Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

INFN

LHCb

Master thesis

Measurement of the strong coupling constant with the LHCb detector

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Thesis co-supervisors Prof. Donatella Lucchesi

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Graduation session September 16th 2024 – A. Y. 2023/2024

Outline

- Goal of the thesis
- The LHCb experiment and hadronic jets
- Analysis strategy
- Final results and conclusions

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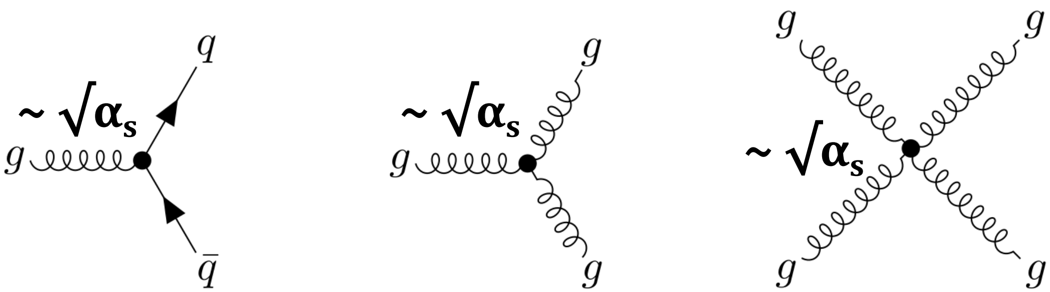
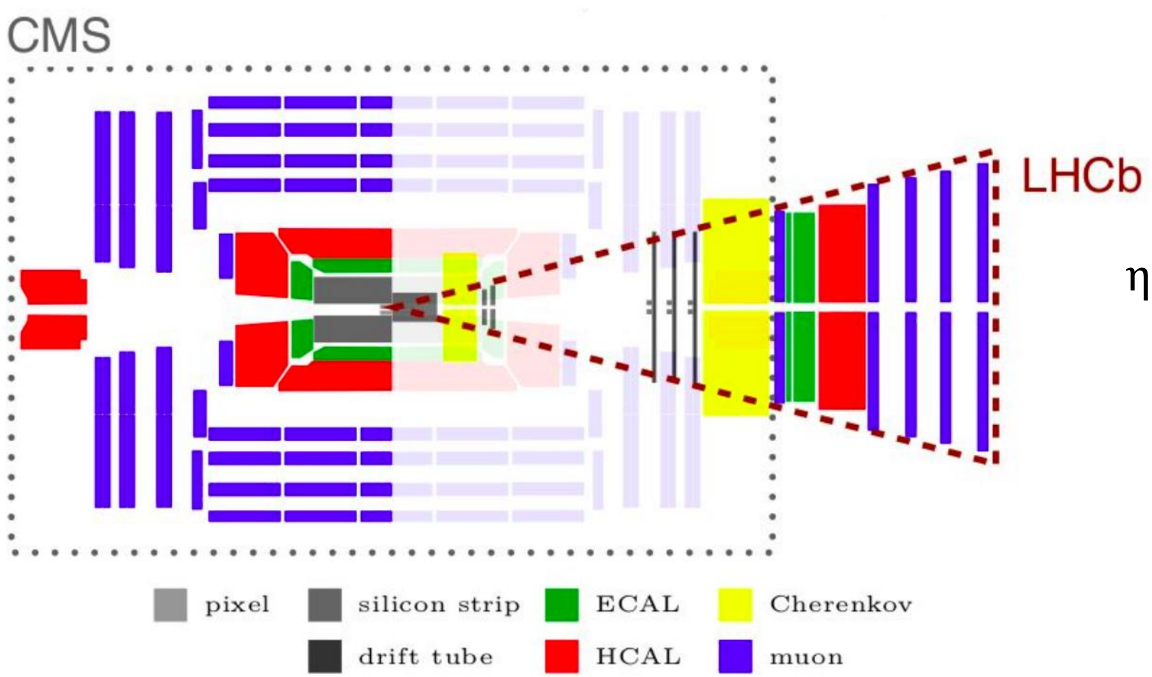
Precise measurement of α_s and main uncertainties from dijet cross section

$$\sigma_{jj}^{data} \propto \sigma_{pp\to jj}\,(s, Q^2, \alpha_s) = \frac{\alpha_s^{\,2}(Q^2)}{s^2}\left|\mathcal{M}_{pp\to jj}\right|^2$$



- Least precisely measured SM coupling constant:
  - $\alpha_s = 0.1180(9) \rightarrow 7.6 \times 10^6$ ppb
  - $\alpha = 1/137.035\,999\,084(21) \rightarrow 0.15$ ppb!
- Limitation to → theoretical predictions / → new physics effects

Employing LHCb data samples containing hadronic jets



$2 < \eta < 5$

$\eta = -\ln(\tan(\theta/2))$

LHCb can measure α_s in complementary kinematic regions

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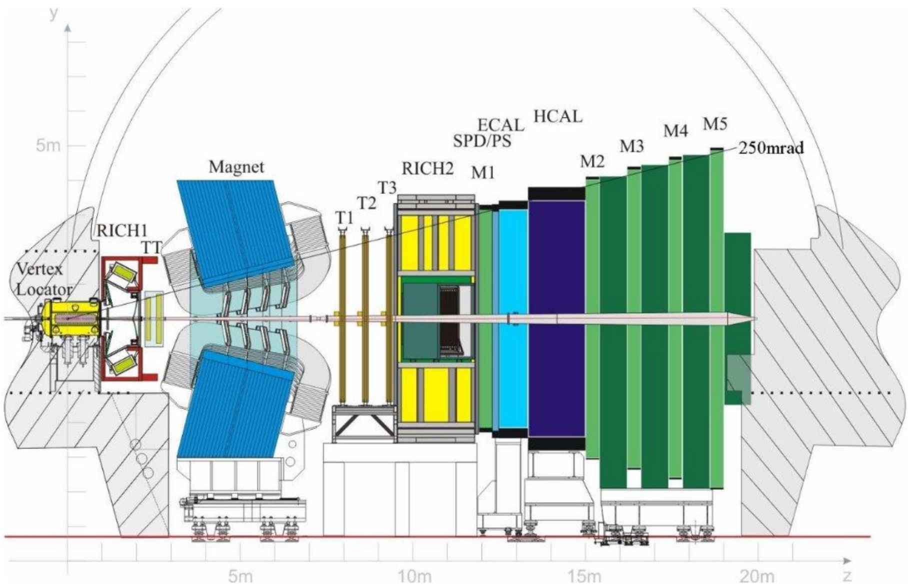
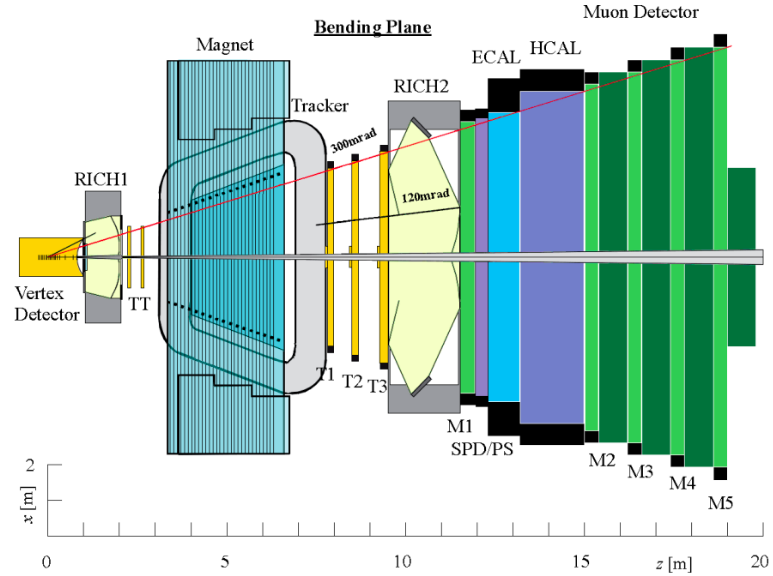
Large Hadron Collider beauty experiment – Run 2 (2015-2018) layout

Side view



Top view



This work: trackers, calorimeters, muon stations

Large Hadron Collider beauty experiment – Run 2 (2015-2018) layout

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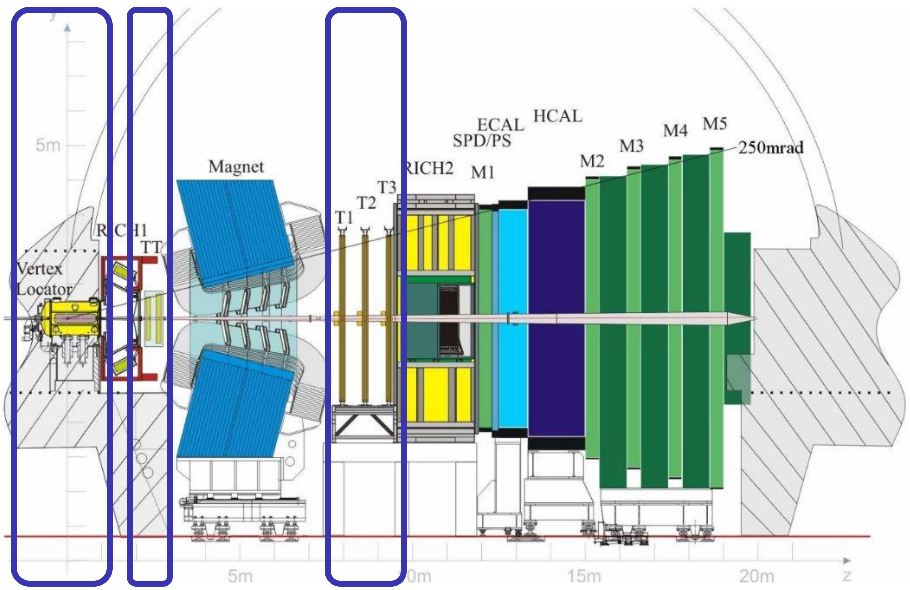

