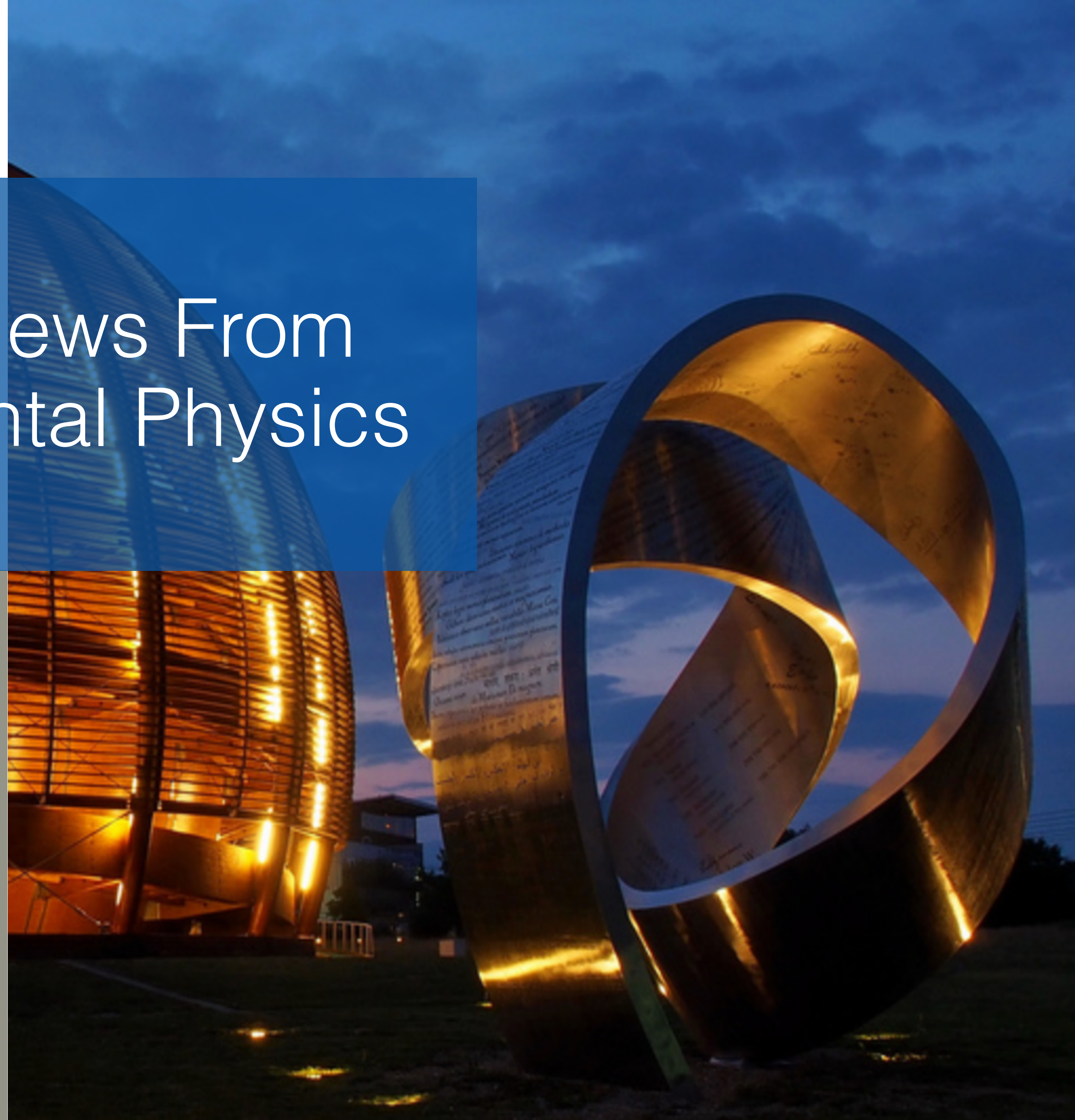
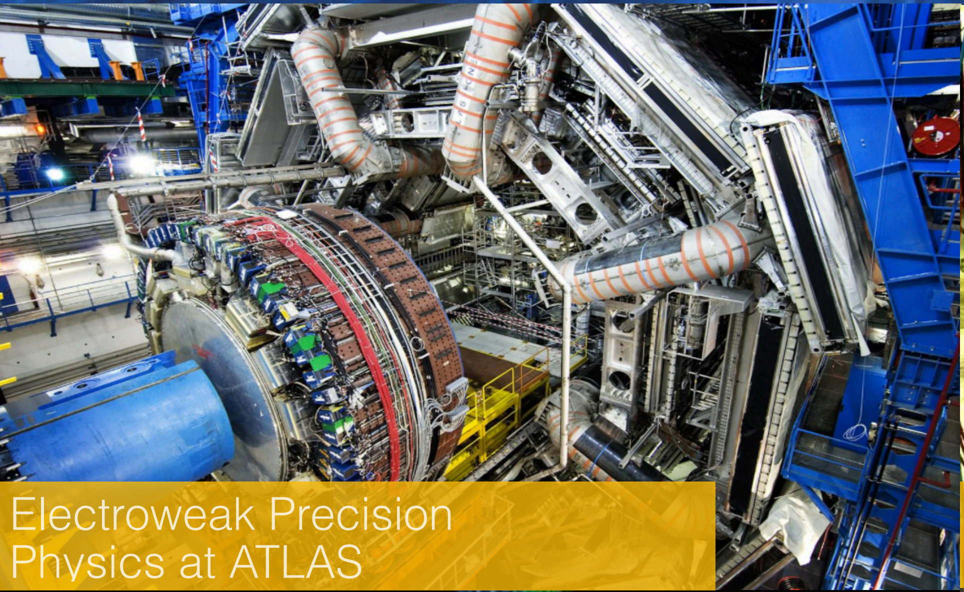
Exciting News From Fundamental Physics

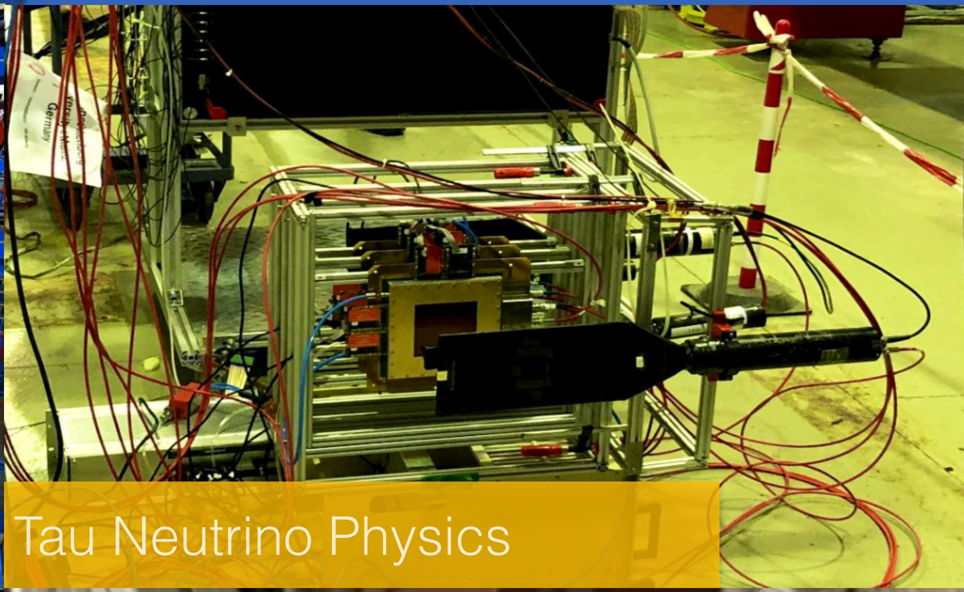


My research team does many amazing things

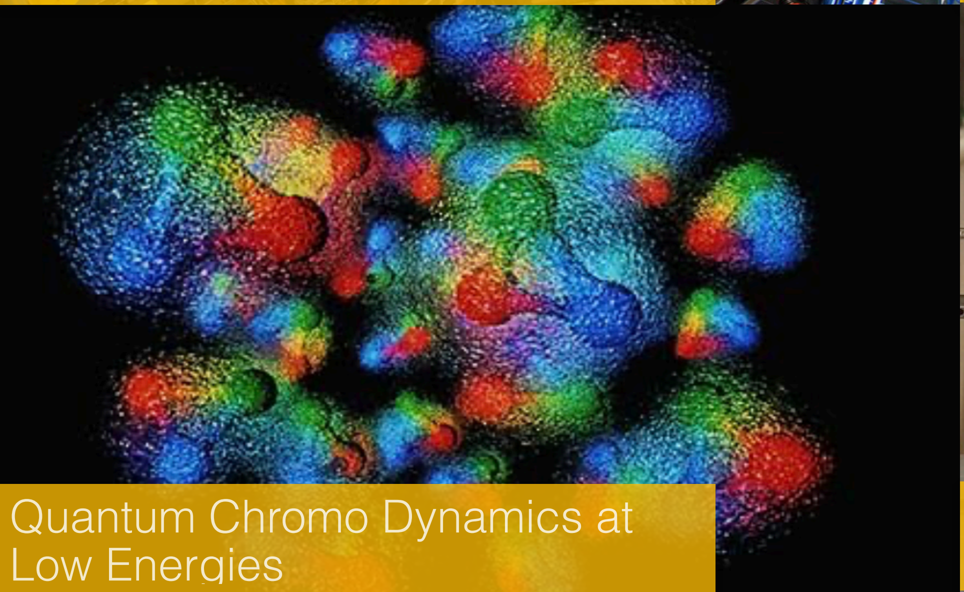
What will we talk about today?



