Probing New Physics with off Z-pole Fermion-pair Production at CEPC

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in collaboration with

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Outline

- Background and Motivation
- Cross Section and Asymmetry
- BSM Sensitivities — Statistics & Systematics
- Conclusion

Background and Motivation

- LEP2 experiment provides abundance of off Z pole measurements (averages of cross sections and FB asymmetries for $e^+e^- \to f\bar{f}$ above Z pole) that constrain the dimension six (dim-6) four-fermion (4f) operators at the cutoff scale $\Lambda \sim 10$ TeV.

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LEP Electroweak Working Group, hep-ex/0612034

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- Off Z pole physics has not yet been studied at CEPC. In the same framework as done at LEP2, it is interesting to see what cutoff scale can CEPC access for the dim-6 4f operators.

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- **Cross Section of process $e^+e^- \to f\bar{f}$ involving D6 4f OP**

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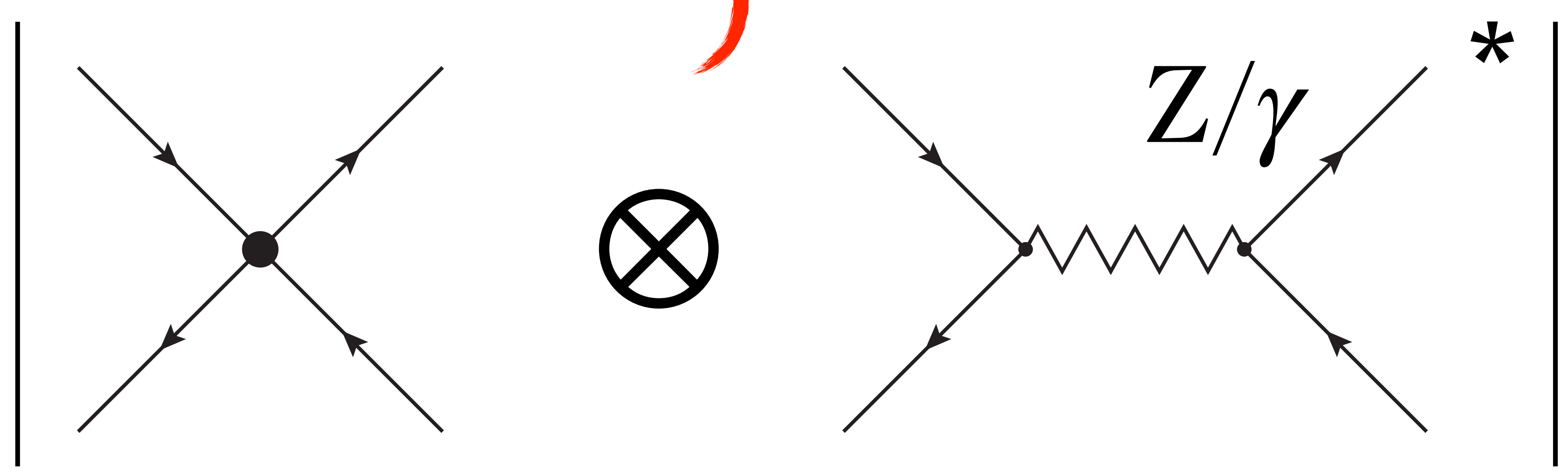

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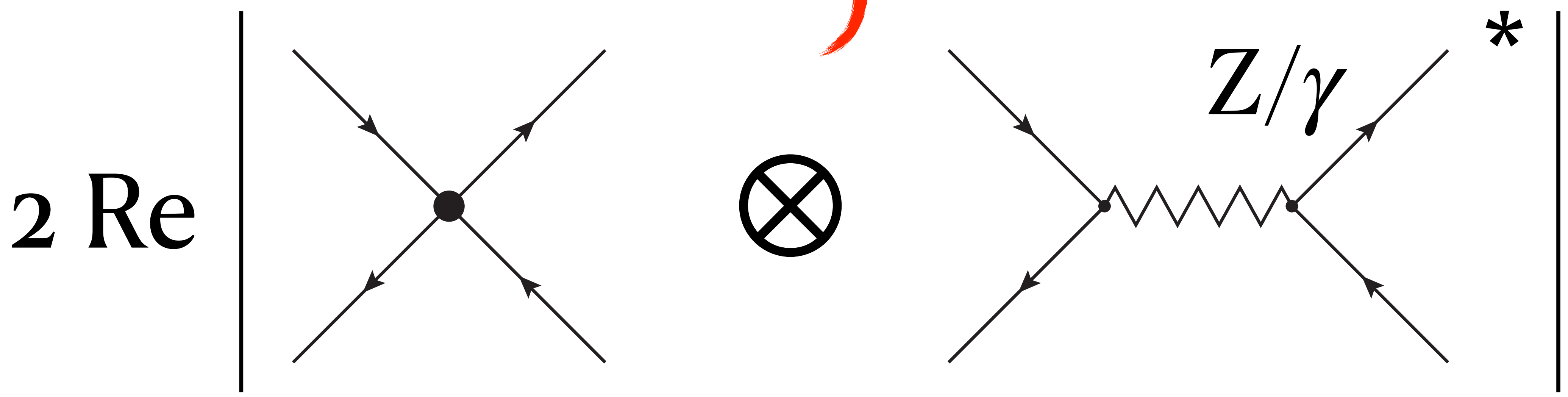

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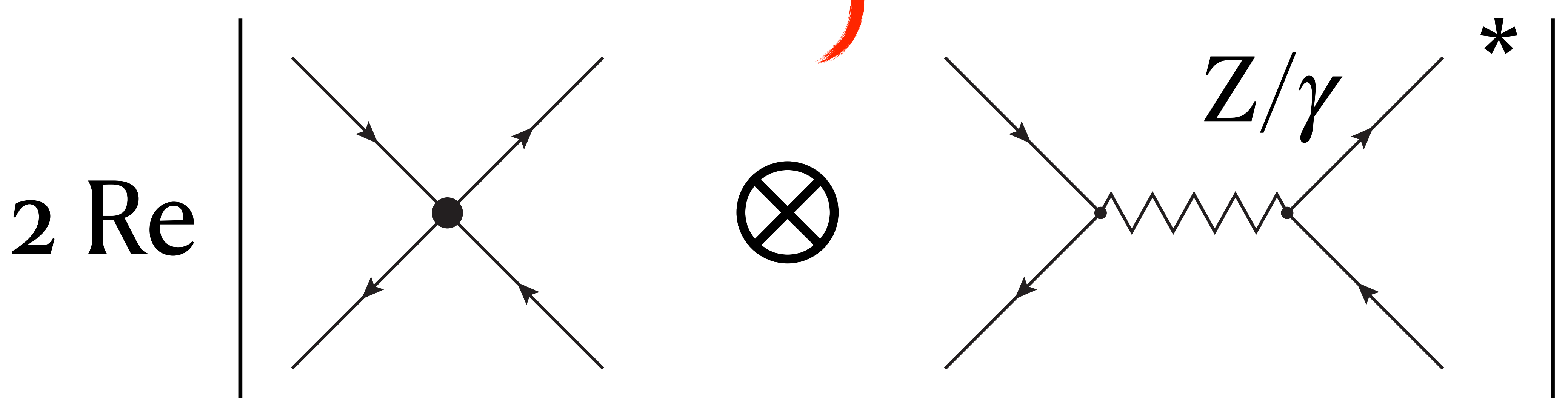

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Xsec asymmetry off Z pole enhances due to the interference terms: $M_{SM}^\gamma \times M_{SM}^{Z*}$, $M_{O_i} \times M_{SM}^{Z*}$, where the Z propagator has power one and thus the contribution flips sign above and below the Z pole. (*Other interference terms also give rise to asymmetry but much less since no flipping of sign*)

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3) Two-sided version of asymmetries in 2): $A^{(2)}_{\rm pol/FB} = A^{(1)+}_{\rm pol/FB} - A^{(1)-}_{\rm pol/FB}$

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Finding

Cut-off scale reach can be as much as $\sim \mathcal{O}(100)$ TeV

Cross Section & Asymmetry

•Cross Section involving D6 4f operators

11 four fermion operators

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Z.Y. Han and W. Skiba, *Phys.Rev.D* 71 (2005) 075009

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- New Physics Signal

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SM+NP → $A_{\rm tot}$

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$$A_{\rm NP} = \delta A = |A_{\rm tot} - A_{\rm SM}|$$

$$A_{\rm NP} \gtrsim \delta A_{\rm exp}$$

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LEP2 constraints $\Rightarrow \Lambda \sim 10$ TeV

$c_i \sim \frac{4\pi\kappa}{\Lambda_i}$

	O^s_{ll}	O^t_{ll}	O^s_{lq}	O^t_{lq}	O_{le}	O_{qe}	O_{lu}	O_{ld}	O_{ee}	O_{eu}	O_{ed}
c_i	−8.45	−0.35	4.07	8.28	−2.23	−5.0	5.07	8.72	−9.17	−11.90	−1.70
Λ_i (10 TeV)	1.22	6.03	1.76	1.23	2.37	1.59	1.57	1.20	1.17	1.03	2.72

- Cross Sections to Asymmetry

SM $\sigma^{\rho\lambda}_{\text{SM}}$, $\sigma^{\text{F(B)}}_{\text{SM}}$ → A_{SM}

NP $\sigma^{\rho\lambda}_{O_i}$, $\sigma^{\rho\lambda}_{O_i,\text{F(B)}}$

SM+NP → A_{tot}

- New Physics Signal

$$A_{\text{NP}} = \delta A = |A_{\text{tot}} - A_{\text{SM}}|$$

$$A_{\text{NP}} \gtrsim \delta A_{\text{exp}}$$

Cross Section & Asymmetry

- **Cross Section Asymmetry**
  - Cross section asymmetry across Z pole:

$$A_\sigma\left(\Delta_\pm\right) = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\sigma\left(M_Z + \Delta_+\right) - \sigma\left(M_Z - \Delta_-\right)}{\sigma\left(M_Z + \Delta_+\right) + \sigma\left(M_Z - \Delta_-\right)}$$

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a) In symmetric off Z pole run: $\Delta_+ = \Delta_- = \Delta$

•Cross Section Asymmetry

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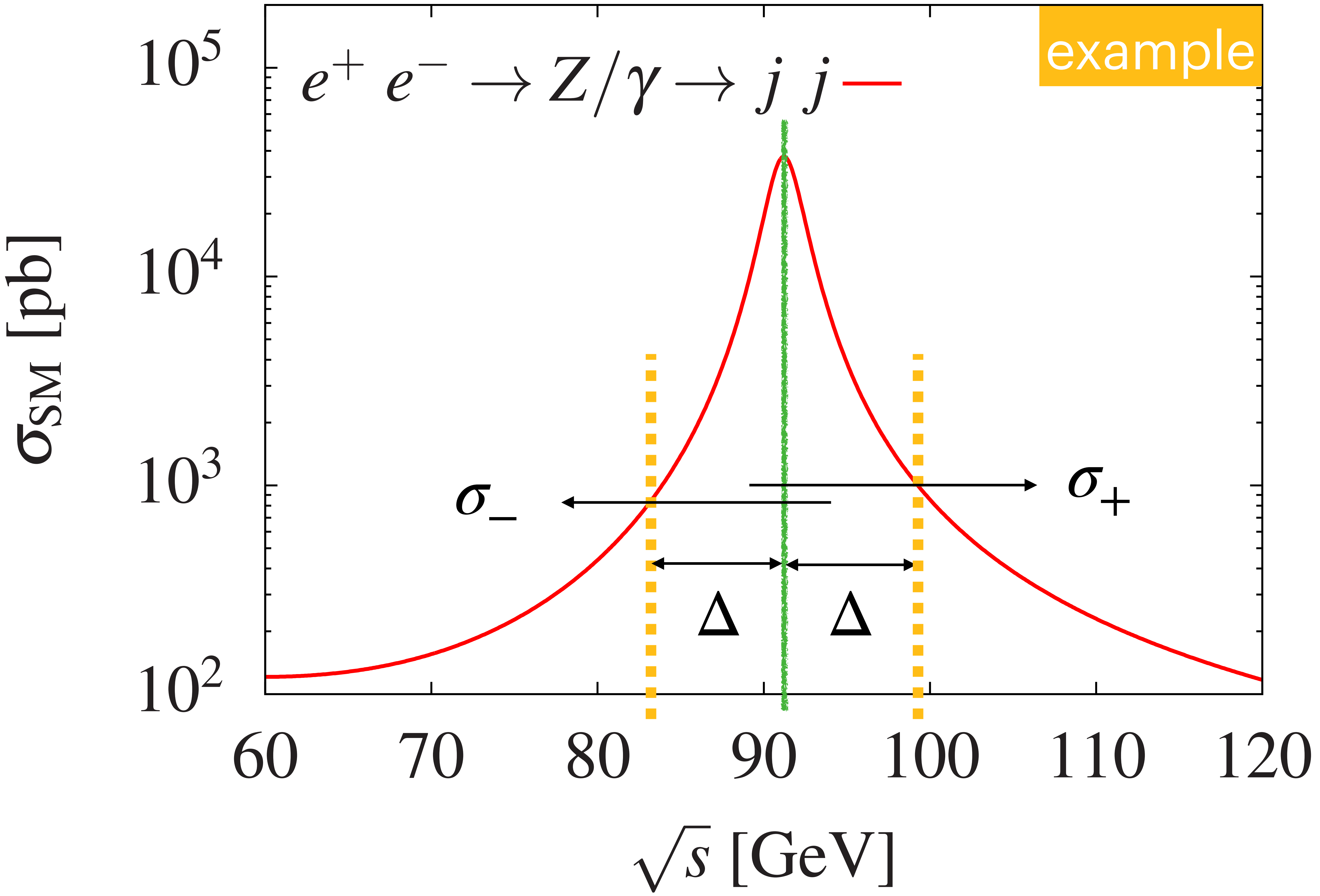
a) In symmetric off Z pole run: $\Delta_+ = \Delta_- = \Delta$

b) In asymmetric off Z pole run: $\Delta_+ \neq \Delta_-$

•Cross Section Asymmetry — Symmetric off Z Pole Run

- Symmetric: energy deviation from the Z pole is measured by a single parameter $\Delta_\pm = \Delta$

$$A_\sigma(\Delta) = \frac{\sigma(M_Z + \Delta) - \sigma(M_Z - \Delta)}{\sigma(M_Z + \Delta) + \sigma(M_Z - \Delta)}$$



Cross Section & Asymmetry

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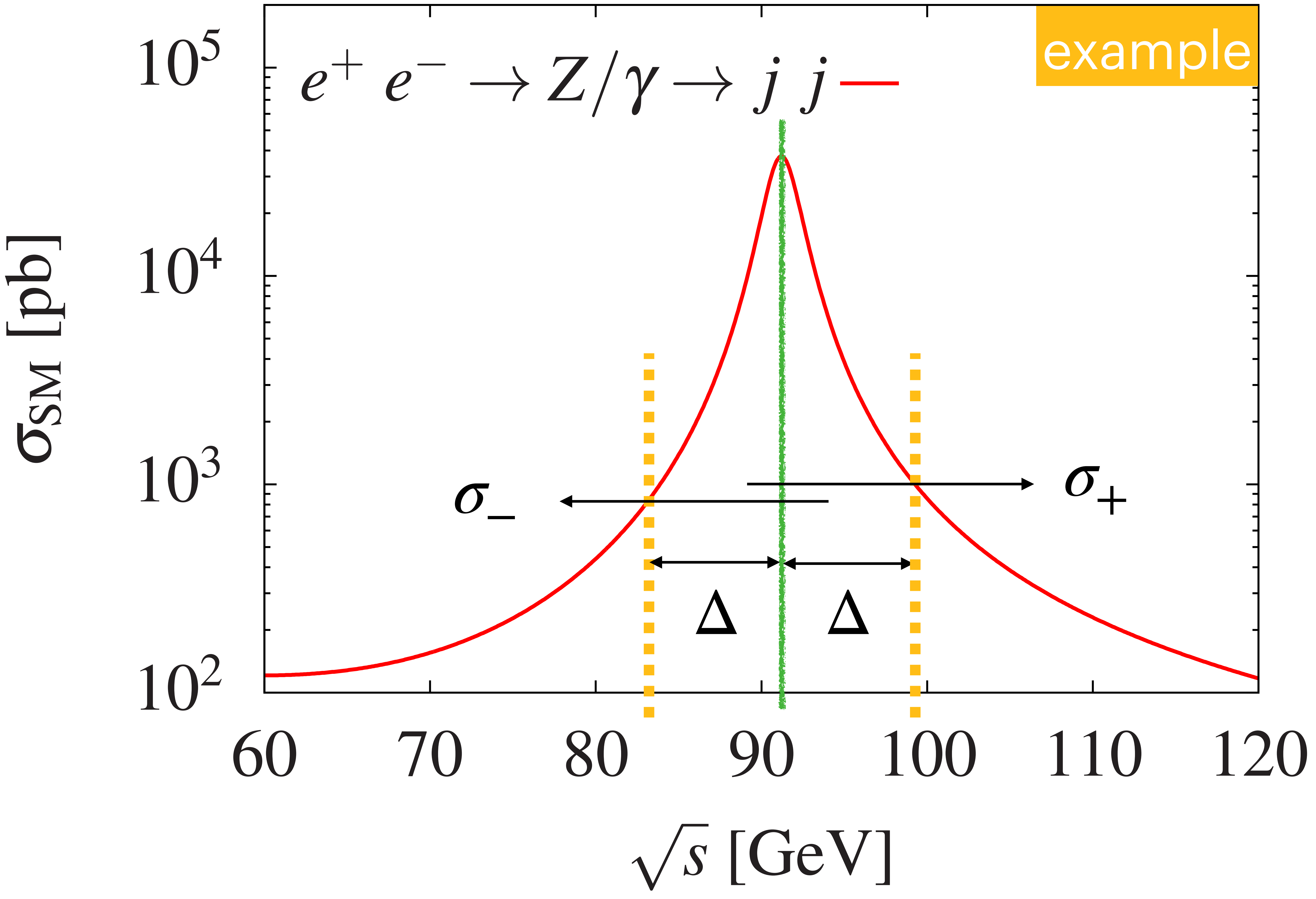
$$\sigma_{\rm SM}\left(M_Z + \Delta\right) \neq \sigma_{\rm SM}\left(M_Z - \Delta\right)$$

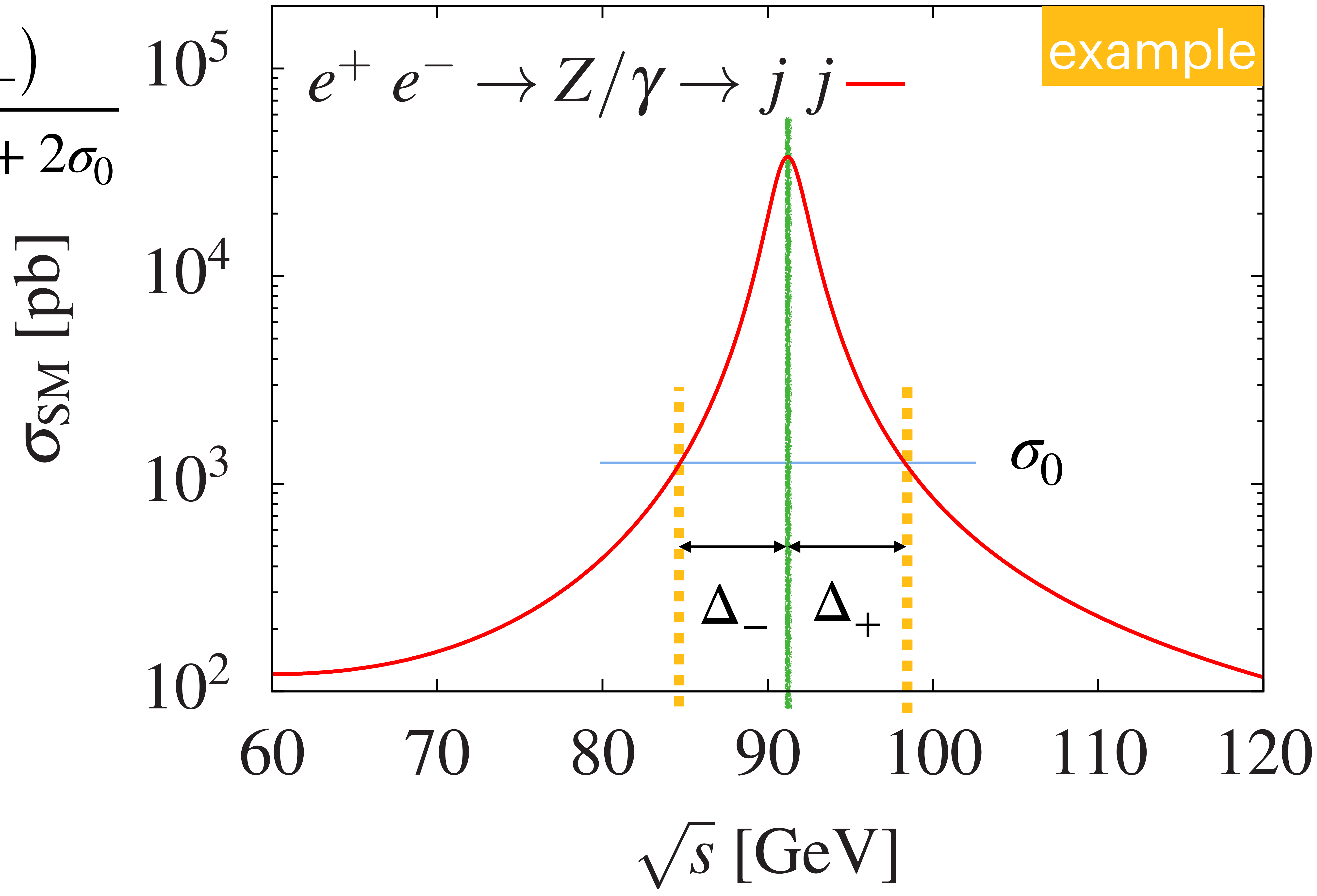


Cross Section & Asymmetry

•Cross Section Asymmetry — Asymmertic off Z Pole Run

- Asymmetric: for a given σ_0 the energy deviations from Z pole are $\Delta_\pm$ so that $A_{\sigma_{\rm SM}}\left(\sigma_0\right) = 0$

$$A_\sigma\left(\sigma_0\right) = \frac{\sigma_{\rm NP}\left(M_Z + \Delta_+\right) - \sigma_{\rm NP}\left(M_Z - \Delta_-\right)}{\sigma_{\rm NP}\left(M_Z + \Delta_+\right) + \sigma_{\rm NP}\left(M_Z - \Delta_-\right) + 2\sigma_0}$$



