Higgs Invisible Decays at the ILC

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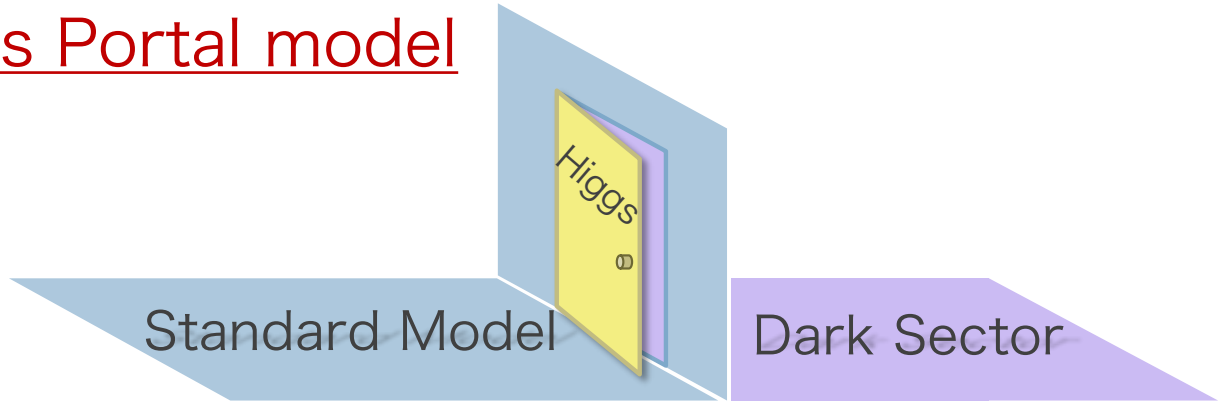
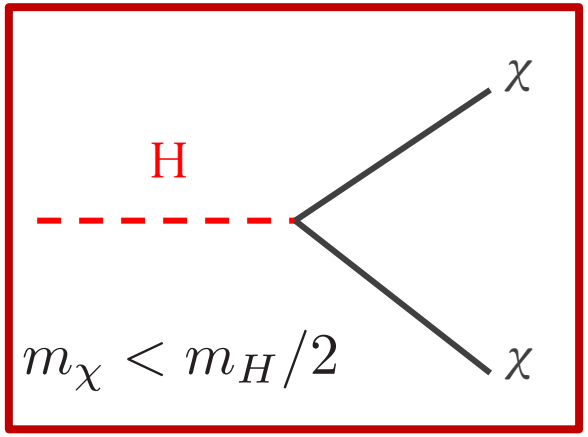
What is Higgs invisible decay for?

- Assuming DM interacts ***only through Higgs:***

  Higgs Portal model



- How do we verify Higgs Portal at colliders?



→ by detecting invisible decay of Higgs

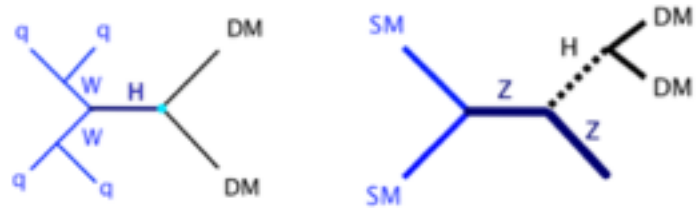
Higgs portal, plot for direct searches

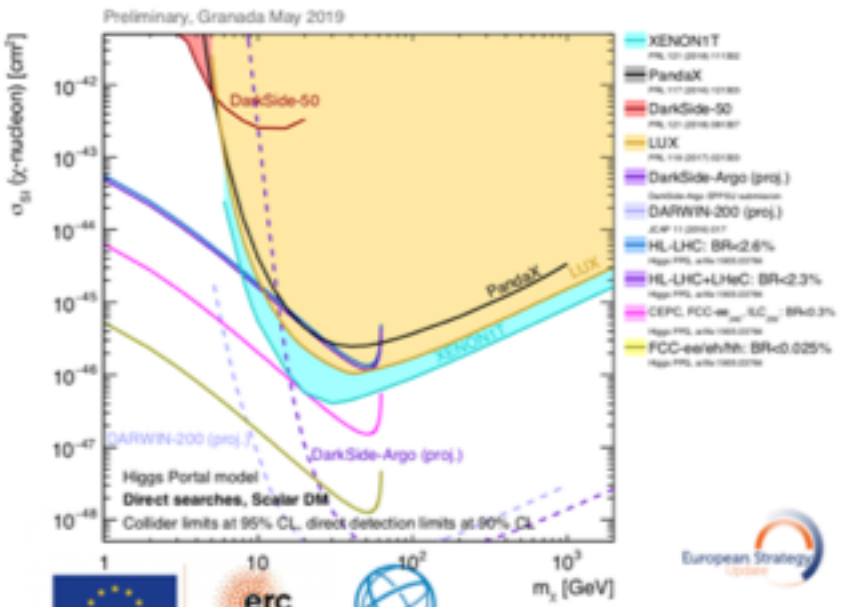
- Limits on BR can be translated to limits in the DM-nucleon plane

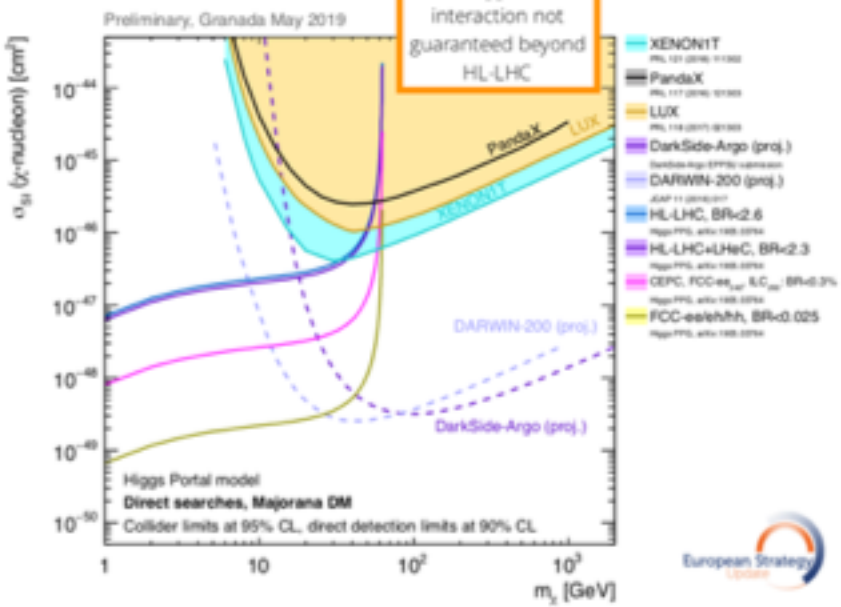
$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_\chi^4 f_\chi^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi \left(\frac{m_h}{m_\chi}\right), \quad (15)$$

arXiv:1708.02245

where $g_S(x) = 1$,
$g_f(x) = 2/(x^2-4)$, $\beta = \sqrt{1-4m_\chi^2/m_h^2}$, $v = 246\,\mathrm{GeV}$







Caterina Doglioni - 2019/05/13 - European Strategy Update 24

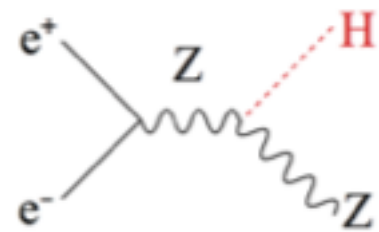
C. Doglioni, "Dark Matter at colliders", European Strategy Update

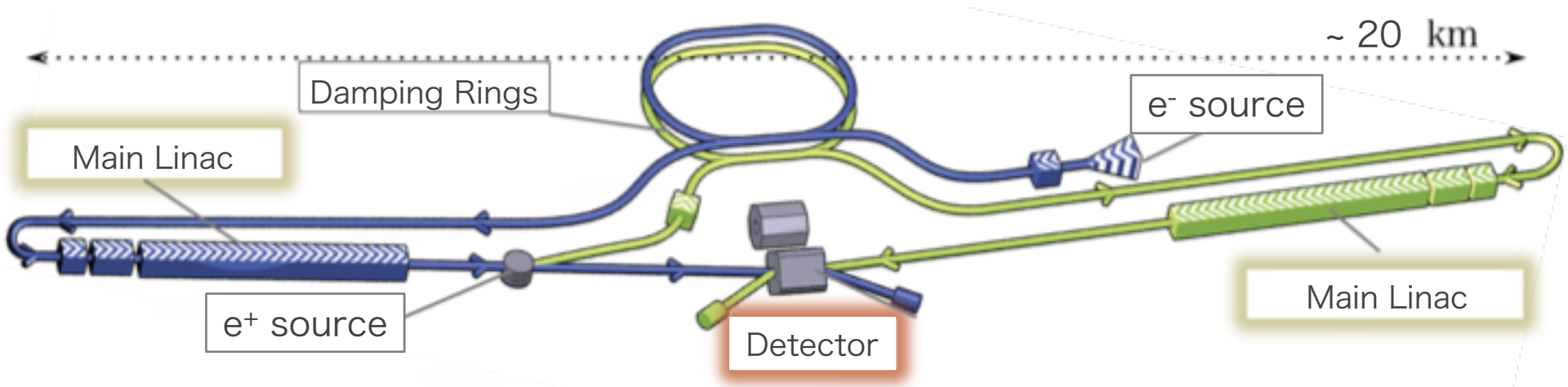
International Linear Collider

- $e^+ e^-$ collider
- $\sqrt{s}$ = 250 GeV, upgradable to 500 GeV - 1 TeV
- beam polarization
- clean environment, known initial state

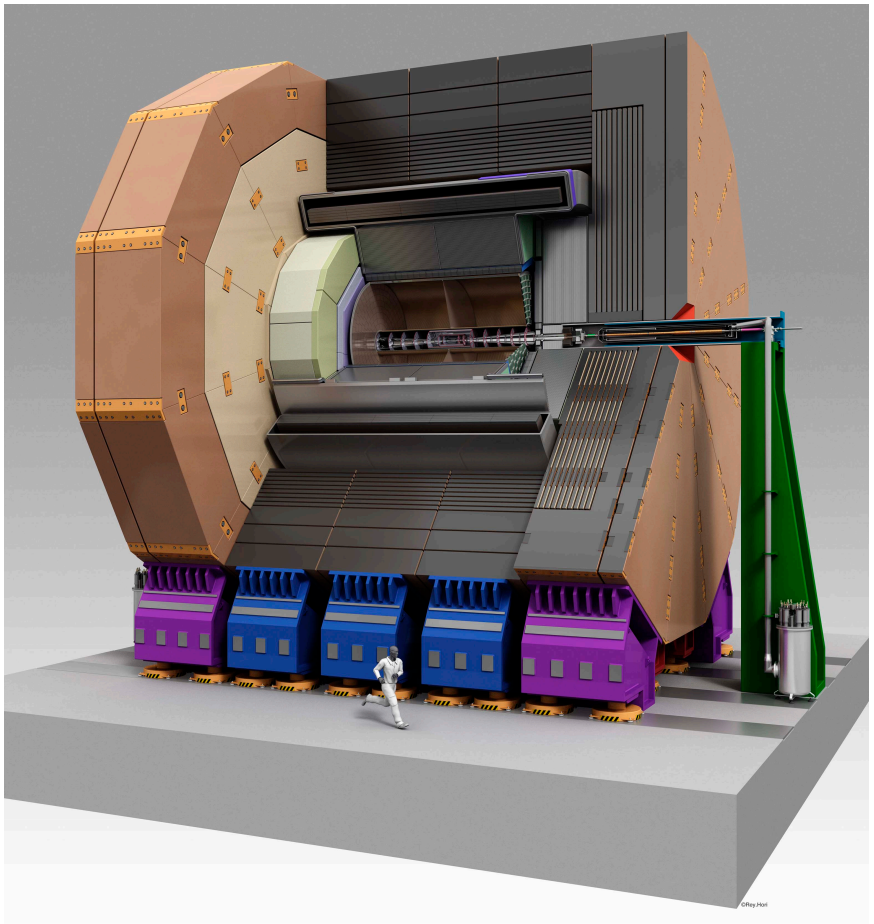
→ **Recoil Mass technique**

$$M_{rec}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

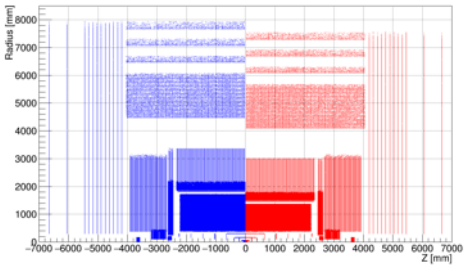


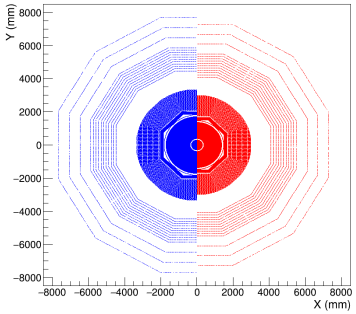


International Large Detector



- One of the detector concepts at the ILC
- Optimized for Particle Flow Algorithm
  - Reconstruct & identify all the particles, especially hadron jets in this study
- Key detector performance
  - Jet Energy Resolution (JER):
    $rms_{90}(E)/E \sim 3\text{-}4\%$
- There are 2 options of detector design:
  - IDR-L / IDR-S

