SQuark mass measurement @ CLIC

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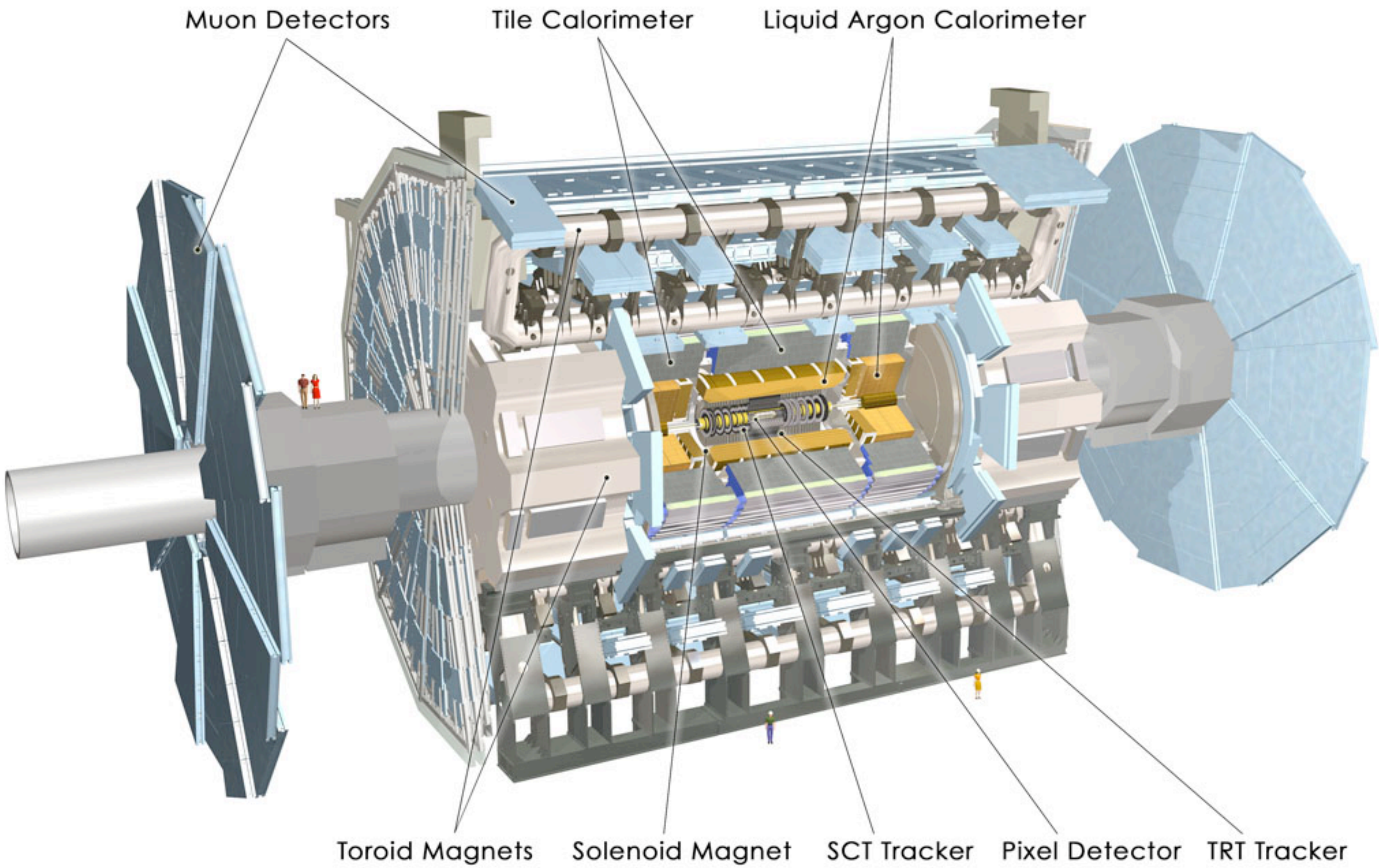
MPI für Physik & Excellence Cluster „Universe“, München

Particle Physics School Munich Colloquium
November 2011

Current Colliders: The Large Hadron Collider

- Current Cutting Edge accelerator: Large Hadron Collider
  - Up to 14 TeV p-p
  - High Luminosity
  - Very good detectors
- Hadron collider ⇒ p-p
  - Initial State unknown
    - Energy
    - Particle
  - Underlying event(s)
  - Pile-Up
  - Huge xs for Background
- For precision measurements we need a much cleaner environment!

➡ Lepton Collider



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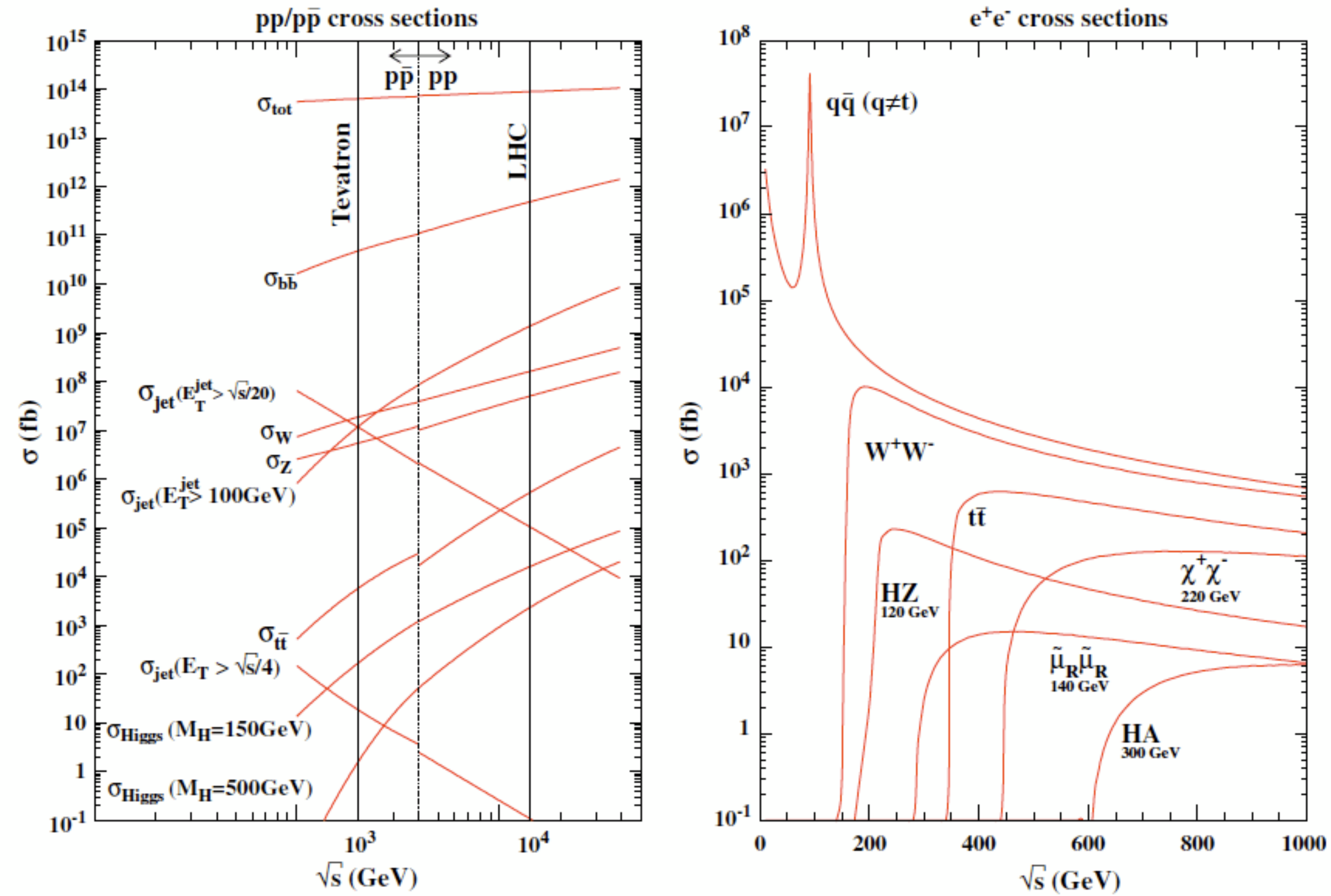
G. Weiglein et al. / Physics Reports 426 (2006) 47–358



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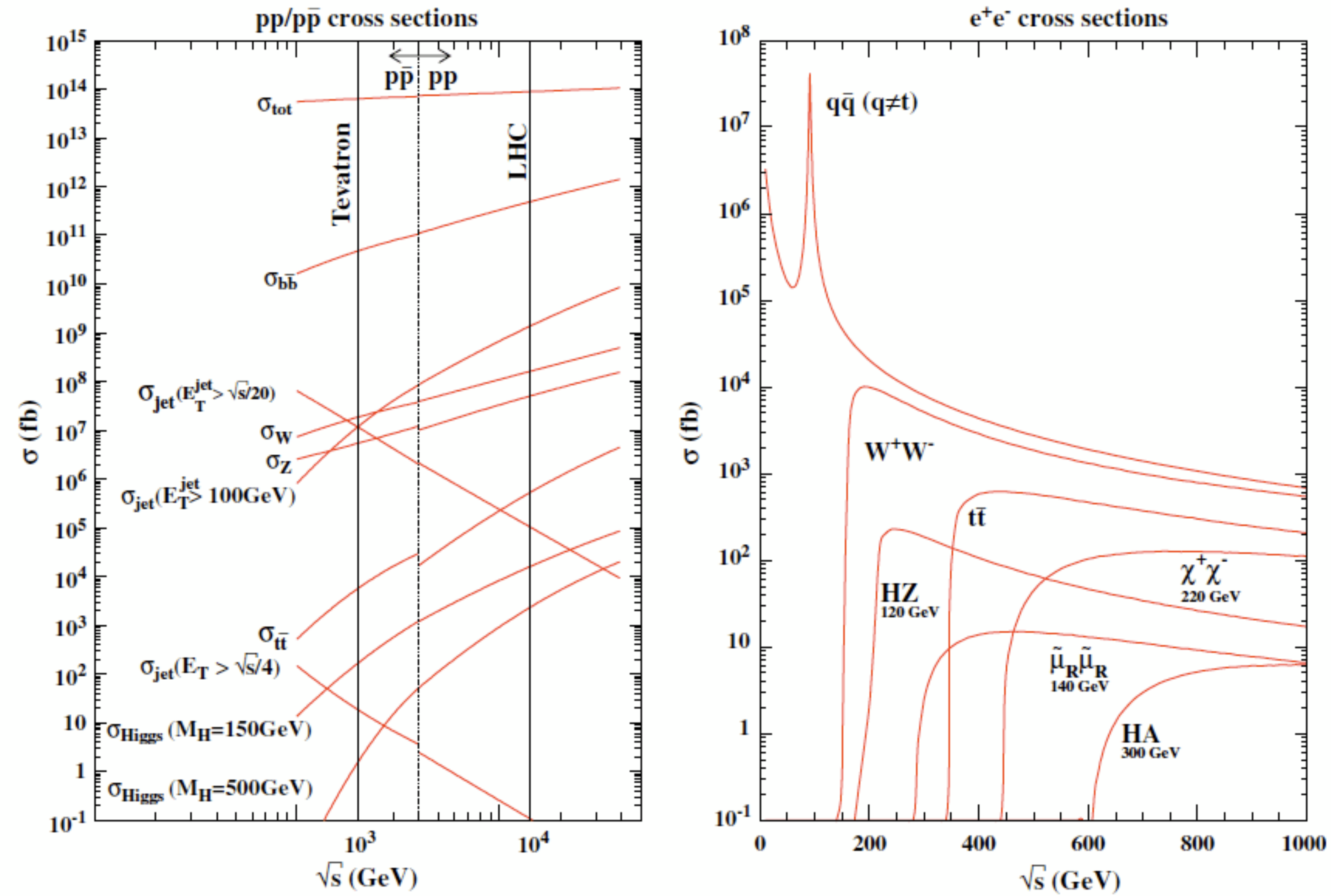

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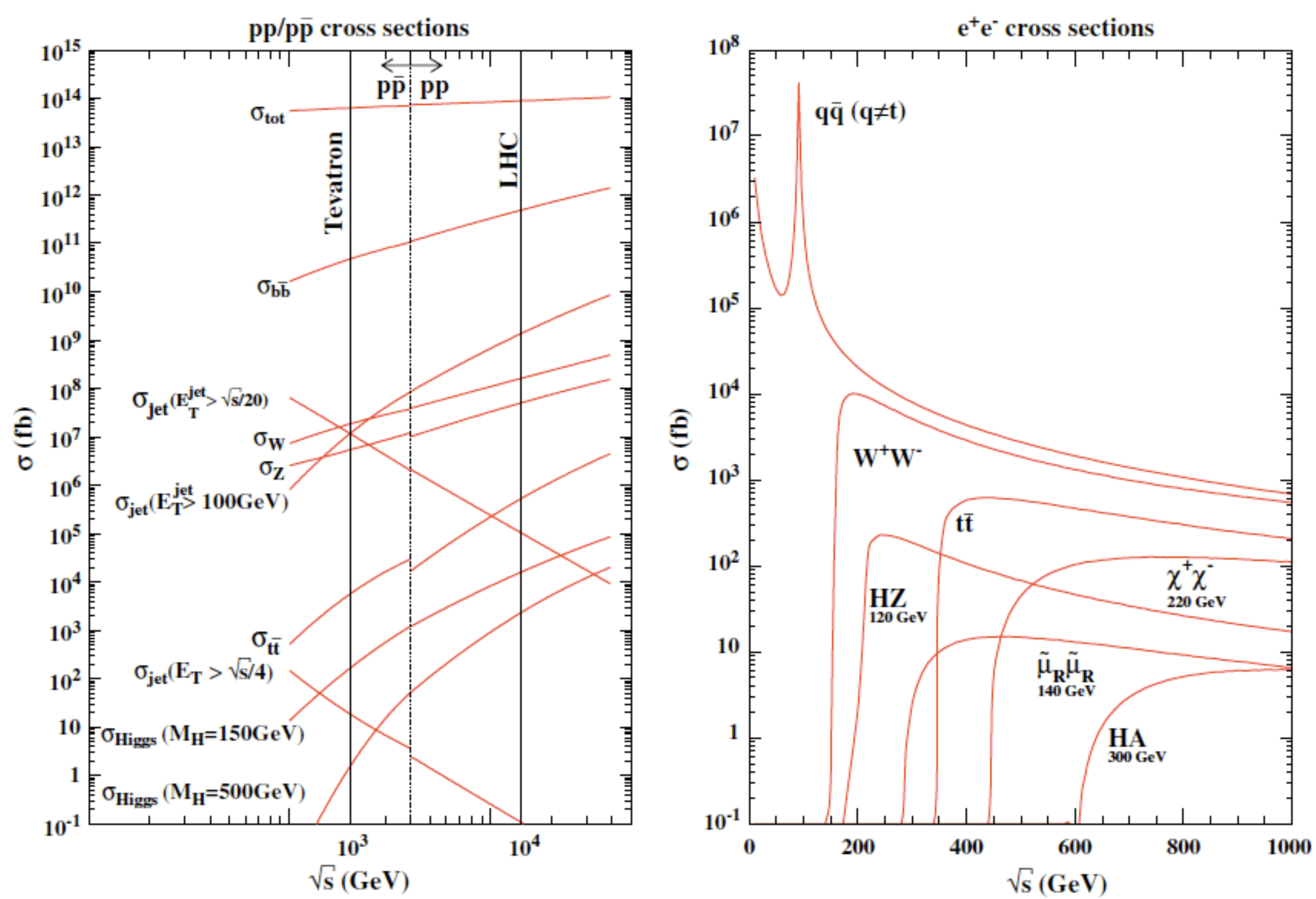

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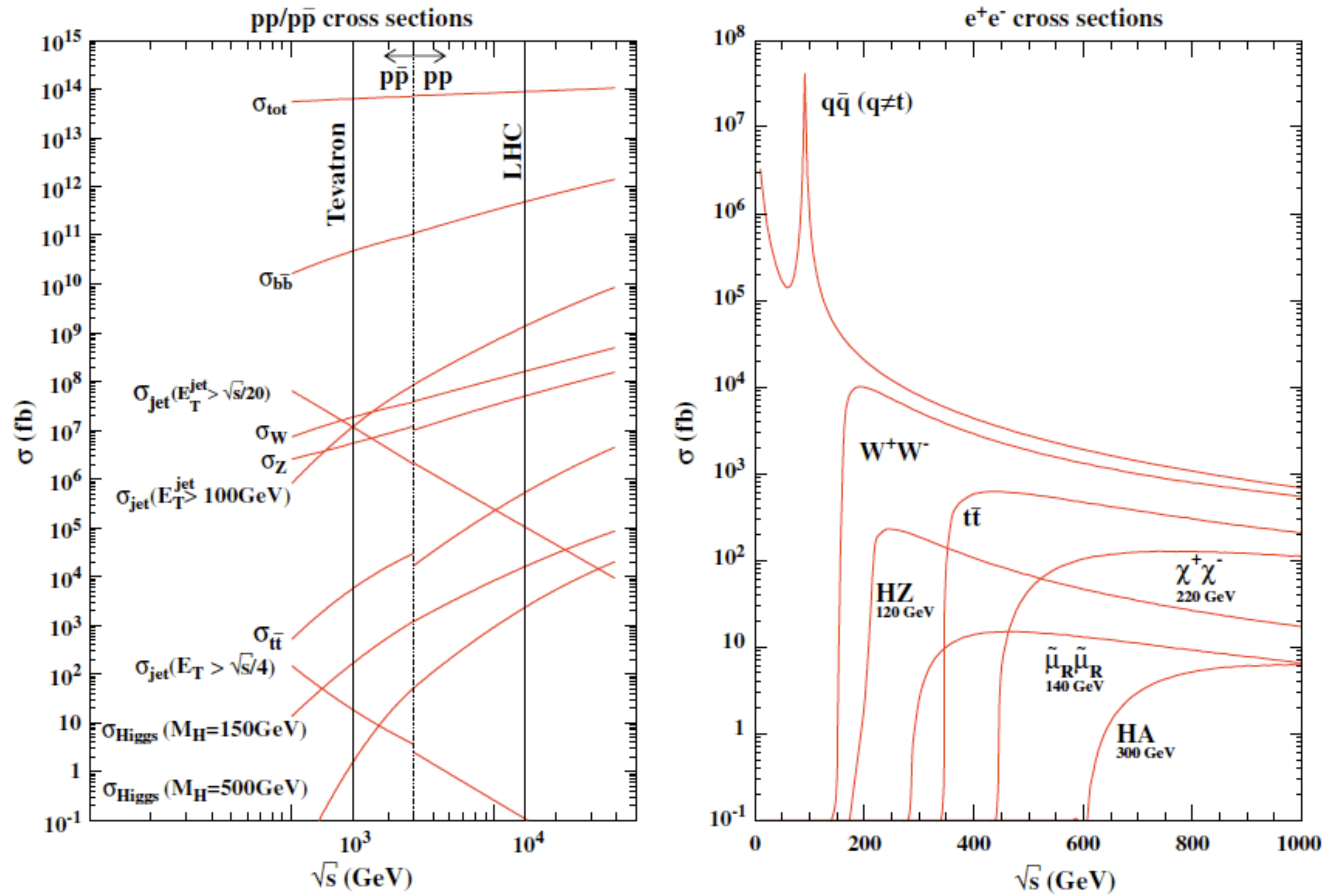

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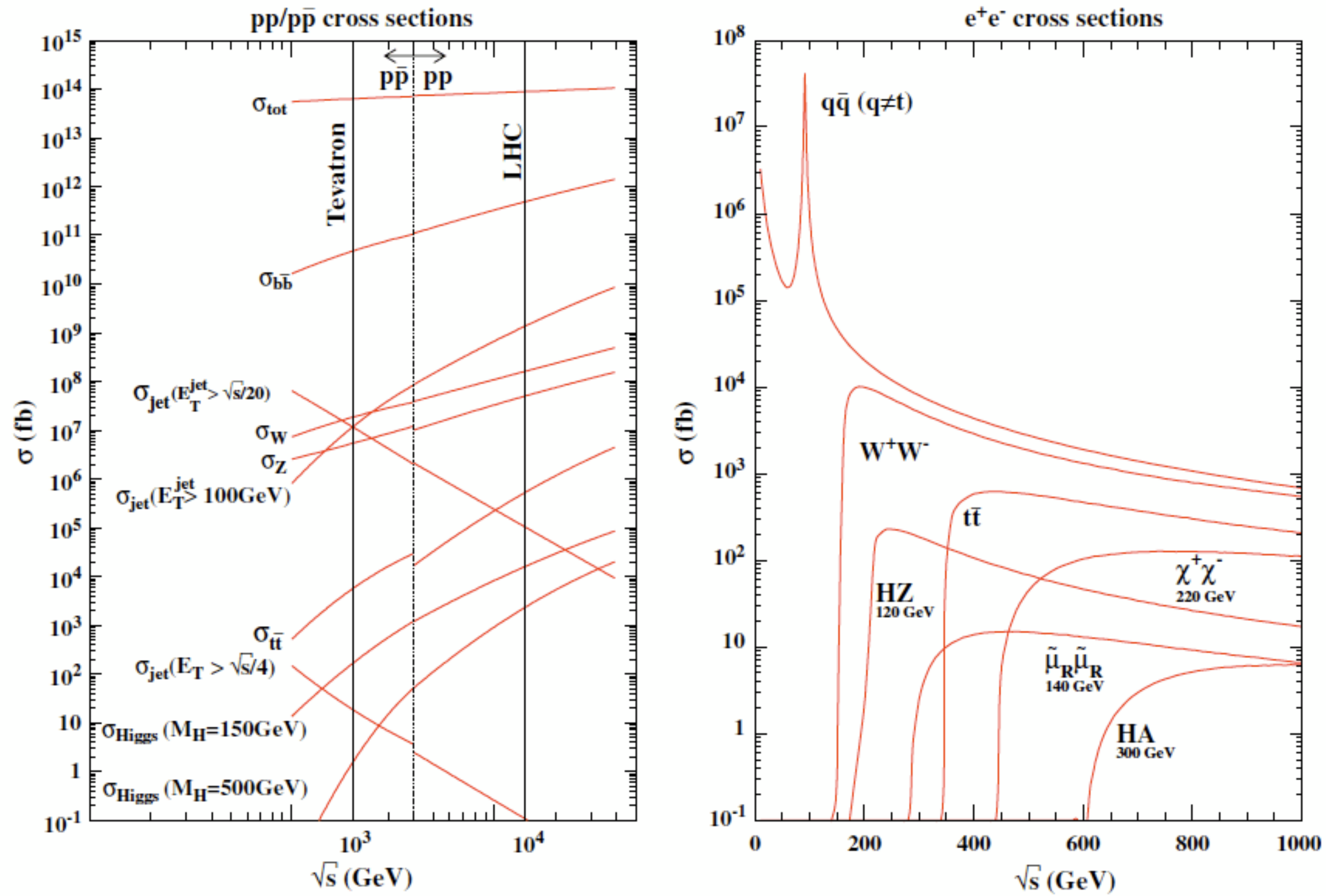

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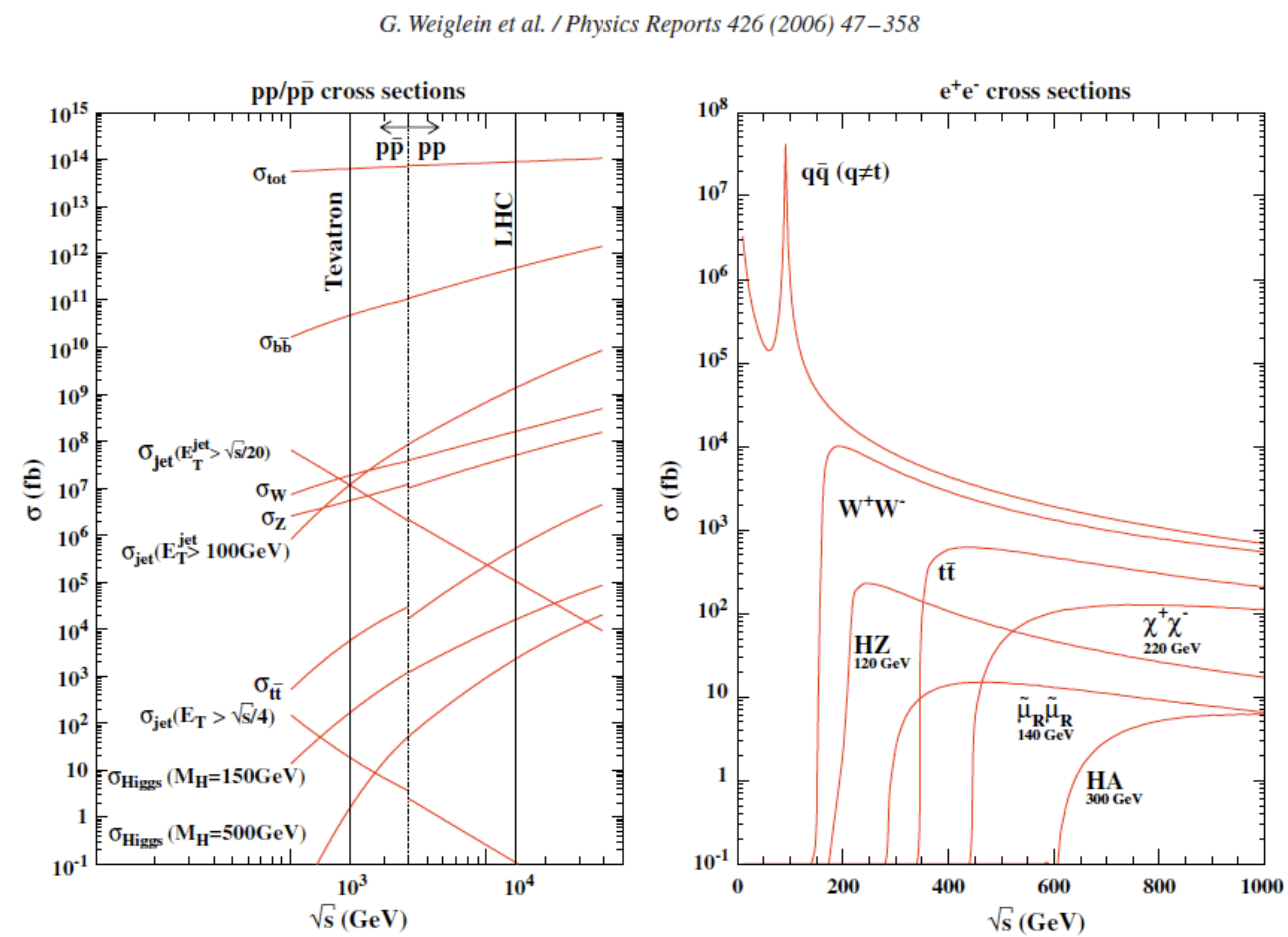
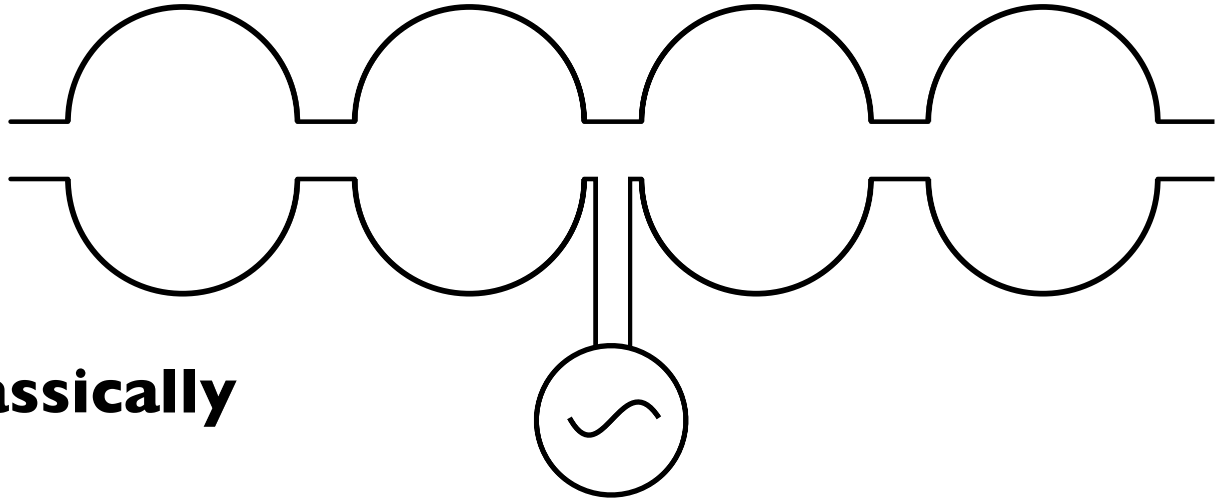


