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CEPC

北京大学
PEKING UNIVERSITY

The top mass and other opportunities at the $t\bar{t}$ threshold with CEPC

CEPC DAY (September 22nd, 2021)

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on behalf of
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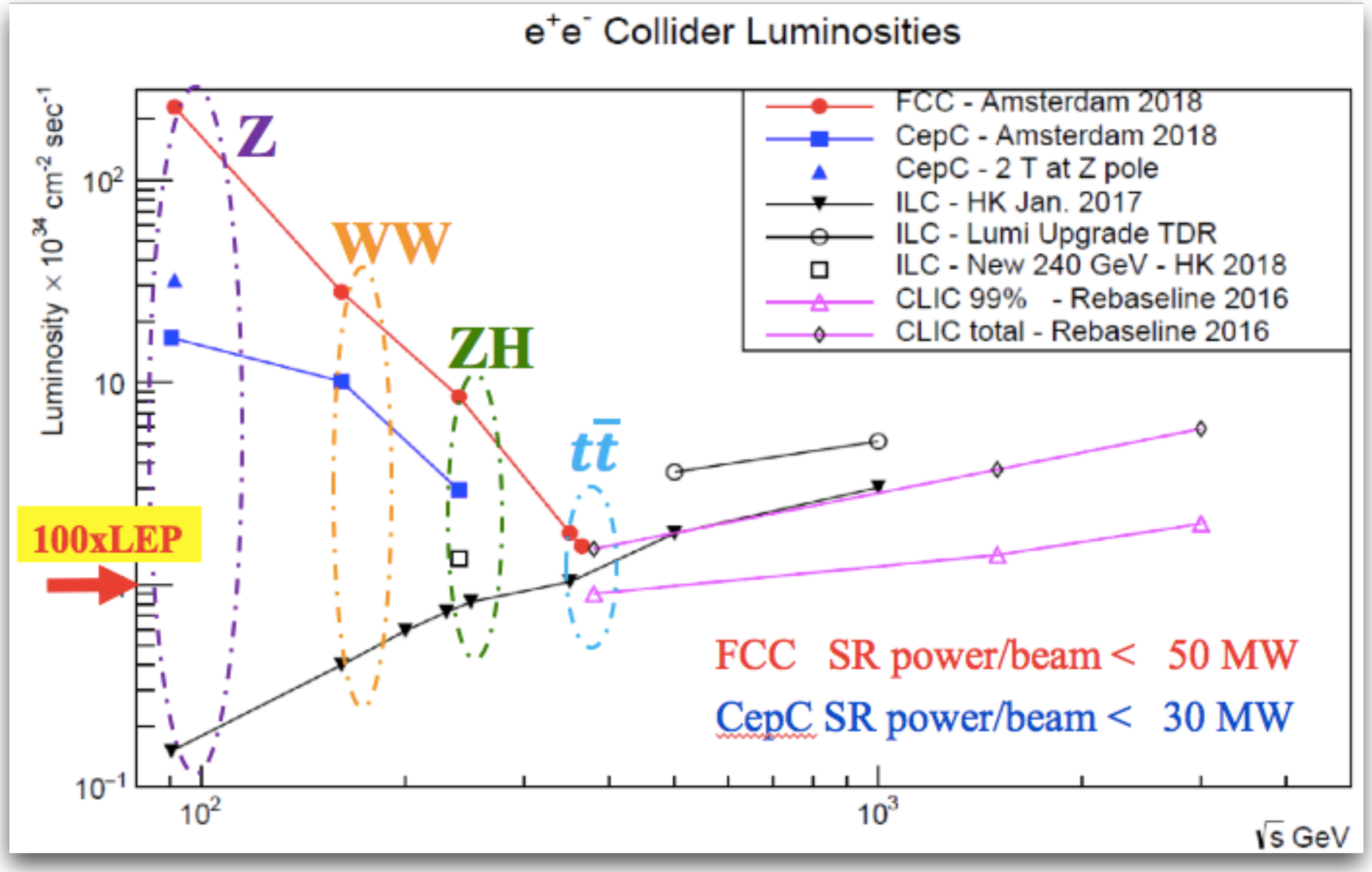
Introduction

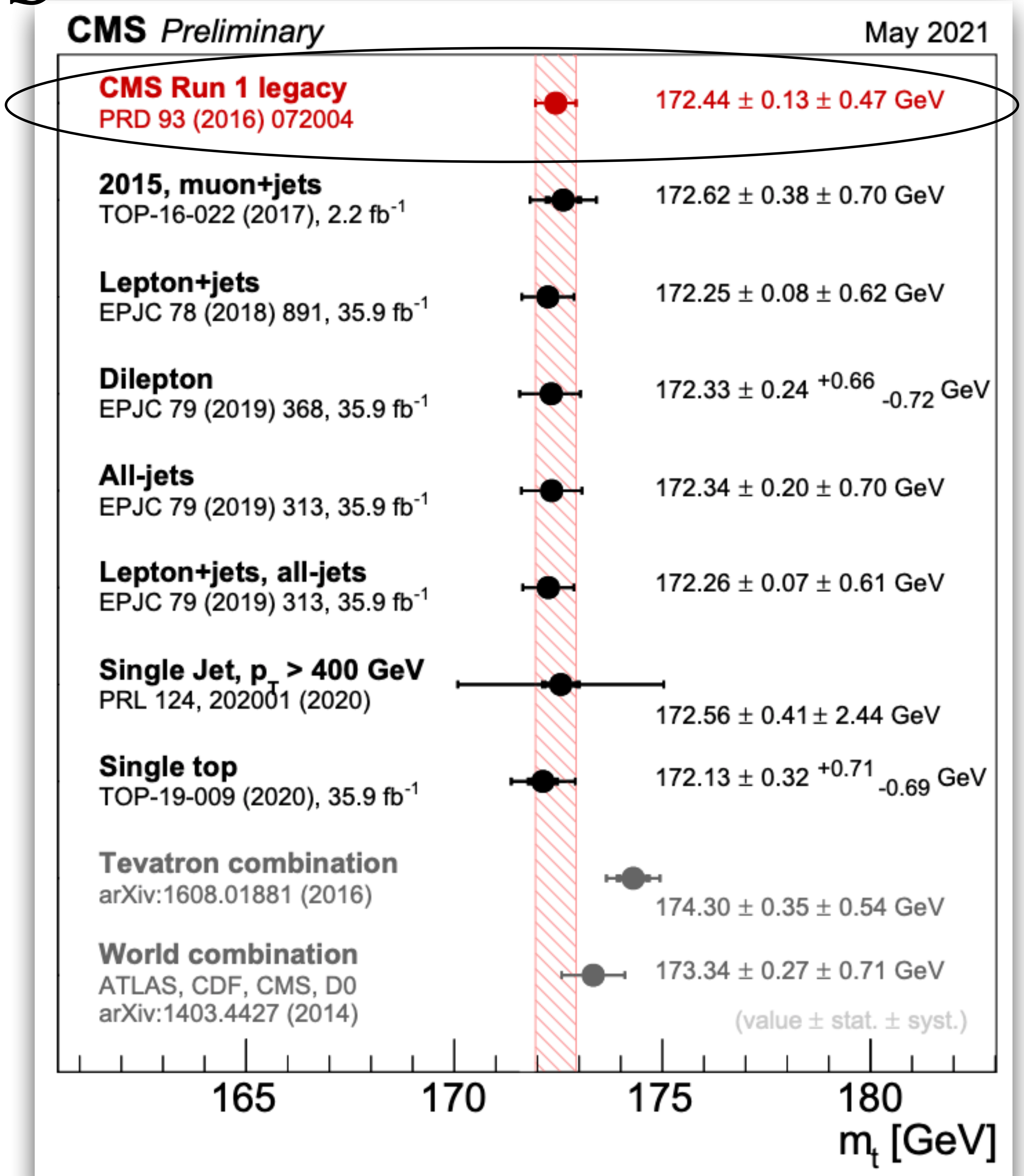
- CEPC will be a versatile machine with many opportunities
  - Higgs factory @~240 GeV
  - Diboson factory @~160 GeV
  - Z factory @~90 GeV
- @~360 GeV it can also be a playground for
  - Top precision measurements
  - Higgs complementary measurements
  - BSM searches



F. Bedeschi

Top mass measurements

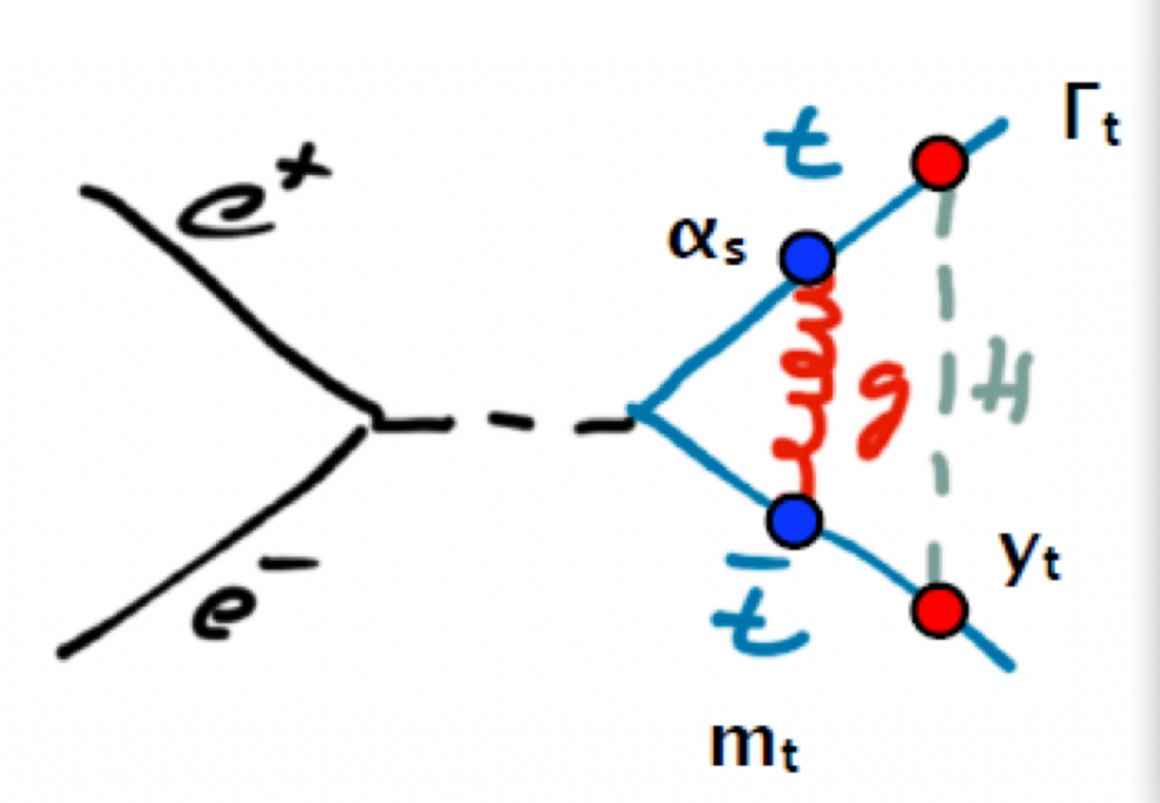
- The top mass is measured using top reconstruction at hadron colliders
  - Heavily relies on the performance of MET (the neutrino) and jet energy scale/resolution uncertainties
- CMS Run1 combined uncertainty reached ~500 MeV dominated by systematic uncertainties
- Very difficult to further improve the precision given dominant systematic uncertainties at hadron colliders



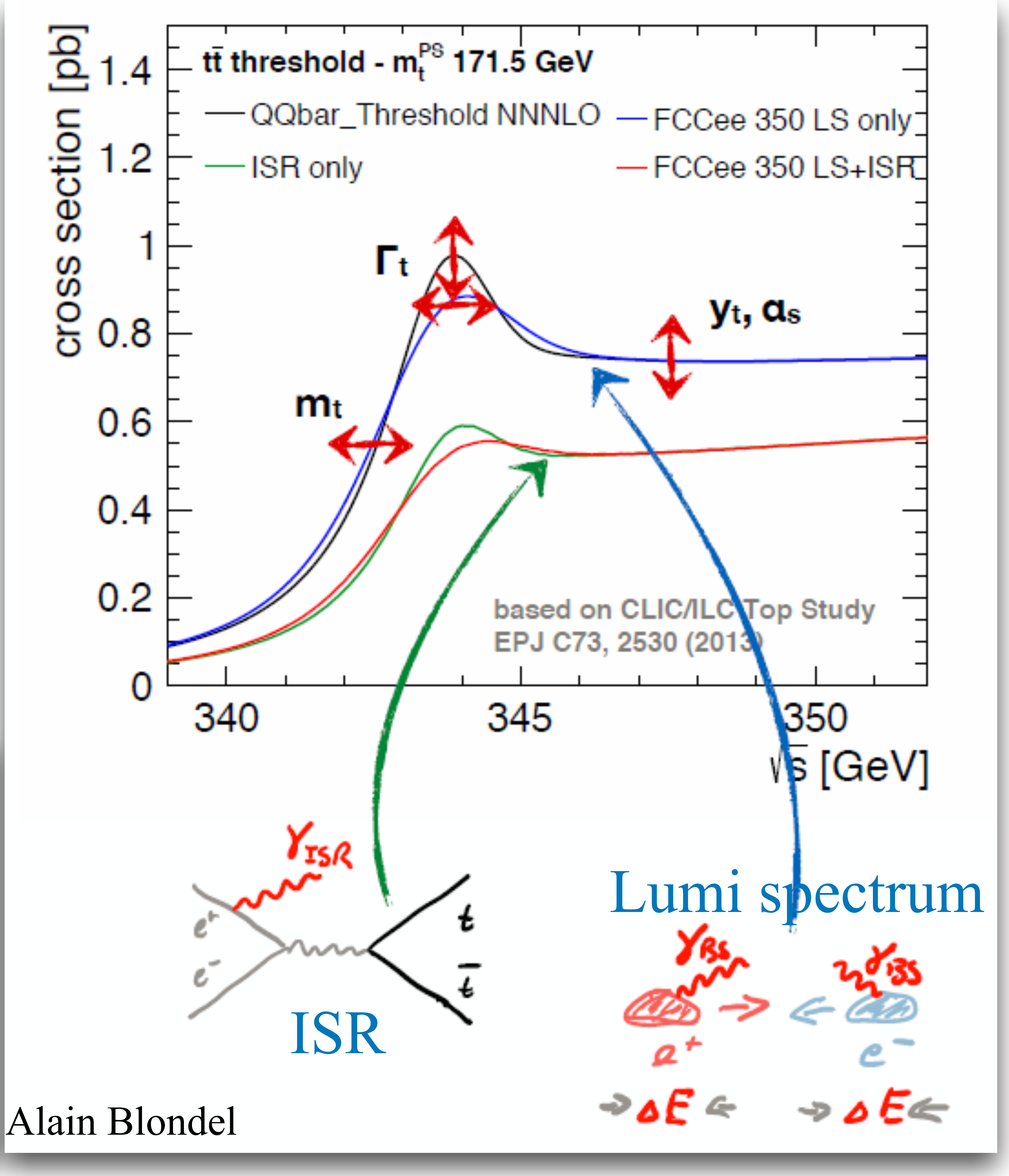
tt threshold scan

- ee-colliders provide not only the top reconstruction method but also the tt threshold scan
- The scan is made against $\sqrt{s}$ and cross-section is the direct observable
- This brings measurements of top mass and a bunch of other parameters
  - Top width
  - Top Yukawa coupling
  - α_S

