Looking Beyond the Standard Model with the Jet Cross Section

Ali Al Kadhim

PhD Prospectus

Outline

- Introduction
- Quantum Chromodynamics (QCD) and Jets
- The Inclusive Jet Cross Section
- Short Term/Long Term Plan Summary
- Research Projects Conducted So Far
- Short and Long Term Plans: Details
- Summary

Introduction: The Standard Model

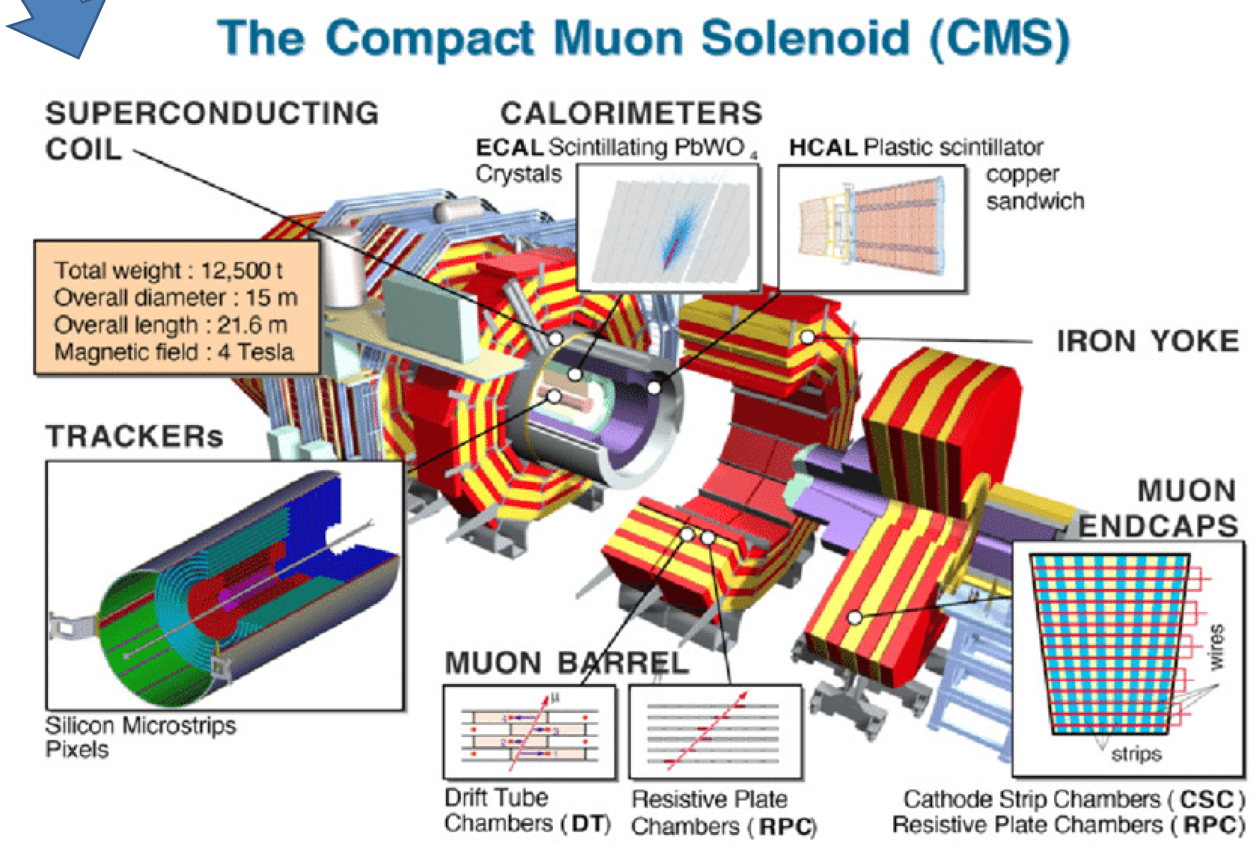
- This is a quantum field theory that describes the fundamental particles in the universe and the interactions between them using 3 out of 4 fundamental forces: Electromagnetism, strong and weak nuclear forces.
- The fundamental particles interact by $SU(3) \times SU(2) \times U(1)$ interactions described by gauge theories.
- Lagrangian:

$$\mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu}^{a} F^{a\,\mu\nu}$$
$$+ i\,\bar{\psi}\, D\, \psi + h.c.$$
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$
$$+ \left| D_\mu \phi \right|^2 - V(\phi)$$

Gauge interactions
Fundamental particles of matter (quarks and leptons)
Yukawa interactions (Higgs to quarks and leptons)
Kinetic term and potential for the Higgs

Introduction: The LHC and CMS

Large **H**adron **C**ollider (**LHC**)



- Largest/most complicated instrument ever built.
- ≈ 600 million proton-proton collisions per second!

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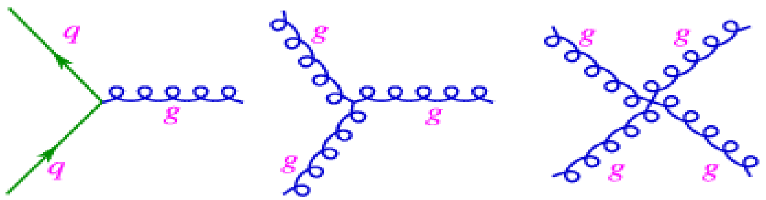
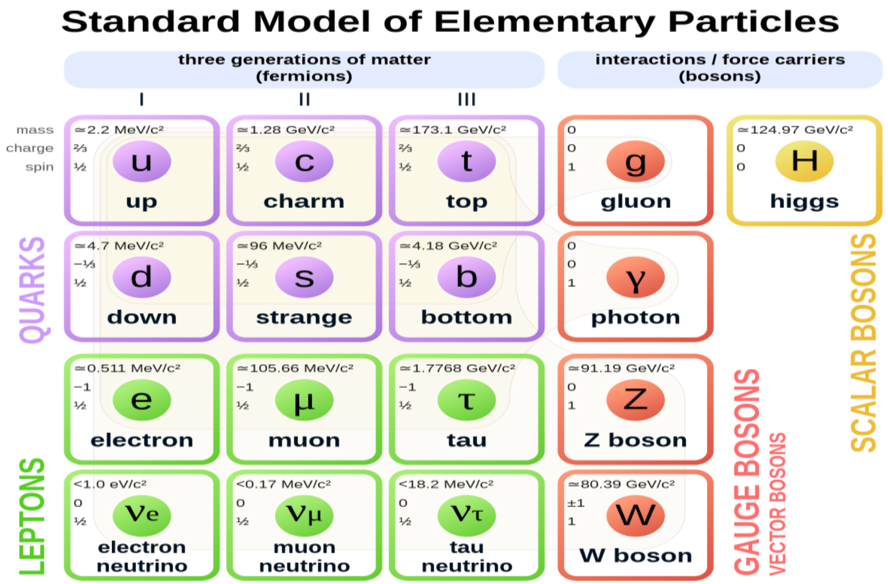
QCD

- My research focuses on the strong force which is described by Quantum Chromodynamics (QCD), which describes the

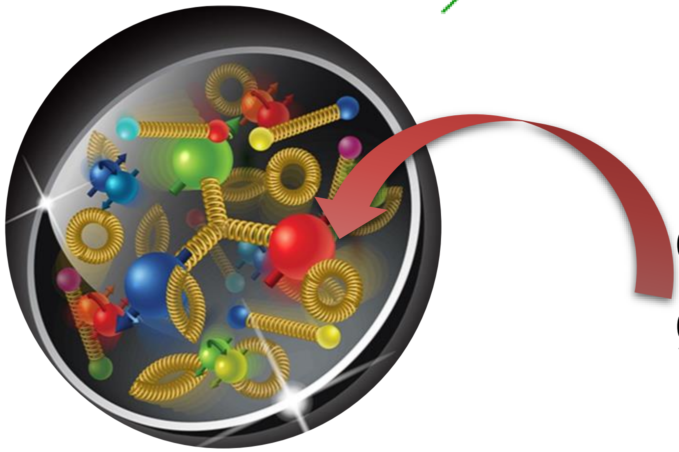
interactions between quarks and gluons.

