The high energy limit of strong interactions

Research done with CMS and TOTEM Collaborations,

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Quantum chromodynamics (QCD)

QCD is the quantum theory of the strong interactions (quarks and gluons).

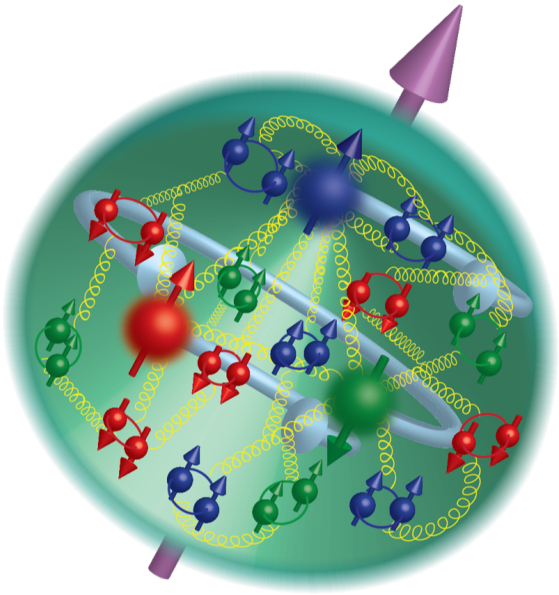
Particles that carry color charge (red, green,blue) are sensitive to the strong interaction, analogous to the electric charge in electromagnetic interactions.

QCD is central to all modern colliders

...and QCD is what we are made of

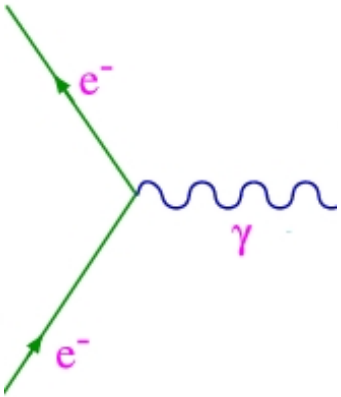
Two key characteristics of QCD:

- **Color confinement:** Quarks and gluons are confined within hadrons. Only hadrons (particles made of quark & gluons) are observed in isolation.
- **Asymptotic freedom:** Quarks and gluons interaction strength decreases with distance (increases with energy) $\rightarrow$ Partons are asymptotically free at high energies.



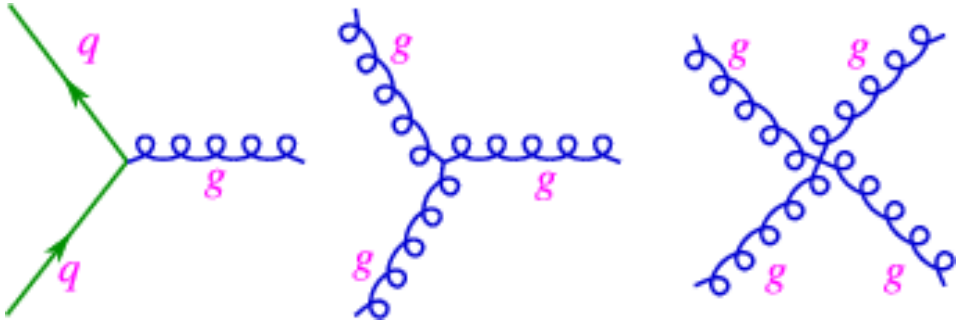
The proton and its substructure (quarks and gluons)

QCD is special!



Quantum electrodynamics (QED)

- Quantum theory of electromagnetic interactions.
- Electrically charged particles interact via exchange of photons.
- Single interaction vertex (abelian **U(1)** gauge symmetry)



QCD

- Color-charged particles interact via exchange of gluons.
- **Key difference with QED:** self-interacting gauge bosons (gluons) → Makes QCD special!!!
  ...*Consequence of non-abelian* ***SU(3)*** *gauge symmetry of QCD*
- **The self-interacting gluons give rise to distinct emergent properties in QCD.**
- I am interested in identifying such emergent properties in the experiment.

Asymptotic freedom in strong interactions

A strong coupling coefficient, α_s, that gets smaller with shorter distances (higher energies).

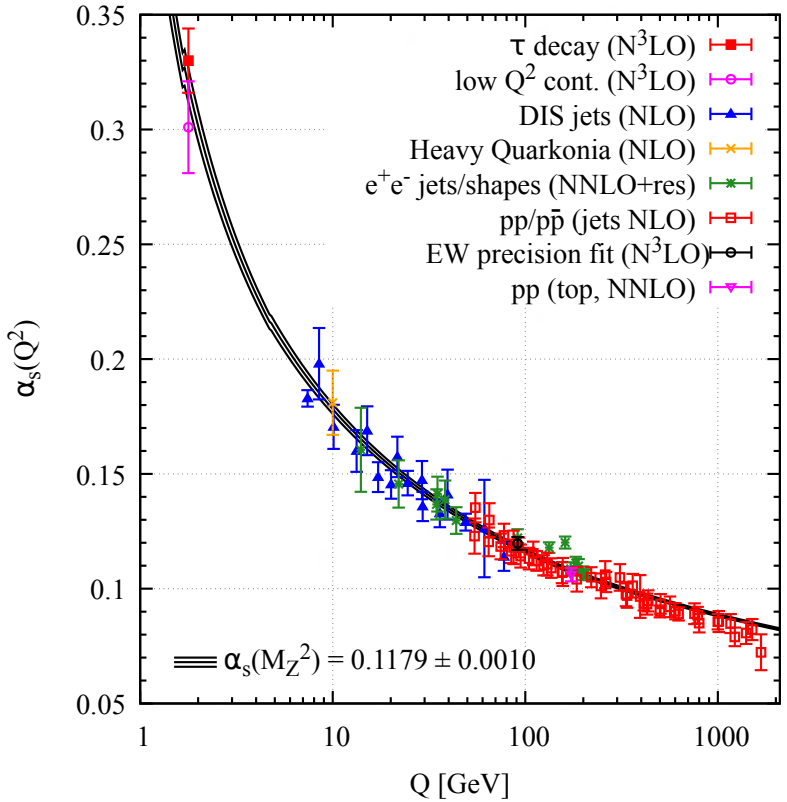
One-loop α_s coupling running with hard energy scale Q:

$$\alpha_s \propto \frac{1}{\ln(Q^2/\Lambda^2_{QCD})}$$

Perturbative expansion on α_s^n converges faster at higher energies. $\alpha_s(100\text{ GeV}) \approx 0.1$

