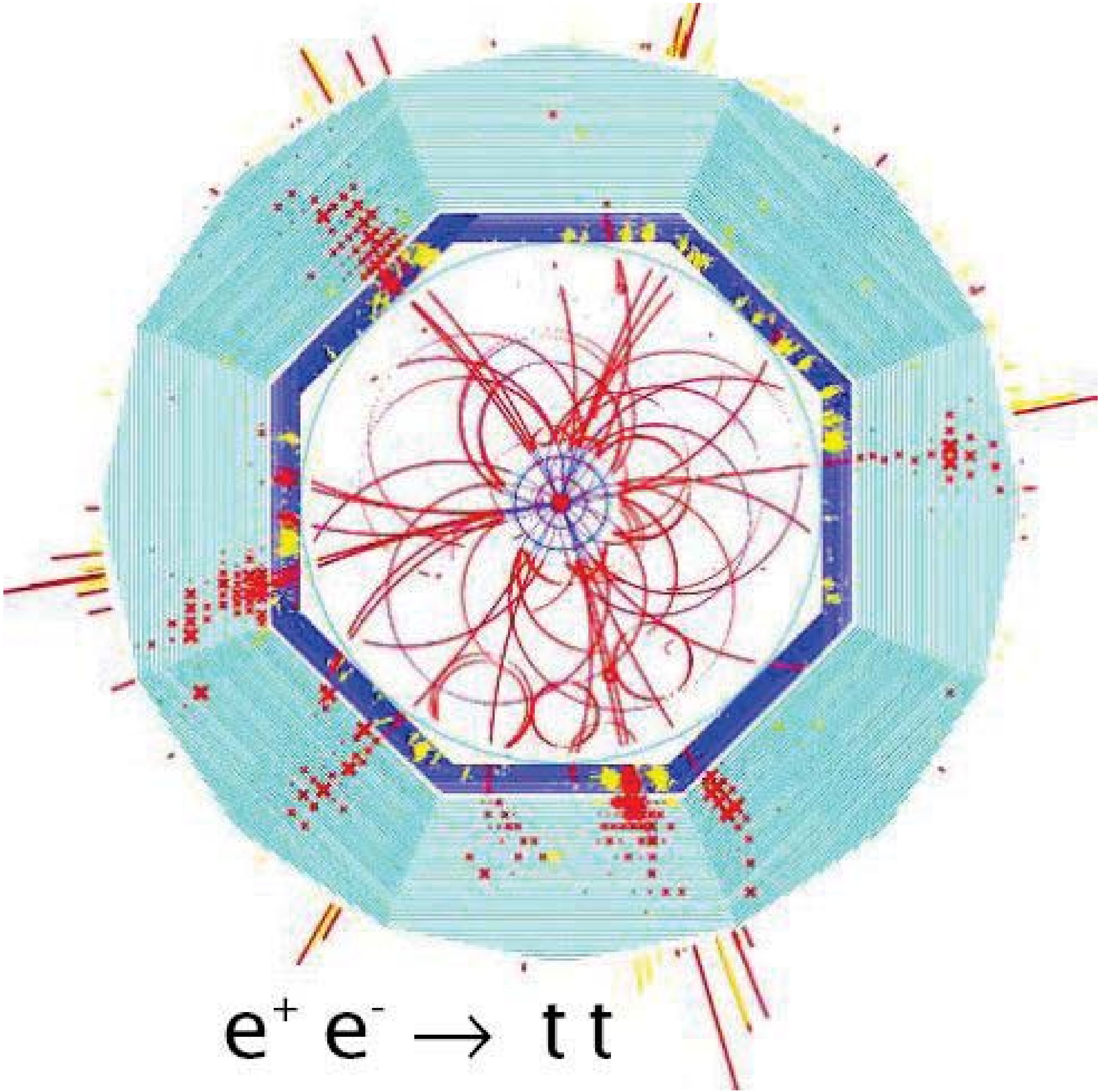
- SM does not provides no explanation
  for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related
  to the origin electroweak symmetry breaking

- Expect residual effects for particles with
  masses closest to symmetry breaking scale

Strong motivation to study chiral structure
of top vertex in high energy e+e- collisions

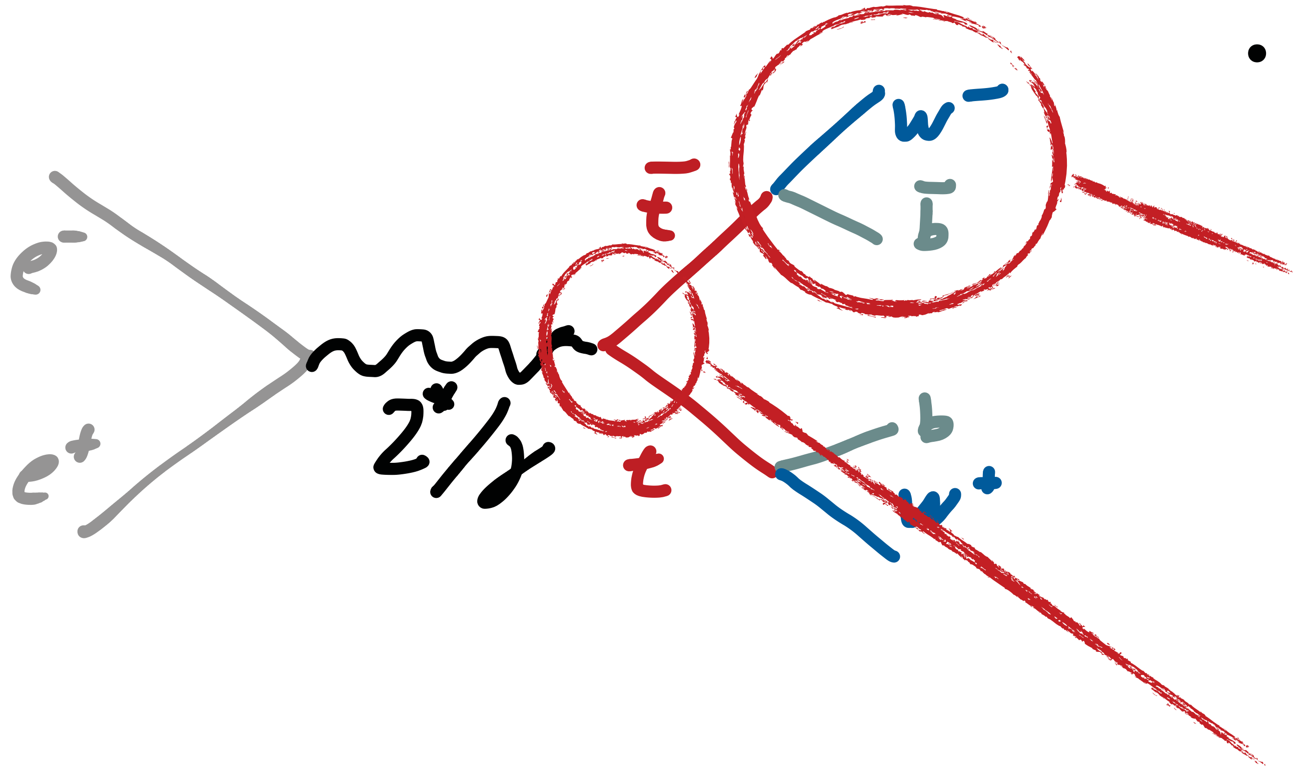
Motivation



$e^+ e^- \rightarrow t\,t$

Top Quark Physics at Linear Colliders

- The dominant production mechanism: Top pair production



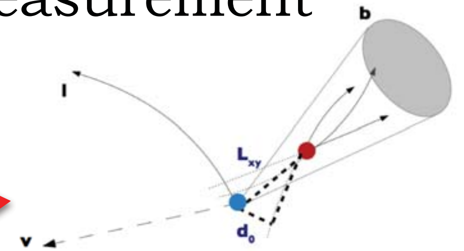
- Rich physics opportunities:
  - Top properties: **mass**, width, decay modes
  - BSM sensitivity: CP violation, flavor-changing decays,…

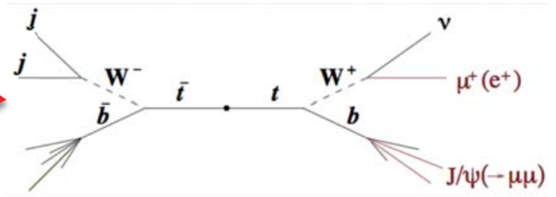
  - Top properties: **mass**, width,
  - Yukawa coupling, strong coupling constant
  - **Electroweak couplings** - sensitivity to BSM physics

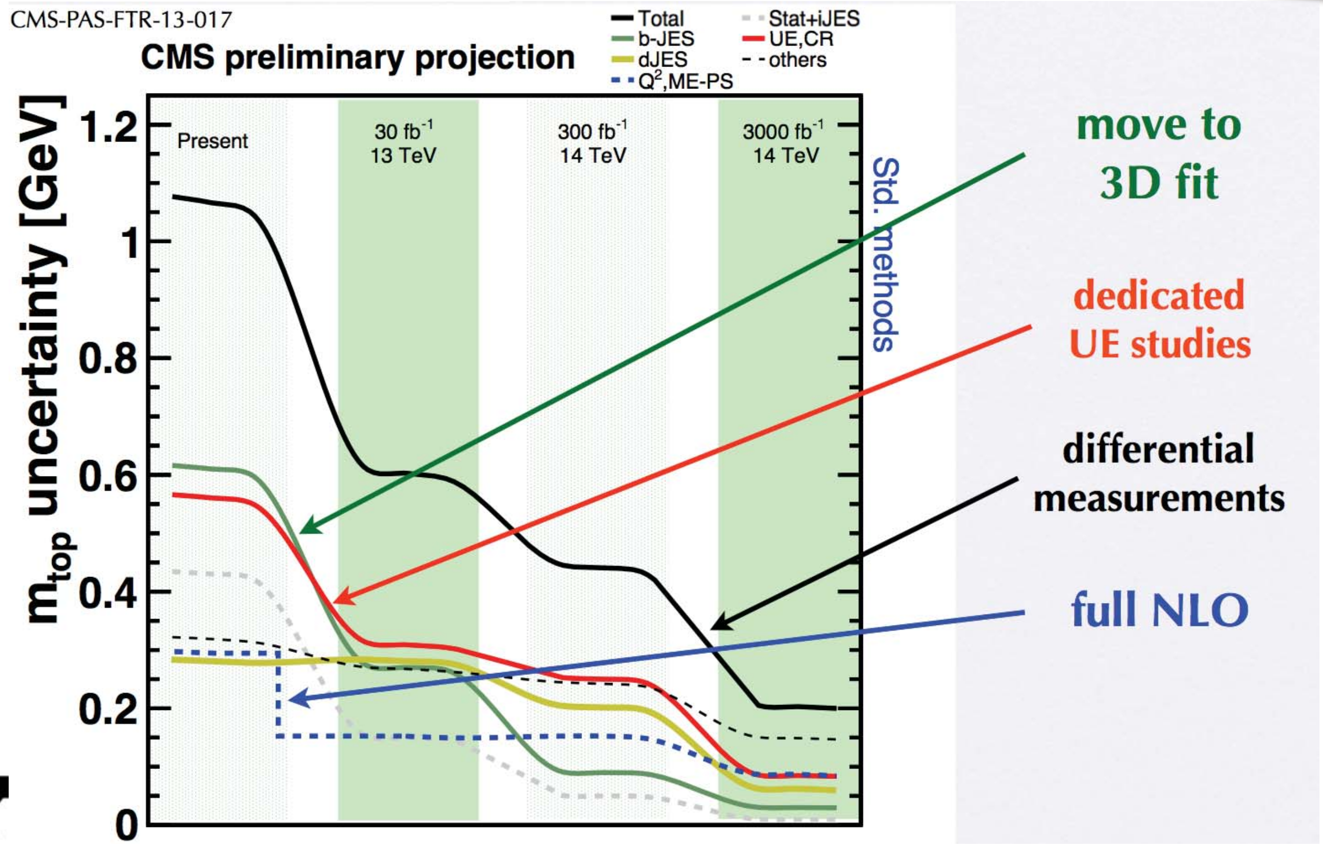
- Measurements enabled by
  - known initial state & clean final state
  - Possibility for **polarized beams** - crucial for coupling measurements

Top Mass Outlook

- For the projections used the baseline lepton+jets measurement at 7 TeV: JHEP **12** (2012) 105
  - CMS PAS FTR-13-017
  - And more methods with higher stats
    - Kinematic endpoints **(M_{lb} distribution)**
    - B-hadron lifetime (aka Lxy)
    - J/Psi method







move to 3D fit

dedicated UE studies

differential measurements

full NLO

CM (TeV)	7	13	14
L int (fb^{-1})	*5*	*30*	*300*
J/ψ		*1.8*	***0.8***
Lxy (8 TeV)	*3.4*	*1.3*	***0.6***
Endpoints	*2.1*	*1.1*	***0.6***
Standard	1.1	0.6	**0.4**

Concept of a Quark Mass

Short-distance mass schemes:

$$m^{\mathrm{sd}}(R) = m^{\mathrm{pole}} - R\left(a_1\frac{\alpha_s}{4\pi} + a_2\left(\frac{\alpha_s}{4\pi}\right)^2 + \ldots\right)$$

Generic form of a short-distance mass scheme.

$\overline{\text{MS}}$ mass: $R = \overline{m}(\mu)\,, \quad a_1 = \frac{16}{3} + 8\ln\frac{\mu}{m}$

Processes where heavy quarks are off-shell and energetic.

Threshold masses (1S, PS, RS, kinetic masses)

$$R \sim m\alpha_s$$

Quarkonium bound states: heavy quarks are close to their mass-shell.

Jet masses (jet mass)

$$R \sim \Gamma_Q$$

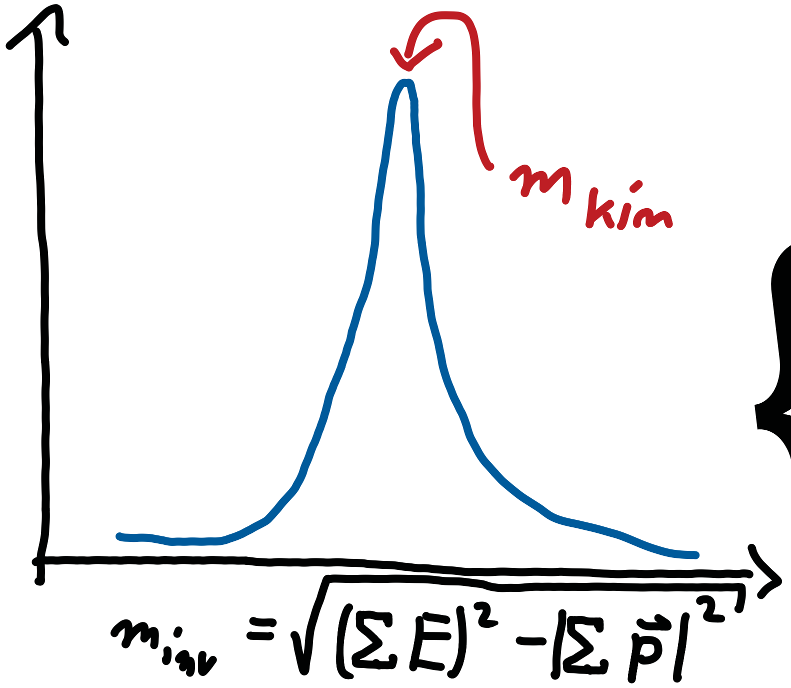
Single quark resonance: heavy quarks are very close to their mass-shell.

The a_i's are chosen such that the renormalon is removed.

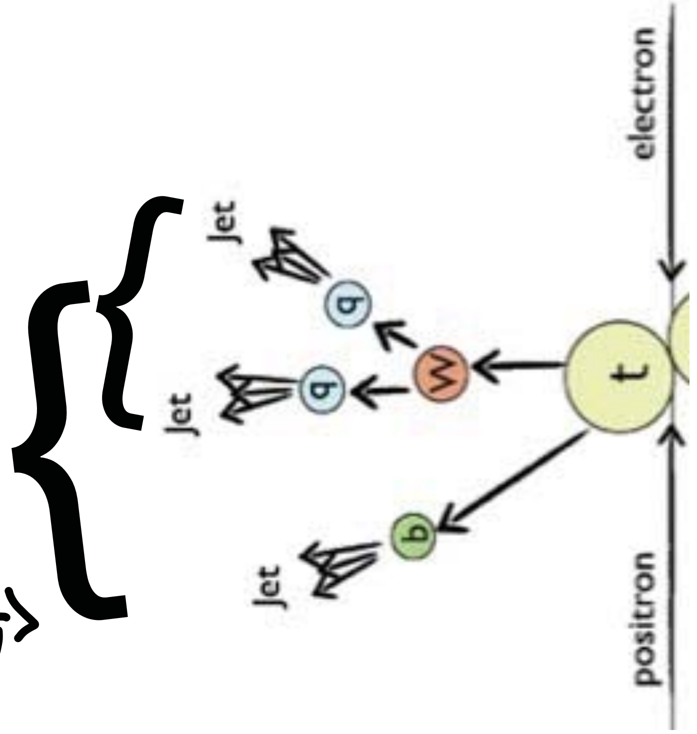
The scale R is of order the momentum scale relevant for the problem.

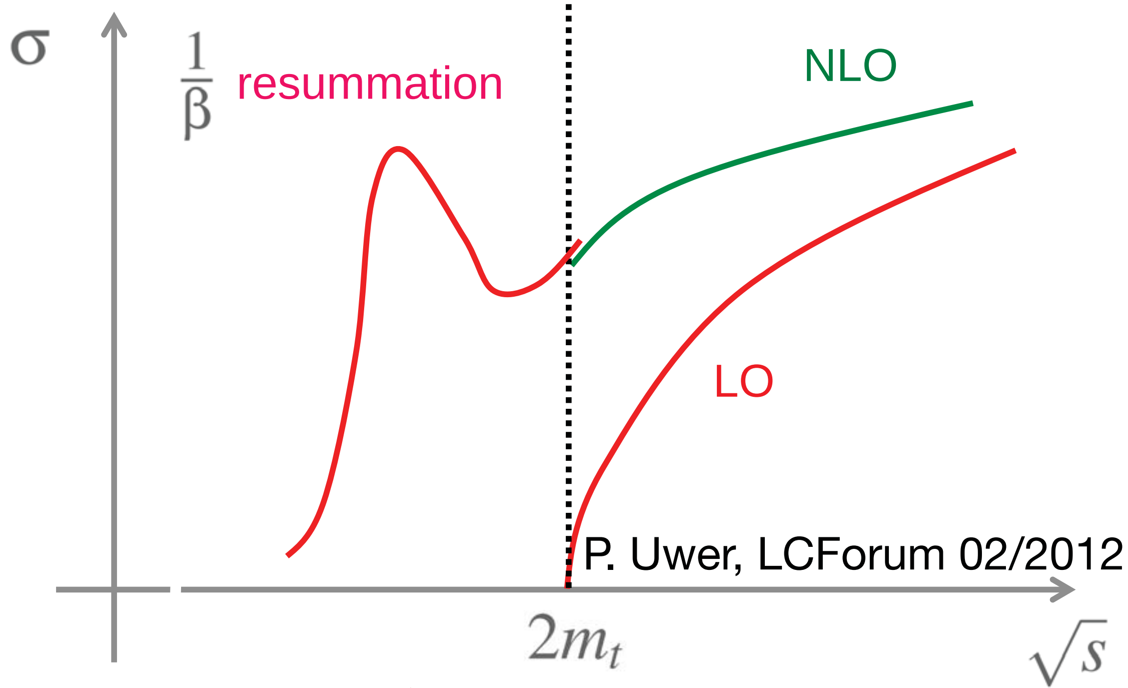
Top Mass at e^+e^- Colliders

- Measurement in top pair production, two possibilities, each with advantages and disadvantages:
  - Invariant mass
    - experimentally well defined (but not theoretically: “PYTHIA mass”)
    - can be performed at arbitrary energy above threshold: high integrated luminosity
  - Threshold scan
    - theoretically well understood, can be calculated to higher orders
    - needs dedicated running of the accelerator (but is also in a sweet spot for Higgs physics)
    - ‣ The “ultimate” mass measurement at a LC!



$m_{inv} = \sqrt{(\Sigma E)^2 - |\Sigma \vec{p}|^2}$



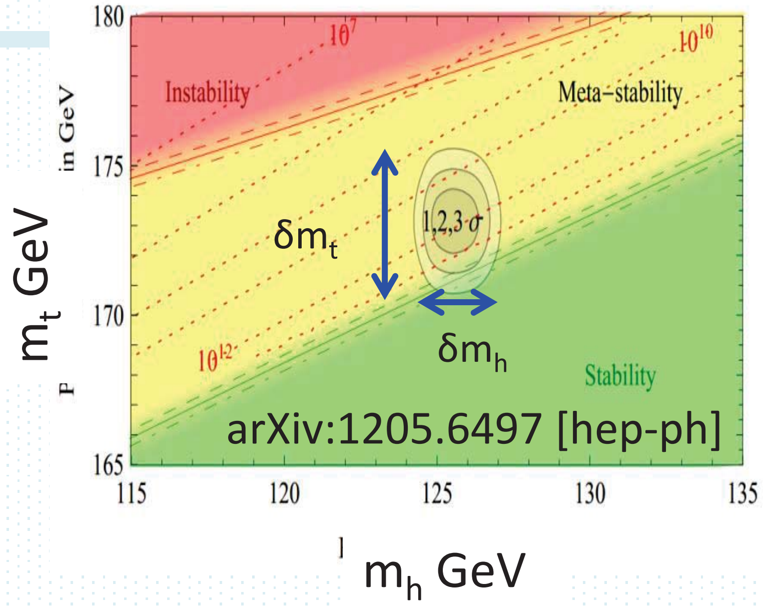


P. Uwer, LCForum 02/2012

arXiv:1205.6497 [hep-ph]

Target around 350GeV

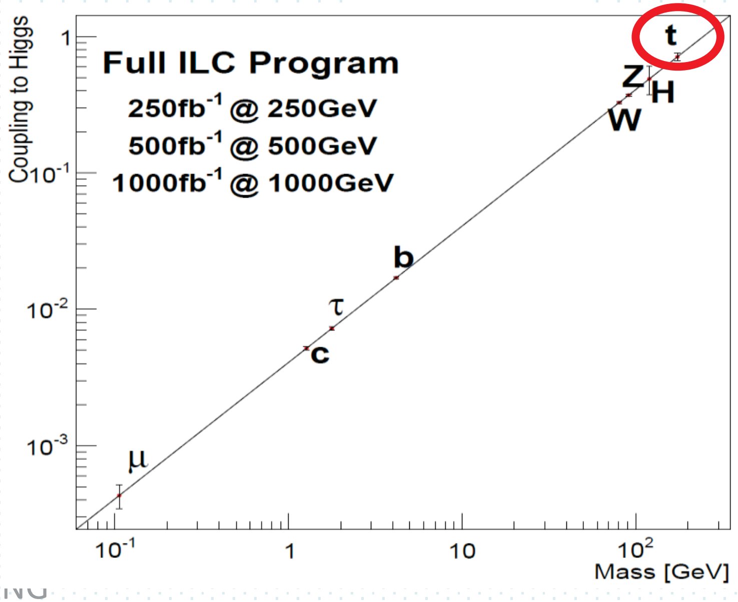
- Top mass($\mathbf{m_t}$)
  - Important input parameter
  - $\overline{\text{MS}}$ scheme mass ($\mathbf{m_t}^{\overline{\mathbf{MS}}}$)
    - ✓ $\mathbf{m_t}^{\overline{\mathbf{MS}}} = 160\ ^{+5}_{-4}$ GeV (PDG)
  - Potential subtracted mass ($\mathbf{m_t}^{\mathbf{PS}}$)
- Decay width($\mathbf{\Gamma_t}$)
  - anomalous coupling
  - exotic decay
- Top yukawa coupling(y_t)
  - Test of higgs mechanism
- α_s
- QCD wave function



δm_t

δm_h

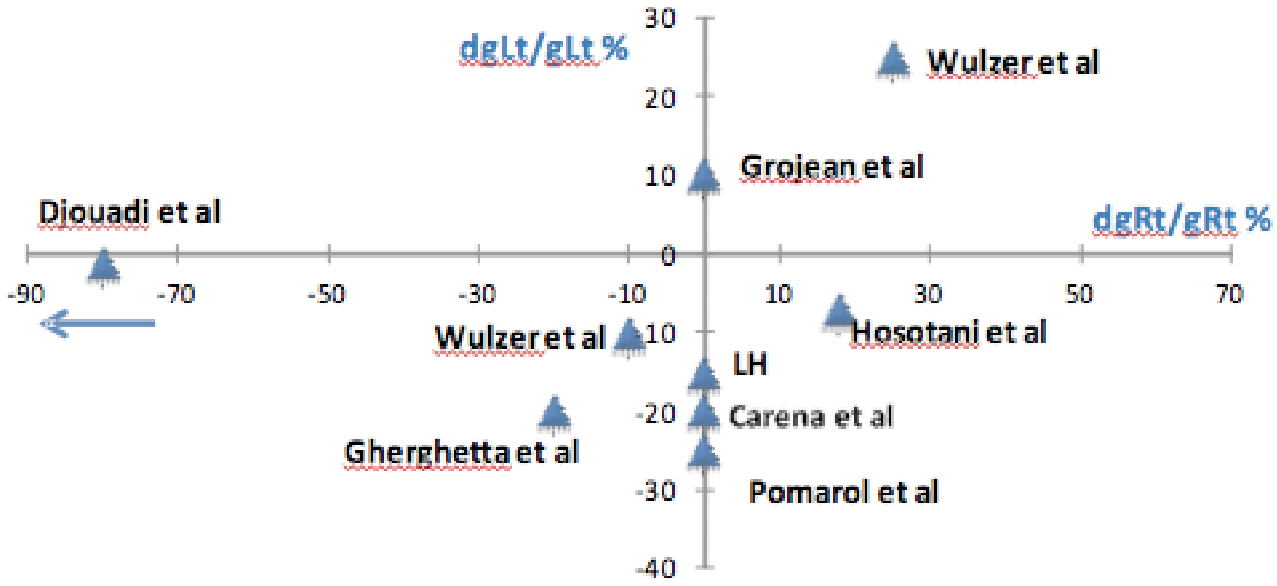
arXiv:1205.6497 [hep-ph]

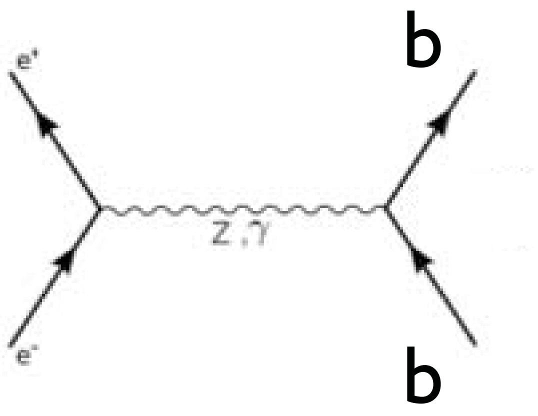


Top-Z coupling

R. Rontsch
R. Poeschl

- Many models predict modifications in the coupling of the Z to top quarks.