- QCD interactions:





Proton

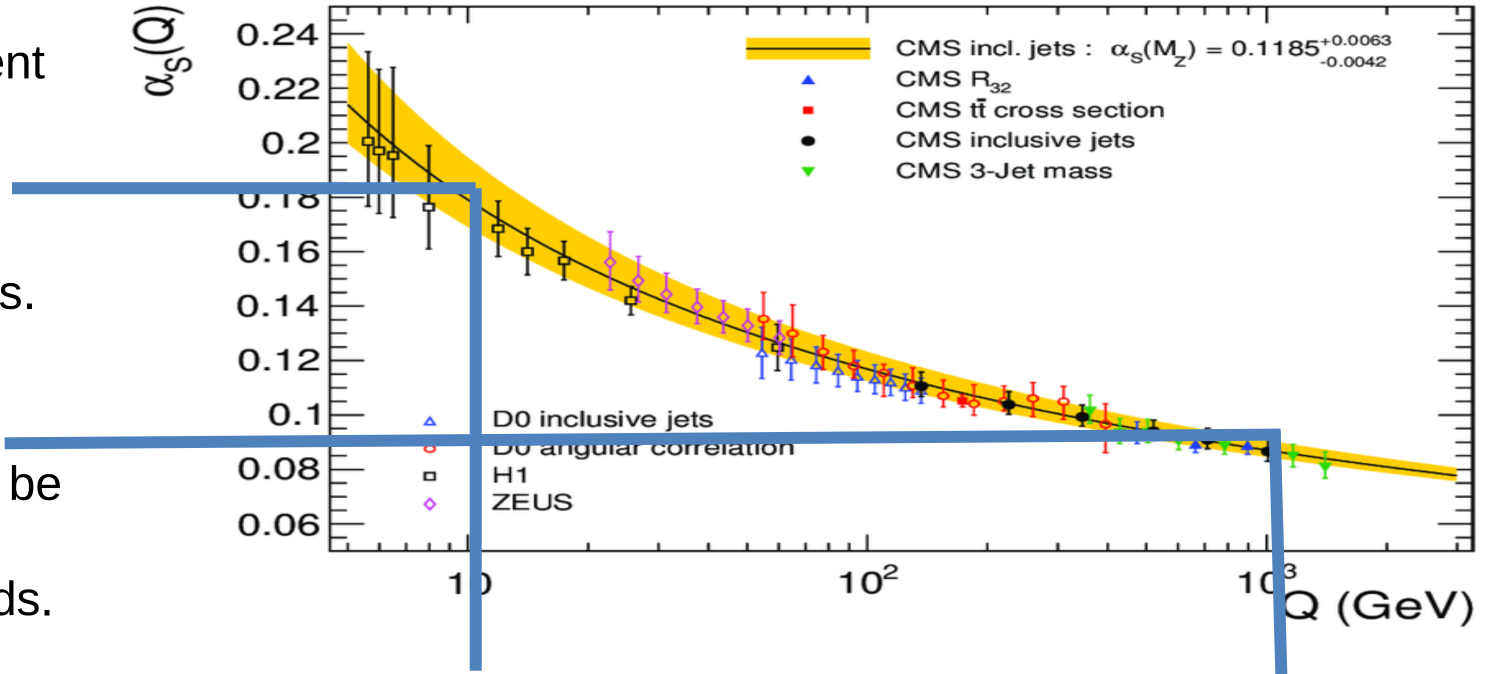


Quarks and gluons: “partons”

What makes QCD special? The coupling parameter α_S decreases with momentum transfer leading to two regimes:

Large α_S: confinement $\rightarrow$ **hadrons** which must be described by non-perturbative methods.

small α_S: **Partons** which can be described with perturbative methods.



Low energy (large distance)

High energy (small distance)

What makes QCD special? The coupling parameter α_S decreases with momentum transfer leading to two regimes:

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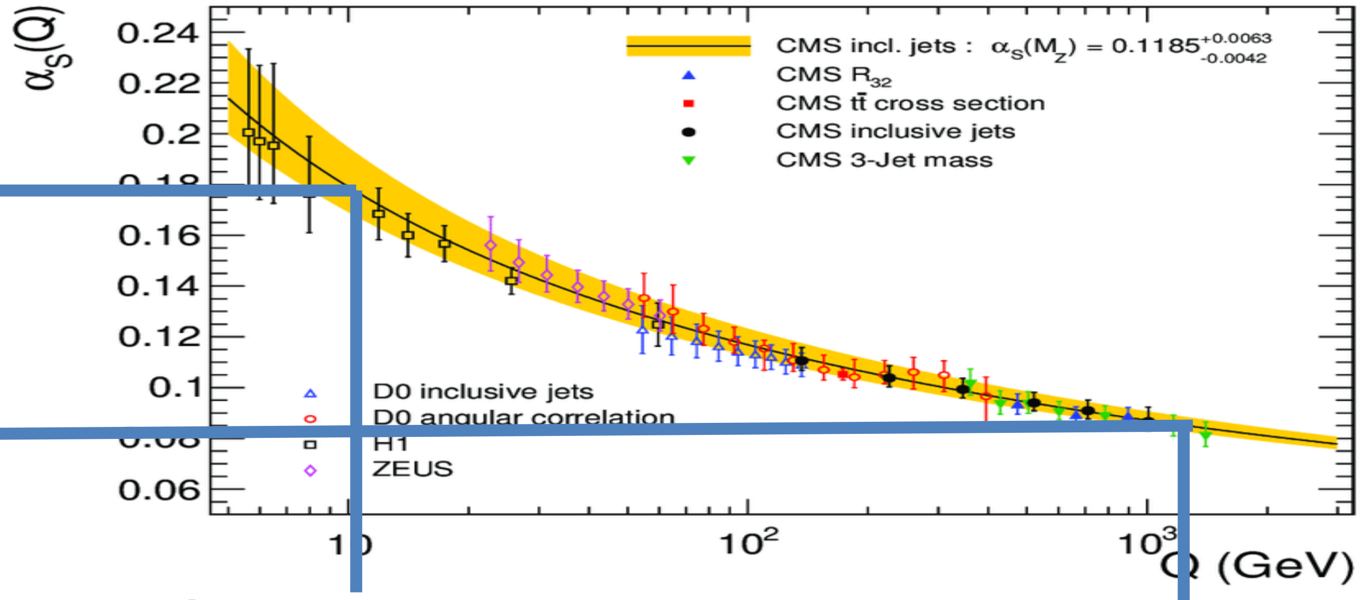
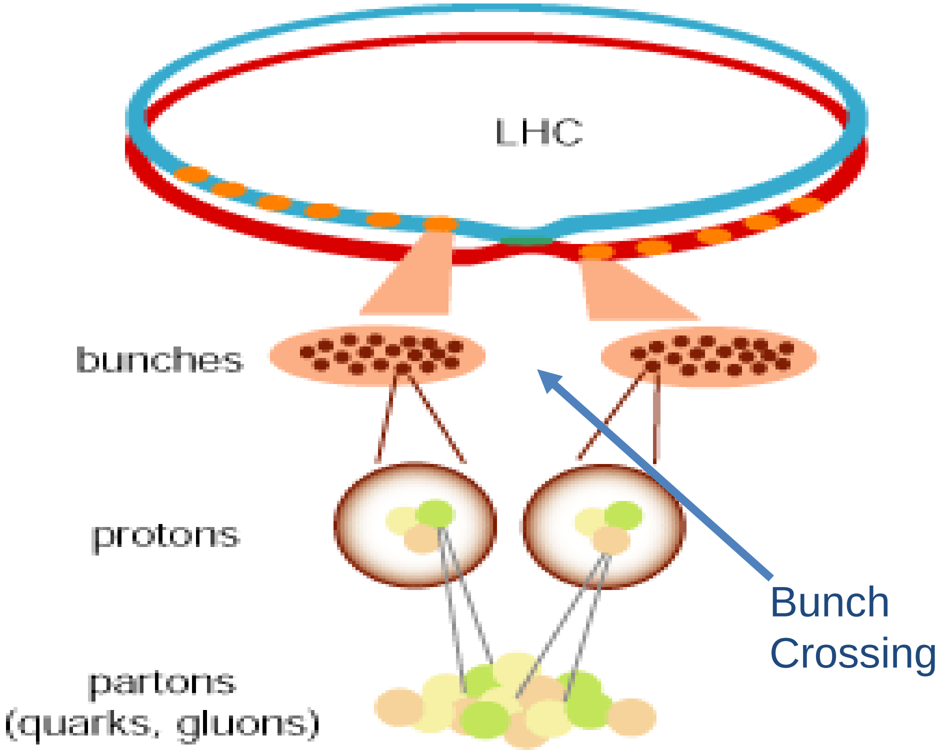


