Master's thesis

Measurement of the strong coupling constant with the LHCb detector

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QEE WG meeting – 23/09/2024

Outline

1. Status of α_s measurement
2. Goal and analysis strategy
3. Simulation of dijet cross section in forward region
4. Extraction of experimental dijet cross section
5. α_s estimation and uncertainty determination
6. Conclusions

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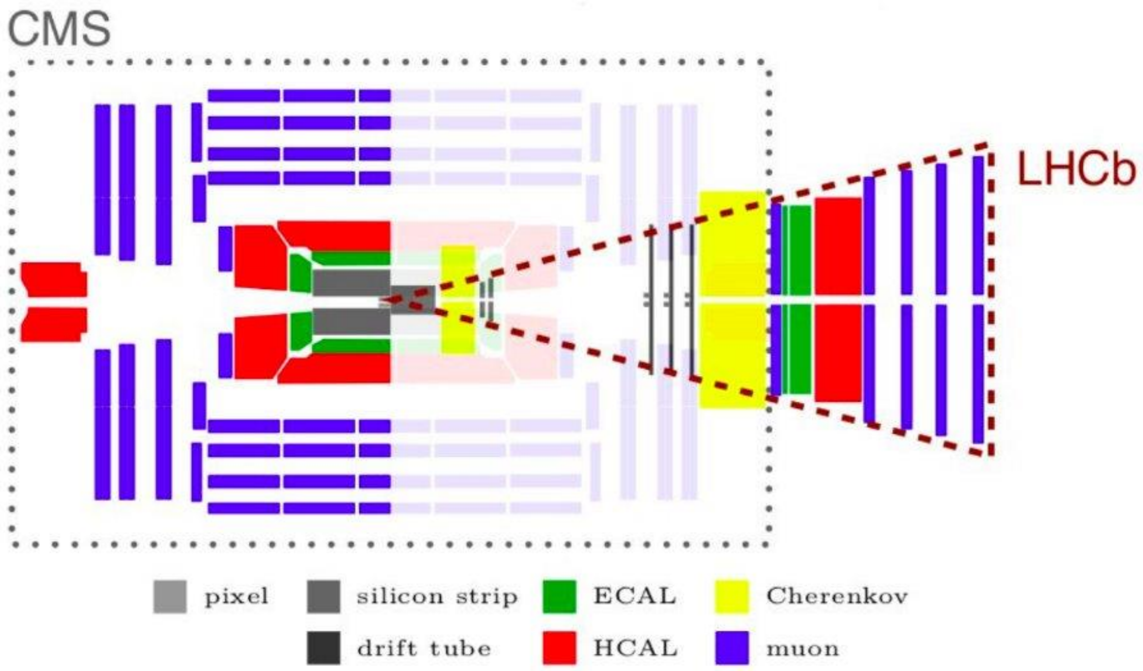
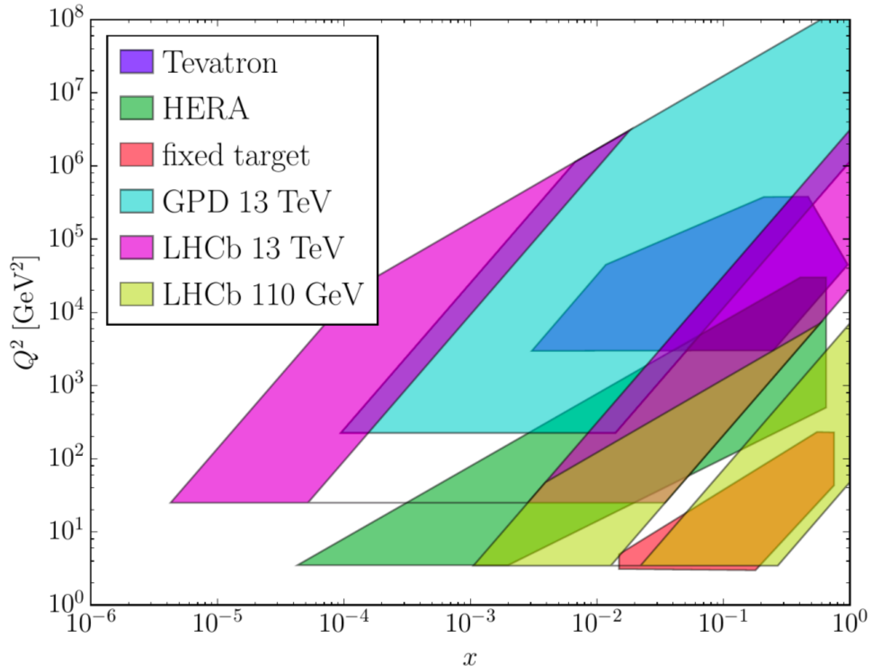
Status of α_s measurement

- Least precisely measured coupling constant
  - $\alpha_s = 0.1180(9) \rightarrow 7.6\times10^6$ ppb
  - $\alpha = 1/137.035\,999\,084(21) \rightarrow 0.15$ ppb!
- LHCb contribution in unexplored kinematic regions





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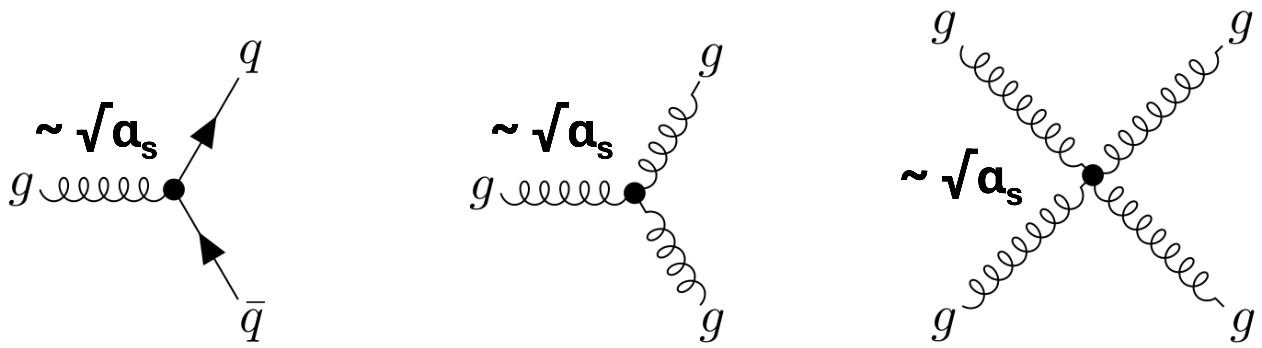
Goal and analysis strategy

