What is the right Linear Collider?

Tuesday Seminar
Sept. 21, 2010
J.List, DESY

Today's Menue

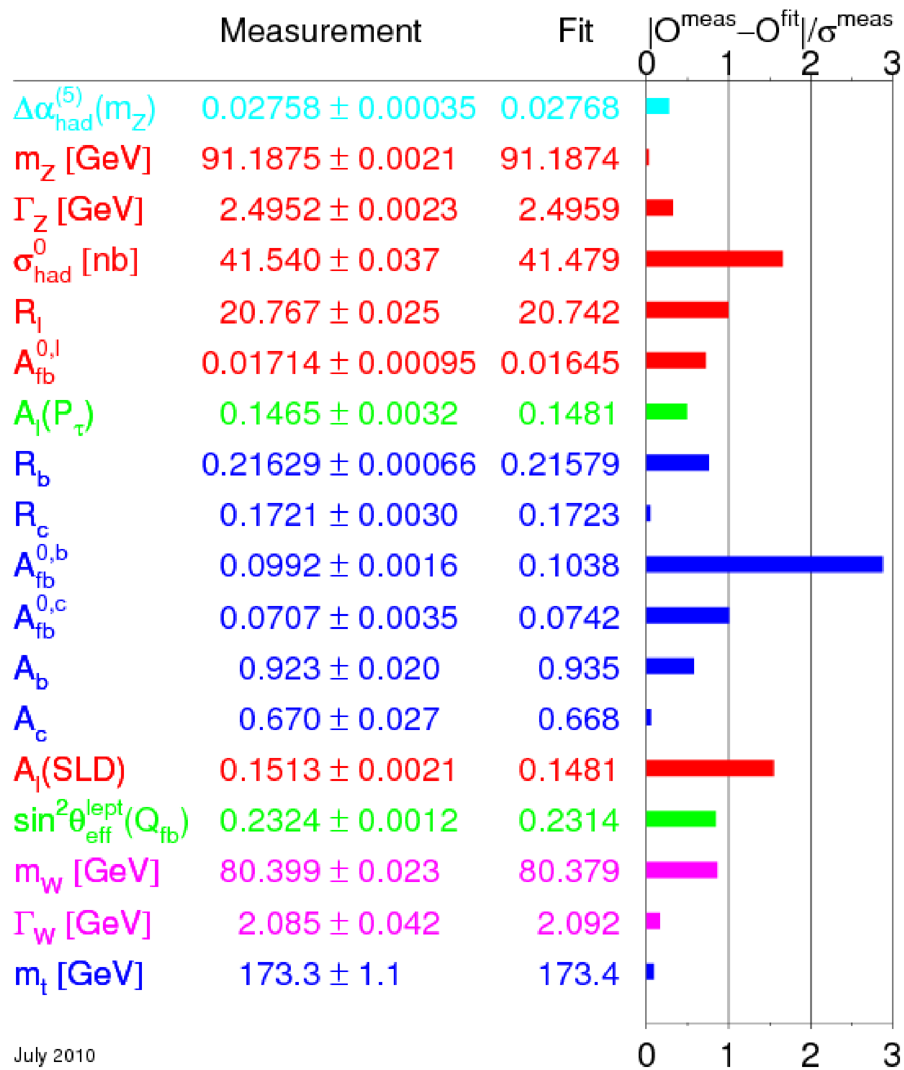
- Introduction
  - e^+e^- Linear Colliders:
    - What we expect of a LC
    - Some features of LCs
  - LC Detectors:
    Tracking calorimeters with (almost) no material in front
- Defining the right Linear Collider - 3 Examples
  - pinning down the mass of a light Higgs boson
  - unraveling a SUSY scenario with small mass differences
  - LC Physics Performance: Accelerator x Detector x
    Reconstruction & Analysis-Techniques
- Conclusions

Introduction

- Standard model of particle physics very successful down to quantum loop level
- but has important omissions and open questions, like
  - Higgs, mass hierarchy and fine tuning
  - dark matter, dark energy, quantum gravity
  - number of generations, unification?
  - ......

=> good reasons for expecting new physics at the Terascale

=> LHC!



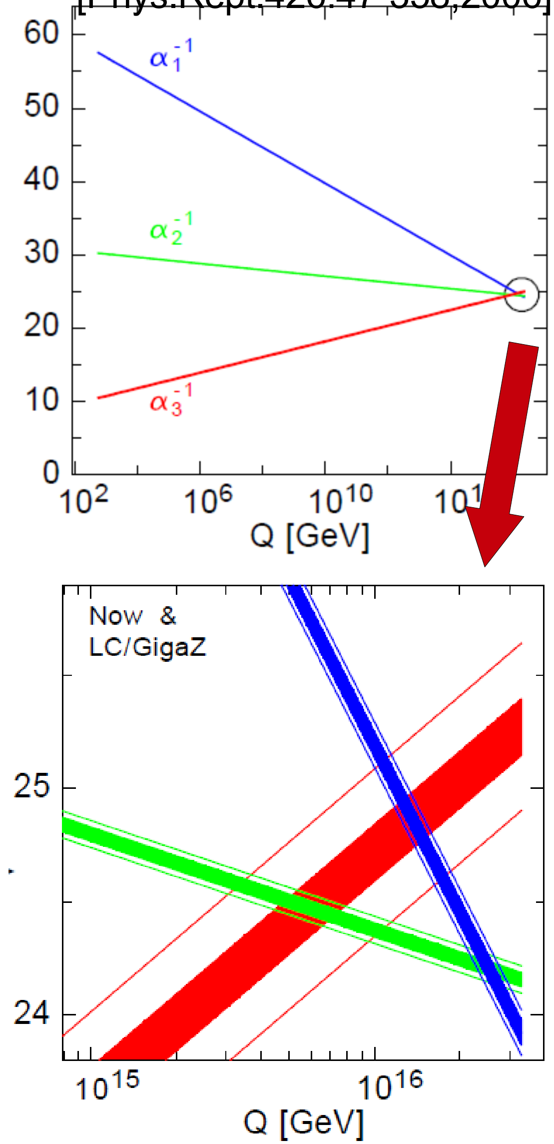
Introduction

- understanding the discoveries:
  - identify kind of new physics
  - find the theory behind
  - and determine its parameters

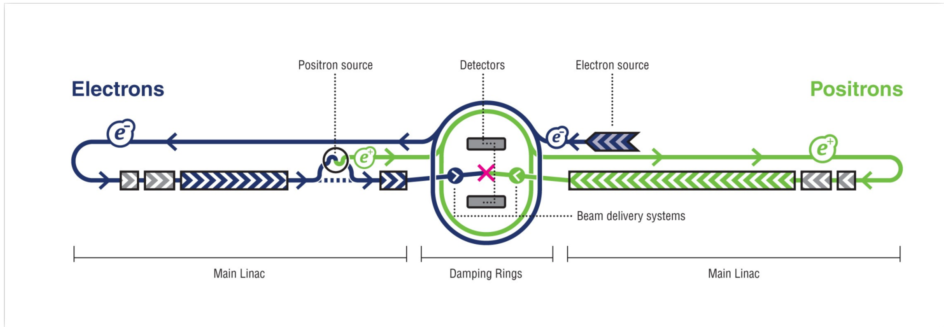
=> high energy frontier ↔ high precision frontier

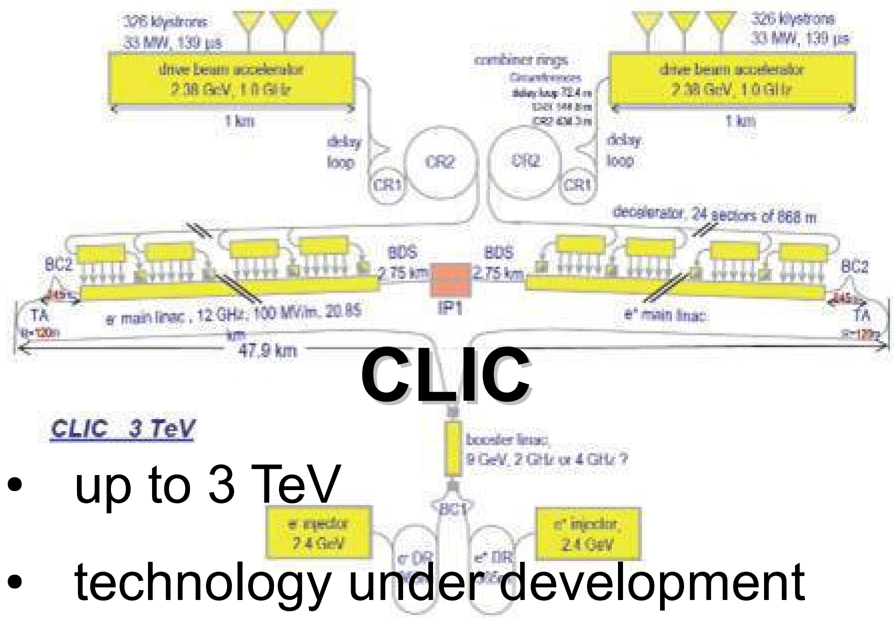
- at an e^+e^- Linear Collider, the initial state is
  - clean
  - tunable in energy
    → threshold scans
  - tunable in helicity
    → test chiral structure

[Phys.Rept.426:47-358,2006]



Two Linear Colliders on the market





ILC

- 90, 200...500 GeV, upgrade 1 TeV
- technology proven (e.g. FLASH)
- 2007: Reference Design Report (RDR)
- 2009: Letters of Intent (LoI)
- 2012: Technical Design Report (TDR)
- 2013: Project Proposal

Today: Focus here – more studies done

CLIC

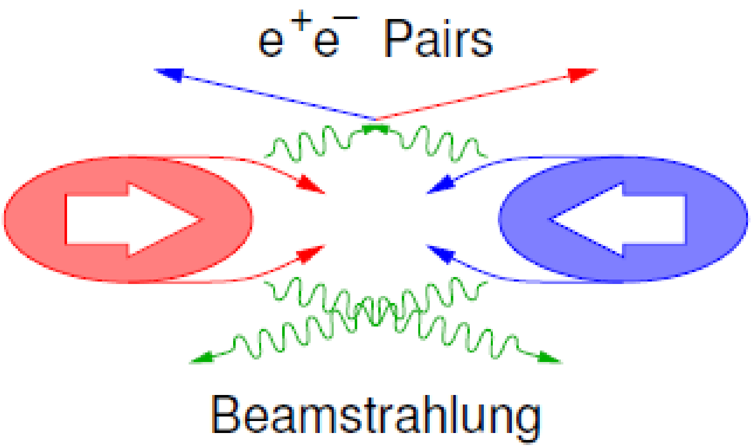
- up to 3 TeV
- technology under development
- 2011: Conceptual Design Report

→ dedicated seminar in November....

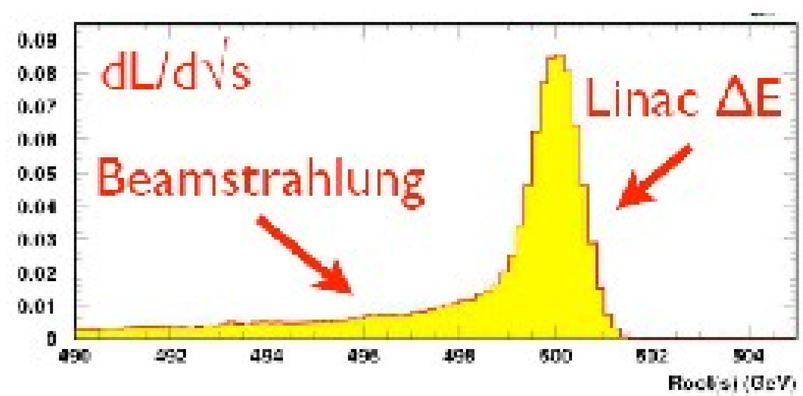
Some features of high energy e^+e^- colliders

- Elementary particles collide
  - $\rightarrow$ well defined collision energy E_{CM}
  - $\rightarrow$ well defined polarisation

  important:
  must be able to choose E_{CM} continuosly

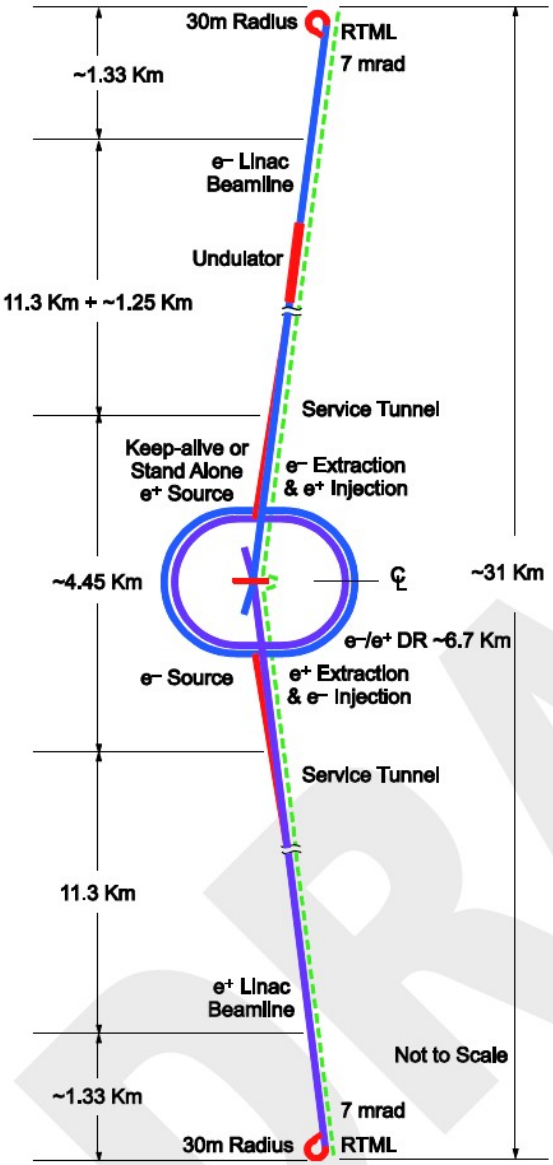


- need high luminosity $O(10^{34}cm^{-2}s^{-1})$
  $\rightarrow$ focus to *O*(nm) beam size
  $\rightarrow$ Beam beam interaction:
  - e^+e^- pair background
  - tail in beam energy spectrum "beam strahlung"
  - effect on polarisation: ~ 0.2% (ILC) .... 5% (CLIC)



- bunch spacing: ~330 ns (ILC) ..... 0.5 ns (CLIC)
  => some detector components will integrate over several bunch crossings

ILC – still several flavours...



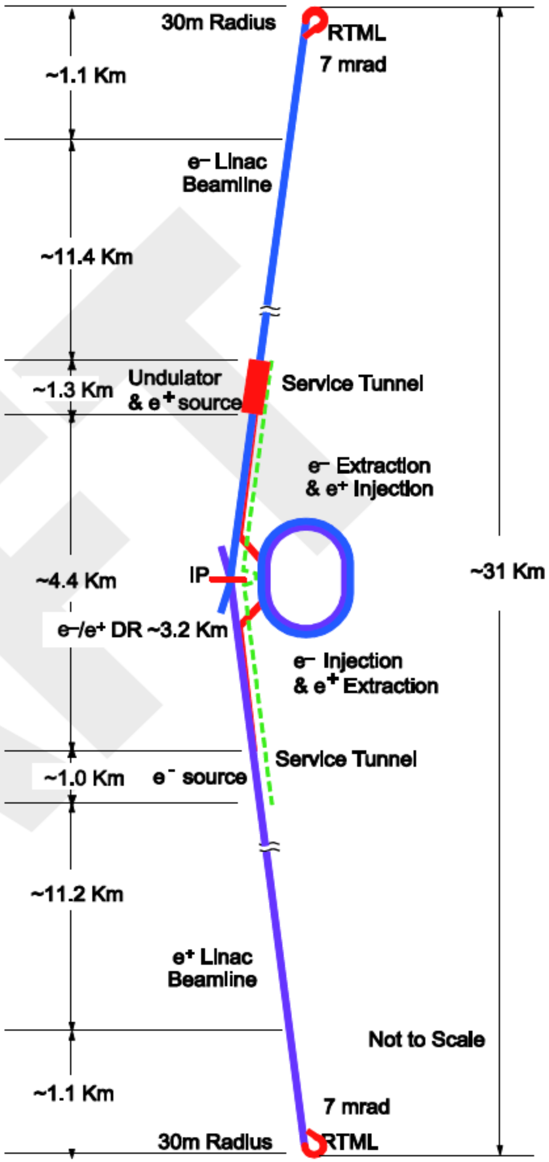
On the way from the RDR to the TDR:

- Are we planning the most "cost effective" machine which is able to reach the physics goals?

