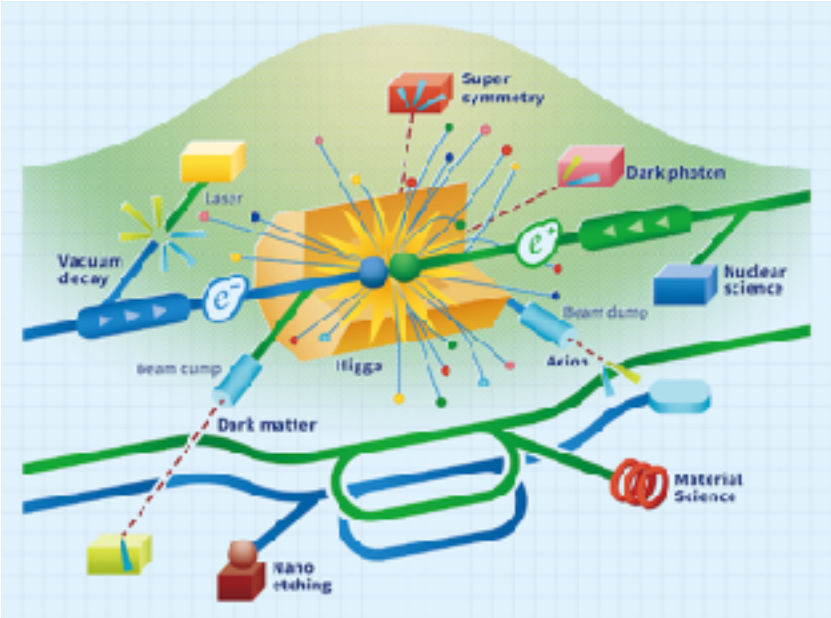
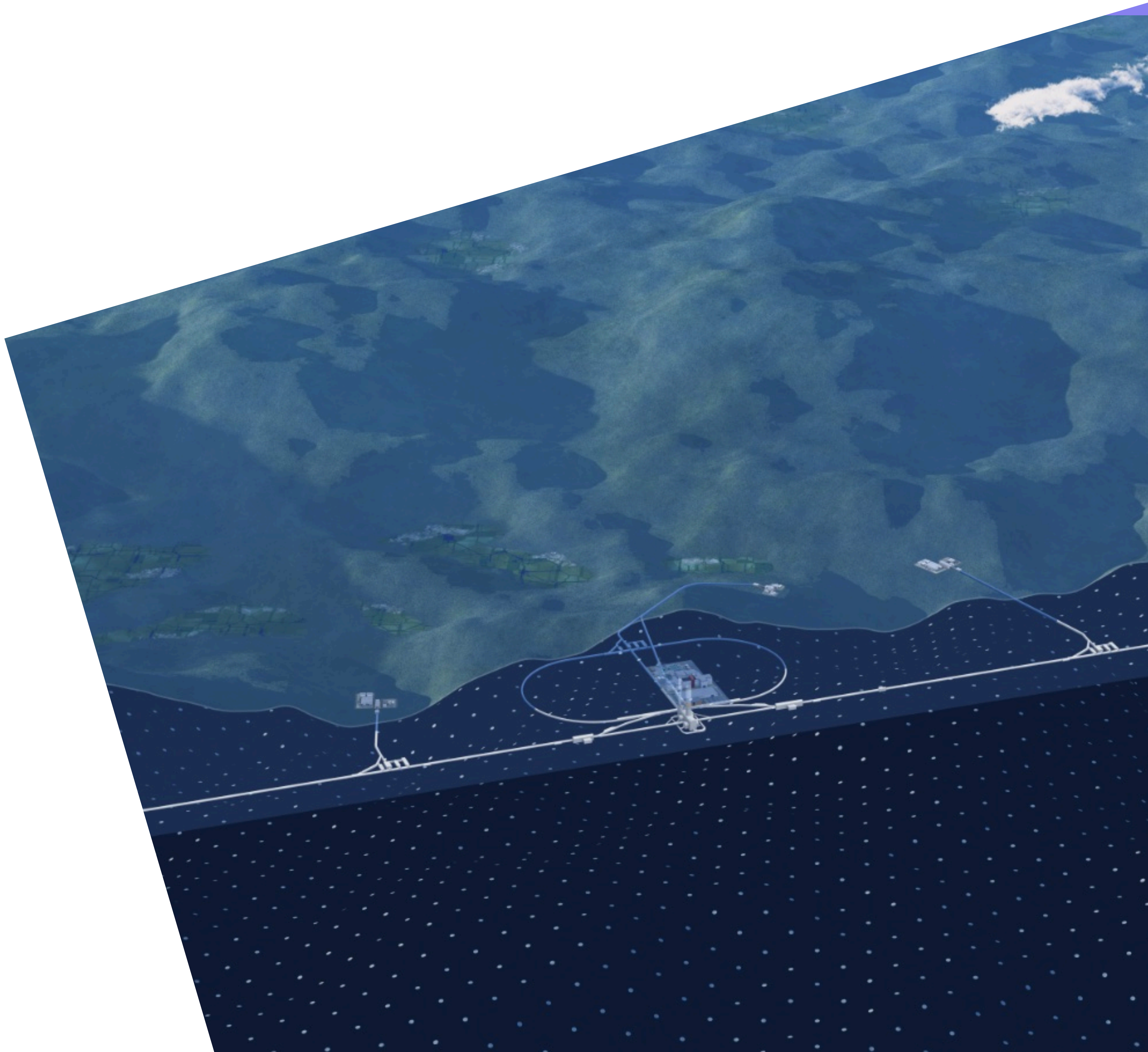


Flavour at the ILC

On behalf of
ILC International Development Team
Detector and Physics Group

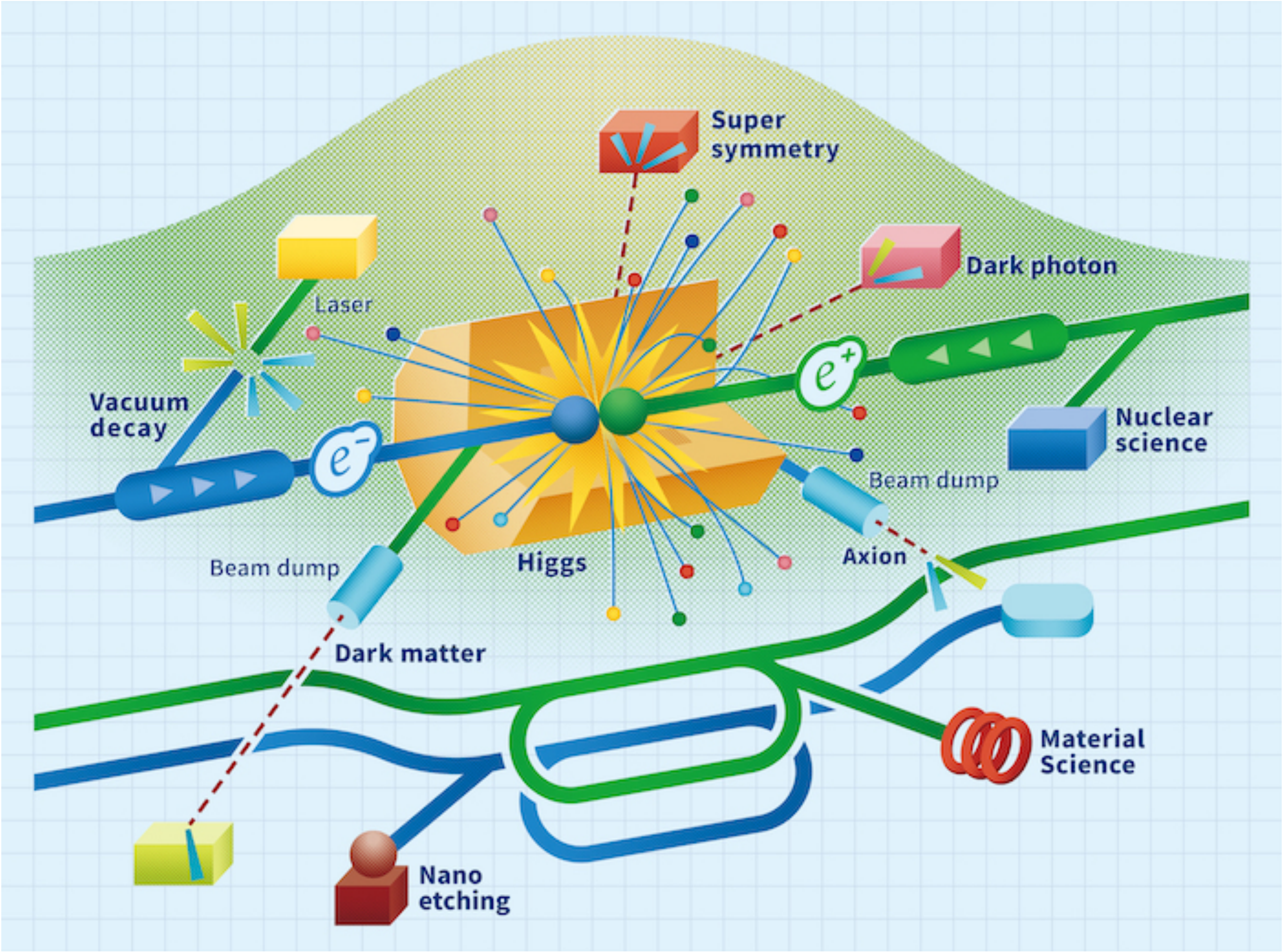
Phillip Urquijo
The University of Melbourne

ECFA Flavour Meeting June 2022



Perennial Flavour Questions

- **Are there new CP-violating phases in the quark sector? (Why is the Universe missing all its antimatter?).**
  - *Searches for new sources of quark sector CP violation, CKM precision metrology.*
  - *CPV in the Higgs sector.*
- **Does nature have multiple Higgs bosons? (Why is there a mass hierarchy in fermions? Why do neutrinos have mass?)**
  - *Semileptonic and Leptonic decays, lepton flavour universality violation.*
  - *Higgs precision studies.*
  - *Direct searches for mass generation mechanisms.*
- **Does nature have a L–R symmetry? (With higher mass interactions)**
  - *Rare flavour decays.*
  - *EW couplings, direct searches.*
- **Is there a dark sector of particle physics at the same mass scale as ordinary matter?**
  - *Dark photons, axion like particles, and dark matter, via flavour transitions and direct production.*



Belle II - LHCb Comparison

+ Important contributions on B and D flavour physics from ATLAS, CMS, BESIII.

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. B→Kνν, μν), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2030.

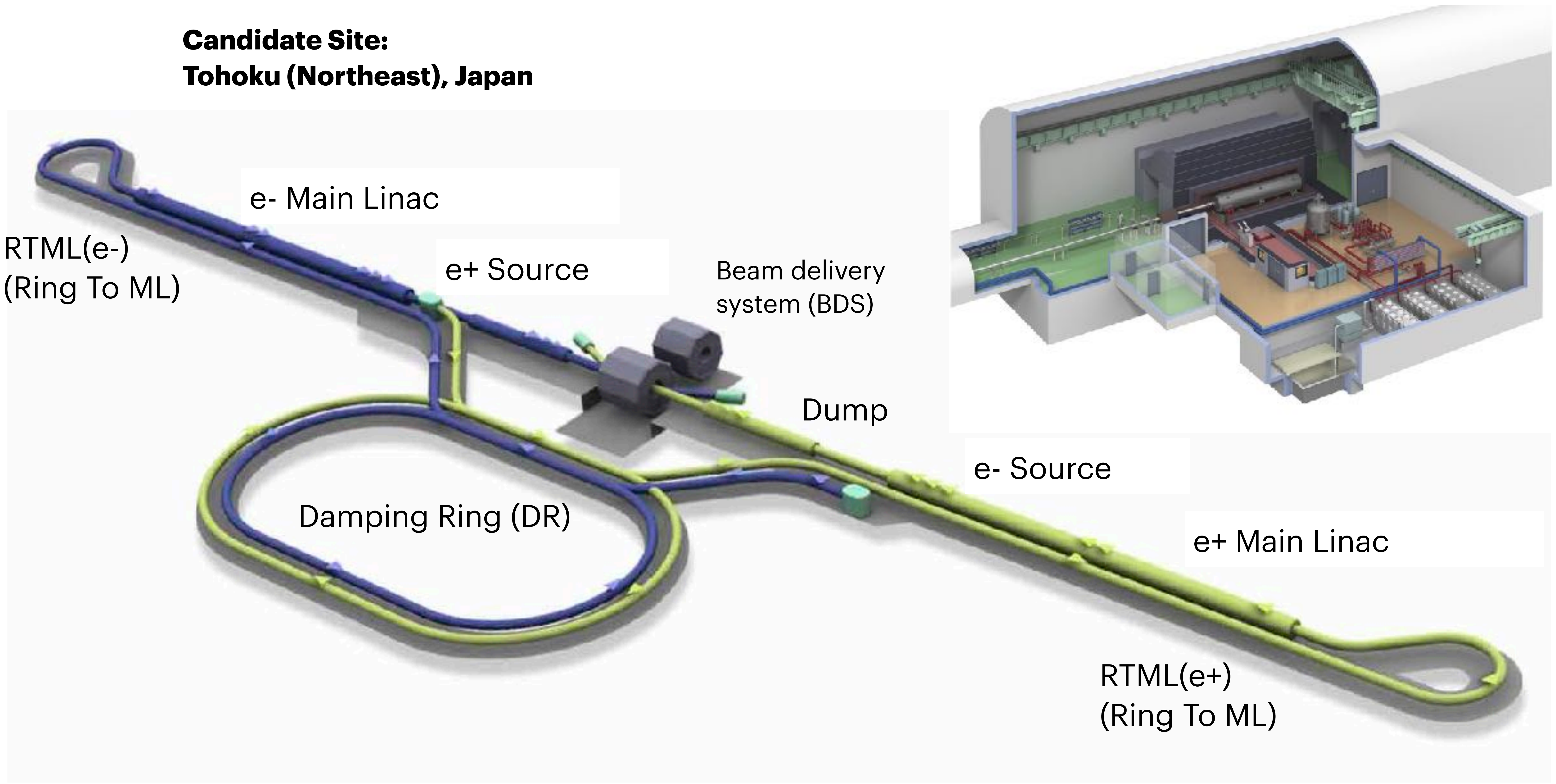
Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\|V_{ub}\|/\|V_{cb}\|$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^* \ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^* \tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D \tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^* \nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

Table 1: Projected precision of selected flavour physics measurements at Belle II and LHCb.(The † symbol denotes the measurement in the $1 < q^2 < 6$ GeV/c^2 bin.)

arXiv: 1808.08865 (Physics case for LHCb upgrade II),
PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book), arXiv:2203.11349 (Snowmass: Belle II Upgrade)

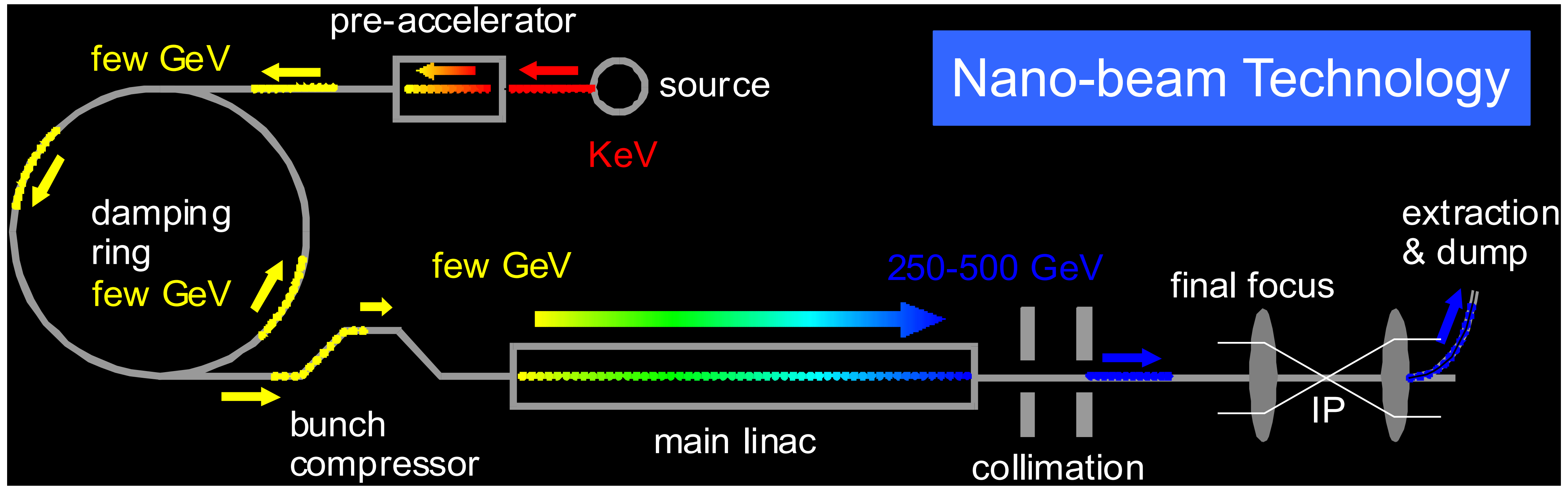
ILC 250 GeV Overview

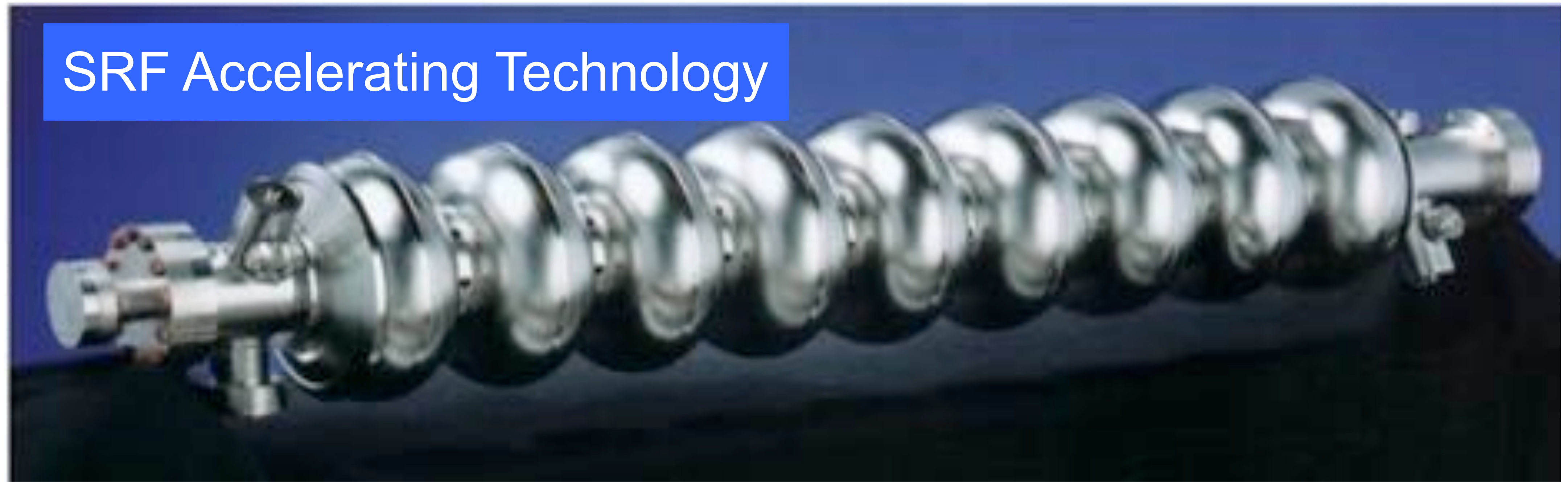
Candidate Site:
Tohoku (Northeast), Japan



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**7.7** nm@250GeV
SRF Cavity G.	**31.5** MV/m (**35** MV/m)
Q_0	Q_0 = 1x10^{10}

A small beam spot is a linear collider speciality - for storing the beams in a ring, the beam-beam interaction has to be much lower, hence much less strong focusing at the IPs.