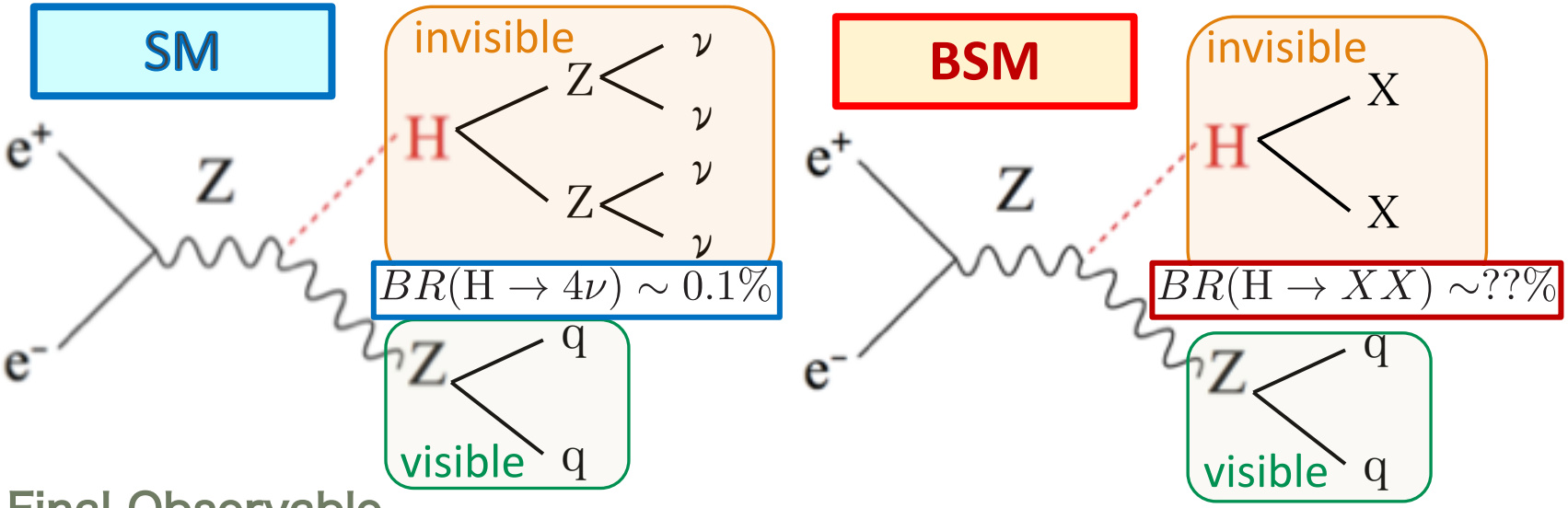




Higgs→invisible at the ILC

Target Channel

e+e- → ZH, Z→qq/ll, H→invisible



Final Observable

95% C.L. upper limit on branching ratio of H→invisible

UL on BR (95% C.L.)	CMS*1 4.9 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV) + 38.2 fb^{-1} (13 TeV)	ATLAS*2 4.7 fb^{-1} (7 TeV) + 20.3 fb^{-1} (8 TeV) + 36.1 fb^{-1} (13 TeV)	HL-LHC*3 6 ab^{-1}	ILC250 2 ab^{-1}
expected	15%	17%	1.9%	0.25%
observed	19%	26%	—	—

*1 Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at √s= 13 TeV, CMS Collaboration
*2 Combination of searches for invisible Higgs boson decays with the ATLAS experiment, ATLAS Collaboration
*3 Higgs Boson studies at future particle colliders - Preliminary Version - , A. Nisati et al.

Topics

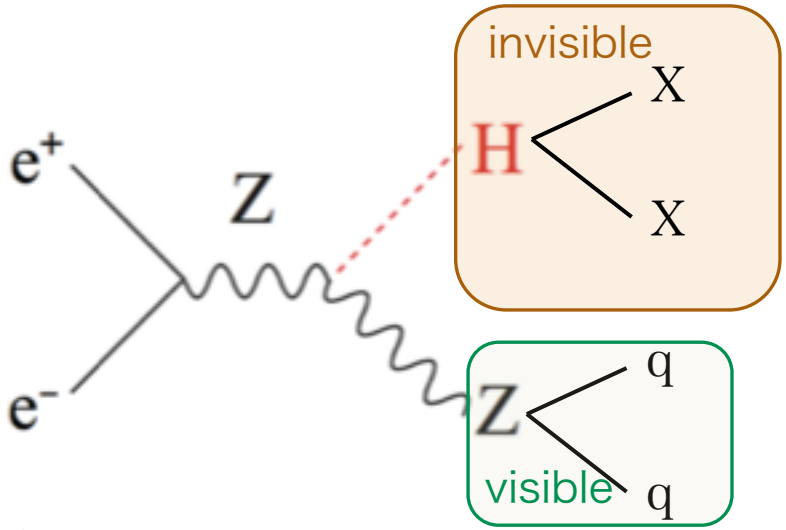
1. Evaluation of UL on BR(H→invisible) at the ILC
2. Impact of JER on H→invisible

Topics

1. **Evaluation of UL on BR(H→invisible) at the ILC**

2. Impact of JER on H→invisible

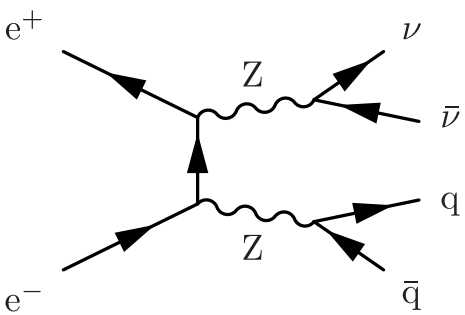
Signal process



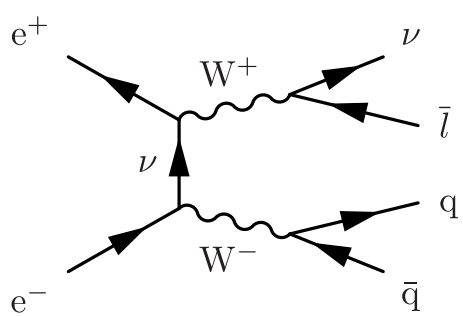
- ✓ 2 jets & missing energy
- ✓ $M_{qq} \approx M_Z$, $BR(\mathrm{Z} \to qq) \sim 70\%$
- ✓ $M_{recoil} \approx M_{Higgs}$
- ✓ s channel process

Backgrounds: all of 2f, 4f and SM Higgs

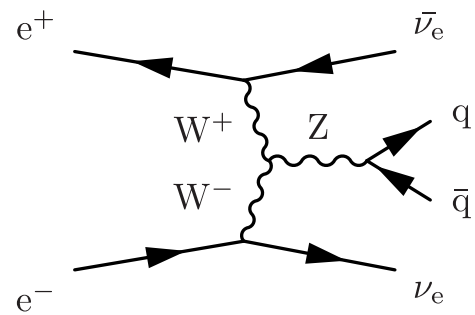
- Main backgrounds:



ZZ semi-leptonic



WW semi-leptonic



$\nu\ \nu$ Z semi-leptonic

Analysis

Setup

- **based on full detector simulation of ILD**
  - $\sqrt{s}$ = 250 GeV : $\int Ldt$ = 900 fb^{-1} × 2(Left & Right)
  - $\sqrt{s}$ = 500 GeV : $\int Ldt$ = 1600 fb^{-1} × 2(Left & Right)

beam polarization	Left	Right
(P_{e^-}, P_{e^+})	$(-0.8, +0.3)$	$(+0.8, -0.3)$

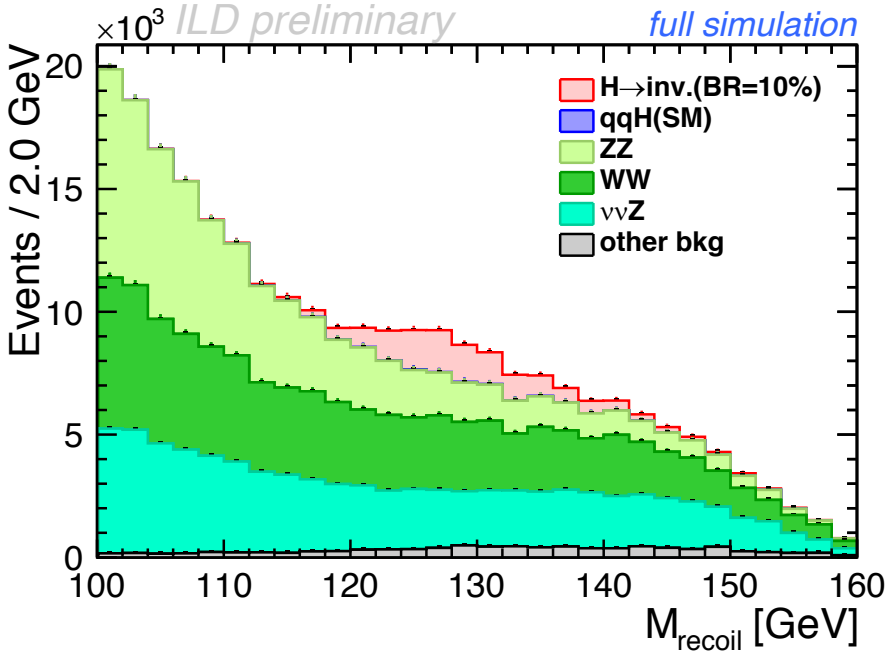
Flow

0. ILD full simulation & event reconstruction w/ PFA
1. Isolated lepton tagging
2. Forced to 2 jets with Durham jet clustering
   - overlaid background removal is applied only at 500 GeV (α=5.0)
3. Event selection: optimized assuming BR(H→invisible) = 10%
   - number of particles
   - transverse momentum
   - di-jet mass
   - recoil mass
4. Estimate upper limit (UL) of BR (95% C.L.)

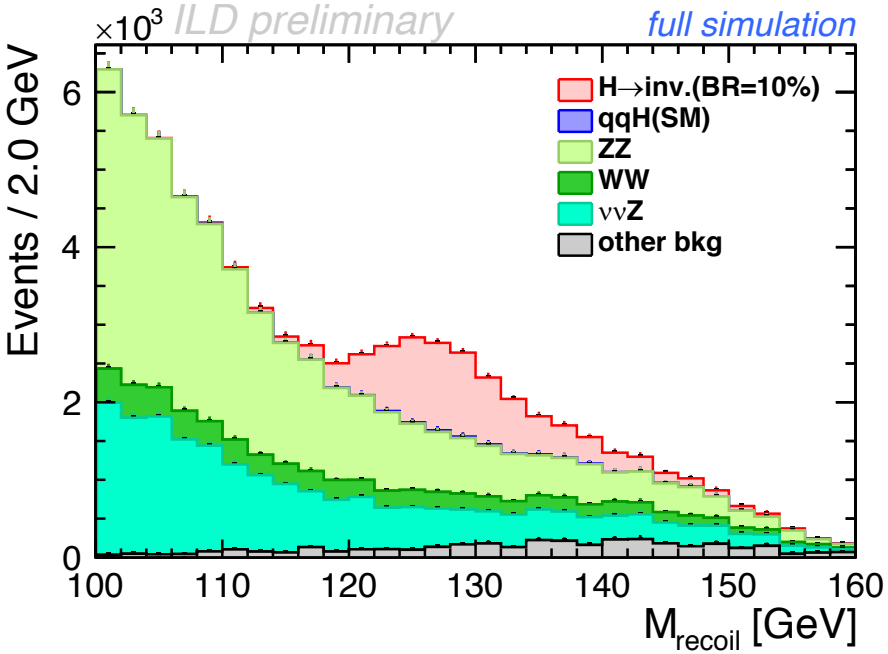
$$UL_{95\%\mathrm{C.L.}}(\%) = \frac{10[\%] \times 1.65\sqrt{N_B}}{N_S(BR = 10[\%])}$$

Recoil Mass distribution $\sqrt{s}$ = 250 GeV

Left: (-0.8,+0.3)



Right: (+0.8,-0.3)



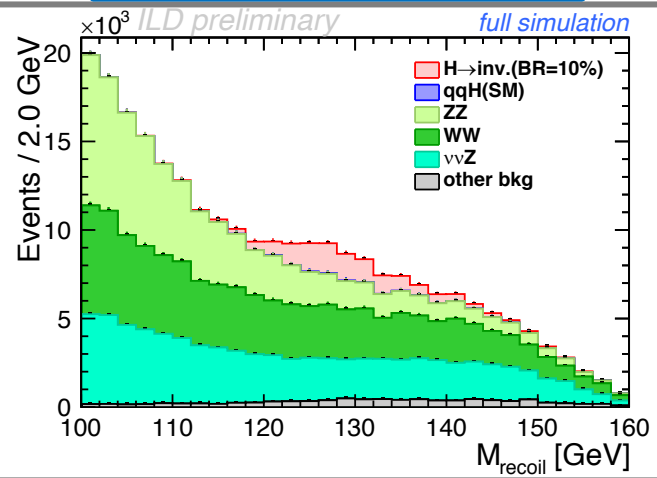
- Main background: $ZZ \to \nu\nu qq,\ WW \to l\nu qq$
- WW bkg is suppressed by right polarization.