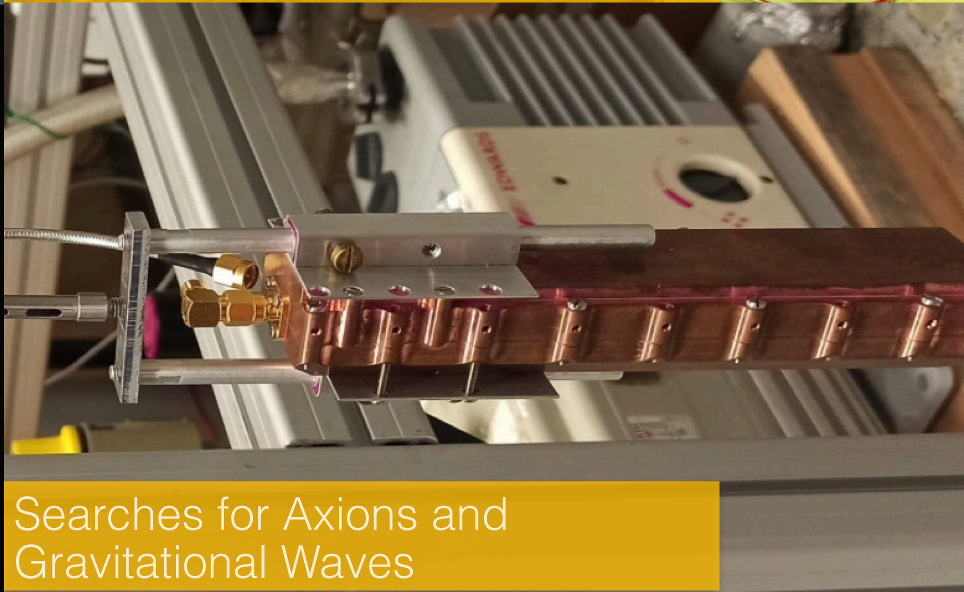
Electroweak Precision Physics at ATLAS



Tau Neutrino Physics

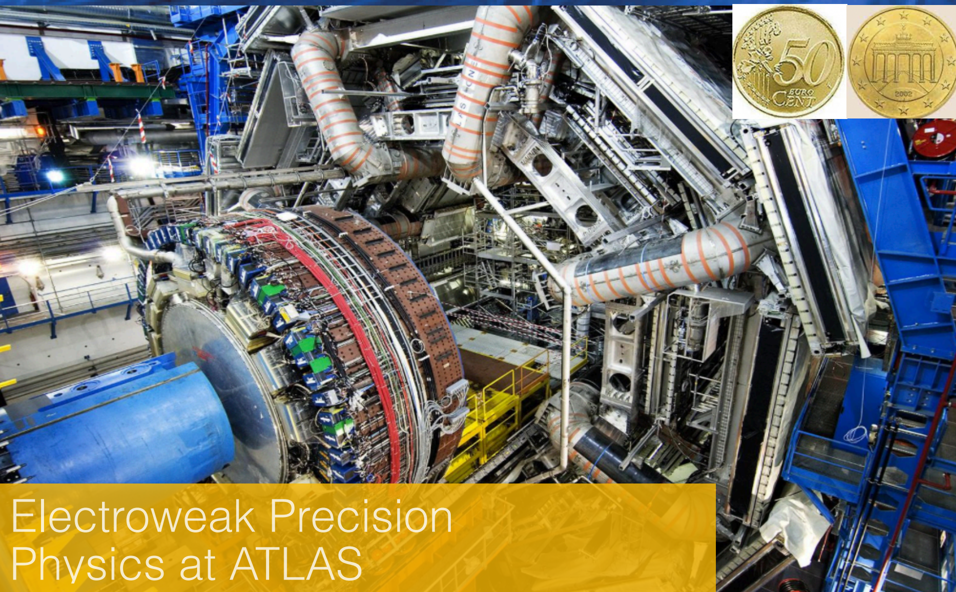


Quantum Chromo Dynamics at Low Energies

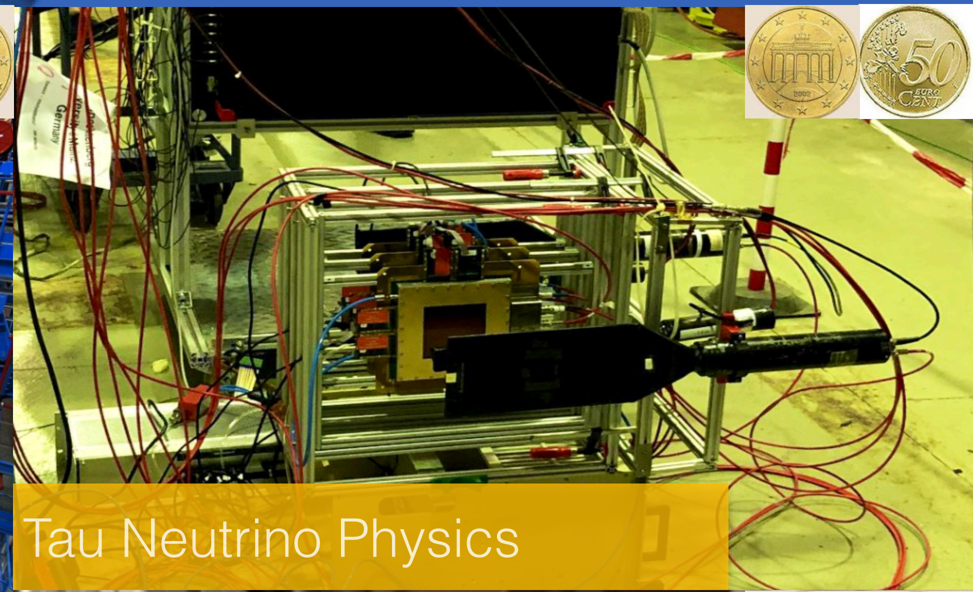


Searches for Axions and Gravitational Waves

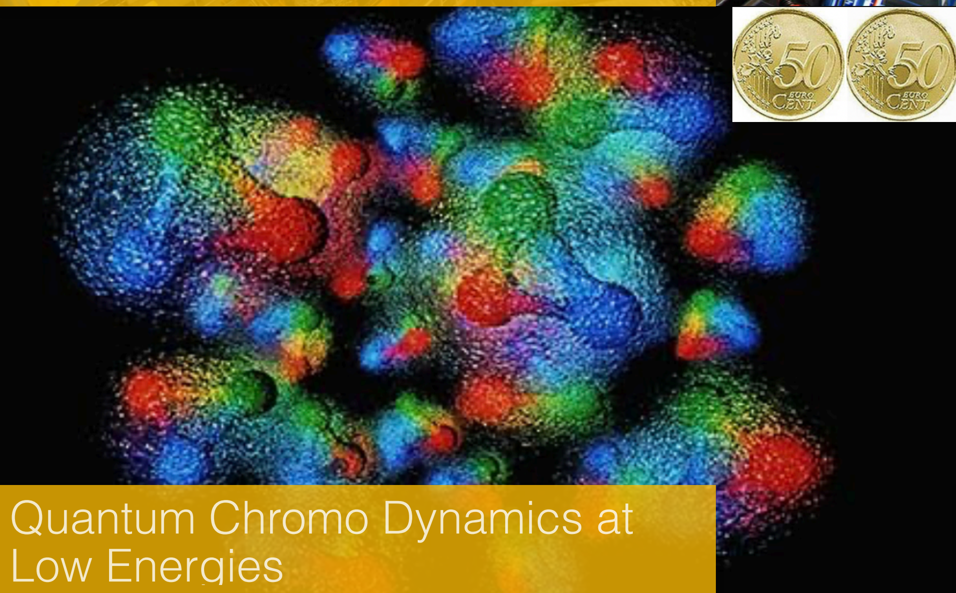
What will we talk about today?



Electroweak Precision Physics at ATLAS



Tau Neutrino Physics



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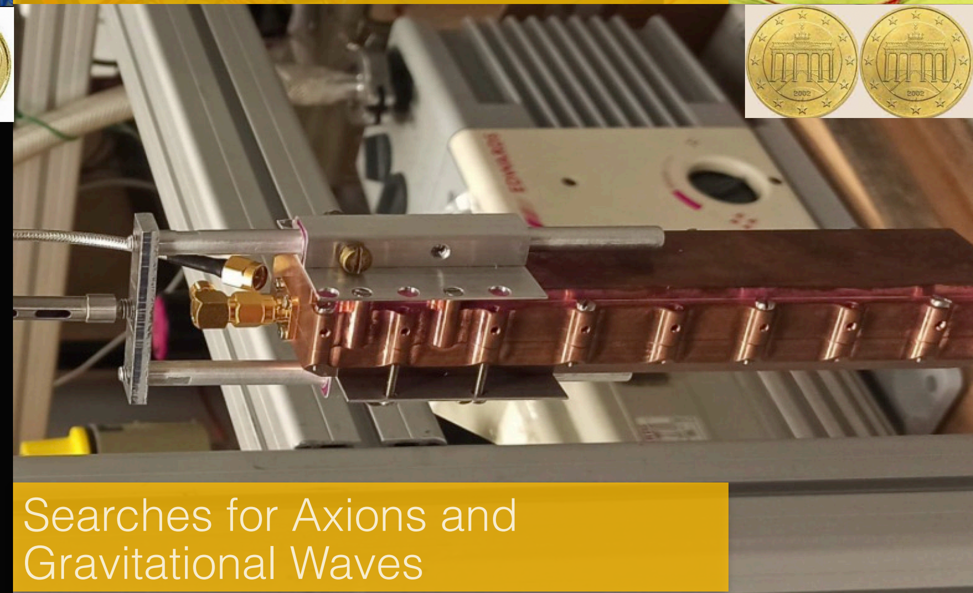


Searches for Axions and Gravitational Waves

Quantum Chromo Dynamics at Low Energies at the LHC

UNIVERSITÄT BONN

Fundamental Aspects in QCD

The Lagrangian

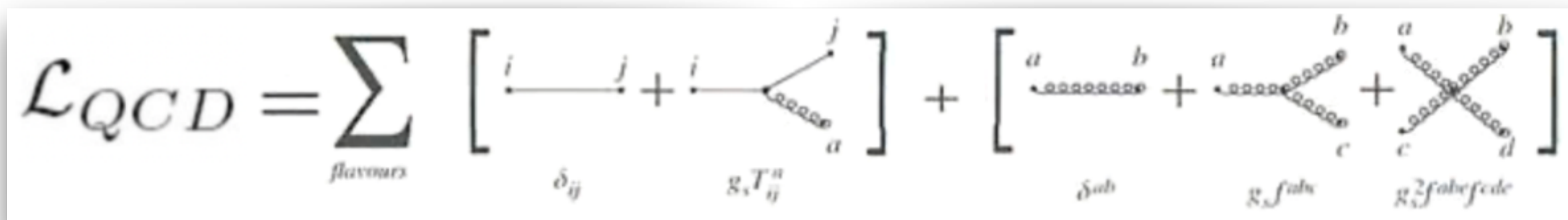
$$\mathcal{L}_{QCD} = \bar{\psi}(i \not{D}_a T_a - m)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu,a}$$

Covariant Derivative

$$D_a^\mu = \partial^\mu + igA_a^\mu$$

Gluon Field Tensor

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

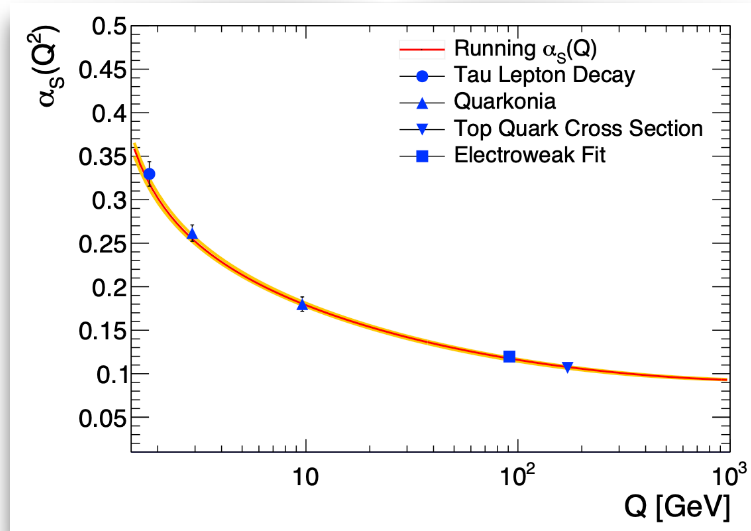


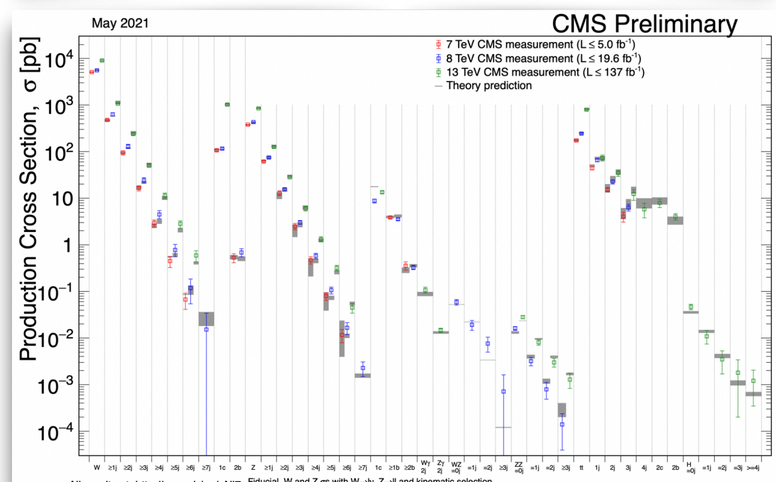
- Free Parameters
  - Quark Masses (by Higgs Yukawa Coupling)
  - Coupling Constant g, known as strong coupling constant α_s

Running of α_S and perturbative QCD

- QCD (as all other QFT) predicts a running of α_S
  - Confinement
  - Asymptotic Freedom
  - Energy Dependence of α_S known to high precision

- Nearly all QCD predictions are based on perturbative calculations
  - Strong coupling constant must be small that the perturbative series converges
  - Only valid at high energies
  - Predictions for several processes available at next-to-next-to-next-to leading order
  - Amazing agreement between theory and data