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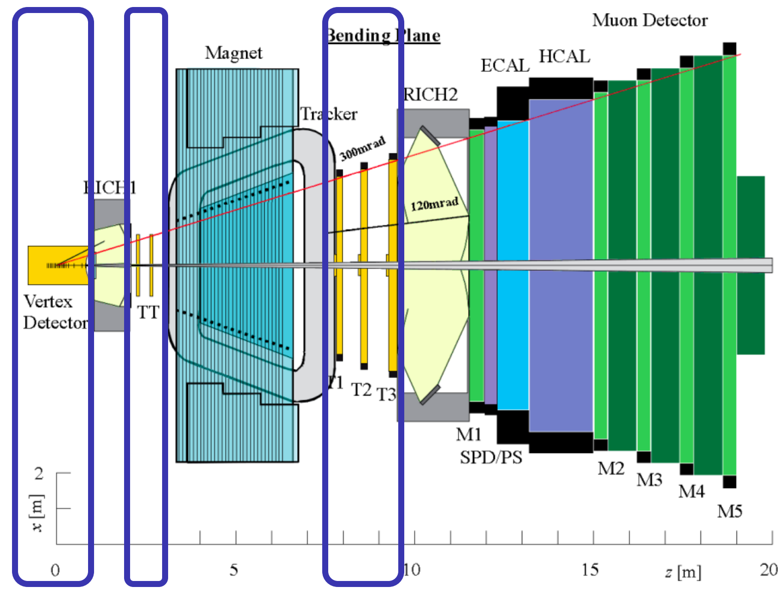

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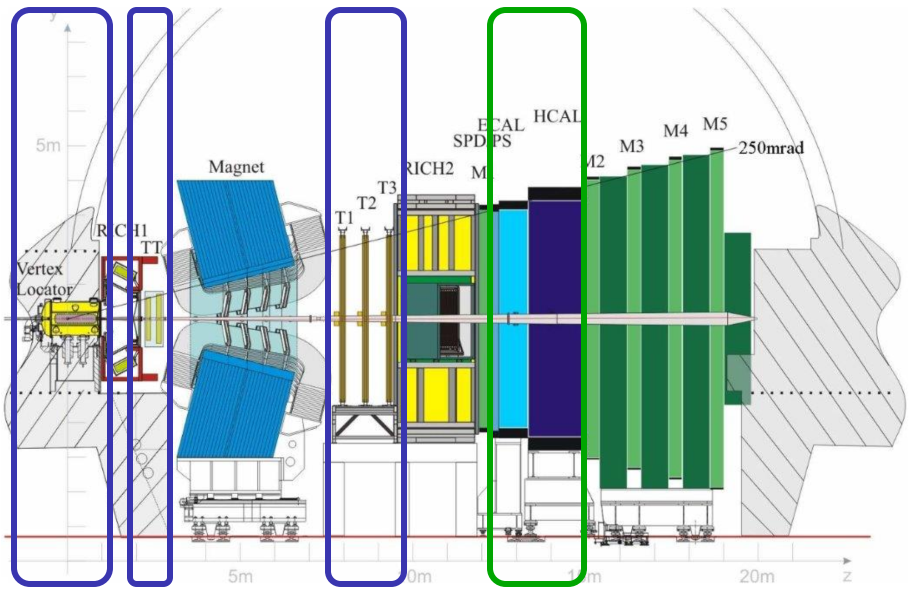

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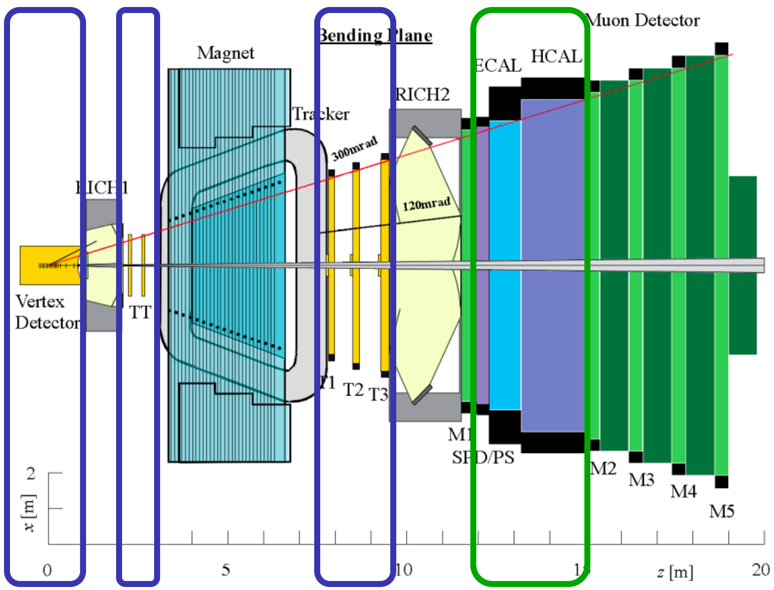

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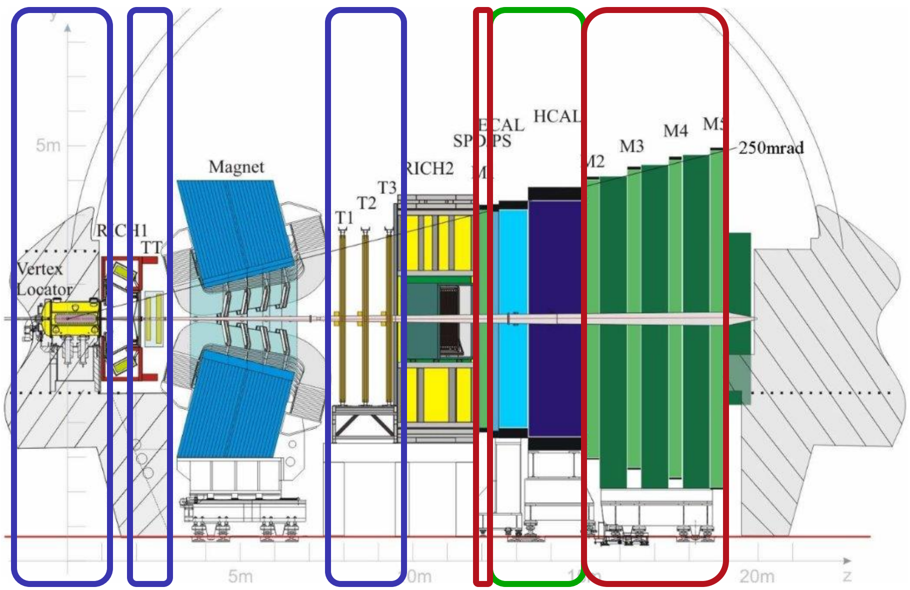