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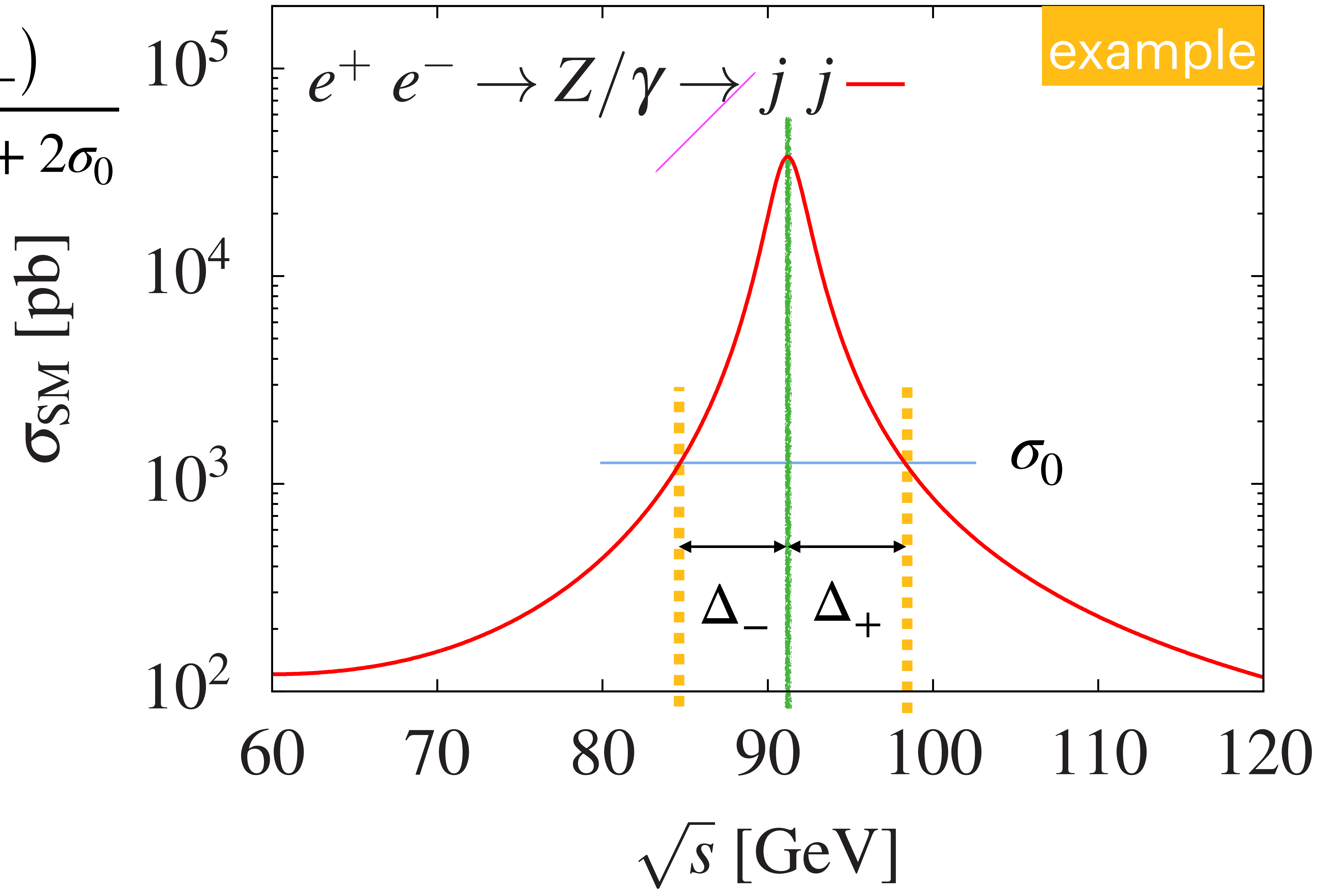

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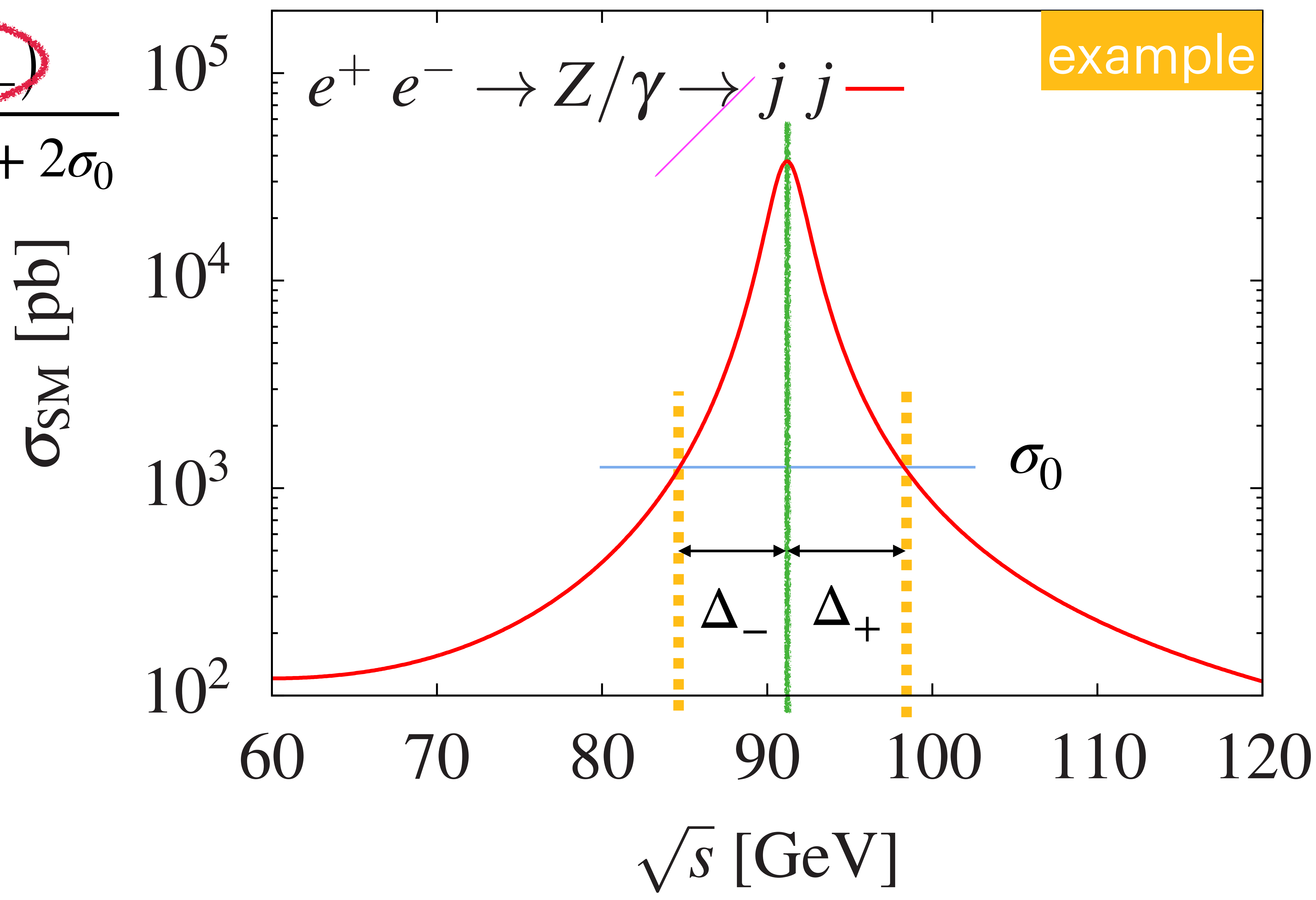
NP may be enhanced if w/o SM contribution

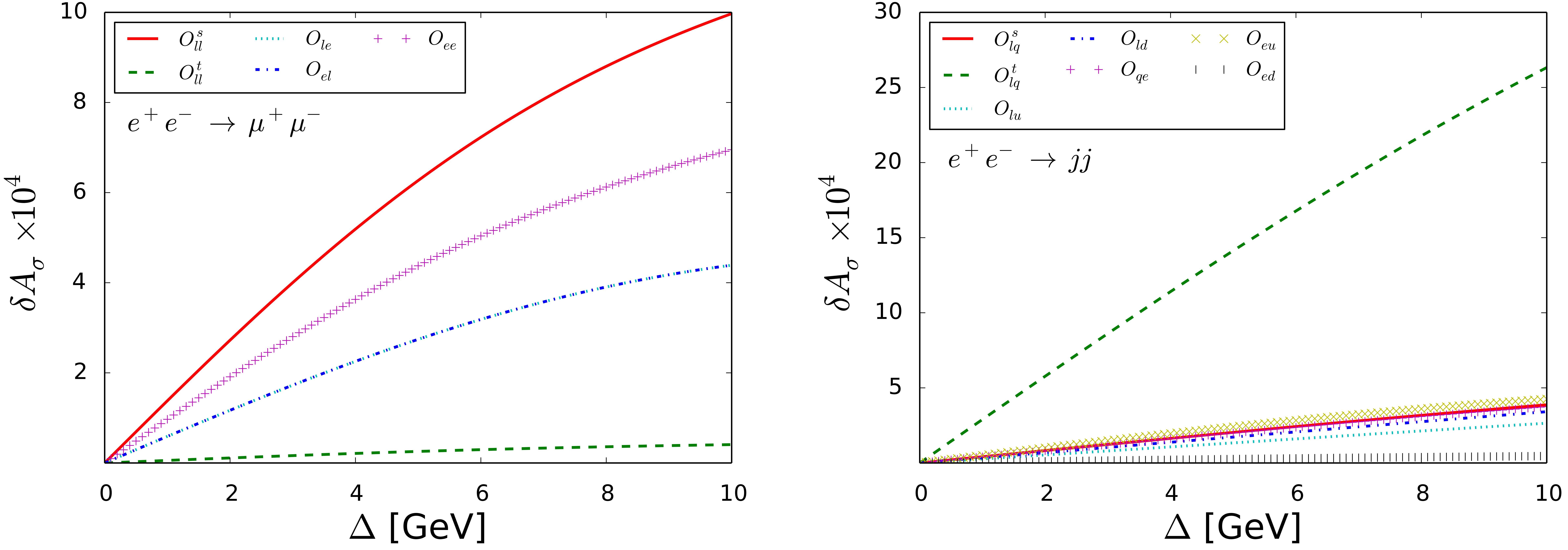
$$\sigma_{\rm SM}\left(M_Z+\Delta_+\right) = \sigma_{\rm SM}\left(M_Z-\Delta_-\right)$$



Cross Section & Asymmetry

•Cross Section Asymmetry — Symmetric off Z Pole Run

δA_σ vs Δ



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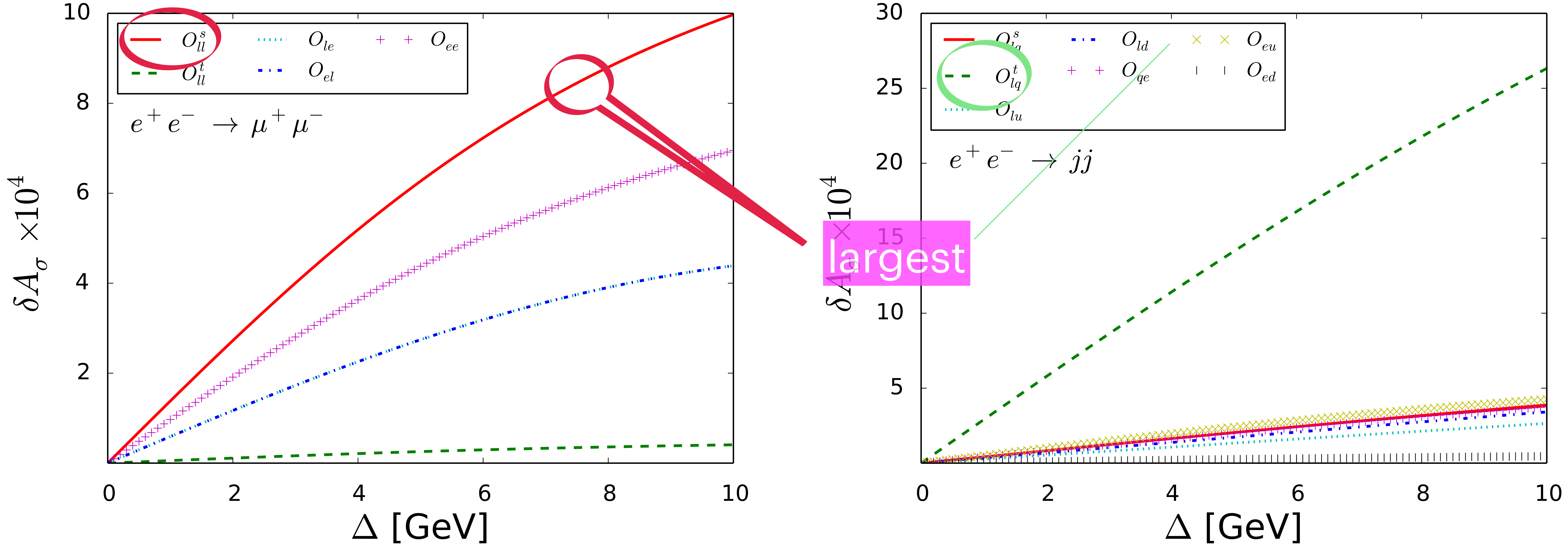
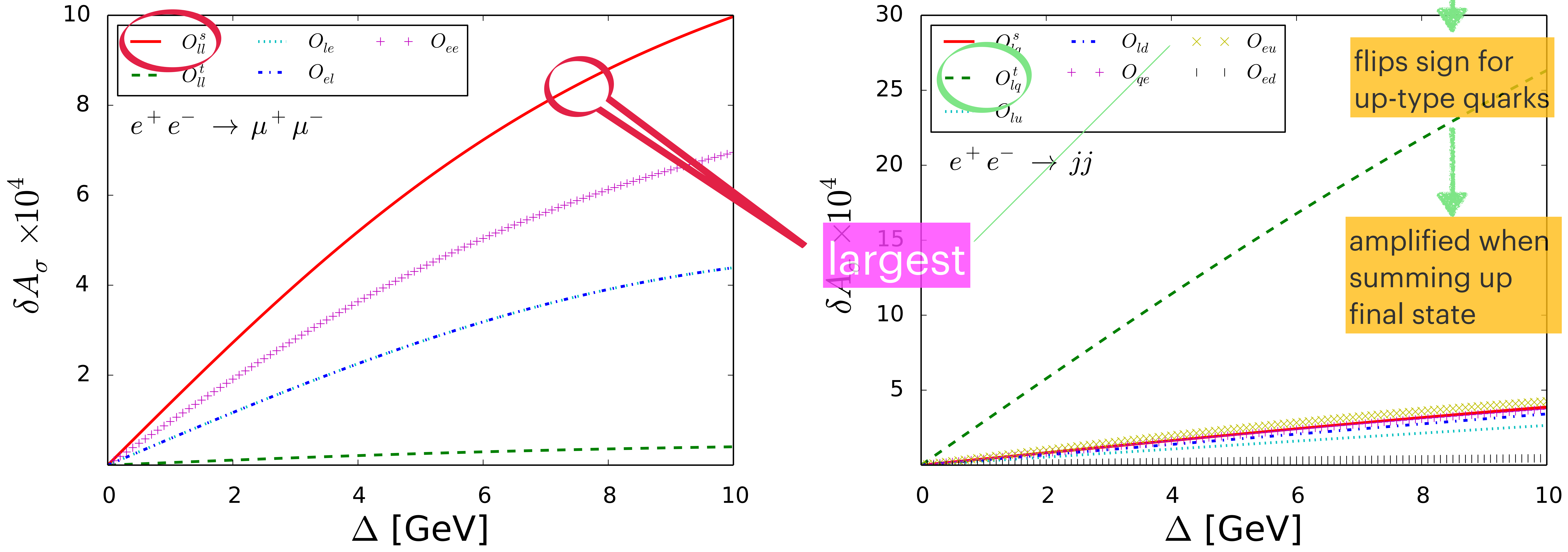


Cross Section & Asymmetry

•Cross Section Asymmetry — Symmetric off Z Pole Run

δA_σ vs Δ

$O^t_{lq} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$



flips sign for up-type quarks

amplified when summing up final state

Cross Section & Asymmetry

•Polarization and Forward-Backward Asymmetry

a) One-sided:

$$A^{(1)}_{\text{pol/FB}}\left(\sqrt{s}\right)=\frac{\sigma_+\left(\sqrt{s}\right)-\sigma_-\left(\sqrt{s}\right)}{\sigma_+\left(\sqrt{s}\right)+\sigma_-\left(\sqrt{s}\right)},\qquad (+,-)=(\text{L, R}),(\text{F, B})$$

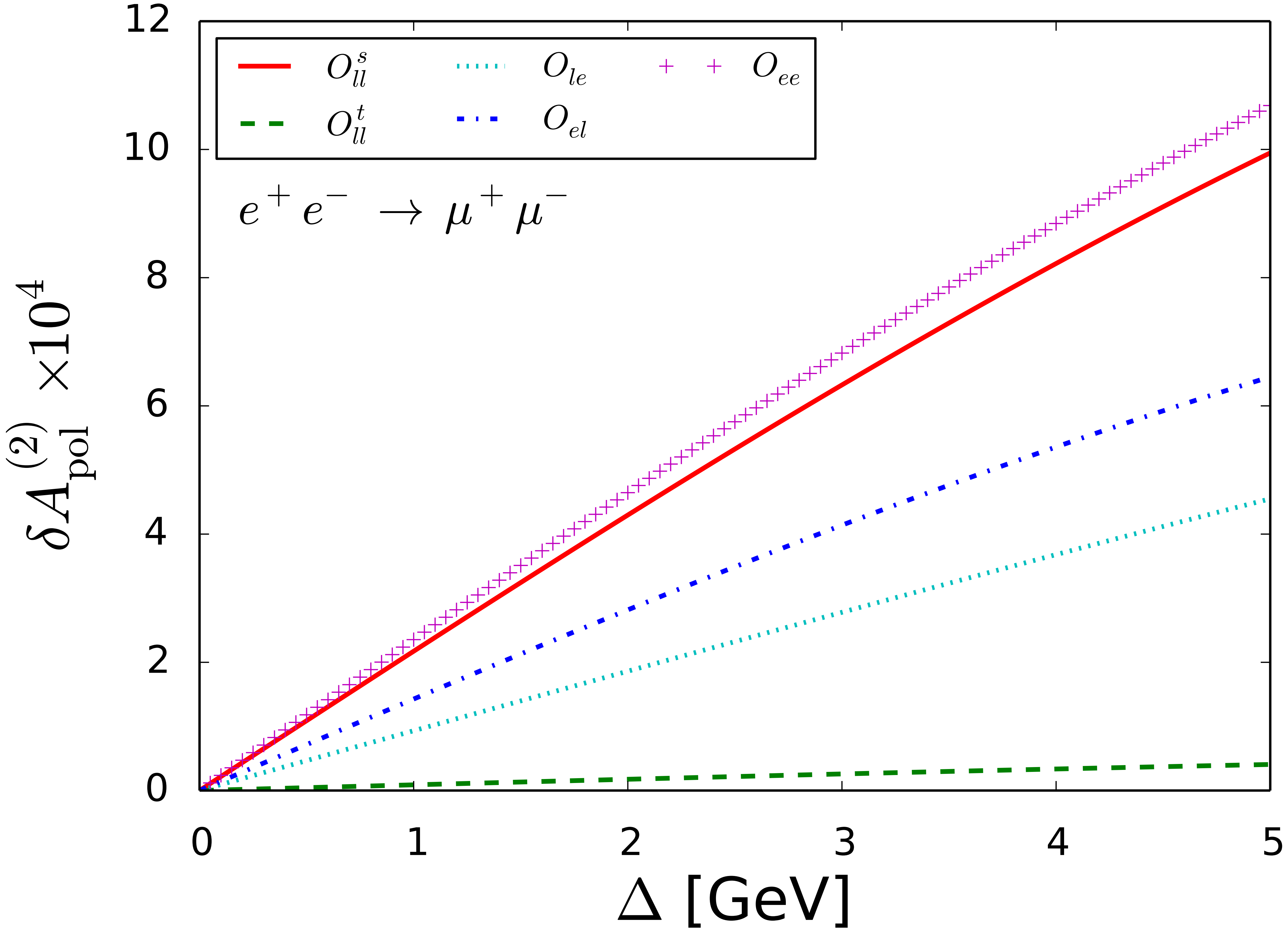
b) Two-sided:

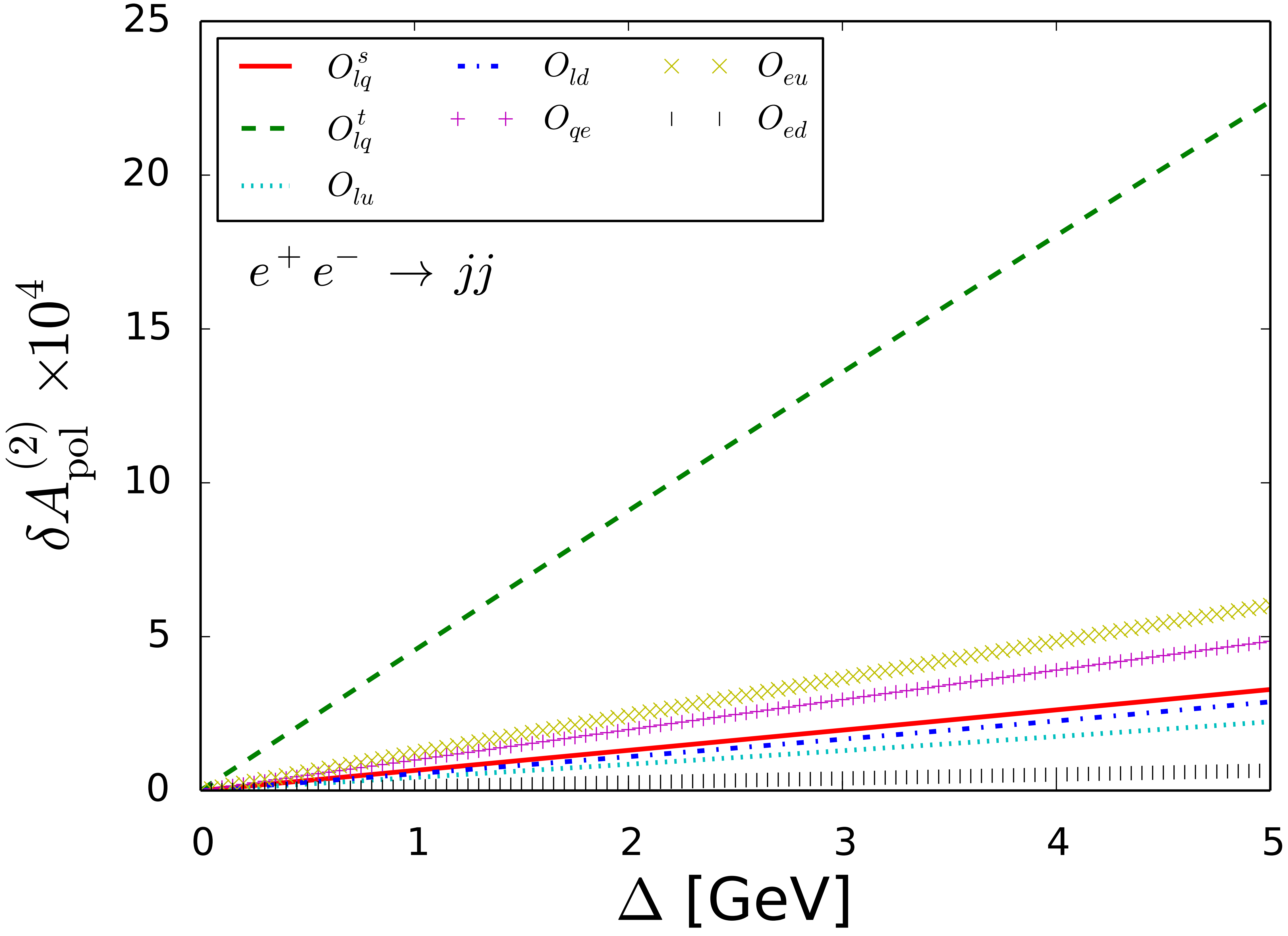
$$A^{(2)}_{\text{pol/FB}}\left(\Delta_\pm\right)=A^{(1)}_{\text{pol/FB}}\left(M_Z+\Delta_+\right)-A^{(1)}_{\text{pol/FB}}\left(M_Z-\Delta_-\right)$$