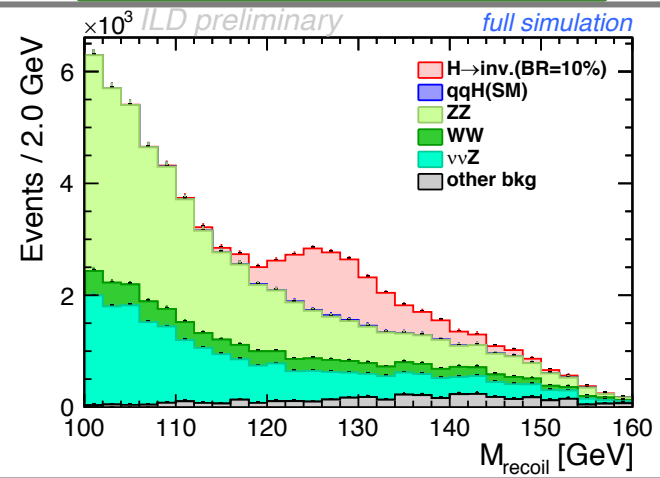
  - w/o BDT cut, kin-fit

Recoil Mass distribution

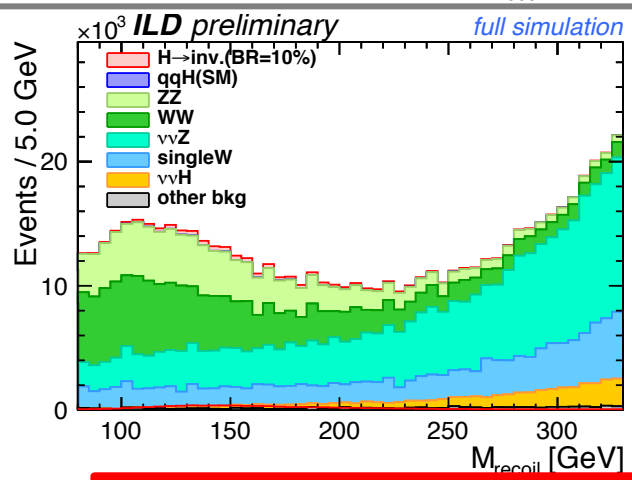
Left: (-0.8,+0.3) | **Right: (+0.8,-0.3)**

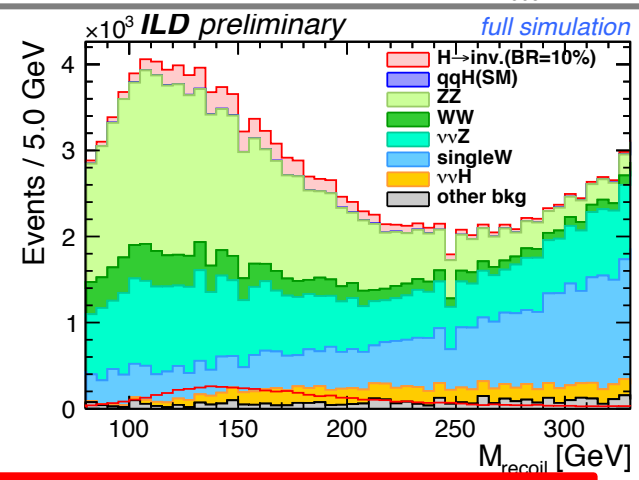
$\sqrt{s}$ = 250 GeV





$\sqrt{s}$ = 500 GeV





- Sensitivity is better at 250 GeV than 500 GeV.

Results

UL on BR (95% C.L.)	$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$	$(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$	Z→qq combined
$\sqrt{s}$ = 250 GeV, 900 fb^{-1}	0.44 %	0.31 %	**0.25 %**
$\sqrt{s}$ = 500 GeV, 1600 fb^{-1}	1.30 %	0.98 %	**0.78 %**
UL on BR (95% C.L.)	Z→qq	Z→ll	combined
$\sqrt{s}$ = 250 GeV, 900 fb^{-1}	0.25 %	0.57 %	0.23 %
$\sqrt{s}$ = 500 GeV, 1600 fb^{-1}	0.78 %	1.19 %	0.65 %
ILC250 + ILC500	-	-	0.22 %

Note: SM decay, H→4ν, is subtracted.
Results of Z→ll are by J. Tian.

- ILC250 hadronic channel plays the dominant role on H→invisible.
- ILC gives factor ~10 better than HL-LHC prospect.
  - cf. 1.9% at HL-LHC

Topics

1. Evaluation of UL on BR(H→invisible) at the ILC
2. **Impact of JER on H→invisible**

H→invisible as a benchmark of ILD

Aim

Evaluate the impact of JER on H→invisible

Target Channel

e+e- → ZH, Z→qq, H→invisible

$\sqrt{s}$ = 250 / 500 GeV

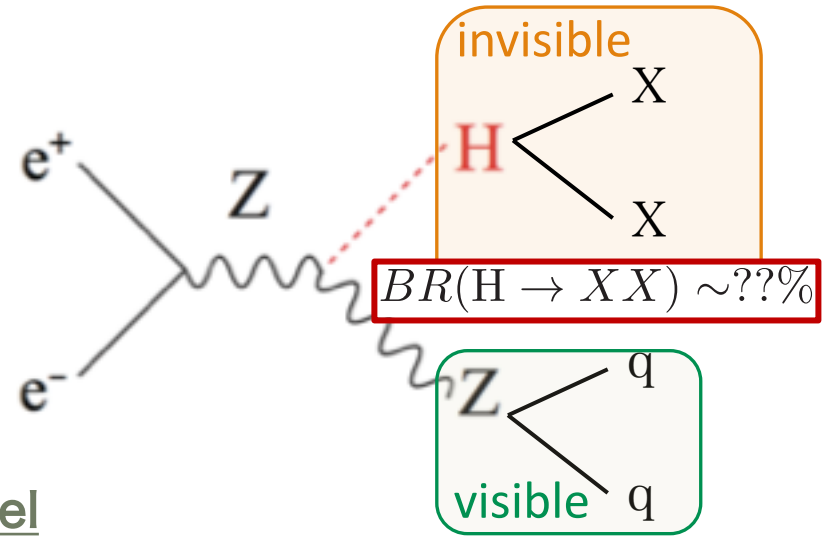
ILD model

Large (IDR-L_{500}, DBD_{250})

Small (IDR-S_{500})

Key Components in hadronic channel

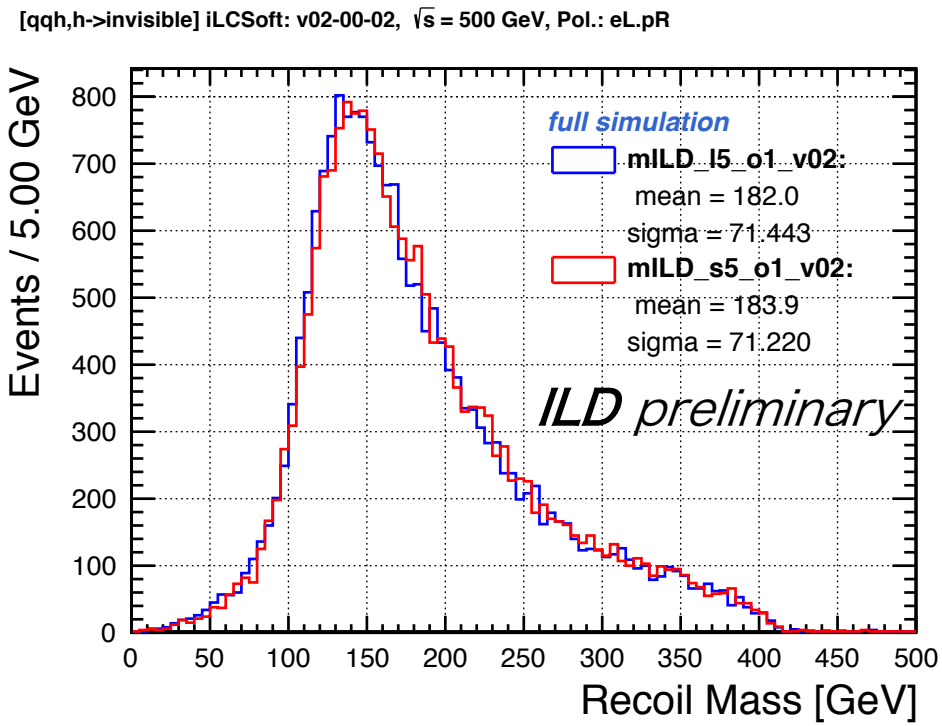
- **Jet energy resolution** (JER)

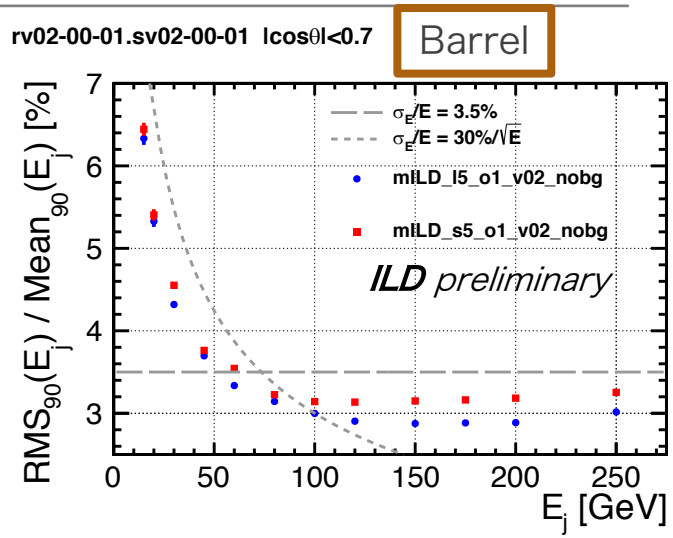


The simplest way is to compare response from Large / Small.

Comparison of Large/Small

$\sqrt{s}$ = 500 GeV





$UL_{95\%CL}$ on BR($H \to invisible$)

IDR-L	IDR-S
0.782%	0.788%

- No significant difference is seen.
  →Other effects need to be disentangled from JER

H→invisible as a benchmark of ILD

Aim

Evaluate the impact of JER on H→invisible

Target Channel

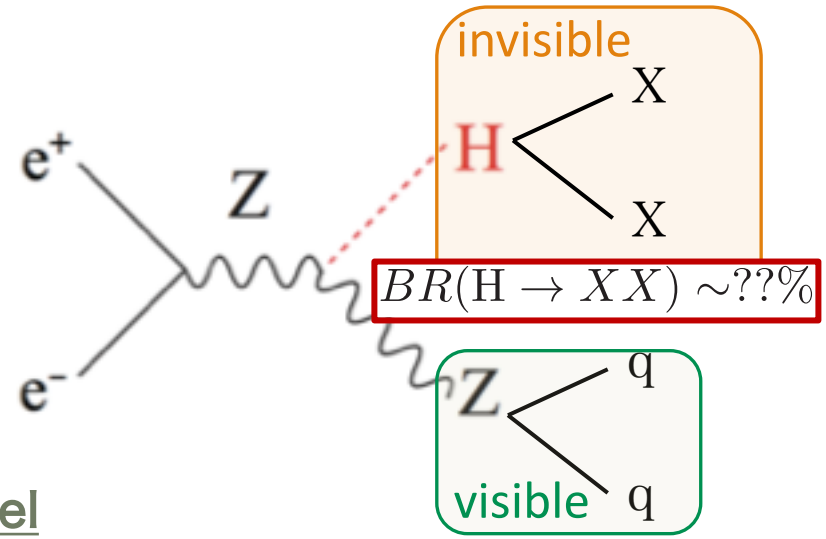
e+e- → ZH, Z→qq, H→invisible

$\sqrt{s}$ = 250 / 500 GeV

ILD model

Large (IDR-L_{500}, DBD_{250})

Small (IDR-S_{500})



Key Components in hadronic channel

- Jet energy resolution (JER)
- Semi-leptonic decay in Z→bb/cc (sld)
- Piled-up beam background by $\gamma\gamma$ interaction (overlay)
- Beam Spectrum (BS)
- Initial State Radiation (ISR)

Quantifying other contributions using generator-level information

w/o semi-leptonic decay in Z→bb/cc (sld)

- P'jj = Pjj + Pmis (all the neutrinos not from Z boson)

w/o overlay backgrounds

- PFOs w/o overlay by OverlayISRRemovalByMCProcessor
- ➢Whenever this cheat is **not** applied at 500 GeV, overlay removal by Durham is done.

w/o Beamstrahlung (Beam spectrum)