Precise measurement of α_s and main uncertainties from σ_{jj}

in forward region with LHCb data

$$@\,\text{LO} \quad \sigma_{jj}^{data} \propto \sigma_{pp\to jj}\,(s, Q^2, \alpha_s) = \frac{\boldsymbol{\alpha_s}^{\mathbf{2}}(Q^2)}{s^2}\,|\mathcal{M}_{pp\to jj}|^2$$



Goal and analysis strategy

LHCb SAMPLES (DATA and MC) 2016 (Run 2), $\sqrt{s}$ = 13 TeV, $\mathcal{L}$ = 1.6 fb^{-1}

Dijet

Selections
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

Trigger stage	Trigger lines: OR of
L0	L0HadronDecision_TOS L0MuonDecision_TOS L0PhotonDecision_TOS L0DiMuonDecision_TOS L0ElectronDecision_TOS L0MuonEWDecision_TOS L0JetPhotonDecision_TOS
HLT1	Hlt1TrackMVADecision_TOS Hlt1TwoTrackMVADecision_TOS Hlt1TrackMuonDecision_TOS Hlt1TrackMVATightDecision_TOS Hlt1TwoTrackMVATightDecision_TOS Hlt1DiMuonHighMassDecision_TOS Hlt1DiMuonLowMassDecision_TOS Hlt1SingleMuonHighPTDecision_TOS Hlt1DiMuonNoL0Decision_TOS
HLT2	HltQEEJetsDiJet pre_{HLT} = 0.001
Stripping	StrippingFullDiJetsLine pre_{strip} = 0.013

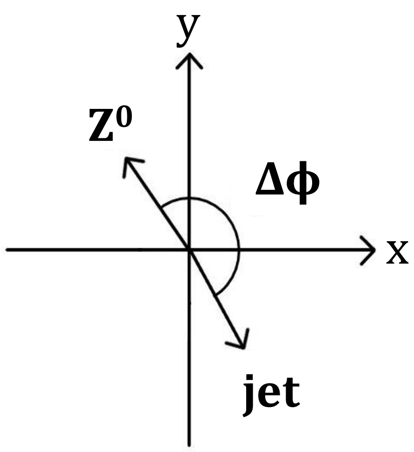
Z+jet (Z^0 ($\rightarrow \mu^+\mu^-$) + jet)

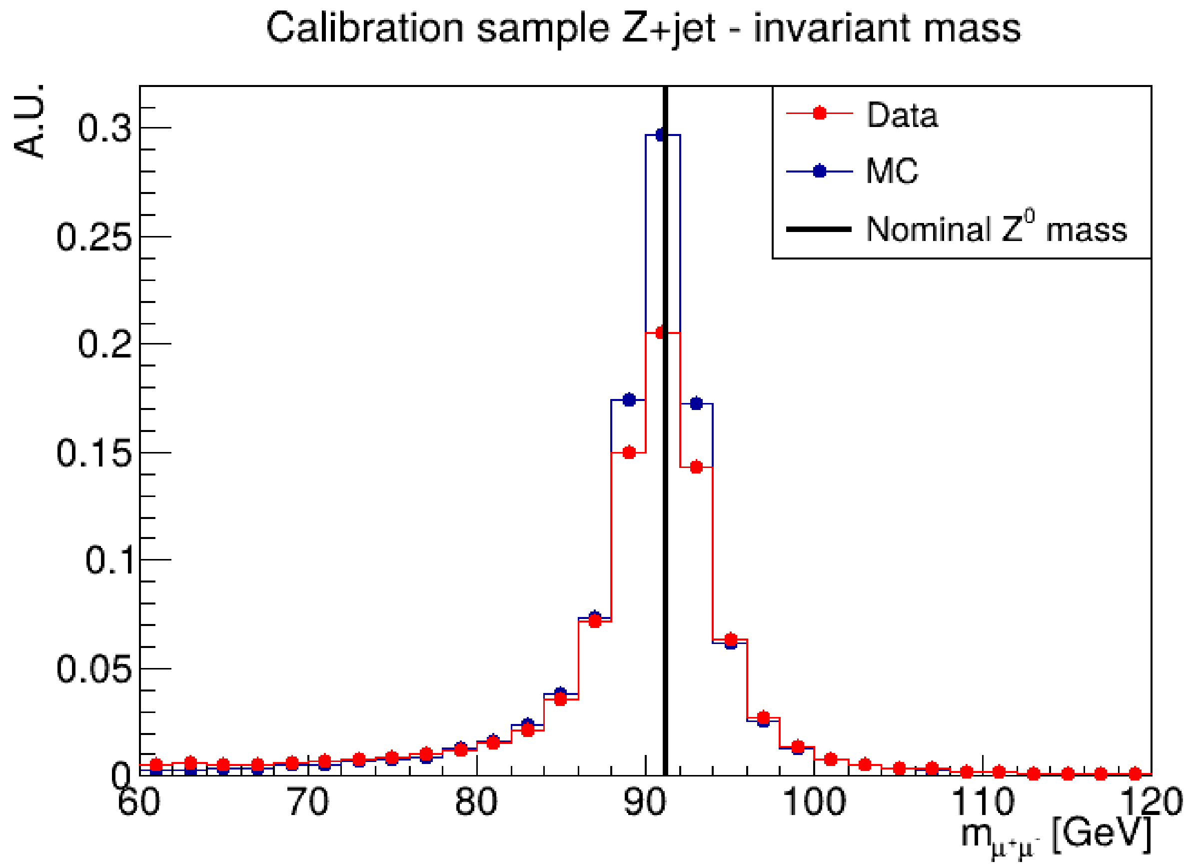
Selections
20 GeV < $p_T(jet)$ < 100 GeV
2.2 < $\eta(jet)$ < 4.2
$p_T(\mu^\pm)$ > 20 GeV
2 < $\eta(\mu^\pm)$ < 4.5
$\Delta\phi(Z^0, jet)$ > 2.8