Cross Section & Asymmetry

•Polarization Asymmetry — Two-sided

Assuming $\Delta_\pm = \Delta$ $\delta A^{(2)}_{\text{pol}}$ vs Δ





Cross Section & Asymmetry

•Polarization Asymmetry — Two-sided

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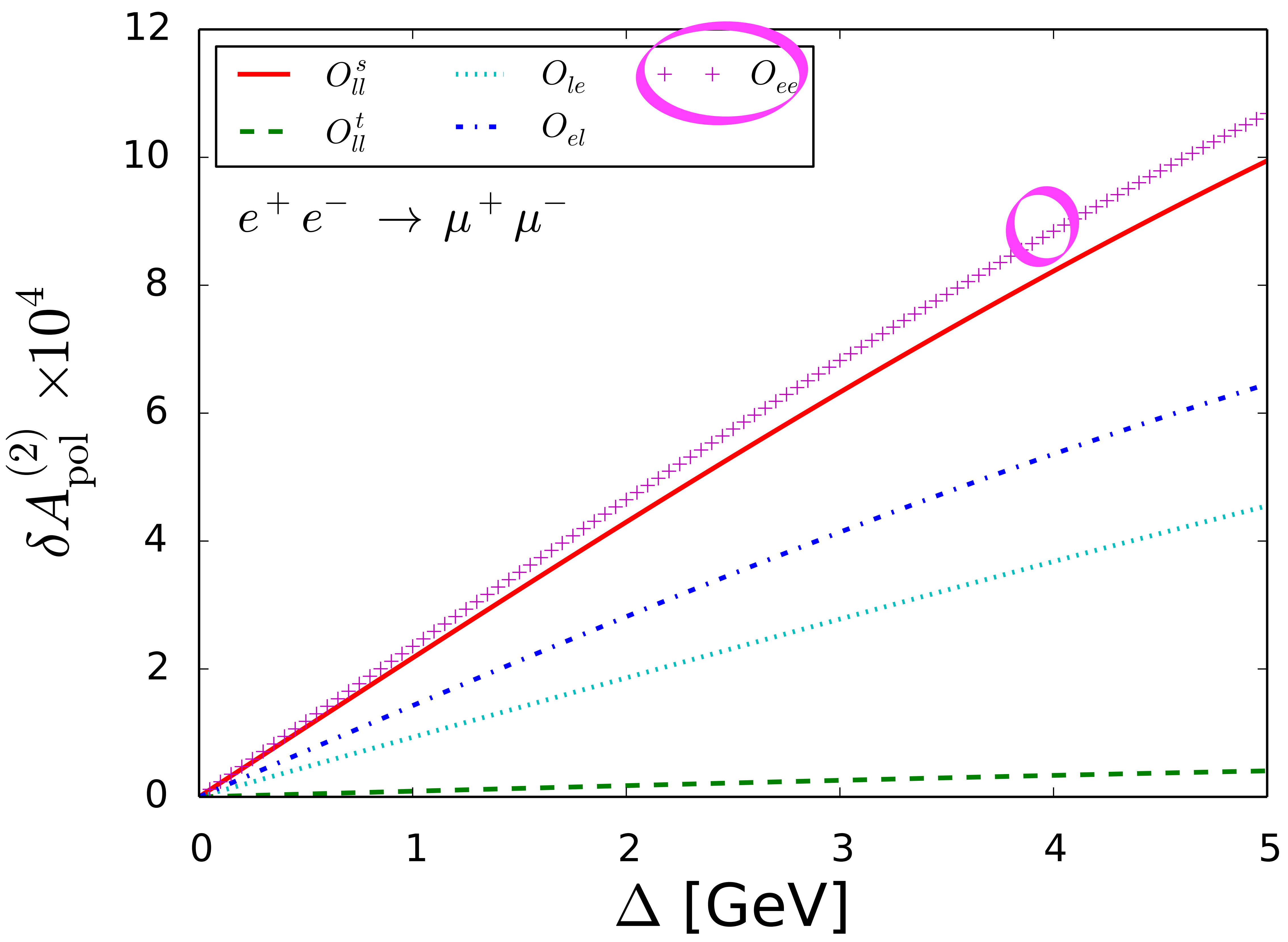

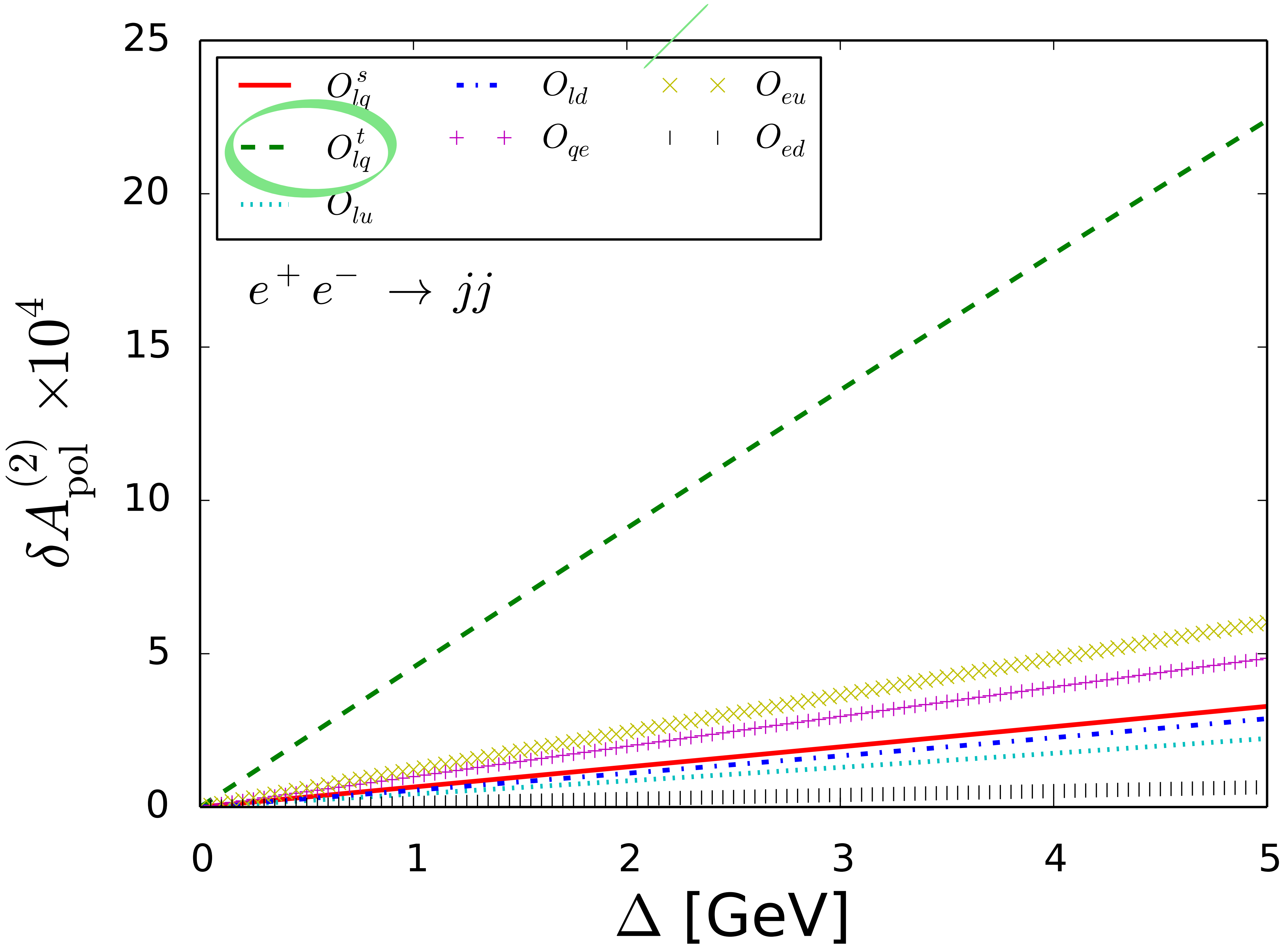

BSM Sensitivities

- **Cutoff Scales in New Physics Asymmetry Signal**
  - A simple estimate of scale dependence in $A_{\rm NP}$

a) For xsec, one-sided pol/FB Asymmetries:

$$A_{\rm NP} = \left|A_{\rm SM+NP} - A_{\rm SM}\right| = \left|\frac{\delta\sigma_{\rm SM} + \delta\sigma_{\rm NP}}{\sigma_{\rm SM} + \sigma_{\rm NP}} - \frac{\delta\sigma_{\rm SM}}{\sigma_{\rm SM}}\right| \approx \left|\frac{\delta\sigma_{\rm NP}}{\sigma_{\rm SM}}\right| \quad \text{since } \left|\frac{\delta\sigma_{\rm SM}}{\sigma_{\rm SM}}\right| \ll \left|\frac{\delta\sigma_{\rm NP}}{\sigma_{\rm NP}}\right|$$

b) For two-sided pol/FB Asymmetries: $A_{\rm NP} \approx \left|\frac{\delta\sigma_{\rm NP}}{\sigma_{\rm SM}}(s_+) - \frac{\delta\sigma_{\rm NP}}{\sigma_{\rm SM}}(s_-)\right|$

Shorthand notation: $\sigma_i = \sigma_{i,+} + \sigma_{i,-}, \quad \delta\sigma_i = \sigma_{i,+} - \sigma_{i,-}, \quad i = \text{SM, NP}$

BSM Sensitivities

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$$\sigma_{\mathrm{NP}} \sim \frac{1}{\Lambda^2}$$

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NP asymmetry signal with new cutoff scale Λ' yields $\Longrightarrow \frac{A'_{\rm NP}}{A_{\rm NP}} \sim \frac{\Lambda^2}{\Lambda'^2}$

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current scale

BSM Sensitivities

•Cutoff Scales in New Physics Asymmetry Signal

- Constraints for cutoff scales by projected precision

Is there NP? —identify NP signal→ $A_{\rm NP} \overset{?}{\gtrsim} n \cdot \delta A_{\rm exp}$ —constrain scales→ $A'_{\rm NP} \sim n \cdot \delta A_{\rm exp}$

n: n-σ level; $\delta A_{\rm exp}$: projected sensitivity

Cutoff scale enhancement: $N = \dfrac{\Lambda'}{\Lambda} = \sqrt{\dfrac{A_{\rm NP}}{A'_{\rm NP}}} = \sqrt{\dfrac{\delta}{n}}, \quad \delta = \dfrac{A_{\rm NP}}{\delta A_{\rm exp}}$

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Example at 2-σ level, $N = 2$ when $\delta = 8$

BSM Sensitivities

• New Physics Sensitivity without Systematic Uncertainties

- Statistical uncertainty

# of events

integrated luminosity

$$\delta A_{\text{stat}} = 2\sqrt{\frac{N_+N_-}{\left(N_+ + N_-\right)^3}}, \quad N_\pm = X_\pm \sigma_\pm$$

Equal luminosity assumption $X_\pm = X_0$

$$\delta A_{\text{stat}} = \frac{2}{\sqrt{X_0}}\sqrt{\frac{\sigma_+\sigma_-}{\left(\sigma_+ + \sigma_-\right)^3}}$$

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CEPC off and on Z pole runs Z mass scan

$\sqrt{s}$ (GeV)	Luminosity (ab^{-1})
87.9	0.25
90.2	0.25
91.2	7
92.2	0.25
94.3	0.25

CEPC CDR Vol 2 (2018)

BSM Sensitivities

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CEPC CDR Vol 2 (2018)

our trial

- Two-sided: $X_0 = 0.5\ \text{ab}^{-1}$
- One-sided: $X_0 = 1\ \text{ab}^{-1}$

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CEPC CDR Vol 2 (2018)

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Investigation

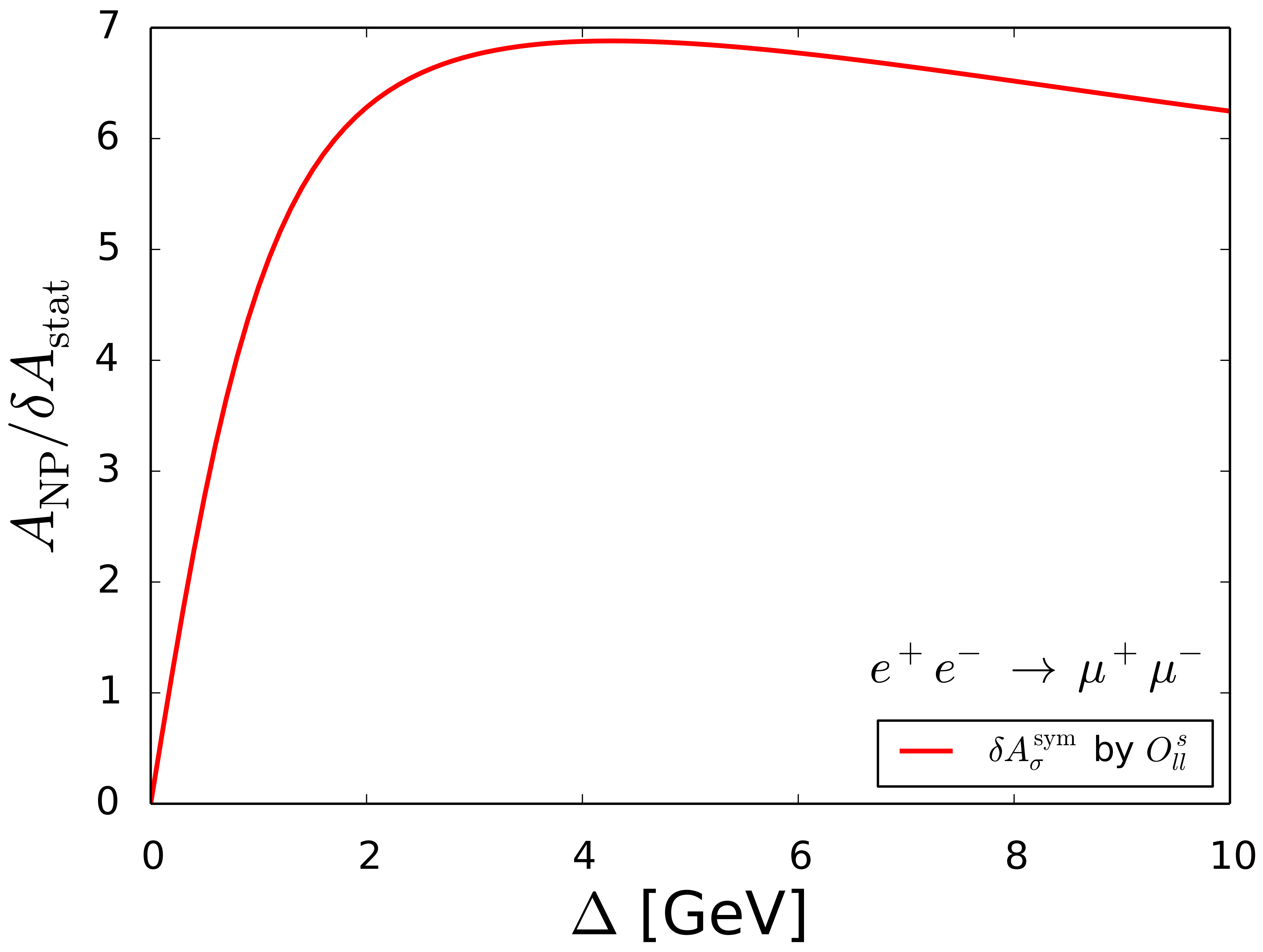
What is the room for scale enhancement?

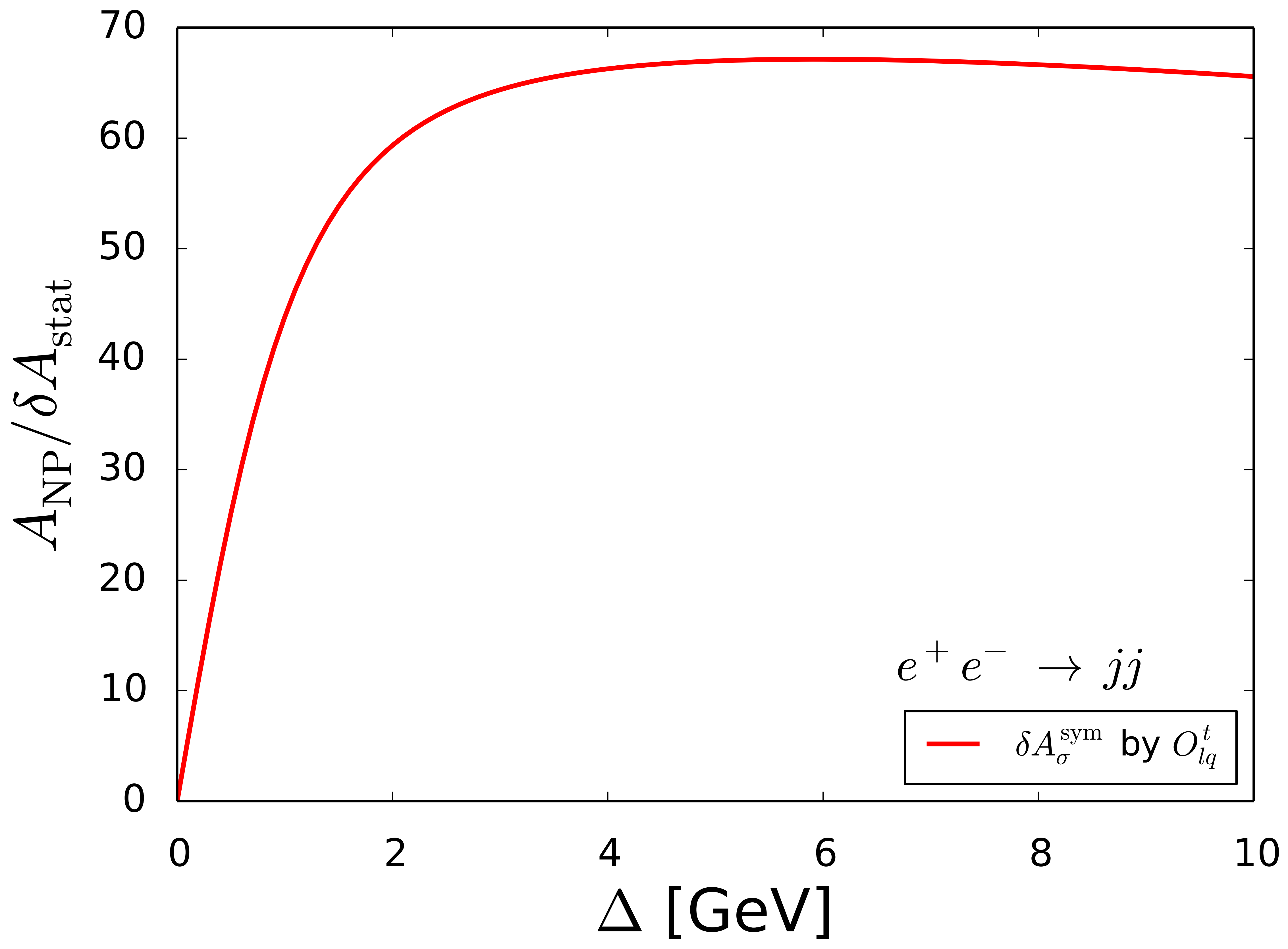
$$\delta = \frac{A_{\rm NP}}{\delta A_{\rm stat}} \text{ vs } \Delta,\ \sigma_0$$

BSM Sensitivities

• New Physics Sensitivity without Systematic Uncertainties

- Xsection asymmetry — symmetric off Z pole run: $A_\sigma^{\mathrm{sym}} = \dfrac{\sigma(M_Z + \Delta) - \sigma(M_Z - \Delta)}{\sigma(M_Z + \Delta) + \sigma(M_Z - \Delta)}$