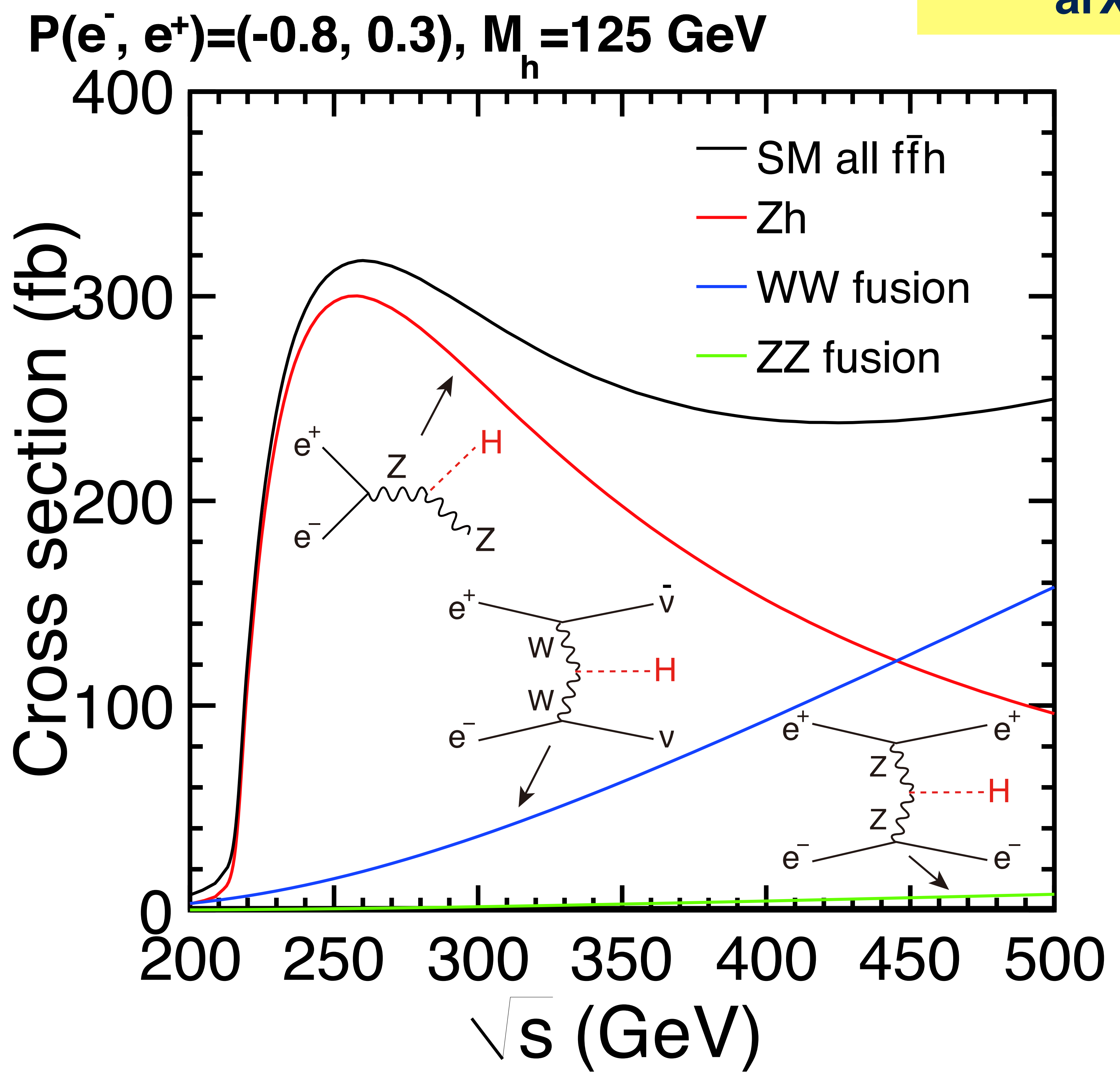


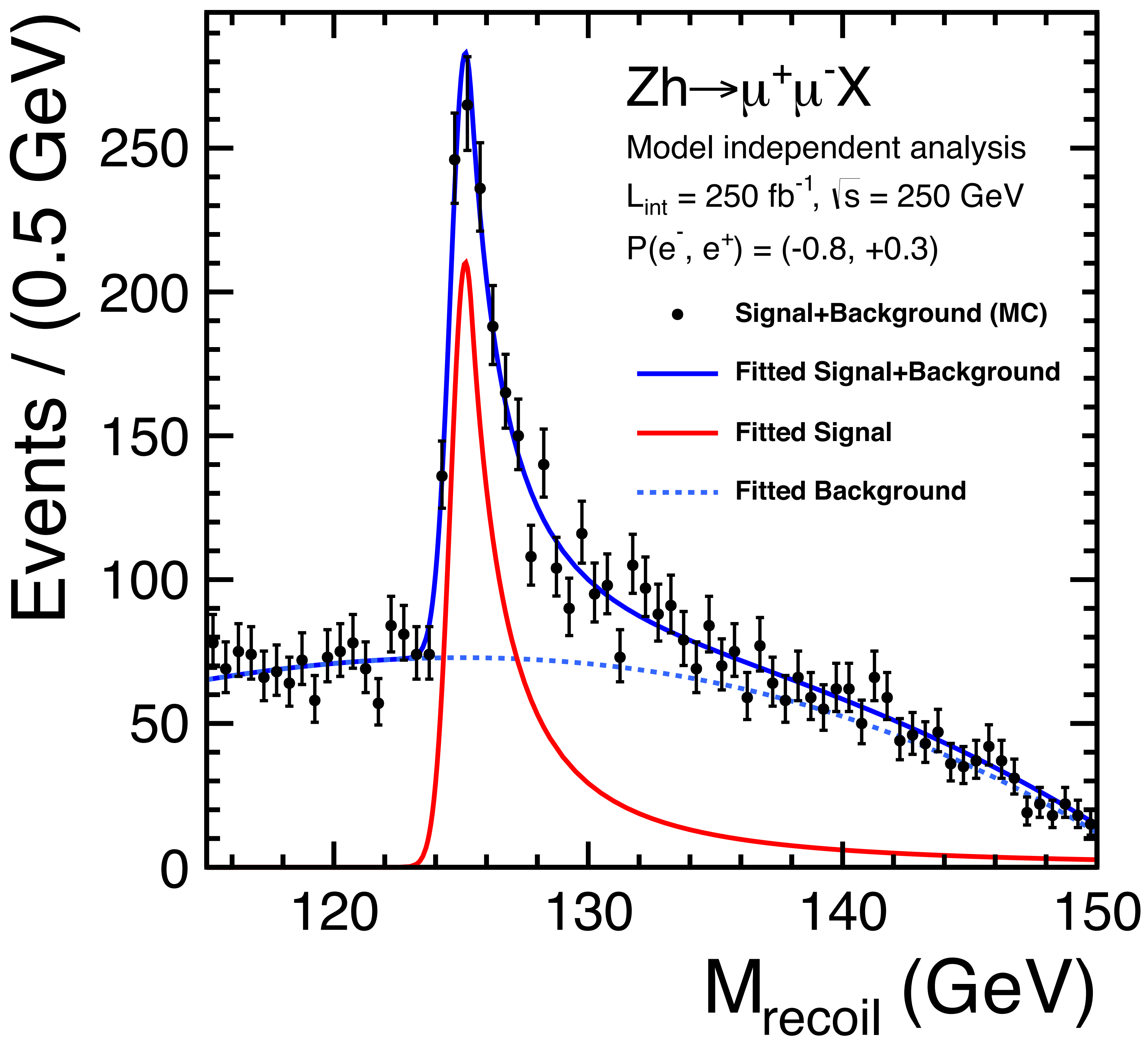
Higgs Factory Physics

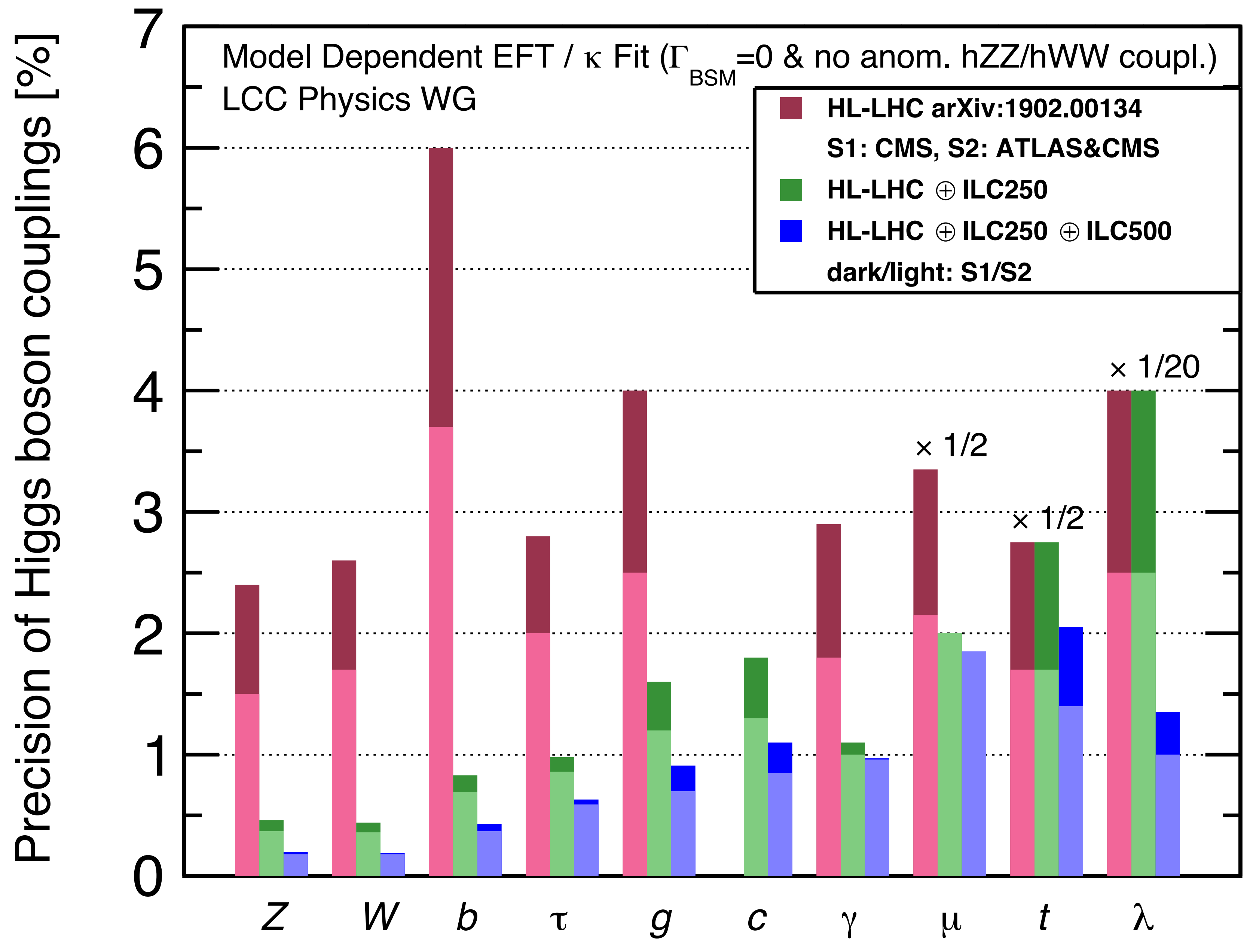
- sqrt(s) = 250 GeV: Higgs-strahlung (Zh) dominant, peak cross section around 250 GeV ---> Higgs factory, O(1M) Higgs events
- sqrt(s) = 500 GeV: WW-fusion dominant, improve many couplings, access to Top-Yukawa, Higgs self-coupling.

arXiv:1506.05992

arXiv: 1903.01629





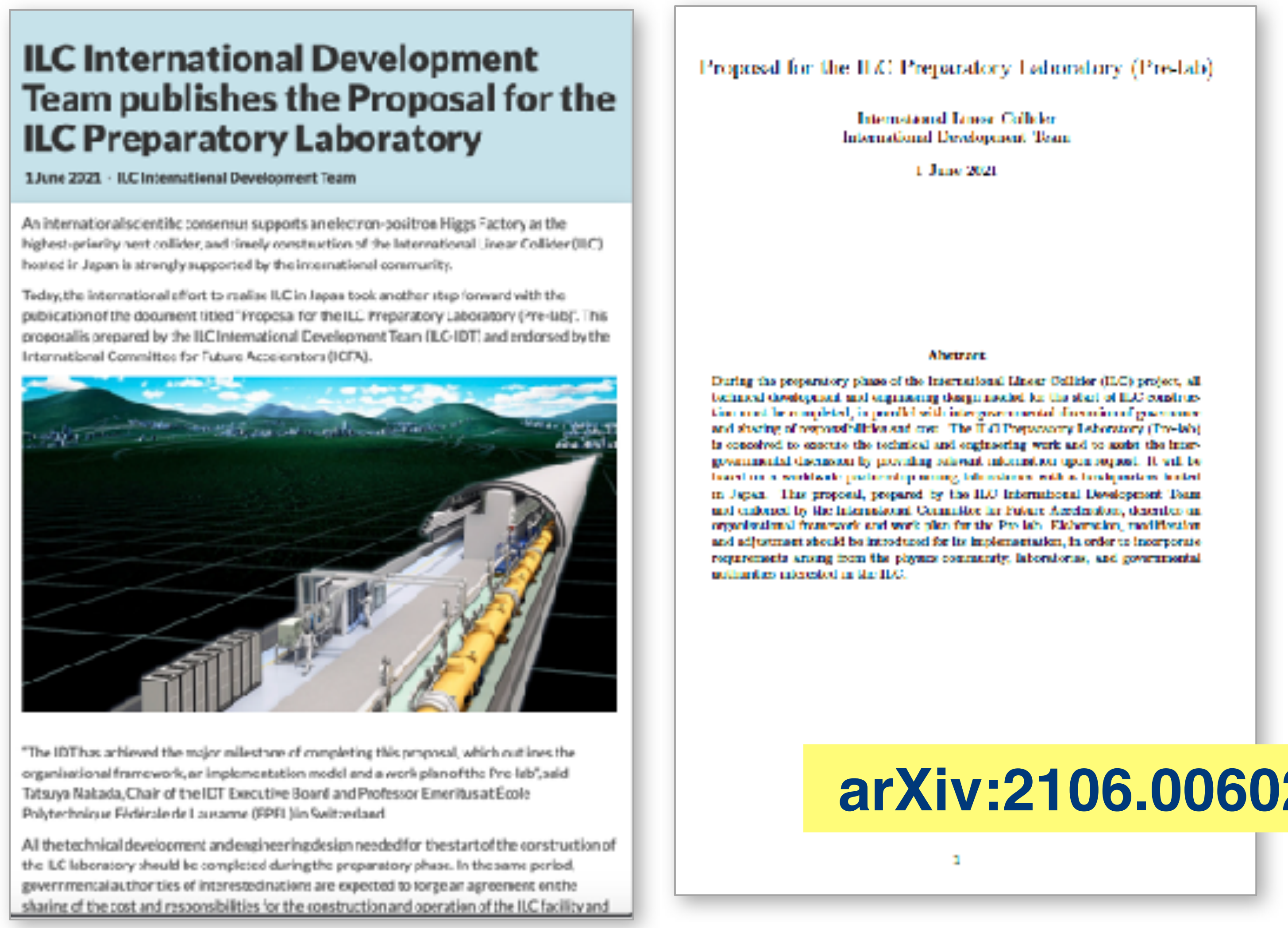


International Development Team

- **2013-Jun 2020**: Linear Collider Collaboration LCC under ICFA Mandate, governed by Linear Collider Board LCB
- **2014-2018**: MEXT appointed ILC Advisory Panel reviews project, incl. new 250GeV baseline
- **Feb-Jun 2020:** LCB proposes International Development Team IDT to prepare an ILC-Pre-Lab
- **Aug 2020**: ICFA establishes IDT and appoints IDT Executive Board (*)
- **Goal**: establish an ILC Pre-Lab within ~2 years. IDT focusses on ILC realisation, KEK provides support (admin., financial)

	IDT	ILC Pre-Lab				ILC Lab.										
	PP	P1	P2	P3	P4	1	2	3	4	5	6	7	8	9	10	Phys. Exp.
Preparation CE/Utility, Survey, Design Acc. Industrialization prep.																
Construction																
Civil Eng.																
Building, Utilities																
Acc. Systems																
Installation																
Commissioning																
Physics Exp.																

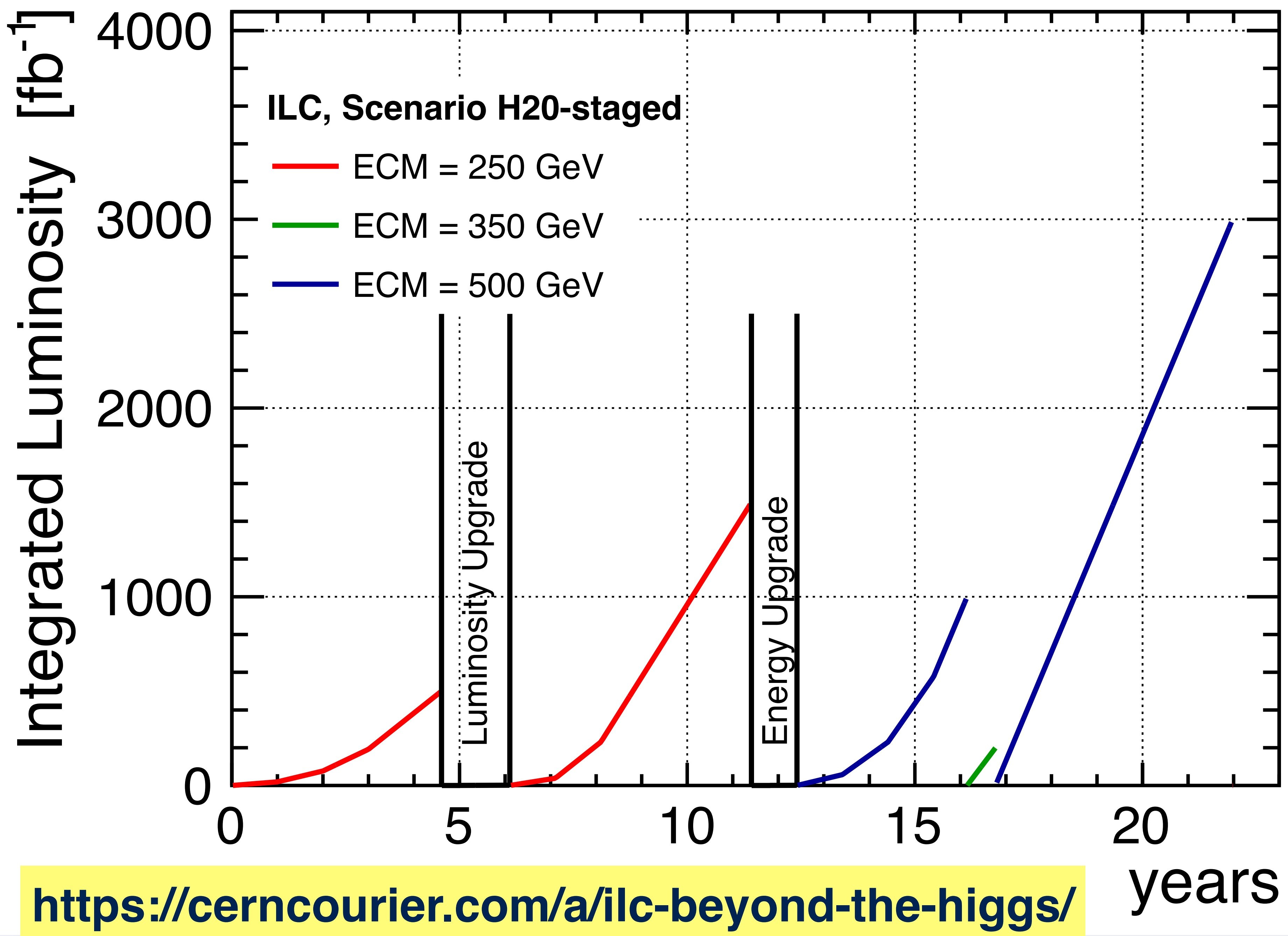
Following a four-year ILC Pre-Lab phase, ILC construction will continue for about ten years.



arXiv:2106.00602

ILC Data Taking Scenario

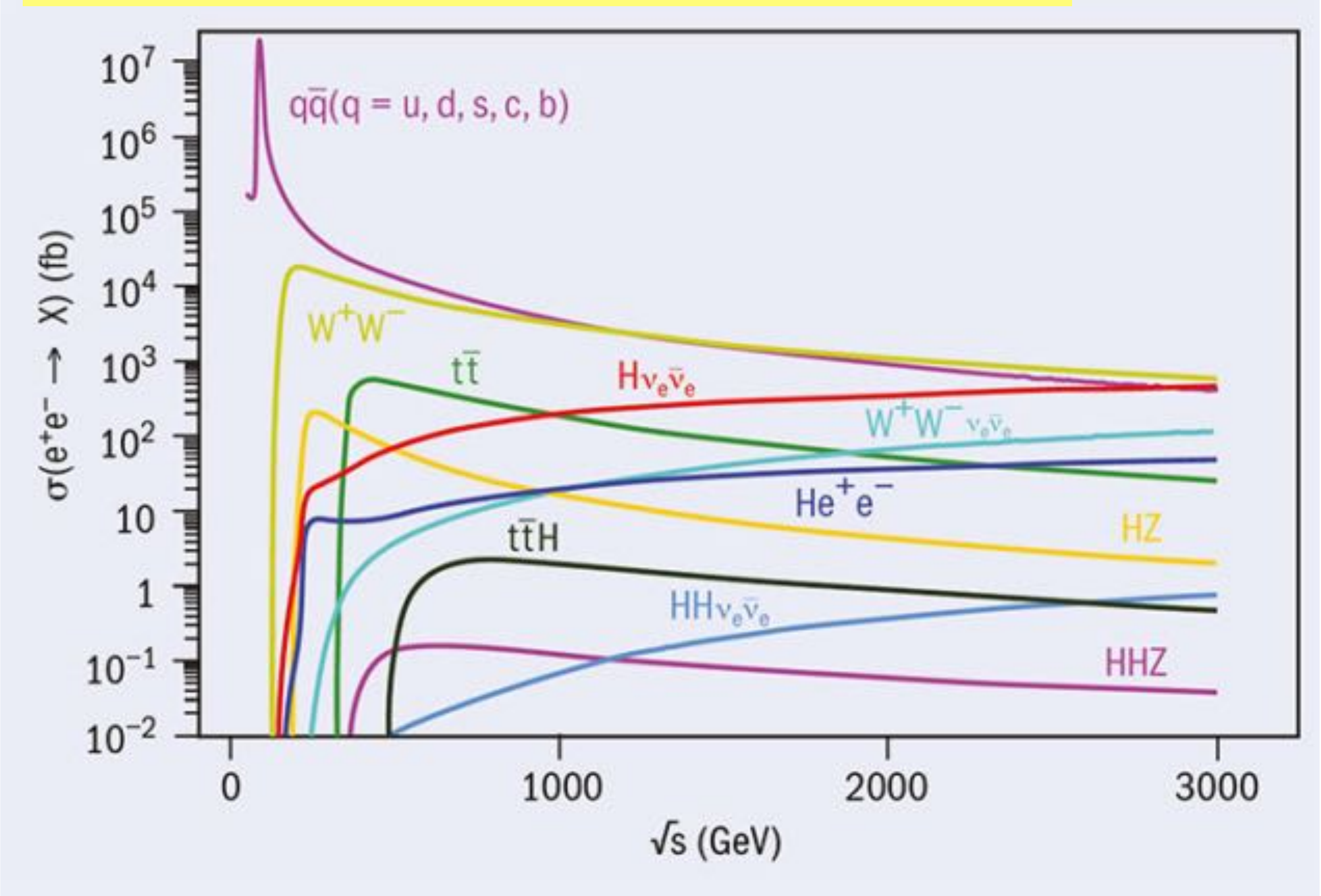
- First stage: 250 GeV (Higgs factory)
- Second stage: 500 GeV and beyond
  - covers *tth* and *Zhh* (self coupling) production
- **Potential to be a GigaZ+ factory (100 fb^{-1} +) in interim**



https://cerncourier.com/a/ilc-beyond-the-higgs/

$P = \frac{N_R - N_L}{N_R + N_L}$

	E_{CM} (GeV)	$\int \mathcal{L}$ (fb^{-1})	fraction with sign$(P(e^-), P(e^+))$ = $(-+)$	$(+-)$	$(--)$	$(++)$
ILC250	250	2000	45%	45%	5%	5%
ILC350	350	200	67.5%	22.5%	5%	5%
ILC500	500	4000	40%	40%	10%	10%
GigaZ	91.19	100	40%	40%	10%	10%
ILC1000	1000	8000	40%	40%	10%	10%



GigaZ
230xLEP

	sign$(P(e^-), P(e^+))$ = $(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	60.4	46.1	35.9	29.4	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

Polarisation

- Longitudinally polarised beams are a key feature of ILC design

Differential cross sections for (relativistic) di-fermion production*:

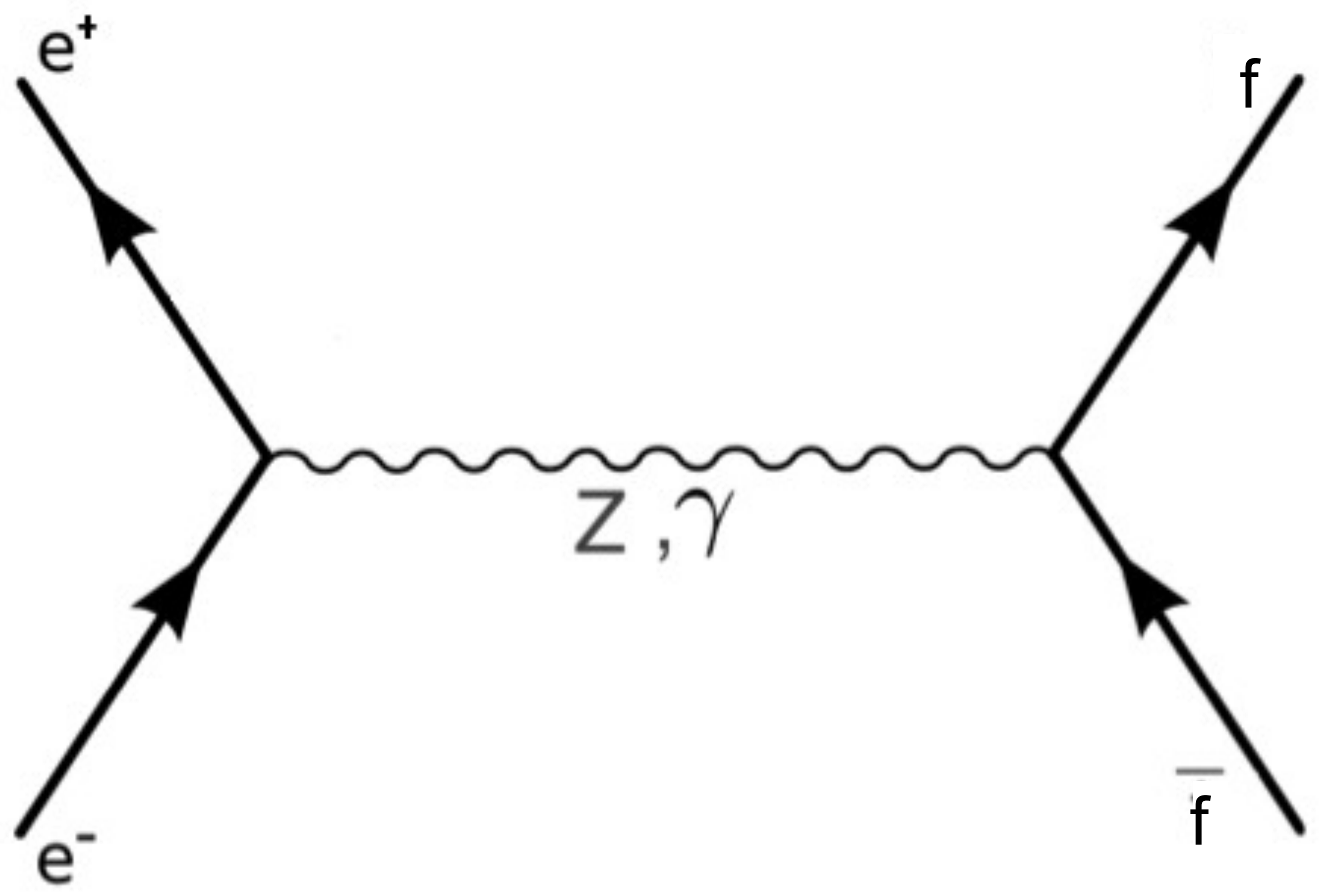
$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2$$

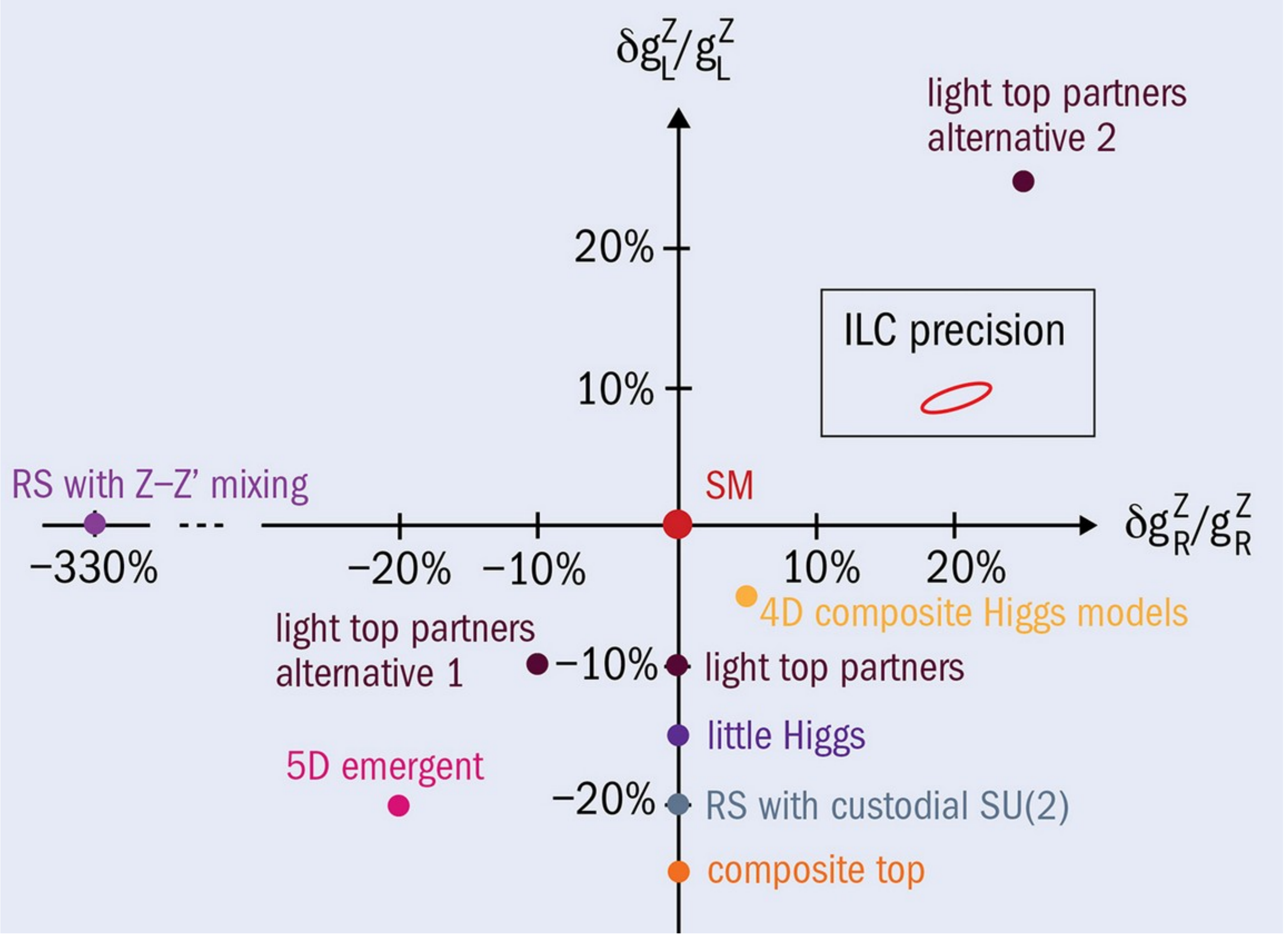
*add term ~$\sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R (or F_V, F_A)

$\Sigma_{IJ} \neq \Sigma_{I'J'}$ => (characteristic) asymmetries for each fermion.