Trigger stage	Trigger lines
L0	L0MuonEWDecision_TOS
HLT1	Hlt1SingleMuonHighPTDecision_TOS
HLT2	Hlt2Global_TOS

Goal and analysis strategy

LHCb SAMPLES (DATA and MC) 2016 (Run 2), $\sqrt{s} = 13$ TeV, $\mathcal{L} = 1.6$ fb^{-1}





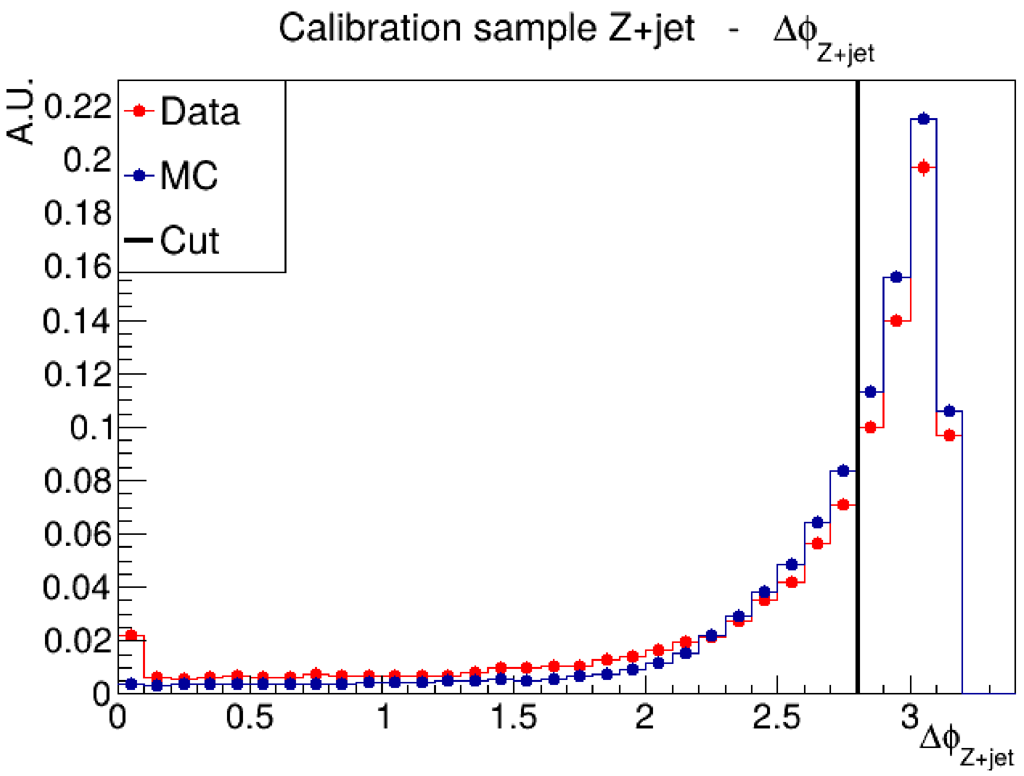
Clear peak → negligible background

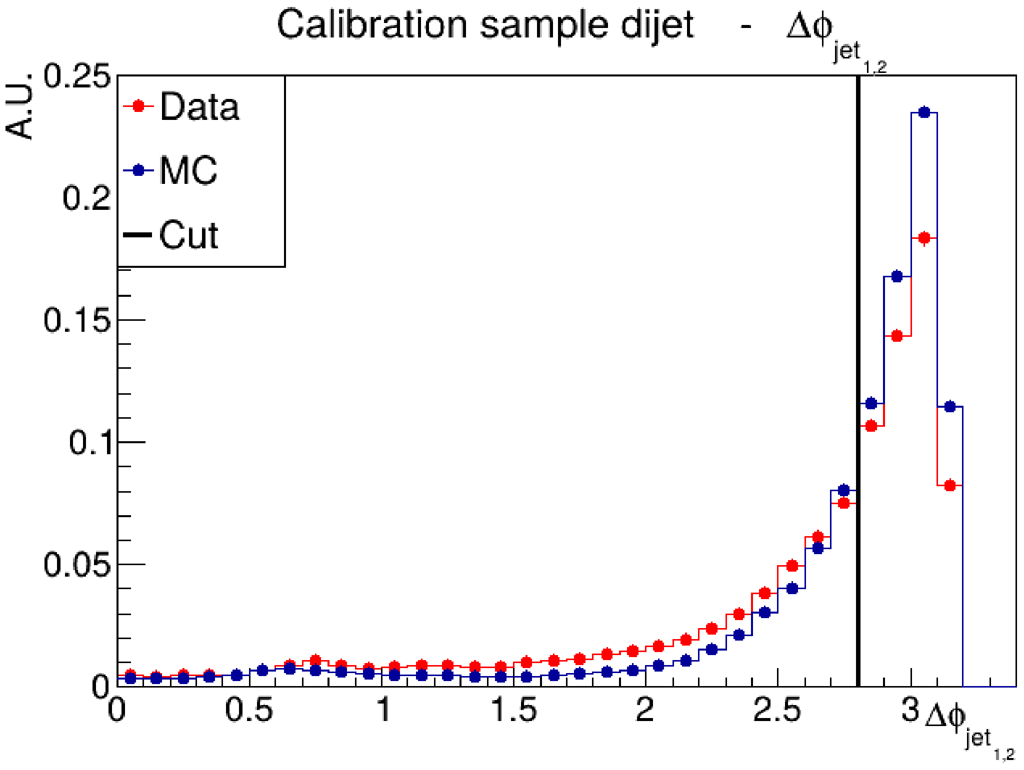
Goal and analysis strategy

LHCb SAMPLES (DATA and MC)