- half the number of bunches
  → half the RF
  → recover lumi by stronger focussing

- position of e^+ source
  → $P(e^+)$ *de*creases with $E(e^-)$
  → $N(e^+)$ *in*creases with $E(e^-)$

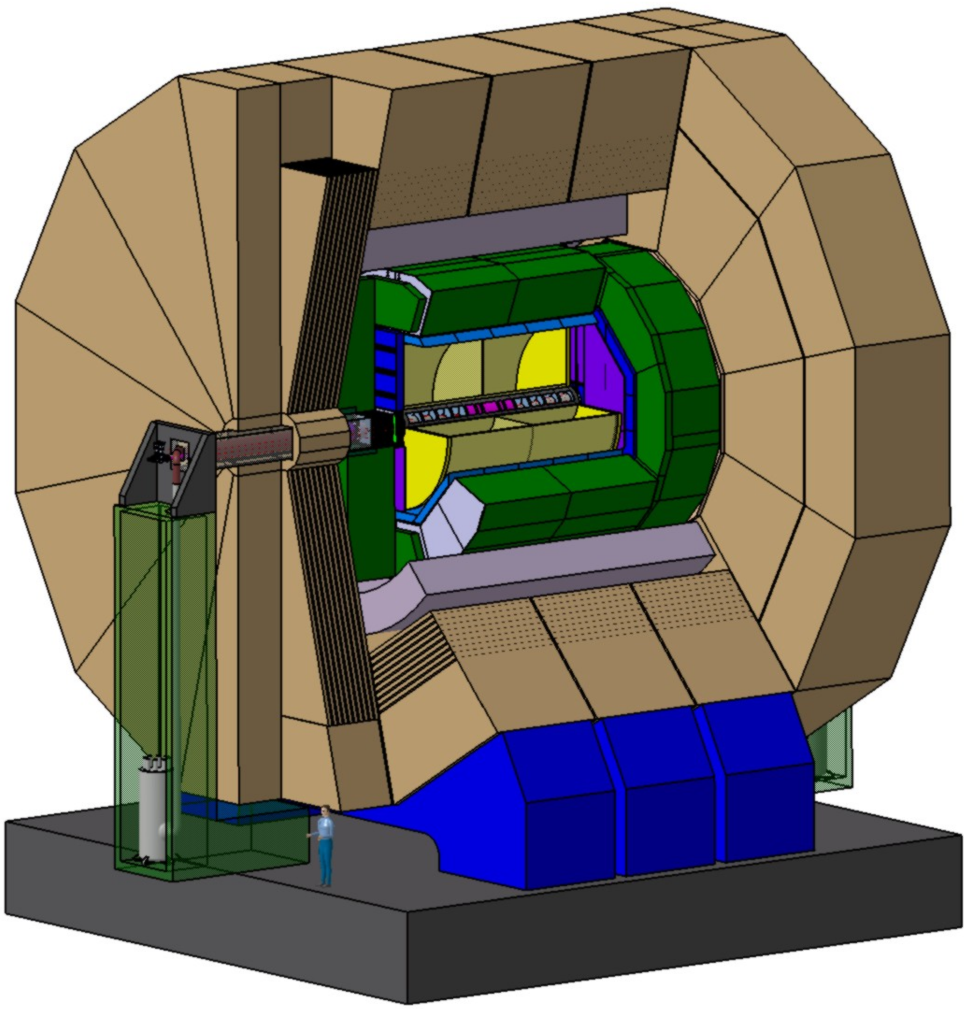
=> study various scenarios of $P(e^+)$, luminosity, beam energy spectrum, backgrounds



An ILC Detector

- two proposals: ILD & SiD
- All-Silicon tracking with 4Tesla B-field (SiD)
- Or: TPC + Si tracking with 3.5T B-field (ILD)
- for issues discussed today, the differences are not substancial

=> Focus on ILD here



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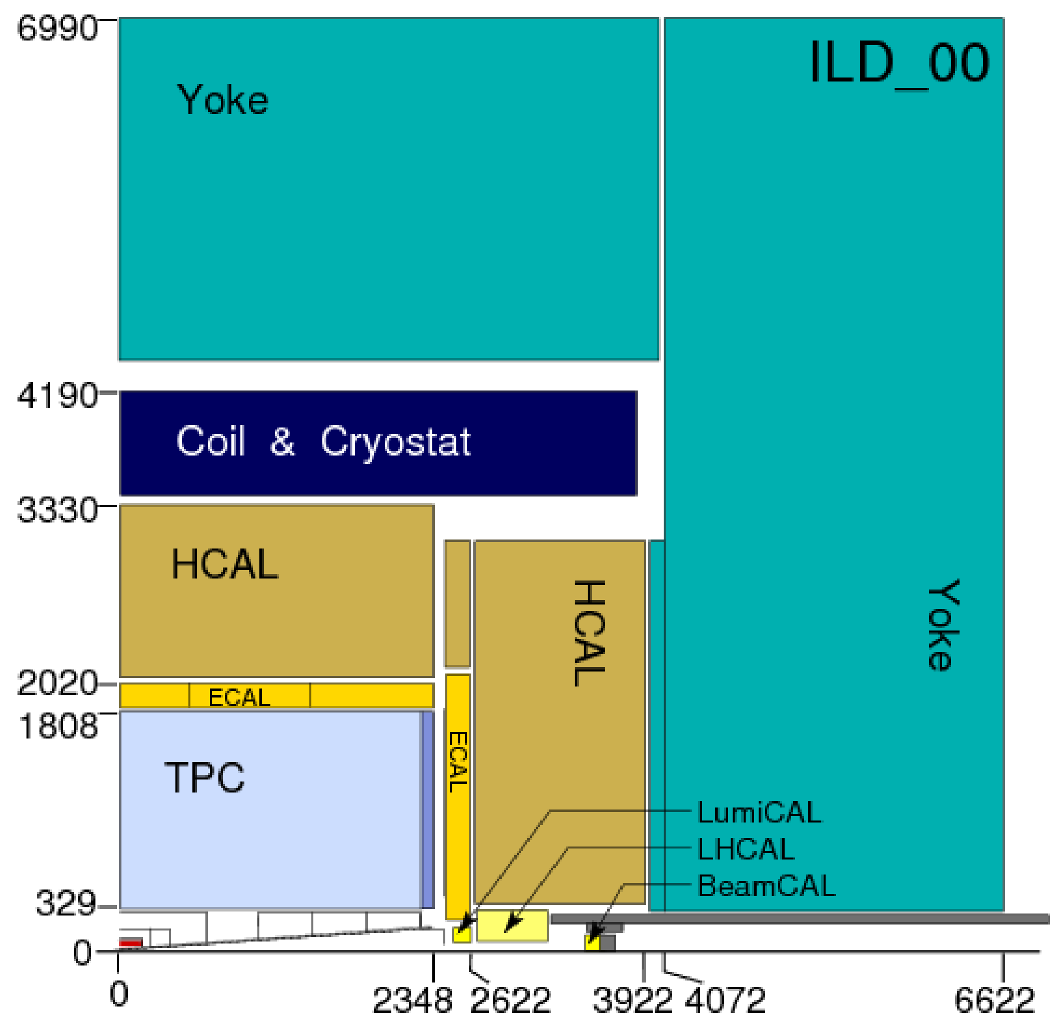
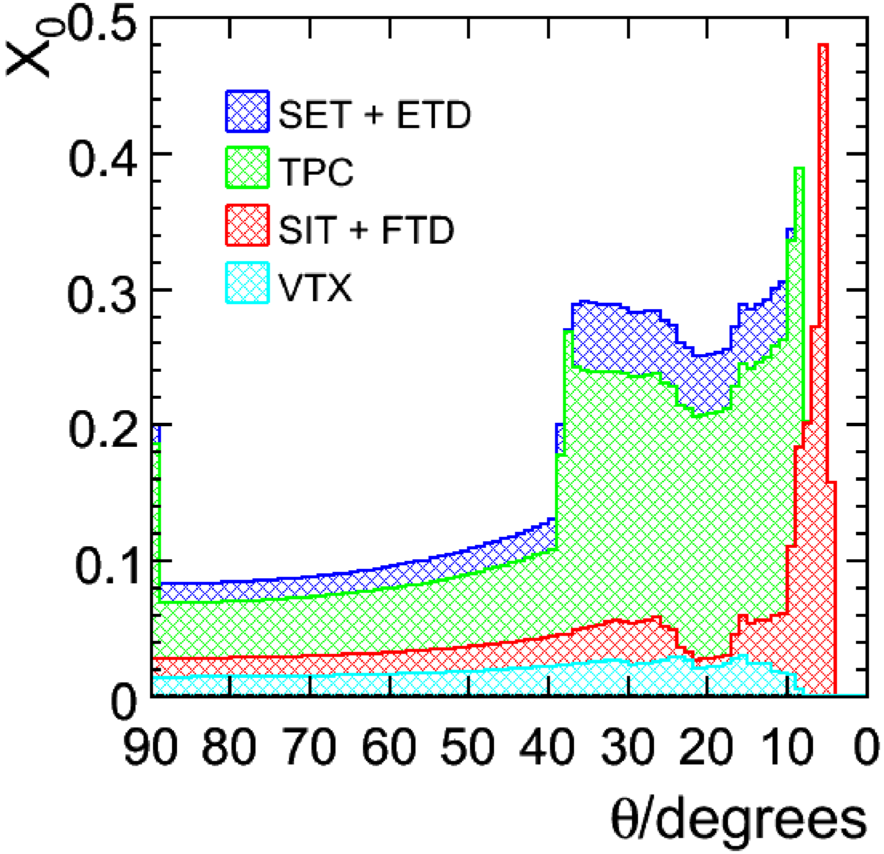


Some features of an ILC detector

- almost no material in front of calorimeter:
  - ~ 10% X_0 in barrel
  - ~ 30% X_0 in endcap
- momentum resolution 10x better than LEP → $\sigma_{1/pt} = 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$



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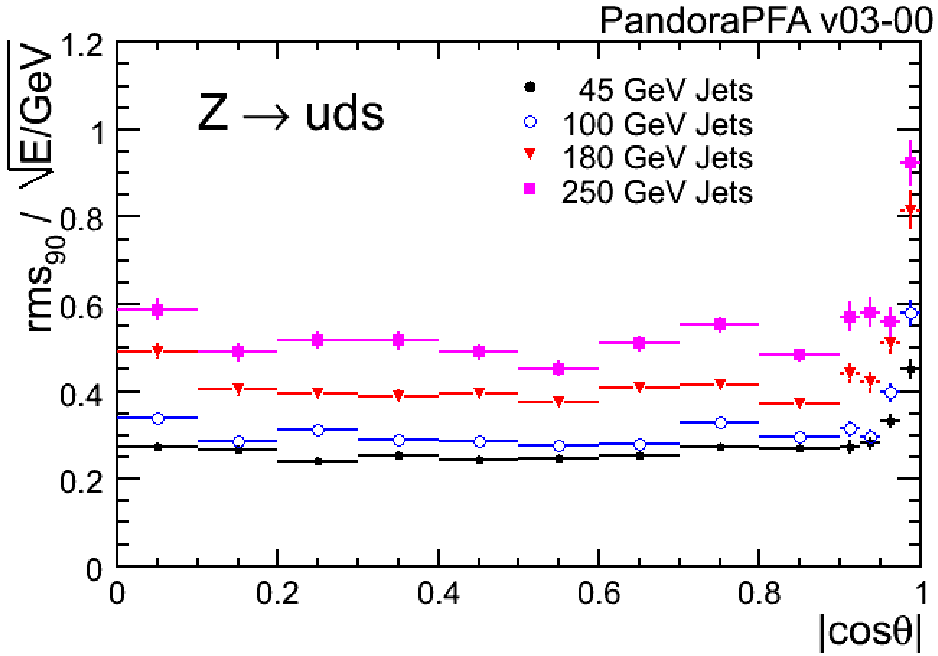

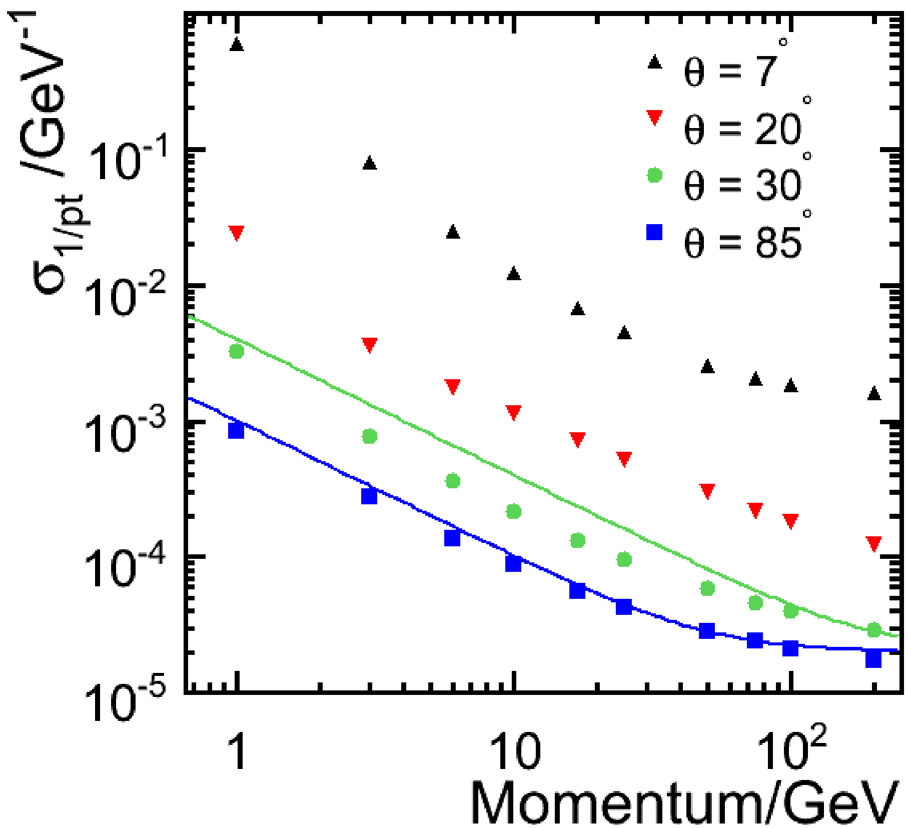

- 3%...4% jet energy resolution
- excellent flavour tag
- ....

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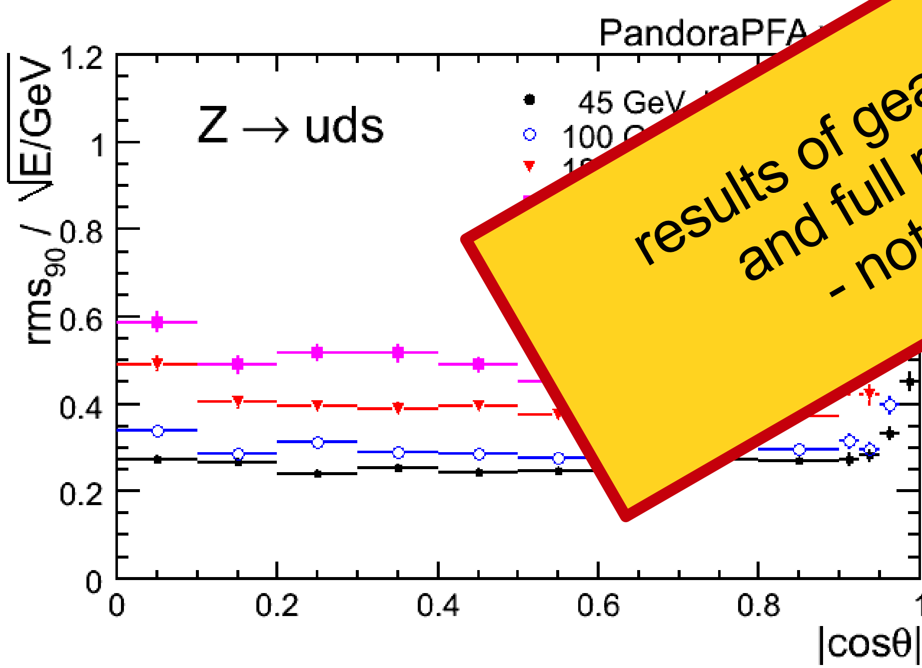
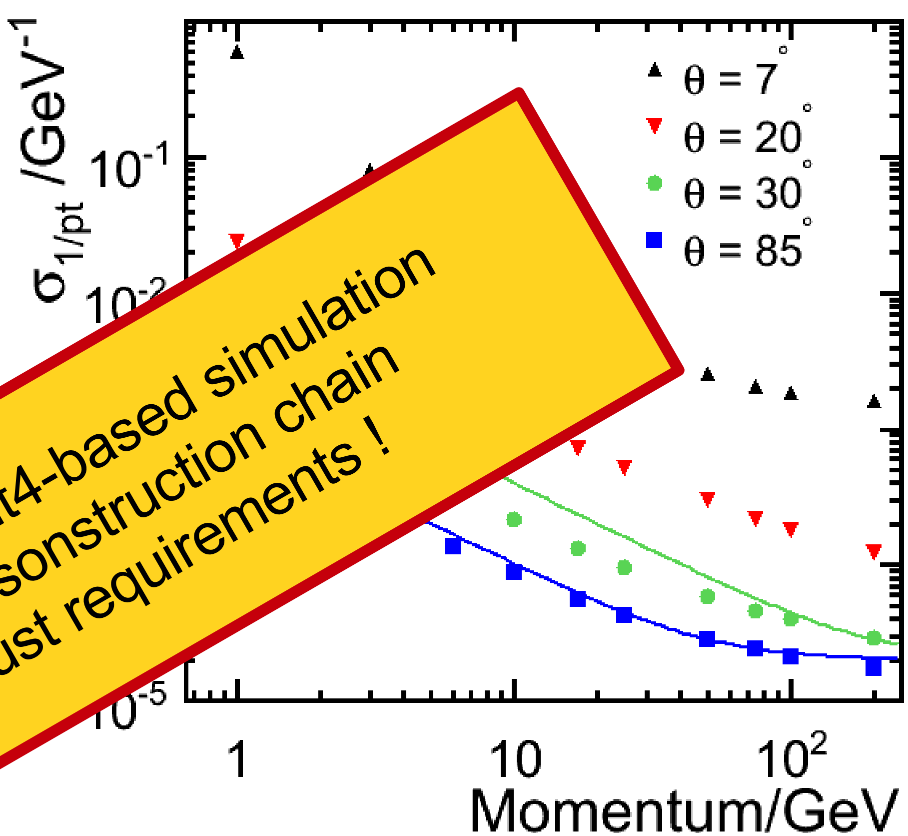
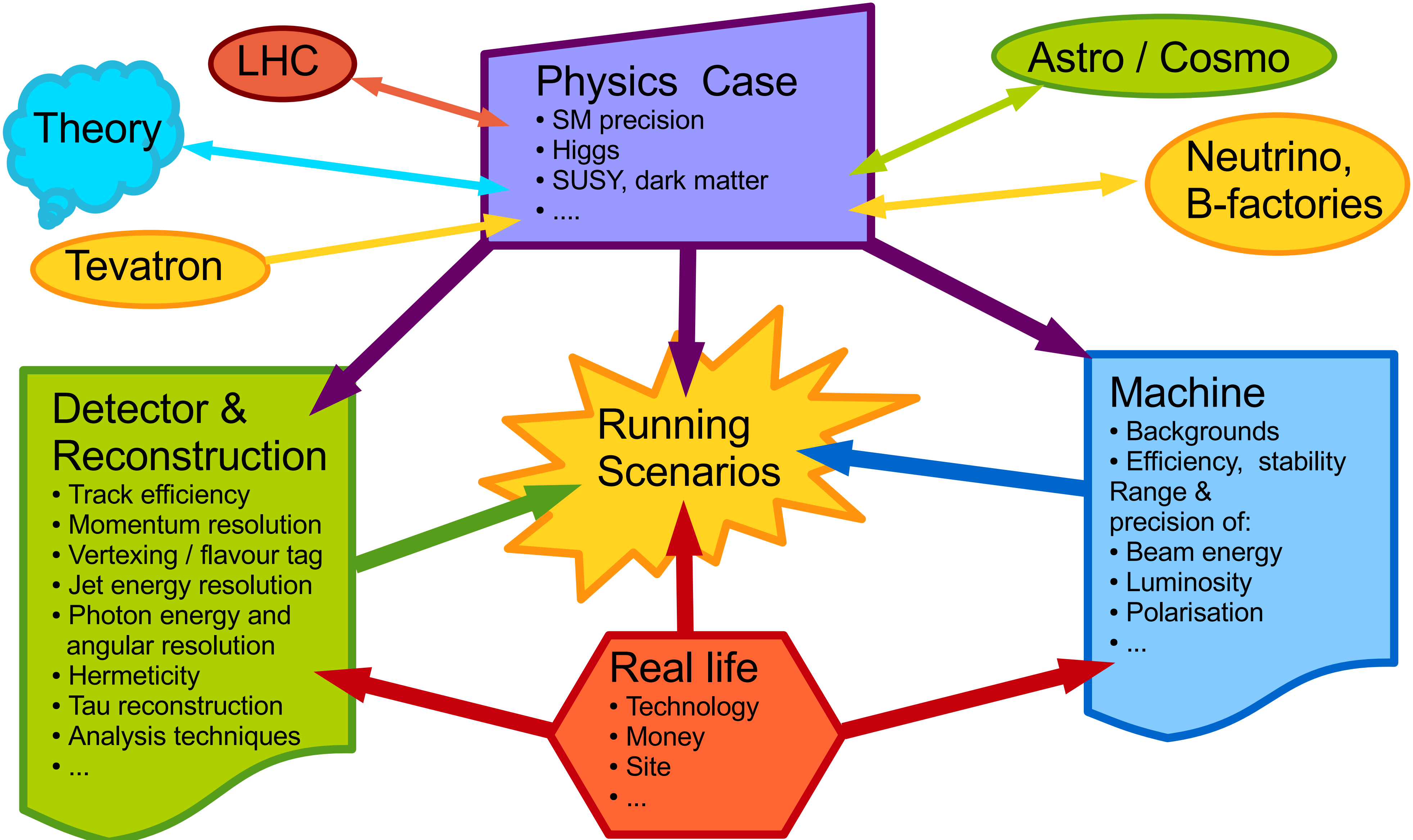




results of geant4-based simulation
and full resonstruction chain
- not just requirements !