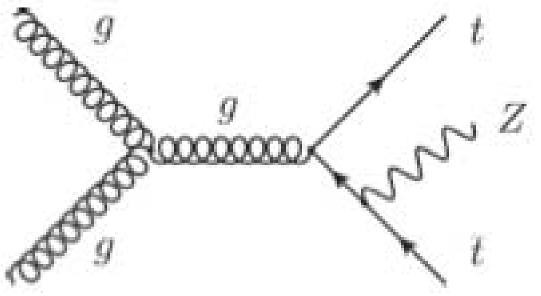




LEP (+LC)

A_{FB}, constrain Zbb coupling, relate to Ztt through SU(2)

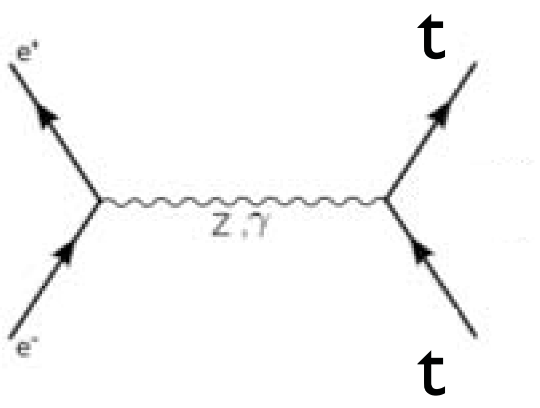
indirect



LHC

σ(ttZ), rare process, previously limited by theory uncertainty

direct



future LC

A_{FB}, for precision must measure b-quark charge

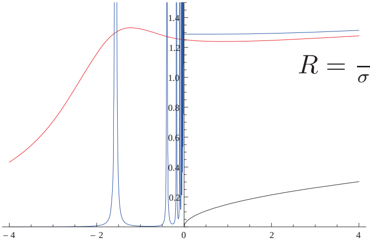
direct

Threshold Production

relative velocity of quark-antiquark pair is small:

$$\sqrt{s} = E + 2m_Q \approx 2m_Q \quad \Rightarrow \quad v = \sqrt{\frac{E}{m_Q}} \ll 1\,; \quad v \sim \alpha_s(m_Q v)$$

- multi-scale problem: mass m_Q, momentum $m_Q v$, energy $m_Q v^2$
- perturbation theory breaks down due to terms proportional to $\frac{\alpha_s}{v}$ $\rightsquigarrow$ Coulomb resummation
- formation of bound states below threshold
- $b\bar{b}$: bound-state resonances
- $t\bar{t}$: large width prevents existence of bound states



$$R = \frac{\sigma(e^+e^- \to t\bar{t})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

E [GeV]

Framework: potential NRQCD

scales: mass, m: hard $\gg$ momentum, mv: soft $\gg$ energy, mv^2: ultrasoft $\gg$ Λ_{QCD}

potential quarks: $\begin{cases} E_{\vec{p}} \sim mv^2 \\ |\vec{p}\,| \sim mv \end{cases}$ $\qquad \dfrac{1}{E_{\vec{p}} - \frac{\vec{p}^{\,2}}{2m}}$

ultrasoft gluons: $\begin{cases} E_{\vec{k}} \sim mv^2 \\ |\vec{k}\,| \sim mv^2 \end{cases}$ $\qquad \dfrac{1}{E_{\vec{k}}^2 - \vec{k}^{\,2}}$

QCD ➪ NRQCD ➪ pNRQCD (potential non-relativistic QCD)

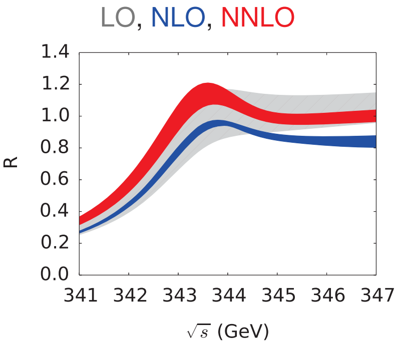
↑ integrate out hard scale “m” from QCD [Caswell,Lepage’86; Bodwin,Braaten,Lepage’95]

↑ integrate out all scales from NRQCD except potential quarks and ultrasoft gluons [Beneke,Smirnov’97; Pineda,Soto’98; Brambilla,Pineda,Soto,Vairo’00]

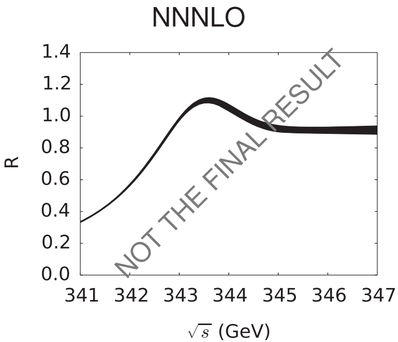
alternative formulation: velocity NRQCD (vNRQCD)

[Luke,Manohar,Rothstein’00; Hoang,Stewart’03]

$\sigma_{\rm tot}(e^+e^- \to t\bar{t})$



LO, NLO, NNLO



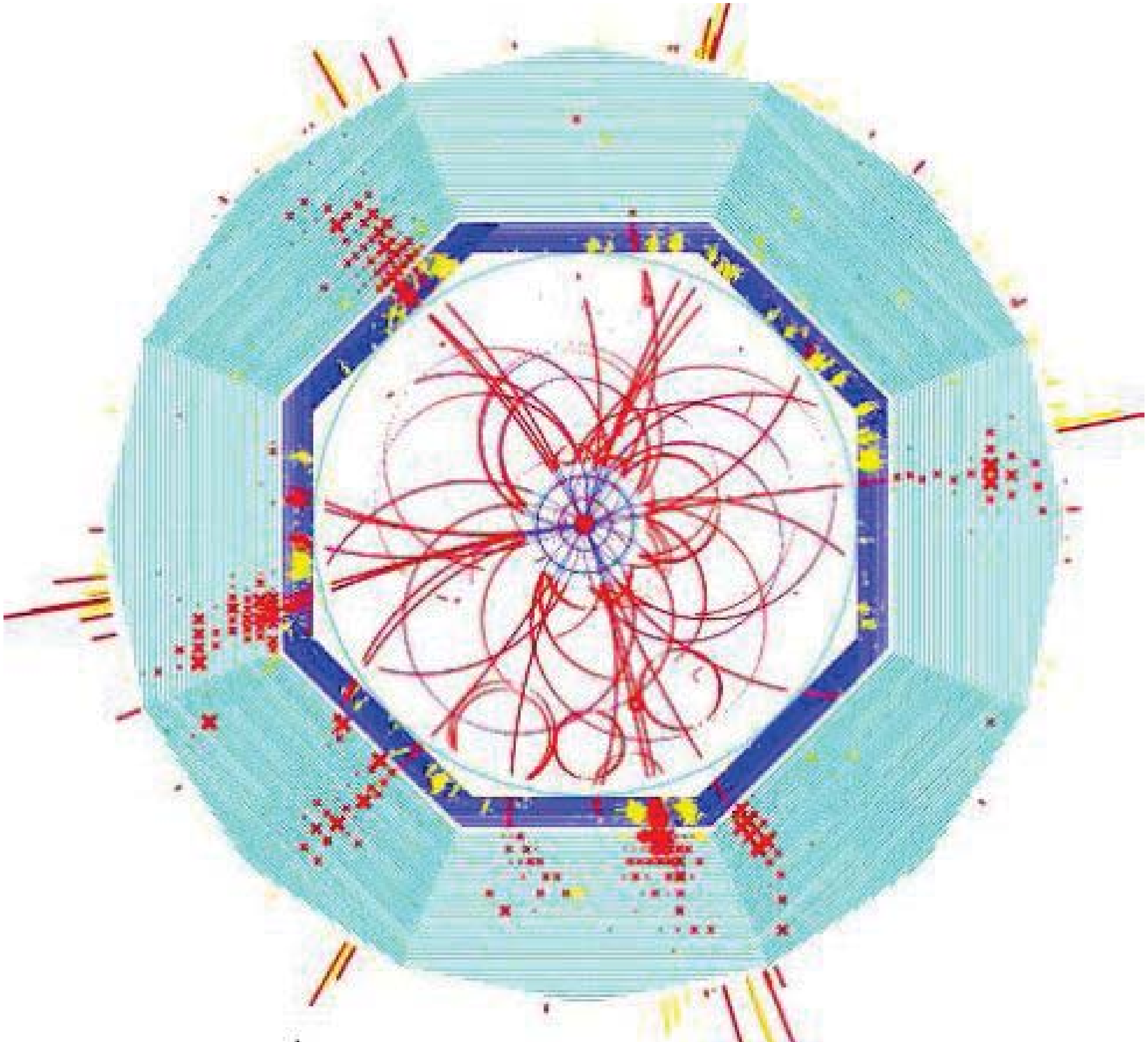
NNNLO

$50 \text{ GeV} \leq \mu \leq 350 \text{ GeV}$

$m_t^{\rm PS} = 171.3 \text{ GeV}$

[Beneke et al.]

Future colliders and experiments

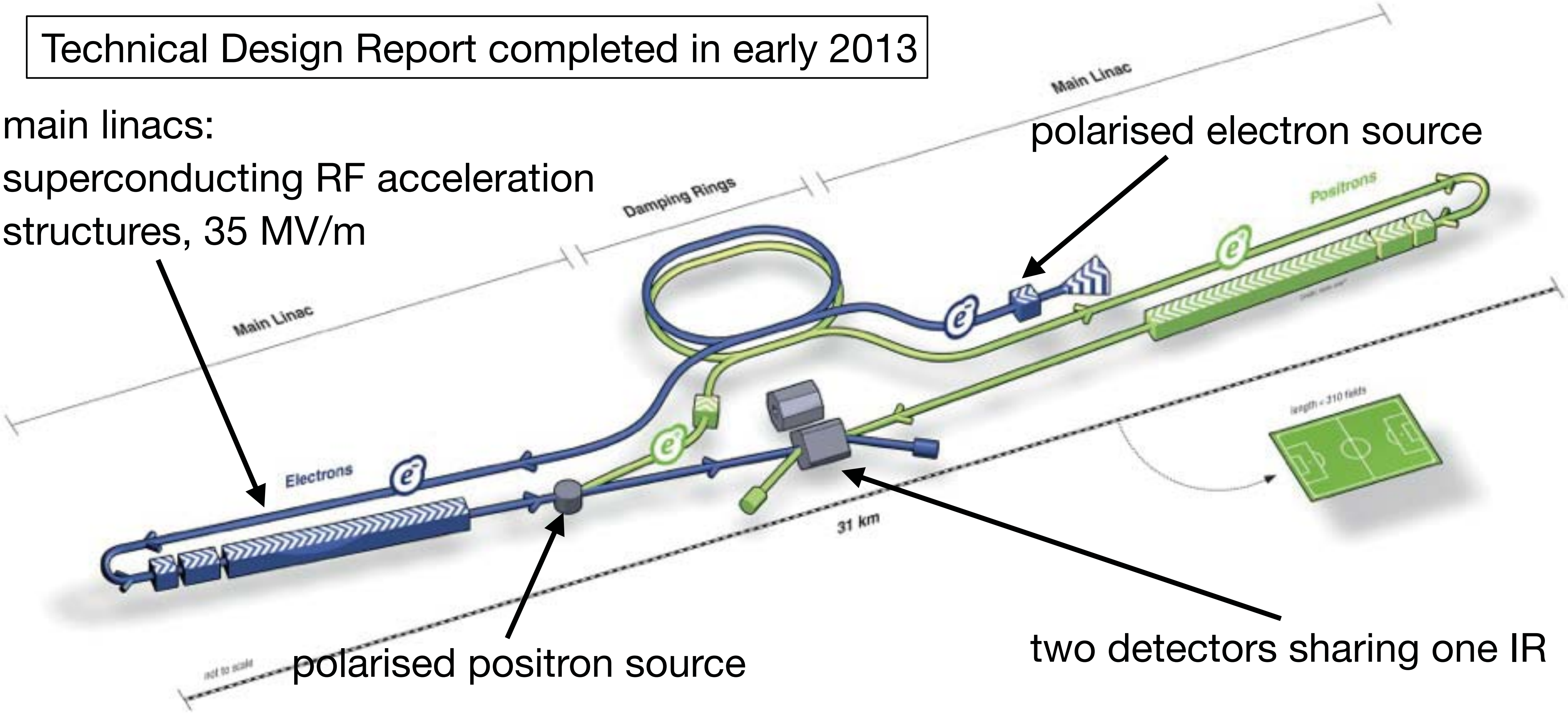


$e^+ e^- \rightarrow t\,t$

ILC - The International Linear Collider

- Currently the most advanced concept for a future energy frontier collider
  - e^+e^- collider, baseline energy 500 GeV, high luminosity: 2×10^{34} $cm^{-2}s^{-1}$
    - staged construction, starting from 250 GeV / 350 GeV
    - upgrade to 1 TeV possible (extension of linacs), luminosity upgrade by rate increase

Technical Design Report completed in early 2013



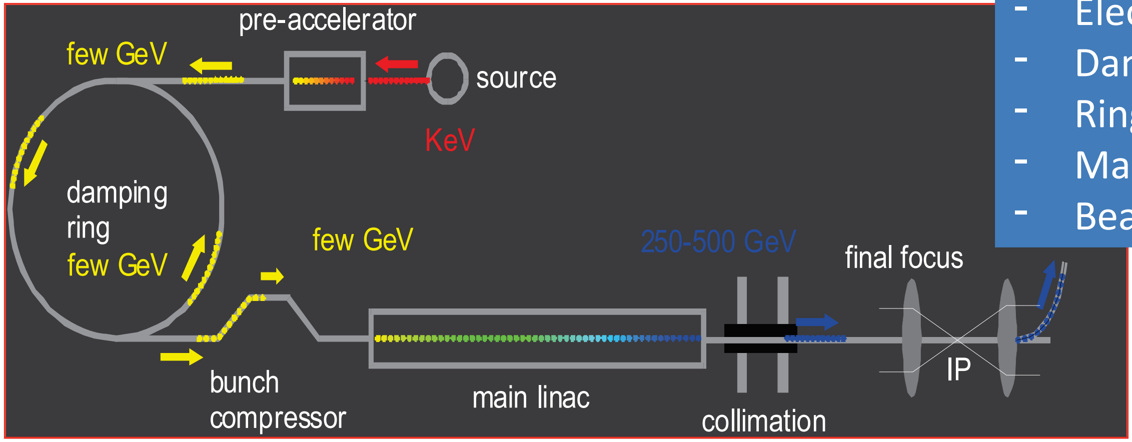
main linacs:
superconducting RF acceleration
structures, 35 MV/m

polarised electron source

polarised positron source

two detectors sharing one IR

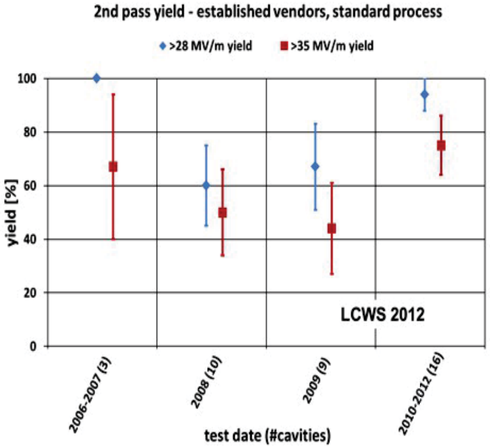
The ILC Accelerator Concept



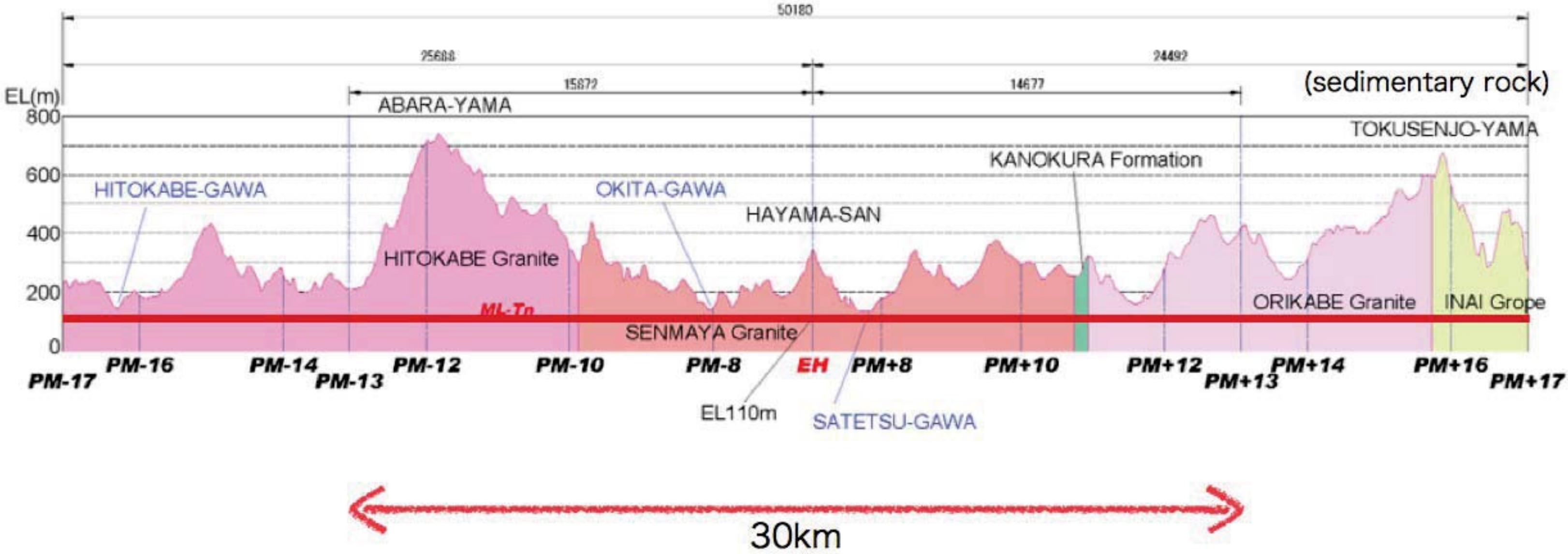
- Electron and Positron Sources (e-, e+)
- Damping Ring (DR)
- Ring to ML beam transport (RTML)
- Main Linac (ML) : SCRF Technology
- Beam Delivery System (BDS)

1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436

Production yield: 94 % at > 35+/-20%
Average gradient: 37.1 MV/m
> R&D goal of 35 MV/m reached (2012)



ILC preferred site - Kitakami



al

CLIC - The Compact Linear Collider

- A possible future energy frontier collider at CERN
  - e^+e^- collisions at up to 3 TeV with high luminosity (~ 6×10^{34} $cm^{-2}s^{-1}$ at 3 TeV)
  - Staged construction 350 - 500 GeV, ~ 1.5 TeV, 3 TeV - detailed energies under study, based on physics and technical considerations
  - Based on two-beam acceleration: gradients of 100 MV/m
  - Development phase until ~2018 - CDR completed in 2012

Frank Simon (fsimon@mpp.mpg.de)

CLIC layout at 3 TeV

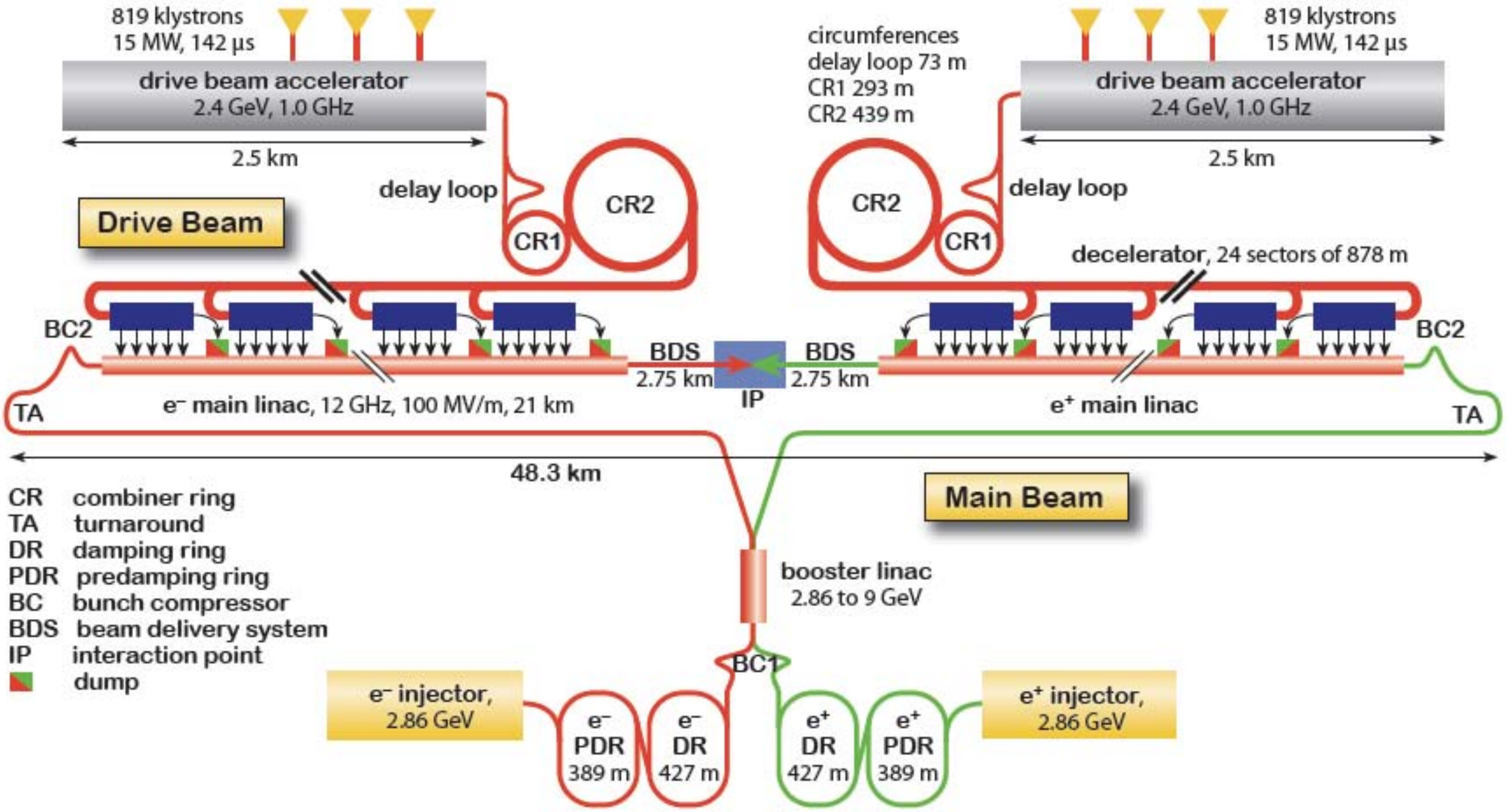


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

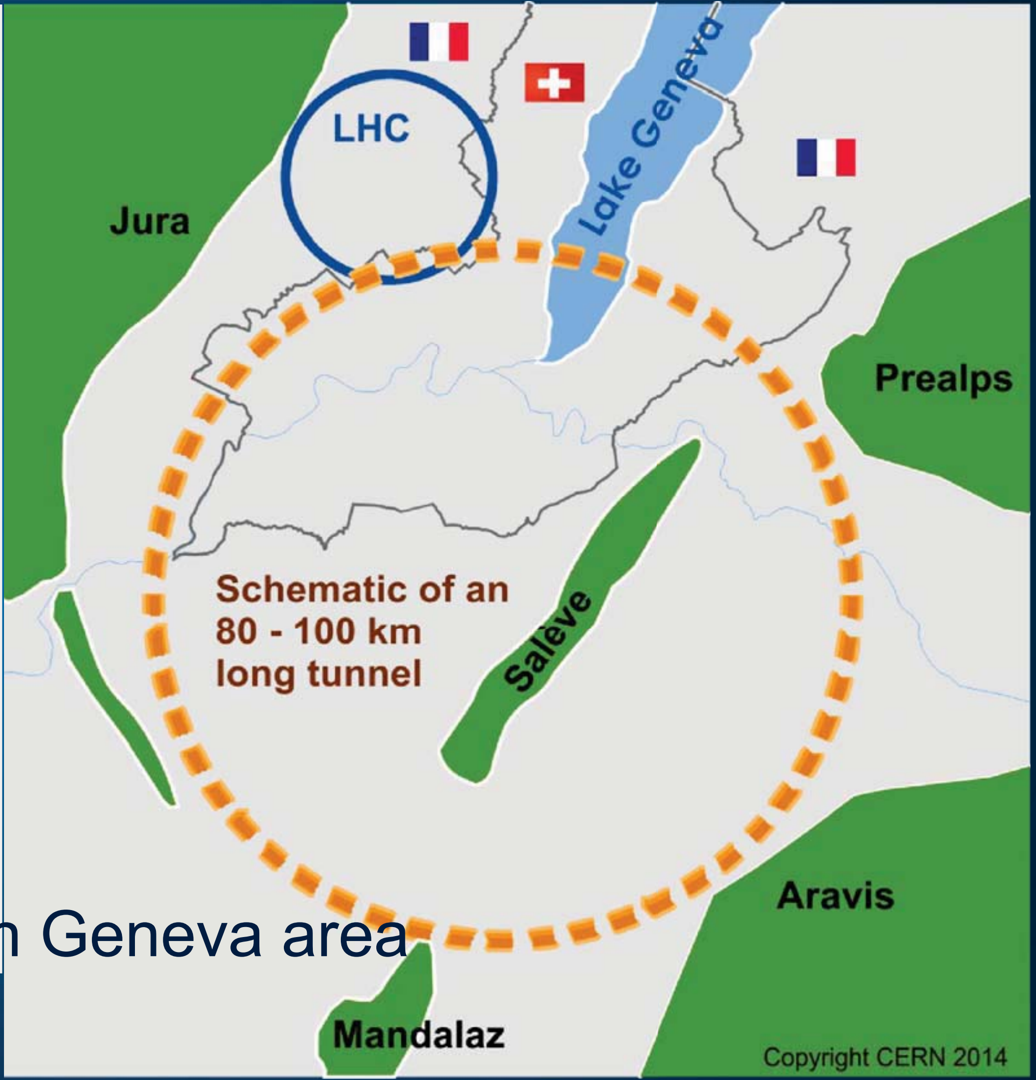
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