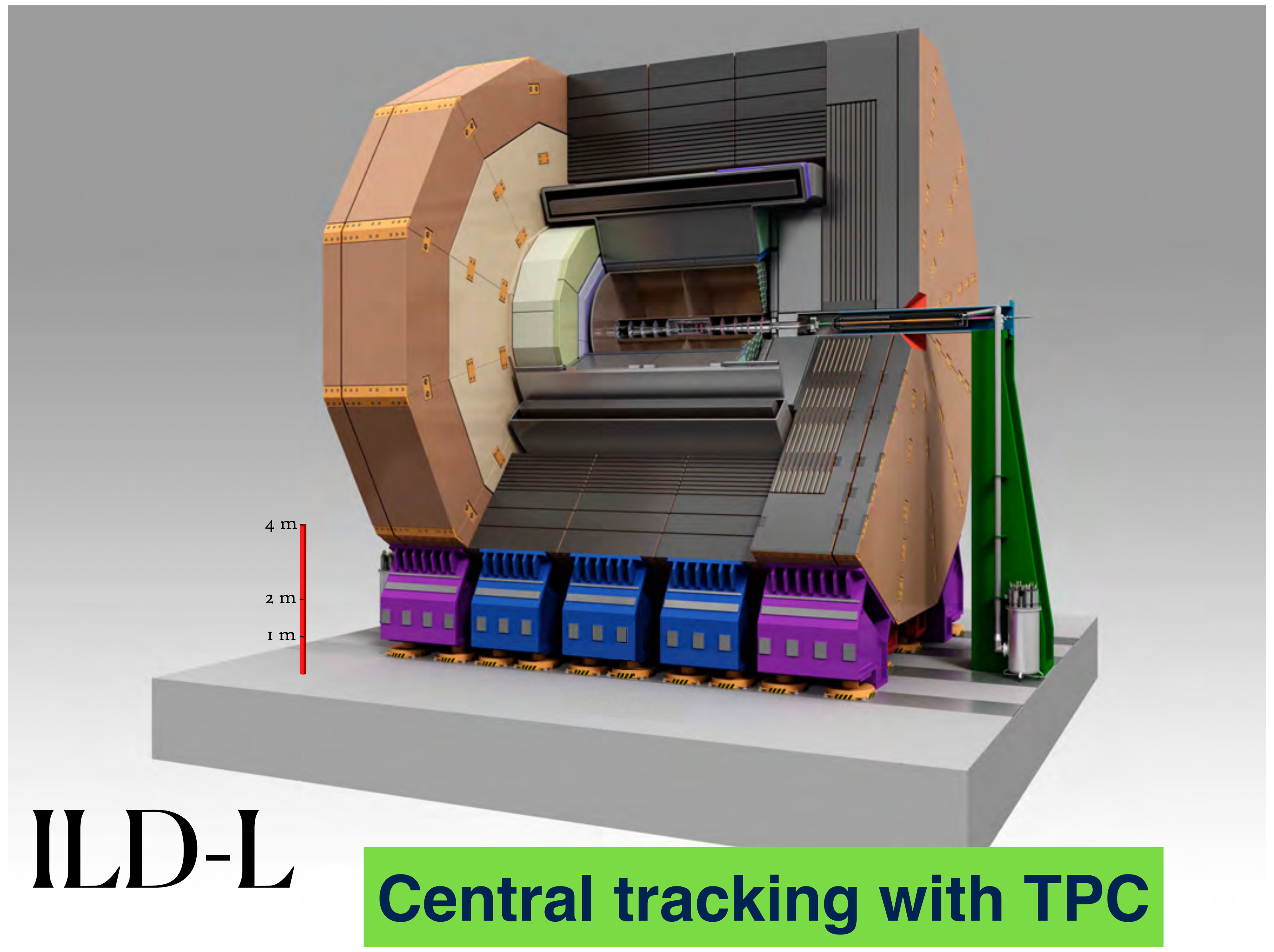


https://cerncourier.com/a/ilc-beyond-the-higgs/
Deviations of the left- and right-handed couplings of the top quark to the Z boson

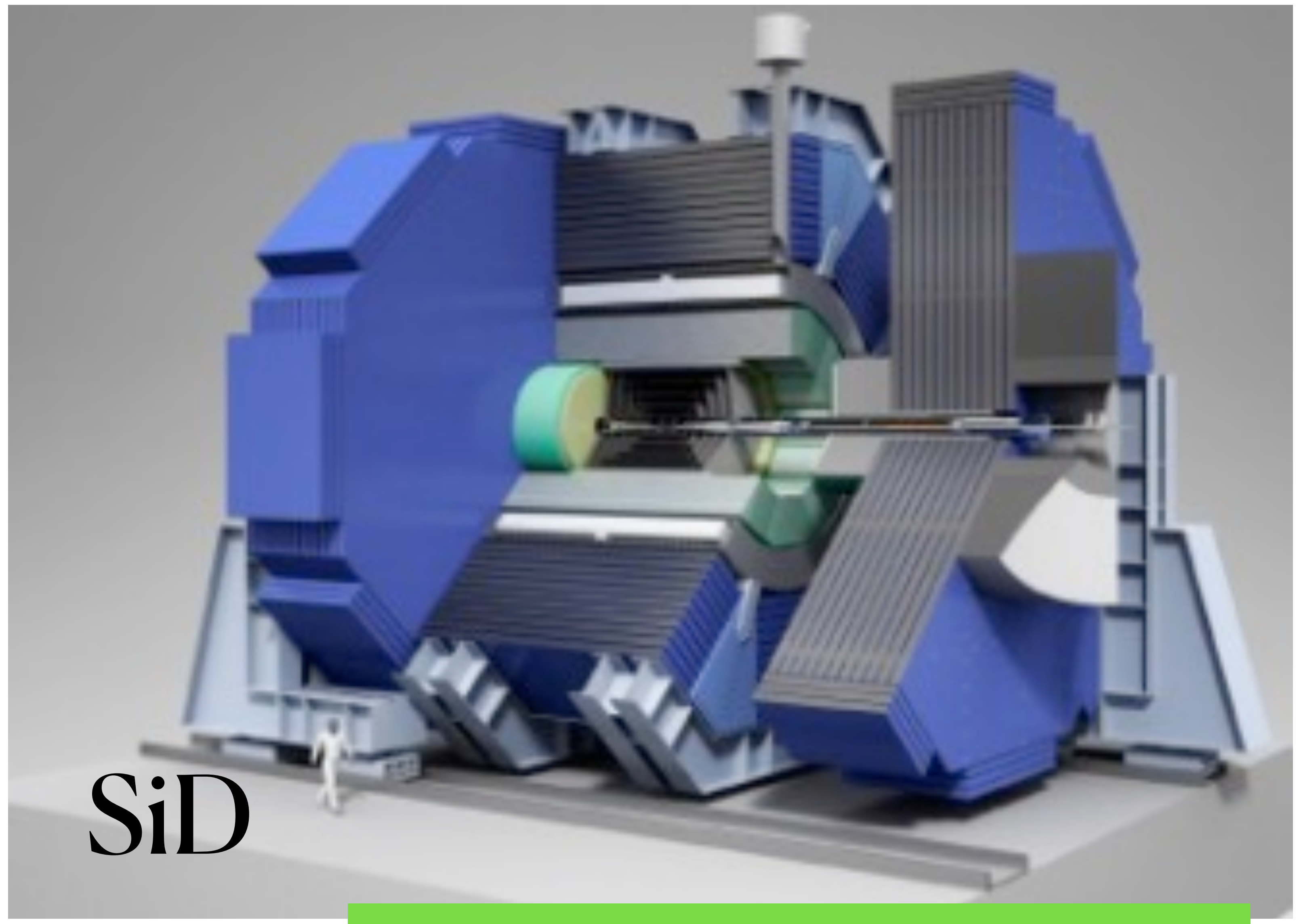


- Beam polarisation can probe the SM/BSM chiral structure.
  - **SM**: Z and γ differ in couplings to L-and R-handed fermions.
  - **BSM**: unknown chiral structure from e.g. Z′!
    - modify L and R **t** and **b** couplings.

ILC Detectors

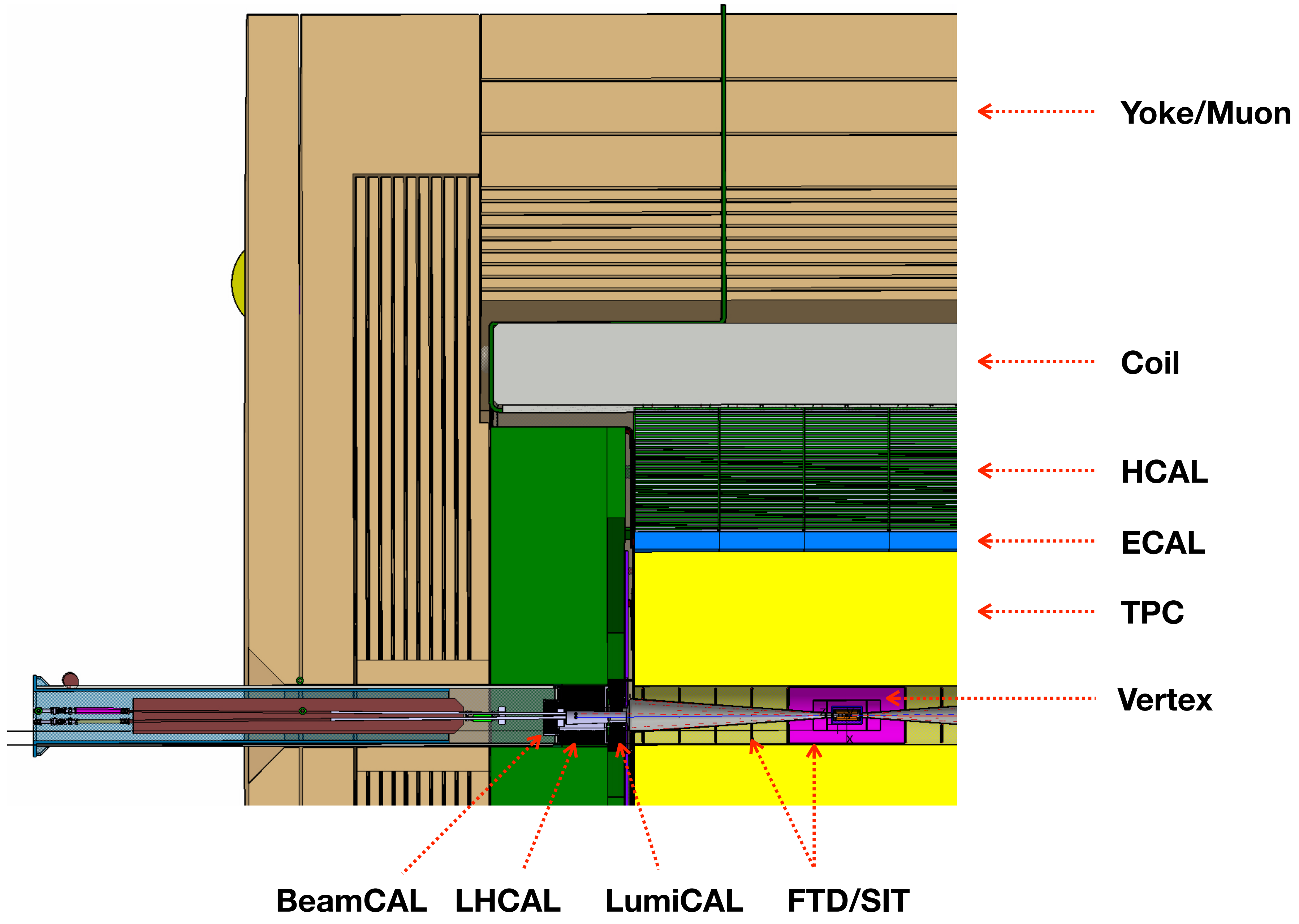


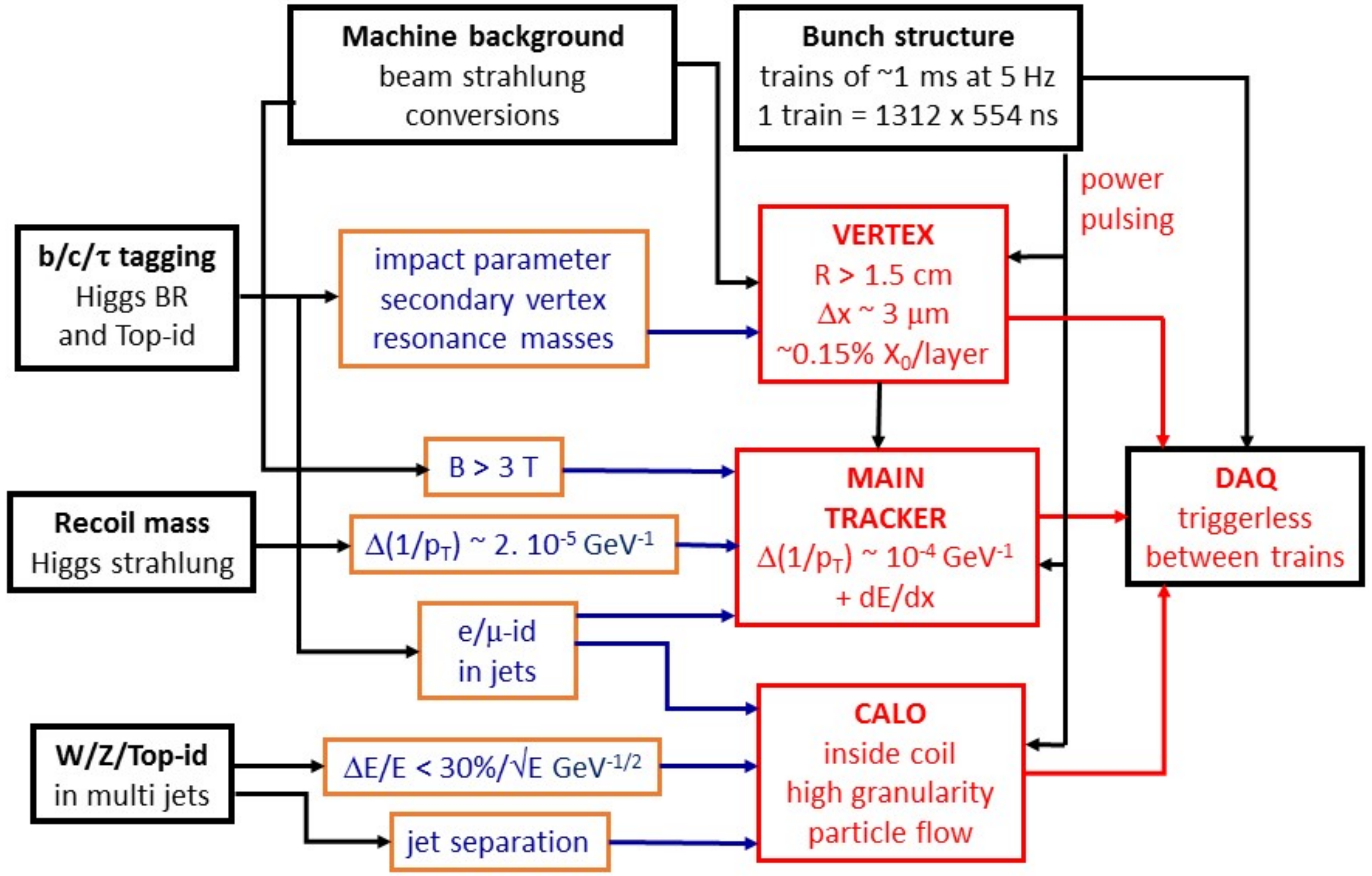
Central tracking with TPC



Highly granular calorimeters

ILD Interim Design Report
arXiv:2003.01116

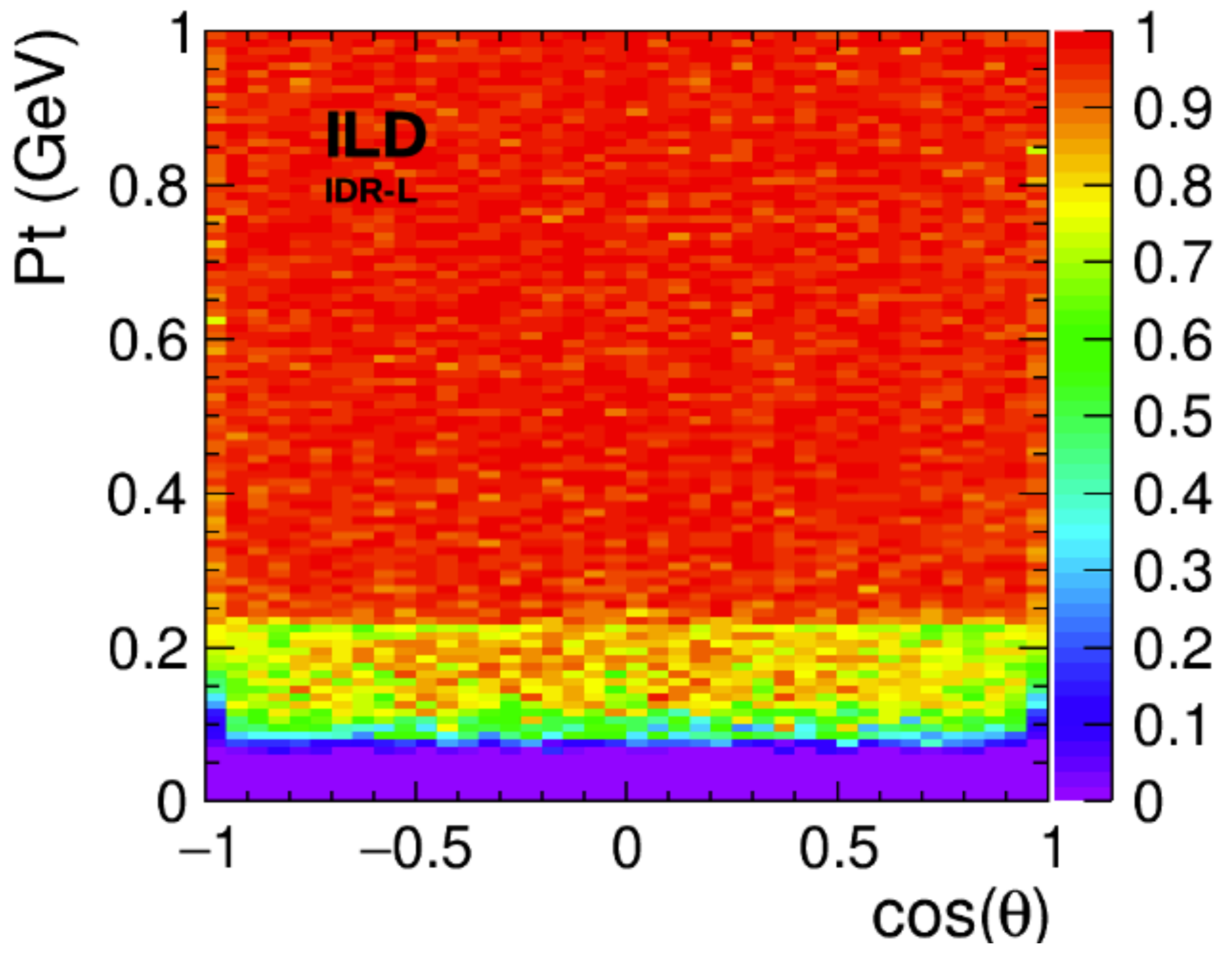




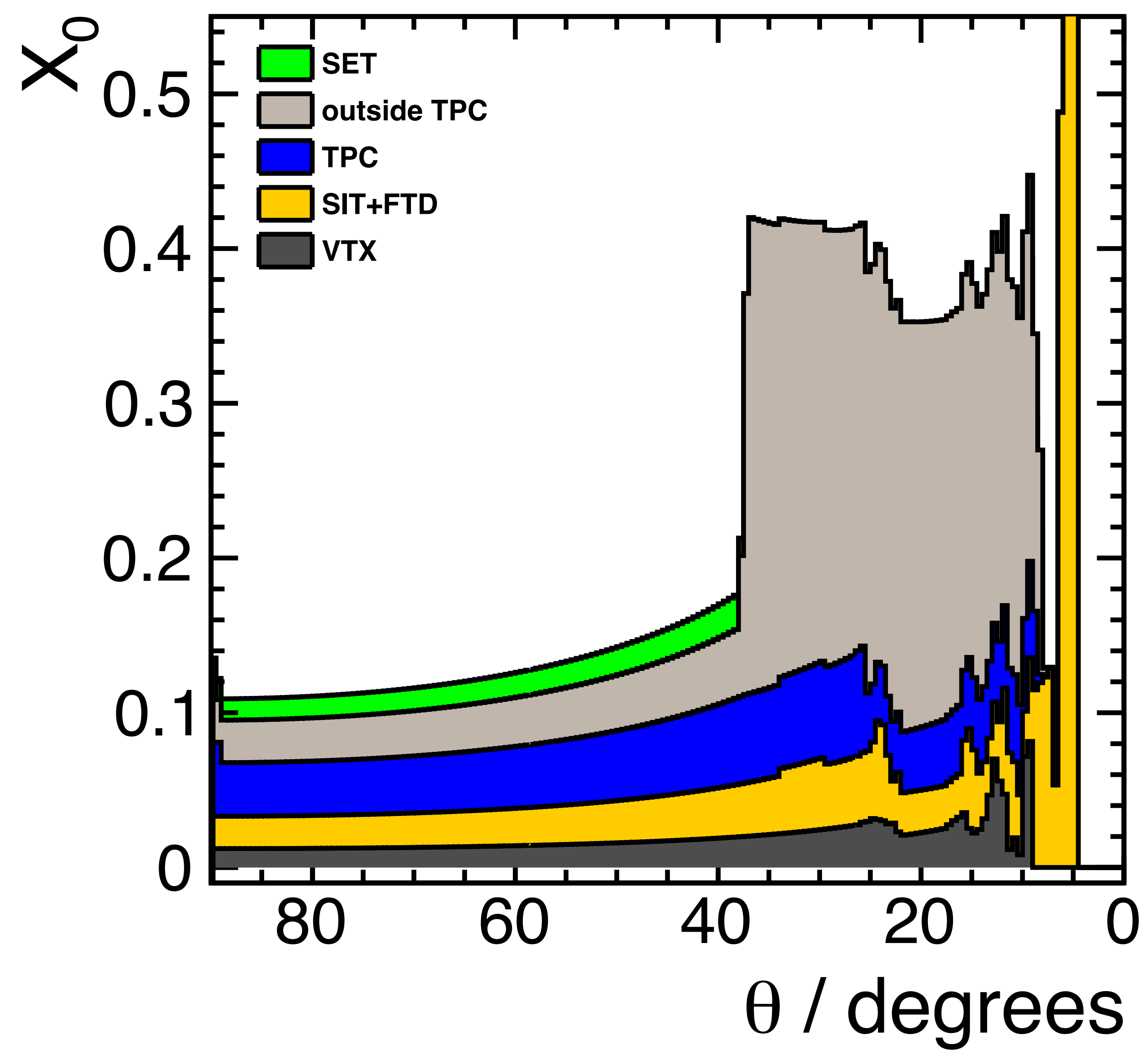
*The time structure of the accelerator also allows for a **gaseous main tracker** to be used (like the **TPC** of ILD) with 4-5% dE/dx resolution, sufficient for good kaon and proton ID.*

Detector Performance

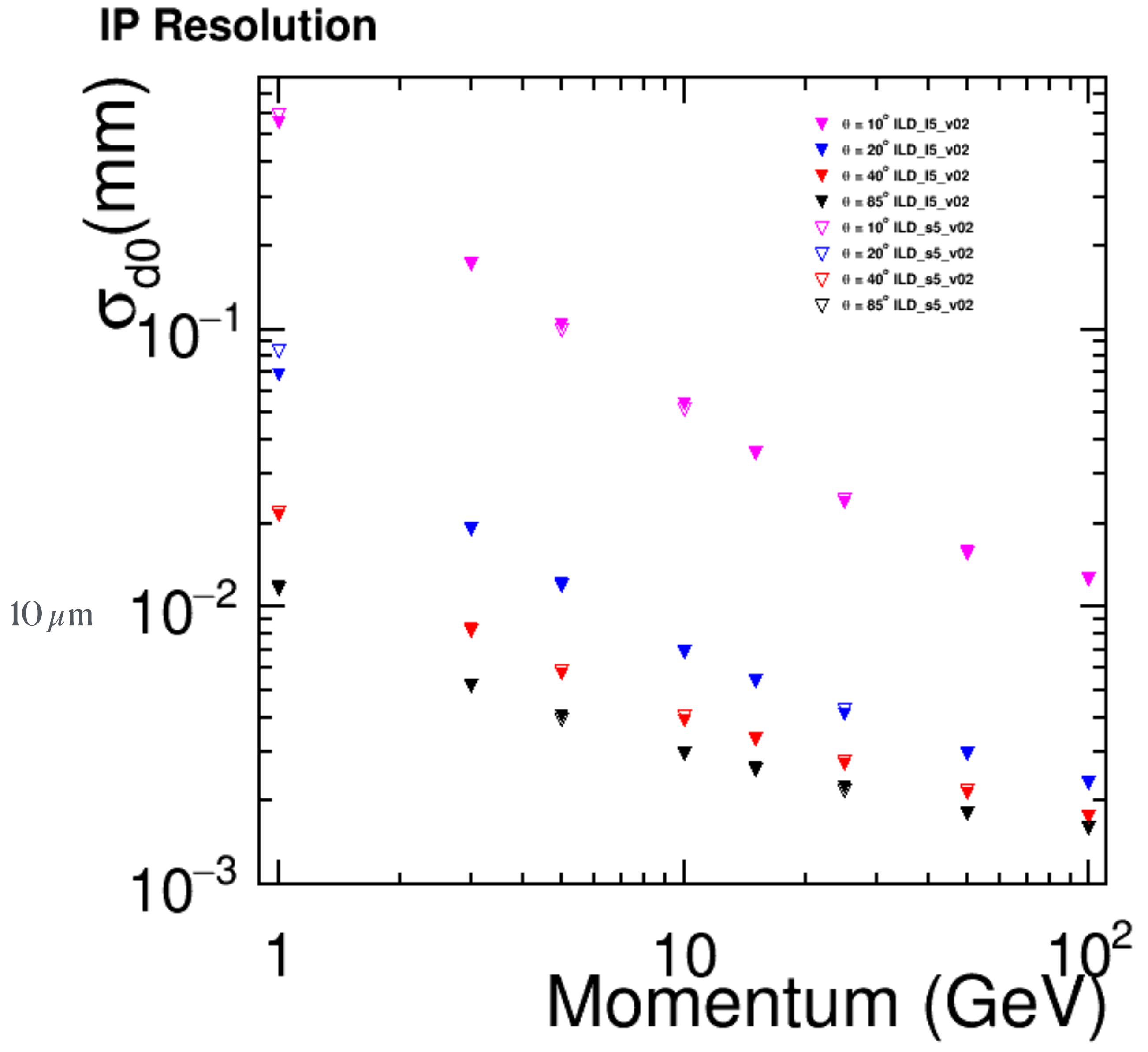
ILD Interim Design Report
arXiv:2003.01116



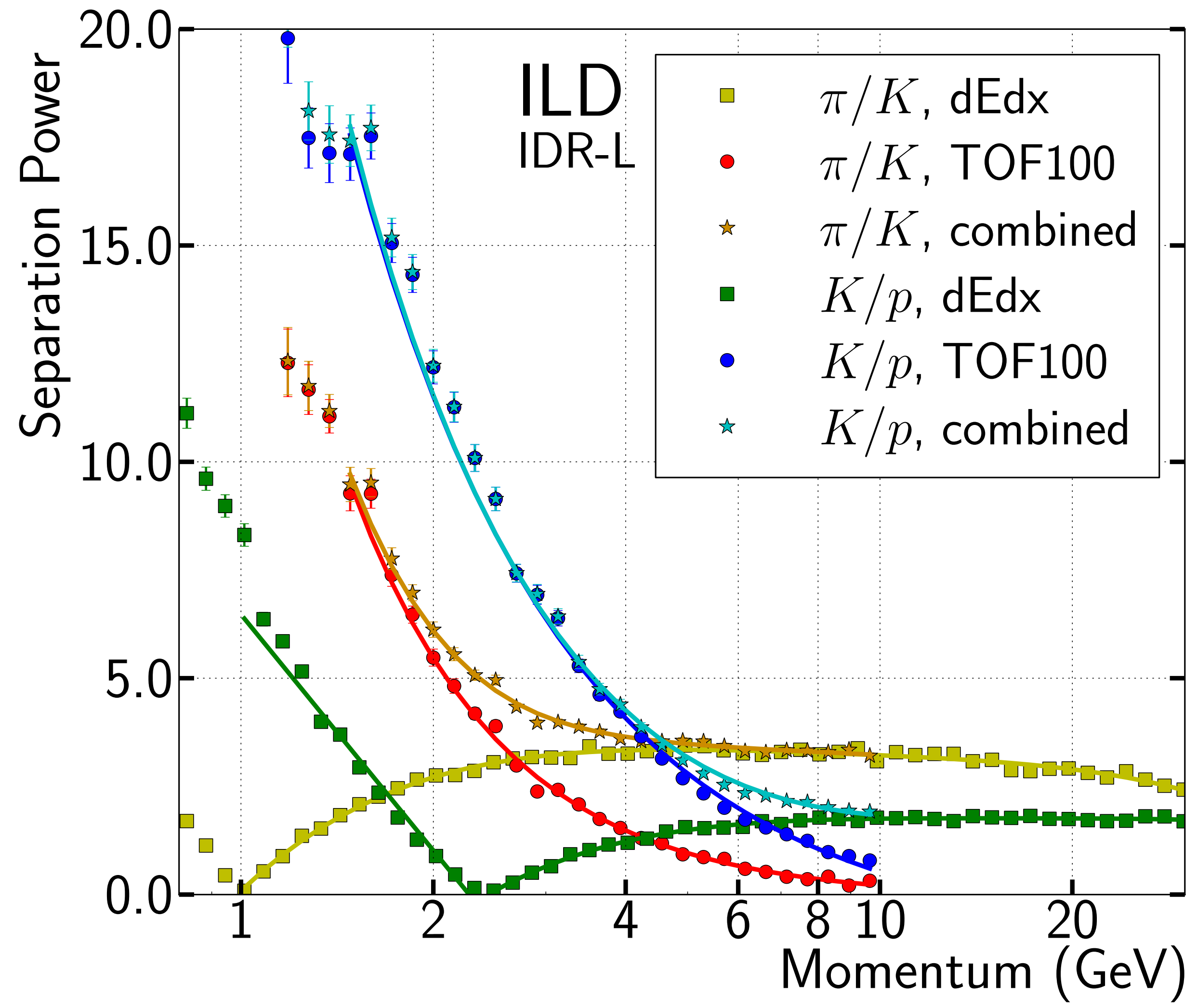
- Tracking, efficient above 200 MeV (good for flavour).
- Momentum resolution 1/3 x SLD.