- 3%...4% jet energy resolution
- excellent flavour tag
- ....

Defining the right Linear Collider



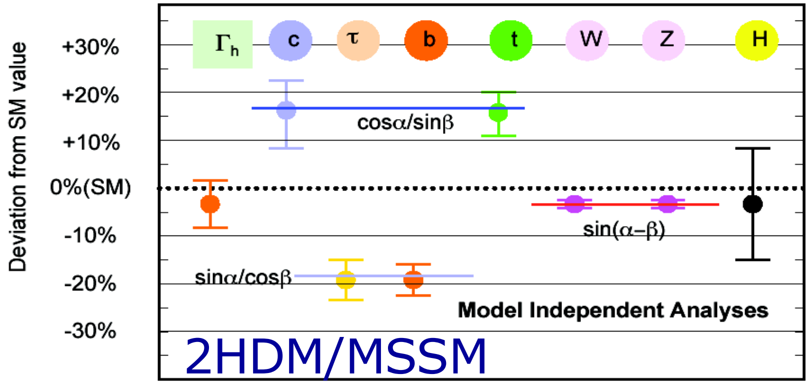
Example 1

Model-independent Higgs mass measurement

Profiling the Higgs Boson

- Reminder - the precision Higgs physics menue:
  - decay-mode-independent observation
  - decay-mode-independent mass (50 MeV)
  - total width (model-independent)
  - absolute couplings (Z,W,t,b,c,τ) (1-5%)
  - spin, CP
  - top Yukawa coupling (~5%)
  - self coupling (~20%, 120-140 GeV)
  - $\Gamma_{\gamma\gamma}$ at photon collider (2%)

=> fully establish Higgs mechanism & distinguish models



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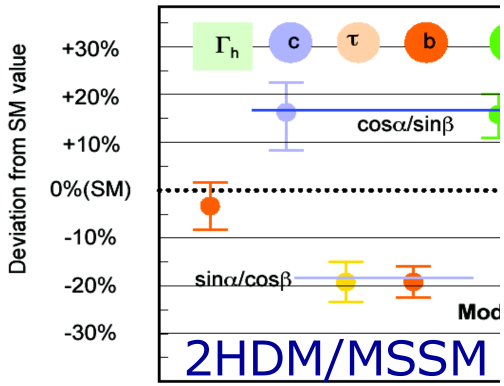
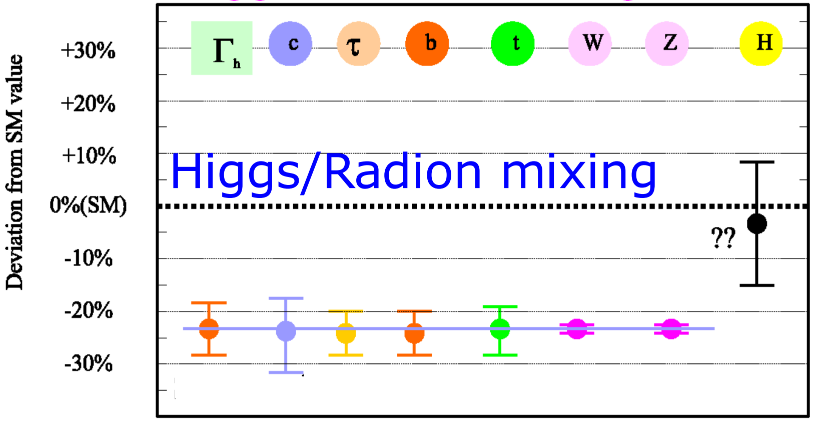
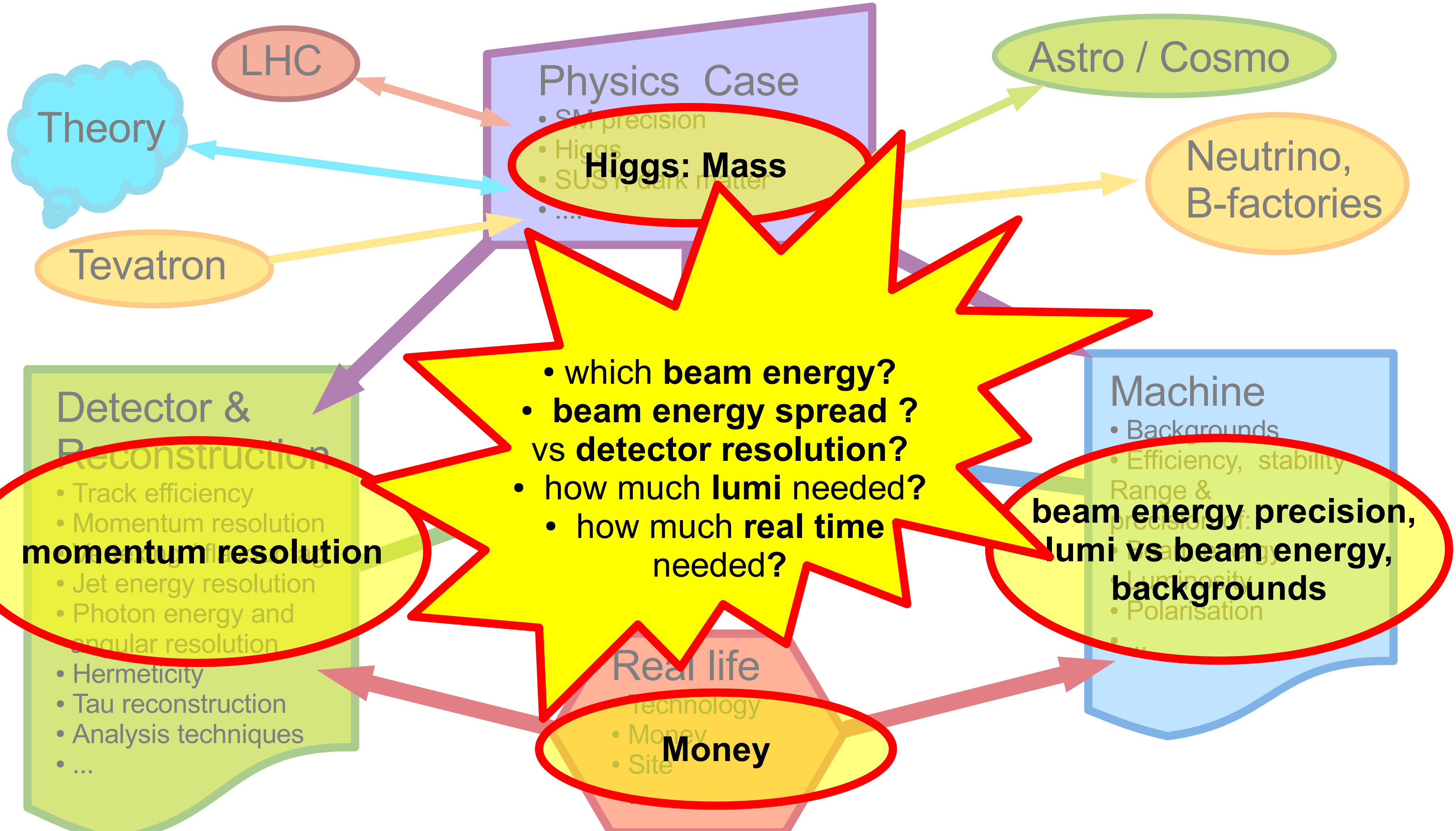




Model-independent Higgs mass measurement



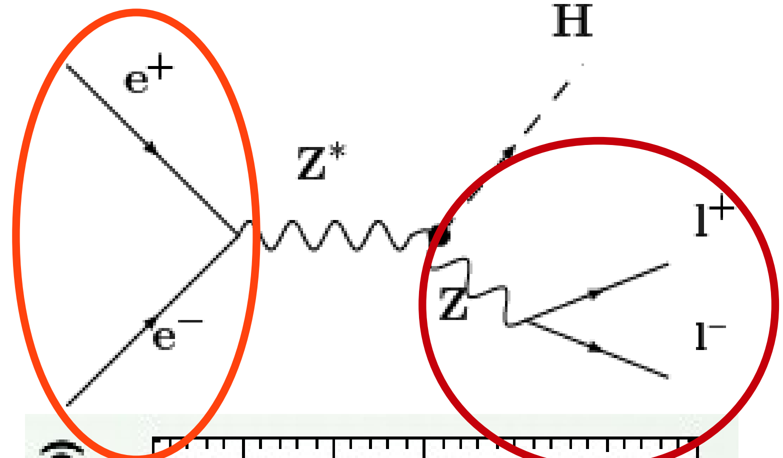
Higgs recoil mass

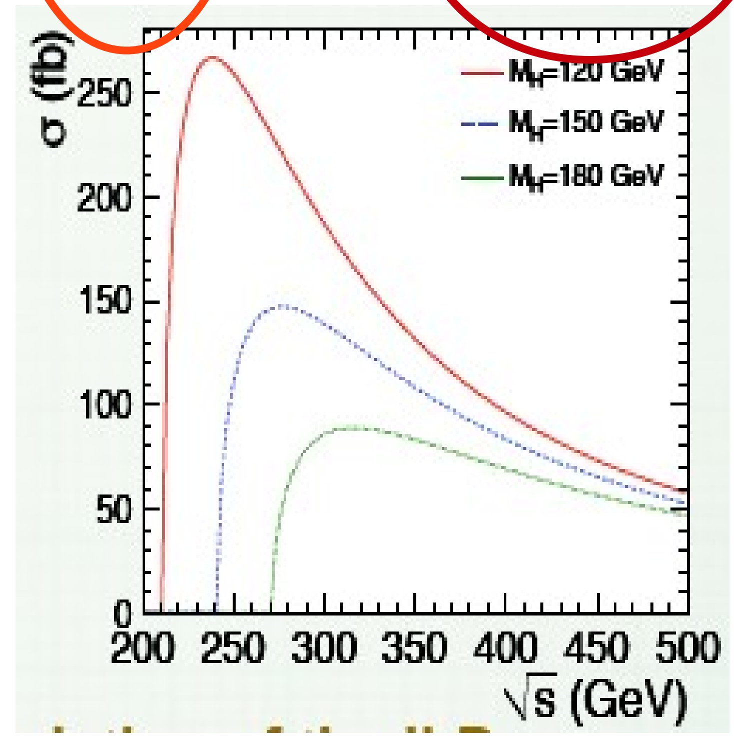
- most precise and model-independent technique:

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

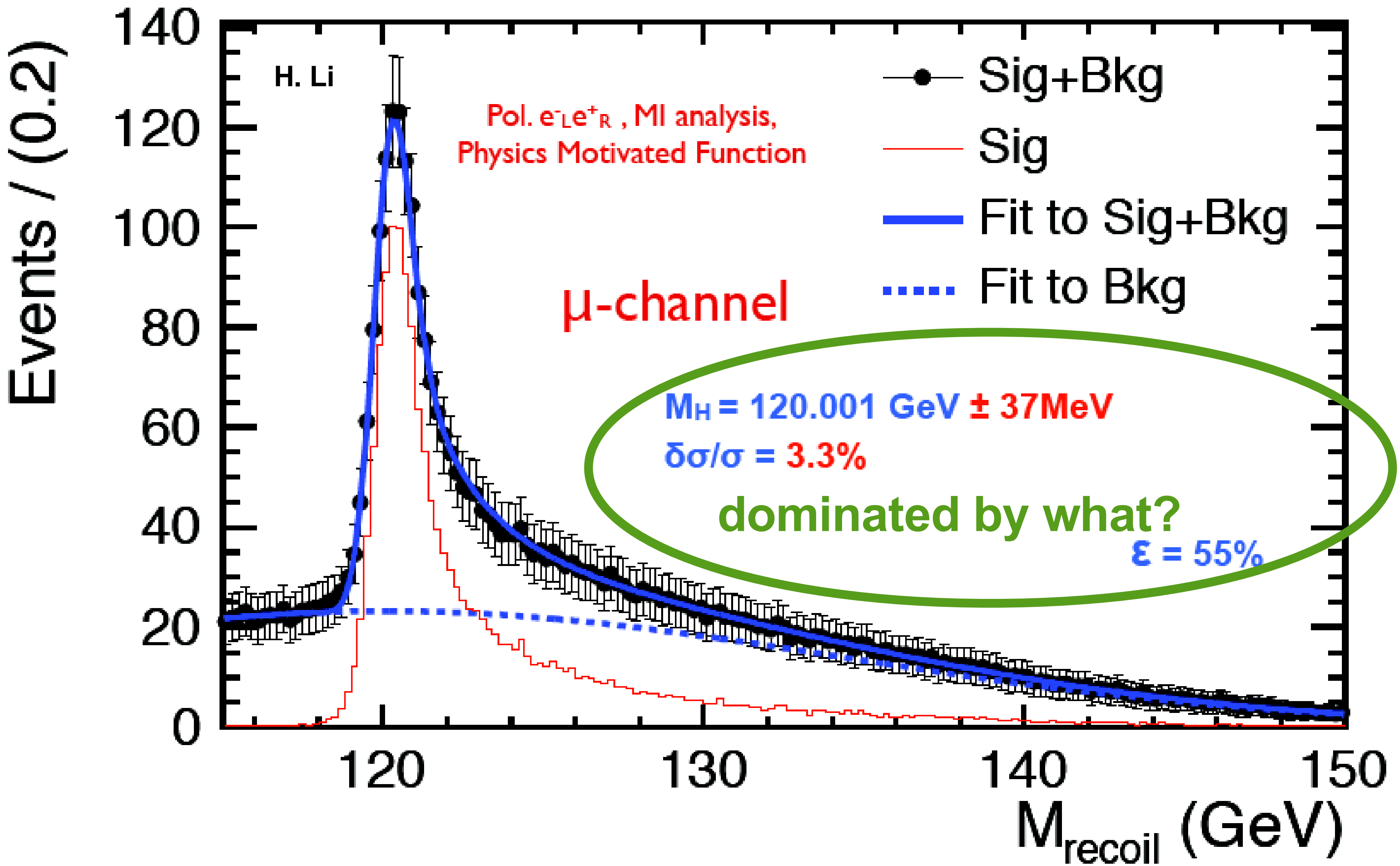
- precision depends only on
  - lepton momenta → tracking
  - knowledge of s → ISR, Beamstrahlung

  but *not* on Higgs decay!
- E_{CM}? Near threshold:
  - largest cross-section
  - Z at rest → leptons "slow"
  - less ISR / beamstrahlung





Results for an "RDR ILC" (with 250fb^{-1} @ 250 GeV)



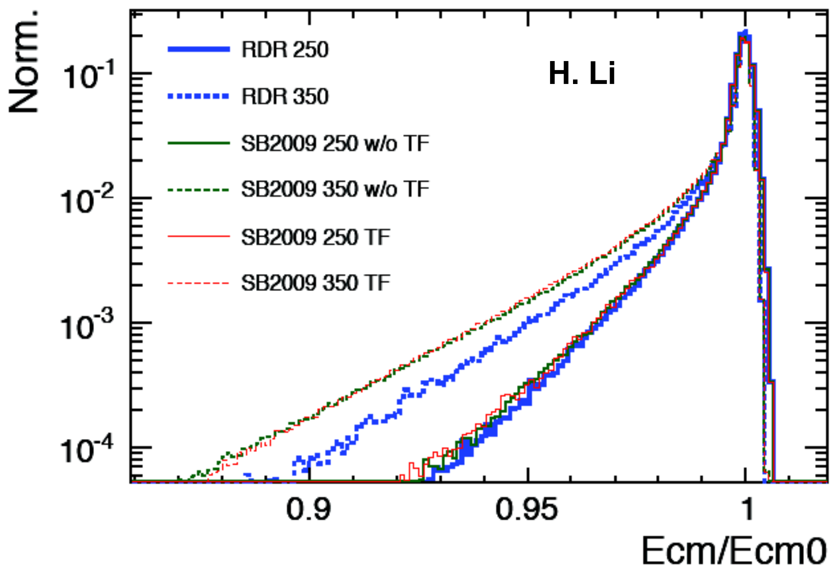
Detector resolution or accelerator?