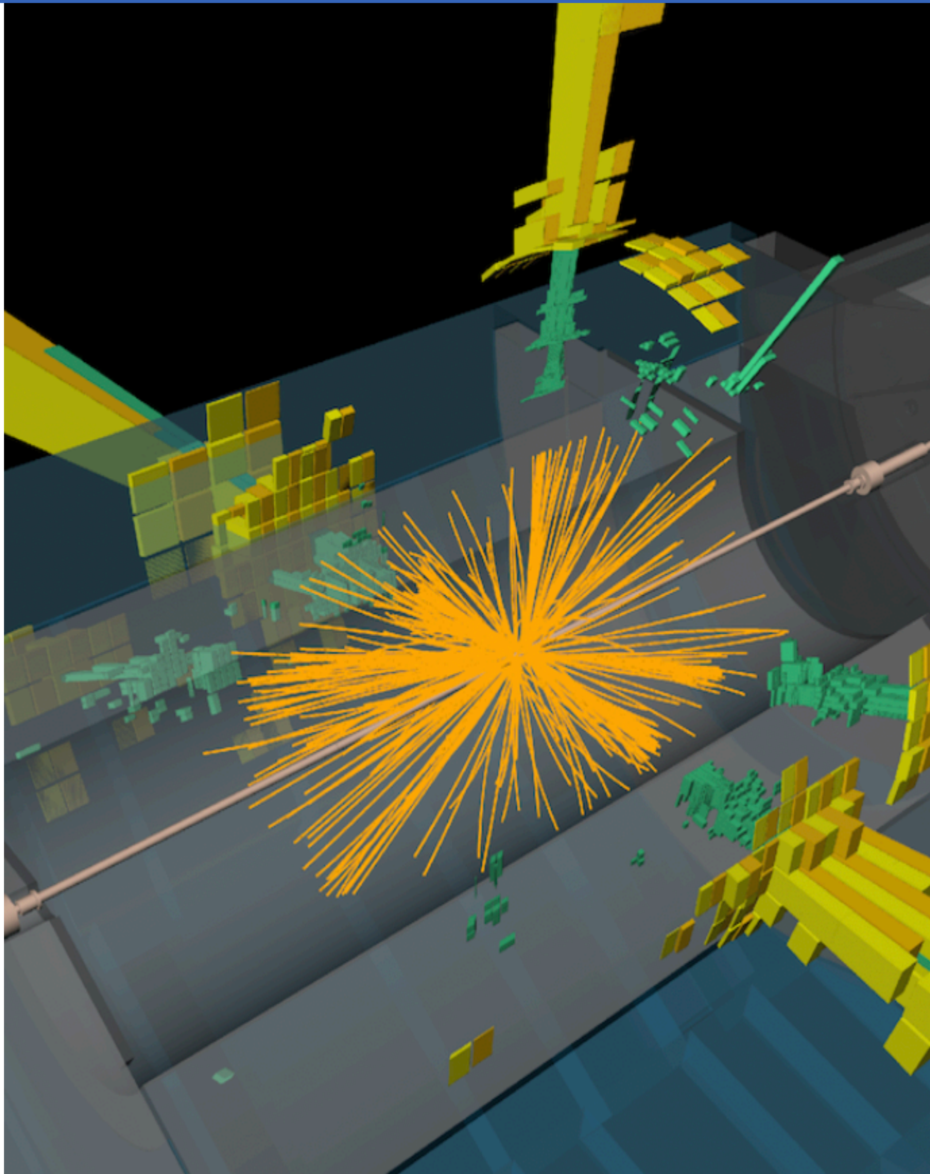
Non-Perturbative QCD

- Nearly all physic studies at ATLAS and CMS aim at high energies
  - However, small energy scales are always there in addition
    - We have nearly no predictions based from first principles
    - Non-Perturbative QCD is therefore always based on phenomenological models
- Essentially all Heavy Ion Physics is Non-Perturbative QCD
  - While QGP should be described by the dynamics of QCD, we have no way to derive that
- Arn’t there any examples, where we have (reliable) predictions at low energies?

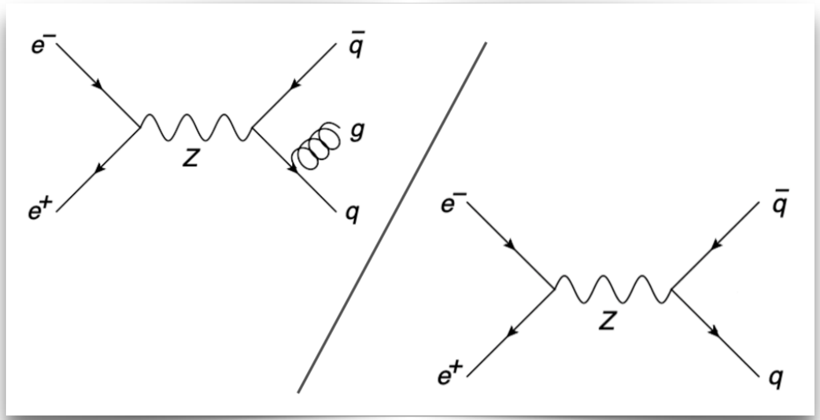
The Strong Coupling Constant

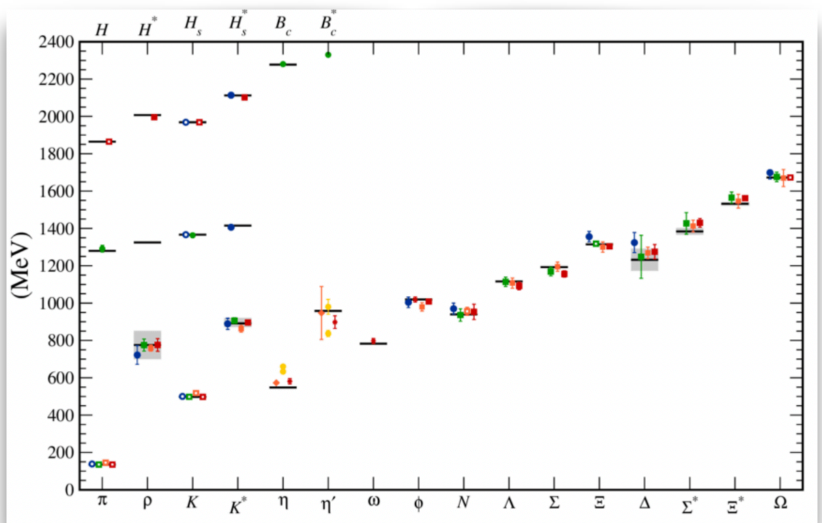
Why is the strong Coupling Constant important?

- The strong coupling constant is present in all perturbative predictions at the LHC
- Its measurement at different scales might be sensitive to physics beyond the SM
- Testing the unification of forces
- And my own motivation: Measure fundamental constants of nature better than anybody else



How to measure the strong Coupling Constant

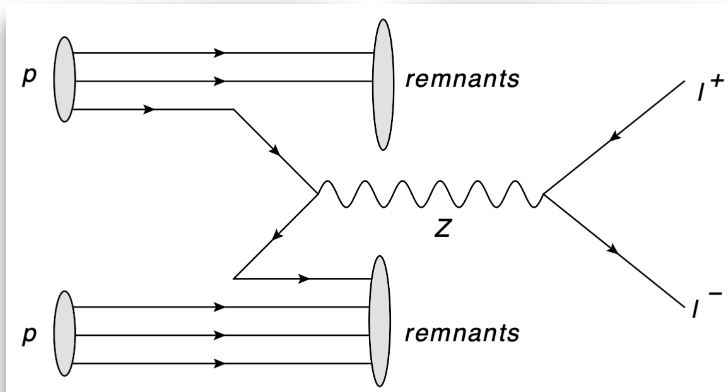


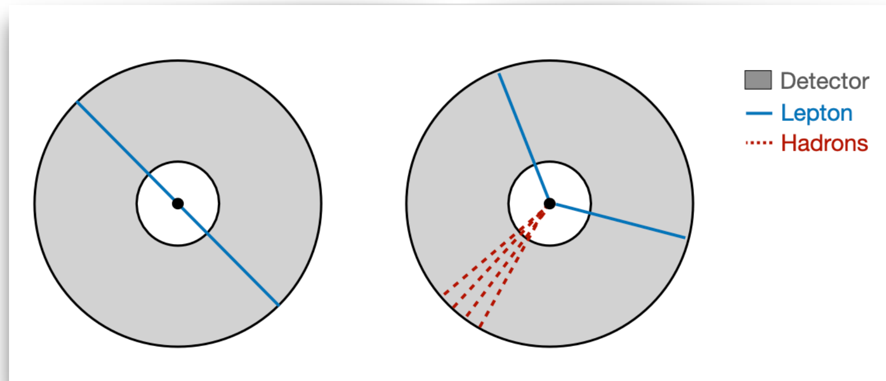


- Most straight forward approach: Look at 3-jet over 2-jet ratios
  - Disadvantage: Final states interact with each other and induce large theory uncertainties on the observable
- Many other approaches: Tau-Lepton Decay, Parton Density Function Fits, Event shapes …
- Most Precise Determination
  - Use Lattice QCD predictions of hadron mass spectra, leave α_S free and fit to observed data

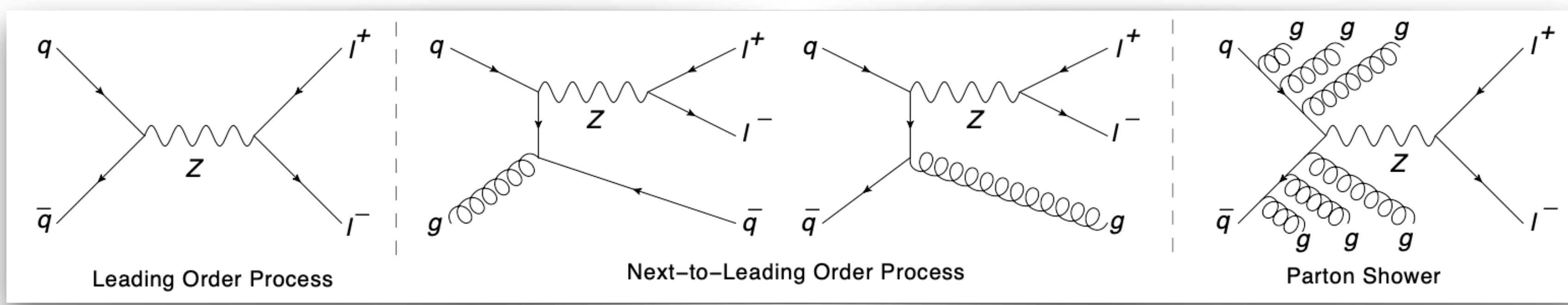
The Drell-Yan Process

- Drell Yan Process describes the creation of lepton pairs in proton-proton collisions via the Z boson exchange