- Low radiation length tracker.
- Hermeticity Θ_{min} ~ 5 mrad.



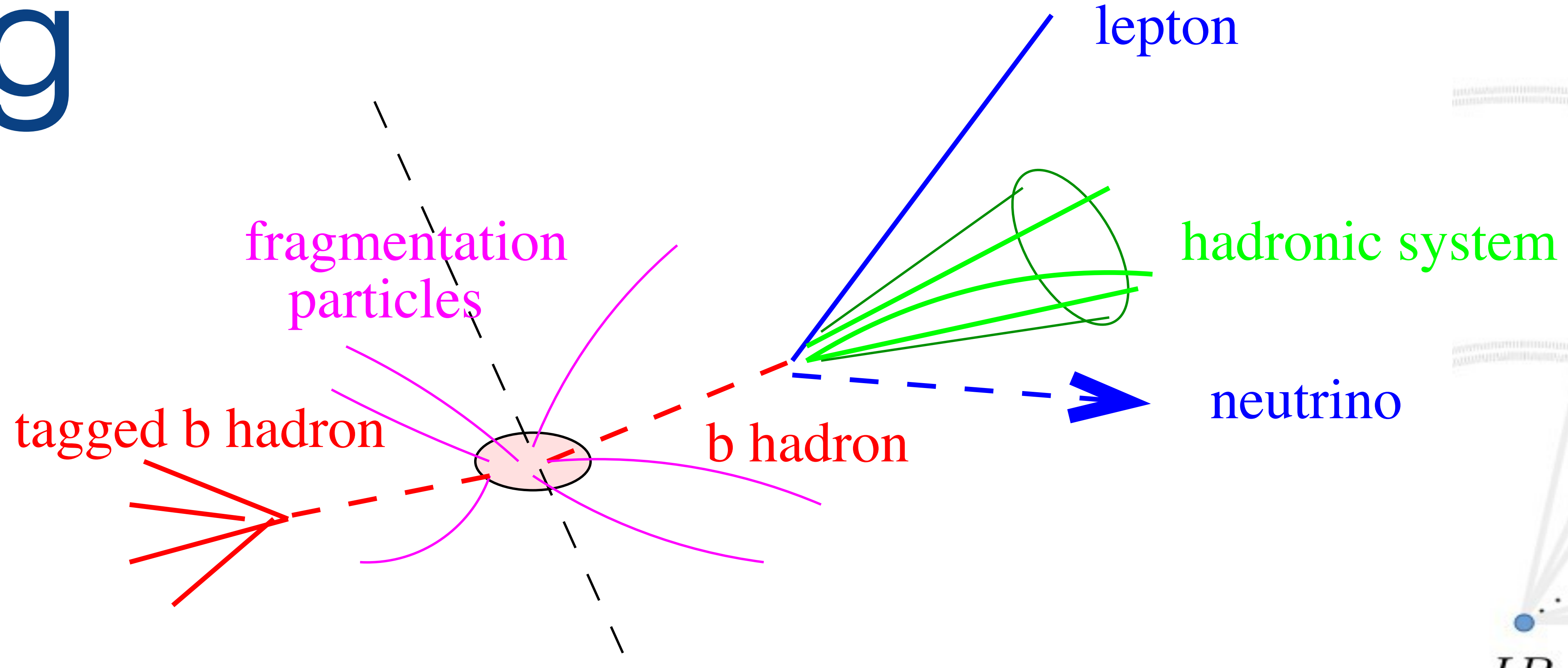
- Impact parameter resolution.
- 1/3 x LEP.

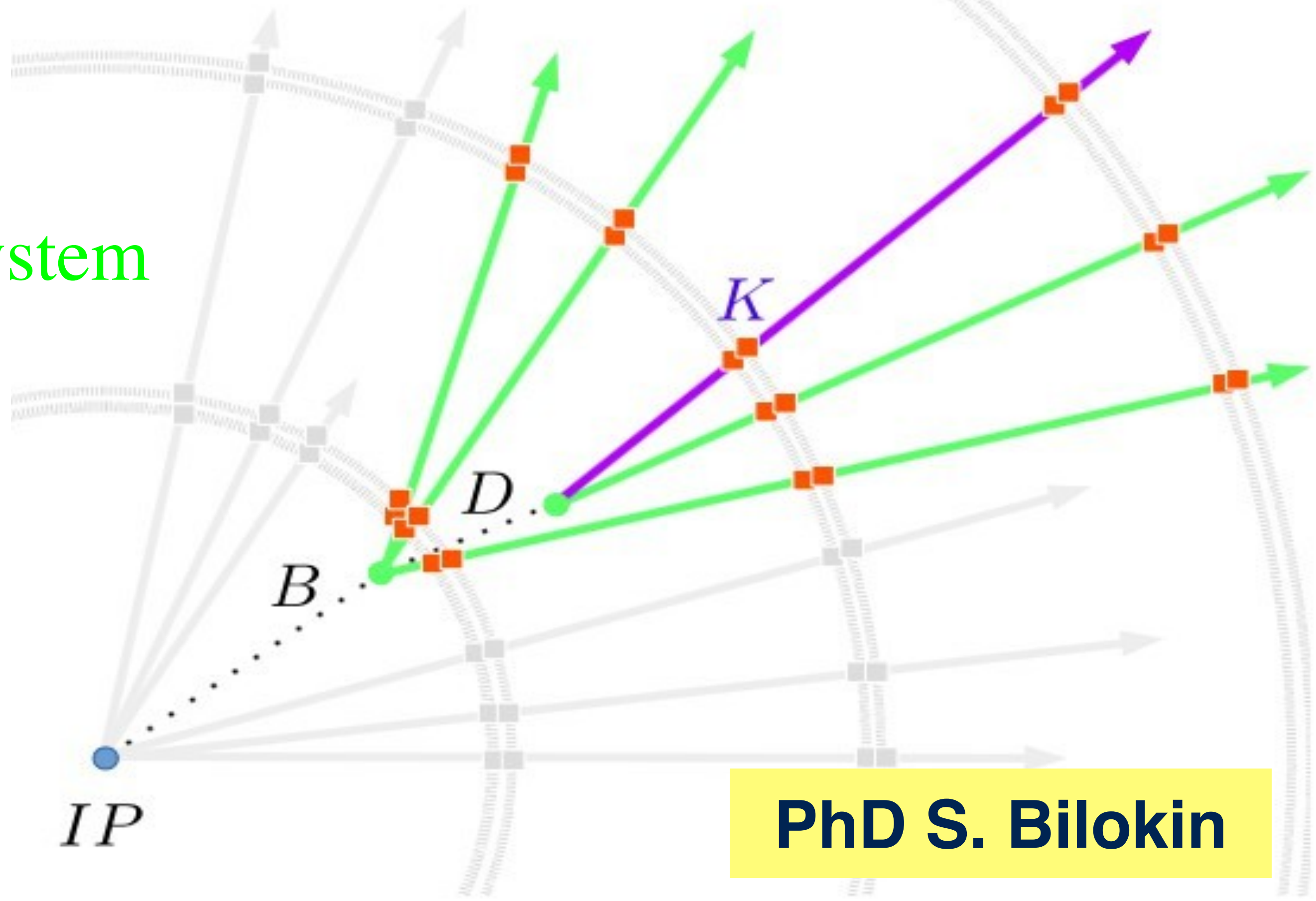


- dE/dx (TPC) + ToF particle ID.
- Particle flow for reconstruction.

b, c, τ -tagging

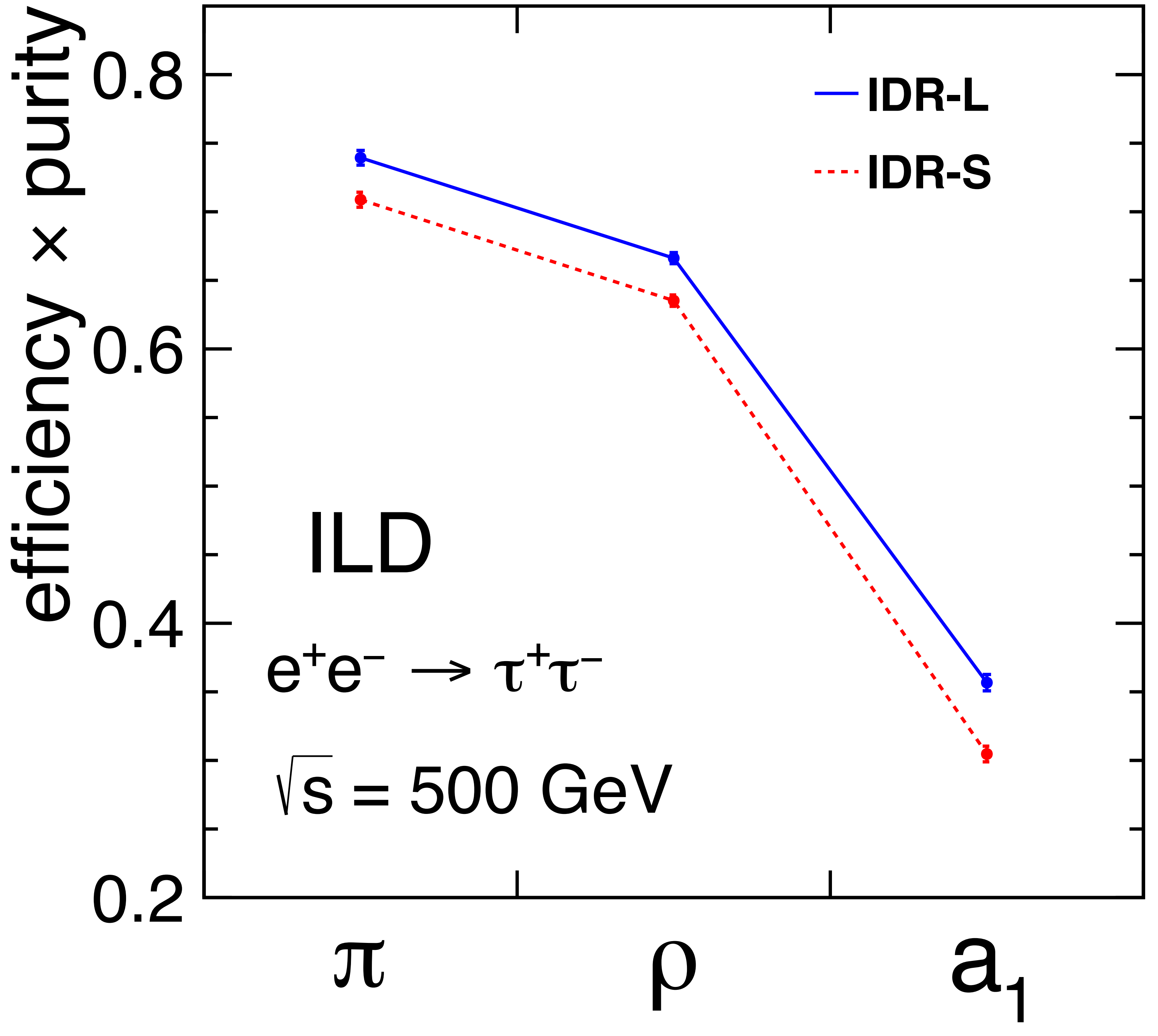
- Production in separate hemispheres.
  - Charge measurements based on vertex and particle ID information.
- Excellent flavour tagging hinges not only on the **vertex detector** performance, but also from the **nano beam spot, 5nm** in the vertical, few 100nm in the horizontal.

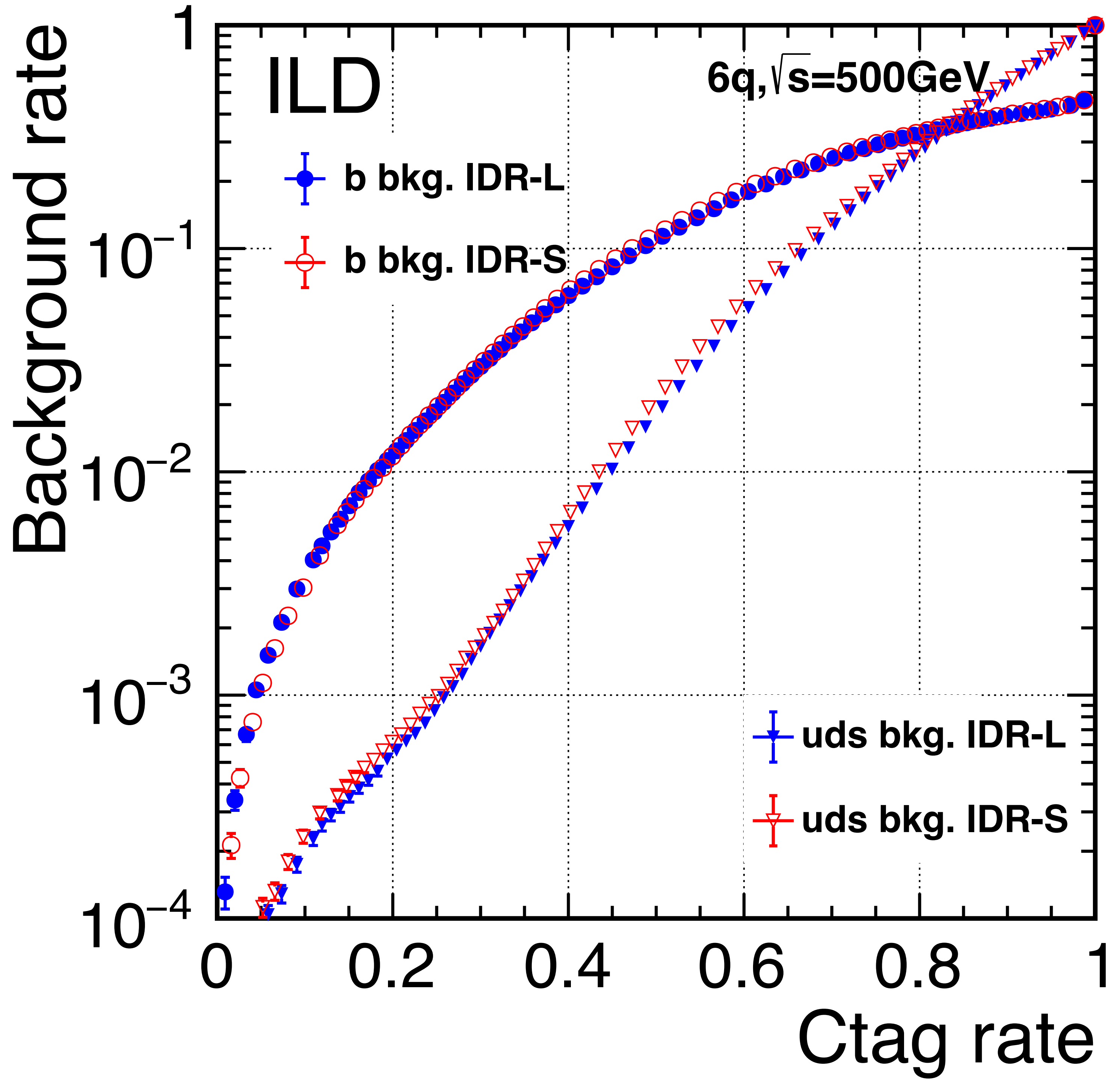


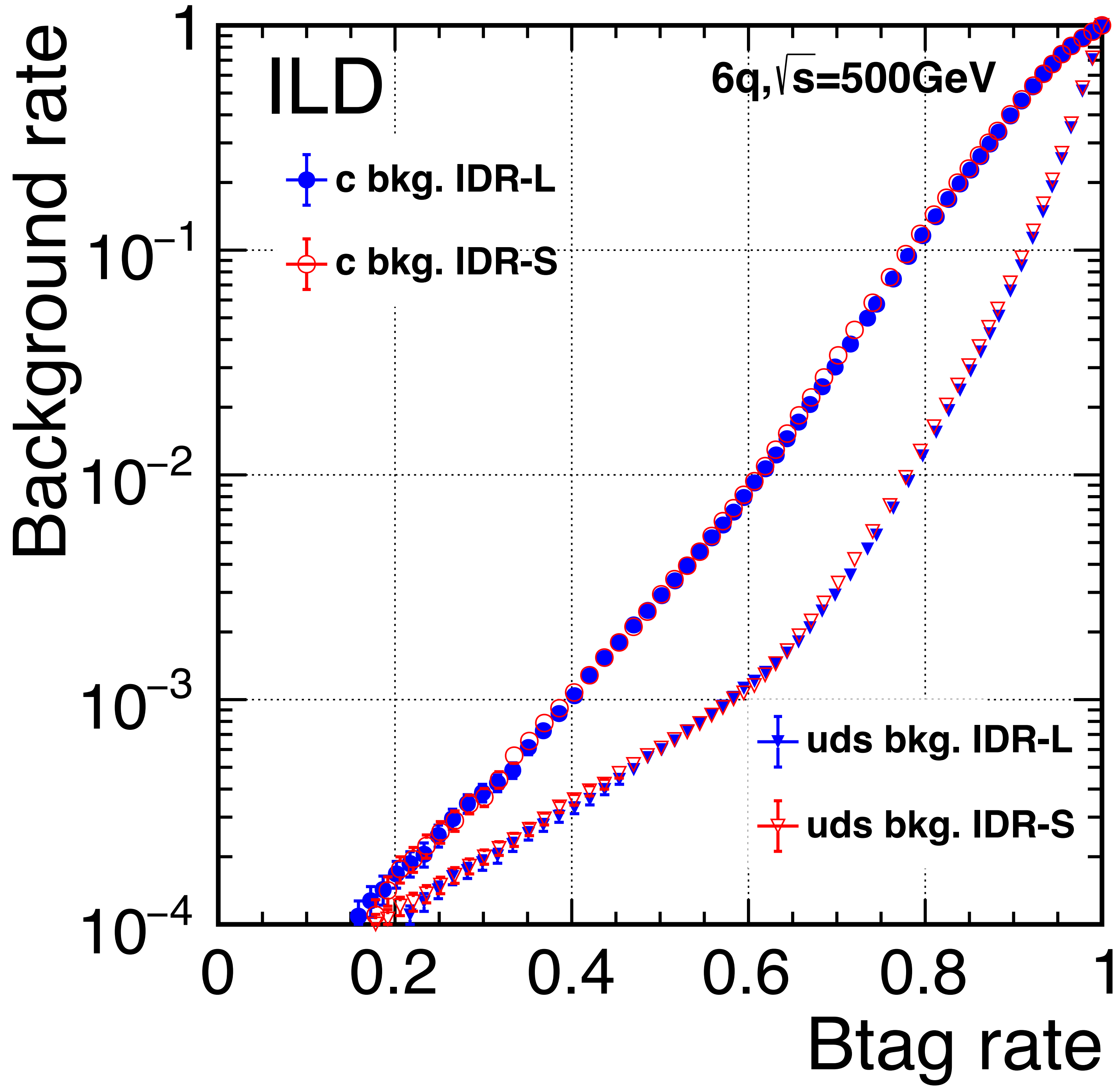


PhD S. Bilokin

ILD Interim Design Report
arXiv:2003.01116





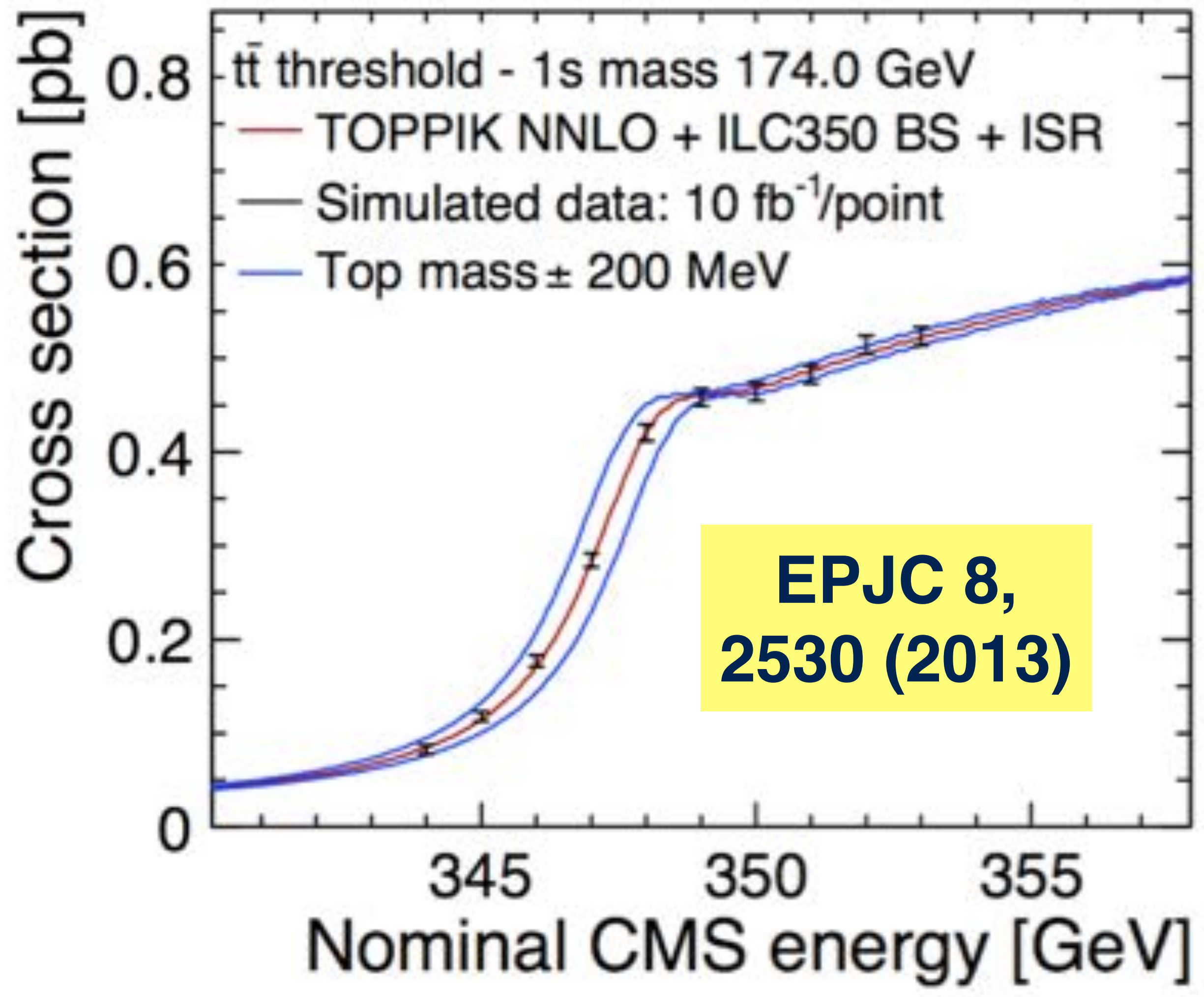


Top mass measurement

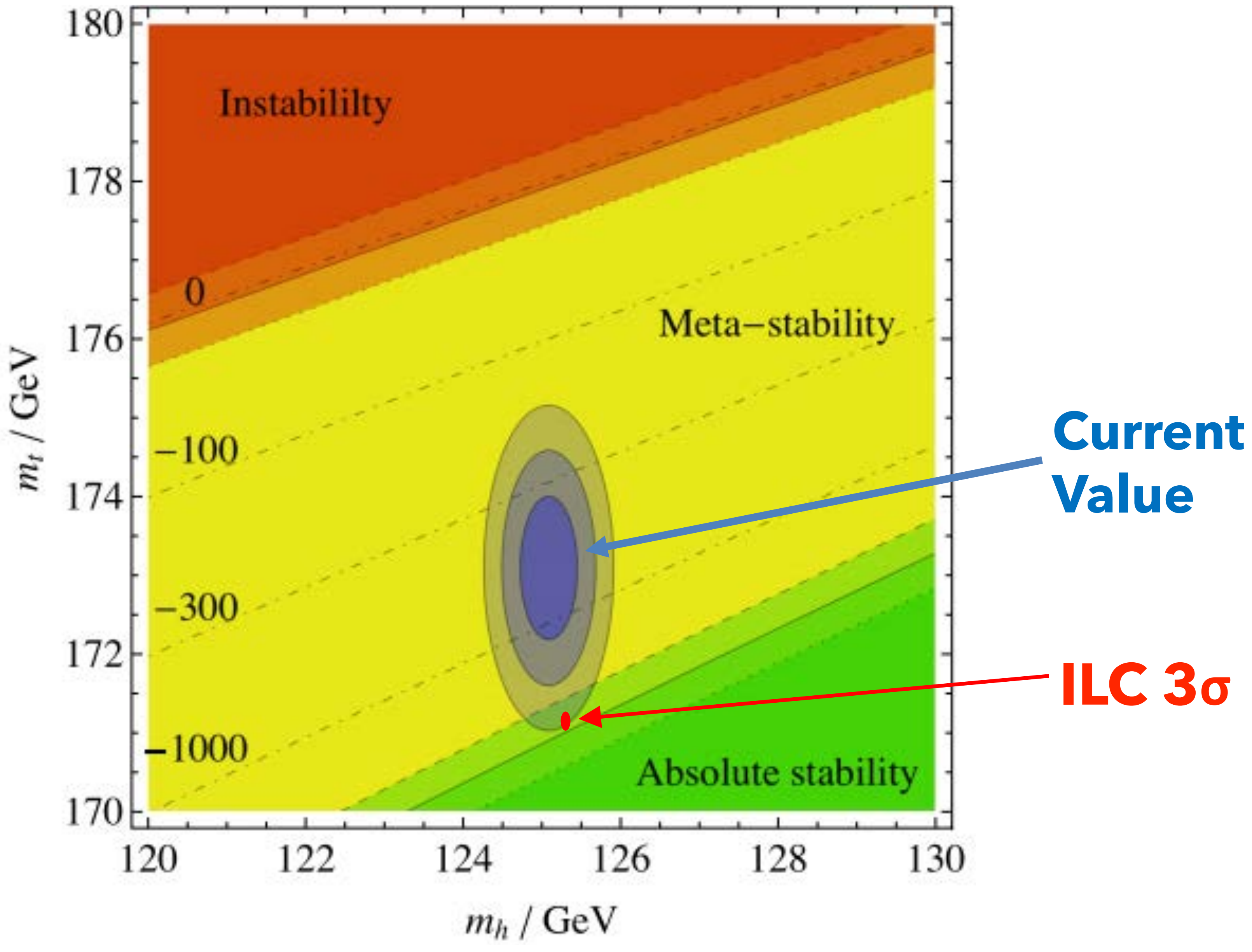
- The top quark mass is a key SM parameter for precision tests at ILC.
  - Mass best determined via cross-section scans.