BSM Sensitivities

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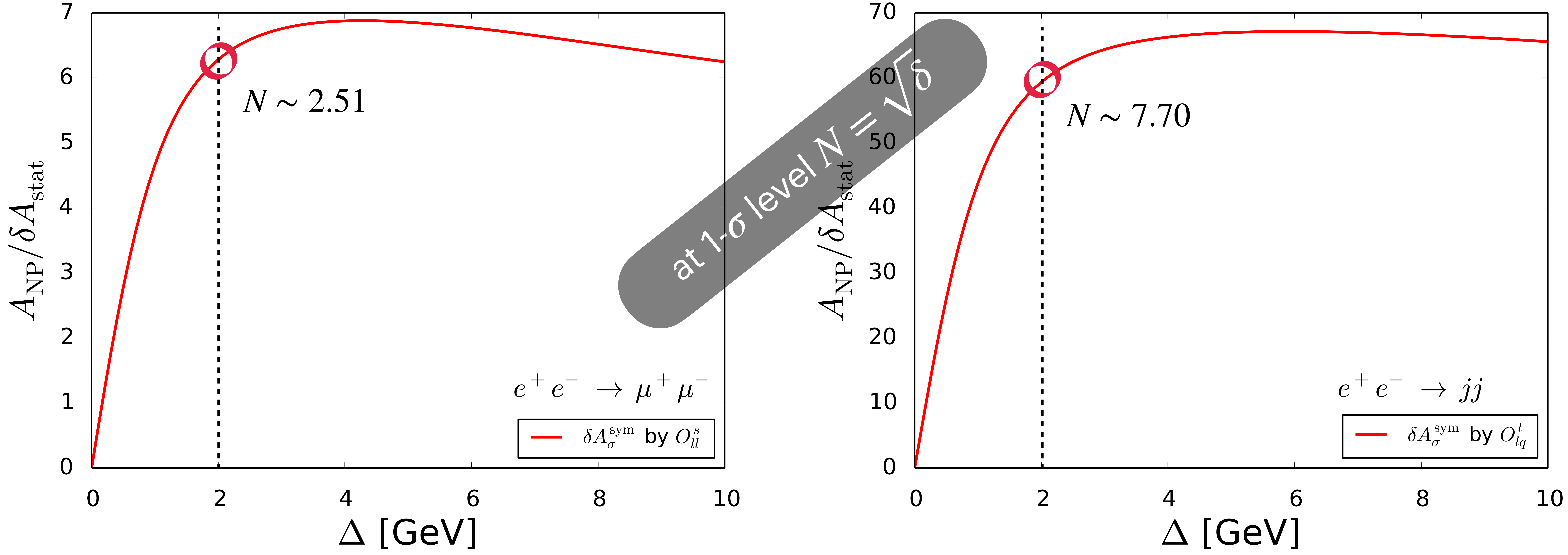
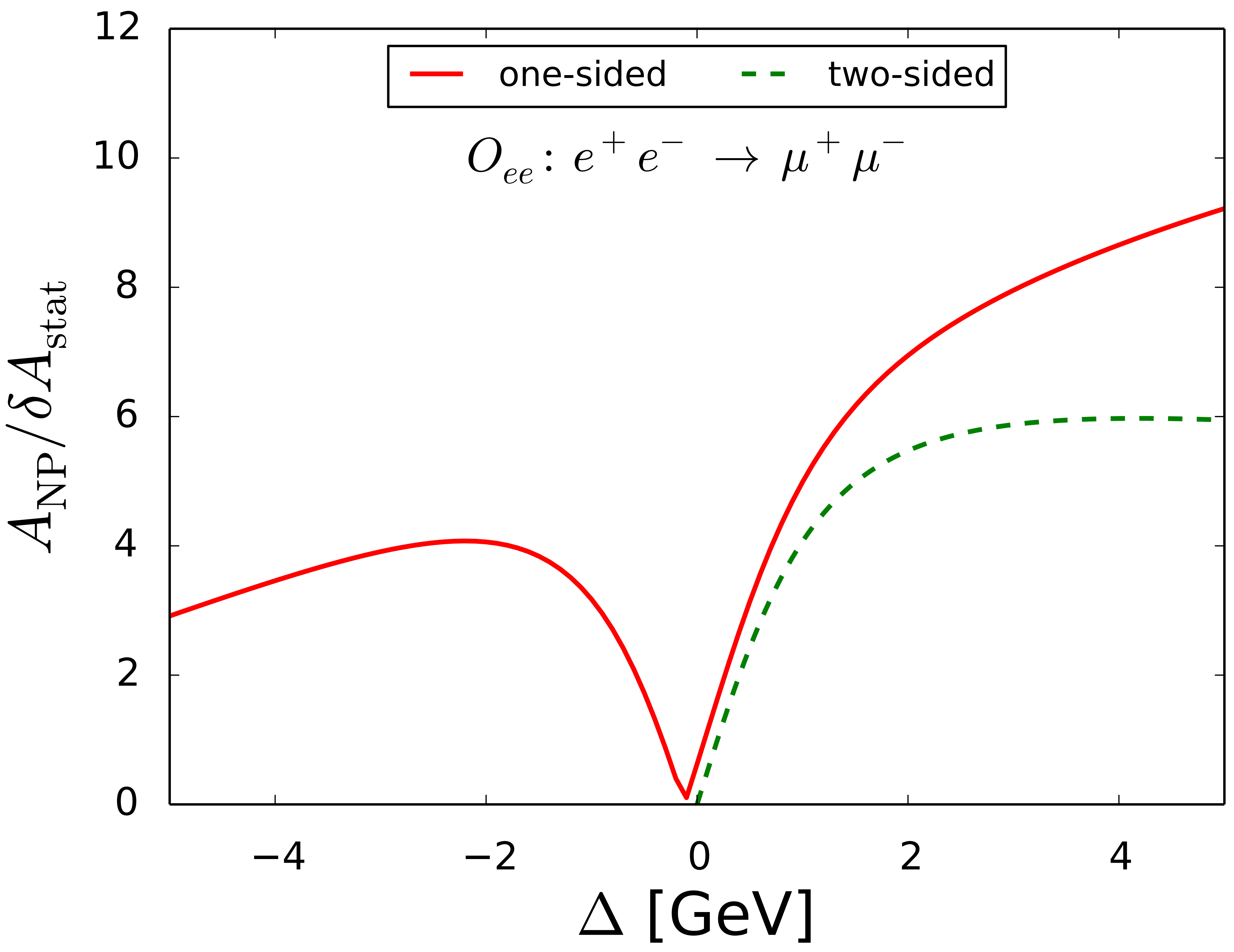
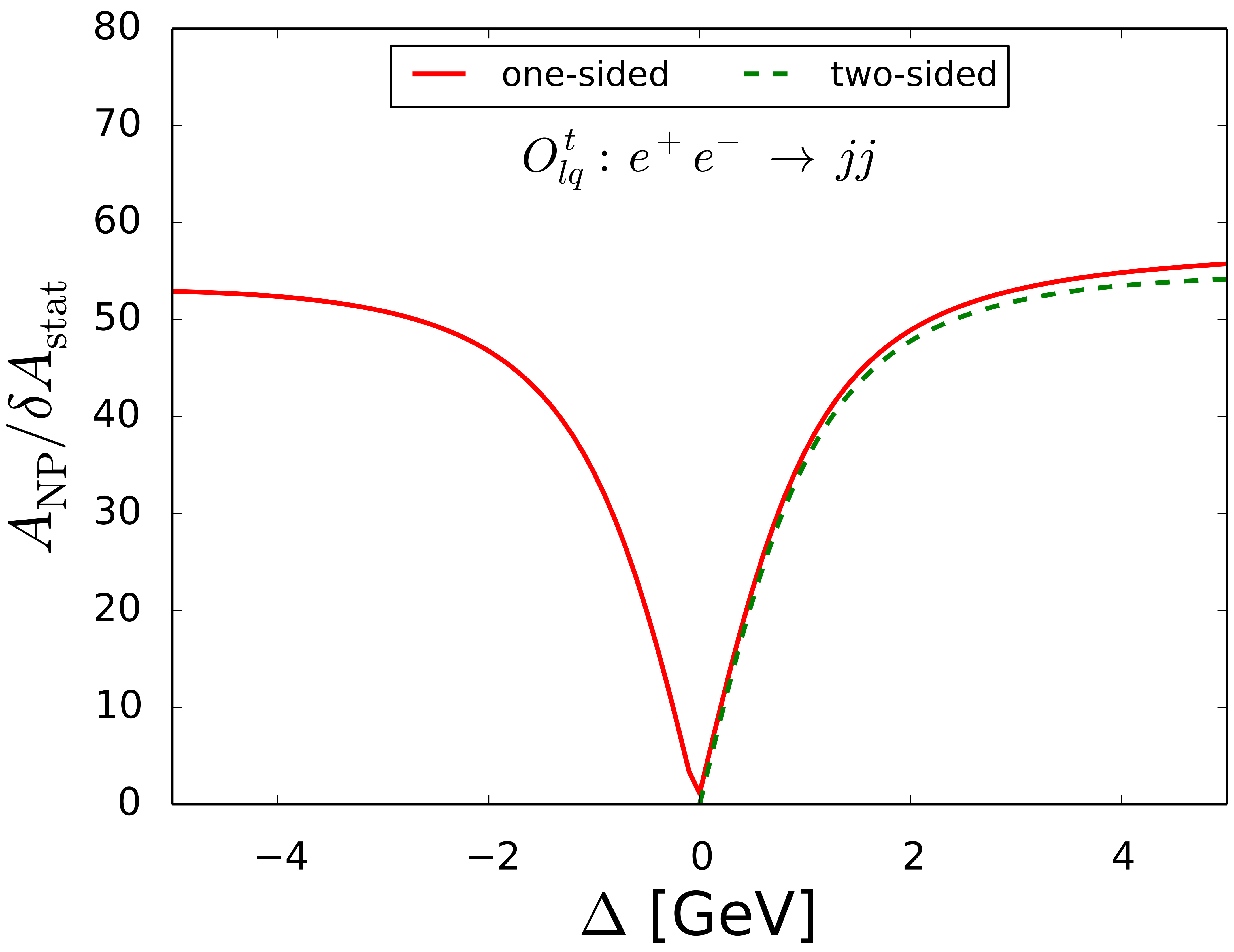


BSM Sensitivities

•New Physics Sensitivity without Systematic Uncertainties

- Polarization asymmetry — one(two)-sided: $A_{\rm pol}^{(1)}, A_{\rm pol}^{(2)}$





BSM Sensitivities

•New Physics Sensitivity without Systematic Uncertainties

- Improved cut-off scales (TeV) at ±3 GeV off Z pole at 1-σ level ✝

	$A_{\sigma}^{\rm sym}$	$A_{\rm pol}^{(1)-}$	$A_{\rm pol}^{(1)+}$	$A_{\rm pol}^{(2)}$	$A_{\rm FB}^{(1)-}$	$A_{\rm FB}^{(1)+}$	$A_{\rm FB}^{(2)}$
O_{ll}^{s}	32 (18, 17)	26 (29, −)	31 (28, −)	29 (29, −)	29 (32, 15)	25 (23, 15)	27 (28, 18)
O_{lq}^{s}	54 (−, −)	50 (57, −)	47 (41, −)	48 (50, −)	53 (28, −)	52 (22, −)	52 (25, −)
O_{lq}^{t}	99 (28, 24)	88 (99, 13)	90 (80, −)	89 (91, 16)	53 (28, −)	52 (22, −)	52 (25, −)
O_{le}	40 (25, −)	48 (51, −)	41 (34, −)	45 (44, −)	32 (33, −)	38 (30, −)	35 (32, −)
O_{qe}	48 (−, −)	50 (52, −)	57 (46, −)	53 (50, −)	56 (28, −)	59 (22, −)	58 (25, −)
O_{lu}	38 (−, −)	39 (44, −)	30 (27, −)	35 (37, −)	−	−	−
O_{ld}	33 (−, −)	34 (38, −)	26 (23, −)	30 (32, −)	28 (14, −)	25 (−, −)	27 (−, −)
O_{ee}	25 (15, 14)	23 (25, −)	33 (27, −)	28 (26, −)	22 (24, −)	21 (19, 13)	21 (22, 14)
O_{eu}	34 (−, −)	31 (32, −)	45 (36, −)	38 (35, −)	−	−	−
O_{ed}	30 (−, −)	− (28, −)	39 (32, −)	33 (30, −)	− (−, −)	− (−, −)	− (−, −)

✝ Numbers in orange & gray will be explained later

BSM Sensitivities

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✝ Numbers in orange & gray will be explained later

BSM Sensitivities

- **New Physics Sensitivity with Systematic Uncertainties**

  - Estimate systematic uncertainties

    Linear expansion on variables $\{x_i\}$

    relate to uncertainties

$$A_{\text{SM}}\left(\{x_i\}\right) = A_{\text{SM}}\left(\{x_{i,0}\}\right) + \sum_i \frac{\partial A_{\text{SM}}\left(x_{i,0}\right)}{\partial x_i}\delta x_i, \quad x_i = x_{i,0} + \delta x_i$$

For independent $\{\delta x_i\}$

$$\delta A_{\text{sys}} = \sqrt{\sum_i \left(\frac{\partial A_{\text{tot}}\left(x_{i,0}\right)}{\partial x_i}\delta x_i\right)^2}$$

BSM Sensitivities

• New Physics Sensitivity with Systematic Uncertainties

- Estimate systematic uncertainties

Linear expansion on variables $\{x_i\}$

relate to uncertainties

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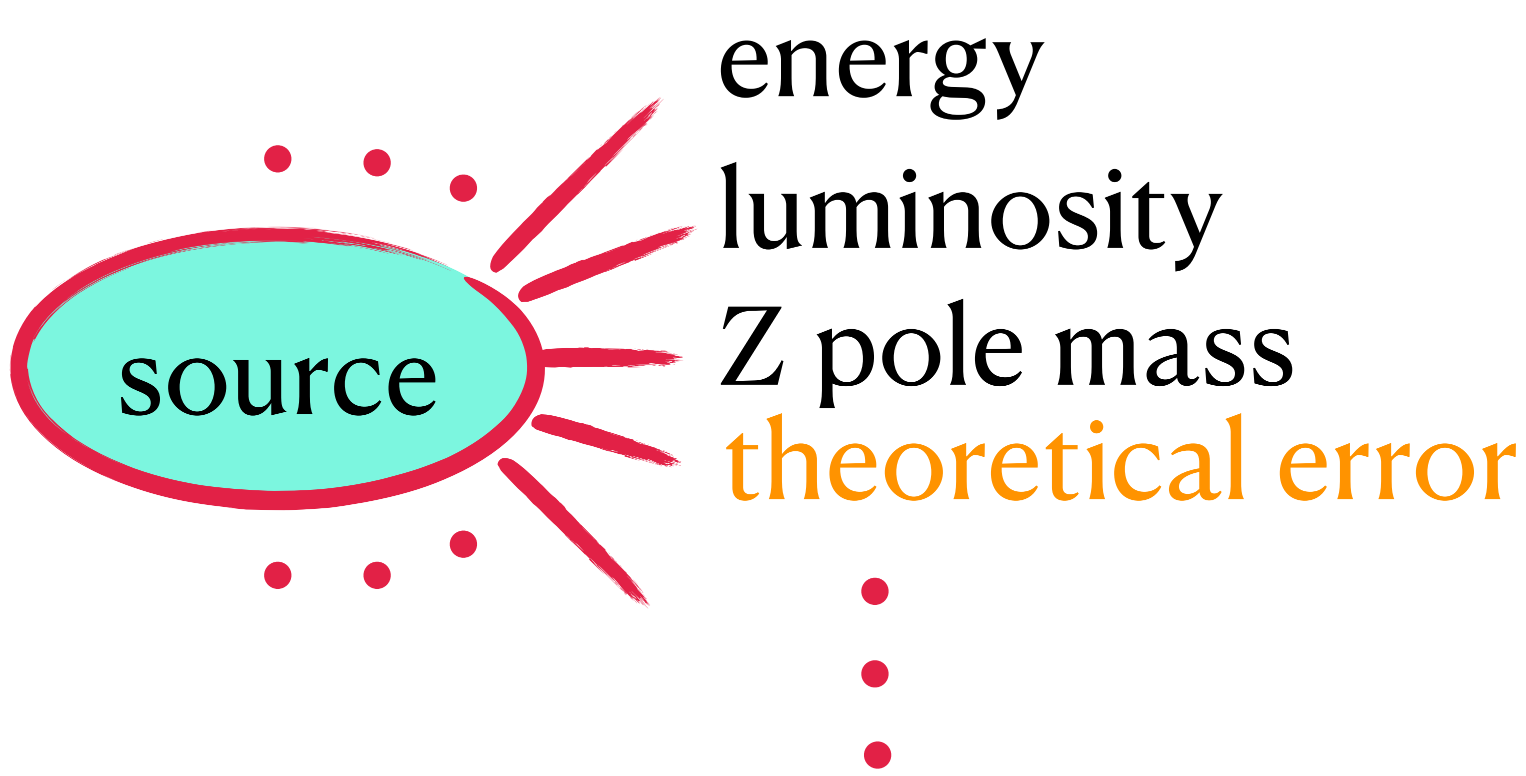

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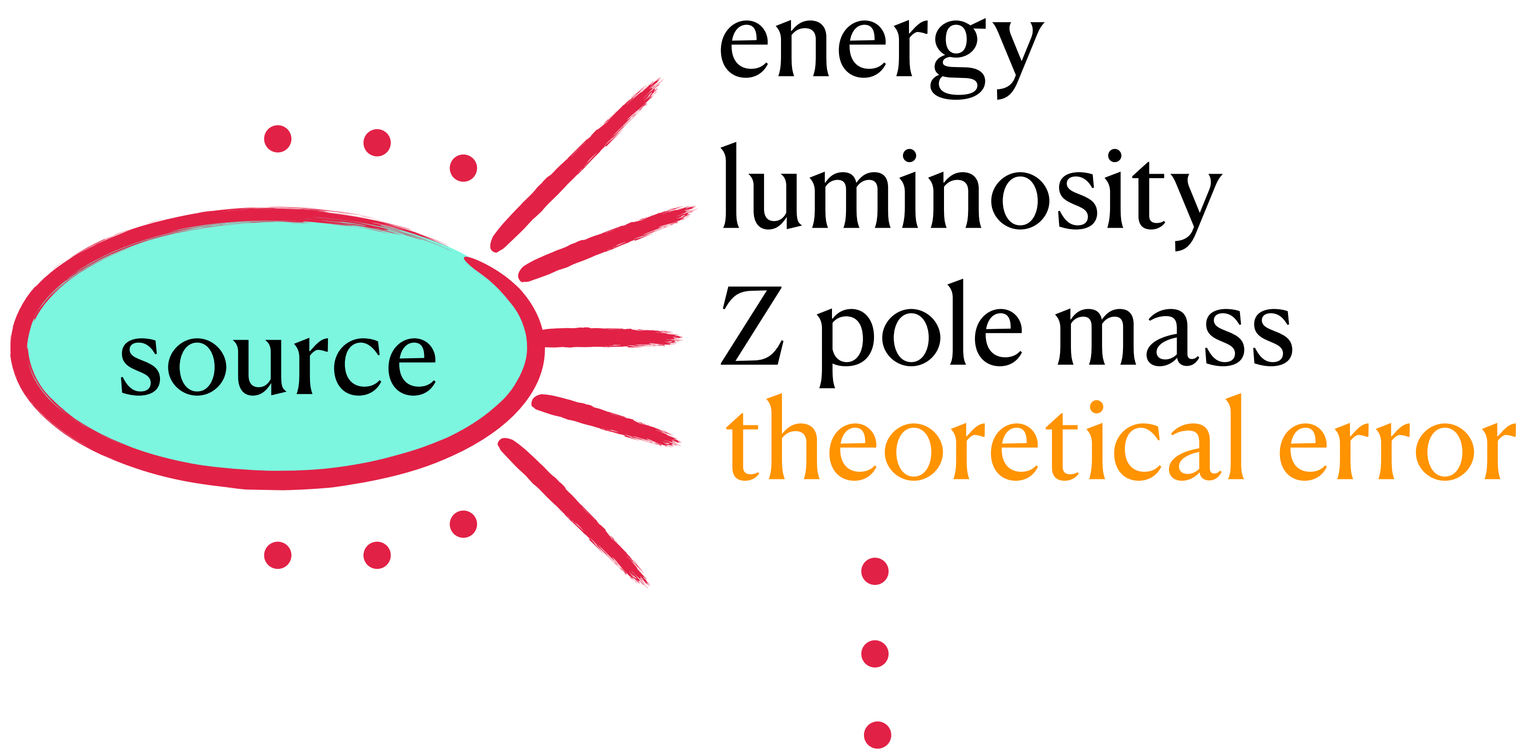

Scale enhancement indicated by $\delta = \dfrac{A_{\rm NP}}{\delta A_{\rm stat+sys}}$

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source: energy, luminosity, Z pole mass, theoretical error, …

Scale enhancement indicated by $\delta = \dfrac{A_{\rm NP}}{\delta A_{\rm stat+sys}}$

Are systematics significant?

BSM Sensitivities

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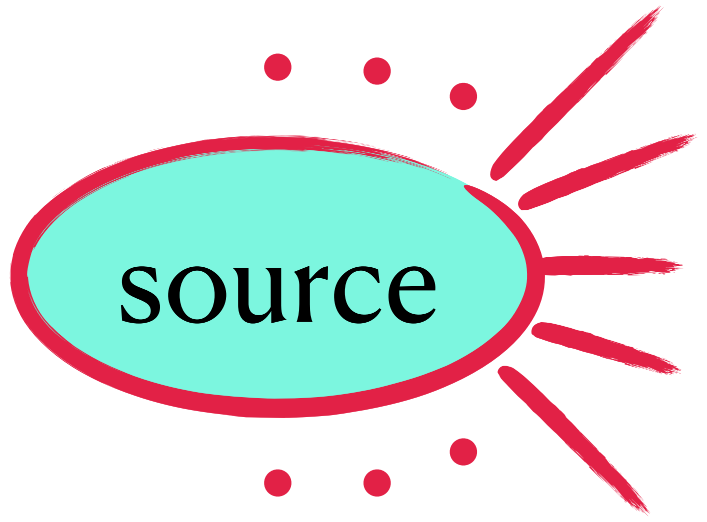

energy
luminosity
Z pole mass
theoretical error
⋮

Scale enhancement indicated by $\delta = \dfrac{A_{\rm NP}}{\delta A_{\rm stat+sys}}$

Are systematics significant?

Investigation

Rescaling factor $\delta A_{\rm stat}/\delta A_{\rm stat+sys}$

BSM Sensitivities

• New Physics Sensitivity with Systematic Uncertainties

- Achievable precision at CEPC and FCC-ee vs LEP

	CEPC	FCC-ee	LEP
$\delta\Delta$ (MeV)	0.1	0.1	1.7
$\delta X/X$ (%)	0.01	0.01	0.034
δM_Z (MeV)	0.5	0.1	2.1
$\delta\Gamma_Z$ (MeV)	0.5	0.1	2.3

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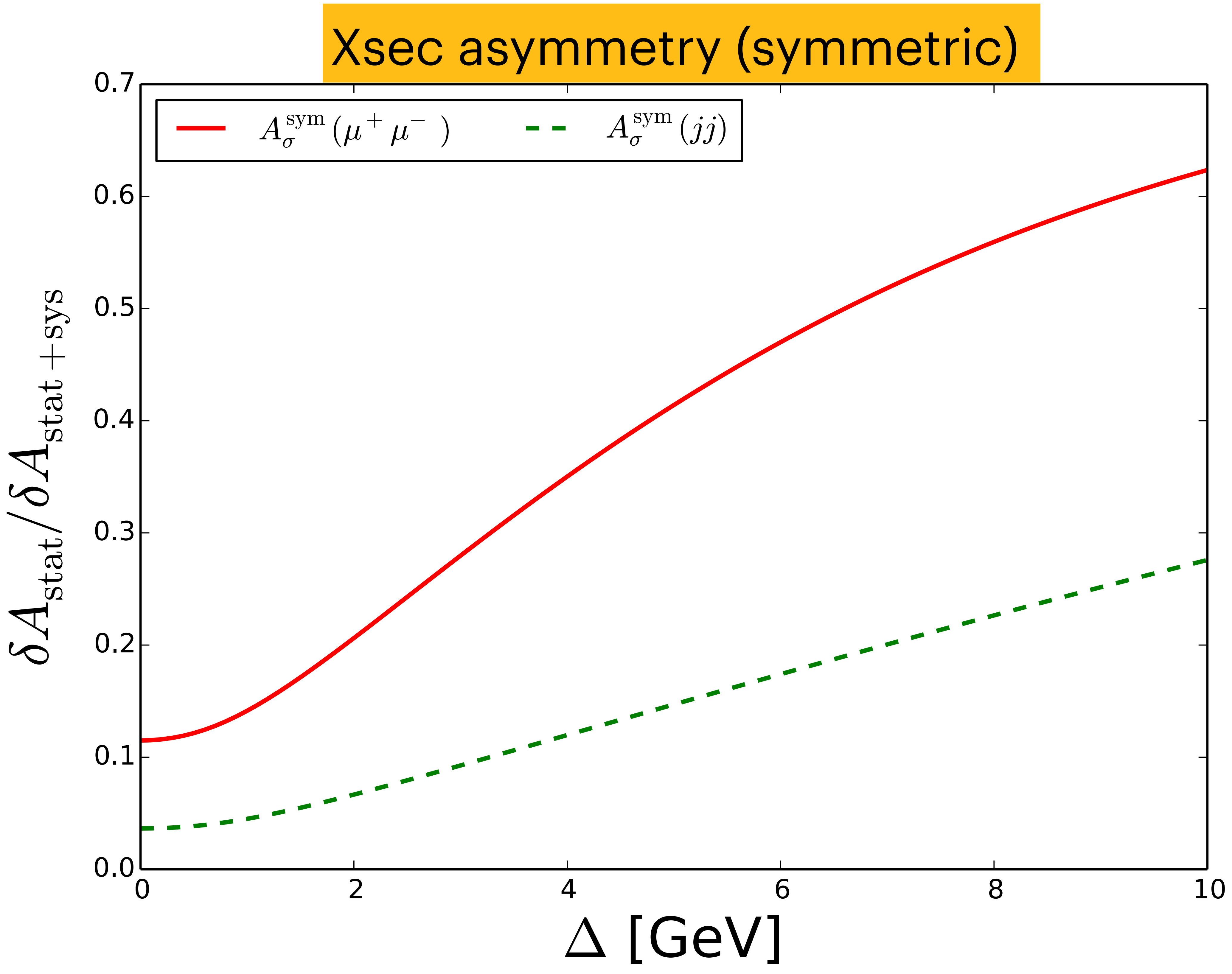