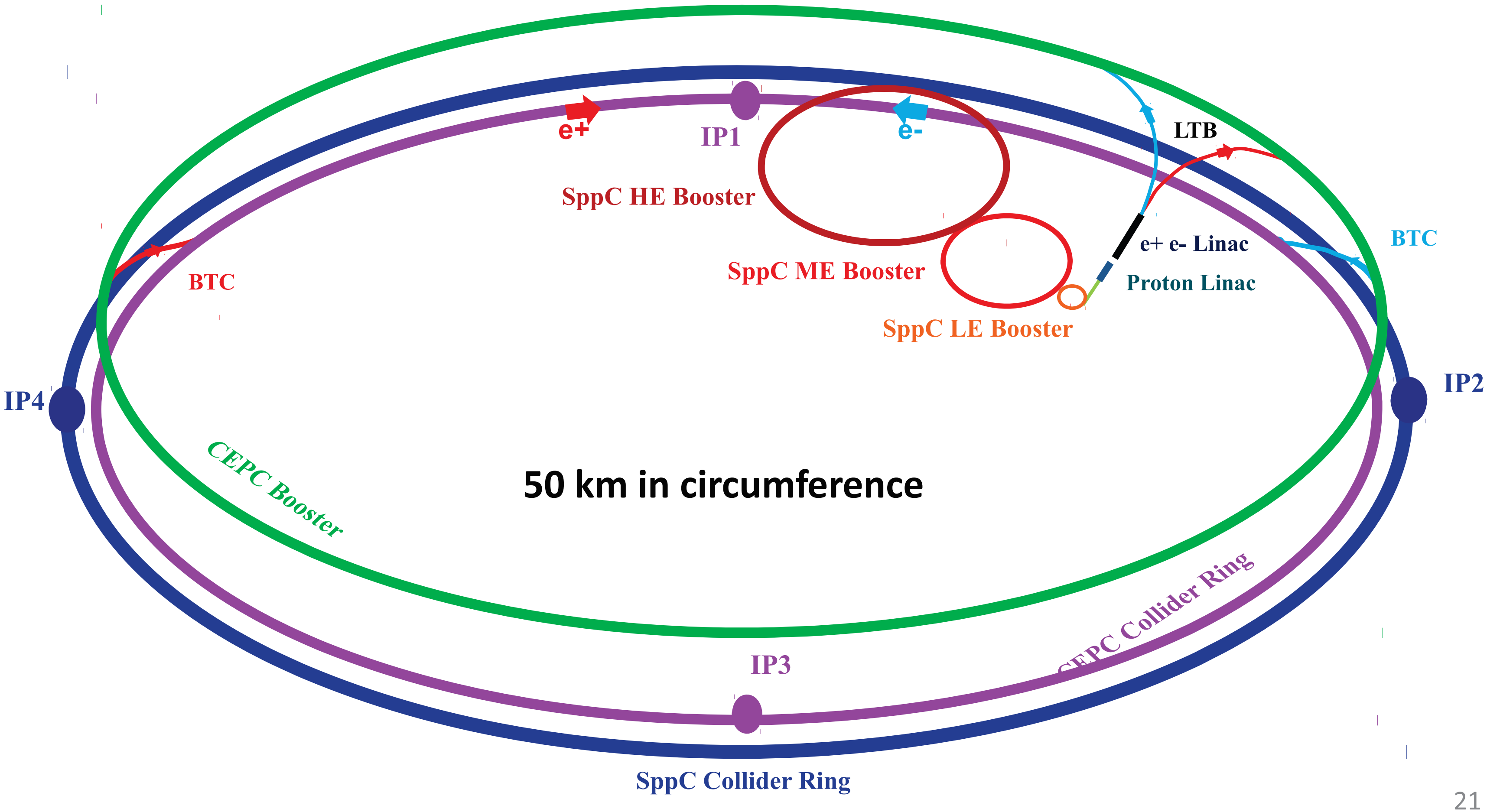
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area

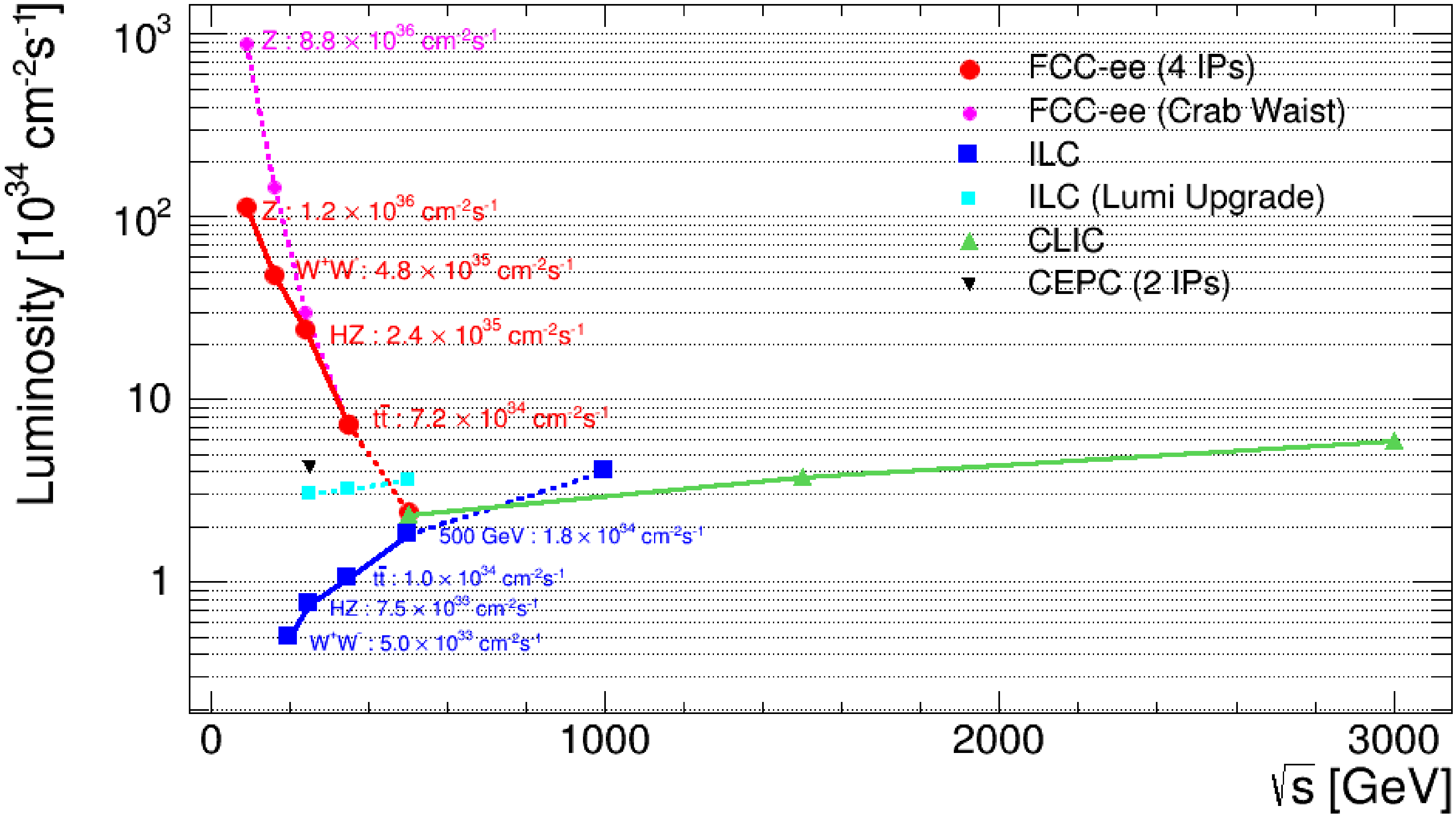


CEPC-SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider **SppC**, to study the new physics beyond the Standard Model.

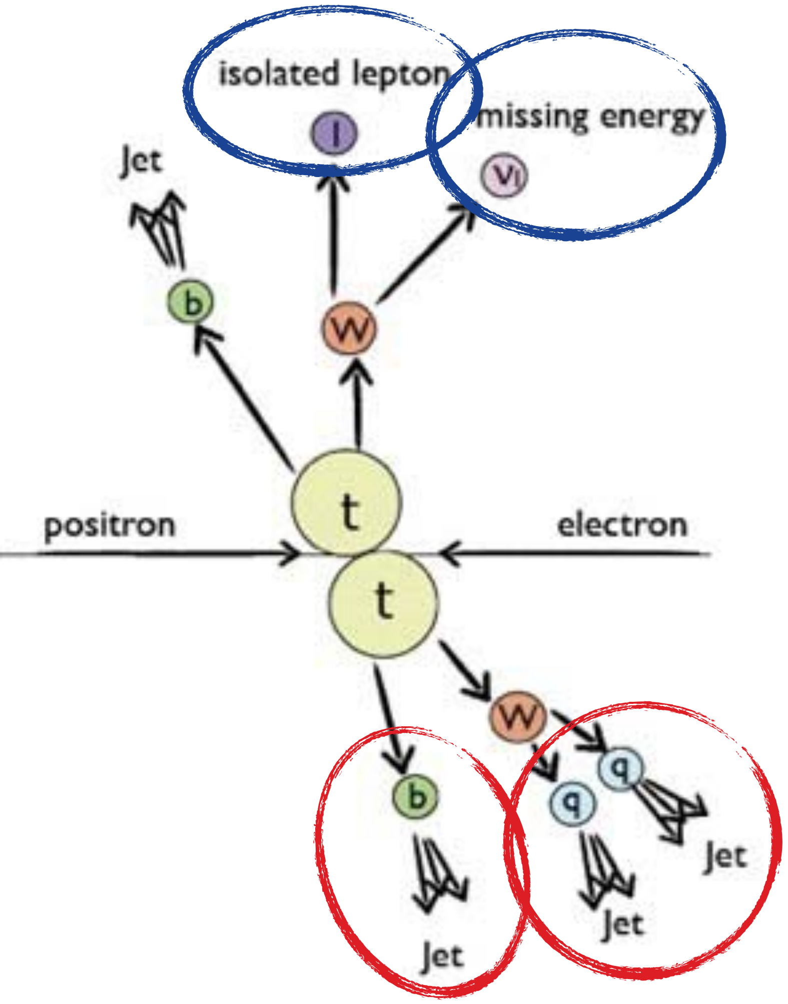


Goal performance of e+ e- colliders



Identifying & Reconstructing Top Quarks

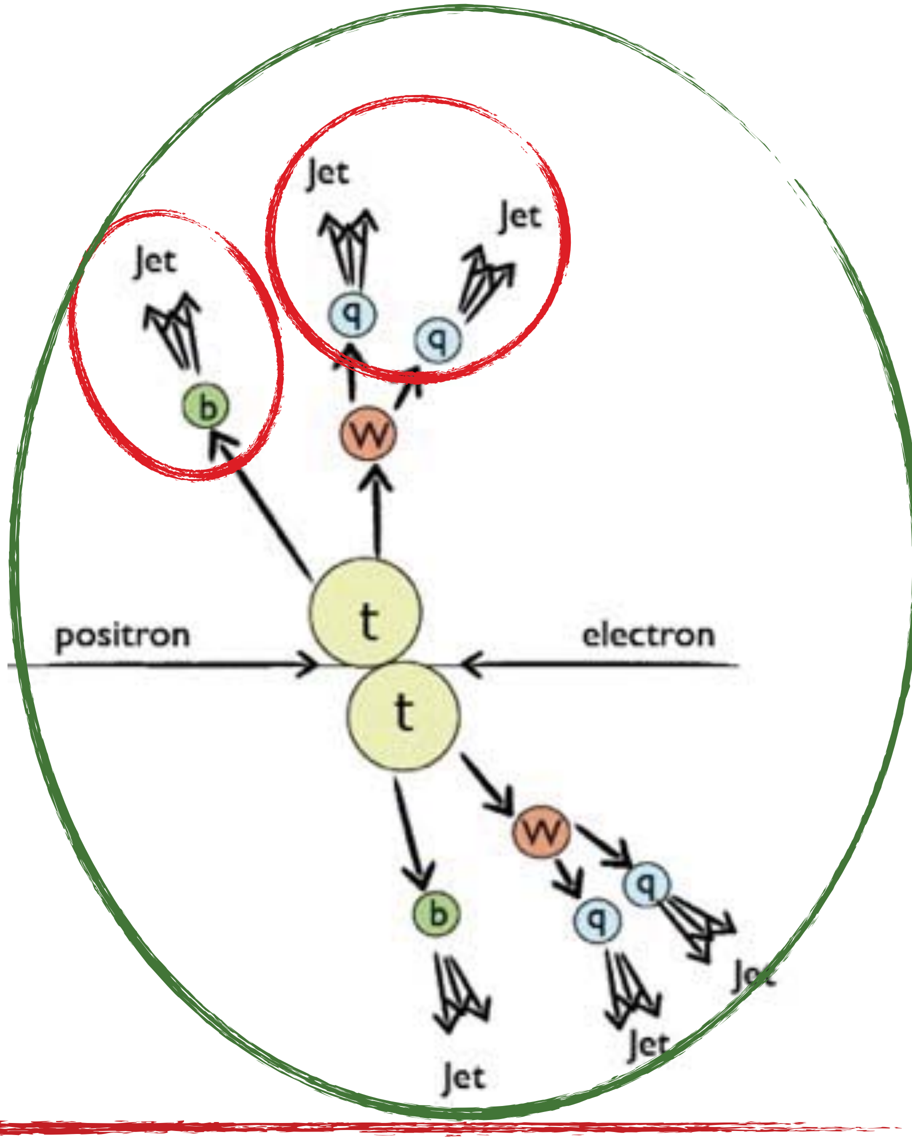
- Strategy depends on targeted ttbar final state



Semi-leptonic:
- isolated lepton ID, momentum measurement
  - provides t / tbar identification
- missing energy measurement

Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement

All-hadronic
- global hadronic energy reconstruction



LC Detector Requirements

Track Momentum: $\sigma_{1/p} < 5 \times 10^{-5}/\mathrm{GeV}$ **(1/10 x LEP)**

(e.g. Z-Mass Measurement with charged Leptons)

Impact parameter: $\sigma_{d0} < 5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)\ \mu\mathrm{m}$ **(1/3 x SLD)**

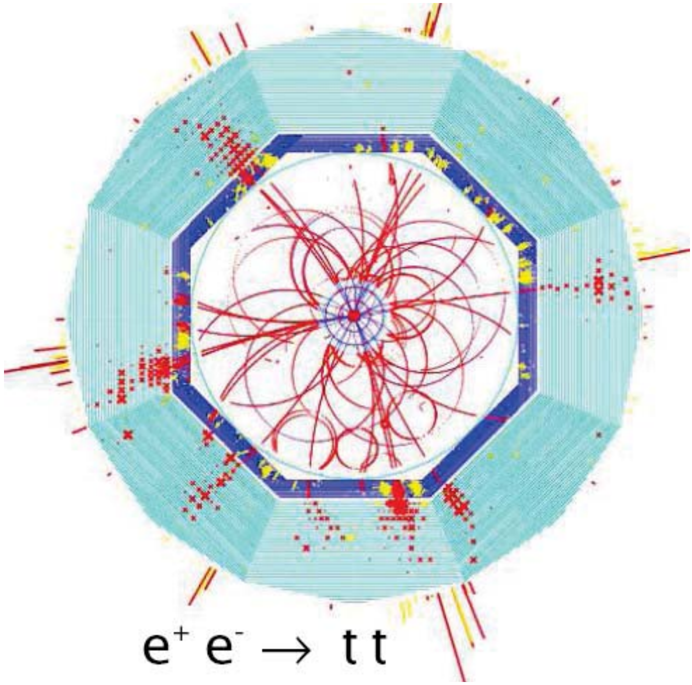
(c/b-tagging)

Jet energy : **dE/E = 3-4%**

(Measurement of W/Z Mass with Jets)

Hermeticity : $\theta_{min} = 5$ **mrad**

(to detect of events with missing energy e.g. SUSY)



$e^+ e^- \rightarrow t\,t$

Events with large track multiplicity and a large number of Jets (6+) are expected.

Therefore:

- **high Granularity**
- **good track Measurement**
- **good Track Separation**
- **"Particle Flow" detectors**

calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

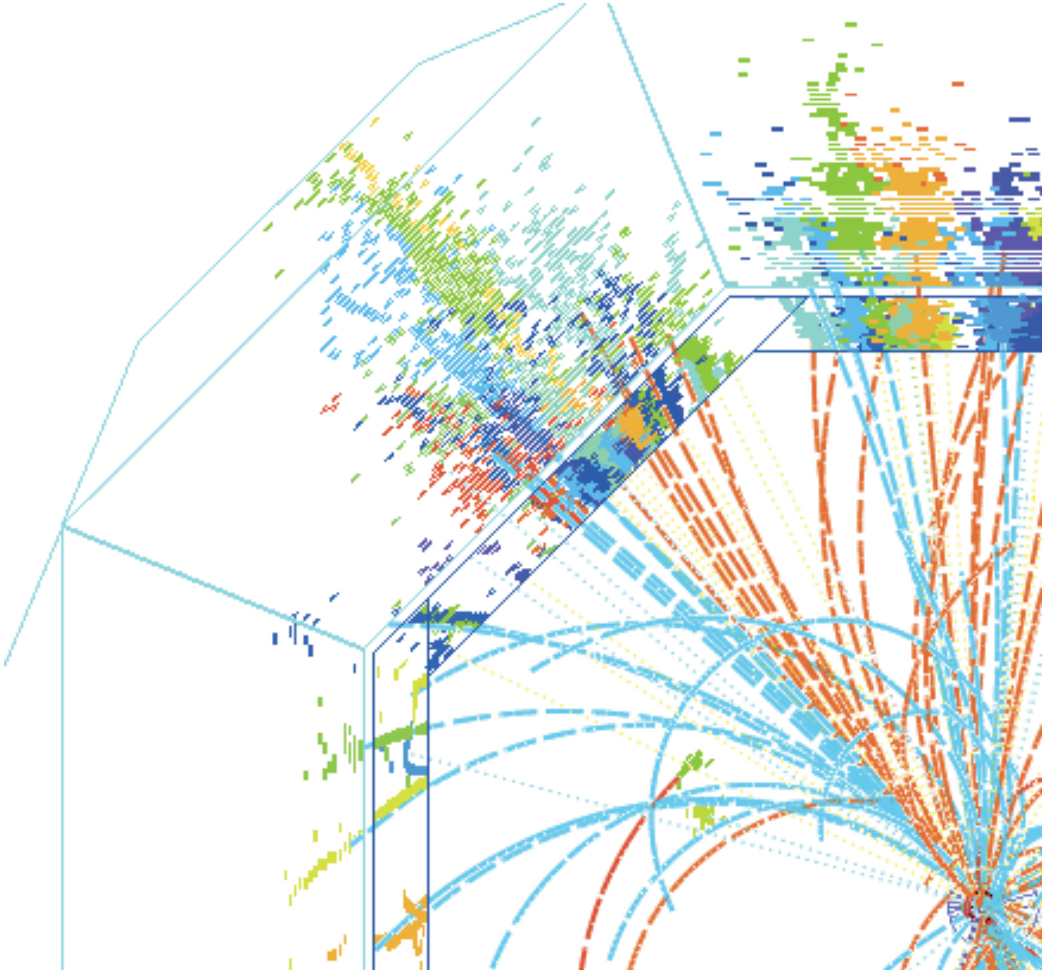
What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutral hadrons

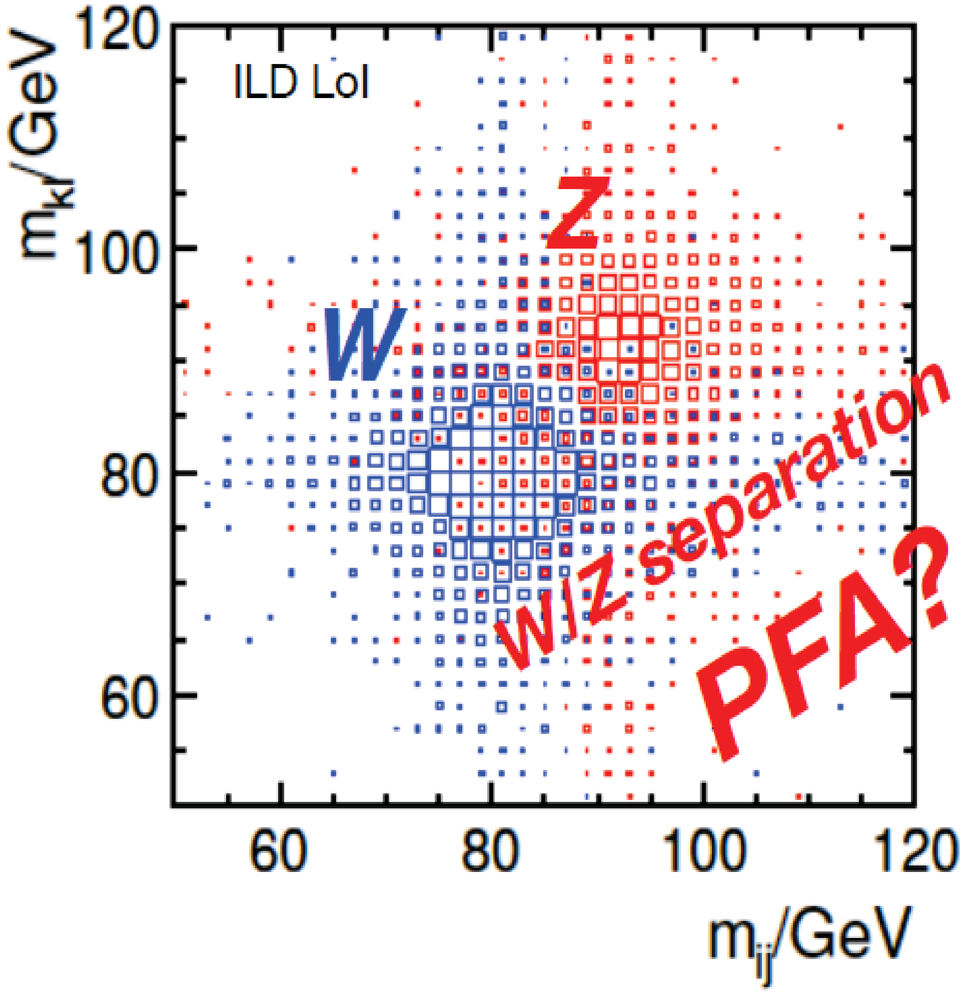
↓

Always use the best info you have:
60% => tracker 🙂 🙂
30% => ECAL 🙂
10% => HCAL 🙁

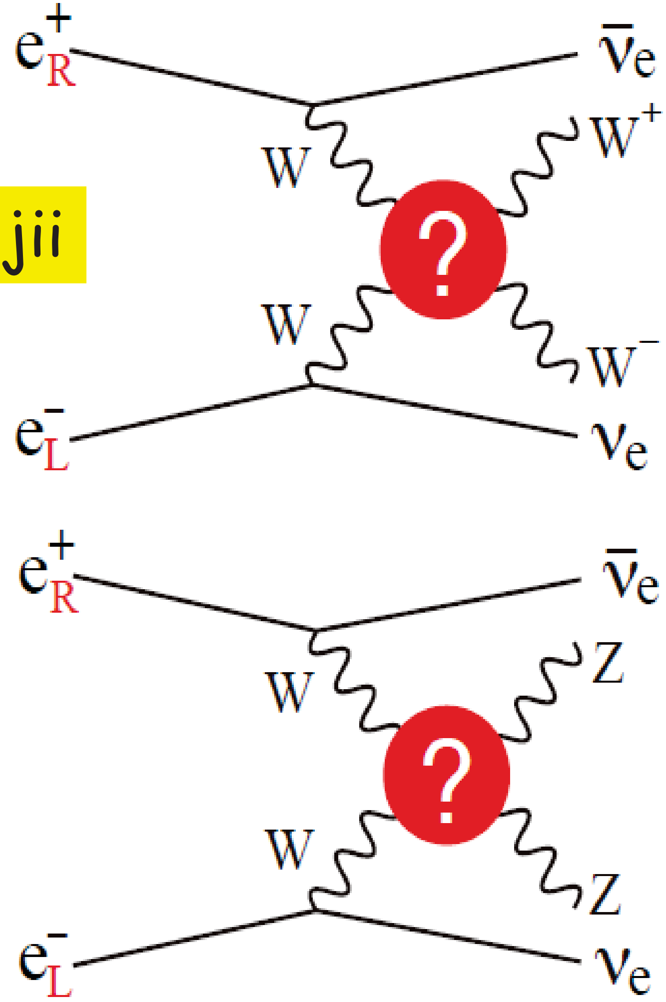
Hardware + software !