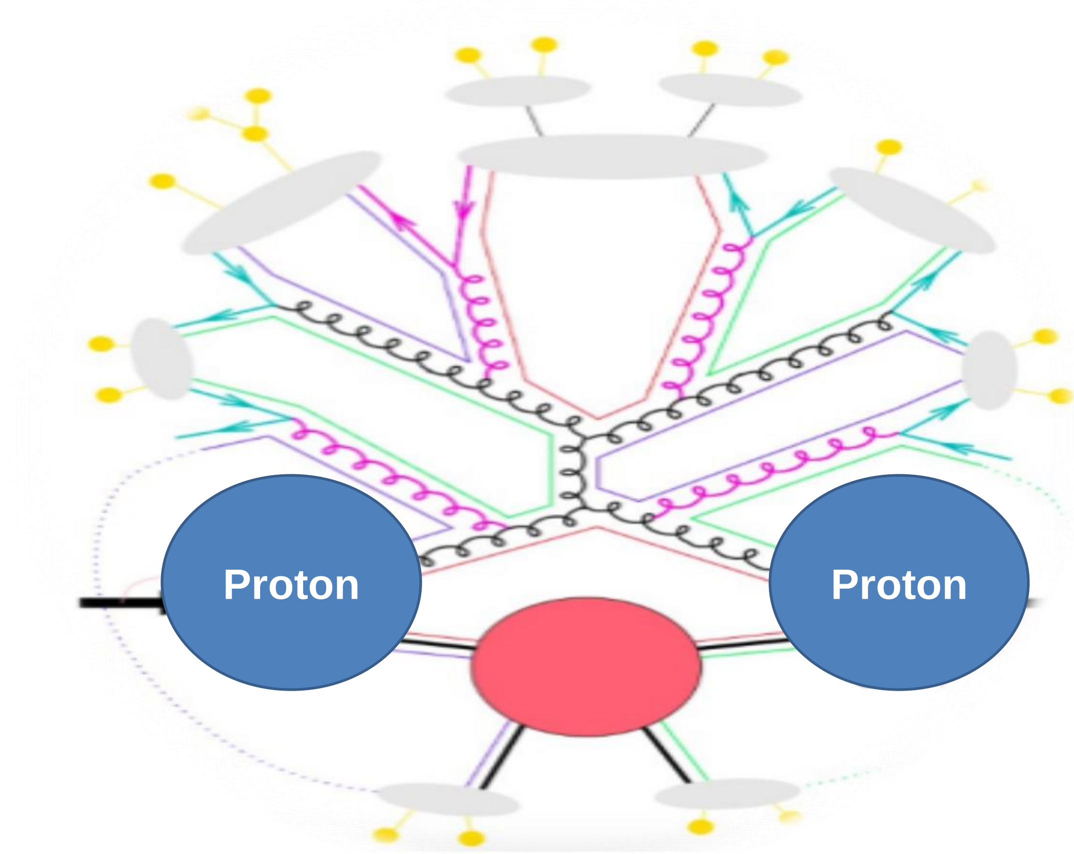
Low energy (large distance)

High energy (small distance)

Quarks have never been observed on their own – instead they form hadrons – they come either in pairs (mesons) or triplets (baryons).

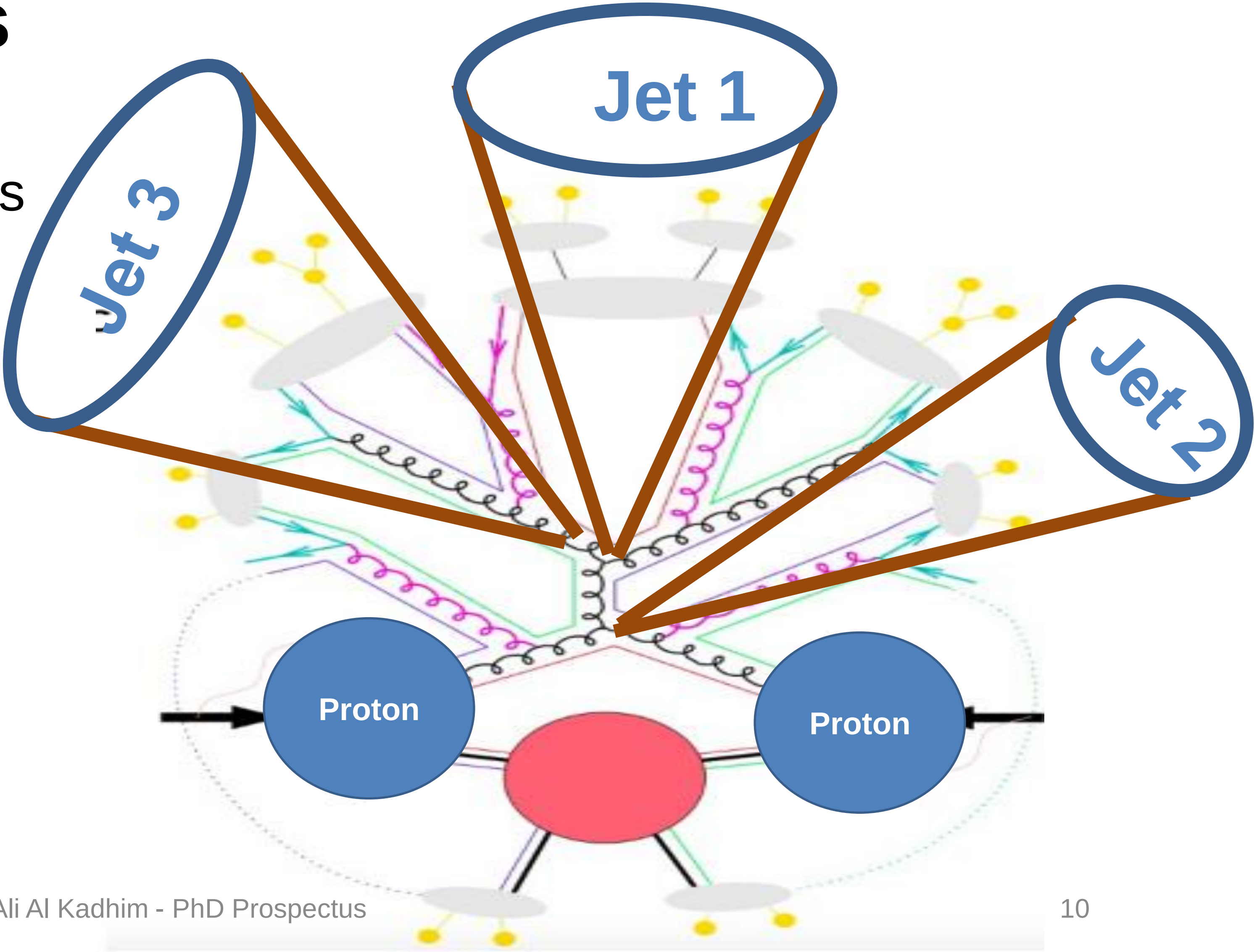
We accelerate protons, collide them, and measure and study the outcomes of the collisions. The collisions between the protons are described in terms of collisions between the partons.





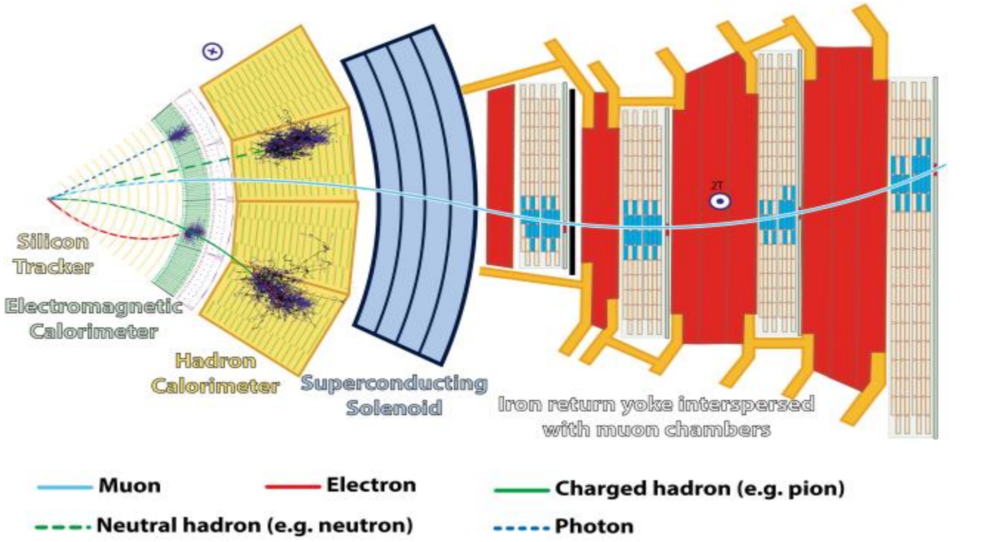
The partons evolve in a shower and combine to form hadrons that form **collimated sprays of particles called jets**

- Jets can be viewed as proxies for the underlying parton interactions.

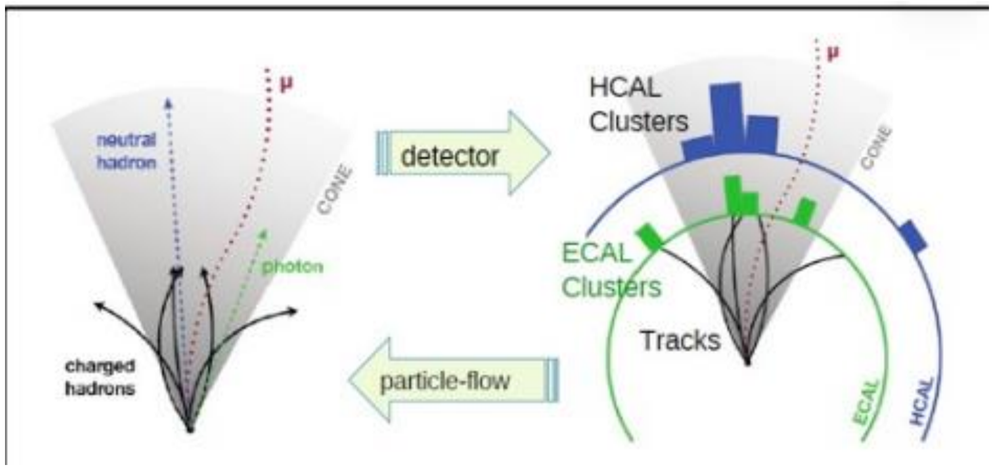


Particle/Jet Reconstruction and Cross Section

- By measuring the energies and paths of particles in the detector, **we can identify the particles**.
- This process is called **reconstruction.**



- Jets are identified, that is, reconstructed using jet algorithms
  - These cluster the hadrons within a “cone” of a given radius which defines a jet.



