Fermilab
50 Years of Discovery

SEARCH FOR CONTACT INTERACTIONS IN DILEPTON CHANNELS AT THE COMPACT MUON SOLENOID EXPERIMENT

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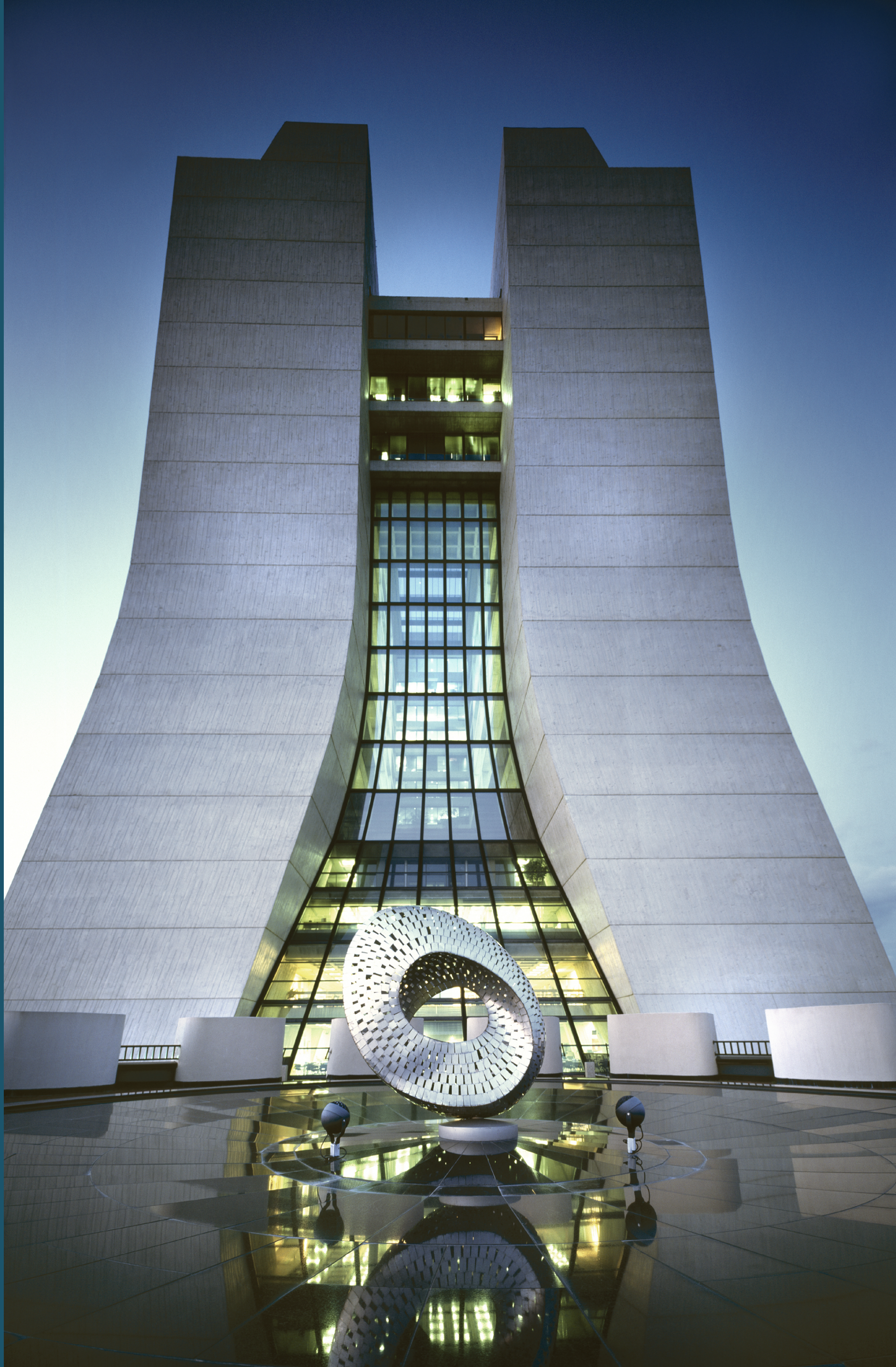


Outline

Introduction:

- What are Contact Interactions and quark/lepton compositeness?
- Why we care? Where we can expect to see it?
- Current Limits on Contact Interactions.
- Analysis Workflow

Sensitive Variables:

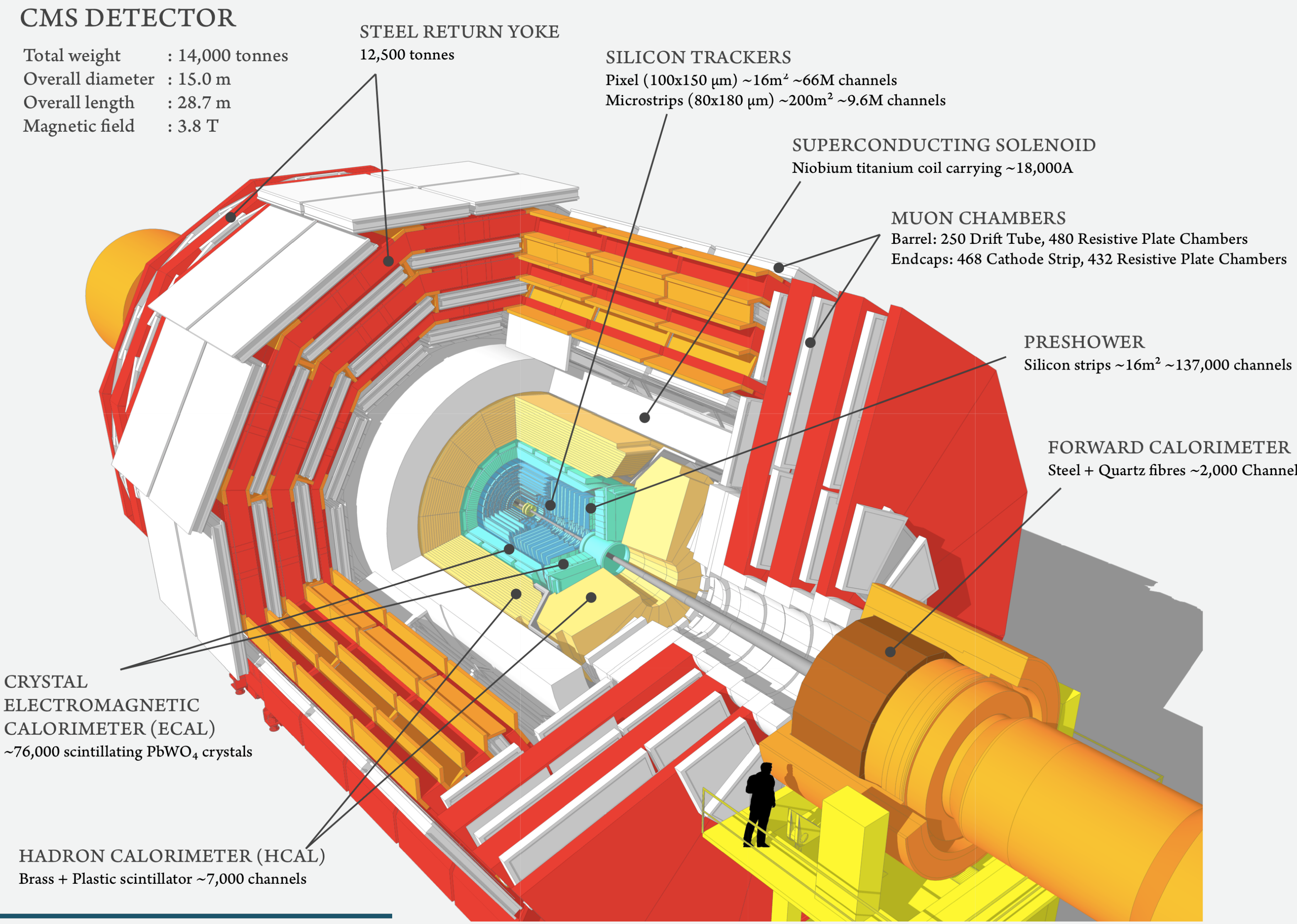
- Invariant Mass Spectrum
- Collins-Soper Frame Angle