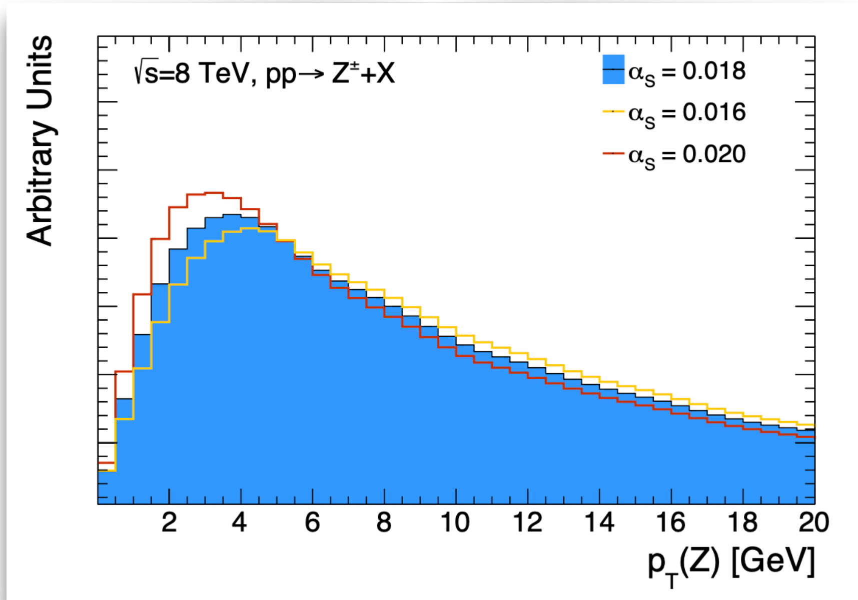


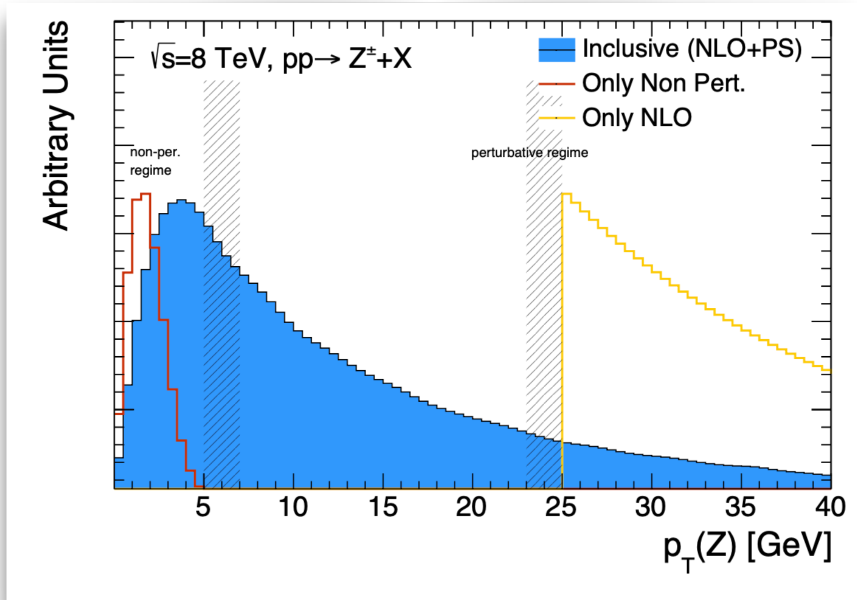


- We except transverse momentum of Z boson only at higher orders



Relation between $P_T(Z)$ and α_S



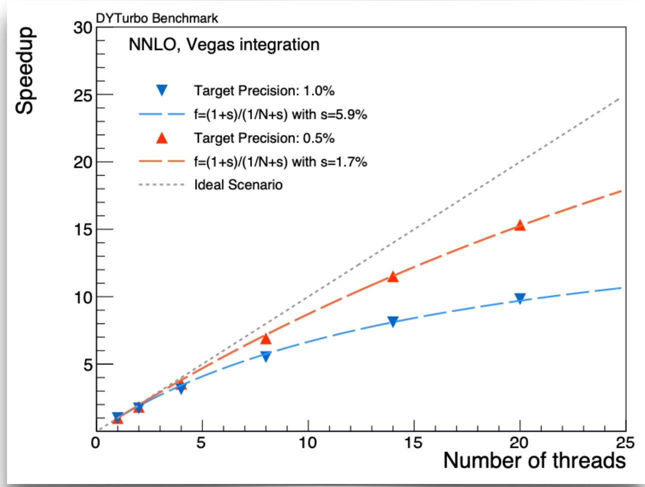


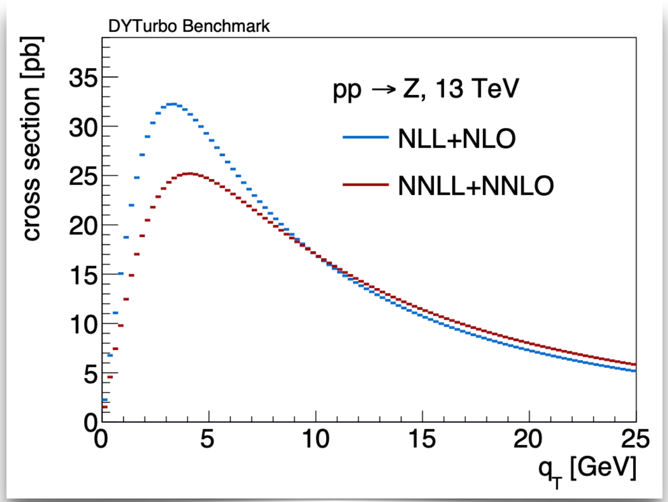
- The Sudakov Region shows a high dependence on the strong coupling constant
  - … and can be precisely predicted

- Non-Perturbative Regime
- Sudakov Region
- Perturbative Regime

The Prediction of $P_T(Z)$

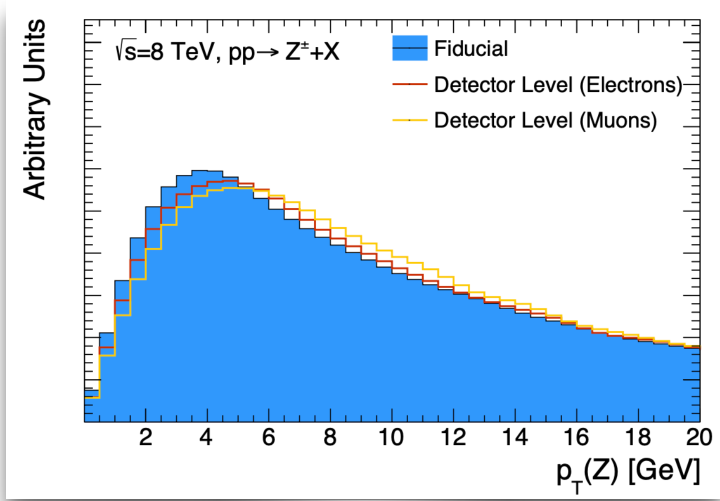
- Sudakov region can be described by resummation approaches
  - emission of soft-gluons in the initial state can be formally correct described in powers of the strong coupling constant α_s
  - DYRes: Resummed Calculation with public code https://arxiv.org/abs/1507.06937
- DYTurbo: Reimplement Integrations of DYRES using the Cuba library and in the Cubature package https://arxiv.org/pdf/1910.07049.pdf
  - Speed-Up by a factor of 10-20
  - This allows for many different predictions for various model scenarios

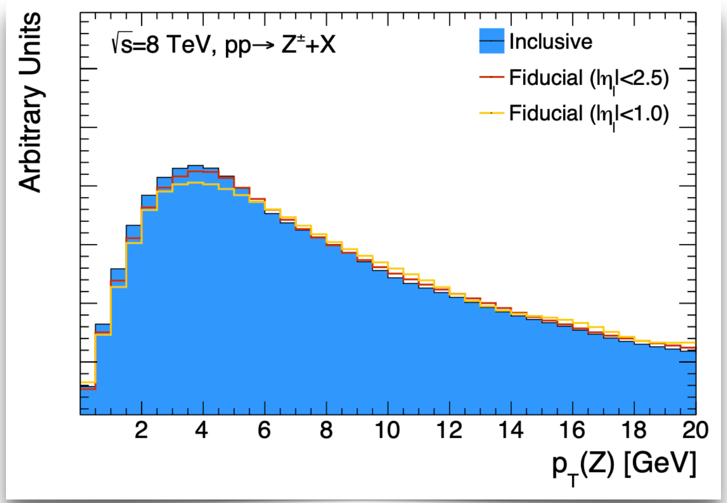




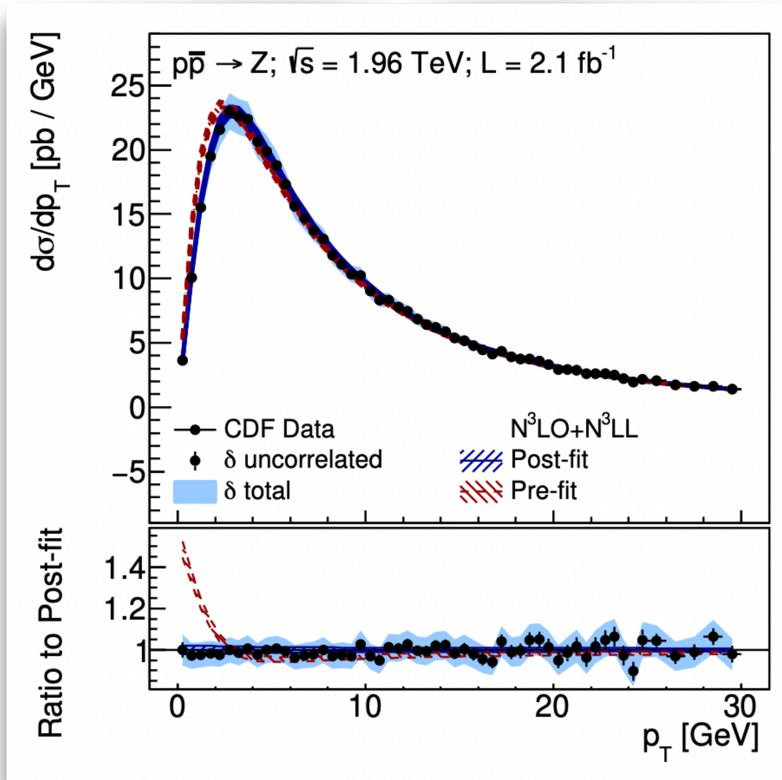
How to measure of $P_T(Z)$

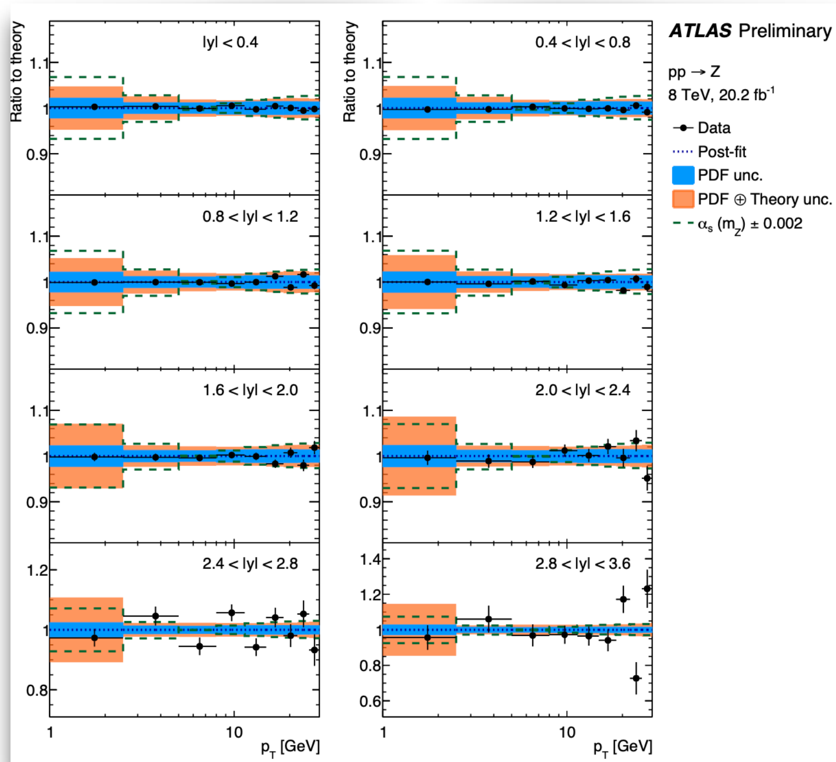
- Some trivial things to do
  - Correct for detector effects
  - Experimental precision at per-mille level
  - Extrapolate to full-phase space
- Problem
  - Extrapolation induces theory uncertainties (similar size than experimental precision)
- Solution
  - Make use of Decomposition of Drell-Yan process in angular coefficients
  - Perform multi-dimensional template fit to data





Determination of $\alpha_s(m_Z)$ from $p_T(Z)$: CDF at 1.96 ZeV, ATLAS at 8 TeV





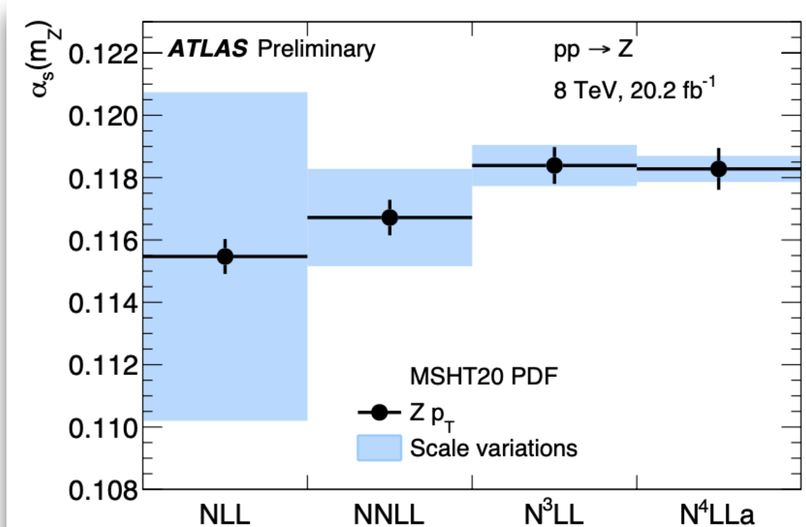
- $a_s(m_Z)$ fit to the double-differential p_T-y_Z cross section measured in full-lepton phase space
- Postfit χ^2/dof and CDF (41/53) and ATLAS (82/72)