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Cross Sections

- The **cross section $\boldsymbol{\sigma}$**, with units of area, is a measure of the rate at which a given final state is produced, for example, a final state containing jets.
- Cross sections are the most studied quantities in HEP.

- The inclusive* jet cross section is

$\sigma(pp \to \text{jet} + X)$ where X signifies "anything".

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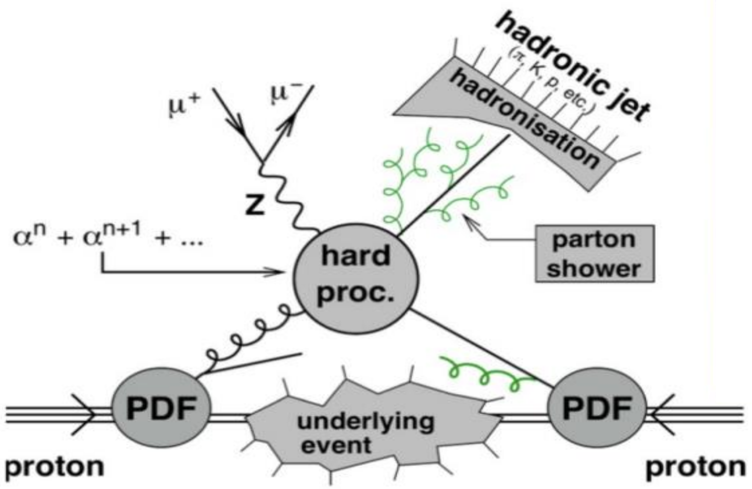
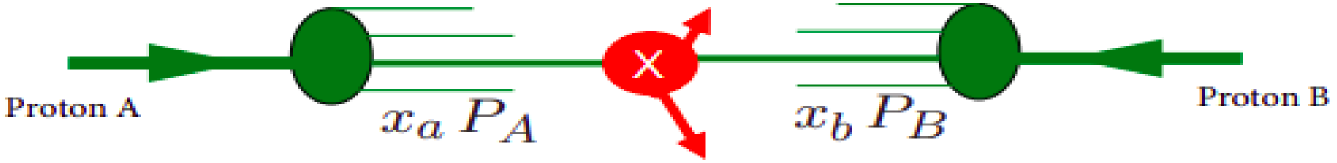


*The word "inclusive" pretains to X, so we mean "X includes everything"

The Inclusive Jet Cross Section: Why is it Interesting?

- The cross section for **any** final state at a hadron collider is given by:

$$\boldsymbol{\sigma = \sum_{a,b} \int_0^1 dx_a dx_b f_{a\in B}(x_a, \mu_F) f_{b\in B}(x_b, \mu_F) \times \int d\Phi_n \frac{1}{2\,\hat{s}} |\mathcal{M}_{ab\to n}|^2 (\Phi_n; \mu_F, \mu_R)}$$



- **The inclusive jet cross section, provides a great deal of information about quarks and gluons**.
- For example, the functions that describe the distributions of quarks and gluons in the proton (Parton Distribution Functions or PDFs) are constrained by these measurements.
- $\boldsymbol{\sigma^{\text{jet}}_{\text{inclusive}}}$ also **tests** various **predictions** of **QCD,** and can be used to measure α_S.
- $\boldsymbol{\sigma^{\text{jet}}_{\text{inclusive}}}$ can also be **used to look for deviations from the Standard Model.**

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Short Term and Long Term Plans: Summary

- **Short Term Plan**: I am joining a team at DESY that will use the full CMS Run 2 dataset to measure the inclusive jet cross section.
  - I plan to go to DESY this summer to work on this project, and our team plans to publish a paper on this measurement within a year of which I will be one of the main co-authors.
- **Long Term Plan**:
  - Perform my own inclusive jet cross section measurement using the early Run 3 data.
  - Having measured this cross section, we will use the measurement to do a Standard Model Effective Field theory (SMEFT) fit to the data to search for physics Beyond the Standard Model (BSM).
  - I will publish the likelihood and full statistical model, such that my results can be used for accurate re-interpretations and predictions.

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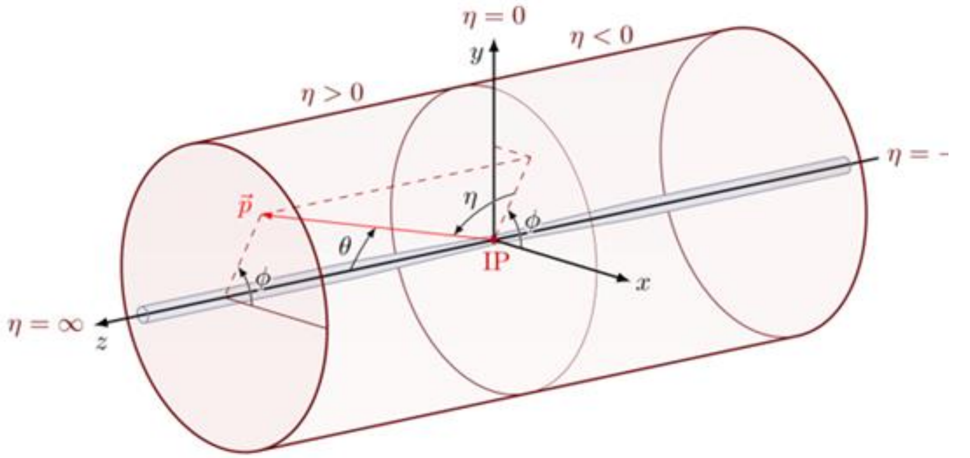
Research and Work So Far

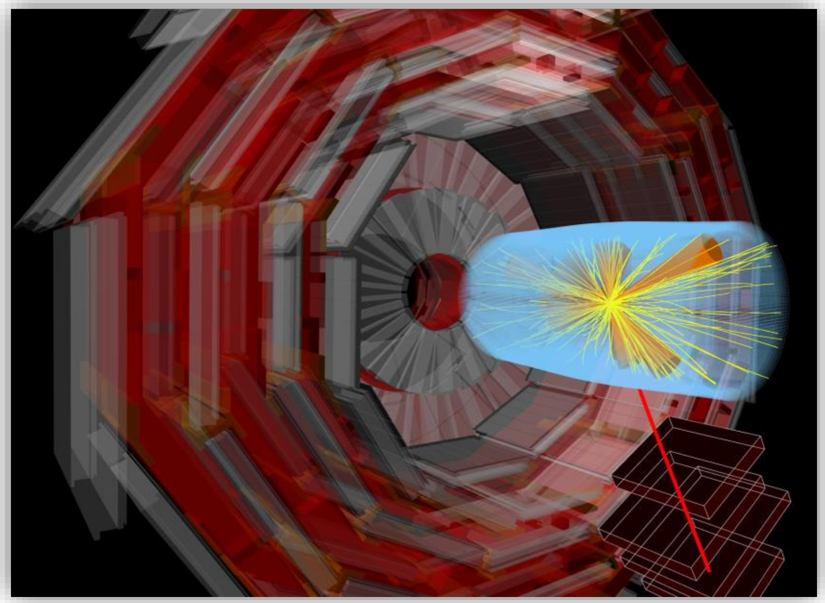
- This measurement requires many areas of expertise and skills, as it is one of the most difficult measurements in HEP.
- In preparation for this measurement, I have been building my skill sets and expertise in relevant particle physics research areas.

- I will present a few research projects that I have conducted so far at FSU, and explain how each of them is relevant for my upcoming research.