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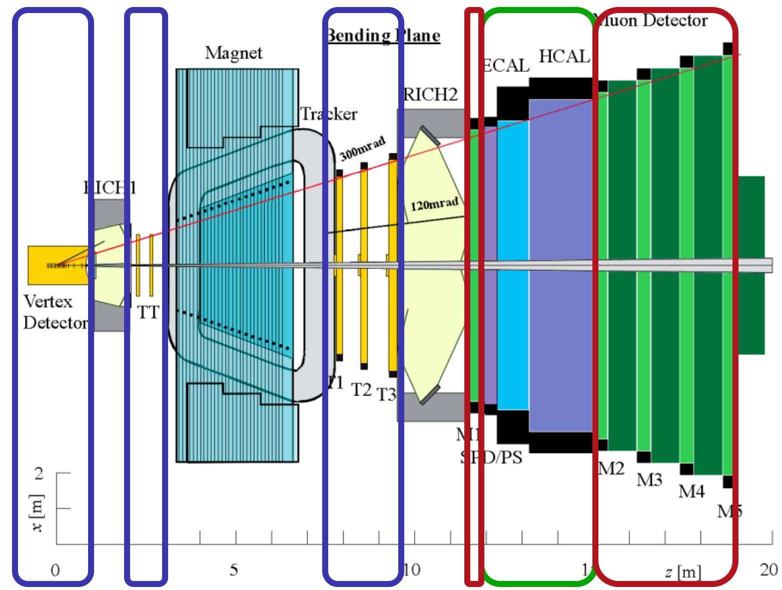
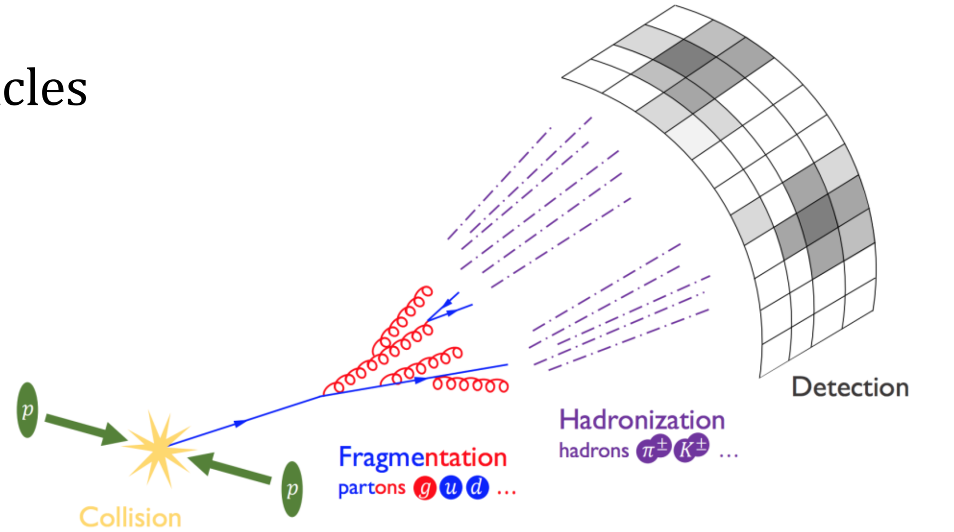
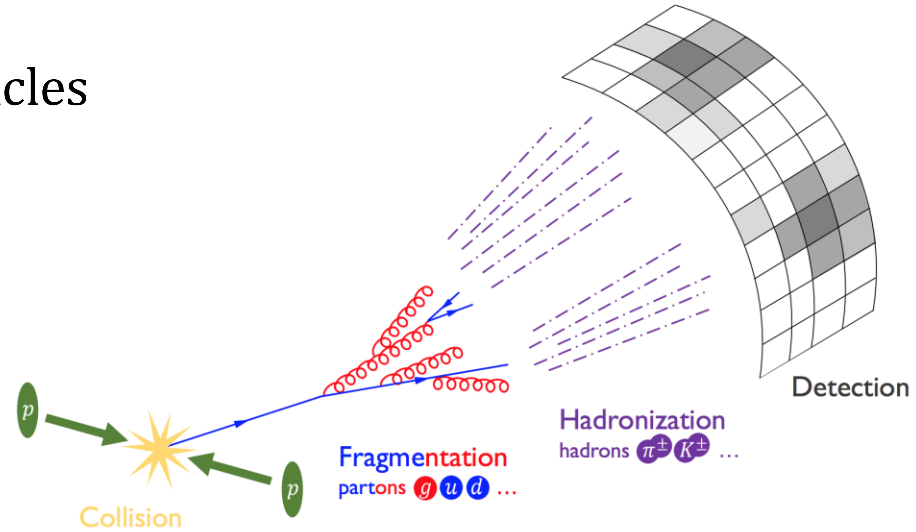


This work: trackers, calorimeters, muon stations

Jet Collimated conical spray of particles

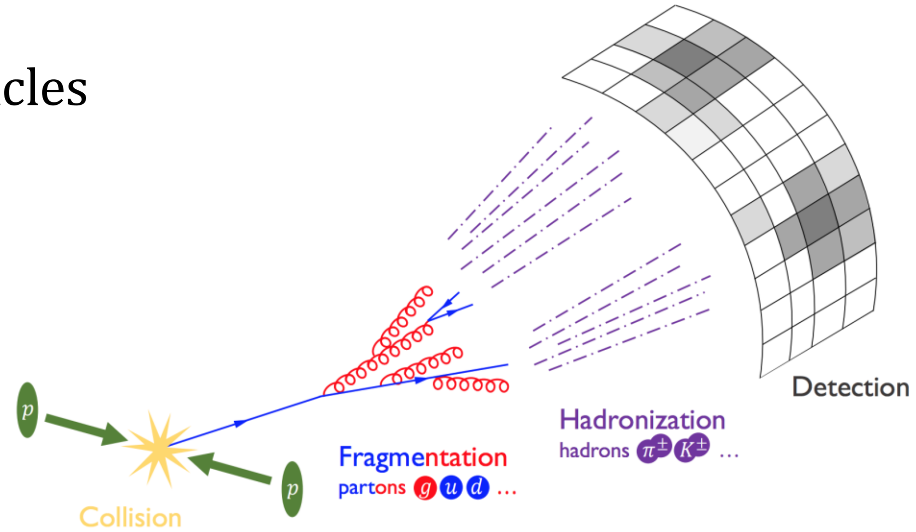


Jet Collimated conical spray of particles



Jet reconstruction

Jet Collimated conical spray of particles

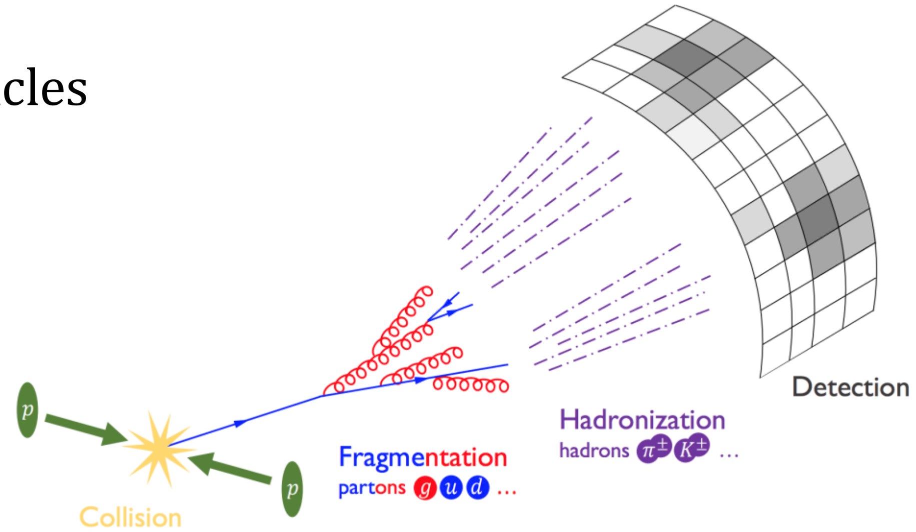


Jet reconstruction

1. Tracks and calorimeter clusters

The LHCb experiment and hadronic jets

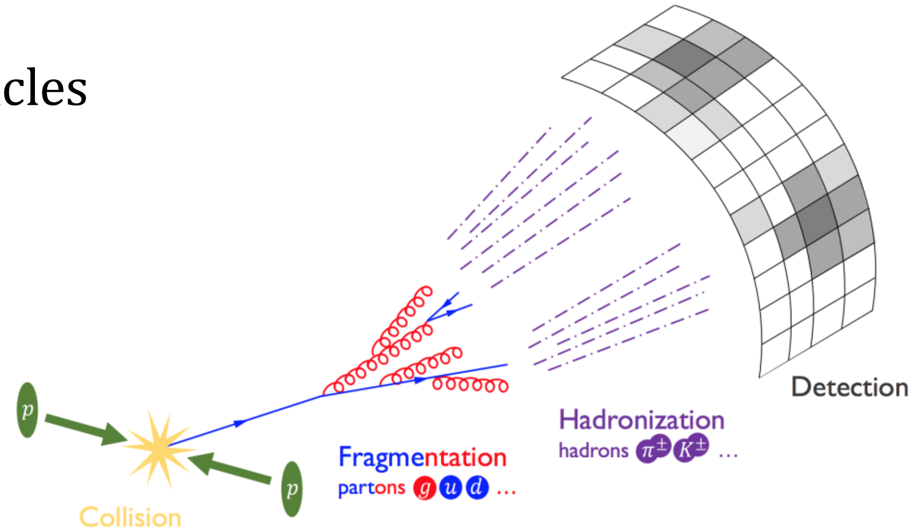
Jet Collimated conical spray of particles



Jet reconstruction

1. Tracks and calorimeter clusters
2. Clustering algorithm

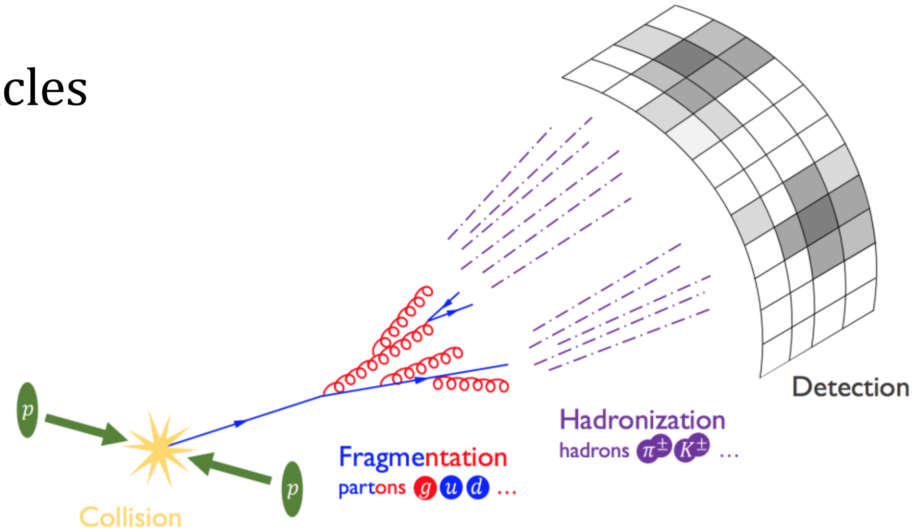
Jet Collimated conical spray of particles