Results and Uncertainties

- Experimental Uncertainties can be further reduced
- PDF Uncertainties will be reduced by combined fits at different center of mass energies
- Non-Perturbative Effects seems to be small …

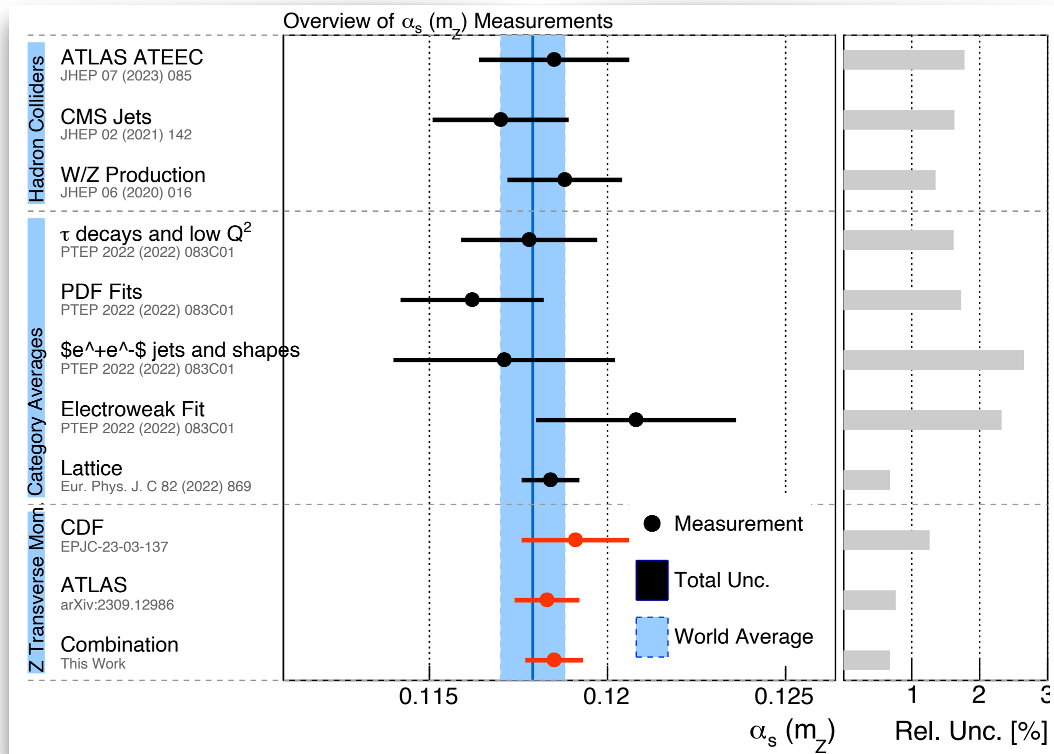
Experimental Uncertainty	0.0007
PDF Uncertainty	0.0008
Scale Variations	0.0008
Non Perturbative Model	0.0002
Flavour Model	0.0005
Total	0.0013

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088



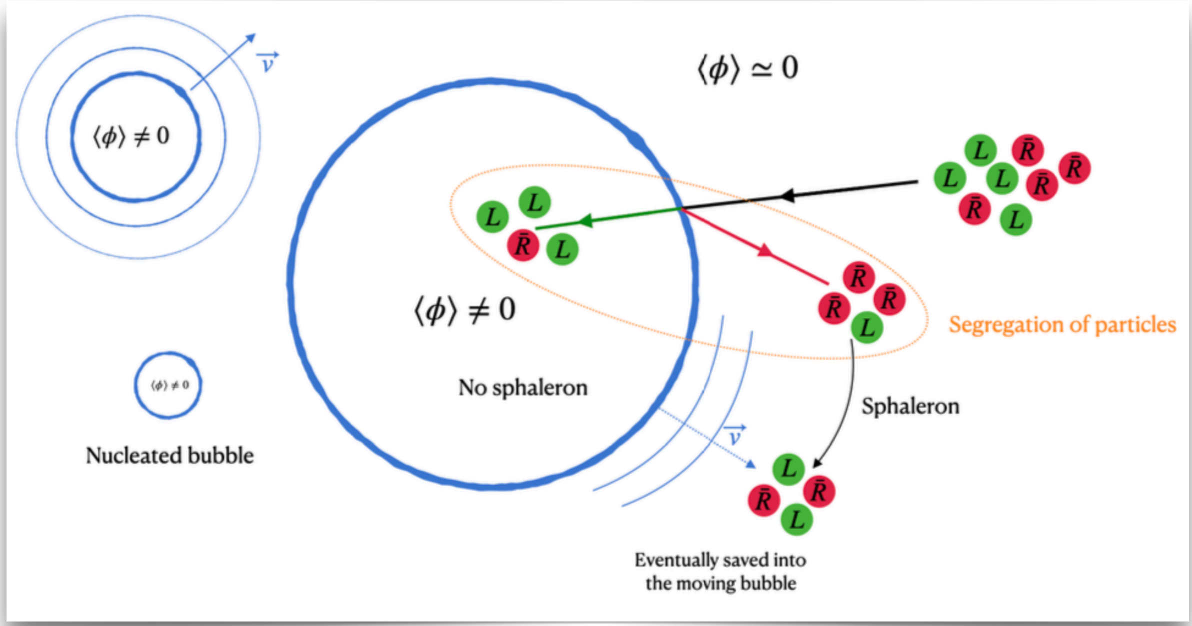
The Final Result

- Determination at N3LO+N4LL
- Clean experimental signature (leptons) with highest exp sensitivity
- Determination focusing on the Sudakov region (usually avoided to determine as)
- Observable not suitable for inclusion in PDF fits
  - → no correlation with $\alpha_s(m_Z)$ determinations from PDF fits
- For 60th Birthday of Bormio: Preliminary Combination of CDF and ATLAS
  - Most precise determination of $\alpha_s(m_Z)=0.1185\pm0.0008$



Topological Phenomena

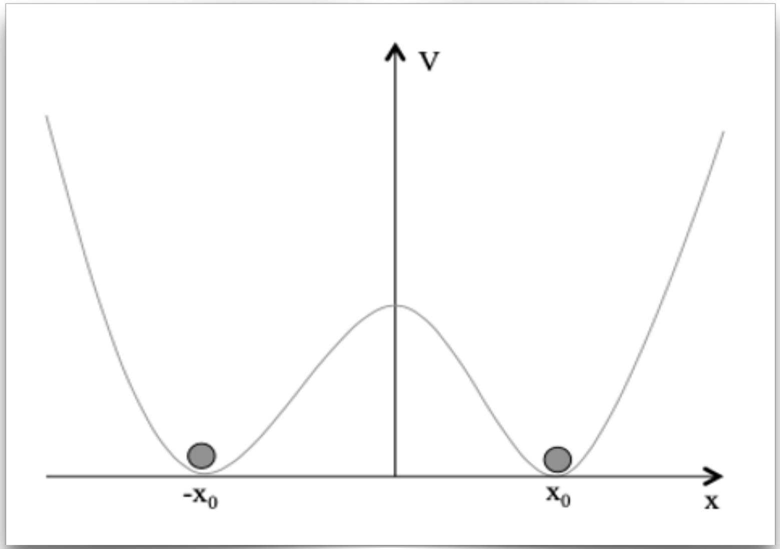
- Sakharov conditions: Baryogenesis
  - Baryon number B violation.
  - C-symmetry and CP-symmetry violation.
  - Interactions out of thermal equilibrium.



- Sphaleron Processes lead to a Baryon Number Violation
  - Conserve the difference between Baryon number and Lepton number
  - Violate the sum of the Baryon number and Lepton number

What are Sphalerons and Instantons ?

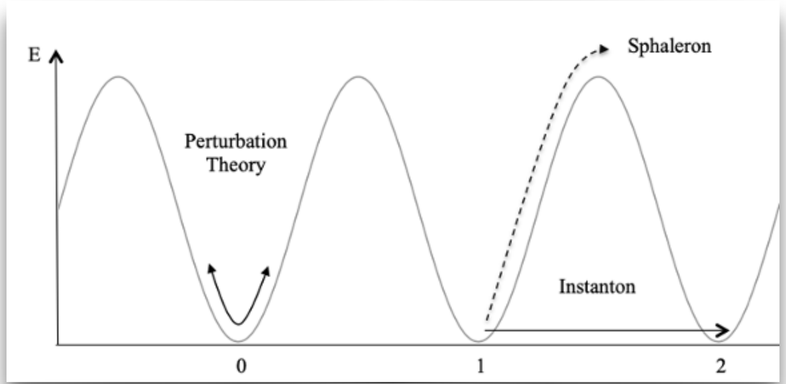
- What do you do in typical Quantum (field) theories?
  - Look for a minimum & apply perturbation theory
  - Sometimes there are also other solution
    - “Instanton” processes in non-relativistic QM describe tunneling transitions of finite action



- Looking at Lagrangian of YM theories

$$L_{QCD} = \overline{\Psi}_i\left(i\gamma^\mu D_\mu^{ij} - m\delta^{ij}\right)\Psi_j - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}$$

  - also degenerate vacua (differ by $\Delta N_{CS} = 1$)
  - same approach: we apply perturbation theory
  - ’t Hooft: concept of instanton solutions can be extended to Yang-Mills theories



Instantons and Sphalerons in the Electroweak Sector

- Electroweak instanton and sphaleron processes imply B + L violation

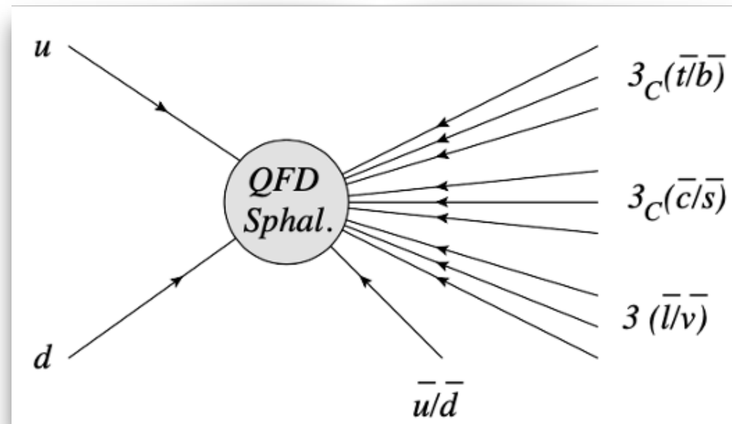
- What is the cross-section in p-p collisions?
  - perturbative approach cannot be used

- Height of the energy barrier between two vacua depends on the underlying theory.

$$M_I \sim \frac{\pi}{\alpha \rho_{eff}} \sim \pi \frac{M_W}{\alpha_W} \sim 10\ TeV$$

  - α_{weak} coupling constant
  - ρ_{eff} the effective instanton size

- Several calculations e.g. Ringwald (2002) hep-ph/0212099
  - Problem: Exponential suppression with M_{Sp}
  - too small for any current or future collider