Excellence Cluster Universe

The Compact Linear Collider

Classically



The Compact Linear Collider

- Synchrotron radiation → Needs to be linear accelerator
- Acceleration of charged particles via Cavity

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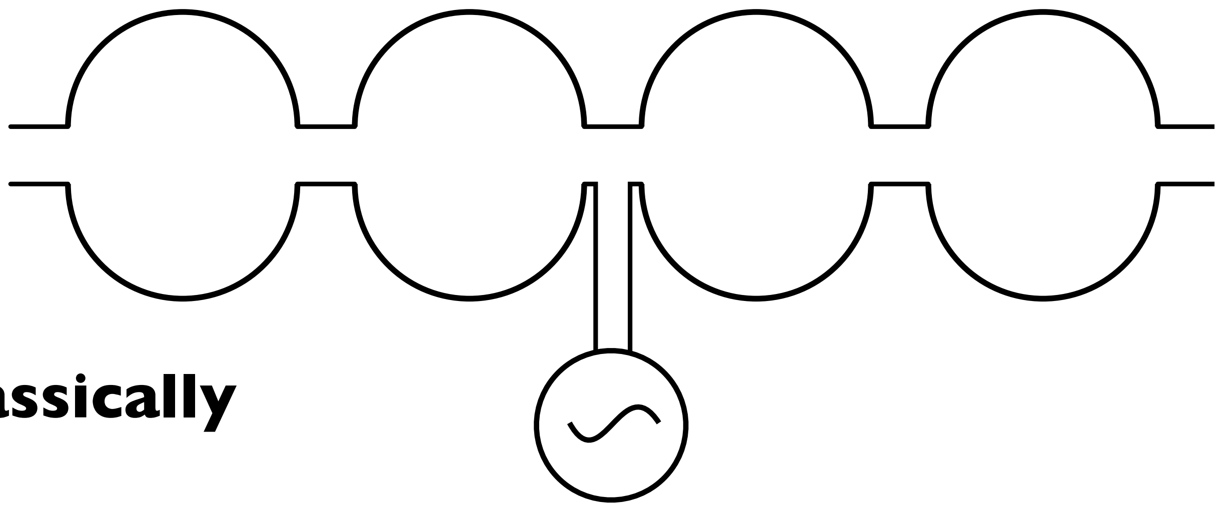

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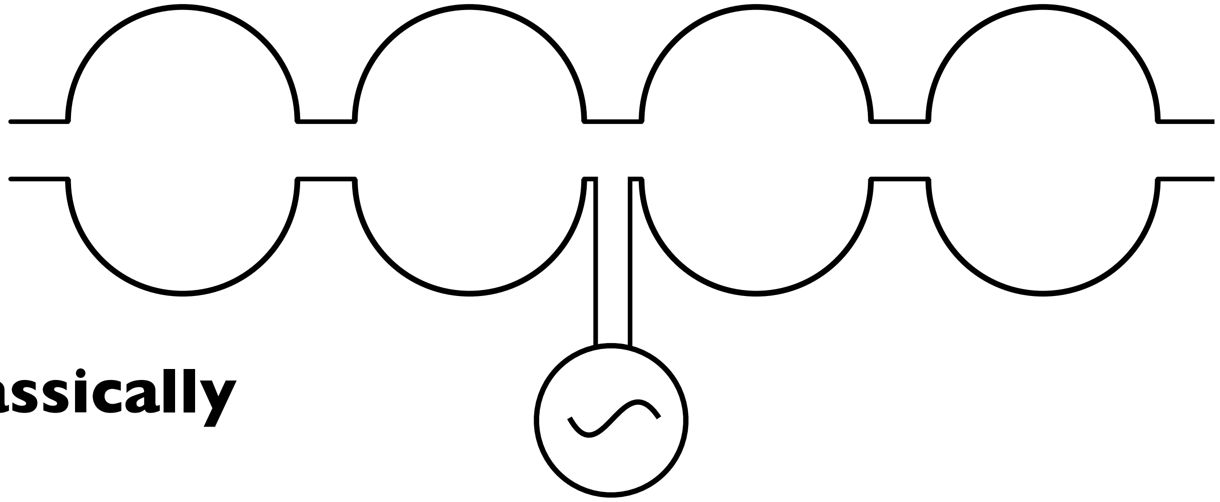

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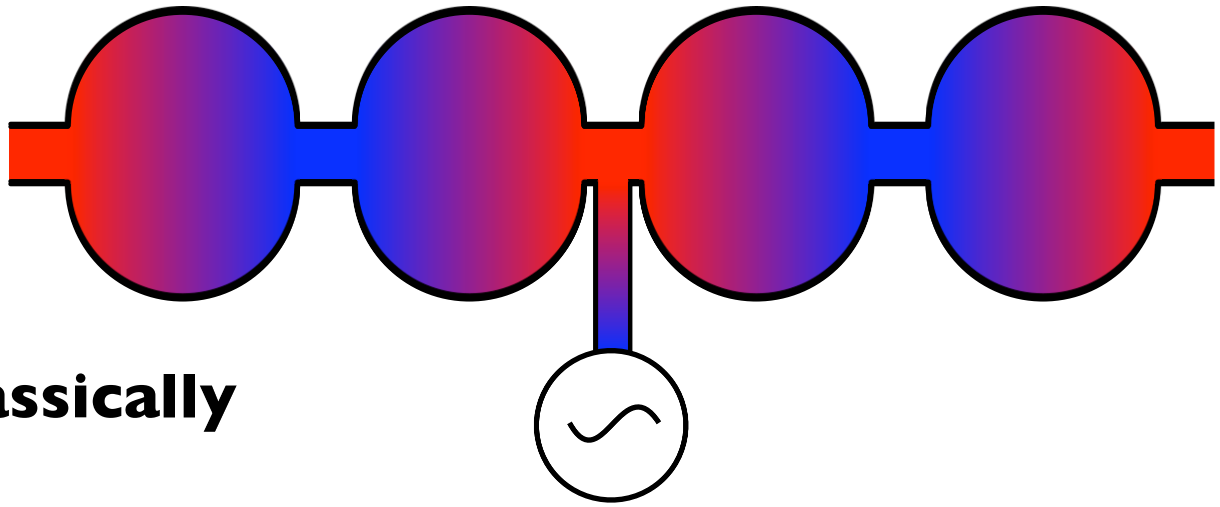

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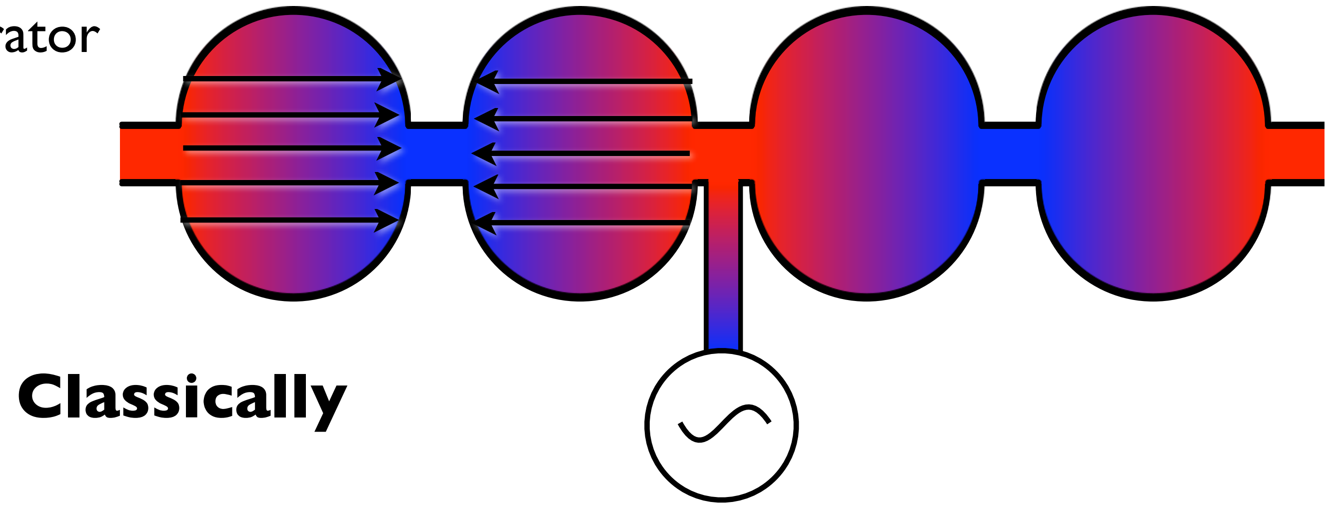

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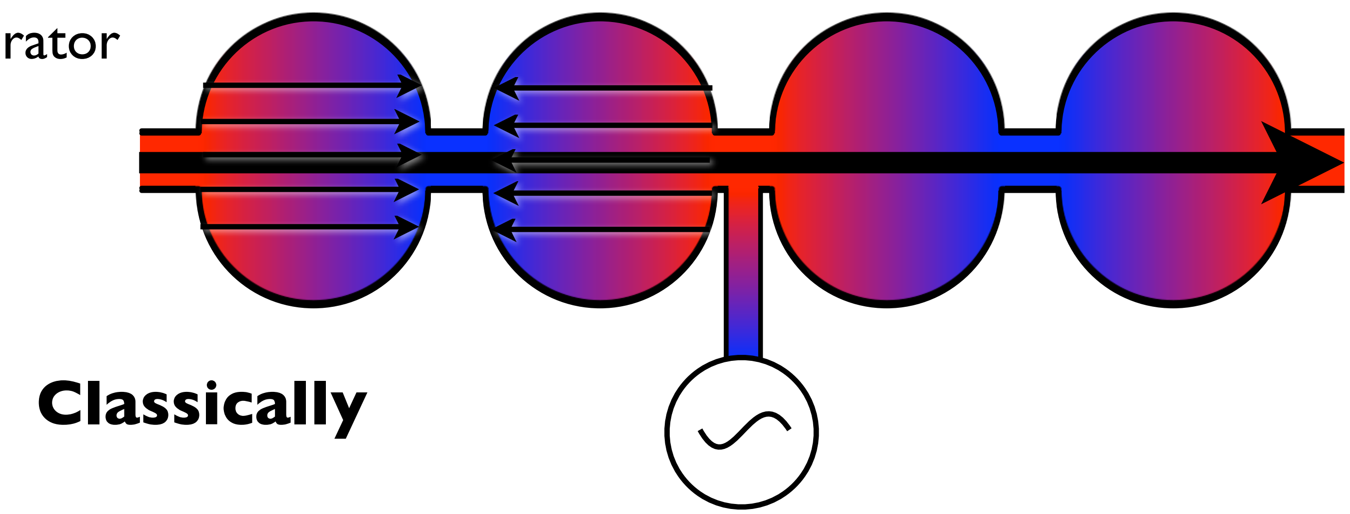

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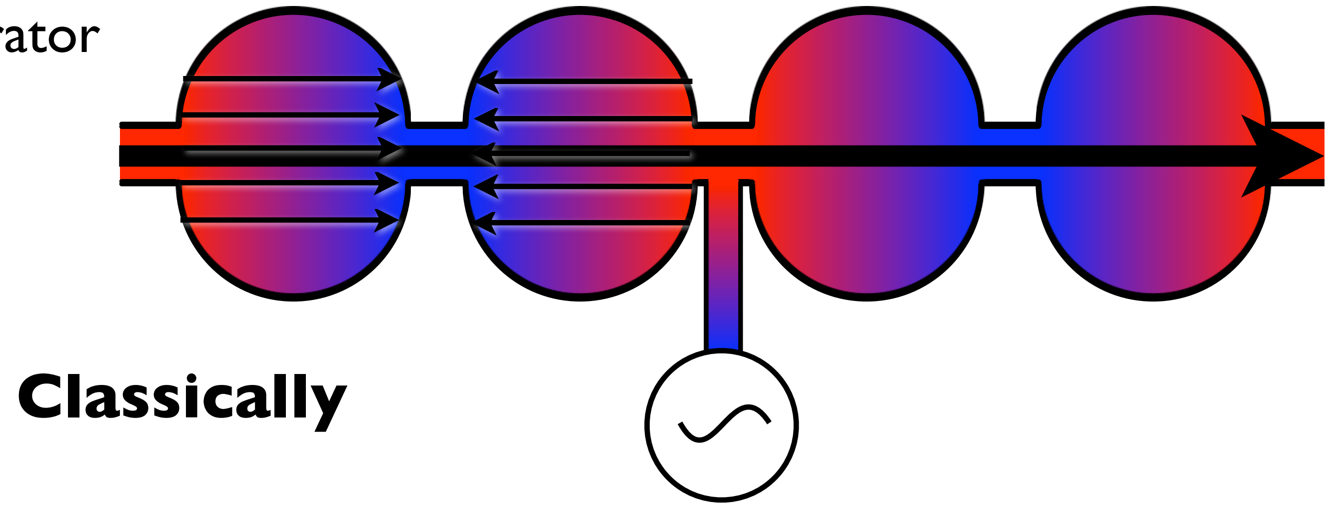
  - 2nd beam
    - Parallel to actual (high energy) beam
    - Low energy
    - High intensity
  - Extract RF from this beam via a „double cavity“



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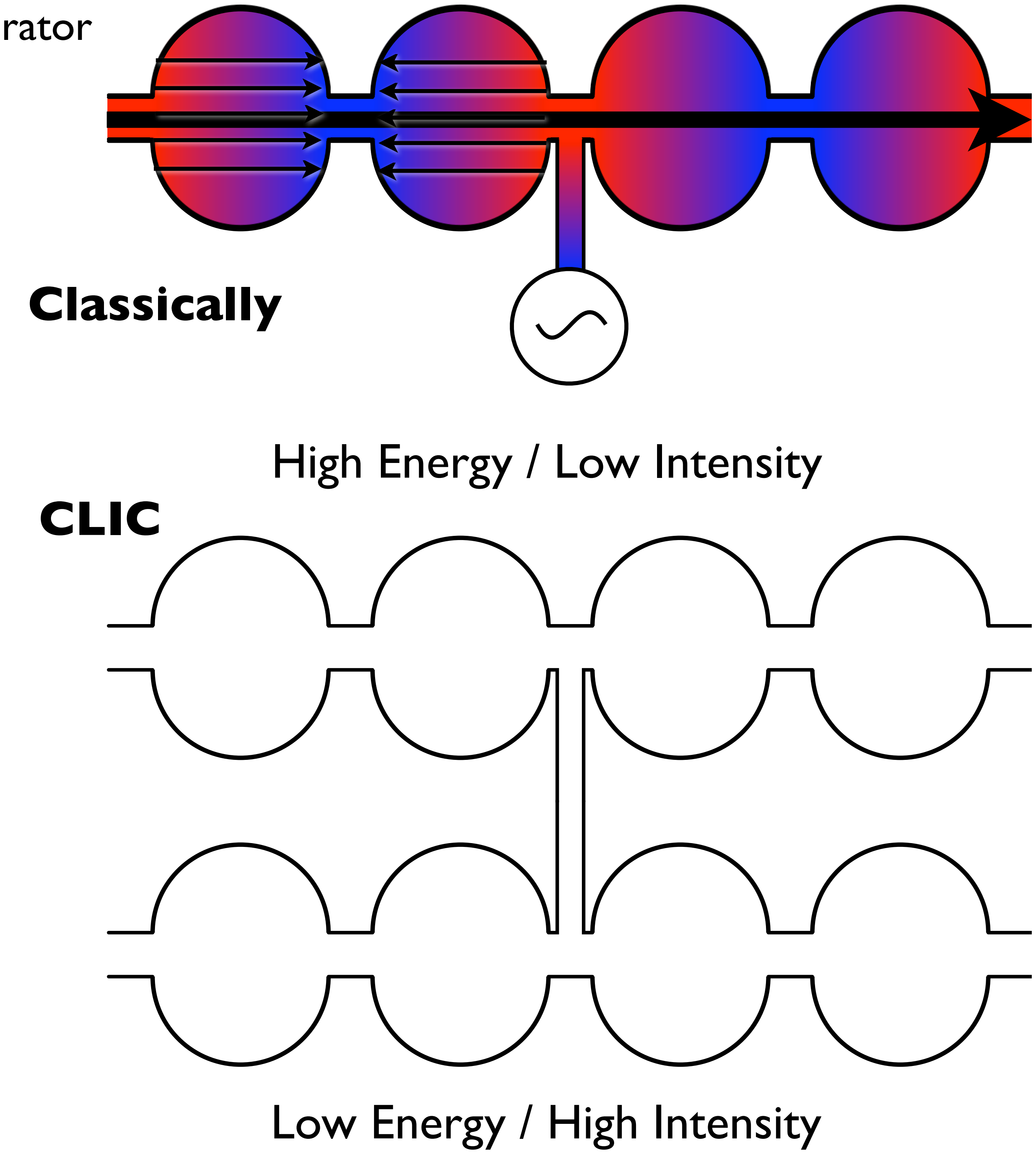

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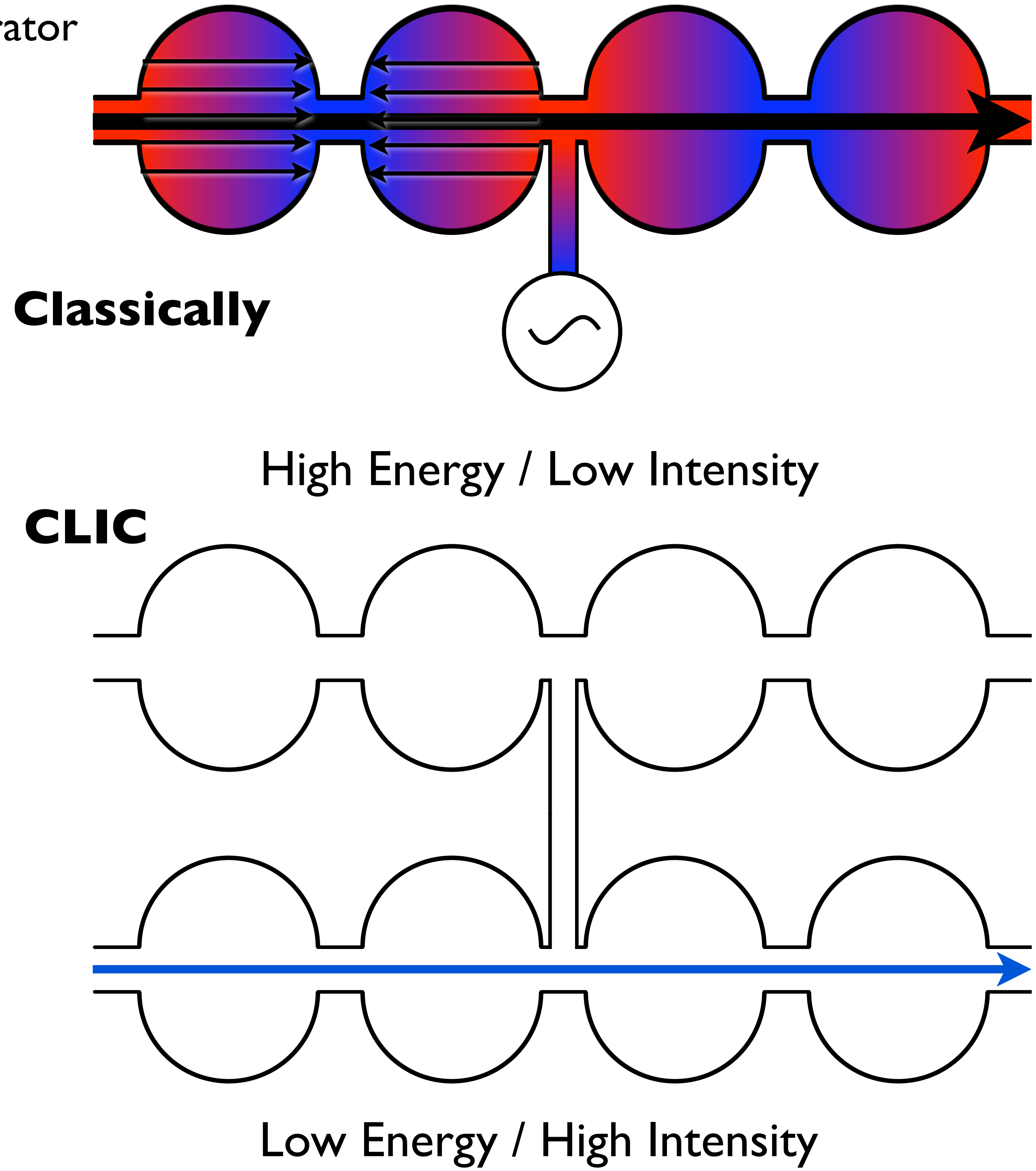

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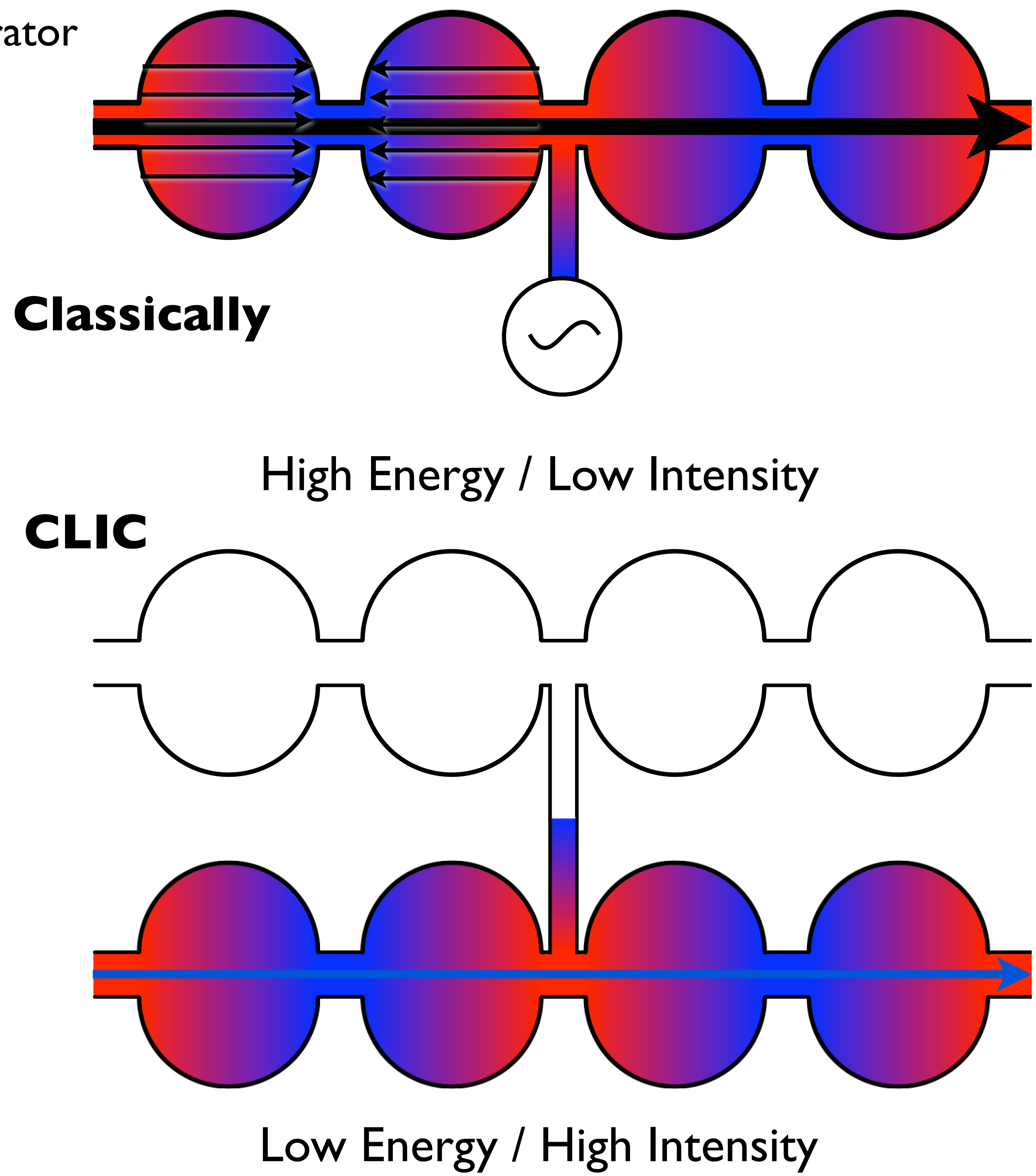