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

$\Delta\phi$ > 2.8





Goal and analysis strategy

STEPS OF THE ANALYSIS

1. $\boldsymbol{\sigma_{jj}^{data} = \frac{N_{data}}{\varepsilon \times \mathcal{L}}}$ from *dijet* sample, $\sigma_{jj}^{data} \propto \sigma_{pp\to jj}\,(s, Q^2, \alpha_s) \propto \frac{\alpha_s^2(Q^2)}{s^2}$

2. Jets p_T correction factors from *dijet* and *Z+jet* samples → **efficiency ε**

3. Comparison simulated and experimental σ_{jj} → **$\boldsymbol{\alpha_s}$ value**

4. Statistics, correction factors, $\mathcal{L}$ → σ_{jj}^{data} uncertainty → **$\boldsymbol{\alpha_s}$ uncertainty**

Outline

Simulation of dijet cross section in forward region

EVENTS GENERATION

- **p p > j j @ LO** with `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~**
  - 10^6 events
  - $\Delta R\,(j,j) = ((\Delta\eta_{j,j})^2+(\Delta\phi_{j,j})^2)^{1/2} = 0.4$
  - $p_{T,\,min}\,(j) = 10$ GeV
  - $\eta_{max}\,(j) = 5$
- PDFs CT10 NNLO
  - $\alpha_s = 0.1100$
  - $\alpha_s = 0.1180$ (PDG: $\alpha_s = 0.1180 \pm 0.0009$)
  - $\alpha_s = 0.1300$

α_s value	Sim. cross section σ_{sim} [$\times10^9$ pb]
0.1100	4.26194 ± 0.00099
0.1180	4.6643 ± 0.0011
0.1300	5.3889 ± 0.0014

Simulation of dijet cross section in forward region

JETS RECONSTRUCTION

- `FastJet` → **anti-k_t** clustering algorithm:
  - $p_{T,\,min} = 5$ GeV, $R = 0.5$, $\Delta R = 0.4$
  - stable (no children) final particles: + hadrons, muons, electrons, photons;

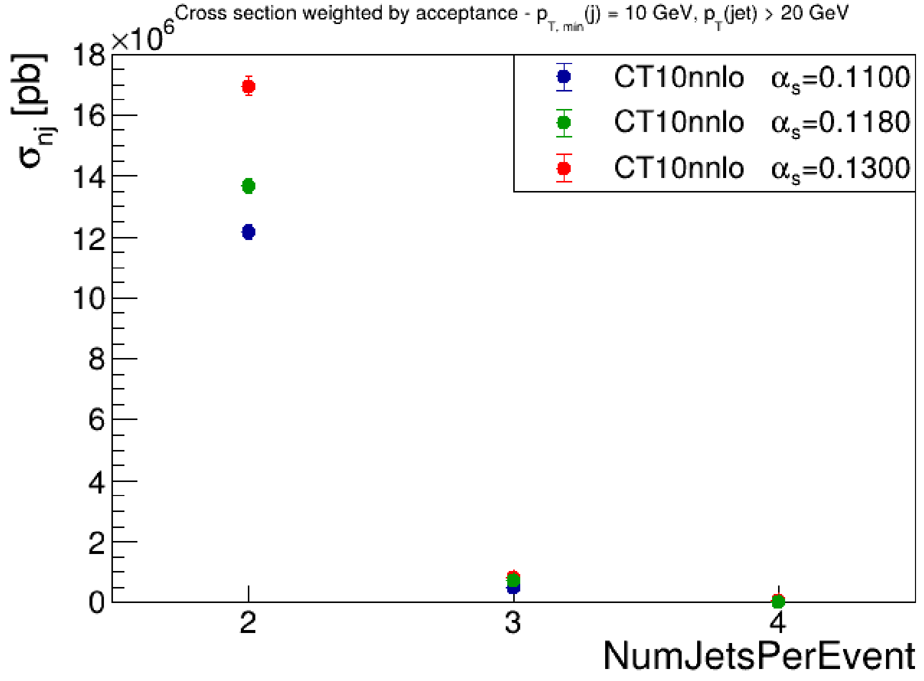
    \- neutrinos
- Energy recombination scheme:
  - jet four-momentum (p_x, p_y, p_z, E) with $E = \Sigma_j E_j$ and $p_i = \Sigma_j p_{ij}$

Simulation of dijet cross section in forward region

SIMULATED INCLUSIVE DIJET CROSS SECTION

N_{jets} after selections	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	$(1.22 \pm 0.02) \times 10^7$	**$(1.37 \pm 0.03) \times 10^7$**	$(1.70 \pm 0.03) \times 10^7$

- Other distributions (Q, m_{12}, $\Delta\phi_{12}$, R_{32}, etc.) showed no significant deviations w.r.t. α_s variation
- Dijet cross section chosen as figure of merit