1) L1 Prefiring

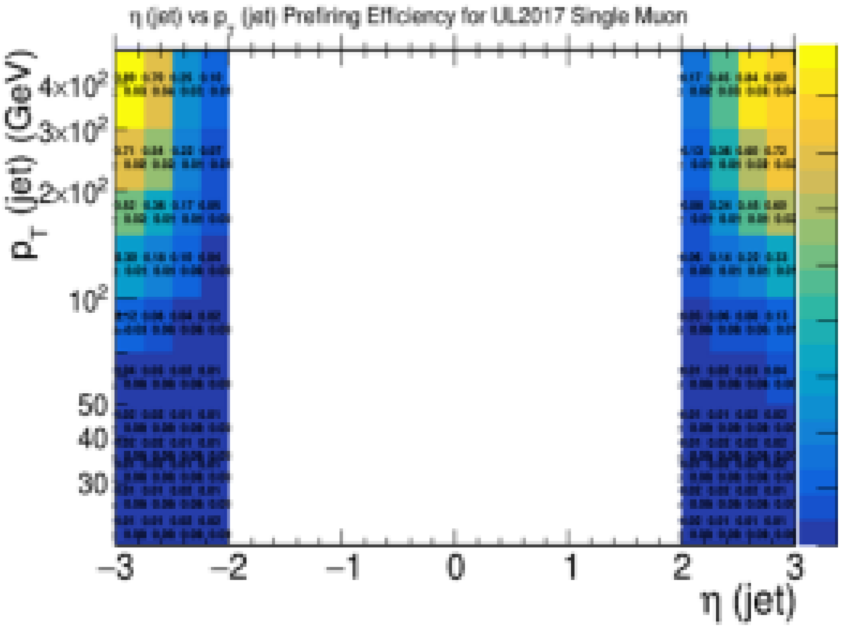
- The CMS Level 1 (L1) Trigger is hardware that decides whether a collision, that is, an event should be kept for further processing (whether the event contains interesting physics).
- From the end of 2016, certain jets and photons in the (forward) region ($2 < |\eta| < 3$, where η is the pseudorapidity) were wrongly associated by the L1 Trigger to the previous bunch crossing, resulting in a loss of events containing jets and photons.
- This effect is not accounted for in the CMS Monte Carlo simulations (MC), so we must correct the simulated events to account for this deficiency.

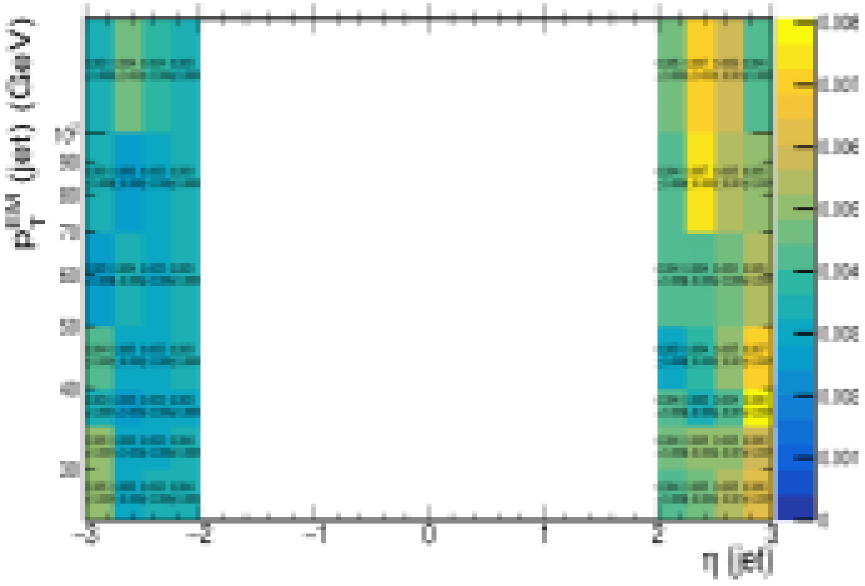




1) L1 Prefiring

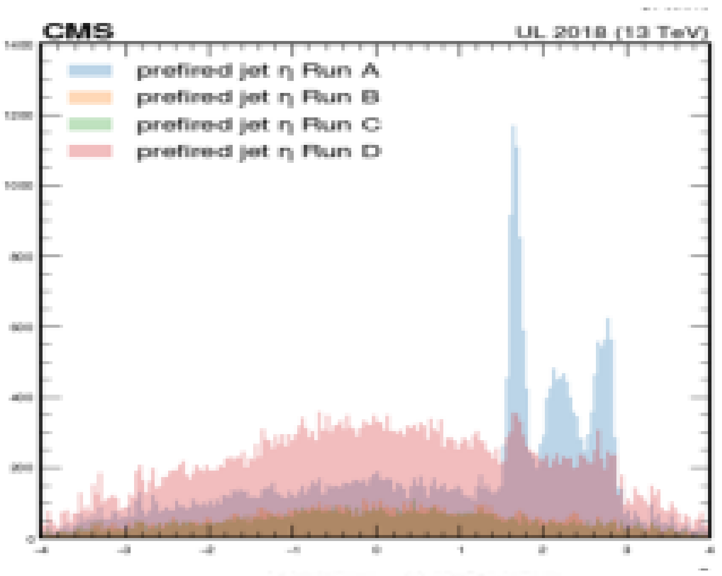
- The L1 trigger can be used to calculate the probabilities of this effect.
- I worked with data from various parts of the detectors and trigger, to produce maps of corrections to be applied to simulated events as a function of transverse momentum (p_T) and η of the jet, for CMS 2017 data.
- The corrections I produced are available centrally (for the entire CMS collaboration) **[1]**.



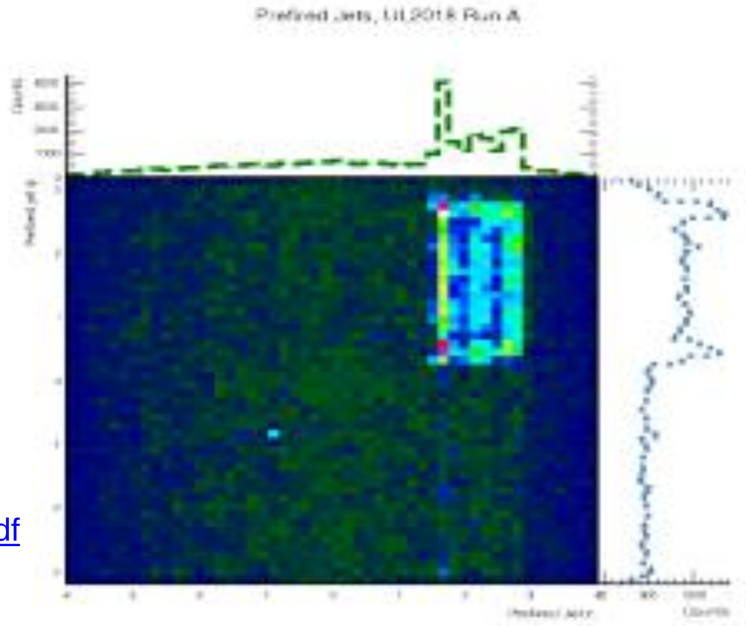


[1] A.A., *Ultra Legacy 2017 Prefiring Maps*. https://indico.cern.ch/event/975504/contributions/4108050/attachments/2144017/3613287/JETMET_UL2017PrefiringMaps.pdf

1) L1 Prefiring: 2018 Discovery



- I discovered a new “prefiring” anomaly in some of the CMS 2018 data – indicating another detector defect **[2]**.
- This effect was confirmed by other groups at CMS.
  - This led to discarding some of the data in which this effect happened from data that was previously deemed to be “good for analysis”, affecting the entire CMS collaboration! **[3]**
- These corrections *must be applied* for future jet measurements using these data!



[2] A.A., *Ultra Legacy 2018 L1 Prefiring Maps*. https://indico.cern.ch/event/1133830/contributions/4757791/attachments/2398918/4102127/L1DPG_UL2018PrefiringMaps.pdf

[3] L.T., *L1 prefiring in run 315705*. https://lathomas.web.cern.ch/lathomas/L1Prefiring/l1prefiringrun315705.pdf

2) PDFs and xFitter

- **PDFs *enter every measurement at the LHC (!),*** therefore, precise determination of them and their uncertainties is paramount for testing SM and looking for new physics.
- PDFs are obtained by fitting theoretical predictions to measurements – assuming that the data are normally distributed and mutually consistent – this affects PDF determination and uncertainties!

$$L(\boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^D|\boldsymbol{\Sigma}|}} \exp\left\{-\frac{1}{2}[\mathbf{x} - g(\boldsymbol{\theta})]^T \boldsymbol{\Sigma}^{-\mathbf{1}}[\boldsymbol{x} - \mathrm{g}(\boldsymbol{\theta})]\right\} \Rightarrow -2\, \boldsymbol{\Delta}\mathbf{log}\, \boldsymbol{L}(\boldsymbol{\theta}) = \boldsymbol{\Delta\chi^2} = \mathbf{1}$$

- **We study to what extent this assumption is true** by recovering the true likelihood of the parameters, using the xFitter code developed at DESY.
- We sample $\theta_i \sim \pi(\theta)$ and weight each parameter point i by $w_\mathrm{i} = \frac{L(\theta_i)}{\pi(\theta_i)}$ **[4,5].**

[4] A.A.,*PDF Uncertainties and Extracting Likelihoods from xFitter* https://github.com/AliAlkadhim/PDF_Uncertainty

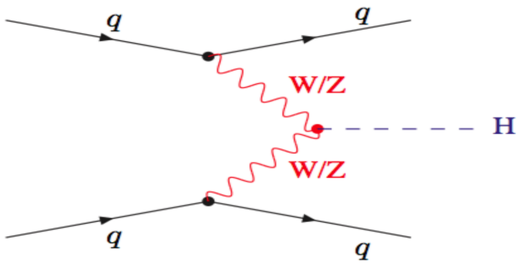
[5] A.A., xFitter Workshop, https://indico.ijclab.in2p3.fr/event/7847/contributions/25471/attachments/18431/24586/xFitter_Workshop2022_Alkadhim2_.pdf

3) Quark/Gluon Jet Discrimination

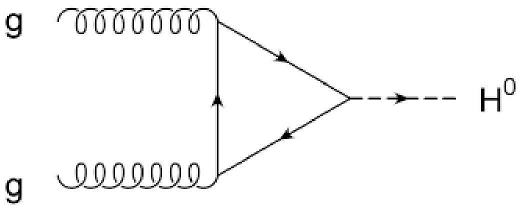
- **Jets can be initiated from either quarks or gluons**.
  - E.g., If one wants distinguish between the process $qq \to Hqq$, which makes quark jets, and the process $gg \to H$, which typically makes gluon jets, the ability to discriminate between quark and gluon jets would be useful.