FCC-ee expects a top mass error of ~17 MeV



EPJC 73,(2013)2530



Alain Blondel

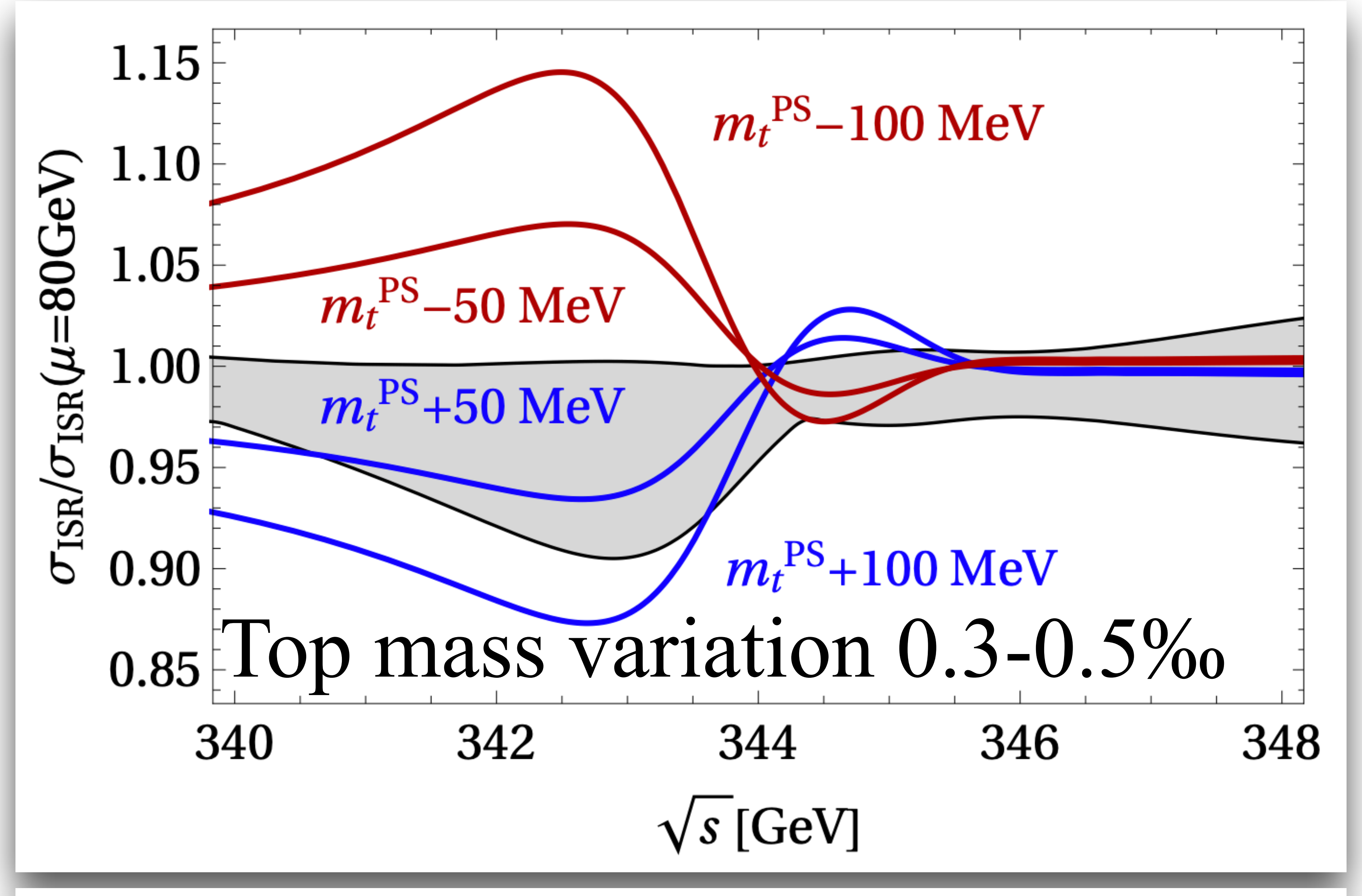
Our setup

Comput. Phys. Commun. 209 (2016) 96-115
JHEP 1802 (2018) 125

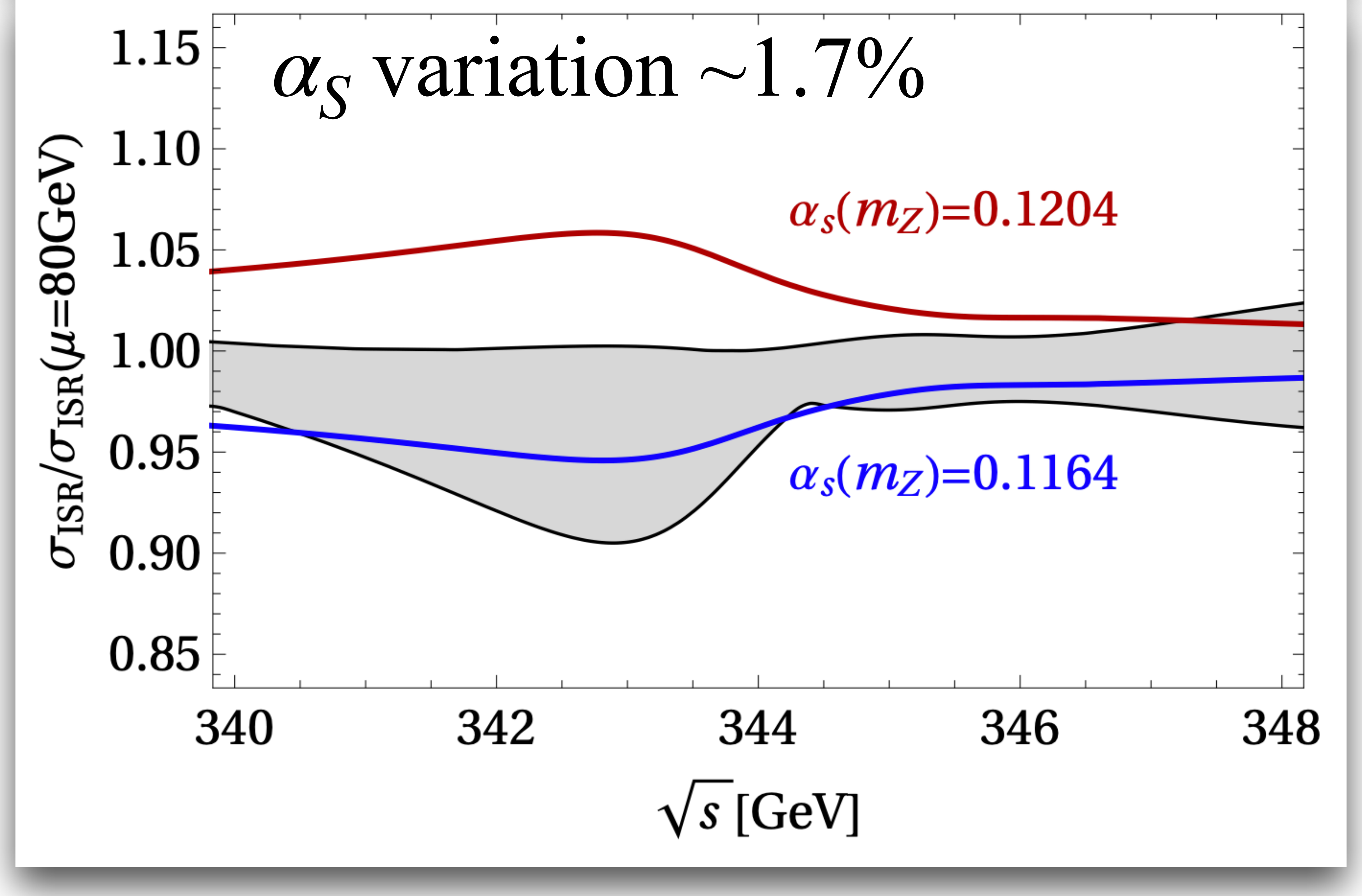
- Use the package “QQbar_threshold” to calculate cross-section near threshold in ee-colliders at N³LO in resummed non-relativistic perturbation theory
  - Coulomb interactions between the quark and the antiquark leading to a strong enhancement of the cross section is included
  - To avoid IR renormalon ambiguities, the PS shift (PSS) mass scheme is applied by default in the package

$$\boxed{m_t^{\rm PS} = 171.5\,\text{GeV}, \qquad \alpha_s(m_Z) = 0.1184}$$

  - ISR effects are also included in the package
- We incorporate luminosity spectrum (LS) by a simple Gaussian function with the CEPC expected beam resolution (~500 MeV) as a function of $\sqrt{s}$



Top mass variation 0.3-0.5‰



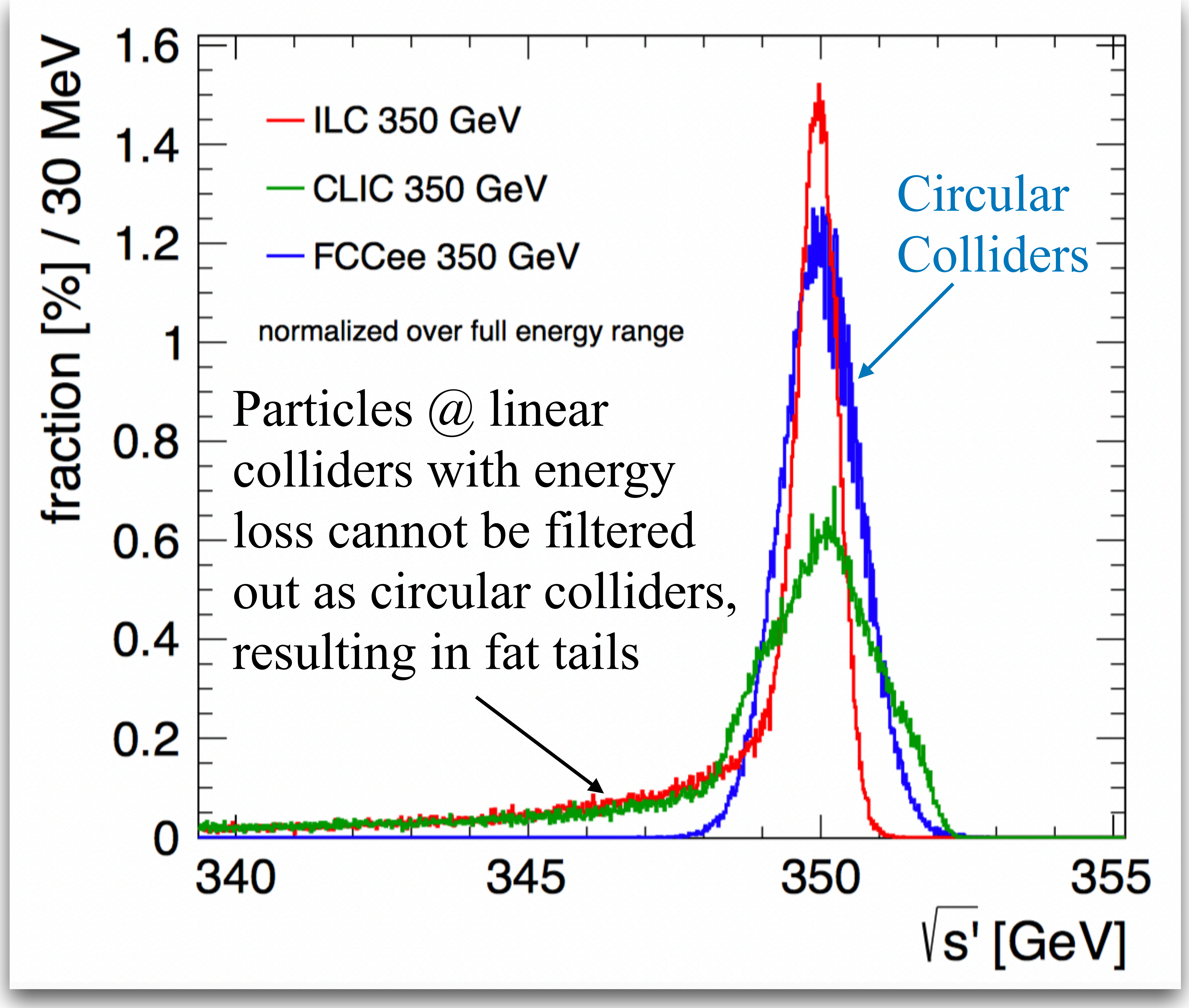
α_S variation ~1.7%

Advantages from circular colliders

- The luminosity spectrum at linear colliders is obviously worse than circular colliders given that the particles with energy loss are not removed by the bending magnets

- This can substantially change the cross-section curve at around the tt threshold

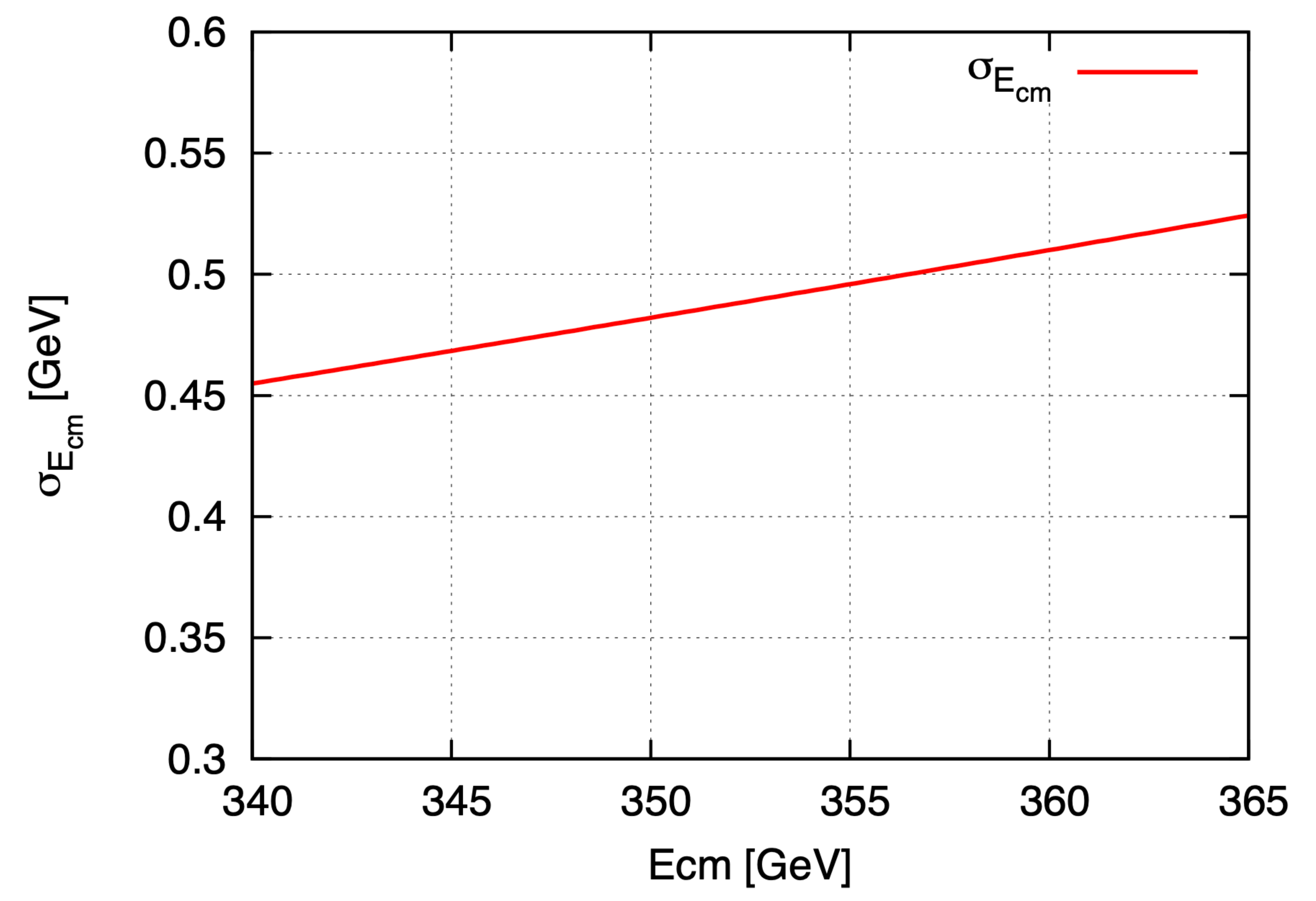
EPJC 73,(2013)2530

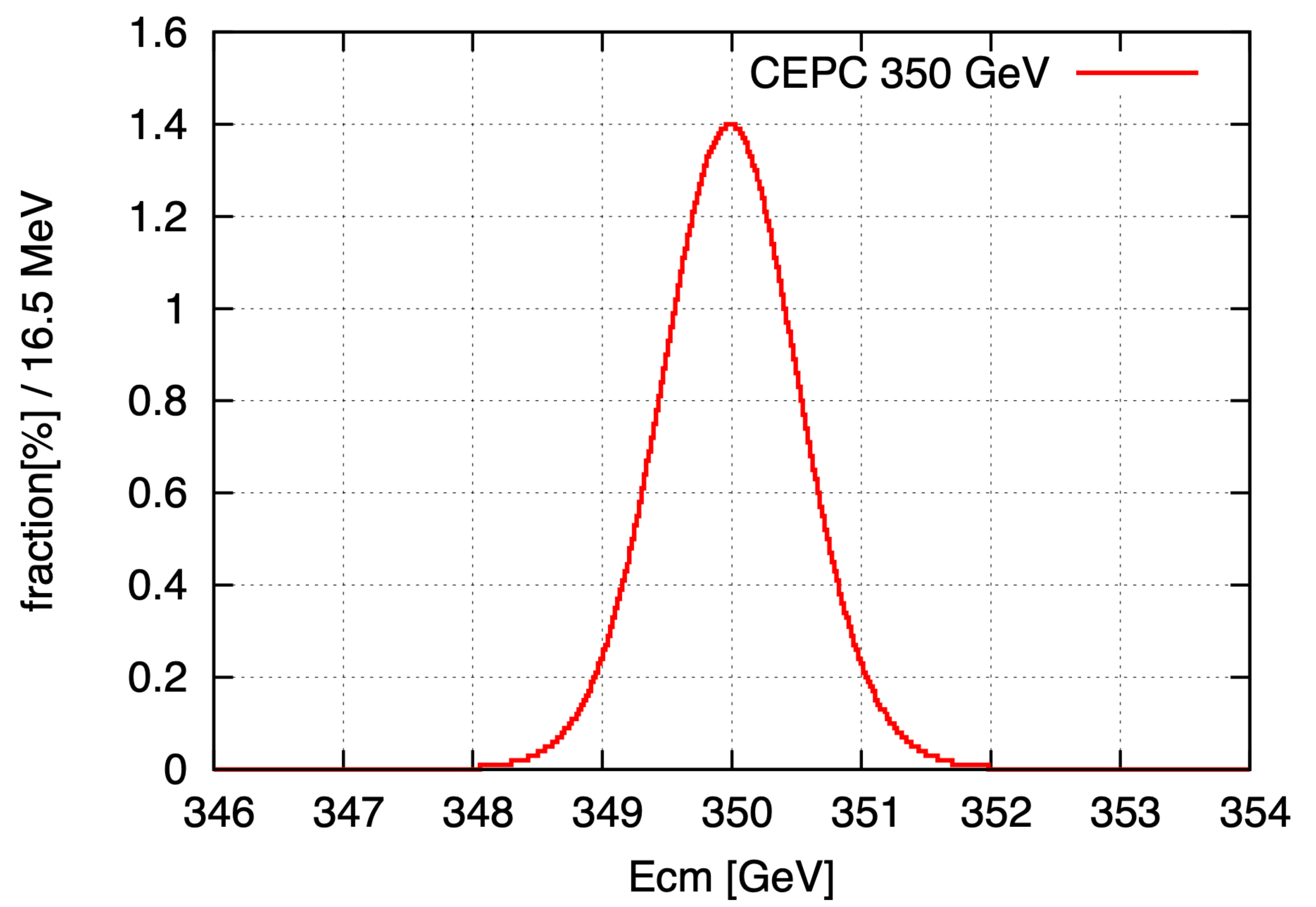


Circular Colliders

Particles @ linear colliders with energy loss cannot be filtered out as circular colliders, resulting in fat tails

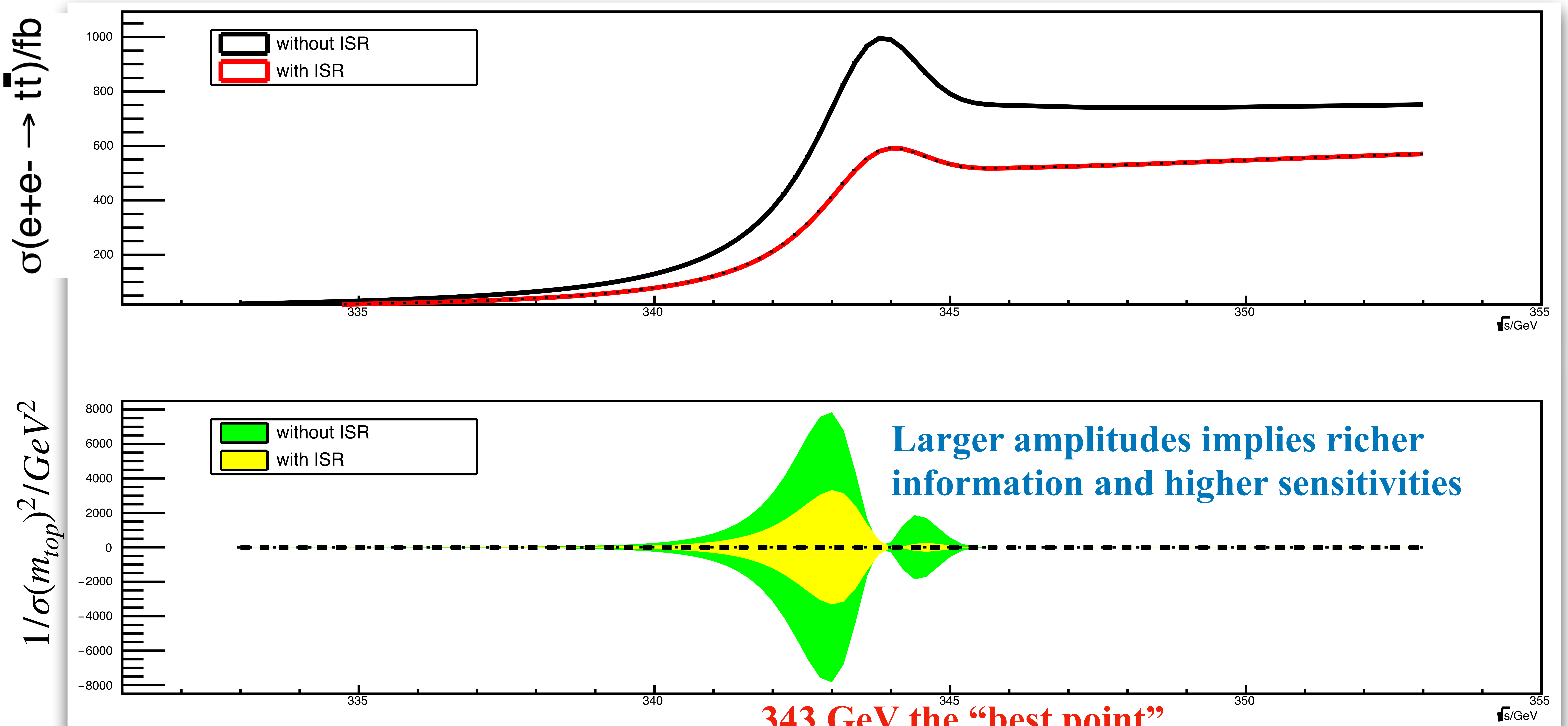
Luminosity spectrum @ CEPC





- The beam energy resolution increases as a function of $\sqrt{s}$
- The luminosity spectrum is shown for $\sqrt{s} = 350$ GeV with a width of ~480 MeV