Jet reconstruction

1. Tracks and calorimeter clusters
2. Clustering algorithm
3. Jet four-momentum

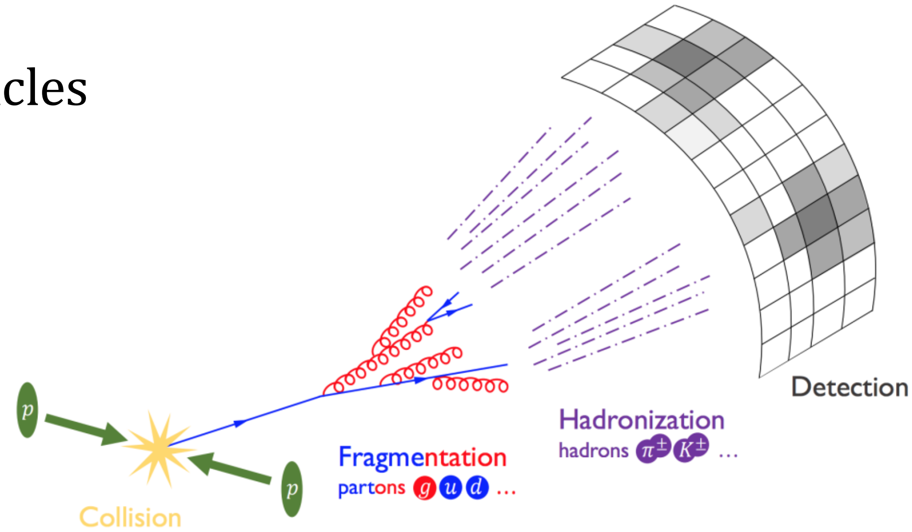
Jet Collimated conical spray of particles



Jet reconstruction

1. Tracks and calorimeter clusters
2. Clustering algorithm
3. Jet four-momentum
4. Jet Energy Correction

Jet Collimated conical spray of particles

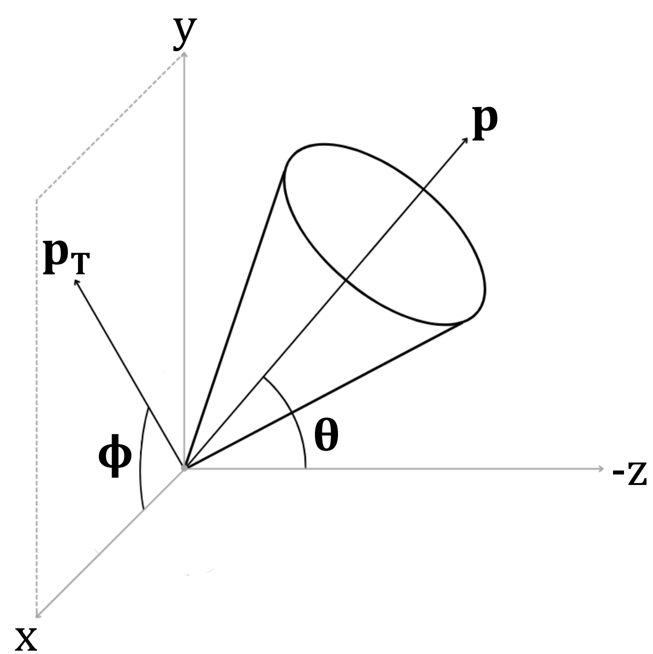


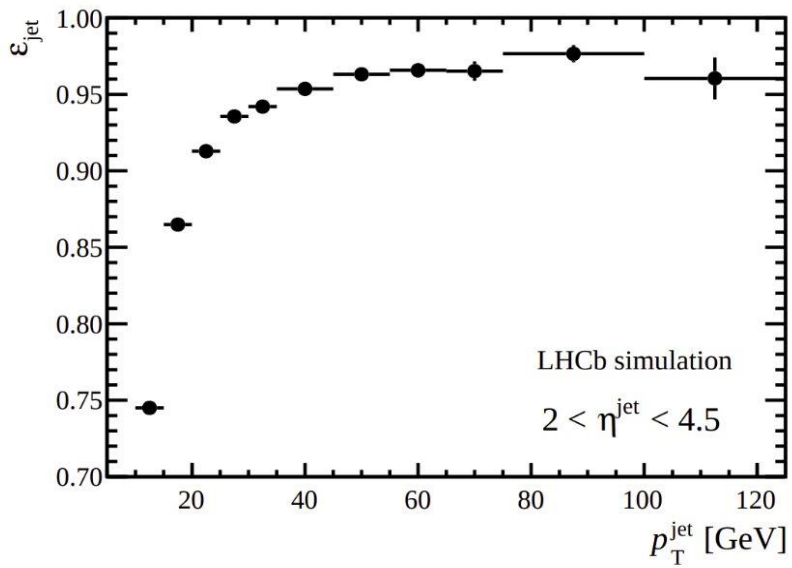
Jet reconstruction

1. Tracks and calorimeter clusters
2. Clustering algorithm
3. Jet four-momentum
4. Jet Energy Correction

Useful quantities

- Transverse momentum, p_T
- Pseudorapidity, $\eta = -\ln(\tan(\theta/2))$
- Azimuthal angle, ϕ

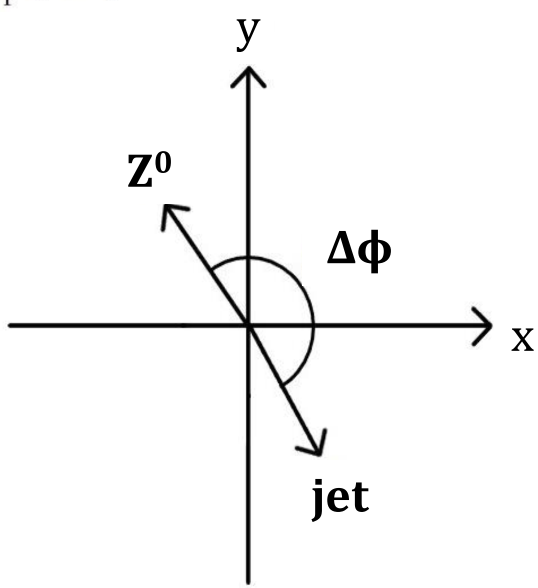




LHCb samples (data and MC)

2016 (Run 2), $\sqrt{s} = 13$ TeV, $\mathcal{L} = 1.6\ \text{fb}^{-1}$

- *Dijet* events with two jets
- *Z+jet* events with Z^0 ($\rightarrow \mu^+\mu^-$) + jet
- Selection - $20\ \text{GeV} < p_T(\text{jet}) < 100\ \text{GeV}$
  - $2.2 < \eta(\text{jet}) < 4.2$



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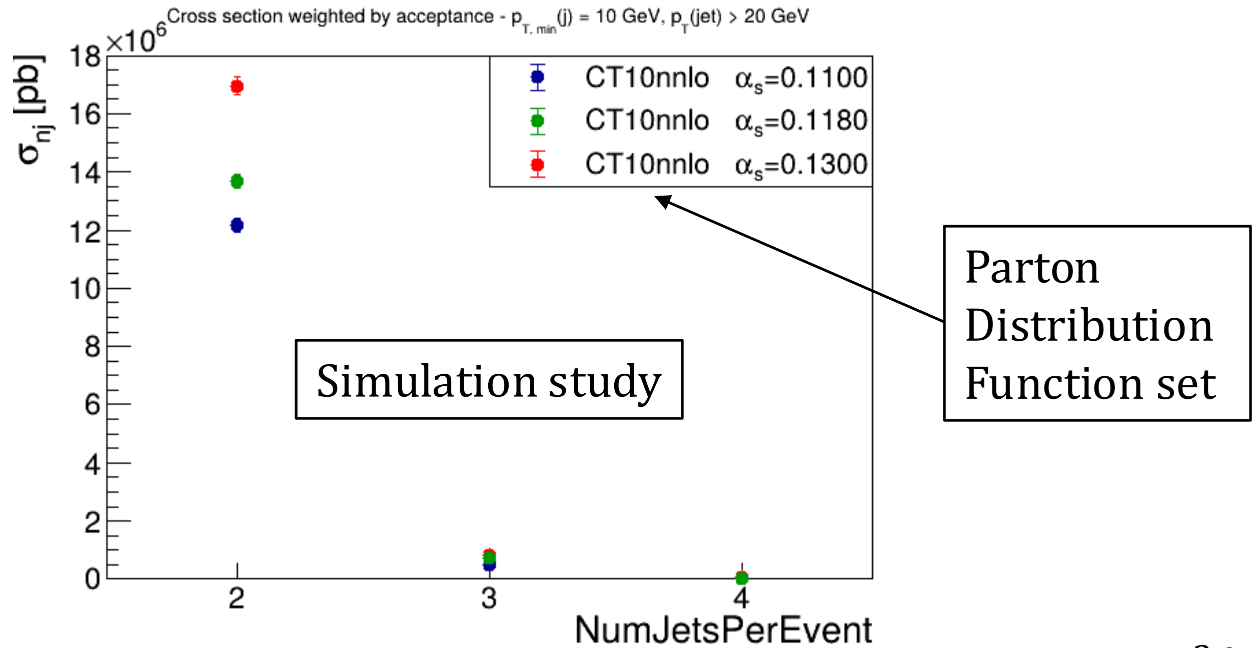
Analysis strategy