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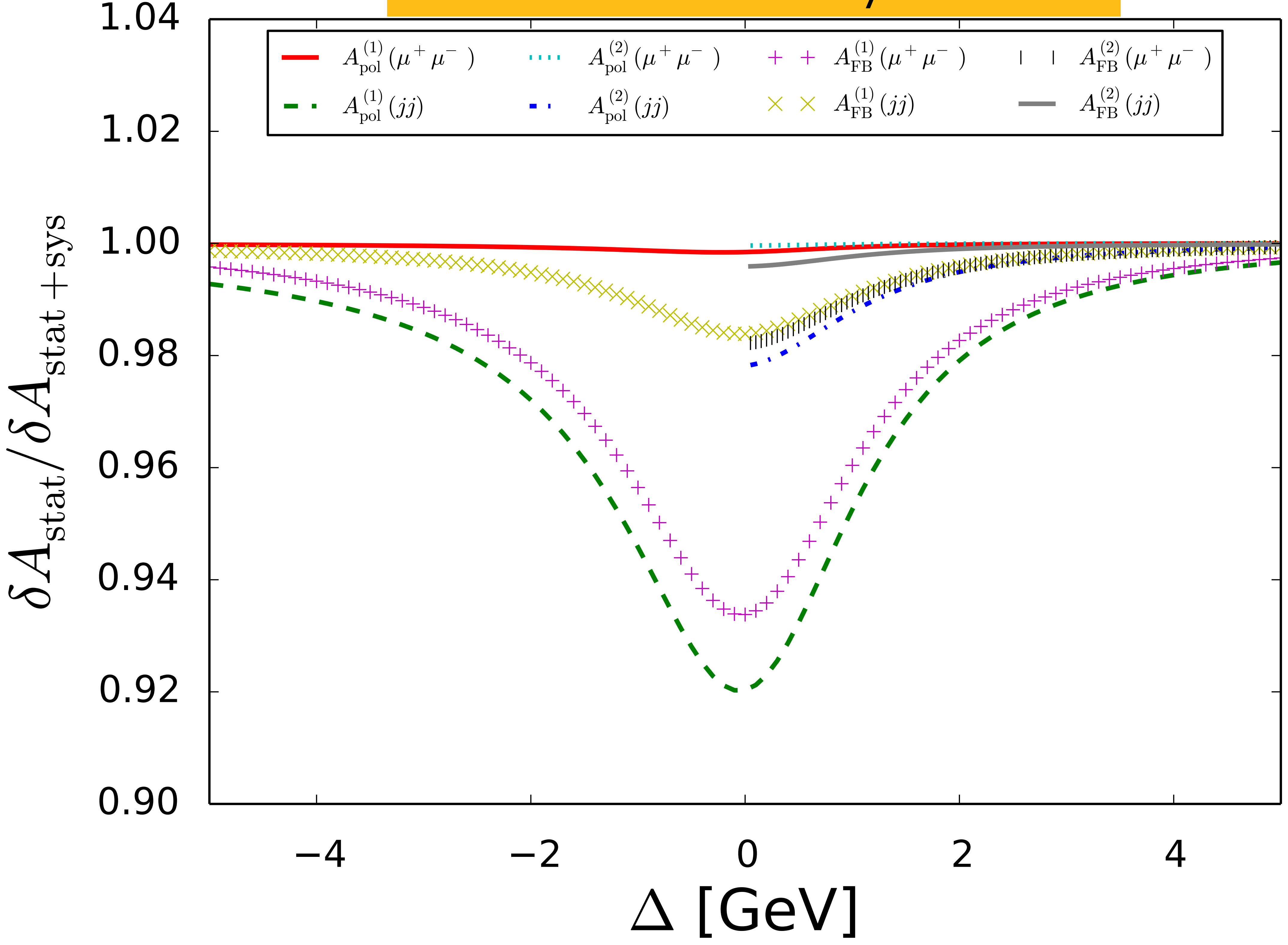
Polarization & FB asymmetries



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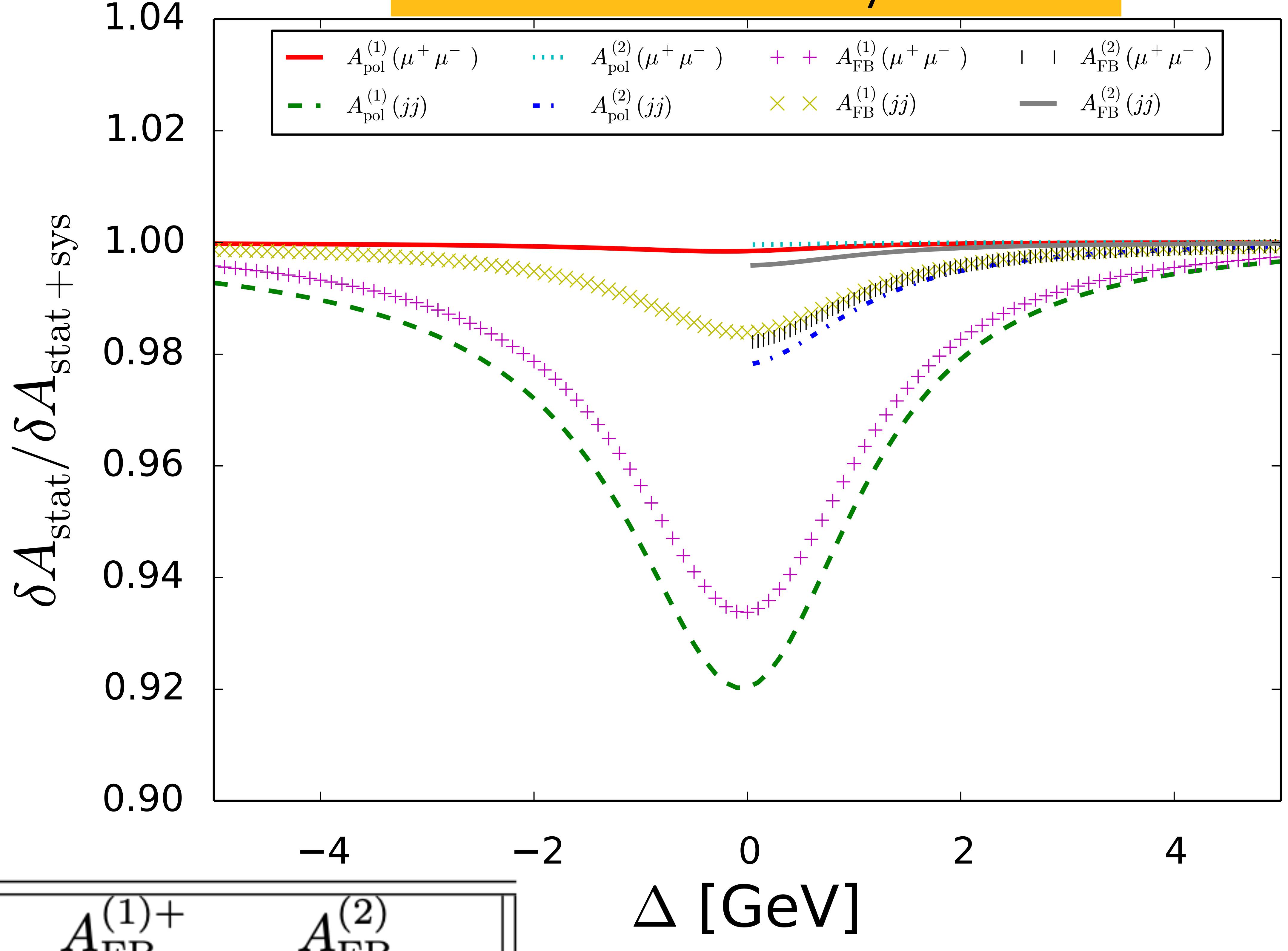

- Rescaling factors for asymmetry measurements ± 3 GeV off Z pole at 1-σ level

	$A^{\rm sym}_\sigma$	$A^{(1)-}_{\rm pol}$	$A^{(1)+}_{\rm pol}$	$A^{(2)}_{\rm pol}$	$A^{(1)-}_{\rm FB}$	$A^{(1)+}_{\rm FB}$	$A^{(2)}_{\rm FB}$
$\mu^+\mu^-$	0.52892	0.99977	0.99995	0.99999	0.99411	0.99570	0.99885
jj	0.30440	0.99175	0.99473	0.99862	0.99851	0.99897	0.99973

BSM Sensitivities

• New Physics Sensitivity with Systematic Uncertainties

- Theoretical uncertainty

Higher order (HO) corrections — Uncertainty in HO corrections

Higher order (HO) corrections → EW & QCD → QED (ISR,FSR & IFI) amounts to 30%

Uncertainty in HO corrections → Parametric; Missing HO ($N^{m}LO$, m ≥ 2)

Ex. Complete EW 2-loop

$\delta\sigma^{0}_{\mathrm{had}}$	0.31%

I. Dubovyk *et al.*
Phys. Lett. B 783, 86-94 (2018)

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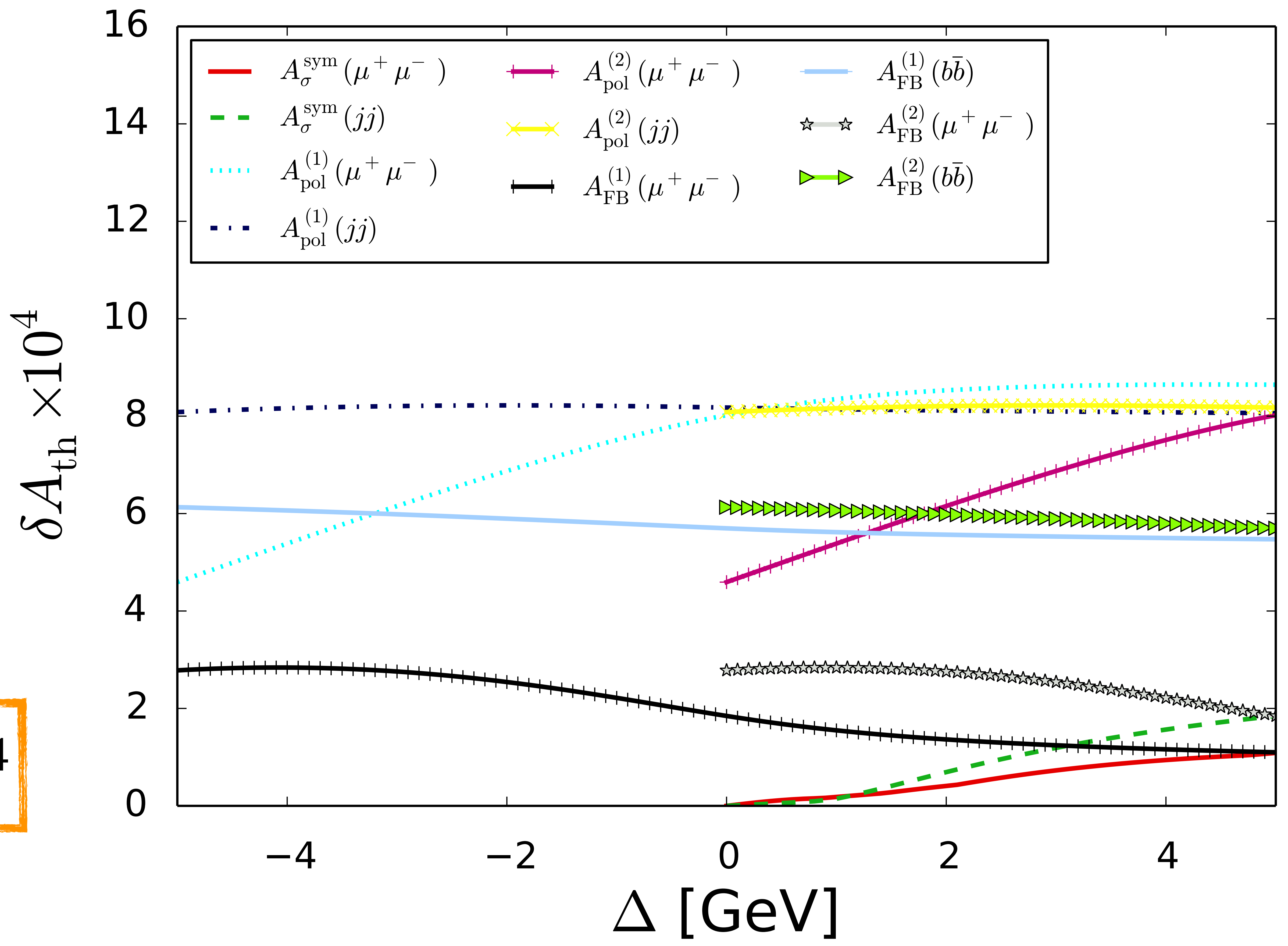
Uncertainties in theoretical predictions

$$\Delta\alpha_{\rm had}^{(5)}(M_Z)\ ,\quad M_t\ ,\quad M_h$$

$\delta A_{\rm th} \sim 10^{-4}$



BSM Sensitivities

New Physics Sensitivity with Systematic Uncertainties

- Improved cut-off scales (TeV) at ±3 GeV off Z pole at 1-σ level ✝

	$A_\sigma^{\rm sym}$	$A_{\rm pol}^{(1)-}$	$A_{\rm pol}^{(1)+}$	$A_{\rm pol}^{(2)}$	$A_{\rm FB}^{(1)-}$	$A_{\rm FB}^{(1)+}$	$A_{\rm FB}^{(2)}$
O_{ll}^s	32 (18, 17)	26 (29, –)	31 (28, –)	29 (29, –)	29 (32, 15)	25 (23, 15)	27 (28, 18)
O_{lq}^s	54 (–, –)	50 (57, –)	47 (41, –)	48 (50, –)	53 (28, –)	52 (22, –)	52 (25, –)
O_{lq}^t	99 (28, 24)	88 (99, 13)	90 (80, –)	89 (91, 16)	53 (28, –)	52 (22, –)	52 (25, –)
O_{le}	40 (25, –)	48 (51, –)	41 (34, –)	45 (44, –)	32 (33, –)	38 (30, –)	35 (32, –)
O_{qe}	48 (–, –)	50 (52, –)	57 (46, –)	53 (50, –)	56 (28, –)	59 (22, –)	58 (25, –)
O_{lu}	38 (–, –)	39 (44, –)	30 (27, –)	35 (37, –)	–	–	–
O_{ld}	33 (–, –)	34 (38, –)	26 (23, –)	30 (32, –)	28 (14, –)	25 (–, –)	27 (–, –)
O_{ee}	25 (15, 14)	23 (25, –)	33 (27, –)	28 (26, –)	22 (24, –)	21 (19, 13)	21 (22, 14)
O_{eu}	34 (–, –)	31 (32, –)	45 (36, –)	38 (35, –)	–	–	–
O_{ed}	30 (–, –)	– (28, –)	39 (32, –)	33 (30, –)	– (–, –)	– (–, –)	– (–, –)

✝ orange — including HO w/o its uncertainty; gray — including HO w/ its uncertainty

• New Physics Sensitivity with Systematic Uncertainties

- Improved cut-off scales (TeV) at ±3 GeV off Z pole at 1-σ level ♰

	A_σ^{sym}	$A_{\text{pol}}^{(1)-}$	$A_{\text{pol}}^{(1)+}$	$A_{\text{pol}}^{(2)}$	$A_{\text{FB}}^{(1)-}$	$A_{\text{FB}}^{(1)+}$	$A_{\text{FB}}^{(2)}$
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♰ orange — including HO w/o its uncertainty; gray — including HO w/ its uncertainty

Conclusion

- We consider several types of asymmetry measurements designed to enhance BSM sensitivity under projected precision at future lepton colliders (e.g., CEPC).

  (a) two-sided cross section asymmetries A_σ

  (b) one- and two-sided initial-state polarization and FB asymmetries $A^{(1,2)}_{\text{pol}}$, $A^{(1,2)}_{\text{FB}}$

- The two-sided asymmetries should have the BSM sensitivities enhanced due to flipping sign across Z pole for the SM-BSM interference contribution, and may have them further enhanced when the SM contributions are completely cancelled (in asymmetric off Z pole run).

Conclusion

- In practice, the enhancement due to cross section asymmetries is limited by the systematics (mainly from luminosity), unlike that due to polarization and FB asymmetries.
- The one-sided polarization and FB asymmetries tend to provide the most enhanced BSM sensitivities in comparison with the two-sided ones in symmetric off Z pole run.
- The cutoff scale of up to $\mathcal{O}(100)$ TeV may be accessible with completion of higher order corrections and their uncertainties being significantly advanced.

Back up

Cross Section & Asymmetry

• **Asymmertic off Z Pole Run**

- Asymmetric: for a given σ_0 the energy deviations from Z pole are $\Delta_\pm$ so that $A_{\sigma_{\rm SM}}(\sigma_0) = 0$

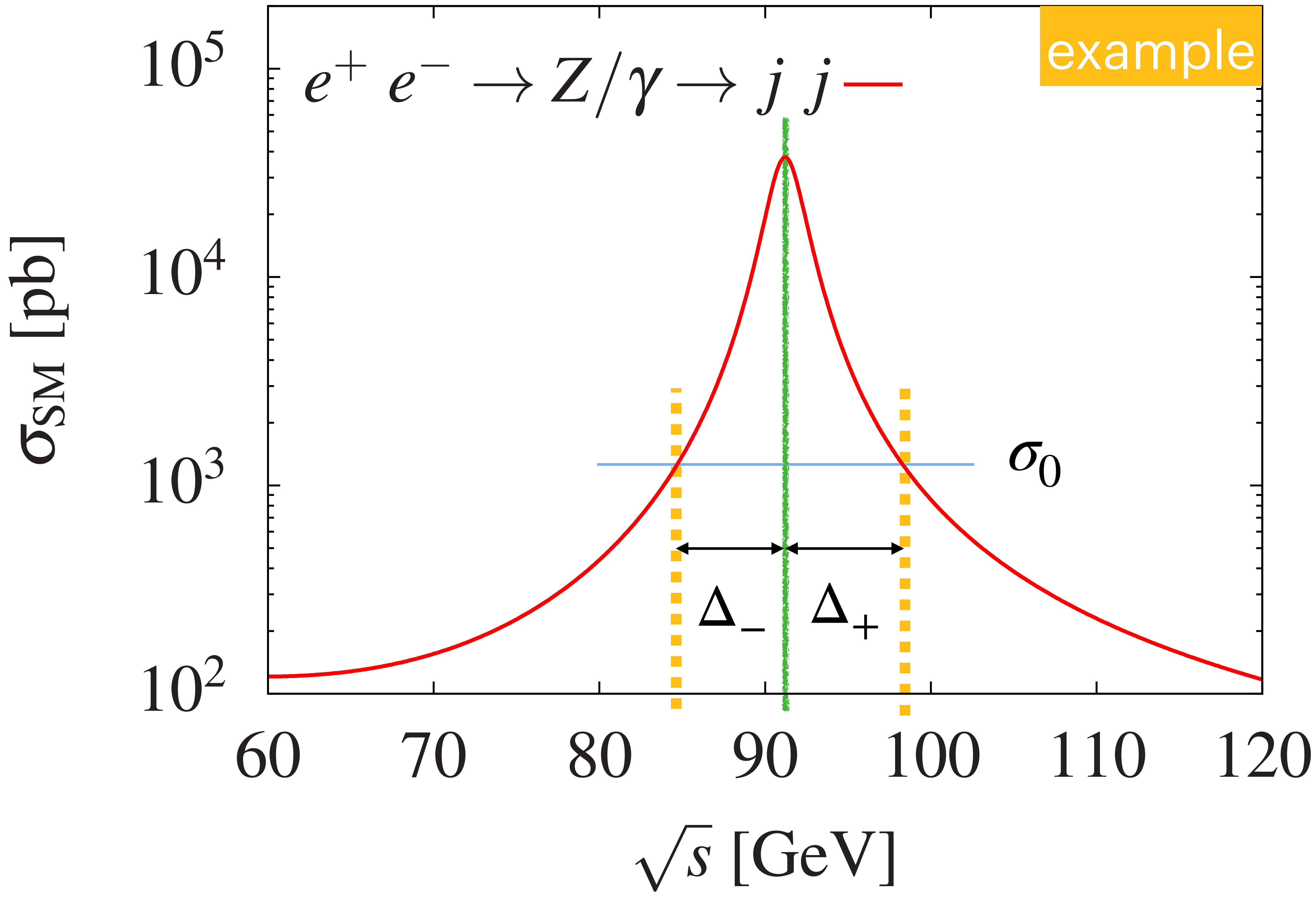
$$\sigma_{\rm SM}(M_Z + \Delta_+) = \sigma_{\rm SM}(M_Z - \Delta_-)$$