Fisher information to get the sensitive energy points



Larger amplitudes implies richer information and higher sensitivities

343 GeV the "best point"

$\sqrt{s}$ scans

- Test with a series of centre-of-mass energy grids
  - 4-$\sqrt{s}$ scheme = {341.5,342.5,**343**,344.5} GeV
  - 6-$\sqrt{s}$ scheme = {341,342,342.5,**343**,343.5,344.5} GeV
  - 8-$\sqrt{s}$ scheme = {340,341,342,342.5,**343**,343.5,344.5,345} GeV
- Top mass is assumed as 171.5 GeV; the acceptance and efficiency is assumed to be 100% at the moment; ISR and LS are considered; backgrounds are included; semi-leptonic and fully-hadronic channels are considered
- A likelihood is constructed to combine the statistical power of all scan points

$$L = \prod_i P(\vec{D}_i \,|\, \vec{E}_i(\sigma(m_{top}, \Gamma_{top}, \alpha_S, \sqrt{s}), \mathscr{L}_i, \vec{\theta}))$$

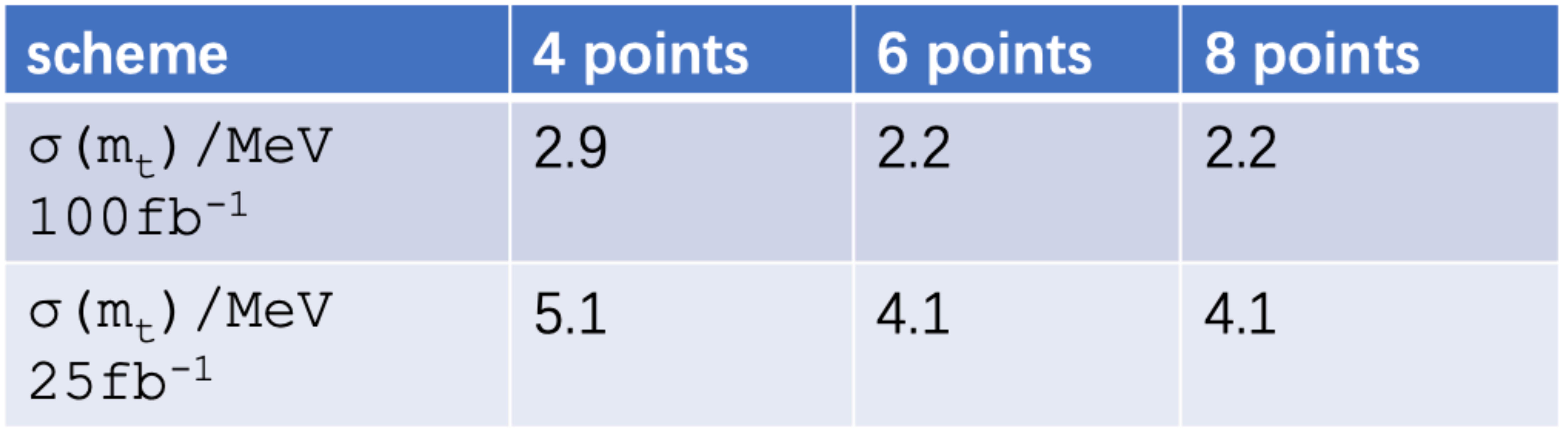
i corresponds to the i-th $\sqrt{s}$ scan point

Different schemes

Old setup: 1 GeV constant LS

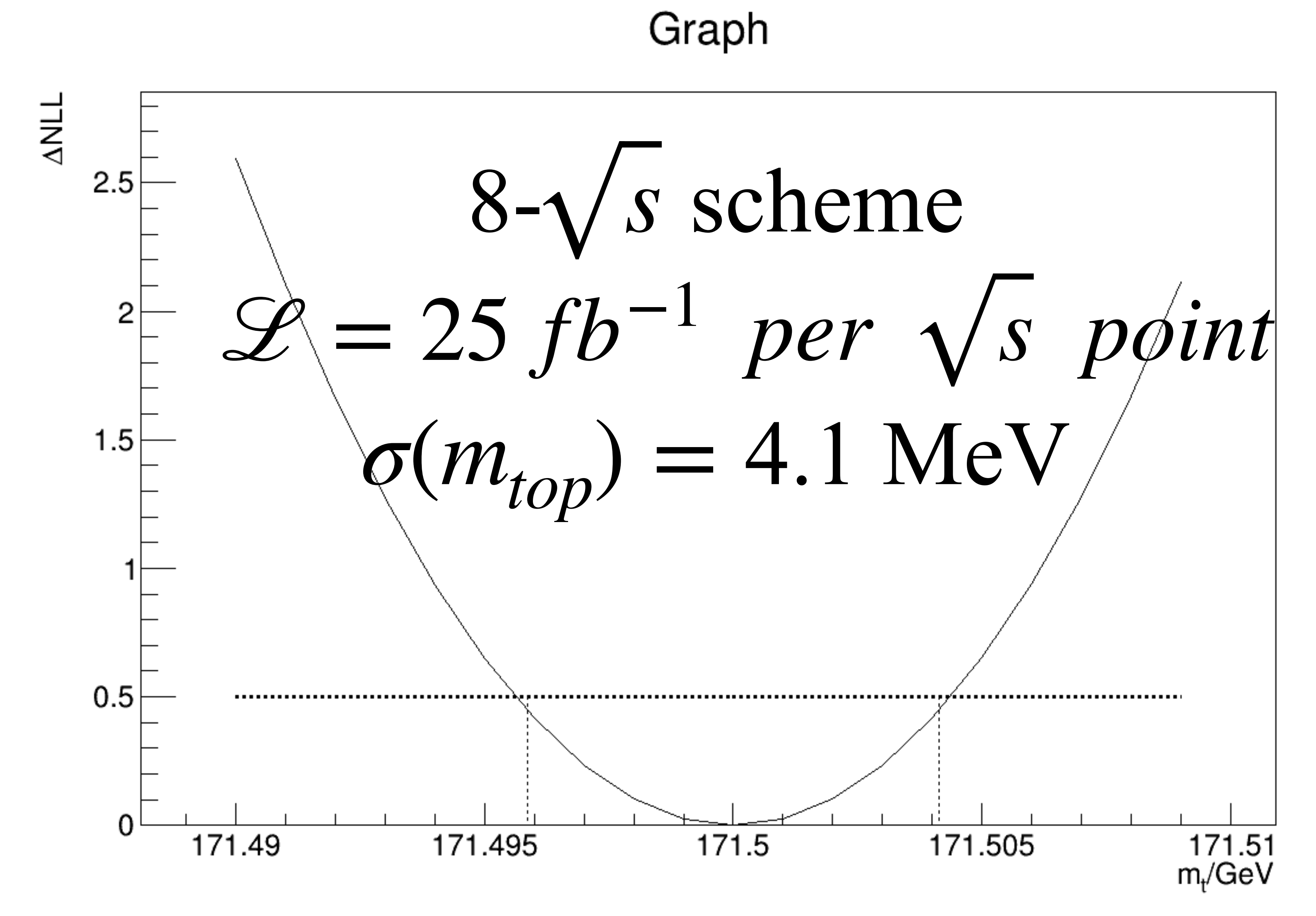
Schemes with different number of scanned $\sqrt{s}$

The luminosity is either 25 fb^{-1} or 100 fb^{-1} per point!



scheme	4 points	6 points	8 points
$\sigma(m_t)$/MeV 100fb^{-1}	2.9	2.2	2.2
$\sigma(m_t)$/MeV 25fb^{-1}	5.1	4.1	4.1

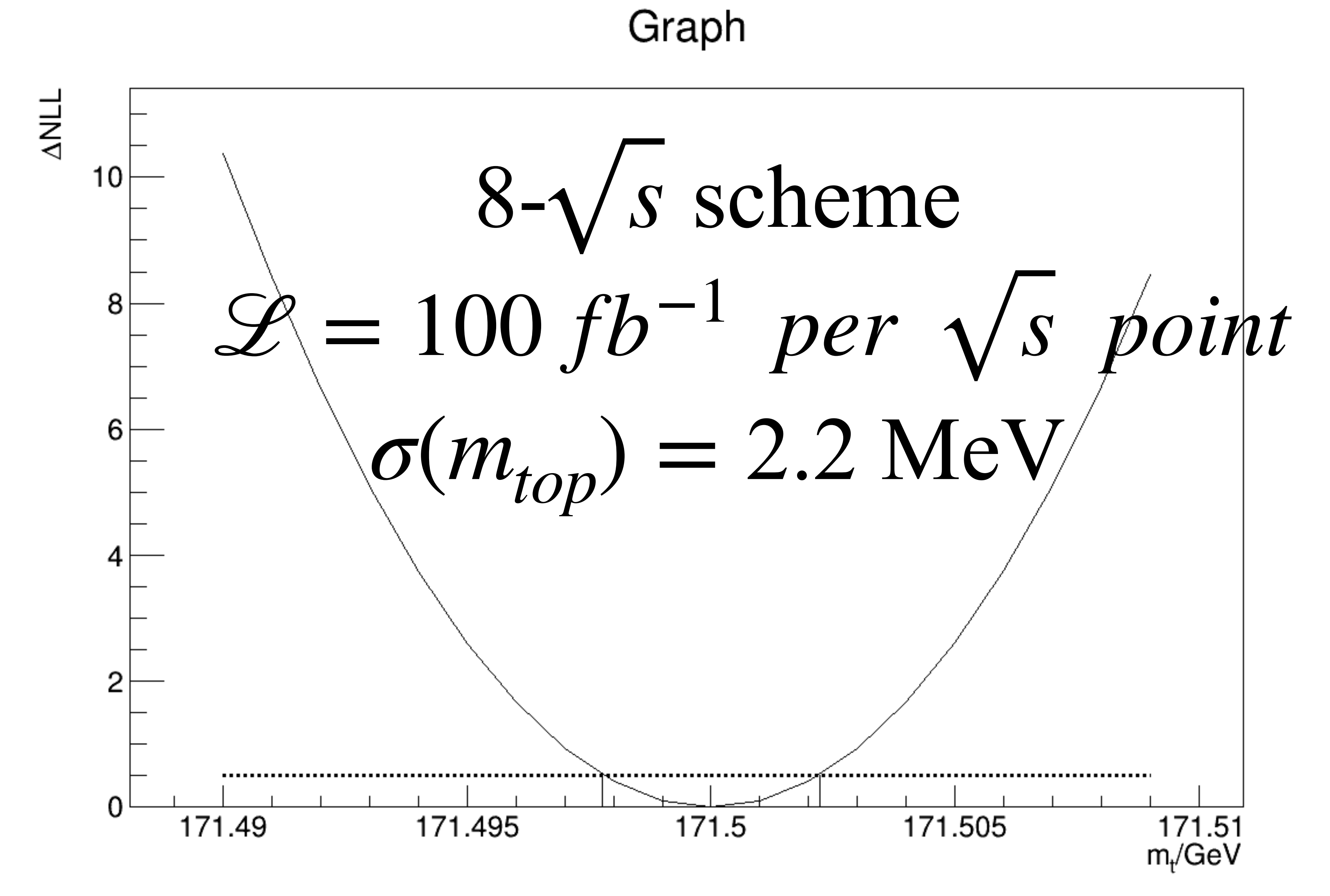
- These early studies built up and validated the analysis chain to study the sensitivity with different scans
- From 4-$\sqrt{s}$ to 6, the improvement is still visible given the extra points close to 343 GeV
- From 6-$\sqrt{s}$ to 8, the improvement is trivial, indicating that **points are less useful if they are far away from 343 GeV** (the "best point" from the fisher info)



8-$\sqrt{s}$ scheme

$\mathscr{L} = 25\ fb^{-1}\ per\ \sqrt{s}\ point$

$\sigma(m_{top}) = 4.1$ MeV



8-$\sqrt{s}$ scheme

$\mathscr{L} = 100\ fb^{-1}\ per\ \sqrt{s}\ point$

$\sigma(m_{top}) = 2.2$ MeV

Drop extra $\sqrt{s}$ points

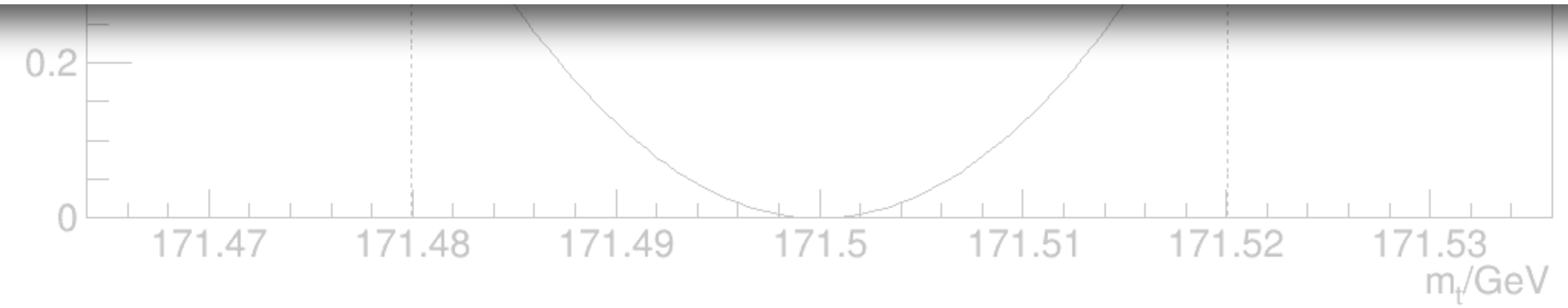
8 $\sqrt{s}$ scheme

In reality, the total operation time is limited, so the total luminosity is limited