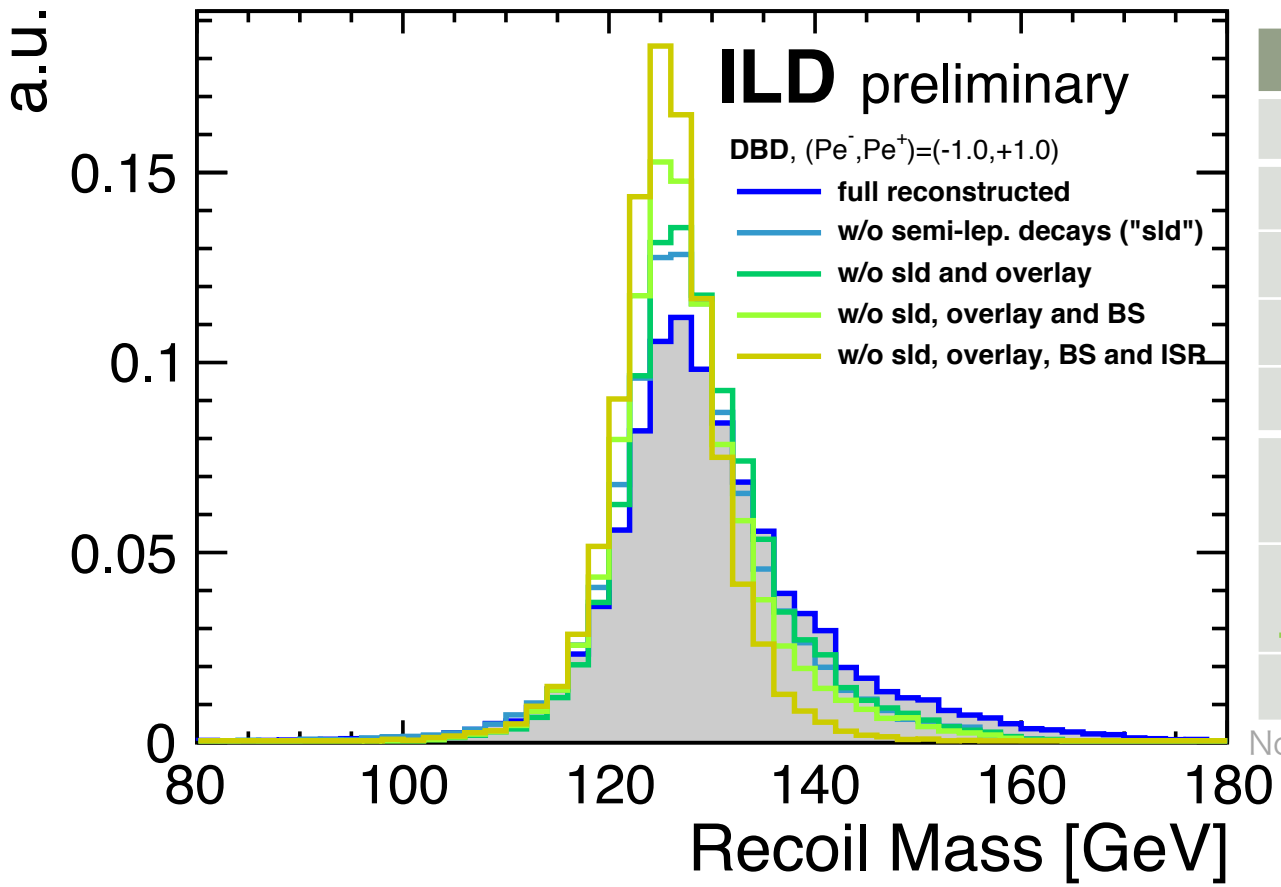
- P'ecm = Ph + Pqq + Pisr

w/o ISR

- P'ecm = Pecm - Pisr & PFOs w/o ISR by OverlayISRRemovalByMCProcessor

Impact of sld/overlay/BS/ISR

$\sqrt{s}$ = 250 GeV



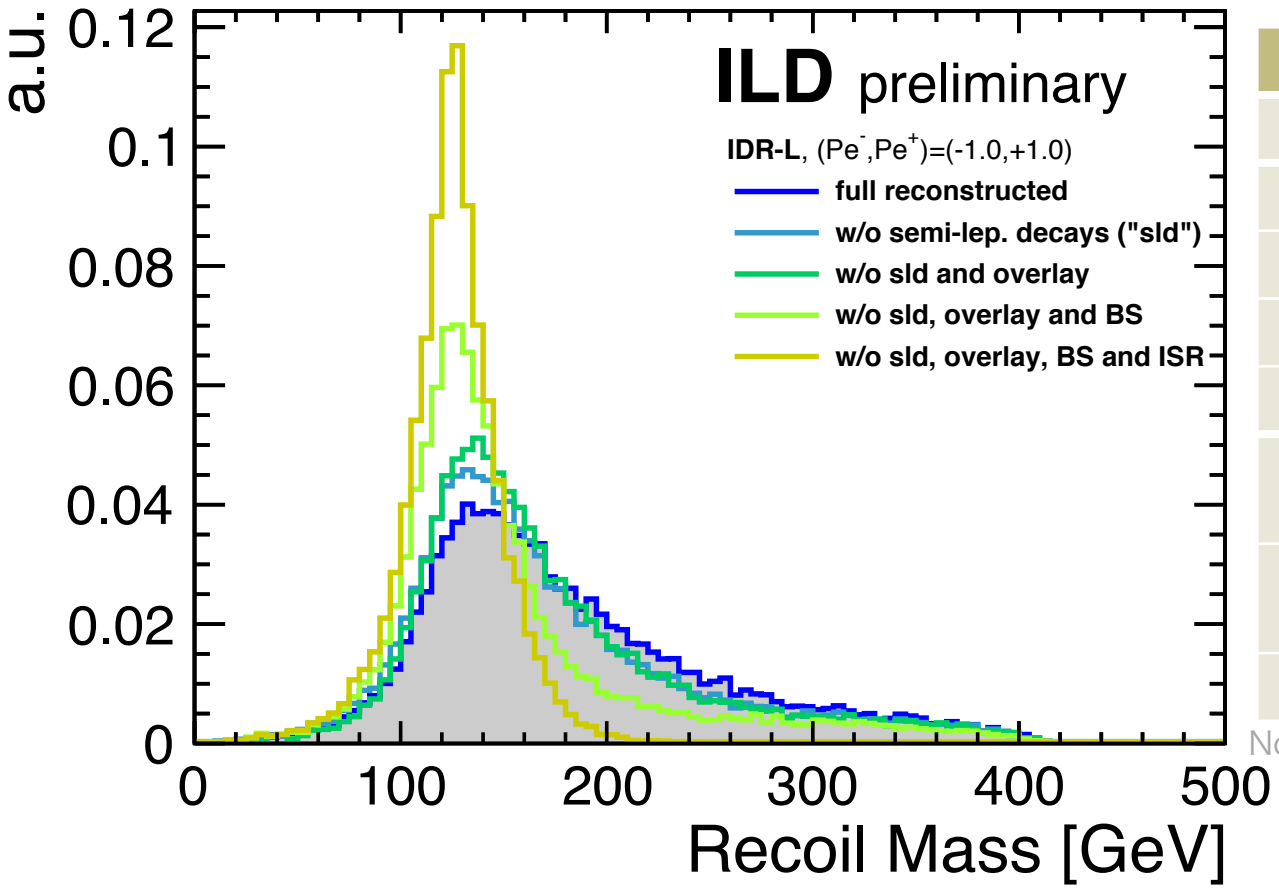
condition	UL on BR
full rec.	0.247 %
w/o sld	0.229 %
w/o overlay	0.237 %
w/o BS	0.242 %
w/o ISR	0.231 %
w/o sld & overlay	0.220 %
w/o sld & overlay & BS	0.214 %
full cheated	0.198 %

Note: only signal sample is changed.

- Yellow distribution looks almost symmetrical
  - We will assume JER effect is the remaining component

Impact of sld/overlay/BS/ISR

$\sqrt{s}$ = 500 GeV



condition	UL on BR
full rec.	0.782%
w/o sld	0.741%
w/o overlay	0.775%
w/o BS	0.749%
w/o ISR	0.632%
w/o sld & overlay	0.726%
w/o sld & overlay & BS	0.668%
full cheated	0.496%

Note: only signal sample is changed.

- For 500 GeV, the effect of BS and ISR on the high energy tail is significant

Strategy to evaluate impact of JER

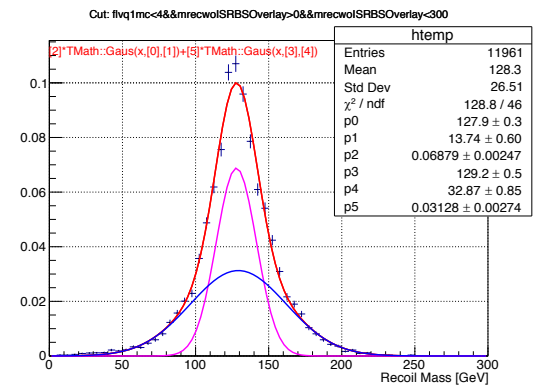
- For more detailed evaluation with current condition, brief reproduction with several JERs are performed.
- ΔMrec should be related to JER almost linearly in ideal case

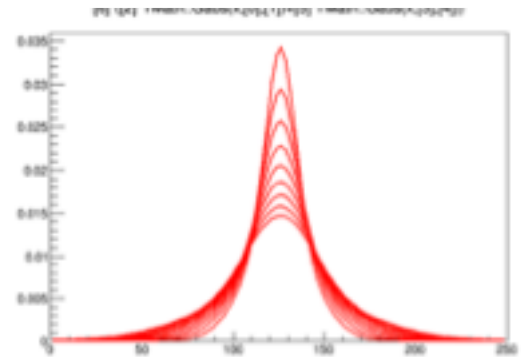
$$\Delta M_{rec} \sim \frac{\sqrt{s}}{M_{rec}} \Delta E_{jj} \propto \sqrt{(\Delta E_{j1})^2 + (\Delta E_{j2})^2}$$

How to reproduce

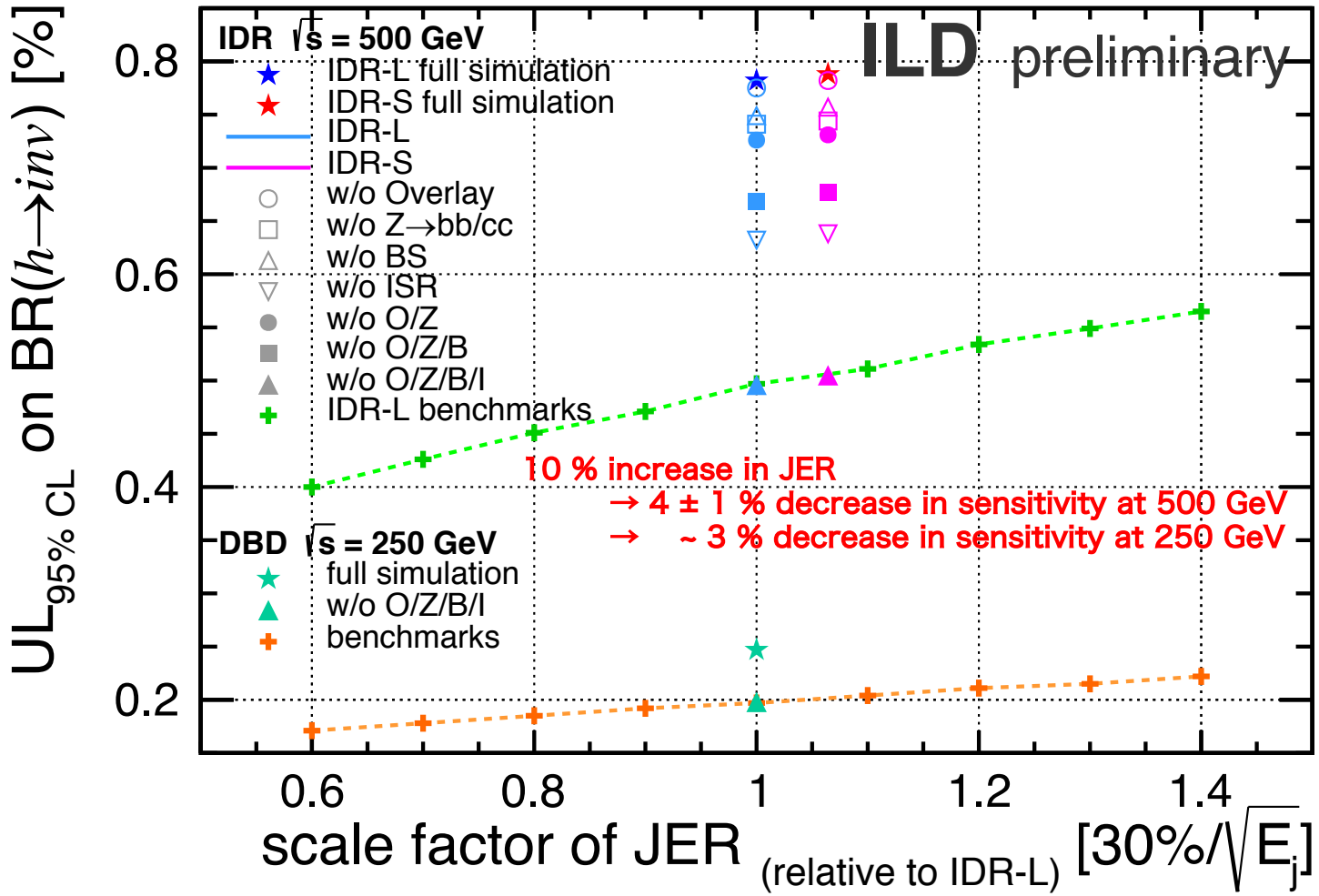
1. Apply cheats to make Mrec dist. as symmetrical as possible
2. Fit signal dist. by double-Gaussian and get p.d.f.
3. Make template function by adjusting sigma of fitted Gaussian

   $F_{temp}(x)$ = p2∗Gaus(x,p0,***factor*** ∗p1)+p5*Gaus(x,p3, ***factor*** ∗p4)
4. Do toy-MC
5. Evaluate upper limit on BR(H→inv.)





Results Summary



Conclusion

- We analyzed H→invisible at ILC with ILD full detector simulation.