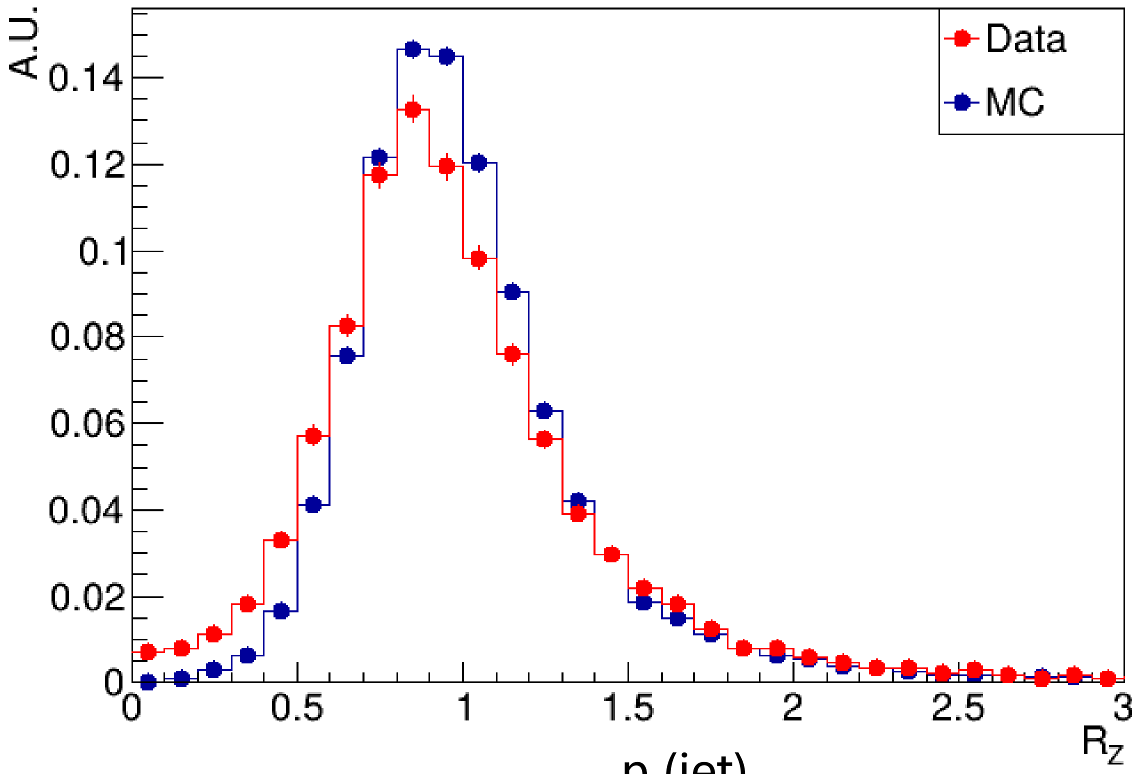
Outline

Extraction of experimental dijet cross section

- Main systematic uncertainty contributions from p_T(jet) correction factors

K* → Jet Energy Scale

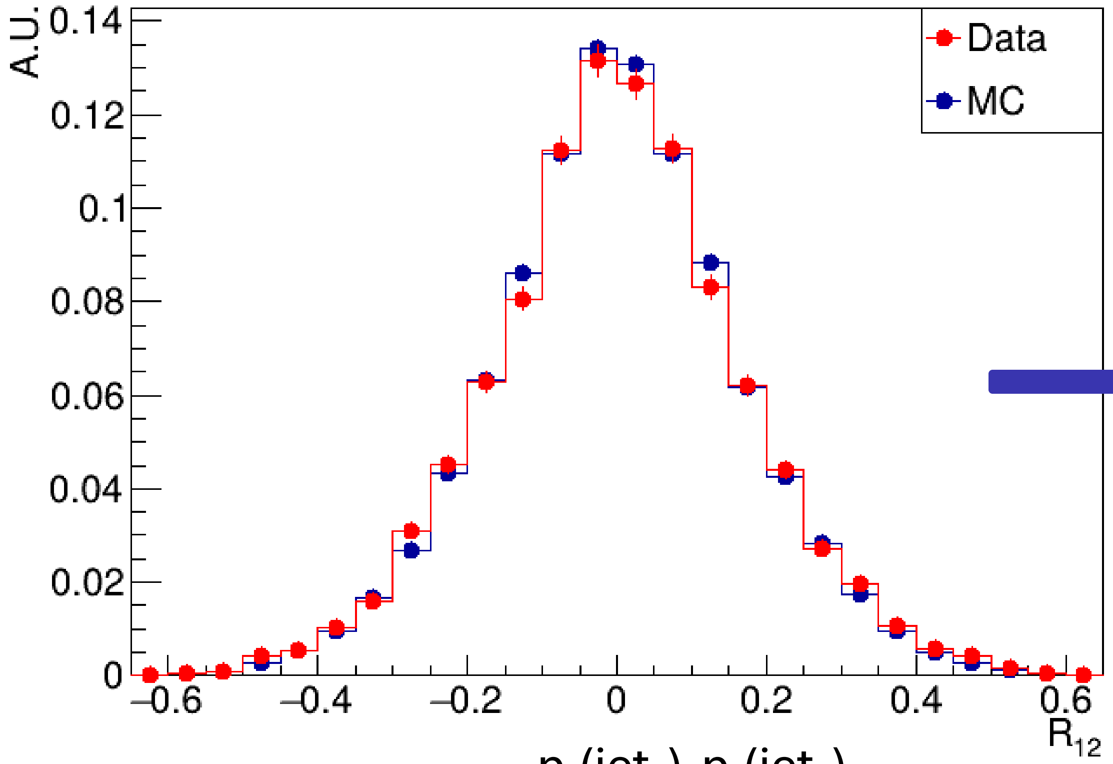
$$JES = \left\langle \frac{p_T^{true}}{p_T^{reco}} \right\rangle$$