Final results and conclusions

Analysis strategy



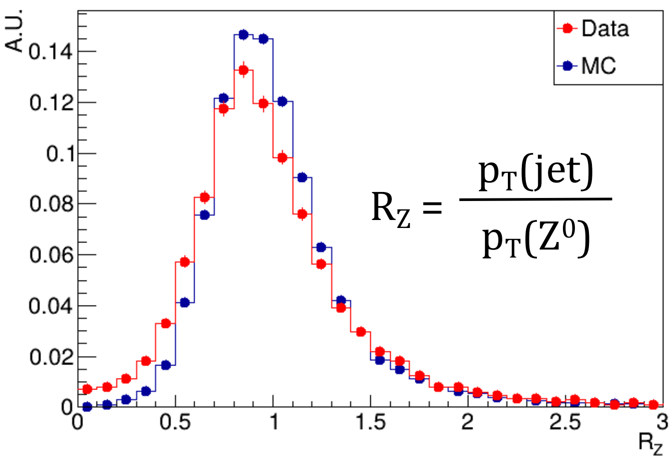
1. **$N = \sigma \times \varepsilon \times \mathcal{L}$** $\rightarrow \sigma_{jj}^{data}$ from *dijet* sample, $\sigma_{jj}^{data} \propto \sigma_{pp\rightarrow jj}\,(s, Q^2, \alpha_s) \propto \dfrac{\alpha_s^2(Q^2)}{s^2}$
2. Jets p_T correction factors from *dijet* and *Z+jet* samples → **efficiency ε**
3. Comparison simulated and experimental σ_{jj} → **α_s value**
4. Statistics, correction factors, $\mathcal{L} \rightarrow \sigma_{jj}^{data}$ uncertainty → **α_s uncertainty**

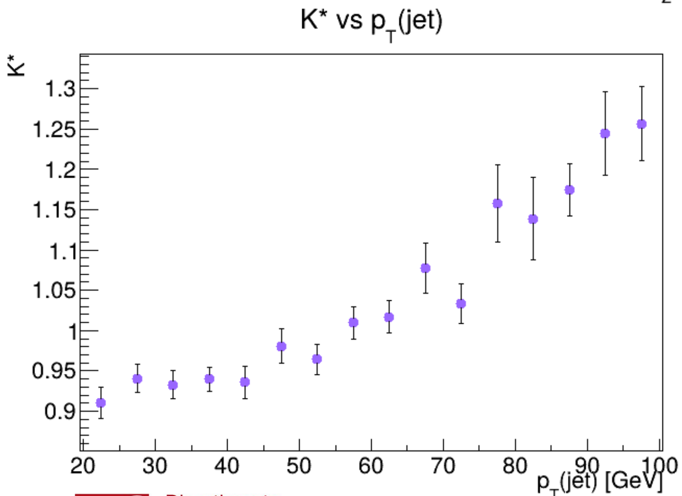
Analysis strategy

Jet Energy Scale

$$JES = \left\langle \frac{p_T^{true}}{p_T^{reco}} \right\rangle$$

$$R_Z = \frac{p_T(jet)}{p_T(Z^0)}$$

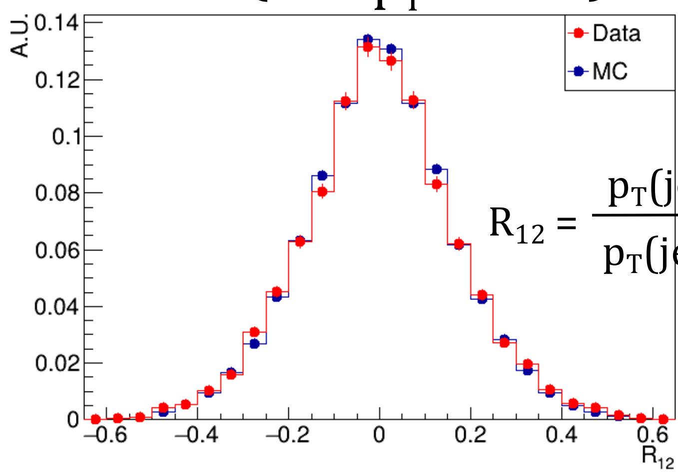


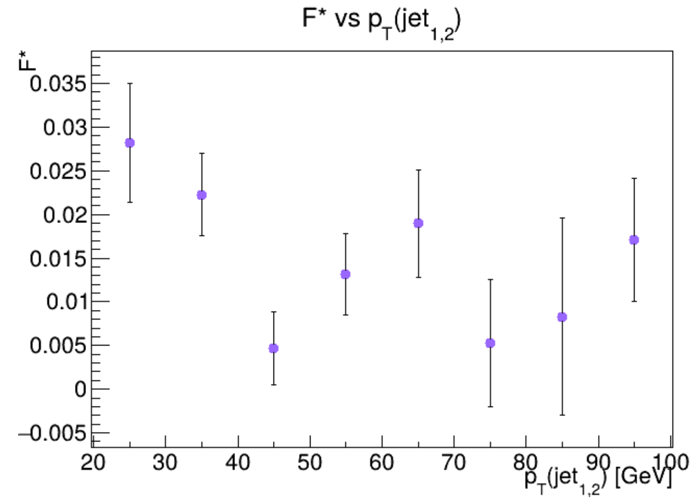


Jet Energy Resolution

$$JER = \sigma\left(\frac{p_T^{reco} - p_T^{true}}{p_T^{true}}\right)$$

$$R_{12} = \frac{p_T(jet_1) - p_T(jet_2)}{p_T(jet_1) + p_T(jet_2)}$$





Total efficiency

$$\varepsilon = \frac{N_{corr}}{N_{MC}} = (1.11 \pm 0.09) \times 10^{-6}$$

N_{MC}: n. of events in *dijet* MC sample

N_{corr}: n. of selected and corrected MC events

Experimental dijet cross section

$$\sigma_{jj}^{data} = \frac{N_{data}}{\varepsilon \times \mathcal{L}}$$

N_{data}: n. of events in *dijet* data sample

$$\sigma_{jj}^{data} = (1.307 \pm 0.009\ (\text{stat.}) \pm 0.1\ (\text{syst.}) \pm 0.03\ (\text{lumi.})) \times 10^{7}\ \text{pb} =$$

$$= \mathbf{(1.3 \pm 0.1) \times 10^{7}\ pb}$$

$$\sigma_{jj}^{sim}\ (\alpha_s = 0.1180) = (1.37 \pm 0.03) \times 10^{7}\ \text{pb}$$

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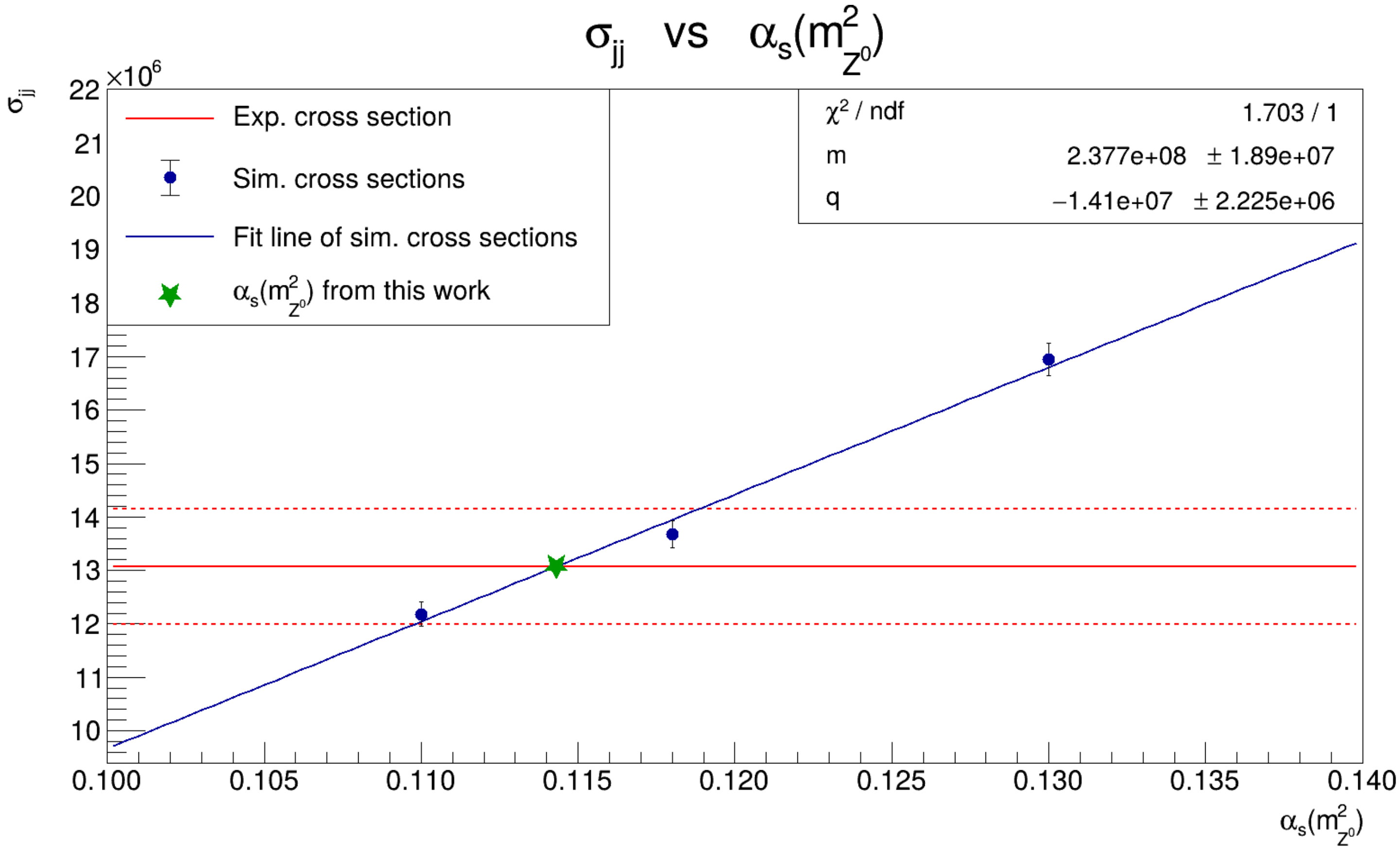