  $UL_{95\%C.L.}$ on BR(H→invisible) = 0.23% at ILC250

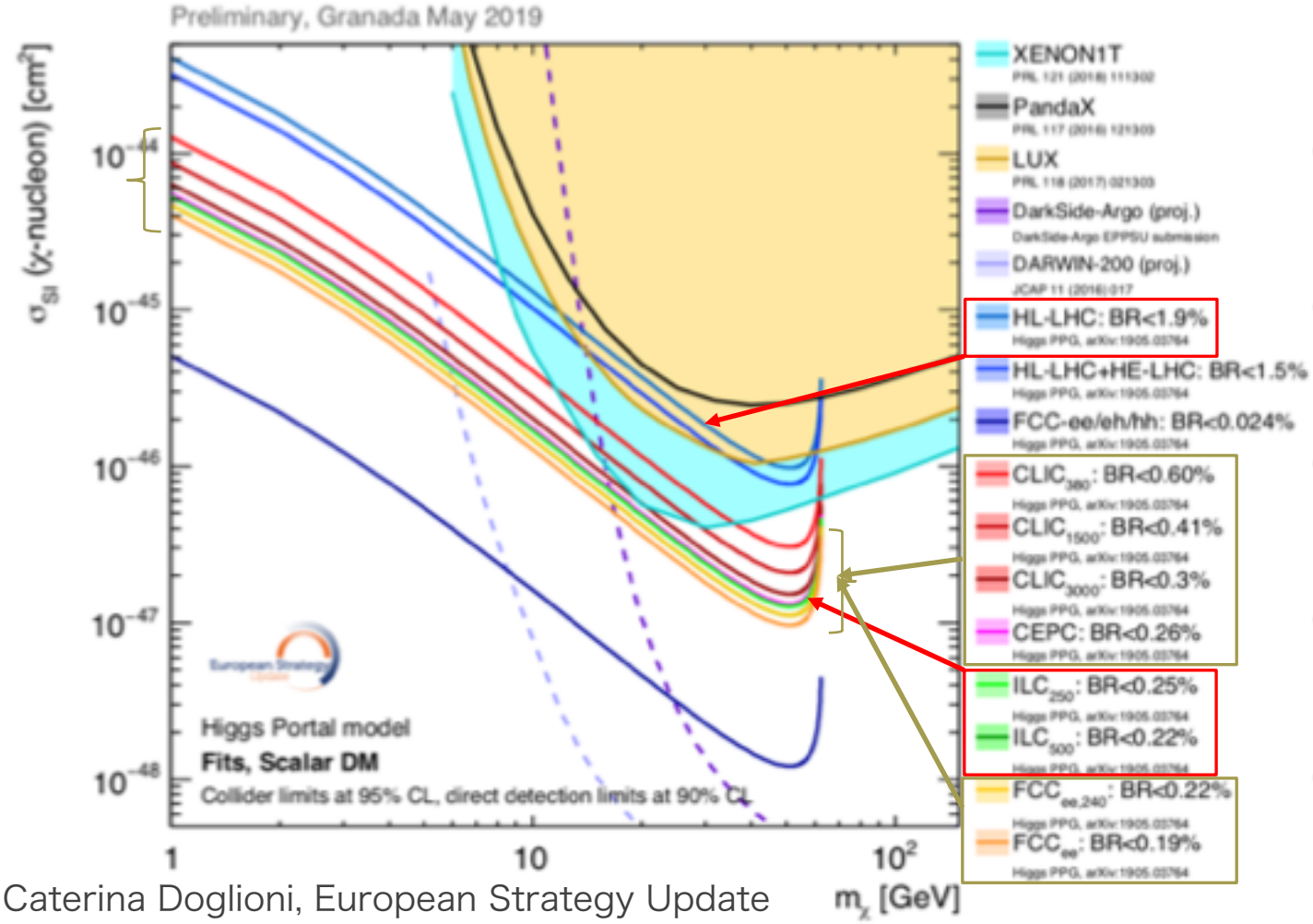
- The limitation of H→invisible at ILC is factor ~10 better than HL-LHC prospect.
- ILC is comparable with the other lepton collider projects and complementary to direct detection.
- We evaluate contamination effects separately.
- The impact of JER on H→invisible is evaluated.

  10 % increase in JER
  → ~ 3 % decrease in sensitivity at 250 GeV
  → 4 ± 1 % decrease in sensitivity at 500 GeV

backup

Impact on search for Dark Matter

- Each of the lines shows the limit of Scalar DM in the κ framework.



Caterina Doglioni, European Strategy Update

Impact on search for Dark Matter

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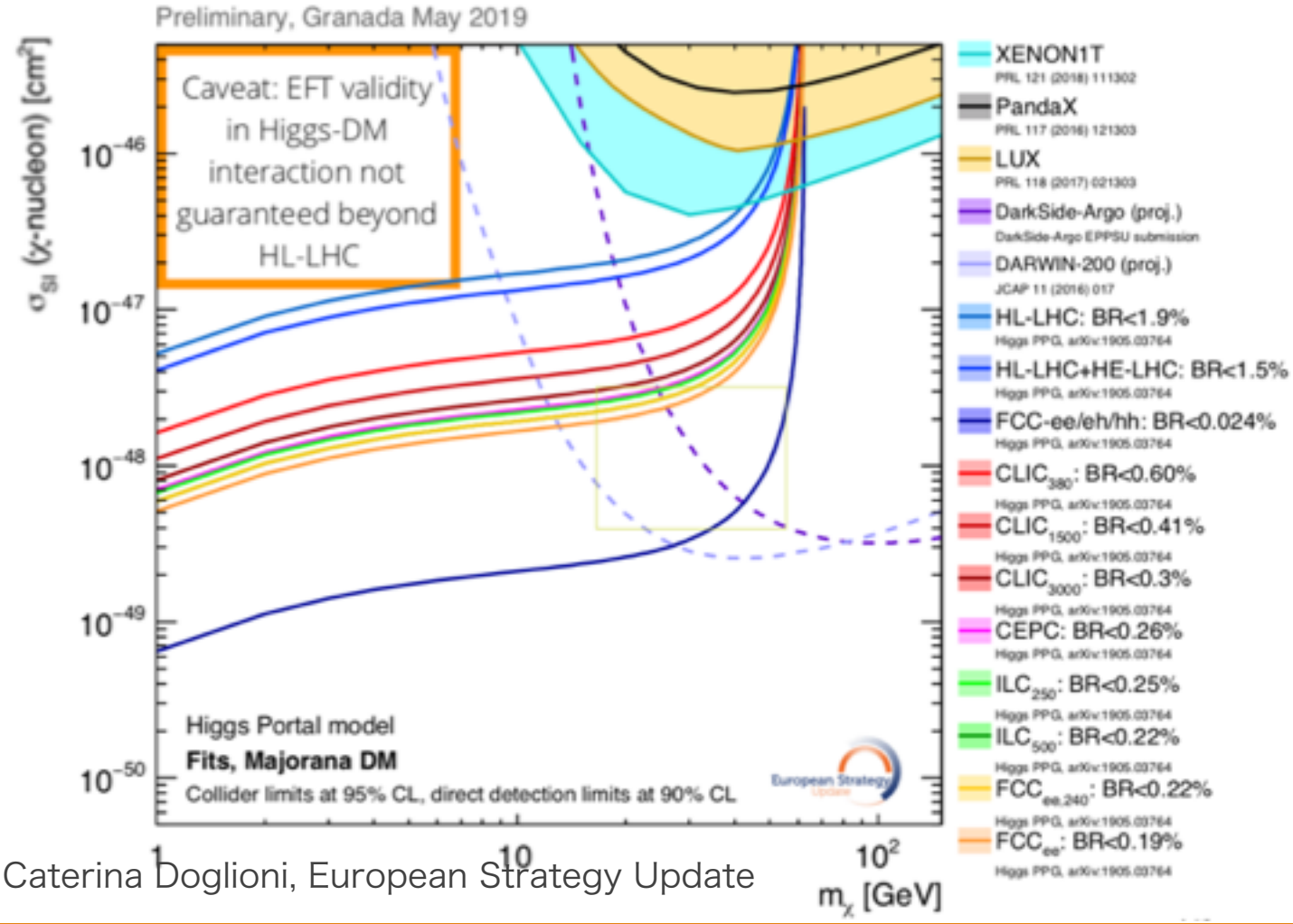


Caterina Doglioni, European Strategy Update

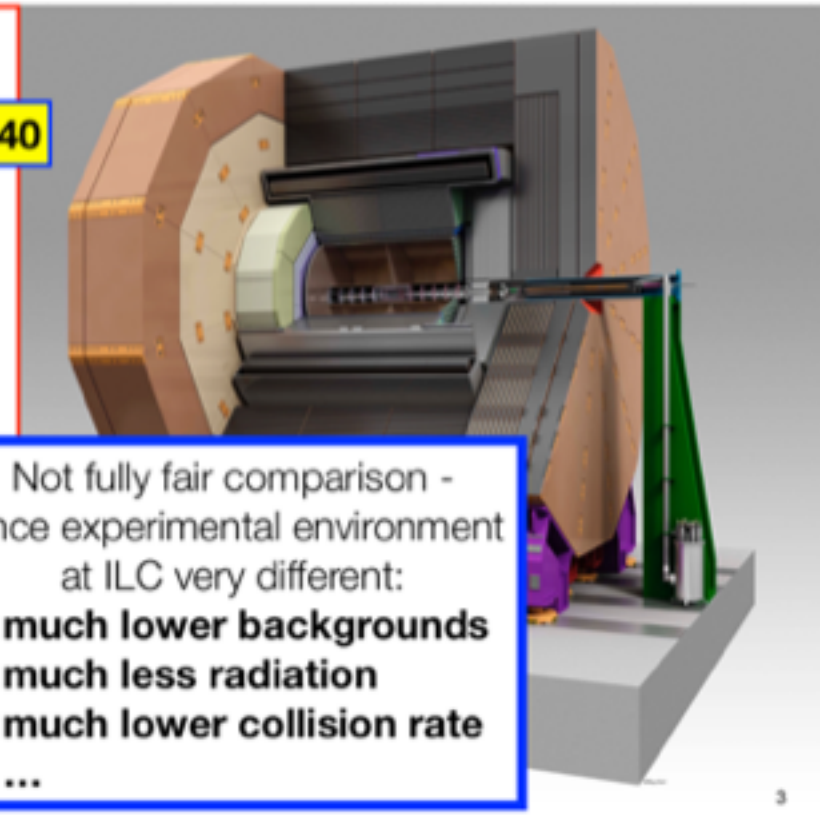
The ILD Concept

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$ **≈ CMS / 40**
- **vertexing** ($H \to bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$ **≈ CMS / 4**
- **jet energy resolution** 3-4% ($H \to$ invisible) **≈ ATLAS / 2**
- **hermeticity** $\theta_{min} = 5$ mrad ($H \to$ invis, BSM) **≈ ATLAS / 3**

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Not fully fair comparison - since experimental environment at ILC very different:

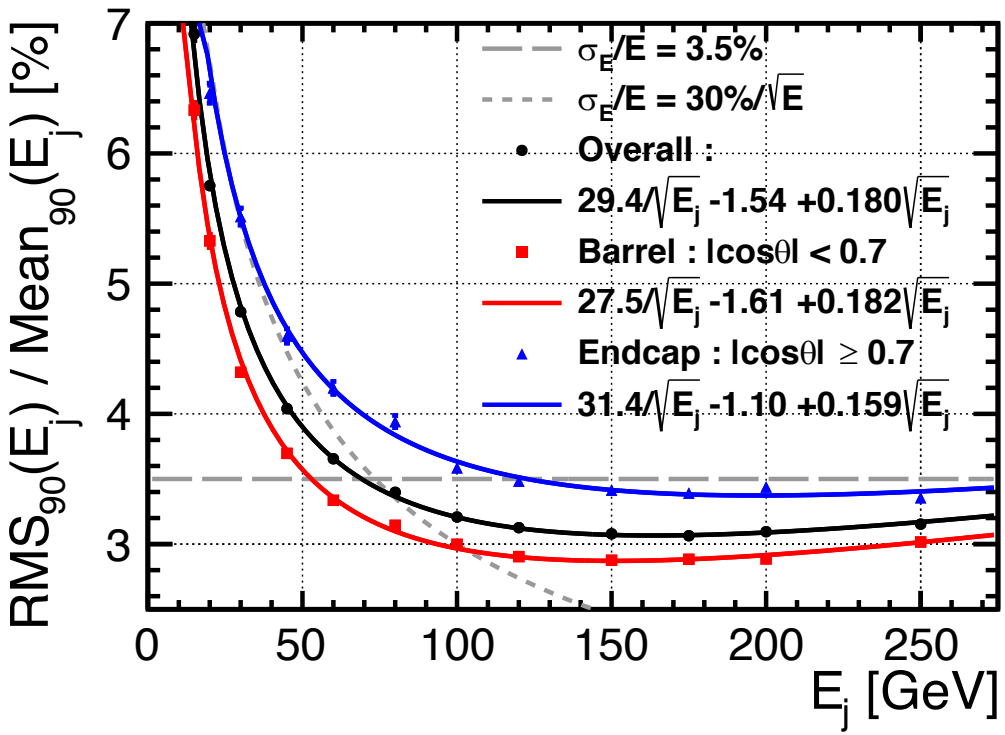
- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**
- **...**

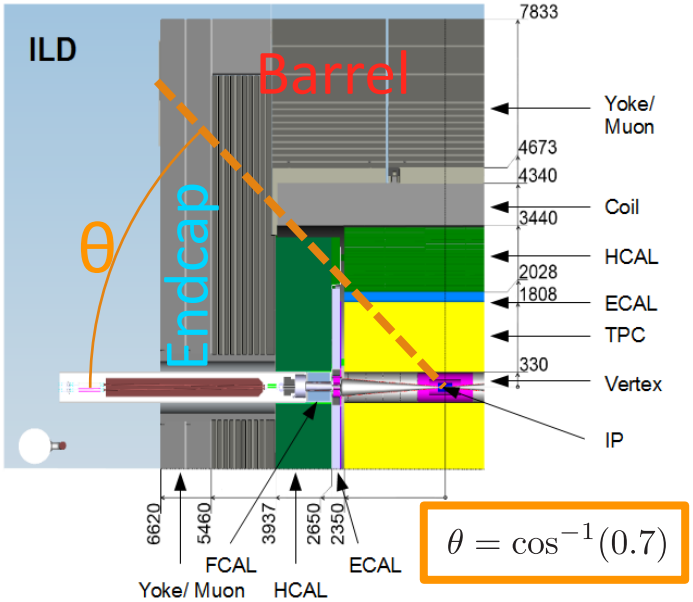
Jenny List, LCWS2018

JER: Comparison Barrel/Endcap

JER was evaluated separately for barrel and endcap regions.