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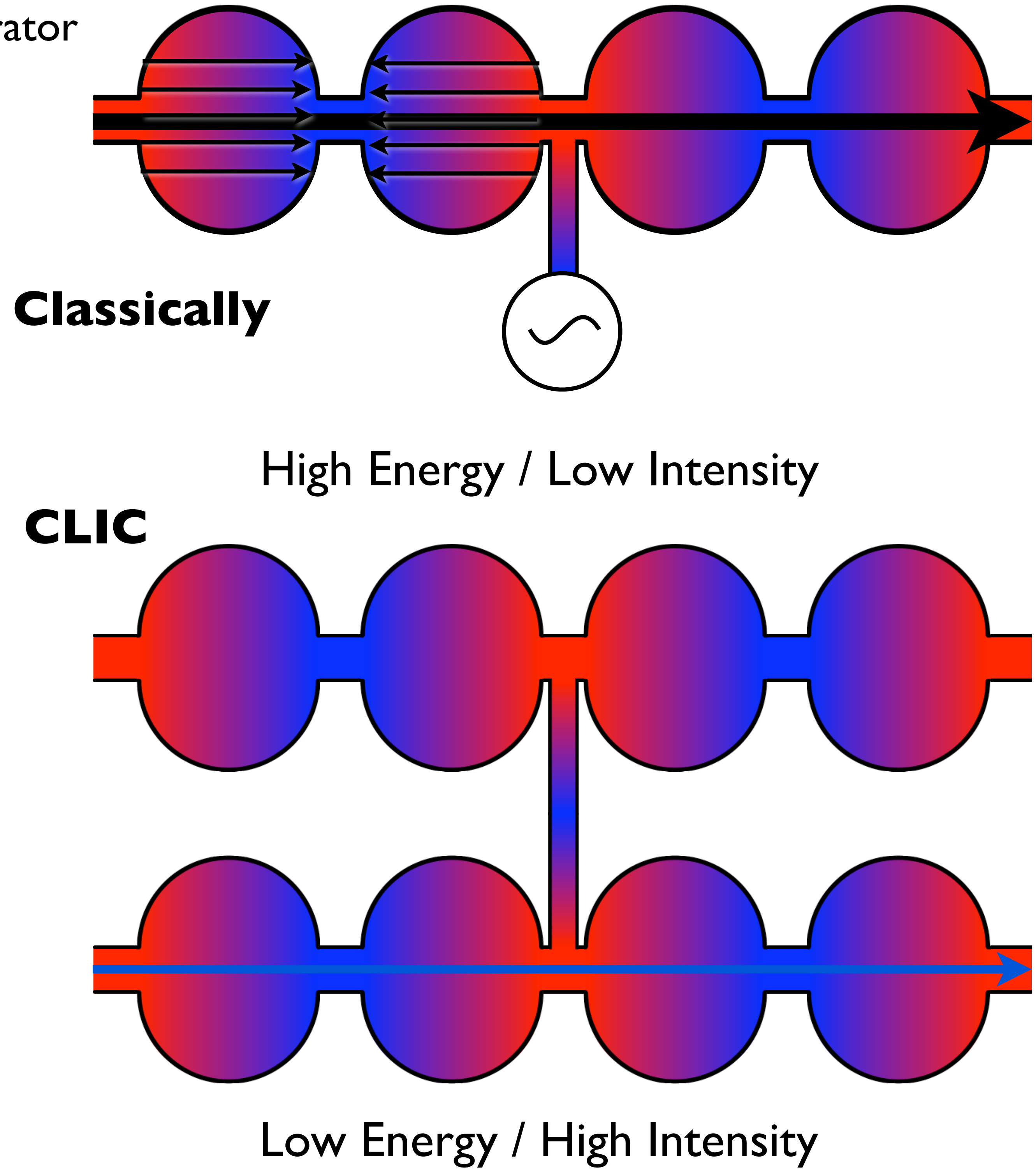

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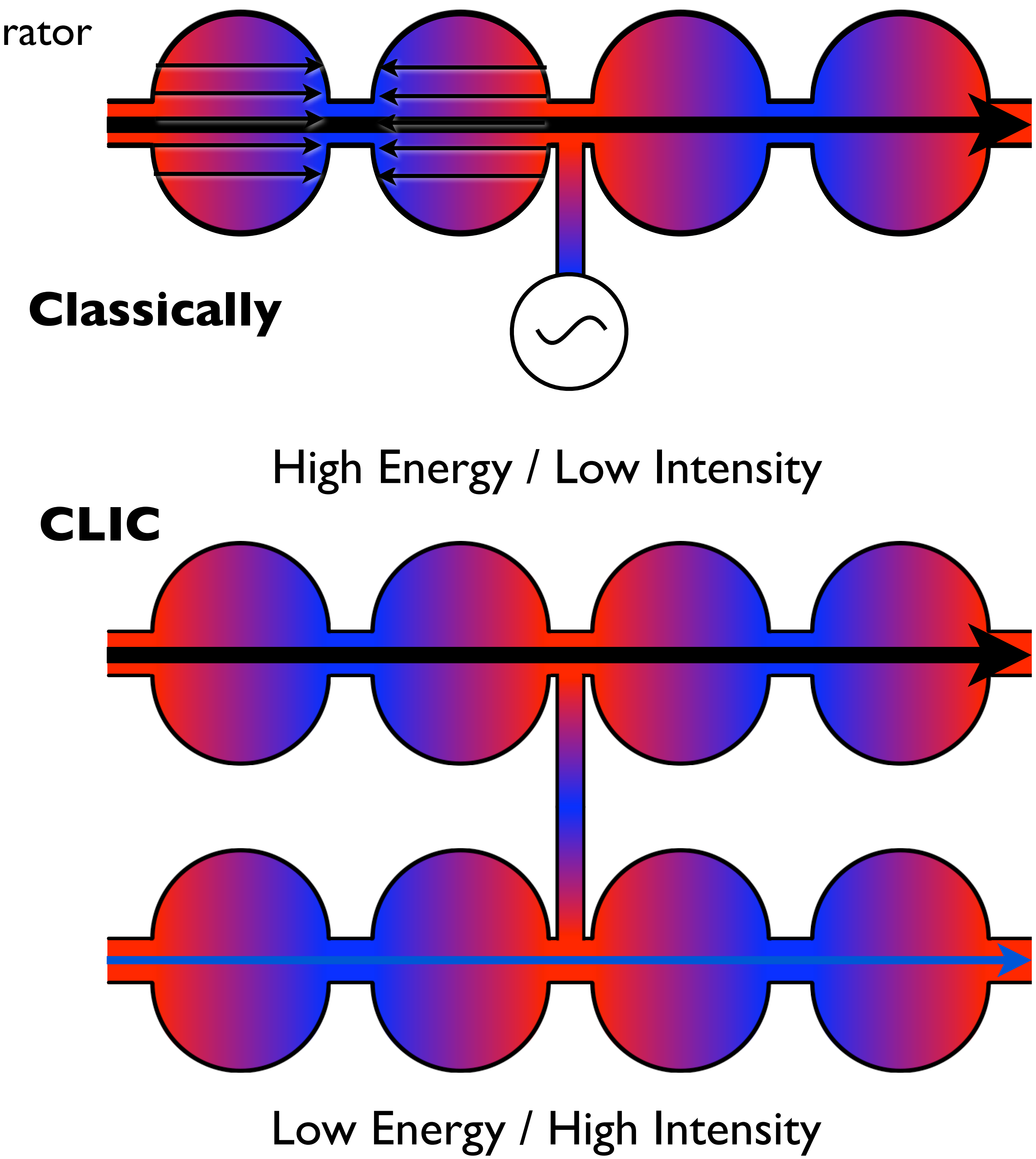

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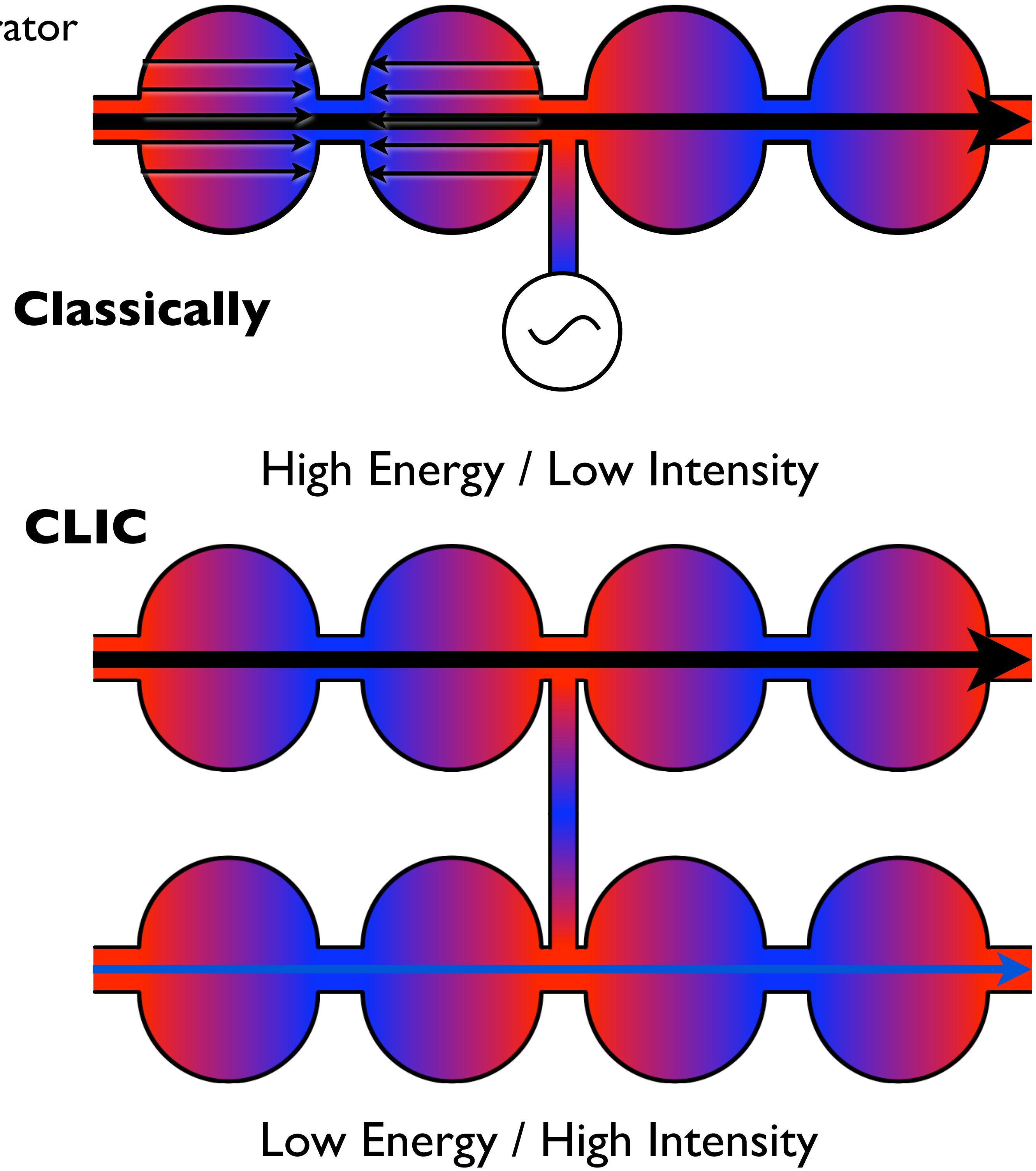
- More than 100MeV/m possible
  - 3 TeV: ~50km length (incl. beam delivery system)
  - ➡ Compact Linear Collider: CLIC
    - 300 Bunches / Train
    - 0.5 ns Repetition Rate

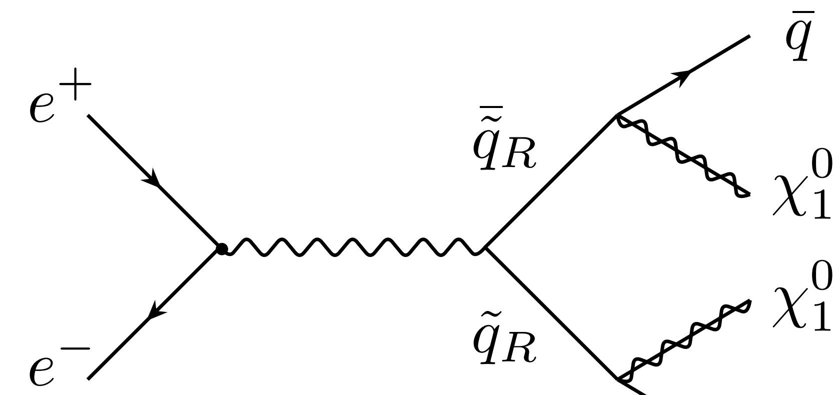


The CLIC Conceptional Design Report: A Benchmark

$$m_0 = 303\text{GeV}$$
$$A_0 = -750\text{GeV}$$
$$\mu > 0$$
$$\tan\beta = 24$$
$$M_1 = 780\text{GeV}$$
$$M_2 = 940\text{GeV}$$
$$M_3 = 540\text{GeV}$$

particle	mass [GeV]
χ_1^0	328.3
$\tilde{u}_R, \tilde{c}_R$	1125.7
$\tilde{d}_R, \tilde{s}_R$	1116.1
$\tilde{g}_R$	1239.7

- To show the Capabilities of CLIC: Conceptional Design Report (CDR)
  - Check performance of Detector/Accelerator
- Dedicated SUSY Scenario
- Benchmark: Measurement of mass of right handed SQuarks
  - Decay almost exclusively into 2 Quarks plus Neutralino
  - Low crosssection (~3000 events after 5 years running)
  - Event shape: 2 Quarks + E_{miss}
    - Very general (not bound to this SUSY scenario)
      - Easy to identify



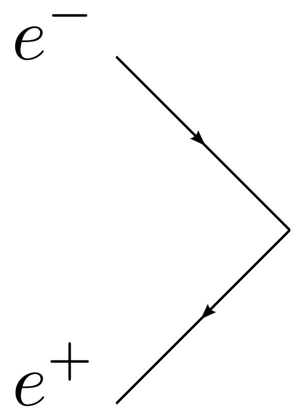
$$\tilde{q} \in \{\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}\}$$

$$e^+e^- \longrightarrow \tilde{q}_R\bar{\tilde{q}}_R$$

$$\tilde{q}_R \xrightarrow{99.7\%} q + \chi_1^0$$

Jets: Footprints of final state particles

$$e^+e^- \rightarrow q\bar{q}$$



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Event

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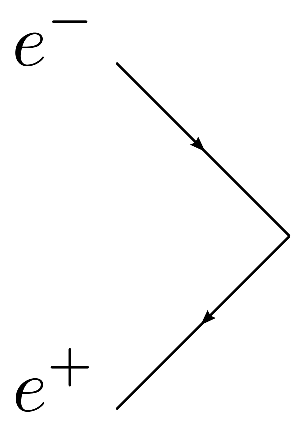

Jets: Footprints of final state particles

$$e^+e^- \to q\bar{q}$$

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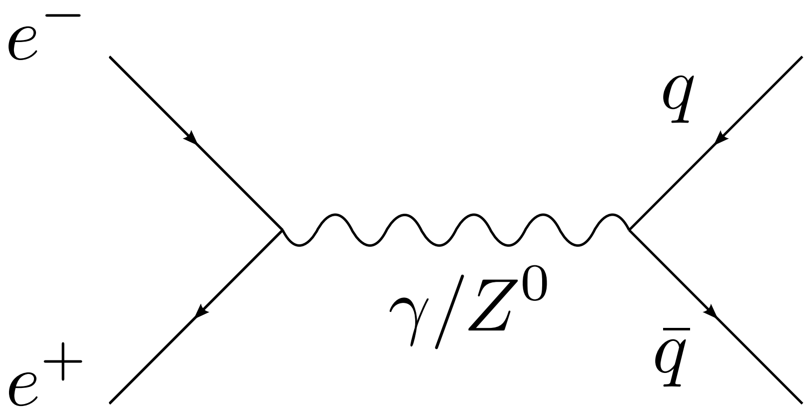
2. Reaction
   ➡ Final state particles (here: 2 quarks)



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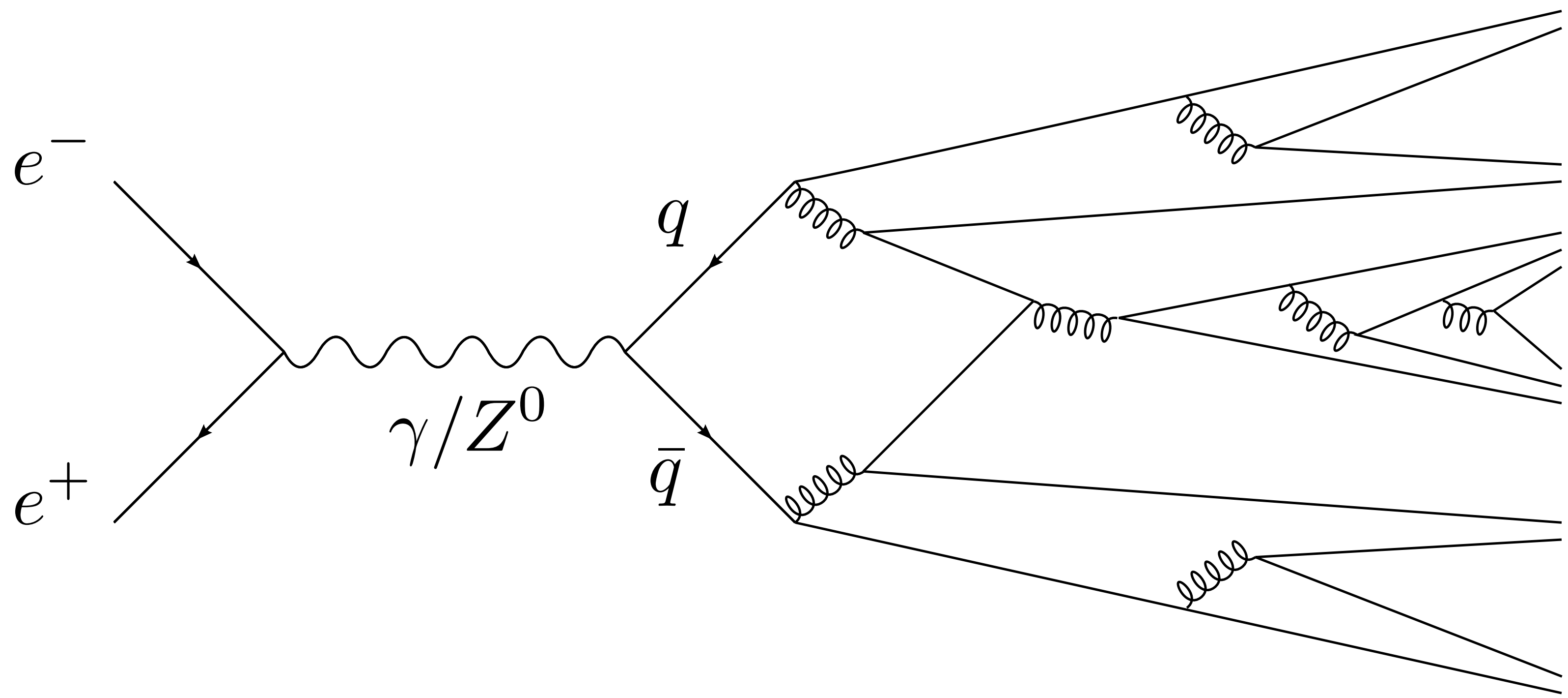
3. Fragmentation
   - Each final state particle

   $\Downarrow$

   Many fragments (≈ same direction)



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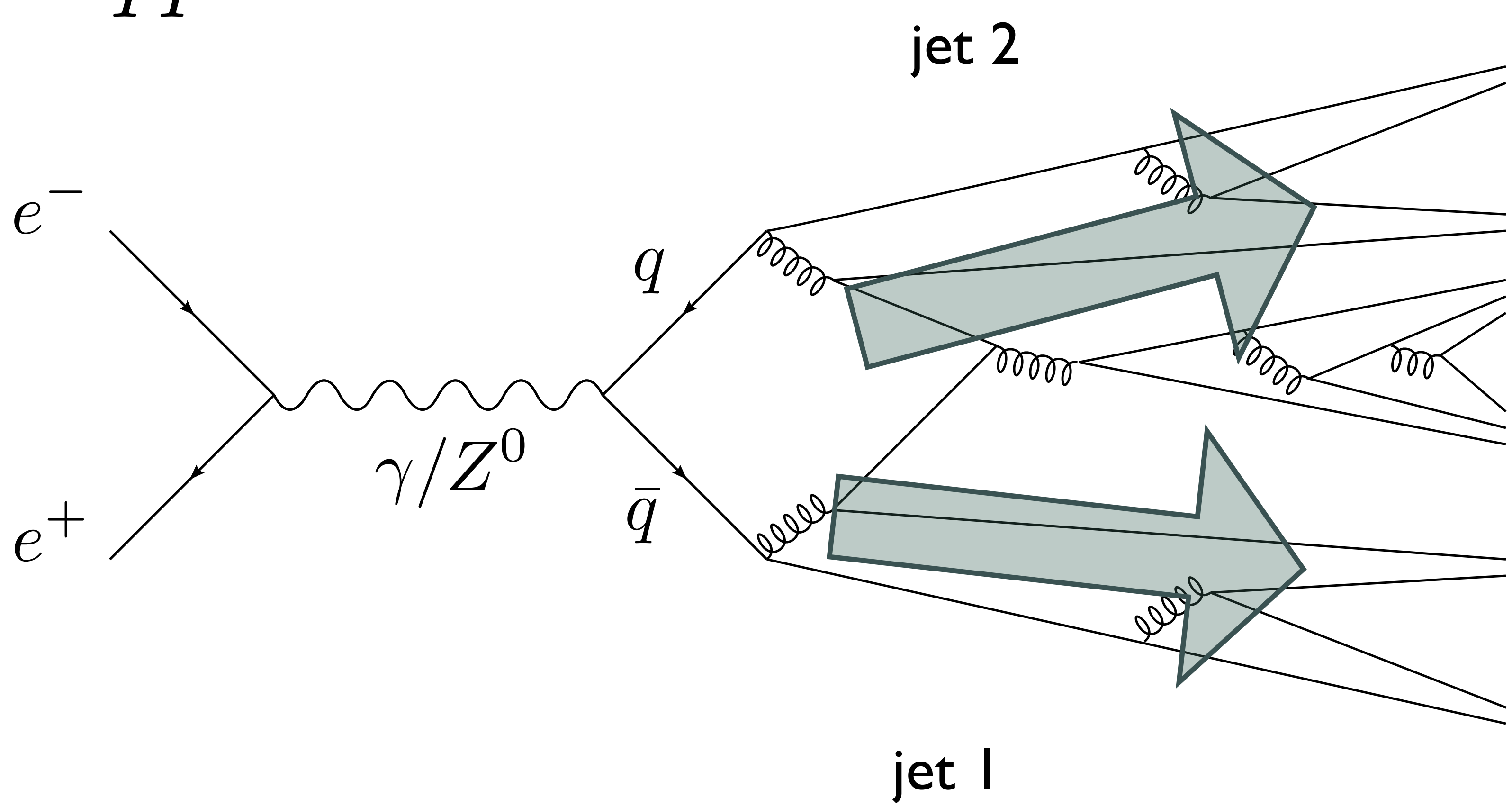

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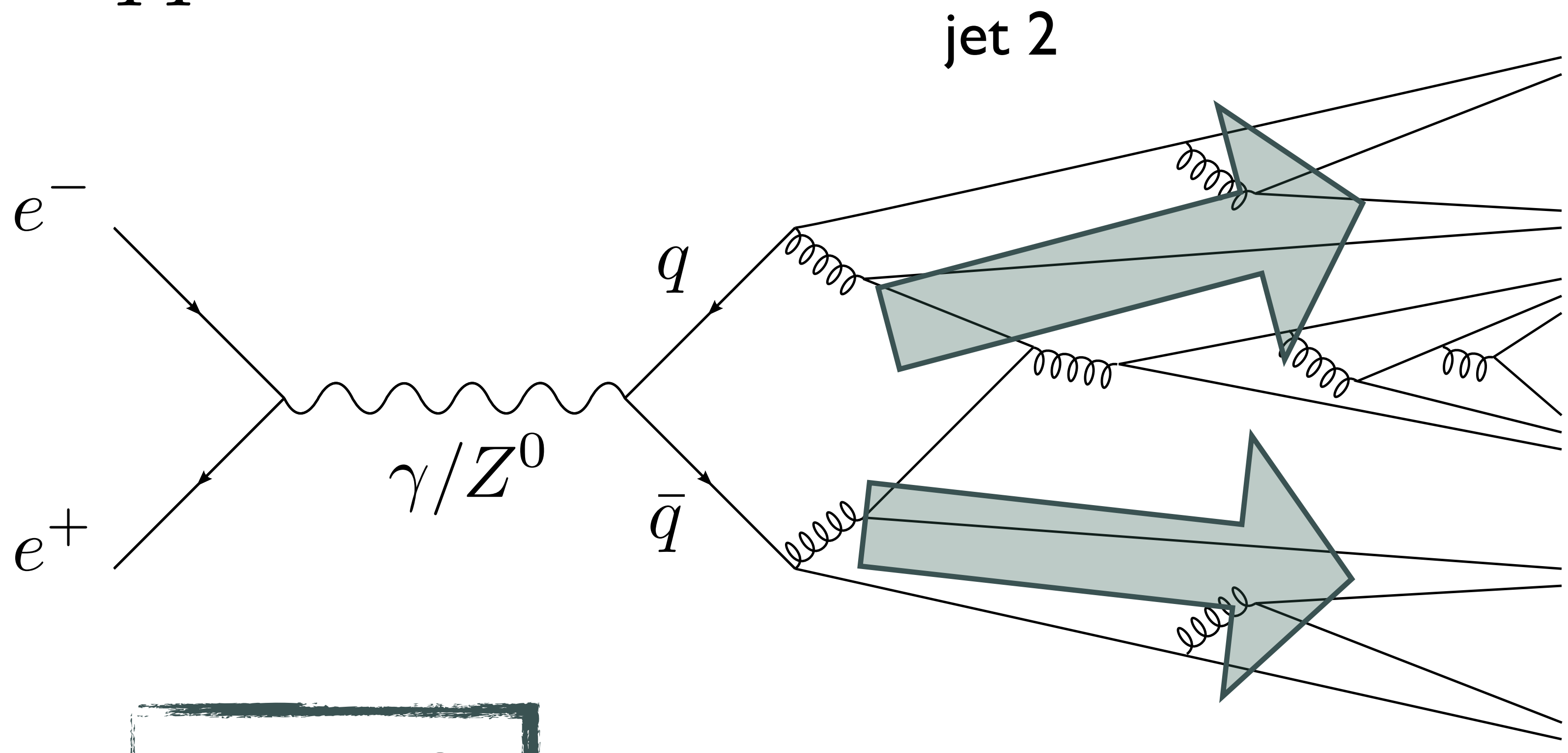