We need to study the scanning schemes with total lumi fixed

Keep total lumi

Use equal lumi

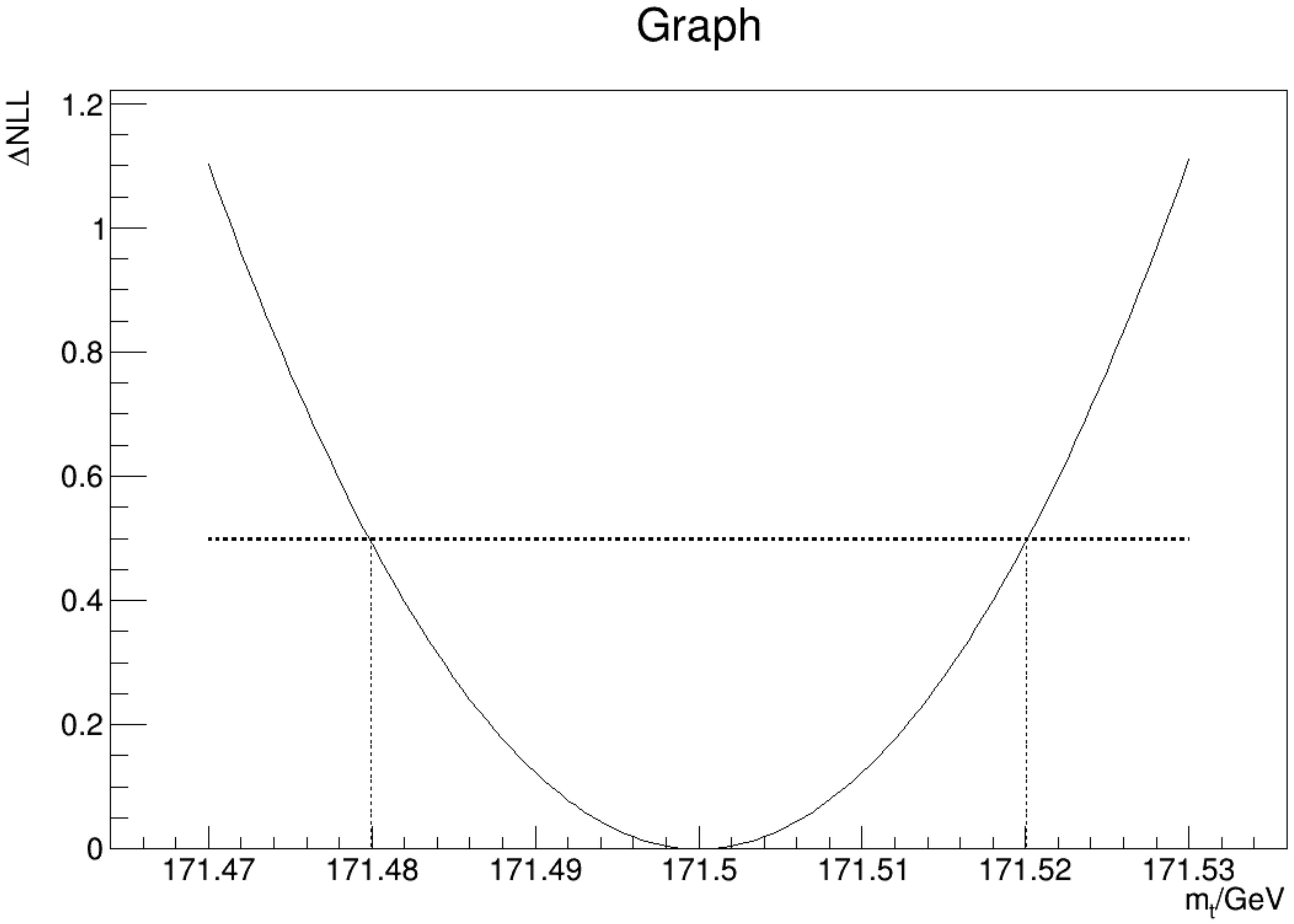


12.5fb^{-1} per point $\sigma(m_t)$:-0.0200625 0.0200625

Drop extra $\sqrt{s}$ points

8 $\sqrt{s}$ scheme
=\{340,341,342,342.5,343,343.5,344.5,345\}

Keep total lumi = 100/fb
Use equal lumi per point

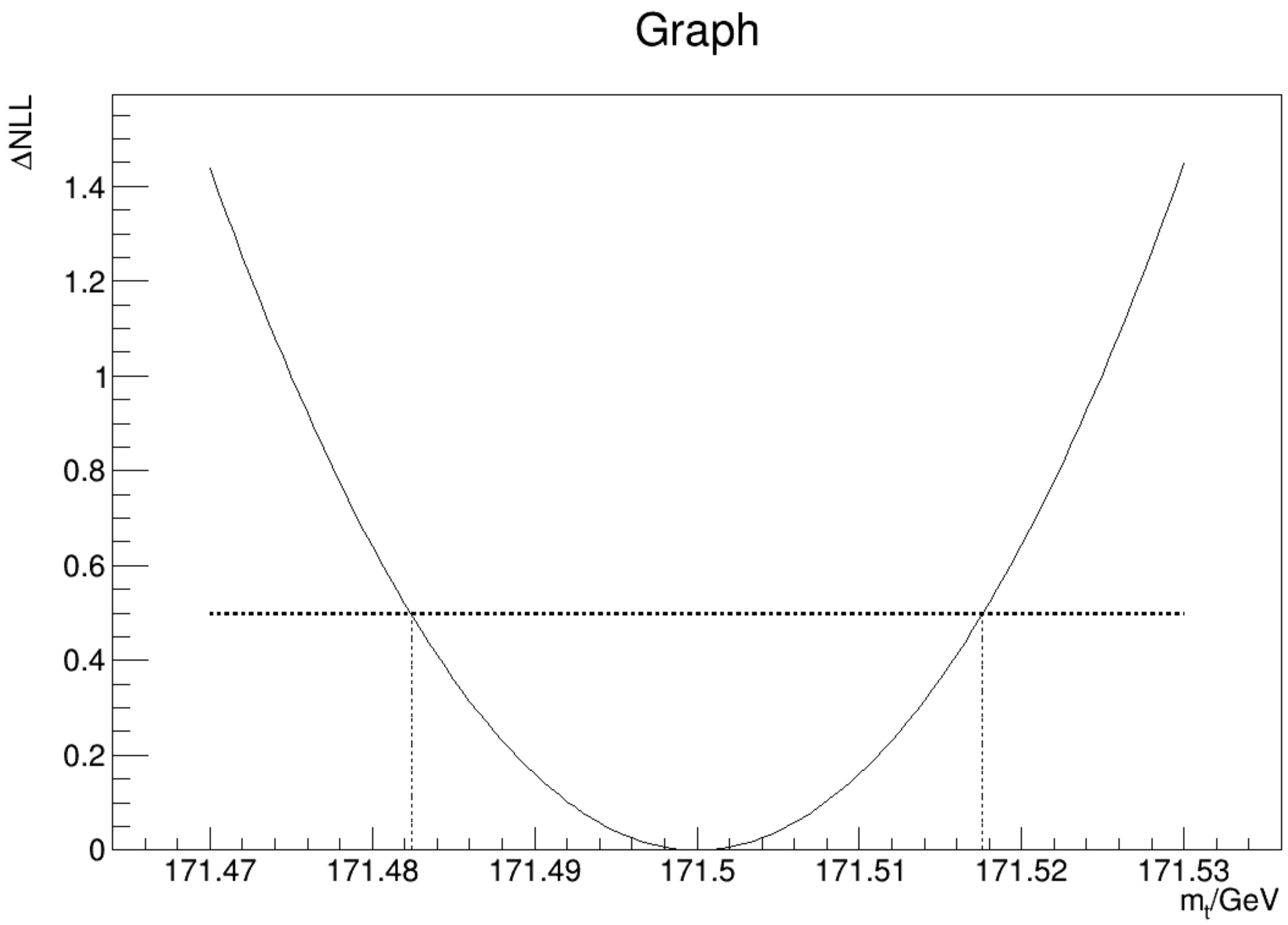


12.5fb^{-1} per point $\sigma(m_t)$:-0.0200625 0.0200625

Drop extra $\sqrt{s}$ points

6 $\sqrt{s}$ scheme={341,342,342.5,343,343.5,344.5}

We dropped 340 and 345.



Keep total lumi = 100/fb
Use equal lumi per point

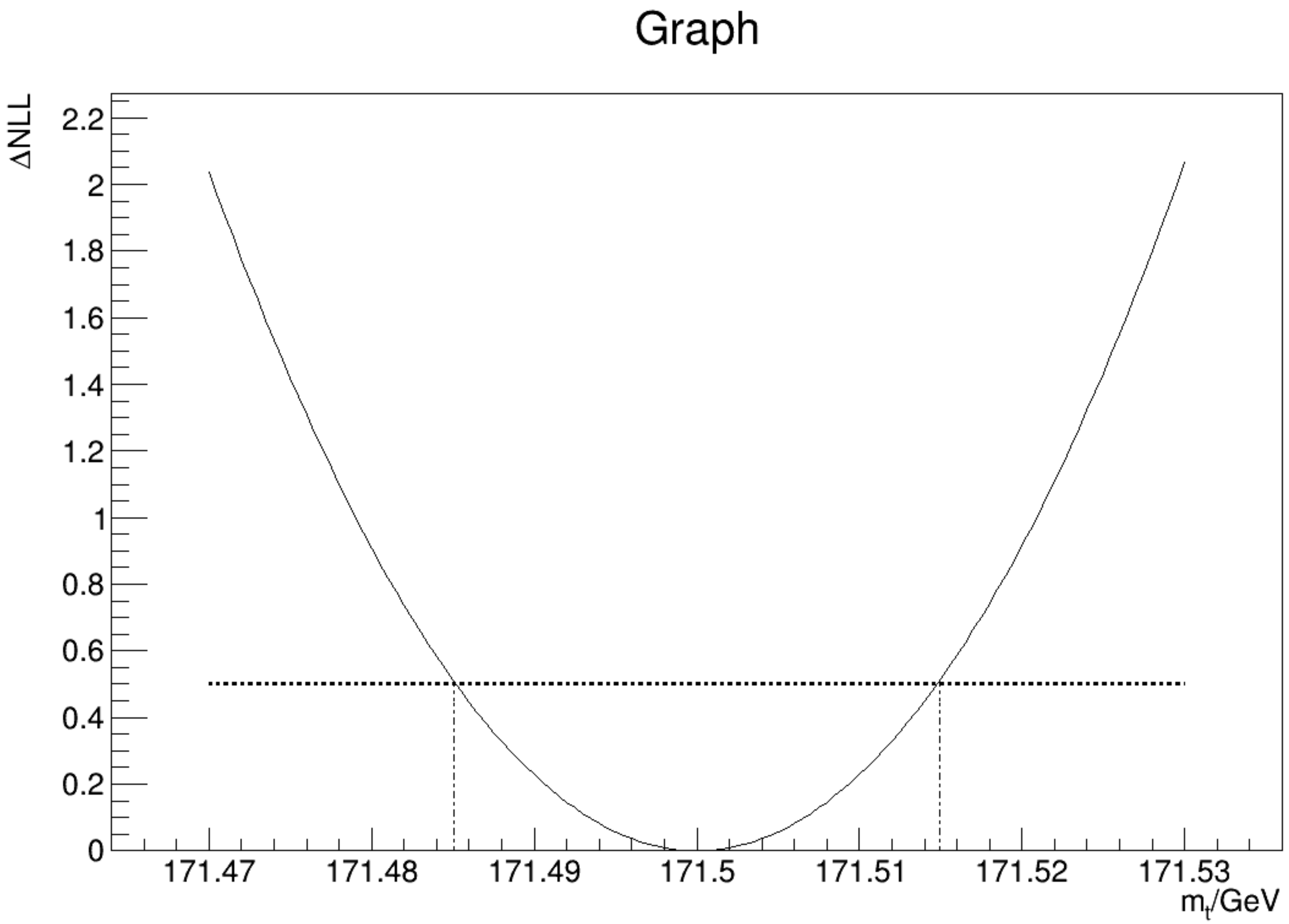
16.7fb^{-1} per point $\sigma(m_t)$: -0.0175625 0.0175625

Drop extra $\sqrt{s}$ points

4 $\sqrt{s}$ scheme={342,342.5,343,343.5}

We dropped 341 and 344.5.

Keep total lumi = 100/fb
Use equal lumi per point

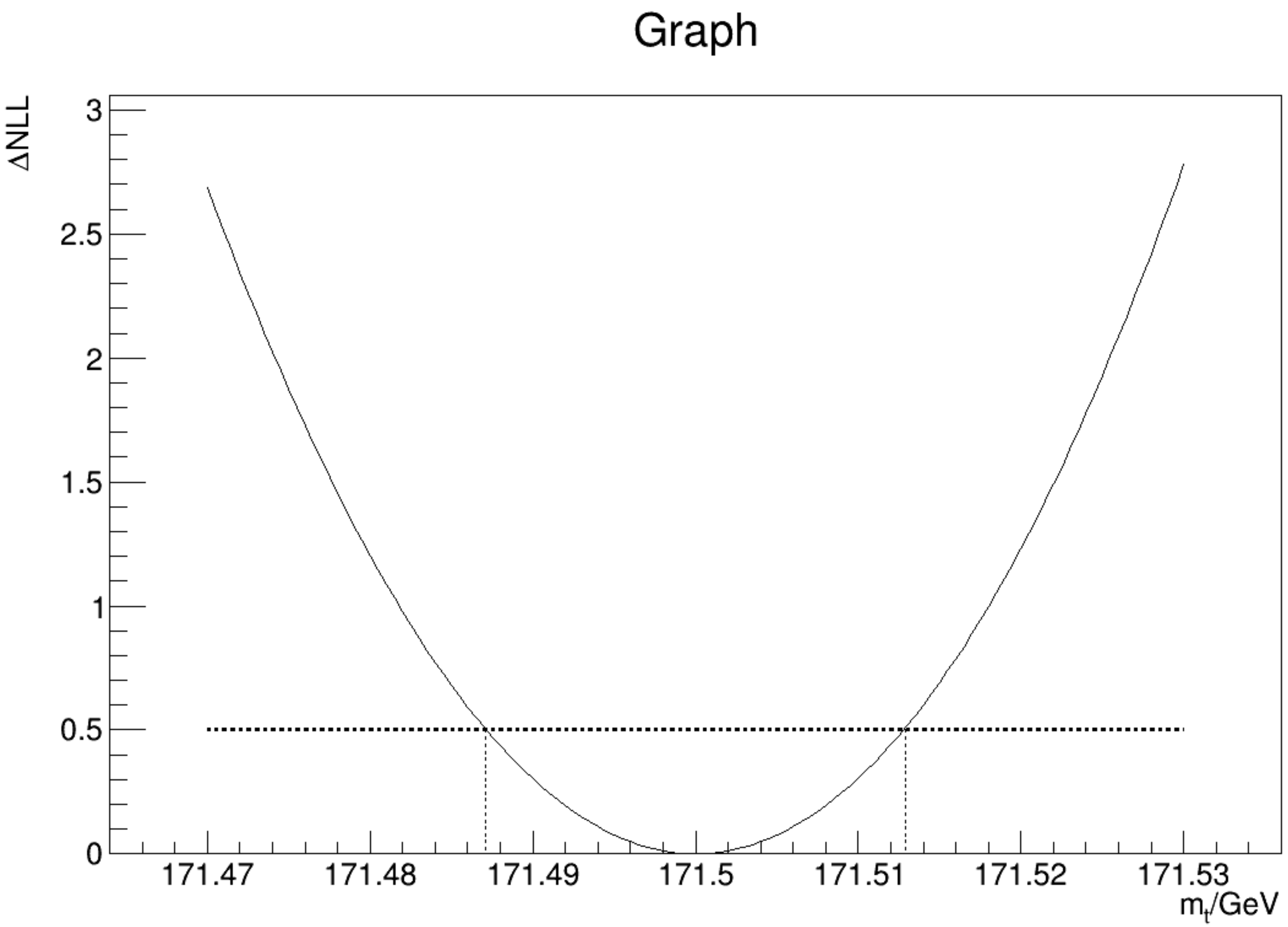


25$\mathtt{fb}^{-1}$ per point $\sigma(m_t)$:-0.0149375 0.0149375

Drop extra $\sqrt{s}$ points

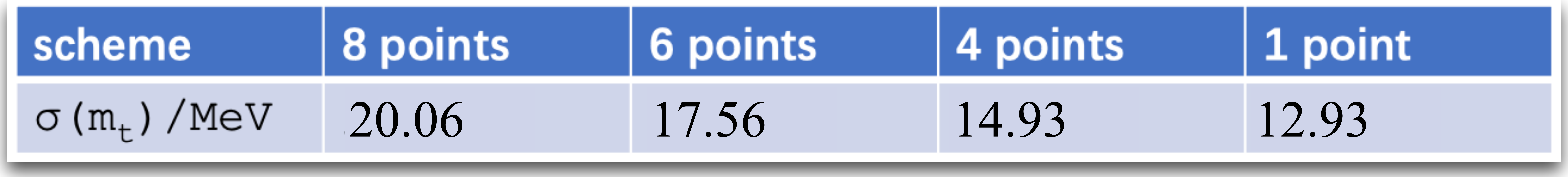
1 $\sqrt{s}$ scheme={343}

Keep total lumi = 100/fb
Use equal lumi per point



$100\mathrm{fb}^{-1}$ per point $\sigma(m_t)$:-0.0129375 0.0129375

1-$\sqrt{s}$ scheme gives the best result



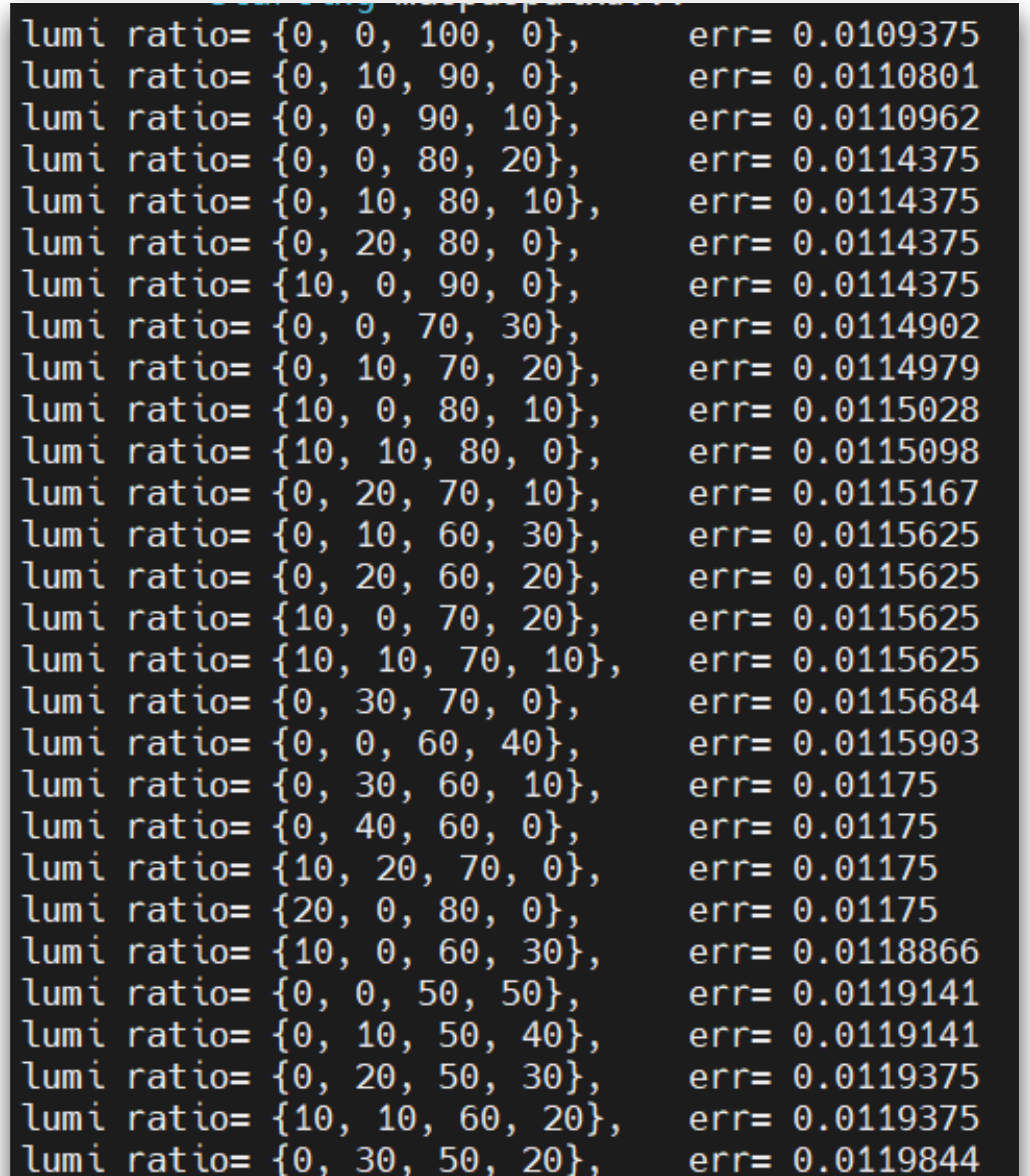
scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$/MeV	20.06	17.56	14.93	12.93

- **Keep** the total luminosity unchanged 100 fb^{-1} and use **equal** lumi each scanned $\sqrt{s}$ point
  - Conclude that $1-\sqrt{s}$ scheme provides the smaller error
  - This $1-\sqrt{s}$ scheme uses the "best point" suggested by the fisher info
- Then the question is
  - We used equal lumi per point, but how about unequal lumi per point?
  - Next page uses a $4-\sqrt{s}$ scheme to test unequal lumi

Unequal lumi

- Still keep the totally lumi 100/fb
- Use $\sqrt{s}$={342,342.5,343,343.5}
- Run over all different combination of fractional lumi distributed on the 4 scanning points
- 286 combinations are tested in total, and the leading ones are shown on the right
- We conclude that putting all lumi given to 343 GeV (the "best point" from fish info) still performs the best
- So the question now is how do we find the "best point"?