Statistical Studies:

- Smearing of the Invariant Mass
- Acceptance x Migration

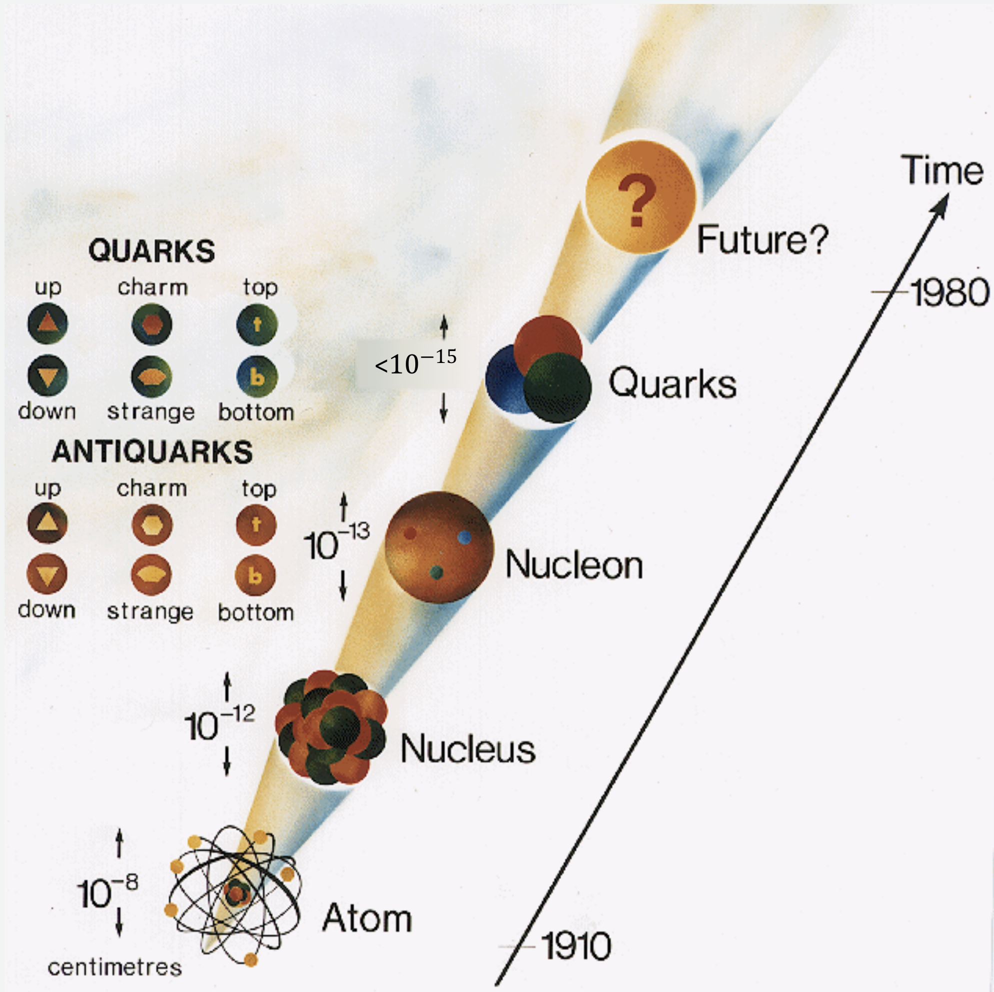
Acknowledgements and Closing Statements

The CMS Detector



Contact Interactions (CI) and Compositeness

- CI Theory suggests quarks and leptons are made up of more fundamental particles (sometimes called preons)
- Preons can be treated as making direct contact. If the exchange particle is very massive we can ignore the propagator and treat the event as a contact interaction.

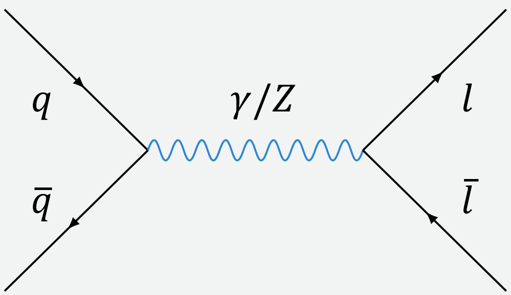


Questions Compositeness Can Answer

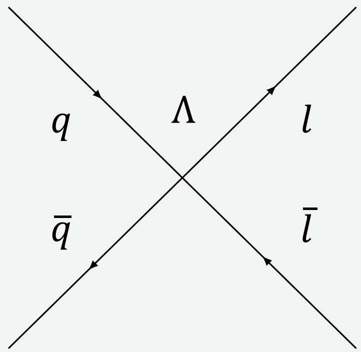
- Why are there multiple generations of quarks/leptons?
- It would also suggest the existence of heavier quarks/leptons as excited states of the lightest generation.
- Points to new physics beyond the Standard Model

Energy Scale Lambda (Λ)