Theory becomes strongly coupled at $\Lambda_{QCD} \approx 200$ MeV

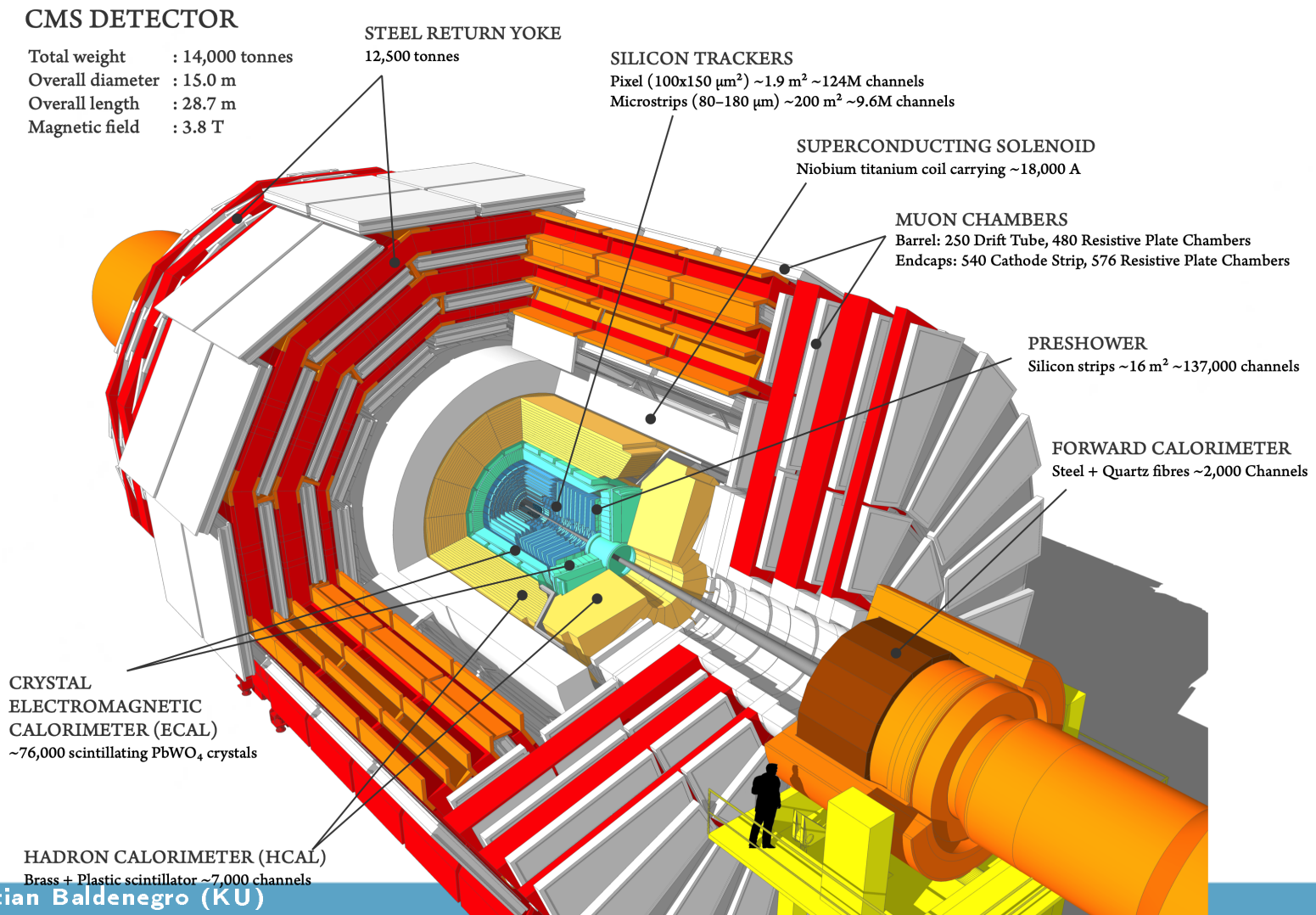
$\rightarrow$ Transition of degrees of freedom (from quarks & gluons to hadrons)



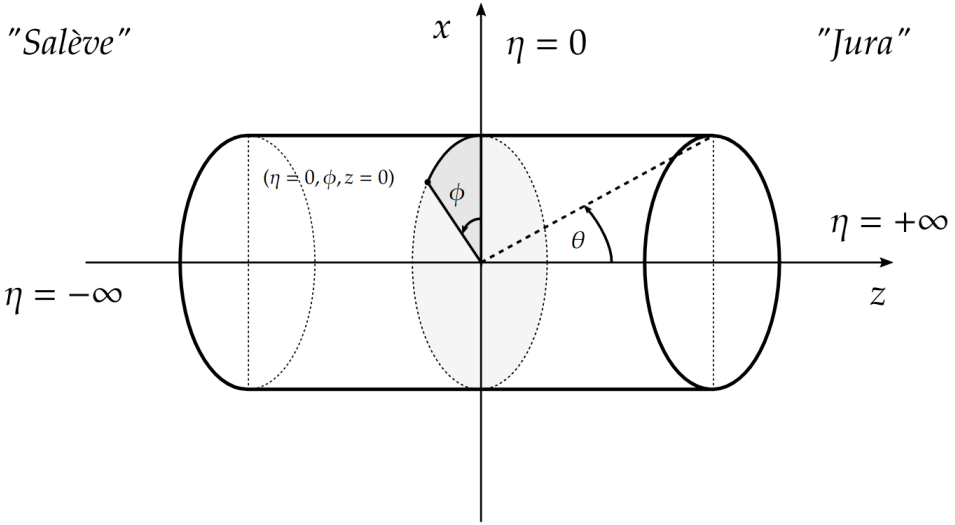
Particle Data Group, Phys. Rev. D 98, 030001 (2018)