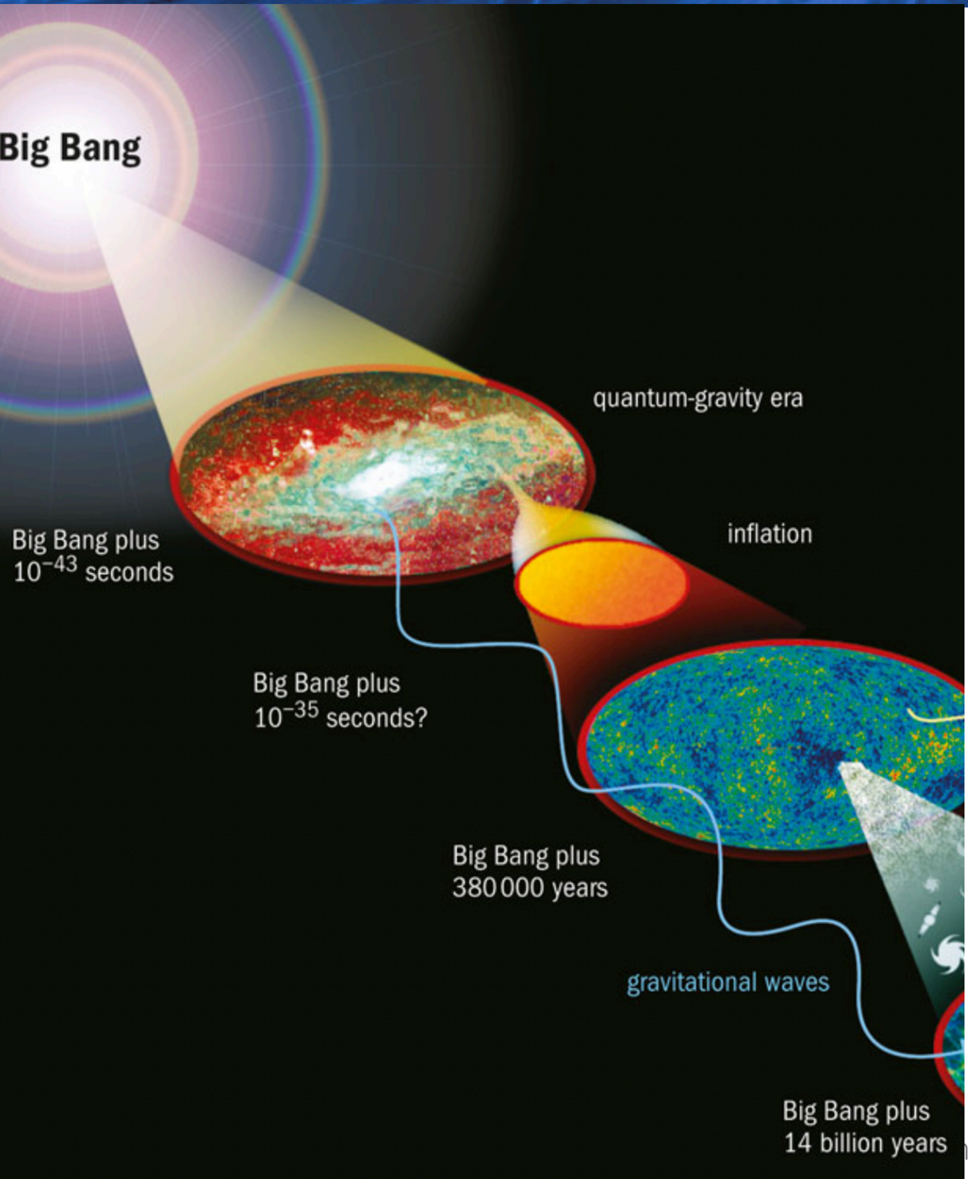


$$\hat{\sigma}^{(I)}_{p_1 p_2} \sim \frac{1}{2\,p_1 \cdot p_2}\,\mathrm{Im} \int \mathrm{d}^4 R\ \mathrm{e}^{\mathrm{i}\,(p_1+p_2)\cdot R}$$

$$\times \int^{\infty} \mathrm{d}\rho \int^{\infty} \mathrm{d}\bar{\rho}\ D(\rho)\,D(\bar{\rho})$$

$$\times \int \mathrm{d}U\ \mathrm{e}^{-\frac{4\pi}{\alpha_g}\Omega\left(U, \frac{R^2}{\rho\bar{\rho}}, \frac{\bar{\rho}}{\rho}, \dots\right)} \dots$$

Instantons and Sphalerons



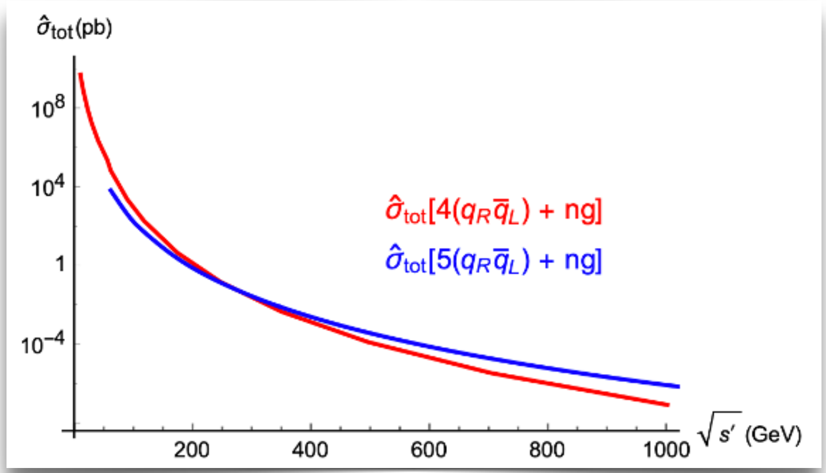
- Sphaleron and Instanton processes seem to be crucial for our understand of the cosmic evolution
- However: We have never observed them experimentally!
- It would be cool to see them!
  - We need to look at a QFT theory, where the barrier between two vacua is low!
- Any ideas?

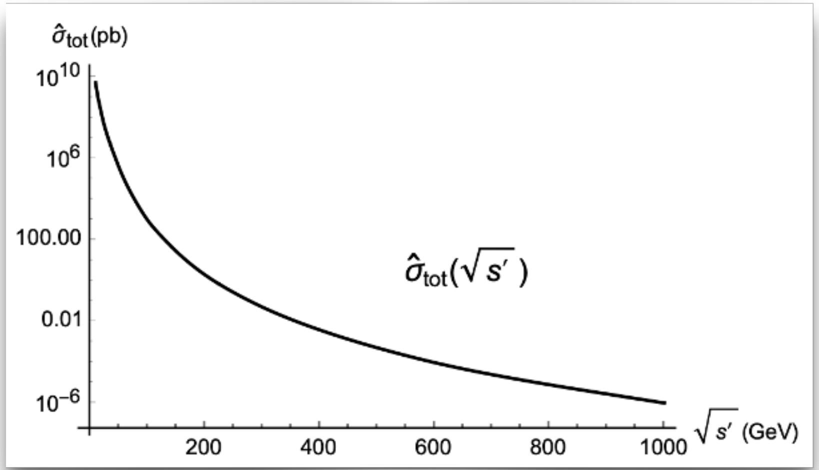
Instantons in QCD

- QCD Instantons are a possible solution to the axial U(1) problem
- Their observation would be
  - A first proof of the vacuum-structure of QCD
  - a way to study chiral symmetry breaking
- Barrier height is governed by α_s

$$M_I \sim \frac{\pi}{\alpha \rho_{eff}} \sim \frac{3\pi}{4\alpha_S \rho_{eff}} \sim Q$$

  - Large α_s → small barrier → large cross section
- What is the cross-section in proton-proton?
  - Recent calculations are based on the optical theorem arXiv:2010.02287v3
  - Problem: Huge uncertainties ($x10^1$-10^3)



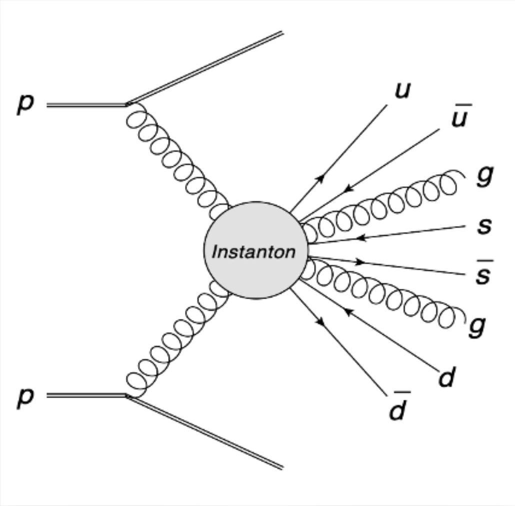


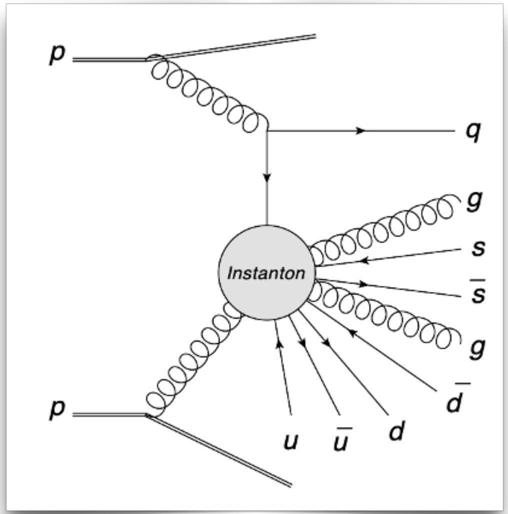
Signatures of QCD Instantons

- Treat Instanton solution as the generation and the decay of a Pseudo-particle with variable mass M
  - No resonance peak, but a falling spectrum
- Instanton production and decay process

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})$$

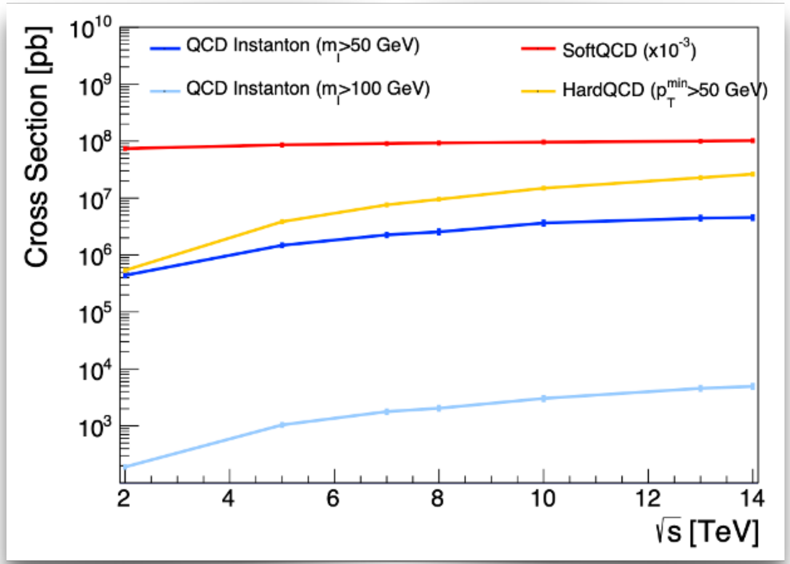
  - Chirality violation: 1 right-handed quark and 1 anti-particle of the left-handed quark for each accessible flavor (for $\Delta N_{CS} = 1$)
  - Problem: not clear which Instanton mass is required e.g. for b-quarks (50 GeV?)
  arxiv.org/abs/2101.02719v2
- A certain (large) number of gluons
  - Problem: Not clear how many (5-10)

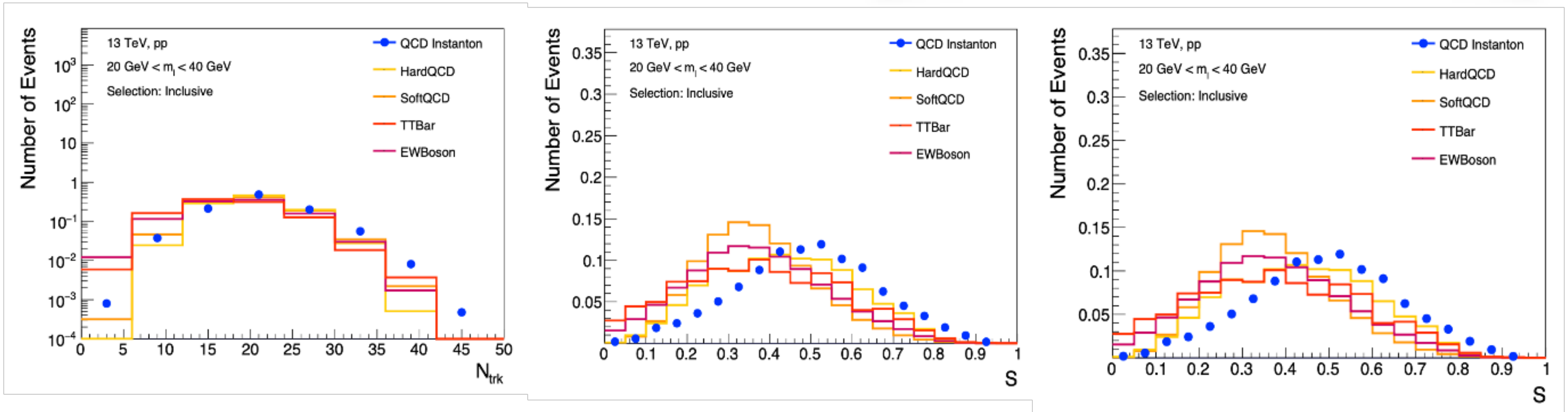




Searches at the LHC: Event Characteristics

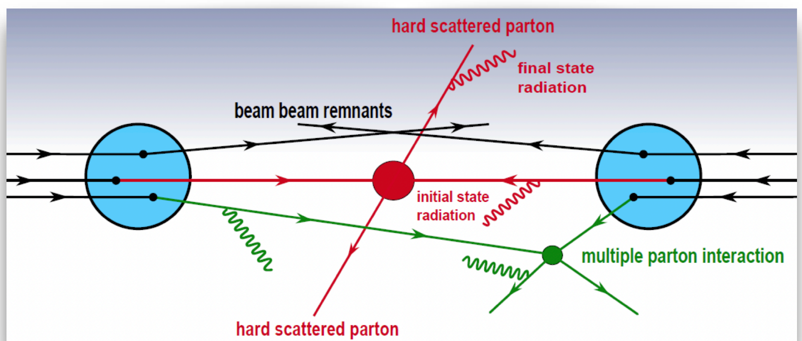
- Experimental Signatures (arXiv:2012.09120v1)
  - Many tracks
  - Spherical events
  - Potentially displaced tracks
  - Tracks localized in eta
- Backgrounds for low mass Instantons (20-40 GeV)
  - Underlying Event
  - Multiple Parton Interactions