- **FCNC** expected sensitivity: 95% CL BR($t \to Hc$)~3×10^{-5} and BR($t \to \gamma c$) ~ 10^{-5} (*Can we probe direct CP quantities?*).

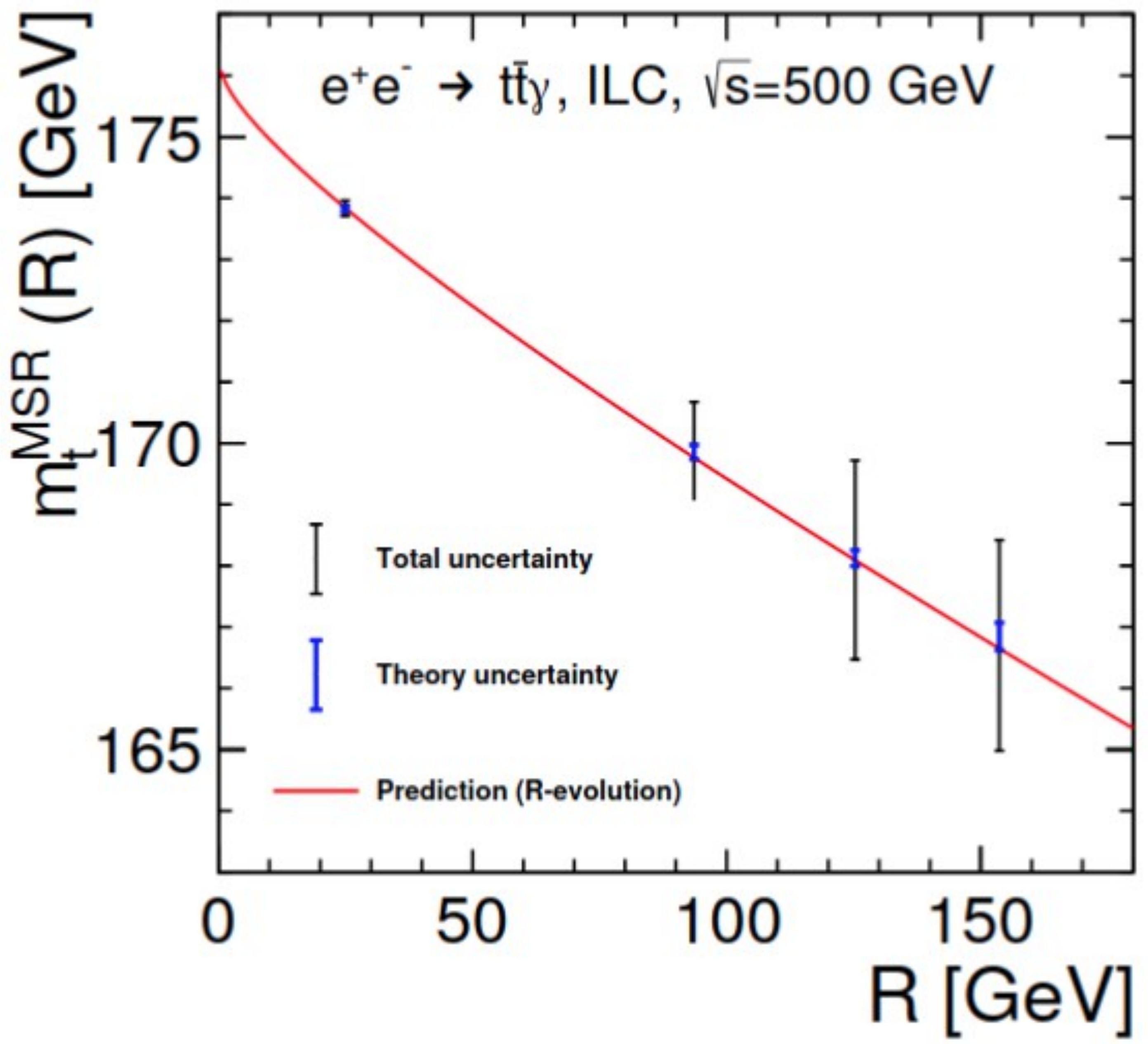
Cross section scan method

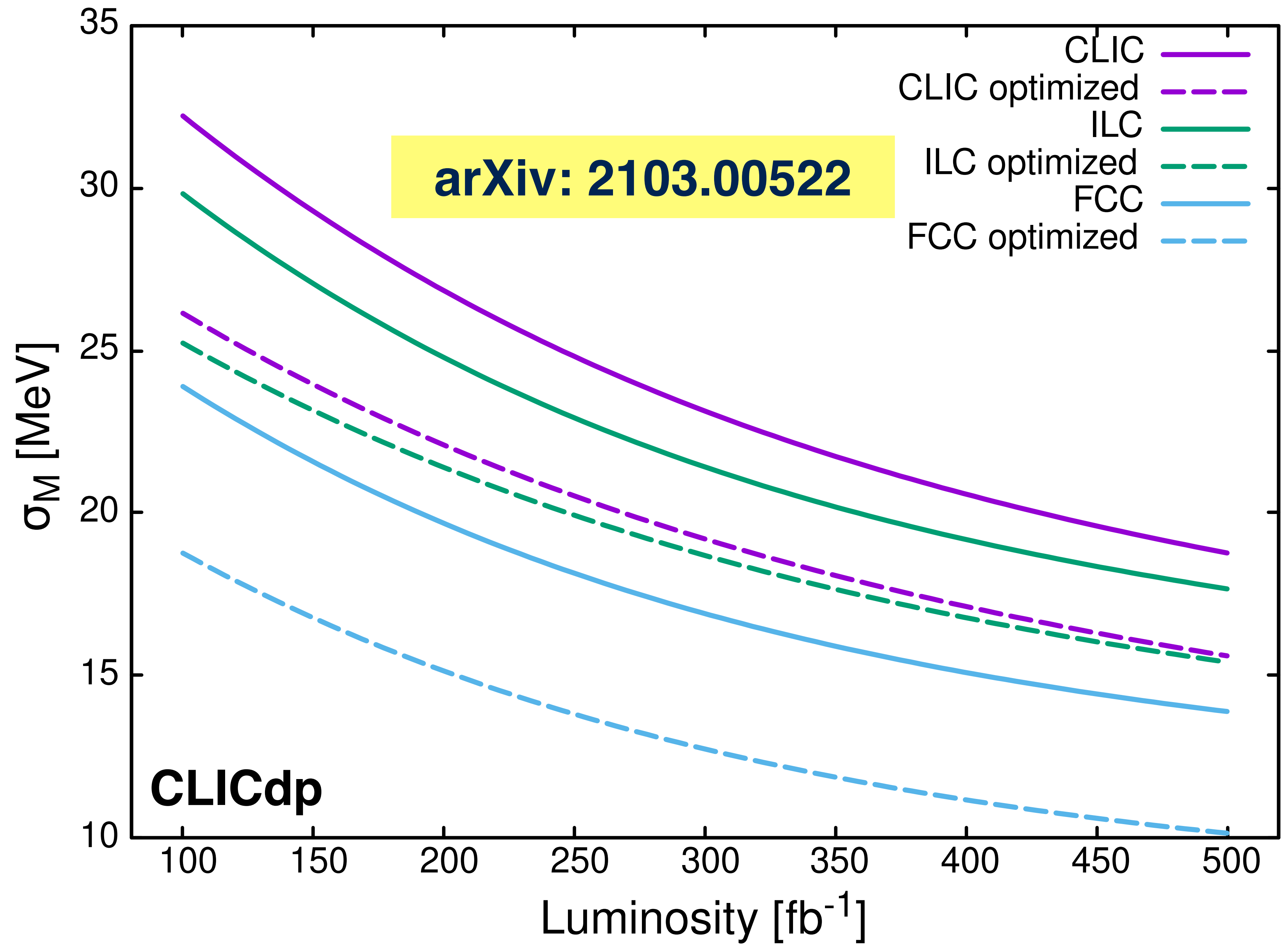


PRD 97, 116012 (2018)



ISR running top mass method

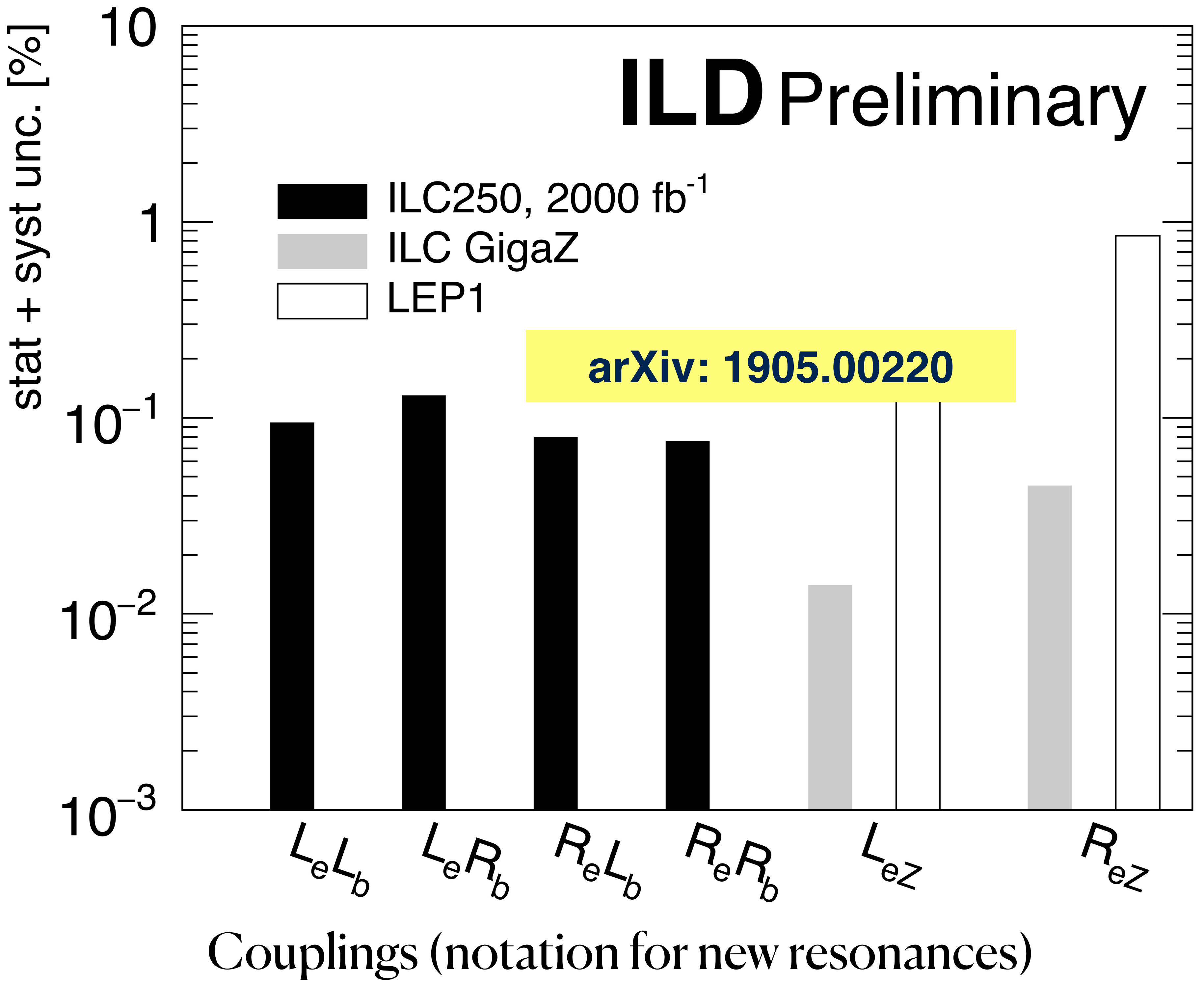




$e_L e_R \rightarrow$ tt, bb

R. Pöschl, EPS 2021
arXiv: 1709.04289

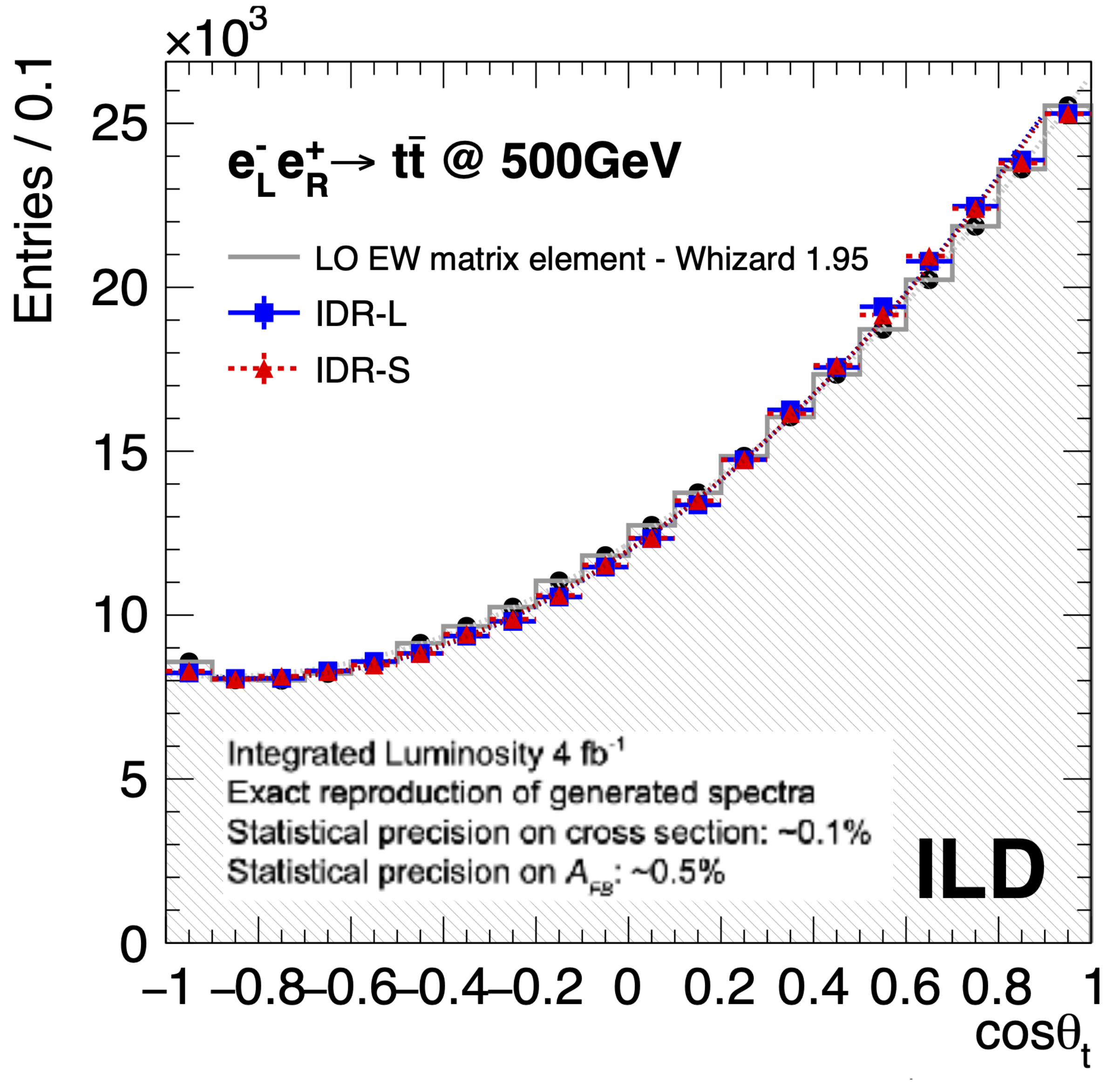
- Polarised beams allow to separate the 4 different chirality combinations LeLb, LeRb, ReRb, ReLb.
- The 4 modes can be differently influenced by NP.

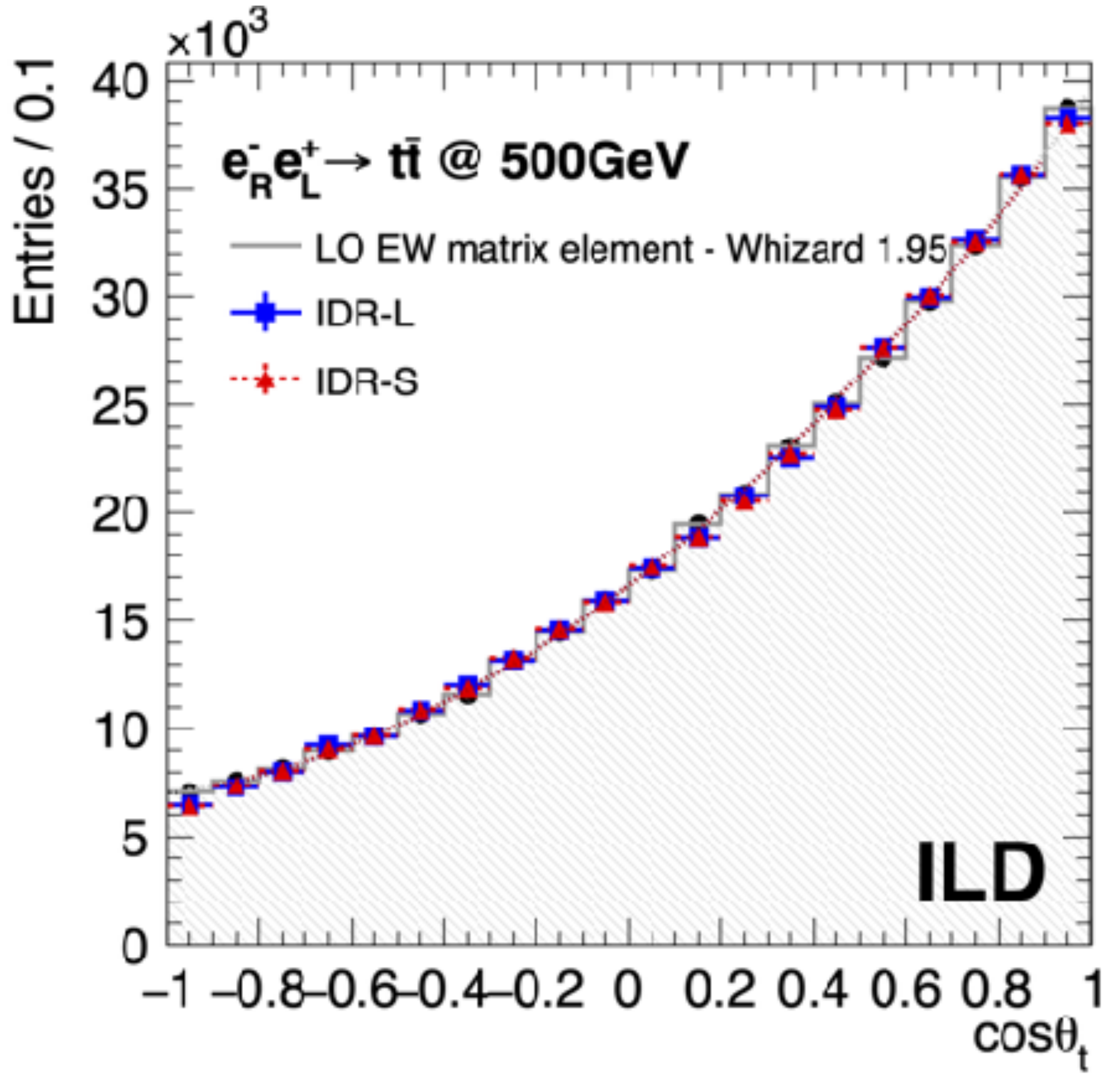


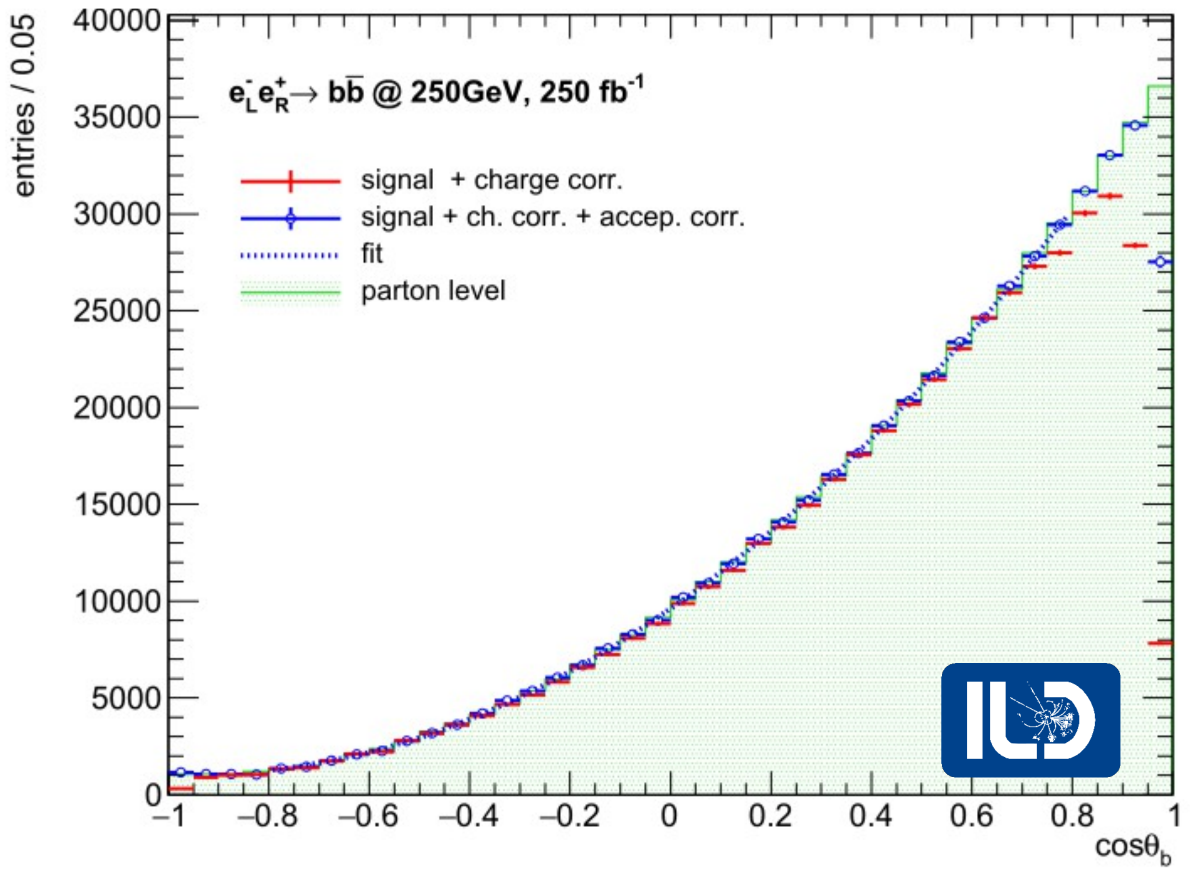
Precisions expected on coefficients of helicity amplitudes defined (here expressed as $I_e J_b$ with $I,J = L,R$) and the left and right-handed couplings of the q quark to the Z as expected from a running of the ILC on tne Z-Pole

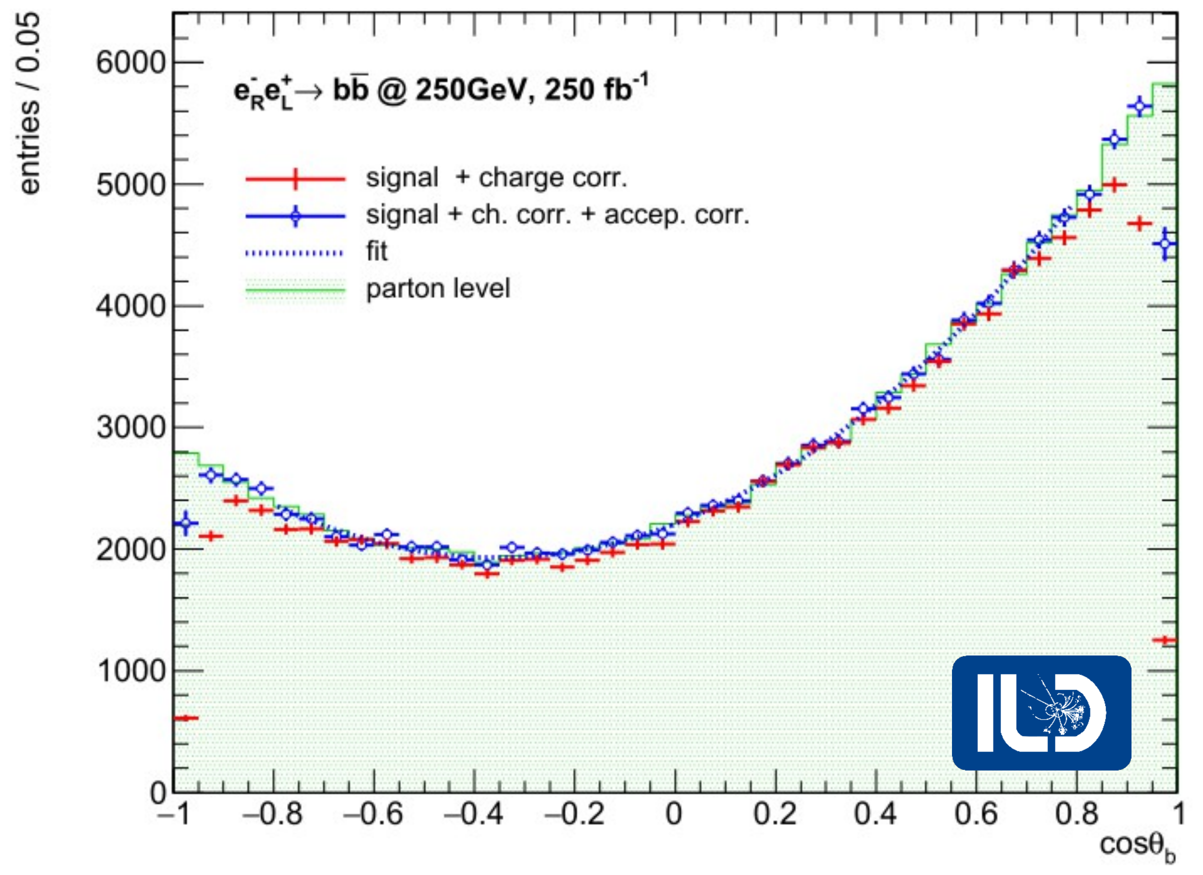
$$\text{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w} BWZ + \sum_{Z'} \frac{LeZ'LbZ'}{s^2wc^2w} BWZ'$$