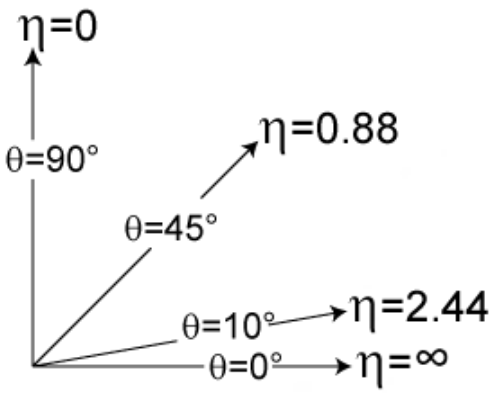
The Compact Muon Solenoid (CMS) experiment

- CMS is a general purpose detector installed at one of the interaction points at the Large Hadron Collider (LHC).
- Several subdetector components dedicated to measure **most of the decay debris in a $\approx 4\pi$ solid angle region of high-energy proton-proton collisions**.



Collider variables definitions





η: Pseudorapidity is a measure of polar angle, $\eta \equiv -\ln\left(\tan[\theta/2]\right)$.

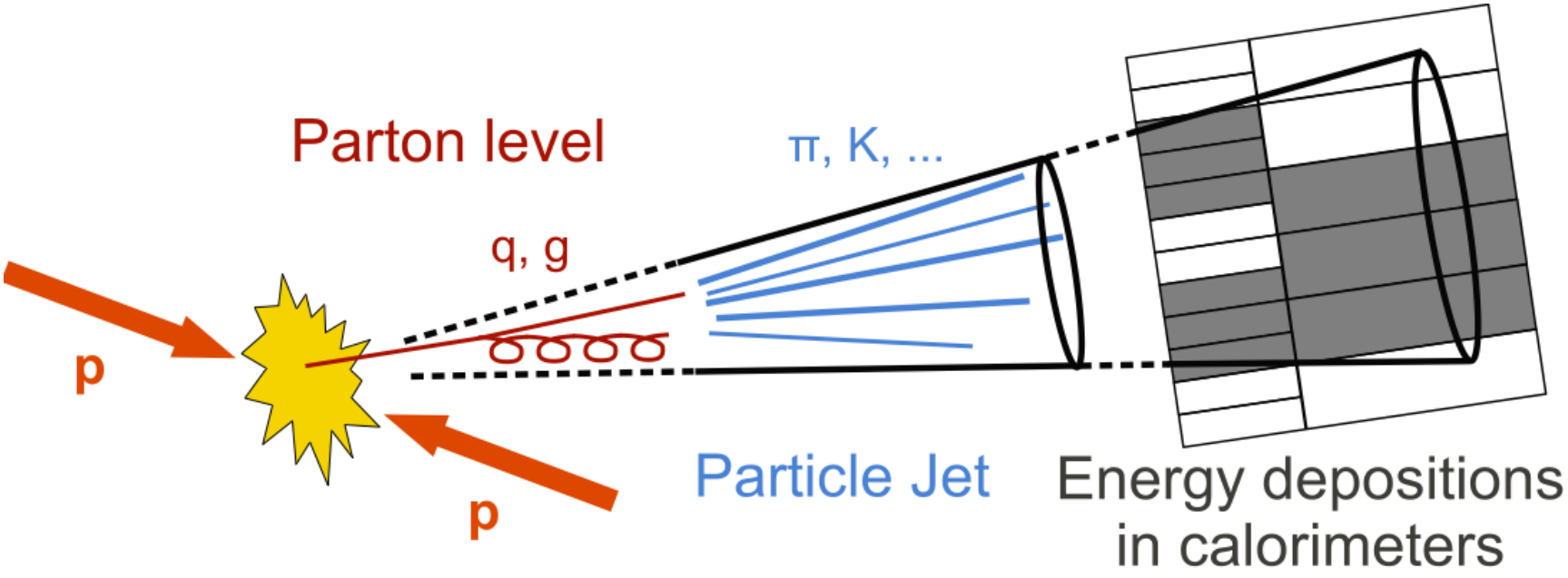
ϕ: Azimuthal angle on plane perpendicular to the beam axis.

p_T: Transverse momentum relative to the beam axis.

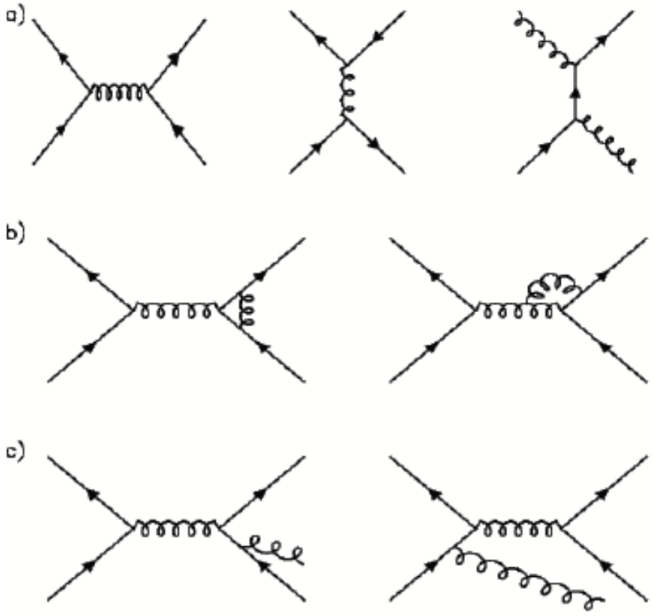
The collimated sprays of particles produced in proton-proton collision are known as "jets." They are a direct manifestation of quark-gluon interactions and color confinement.

Jets are used as proxies of struck quarks and gluons.

In CMS, jets are clustered with the anti-k_T algorithm based on the detected hadrons, photons, electrons and muons.