- A Machine Learning (ML) classifier, $D(x)$, can be used to discriminate between objects, such as quark and gluon jets.

$qq \to Hqq$



$gg \to H$

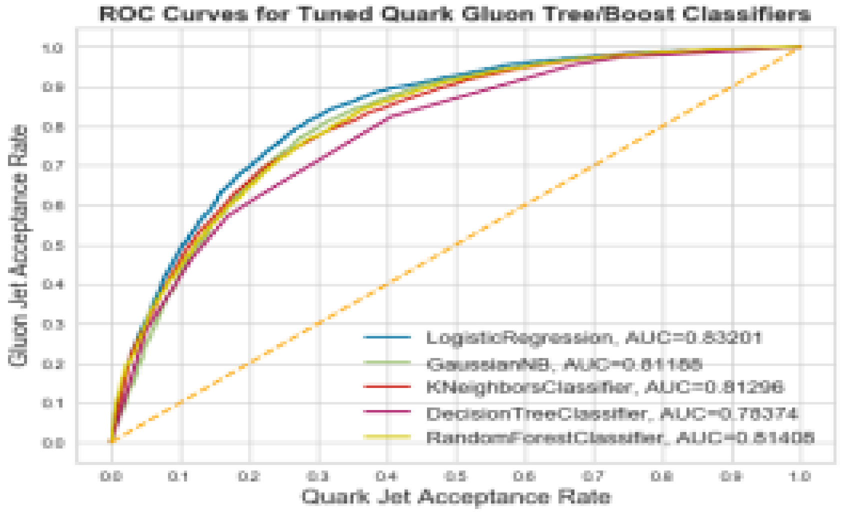


3) Quark/Gluon Jet Discrimination

- Given pure samples of quark and gluon jets, the classifier returns

$$D(x) = \mathrm{P}(\mathrm{gluon}|x) = \frac{\mathrm{P}(x|\mathrm{gluon})\mathrm{P}(\mathrm{gluon})}{\mathrm{P}(x|\mathrm{gluon})\mathrm{P}(\mathrm{gluon}) + \mathrm{P}(x|\mathrm{quark})\mathrm{P}(\mathrm{quark})}$$

$$= \frac{g(x)}{g(x)+q(x)}$$



- But the actual samples are described by mixture models (composed of quark *and* gluon jets):

$G(x) = (1-\epsilon_q)g(x) + \epsilon_q q(x)$,

$Q(x) = (1-\epsilon_g)q(x) + \epsilon_g g(x)$.

- $D'(x) = \frac{G(x)}{G(x)+Q(x)} = \frac{(1-2\epsilon_q)D(x)+\epsilon_q}{1-\epsilon_g+\epsilon_q+2(\epsilon_g-\epsilon_q)D(x)}$
- $D'(x)$ is a function of $D(x)$ only since the fractions are constants, so we can reach optimal classification by studying the range of fractions where $D'(x)$ and $D(x)$ are one-to-one!

4) Highest p_T Jet observable

- A jet cross section can be studied as a (differential) function of a jet observable, e.g.

$$\frac{d\sigma_{\text{jet}}}{dp_T} \sim \sum_{a,b} \int dx_a f_{a\in \mathrm{A}}(x_A,\mu) \int dx_b f_{b\in B}(x_B,\mu) \frac{d\sigma_{\text{partons}}}{dp_T}$$

- The aim of this study was to determine the extent to which the p_T of the highest-p_T jet in an event is a suitable observable.
- We choose this observable so that there is only one instance per event, to avoid cumbersome bin correlations that occur in past and ongoing measurements.

4) Highest p_T Jet observable

- Due to finite detector resolution and other detector effects, the observed spectra differ from the predicted ones.

- To carry out comparisons between data and theory, we either:
  - "**unfold**" the data (remove detector effects), or
  - "**fold**" (smear) theory predictions.
- The commonly used unfolding techniques uses a "response matrix" which entails assumptions and approximations.

4) Highest p_T Jet observable

- We study if we can use this observable to fold the predicted (generated, or gen) observable spectrum to the measured (reconstructed, or rec) observable spectrum using ML techniques.

$$p_T^{\text{gen}} \xrightarrow{\textbf{ML model}} p_T^{\text{rec}} \quad : \quad f(p_T^{\text{rec}}) = \int R\left(p_T^{\text{rec}} \middle| p_T^{\text{gen}}\right) g\left(p_T^{\text{gen}}\right) dp_T^{\text{gen}}$$

- We found that if we wanted to use the highest jet p_T as an observable, we must account for the probability that the order of the highest jet p_T^{rec} is flipped with respect to highest jet p_T^{gen}.
  - The relative frequency at which this flipping occurs was found to be $\approx 4\%$.

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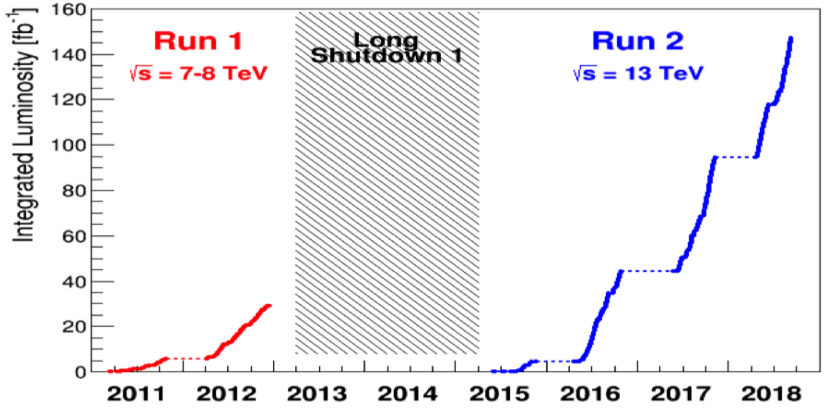
Short Term Plan: Inclusive Jet Cross Section Measurement

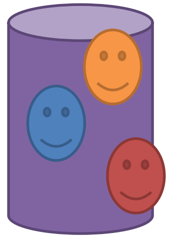


- I am joining the team at DESY that will use the full Run 2 dataset to measure $\frac{d^2\sigma_{\text{jet}}^{\text{inclusive}}}{dp_T\, d|y|}$.
- We plan to publish this measurement, for which I will be one of the main co-authors.

$$\frac{d^2\sigma_{\text{jet}}}{dp_T\, d|y|} = \sum_{a,b} \int dx_a f_{a\in \text{A}}(x_A,\mu) \int dx_b f_{b\in B}(x_B,\mu) \frac{d^2\sigma_{\text{partons}}}{dp_T\, d|y|}$$

Experimentally

$$\frac{d^2\sigma_{\text{jet}}}{\mathrm{d}p_\mathrm{T}\mathrm{d}|\mathrm{y}|} = \frac{1}{\epsilon\mathcal{L}} \frac{N_{\text{jets}}}{\Delta p_T \Delta|y|}$$

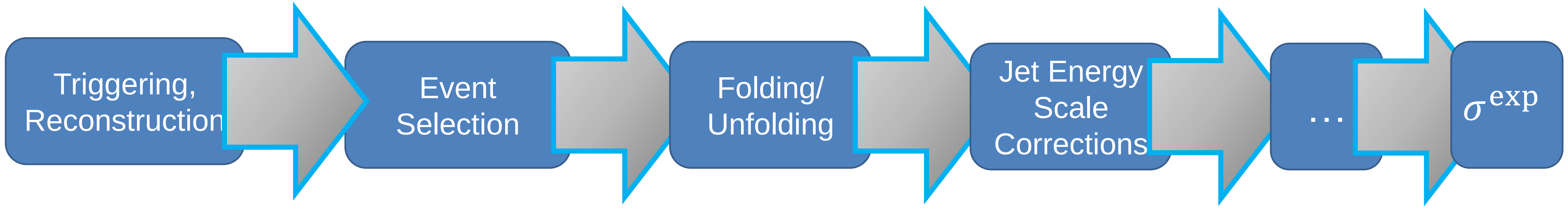


Jet 1
Jet 2
…

Bin of jets

Long Term Plan in Depth

- Run 3 of the LHC will start next year.
- I will use the early Run 3 data to do my own measurement of the inclusive jet cross section.
  - I will be among the first to analyze the early Run 3 Data.
- The inclusive jet cross section is a very complicated measurement!