Note

- Intermediate observable σ_0
- Experimental measurements $\Delta_\pm$
- Theoretical guidance

$$\mathscr{A}_{\rm SM} = \mathscr{A}_Z + \mathscr{A}_\gamma + \mathscr{B}$$

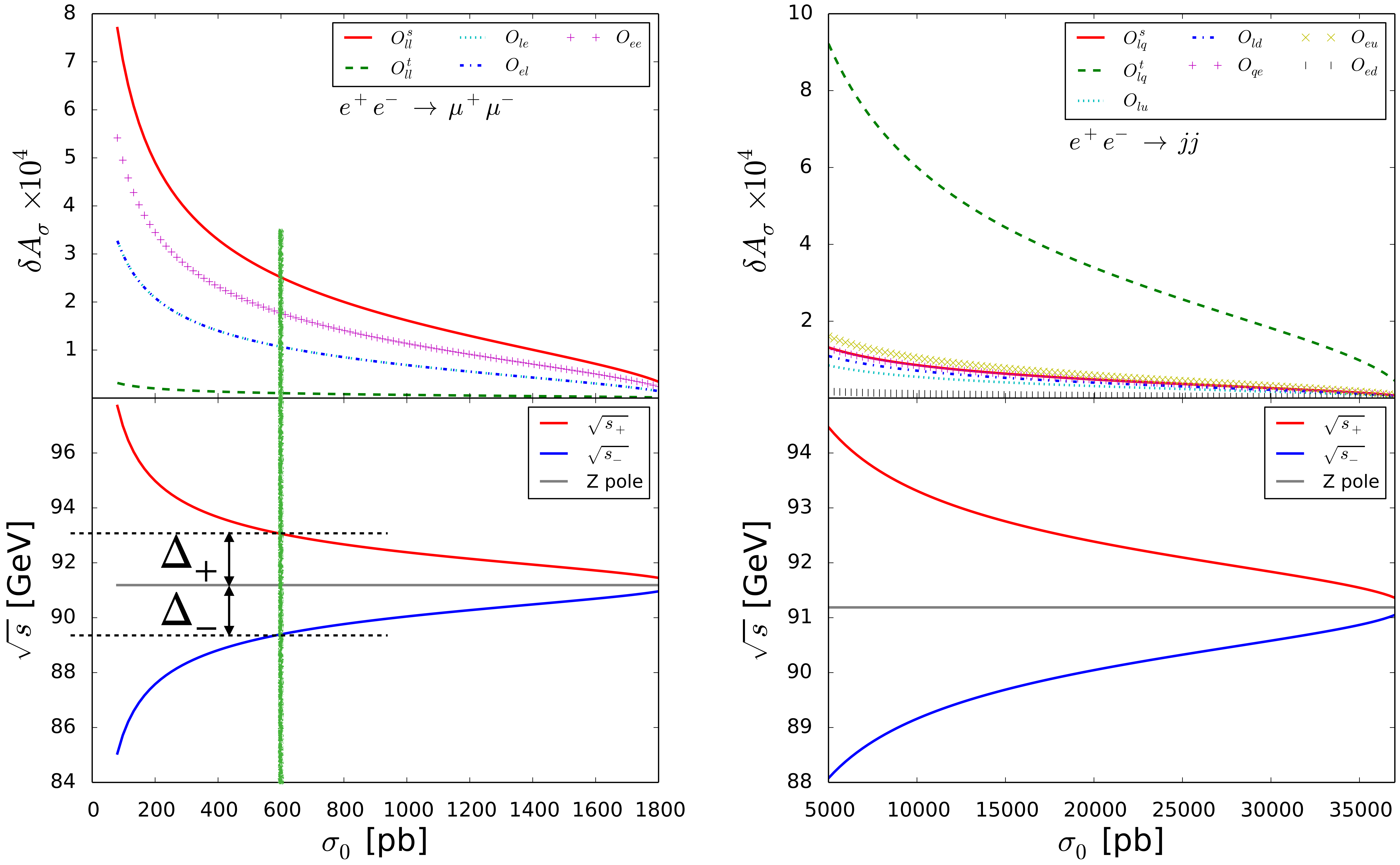
box



Cross Section & Asymmetry

•Cross Section Asymmetry — Asymmertic off Z Pole Run

δA_σ vs σ_0



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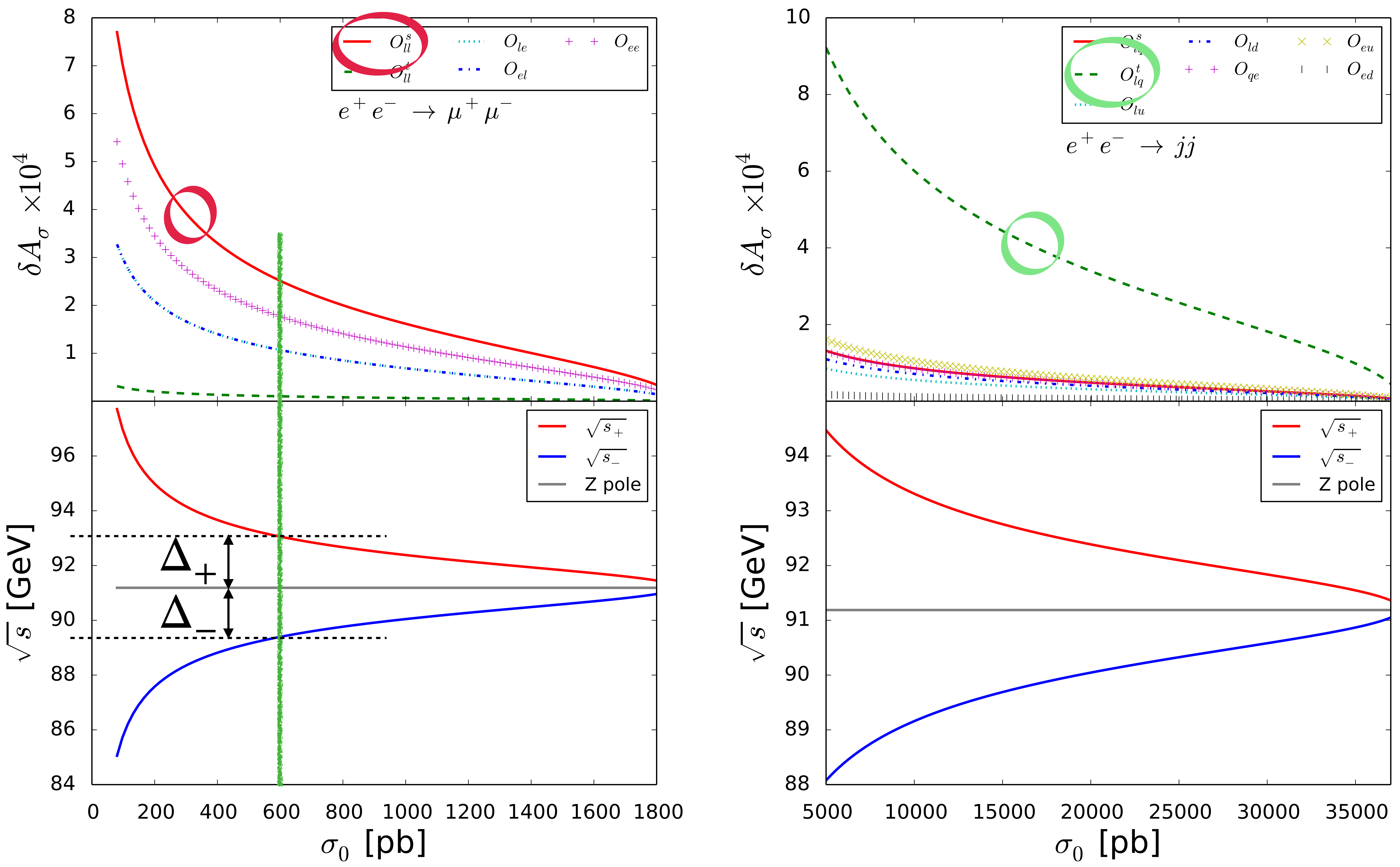
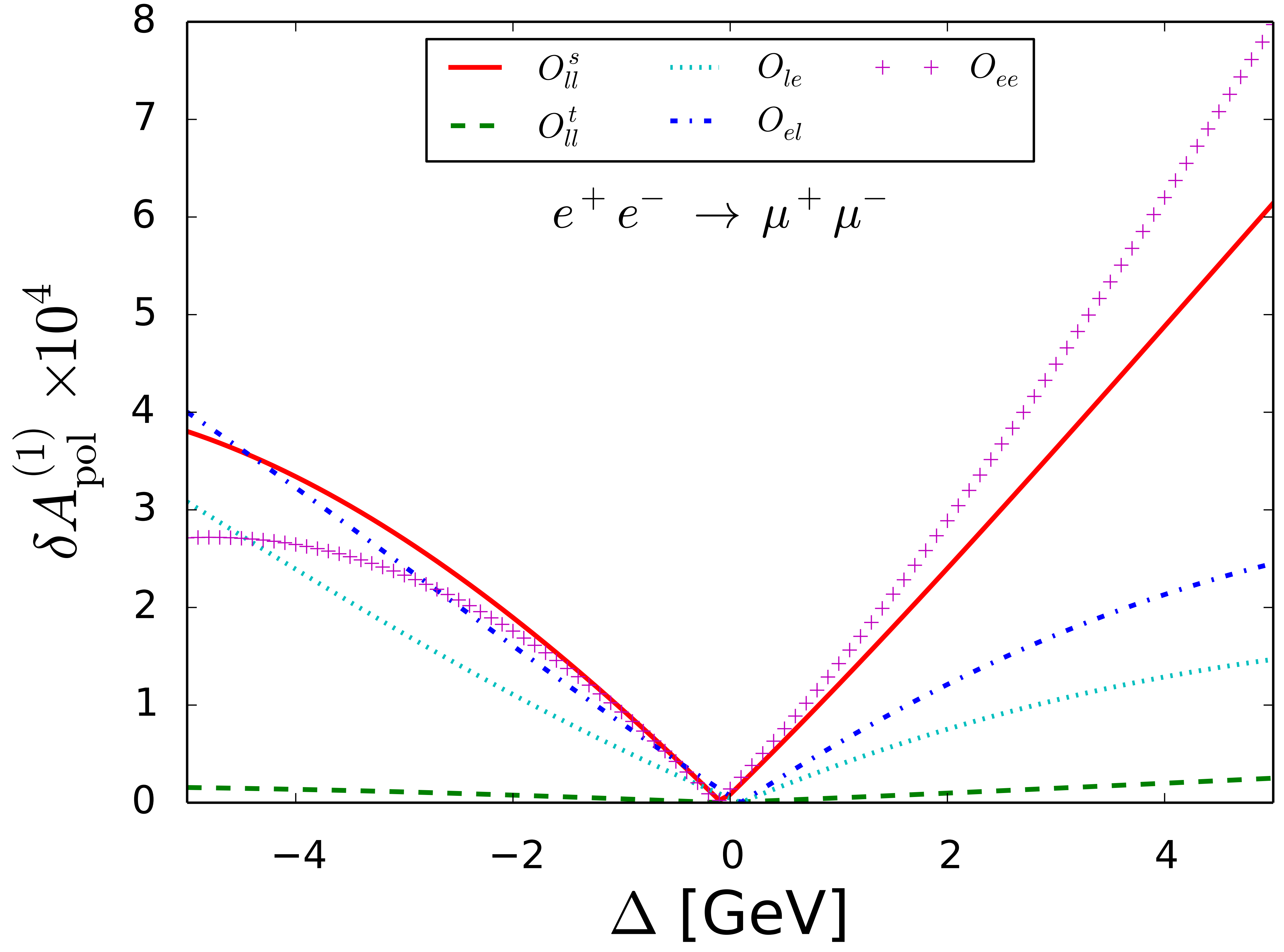
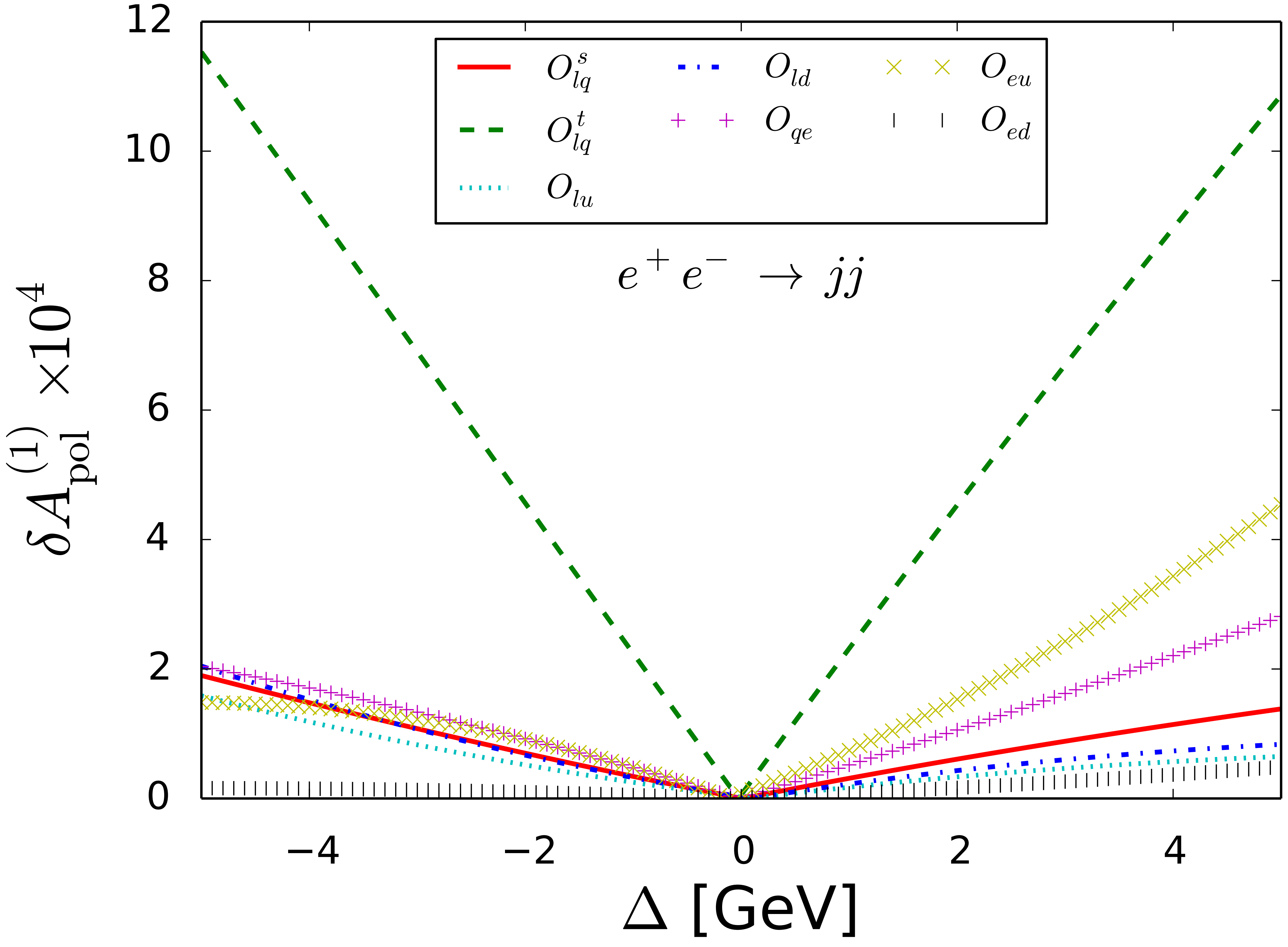


Cross Section & Asymmetry

•Polarization Asymmetry — One-sided

$\delta A^{(1)}_{\rm pol}$ vs Δ





Cross Section & Asymmetry

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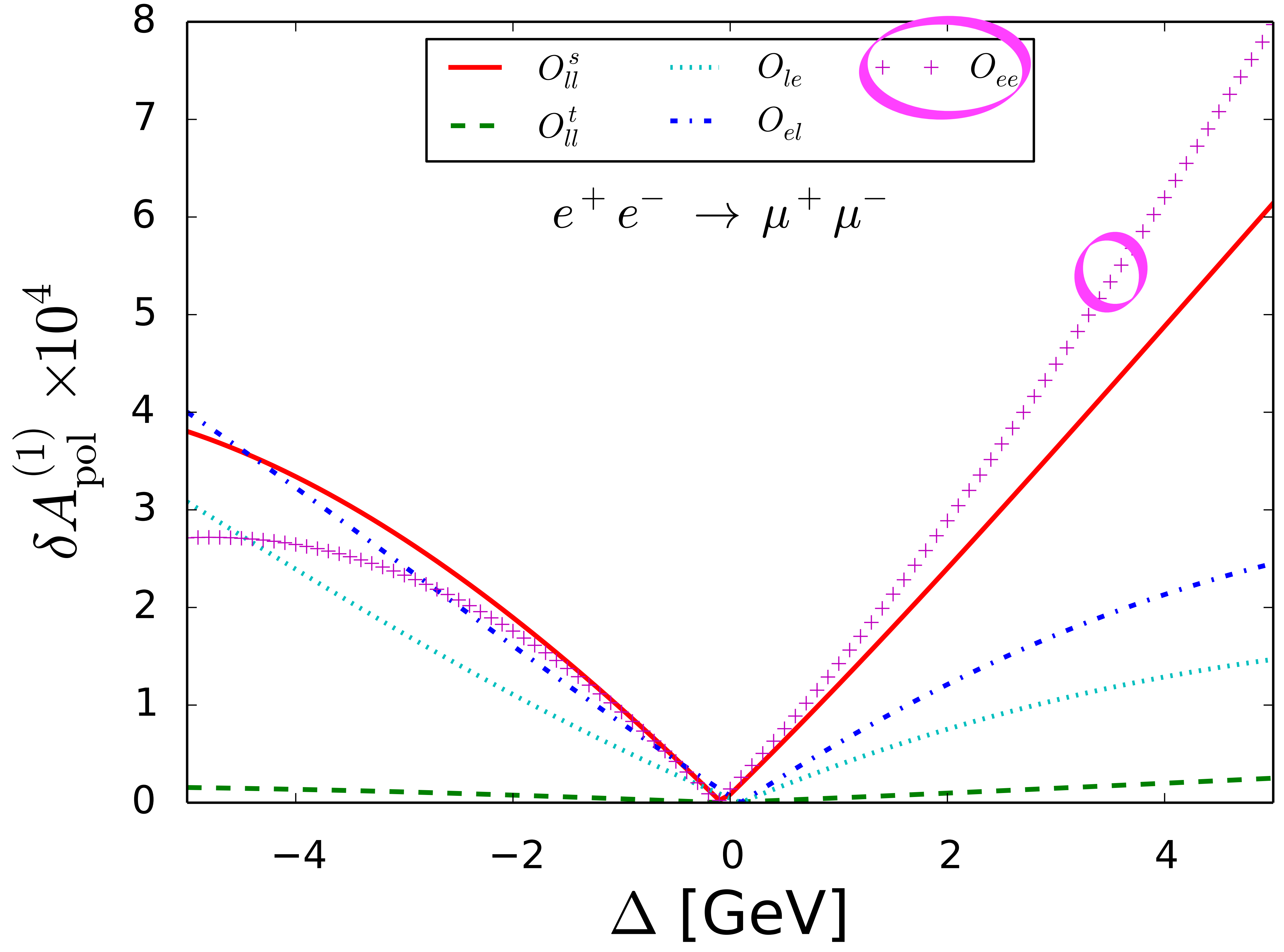
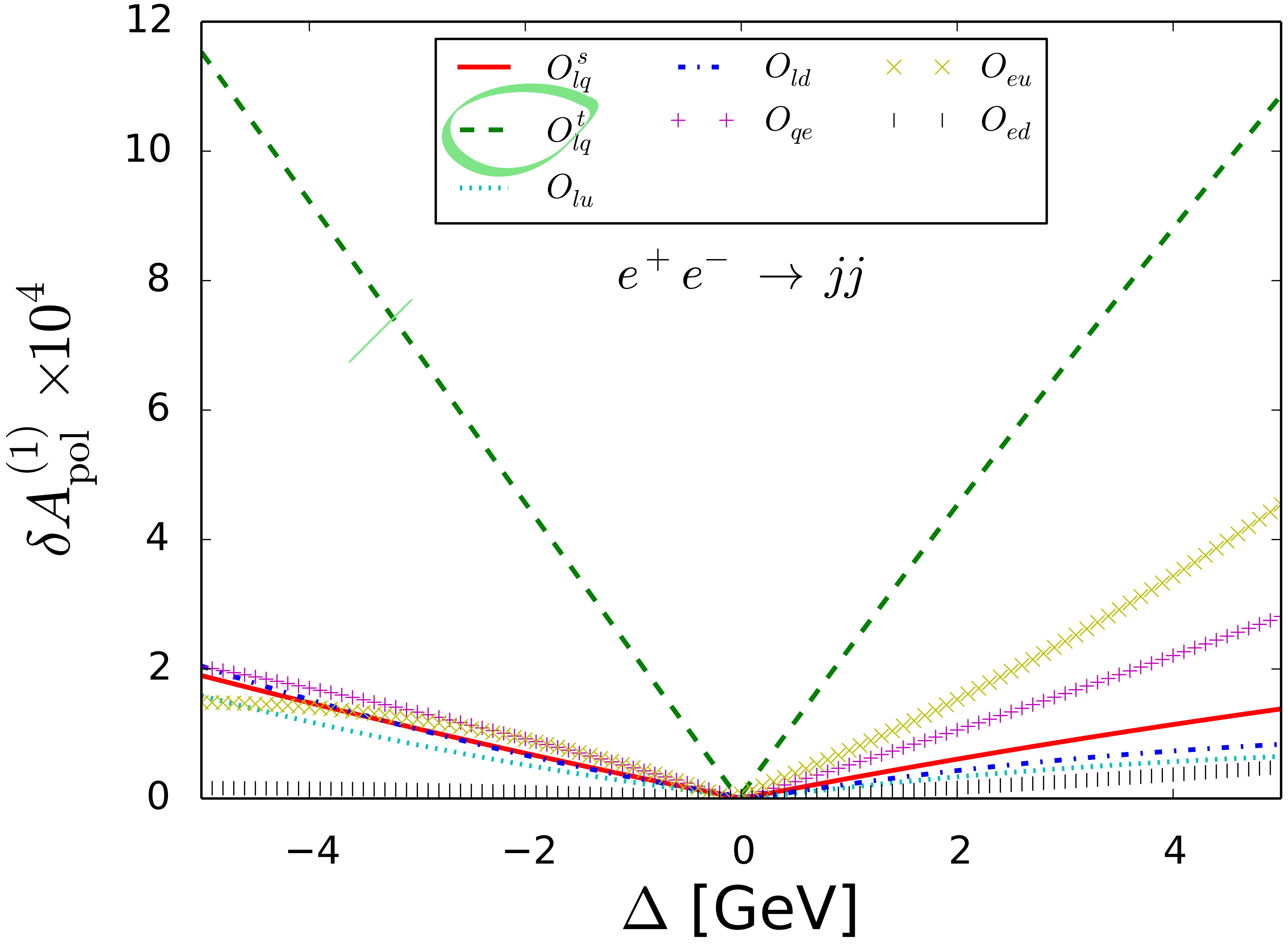
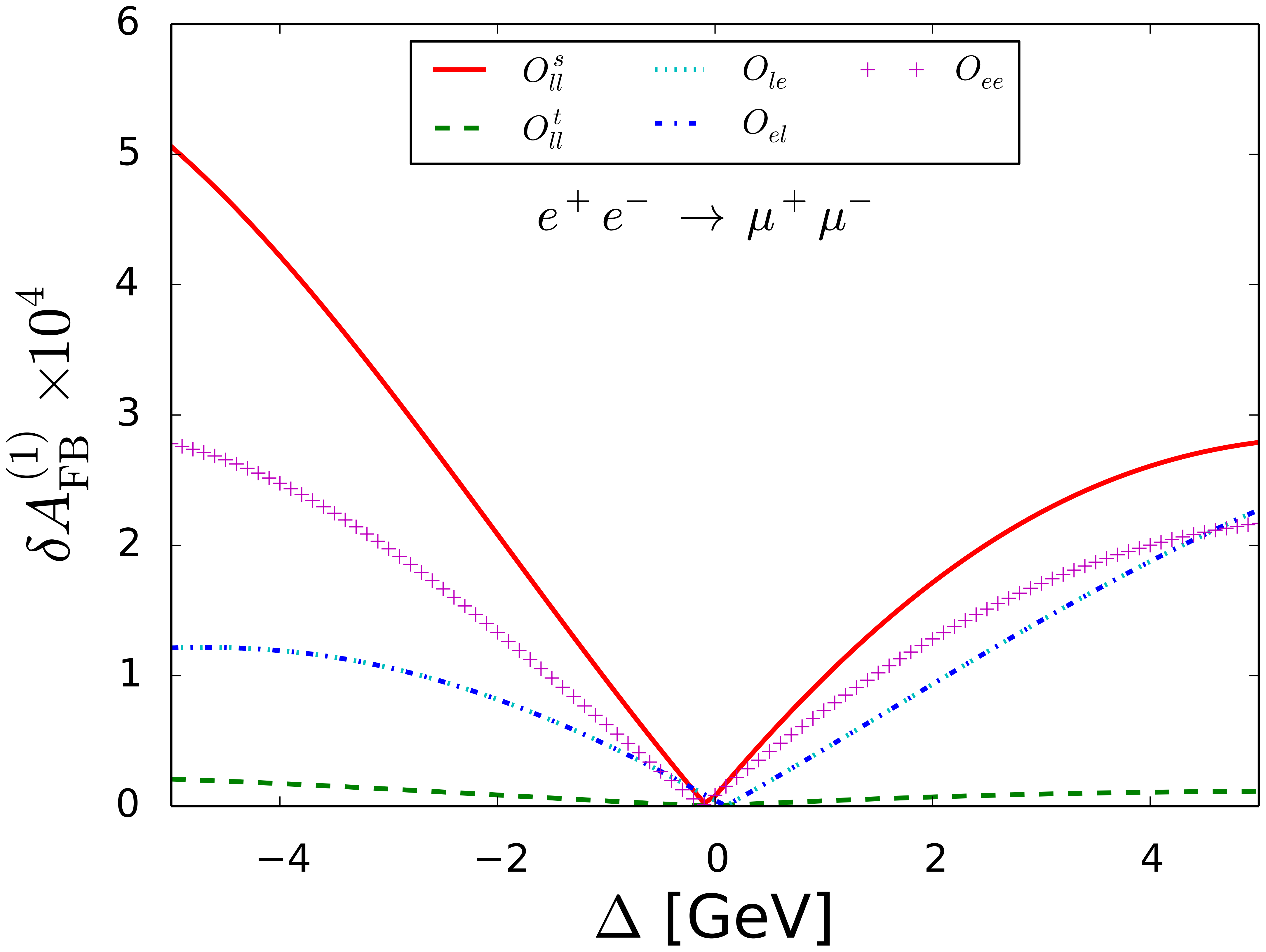