Standard "fixed-order" perturbation theory machinery



In fixed-order pQCD, we calculate the hard cross sections in powers of $\alpha_s \ll 1$, *symbolically* (ignoring pre-factors) represented by

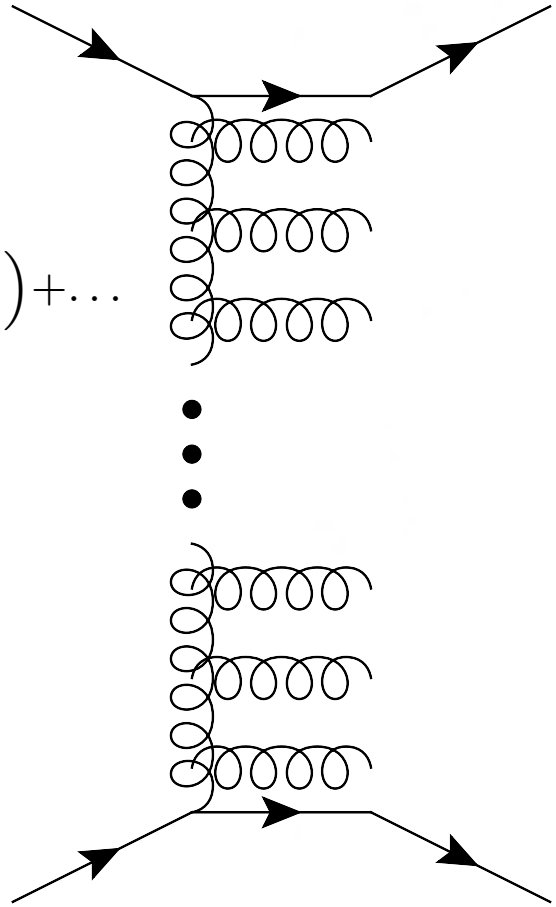
$$\mathrm{d}\hat{\sigma} \sim \alpha_s^2 + \alpha_s^3 + \alpha_s^4 + \ldots$$

Calculations are known up to leading order (LO), next-to-LO (NLO), next-to-NLO (N^2LO), and in very few cases for next-to-NNLO (N^3LO).

These are then convoluted with parton distribution functions (PDFs) to predict cross section rates at the LHC.

In the high energy limit ($\hat{s} \gg -\hat{t} \gg \Lambda^2_{\mathrm{QCD}}$), **the fixed-order approach breaks down**. The perturbative expansion should be rearranged (symbolically) as,

$$\mathrm{d}\hat{\sigma} \sim \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \ldots$$



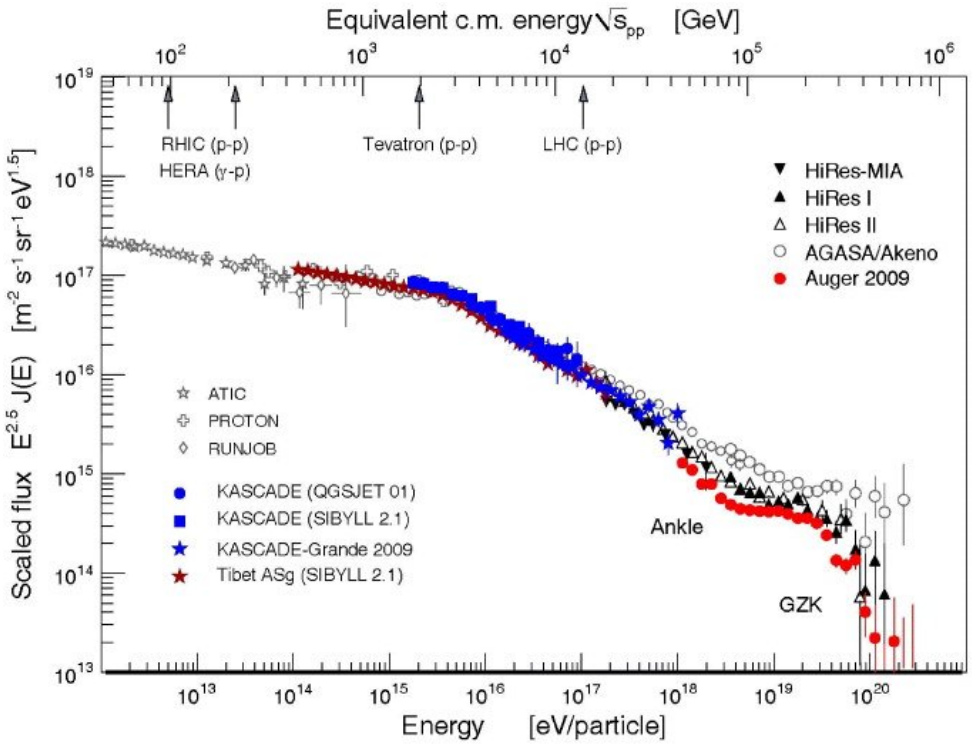
where $\hat{s}$, $\hat{t}$ are the square center-of-mass energy and four-momentum transfer squared of the outermost partons, and $\alpha_s^n \ln^n \left(\hat{s}/|\hat{t}\right) = \alpha_s^n (\Delta y)^n \lesssim 1$.

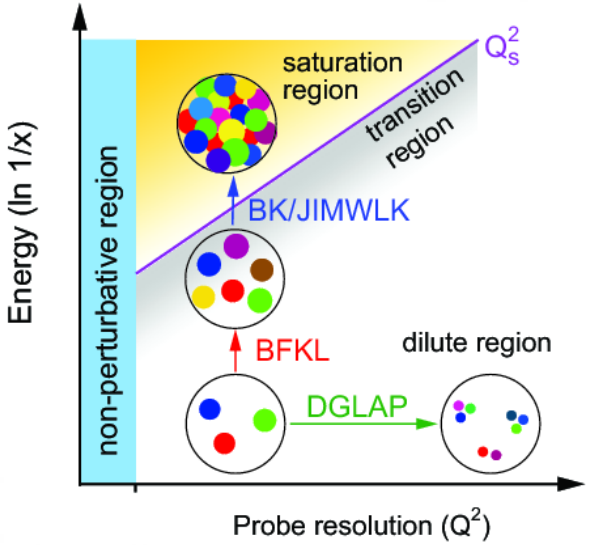
Resummation of large logarithms of $\hat{s}$ to all orders in α_s is needed to obtain finite results.