Old setup: 1 GeV constant LS

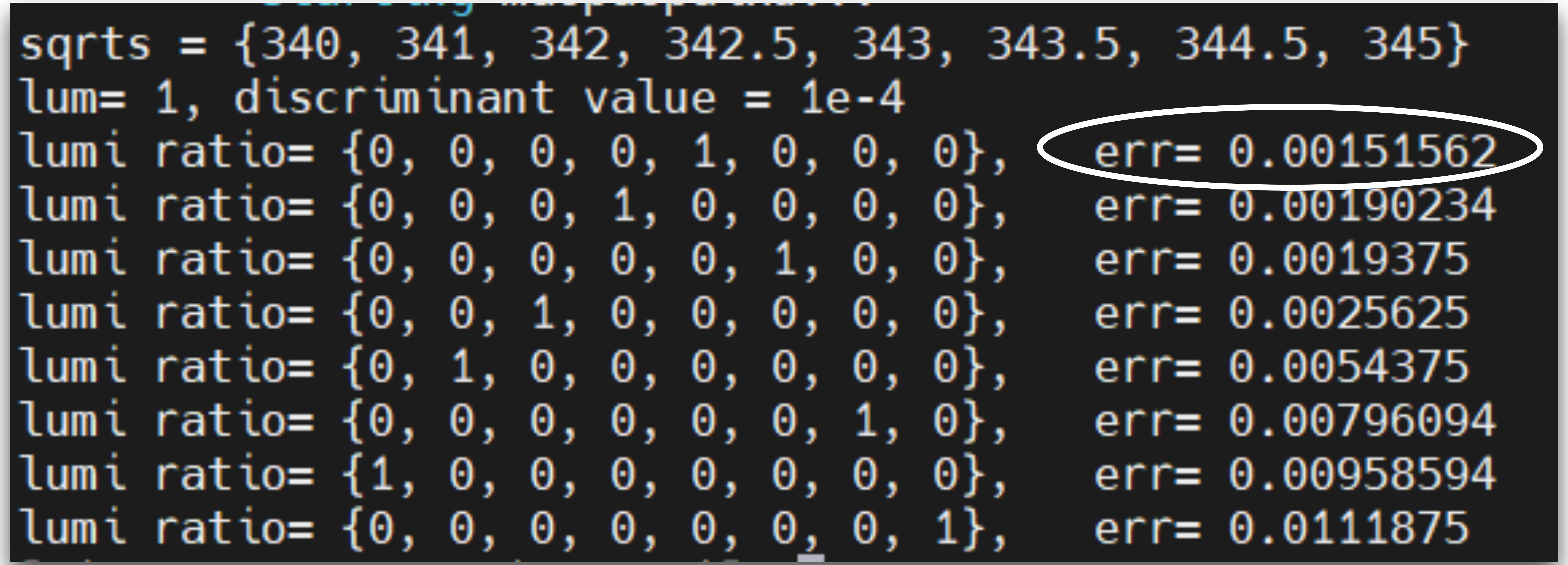


```
lumi ratio= {0, 0, 100, 0},      err= 0.0109375
lumi ratio= {0, 10, 90, 0},      err= 0.0110801
lumi ratio= {0, 0, 90, 10},      err= 0.0110962
lumi ratio= {0, 0, 80, 20},      err= 0.0114375
lumi ratio= {0, 10, 80, 10},     err= 0.0114375
lumi ratio= {0, 20, 80, 0},      err= 0.0114375
lumi ratio= {10, 0, 90, 0},      err= 0.0114375
lumi ratio= {0, 0, 70, 30},      err= 0.0114902
lumi ratio= {0, 10, 70, 20},     err= 0.0114979
lumi ratio= {10, 0, 80, 10},     err= 0.0115028
lumi ratio= {10, 10, 80, 0},     err= 0.0115098
lumi ratio= {0, 20, 70, 10},     err= 0.0115167
lumi ratio= {0, 10, 60, 30},     err= 0.0115625
lumi ratio= {0, 20, 60, 20},     err= 0.0115625
lumi ratio= {10, 0, 70, 20},     err= 0.0115625
lumi ratio= {10, 10, 70, 10},    err= 0.0115625
lumi ratio= {0, 30, 70, 0},      err= 0.0115684
lumi ratio= {0, 0, 60, 40},      err= 0.0115903
lumi ratio= {0, 30, 60, 10},     err= 0.01175
lumi ratio= {0, 40, 60, 0},      err= 0.01175
lumi ratio= {10, 20, 70, 0},     err= 0.01175
lumi ratio= {20, 0, 80, 0},      err= 0.01175
lumi ratio= {10, 0, 60, 30},     err= 0.0118866
lumi ratio= {0, 0, 50, 50},      err= 0.0119141
lumi ratio= {0, 10, 50, 40},     err= 0.0119141
lumi ratio= {0, 20, 50, 30},     err= 0.0119375
lumi ratio= {10, 10, 60, 20},    err= 0.0119375
lumi ratio= {0, 30, 50, 20},     err= 0.0119844
```

Proposal of finding the best point

- Run with low lumi to scan $\sqrt{s}$ in a range (inputs from LHC top mass combined by then)
- Use each single scanned point to measure the top mass
- The one providing the best precision is most close to the true "best point" from the fish info
- **One unique top mass -> one unique "best point" (fisher info) -> one unquie $\sqrt{s}$ to reach the smallest error**

Old setup: 1 GeV constant LS



```
sqrts = {340, 341, 342, 342.5, 343, 343.5, 344.5, 345}
lum= 1, discriminant value = 1e-4
lumi ratio= {0, 0, 0, 0, 1, 0, 0, 0},    err= 0.00151562
lumi ratio= {0, 0, 0, 1, 0, 0, 0, 0},    err= 0.00190234
lumi ratio= {0, 0, 0, 0, 0, 1, 0, 0},    err= 0.0019375
lumi ratio= {0, 0, 1, 0, 0, 0, 0, 0},    err= 0.0025625
lumi ratio= {0, 1, 0, 0, 0, 0, 0, 0},    err= 0.0054375
lumi ratio= {0, 0, 0, 0, 0, 0, 1, 0},    err= 0.00796094
lumi ratio= {1, 0, 0, 0, 0, 0, 0, 0},    err= 0.00958594
lumi ratio= {0, 0, 0, 0, 0, 0, 0, 1},    err= 0.0111875
```

Assume that we do not know it is 343 GeV the best point and **blindly scan** over the range

The one that brings the smaller top mass error is the best point to find

Comparison to other experiments

Compare with CLIC and FCC-ee

scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$ /MeV	20.06	17.56	14.93	12.93

Comparable with FCC-ee under similar conditions (lumi differ by a factor of 2)

- The estimation of FCC-ee:
  - ~17 MeV for top mass (stat. uncert.)
  - ~45 MeV for top width (stat. uncert.)
  - with 25fb^{-1} taken at each of the 8 centre-of-mass energy points N3LO cross-section calculation brings 40 MeV uncertainty additionally

2d fit results of CLIC Eur. Phys. J. C (2013) 73:2530

Table 4 Summary of the 2D simultaneous top mass and α_s determination with a threshold scan at ILC for 10 points with a total integrated luminosity of 100 fb^{-1}. Event selection and background rejection from CLIC_ILD is used

1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1 %/3 %)	5 MeV/9 MeV
α_s stat. error	0.0008
α_s theory syst. (1 %/3 %)	0.0007/0.0022

Zhan LI

The Higgs width measurements @ ~360 GeV

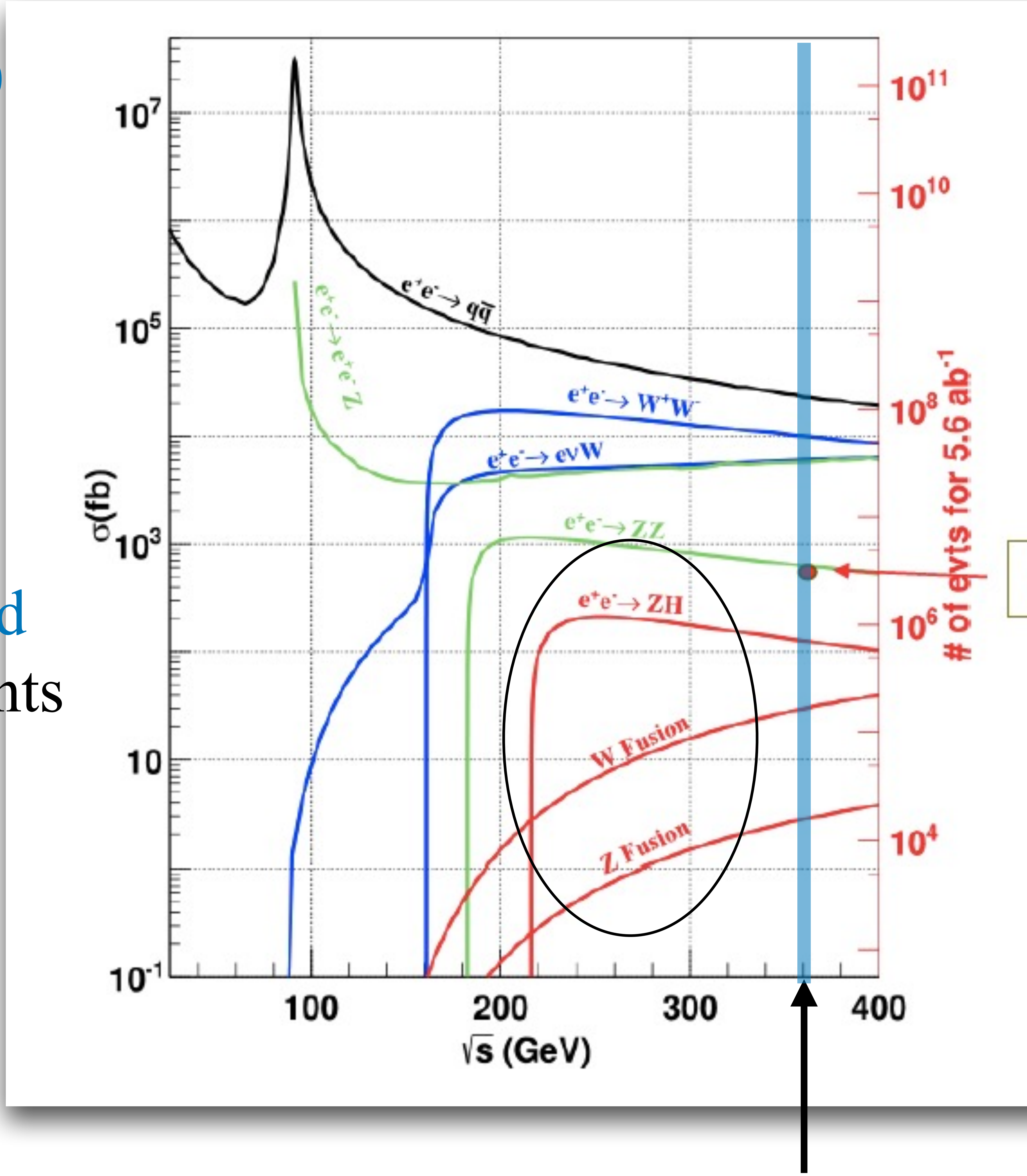
- The Higgs width can be measured using $\sigma(ZH)$ at ~240 GeV

$$\Gamma_H \propto \frac{\Gamma(H\to ZZ^*)}{\mathrm{BR}(H\to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H\to ZZ^*)}$$

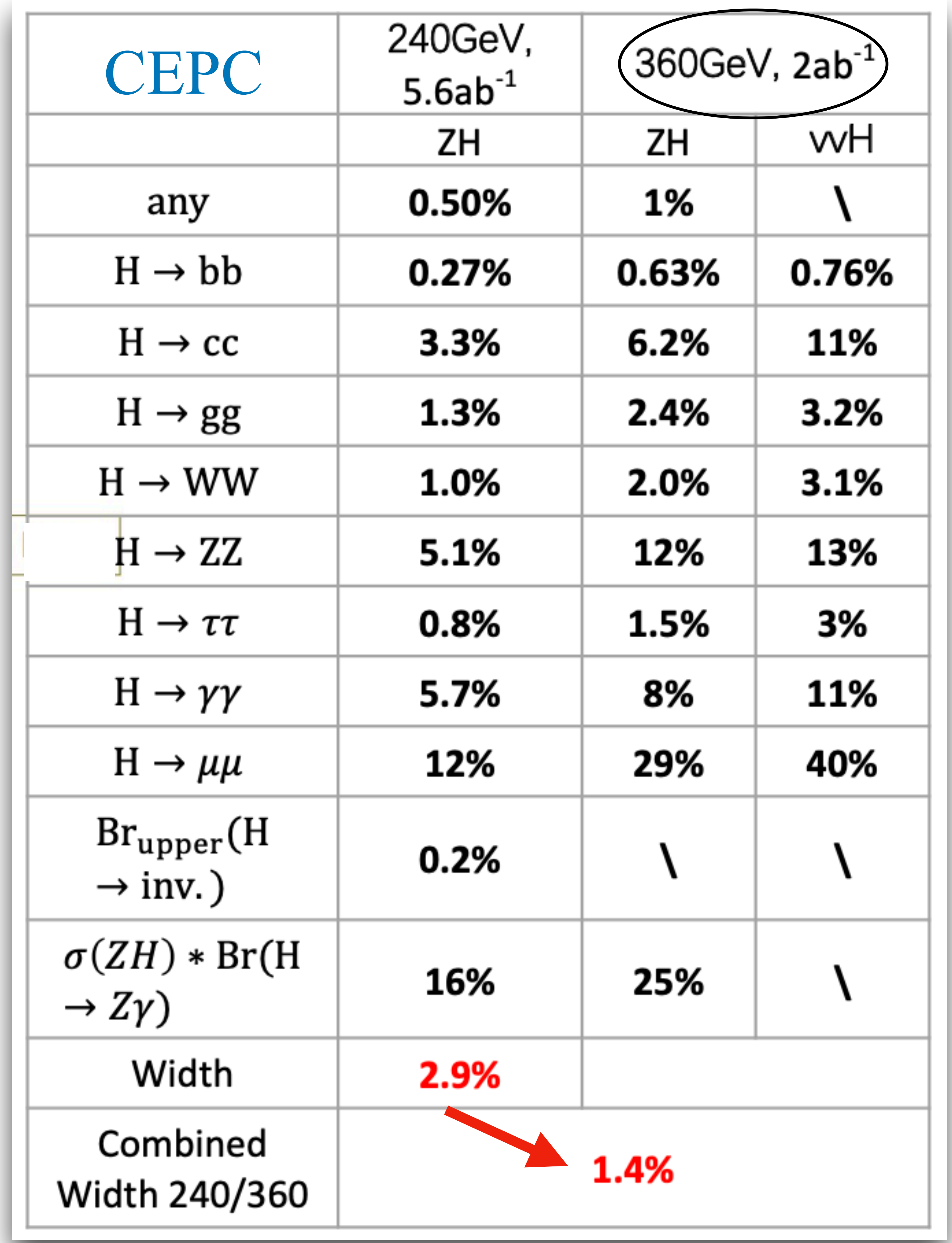
- The Higgs width can **also** be measured using $\sigma(ZH)$ and $\sigma(\nu\nu H)$ at ~360 GeV when we scan for top measurements

$$\Gamma_H \propto \frac{\Gamma(H\to bb)}{\mathrm{BR}(H\to bb)} \propto \frac{\sigma(\nu\bar{\nu}H\to \nu\bar{\nu}b\bar{b})}{\mathrm{BR}(H\to b\bar{b})\cdot \mathrm{BR}(H\to WW^*)}$$

The two can be combined!

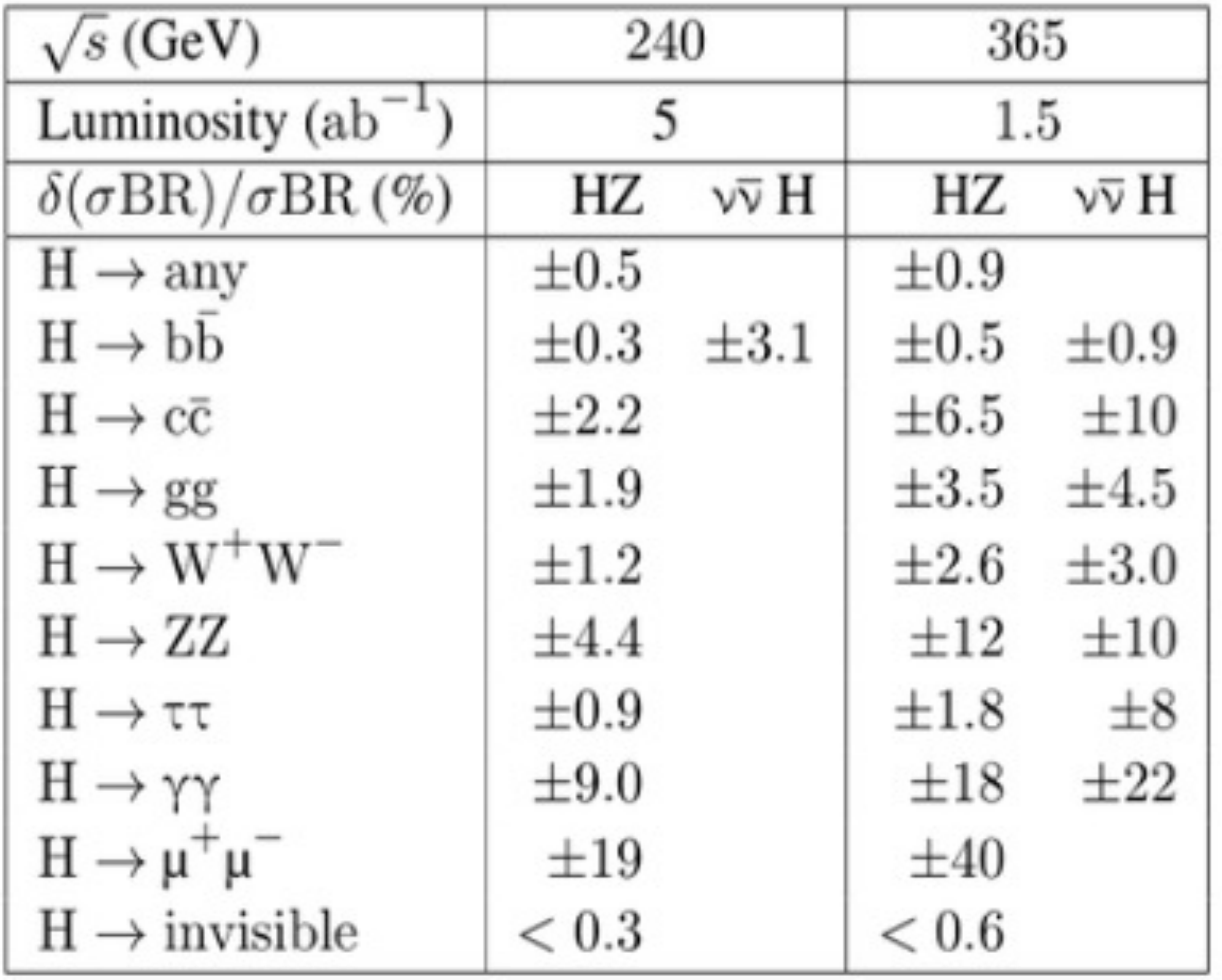


Improve Higgs width precision



CEPC	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	ννH
any	**0.50%**	**1%**	****
H → bb	**0.27%**	**0.63%**	**0.76%**
H → cc	**3.3%**	**6.2%**	**11%**
H → gg	**1.3%**	**2.4%**	**3.2%**
H → WW	**1.0%**	**2.0%**	**3.1%**
H → ZZ	**5.1%**	**12%**	**13%**
$H \to \tau\tau$	**0.8%**	**1.5%**	**3%**
$H \to \gamma\gamma$	**5.7%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$Br_{upper}(H \to inv.)$	**0.2%**	****	****
$\sigma(ZH) * Br(H \to Z\gamma)$	**16%**	**25%**	****
Width	**2.9%**		
Combined Width 240/360		**1.4%**	