Jet ≅ FSP

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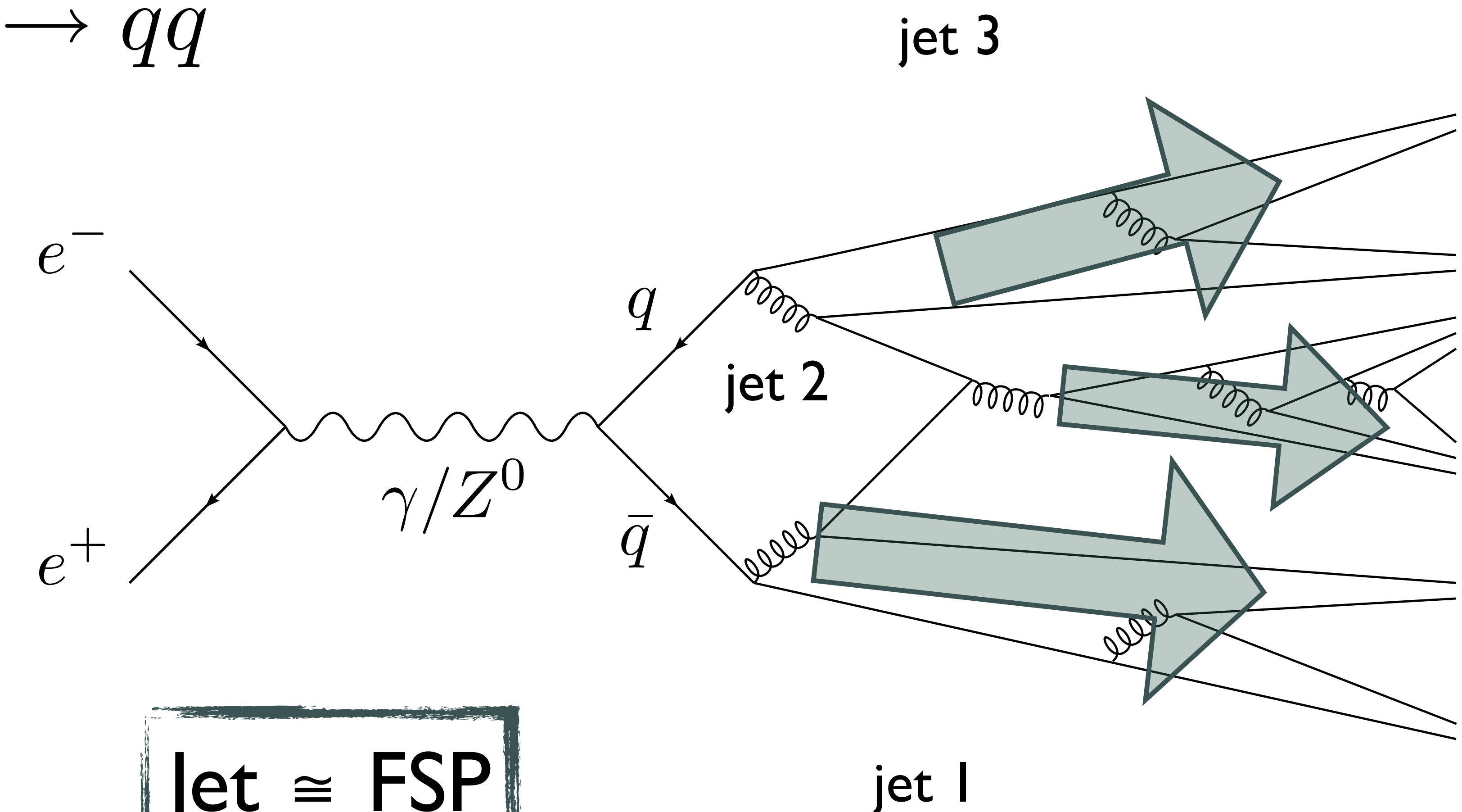
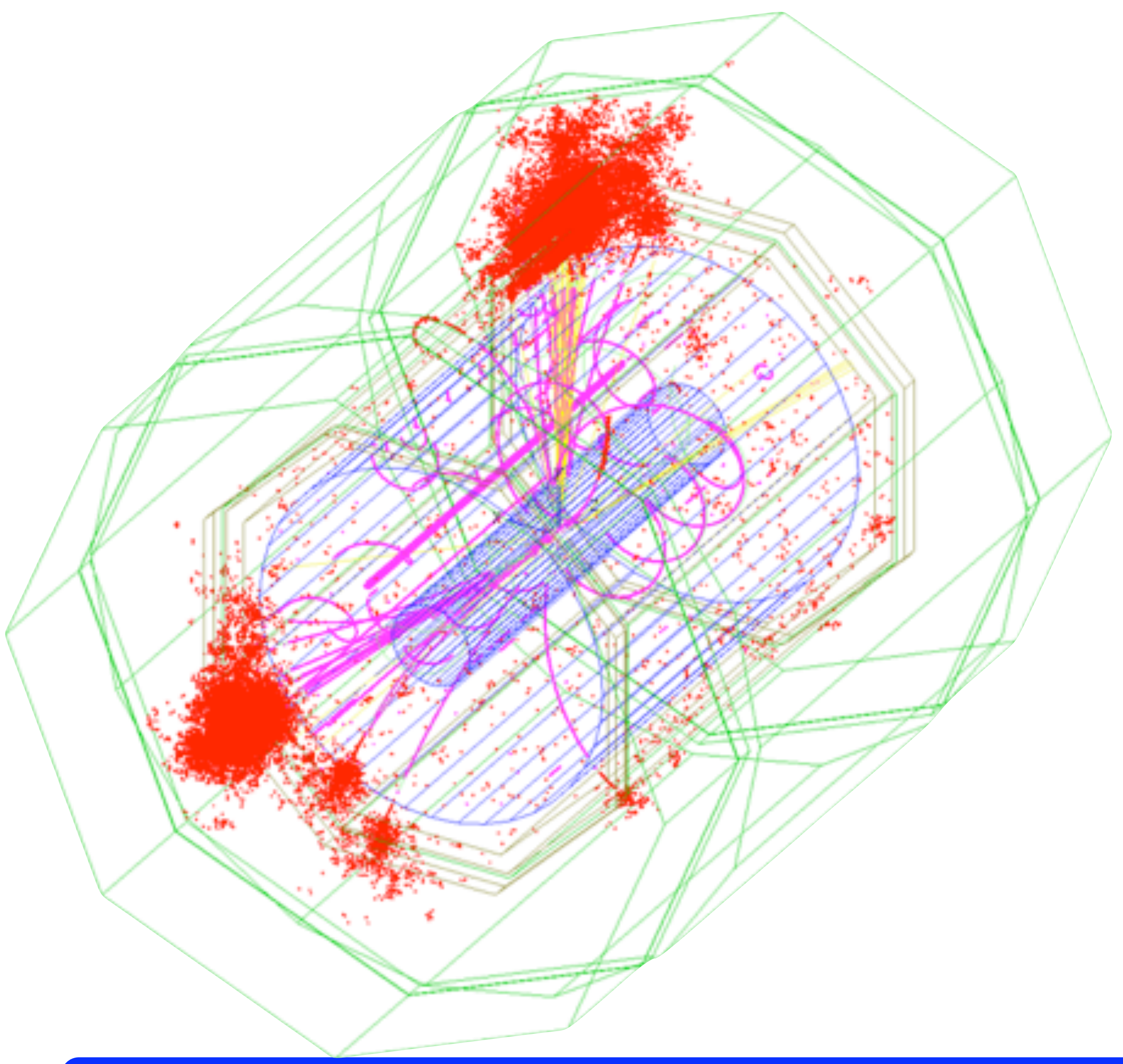


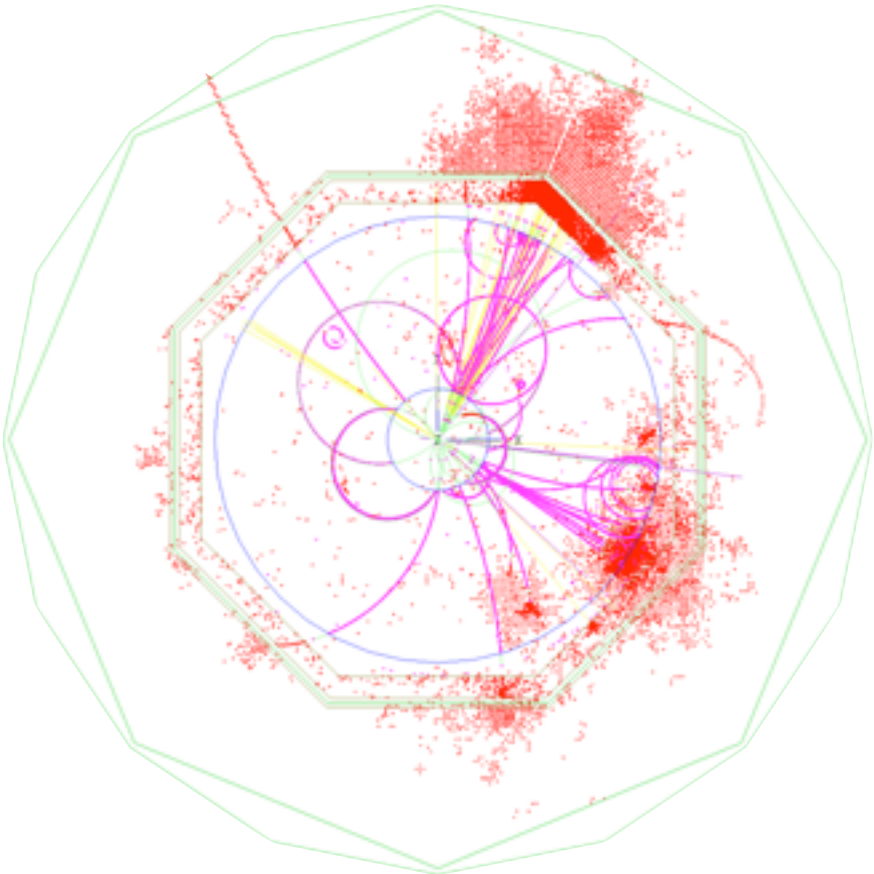
Jet ≅ FSP

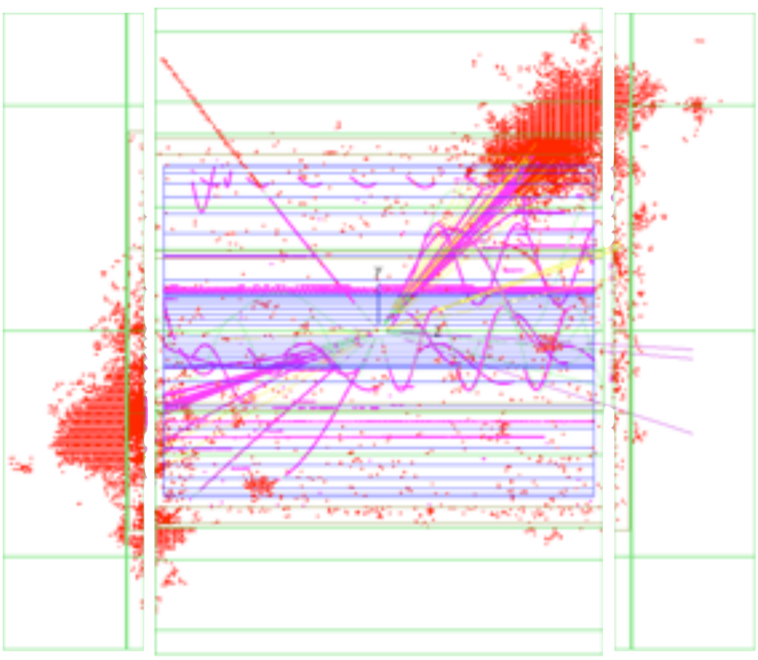
But: Each fragment can create additional fragments (e.g. gluon radiation)

How to find jets

$e^+e^- \to q\bar{q} + E_{\text{miss}}$







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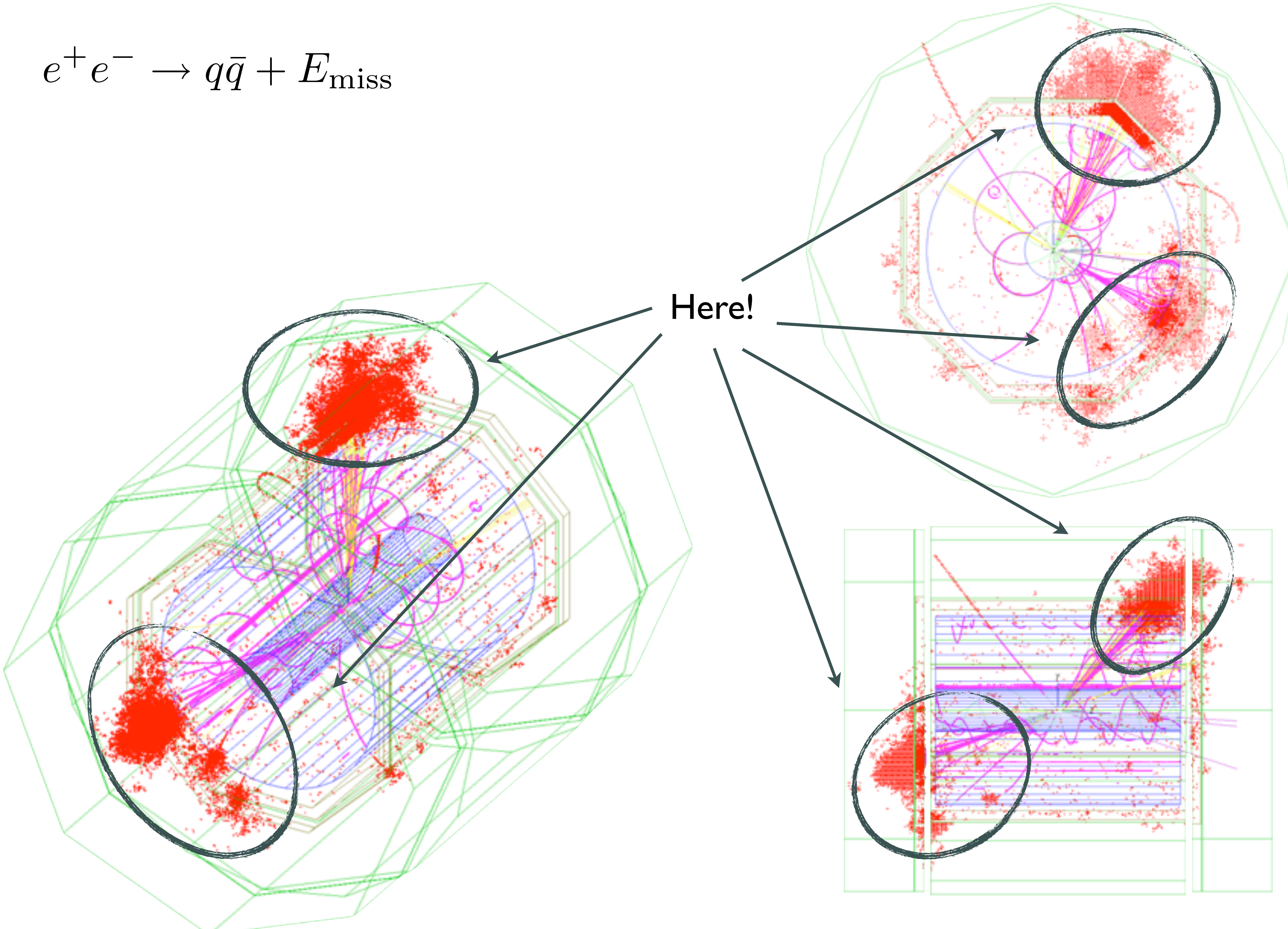

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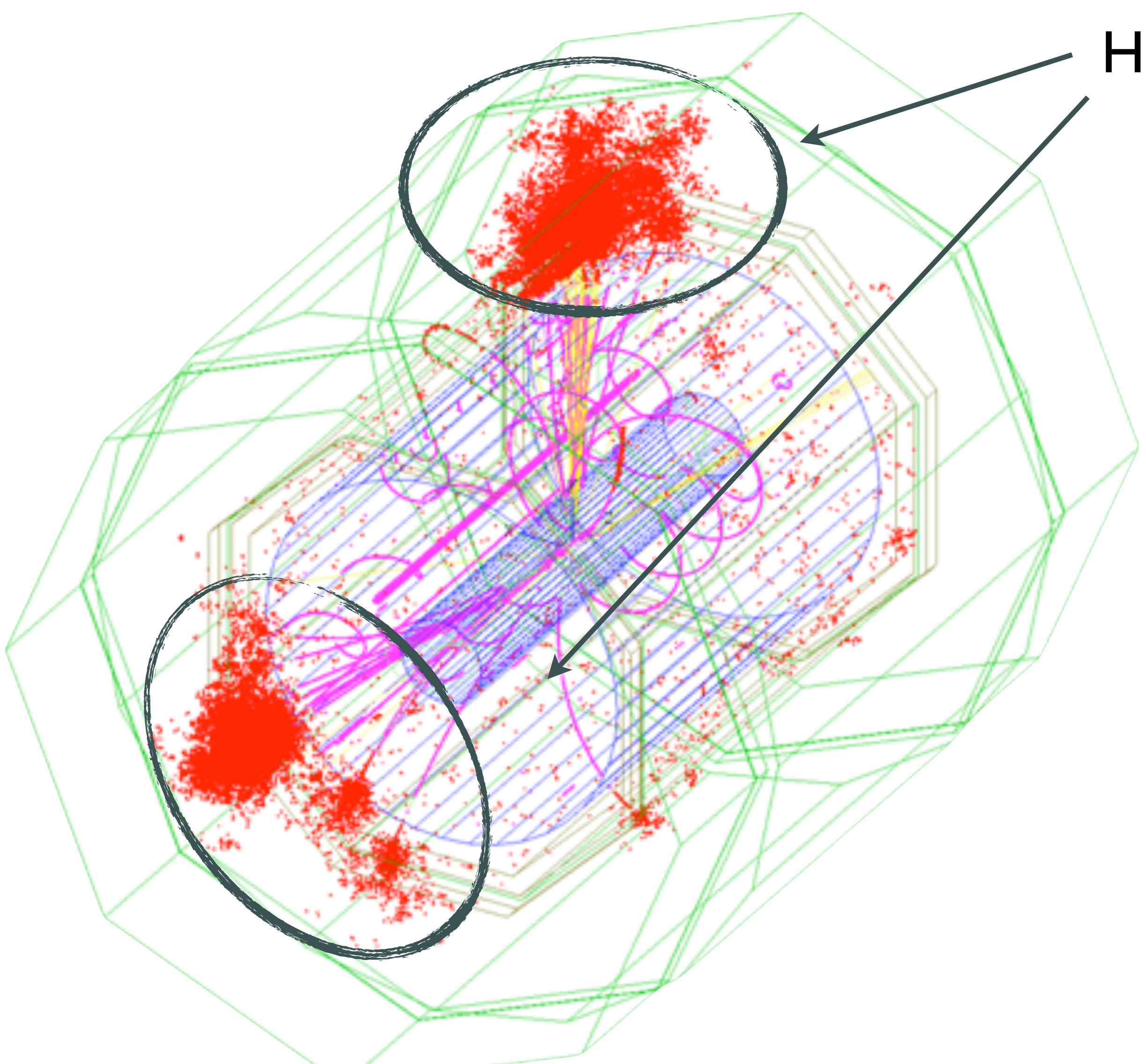
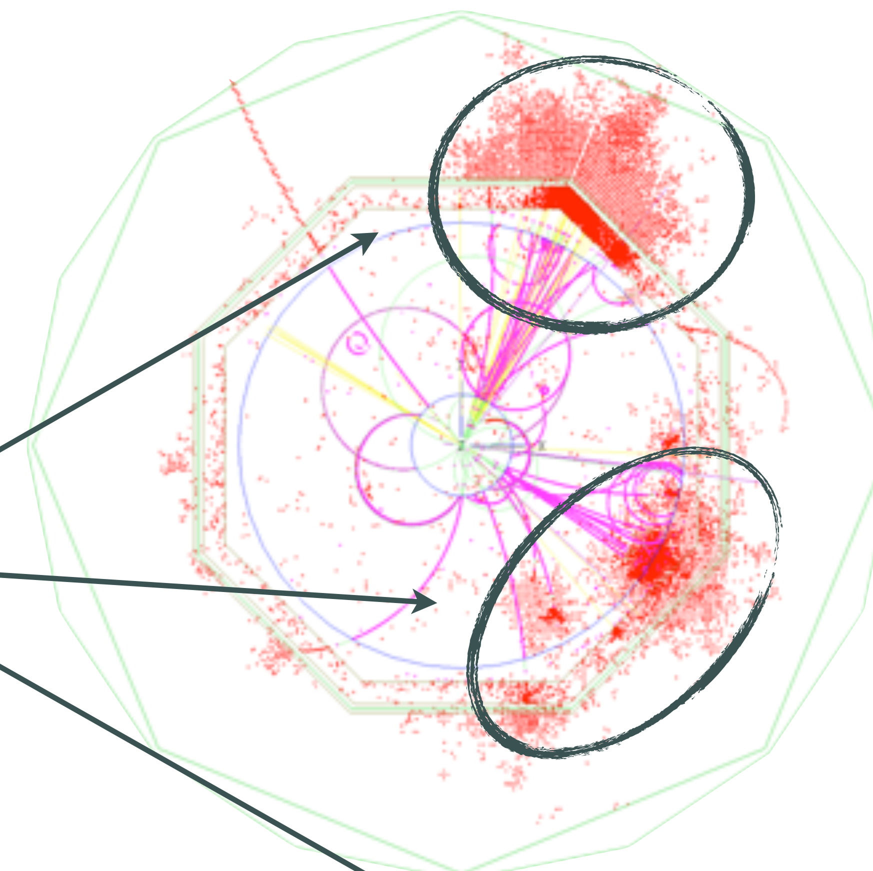
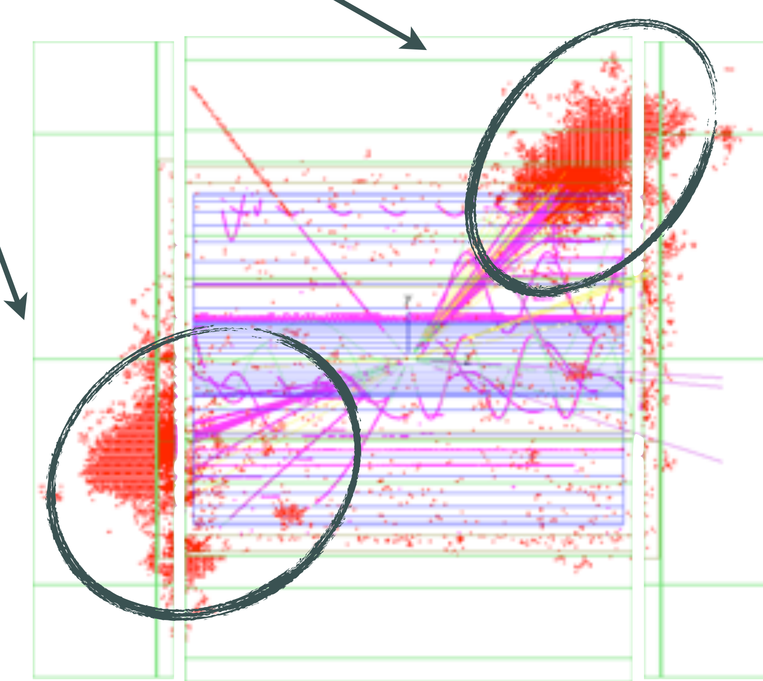
Computer: Algorithms



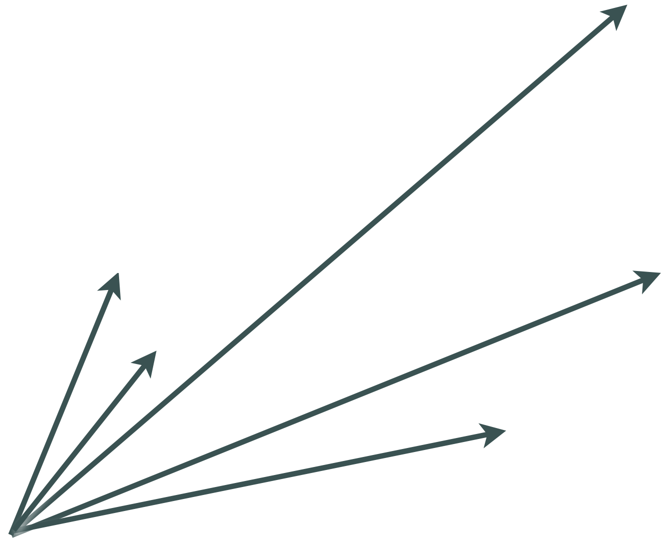
Here!





Geometric Jet Algorithm

- How to find Jets?
  - Jets consist of particles flying ≈ same direction
  - Most simple approach: Cone algorithm
- Example: Iterative Cone
  - Take high energy (or p_t) particle as seed
    - Collect all particles within cone of radius R
    - Calculate new cone/jet axis by 4-Vec addition
    - Recollect all particles around this axis
    - If particles before recollection = after recollection: declare jet as final
- Problem:
  - Collinear Safety
  - Infrared Safety



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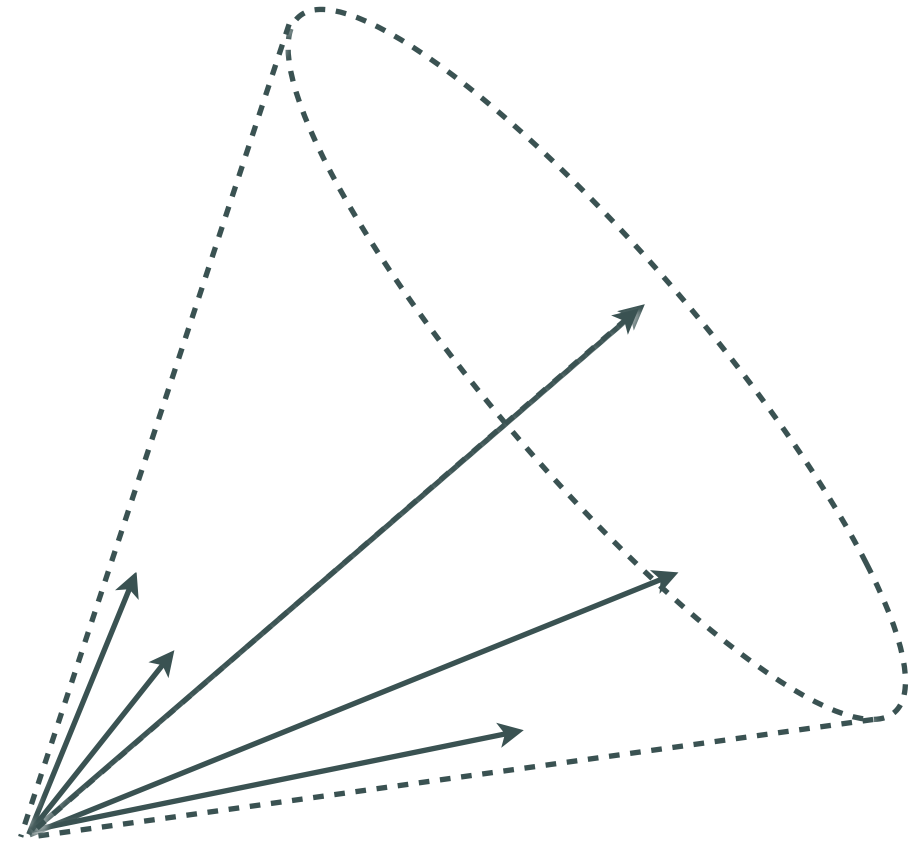