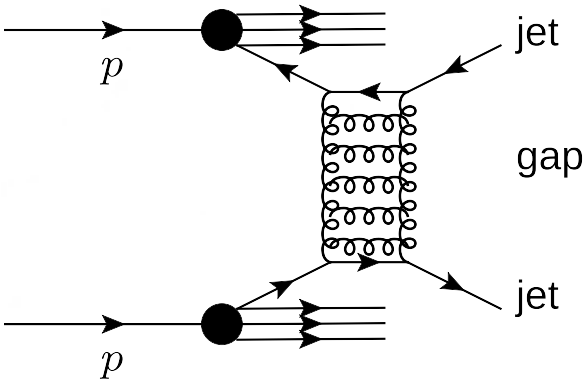
Resummation is done via the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation of QCD.

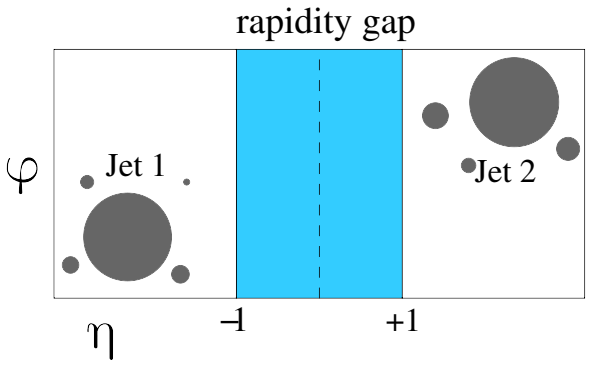
Why should we care about the high energy limit of QCD?

- Important to get an insight into the quantum field theory description of particle scattering when $\sqrt{s}$ is much larger than ANY other energy scale.
- **Cosmic ray physics:** cosmic ray interactions with the atmosphere can occur at the multi-TeV scale and beyond. The dominating interactions are mediated by the strong force.
- **Gluon saturation effects:** need to understand initial-state high gluon densities in proton and heavy-ion collisions. A future Electron Ion Collider will be investigate such aspects in the next decades, need intermediary measurements at the LHC now.







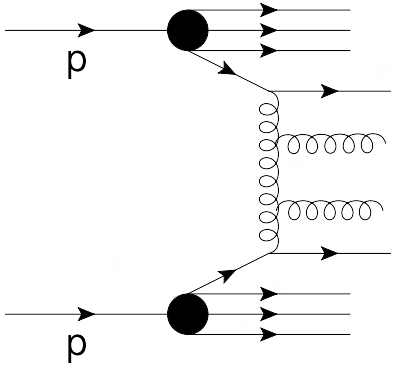


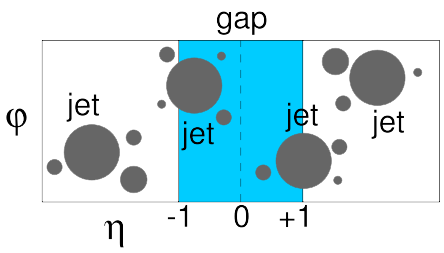
In collisions with color-singlet exchange between partons (two-gluon exchange), color-flow is neutralized $\rightarrow$ Pseudorapidity interval void of particle production between jets (rapidity gap).

In the BFKL limit of QCD, color-singlet exchange corresponds to perturbative pomeron exchange (BFKL two-gluon ladder exchange). Jet-gap-jet process was first proposed by A. Mueller and W-K. Tang (Phys. Lett. B284,123 (1992)) as a probe of BFKL evolution.

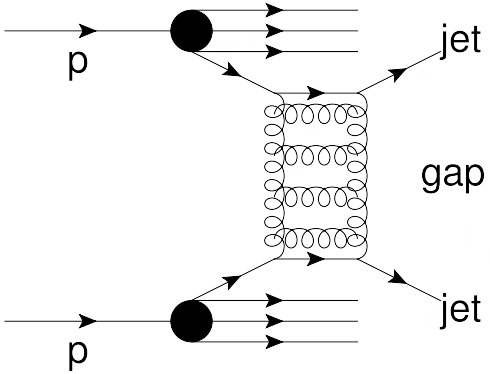
Color-exchange dijet versus color-singlet exchange dijet

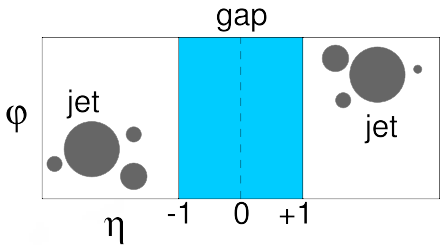
Color-exchange
(single-gluon in
t-channel)

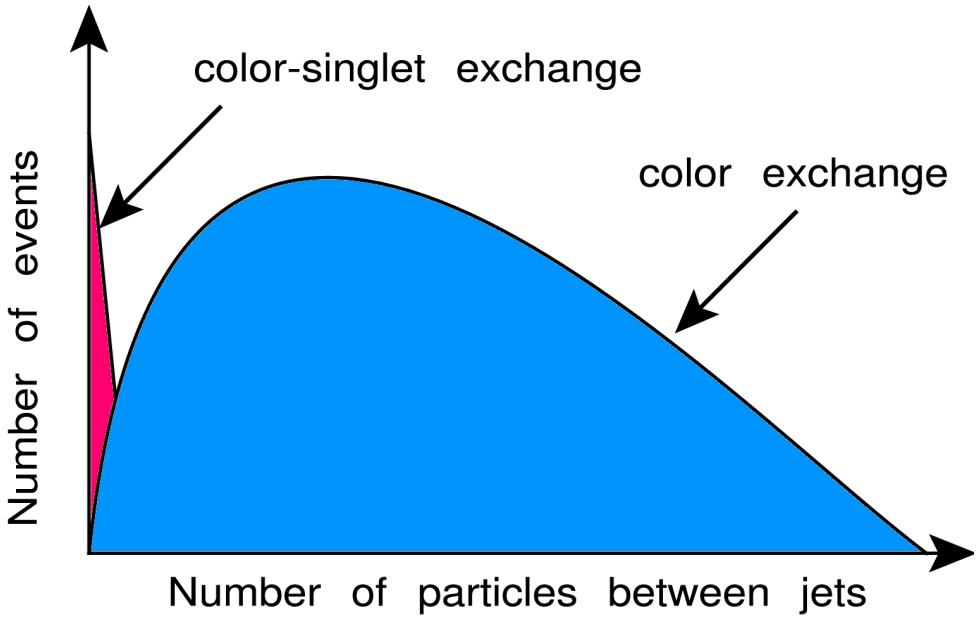




Color-singlet exchange
(two-gluon in t-channel)