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

F* → Jet Energy Resolution

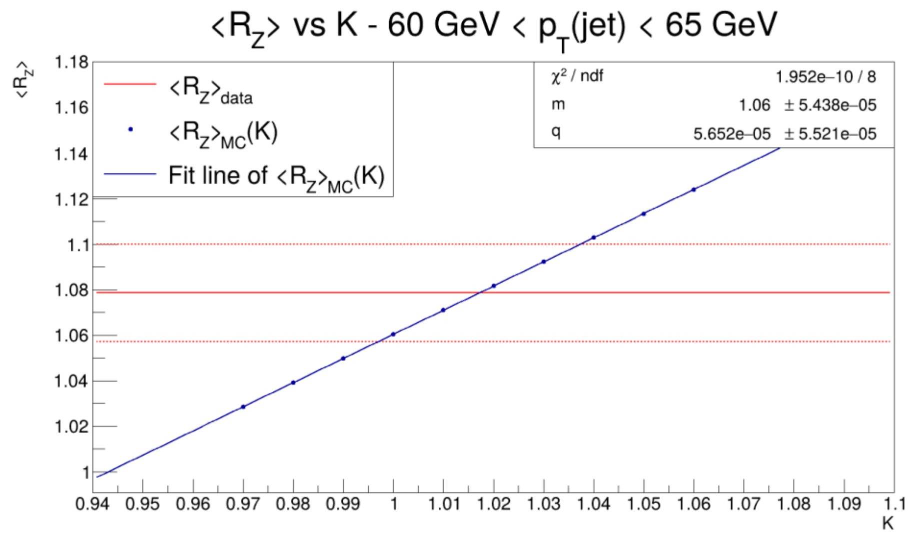
$$JER = \sigma\left(\frac{p_T^{reco} - p_T^{true}}{p_T^{true}} \right)$$

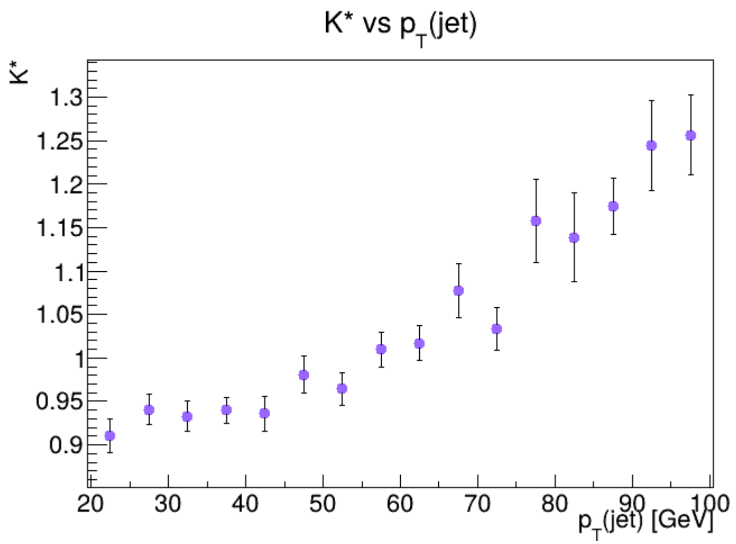


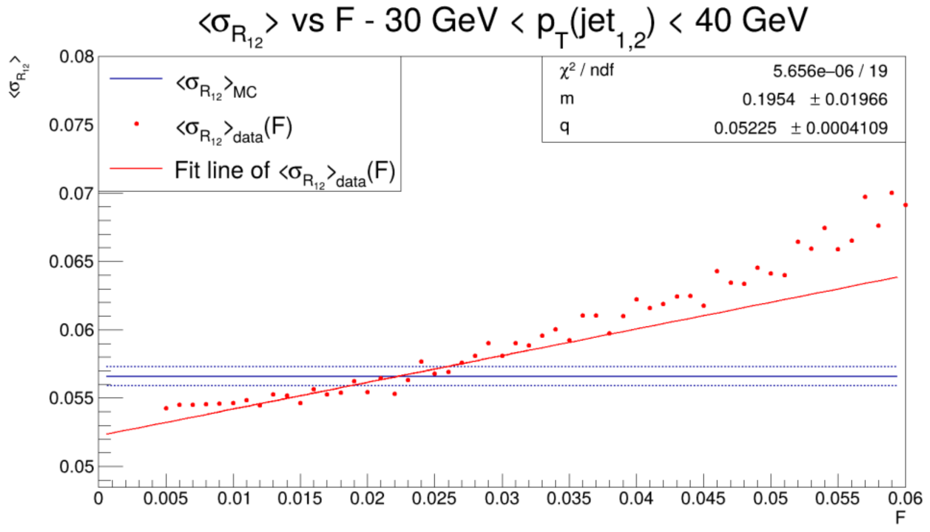
$$R_{12} = \frac{p_T(jet_1)-p_T(jet_2)}{p_T(jet_1)+p_T(jet_2)}$$

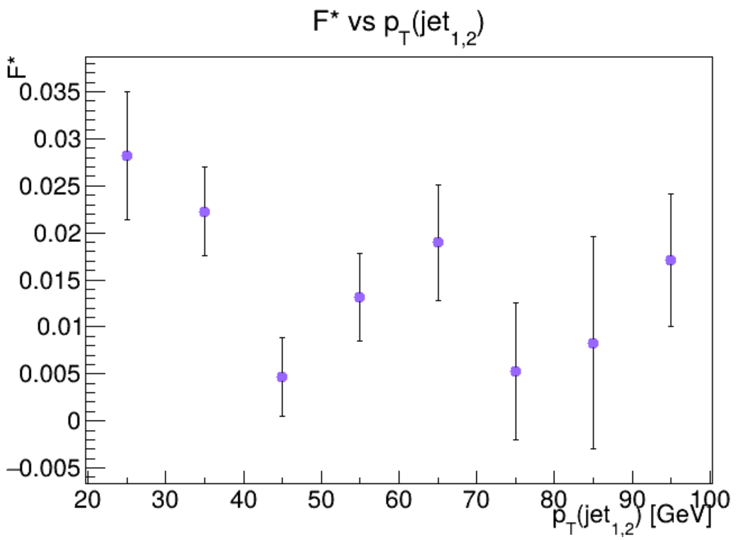
Extraction of experimental dijet cross section

K* AND F* p_T CORRECTION FACTORS









$p_T^{MC}(\text{jet})$

$\downarrow$

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

$p_T^{data}(\text{jet}_{1,2})$

$\downarrow$

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

Extraction of experimental dijet cross section

TOTAL EFFICIENCY

$$\varepsilon_{\text{sel, corr}} = \frac{N_{\text{sel, corr}}}{N_{MC}} = (2.3 \pm 0.2) \times 10^{-3}$$

$$\boldsymbol{\varepsilon_{TOT}} = \frac{\varepsilon_{\text{sel, corr}} \times \varepsilon_{GEC} \times pre_{HLT} \times pre_{strip}}{\textbf{PS}} = (1.11 \pm 0.09) \times 10^{-6}$$