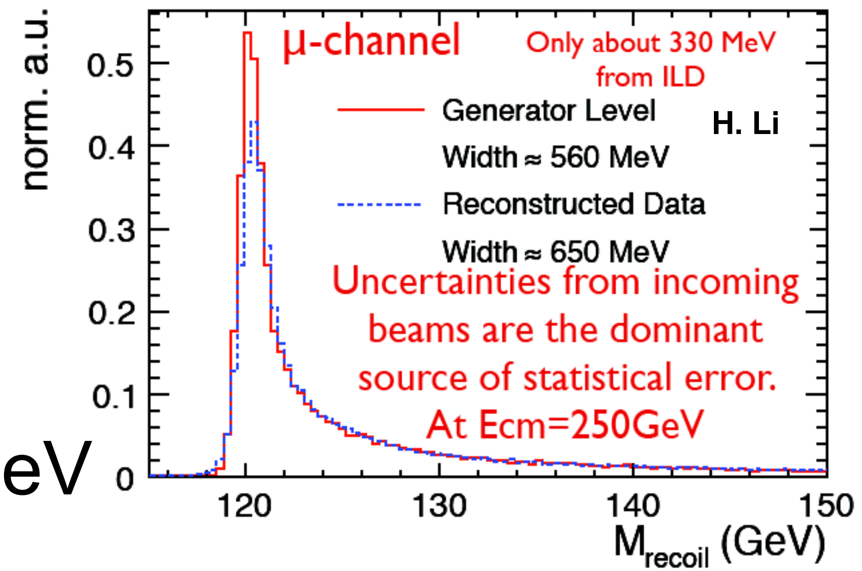
- beam energy spread & beamstrahlung
  => beam energy *spectrum*
- compare Higgs recoil mass at generator level and after reconstruction

=> for M_H = 120 GeV, E_{CM} = 250 GeV:

- width of recoil peak dominated by beam energy spread:

$$\Gamma_{rec} \approx 650 \text{ MeV}$$
$$\approx \sqrt{560^2|_{beam} + 330^2|_{det}} \text{ MeV}$$

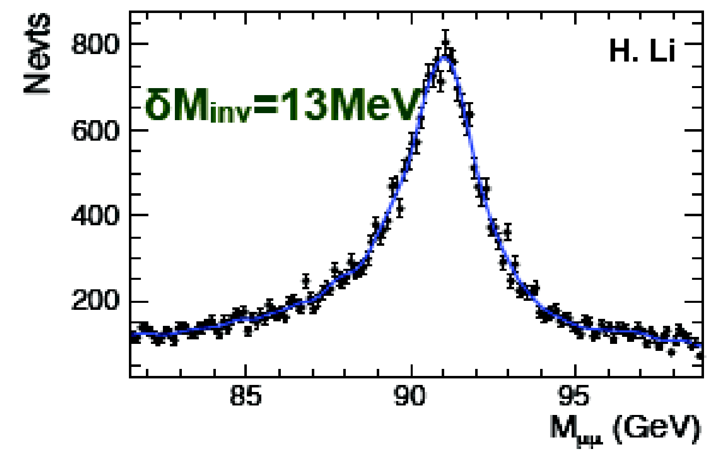




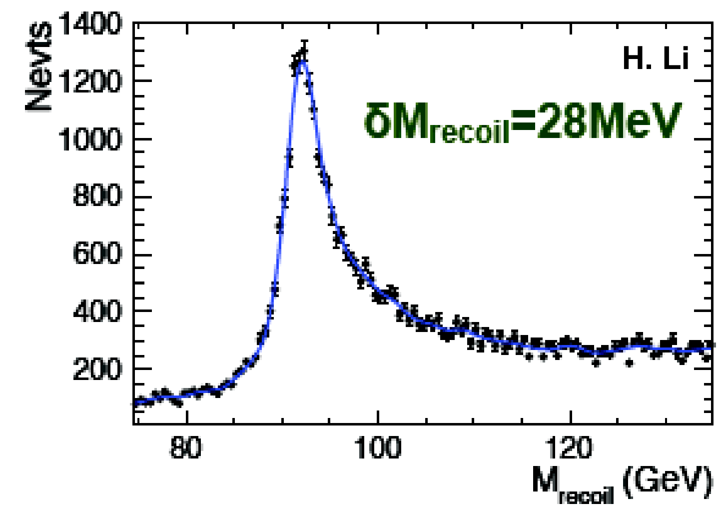
What about systematic uncertainties?

- can be controlled using $ZZ \to \mu^+\mu^- f\bar{f}$:
  i.e. syst. error on M_H given by ZZ statistics

  - Di-muon invariant mass
    controls tracking & muon ID



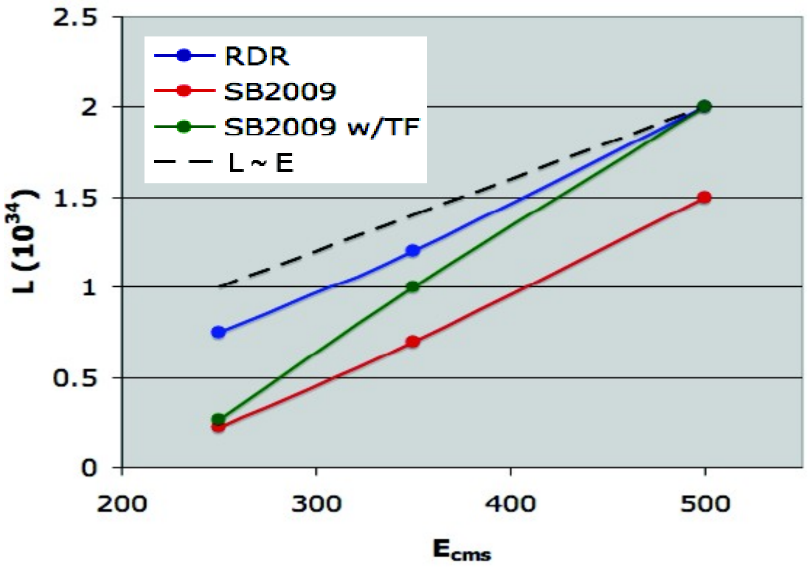
  - Z recoil mass
    controls center of mass energy
    and radiative effects



=> $\delta M_{H,sys} \approx 30....35$ MeV (c.f. $\delta M_{H,stat} \approx 37$ MeV) ✓

Higgs threshold data are 'expensive'

- data not useful for other important studies ($t\bar{t}$, NP, …)
- luminosity decreases at lower E_{CM}



  - 250fb^{-1} takes with RDR ILC:
    ~ 1 year @ 500 GeV
    ~ 2.5 years @ 250 GeV
  - depending on its position, the positron source might be less efficient
  - in addition: alternative beam parameter sets could save construction costs but would lower the luminosity even further - worst case: 250fb^{-1} @ 250 GeV ~ 10 years

=> can we do it at higher energy, e.g. the $t\bar{t}$-threshold ?

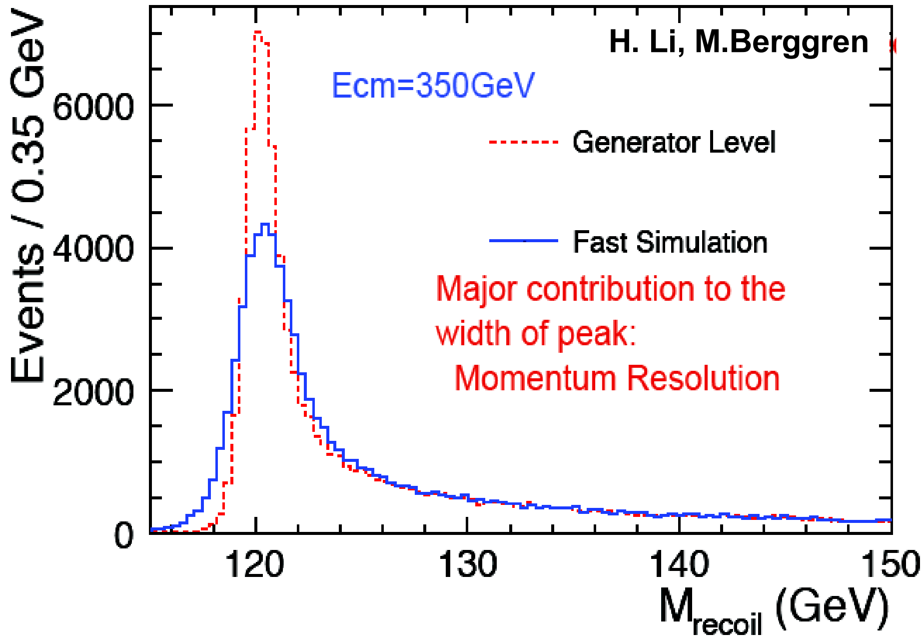
- higher luminosity
- do top physics and possibly some BSM simultaneously

How crucial are the Higgs threshold data?

- $300 fb^{-1}$ @ 350 GeV
  ~ 2 years with RDR ILC

- Z decays boosted,
  i.e. higher lepton momenta

=> δM_H increases by factor 2
now dominated by
momentum resolution!



- add other cost saving proposals, plus systematics
  => $\delta M_H \approx$ 50 MeV (RDR, 250 GeV, 2 years)
  $\delta M_H \approx$ 150 MeV (SB2009 w/o TF, 350 GeV, 2 years)

➡ For mass measurement, Higgs threshold data *cannot* be replaced by higher E_{CM}!

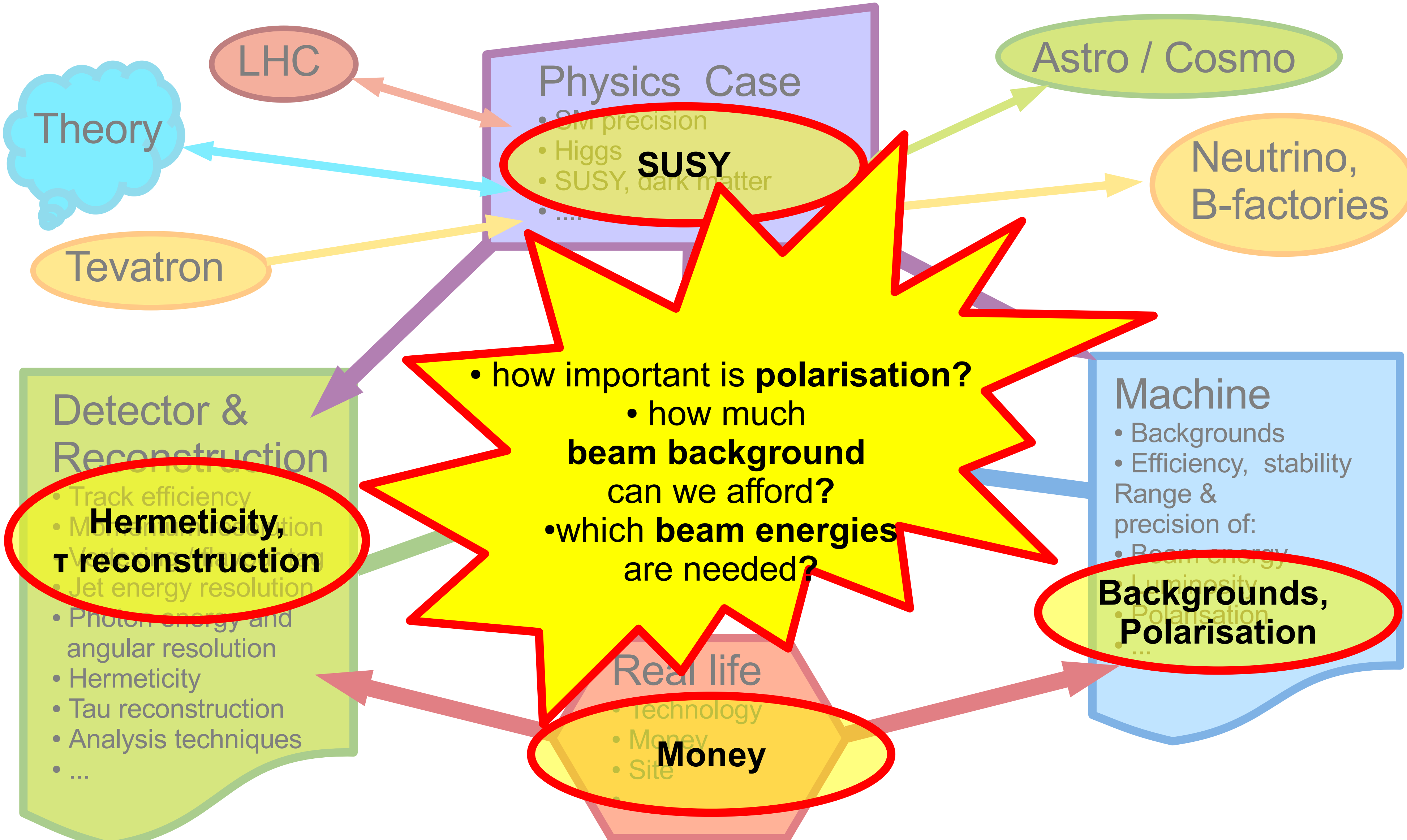
"Take home message" from Higgs mass studies

- Simulating accelerator effects *is* important
- Make sure that luminosity is high enough at *all* E_{CM}
- Only the luminosity *inside the peak* counts
- Beam energy spread is finally limiting
- Discussion on best solution is ongoing *now* -
  decisive suggestion for improvement:
  Double the train repetition rate from 5 Hz to 10 Hz at low E_{CM}?
- Watch it!

Example 2

Understanding a SUSY scenario
with small mass differences

SUSY with small mass differences

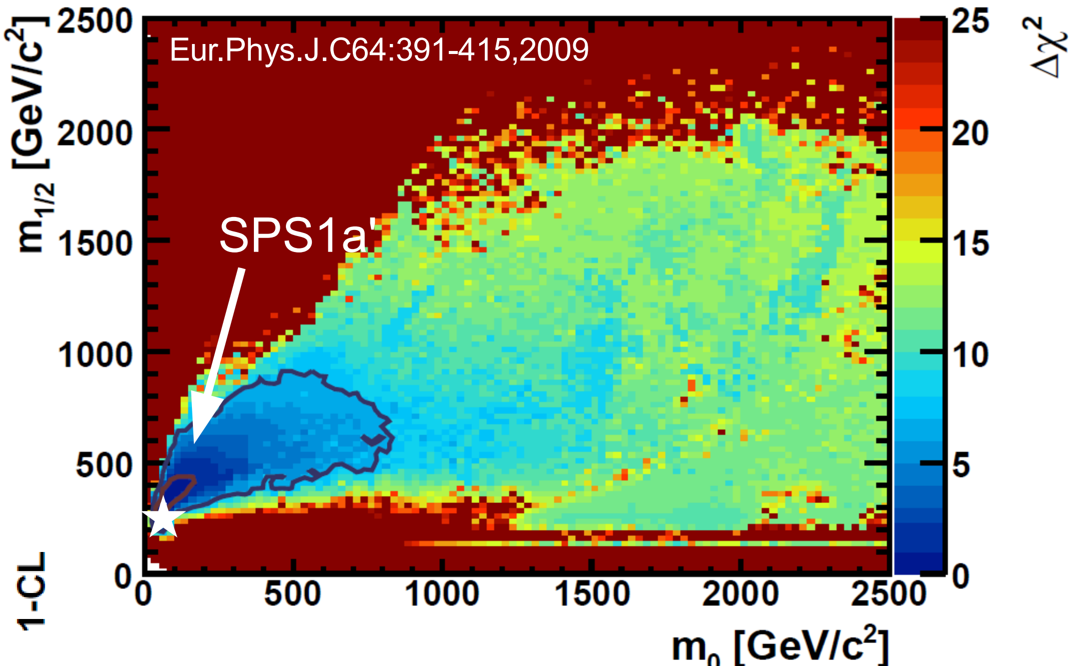


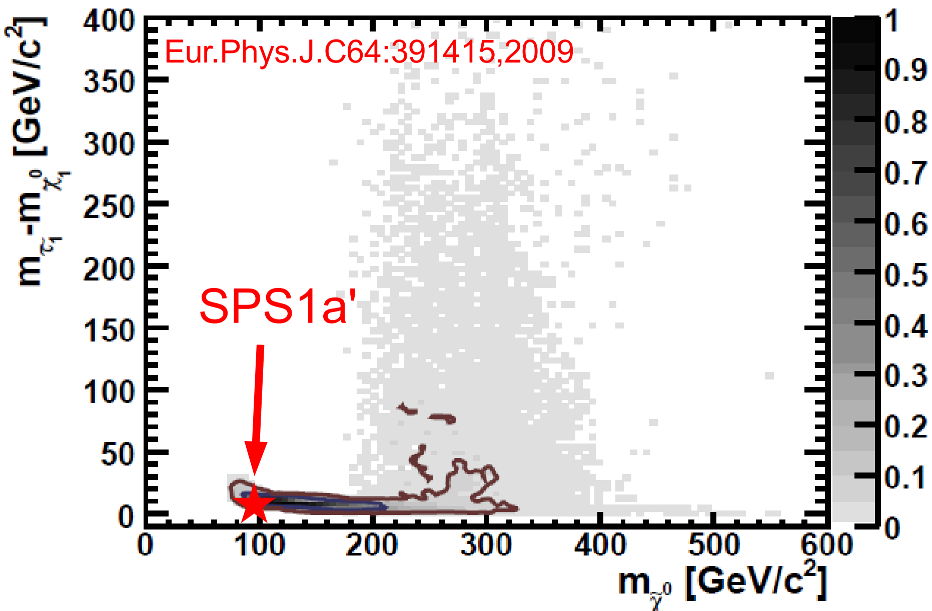
Sample scenario: SPS1a'

- very close to best fits to SM data in CMSSM / MSSM18
- small $\Delta M(\tau_1, \chi^0_1) = 10.2$ GeV

=> typical signature:
soft τ-leptons + missing momentum

=> prone to backgrounds!





Measurement Strategies

- Continuum 500 GeV:
  - get overview
  - Masses from edges,
    x-sections from rates
    mixing angles, ...
  - Which helicity configurations?
- Scan as many thresholds as necessary

Detector and accelerator interplay

- Background in trackers:
  - fake tracks from bkg hits
  - real tracks from bkg particles

=> effect on reconstruction of τ-decays?