Fcc-ee 240 GeV/365 GeV:
CERN-ACC-2018-0057 combined precision 1.3%

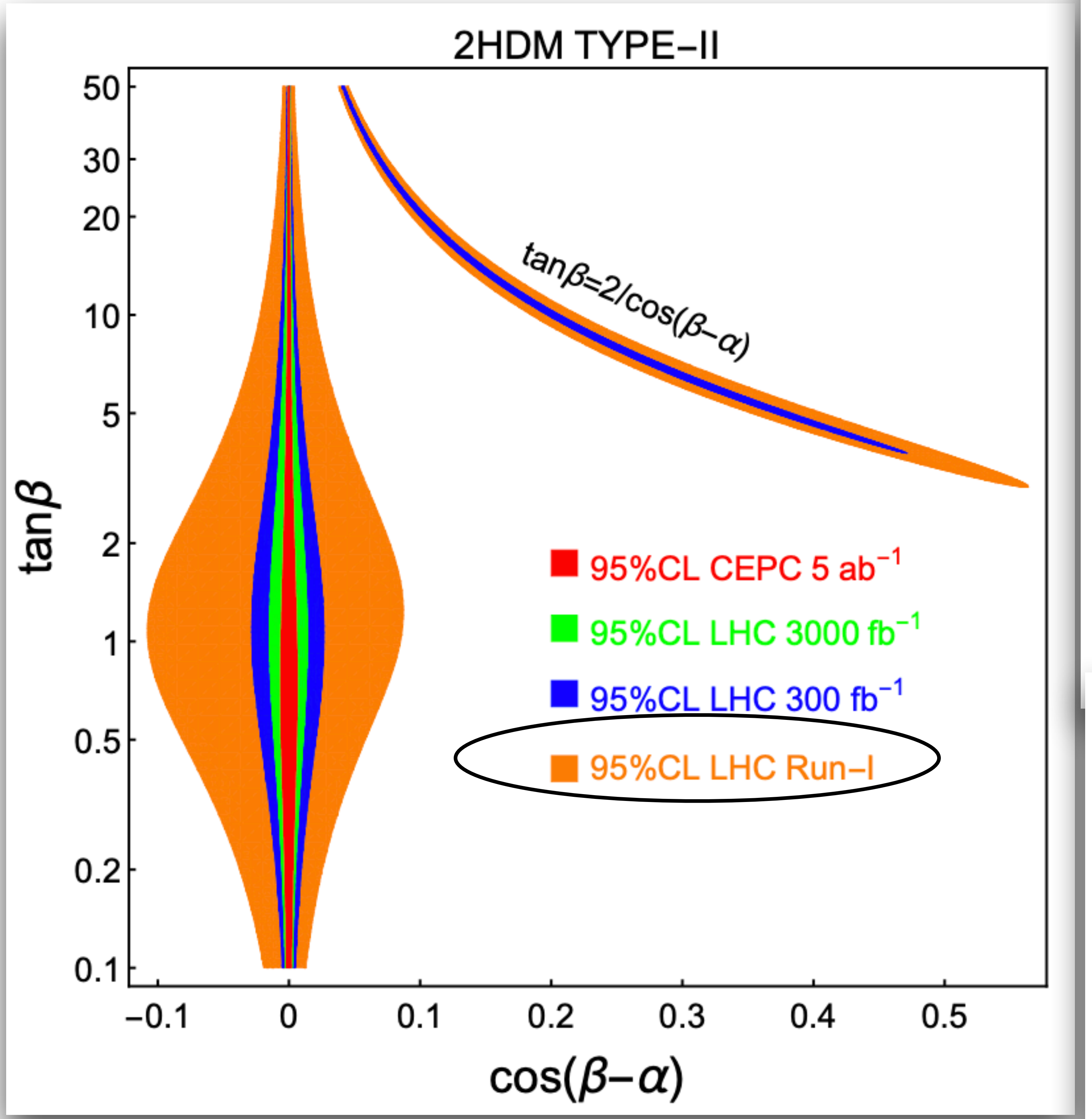


$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H → any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
H → gg	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
H → ZZ	±4.4		±12	±10
$H \to \tau\tau$	±0.9		±1.8	±8
$H \to \gamma\gamma$	±9.0		±18	±22
$H \to \mu^+\mu^-$	±19		±40	
H → invisible	< 0.3		< 0.6	

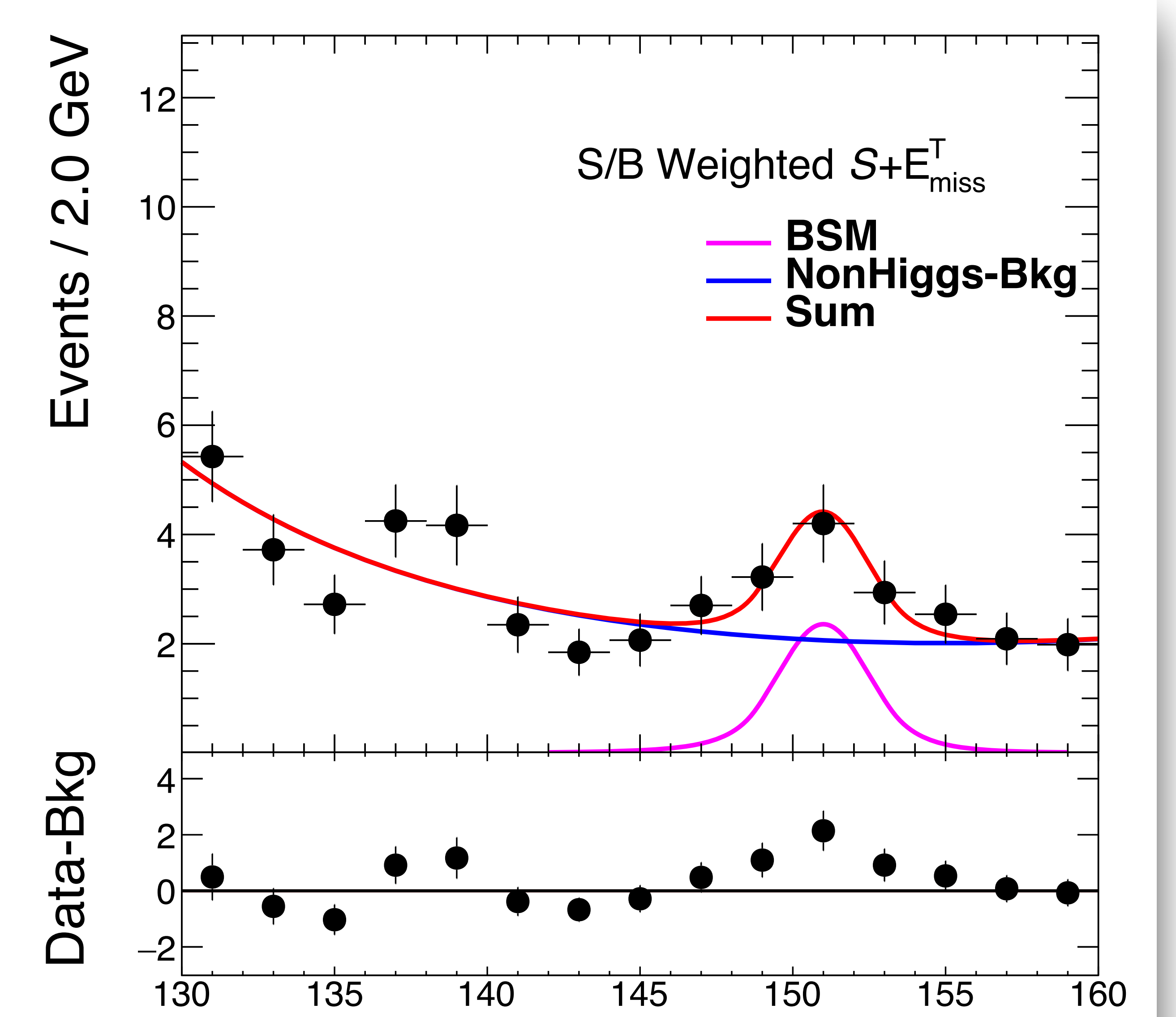
360 GeV runs can significantly improve the Higgs width measurements

BSM opportunities at 360 GeV

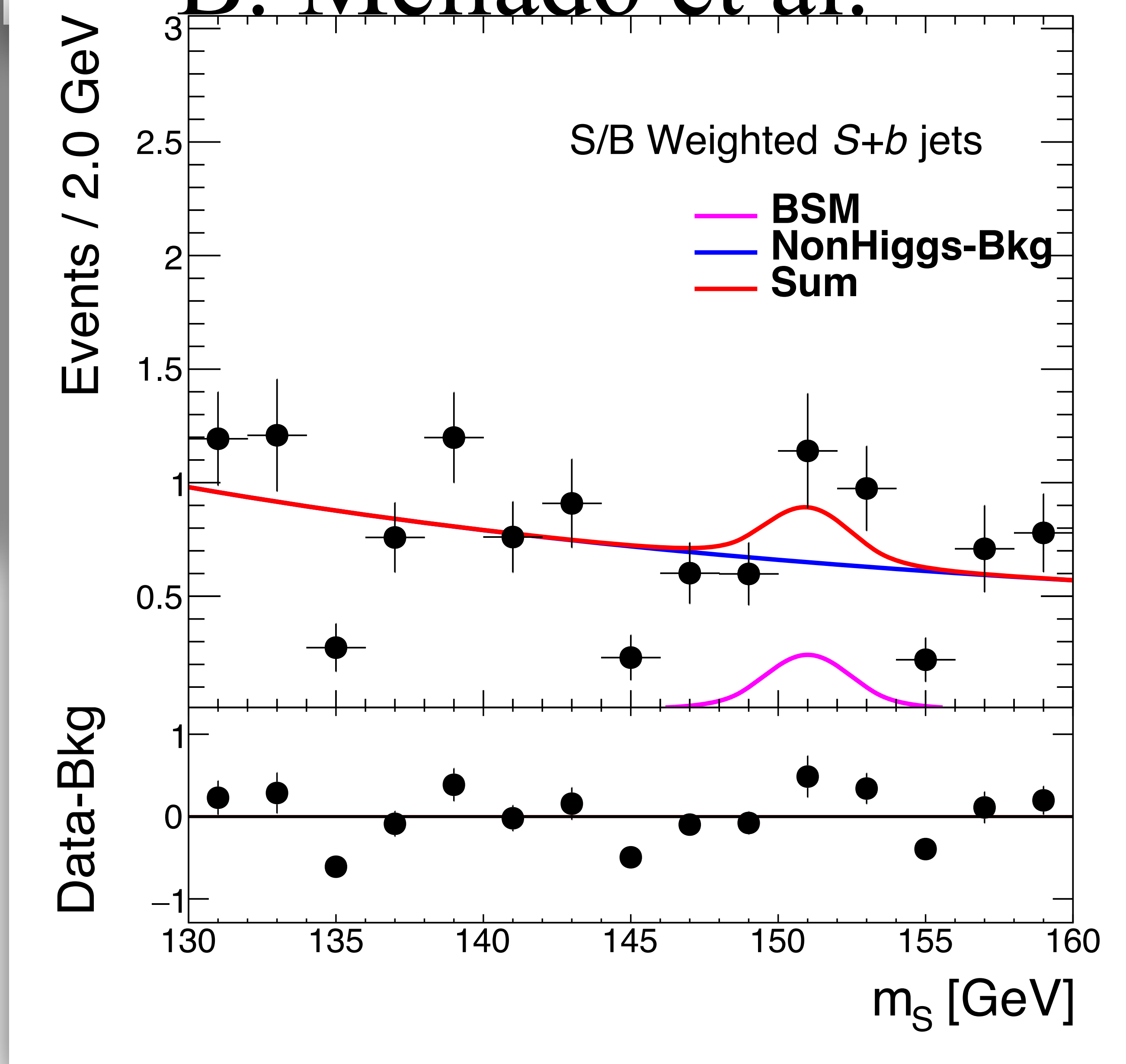
- In the indirect searches, the Higgs precision measurements play a key role
  - 360 GeV runs in general improves the Higgs width by a factor of 2
  - This brings even more stringent constraints on the new models, e.g. 2HDM Type-II
- In the direct searches, many models can be probed for heavy Higgs with a mass of ~ 360 GeV, such as $H \rightarrow Sh/SS$



S. Su et al.



B. Mellado et al.



BSM (EFT) opportunities at 360 GeV

- Higgs-top related EFT couplings are particularly accessible from 360 - 500 GeV collisions given a much lower background level
- A typical playground is ttV productions, starting from 3-point functions (bottom left)

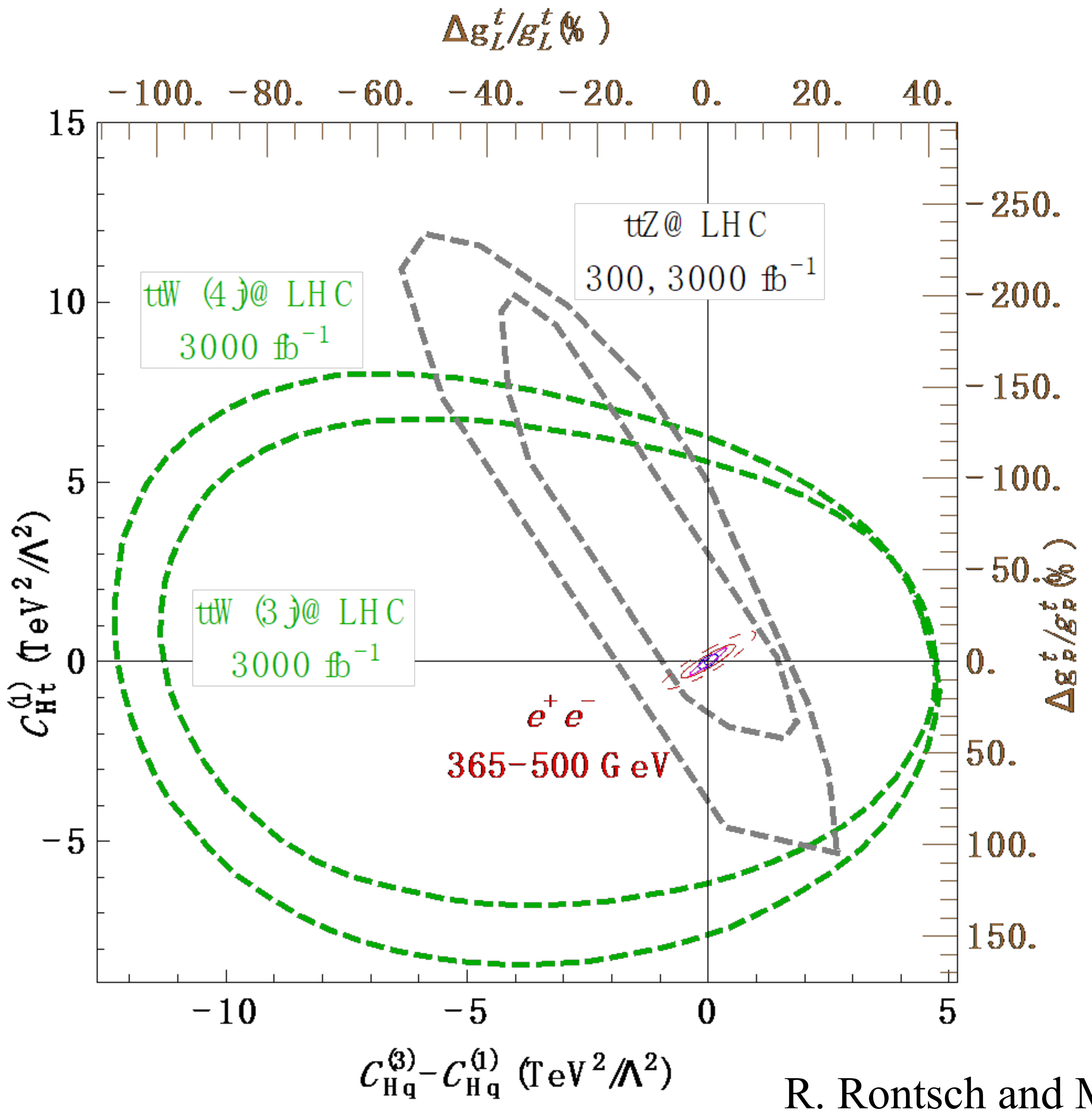
$$Z_\mu \bar{b}_R \gamma^\mu b_R : \quad -g_Z \frac{v^2}{2\Lambda^2} C_{Hb}^{(1)}$$