$\alpha_s(m_{Z^0}{}^2) = 0.1143 \pm 0.0007\ (\text{stat.}) \pm 0.009\ (\text{syst.}) \pm 0.002\ (\text{lumi.}) =$

$= \mathbf{0.114 \pm 0.009}$

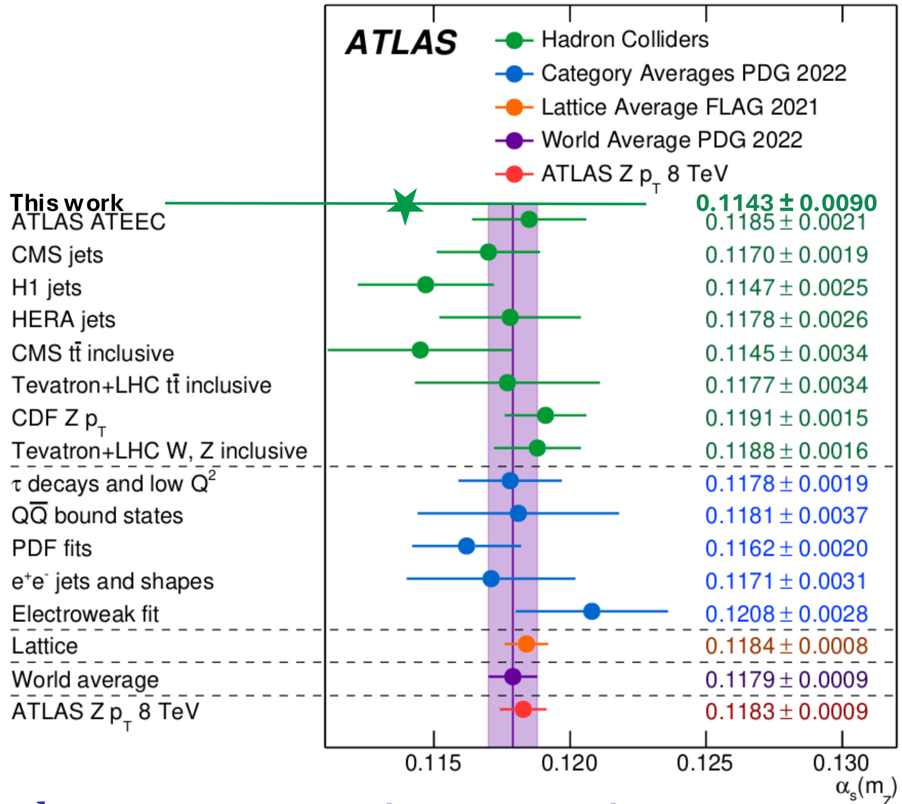
Final results and conclusions

This work $\alpha_s(m_{Z^0}^2) = 0.1143 \pm 0.0007\ (\text{stat.}) \pm 0.009\ (\text{syst.}) \pm 0.002\ (\text{lumi.}) =$

$= 0.114 \pm 0.009$

PDG/ATLAS $\alpha_s(m_{Z^0}^2) = 0.1180 \pm 0.0009$

CMS jets $\alpha_s(m_{Z^0}^2) = 0.1170 \pm 0.0019$



First measurement of α_s
in forward region
with the LHCb detector!

- Statistics is not the limiting factor
- Jet energy correction must be refined to lower systematic uncertainty
- Uncertainty from $\mathcal{L}$ gives constant contribution, potentially limiting

Future improvements

- Jet energy correction refinement
- Enhanced simulation study

Other analysis approaches

- Differential measurements
- Multi-jet events → R_{32}

LHCb detector development

- Run 3 and Upgrades
- ECAL development → *γ+jet* sample

UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia Galileo Galilei

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LHCb

Thank you for your attention!

Back-up slides

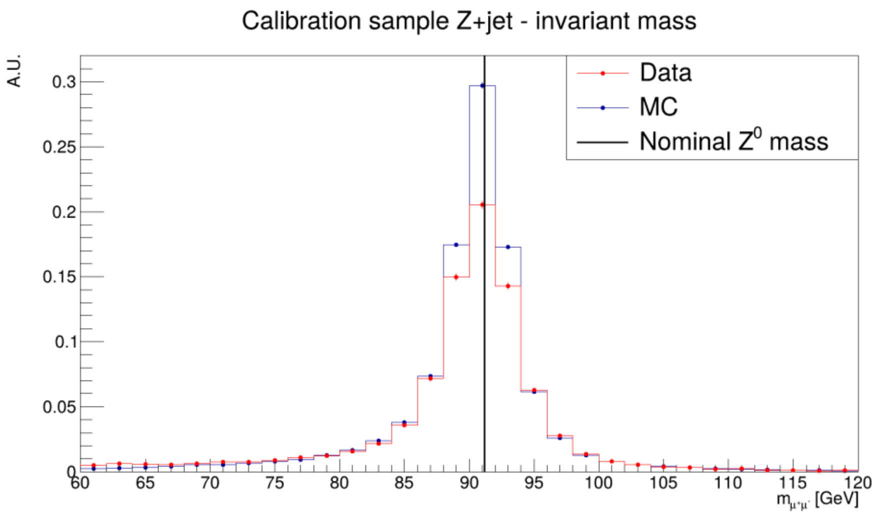
LHCb samples (data and MC)

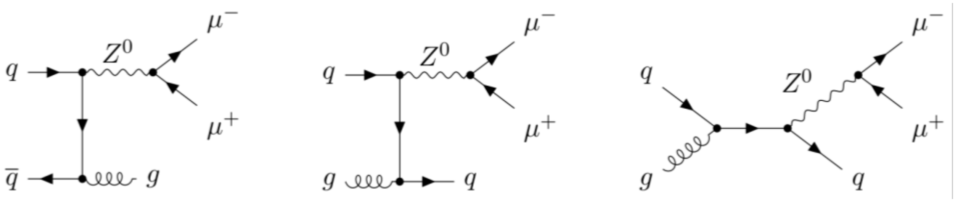
Two jets

Dijet
20 GeV < $p_T(jet_{1,2})$ < 100 GeV
2.2 < $\eta(jet_{1,2})$ < 4.2
$\Delta\phi(jet_{1,2})$ > 2.8 or 1

Z^0 ($\rightarrow \mu^+\mu^-$) + jet

Z+jet
20 GeV < $p_T(jet)$ < 100 GeV
2.2 < $\eta(jet)$ < 4.2
$p_T(\mu^\pm)$ > 20 GeV
2 < $\eta(\mu^\pm)$ < 4.5
$\Delta\phi(Z^0,jet)$ > 2.8