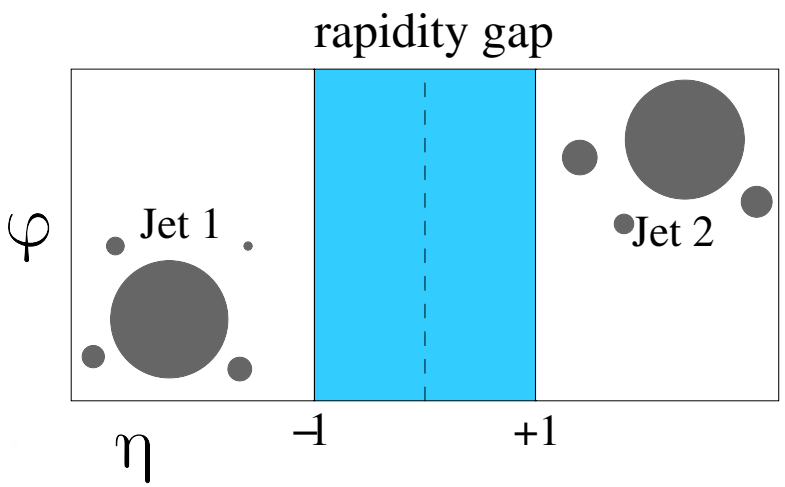




Experimental analysis at $\sqrt{s} = 13$ TeV

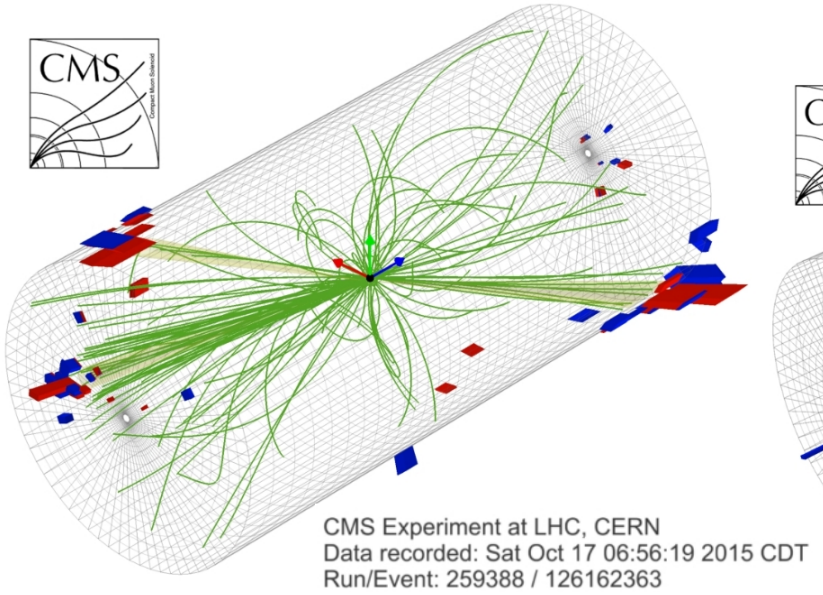
Analysis based on special LHC runs with single proton-proton collisions per bunch crossing.
Offline event selection:

- Particle-flow, anti-k_t jets $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$.
- Two highest p_T jets have $p_T > 40$ GeV each.
- Leading jets satisfy $1.4 < |\eta_{\text{jet}}| < 4.7$ and $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$
  $\rightarrow$ **Favors t-channel color singlet exchange.**
- At most one reconstructed primary vertex.

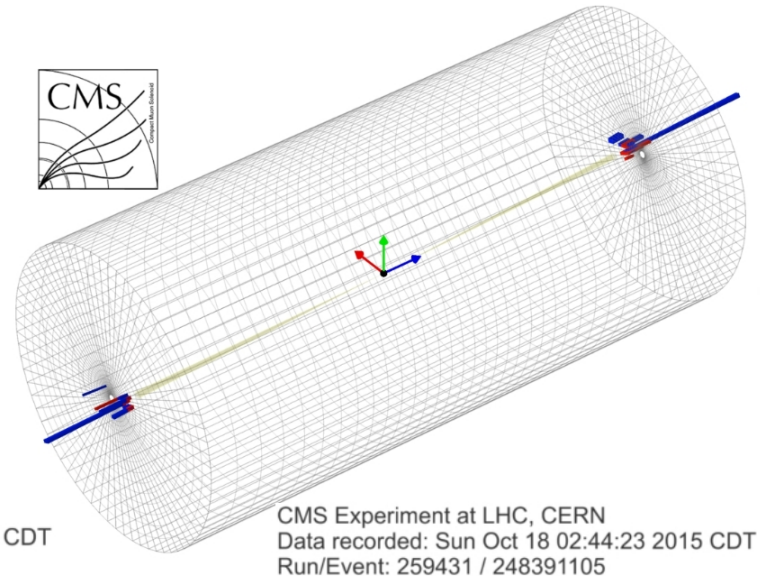


Pseudorapidity gap is defined by means of the charged particle multiplicity N_{tracks} between the leading two jets. Each charged particle has $p_T > 200$ MeV in $|\eta| < 1$.