ILC250 SM GigaZ New resonances





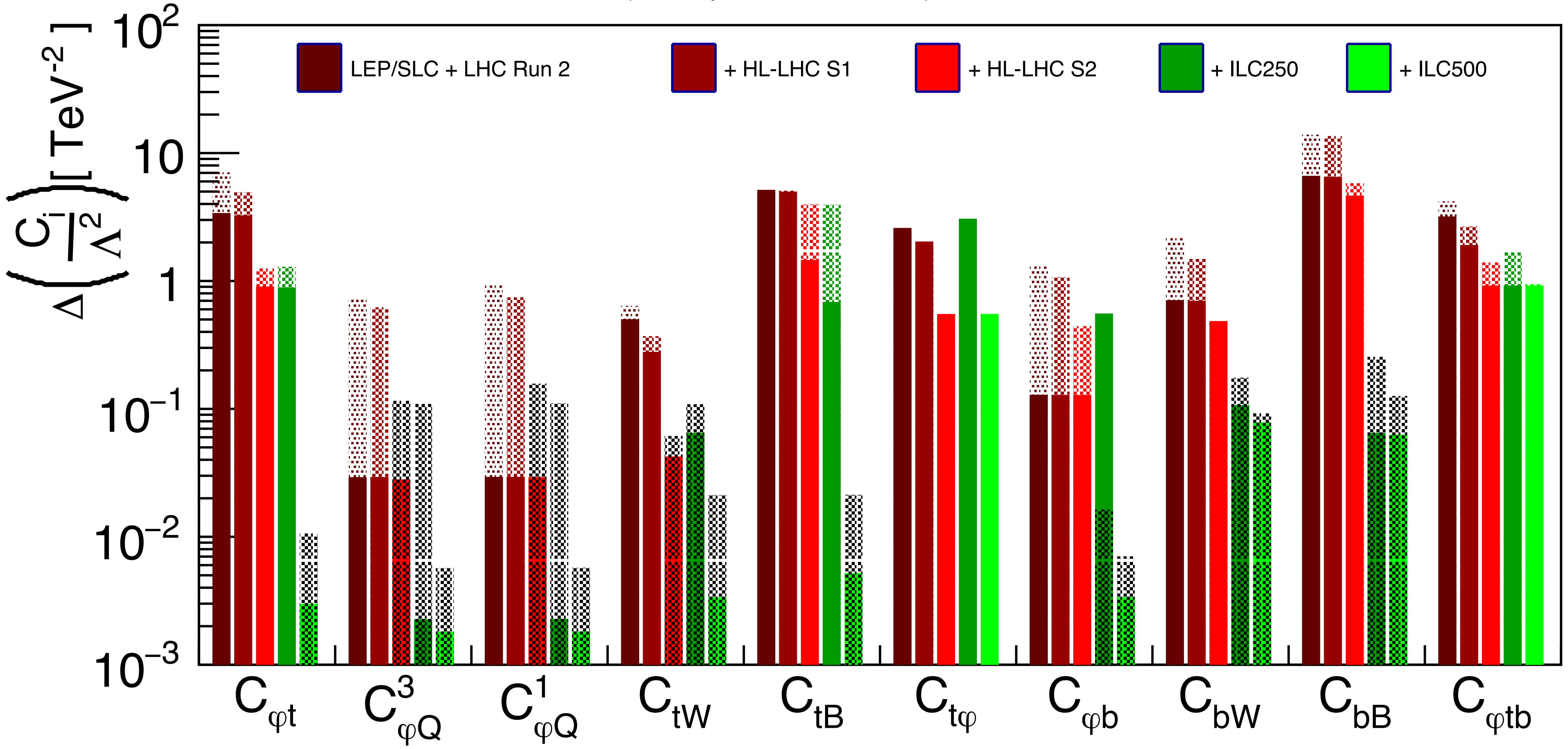




Electroweak top couplings & top Higgs couplings

- The two-fermion NP operators that affect top and bottom-quark interactions with vector, tensor, or scalar Lorentz structures can be well constrained with 500 GeV operation.

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + \mathcal{O}\left(\Lambda^{-4}\right)$$

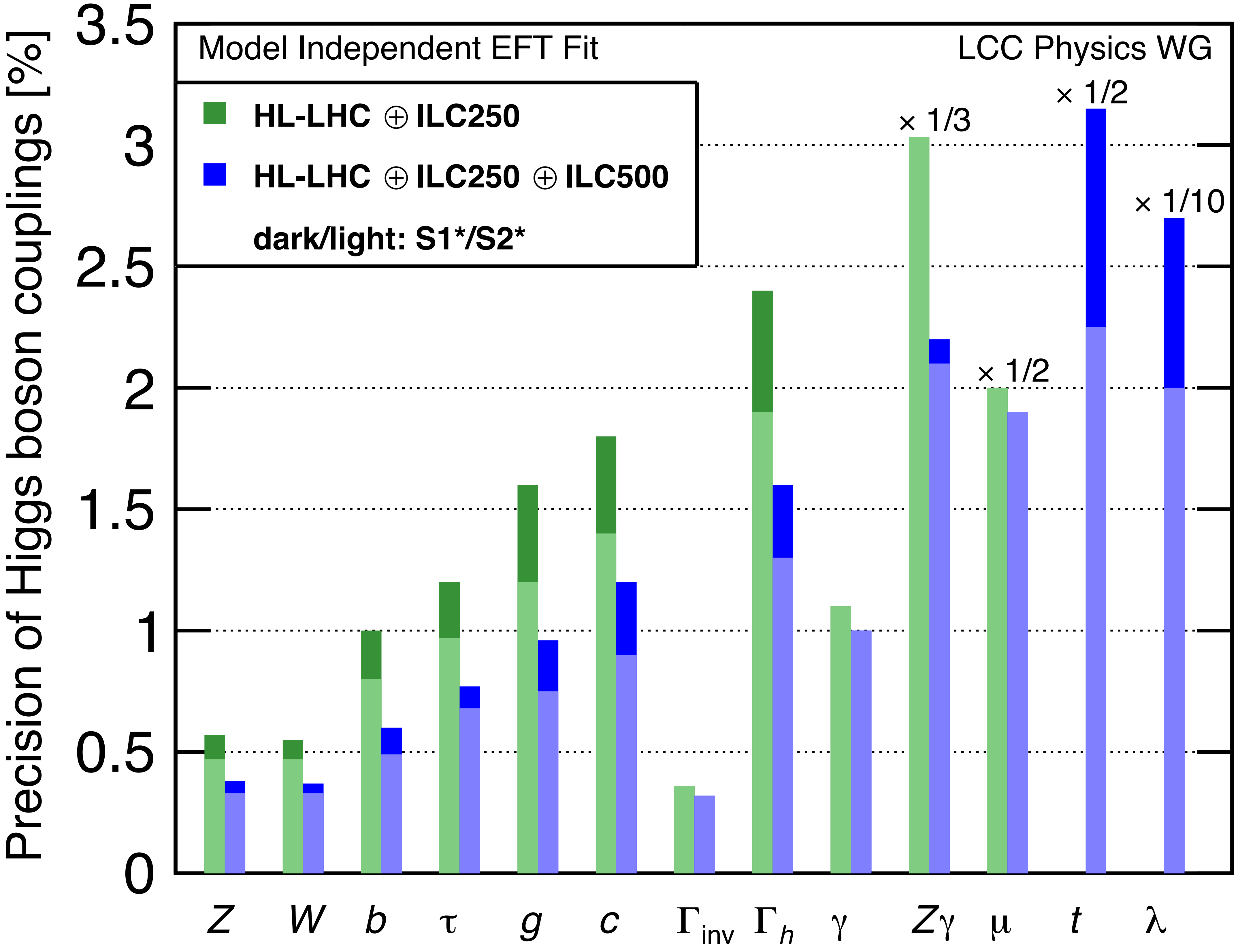


$$O^1_{\varphi Q} \equiv \frac{y_t^2}{2}\ \bar{q}\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi,$$
$$O^3_{\varphi Q} \equiv \frac{y_t^2}{2}\ \bar{q}\tau^I\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi,$$
$$O_{\varphi u} \equiv \frac{y_t^2}{2}\ \bar{u}\gamma^\mu u\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi,$$
$$O_{\varphi d} \equiv \frac{y_t^2}{2}\ \bar{d}\gamma^\mu d\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi,$$
$$O_{\varphi ud} \equiv \frac{y_t^2}{2}\ \bar{u}\gamma^\mu d\ \ \varphi^T\epsilon i D_\mu\varphi,$$

$$O_{uW} \equiv y_t g_W\ \bar{q}\tau^I\sigma^{\mu\nu}u\ \ \epsilon\varphi^* W^I_{\mu\nu},$$
$$O_{dW} \equiv y_t g_W\ \bar{q}\tau^I\sigma^{\mu\nu}d\ \ \varphi W^I_{\mu\nu},$$
$$O_{uB} \equiv y_t g_Y\ \bar{q}\sigma^{\mu\nu}u\ \ \varphi B_{\mu\nu},$$
$$O_{dB} \equiv y_t g_Y\ \bar{q}\sigma^{\mu\nu}d\ \ \epsilon\varphi^* B_{\mu\nu},$$

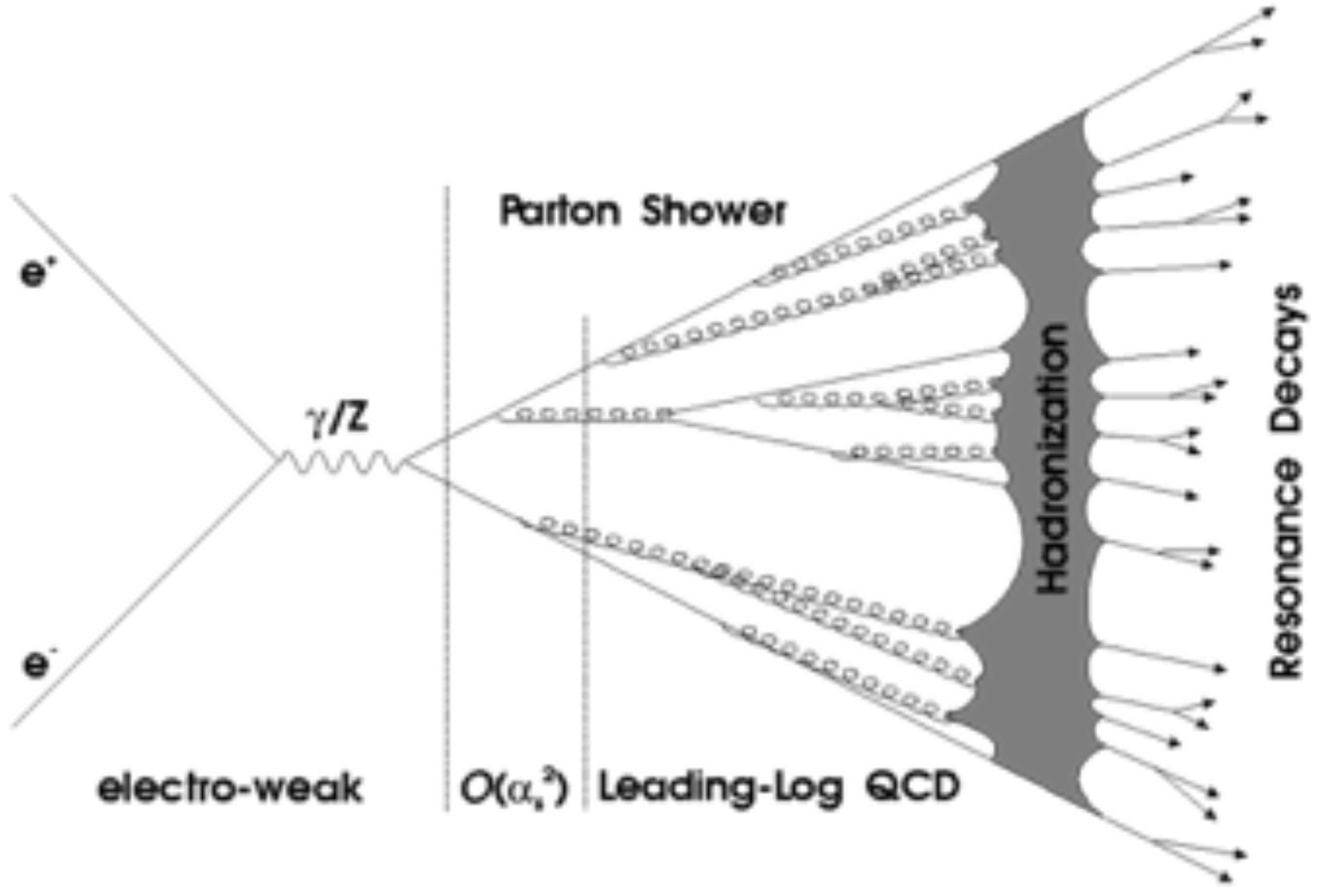
$$O_{u\varphi} \equiv \bar{q}u\ \ \epsilon\varphi^*\ \varphi^\dagger\varphi,$$
$$O_{d\varphi} \equiv \bar{q}d\ \ \epsilon\varphi^*\ \varphi^\dagger\varphi,$$

- Excellent model independent top Higgs coupling precision through ttH production.

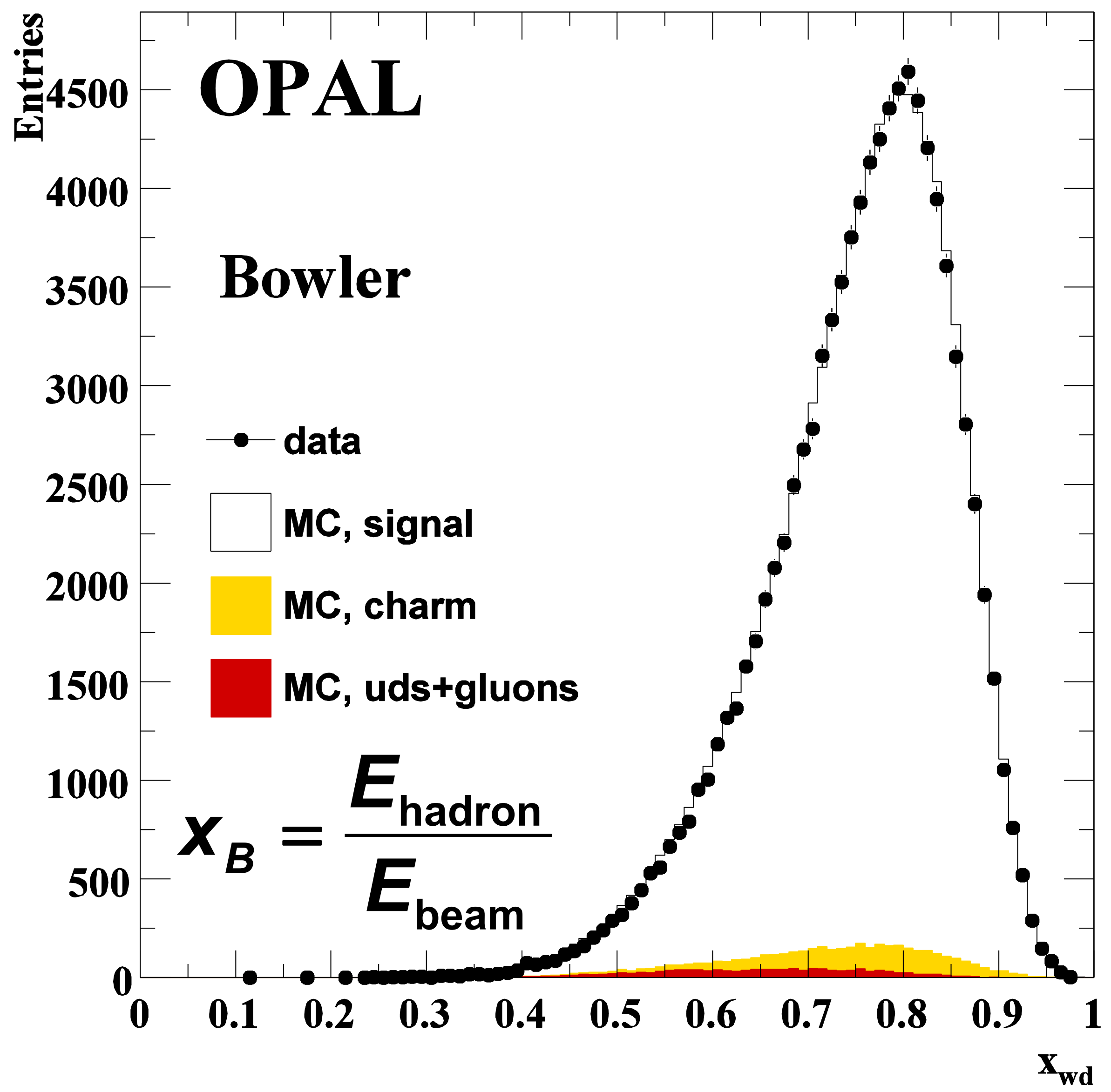


b-physics at Z (a look back at LEP)

$R_b = 0.21629 \pm 0.00066$



Phys.Lett.B395:373-387,1997



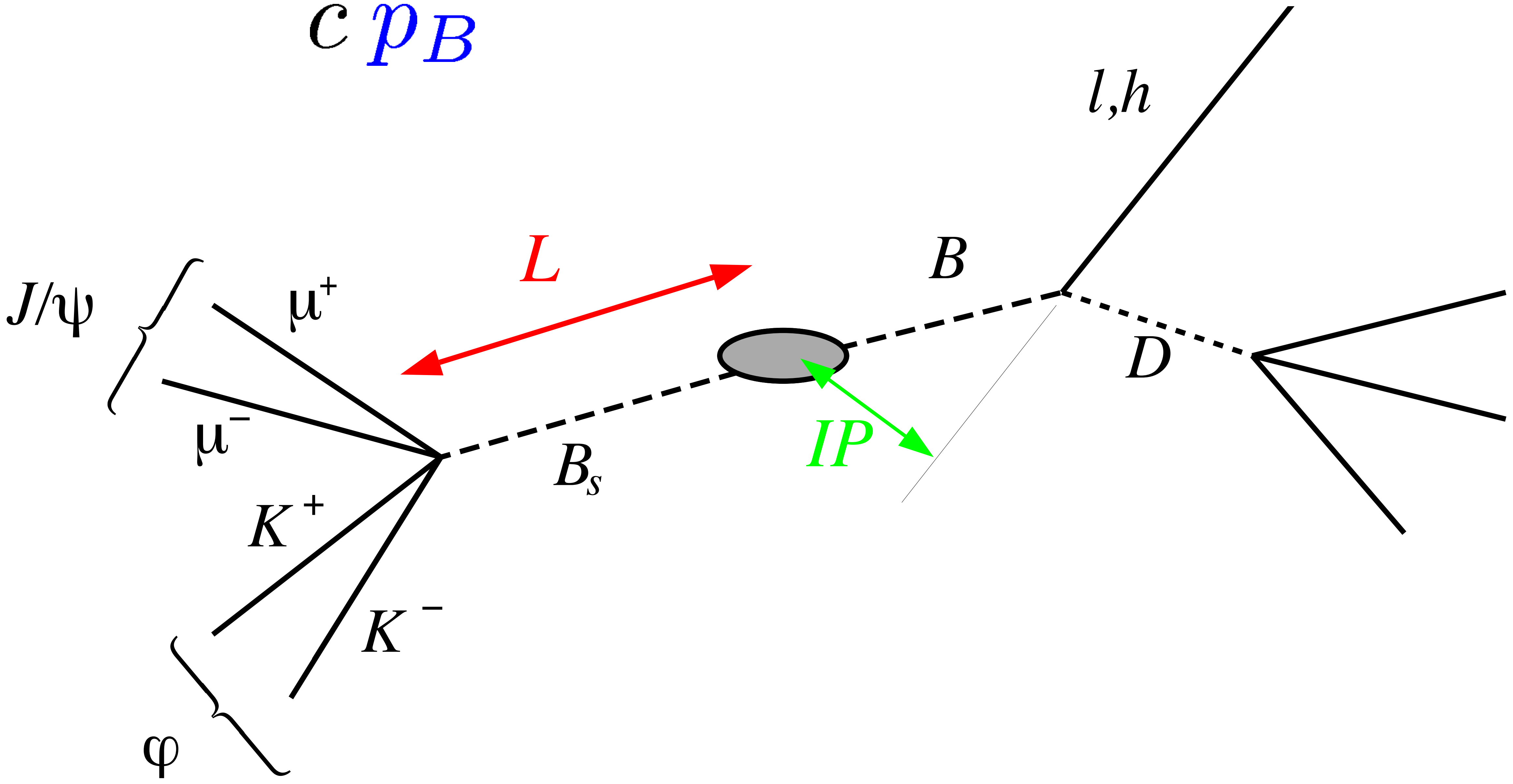
- Large boost of b hadrons ($\langle P_B \rangle \sim 32$ GeV/c).
- Very well separated b (in opposite hemisphere).
- b hadron energy from rest of event → good calorimetry and tracking (LEP/SLD ~ 3-5 GeV resolution).

nB	GigaZ 100 fb^{-1}	GigaZ+ 1 ab^{-1}	Belle II 50 ab^{-1}	LHCb
B^+	$7 . 10^8$	$7 . 10^9$	$5 . 10^{10}$	$3 . 10^{13}$
B^0	$7 . 10^8$	$7 . 10^9$	$5 . 10^{10}$	$3 . 10^{13}$
B_s	$3 . 10^8$	$3 . 10^9$	$6 . 10^8$	$8 . 10^{12}$
b-baryon	$1 . 10^8$	$1 . 10^9$		$1 . 10^{12}$
Λ_b	$1 . 10^8$	$1 . 10^9$		$1 . 10^{12}$