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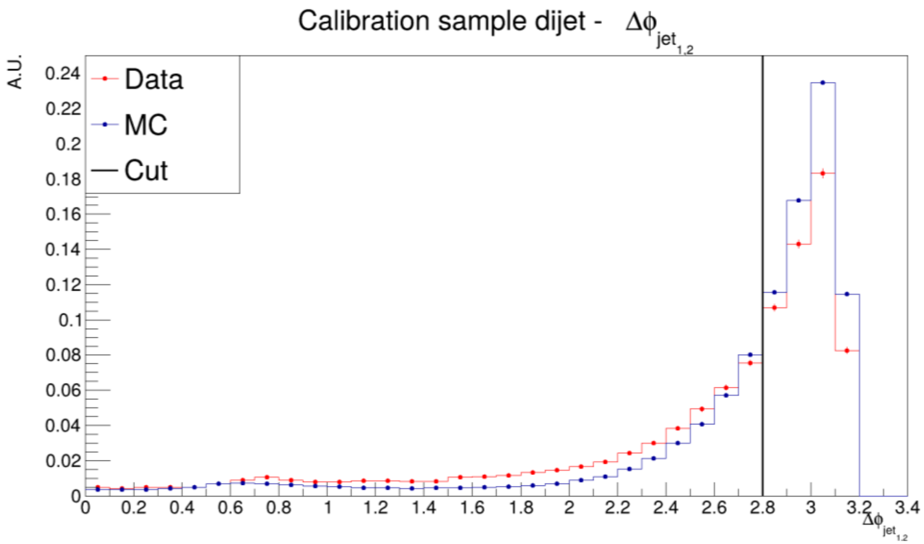
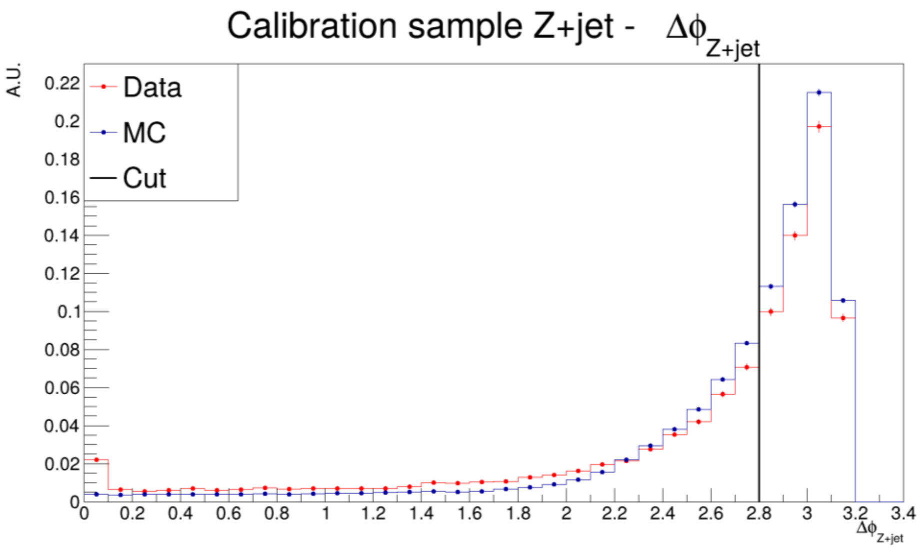
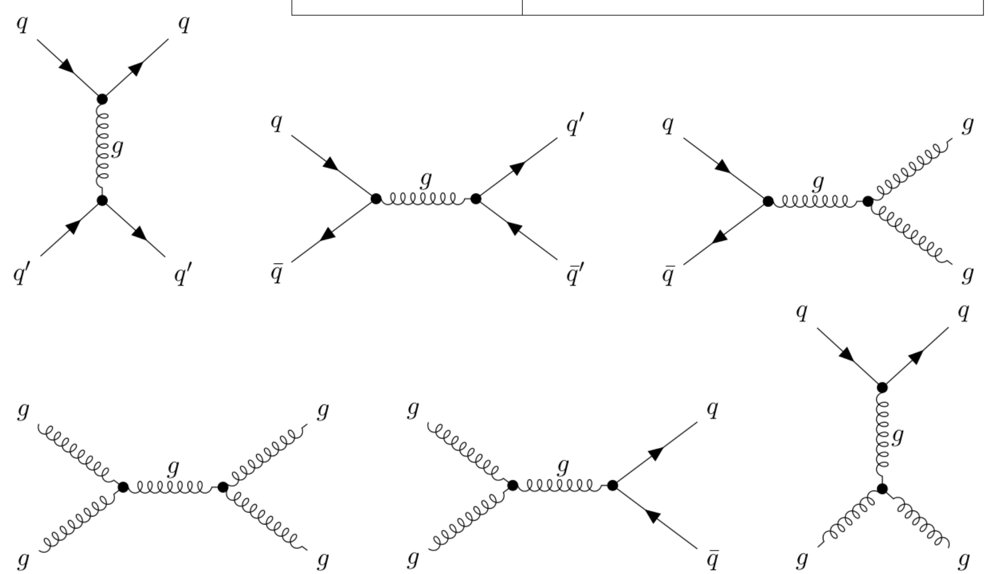




Events generation

- **p p > j j** @ LO, `MadGraph5_aMC@NLO` + `Pythia8`
  - p = g u c d s u~ c~ d~ s~
  - j = g u c d s **b** u~ c~ d~ s~ **b~**
  - $N_{gen} = 10^6$ events
  - ΔR (j,j) = 0.4
  - $p_{T,\,min}$ (j) = 10 GeV
  - η_{max} (j) = 5
- PDFs CT10 NNLO
  - $\alpha_s = 0.1100$
  - $\alpha_s = 0.1180$
  - $\alpha_s = 0.1300$

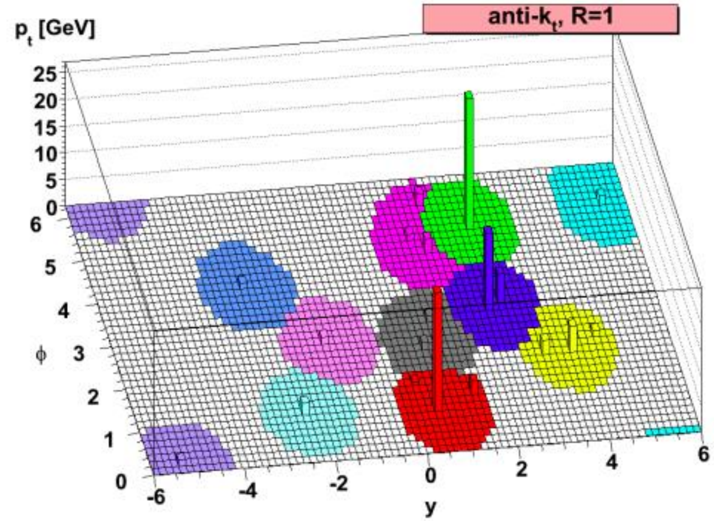
α_s value	σ_{sim} [$\times 10^9$ pb]
0.1100	4.26194 ± 0.00099
0.1180	4.6643 ± 0.0011
0.1300	5.3889 ± 0.0014



Back up

Jets reconstruction

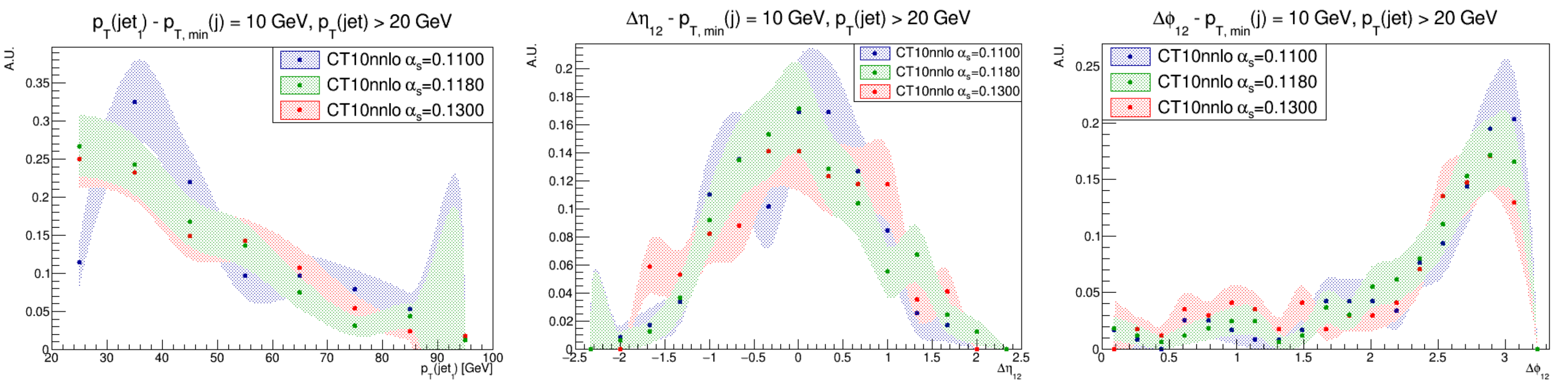
- `FastJet` → anti-k_t clustering algorithm:
  - $p_{T,\,min}$ = 5 GeV, R = 0.5, ΔR = 0.4
  - stable (no children) final particles: + hadrons, muons, electrons, photons;
    - neutrinos
- Energy recombination scheme:
  - jet four-momentum (p_x, p_y, p_z, E) with $E = \Sigma_j E_j$ and $p_i = \Sigma_j p_{ij}$



Jets selection and distributions

$$\text{Scale factor } F = \frac{\mathcal{L} \times \sigma_{sim}}{N_{gen}}$$

α_s value	N_{sel}	F [$\times 10^6$]	$N_{exp} = F \times N_{sel}$ [$\times 10^8$]
0.1100	111	6.8 ± 0.1	8.0 ± 0.7
0.1180	152	7.5 ± 0.1	12 ± 1
0.1300	156	8.6 ± 0.2	15 ± 1