CMS event displays (single proton-proton collision)



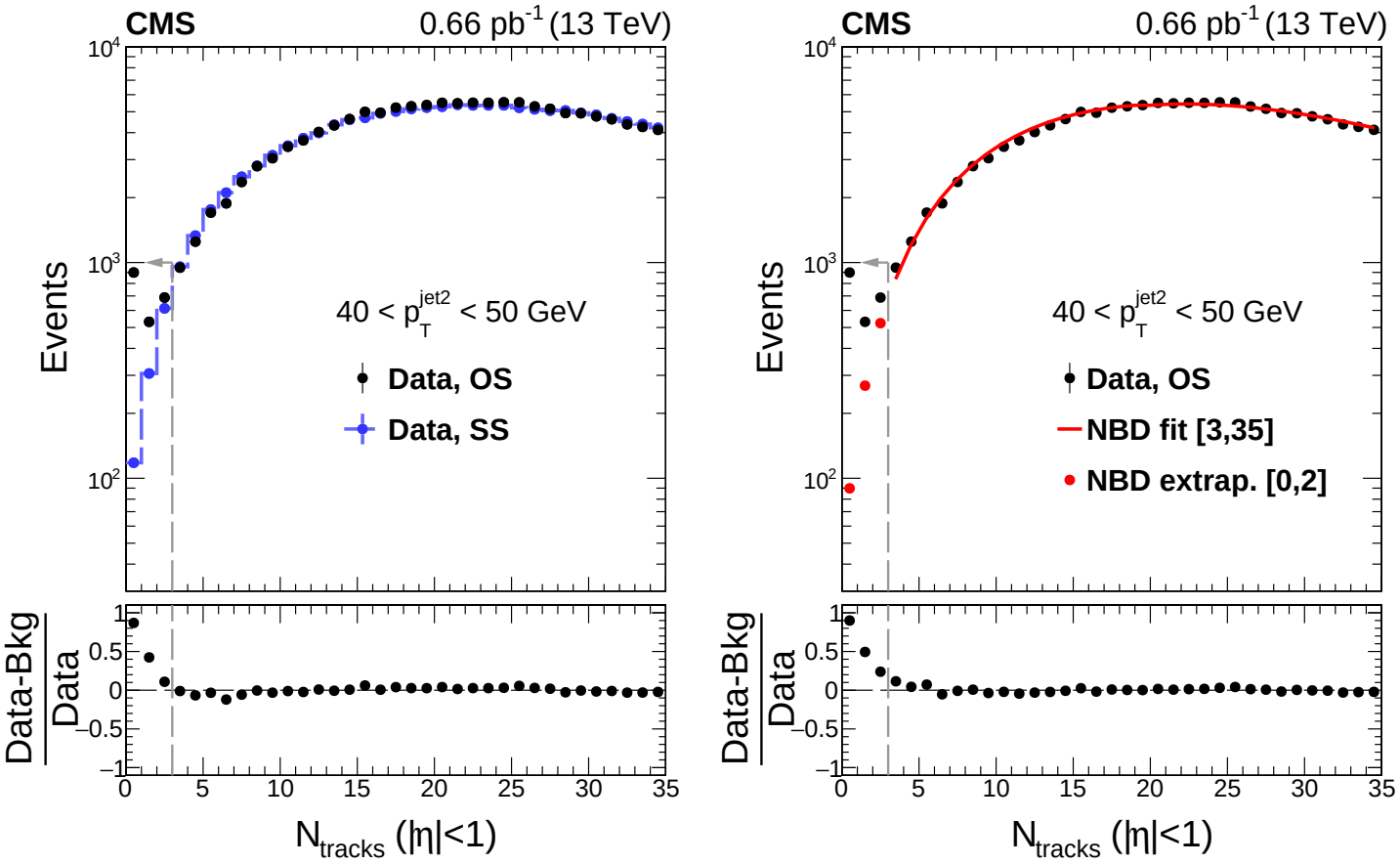
Color-exchange event candidate
(Background-like)



Color-singlet exchange event candidate
(Signal-like)

Leading two jets $p_T > 40$ GeV, all other jets $p_T > 15$ GeV, calorimeter towers with $E > 1$ GeV, charged particles with $p_T > 200$ MeV

Multiplicity of charged particles between the jets



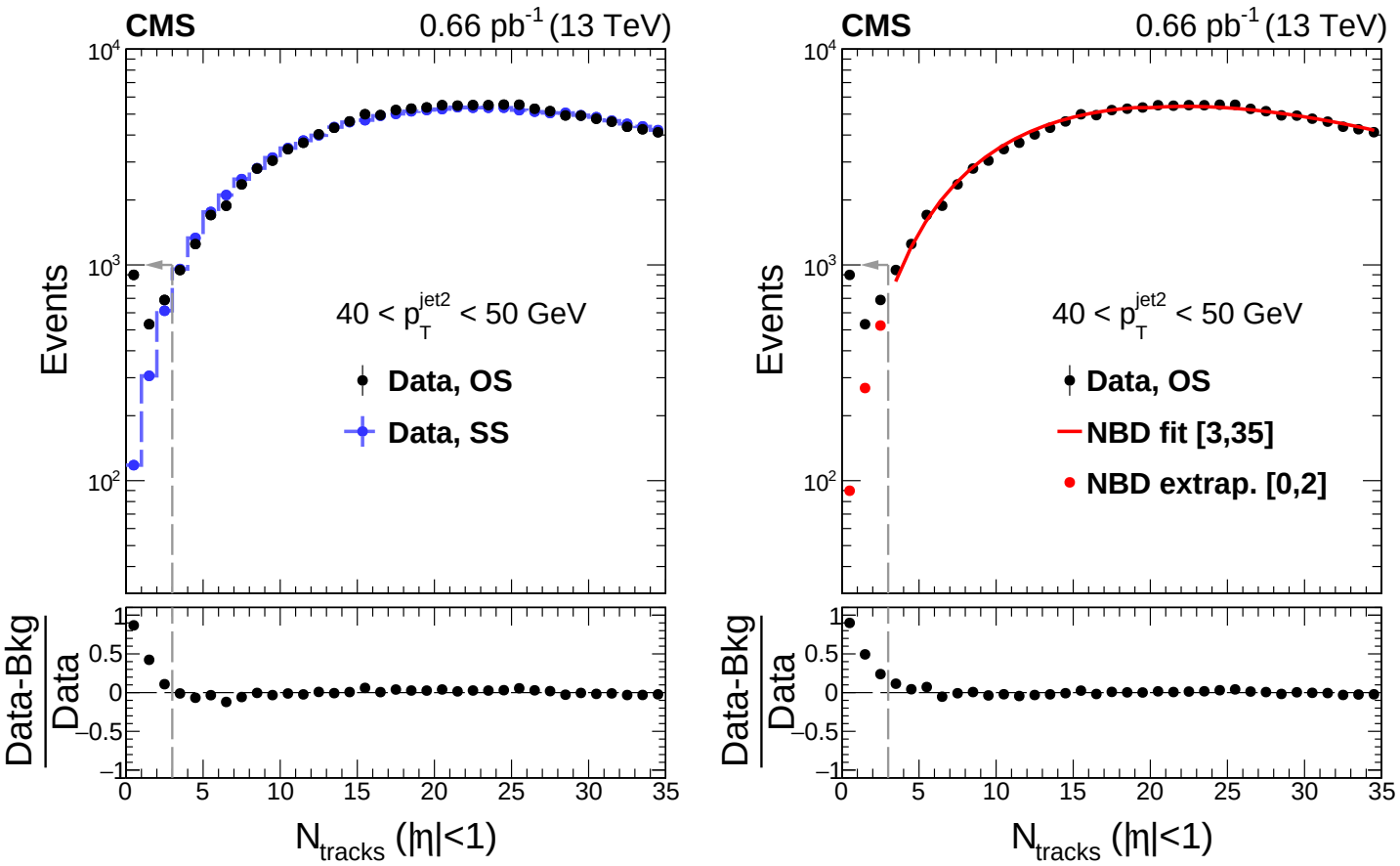
Color-exchange events dominate at high-multiplicities → Use as control region to estimate fluctuations at low multiplicities. Two data-based approaches:

- Control sample: two jets on the same-side (SS) of the CMS detector, $\eta^{\text{jet1}}\eta^{\text{jet2}} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$, in $N_{\text{tracks}} > 3$.
- Negative binomial distribution (NBD) function: Fit data with NBD in $3 \leq N_{\text{tracks}} \leq 35$, extrapolate down to $N_{\text{tracks}} = 0$. (Baseline method)

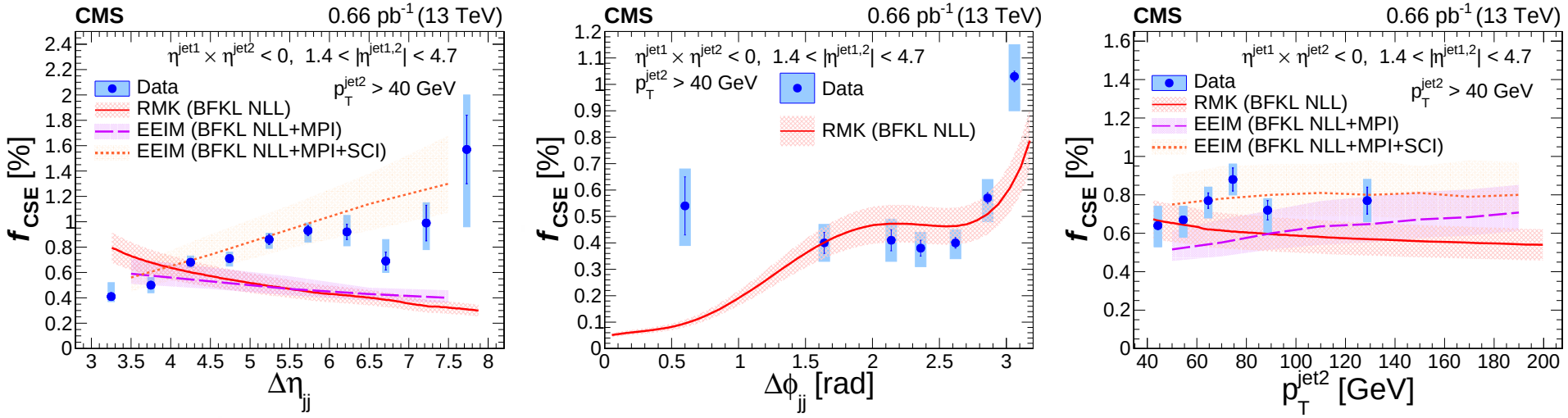
Hard color singlet exchange fraction f_{CSE}

We extract the fraction f_{CSE} based on the charged particle multiplicity distribution between the jets:

$$f_{CSE} \equiv \frac{N(N_{tracks} < 3) - N_{bkg}(N_{tracks} < 3)}{N_{all}} \equiv \frac{\text{color singlet exchange dijet events}}{\text{all dijet events}}$$



Results on color-singlet exchange fraction f_{CSE}



- Bars represent stat uncertainties, boxes represent stat + syst uncertainties.
- $f_{CSE} = 0.5$–1.0%. f_{CSE} increases with $\Delta\eta_{jj}$, with $\Delta\phi_{jj} \approx \pi$, and is weakly dependent on p_T^{jet2}.
- Comparisons to pQCD-based predictions:
  - Royon, Marquet, Kepka (RMK) predictions (Phys. Rev. D 83.034036 (2011), arXiv:1012.3849), and survival probability $|S|^2 = 0.1$.
  - Ekstedt, Enberg, Ingelman, Motyka (EEIM) predictions (Phys. Lett. B 524:273, arXiv:hep-ph/0111090 and arXiv:1703.10919) with multiple-parton interactions (MPI) to simulate $|S|^2$, which can also be supplemented with soft color interactions (SCI).
- EEIM model describes data within uncertainties, only when including both MPI and SCI together.
- Challenging to describe theoretically all aspects of the measurement simultaneously.

Unique opportunity to study hard color singlet exchange at the CERN LHC.

Observation of jet-gap-jet events at 13 TeV:

- About 0.6% of dijet events are produced by hard color-singlet exchange.
- BFKL calculations + soft-parton exchanges is able to describe most of the data.

Other aspects of the measurement not discussed in this talk (e.g., a joint measurement with CMS-TOTEM), but stay tuned for a future graduate colloquium for a more thorough discussion!

Corresponding paper has been submitted for publication to Phys. Rev. D. (arXiv:2102.06945)

Thanks!

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