Phase Space factor

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

$N_{\text{sel, corr}}$: n. of sel. and corr. MC events

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

Quantity	Value
ε_{GEC}	0.6
pre_{HLT}	0.001
pre_{strip}	0.013
PS	~ 0.016

EXPERIMENTAL DIJET CROSS SECTION

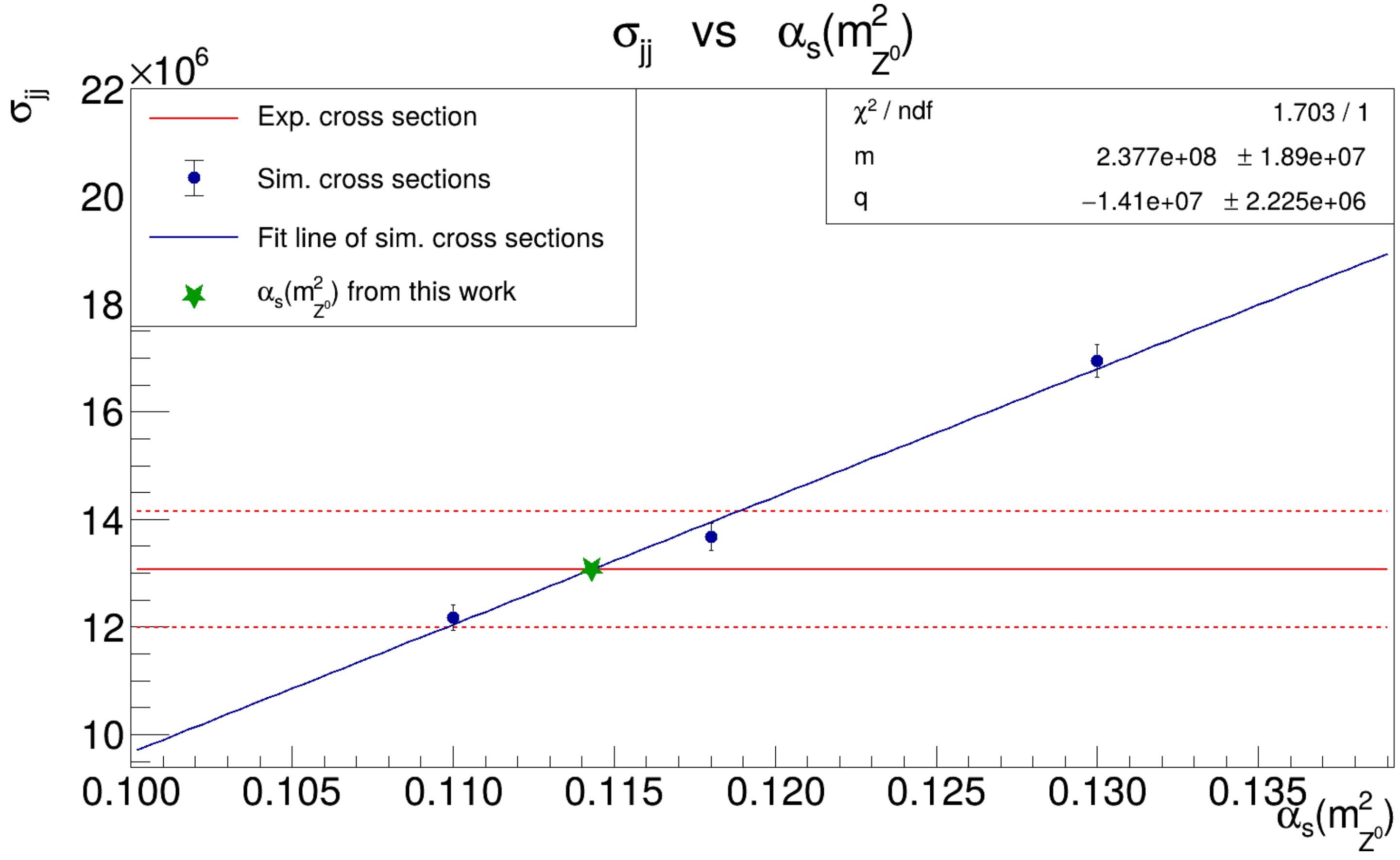
$$\sigma_{jj}^{data} = \frac{N_{data}}{\boldsymbol{\varepsilon_{TOT}} \times \mathcal{L}} =$$

$$= (1.307 \pm 0.009\ (\text{stat.}) \pm 0.1\ (\text{syst.}) \pm 0.03\ (\text{lumi.})) \times 10^{7}\ \text{pb} = \mathbf{(1.3 \pm 0.1) \times 10^{7}\ pb}$$

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

Outline

α_s estimation and uncertainty determination



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

$= \mathbf{0.114 \pm 0.009}$

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Conclusions

- [S. Navas et al. (PDG Collaboration). Review of Particle Physics. Phys. Rev. D, August 2024]
- [ATLAS Collaboration. Determination of the strong coupling constant from transverse energy-energy correlations in multijet events at s = √13 TeV with the ATLAS detector. Journal of High Energy Physics, July 2023]