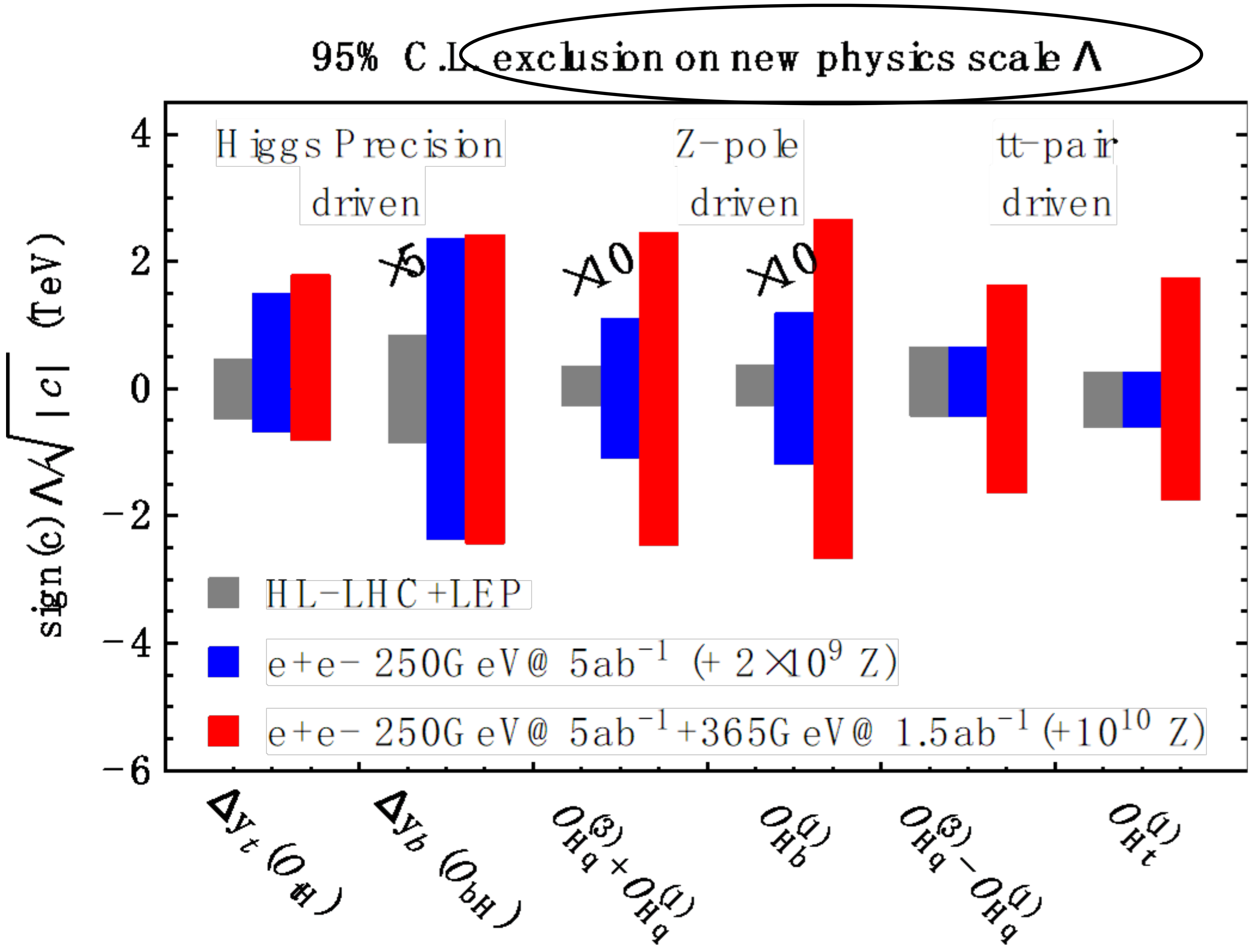
$$Z_\mu \bar{b}_L \gamma^\mu b_L : \quad -g_Z \frac{v^2}{2\Lambda^2} (C_{Hq}^{(1)} + C_{Hq}^{(3)})$$

$$Z_\mu \bar{t}_R \gamma^\mu t_R : \quad -g_Z \frac{v^2}{2\Lambda^2} C_{Ht}^{(1)}$$

$$Z_\mu \bar{t}_L \gamma^\mu t_L : \quad -g_Z \frac{v^2}{2\Lambda^2} (C_{Hq}^{(1)} - C_{Hq}^{(3)})$$

$$W^+_\mu \bar{t}_L \gamma^\mu b_L : \quad g_2 \frac{v^2}{\sqrt{2}\Lambda^2} C_{Hq}^{(3)},$$





R. Rontsch and M. Schulze, 1404.1005 , J. Dror, M. Farina, E. Salvioni, J. Serra, 1511.03674

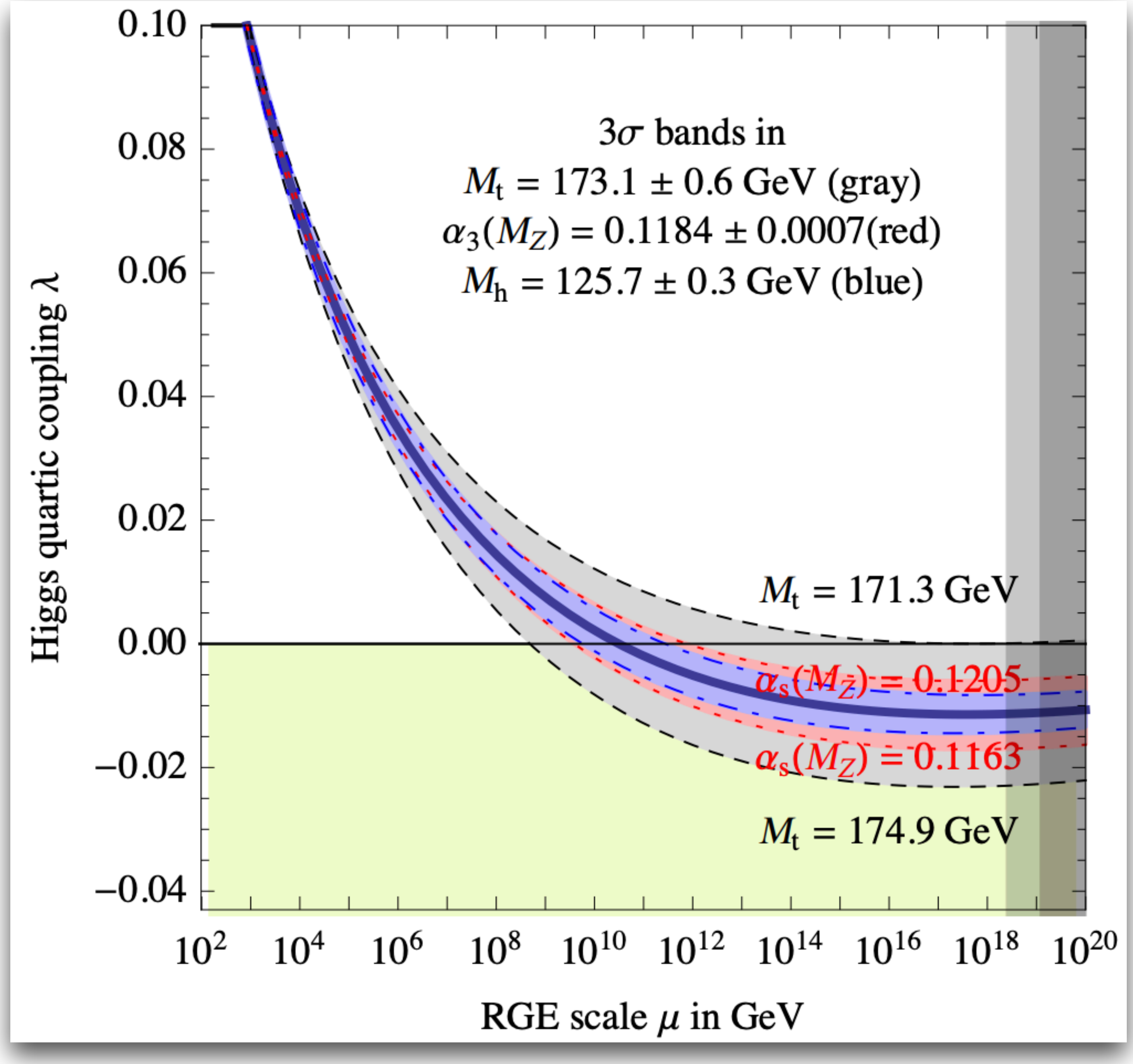
Summary

- Many opportunities @ CEPC 360 GeV
  - Top properties, Higgs BR/width, BSM (direct, EFT) etc.
- Top mass can be measured with a precision 1 order of magnitude better than hadron colliders at the moment
- Higgs width can be improved by a factor of 2 in general
- Higgs-top related EFT couplings can be strongly constrained given much lower background level
- Focusing on the **recent progresses of the CEPC top mass team (us!)**
  - Validated the full machinery of this analysis
  - Studied the scanning schemes and found the best solution: 1-$\sqrt{s}$ point if we keep the total luminosity limited
  - Proposed a way to find which $\sqrt{s}$ point to scan for 1-$\sqrt{s}$ scheme
- Heading towards the physics white paper for higher energy (~360 GeV) in ~one year

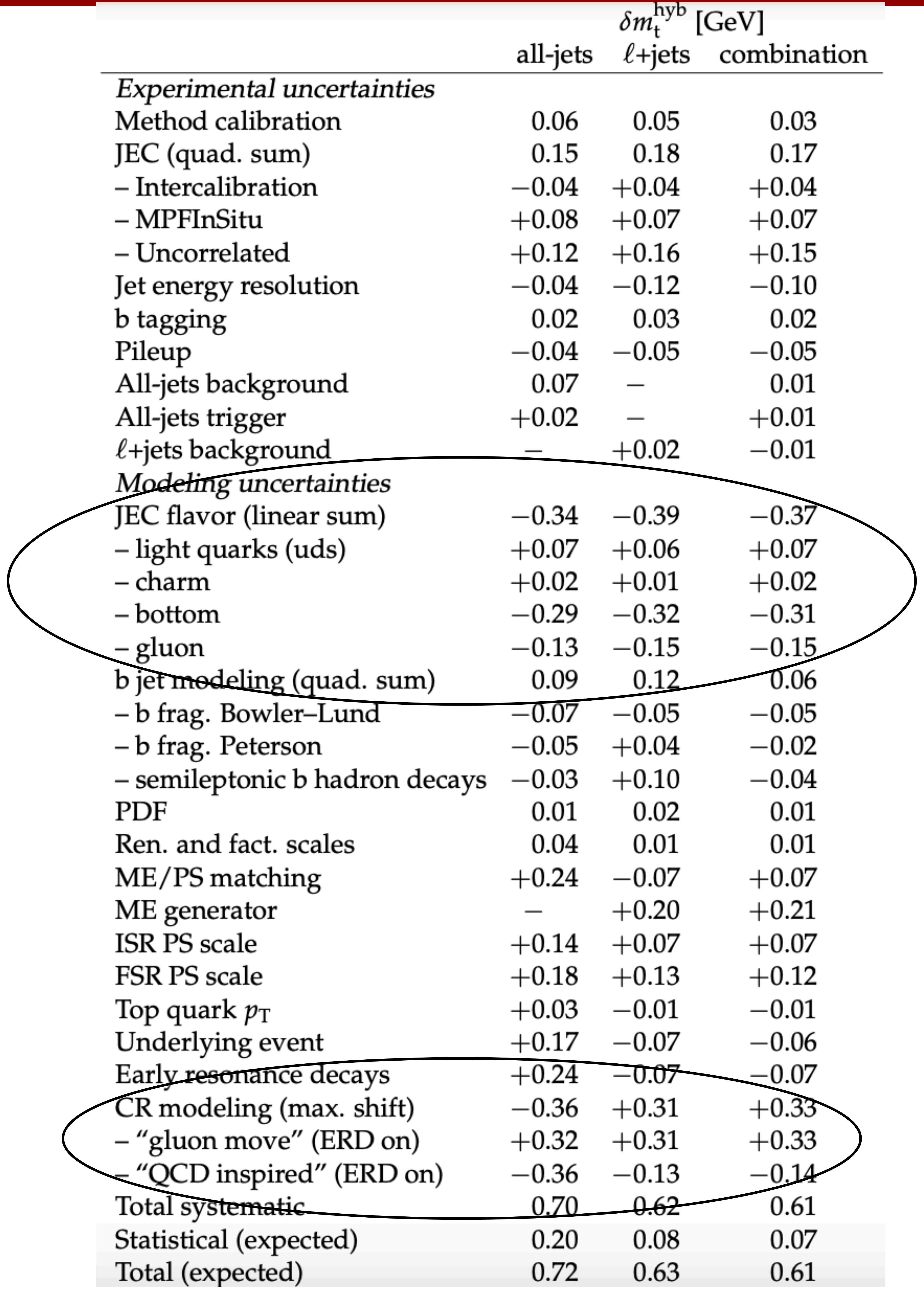
Backup

Why top mass?

- A fundamental parameter in SM
- A stringent check of the internal consistency of SM
- Required in the evolution of Higgs quartic coupling affecting the Higgs potential stability at high energy scale
- Of course, the top mass is the heaviest particle "so far", why?



JHEP08(2012)098



	$\delta m_{\mathrm{t}}^{\mathrm{hyb}}$ [GeV]		
	all-jets	ℓ+jets	combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
– Intercalibration	−0.04	+0.04	+0.04
– MPFInSitu	+0.08	+0.07	+0.07
– Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
All-jets trigger	+0.02	–	+0.01
ℓ+jets background	–	+0.02	−0.01
Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
– light quarks (uds)	+0.07	+0.06	+0.07
– charm	+0.02	+0.01	+0.02
– bottom	−0.29	−0.32	−0.31
– gluon	−0.13	−0.15	−0.15
b jet modeling (quad. sum)	0.09	0.12	0.06
– b frag. Bowler–Lund	−0.07	−0.05	−0.05
– b frag. Peterson	−0.05	+0.04	−0.02
– semileptonic b hadron decays	−0.03	+0.10	−0.04
PDF	0.01	0.02	0.01
Ren. and fact. scales	0.04	0.01	0.01
ME/PS matching	+0.24	−0.07	+0.07
ME generator	–	+0.20	+0.21
ISR PS scale	+0.14	+0.07	+0.07
FSR PS scale	+0.18	+0.13	+0.12
Top quark p_{T}	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
– "gluon move" (ERD on)	+0.32	+0.31	+0.33
– "QCD inspired" (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61

CMS top mass
Eur. Phys. J. C 79 (2019) 313

tt threshold scan

EPJC 73,(2013)2530

It is expected to measure the top properties using the tt threshold scan with ee-colliders at a precision level of

- ~17 MeV for top mass (stat. uncert.)
- ~45 MeV for top width (stat. uncert.)

Estimated by FCC-ee with 25fb^{-1} taken at each of the 8 centre-of-mass energy points

N^{3}LO cross-section calculation brings 40 MeV uncertainty additionally

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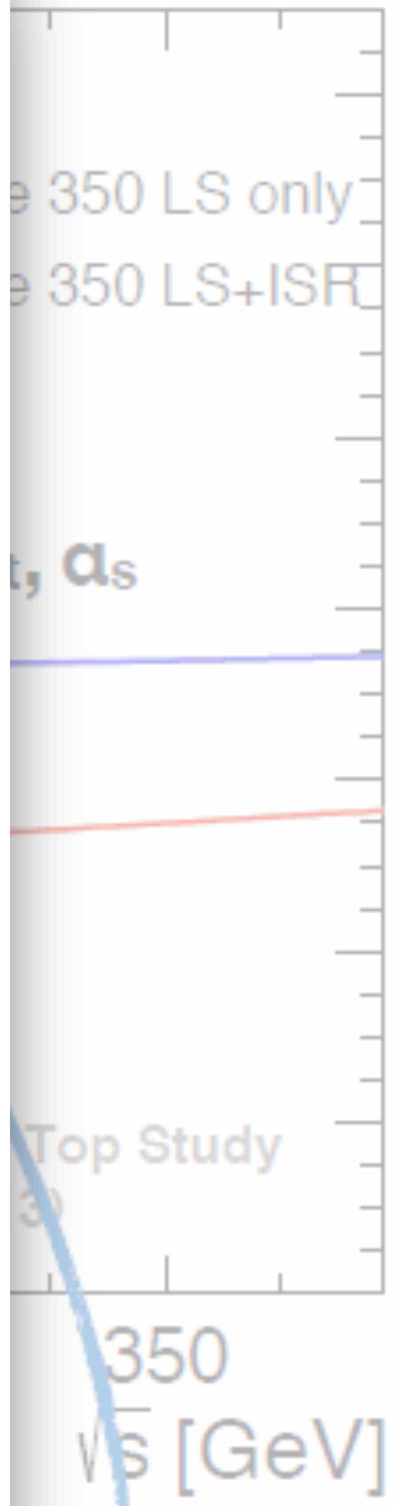
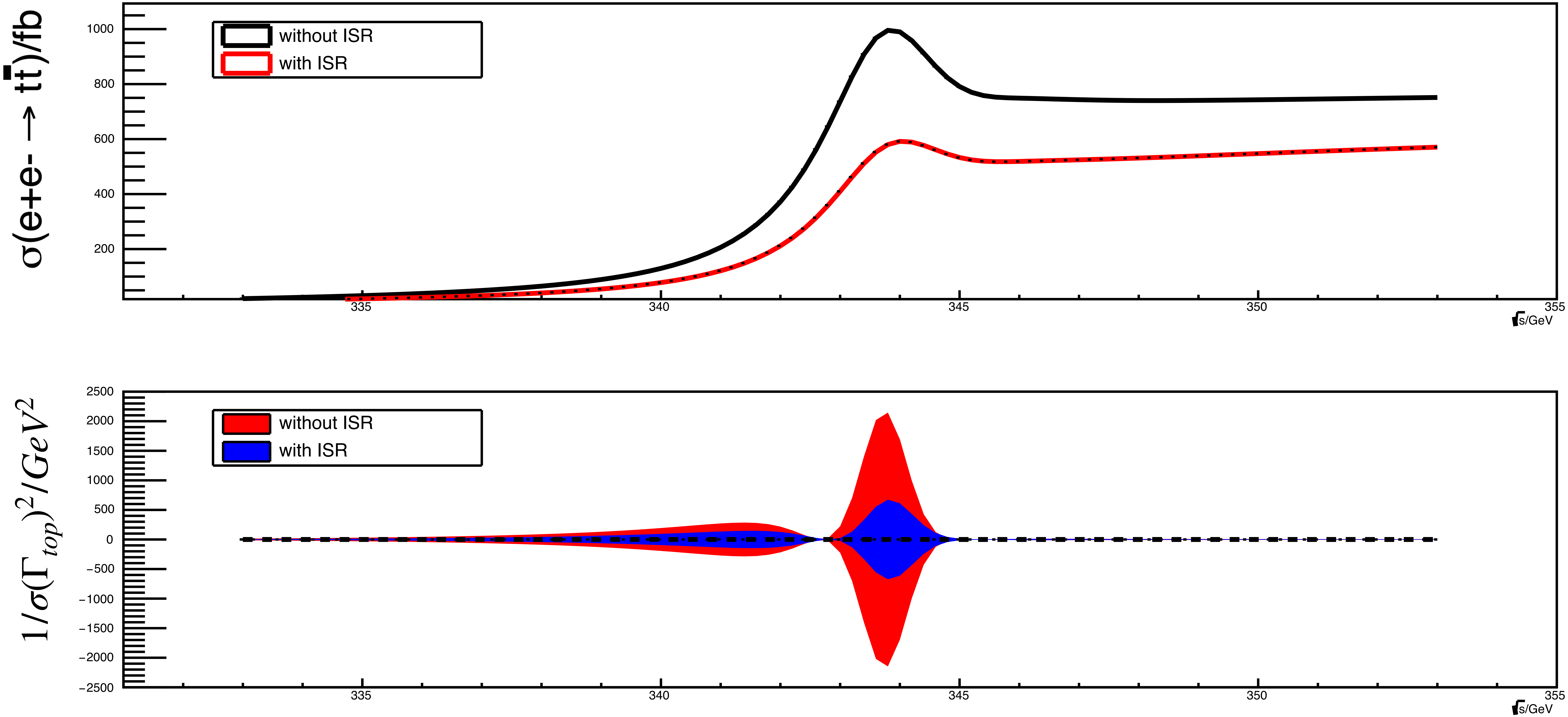
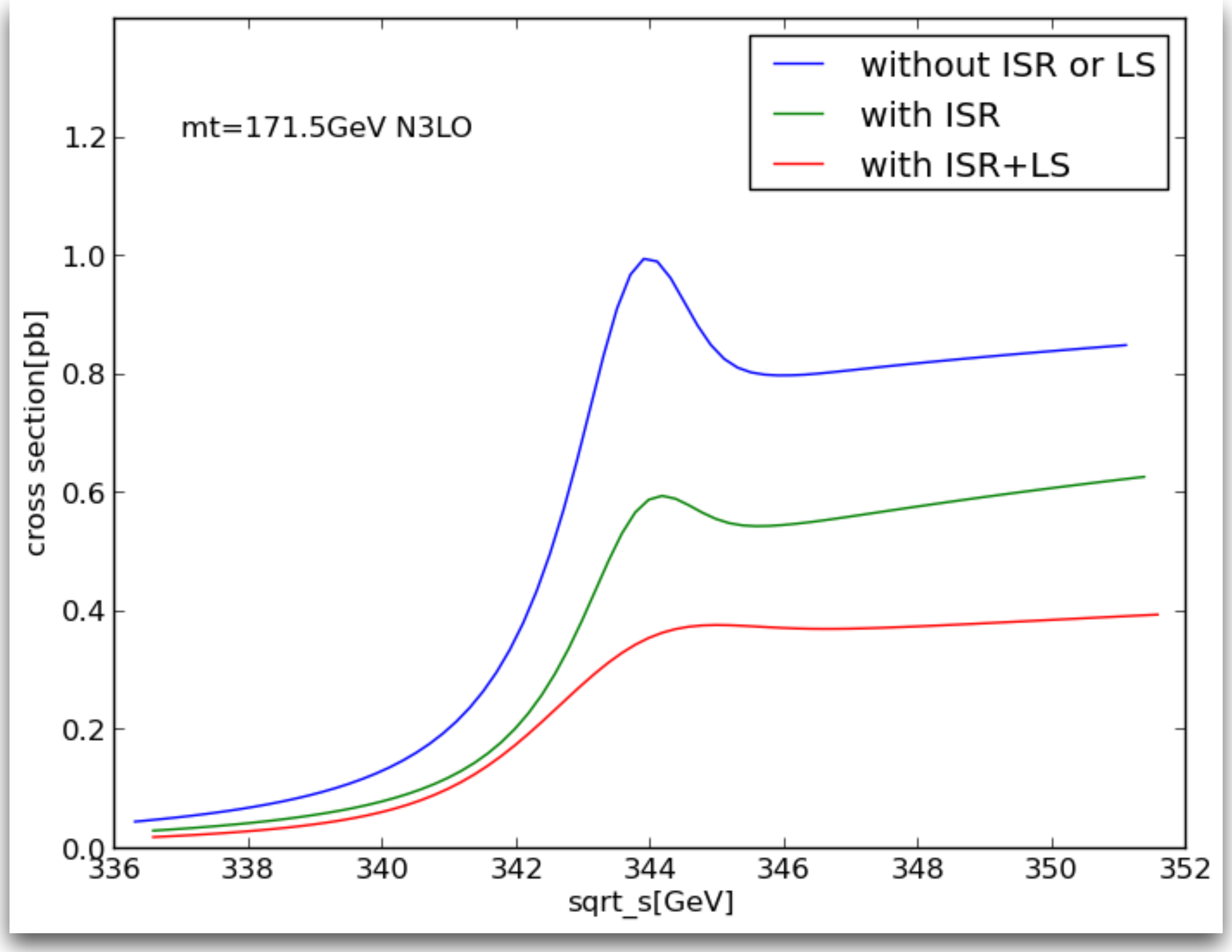