Drell-Yan



Contact Interactions



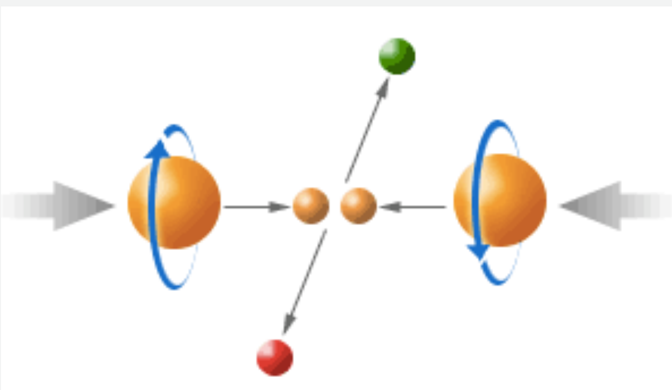
CI terms for muon-muon interactions

$$\frac{d\sigma^{\mathrm{CI/DY}}}{dM_{\mu\mu}} = \frac{d\sigma^{\mathrm{DY}}}{dM_{\mu\mu}} - \eta_{ij}\frac{I}{\Lambda^2} + \eta_{ij}^2\frac{\mathcal{C}}{\Lambda^4},$$

- (Left) Drell-Yan process which is the main background to the signal. Mediated by a Z or photon.
- (Right) Contact Interaction process where new physics emerges. Lambda is the energy scale where compositeness effects are manifest.

Compositeness Expanded

Example of a Left-Left Collision



Hamiltonian for Contact Interactions

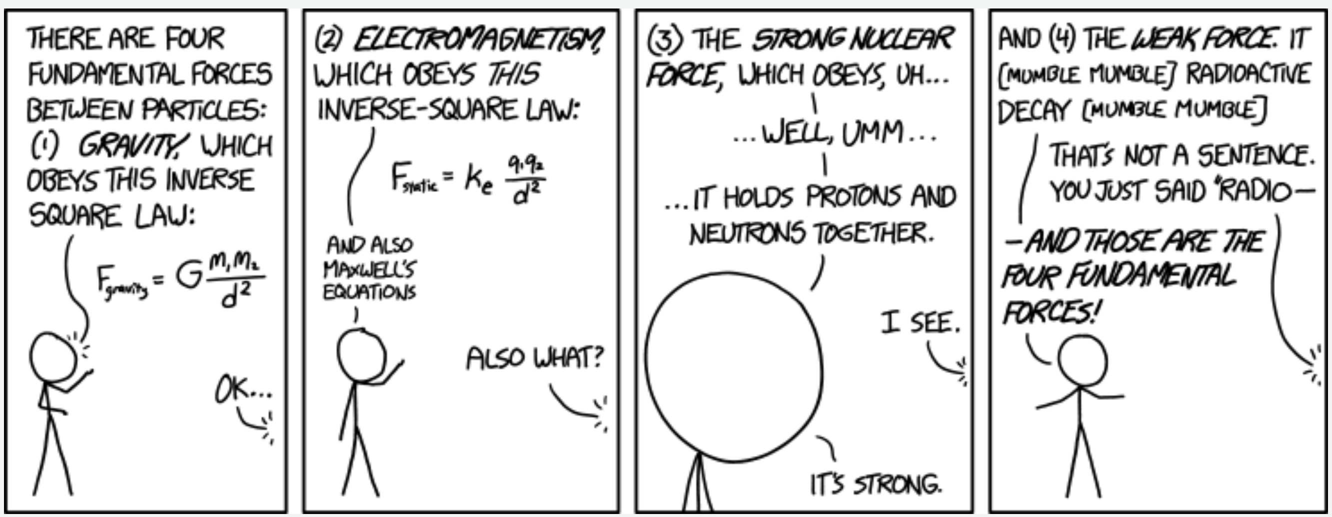
$$\begin{aligned}\mathcal{L}_{ql} = (g_0^2/\Lambda^2)\{&\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_L\gamma_\mu\mu_L)\\ &+\eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_R\gamma_\mu\mu_R)\\ &+\eta_{RL}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_L\gamma_\mu\mu_L)\\ &+\eta_{RL}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_L\gamma_\mu\mu_L)\\ &+\eta_{RR}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_R\gamma_\mu\mu_R)\\ &+\eta_{RR}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_R\gamma_\mu\mu_R)\},\end{aligned}$$

Current Limits on Λ from CMS

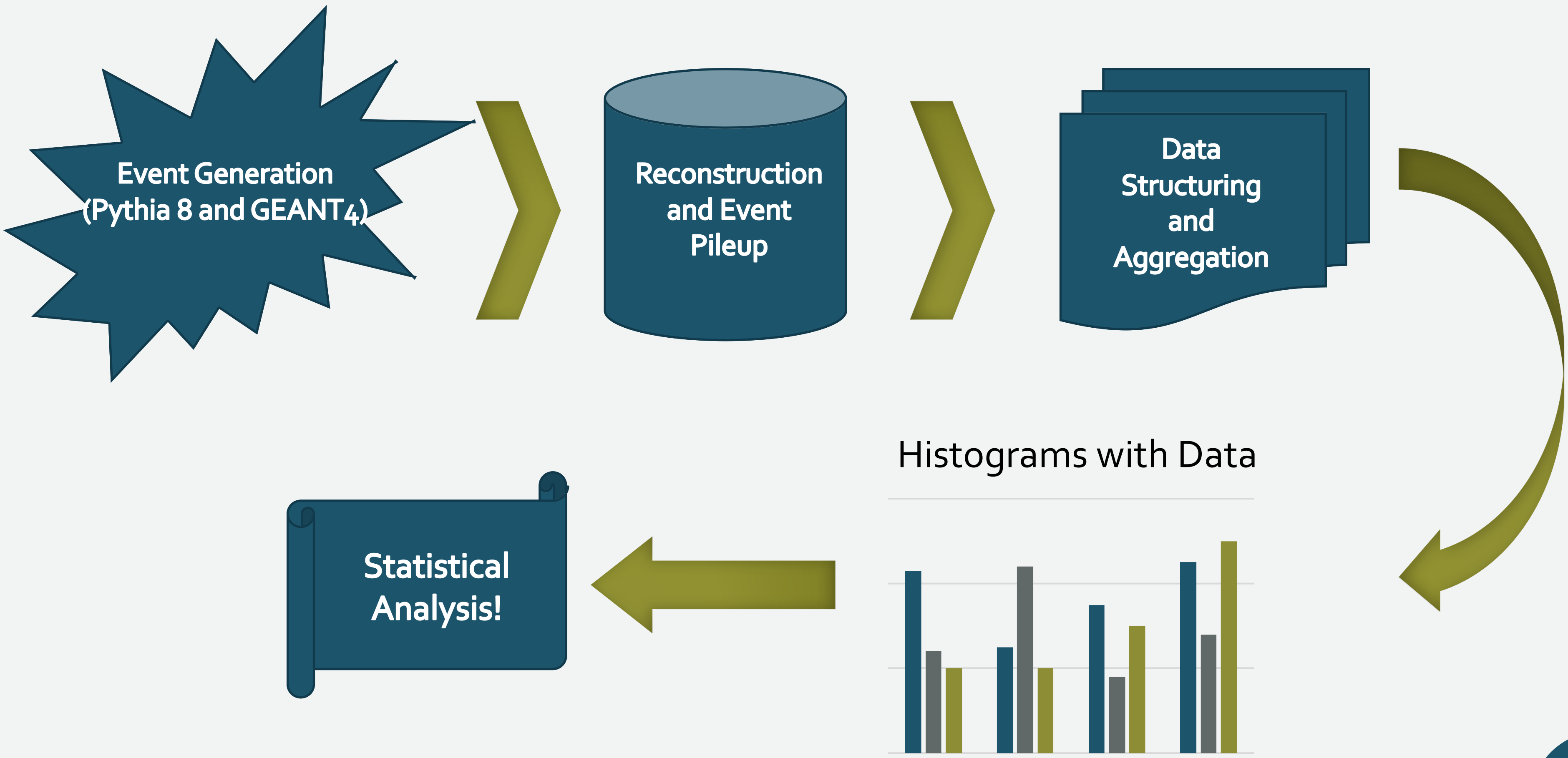
Source: The CMS Collaboration. 2013. Search for contact interactions in $\mu^+\mu^-$ events in pp collisions at $\sqrt{s} = 7$ TeV. Eur. Phys (2013)