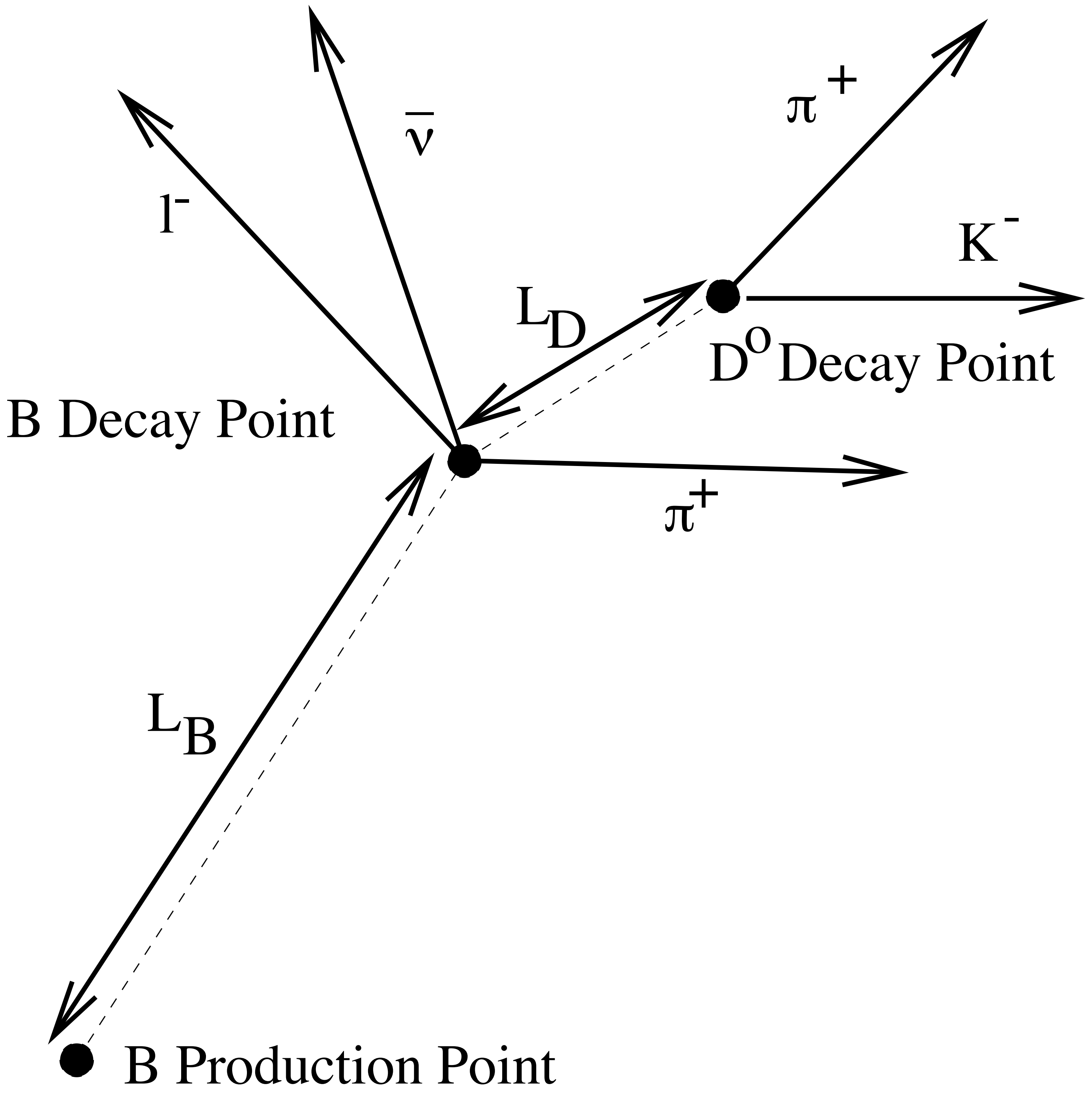
GigaZ+ for reference only

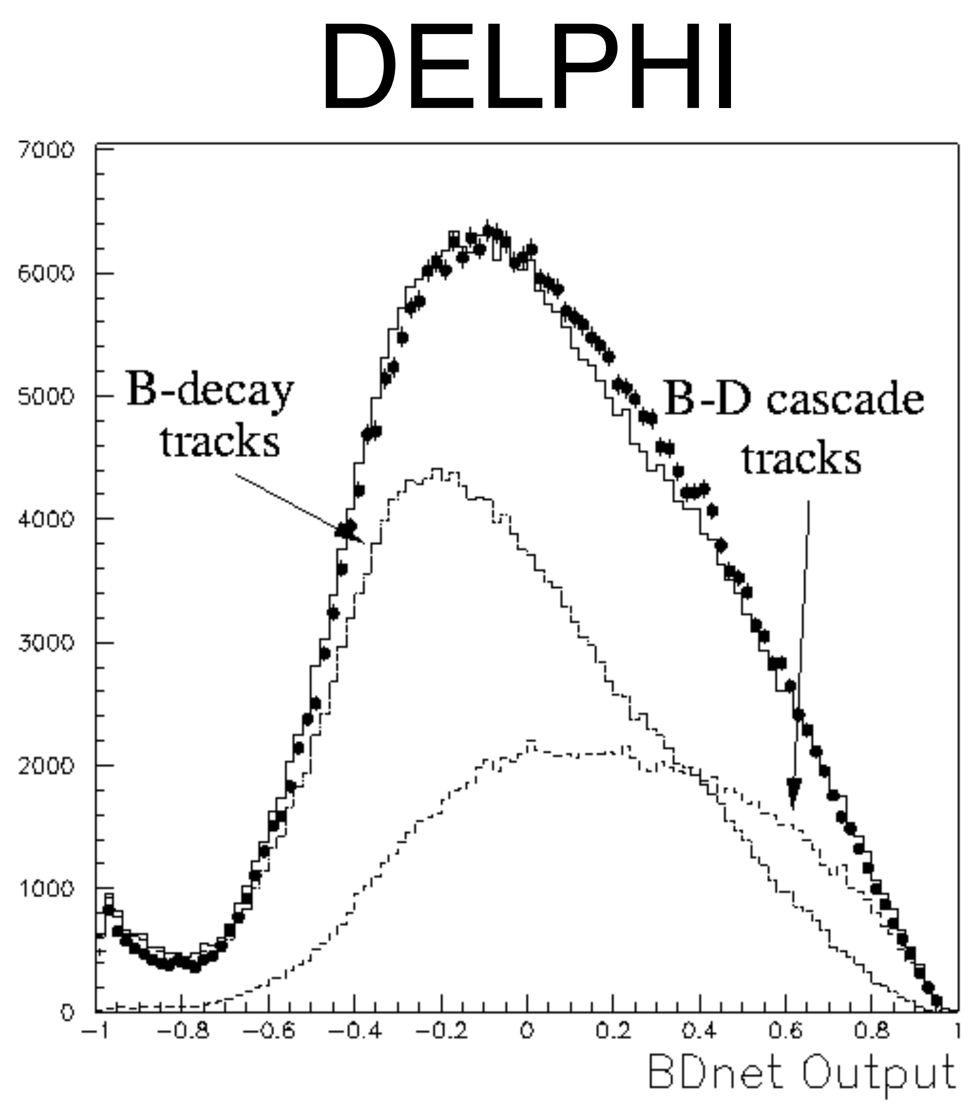
b-physics at Z

$$t = \frac{m_B}{c\,p_B} L$$



$B \rightarrow D^{(*)} l \nu (X)$



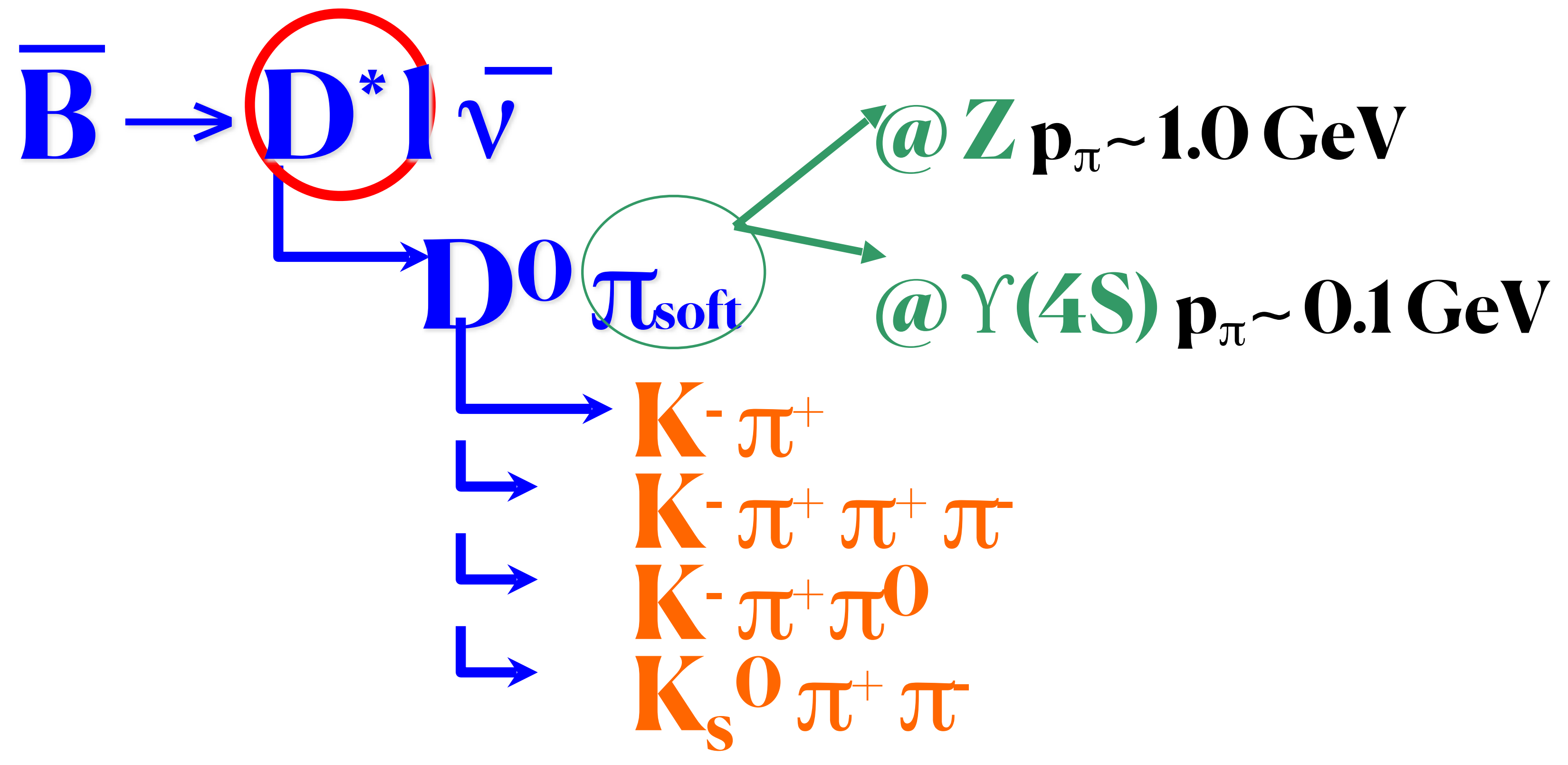


- b produced @Z decay length L~3 mm
- b-direction and L_D from vertex detector and tracking —> need good vertex detector, small beam pipe, small beam spot (**nano beam spot** at ILC!)

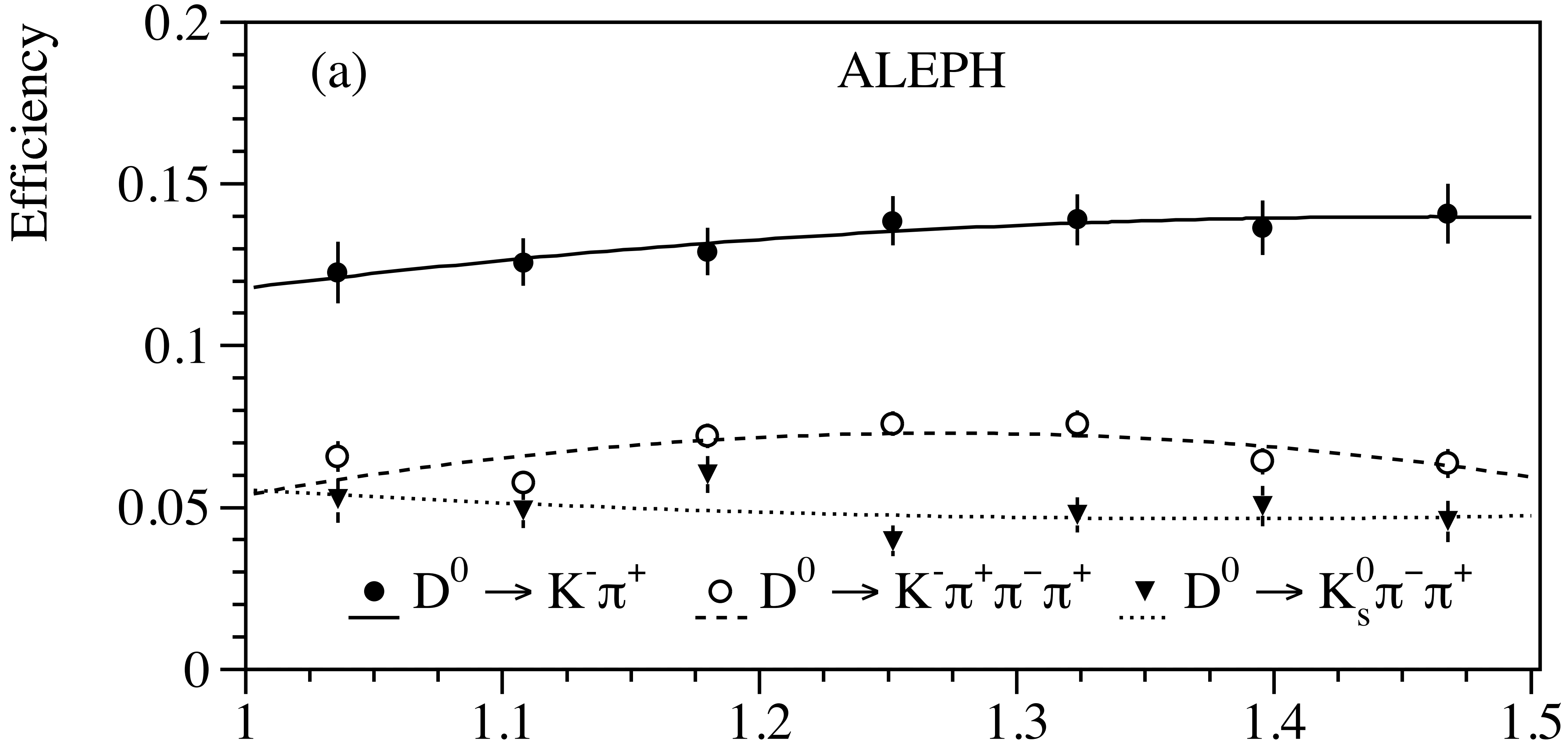
Z factory

	Belle II → Z factory	
D* slow pion tracking efficiency	30-60%	>90%
Boost (decay length of a B)	120 μm	3mm
B isolation	Overlapping	Highly displaced
Low B-frame momentum (<0.7 GeV) lepton ID	Poor/moderate	Very good
Neutrino reconstruction	B tagging	Vertex + energy flow
	LHCb → Z factory	
Flavour tagging efficiency	5%	40-80%
EM showers	Pileup	Not an issue
K_S acceptance (decay inside tracking)	Moderate	Good
Hermetic acceptance	Forward	Barrel/Symmetric
Trigger	Finite for hadronic	~100%

B→D* l ν and $|V_{xb}|$



Phys.Lett.B395:373-387,1997



Efficiency $$w = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}}$$

Belle II: B→D* l ν experiment precision limited by efficiency in low hadronic recoil region. (Used in a variety of analyses beyond V_{xb}). Limited access to B_s.

LHCb: Model dependent, does not calculate absolute BR.

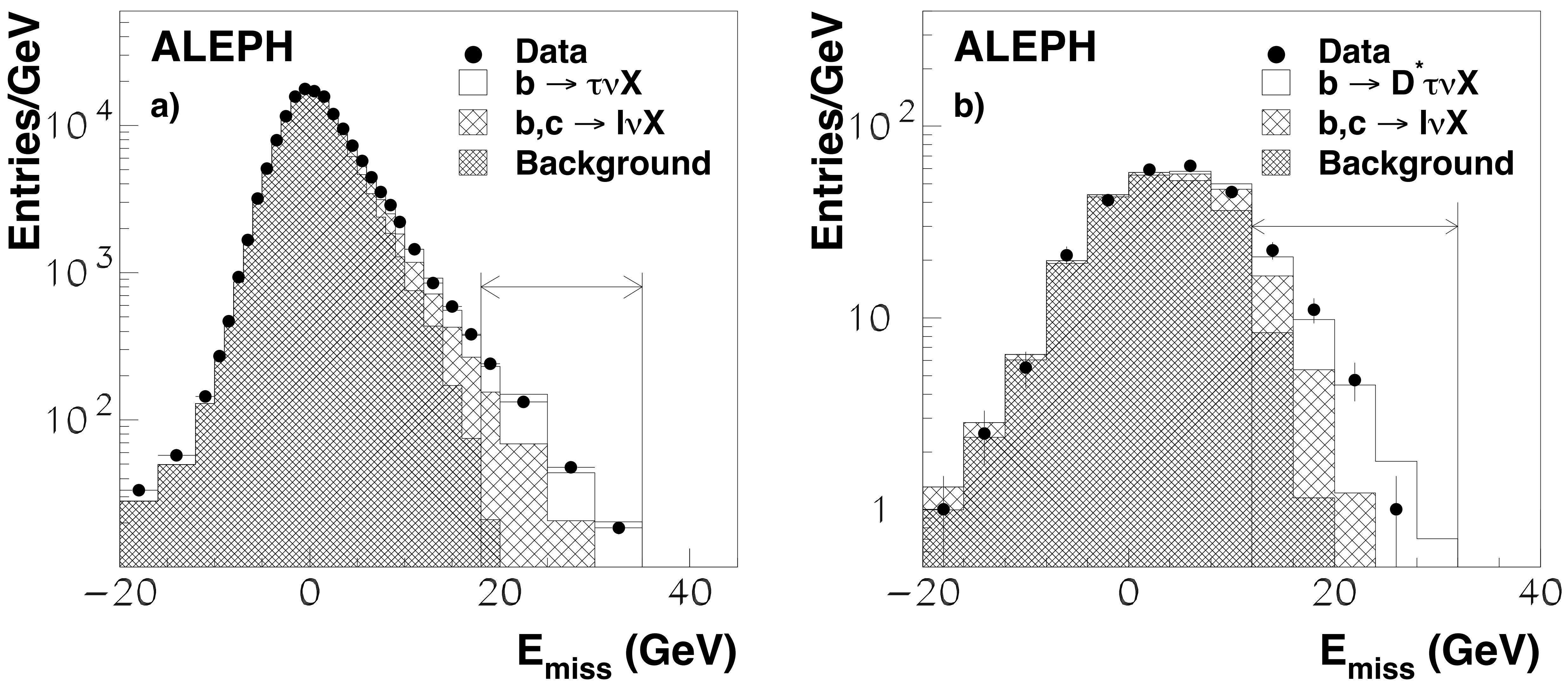
Z-factory: **Efficiency flat even for slow pions.** Good potential for wide variety of missing energy analyses due to clean events.

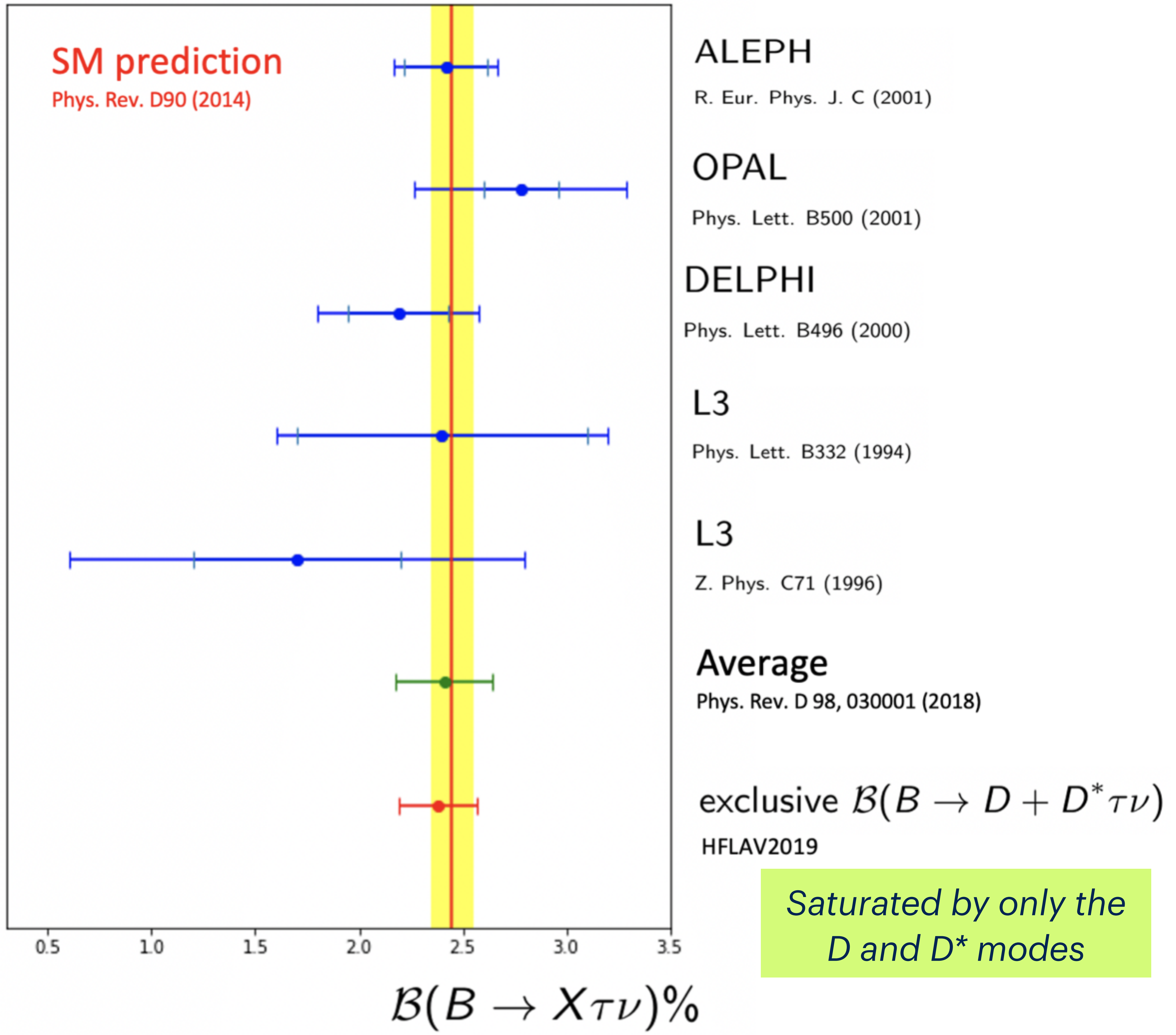
	b→c l ν, $|V_{cb}|$	**b→u l ν, $|V_{ub}|$**
B	$B \to D^{(*)}$ l ν	B→π l ν, B→ρ l ν
B_s	$B_s \to D_s^{(*)}$ l ν	$B_s \to K^{(*)}$ l ν
B_c	$B_c \to \eta_c$ l ν, $B_c \to J/\psi$ l ν	$B_c \to D^{(*)}$ l ν
Λ_b	$\Lambda_b \to \Lambda_c^{(*)}$ l ν	$\Lambda_b \to$ p l ν

$b \to X \tau \nu$ ($b \to c \tau \nu$)

- This Z result is still unique….
- Belle II: Challenging for lepton ID at low momentum and very small separation of B and τ vertices in hadronic B decays.
- Various b modes with τ could be accessible, inclusive and exclusive.

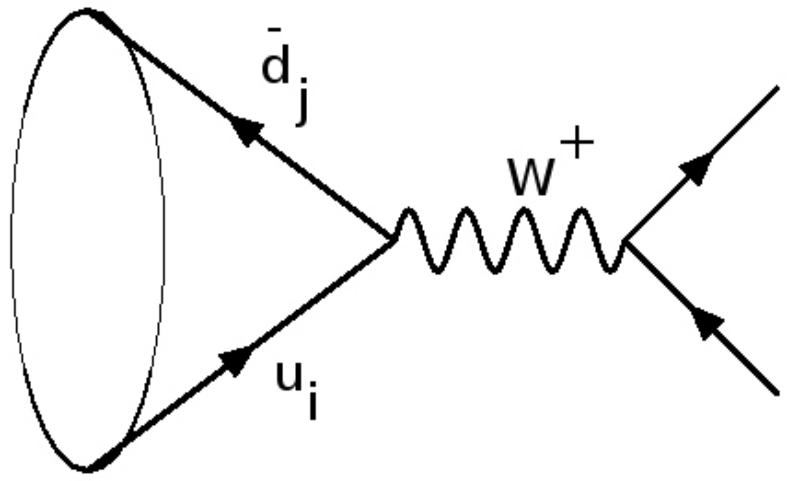
Eur.Phys.J.C 19 (2001) 213-227





Saturated by only the D and D modes*

$B_c \to \tau^- \bar{\nu}_\ell$



$f_{B_c} = 427 \pm 6$ MeV (McNeile et al. 2012)
$f_{B_c} = 434 \pm 15$ MeV (Colquhoun et al. 2015)

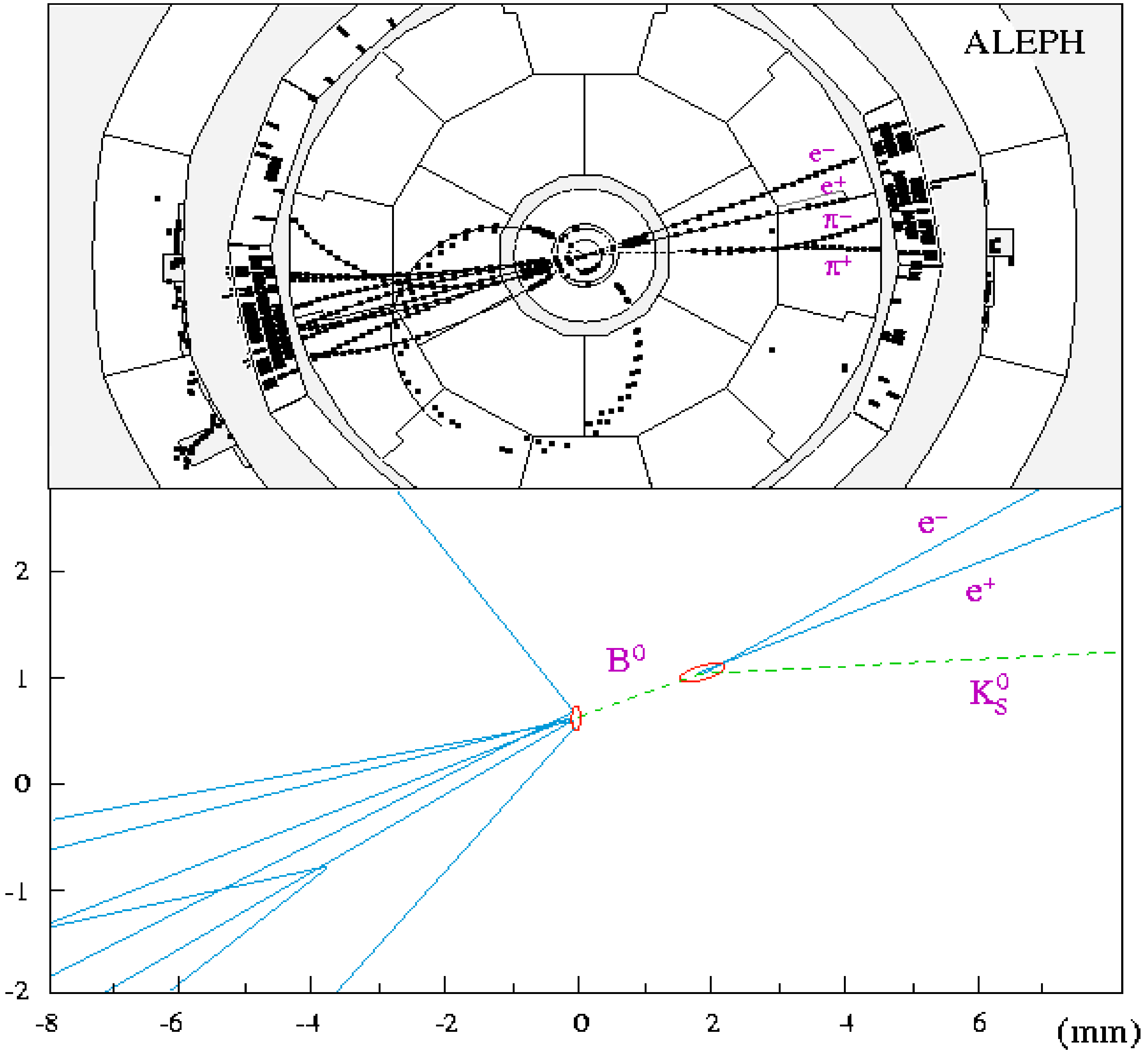
Time dependent CPV $S_{CP}(B \to J/\psi K_S)$

- CDF (February 1999)
  - $\sin 2\Phi_1 = 0.79^{+0.41}_{-0.44}$
  - From 400 $B \to J/\psi K_S$
- ALEPH (November 1999)
  - $\sin 2\Phi_1 = 0.82^{+0.84}_{-1.05}$ ***Phys.Lett.B* 492 (2000) 259-274**
  - From 23 $B \to J/\psi K_S$ in 4 million hadronic Z events.

Very clean, could be competitive with a B factory

Belle II: Tag side vertex resolution and signal Δt resolution (both limited by lower boost).

LHCb: Lower K_S acceptance (factor ~10 reduction) and high dilution in b-tagging.



Giga-Z time dependent CPV:
Good timing resolution, flavour tagging, vertex separation.

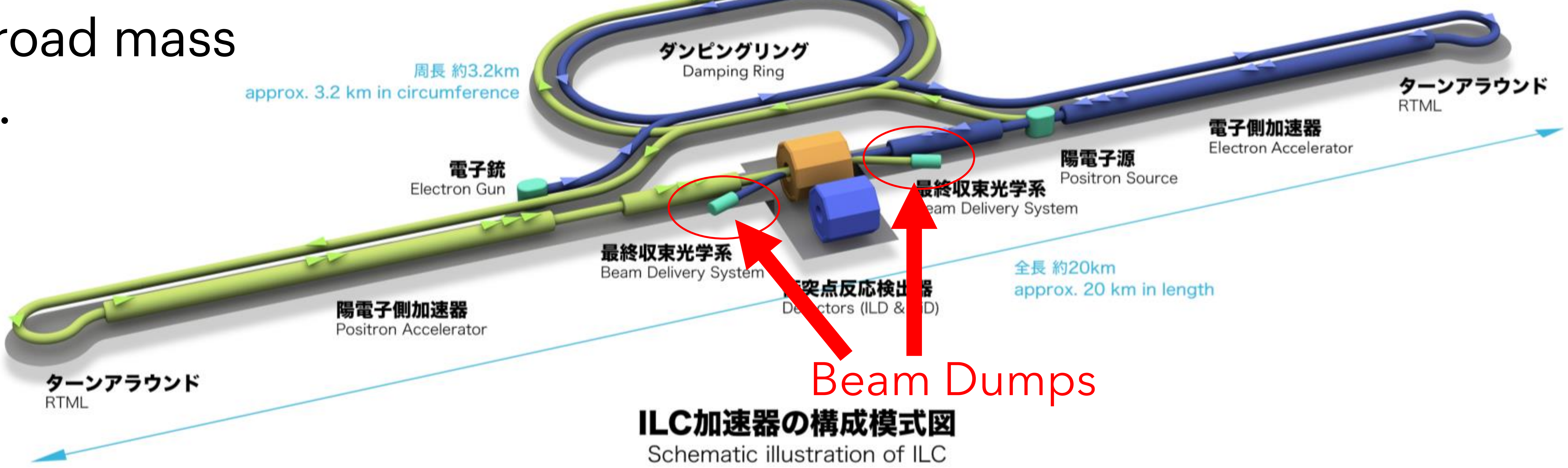
GigaZ(+) channels

- Difficult to say what open questions we will have after Belle II and LHCb mid 2030s.
- **No doubt the detector and Z-factory environment makes for an excellent B-factory. (The question is about luminosity at that region … a TeraZ would be amazing)**
  - There may also be more to exploit on polarisation.