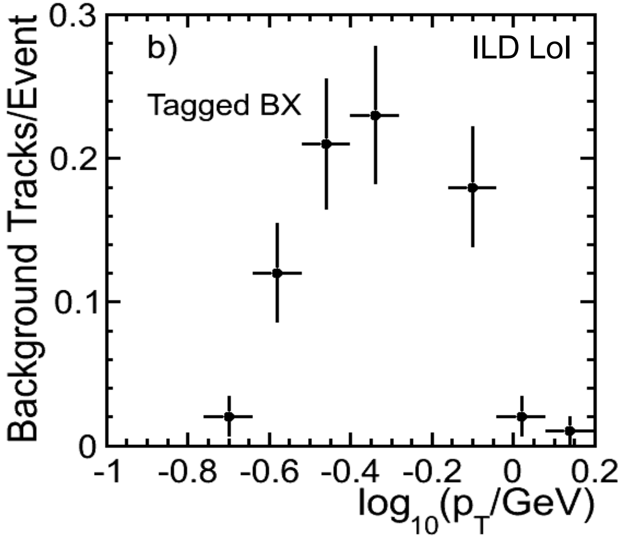
- Background in forward region:

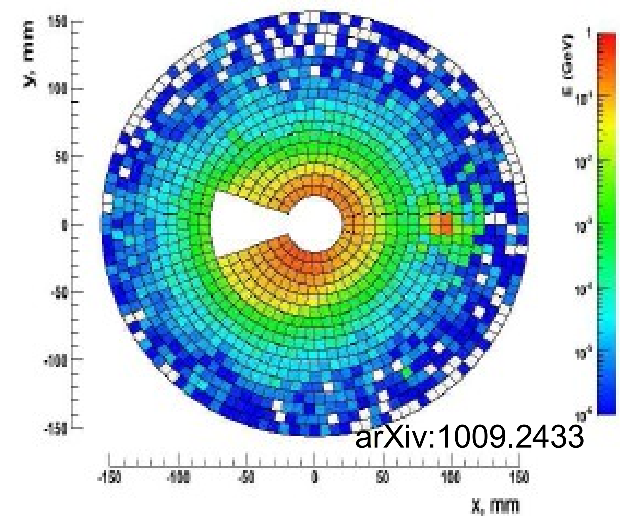
=> effect on low angle electron veto against gamma-gamma events?

- Beam energy spectrum:

=> deterioration of τ energy endpoint?

- Polarisation:
  - signal to background ratio
  - distinguishing SUSY channels





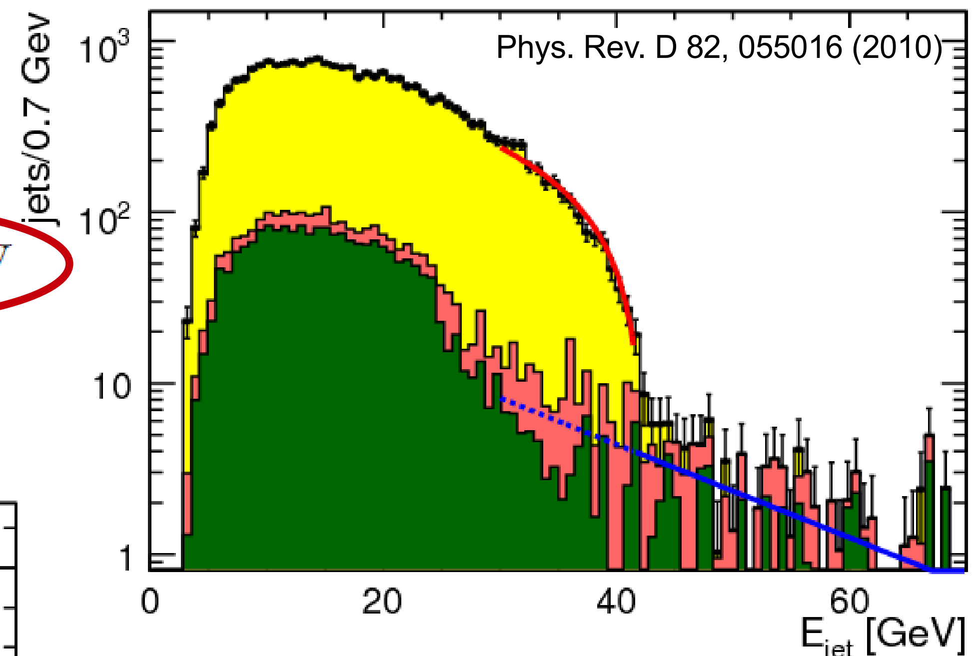
Results for 500fb^{-1} @ 500GeV, RDR ILC

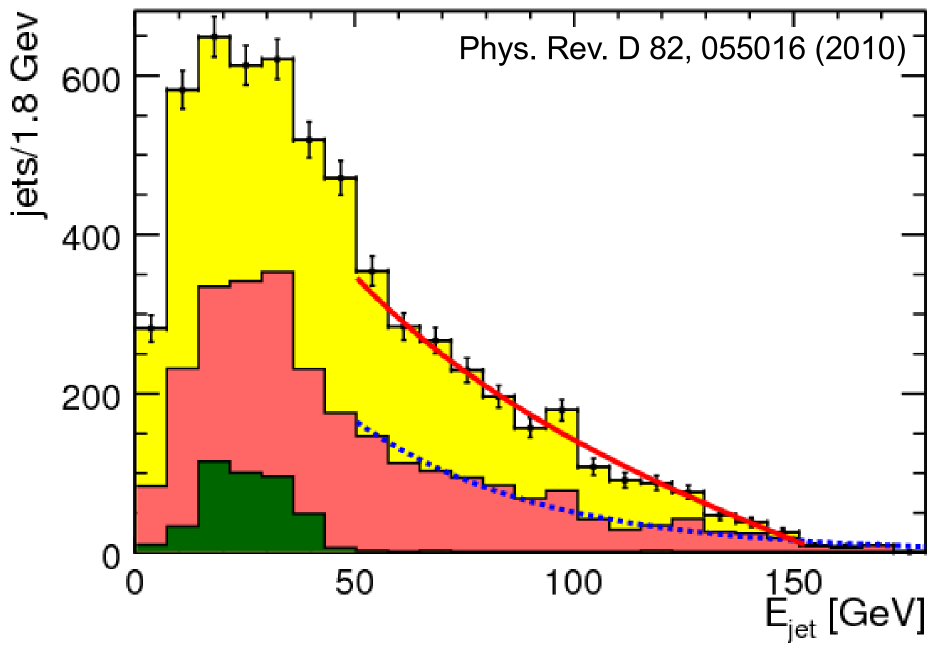
τ_1:

$$E_{\tau,max} = 42.11^{+0.14}_{-0.12}\ \mathrm{GeV}$$

$$M_{\tilde{\tau}_1} = 107.73^{+0.03}_{-0.05} \pm 1.1 \cdot \delta M_{\tilde{\chi}^0_1}\ \mathrm{GeV}$$

$$\frac{\delta\sigma}{\sigma} = 3.1\ \%$$





τ_2:

$$E_{\tau,max} = 151.0^{+2.0}_{-1.7}\ \mathrm{GeV}$$

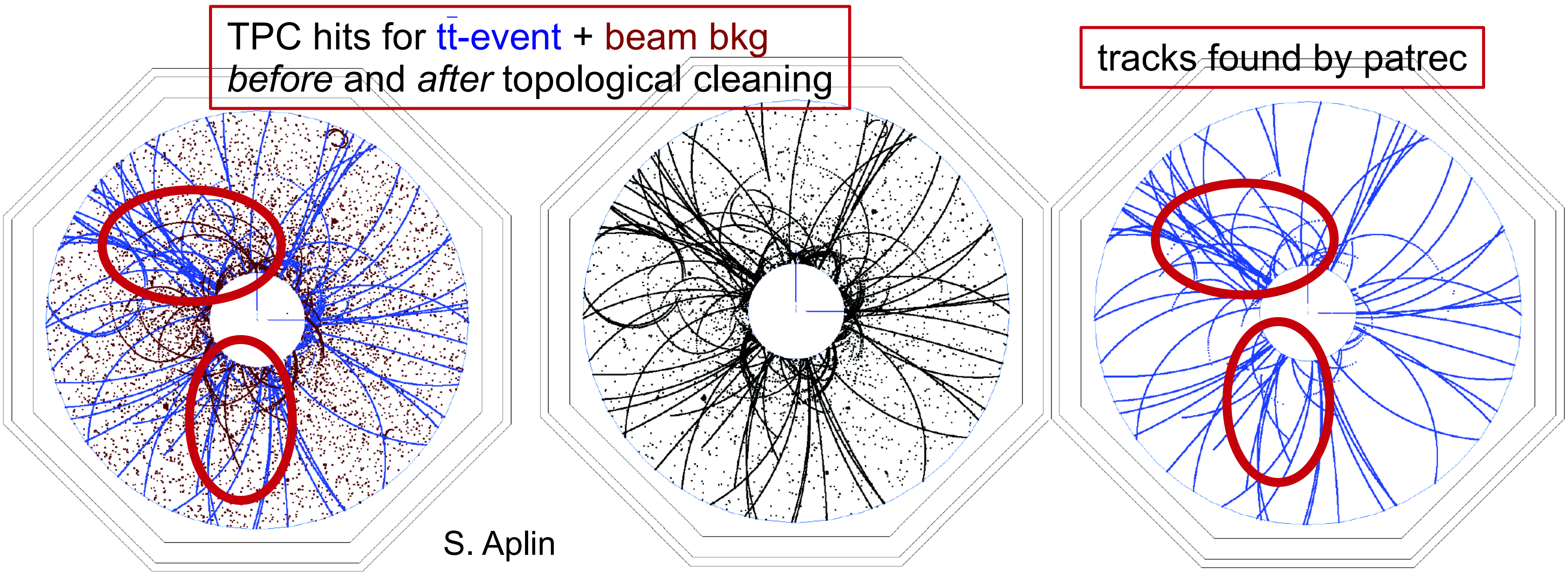
$$M_{\tilde{\tau}_2} = 183^{+11}_{-5} \pm 18 \cdot \delta M_{\tilde{\chi}^0_1}\ \mathrm{GeV}$$

$$\frac{\delta\sigma}{\sigma} = 4.2\ \%$$

Intermezzo:
Realistic reconstruction & analysis *does* matter

- pattern recognition and track fitting have to be able to cope
- additional soft tracks: spoils simplistic τ-finding
  => switch to a real experiment's τ-finder (DELPHI)

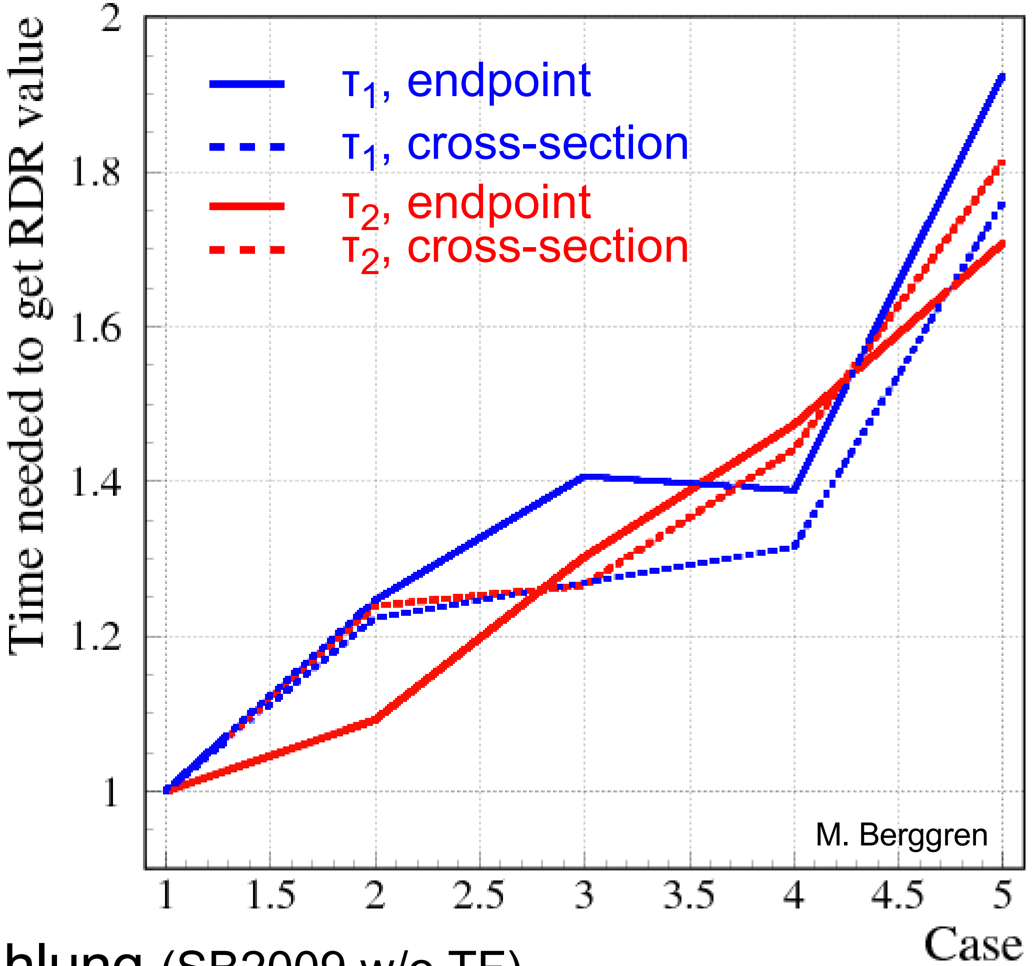
=> reconstruction and analyses need to be done with a realistic level of detail to get realistic answers!



Varying accelerator parameters

Time for reaching RDR (=case 1) precision:

- case 2: more beam induced background (a la SB2009 TF)
- case 3: reduced positron polarisation (33% → 22%)
- case 4: increased beam energy spread (0.16 → 0.21 %), more beamstrahlung, i.e.reduced luminosity within 1% of nominal energy (0.83 → 0.72)
- case 5: even more beamstrahlung (SB2009 w/o TF)



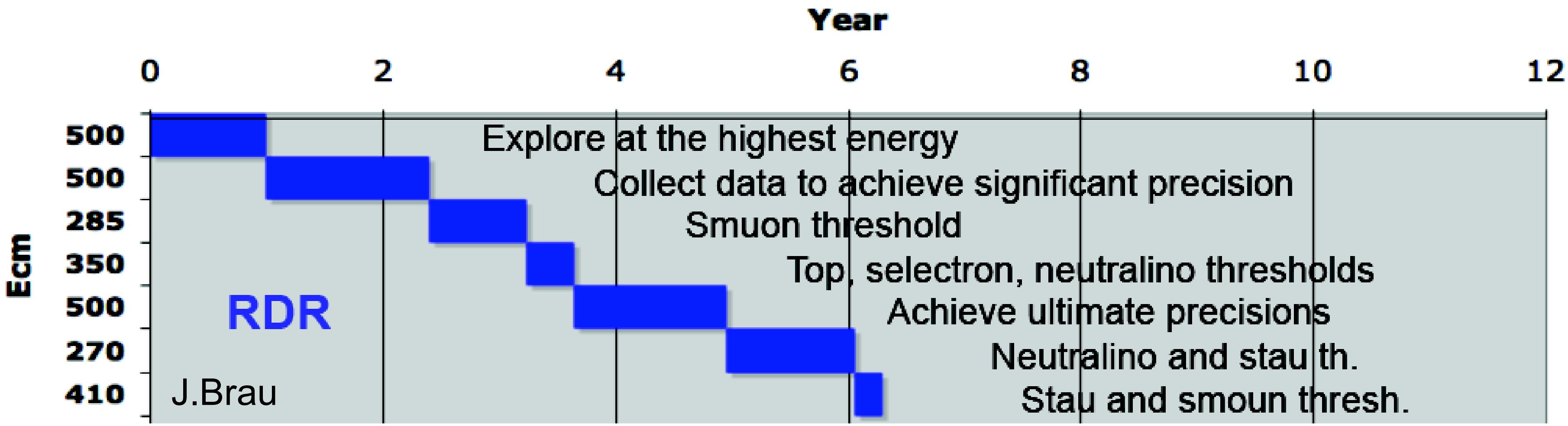
Does this matter?

Ex: study of a similar SUSY scenario: SPS1[arXiv:hep-ex/0211002]
(N.B.: this is just mSugra... the real stuff will be more complicated!)

• consider continuum running plus all necessary SUSY threshold scans
  (not counting Higgs threshold run!)
  => with an RDR ILC, after more than 6 years of running:

parameter	SPS1
m_0	100 ± 0.08 GeV
$m_{1/2}$	250 ± 0.20 GeV
A_0	0 ± 13 GeV
$\tan\beta$	10 ± 0.47

• need 1.5...1.8 x more running time @ 500 GeV, even larger factors at lower energies......



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- need 1.5...1.8 x more running time @ 500 GeV,
  even larger factors at lower energies......
  => pay attention that you get the *right* Linear Collider!