	Run I	Run II
Luminosity	5.7 fb^{-1}	36.3 fb^{-1}
Model	LL	LL, LR, RR
θ_{CS}	No	yes

Dileptons	Λ_C (TeV)	Λ_D (TeV)
e^+e^-	18.3	13.5
$\mu^+\mu^-$	15.2	12.0



Analysis Workflow



Compositeness Signals

Invariant Dilepton Mass Spectrum

DY process compared to the CI will have more low mass events and fewer high mass events. At higher invariant mass, the CI model will dominate the signal.

Collins-Soper Angle Distribution

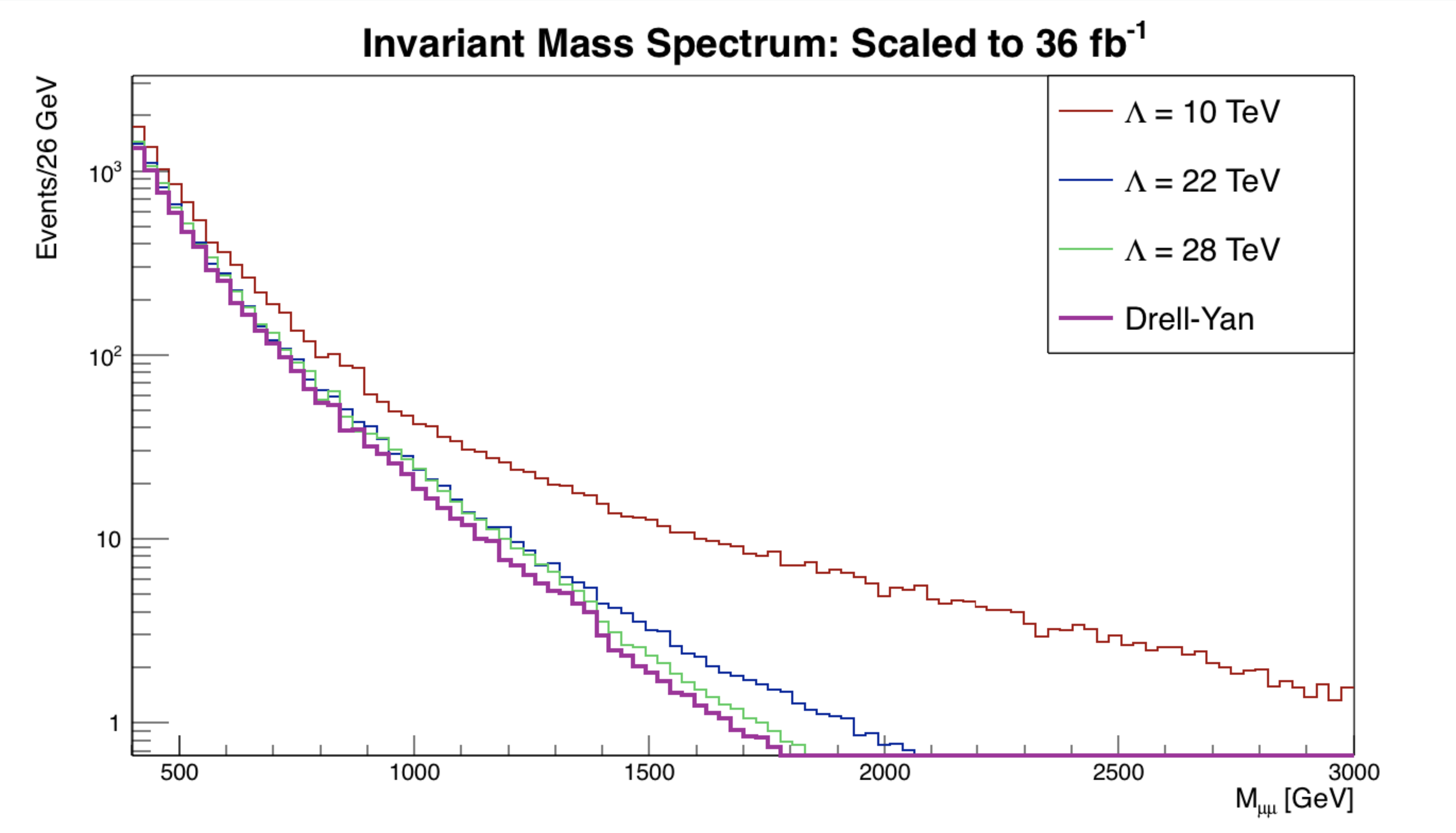
DY also predicts a generally non-isotropic distribution for the angle θ in the center of mass frame for the dileptons whose cosine is defined as

$$cos(\theta_{CS}) = \frac{k_z(l^+l^-)}{|k_z(l^+l^-)|}\frac{2(k_1^+k_2^- - k_1^-k_2^+)}{m(l^+l^-)\sqrt{m(l^+l^-)^2 + k_T(l^+l^-)^2}}$$