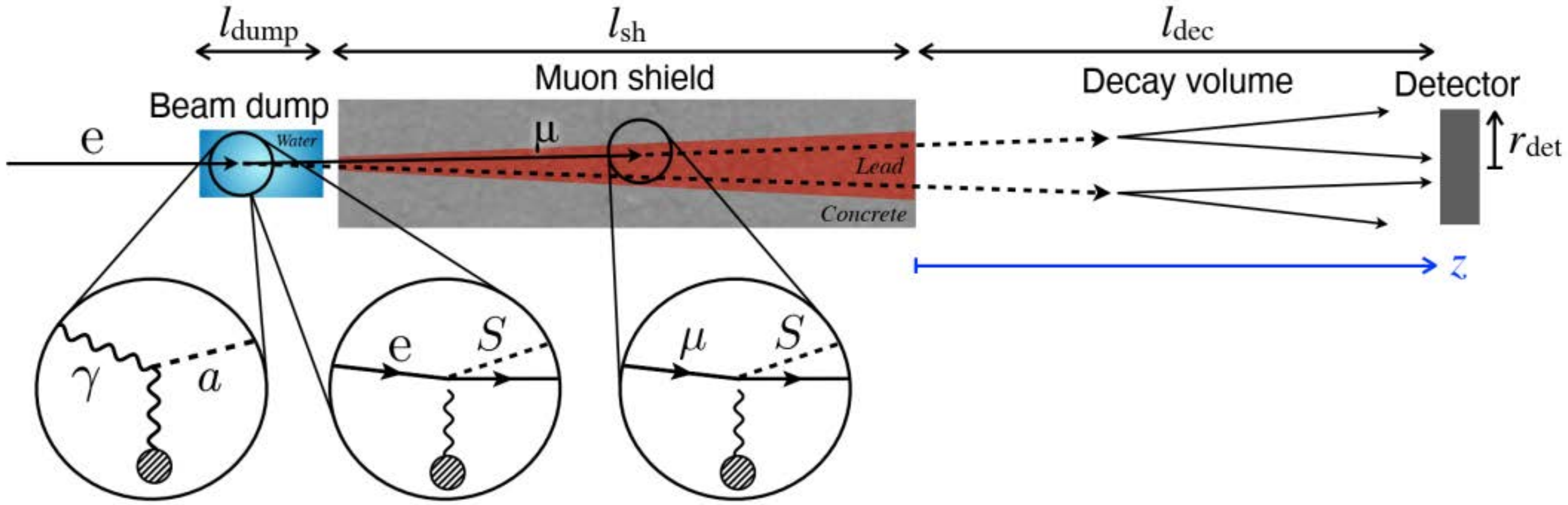
Missing energy and semileptonic	$b \to s\ \tau\tau X$, $b \to c\ \tau\ X$, $b \to \nu\nu\ X$ in b-hadron decays (not just B). Excellent b/c/tau vertex separation.
Inclusive Exploration of B_c, B_s, Λ_b	Explores a relatively new areas. No trigger effects, allowing exploration of full decay width.
Complementarity to LHCb and Belle II	Flat efficiency in Dalitz space (see slow pion example) - high precision strong phase measurements in Φ_3. Good for inclusive measurements via sum-of-exclusive.
New observables	Lifetimes in rare decays, Time dependent CPV in a variety of mode with neutrals.

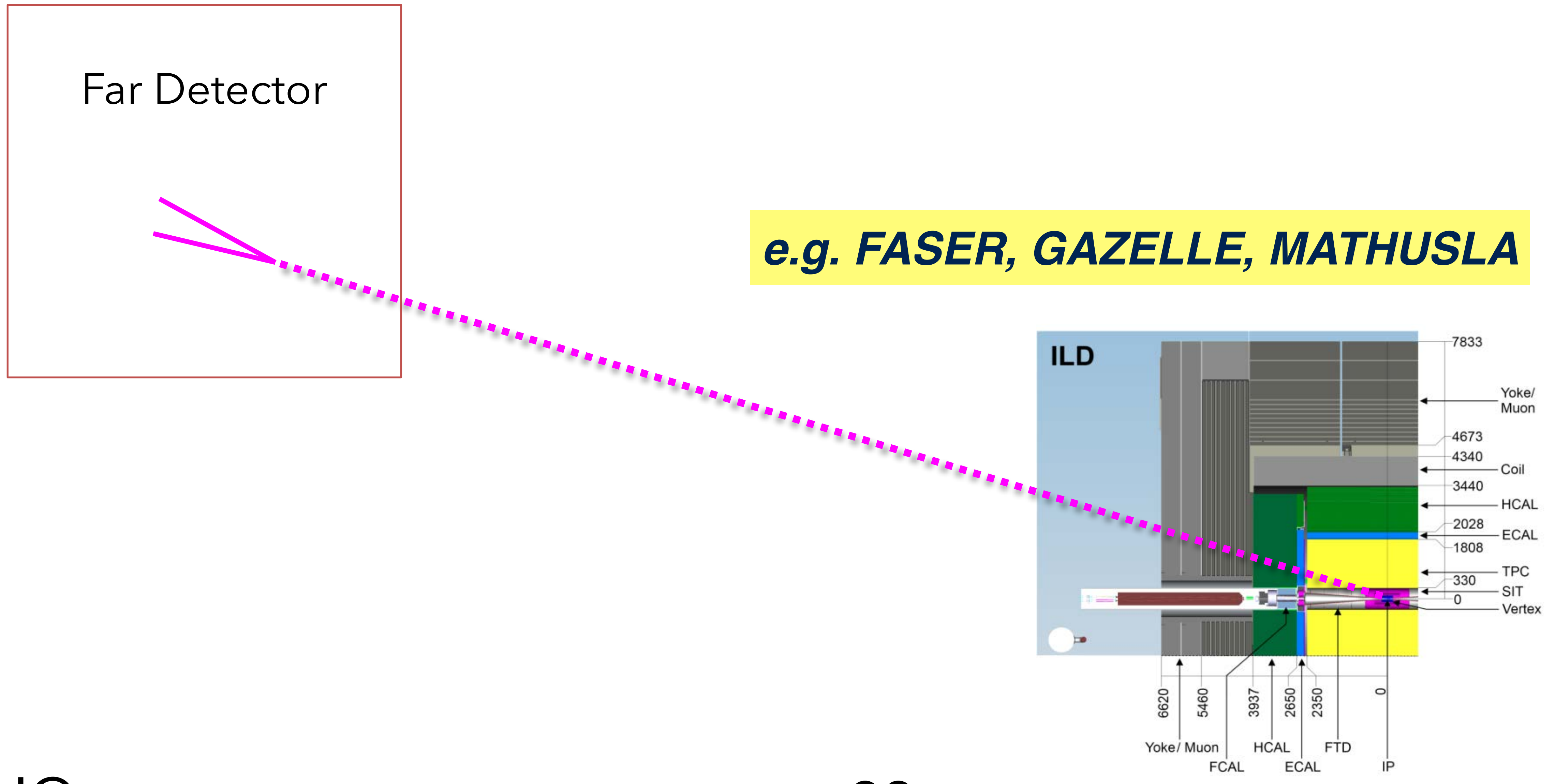
Beam Dump or Far Detector Experiments?

- Interesting potential for dark/hidden sector studies over a very broad mass range with satellite facilities.



arXiv: 2009.13790





e.g. FASER, GAZELLE, MATHUSLA

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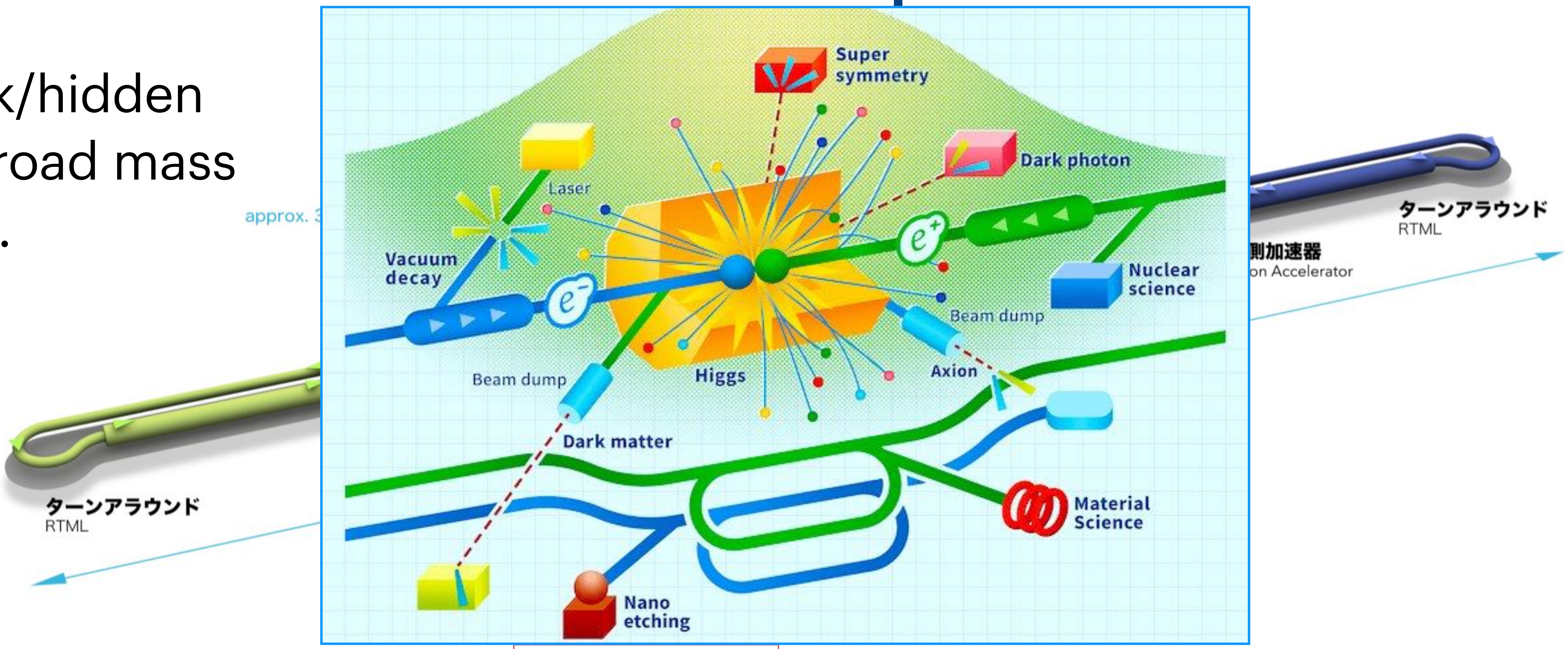

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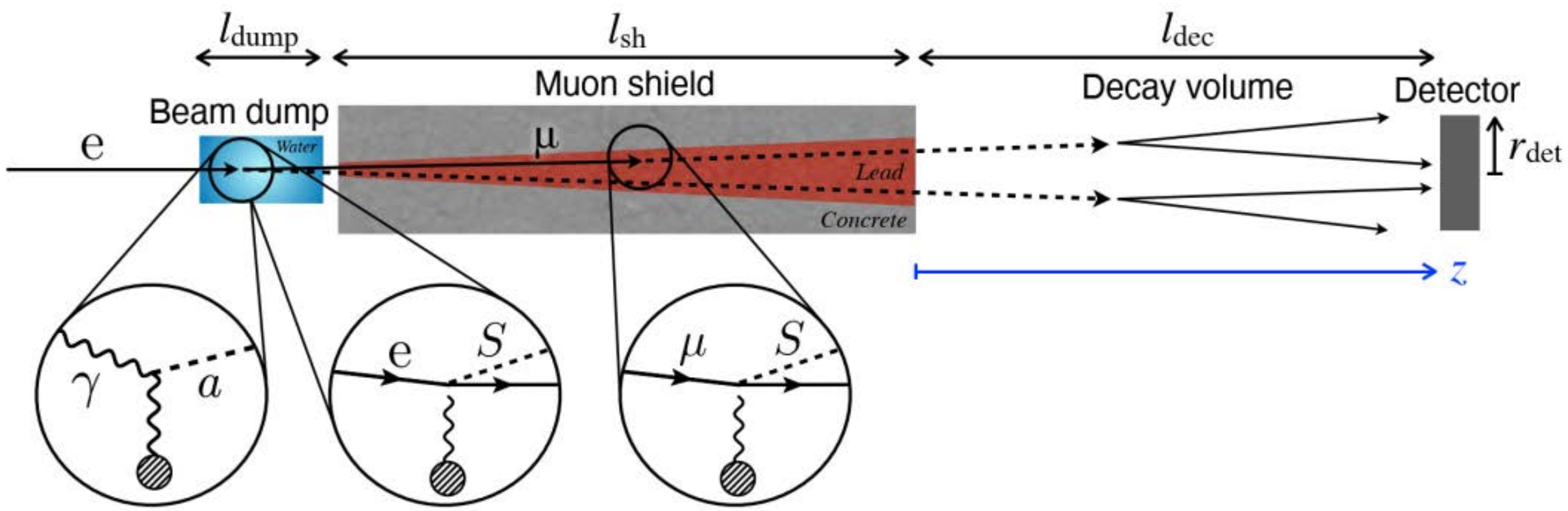
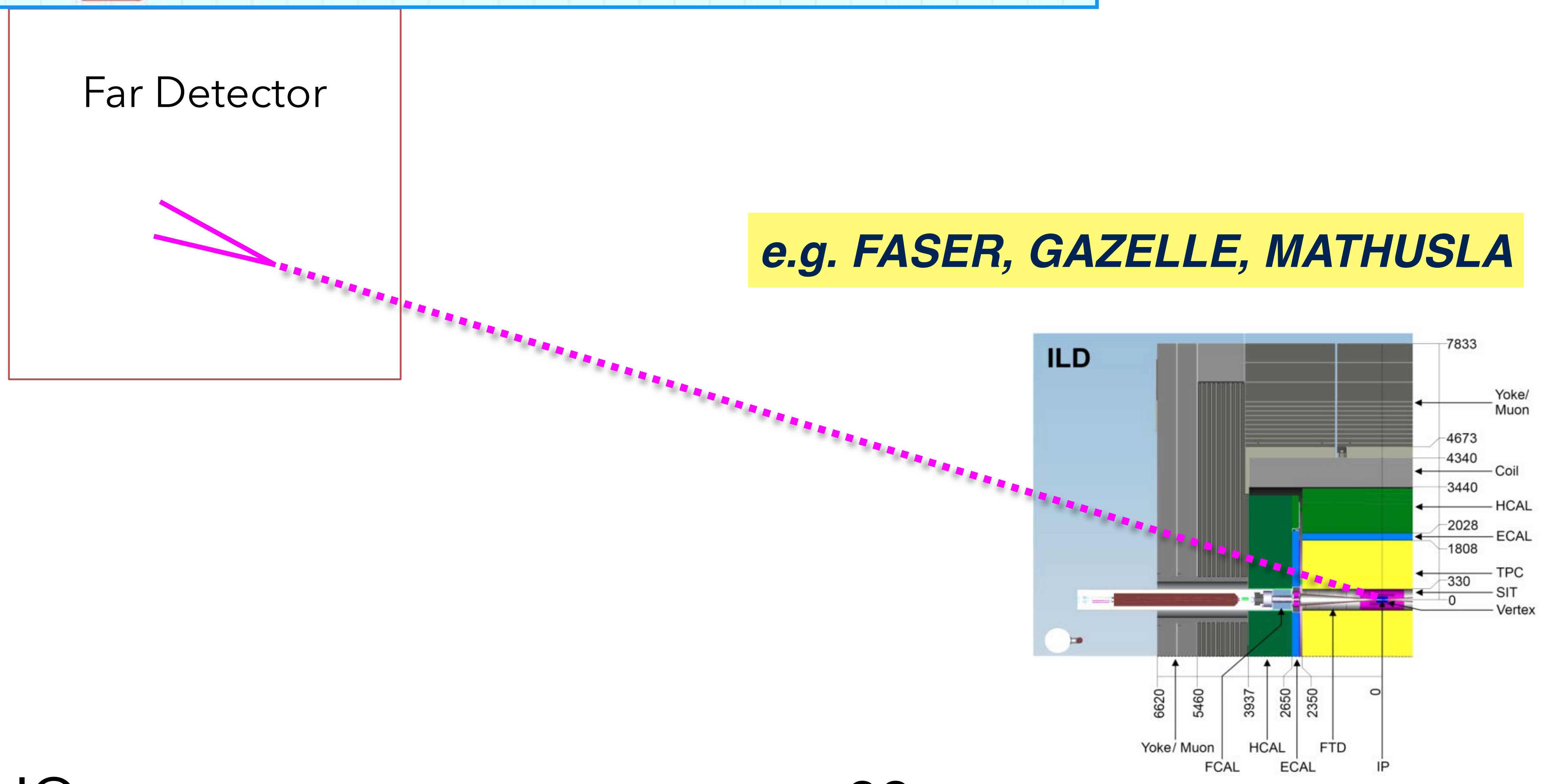




e.g. FASER, GAZELLE, MATHUSLA

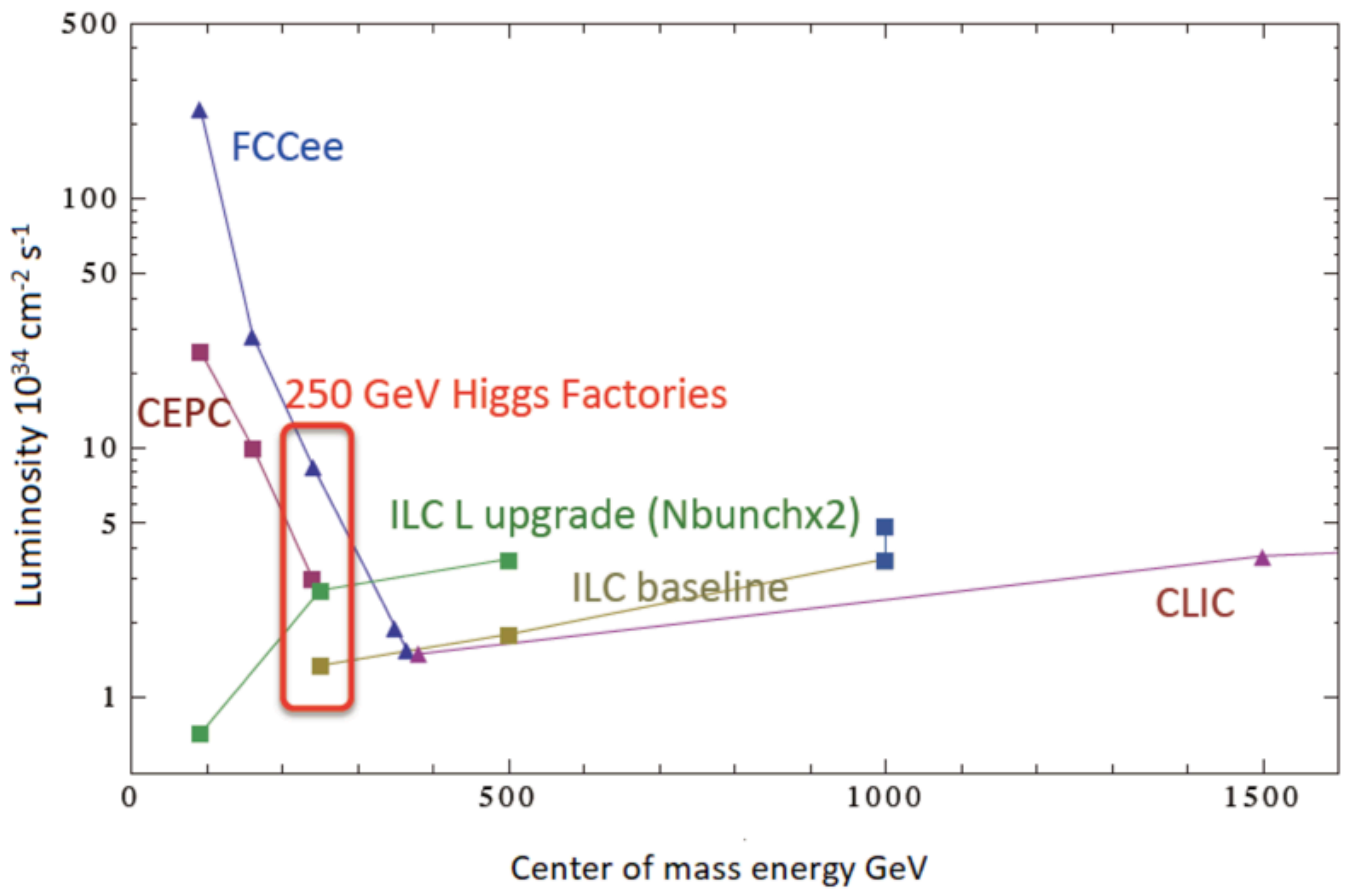
Conclusion (top and beauty prospects)

- ILC - IDT has submitted a pre-lab proposal for the ILC.
  - Anticipated 4 year pre-lab phase.

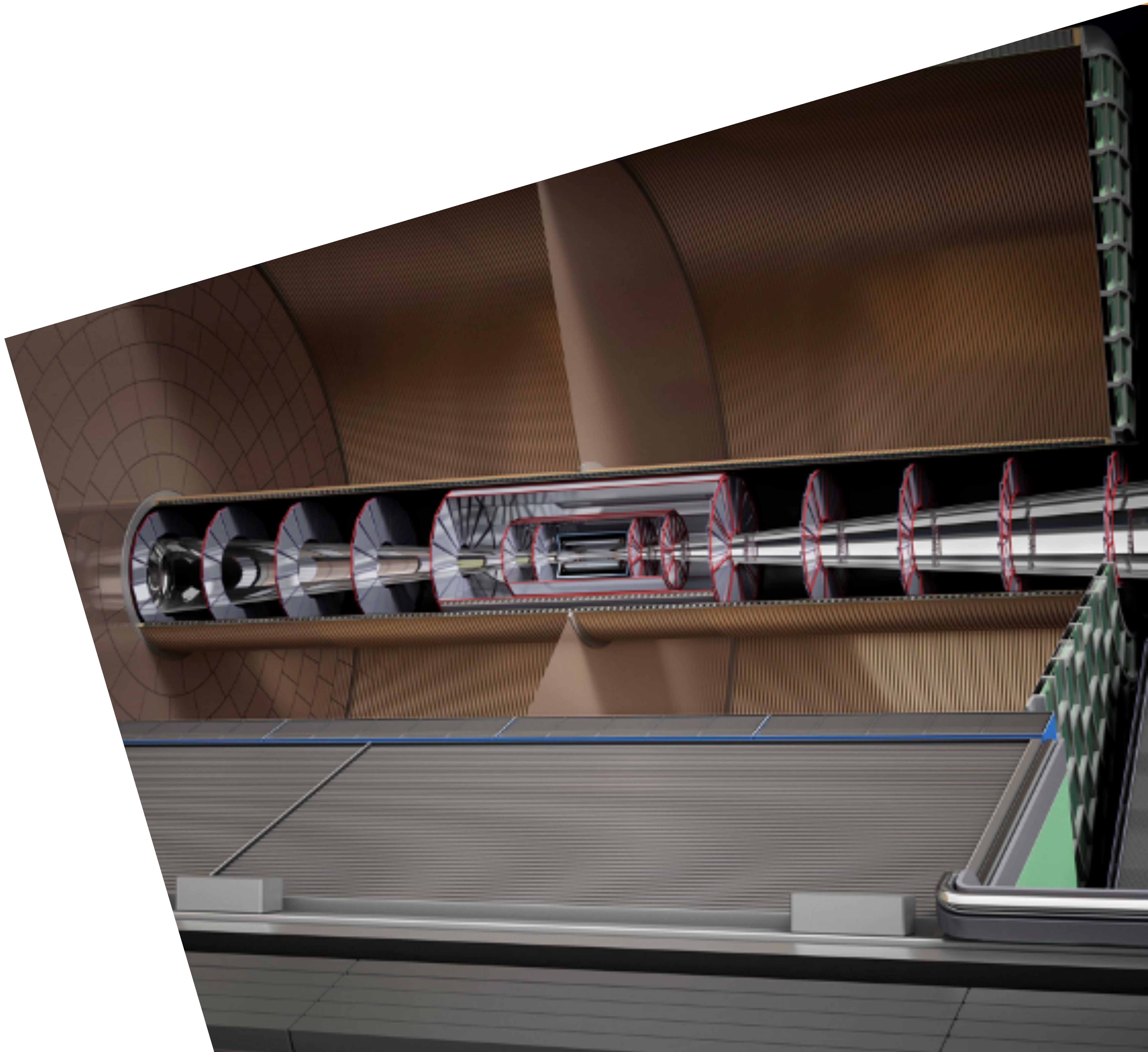
- 3 main stages currently planned: 250 GeV, 350 GeV, 500 GeV.
  - Polarised beams.
  - Possibility for GigaZ operation, and for 1 TeV.

- The target is to search for NP through precision at high energy: in addition to heavy flavour Higgs couplings, there are excellent opportunities to study EW couplings of heavy quarks.

- The flavour and low energy new particle program is more nascent but could help inform detector and accelerator requirements.



Backup slides



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- *Proposal for the ILC Preparatory Laboratory (Pre-lab)* arXiv:**2106.00602**
- *ILC Study Questions for Snowmass 2021* arXiv:**2007.03650**
- *International Large Detector: Interim Design Report* arXiv:**2003.01116**
- *Tests of the Standard Model at the International Linear Collider* arXiv:**1908.11299**
- *The International Collider. A Global Project* arXiv:**1903.01629**
- *The ILD Detector at the ILC* arXiv:**1912.04601**
- *Physics Case for the International Linear Collider* arXiv:**1506.05992**

Machine parameters

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrades	Energy Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7 / 5.4	1.8 / 3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5 / 10	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312 / 2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	5.8 / 8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5 / 21	10.5 / 21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	111	138 / 198	173 / 215	300
Site length	L_{site}	km	20.5	20.5	31	40