rv02-00-01.sv02-00-01.mILD_l5_o1_v02_nobg



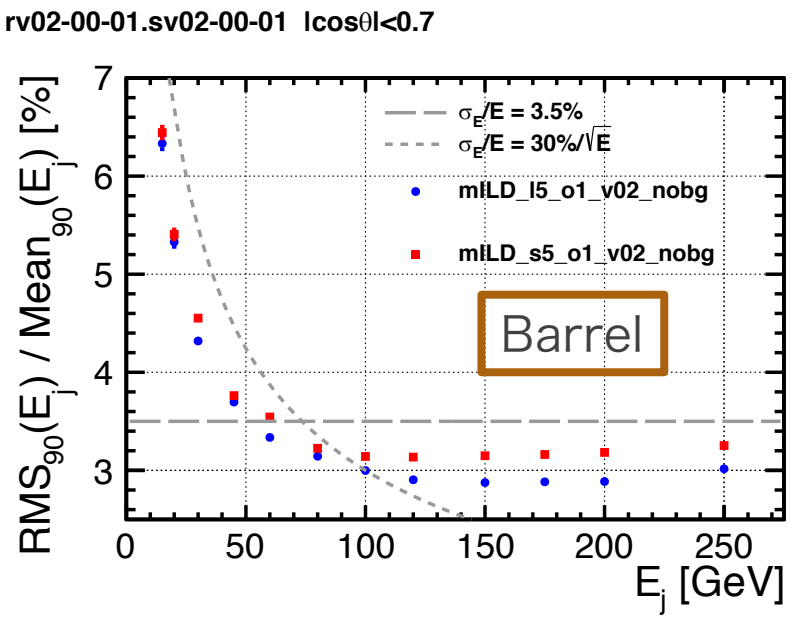


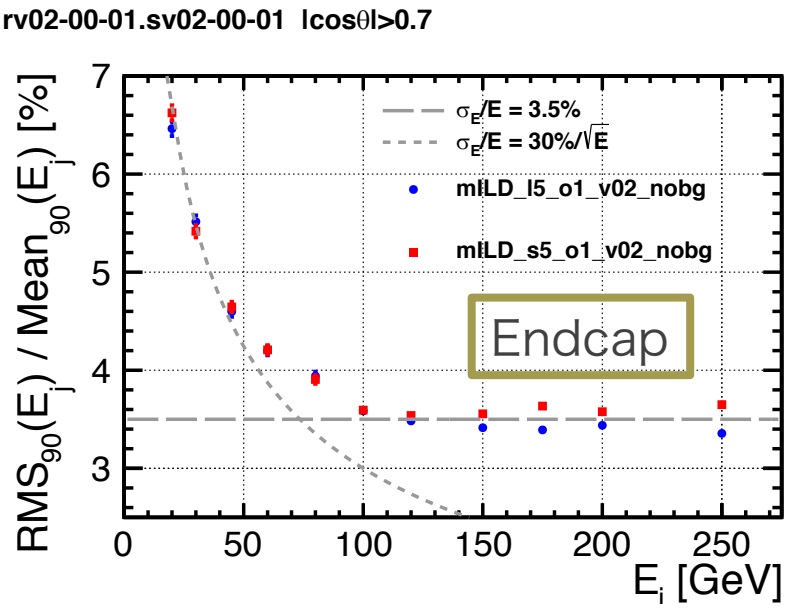
$$\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta(E)$$

	α	β
Overall	29.4	-1.54+0.180√E
Barrel	27.5	-1.61+0.182√E
Endcap	31.4	-1.10+0.159√E

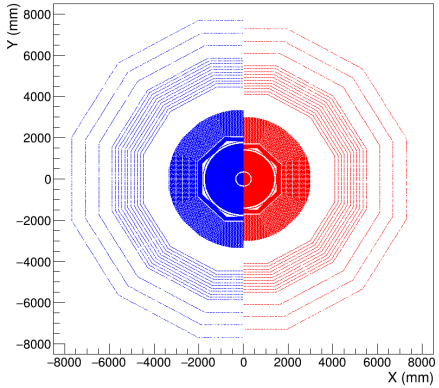
JER: Comparison Large/Small

The two detector models (large/small) were evaluated for comparison.





There are Just a little, but significant difference.



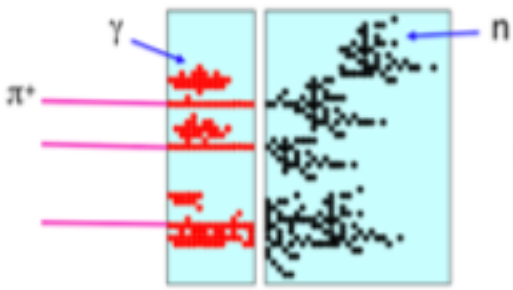
Particle Flow Algorithm

Particle Flow Algorithm

The energy(momentum) of each particle is extracted from the subdetector system in which we expect the most accurate measurement.

Charged particles → Tracker
Photon → E Cal.
Neutral particles → H Cal.

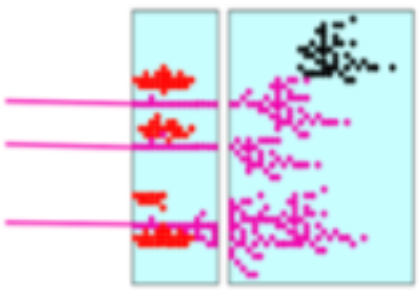
Previous



$E_{JET} = E_{ECAL} + E_{HCAL}$

$\gtrsim 55\%/\sqrt{E(\mathrm{GeV})}$

PFA



$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

$\lesssim 30\%/\sqrt{E(\mathrm{GeV})}$

Event Selection

1. isolated lepton veto: $N_{lep}=0$
2. loose restriction
   [transverse di-jet momentum, di-jet mass, recoil mass]
3. # of PFOs and charged tracks: $N_{pfos} > 15$, $N_{tracks} > 6$
4. di-jet trans-momentum: $Pt_Z = \{(20,80)_{250},(50,250)_{500}\}$
5. di-jet mass: $M_Z = \{(80,100)_{250},(80,120)_{500}\}$
6. di-jet polar angle: $|\cos\theta_Z| < \{0.9_{250},0.98_{500}\}$
7. recoil mass: M_{recoil}

not yet:

- multi-variate analysis: Boosted Decision Tree (BDT)
- kinematic fit: Z mass constraint, JER

J. Tian, the 41th ILC General Physiscs Meeting

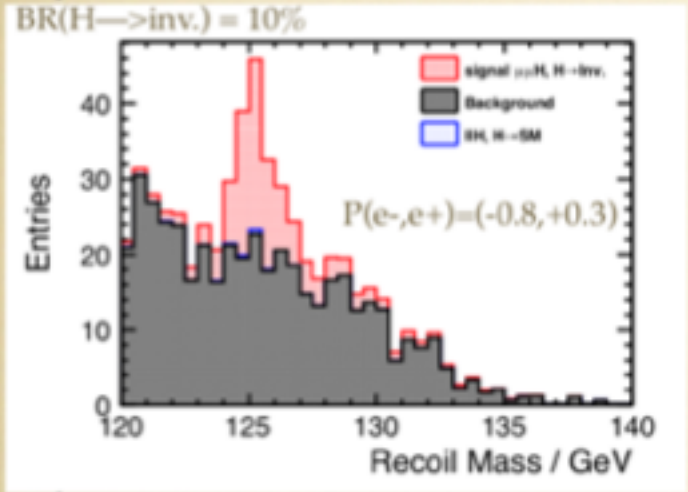
upper limit of H—>invisible (95% CL)

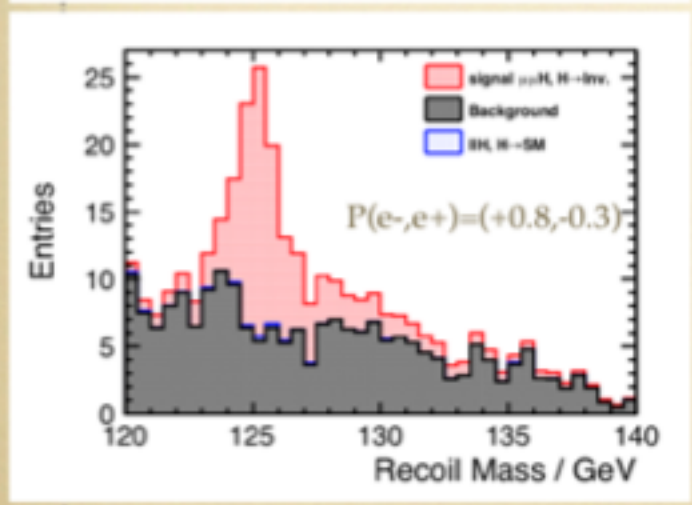
BR(inv) upper limit	Z—>ll	(-0.8,+0.3)	(+0.8,-0.3)
250 fb^{-1} @ 250 GeV	μμH	2.46%	1.57%
	eeH	3.56%	2.22%
	combined	2.02%	1.28%
330 fb^{-1} @ 350 GeV	μμH	2.36%	2.09%
	eeH	4.17%	3.42%
	combined	2.05%	1.78%
500 fb^{-1} @ 500 GeV	μμH	4.31%	3.28%
	eeH	6.78%	4.46%
	combined	3.64%	2.64%

J. Tian, ALCW2015

ILC 250 & 350 GeV & 500 GeV

update of H—> invisible analysis





new: include Z—>ll contribution, though Br is much smaller than Br(Z—>qq), S/B is much higher;
comparable in particular at higher centre-of-mass energies

BR(inv) upper limit	P(e-,e+) =(-0.8,+0.3)	P(e-,e+) =(+0.8,-0.3)
250 fb^{-1} @ 250 GeV	0.86%	0.61%
330 fb^{-1} @ 350 GeV	1.23%	1.10%
500 fb^{-1} @ 500 GeV	2.39%	1.73%

combined results including Z—>qq

J. Tian at the 41st ILC General Physics Meeting

A. Ishikawa at LCWS14

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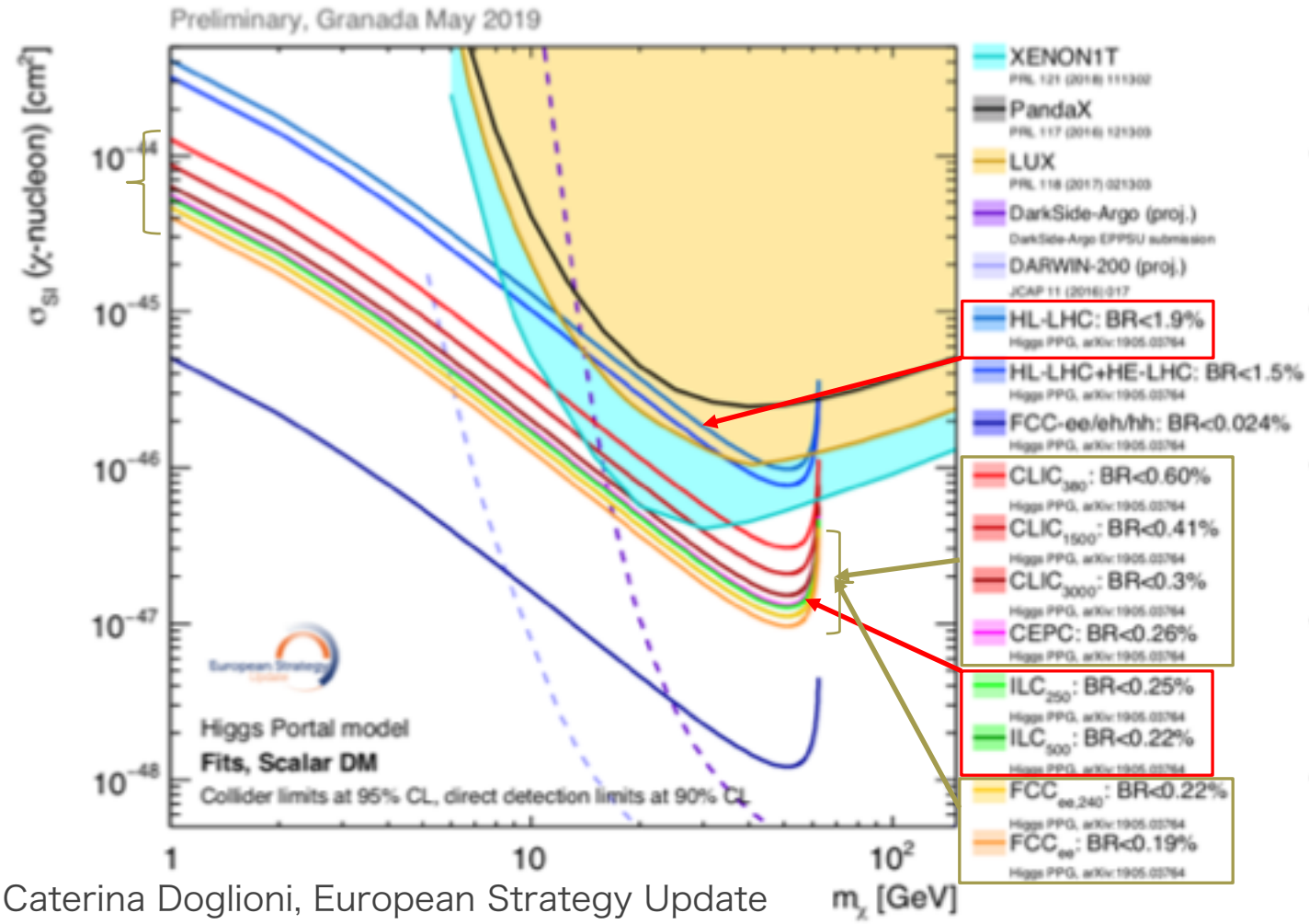
Higgs Boson studies at future particle colliders - Preliminary Version -

Table 13. Limits on the invisible BR of the Higgs boson for decays to new particles. The SM decay, $H \to 4\nu$, has been subtracted as a background. Given are the values of the direct searches using missing (transverse) momentum searches, the constraint derived from the coupling fit (see Table 5) in the kappa-3 scenario, and the result from a fit in the κ framework where only modifications of BR_{inv} are allowed.

Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
FCC-ee_{240}	0.3	0.22	0.22
FCC-ee_{365}		0.19	0.19
ILC_{250}	0.3	0.26	0.25
ILC_{500}		0.22	0.22
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30

Impact on search for Dark Matter

- Each of the lines shows the limit of Scalar DM in the κ framework.



Caterina Doglioni, European Strategy Update

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M. Kurata, LCWS2018

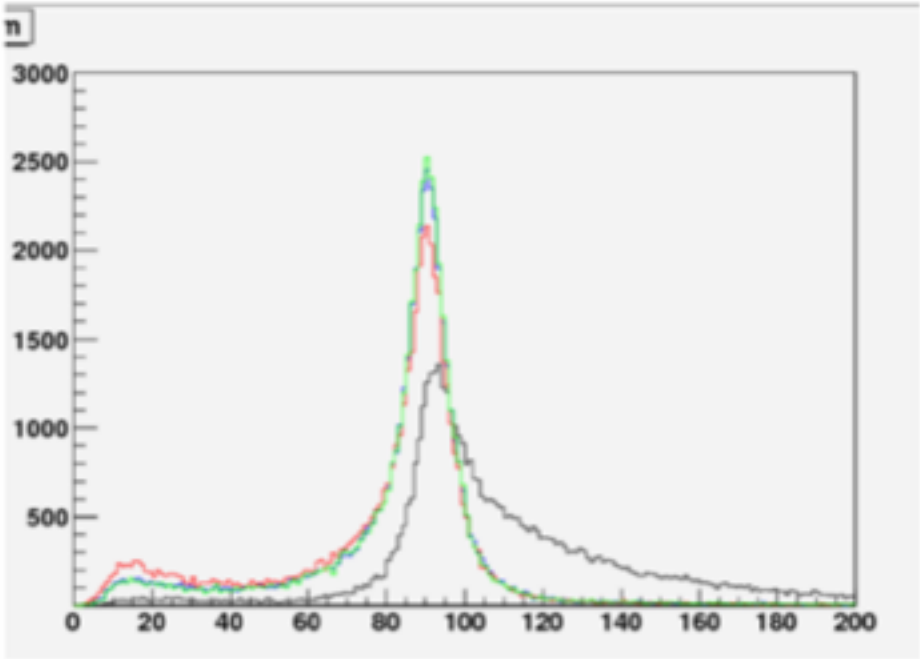
Beam background rejection

- $y_{ij} = \frac{\min(E_i^2, E_j^2)(1-\cos\theta)}{E_{vis}^2}$, $y_{beam} = \frac{2E_i^2\alpha^2(1-\cos\theta)}{E_{vis}^2}$

  α: beam rejection parameter

  smaller→ beam rejection becomes stronger

  - Particle i with $y_{ij}>y_{beam}$ is discarded



vvZ@500GeV(DBD)