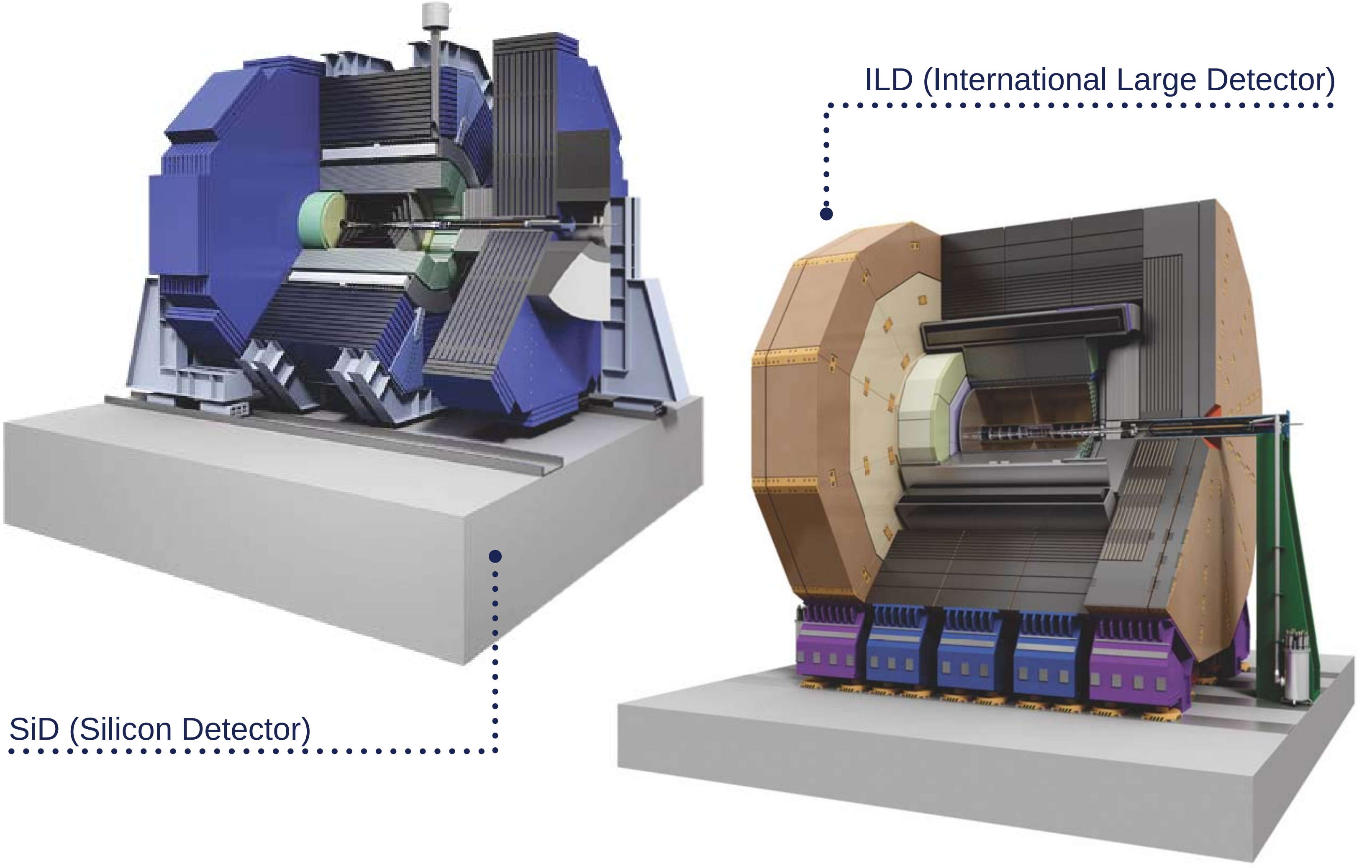
Physics Drivers II



K. Fujii



Detector Systems at Linear Colliders



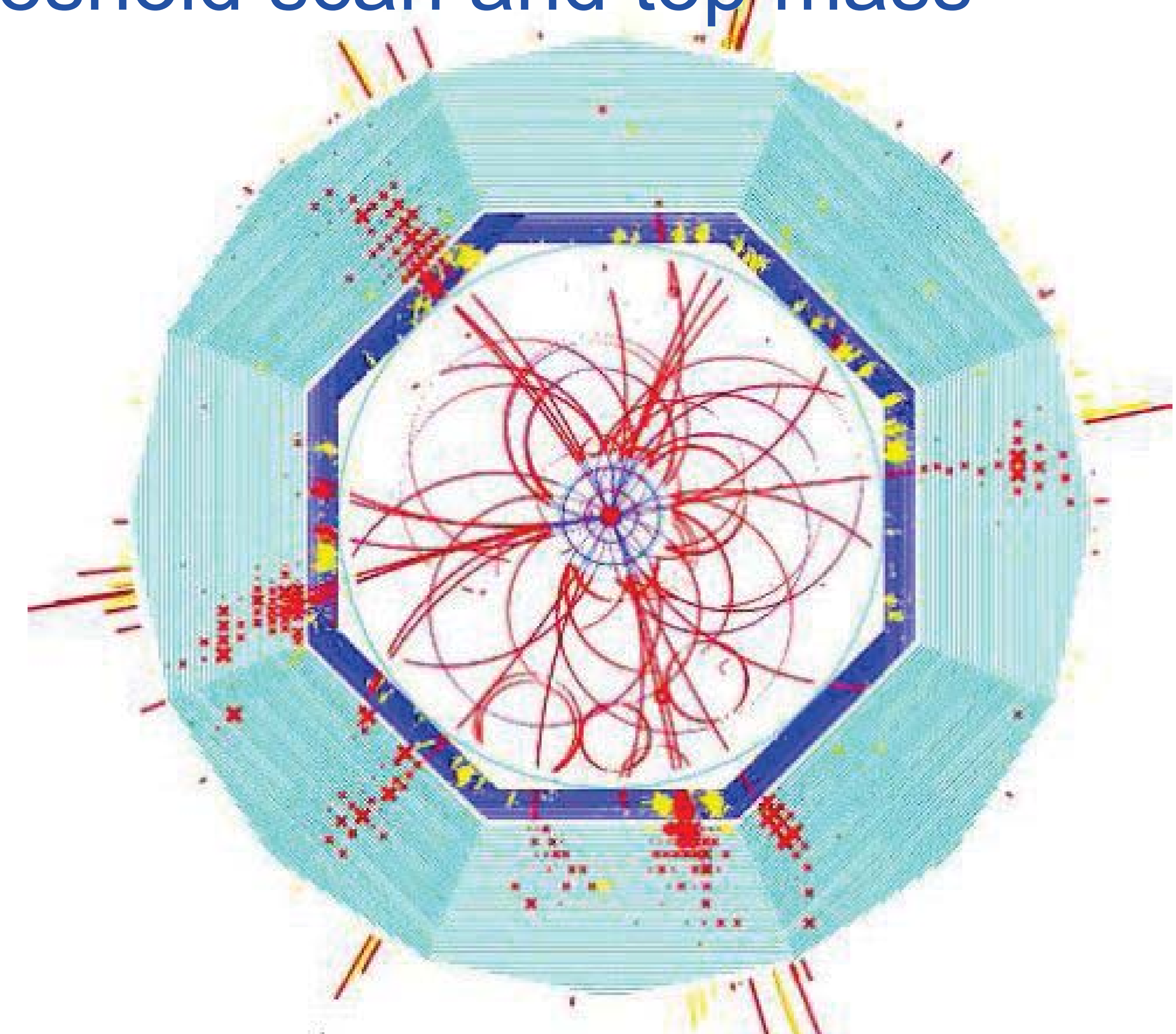
- Low-mass, high precision vertexing & tracking
- Highly granular calorimeters
- Particle flow event reconstruction

- CLIC detectors based on ILC concepts, with modifications in the calorimeters, vertex and forward regions to account for higher energy and higher backgrounds

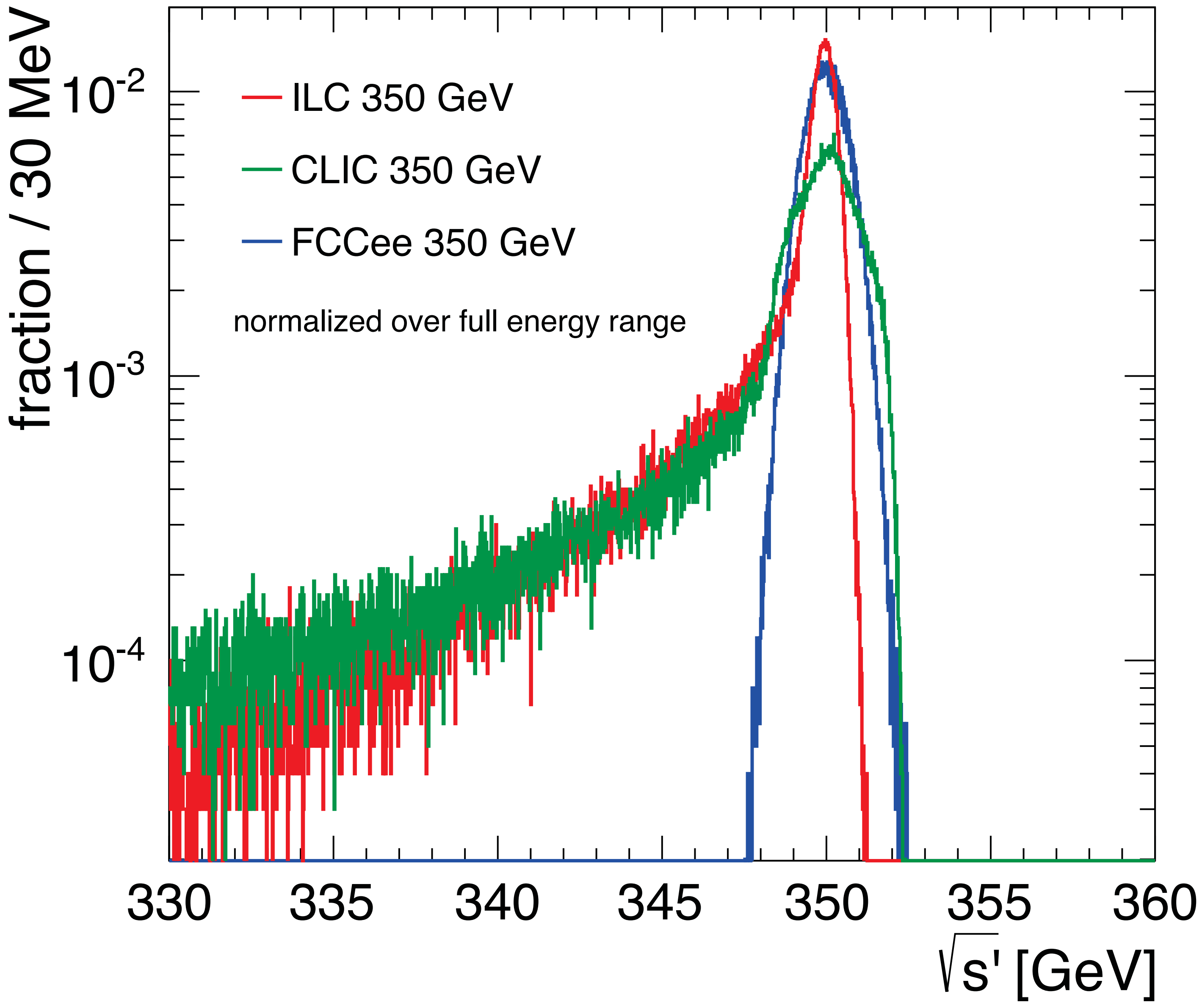
- Detailed simulation models implemented in GEANT4
- Realistic event reconstruction including pattern recognition, tracking, PFA
- ‣ Full simulation studies used for all results presented here

Top measurements

- Threshold scan and top mass

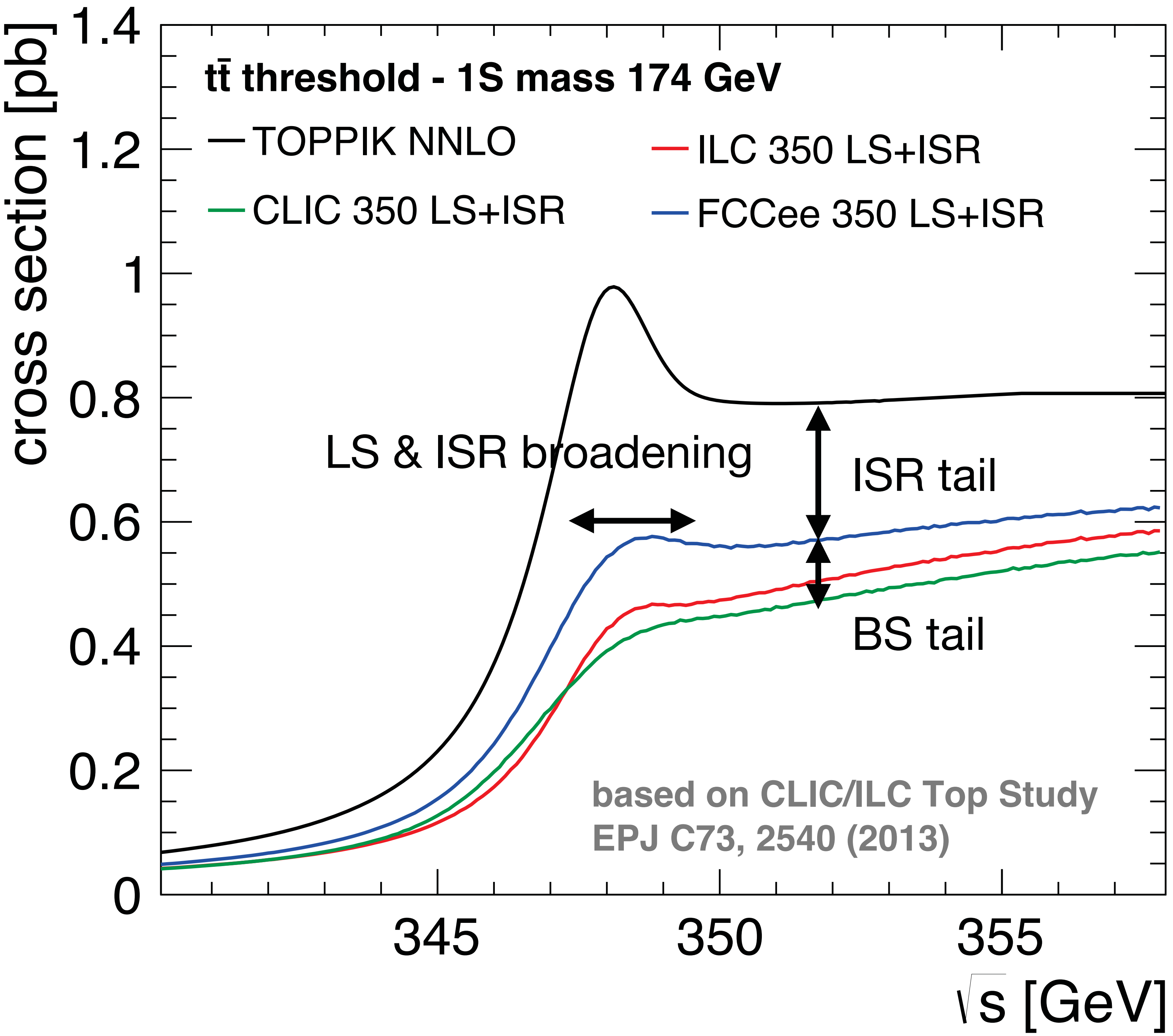


The Luminosity Spectrum of different Colliders…



- The luminosity spectrum of different e^+e^- colliders
  - ILC & CLIC - Full machine simulations (GuneaPig)
  - FCCee (TLEP): Gaussian, with 0.19% sigma (includes BS)

… and what it does to the Top Threshold



based on CLIC/ILC Top Study EPJ C73, 2540 (2013)

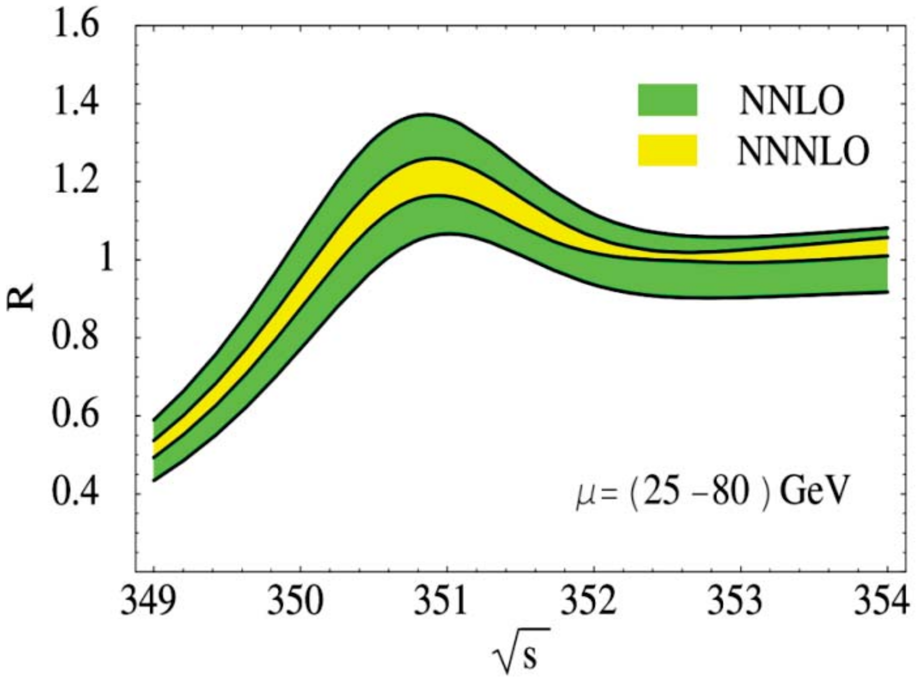
The effects:

- ISR tail: lowering of effective L at top energy
- BS tail: lowering of effective L at top energy - not at FCCee - Gaussian spectrum, 100% of L at > 99%
- LS & ISR broadening: smearing of Xsection due to beam energy spread, BS tail and ISR - most pronounced at CLIC - comparable at ILC and FCCee

σ_{tt} Measurement

Near the threshold region of top pair production ($\sqrt{s}$=$2m_t$), the energy dependence of σ_{tt} is large. And σ_{tt} depend on fundamental parameters. Then, using threshold scan technic, measuring σ_{tt} precisely and fitting it, these parameters are determined !!

$$\sigma_{tt} \propto f(\sqrt{s}, m_t, \Gamma_t, \alpha_s, y_t, m_h)$$



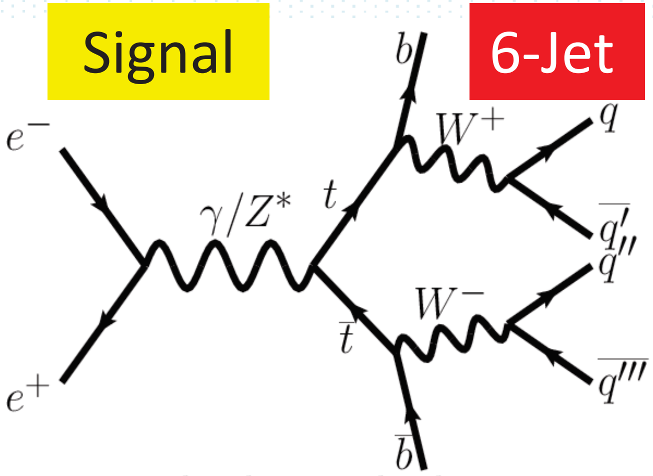
$\sigma/\delta\sigma$(theoretical) ~ 4-5 %

arXiv:0801.3464 [hep-ph]
M. Beneke, Y. Kiyo and K. Schuller,

Signal and background

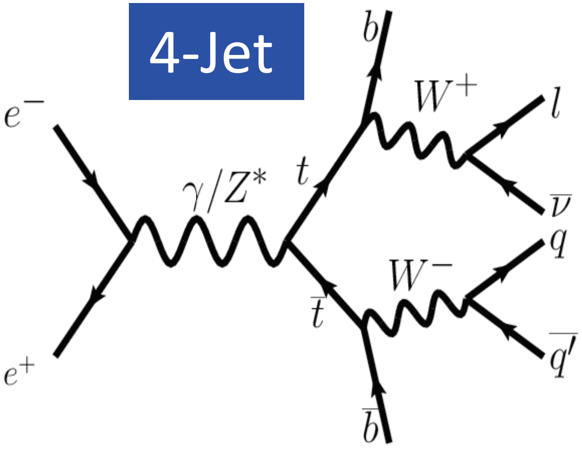
Signal

6-Jet



$t\bar{t} \to bWbW \to bqqbqq$

4-Jet



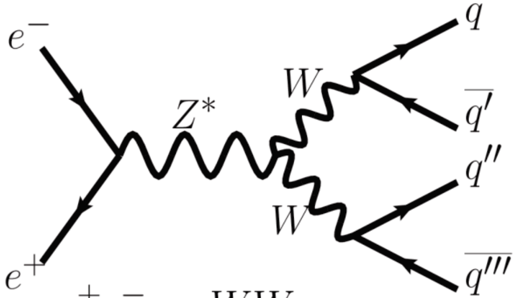
$t\bar{t} \to bWbW \to bqqbl\nu$

Branching Ratio	
6-Jet	45%
4-Jet	44%
2-Jet	11%

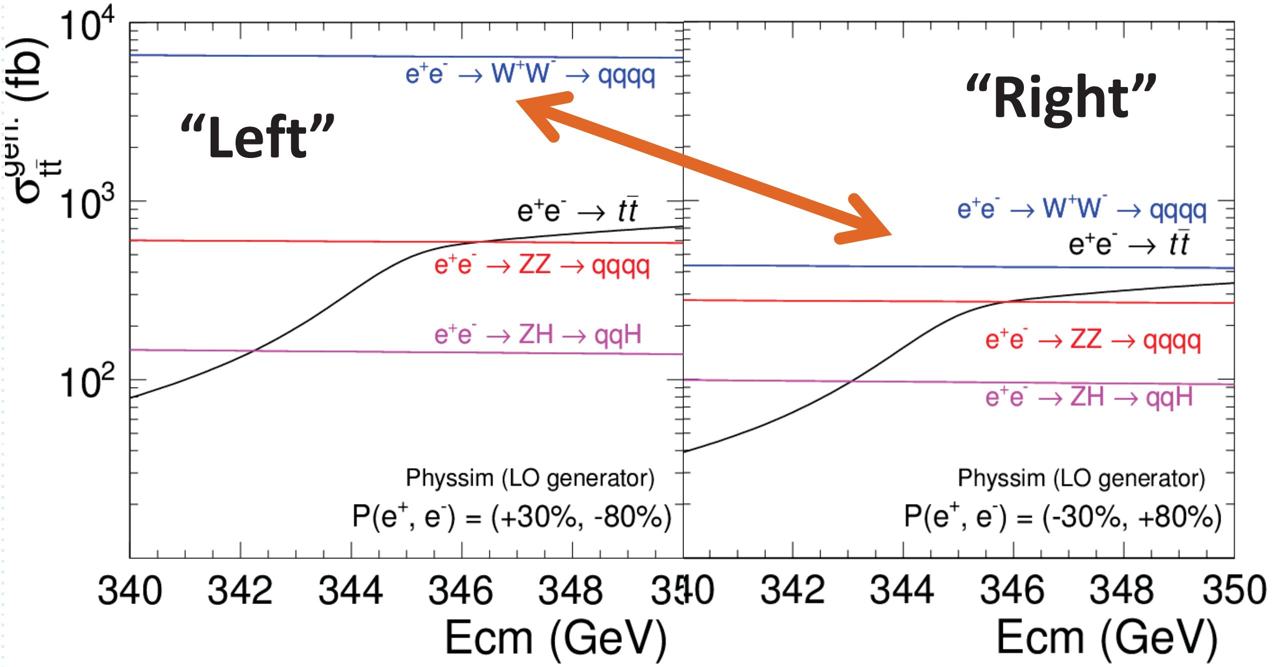
background

SM bkg. which have 4 or 6 fermions in final state

Main bkg. : WW, ZZ, ZH



$e^+e^- \to WW \to qqqq$



Top Quark Reconstruction (6-Jet & 4-Jet)

Reconstruction method	6-Jet	4-Jet
Suppressing the background overlay using anti-k$_T$ algorithm (R=0.7)		
Isolated Lepton(l_{iso}) finding using cone energy cut	# of l_{iso} = 0	# of l_{iso} = 1
Jet clustering using Durham algorithm	Cluster to 6jets	Cluster to 4jets
2 b-likeness Jets were found using LCFIPlus	-	-
Reconstruction of two W bosons	$q_1 + q_2$ & $q_3 + q_4$	q_1+q_2 & $l_{iso}+\nu$
Reconstruction of two top quarks	-	-
Minimizing the χ^2	①	②

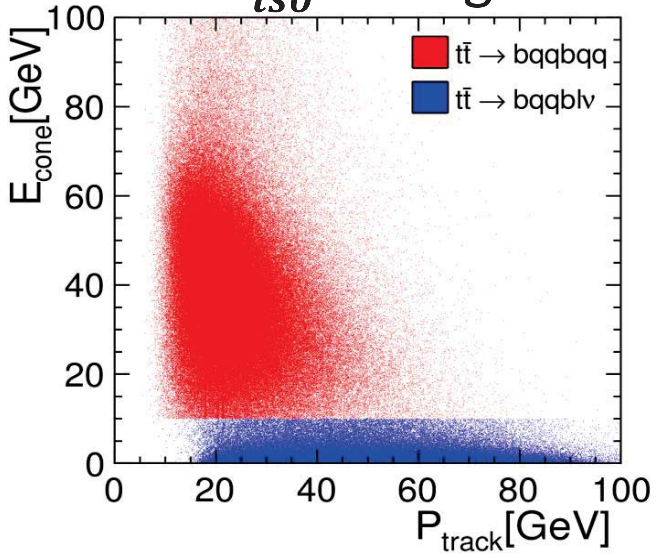
①

$$\chi^2_{6-\mathrm{Jet}} = \frac{(m_{3j^a\mathrm{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{3j^b\mathrm{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{2j^a\mathrm{reco.}} - m_w)^2}{\sigma_w^2} + \frac{(m_{2j^b\mathrm{reco.}} - m_w)^2}{\sigma_w^2}$$

②

$$\chi^2_{4-\mathrm{Jet}} = \frac{(m_{3j\mathrm{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{jl\nu\mathrm{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{2j\mathrm{reco.}} - m_w)^2}{\sigma_w^2}$$

l_{iso}finding



Selection Table 6-Jet @350GeV

$$\int \mathcal{L}(t)dt = 5(\text{fb}^{-1}) \qquad S = \frac{N_{Sig}}{\sqrt{N_{Sig} + N_{BG.}}}$$

Left	tt6j	tt4j	tt2j	WW	ZZ	ZH	6f+4f	S_{6j}
Generated	1643	1583	381	32664	3004	694	71691	4.9
# of lepton = 0	1592	357	19	32079	2957	638	39983	5.7
btag > 0.1 × 2	1515	340	18	3601	1398	471	7399	12.5
Thrust<0.84	1485	313	13	398	433	383	1084	23.2
Evis>290 GeV	1481	159	1	218	310	309	90	29.2
missPt<38GeV	1473	72	0	217	307	303	80	29.7
m_t>100 GeV × 2	1467	69	0	180	253	255	63	30.7
y45> 0.0015 y56 >0.0007	1419	45	0	68	71	80	36	34.2
# of pfos>86	1406	38	0	45	59	73	33	**34.6**

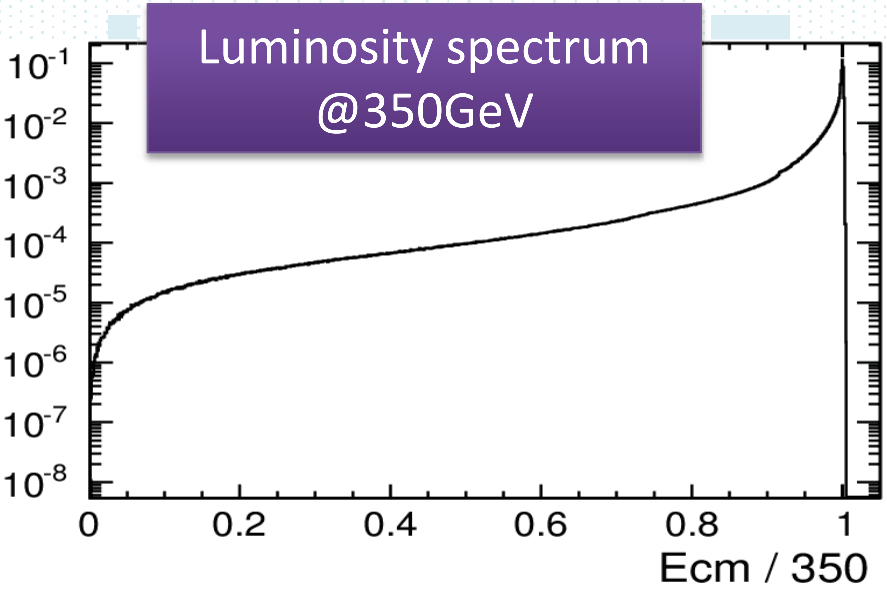
S/N	**5.67**
δσ/σ	**2.9%**

6f: 6 fermion final state except ttbar

Fit - convolution -

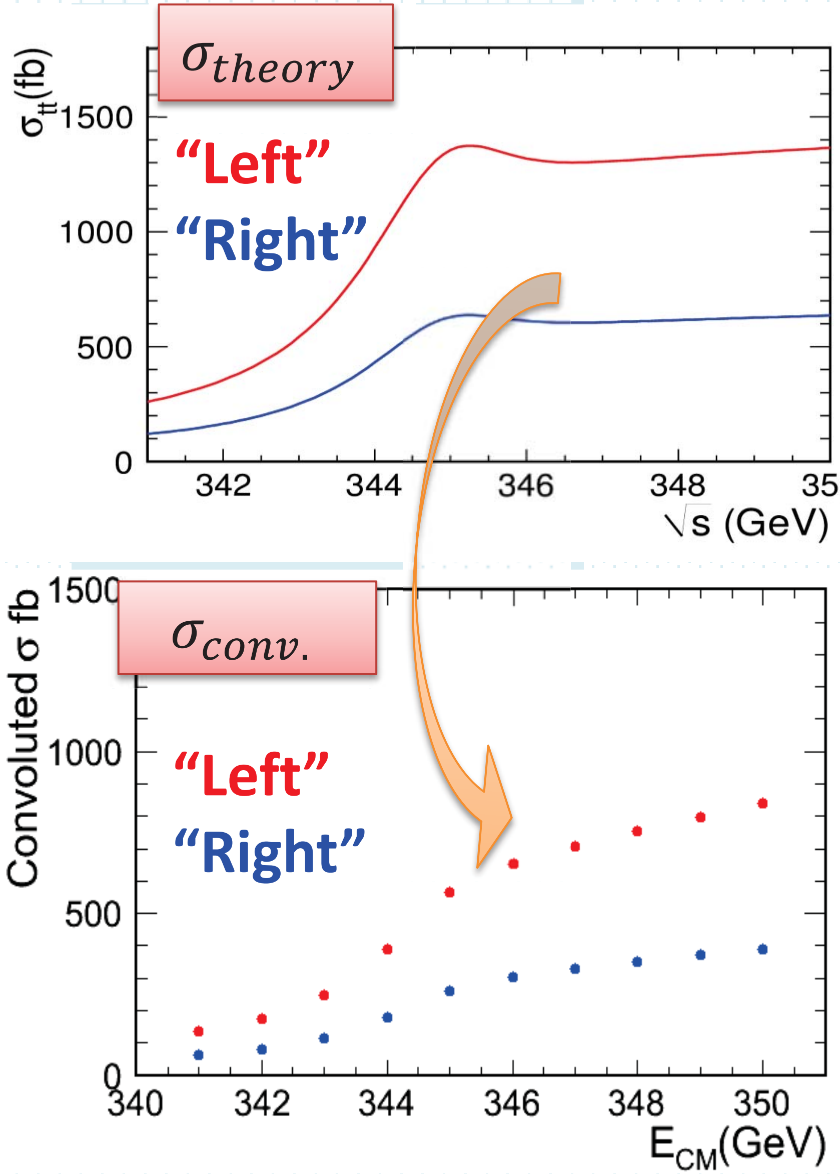
◎We must consider “Beam effects” around threshold.