Cross Section Measurement

- I will measure this using an **observable for which there is only a single observable per event.**
  - This is done so that we can avoid problematic correlations between the different observable bins. This will simplify the construction of the likelihood function.
  - It will also make finding signals for BSM physics more feasible, since every bin will be independent, increasing the sensitivity of the search.
  - This **observable must be one for which predictions can be made** at next-to-leading-order (NLO) or next-to-next-to-leading-order (NNLO) in QCD.
- I will work with theorist Jun Gao, to find such a suitable observable.

SMEFT Fit Using My Cross Section Measurement

- The Standard Model Effective Field Theory (SMEFT) is a generalization of the SM built out of higher dimensional operators ($\mathcal{O}_i$), composed of SM fields.
- $d = 6$ SMEFT is the most theoretically-motivated and studied SMEFT:

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{SM} + \sum_{i=1}^{n_{op}} \frac{c_i^{(d=6)}}{\Lambda^2} \, \mathcal{O}_i^{(d=6)}$$

- The $d = 6$ operators can model, for example, 4-quark contact interactions.

SMEFT Fit and Search for Contact Interactions

- The theoretical cross section could be calculated in terms of the SMEFT (Wilson) Coefficients $\boldsymbol{c}$; $\sigma^{\text{theor}} = \sigma^{\text{theor}}(\boldsymbol{c})$.
- Of particular interest to me are the operators in $d = 6$ SMEFT which could signify quark compositeness.

- Having measured the inclusive $\sigma_{\text{jet}}^{\text{exp}}$, I will work with theorist Jun Gao to compare $\sigma_{\text{jet}}^{\text{exp}}$ to $\sigma_{\text{jet}}^{\text{theor}}(\boldsymbol{c})$, and fit ***all*** the Wilson coefficients $\boldsymbol{c}$ that are relevant for 4-quark contact interactions simultaneously.

Publishing the Statistical Model/Likelihood

$$\mathrm{P}(\boldsymbol{X} = \boldsymbol{x} | \boldsymbol{\theta}) = L(\boldsymbol{\theta})$$

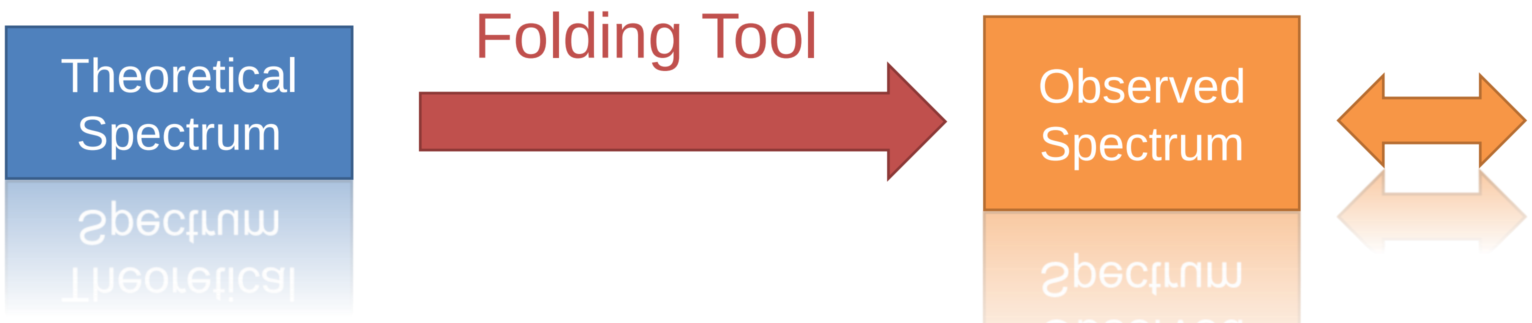
Observed data Parameters Likelihood

- **A likelihood function is *all that is needed*** for fitting different models to results, re-interpretations, and combining results from multiple experiments, ***without any approximations*** *(such as those assumed by unfolding techniques)**!*** (See **[6]**).
- I plan to publish the differential cross section in the form of a likelihood function.
- I will be the first person in CMS to publish the full statistical model, e.g., on HEPData, in a form that could be used by theorists and other interested parties.
- The best-fit parameters of a particular model, $\hat{\theta}$ can be found simply by minimizing $-\sum_{i=1}^{n_{\text{datasets}}} \log L_i(\theta_i)$.

[6] K. Cranmer, S. Kraml, H.B.P. et. al. "*Publishing statistical models: Getting the most out of particle physics experiments*" https://scipost.org/SciPostPhys.12.1.037/pdf

Publishing the Statistical Model + Folding Tool

- We want to do a paradigm shift in HEP such that experimental collaborations *routinely* publish their likelihoods.
  - This avoids all the assumptions and approximations of unfolding.
- This motivates the publication of fast and accurate folding tools *along with* the likelihood that would allow theorists to quickly fold their predictions and compare with the experimental results.



Now this is what will be used to compare with the results in the likelihood function

Summary

- The jet cross section is ***one of the most important measurements at the LHC***, as offers a great deal of information about quarks and gluons, and tests various predictions of the SM.
- During my time at FSU so far, I have conducted various research projects, and ***have built my skill sets in many areas of particle physics that are directly relevant for my future research plans***.
  - The results of my previous research will also be crucial to apply in future research plans.
- **Short term plan**: finish inclusive $\sigma_{\text{jet}}^{\text{exp}}$ measurement for Run 2.
- **Long term plan**:

Measure the inclusive $\sigma_{\text{jet}}^{\text{exp}}$ for Run 3 using a new observable → Compare σ_{jet}^{exp} to $\sigma_{jet}^{theor}(c)$ in SMEFT to fit $\boldsymbol{c}$ → Search for contact interactions → Publish the likelihood along with ML folding tools

Thank you!

Backup

Cross Sections: How they would be changed by CI’s, Inclusive vs Exclusive and Contact Interactions Meaning

- $\boldsymbol{\sigma}^{\boldsymbol{inclusive}} = \boldsymbol{\sigma}(\boldsymbol{pp} \to \boldsymbol{jet} + \boldsymbol{X})$ **where $\boldsymbol{X}$ means “anything” . It is the $\boldsymbol{X}$ that is inclusive, ie includes every possible object one can think of. $\boldsymbol{\sigma}^{\boldsymbol{exclusive}}$ You specify exactly what you want in your final state – e.g. exactly one jet, exactly one lepton, etc.**

- If there are Cis we expect the cross section to increase in the small rapidity bin(s). During the 1960s DIS experiments, they observed the cross section to increase (as a consequence of quarks), because as they reached those energies, you have more scattering centers. If you’re a point particle with no substructure, then the higher the energy the lower the cross section would be, because its still a point particle. But if at some point the point particle resolves itself into multiple point particles, then the cross section would be larger than it would otherwise be, because now you have lots of points, so lots of chances for scattering.

- There is no such thing as 4-quark point interactions called contact interaction – all interactions, as far as we can tell, are mediated by bosons. But if you look through a poor microscope then you would notice that this exchange that was carried out by the boson, so you can approximate this interaction as if it occurred at a point. At the energy of the LHC, we can approximate that as a CI.

2 Reasons that unfolding is an approximation

- **The basic assumption is that the response spectrum is independent of the response matrix is independent of the theoretical spectrum. But that cannot be. From the long version of my prospectus:**

$$\vec{\nu} = R\vec{\mu} \tag{4.8}$$

Or $\nu_i = \sum_{j-1}^{N} R_{ij}\mu_j$, where R is an $N \times M$ the response matrix such that R_{ij} represents the probability to measure ν in bin i given that its true value μ was in bin j. Please not that 4.8 is not strictly correct as it entails an approximation. The actual formula that is meant by such an expression is

$$\nu(x) = \int \underbrace{P(x|y)}_{"R"} \mu(y)\ dy \tag{4.9}$$

And even if we discritize this integral in equation 4.9, it's still that for every bin this holds; suppose that i labels the bins in the space of observations, and j labels the bins in the space of theory, then we have $\nu_i = \int P(x_i|y_j)\mu(y_j)dy_j$. If we have the bins being very narrow, [4] then one could argue that the expression actually reaches the continuous expression in equation 4.9, or in a binned scenario, $\nu_i = R(x_i|y_j)\mu(y_j)\Delta y_j$. However, if the bins are wide, then R in equation 4.8 actually depends on μ. Therefore we argue that unfolding is misguided and mathematically ill-defined [5] and that we should avoid this unfolding completely!