LHC / ILC comparison at SPS1a [Phys.Rept.426:47-358,2006]

	SPS1a	StartFit	LHC	Δ_{LHC}	LC	Δ_{LC}	LHC+LC	Δ_{LHC+LC}
m_0	100	500	100.03	4.0	100.03	0.09	100.04	0.08
$m_{1/2}$	250	500	249.95	1.8	250.02	0.13	250.01	0.11
$\tan\beta$	10	50	9.87	1.3	9.98	0.14	9.98	0.14
A_0	-100	0	-99.29	31.8	-98.26	4.43	-98.25	4.13

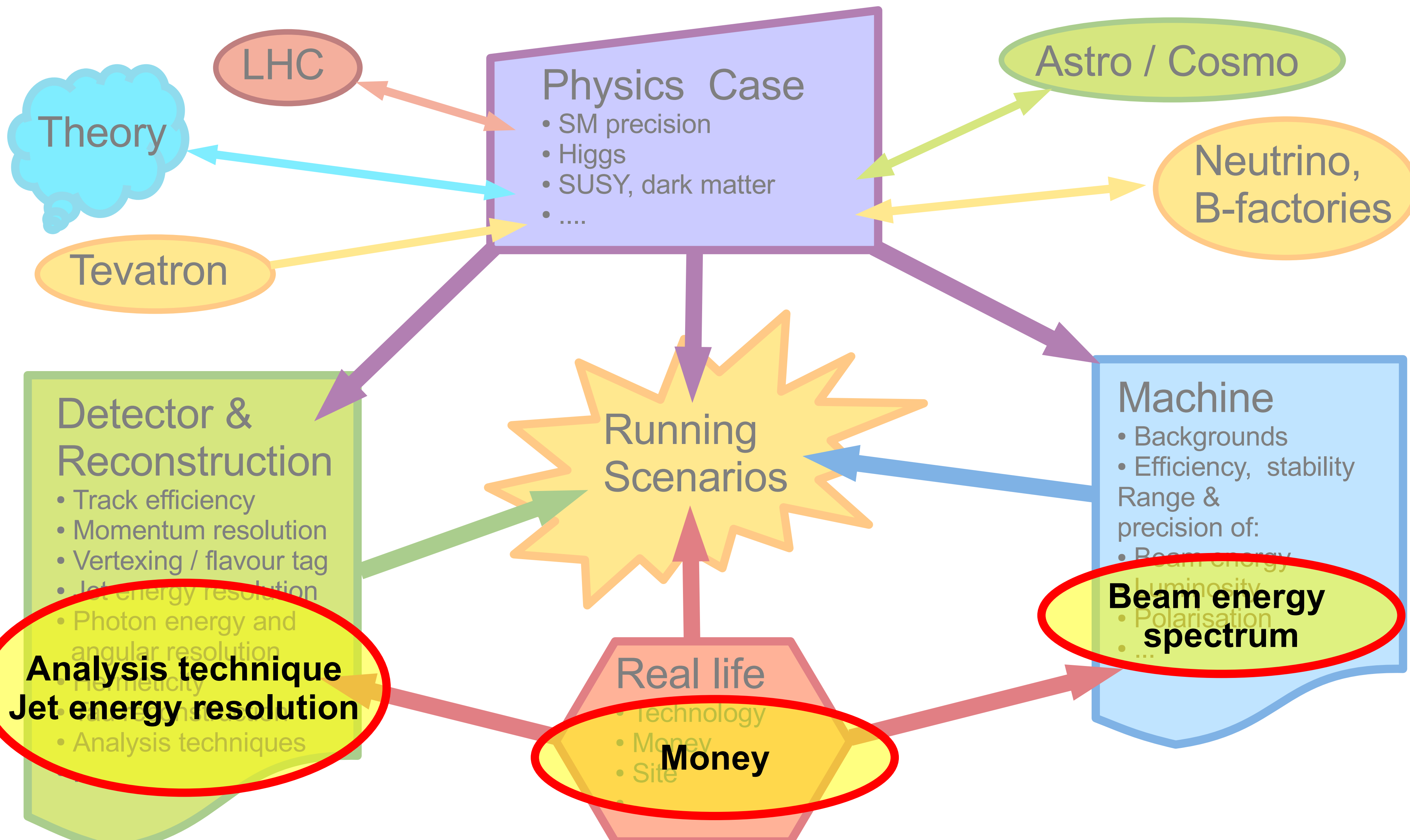
Next steps

- studies of many more physics examples in progress
- available soon: similar studies for CLIC
- discussion of accelerator parameters is ongoing
  => find the most cost effective design
  which allows to reach the physics goals!
- don't forget:
  meaningful comparison of detector / machine options
  needs appropriate reconstruction & analysis techniques
  => continue with one example for recent developments

Example 3

Kinematic Fitting in the presence of Initial State Radiation and Beamstrahlung

Kinematic fitting



Improved treatment of Beamstrahlung ?

- Beamstrahlung...
  - creates e^+e^- pair background
  - reduces the effective statistics
    (events from low energy tail don't contribute to peaks,edges, ...)

  => if amount of radiated energy could be determined with *sufficient precision* on an *event-by-event* basis, effective luminosity could be recovered!

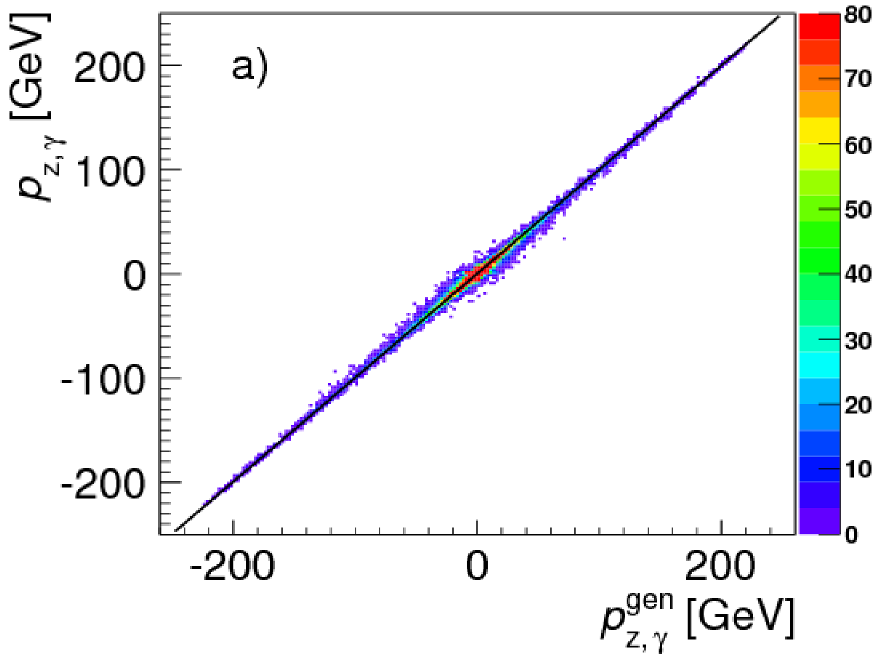
- Problem: radiation dominantly along beam axis → not measured!

- Idea: use kinematic constraints:
  - perform kinematic fit of all *measured* particle momenta...
  - ...and a “photon” || z-axis, with $E_\gamma = 0$, and δE_γ according to the (known) probability density function of E_γ
  - apply energy and momentum conservation constraints

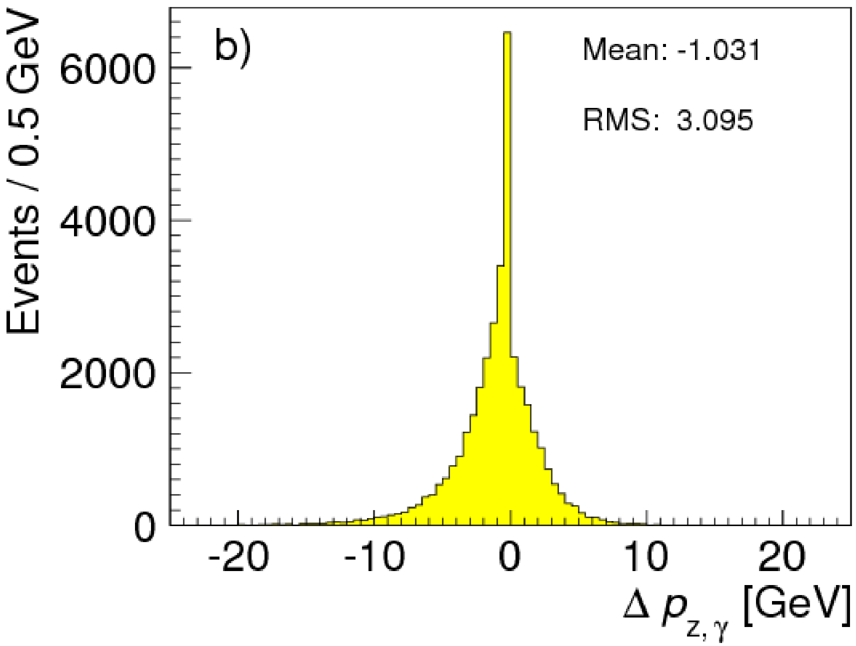
=> can we reconstruct the correct photon energy?

Yes, we can!

[arXiv:1006.0436, accepted by NIM A]



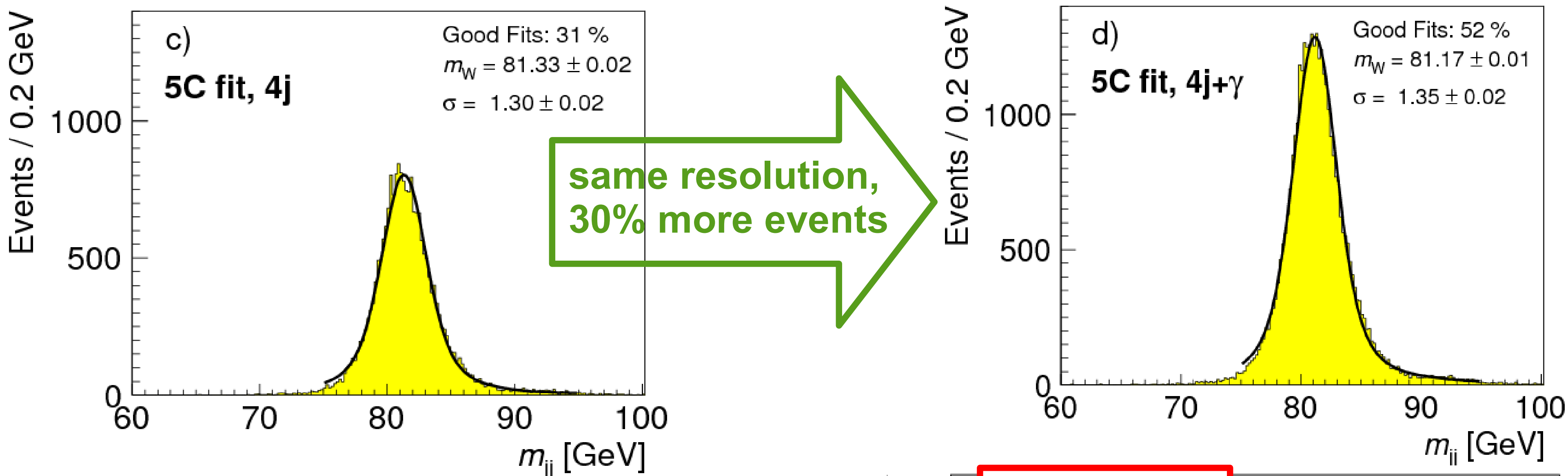
- tested on $e^+e^- \rightarrow$ 4 light jets in full ILD simulation
- kinematic fit with 4 jets and 1 photon
- imposing ΣE = 500 GeV; $\Sigma p_{x,y,z} = 0$; $M_{12} = M_{34}$



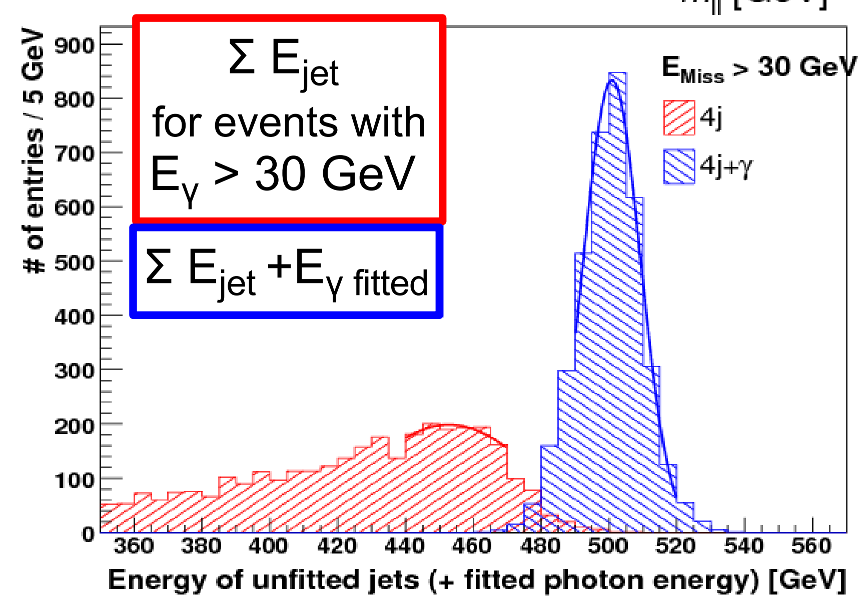
- the complete range of photon energies can be reconstructed
- with a resolution of 3 GeV

=> ~ 2x better than expected from E_{CM}-ΣE_{jet}

Recovering luminosity



- Photon consideration in kinematic fit recovers ~30% of luminosity
- not yet used in any physics study → apply to Higgs, tt, WW, ZZ, …
- tested now on ILC samples - impact for CLIC?



Conclusions

- An e^+e^- Linear Collider is essential to complement the LHC at the high precision frontier
- Physics case and conceptual designs have been established more than 10 years ago – maybe new input soon?
- The ILC plans a TDR and a Project Proposal in 2012/13. Its design is currently revisited to make sure that we really get a bang for every buck

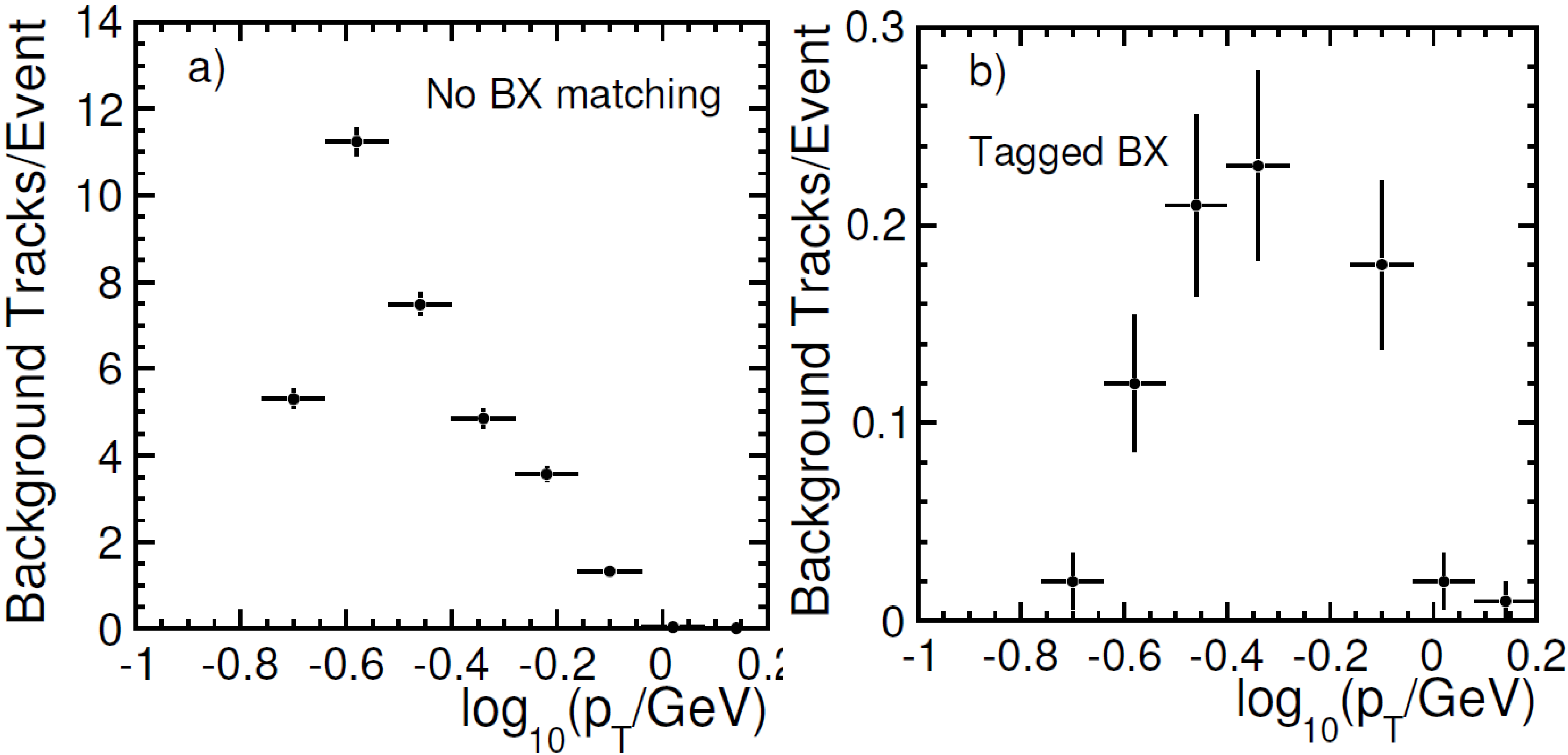
  => many machine parameters matter for physics - no only highest E_{CM} and luminosity at highest energy

  => need realistic simulation, reconstruction & analyses in order not to draw false conclusions

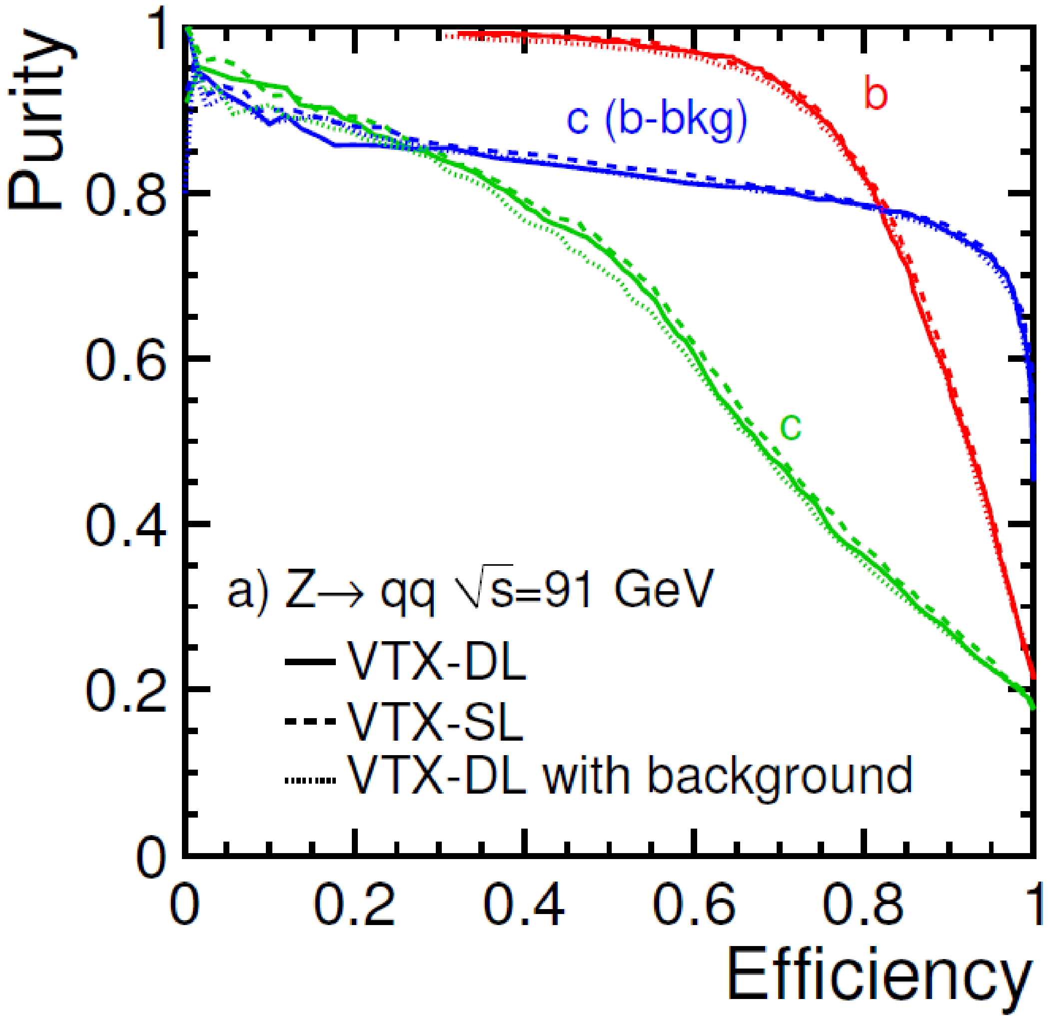
- CLIC plans a CDR in 2011 – similar studies ongoing
- *We* make sure that *you* get the right Linear Collider!