Using luminosity spectrum,
theoretical cross section is convoluted.



$$\sigma_{conv.}(\sqrt{s}) = \int \mathcal{L}(t)\sigma_{th}(t)dt$$

$\mathcal{L}$: luminosity spectrum, $\sqrt{s}$: nominal, σ_{th} : theoretical σ,
$\sigma_{conv.}$: convoluted σ, t(=$\sqrt{s'/s}$) where $\sqrt{s'}$ is collision energy



Fit -Result-

Stat. Error (MeV)	**6-Jet**		**4-Jet**	
	m_t^{PS}	Γ_t	m_t^{PS}	Γ_t
Left(50fb^{-1})	28	40	33	48
Right(50fb^{-1})	42	63	48	67
Left (50fb^{-1}) + Right(50fb^{-1})	**23**	**34**	**27**	**39**

Center value: $m_t^{PS} = 172.000$ GeV, $\Gamma_t = 1.400$ GeV

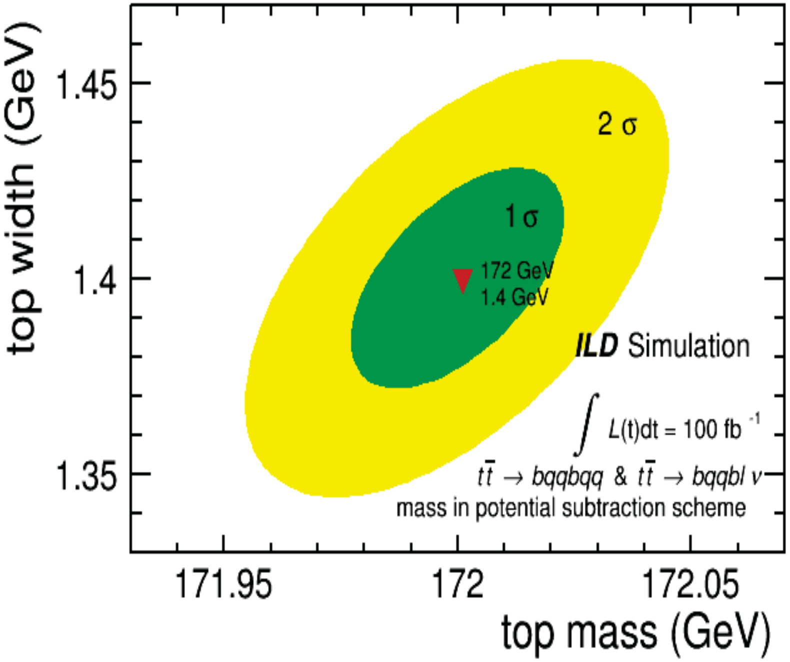
Combined ALL

m_t^{PS}(GeV)	Γ_t(GeV)
172.001 ± 0.018	1.399 ± 0.026

◎PS→$\overline{\text{MS}}$

$$m_t^{\overline{MS}} \sim m_t^{PS} - \frac{4}{3\pi}(m_t^{PS} - 20)\alpha_s + \ldots$$

$m_t^{\overline{MS}} = 163.800 \pm 0.017$ (stat.)(GeV)

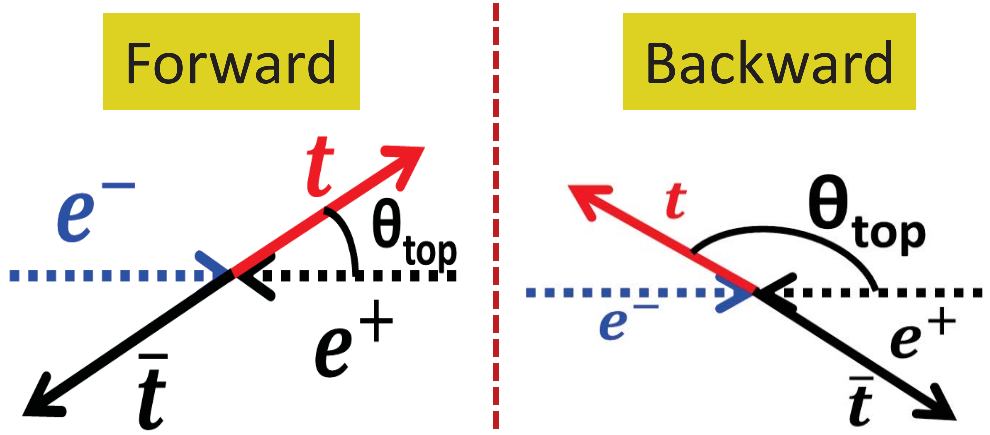


A_{FB} near ttbar threshold

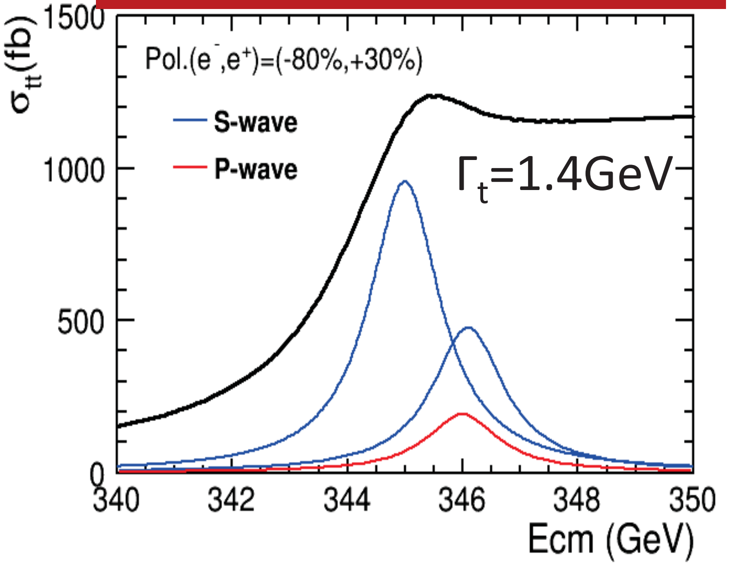
★Forward backward asymmetry of top quark（A_{FB}）

- ☐ Since top has large Γ_t, we can measure A_{FB} by interfering the resonance of S- and P- wave.
- ☐ The level split which is separation of two resonances depends on α_s.

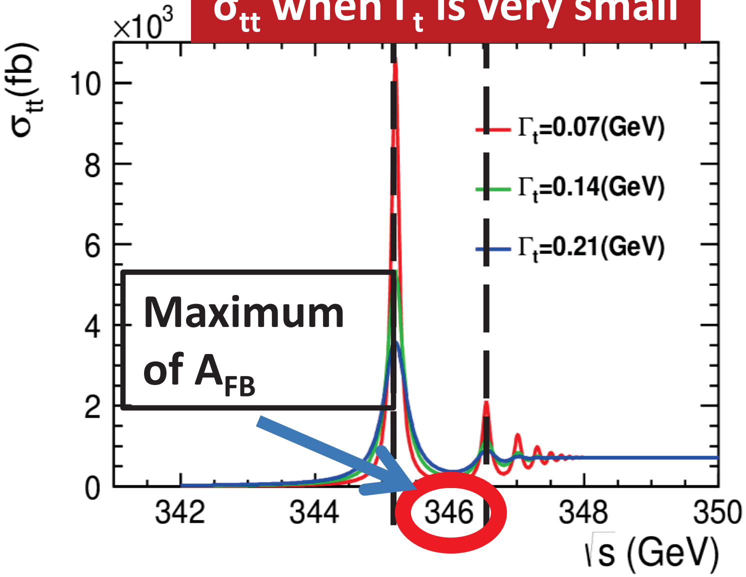
$$A_{FB} \equiv \frac{N(cos\theta_{top} > 0) - N(cos\theta_{top} < 0)}{N(cos\theta_{top} > 0) + N(cos\theta_{top} < 0)}$$



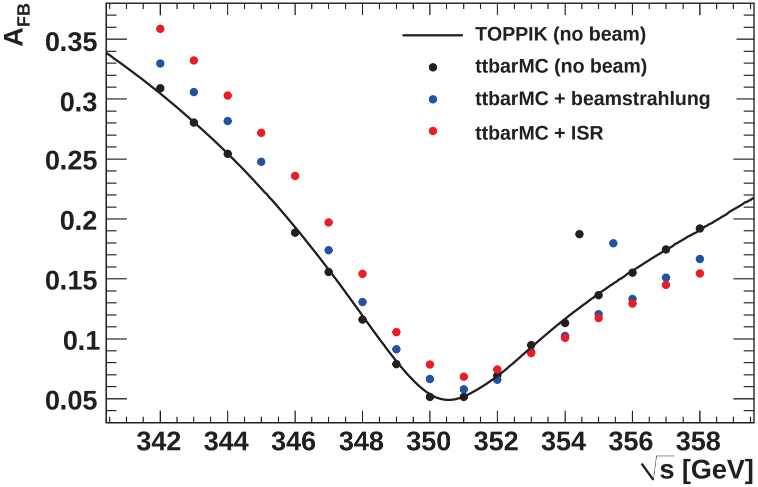
Interference of S- and P-wave

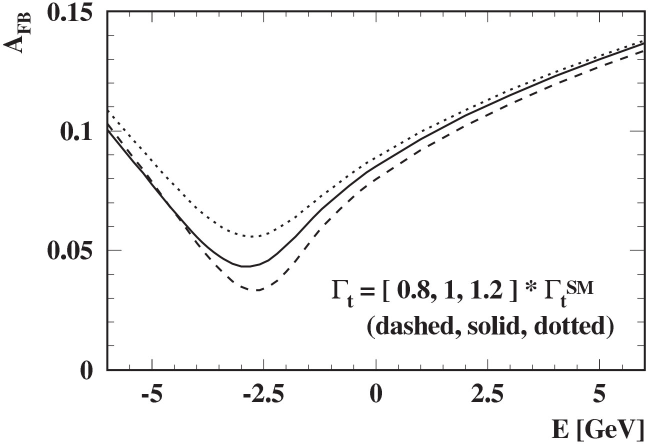


σ_{tt} when Γ_t is very small



A_{FB} at the threshold

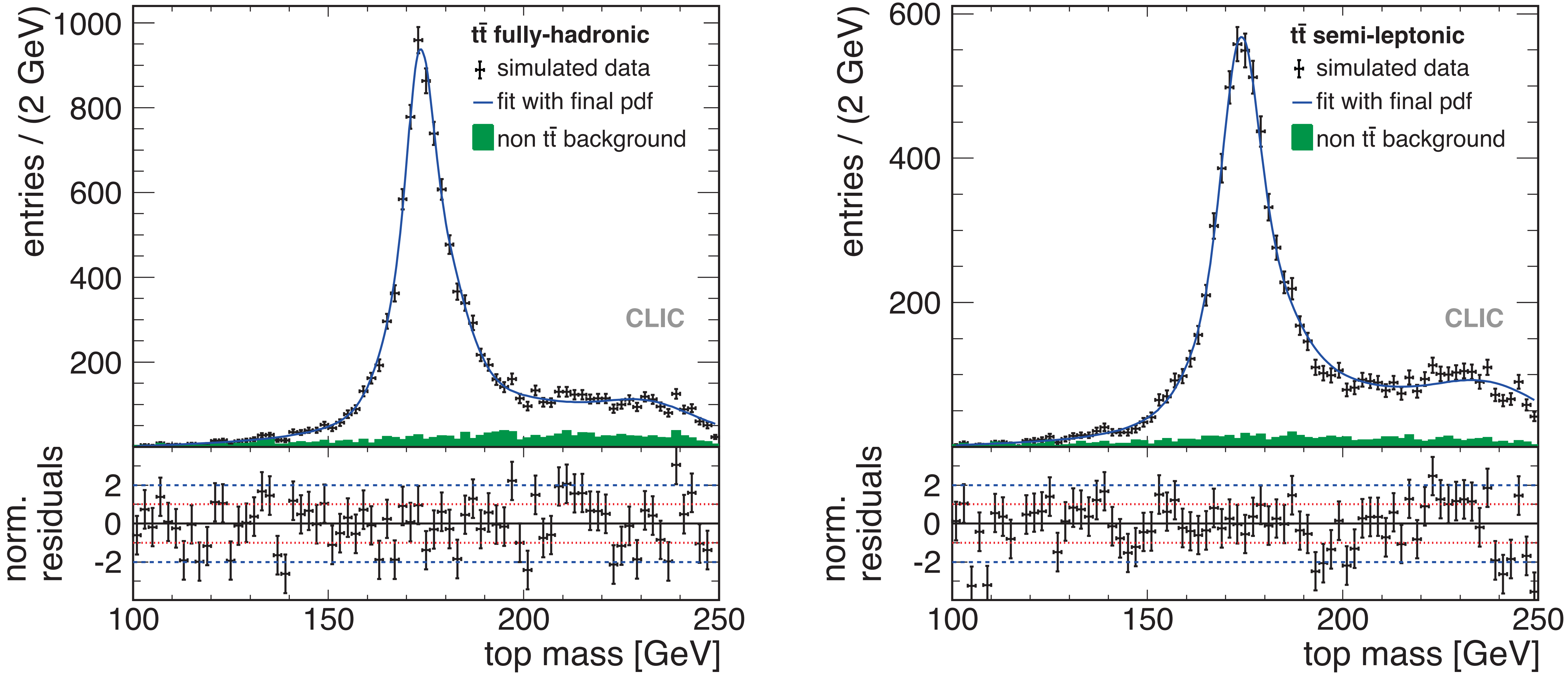




Can contribute to m_t and Γ_t measurement

☹ Detector level analysis still missing (?)

Mass Reconstruction Above Threshold



- Width less constrained than mass: substantial detector effects (peak width ~ 5 GeV compared to 1.4 GeV top width)

channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{\mathrm{top}}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

The Valencia jet algorithm

A new clustering jet reconstruction algorithm that combines the good features of lepton collider algorithms, in particular the **Durham-like distance criterion;**

$$d_{ij} = min(E_j^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

with the **robustness against background of** the longitudinally invariant **k_t algorithm**

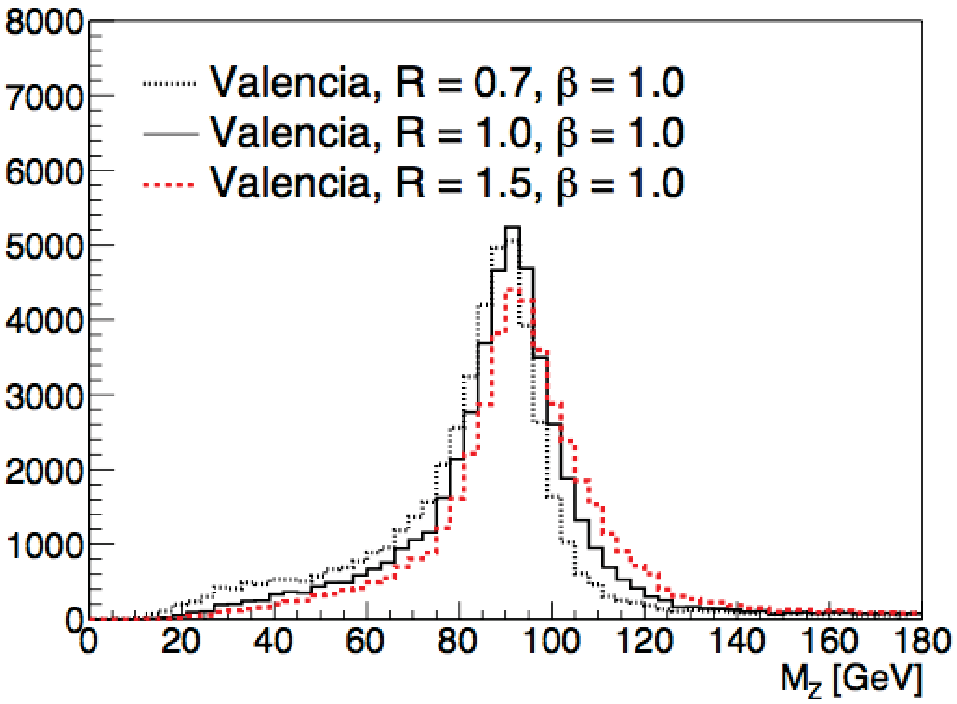
$$d_{iB} = p_T^{2\beta}$$

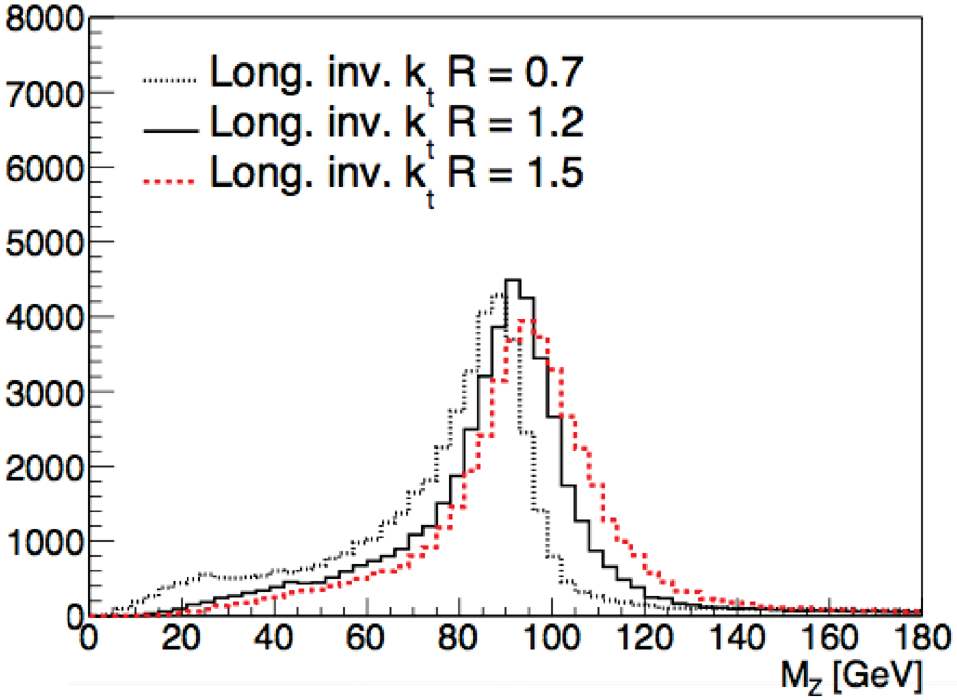
The exponent β allows to ***tune* the background rejection** level

The algorithm has been implemented as a **plugin for the *FastJet*** package and is available in fjcontrib

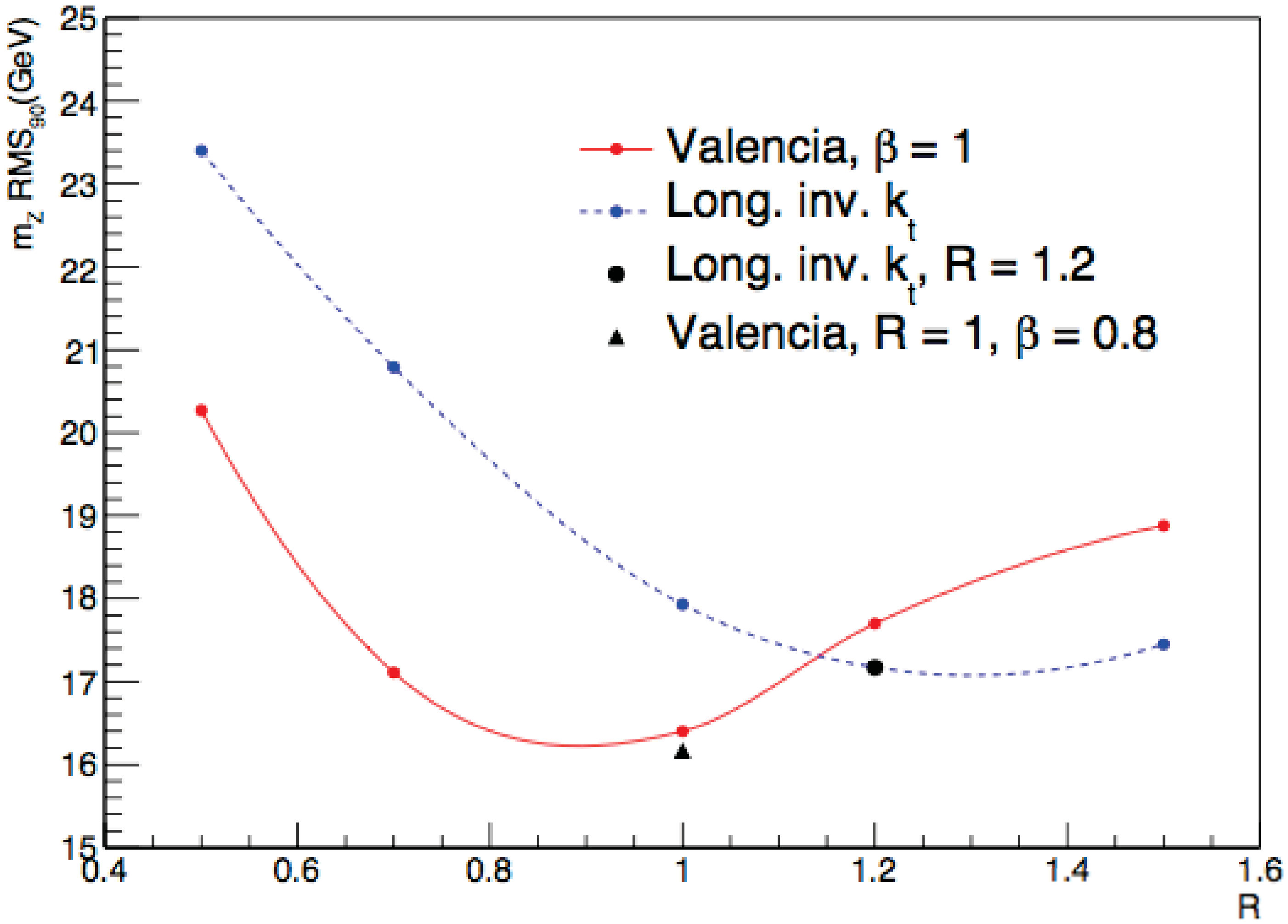
https://fastjet.hepforge.org/trac/browser/contrib/contribs/ValenciaJetAlgorithm

Parameter optimisation: R scan





The choice of parameters corresponds to the optimal setting determined in a scan over a broad range of parameters.