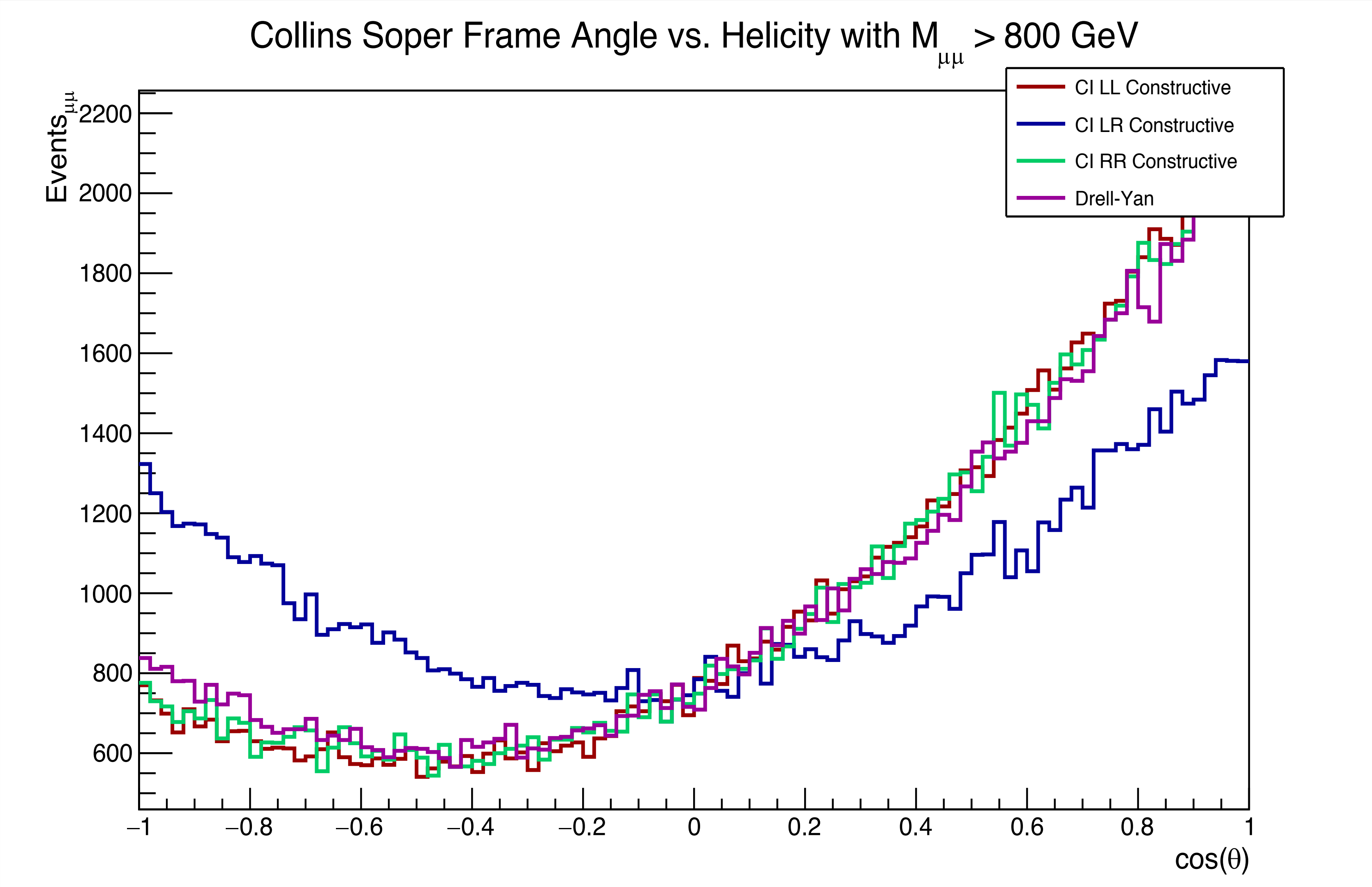
Here the kinematic variables are defined in the lab frame.

The variables $k_{1,2}^{+,-}$ are defined as $\frac{E_{(1,2)} \pm k_{(1,2)z}}{\sqrt{2}}$. Where 1 and 2 correspond to the negative/positive lepton respectively.

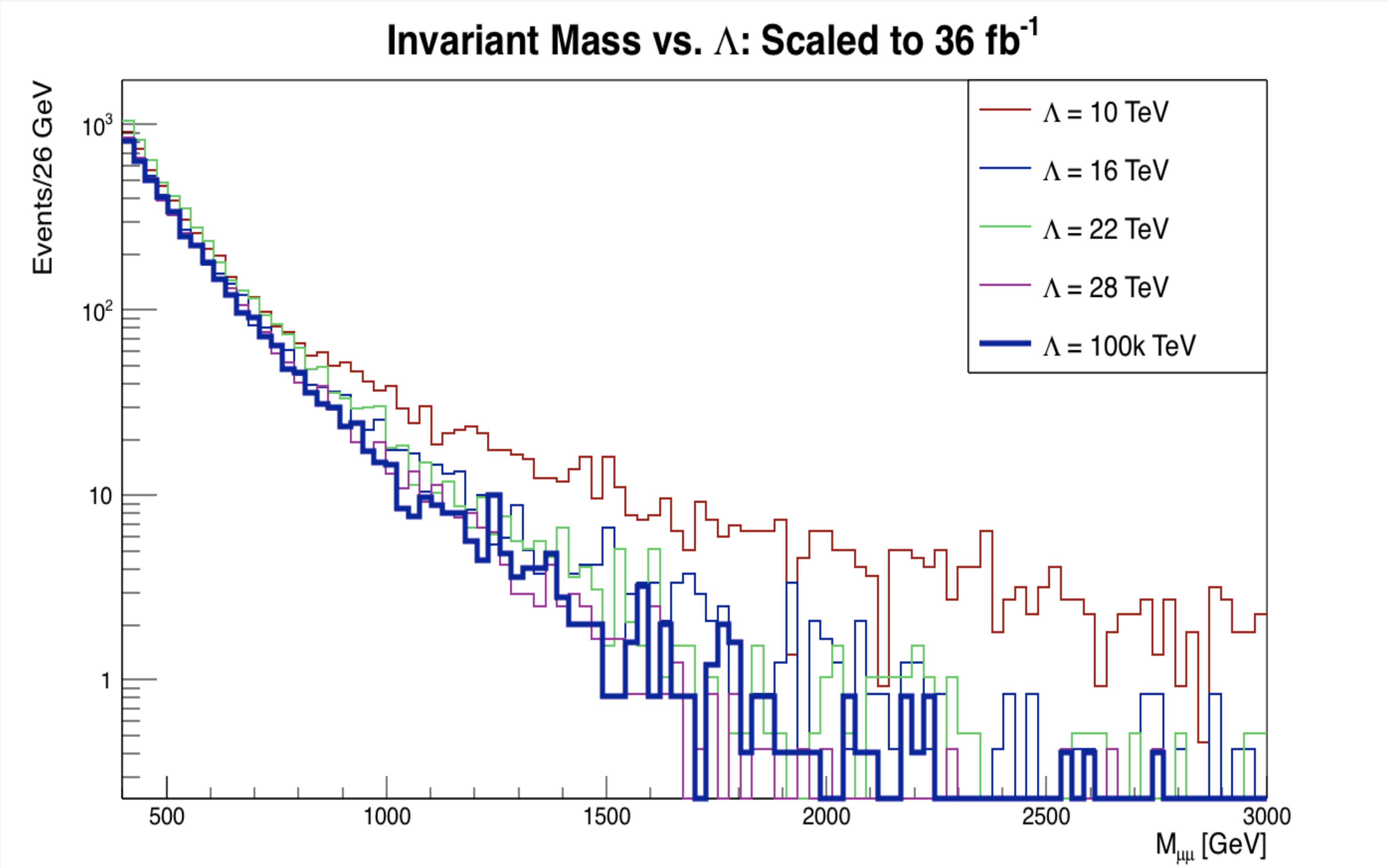
Monte Carlo Simulation of Signal Regions