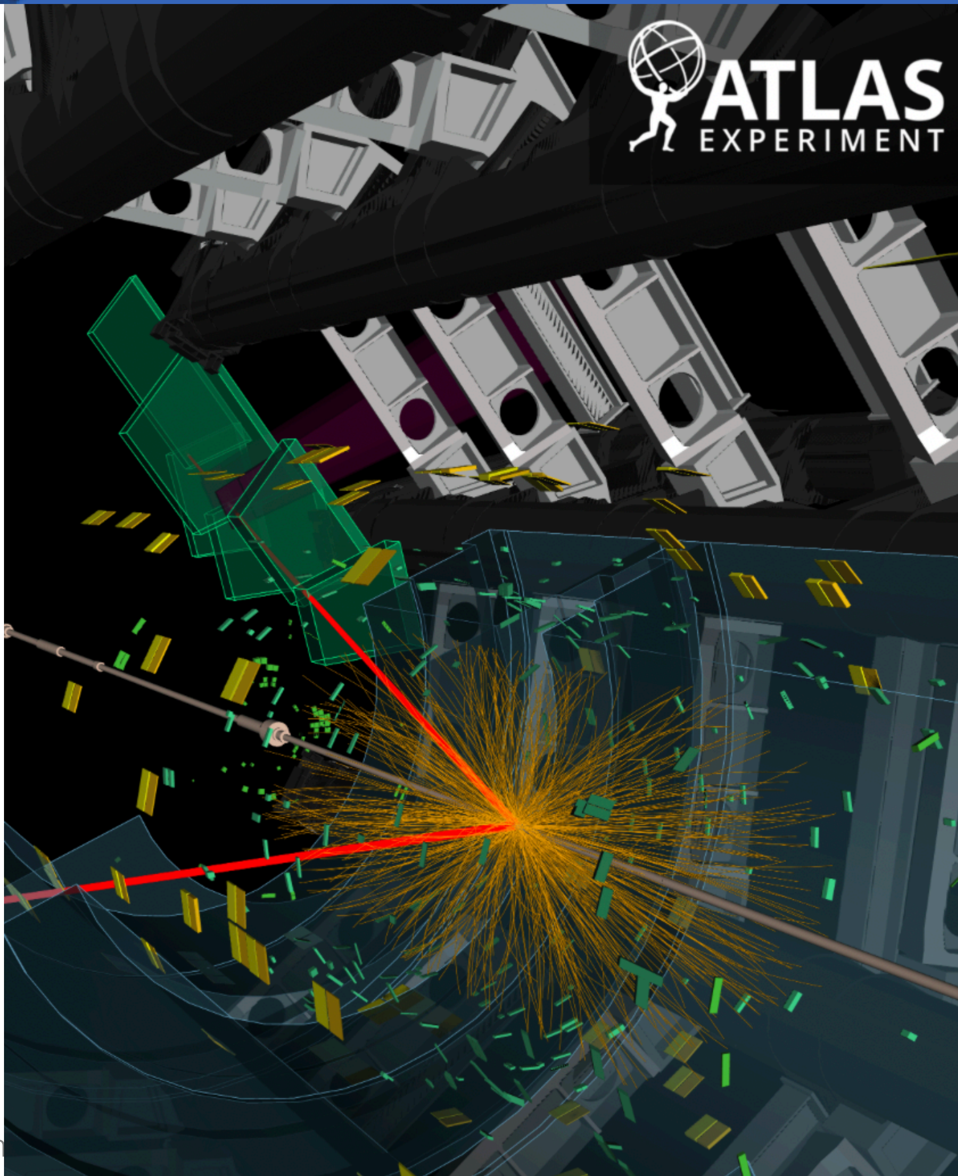


Searches at the LHC: Event Characteristics – Experimental Challenges

- How to distinguish QCD Instanton events from SoftQCD Models?
- Multiple Parton Interactions (MPI) also lead to high multiplicity, spherical events

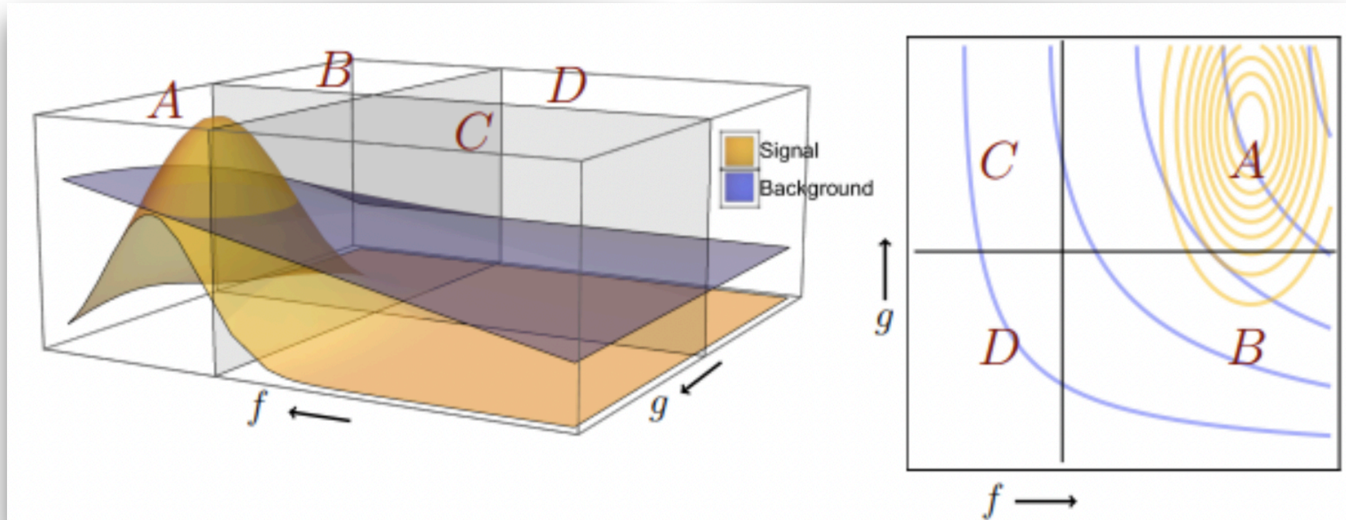


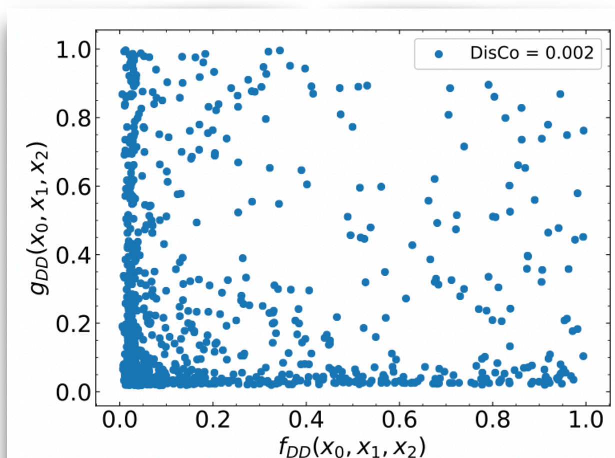
- Problem: These signatures are already included in the MC Generator tunes!
  - Are Instantons tuned away?

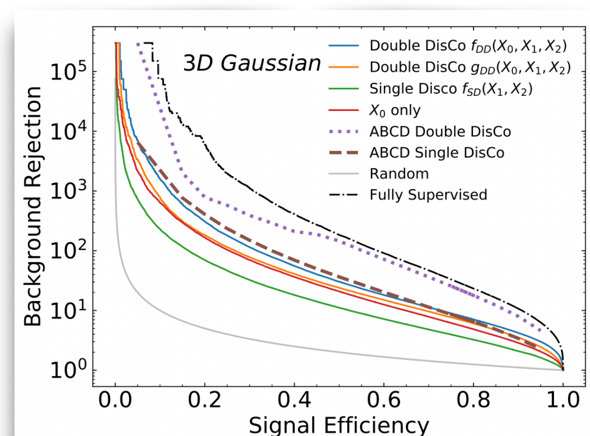


ABCD Method with Neural Networks

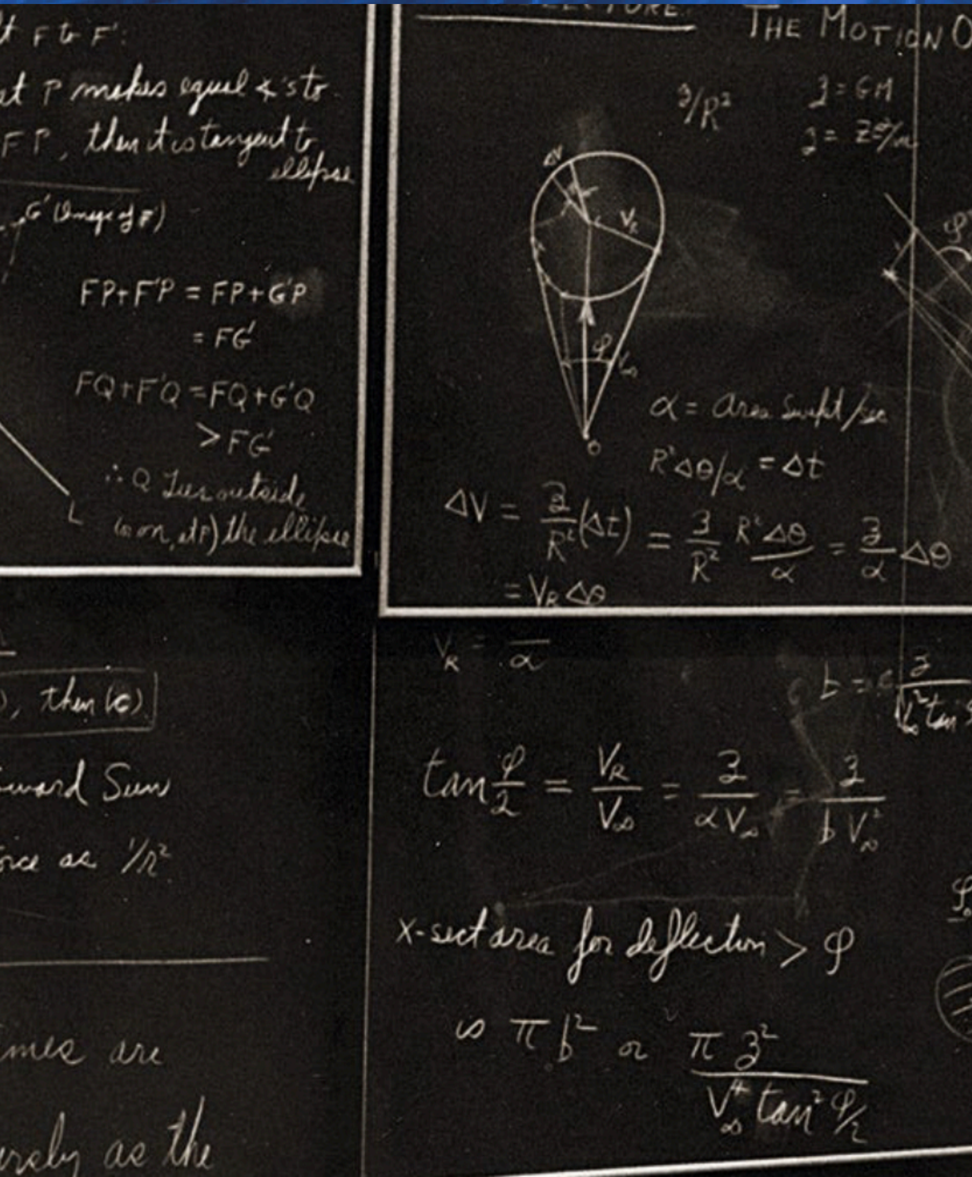
- ABCD method widely used to estimate background in a data-driven way
- New approach uses two decorrelated classifiers to optimise signal selection and background estimation
  arXiv:2007.14400







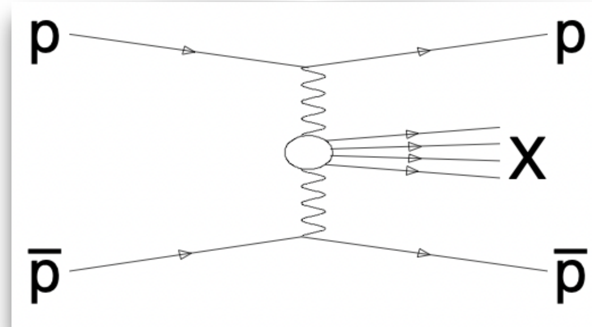
More Theory Developments Needed!