- 2 jet clustering
- Parameters are tuned for better result

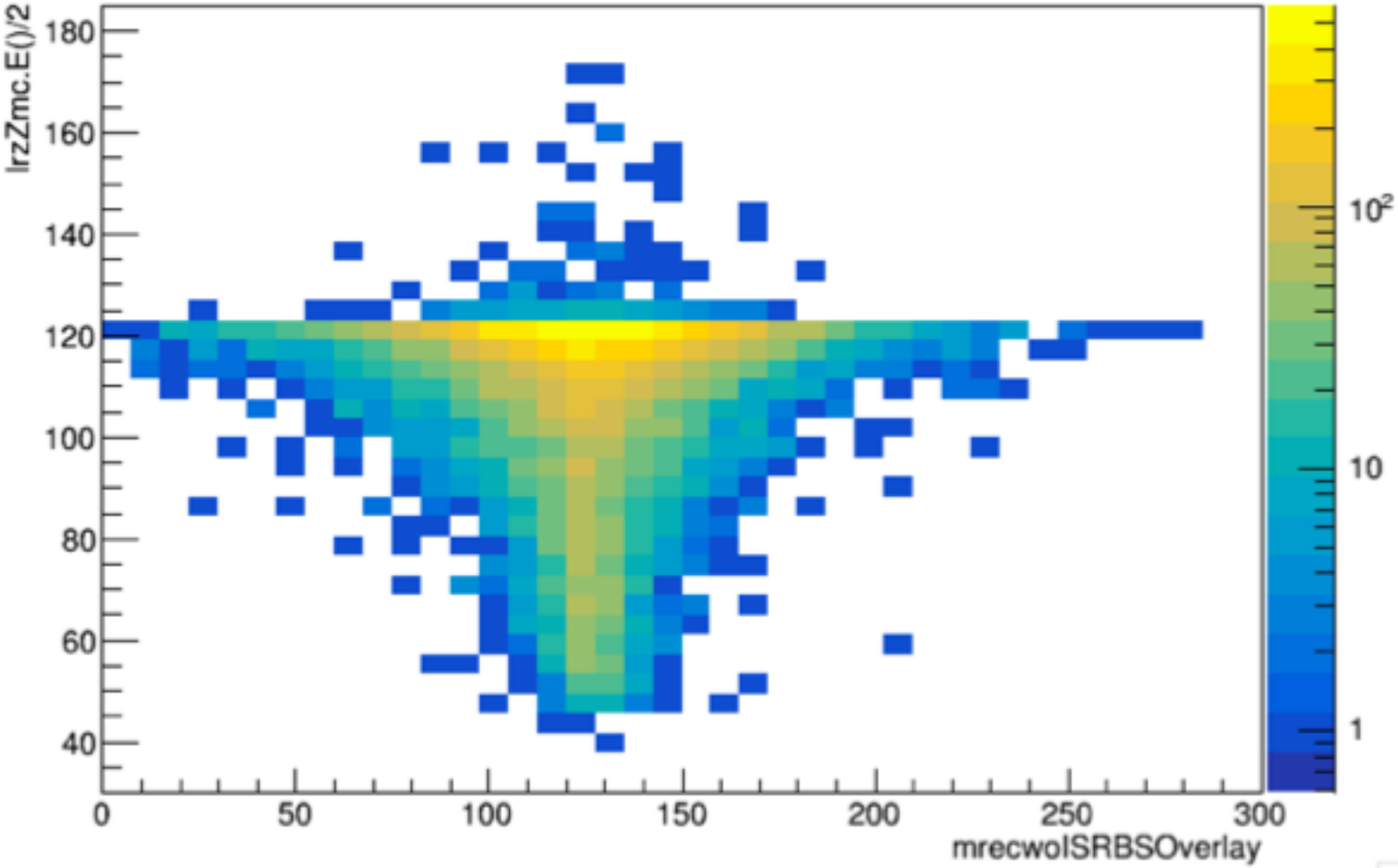
w/o beam b.g. rejection

Kt

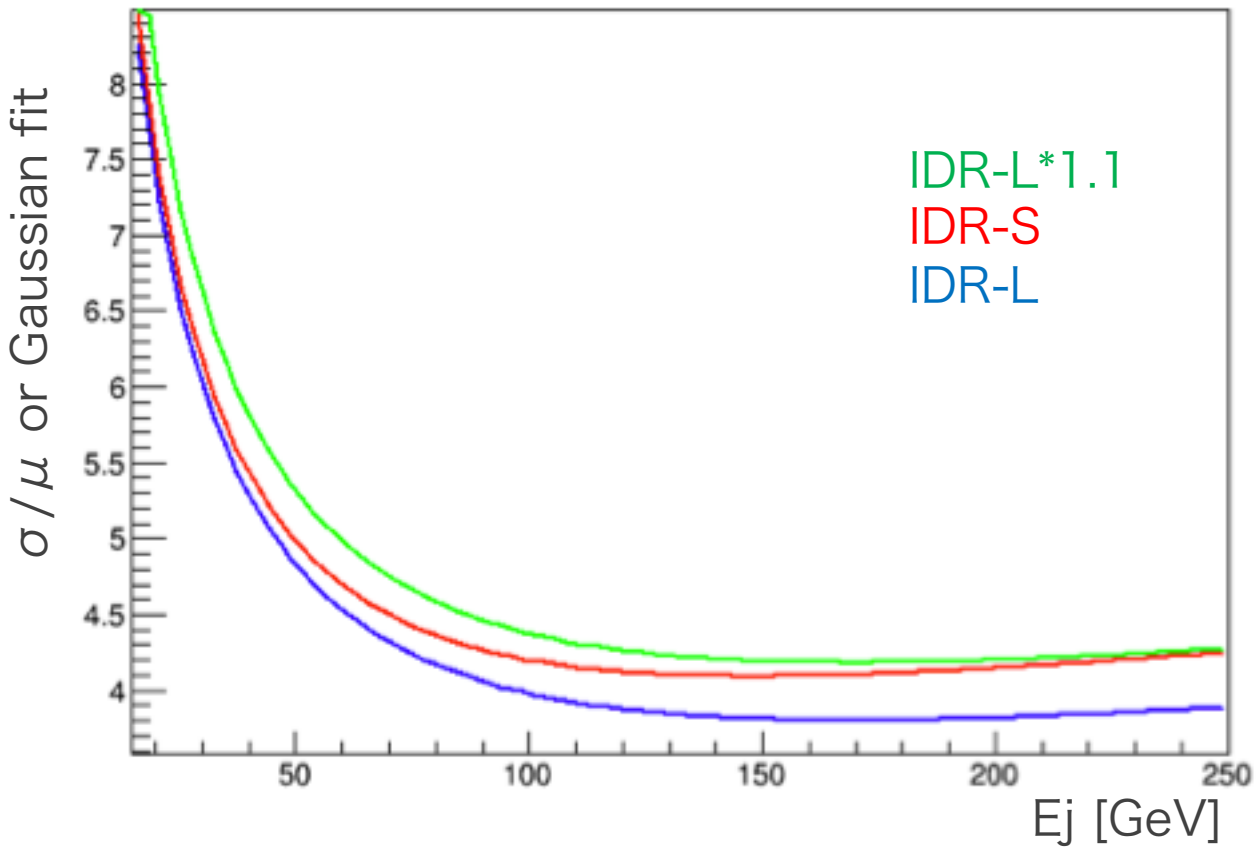
Durham

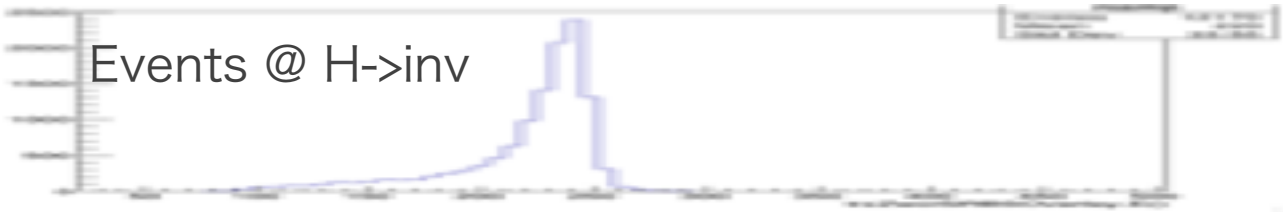
Valencia

ΔMrec vs Ej^{mc}

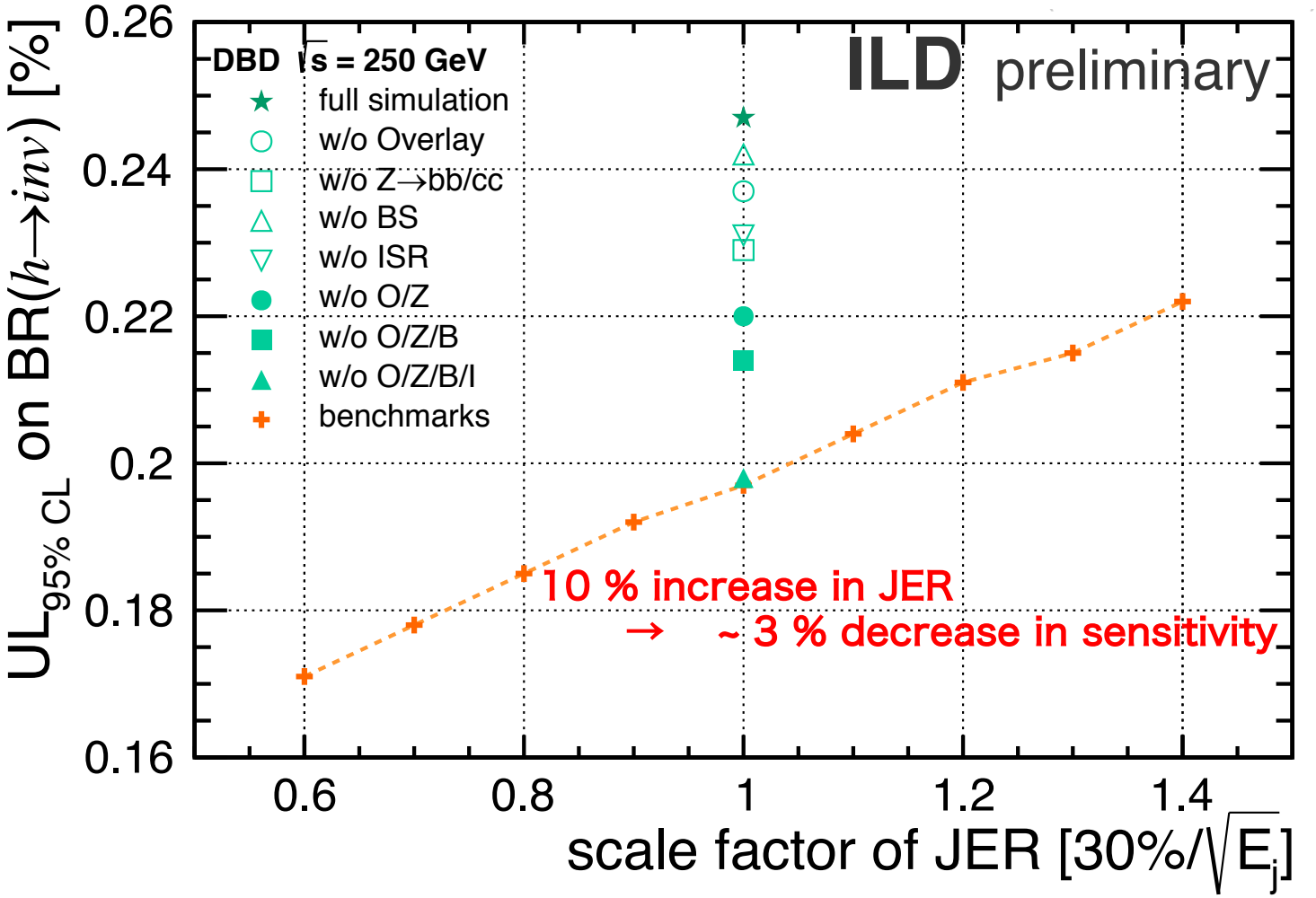


How to relate ΔMrec and JER...?

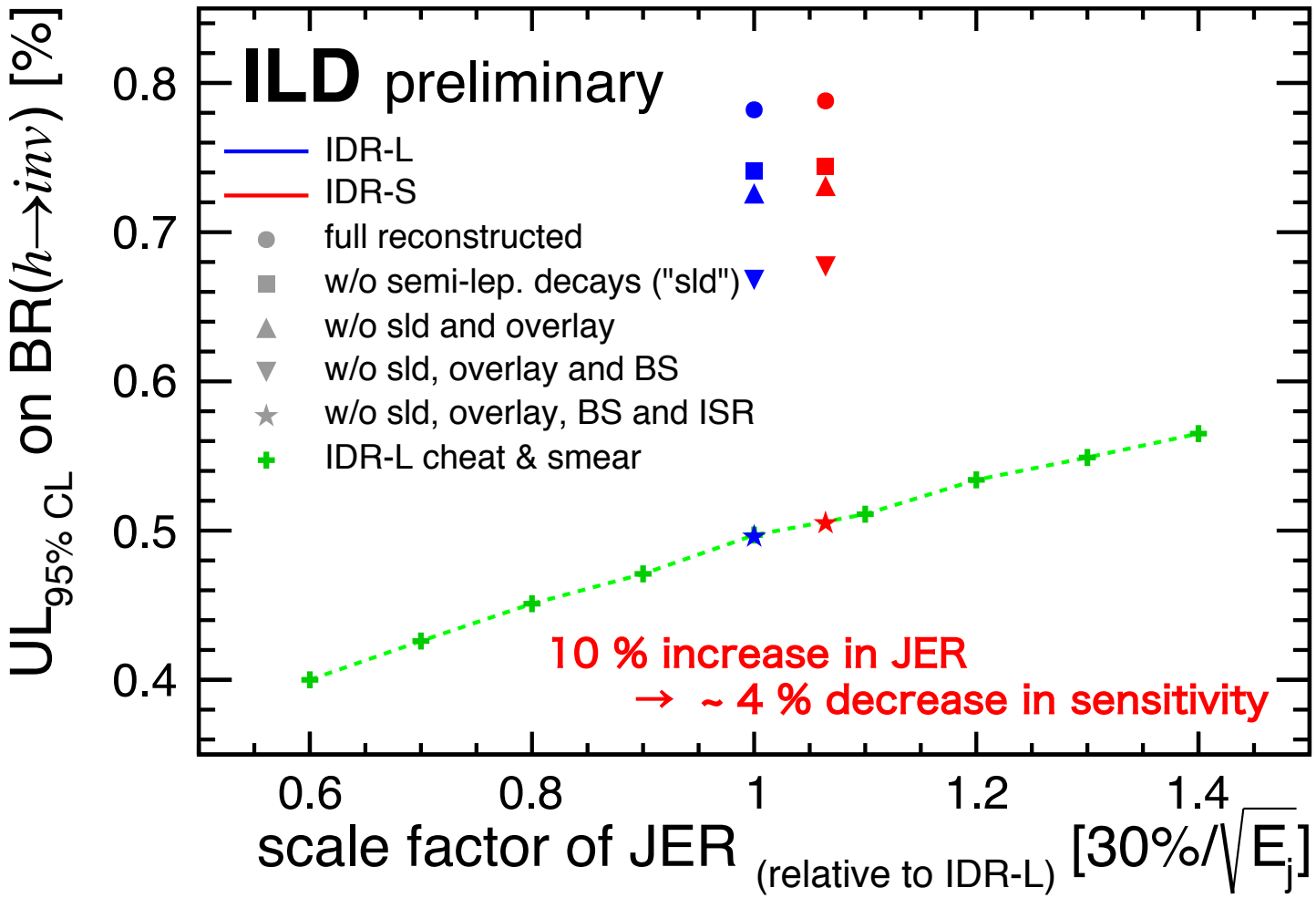




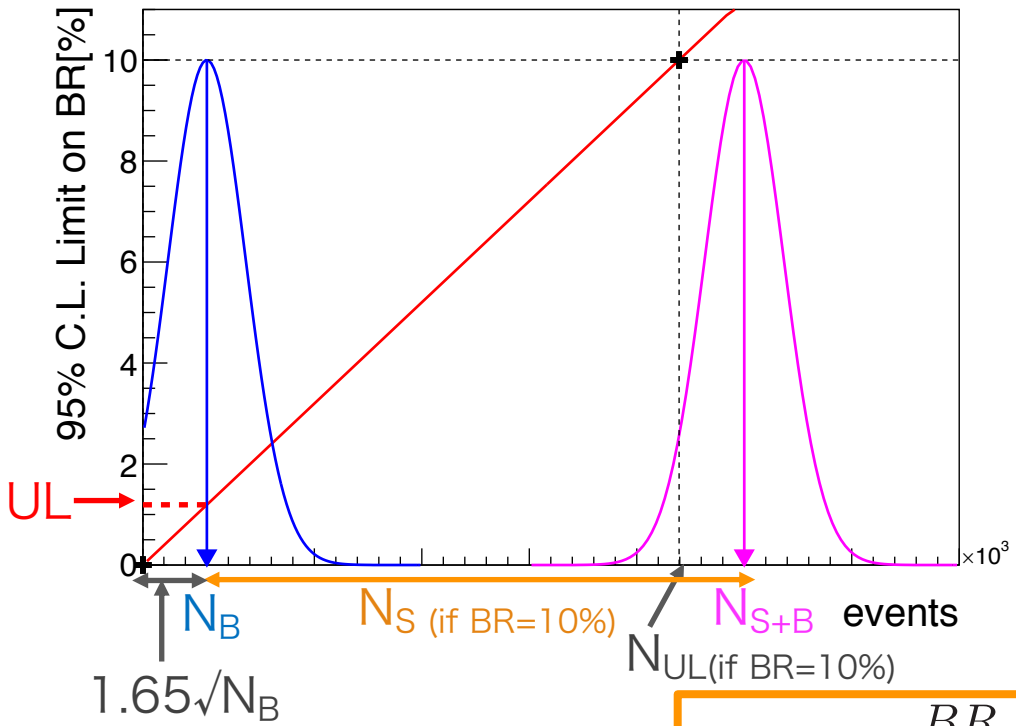
Benchmark Results @ 250 GeV



Benchmark Results @ 500 GeV



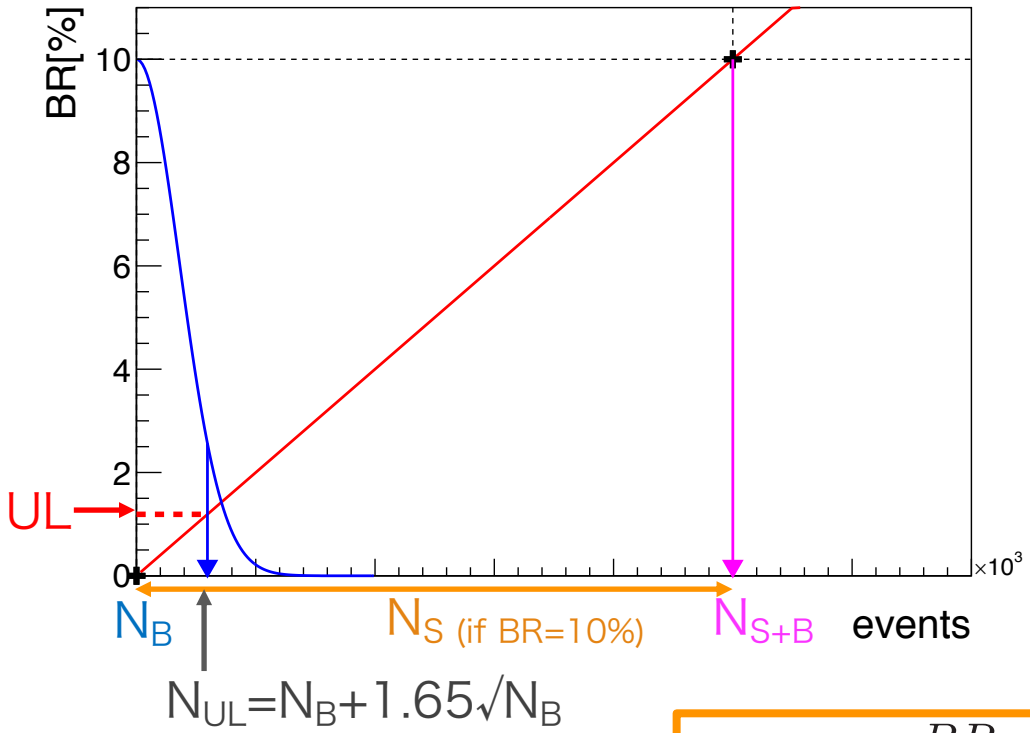
How to set Upper Limit (1)



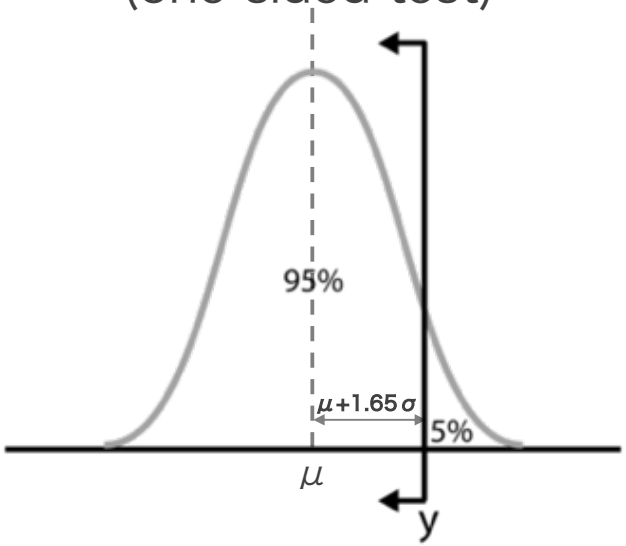
definition of 95% C.L.
(one-sided test)

$$
\begin{aligned}
UL(\%) &\equiv \frac{BR_{\text{assumed}}[\%]}{N_S(BR_{\text{assumed}})} \times \sigma(N_B, \text{CL}) \\
&\cong \frac{10[\%]}{N_S(BR = 10[\%])} \times 1.65\sqrt{N_B}\ (\text{CL} = 95\%) \\
&\simeq \frac{10[\%] \times 1.65}{significance(BR = 10[\%])}
\end{aligned}
$$

How to set Upper Limit (2)



definition of 95% C.L.
(one-sided test)



$$
\begin{aligned}
UL(\%) &\equiv \frac{BR_{\text{assumed}}[\%]}{N_S(BR_{\text{assumed}})} \times \sigma(N_B, \text{CL}) \\
&= \frac{10[\%]}{N_S(BR = 10[\%])} \times 1.65\sqrt{N_B}\ (\text{CL} = 95\%) \\
&\simeq \frac{10[\%] \times 1.65}{significance(BR = 10[\%])}
\end{aligned}
$$