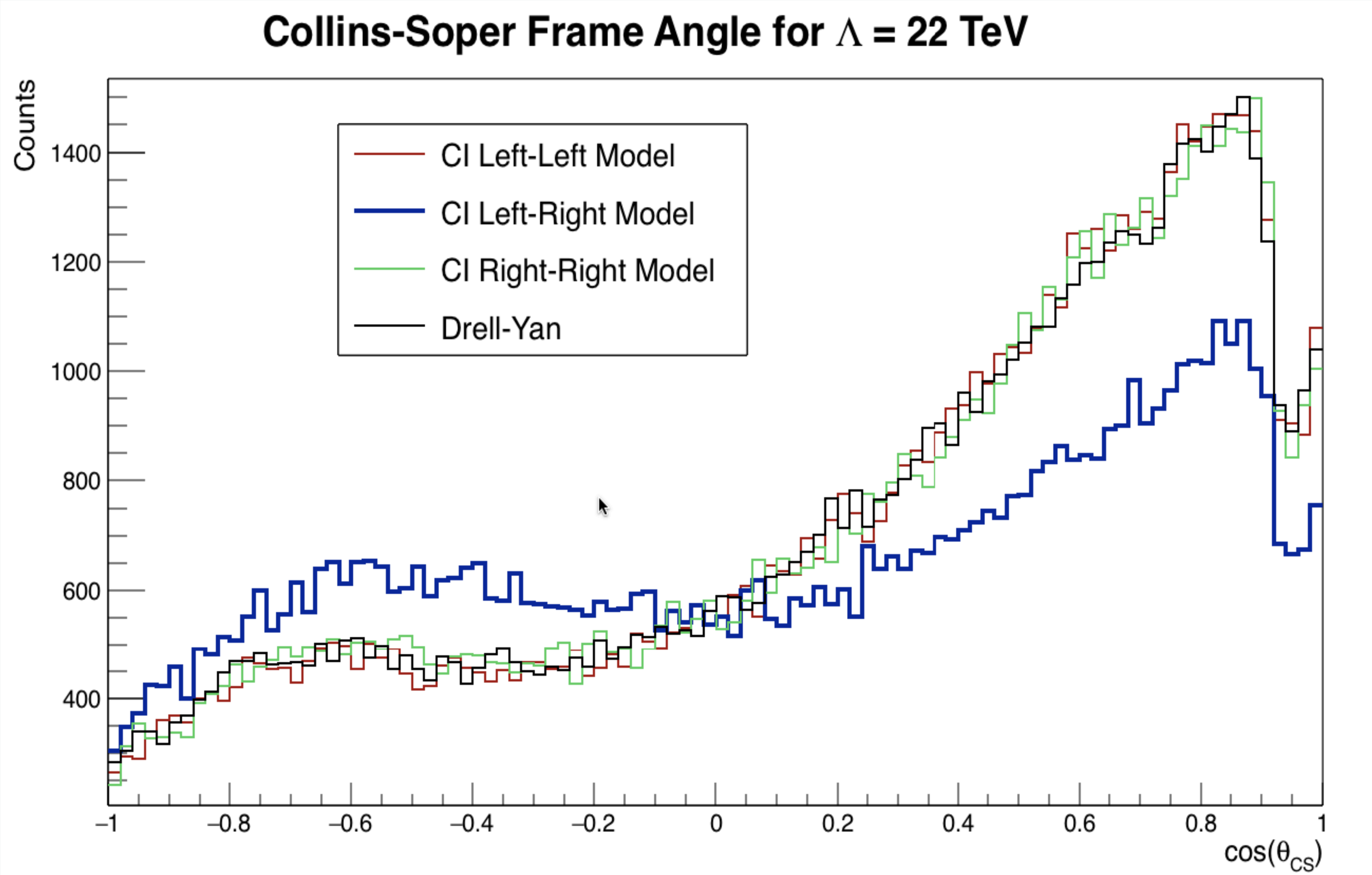
MC of Signal Continued $\Lambda = 22$ TeV