Suppose we chose our observable to be something like the dijet invariant mass M_{jj} or the dijet average p_T^{avg}, then the question becomes whether will we define the spectrum such that we will restrict the jets to be in the same rapidity bin or not.

How to convert σ to a probability, and why $L(\theta) = L(\sigma)$

- A cross section has units of area so in order to get a probability you divide by another cross section like the total cross section.
- **This is one of the reasons that we want to avoid correlations across bins, is that if the bins are independent, then you can just multiply together a bunch of poisson distributions, or if you divide by the total cross section you can have a multinomial distribution, which makes the construction of your likelihood function much simpler because you're not taking into account any correlations.**

- The likelihood should be parameterized by σ, ie we want $L(\theta = \sigma)$ so that assuming a theory (like SUSY, dark matter, etc) which predicts σ , you can compare to it.
- Imagine if I have my likelihood parameterized in terms of say the Wilson coefficients, then comes theorists who want to use my result for SUSY or dark matter fit and they are stuck. Because my likelihood is parameterized in terms of something else so they cant directly compare.

Gauge Symmetry of the SM

- The SM is a gauge (local, meaning having different phases at different spacetime points) theory based on the symmetry group (**which makes $\mathcal{L}$ invariant under these tranformations**)

$$\underbrace{\mathrm{SU}(3)_c}_{\text{strong}} \otimes \underbrace{\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y}_{\text{electroweak}} \rightarrow \mathrm{SU}(3)_c \otimes \underbrace{\mathrm{U}(1)_Q}_{\text{em}}$$

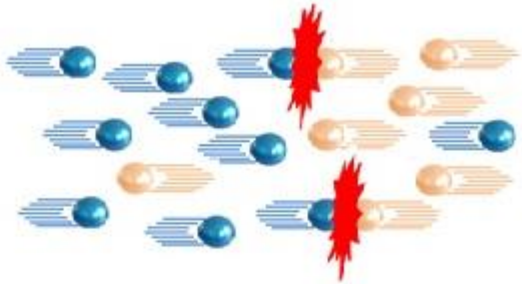
- With the electroweak symmetry spontaneously broken to the electromagnetic $\mathrm{U}(1)_\mathrm{Q}$ symmetry by the Higgs mechanism.
- **If you have a symmetry group you have conserved quantities like charges**. For example for QCD, the physical consequence of gauge inv is that you have conserved charge.
- Interaction vertices come as a consequence of gauge invariance.
- Typical reasoning for imposing gauge invariance is that if you assume a global symmetry you assume that the phase (that you multiply the field by) is the same everywhere in spacetime, whereas in a local symmetry you could have a different phase in every point in space and time. The typical argument is just an assumption: "why would people very far away in the universe should have the same phase to rotate their field as we do here?".
- When you introduce gauge invariance your Lagrangian might not work anymore, you introduce gauge fields (bosons) to make it work again (which give you interactions).

- SM can be summarized in terms of its particles and symmetry group representation (color, weak isospin, hypercharge):

Symmetry Group	Number of generators (= number of gauge bosons that mediate it)	Abelian?
$\mathrm{U}(1)$	1	Yes
$\mathrm{SU}(\mathrm{n})$	$n^2 - 1$	No

Multiplets	$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	I	II	III	$\boxed{Q = T_3 + Y}$
Quarks	$(\mathbf{3},\ \mathbf{2},\ \frac{1}{6})$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\frac{2}{3} = \frac{1}{2} + \frac{1}{6}$ $-\frac{1}{3} = -\frac{1}{2} + \frac{1}{6}$
	$(\mathbf{3},\ \mathbf{1},\ \frac{2}{3})$	u_R	c_R	t_R	$\frac{2}{3} = 0 + \frac{2}{3}$
	$(\mathbf{3},\ \mathbf{1},\ -\frac{1}{3})$	d_R	s_R	b_R	$-\frac{1}{3} = 0 - \frac{1}{3}$
Leptons	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2})$	$\begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu_L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau_L} \\ \tau_L \end{pmatrix}$	$0 = \frac{1}{2} - \frac{1}{2}$ $-1 = -\frac{1}{2} - \frac{1}{2}$
	$(\mathbf{1},\ \mathbf{1},\ -1)$	e_R	μ_R	τ_R	$-1 = 0 - 1$
	$(\mathbf{1},\ \mathbf{1},\ 0)$	ν_{e_R}	ν_{μ_R}	ν_{τ_R}	$0 = 0 + 0$
Higgs	$(\mathbf{1},\ \mathbf{2},\ \frac{1}{2})$	(3 families of quarks & leptons)			

Bunch Crossings and Luminosity



- We aim to squeeze the beam size down as much as possible at the collision point to increase the chances of a collision, therefore we collide protons in bunches.
- We squeeze $1{,}15 \cdot 10^{11}$ protons per bunch down to 64 microns

$$N = L\,\epsilon\,\sigma$$

Number of observed events

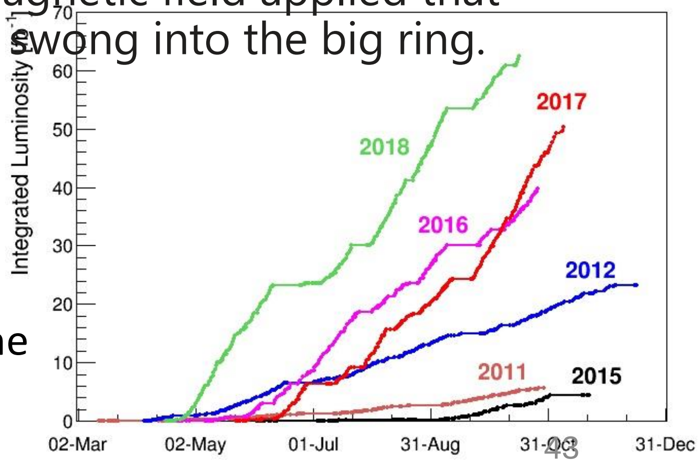
Integrated luminosity (m^{-2})

Efficiency (acceptance)

Production cross section (m^2)

- Protons in LHC start in a hydrogen gas tank, atoms are then stipped of their electrons leaving just the protons. Then they are accelerated by an electric field linearly. They then enter (4) loops where the electric field is now **pulsed at a frequency** (oscillating system), as well as there is a magnetic field applied that makes them bend around the circles. Then these packets or bunches are then swong into the big ring.
- Luminosity measures how tightly packed the particles are in the beams

that cross. The tighter the squeeze, the more likely it is that some of the particles will collide.. It is also important to keep the luminous region, that is the region in space across which events are distributed, optimised to the acceptances of the detectors.



Units

- In HEP we use "natural units" in which there is only one fundamental dimension, energy (or mass). This is accomplished by setting $\hbar = c = k_B = 1$, such that the units of quantities (indicated by [ ]) is
- $[\text{Energy}] = [\text{Mass}] = [\text{Temperature}] = [\text{Length}]^{-1} = [\text{Time}]^{-1}$.
- $L_{SI} = L_{natural} \times hc$ -> size of proton ~ 1 Fermi=10^-15 m

Coupling Constants		
Strong	α_s	1
Electromagnetic	α	1/137
Weak	α_W	10^{-6}
Gravity	α_g	10^{-39}

What’s PT? And what are renormalizable theories?

- A perturbative process is a process in which the energy transfer is small and if you look at the α_S plot, high energy mean low values of α_S so that you can get good results by using perturbation theory in QCD. Of course this regime is also small distances (interactions between partons). PT works in this regime because you can do expansions in α_S such that your series converge. Whereas in low energy (high α_S and long distance) the coupling is too big to use PT so your series in PT do not converge – you have non perturbative (confining) dynamics.
- When you have a finite number of functions (counterterms) in which you can absorb those infinities, and this finite number of functions doesn’t change as you go to higher and higher orders, such theories are called renormalizable theories.

QCD, and $\boldsymbol{\mu_{F,R}}$ scales

- **Factorization** means $\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \; \hat{\sigma}_{ab\to X}$.

The Q^2 that appears in the PDFs is a large momentum scale that characterizes the hard scattering, eg $M_{dilepton}$

- $\boldsymbol{\mu_F}$ can be thought of as the scale that separates short and long-distance physics.
- μ_R is the renorm alization scale for the QCD running coupling. In QED, the natural scale (Q^2) which you define the electric charge is $Q^2 = 0$, because you can define the electric charge very far away from the electron. The scale at which you define these charges is μ_R .

- In order to avoid unnaturally large logarothms appearing in the perturbation series it is sensible to choose μ_R and μ_F as the typical momentum scales in the hard scattering process. EG in Drell yann production you can choose $\mu_R = \mu_F = M_{final\ state} = M_{dilepton}$
- **the PDFs and hard scattering cross section be calculated in the same order in QCD because of the arbitrariness of these scales.** The physical thing is the LHC which is the cross section. The RHS is an approximation, and you are free to shift between the red and green pieces… Factorization scale tells you where to draw that boundary between short and large distance (which is arbitrary of course). If you were to calculate the cross section to infinite order, then the choice of μ_F has no consequence.