BACK UP

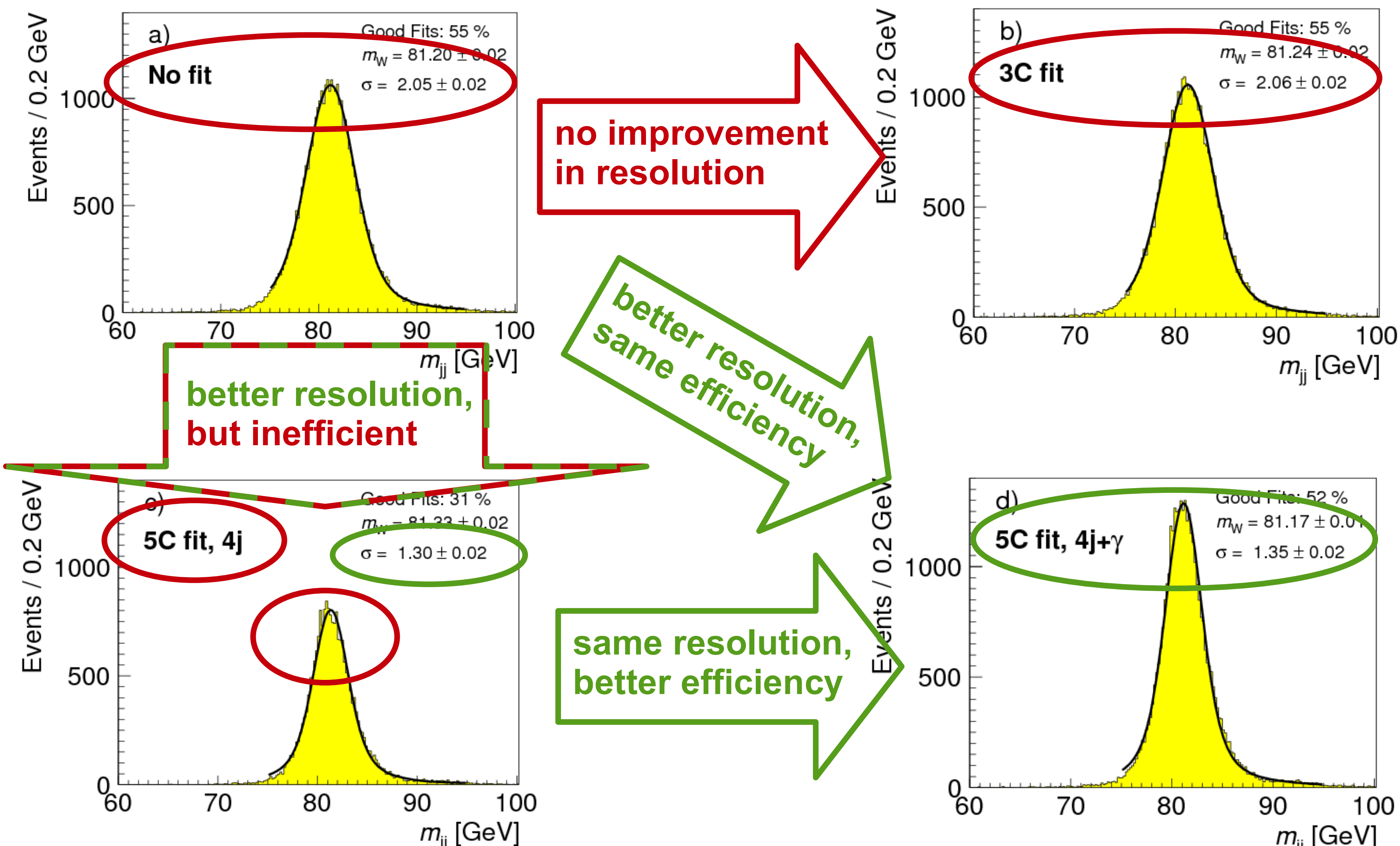
Ghost tracks in vertex detector



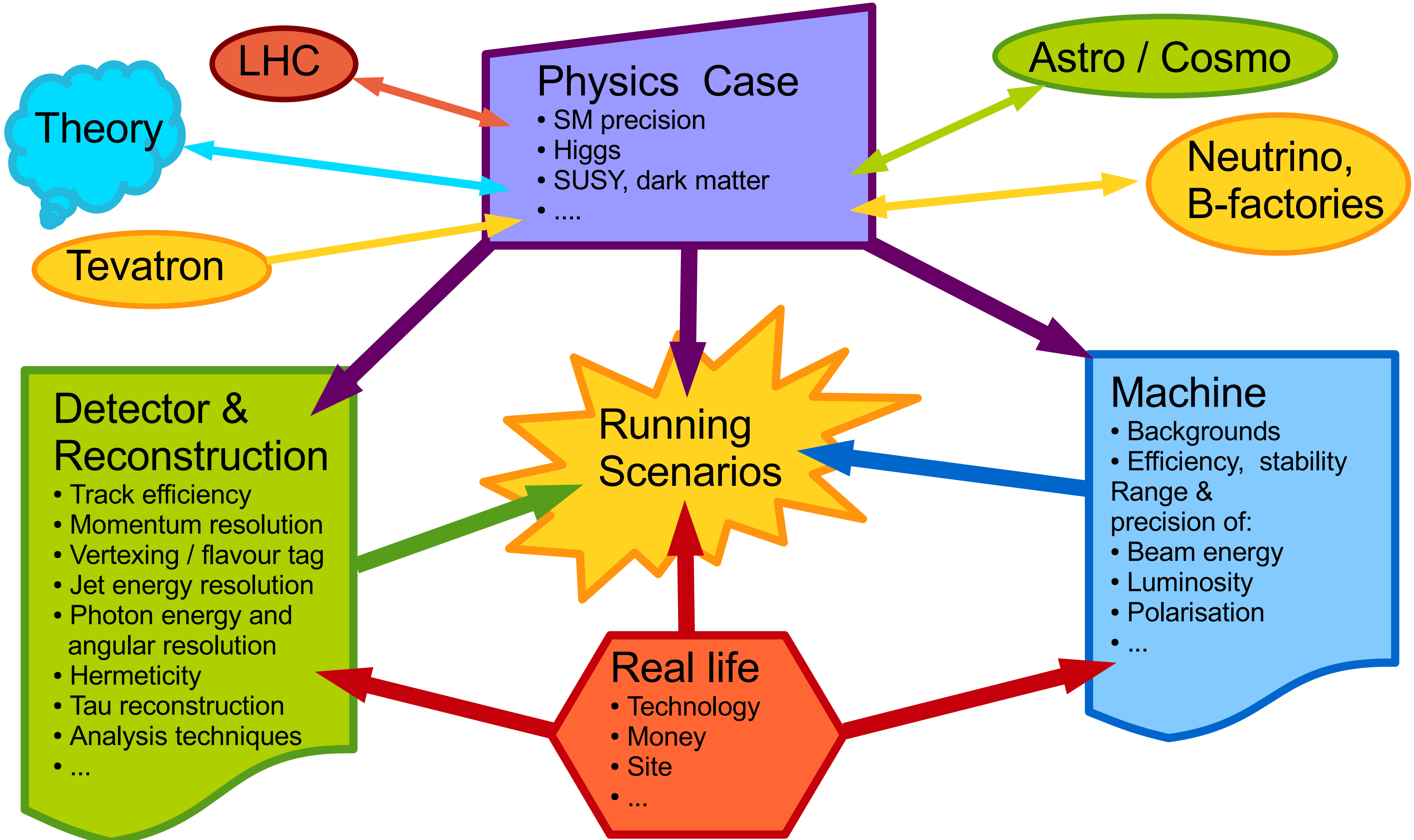
Flavour Tag with machine background



Improved di-jet mass resolution



Defining the right Linear Collider

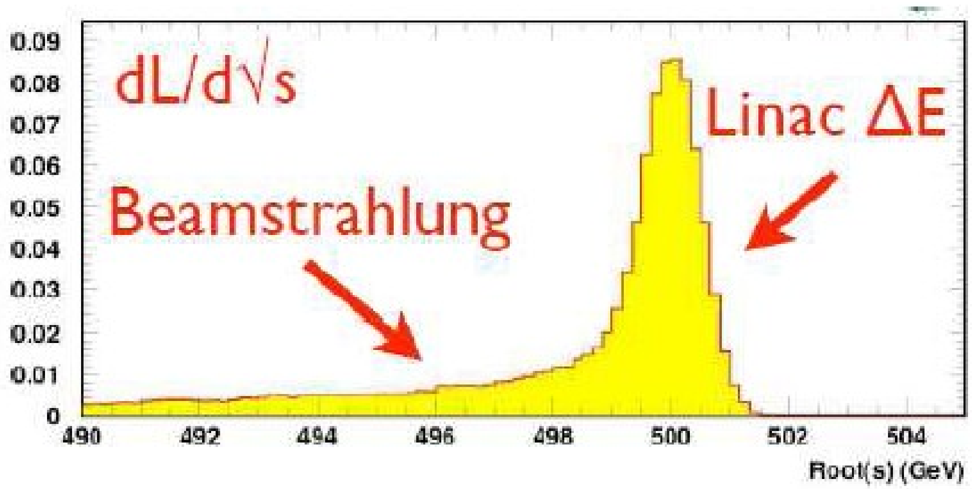


Luminosity, Energy & Polarisation

Goals & Requirements

- luminosity: 10^{-3} (ew precision 10^{-4})
- beam energy: 10^{-4} (ew precision: few 10^{-5})
- polarisation: $\Rightarrow 2.5 \cdot 10^{-3}$ (ew precision 10^{-3})

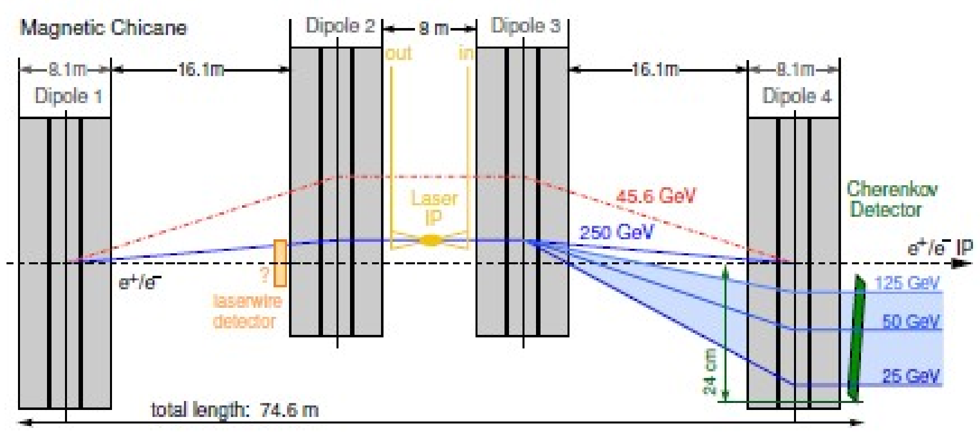
- but: measurement location usually *not* e^+e^- IP $\Rightarrow$ "interpolation"
- and: physics analyses assume not only E and $L = \int \mathcal{L} dt$ known, but full luminosity spectrum, i.e $dL/d\sqrt{s}$



The key players – upstream of IP

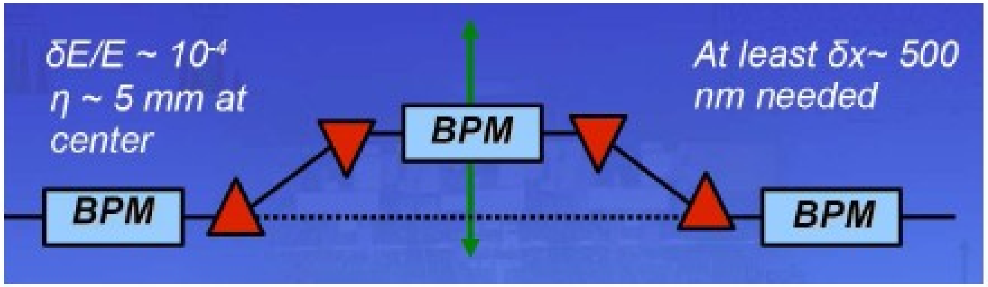
Compton-Polarimeter

- 1.8 km upstream of IP
- backscattering of circular polarised laser
- asymmetry w.r.t. laser helicity $\rightarrow$ polarisation

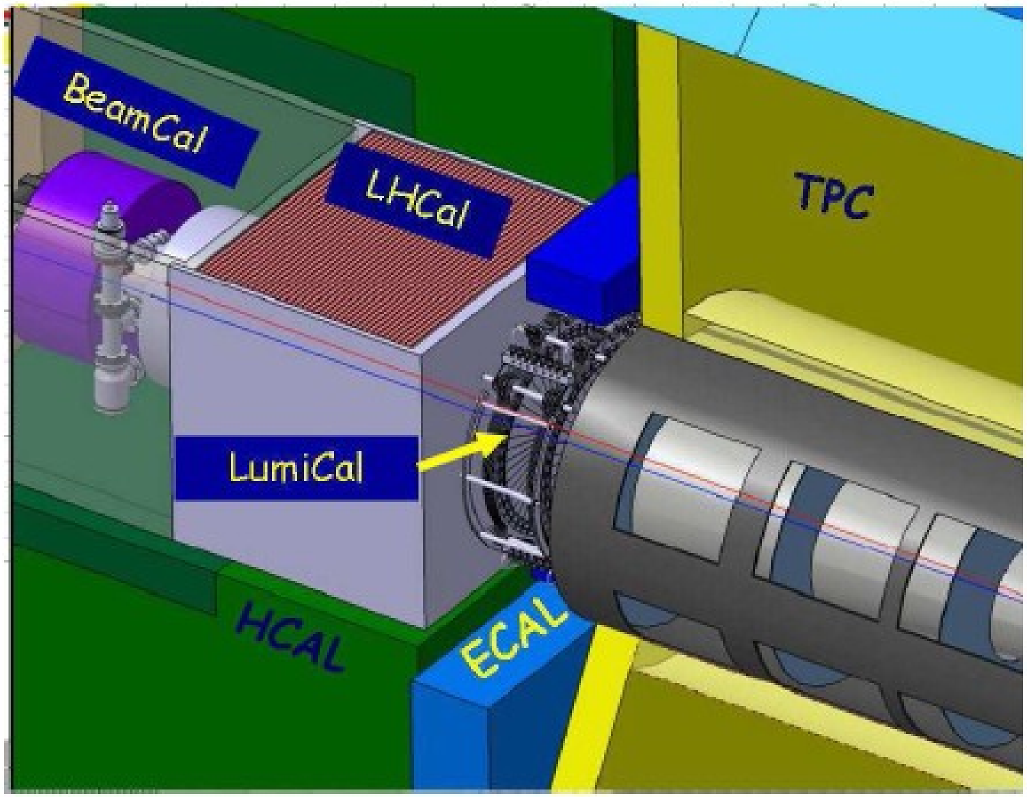


BPM based Energy Spectrometer

- 700 m upstream of IP
- measure beam position in chicane
- resolutions of $\simeq 1\mu m$ achieved



The key players – at the IP

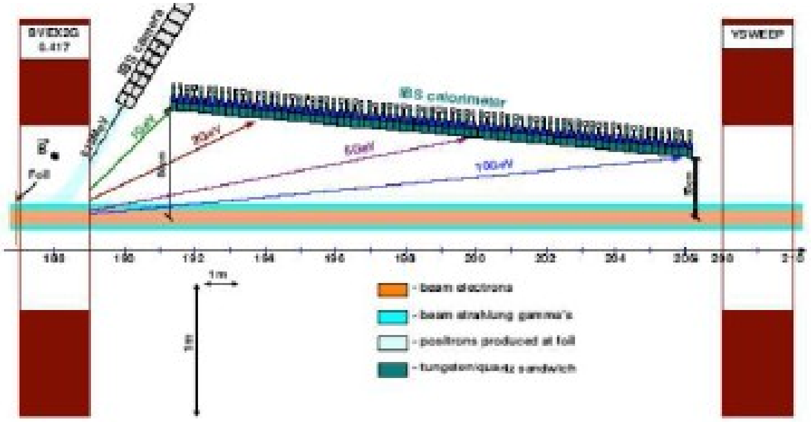


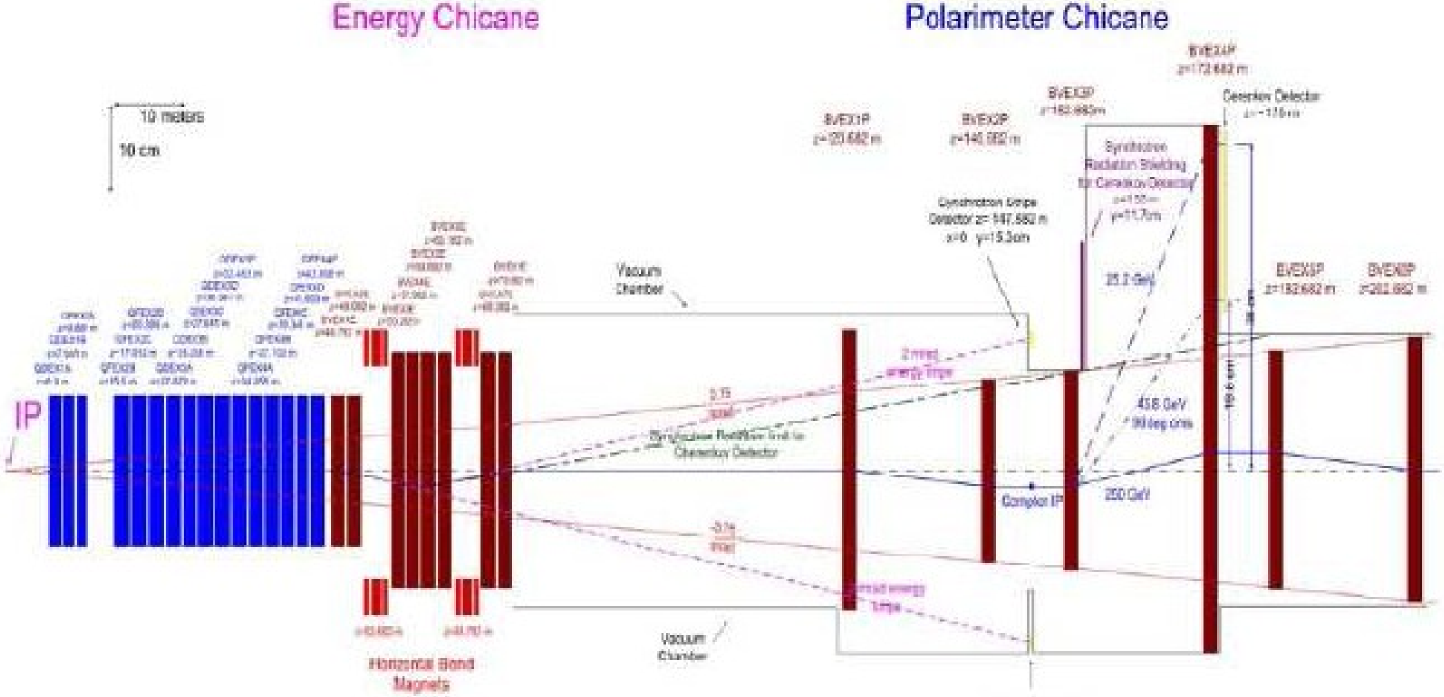
- LumiCal: 20 - 50 mrad, high precision lumi, hermeticity
- BeamCal: 5 - 20 mrad, fast lumi (tuning), collision diagnostics, hermeticity
- PairMonitor: in front of BeamCal, collision diagnostics
- LHCal: more hermeticity

common challenges:
precision & radiation hardness!