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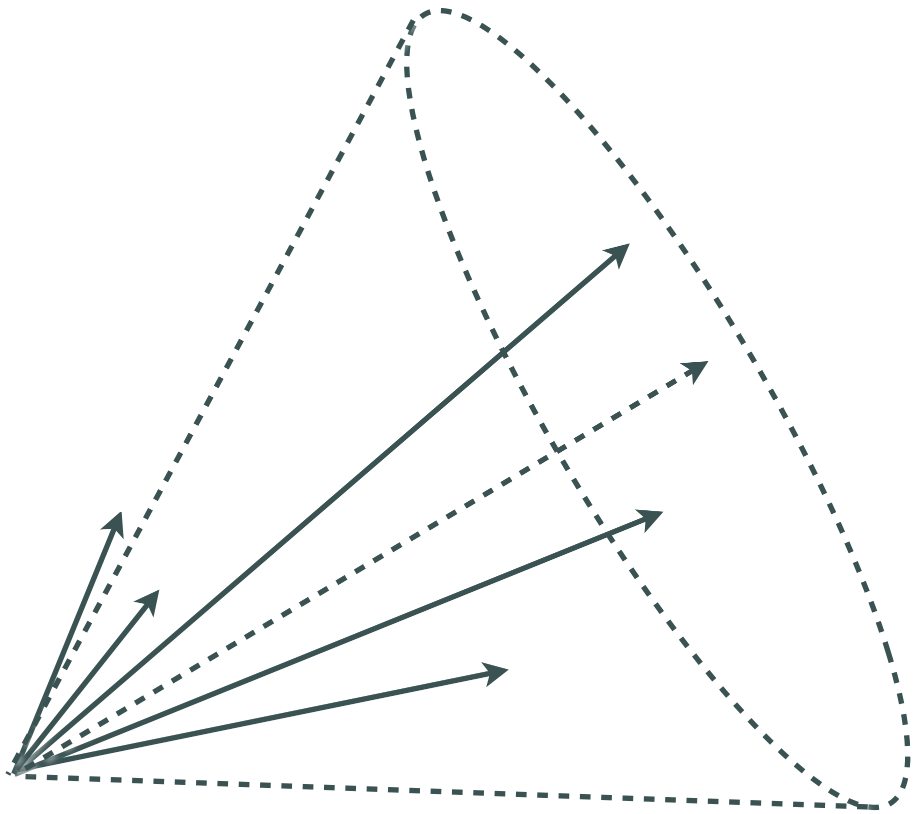

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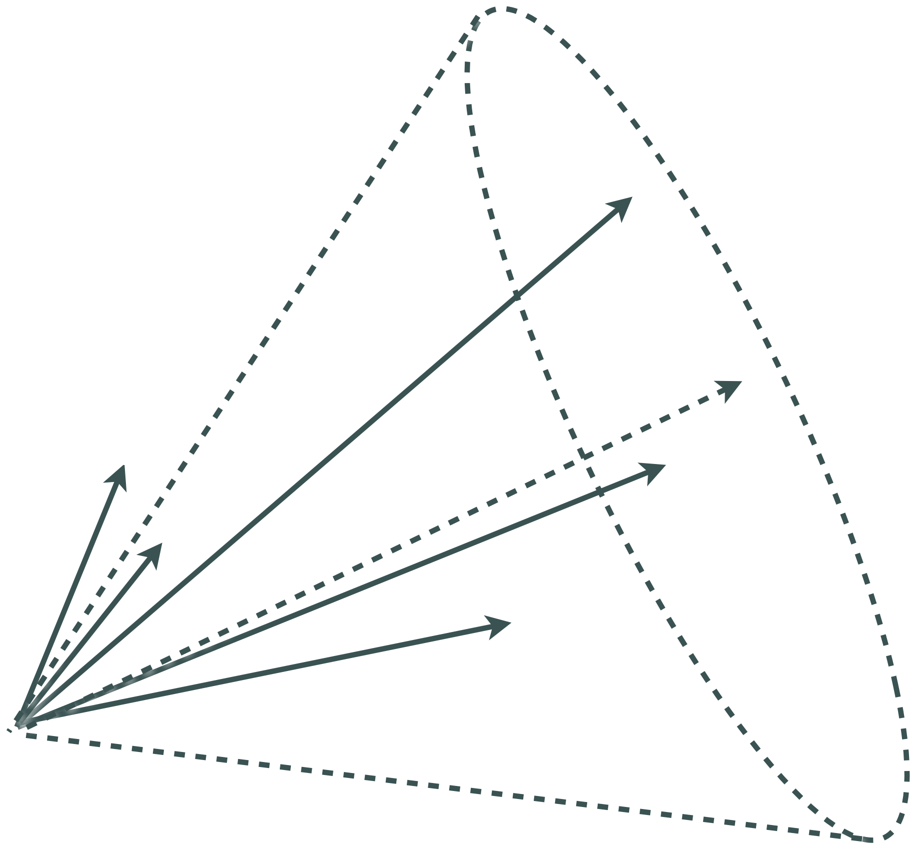
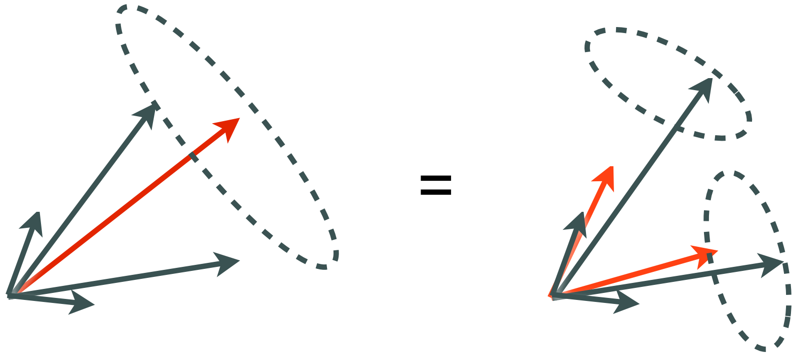
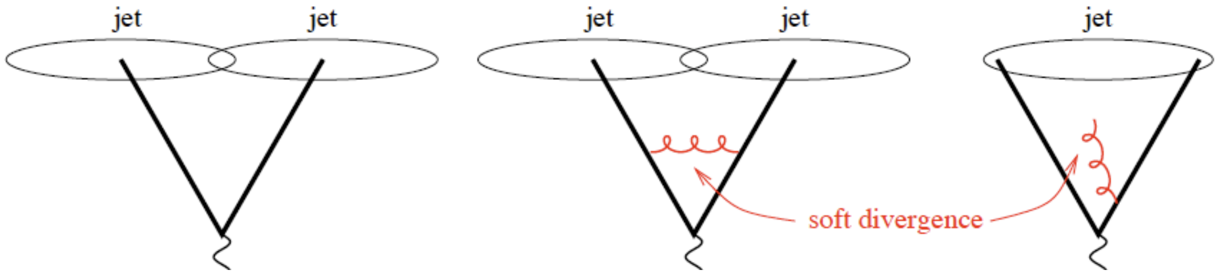


Jet algorithms: Collinear/Infrared Safety

- Collinear Safety
  - Decay (collinear split) of a jet particle must not change jets



- Infrared Safety
  - Adding of soft particles must not change jets



- Reason: At fixed-order pertubative QCD calculations:
  - Infinities at tree level
  - Infinities at loop level

  } Normally: Cancellation

  - Different jets for tree level and loop level
    - Crosssection $\rightarrow \infty$

more info:
arXiv: 0906.1833 [hep-ph]

- Implementation by G. Salam et al:
  Seedless Infrared Safe Cone: SISCone

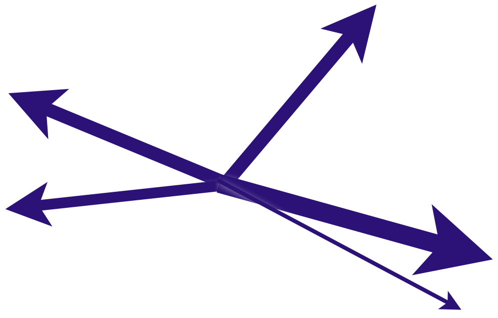
arXiv: 0704.0292 (hep-ph)

Recombination Jet Algorithm: Principle

- Recombination Algorithms
  - Merging of „close“ particles ⇒ Jets
  - IR/C safe
- Example: Durham/kT
  - One of the first Jet finding algorithms
- Principle:
  - Define „distance“ for each pair of reconstructed particles
  - Merge that pair of particles with smallest distance:

$$d_{ij} = (1 - \cos\theta_{ij}) \frac{2\min(E_i^2, E_j^2)}{s}$$

  - Redo until
    - Either $\min(d_{ij}) > d_{\mathrm{cut}}$
    - Alternatively: number of requested Jets is reached
  - Declare all remaining pseudo-particles as Jet



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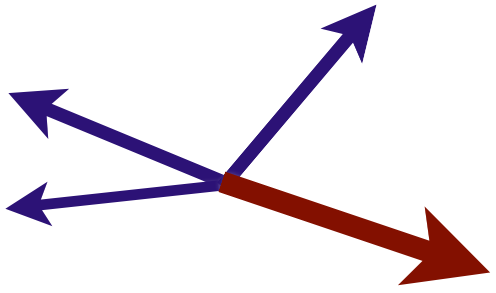

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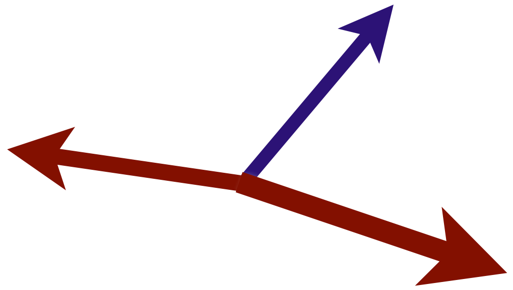

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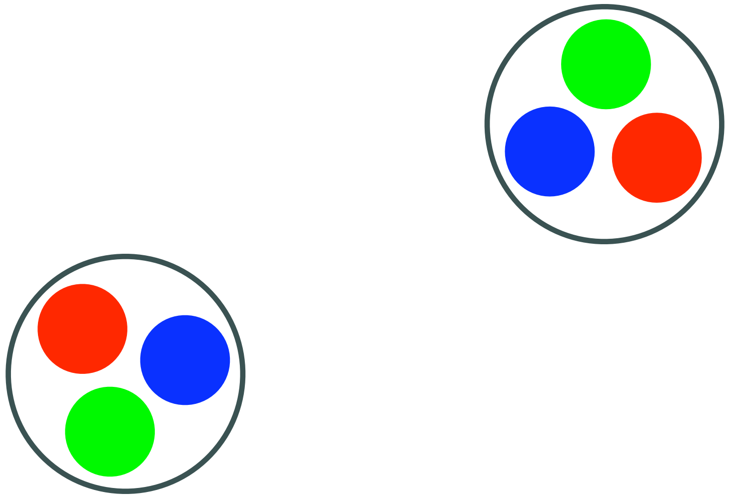
Recombination Jet Algorithm: Exclusive Mode



- Special case for hadron colliders:
  - Collision with Partons only
  - Proton Remnants ⇒ Jets in forward region
- Exclusive Mode in Recombination Jet Algorithms:
  - Introduces „beam-jets“
  - Each particle close to beam: merge into beam jet (= discard)
  - For „clean“ e^+e^- colliders: Useful to reject Background in forward region

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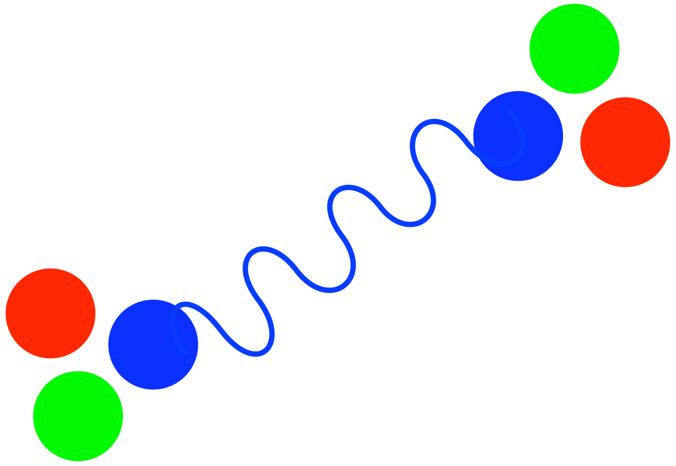

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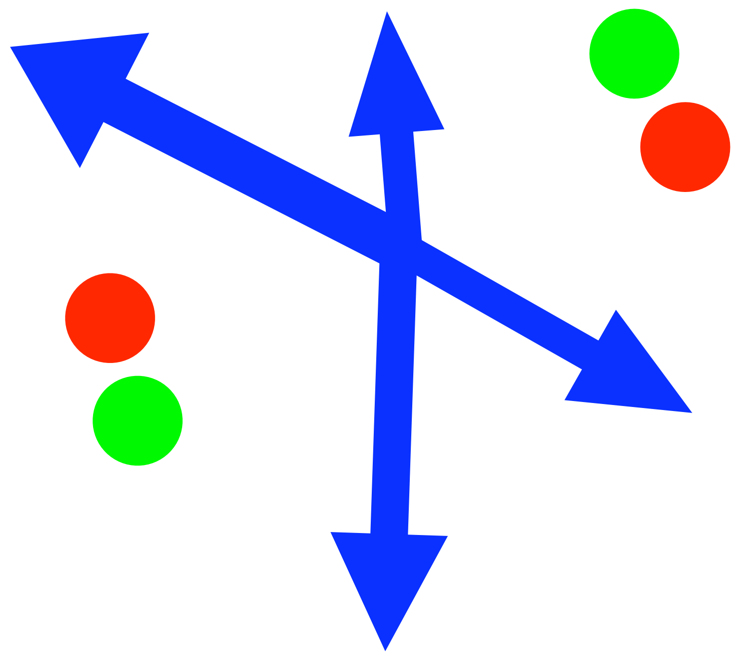

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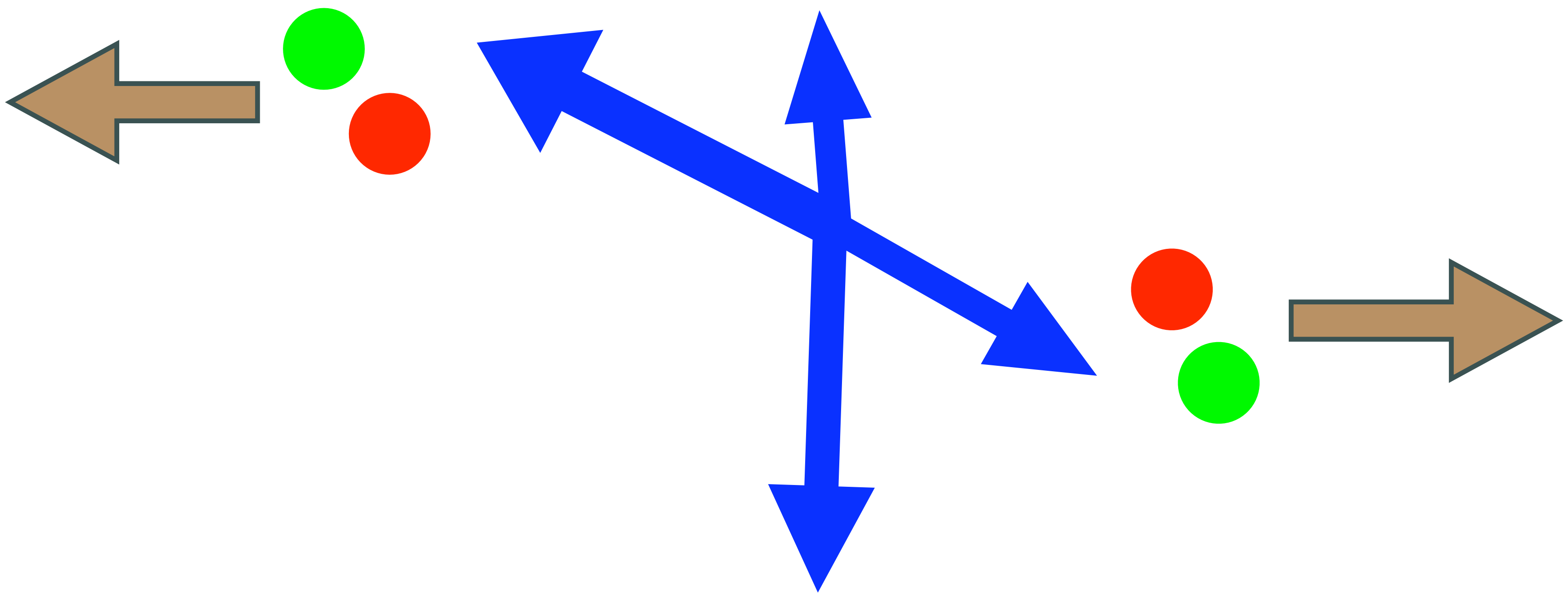

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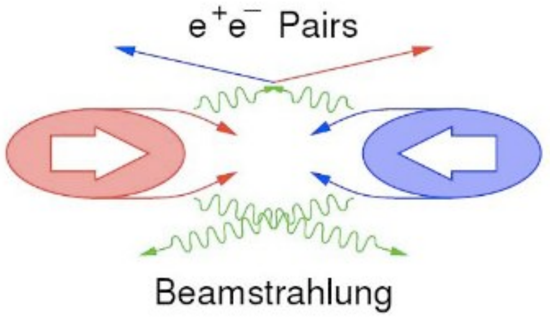
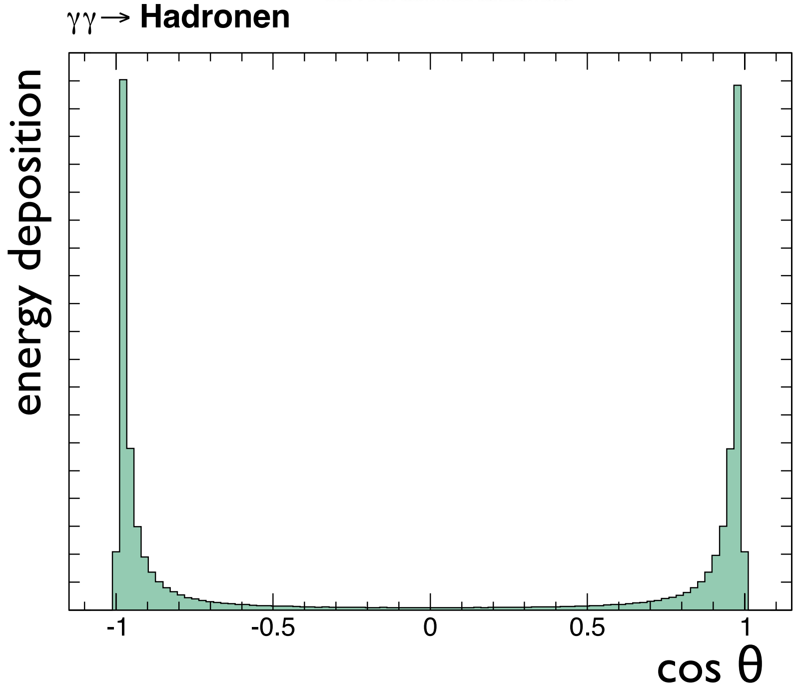
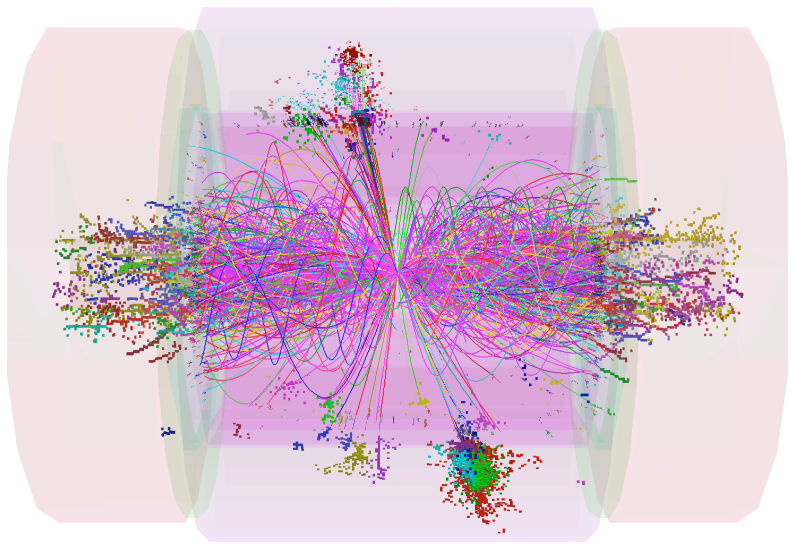
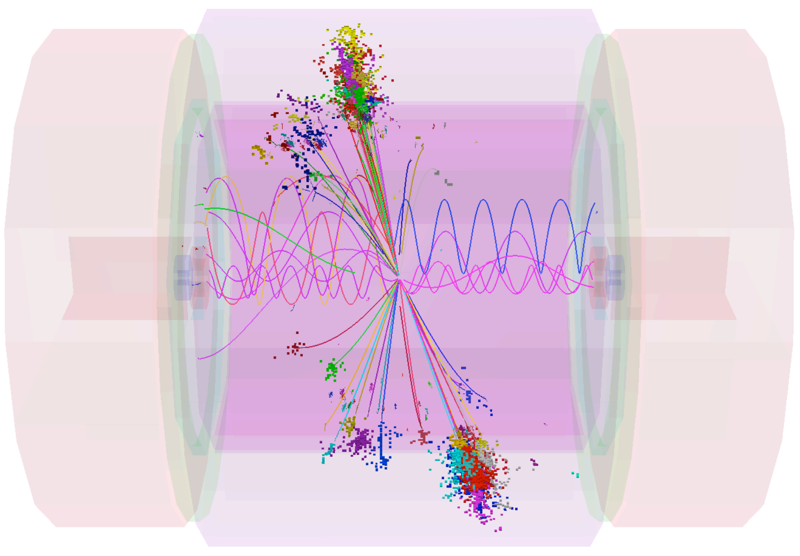
Jet algorithms as Background rejector







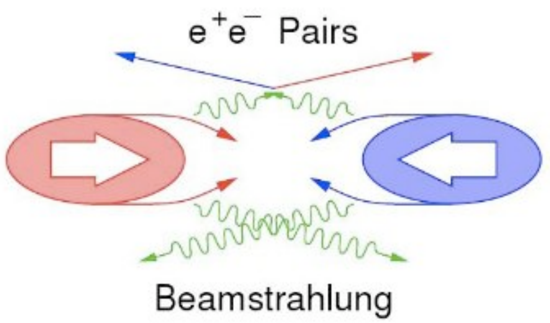
before Timing Cuts:
1.4 TeV

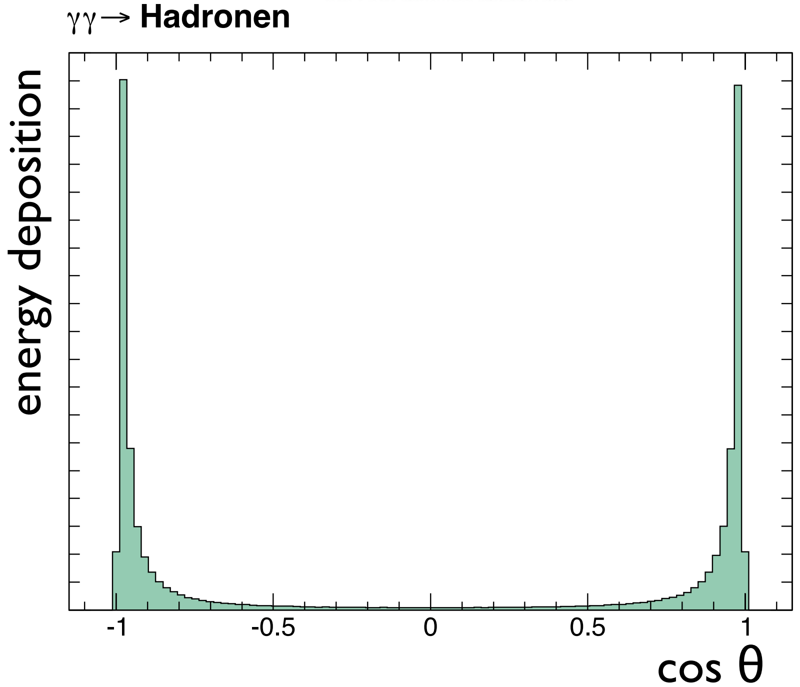


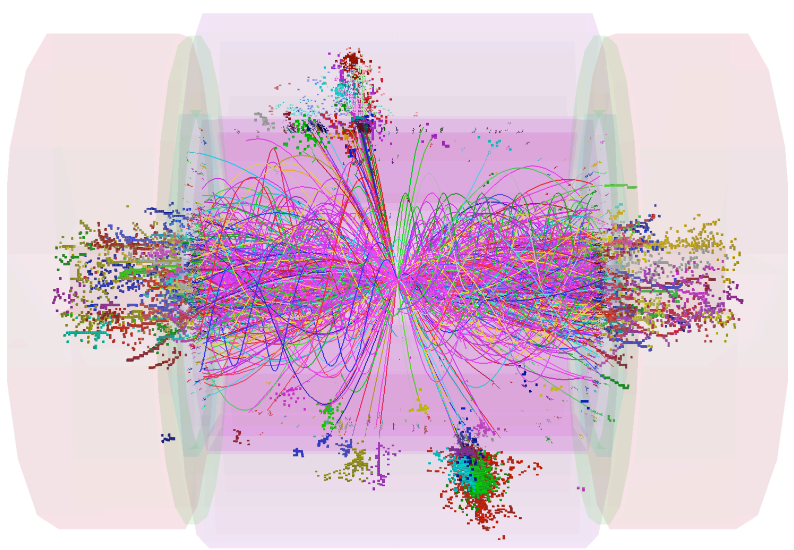
after Timing Cuts:
0.2 TeV

Jet algorithms as Background rejector

- The „clean“ CLIC environment:
  - no Underlying Event / CMS known / ...
  - Still: Beam induced Background at each event: $\gamma\gamma \rightarrow$ Hadrons
    - Peaks in forward region
  - Repetition rate of 0.5ns between two Bunch Crossings
    - Detector much slower ⇒ „Pile-Up“
    - Event selection via sophisticated Time-Stamping + Cuts







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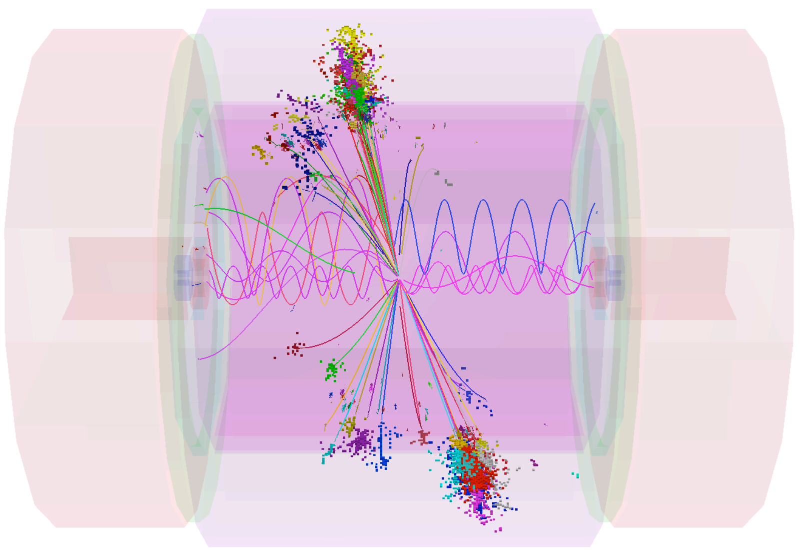