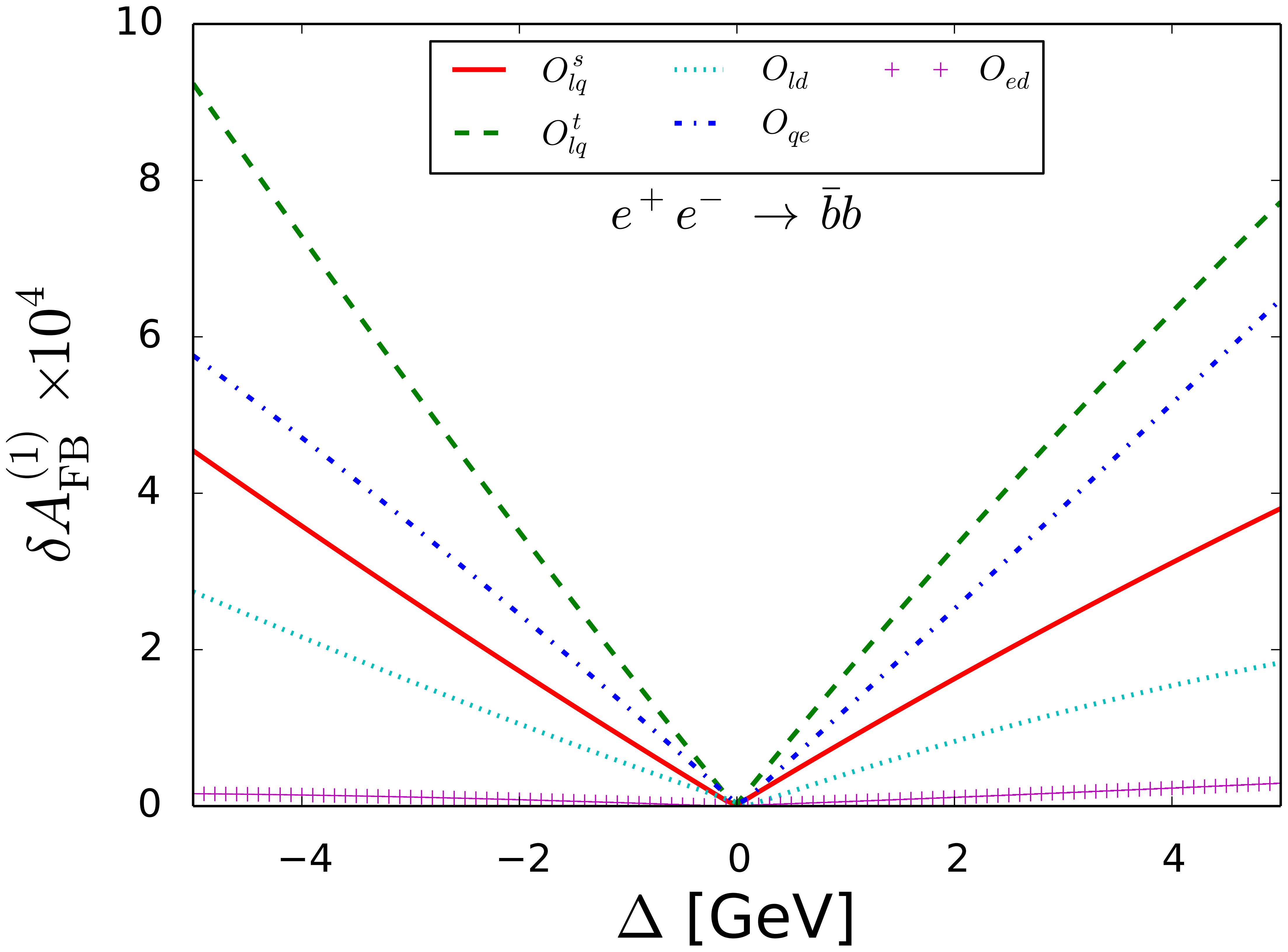


Cross Section & Asymmetry

- **FB Asymmetry — One-sided**

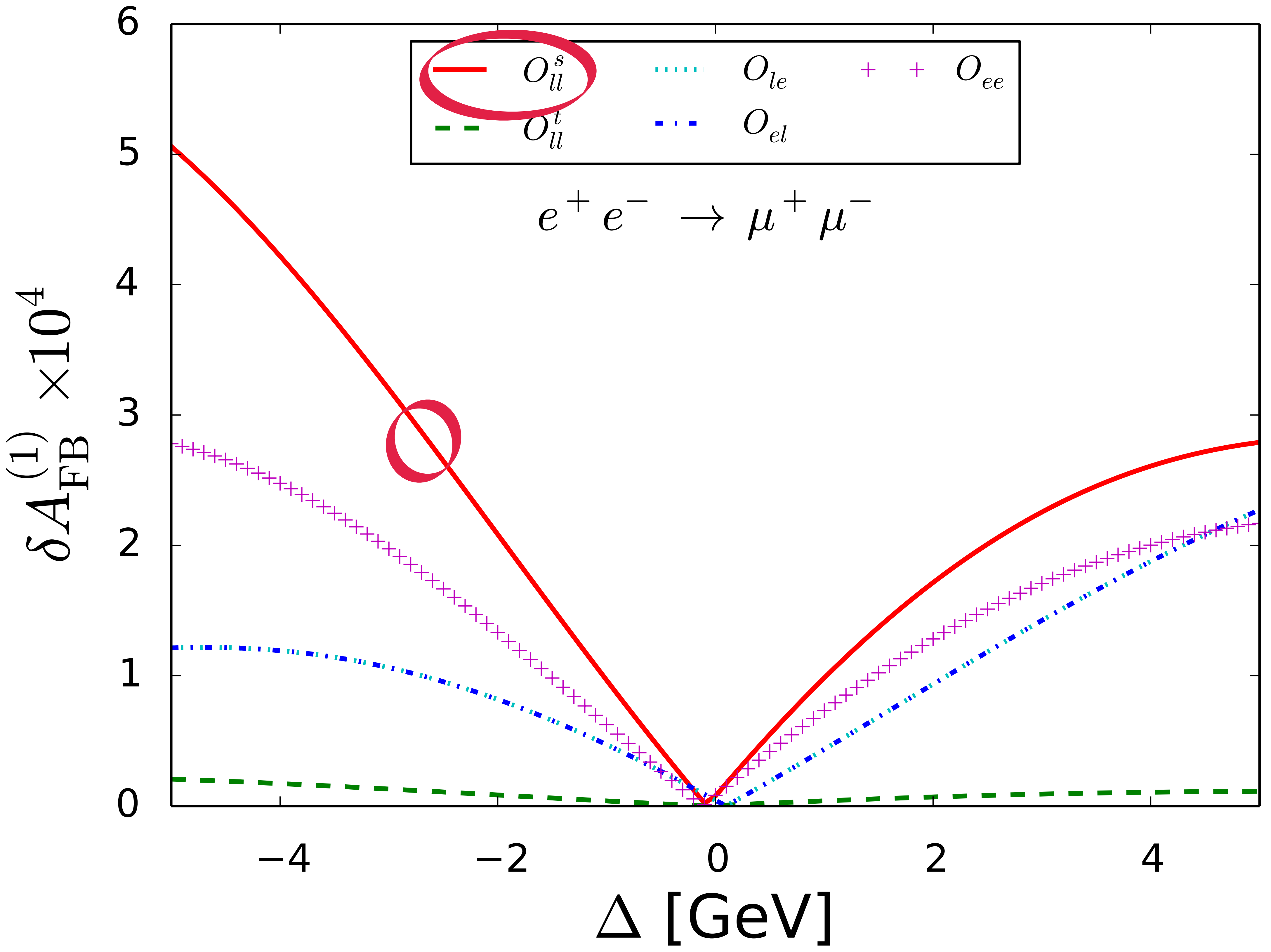
$\delta A_{\rm FB}^{(1)}$ vs Δ

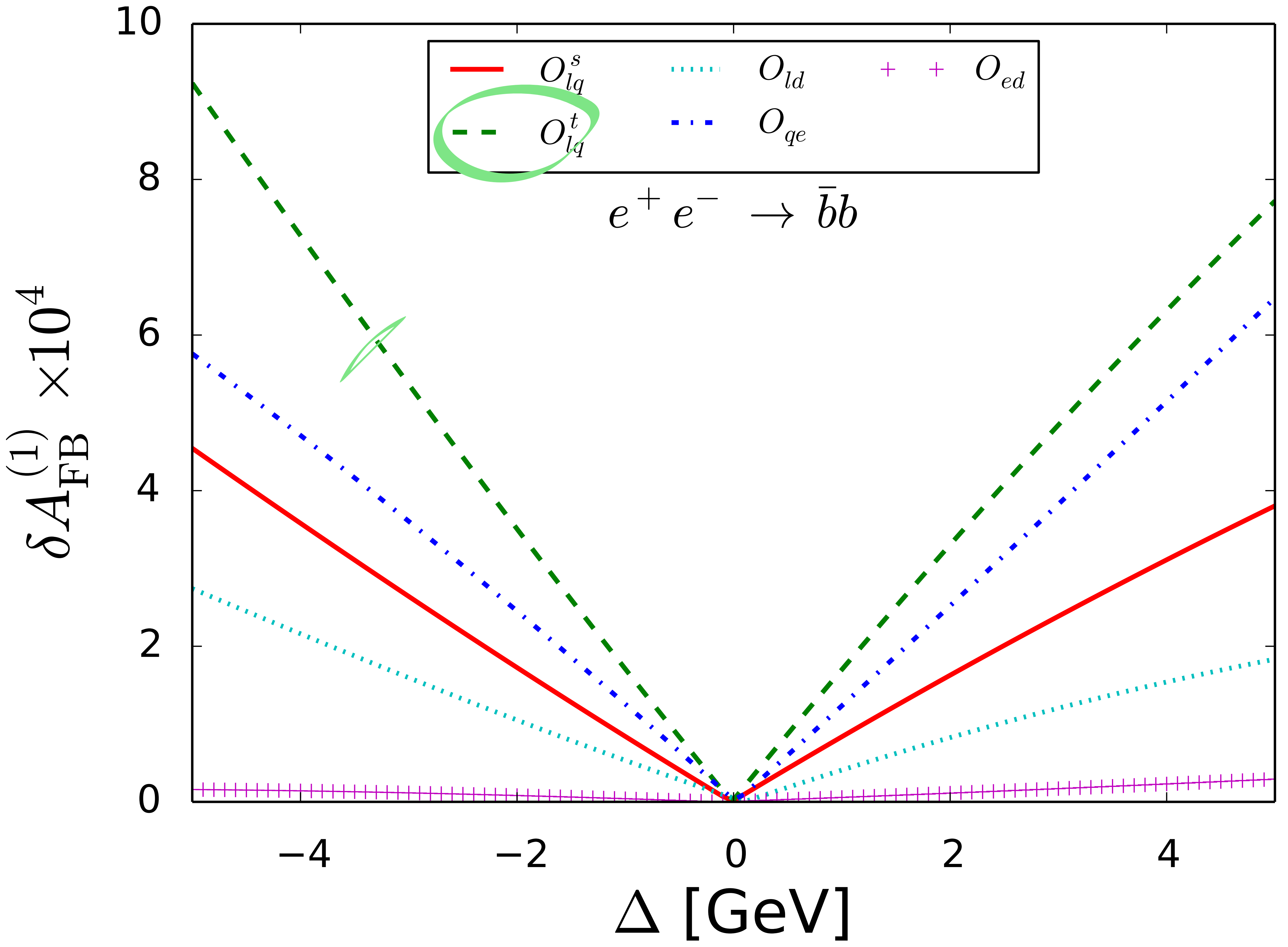




•FB Asymmetry — One-sided

$\delta A_{\rm FB}^{(1)}$ vs Δ

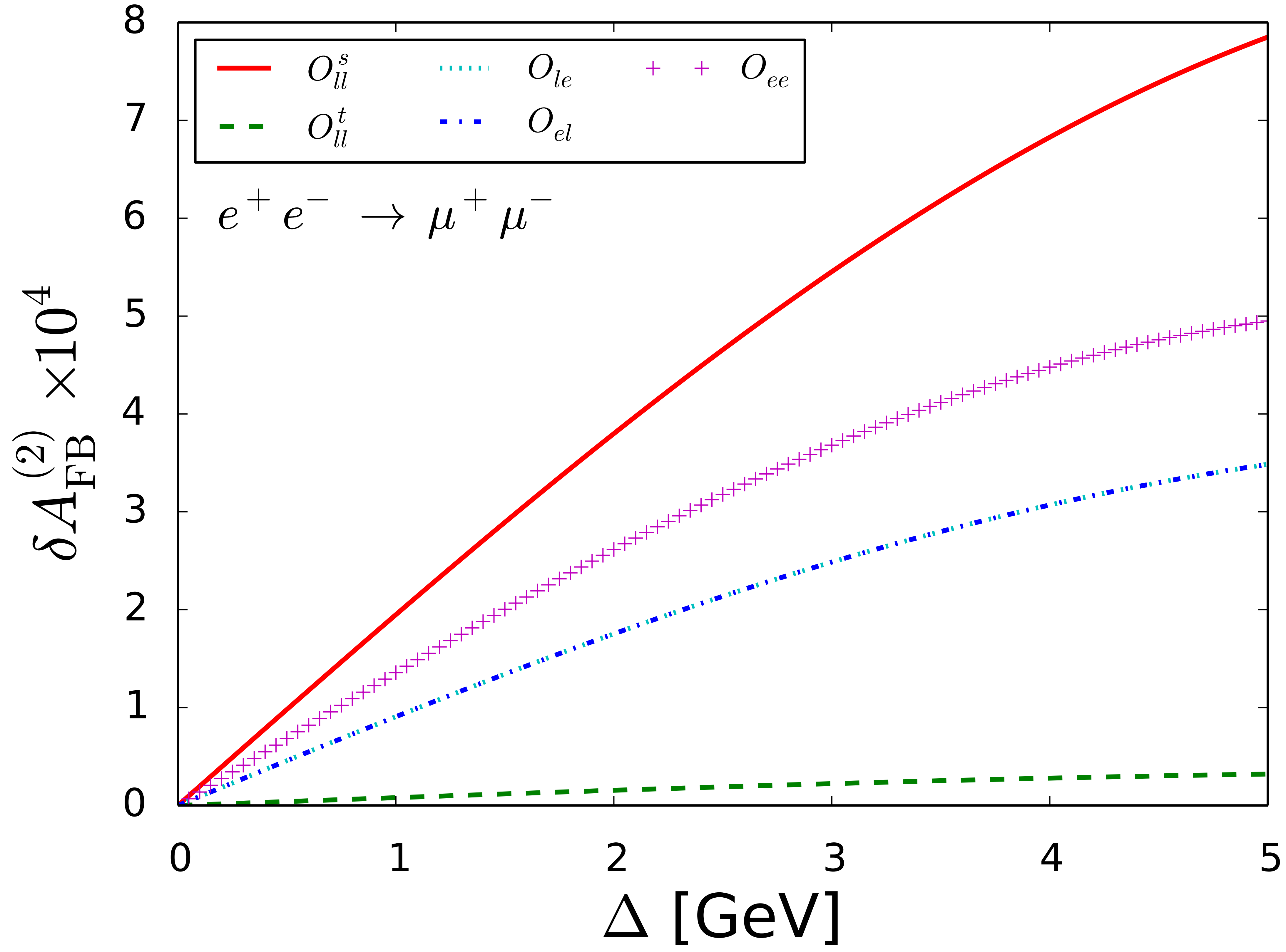


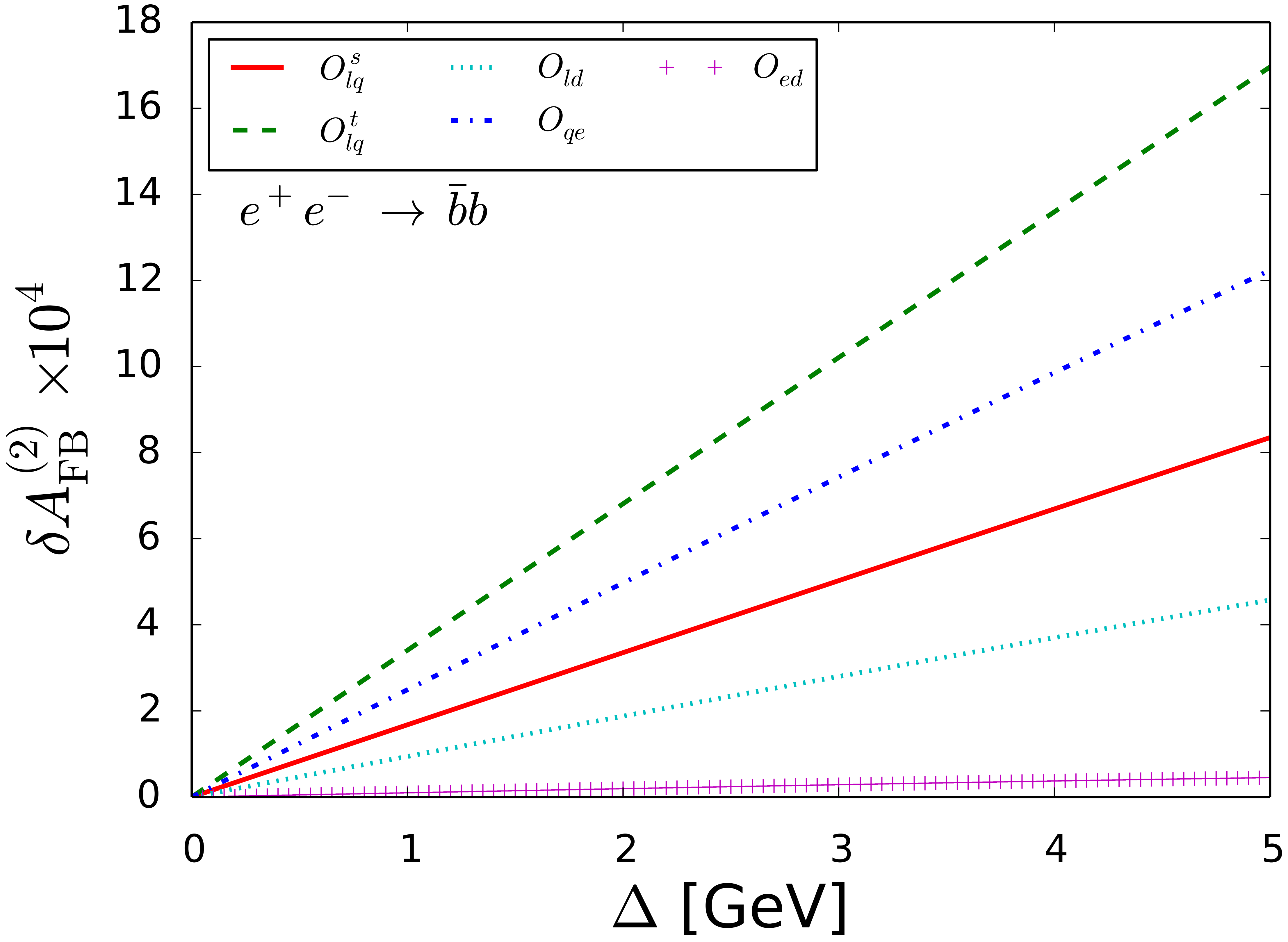


Cross Section & Asymmetry

•FB Asymmetry — Two-sided

Assuming $\Delta_{\pm} = \Delta$ $\delta A_{\mathrm{FB}}^{(2)}$ vs Δ





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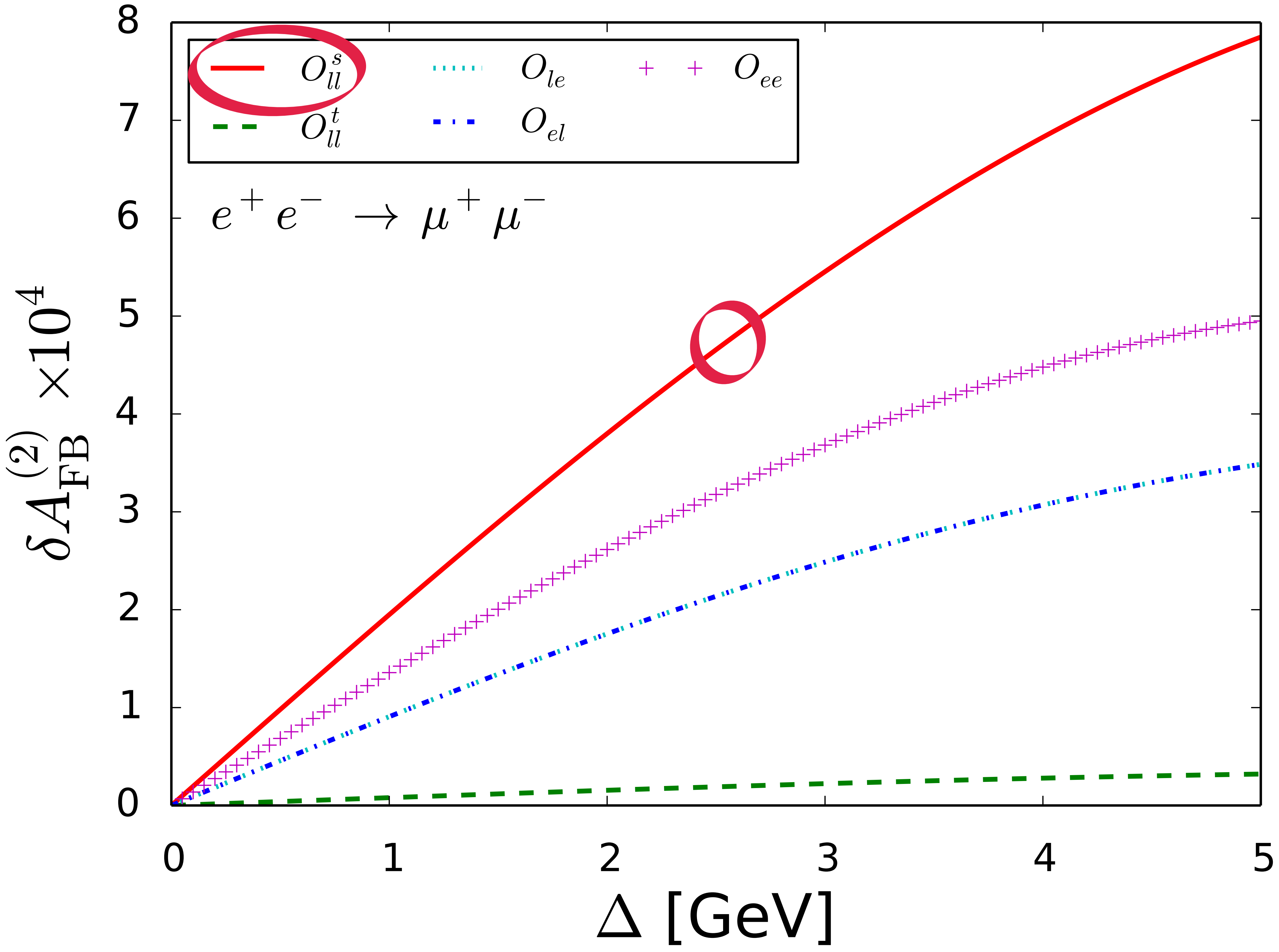
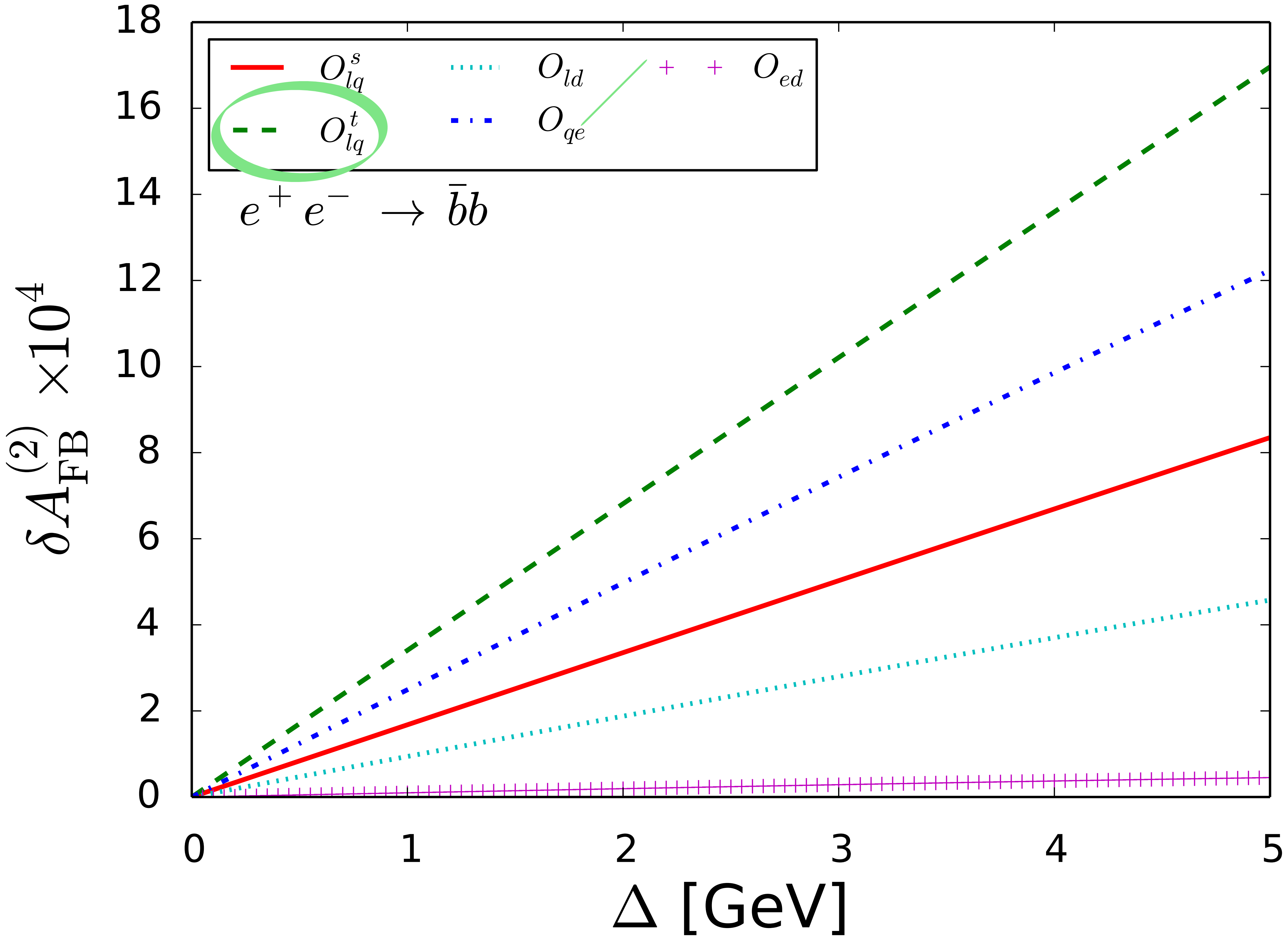
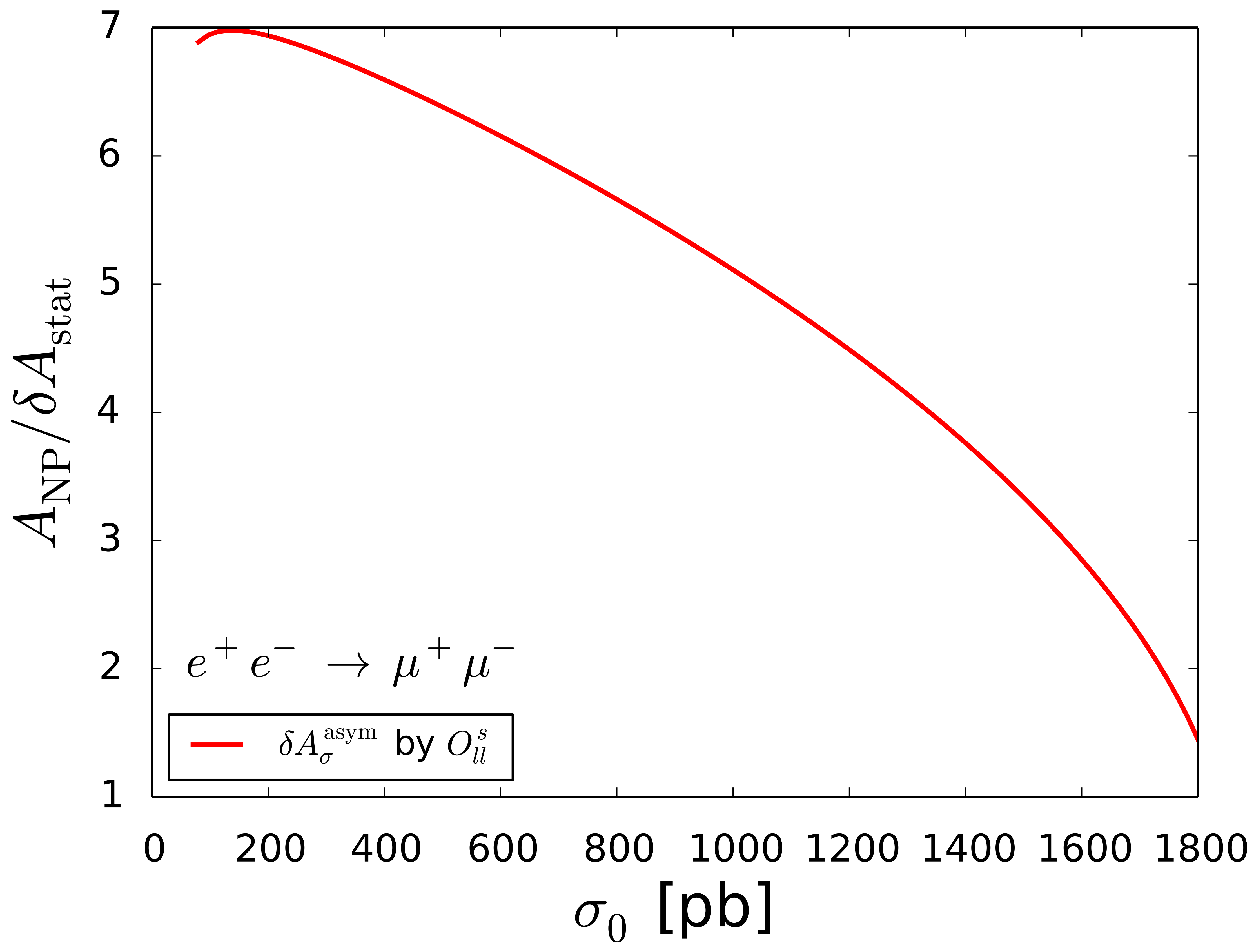