The key players – downstream of IP

- GamCal: 0 - 5 mrad, ca 100 m from IP, total radiation loss
- Compton-Polarimeter
- Energy Meas. (Synchr. Imaging)



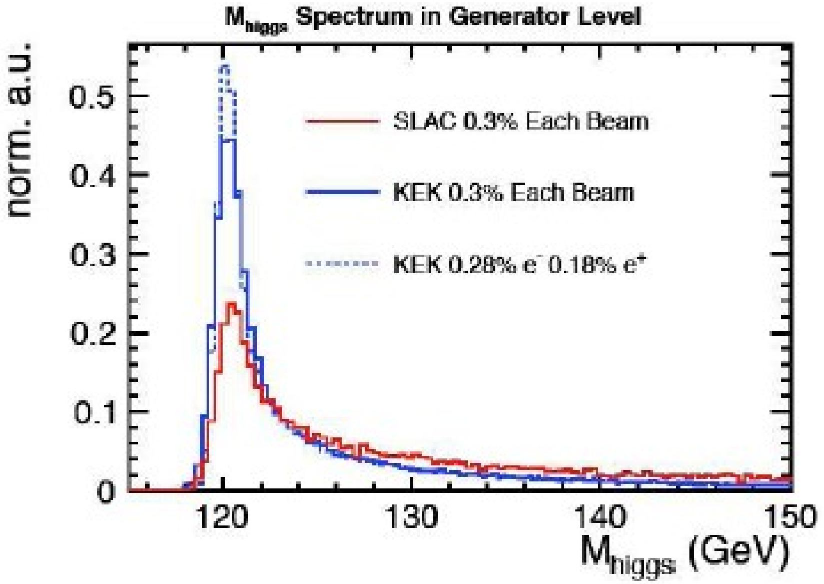


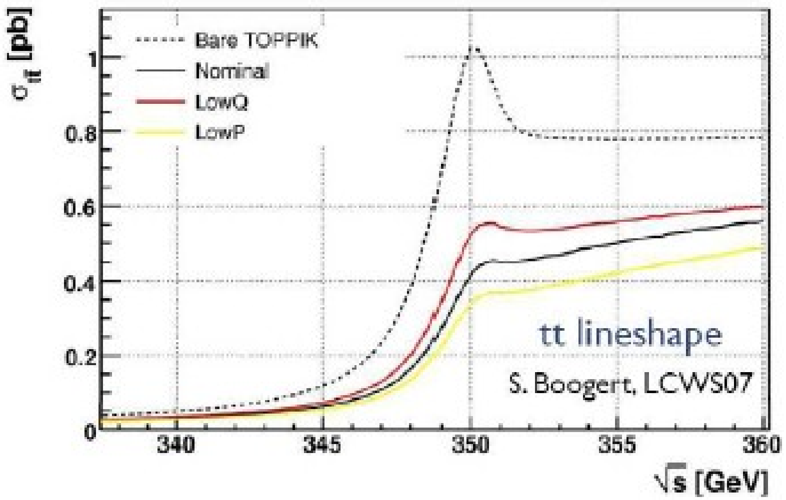
Luminosity, Beam Energy and all that

recall LoI studies:

- $dL/d\sqrt{s}$ assumed to be know perfectly - not only $< dL/d\sqrt{s} >$
- analyses are sensitive to beam energy spread & beamstrahlung (Higgs recoil!)
- not studied in LoI: threshold scans!

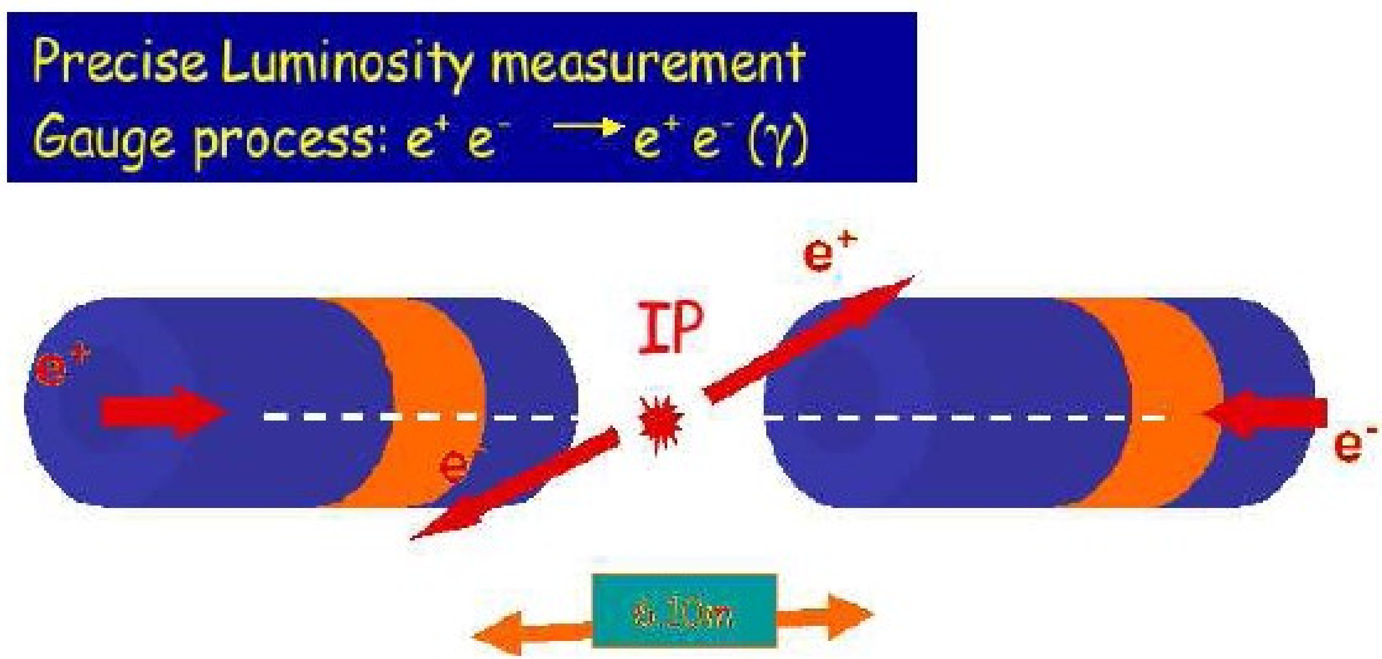
$\Rightarrow$ How do we get $dL/d\sqrt{s}$?





LumiCal

- count Bhabha events, typ. $E_{e^+} + E_{e^-} > 0.8 \cdot \sqrt{s}$
- $\int \mathcal{L} dt = N/\sigma$
- σ: theoretical cross-section $\longrightarrow$ needs energy spectrum...
- outgoing Bhabhas might be deflected by bunch charge!



Measuring Beam Parameters

Beam Parameter Determination

- BeamCal & PairMonitor : $N(e^{\pm})$, emittances, bunch sizes, waists, offsets,.. (limited by correlations amoung parameters)
- fit from up-down, left-right asymmetries, energy ratios...
- double read-out: fast coarse read-out for lumi tuning detailed read-out for full analysis
- GamCal: total energy loss into photons $\longrightarrow$ improves resolution

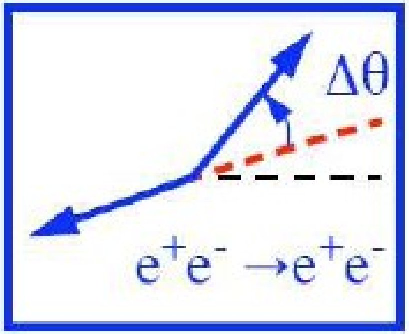
Energy Spectrometers

- upstream: measure energy after linac (no beamstrahlung!)
- downstream: minimize beamstrahlung, measure peak energy and energy spread

Direct measurement of dL/d$\sqrt{s}$ from physics

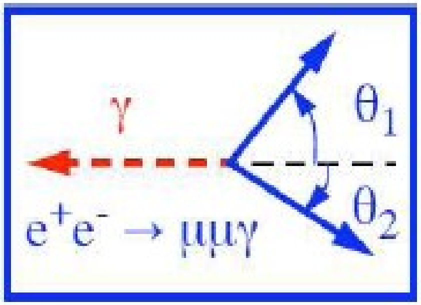
Acolinear Bhabhas

- $\frac{\sqrt{s'}}{\sqrt{s}} = 1 - \frac{\Delta\Theta}{2\sin\Theta_0}$
- $\Rightarrow$ need excellent forward tracking
- what about machine background?



Radiative Returns

- $e^+e^- \rightarrow \mu^+\mu^-\gamma$
- $\frac{s'}{s} = \frac{\sin\Theta_1 + \sin\Theta_2 - |sin(\Theta_1+\Theta_2)|}{\sin\Theta_1 + \sin\Theta_2 + |sin(\Theta_1+\Theta_2)|}$
- absolute $\sqrt{s'}$ calibration via Z resonance
- needs $\delta\Theta = 10^{-4}$



How can all these tools be combined to give the best $dL/d\sqrt{s}$?

Positron Polarisation

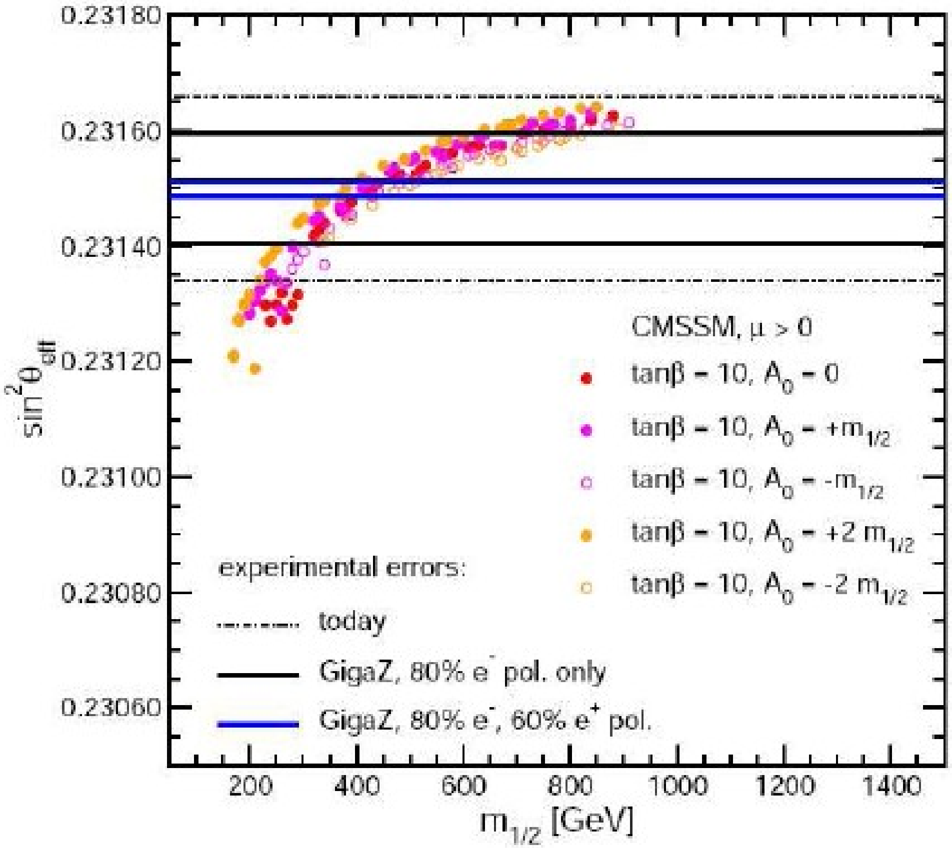
- baseline source delivers 30-45%
- but positron polarisation for experiments is NOT baseline
  $\longrightarrow$ could be destroyed
- consequences:
  - damping rings are not enough, need to actively destroy it
  - need to measure extremely precisely if it is really destroyed
  - polarimeter calibration from e^+e^- data much more luminosity demanding,
  - no cancelations of systematics
  - some physics cannot be done at all
    Ex.: disentangling helicity states of new physics

Better keep it!

- positron polarimeters forseen
- but no fast helicity flip!
  - e^-: can quickly flip source laser helicity
  - e^+: undulator polarity cannot be reversed, need spin rotators $\Rightarrow$ slow!
- $\Rightarrow$ no cancellation of systematics
- $\Rightarrow$ reduced gain through $P_{\text{eff}} = \frac{P_L + P_R}{1 + P_L \cdot P_R}$
- spending a lot of time on "uninteresting" states LL, RR

Polarimetry at the Z pole?

- $\delta \sin^2 \theta_{eff}$ today: $18 \cdot 10^{-5}$
- with $P(e^+, e^-) = (40\%, 90\%)$: $6 \cdot 10^{-5}$ with $\int \mathcal{L} dt = 0.5 \text{ fb}^{-1}$
- needs
  - positron polarisation at the Z pole (source location?!)
  - fast positron helicity flip
  - best possible polarimetry (systematics limited at $\simeq$ 1 fb^{-1} with $\delta P/P = 0.25\%$)



- $\Rightarrow$ interesting physics with lumi not far from accumulated calibration runs over $\simeq$ 10 years
  - might even investigate a few weeks dedicated running?

Polarimetry with annihilation data

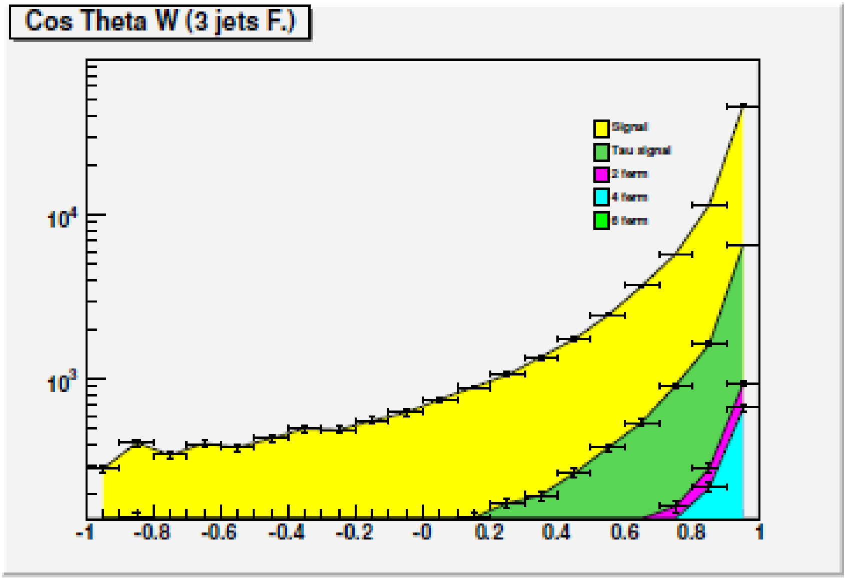
if positron polarisation

- $\sigma = \sigma_0[1 - P(e^+) \cdot P(e^-) + (P(e^+) - P(e^-))A_{LR}]$
- $\Rightarrow$ correlations matter!
- can calibrate polarimeters with modified Blondel Scheme:
  $|P(e^\pm)| = \sqrt{\frac{(\sigma_{LR}+\sigma_{RL}-\sigma_{LL}-\sigma_{RR})\cdot(\pm\sigma_{LR}\mp\sigma_{RL}+\sigma_{LL}-\sigma_{RR})}{(\sigma_{LR}+\sigma_{RL}+\sigma_{LL}+\sigma_{RR})\cdot(\pm\sigma_{LR}\mp\sigma_{RL}-\sigma_{LL}+\sigma_{RR})}}$
- **if $P_L = P_R$** (for each beam)
- if not: corrections $\simeq$ uncorrelated polarimeter error on $P_L - P_R$
- advantage: model independent!
- need to spend substancial amount of running time on LL and RR $\longrightarrow$ expensive!

$e^+e^- \rightarrow W^+W^-$

preliminary results from full simulation (ILD)

- Blondel scheme for 100 fb^{-1} for each helicity state: $\delta P(e^-)/P(e^-) = 0.1\%$, $\delta P(e^+)/P(e^+) = 0.2\%$
- from $\frac{d\sigma}{d\cos\theta}$: large $\cos\theta$ t-channel domianted, P changes relative contribution of t-channel
- contribution of new physics? $\Rightarrow$ common determination with triple gauge couplings



fit yields for 20 fb^{-1}:
$P(e^-) = 80.17 \pm 0.15$,
$P(e^+) = 60.10 \pm 0.20$
(no backgrounds yet)