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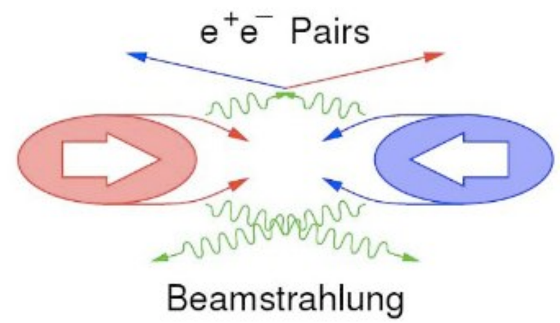
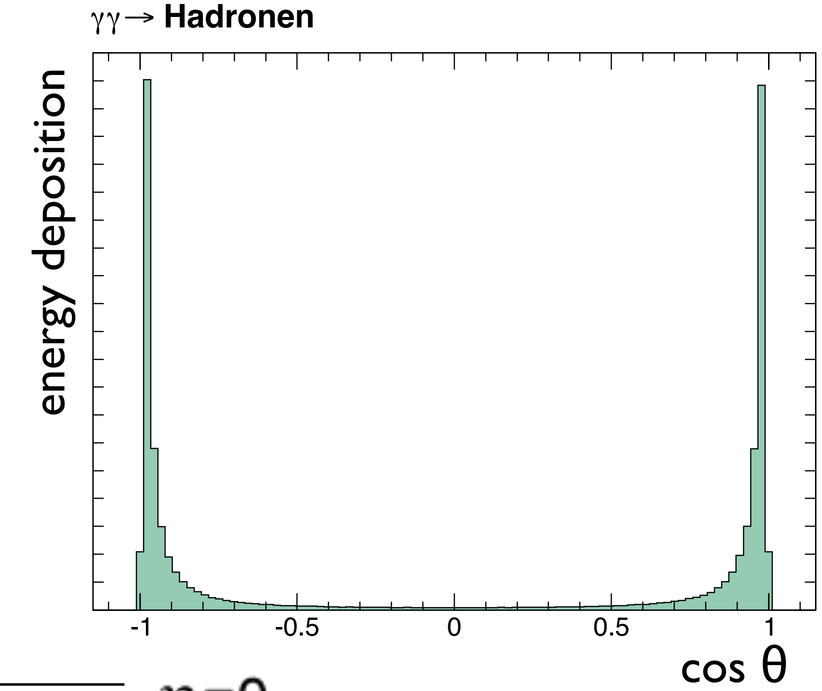
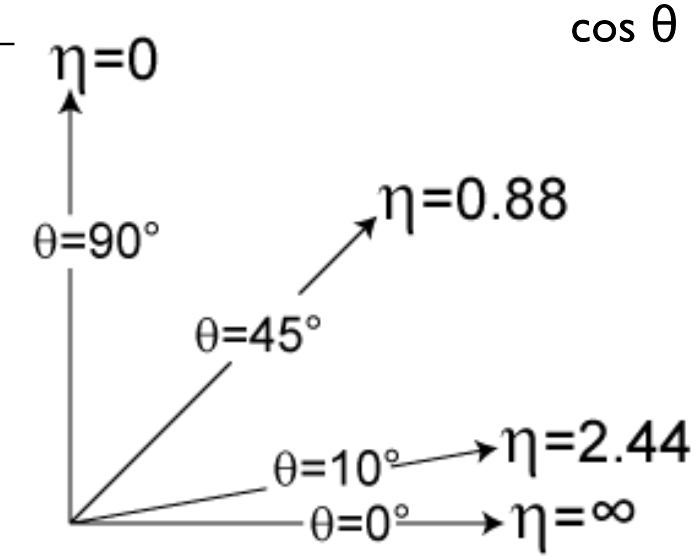




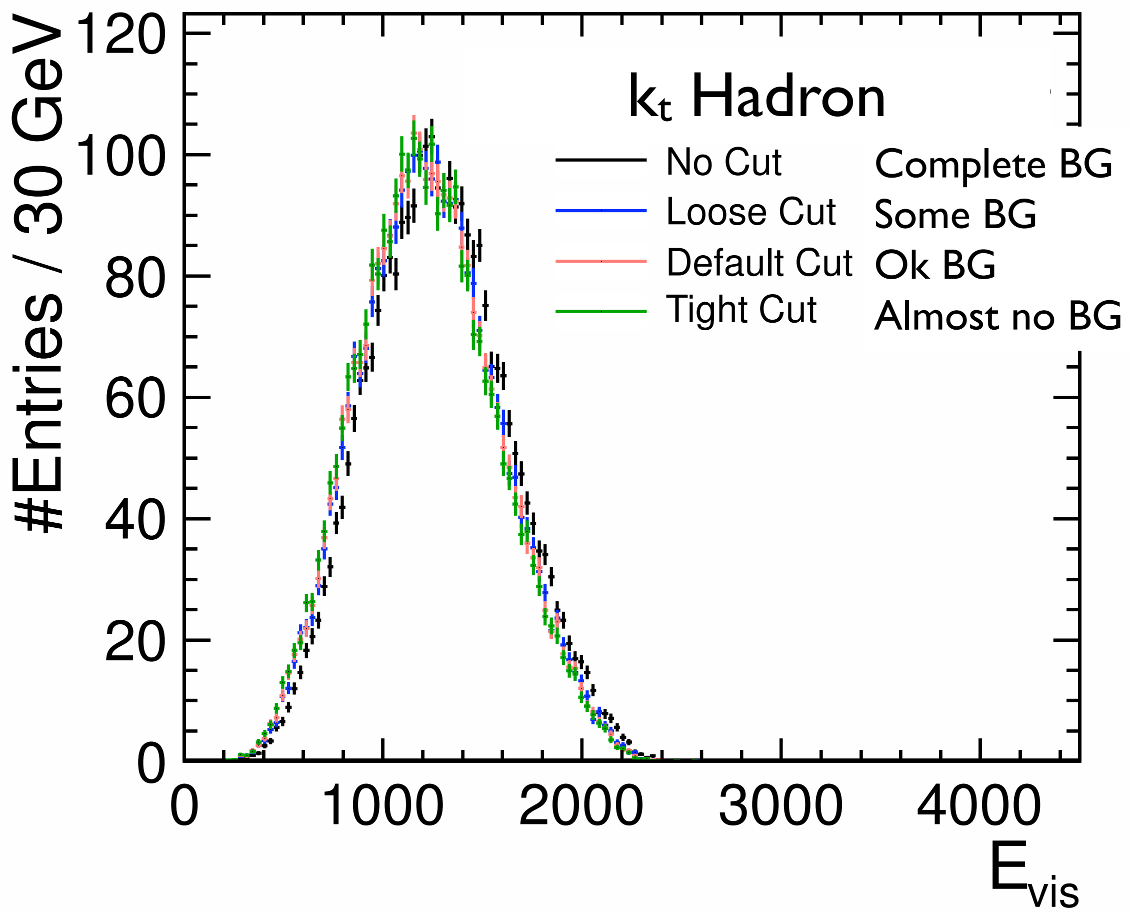
- Different k_t - Algorithms:

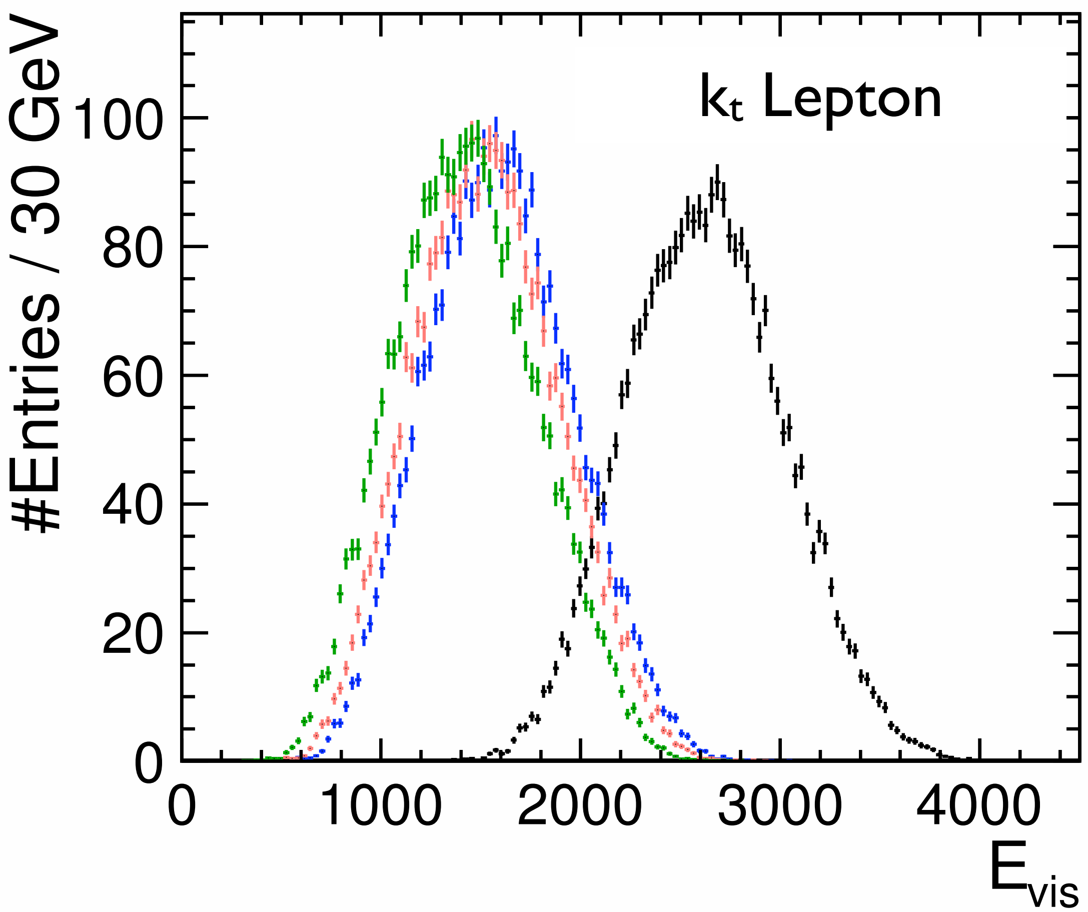
Name	Distance $d_{ij} \propto$	Remark
Lepton	$\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$	θ_{ij} : Angle
Hadron	$\min(k_{t,i}^2, k_{t,j}^2)(\phi_i-\phi_j)(\eta_i-\eta_j)$	η : Pseudorapidity



  - Pseudorapidity invariant under Boost along z-axis
    - „Stretches“ forward region

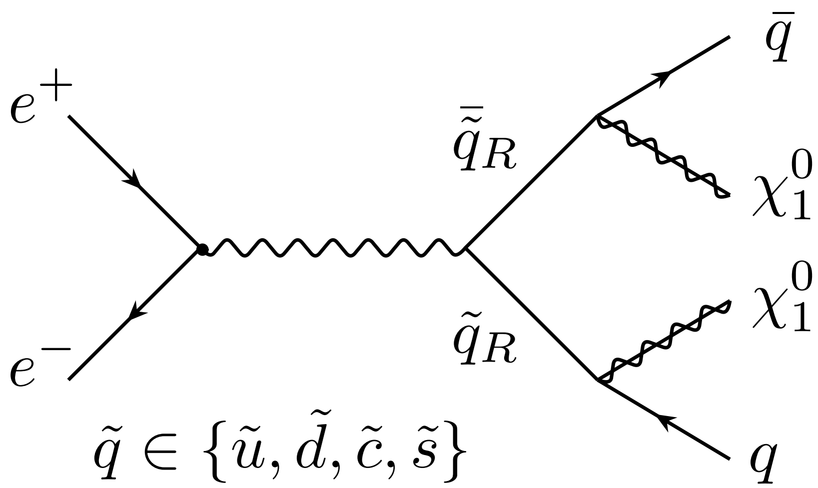
Jet algorithm as Background rejector (2)





- Different Timing Cuts indicate amount of yy-hadron Background in forward region
  - No cut: entire Background
  - Tight cut: reduced significantly
- Lepton k_t: Picks up almost complete yy-hadron Background
- Hadron k_t: Even without timing cuts no severe changes to distribution

The Process + Background



$$e^+e^- \rightarrow \tilde{q}_R\tilde{\bar{q}}_R$$

$$\tilde{q}_R \xrightarrow{99.7\%} q + \chi_1^0$$

	Final State	σ
Signal	qqχχ (u,d,s,c)	~ 1.45 fb
SM	qq	~ 3000 fb
	qqee	~ 3300 fb
SM E_{miss}	qqνν	~ 1500 fb
	qqeν	~ 5300 fb
	ττνν	~ 130 fb
SUSY	qqννχχ	~ 1.0 fb
	qqlνχχ	~ 8.5 fb
	qqllχχ	~ 0.6 fb

} no E_{miss} (SM: qq, qqee)

} dominant BG (SM E_{miss}: qqνν, qqeν, ττνν)

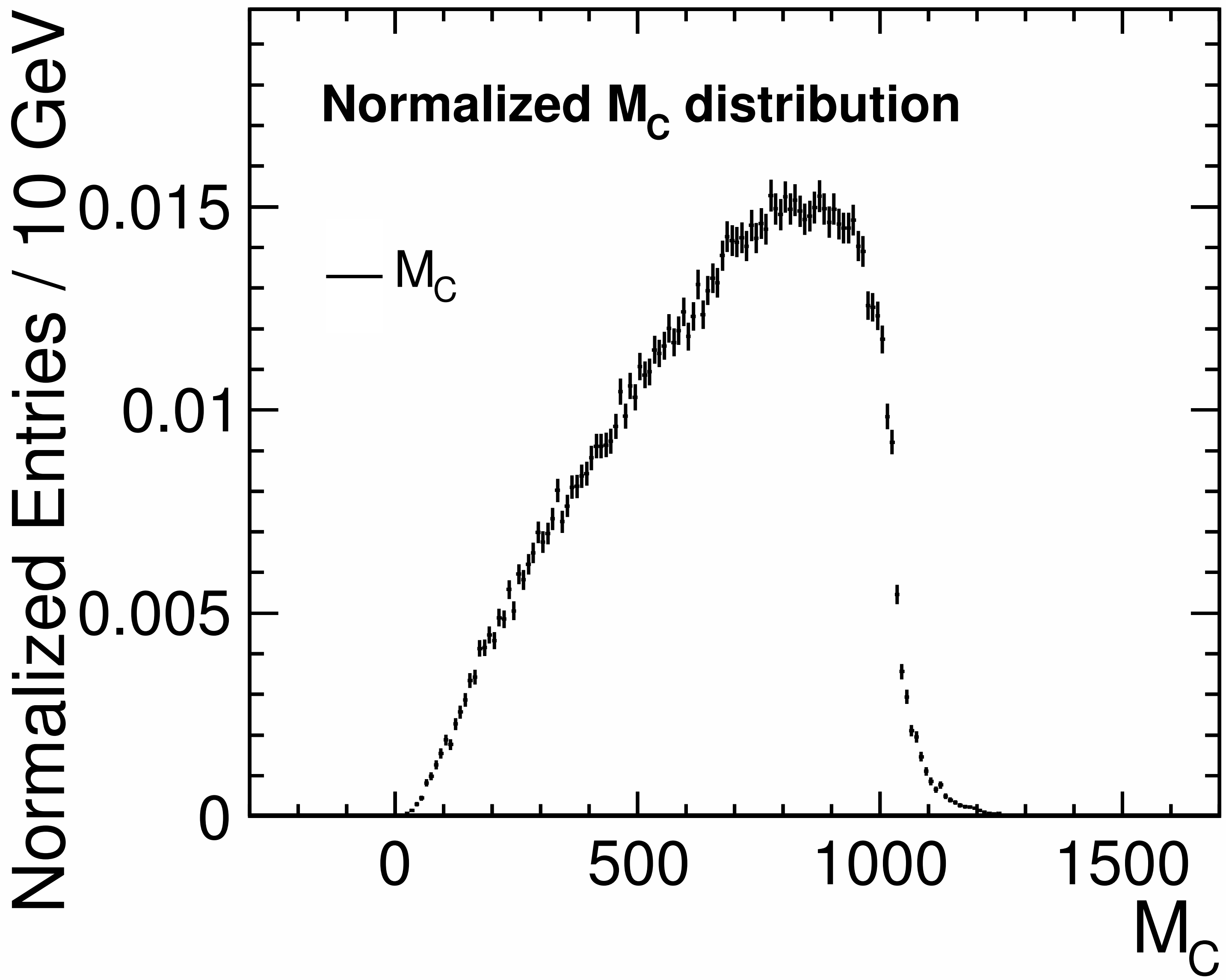
- Signal Process signature:
  - 2 Jets + E_{miss}
- Background
  - Dominated by SM Neutrino Processes
  - Crosssection 3-4 orders higher!

- Good Background rejection needed
  - first step: p_t > 600 GeV
  - ➡ only SM E_{miss} relevant

Measurement Techniques: Mc

$$M_C^2 = (E_1 + E_2)^2 - (\vec{p}_1 - \vec{p}_2)^2$$
$$= 2(E_1 E_2 + \vec{p}_1^2 \vec{p}_2^2)$$

- Modification of invariant Mass
- Use @ LHC as transversal variant
- Neutralino mass has to be known
- Squark mass extraction:
  - Formula (using the upper edge)
  - Template Fit (used in this analysis)

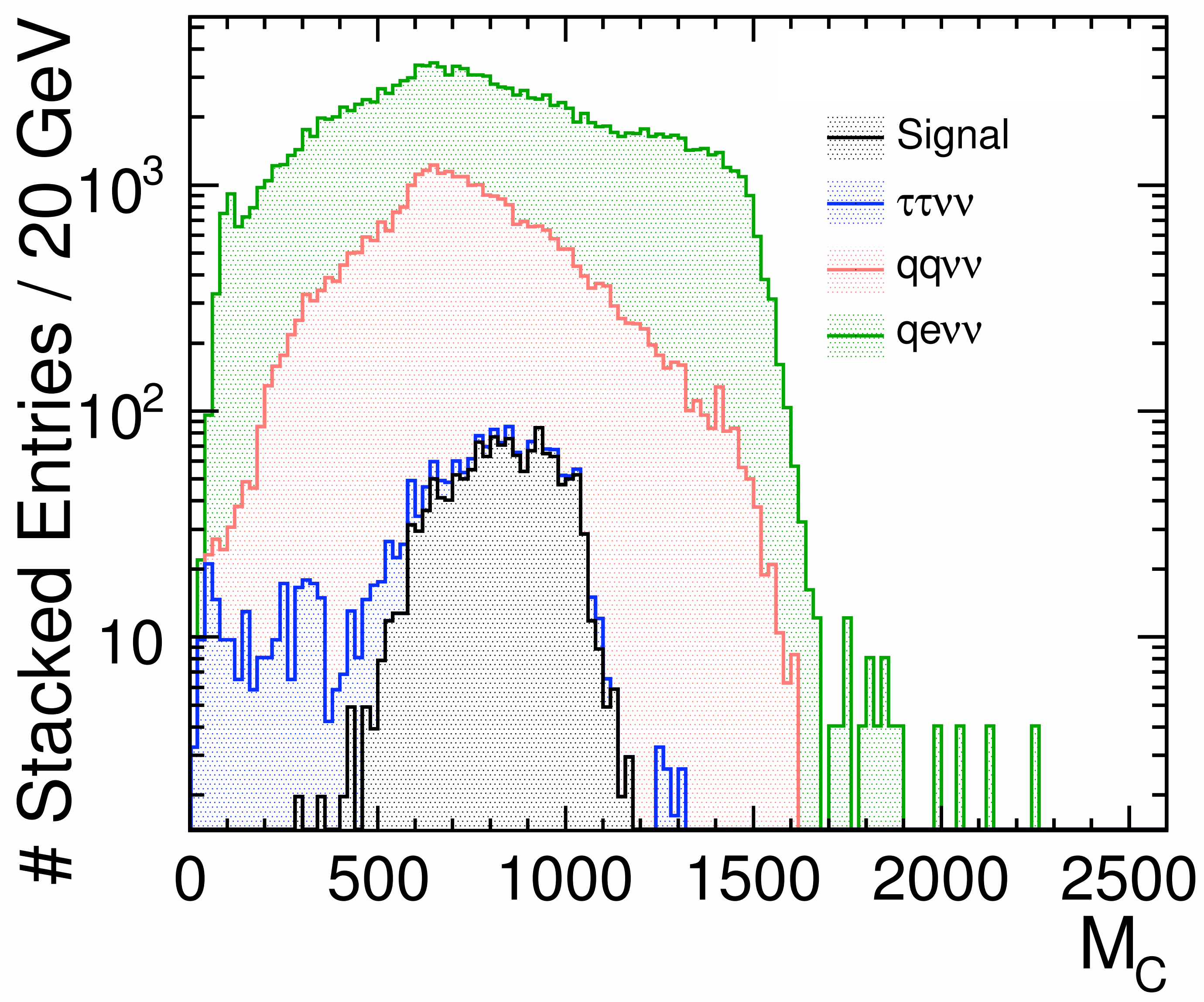


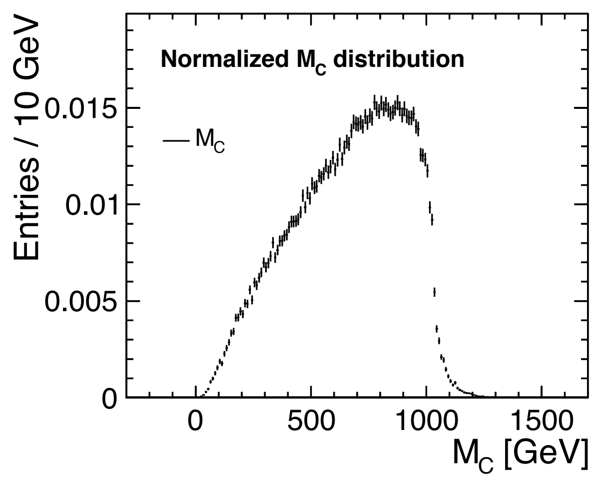
$$M_{C,\max} = \frac{m_{\tilde{q}}^2 - m_\chi^2}{m_{\tilde{q}}}$$

Mc: Signal plus Background

- After full reconstruction: p_t > 600GeV
  - ⇒ S/B = 1/1000
- Background rejection needed
  - Cut based
    - 1D Cuts on various distributions (e.g. E_{vis}, Jet angle,/energy, ...)
    - prooved inefficient
  - Multi dimensional Analysis
    - Boosted Decision Trees

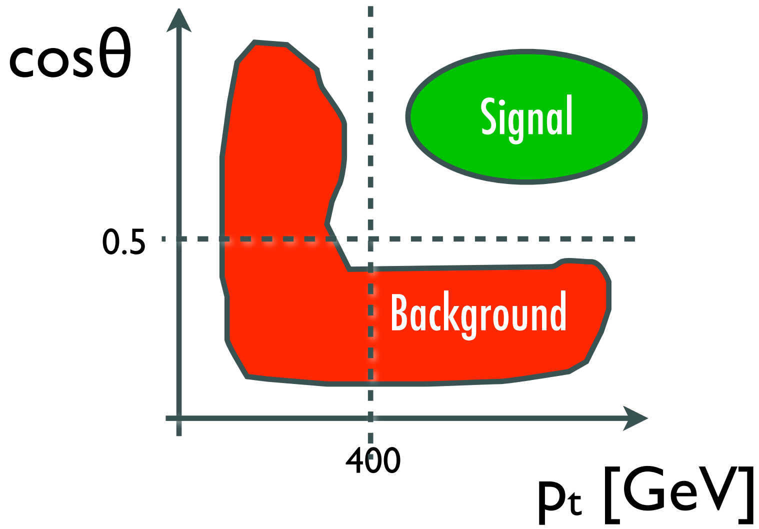
p_t>600GeV	# Events
Signal	1430
Background	145000

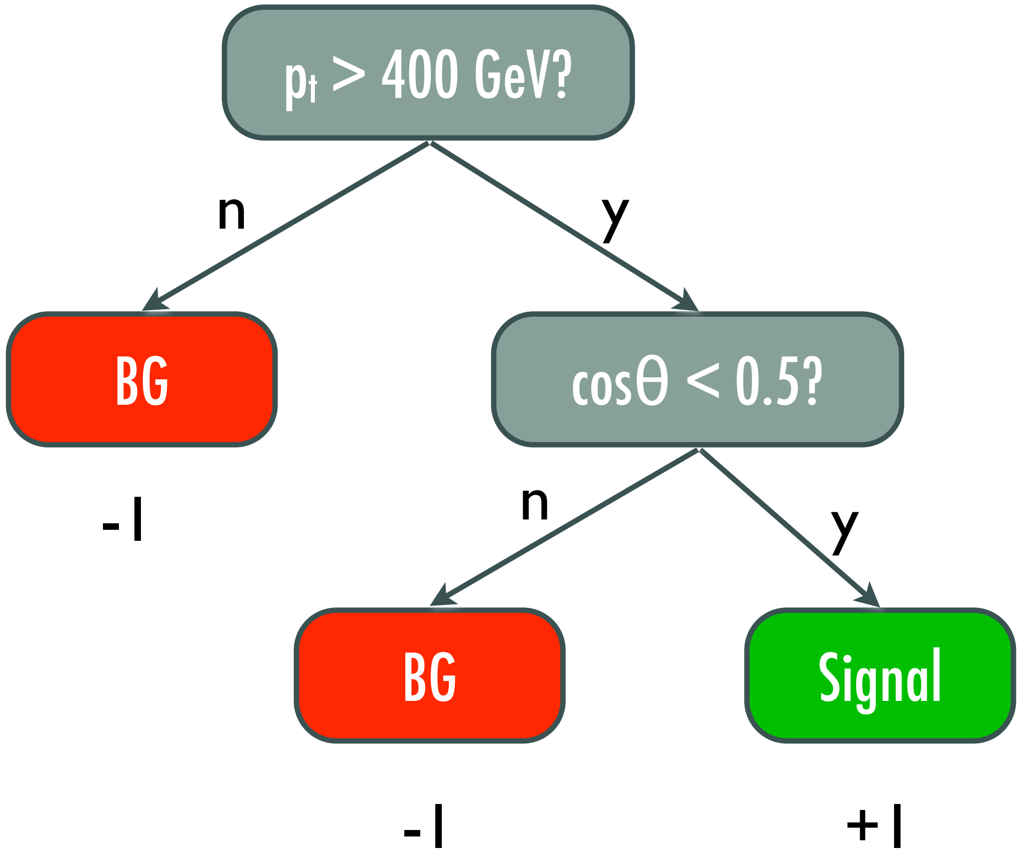




Event Classification: Boosted Decision Trees

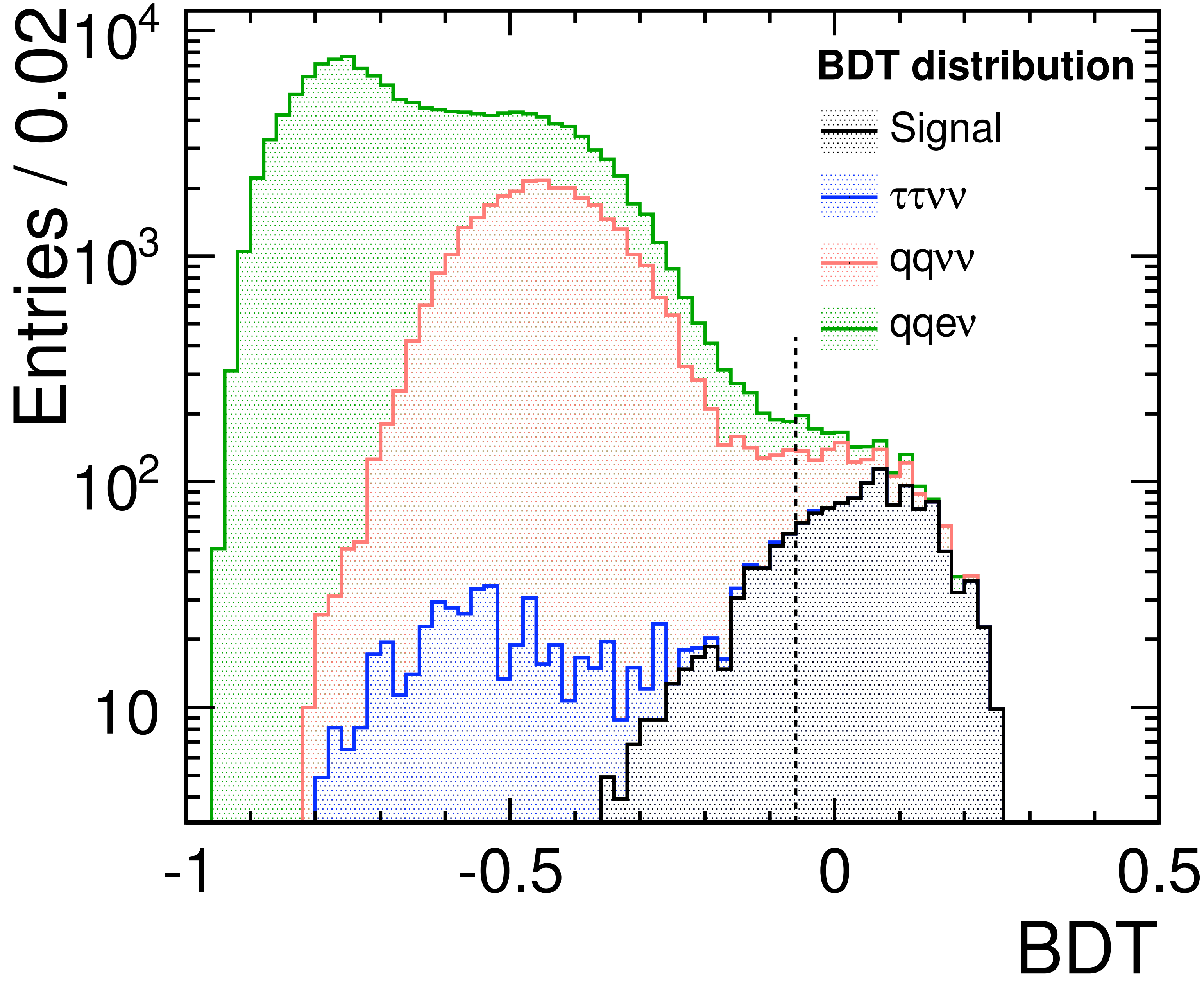
- Decision trees are used for general classification
  - here: Signal (+1) vs Background (-1)
- „Weak Learner“:
  - Gives better results than flipping a coin
- Boosting: (⇒ „Strong Learner“)
  - Tree building requires training sample
    - Choose cut with maximum splitting of BG/Signal
  - Apply trees on sample:
    - Check if classification was correct
    - Weight misclassified events higher in next step
  - Build next tree
  - ➡ Forest of Trees
    - Classification via majority vote:
    - ➡ single variable BDT ∈ [-1;+1]