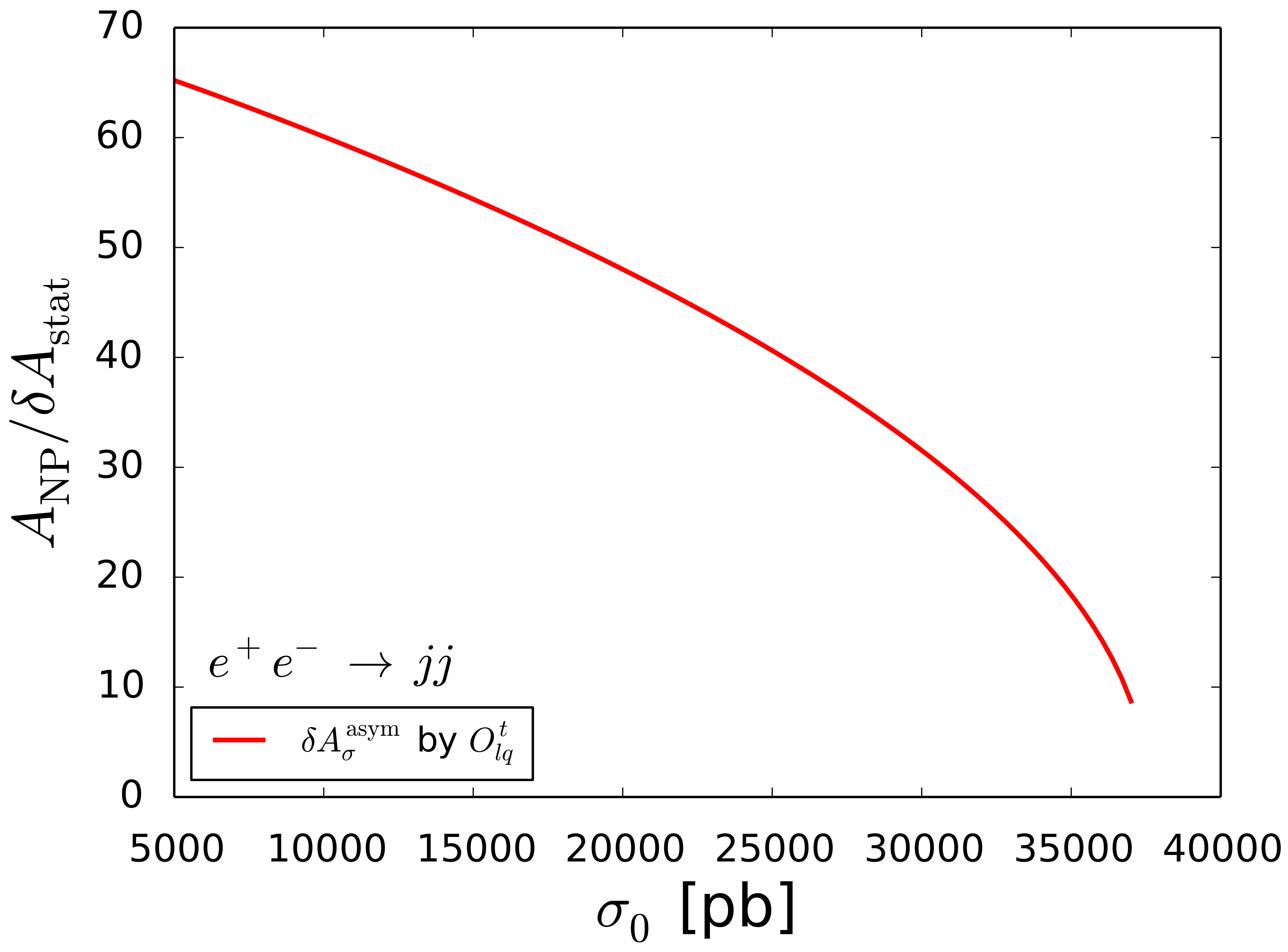


BSM Sensitivities

•New Physics Sensitivity without Systematic Uncertainties

- Xsection asymmetry — asymmetric off Z pole run: $A_\sigma^{\rm asym} = \dfrac{\sigma(M_Z + \Delta_+) - \sigma(M_Z - \Delta_-)}{\sigma(M_Z + \Delta_+) + \sigma(M_Z - \Delta_-)}$





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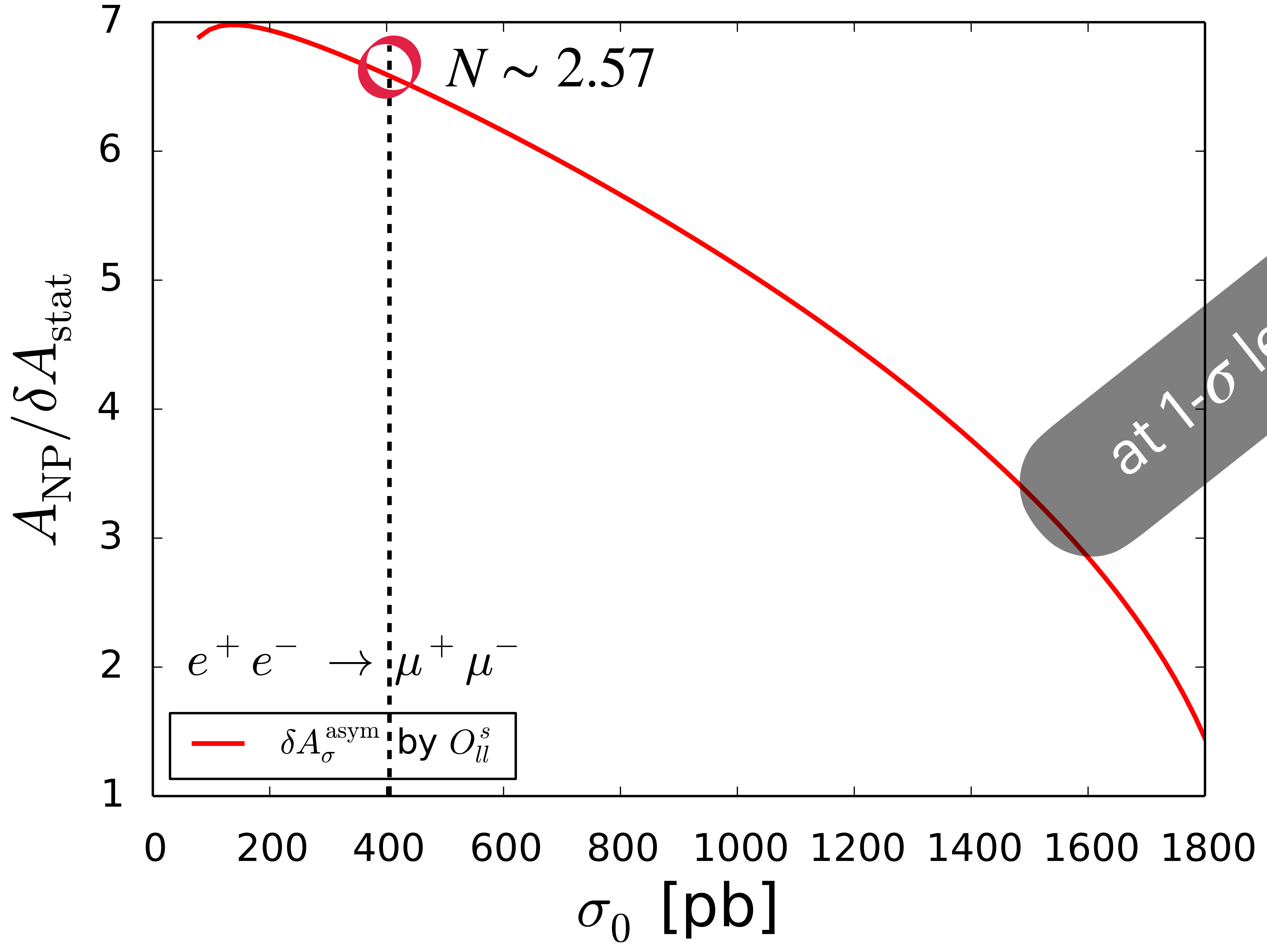

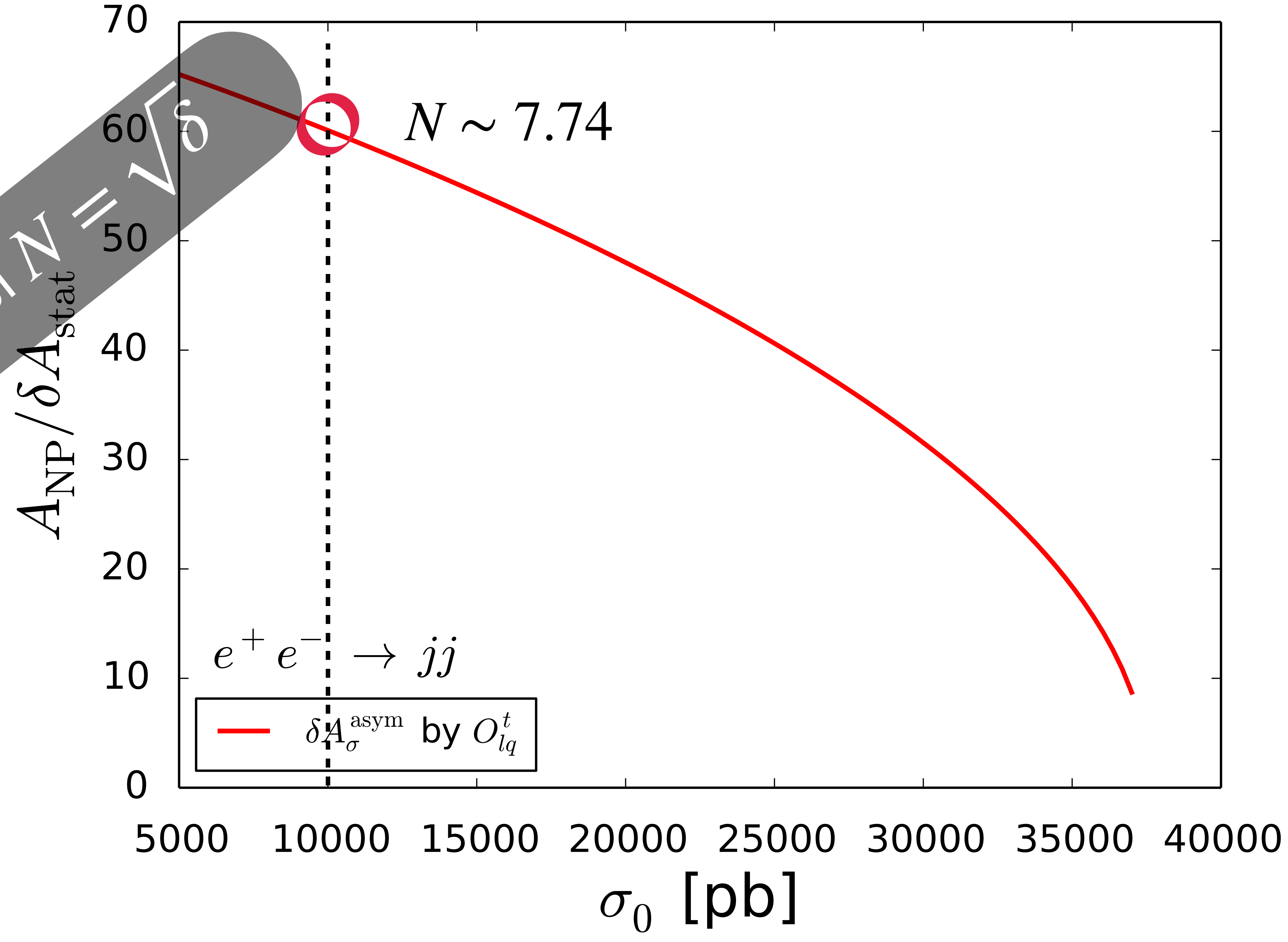

at 1-σ level $N = \sqrt{\delta}$

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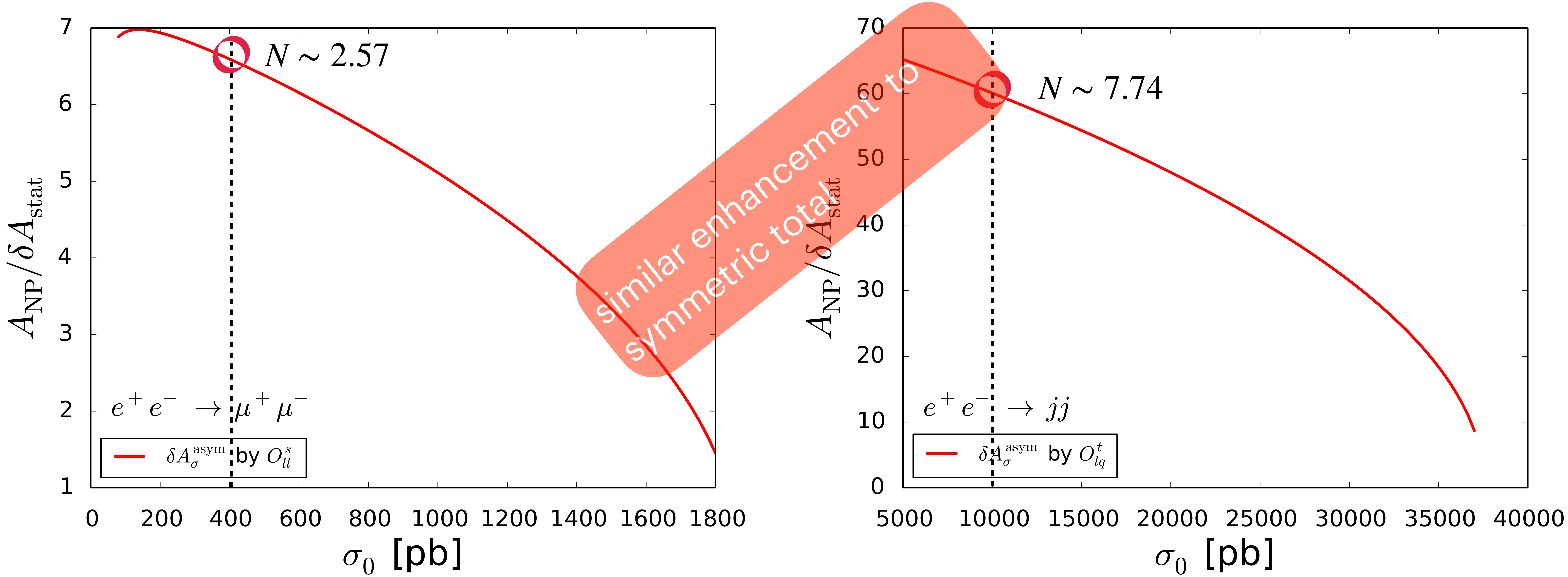

BSM Sensitivities

•New Physics Sensitivity without Systematic Uncertainties

- FB asymmetry — one(two)-sided: $A_{FB}^{(1)}, A_{FB}^{(2)}$