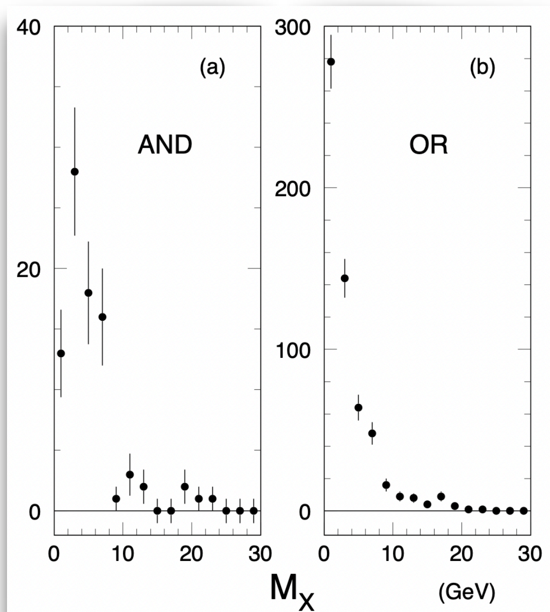
- Status Quo
  - One approach to calculate the cross-section of QCD Instantons
  - Implementation in Sherpa3.0 for the decay of QCD Instantons available (by Frank Kraus)
  - We need alternative approaches to calculate the Instanton cross-section
- The decay of QCD Instantons is subject to hadronization and color-reconnection
  - We need different generators!
- The most striking feature of QCD Instanton decays is the chirality violation
  - We need hadronization models which preserve the chirality information

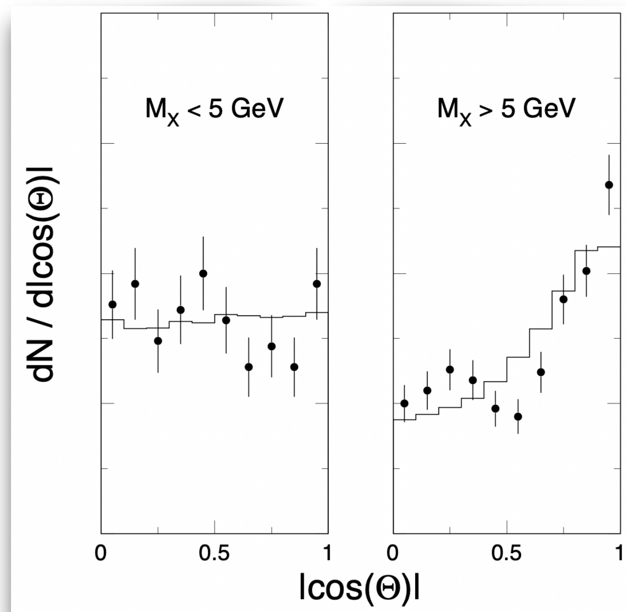
Evidence of Sphaleron Processes in Diffractive Events?

- UA8 Experiment in p-p collisions at 630 GeV
  - Double-Pomeron production hep-ex/0205037
  - Unexpected peak at 2-8 GeV
  - Theory Prediction by E. Shuryak and I. Zahed arXiv:hep-ph/0302231v1



- Looking at angular distributions of final states:
  - Observe spherical symmetrical distribution for <5 GeV
  - Observed „forward" distribution for >5 GeV
  - Sphaleron?





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Summary

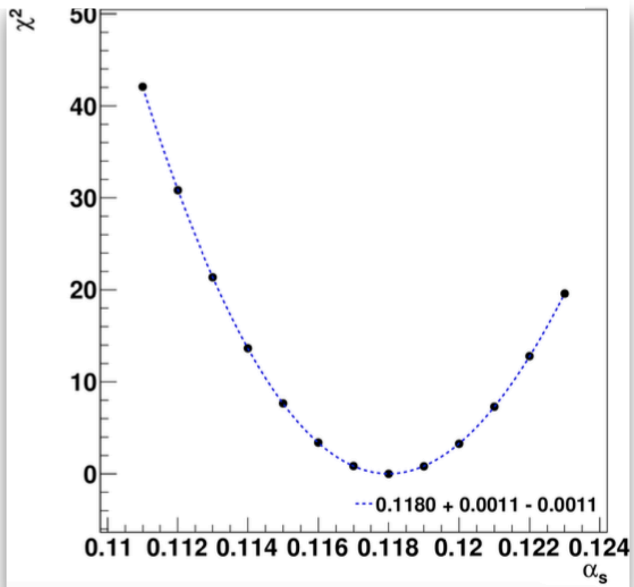
- Most precise (combined) measurement of the strong coupling constant presented here in Bormio
- Physics at the LHC is not only fun at high energies
- Precision Physics at the LHC relies on the understanding of non-perturbative effects
- Topological aspects of QCD deserve more attention, as they tell us about the beginning of the universe!

For to fit $\alpha_s(m_Z)$

- DYTurbo interfaced to xFitter arXiv:1410.4412
- Evaluate $\chi^2(\alpha_s)$ with as variations as provided in LHAPDF
- Include experimental ($\beta_{j,exp}$) and PDF ($\beta_{k,th}$) uncertainties in the χ^2

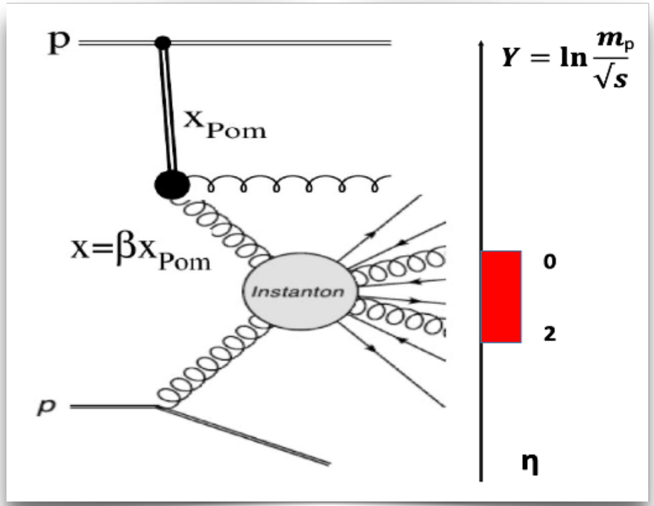
$$\chi^2(\boldsymbol{\beta_{exp}}, \boldsymbol{\beta_{th}}) = \sum_{i=1}^{N_{data}} \frac{\left(\sigma_i^{exp} + \sum_j \Gamma_{ij}^{exp}\beta_{j,exp} - \sigma_i^{th} - \sum_k \Gamma_{ik}^{th}\beta_{k,th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,exp}^2 + \sum_k \beta_{k,th}^2$$

- At each value of $\alpha_s(m_Z)$ the $\beta_{k,th}$ terms explore the PDF space to find the best fit to the $p_T(Z)$ data
  - → equivalent to including the new dataset in the PDF without refitting, using profiling/reweighting Eur.Phys.J.C 75 (2015) 9, 458
- The non-perturbative form factor is added with unconstrained nuisance parameters (b = 0) i.e. left free in the fit
- Fit the region of $p_T(Z)$ <29GeV



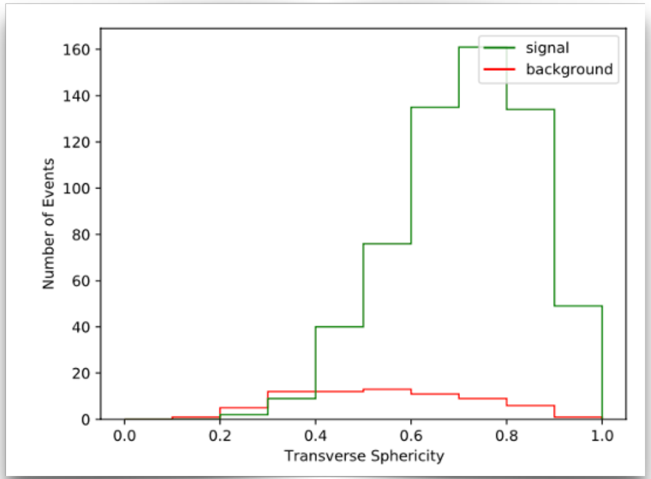
Searches at the LHC: Rapidity Gaps

- Alternative Solution: Look at Pomeron-induced production process Khoze et. al. arXiv:2104.01861v2



- Large Rapidity Gaps (LRG)
  - each MPI qq→ dijet even will be accompanied by the color flow created by the parton cascade

- Signal Selection: Reconstructed mass 20 – 60 GeV in the events with an LRG
  - detecting the leading forward proton with beam momentum fraction close to 1
  - No activity in the forward calorimeters



Non perturbative QCD model

- NP model is generally determined from the data, parameters values depend on the chosen prescription to avoid the Landau pole in b-space

$$S_{NP}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0}\right]$$

$$b_\star = \frac{b}{1 + b^2/b_{\lim}^2}$$

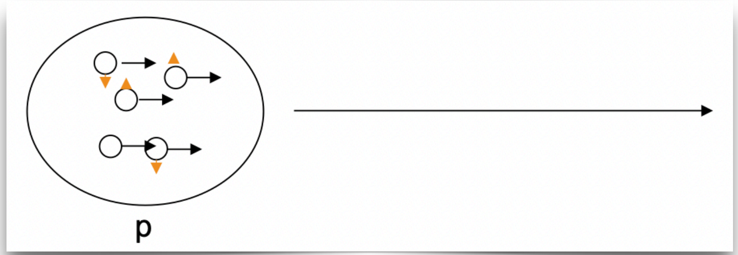
$$g_j(b) = \frac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \mathrm{sign}(q)\left(1-\exp\left[-|q|\,b^4\right]\right)$$

$$g_K(b) = g_0\left(1-\exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b_{\lim}^2}\right]\right)$$

- g_j functions include a quadratic/quartic term: g and q free parameters of the fit
  - The theory should not depend on b_{lim} (freezing scale) and Q_0 (starting scale), provided SNP is flexible enough. Q_0 and b_{lim} estimated as parameterisation unc.
- g_0 controls the very high b (very small p_T) behaviour, should be fitted to data, but we have no sensitivity to it, so it is varied
- Lambda controls transition from Gaussian to exponential: varied between 0.5-2
  - Test Non-Perturbative effects by excluding 0-5 GeV region

Non-Perturbative effects which should be investigated more

- Intrinsic k_T (transverse momentum of partons) can be studied
    - Only Pheno-Models available
    - Tune intrinsic k_T parameters at low DY mass processes (Little room for QCD evolution)



- Maybe more problematic
    - Resummed calculations do not consider diffractive production of vector Bosons
    - Cross-Section is at %-level
    - Difference on $p_T(Z^{Diff})$ directly impacts α_s determination