Background rejection: Boosted Decision Trees

- Background rejection with Boosted Decision Trees:
  - Framework: TMVA (ROOT package)
  - Splitting Data into 2 independent samples:
    1. Training and Testing
    2. Analysis
- Used BDT Cut
  - BDT > -0.05
  - $S/\sqrt{S+B} \approx 25$



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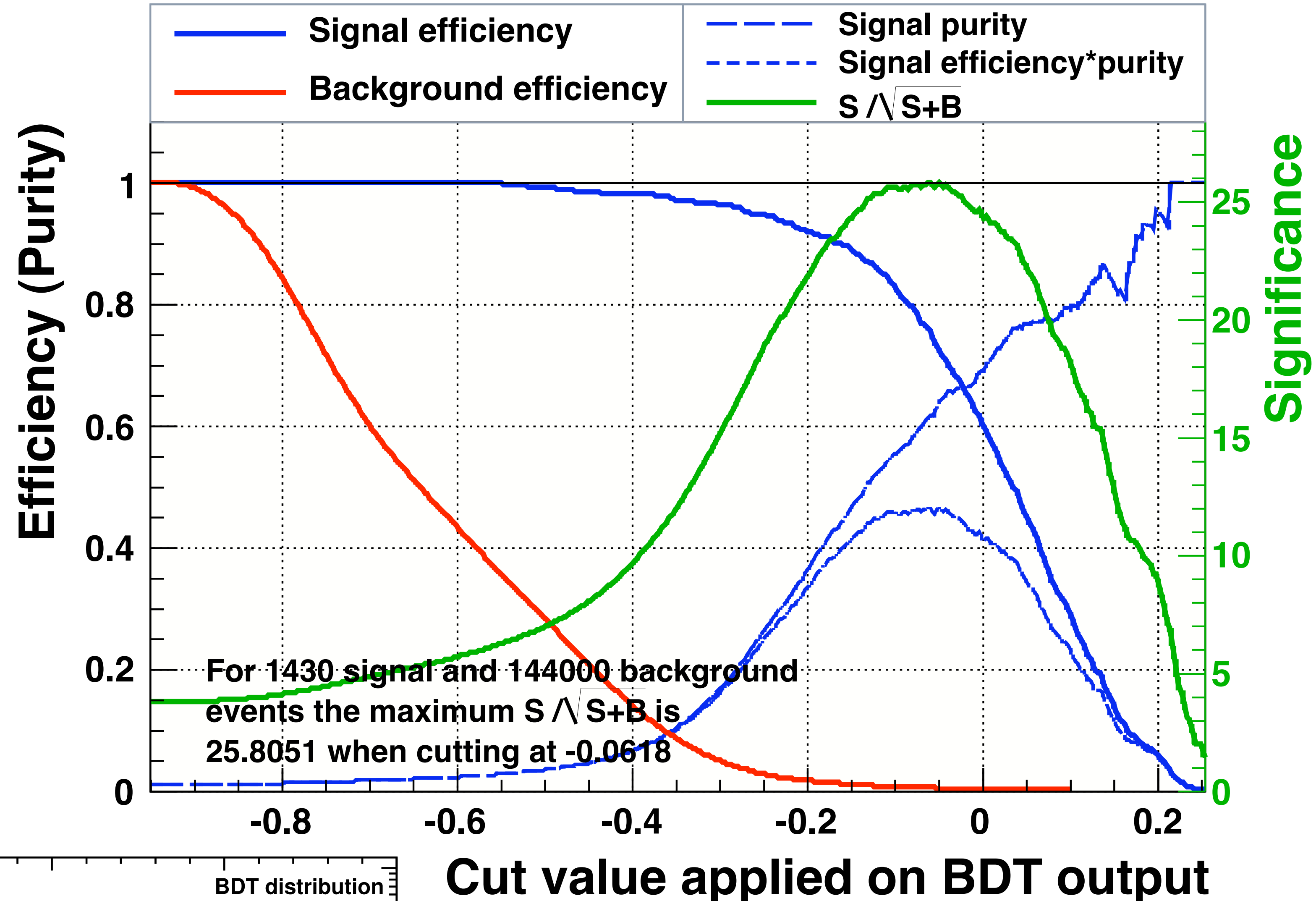
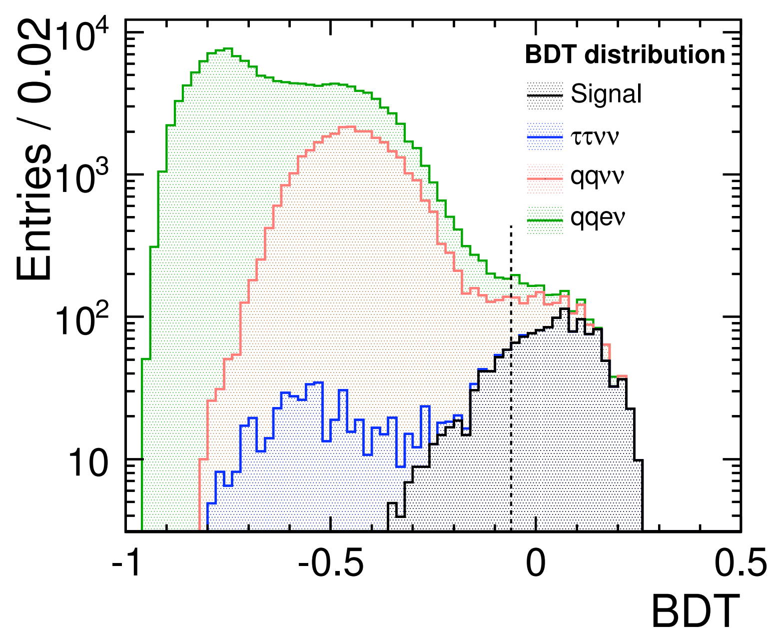
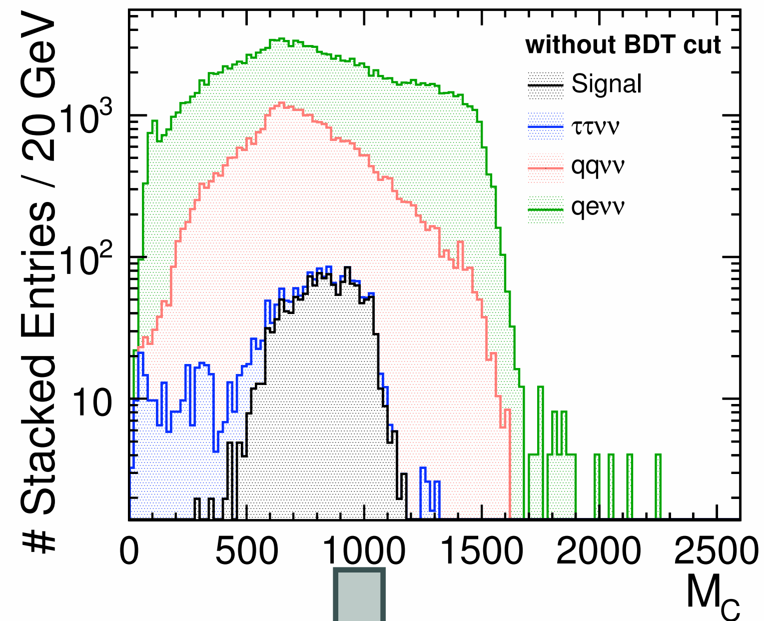


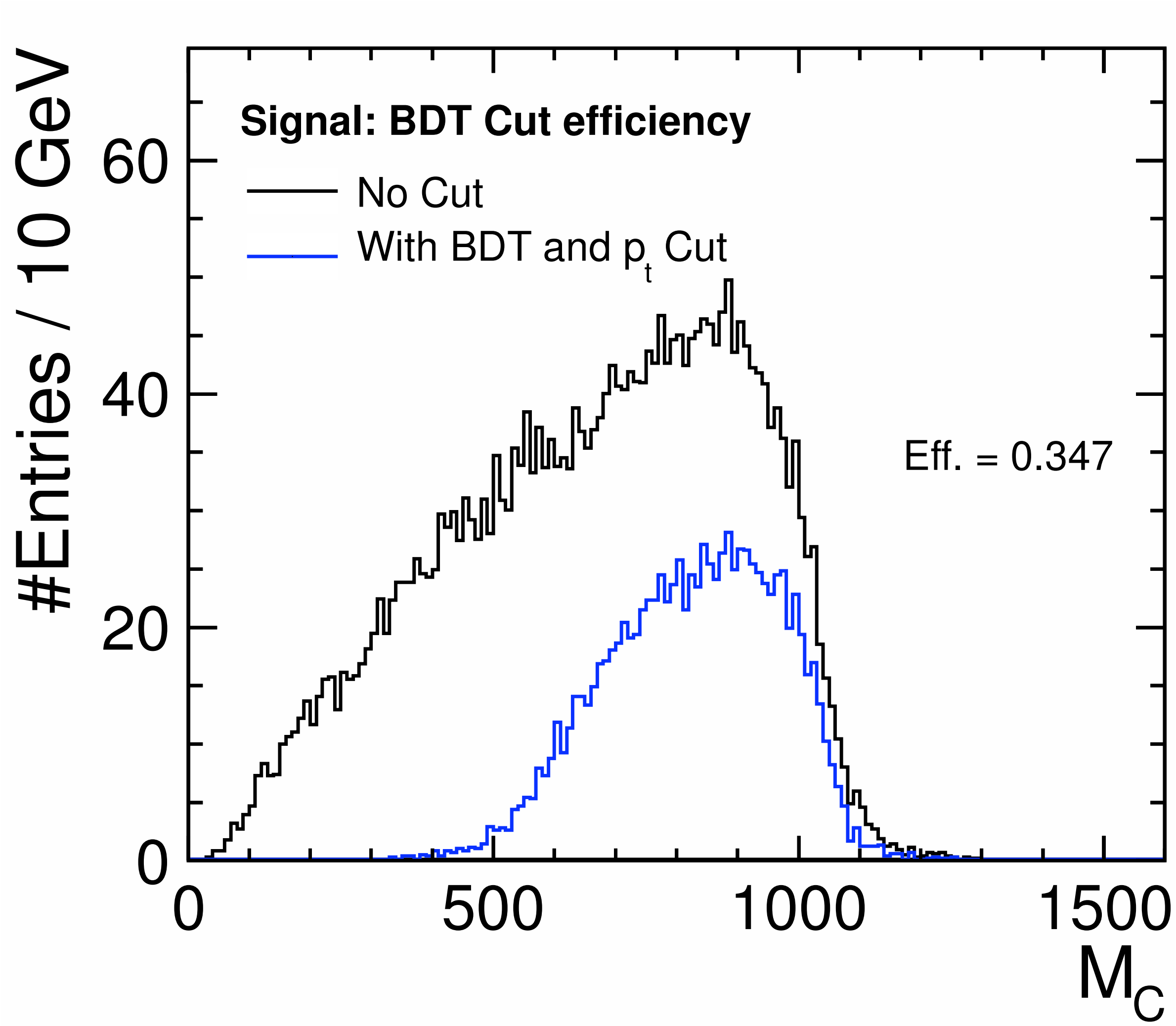


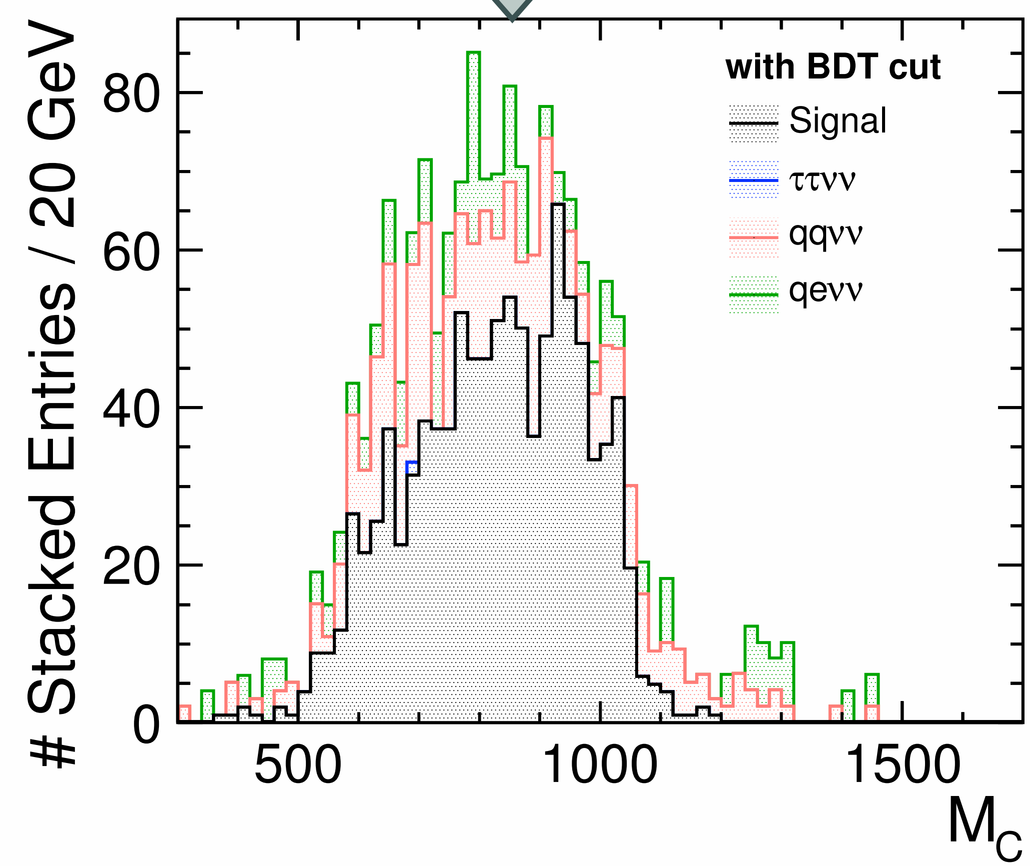
Background rejection: Boosted Decision Trees: Cut eff.

- After BDT and p_t Cut:
  - Purity: 0.60
  - Cut efficiency: 0.347 (determined from independent sample)



Cut on BDT





Background rejection: Fit Background

- M_C Distribution not Background free after BDT cut
  - Fit Background on Train Sample
    - Gaussian
  - Subtract Fit on Analysis Sample

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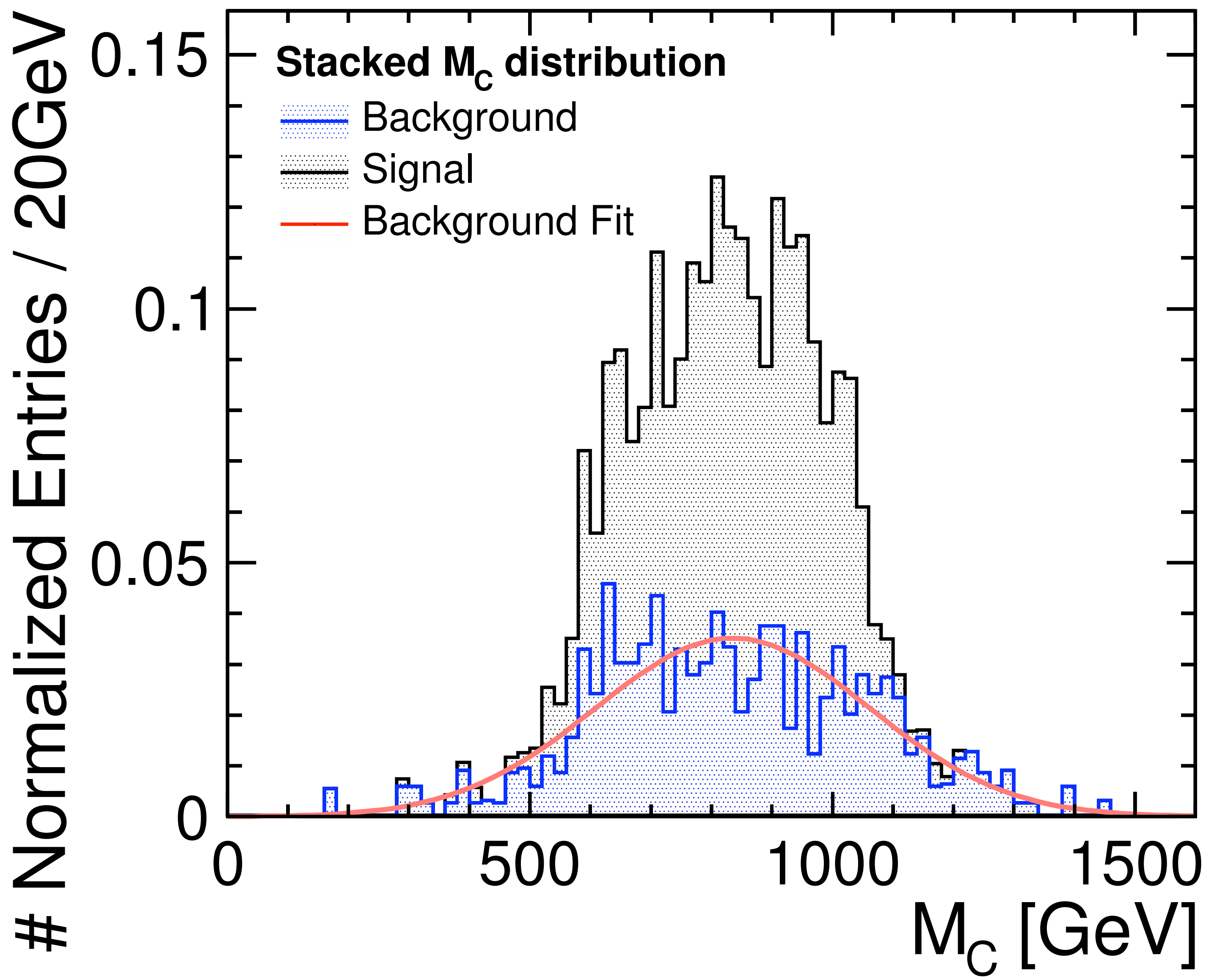

Squark mass extraction: Template Fit

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- Squark mass extraction with M_C: Template Fit

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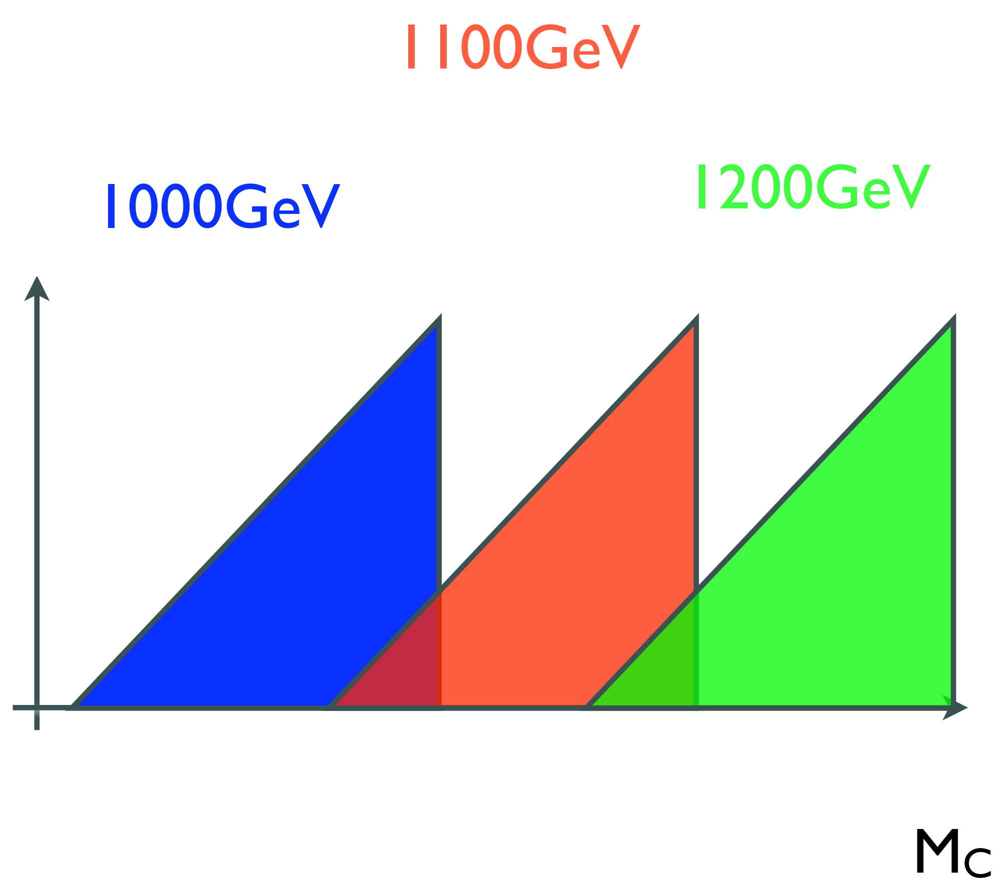
  - Create templates in steps of 3 GeV



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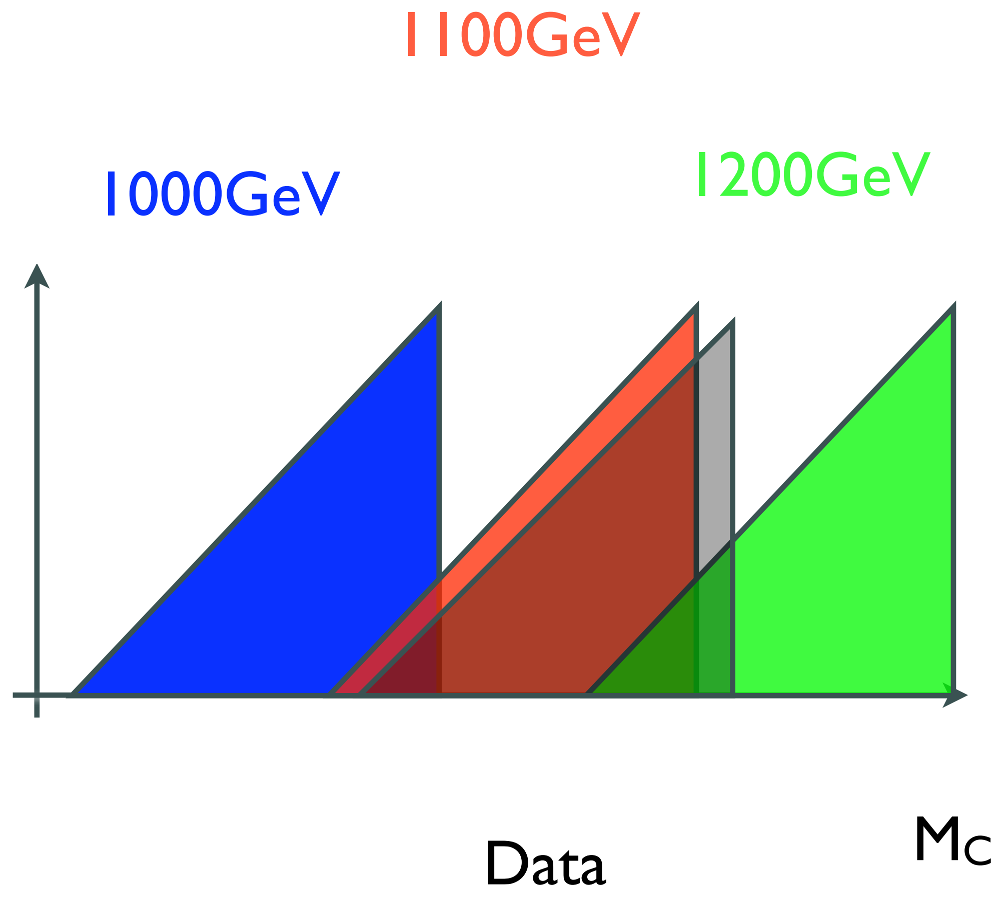
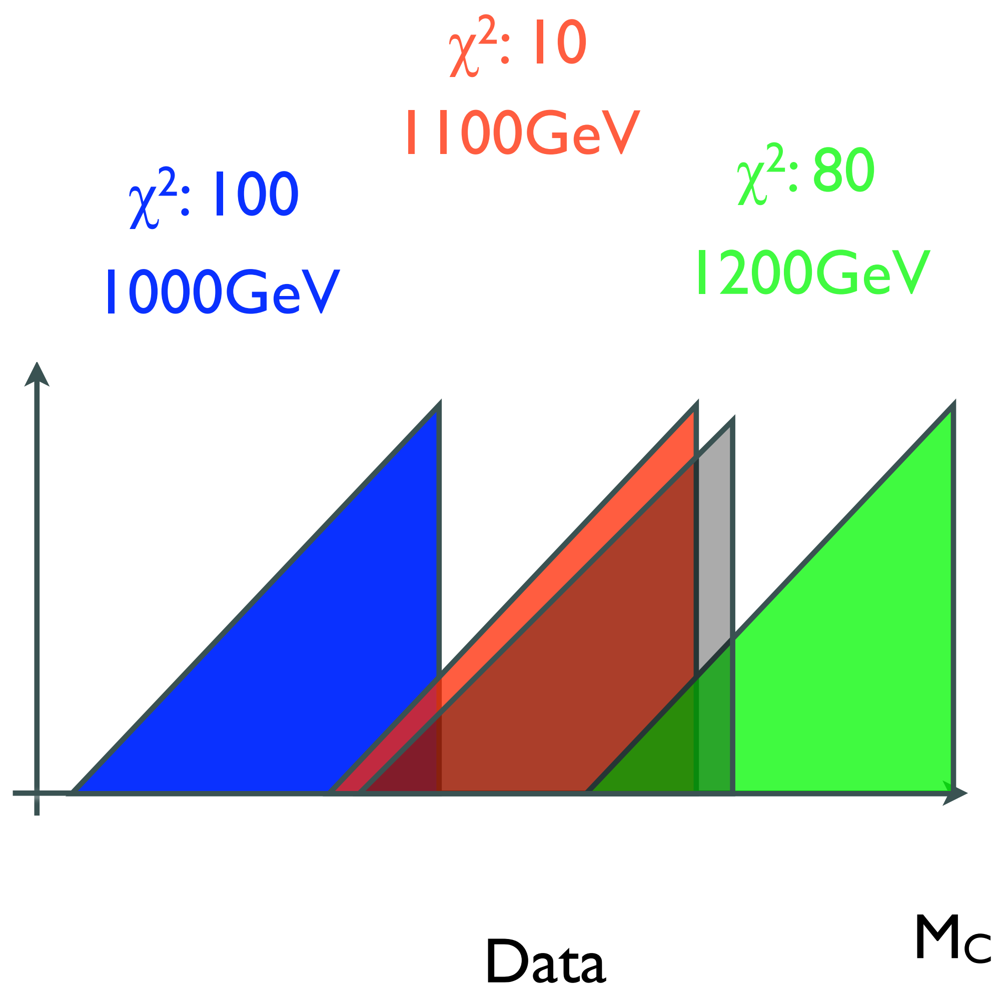