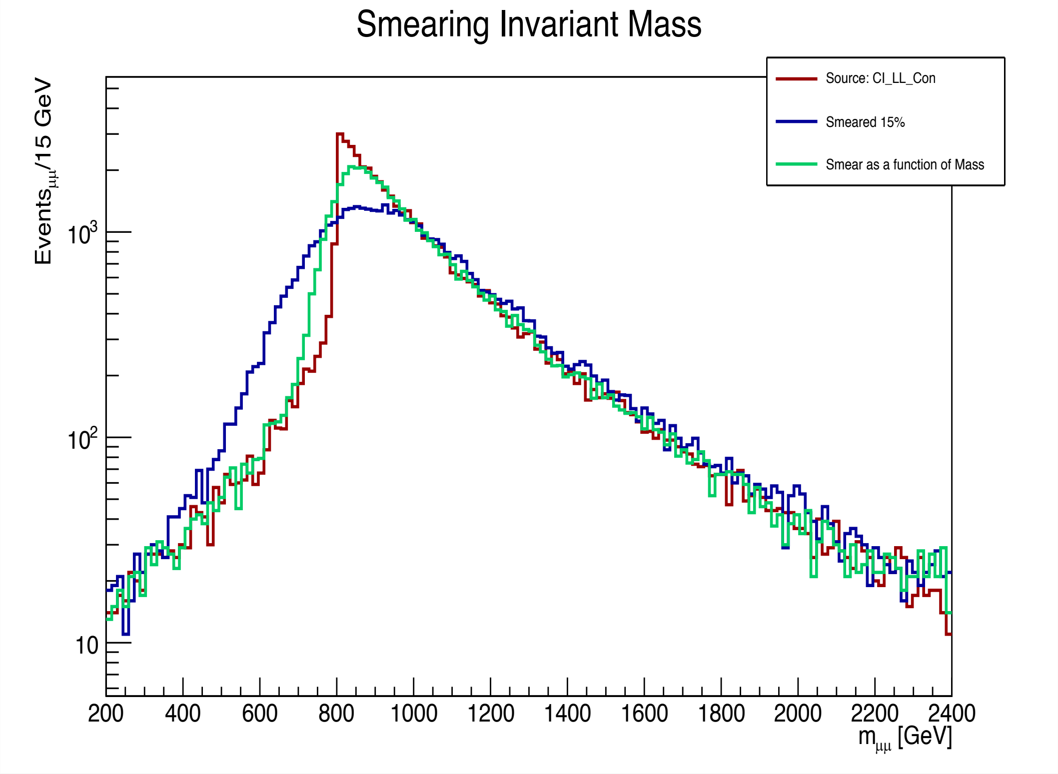
MC Reconstructed Signal



MC Reconstructed Signal; M > 800 GeV

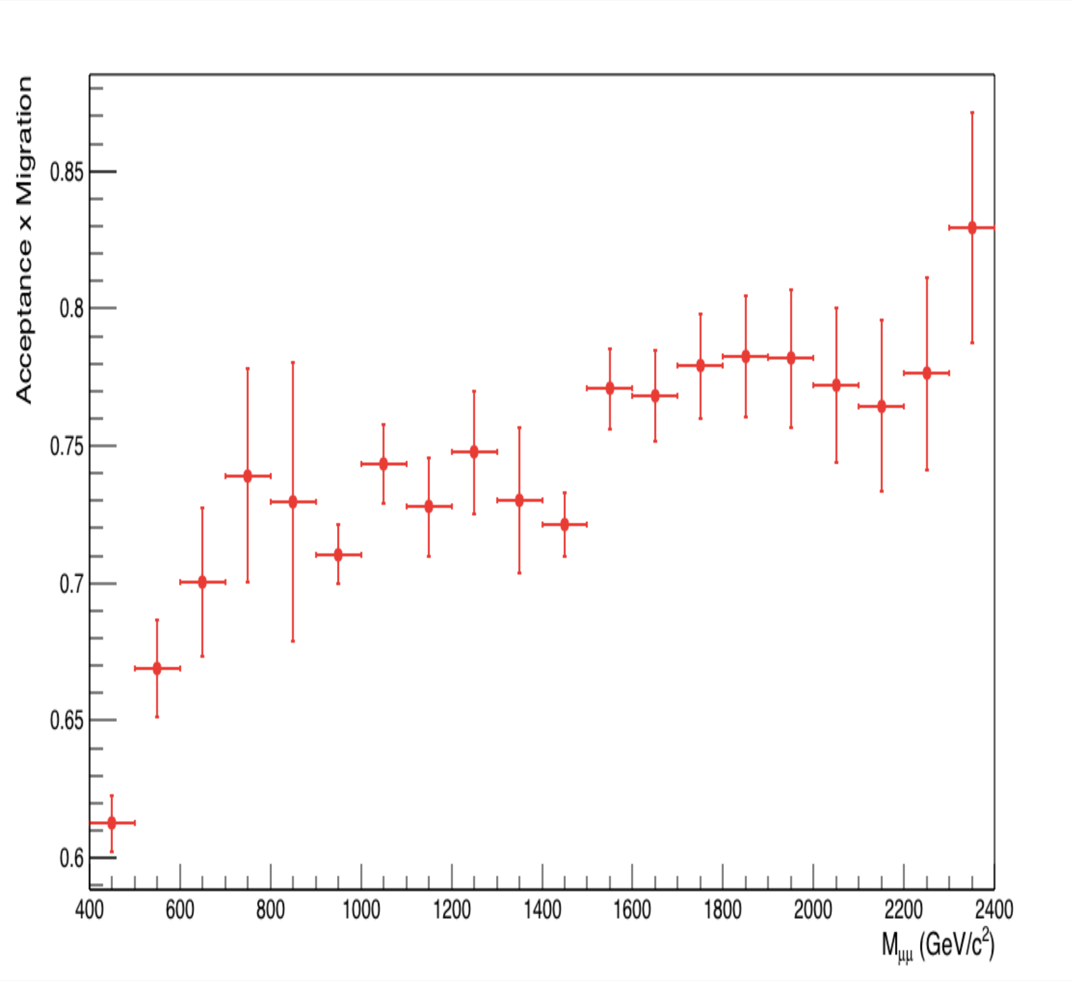


Understanding the Uncertainties



- Performed Studies on [1] Smearing of Invariant mass and [2] Acceptance x Migration.
- In order to develop the analysis, smeared histograms were generated in order to test and validate our combination tool which will use Bayesian statistics to set new limits on Lambda
- Smearing was done using a random number generator on GENSIM samples.

Measurement and Resolution Uncertainty



- Migration – Movement of events from source bin to neighboring bins. Usually due to measurement uncertainties.
- Acceptance – events accepted after reconstruction and standard lepton cuts. Sensitive to detector inefficiencies.
- The error bars indicate uncertainty based on simulation of Contact Interaction at 22 TeV.
- Trends show that events migrate from lower mass to higher mass. This is because the cross section falls steeply with mass.

Conclusion and Future Directions

- Finish development of MC/data workflow for compositeness analysis.
- With MC fully generated, analysis with data can begin!
- From there we either make a discovery, or set new limits on Λ

Worked on:

- Validation and generation of Monte Carlo Samples. Particularly for $\Lambda =$ 22 TeV
- Implementation and development of analysis tools.
- Validation and building of data readers.
- Code base and scripts that automate the procedures above.
- Statistical studies needed for developing our statistics combination tool.