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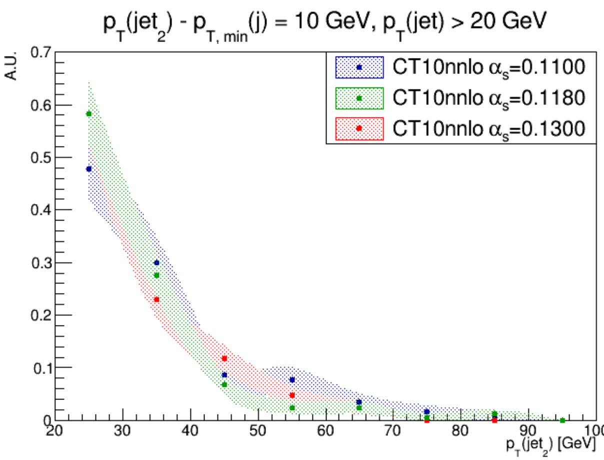
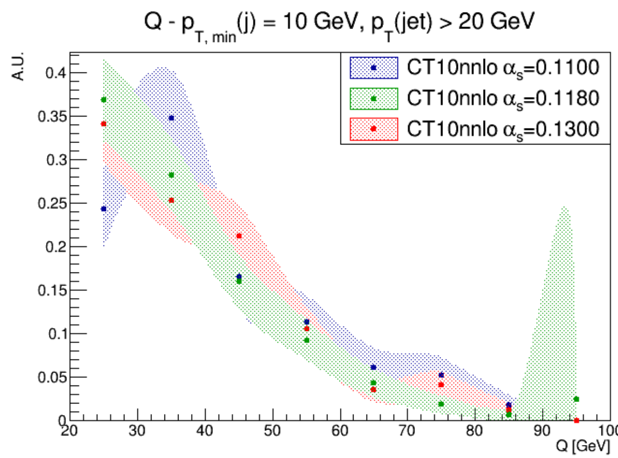
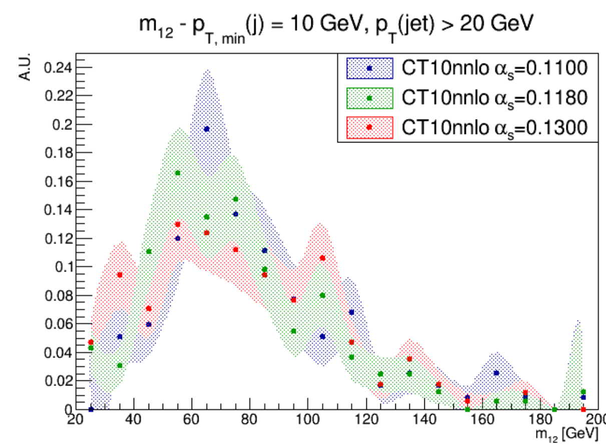
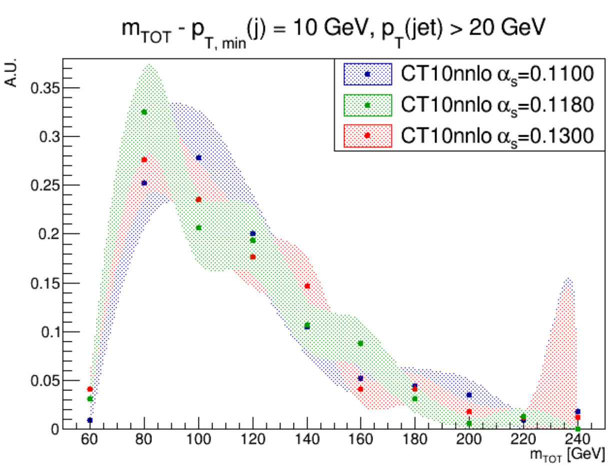
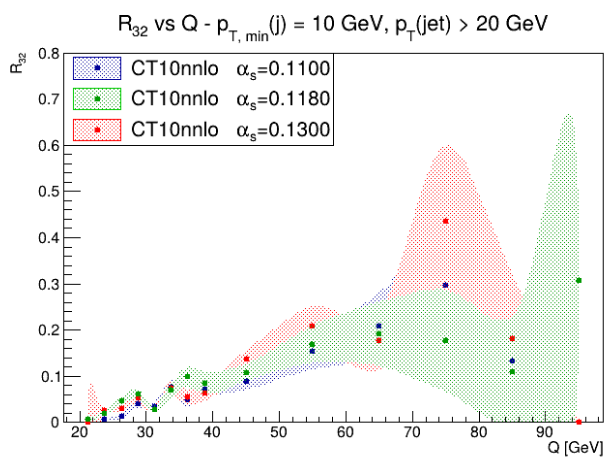
Jets selection and distributions

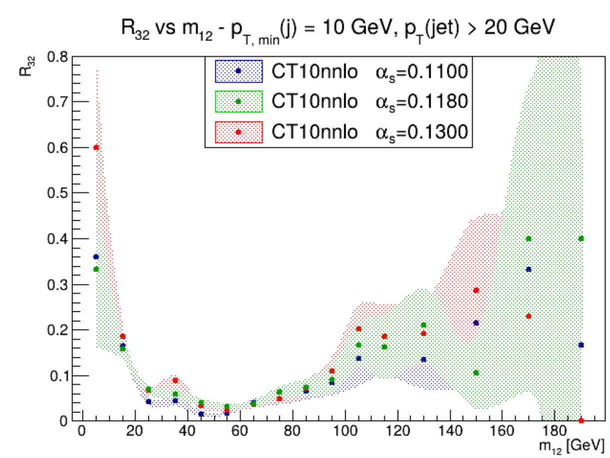








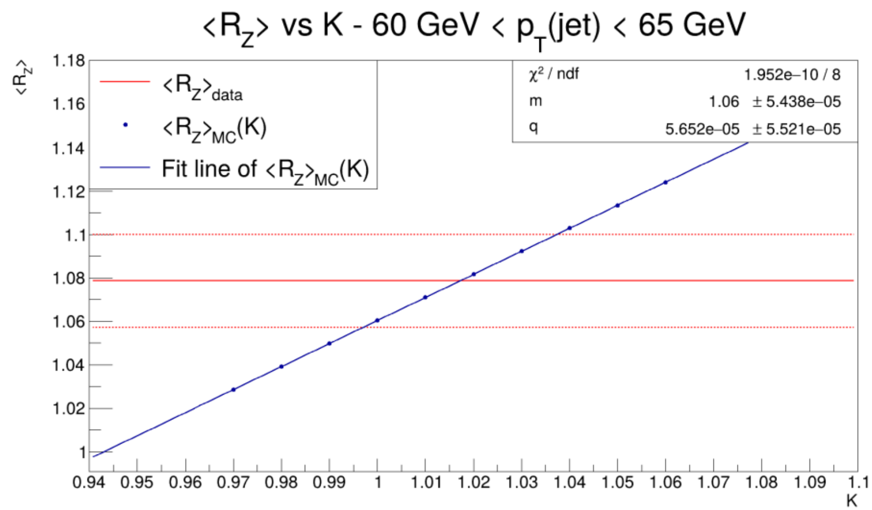




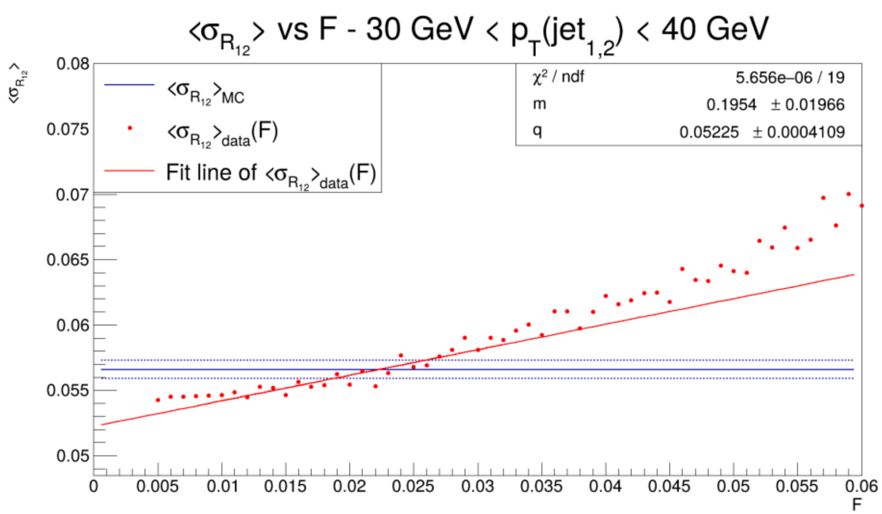
Simulated weighted inclusive cross sections

Njets	Weighted cross section $\sigma_{nj} = A_{nj} \times \sigma_{sim}$ [pb]		
	$\alpha_s = 0.1100$	$\alpha_s = 0.1180$	$\alpha_s = 0.1300$
≥ 0	$(4.094 \pm 0.004) \times 10^9$	$(4.475 \pm 0.005) \times 10^9$	$(5.163 \pm 0.005) \times 10^9$
≥ 1	$(1.551 \pm 0.008) \times 10^8$	$(1.750 \pm 0.009) \times 10^8$	$(2.08 \pm 0.01) \times 10^8$
≥ 2	$(1.22 \pm 0.02) \times 10^7$	$(1.37 \pm 0.03) \times 10^7$	$(1.70 \pm 0.03) \times 10^7$
≥ 3	$(4.7 \pm 0.4) \times 10^5$	$(7.1 \pm 0.6) \times 10^5$	$(8.4 \pm 0.7) \times 10^5$
≥ 4	$(2 \pm 1) \times 10^4$	$(4 \pm 1) \times 10^4$	$(5 \pm 2) \times 10^4$

K* and F* correction factors



$$p_T^{MC}(\text{jet})$$
$$\downarrow$$
$$\mathbf{K^*} \times p_T^{MC}(\text{jet})$$



$$p_T^{data}(\text{jet}_{1,2})$$
$$\downarrow$$
$$\text{Gauss}(p_T^{data}(\text{jet}_{1,2}) \, , \, \mathbf{F^*} \times p_T^{data}(\text{jet}_{1,2}))$$

Total efficiency – complete formula

$$\varepsilon = \frac{\varepsilon_{corr} \times \varepsilon_{GEC} \times pre_{HLT} \times pre_{strip}}{PS}$$

Quantity	Value
ε_{corr}	$(2.3 \pm 0.2) \times 10^{-3}$
ε_{GEC}	0.6
pre_{HLT}	0.001
pre_{strip}	0.013
PS	$\sim$ 0.016

Experimental dijet cross section – complete formula

$$\sigma_{jj}^{data} = \frac{N_{data}}{\varepsilon_{corr} \times \varepsilon_{GEC} \times pre_{HLT} \times pre_{strip} \times \mathcal{L}} \times PS$$

$$\sigma_{jj}^{data} = (1.3 \pm 0.1) \times 10^{7}\ \text{pb}$$

$$\sigma_{jj}^{sim}\ (\alpha_s = 0.1180) = (1.37 \pm 0.03) \times 10^{7}\ \text{pb}$$