Marcel Vos, AWLC14

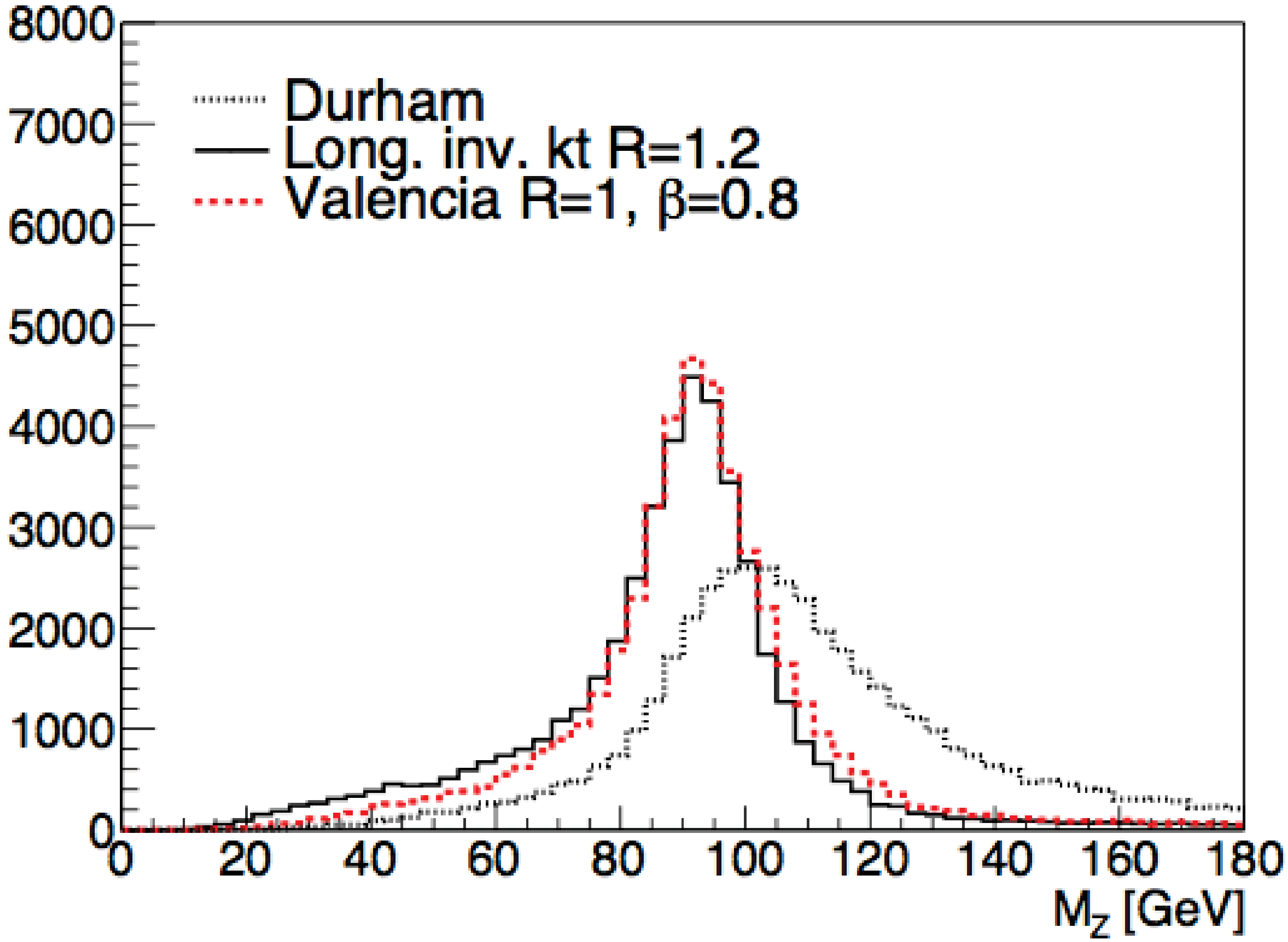
Jet reconstruction performance

CLIC di-boson (ZZ) production @ 500 GeV
+ 300 BX of γγ → hadrons

Reconstruct Particle Flow objects using PANDORA
+ quality and timing cuts

Reconstruct jets (exclusive, n=4)

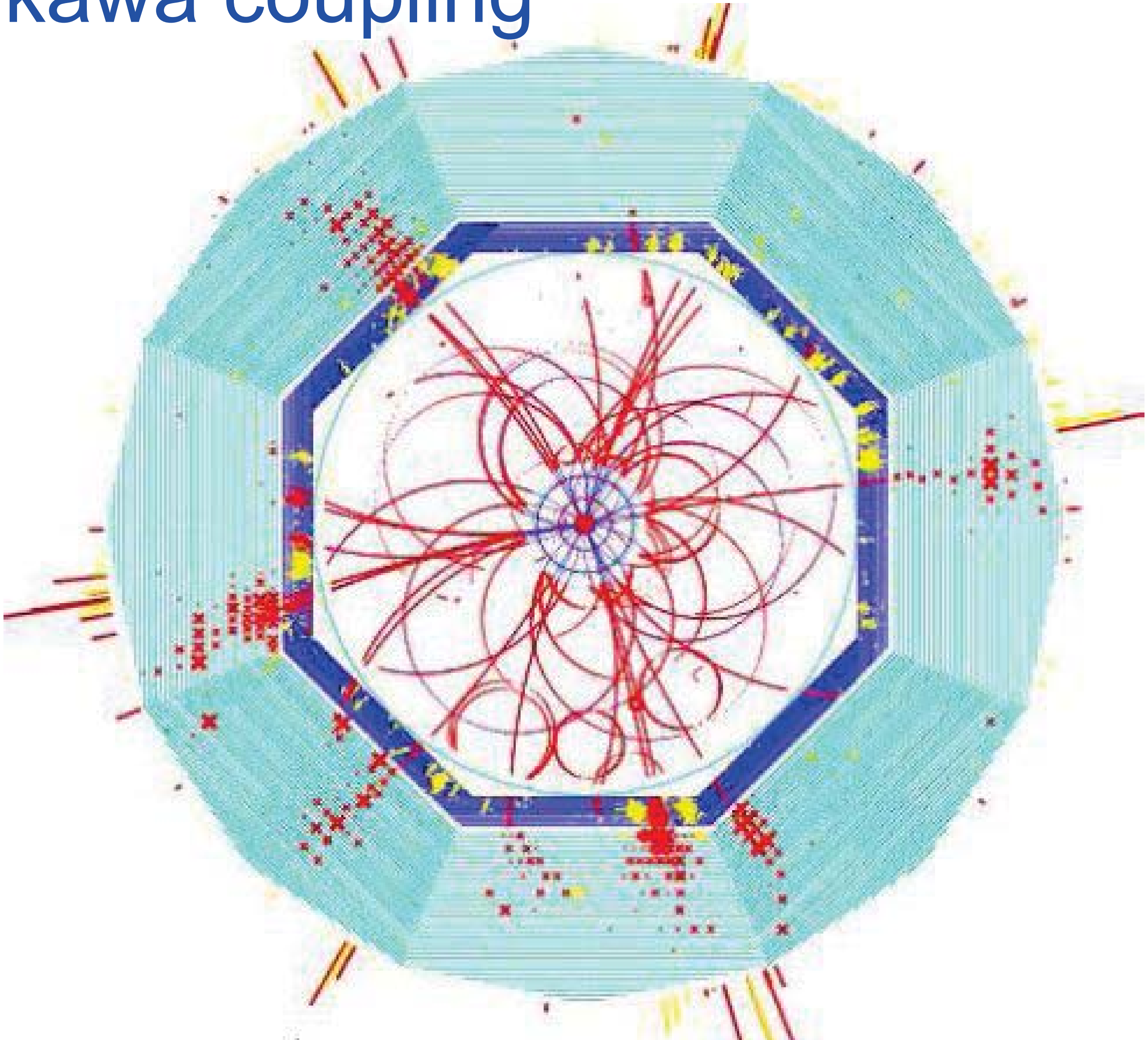
Form Z boson candidates, selecting best jet pairs



Nominal background: Durham is severely affected, longitudinally invariant k_t and Valencia OK

Top measurements

- Yukawa coupling

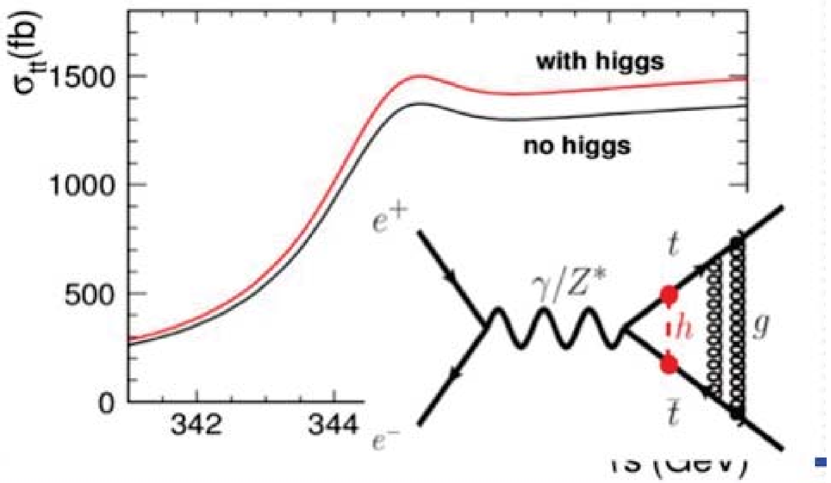


Top Yukawa coupling at threshold

The cross section is enhanced about 9% by exchanging the Higgs boson !!

$$\sigma_{tt} \propto \left|\mathcal{M}_{w/o\ higgs} + y_t^2 \mathcal{M}_{w/\ higgs}\right|^2$$

$$\frac{\delta y_t}{y_t} \sim \frac{109 \times \frac{1}{2} \times \frac{\delta\sigma}{\sigma}}{9}$$



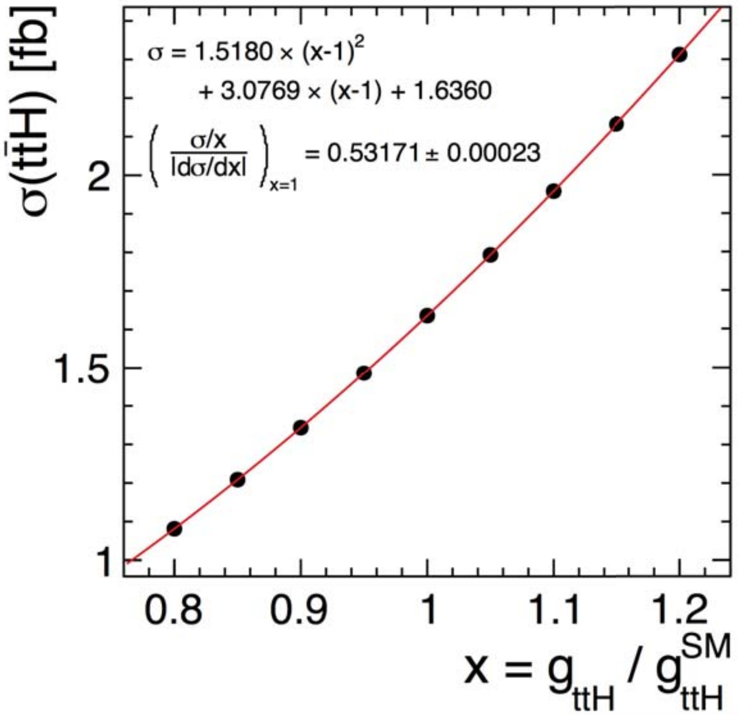
$\int \mathcal{L}dt = 100$ fb^{-1}

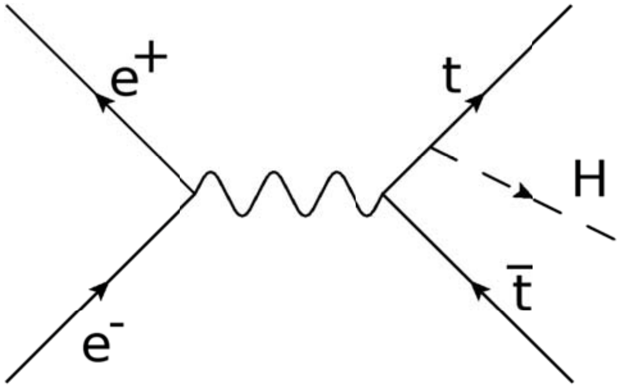
	(2 + 1) param fit	3 param fit
mt	19 MeV	29 MeV
Γt	38 MeV	39 MeV
yt	4.6%	5.9%

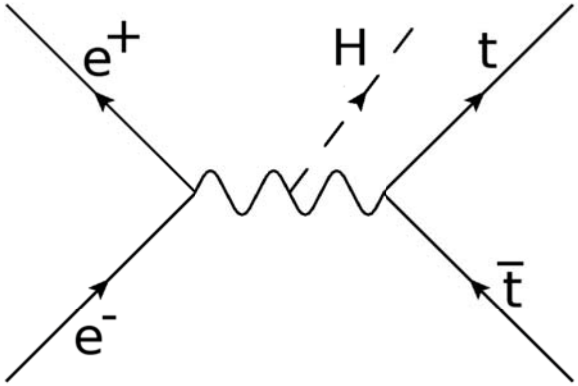
Stat. Uncertainties
'add'
Theoretical
uncertainties ~70 MeV

T. Horiguchi

Extraction of the top Yukawa coupling







$$\boxed{\frac{\Delta y_t}{y_t} = 0.53\,\frac{\Delta \sigma}{\sigma}}$$

(0.5 without contribution from Higgsstrahlung)

Expected # of events @ 500fb^{-1}

- $\sqrt{s}$ = 500 GeV, Mh = 125 GeV, $(Pe^-, Pe^+) = (-0.8, +0.3)$

- production cross section

Process	**σ (fb)**
$e^-e^+ \rightarrow tth$	0.485
$e^-e^+ \rightarrow ttZ$	1.974
$e^-e^+ \rightarrow ttg(bb)$	1.058
$e^-e^+ \rightarrow tbW$	979.8

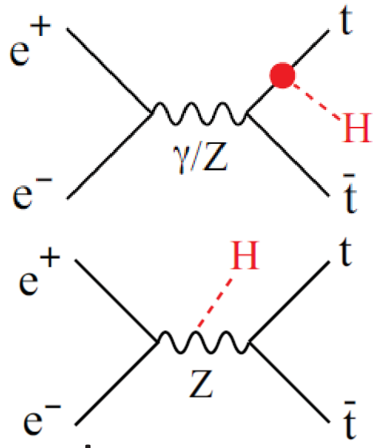
- Branching ratio

Decay mode	**Branching ratio**
h→bb	0.577
tt→bqqbqq	0.457
tt→blvbqq	0.438
tt→blvblv	0.105

- expected # of signals and Backgrounds(@500fb^{-1})

tth(tt6j, hbb)	**63.9**	**tth(ttln4j,hbb)**	**61.3**
tth(ttall, hnobb)	102.6	ttZ	987
tth(ttlvlv2j, hbb)	14.6	ttg(bb)	529
		tbW	489902

tth→8jets(lν+6jets) analysis



- interference term is negligible
- counting analysis with cut based event selection

In this analysis, higgs decays into two b jets

- 4 b jets out of 8(6) jets (b tagging: LCFIPlus)
- No (one) isolated lepton
- Use Kt clustering only for removing low Pt background

Event Selection

- signal topology

✓ Y cut (6, 8 jet event)

✓ No(one Isolated Lepton)

✓ B jet candidate ≥ 4

- detector acceptance

$|\text{Jet} \cos\theta| \leq 0.99$

- jet pairing

✓ $\chi 2 \leq 11.2$ (16.5)

- kinematics

✓ Leading 2 Jet Energy Sum

✓ Lowest 3 Jet Energy Sum (for 8jets mode)
(Lowest 2 Jet Energy Sum (for 6jets mode))

✓ Missing momentum > 20 GeV (for 6jtes mode)

- reconstructed mass

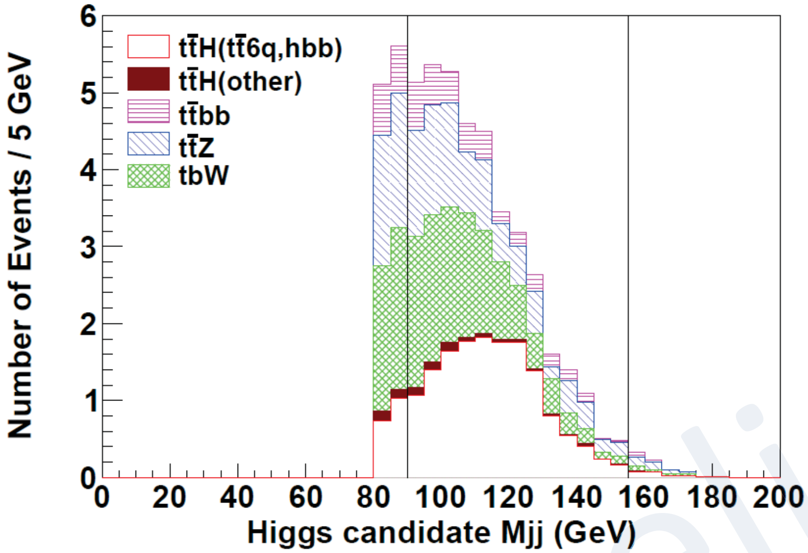
✓ top candidate Mjjj $\geq$ 140 GeV

✓ higgs candidate Mjj $\geq$ 80 GeV

✓ 90GeV $\leq$ h candidate Mjj $\leq$ 155GeV

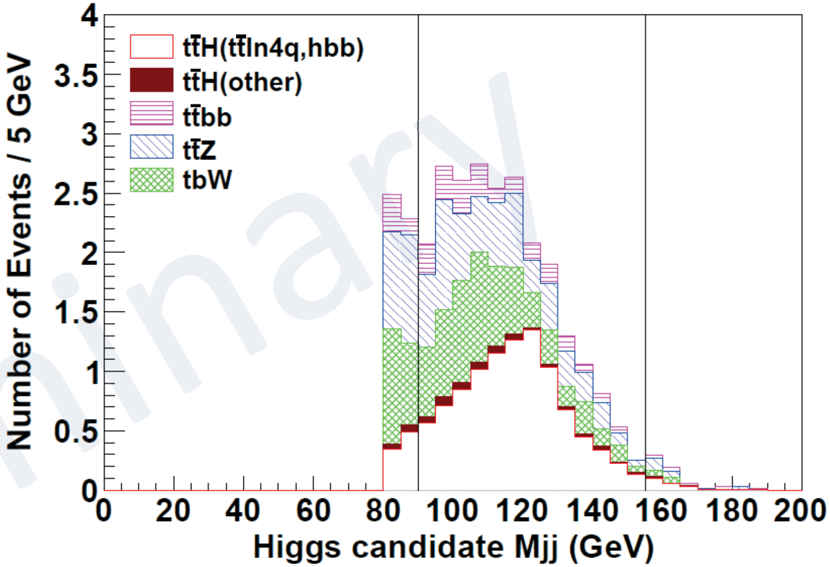
Result of ILD Full Simulation

tth→8jets



- $\sqrt{s}$ = 500 GeV, 500 fb^{-1}
- Nsig = 14.7
- Nbkgd = 24.5
- Nsig/$\sqrt{\text{Nsig} + \text{Nbkgd}}$ = 2.351,

tth→lν+6jets



- $\sqrt{s}$ = 500 GeV, 500 fb^{-1}
- Nsig = 9.77
- Nbkgd = 13.4
- Nsig/$\sqrt{\text{Nsig} + \text{Nbkgd}}$ = 2.029,

- W→e, μ, τ +ν inclusive analysis

Significance and Precision of top-Yukawa coupling measurement with Systematic Uncertainties

- Mh=125 GeV, $\sqrt{s}$ = 500 GeV, 500 fb^{-1}
- systematics: b tag eff.±1,3%, JESF±1,3%
  Br 1%, L 0.1%, pol 0.1%

tth→8 Jets

with systematics	signficance	$\|\Delta g_t/g_t\|$
0% (stat. only)	2.351	22.11%
1% (b, JESF)	2.343	22.19%
3% (b, JESF)	2.240	23.2%

tth→lν+6jets

with systematics	signficance	$\|\Delta g_t/g_t\|$
0% (stat. only)	2.029	25.62%
1% (b, JESF)	2.019	25.75%
3% (b, JESF)	1.958	26.55%

Rough estimation of significance and $|\Delta g_{tth}/g_{tth}|$ @$\sqrt{s}$ = 500-550 GeV, 500 fb^{-1} Combined result of 8jets and 6jets mode (* syst. error is not included)

$\sqrt{s}$	: $S/\sqrt{S+B}$	: $\lvert\Delta g_{tth}/g_{tth}\rvert$ %
500	: 3.105	: 16.74
520	: 5.113	: 10.16
550	: 7.403	: 7.023

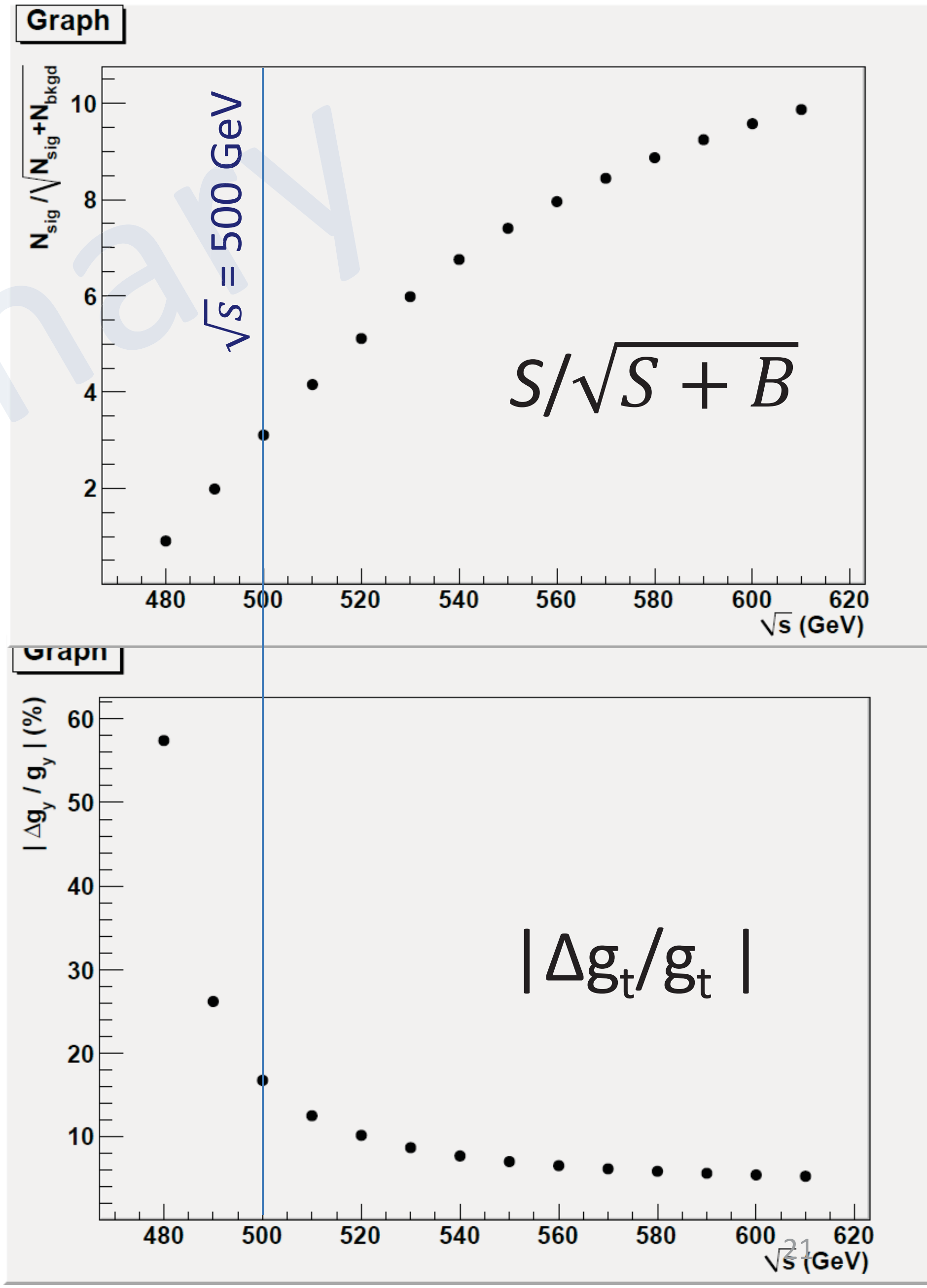
cross section (fb)

$\sqrt{s}$	: tth(total)	: ttz	: ttbb	: tbw
500	: 0.485	: 1.974	: 1.058	: 979.8
520	: 0.981	: 2.753	: 1.151	: 953.5
550	: 1.743	: 3.806	: 1.285	: 909.5

- ILC 1600fb^{-1} at $\sqrt{s}$ = 500 GeV

$|\Delta g_{tth}/g_{tth}|$ ~ 9.48% (1% syst. included)

9.36% (stat. only)

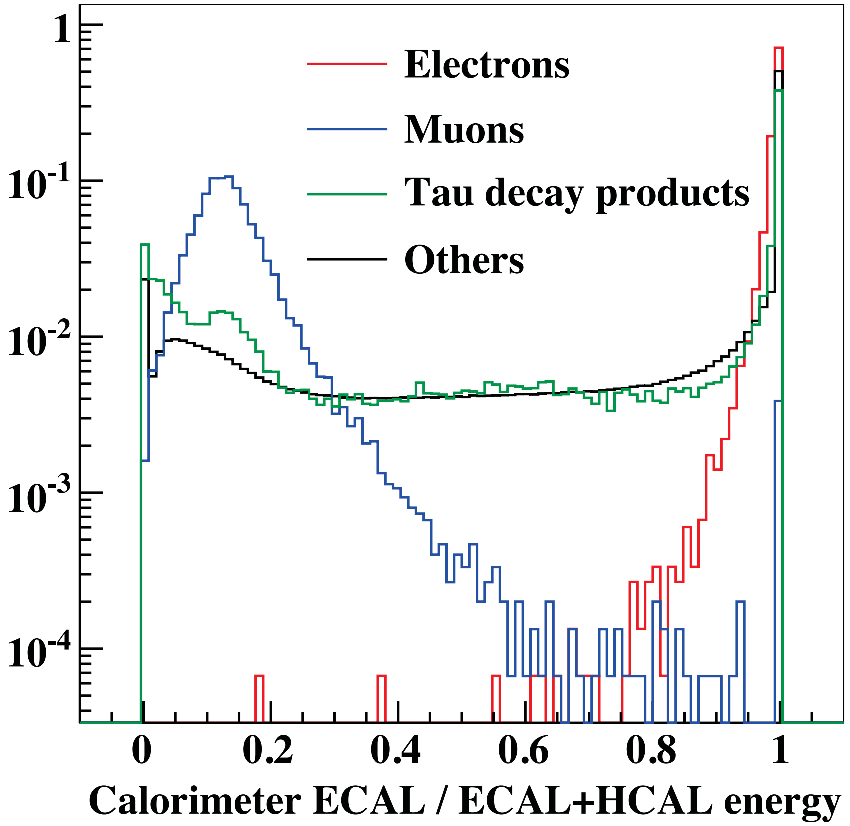


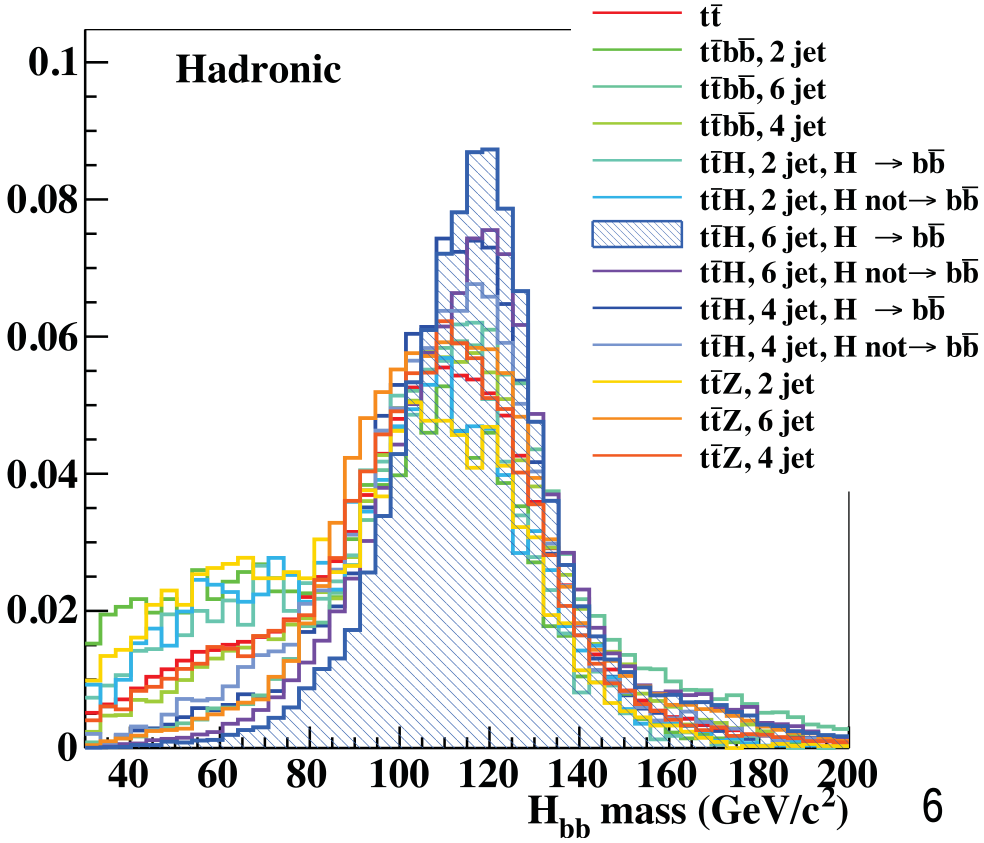
CLIC Analysis

1) Lepton finding
2) Jet clustering
3) Flavour tagging
   - 4 b jets!
4) Jet grouping
   - Choose permutation with smallest χ^2:

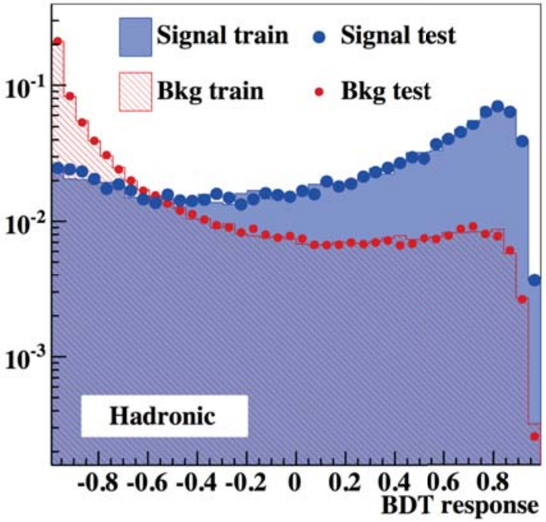
$$\chi^2 = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_h)^2}{\sigma_h^2}$$

5) MVA selection on discriminating variables
6) Channel combination and compensation for Higgsstrahlung



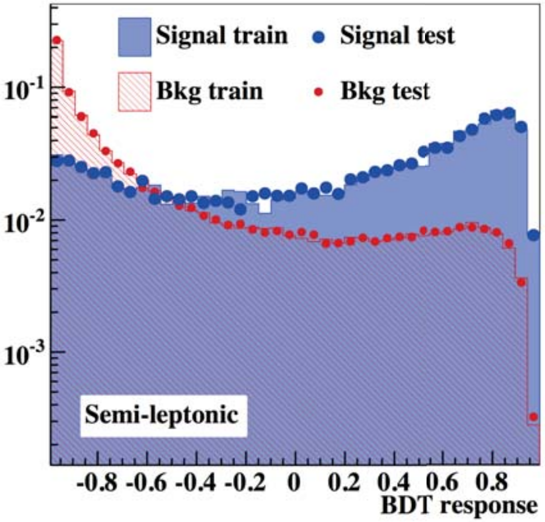


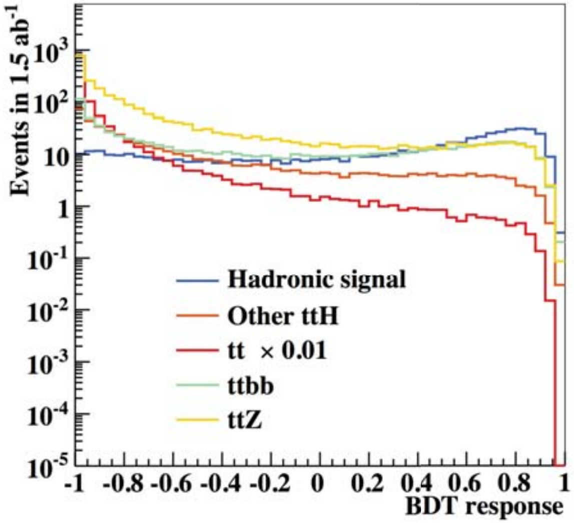
MVA selection



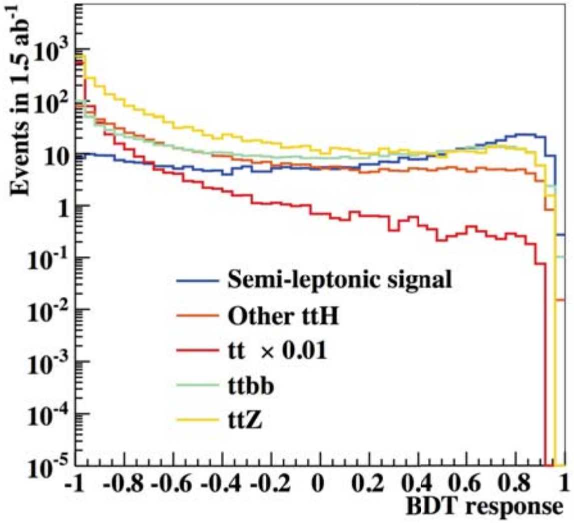
- Similar discrimination in both channels

- No sign of overtraining

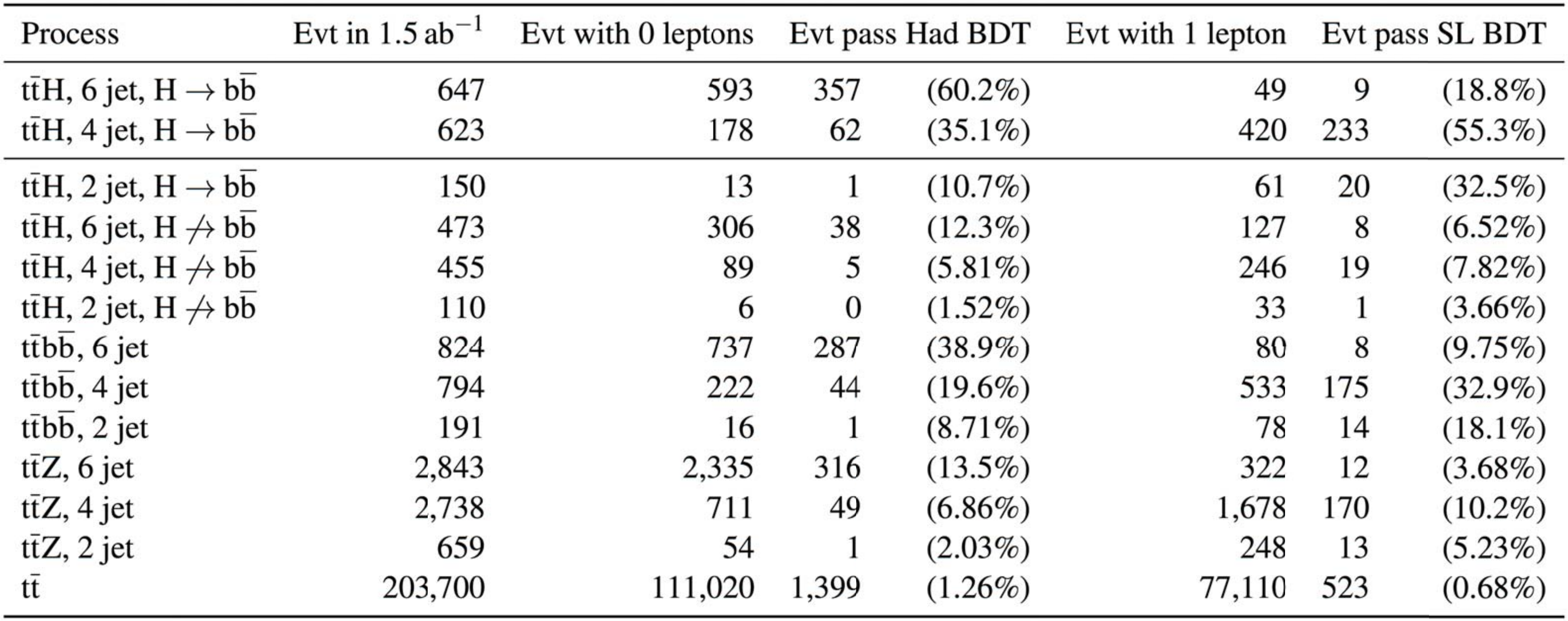




- Cuts on BDT response providing maximum significance (S / $\sqrt{S + B}$) used for cross section extraction



Details on the MVA selection



Process	Evt in 1.5 ab^{-1}	Evt with 0 leptons	Evt pass Had BDT		Evt with 1 lepton	Evt pass SL BDT	
$t\bar{t}H$, 6 jet, $H \rightarrow b\bar{b}$	647	593	357	(60.2%)	49	9	(18.8%)
$t\bar{t}H$, 4 jet, $H \rightarrow b\bar{b}$	623	178	62	(35.1%)	420	233	(55.3%)
$t\bar{t}H$, 2 jet, $H \rightarrow b\bar{b}$	150	13	1	(10.7%)	61	20	(32.5%)
$t\bar{t}H$, 6 jet, $H \not\rightarrow b\bar{b}$	473	306	38	(12.3%)	127	8	(6.52%)
$t\bar{t}H$, 4 jet, $H \not\rightarrow b\bar{b}$	455	89	5	(5.81%)	246	19	(7.82%)
$t\bar{t}H$, 2 jet, $H \not\rightarrow b\bar{b}$	110	6	0	(1.52%)	33	1	(3.66%)
$t\bar{t}b\bar{b}$, 6 jet	824	737	287	(38.9%)	80	8	(9.75%)
$t\bar{t}b\bar{b}$, 4 jet	794	222	44	(19.6%)	533	175	(32.9%)
$t\bar{t}b\bar{b}$, 2 jet	191	16	1	(8.71%)	78	14	(18.1%)
$t\bar{t}Z$, 6 jet	2,843	2,335	316	(13.5%)	322	12	(3.68%)
$t\bar{t}Z$, 4 jet	2,738	711	49	(6.86%)	1,678	170	(10.2%)
$t\bar{t}Z$, 2 jet	659	54	1	(2.03%)	248	13	(5.23%)
$t\bar{t}$	203,700	111,020	1,399	(1.26%)	77,110	523	(0.68%)

MVA selection efficiencies for the signal samples:
60% for the hadronic channel
55% for the semileptonic channel

Results

Hadronic channel:

$S / \sqrt{S + B} = 8.36$

$\Delta(\sigma(t\bar{t}H)) = 12.0\%$

Semileptonic channel:

$S / \sqrt{S + B} = 9.17$

$\Delta(\sigma(t\bar{t}H)) = 10.9\%$

Combined:

$\Delta(\sigma(t\bar{t}H)) = 8.1\%$

$\rightarrow \Delta(g_{ttH}) = 4.3\%$

$L = 1.5\ \mathrm{ab}^{-1}$

→ Precision on g_{ttH} would improve to better than 4% with -80% electron polarisaion

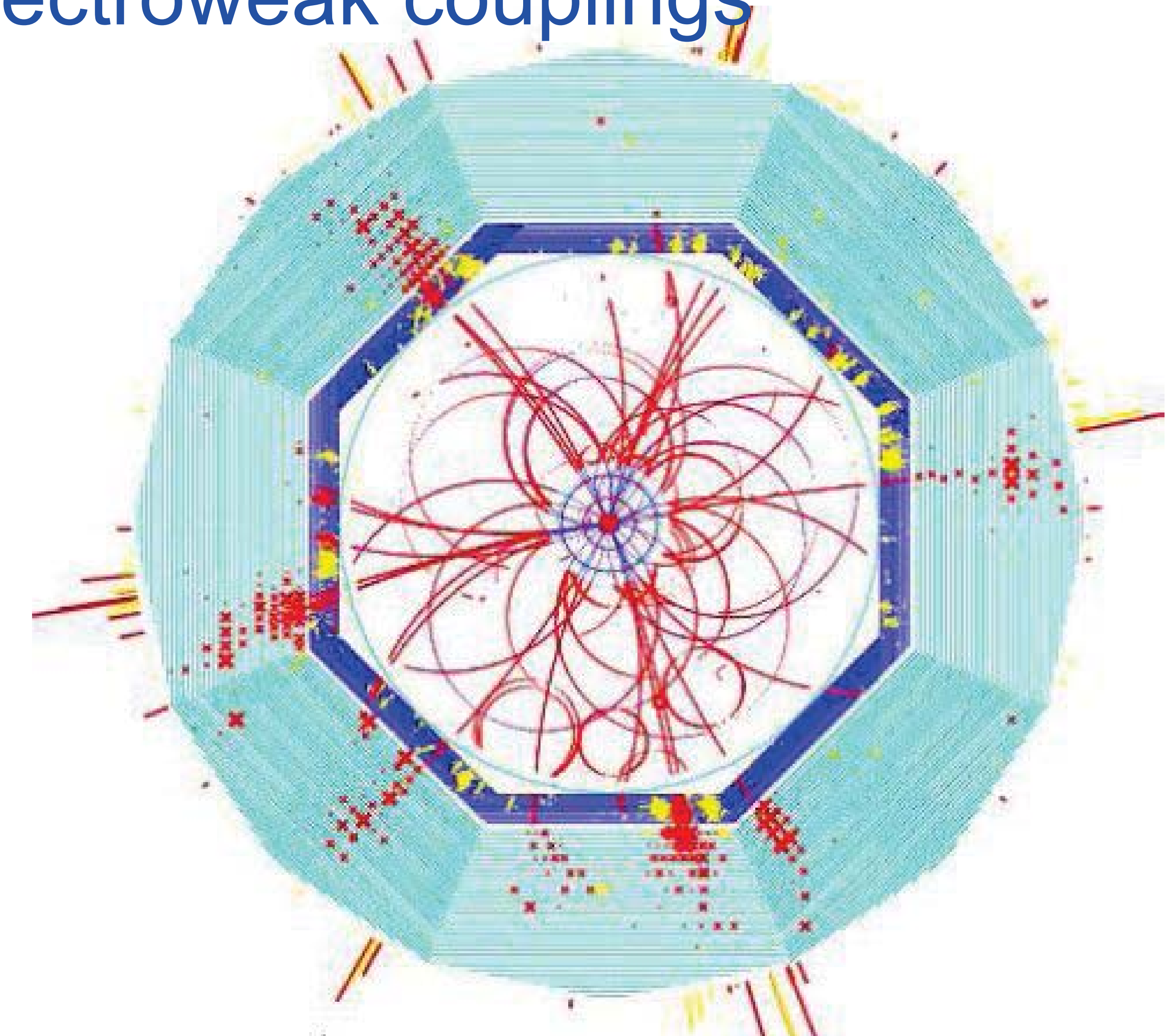
---

For comparison:

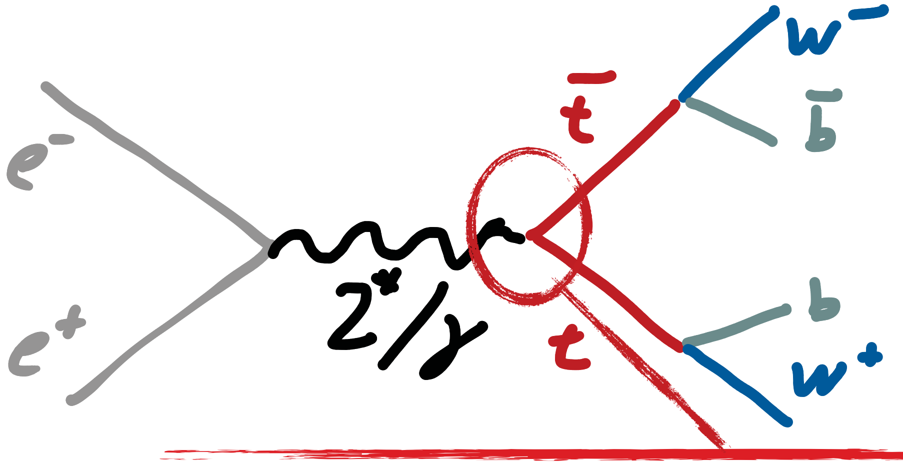
$\Delta(g_{ttH}) = 4.3\text{-}4.5\%$ expected at 1 TeV ILC (form ILC TDR)

Top measurements

- Electroweak couplings



Electroweak Couplings of the Top Quark



- The production of top pairs provides direct access to electroweak couplings - axial and vector form factors

$$\boxed{\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^{X}(k^2) + \gamma_5\widetilde{F}_{1A}^{X}(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^{X}(k^2) + \gamma_5\widetilde{F}_{2A}^{X}(k^2)\right)\right\}}$$

X: Z, γ

A: axial coupling

V: vector coupling

- In total: 5 non-trivial CP-conserving form factors:

$$\begin{array}{ccc} F_{1V}^{\gamma} & \boxed{F_{1A}^{\gamma}} & F_{2V}^{\gamma} \\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z} \end{array}$$

= 0 due to gauge invariance

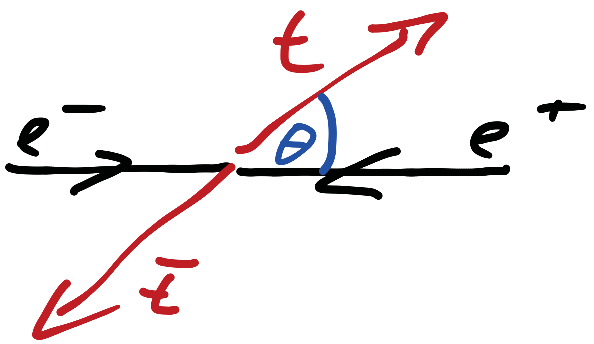
- Accessible through measurements of:
  - ***Total cross-section***
  - ***Forward-backward Asymmetry A_{FB}***
  - ***Helicity Angle λ*** distribution (related to fraction of left- and right-handed tops)
- For each: Two polarizations e^-_L - e^+_R, e^-_R - e^+_L

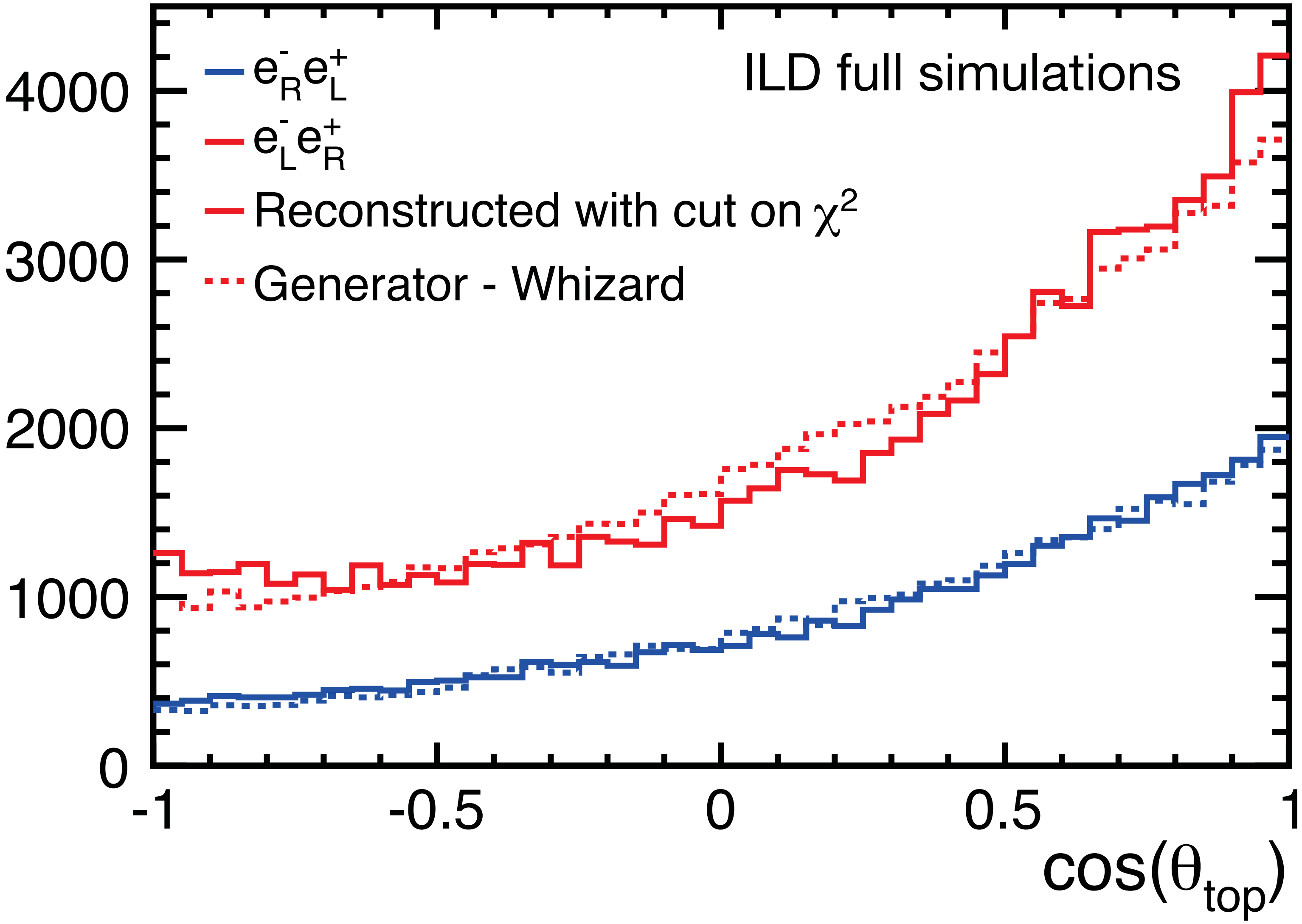
⇨ LC polarised beams crucial!

Accessing EW Couplings: Asymmetries & Angles

- Forward-backward asymmetry:

$$A^t_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$





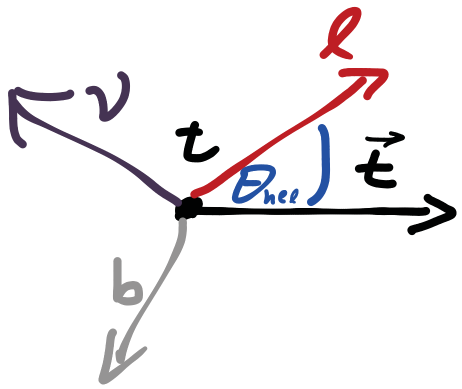
- ILC, 500 GeV, 500 fb^{-1}
- Two polarisation configurations:
  - $e^-_R e^+_L$: P(e^-) -80%, P(e^+) +30%
  - $e^-_L e^+_R$: P(e^-) +80%, P(e^+) -30%

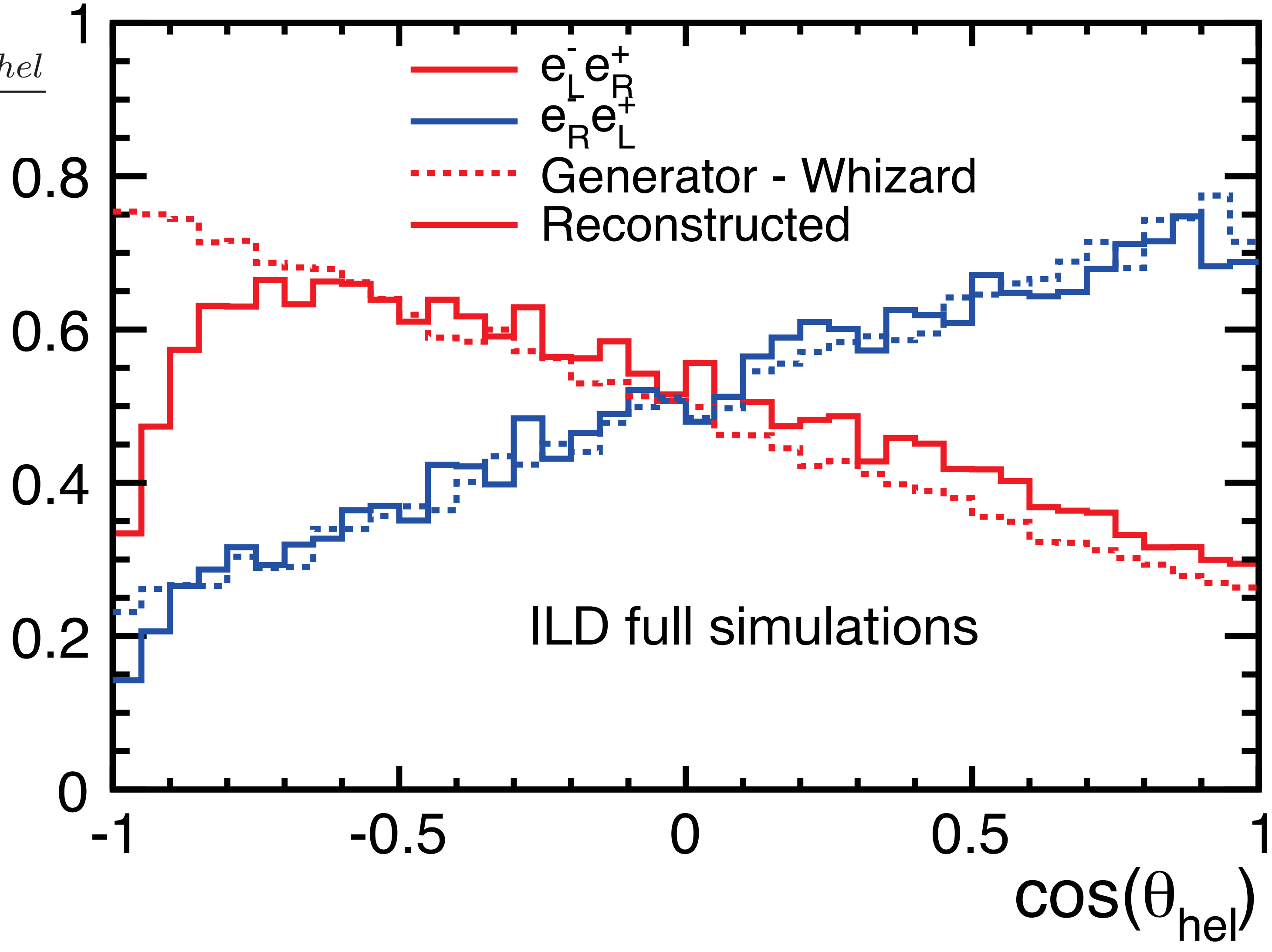
precision on asymmetry: ~2% (stat+ syst)

Accessing EW Couplings: Asymmetries & Angles

- Helicity Angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_{hel}} = \frac{1+\lambda_t cos\theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1)\frac{cos\theta_{hel}}{2}$$





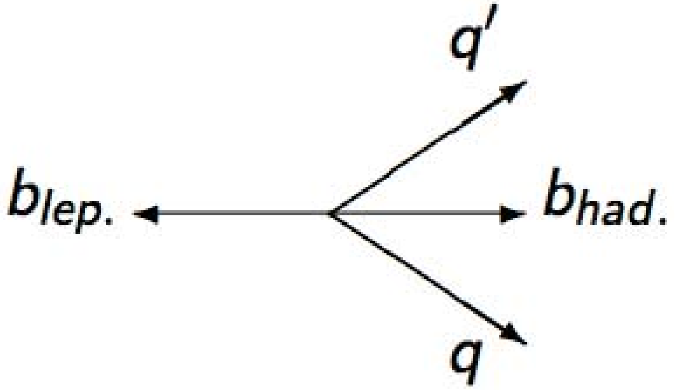
- ILC, 500 GeV, 500 fb^{-1}
- Two polarisation configurations:
  - $e^-_R e^+_L$: P(e^-) -80%, P(e^+) +30%
  - $e^-_L e^+_R$: P(e^-) +80%, P(e^+) -30%

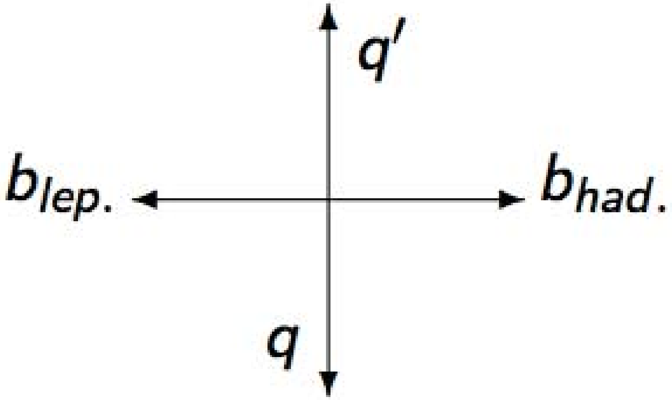
precision on helicity angle:
~4% (stat+ syst)

Experimental challenge b-charge reconstruction - Motivation

- To measure A_{FB} in fully hadronic decays there is no choice

- In semi-leptonic decays there is the charged lepton but ….