Squark mass extraction: Template Fit

- Squark mass extraction with M_C: Template Fit
  - Create templates in steps of 3 GeV
  - Compare template with Data via χ^2

$$\chi^2 = \sum_n^{\text{bins}} \frac{\Delta_n^2}{\sigma_{n,\text{t}}^2 + \sigma_{n,\text{m}}^2}$$



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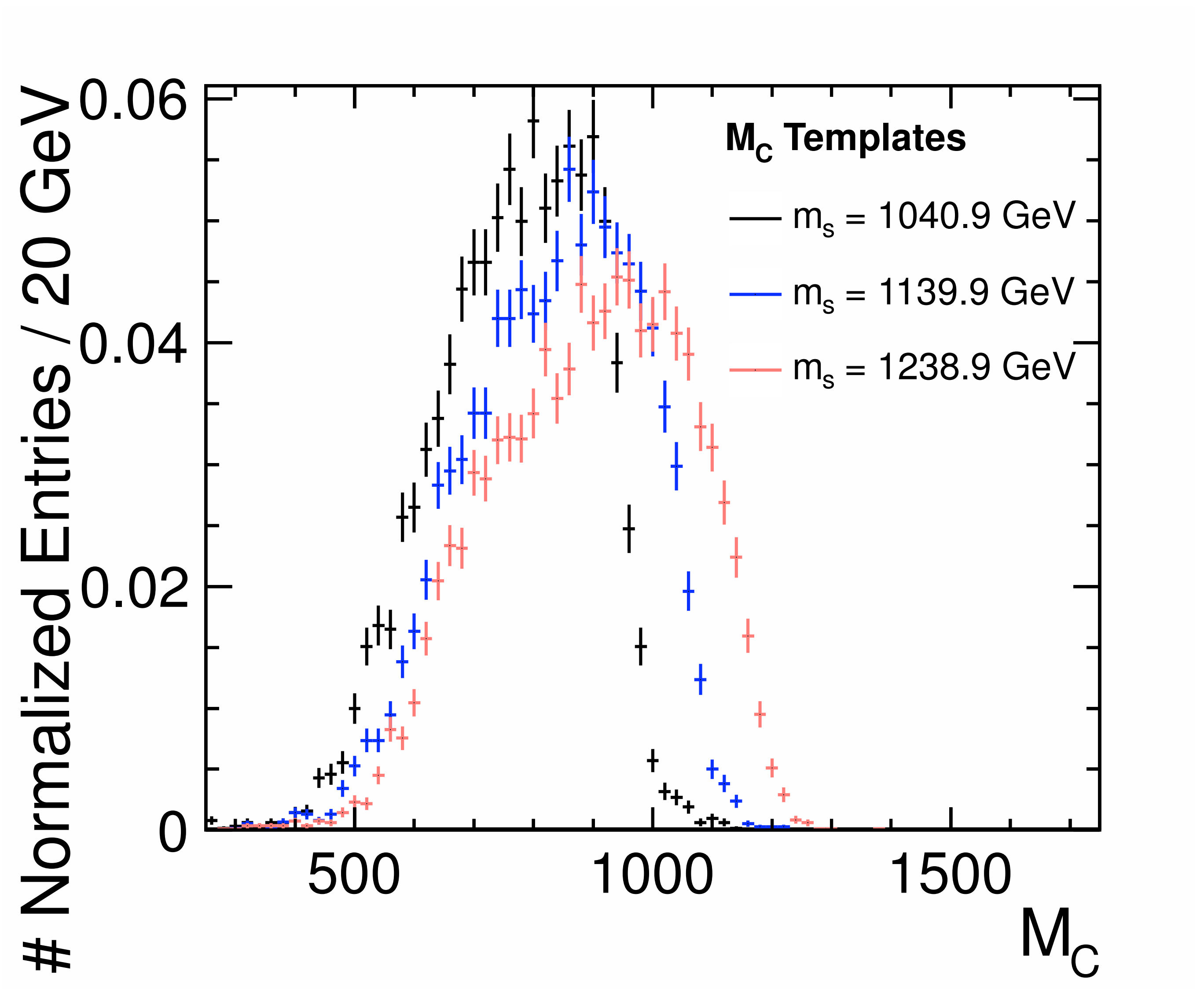

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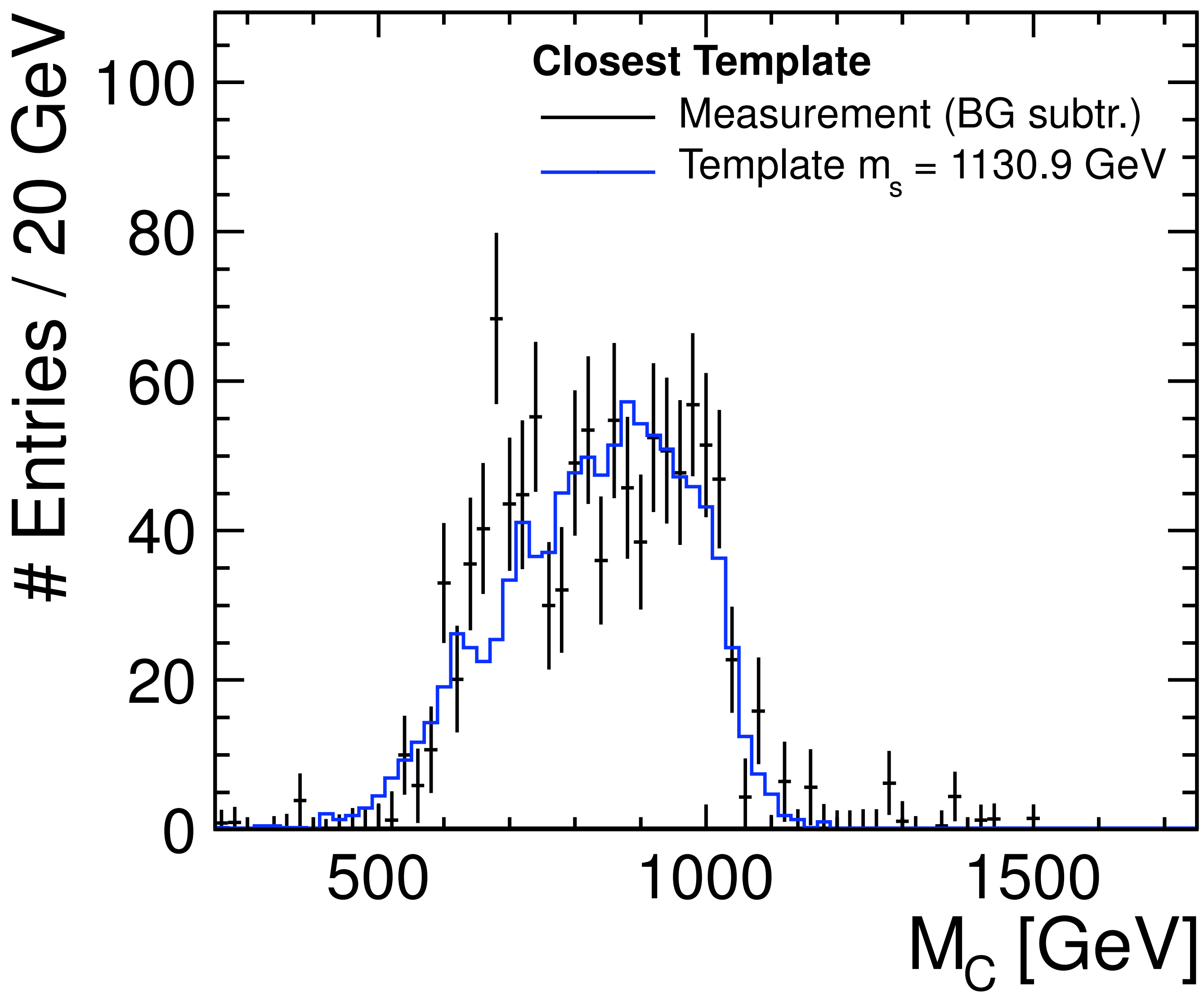

Squark mass extraction: Template Fit

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  - Create templates in steps of 3 GeV
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  - Fit resulting parabola
    - Minimum = m_{squark} = 1127.9 GeV

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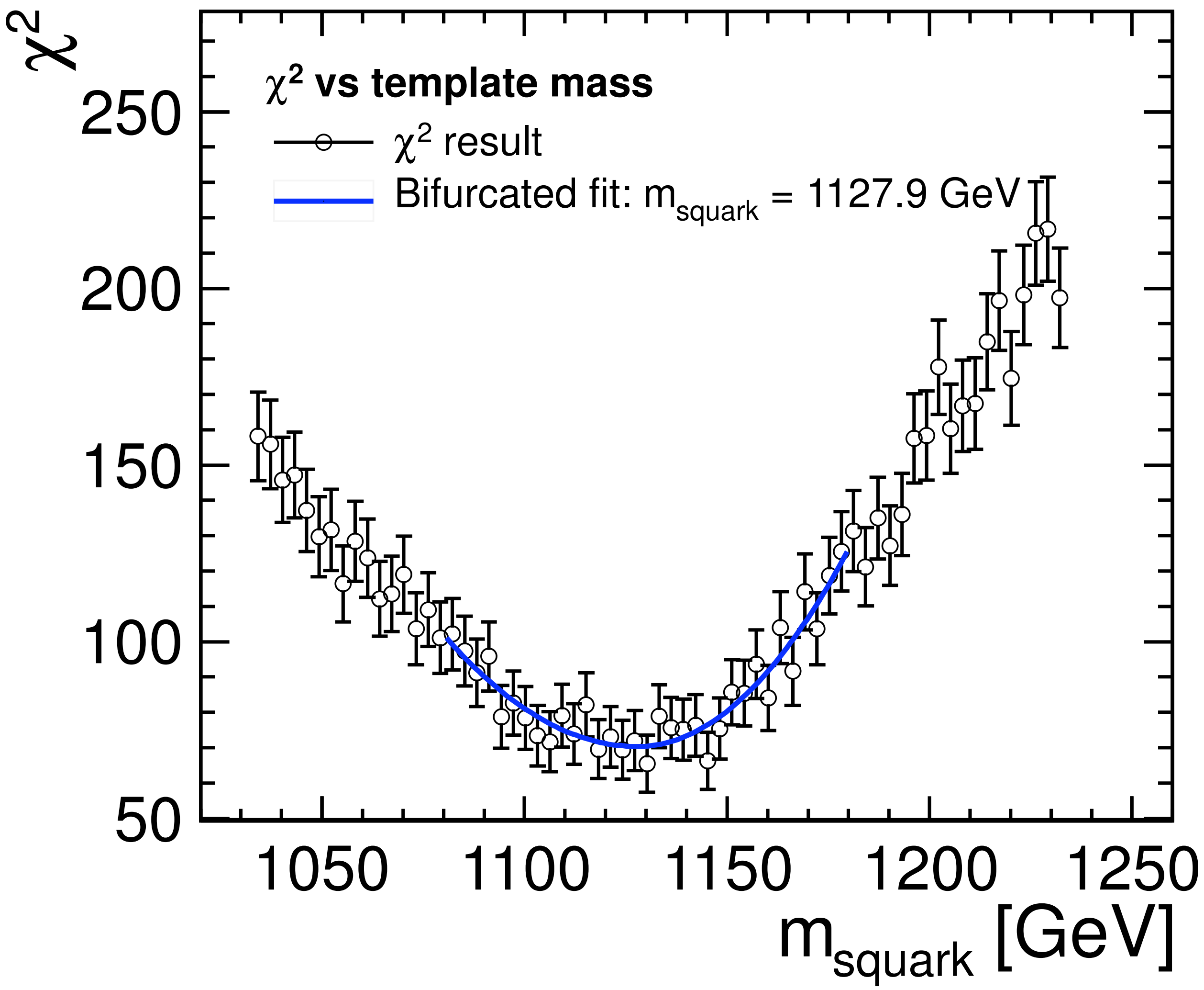

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- Templates created via 4-Vector smearing (no full simulation)
  - Systematic offset
    - Redo analysis on signal only sample
    - Offset = $m_{squark,output} - m_{squark,input}$

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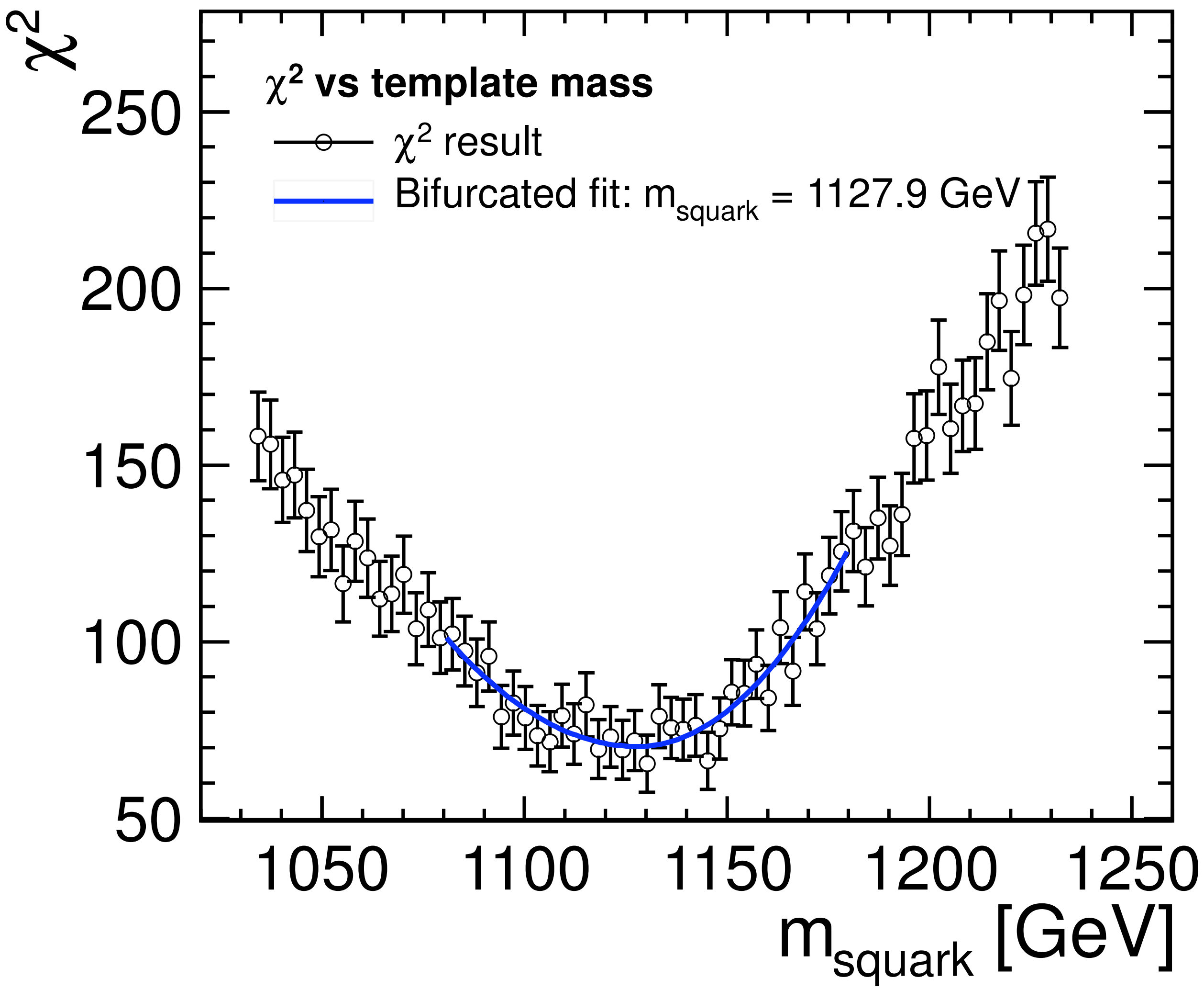

Squark mass extraction: Template Fit

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    - ➡ m_{offset} = 13.7 GeV ± 1.6 GeV

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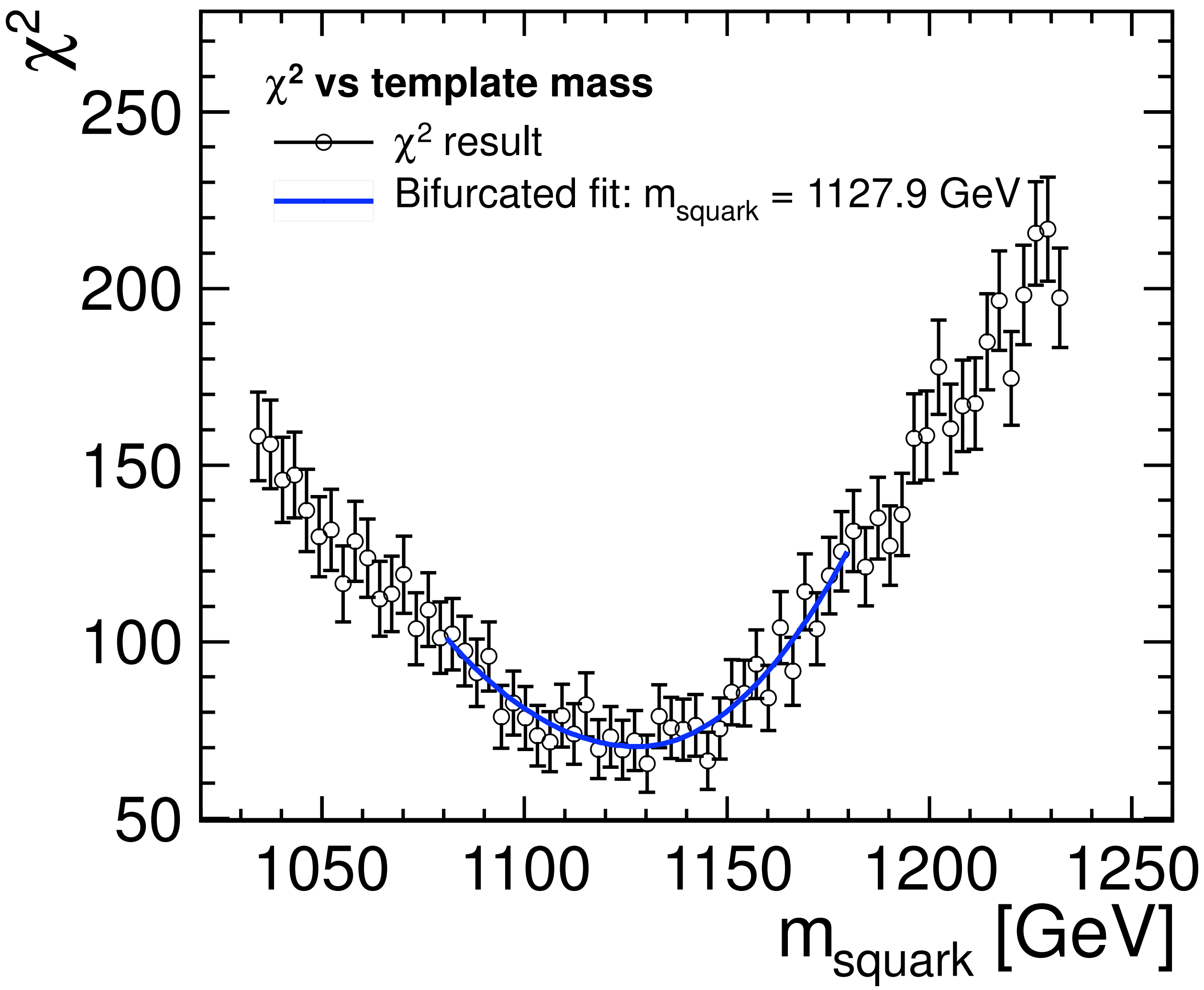
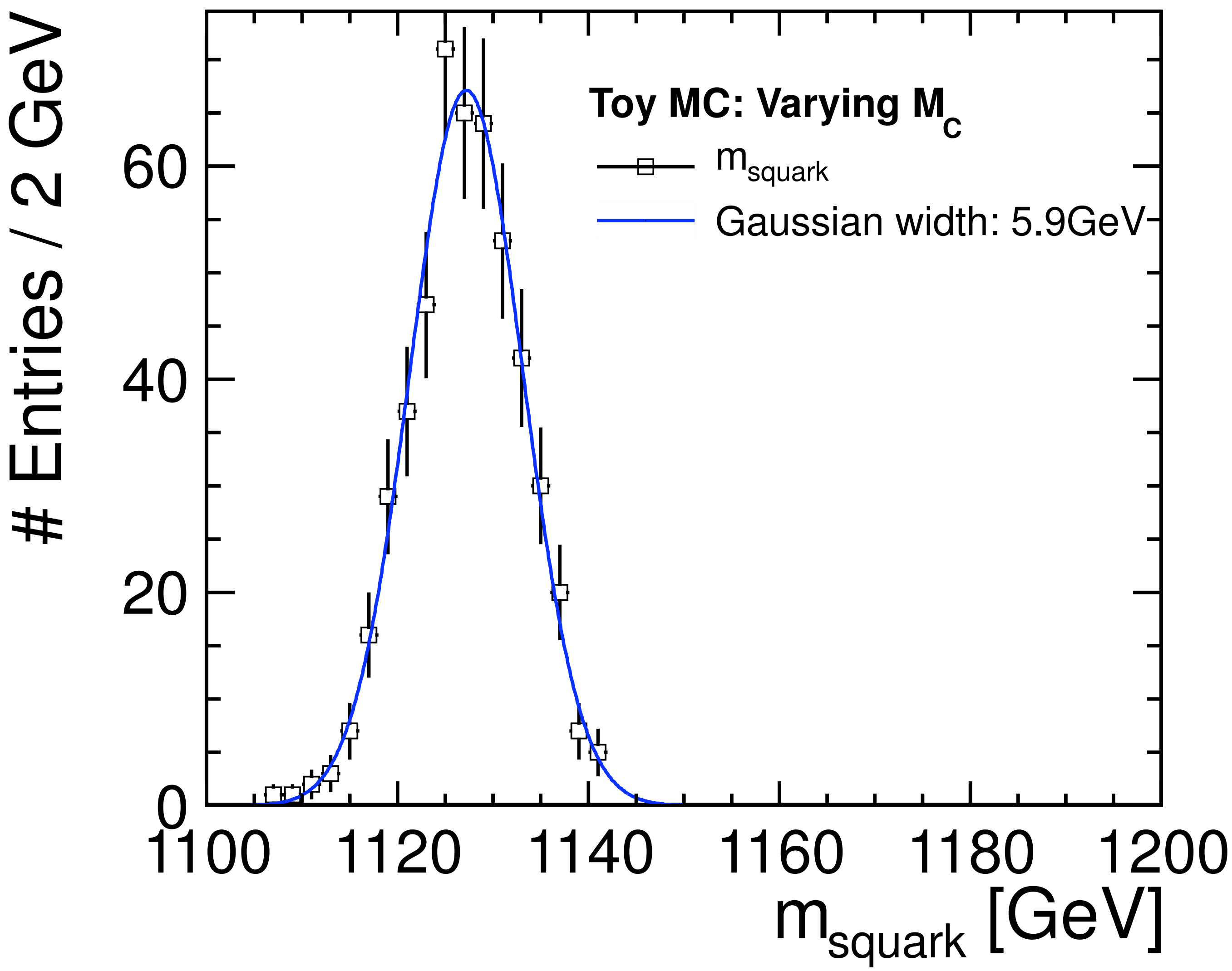


Squark mass measurement: Statistical Error

- Extract statistical error with a Toy-MC
  - Repeat 500 times:
    - Bin-by-bin Gaussian smearing of measured M_C distribution
    - Extract m_{squark} for smeared M_C
- Final result within 1σ of input value



$$m_{squark} = 1127.9 \text{ GeV} \pm 5.9 \text{ GeV}_{(stat)} \pm 1.9 \text{ GeV}_{(calib)}$$

$m_{squark,input}$ = 1123.7 GeV

Crosssection

- Crosssection measurement
  - Analysis done for Luminosity of $L = 2000\ fb^{-1}$
  - Subtract the Background from M_C distribution using the Fit
  - Integral = # Events after BDT and p_t cut ($N_{after\ cut}$)
  - Cut efficiency ε of BDT and p_t cut known

$$N_{\text{real}} = \frac{N_{\text{after cut}}}{\epsilon}$$

$$\sigma = \frac{N_{\text{real}}}{\mathcal{L}} = \frac{N_{\text{after cut}}}{\epsilon\mathcal{L}}$$

$$\sigma_{squark} = (1.51 \pm 0.07)\ fb$$

$\sigma_{squark,input} = 1.47\ fb$

Summary

- New accelerator technology: Compact Linear Collider
- Conceptional Design Report Benchmark: Squark pair production
  - Decay mainly into 2 jets an missing energy
- Background rejection done with Boosted Decision Trees
- Remaining Background fitted with Gaussian
- Squark mass extracted via Template Fit
- Statistical Error extracted with a Toy-MC