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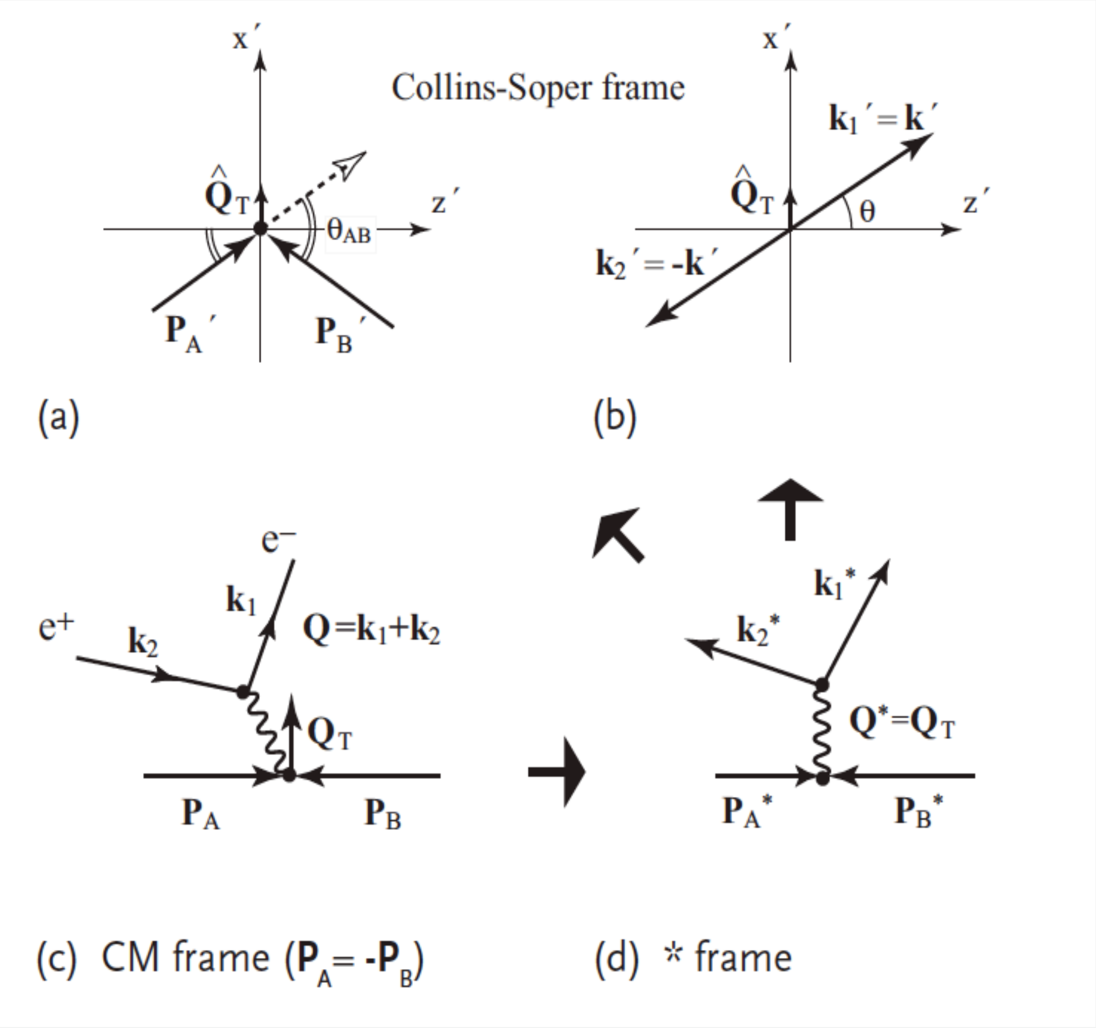
BACKUP

Collins-Soper Frame Angle Expanded



CS Derivation Lite

$$k = \frac{Q}{2}$$

$$k_1' = \begin{pmatrix} k \\ k\sin(\theta) \\ 0 \\ k\cos(\theta) \end{pmatrix}$$

$$k_2' = \begin{pmatrix} k \\ -k\sin(\theta) \\ 0 \\ -k\cos(\theta) \end{pmatrix}$$

Then Boost in transverse

$$k_1^* = \begin{pmatrix} \gamma k + \gamma\beta k\sin(\theta) \\ \gamma\beta k + \gamma k\sin(\theta) \\ 0 \\ k\cos(\theta) \end{pmatrix}$$

$$k_2^* = \begin{pmatrix} \gamma k - \gamma\beta k\sin(\theta) \\ \gamma\beta k - \gamma k\sin(\theta) \\ 0 \\ -k\cos(\theta) \end{pmatrix}$$

The value $(k_1^{*+}k_2^{*-} - k_1^{*-}k_2^{*+})$ is invariant in z-boosts so first we define each value

- $k_1^{*+} = \frac{k}{\sqrt{2}}(\gamma(1+\beta\sin(\theta)) + \cos(\theta))$
- $k_1^{*-} = \frac{k}{\sqrt{2}}(\gamma(1+\beta\sin(\theta)) - \cos(\theta))$
- $k_2^{*+} = \frac{k}{\sqrt{2}}(\gamma(1-\beta\sin(\theta)) - \cos(\theta))$
- $k_1^{*+} = \frac{k}{\sqrt{2}}(\gamma(1-\beta\sin(\theta)) + \cos(\theta))$

Then plug in. Here "C" is cosine and "S" is sine

$$(k_1^{*+}k_2^{*-} - k_1^{*-}k_2^{*+}) =$$

$$\frac{k^2}{2}[(\gamma(1+\beta S)+C)(\gamma(1-\beta S)+C) - (\gamma(1+\beta S)-C)(\gamma(1-\beta S)-C)] =$$

$$\frac{k^2}{2}[\gamma^2(1-\beta^2S^2) + \gamma C(1+\beta S) + \gamma C(1-\beta S) + C^2 - (\gamma^2(1-\beta^2S^2) - \gamma C(1+\beta S) - C\gamma(1-\beta S) + C^2)]$$

$$= \frac{k^2}{2}(4\gamma C) = 2k^2\gamma\cos(\theta)$$

$$= \frac{2\sqrt{Q^2+Q_T^2}}{Q}\left(\frac{Q}{2}\right)^2 \cos(\theta)$$

$$\therefore \cos(\theta) = 2\frac{(k_1^{*+}k_2^{*-} - k_1^{*-}k_2^{*+})}{Q\sqrt{Q^2+Q_T^2}}$$

Compositeness; Harari Fermions and Bosons

Charge	Preon Makeup	Particles
+1	+++000	W^+
-1	---000	W^-
0	---+++/-+-+00/000000/-+0000	Z_0
0	+-	γ

Charge	Preon Makeup	particle
+1	+++	positron
+2/3	++0	Up quark
+1/3	+00	Anti Down-quark
0	000	e-neutrino
0	000	Anti e-neutrino
-1/3	-00	Down-quark
-2/3	--0	Anti Up quark
-1	---	electron