Right handed electron beam:

- mainly right handed tops In final state (V-A)
- <u>Hard W</u> in flight direction of Top and soft b's
- Flight direction of t from flight direction of W

Left handed electron beam:

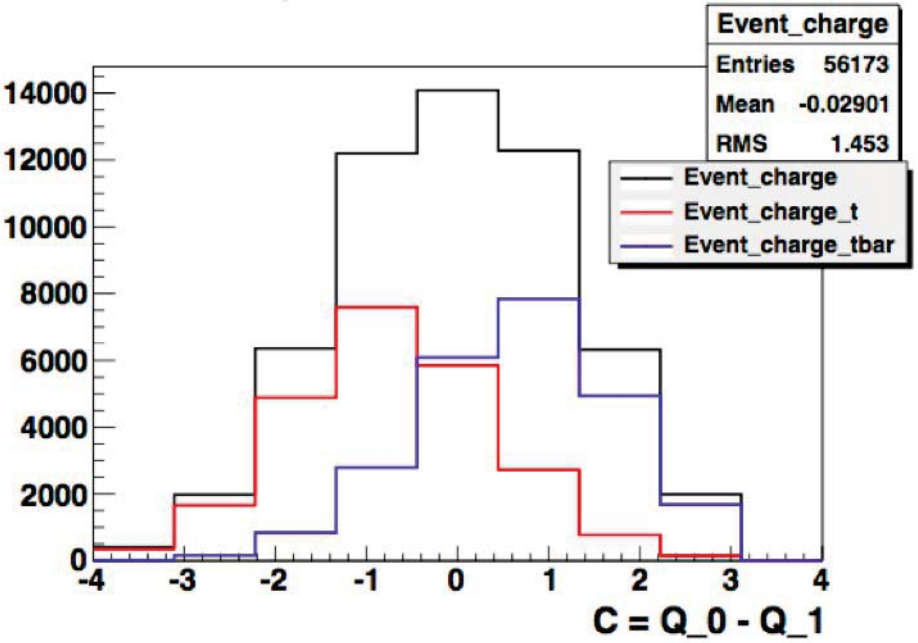
- mainly left handed tops
- <u>Hard b</u> in flight direction of Top and soft W's
- Flight direction of t from flight direction of b

=> Wrong association ↔ top flip

Measurement of b-charge to resolve ambiguities

Top polar angle using b charge

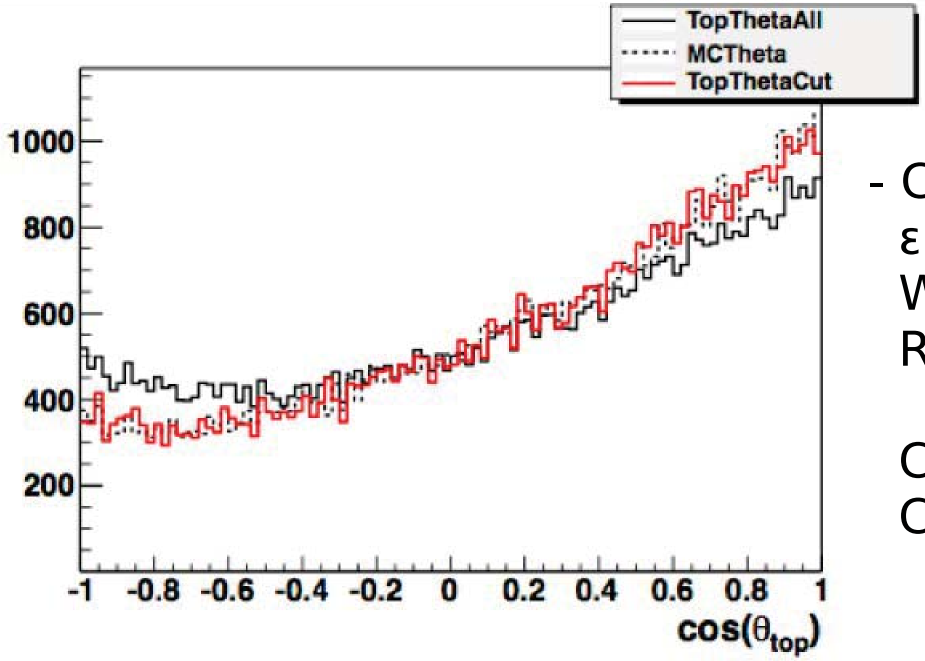
(SL Analysis)



Event charge C = b1 -b2

In SL can compare charge C with lepton charge to select clean sample

Use only events with correct C or C=0 (plus another cut on the Lorentz Factor)



- Clean reconstruction of top quark direction
  ε ~ 30%
  Will improve with improving charge Reconstruction

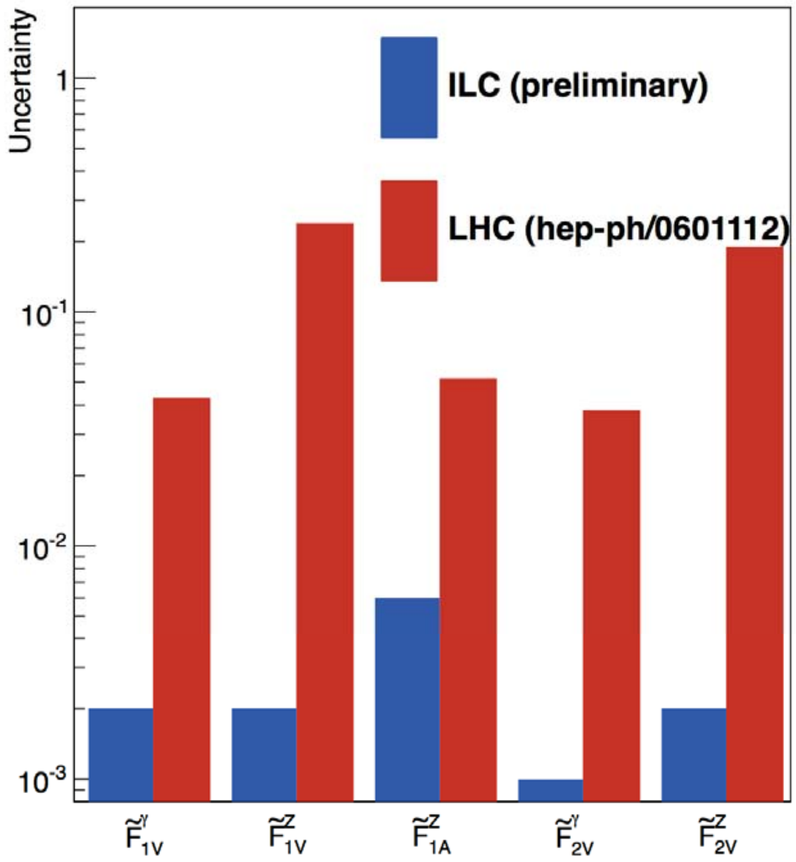
  Can already be considered as indpendent Cross check of existing results

Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

IFICLAL ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of vector/axial vectol couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

- Potential for CP violating couplings at ILC under study
  (However CP violation would rather show up at threshold)

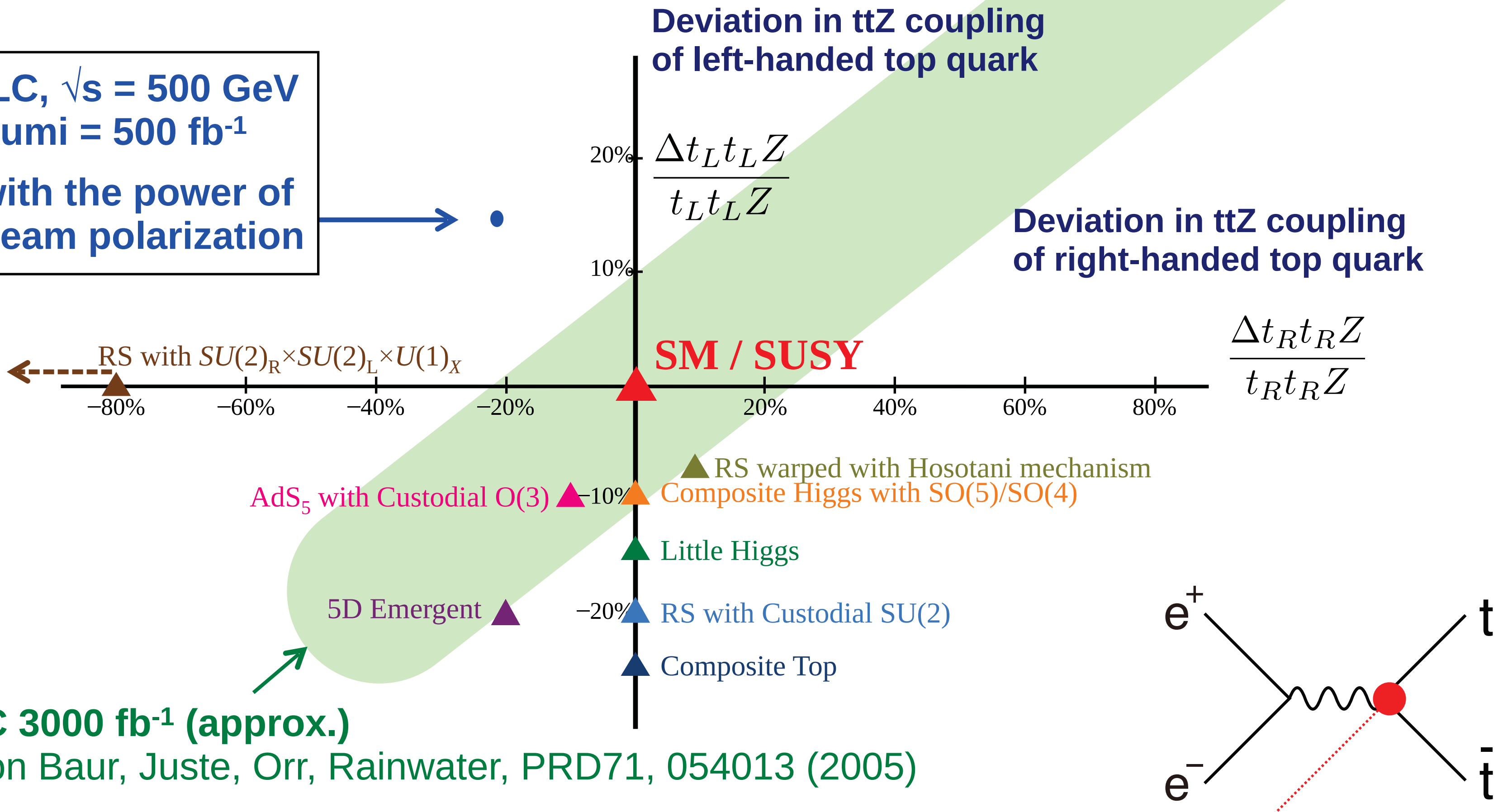
ILC will be indeed high precision machine for electroweak top couplings

Impact of BSM on Top Sector

In composite Higgs models, it is often said that ***the top quark is partially composite***, resulting in ***form factors in ttZ couplings***, which can be measured at ILC. ***Beam polarization is essential*** to distinguish the ***left- and right-handed couplings***.

ILC, √s = 500 GeV
Lumi = 500 fb^{-1}

with the power of beam polarization

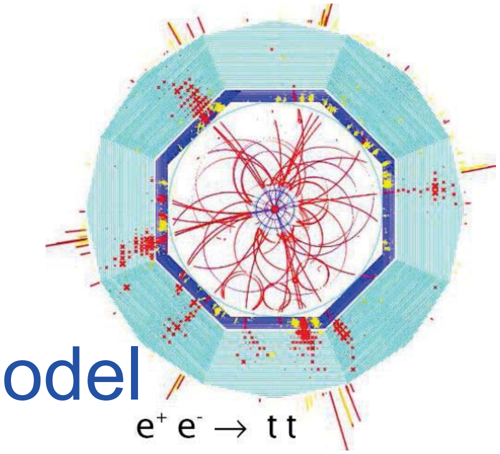


HL-LHC 3000 fb^{-1} (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\tilde{F}_{1V}^X(k^2) + \gamma_5 \tilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X(k^2) + \gamma_5 \tilde{F}_{2A}^X(k^2)\right)\right\}$$

Conclusions


$e^+ e^- \rightarrow t t$

- Precise determination of top parameters is crucial for validation of the Standard Model (or any alternative BSM theory)

- Top threshold scan at the e^+e^- collider gives unique oportunities for precise mass, width and coupling determination

- Determination of Yukawa and electroweak couplings require running at higher beam energies

- Even in clean e^+e^- environment top event reconstruction is very challenging. Stringent requirements are imposed on detector performance.

The solid pillars of the LC physics program

Top quark

Discovered 1995 at Tevatron

LHC and ILC are/would be
Top factories

W Boson

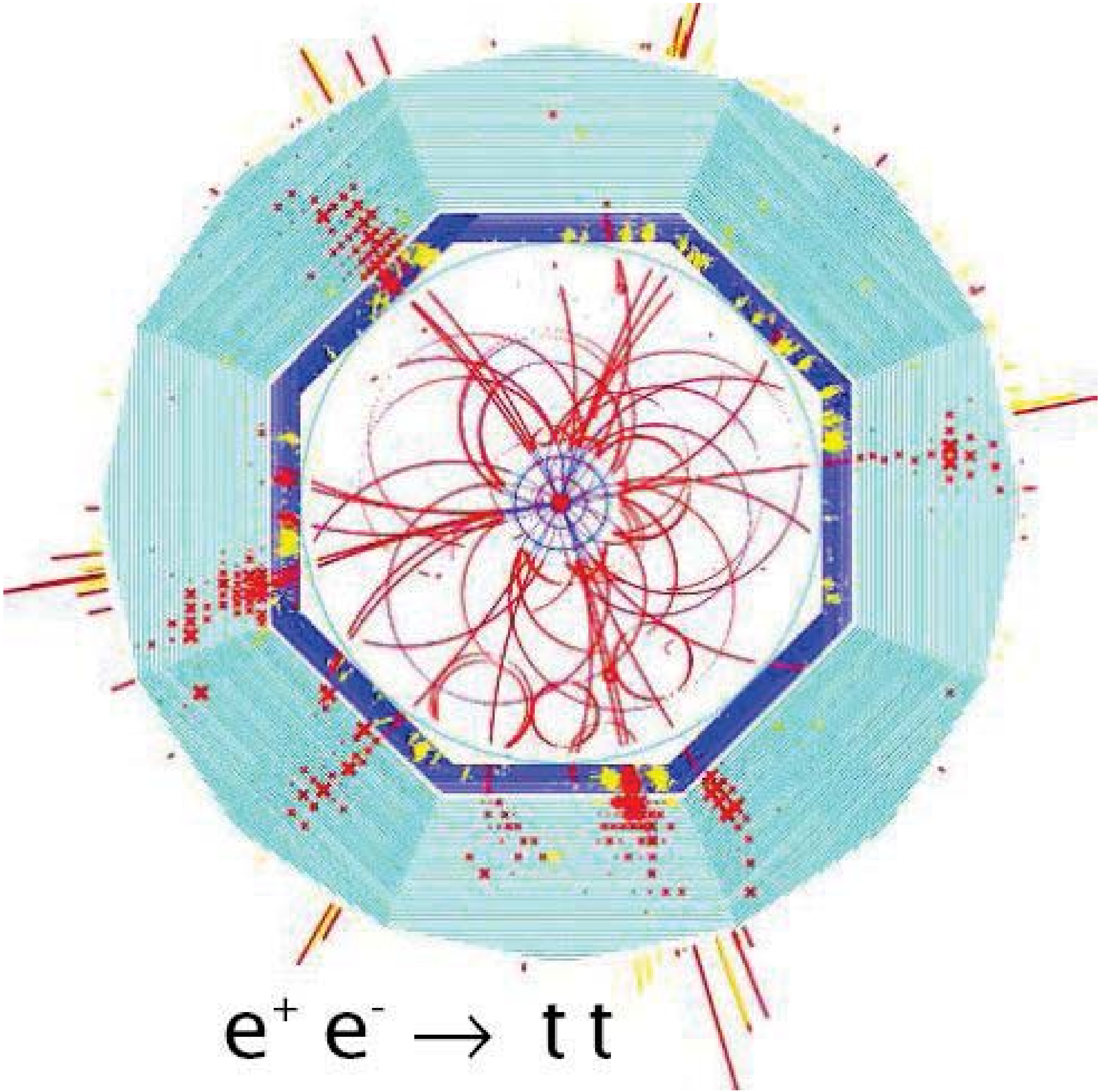
Discovered 1979 at SPS
Mass precisely at Tevatron
LHC and ILC are/would be
W factories

Higgs Boson

Discovered 2012 at LHC

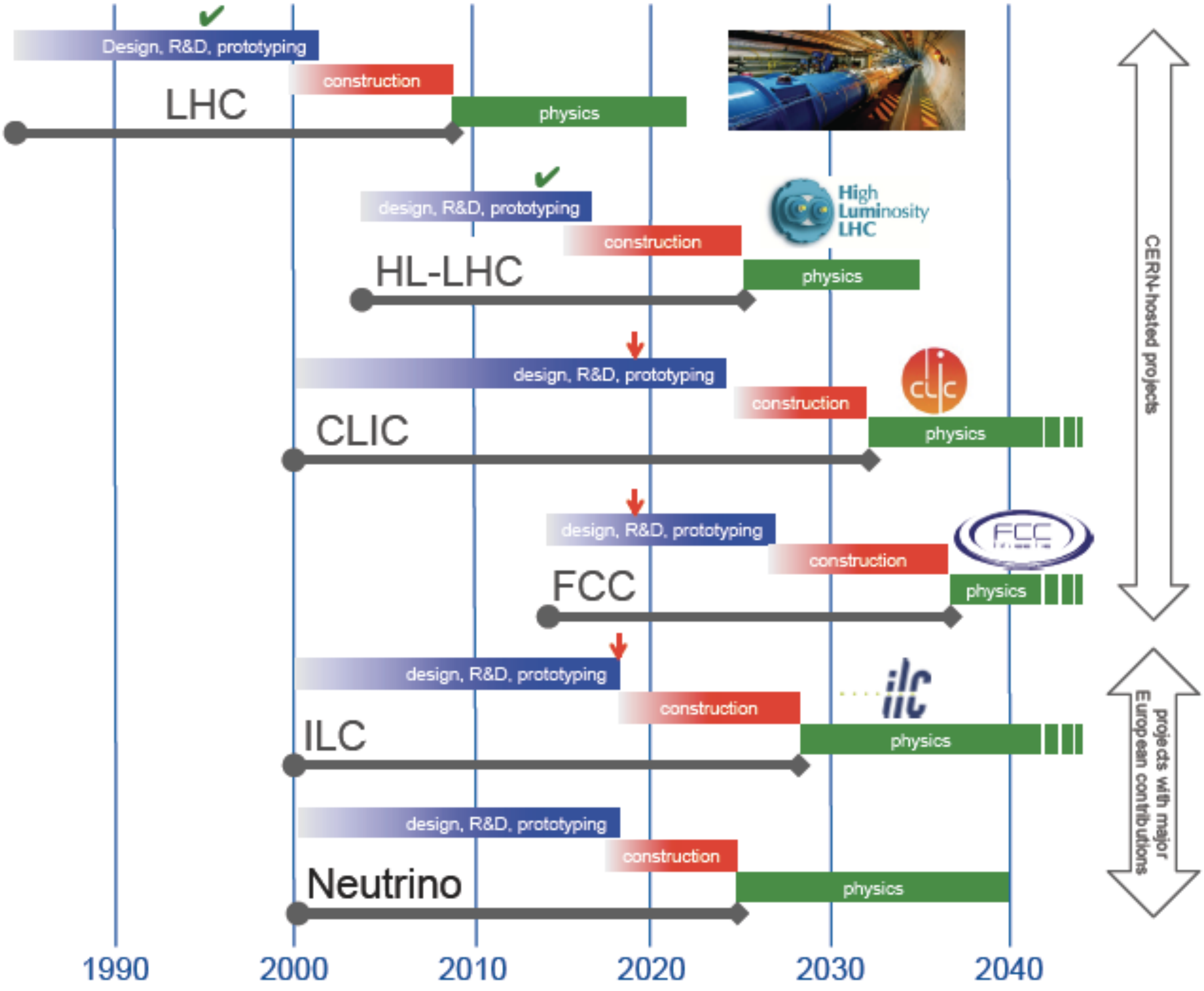
ILC are/would be
Higgs factories
See talk by Klaus

Backup slides



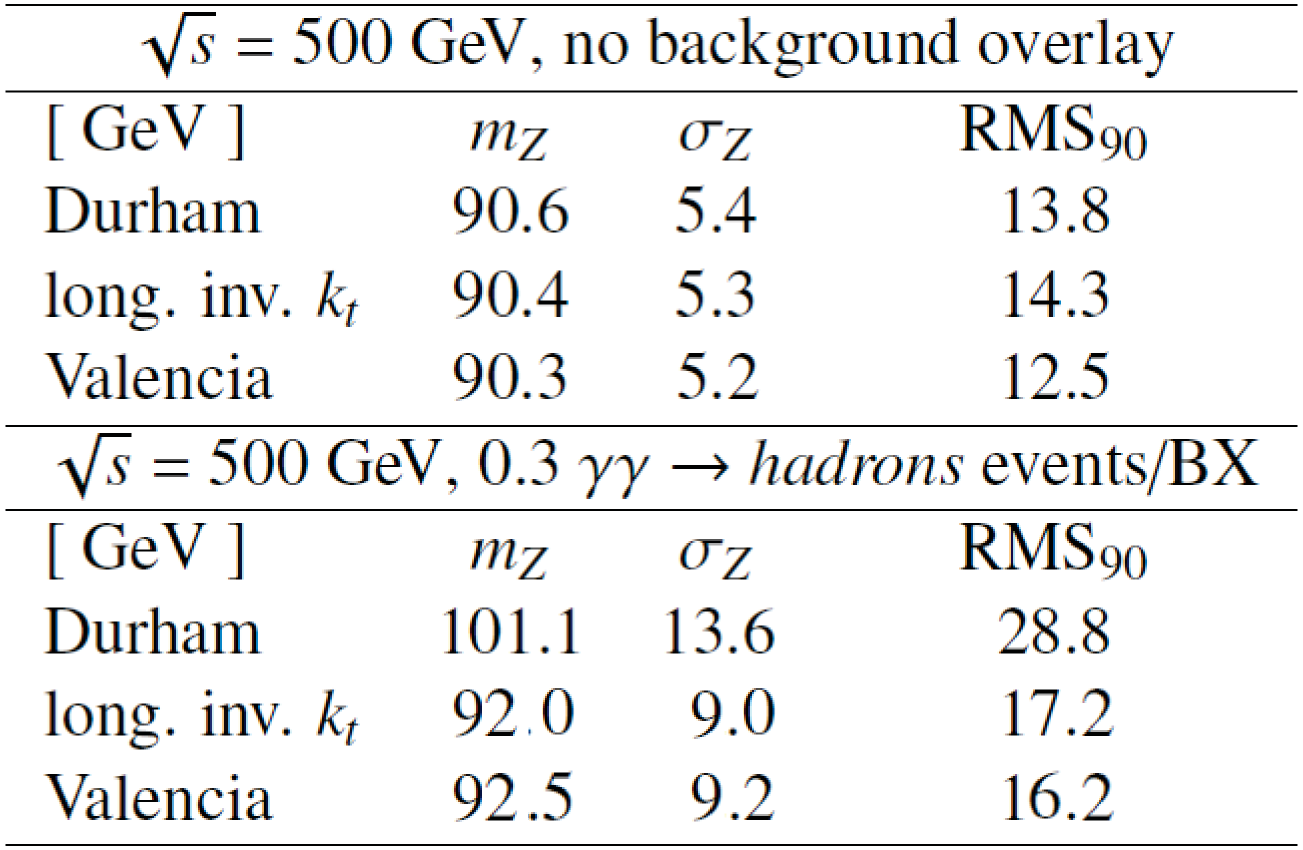
$e^+ e^- \rightarrow t\,t$

timeline: (HL-)LHC and future collider options



Jet reconstruction performance

The previous results in numbers: central value, width of the Z-boson mass peak and RMS_{90}



$\sqrt{s} = 500$ GeV, no background overlay			
[GeV]	m_Z	σ_Z	RMS_{90}
Durham	90.6	5.4	13.8
long. inv. k_t	90.4	5.3	14.3
Valencia	90.3	5.2	12.5

$\sqrt{s} = 500$ GeV, 0.3 $\gamma\gamma \rightarrow$ *hadrons* events/BX			
[GeV]	m_Z	σ_Z	RMS_{90}
Durham	101.1	13.6	28.8
long. inv. k_t	92.0	9.0	17.2
Valencia	92.5	9.2	16.2

e^+e^- style algorithm can compete with hadron collider algorithm