spectrum

Fisher information

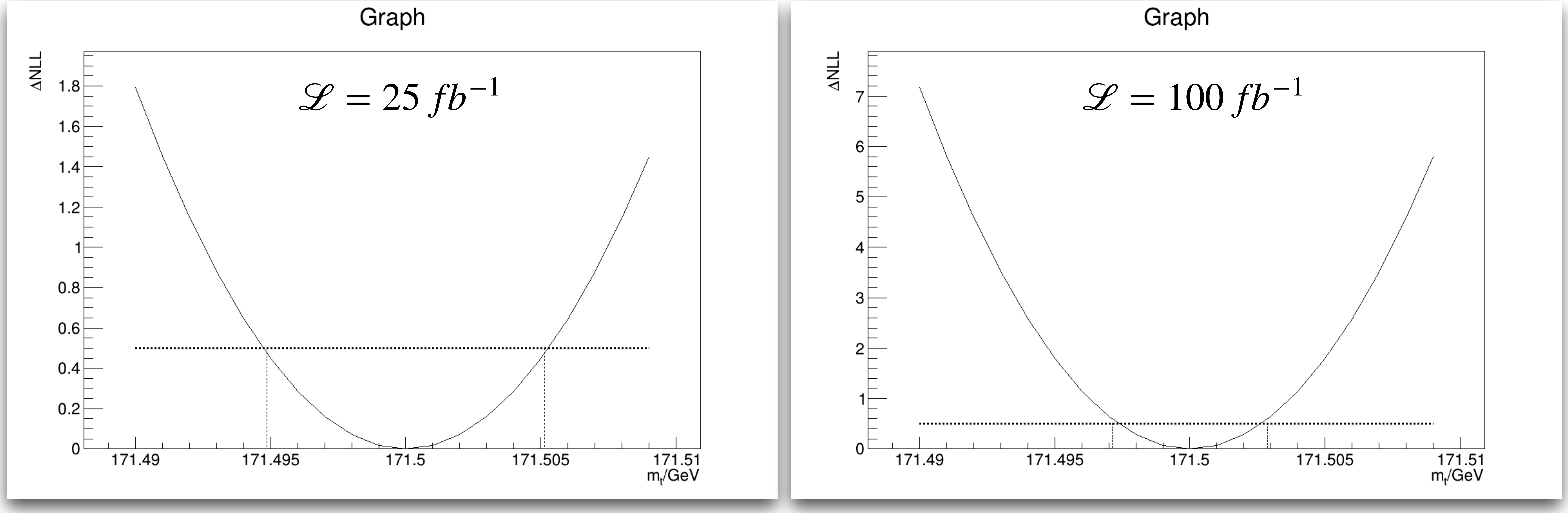


ISR and LS effects



- The cross section as a function of centre-of-mass energy
  - A clear peak of production can be seen at around the tt threshold
  - Adding ISR and LS (1 GeV width), the position of peak is hardly affected, but the sharpness is weakened and the total rate is suppressed in this region

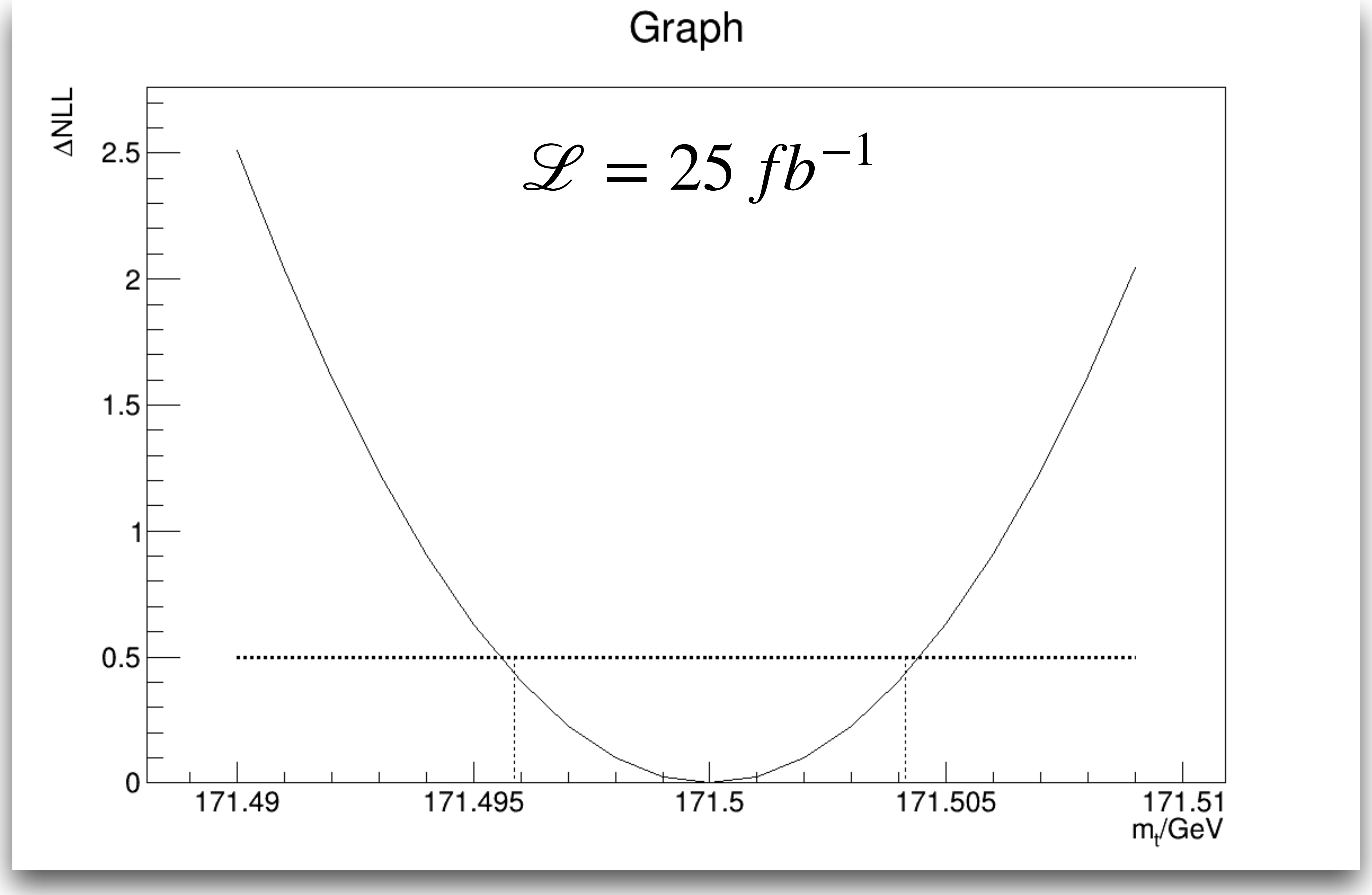
4-$\sqrt{s}$ scheme

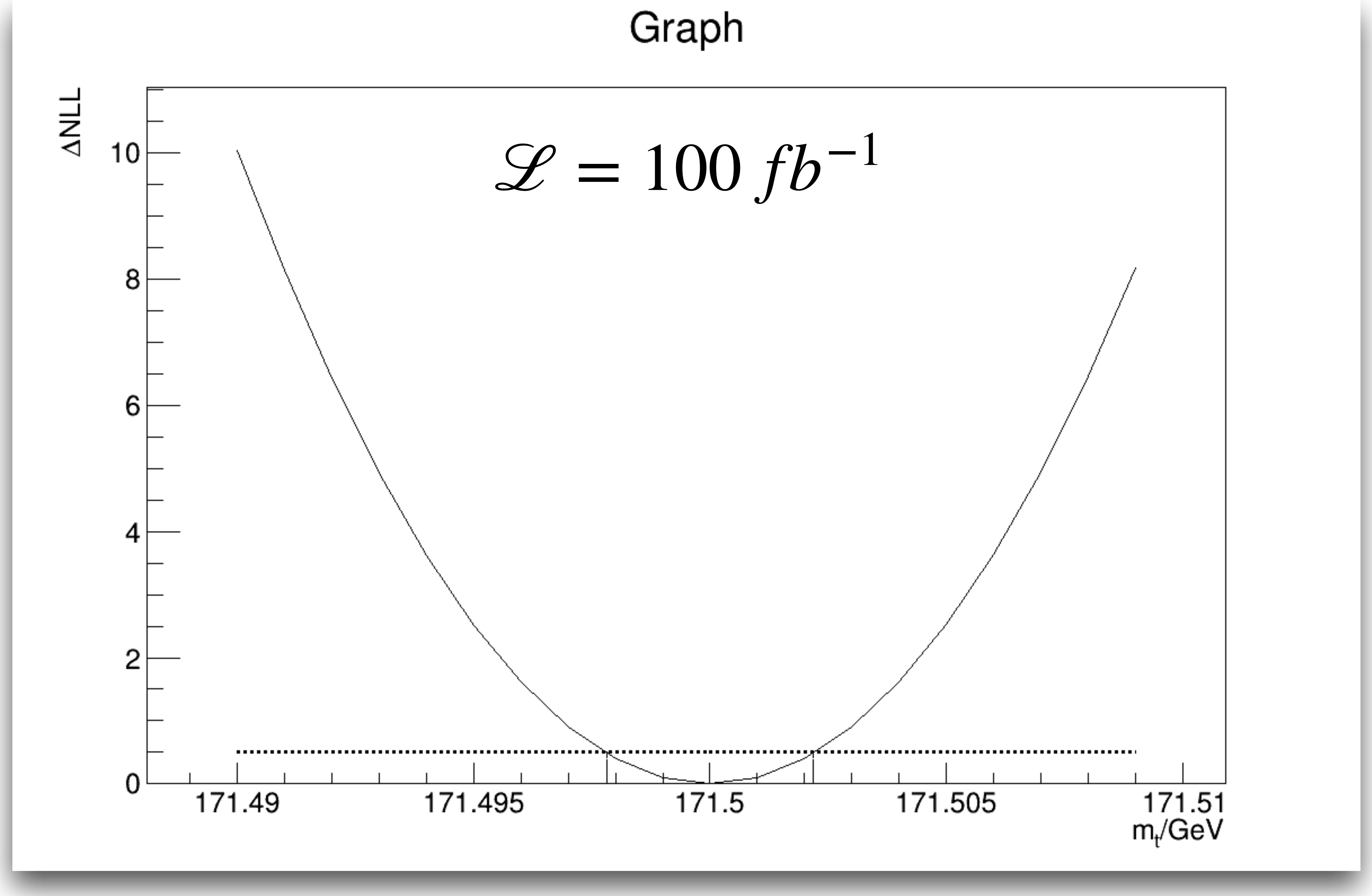


$\sigma(m_{top}) = 5.1$ MeV

$\sigma(m_{top}) = 2.9$ MeV

6-$\sqrt{s}$ scheme





$\sigma(m_{top}) = 4.1$ MeV

$\sigma(m_{top}) = 2.2$ MeV

Acceptance, efficiency, background

- The number read from CLIC Eur. Phys. J. C (2013) 73:2530
  - Semi-leptonic :
    - Data: 8296, Bkg: 643, extracted signal: 7653, acceptance*selection efficiency = 48.13%, Branch ratio=30%
  - Full-hadronic
    - Data: 11396, Bkg: 1393, extracted signal: 10003, acceptance*selection efficiency = 41.0%, Branch ratio=46%
- These numbers are calculated with $\sqrt{s} = 500$ GeV. At the moment we assume that the same acceptance and selection efficiency can apply to $\sqrt{s} = 352$ GeV.

Acceptance, efficiency, background

- Background events are directly scaled from 500GeV to 352GeV, according to their cross section estimated by CLIC paper.
  - For CLIC's 500GeV situation, the luminosity is 100 fb^{-1}
  - Because there is no information about background yields under 352GeV in the paper of CLIC.
- Result:
  - semi leptonic bkg event number:2380
  - fully hadronic bkg event number:5156
    - The signal yields of our pseudo data:
    - At 343GeV, 100 fb^{-1}
    - semi leptonic 4009.14
    - fully hadronic 5236.67

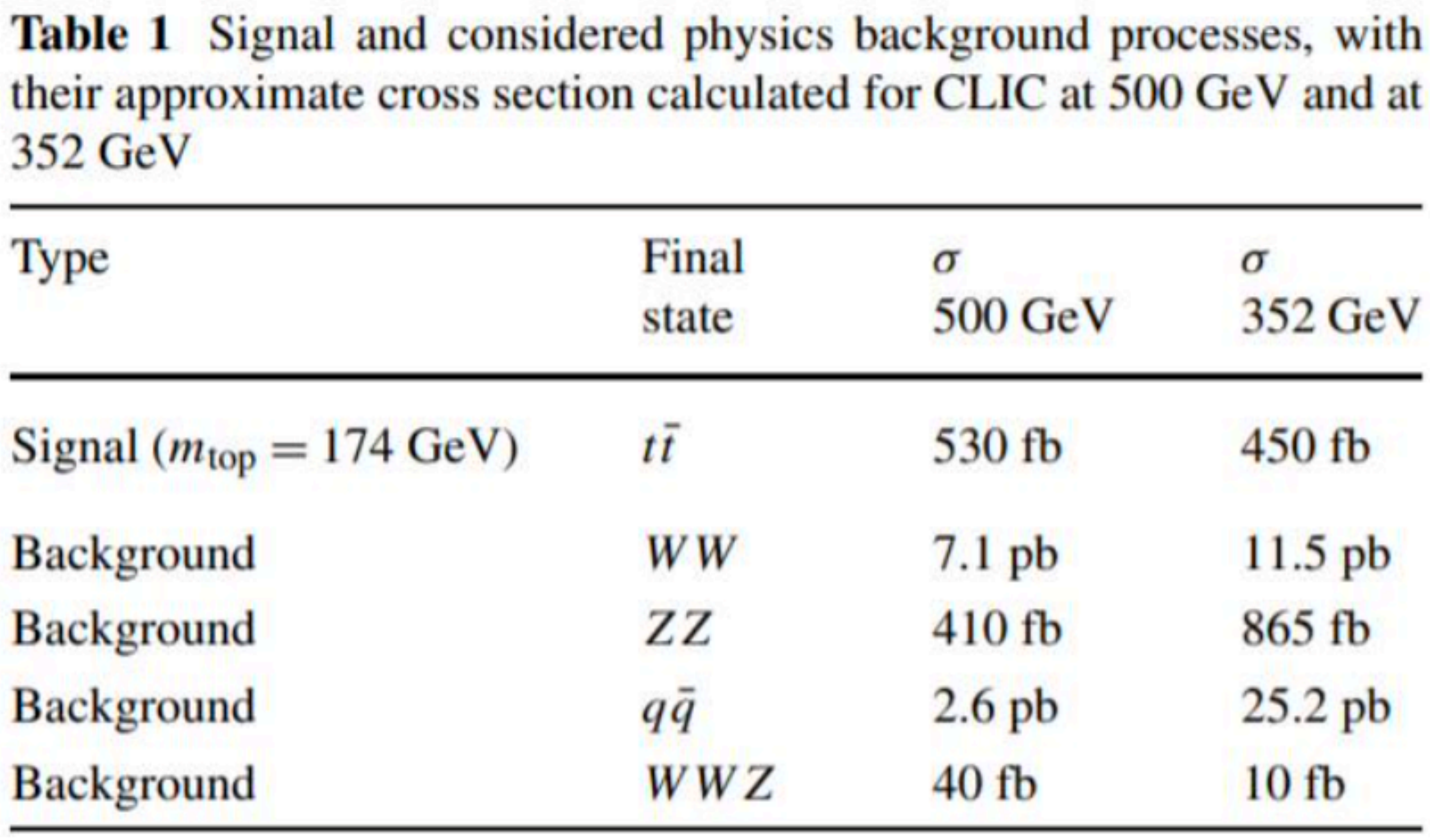


Table 1 Signal and considered physics background processes, with their approximate cross section calculated for CLIC at 500 GeV and at 352 GeV

Type	Final state	σ 500 GeV	σ 352 GeV
Signal ($m_{\mathrm{top}} = 174$ GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

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