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

$= 0.114 \pm 0.009$

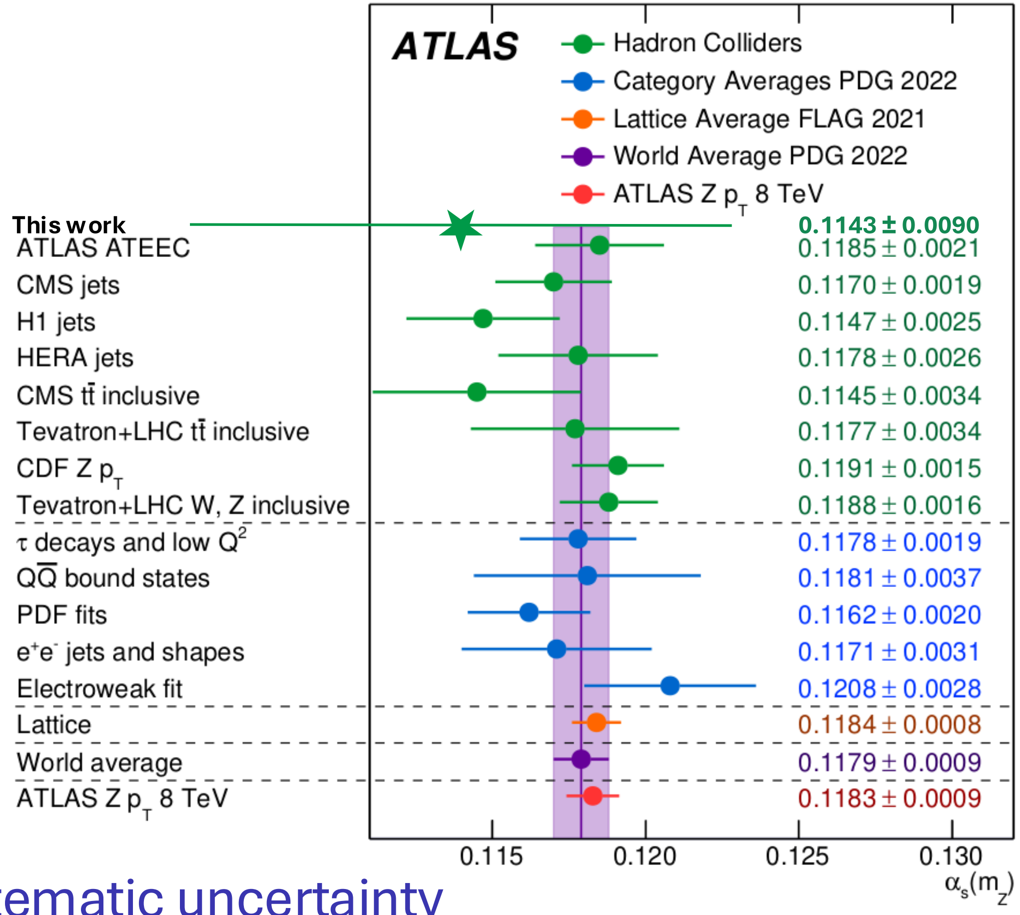
PDG/ATLAS $\alpha_s(m_{Z^0}^2) = 0.1180 \pm 0.0009$

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

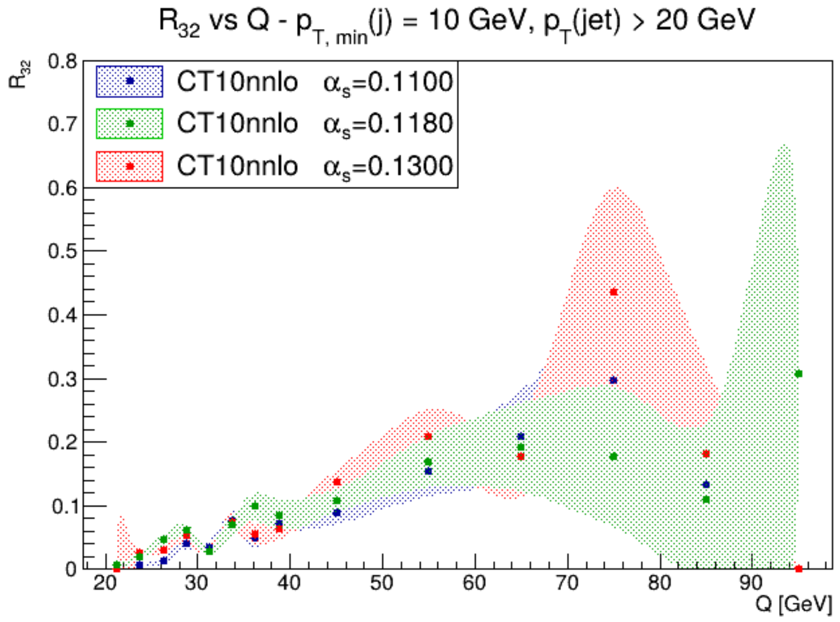
Conclusions

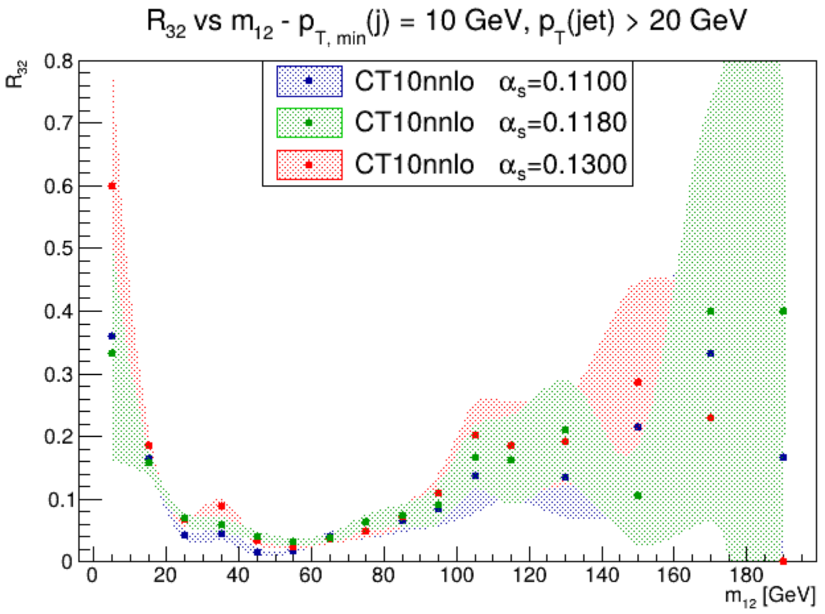
FUTURE IMPROVEMENTS

- Jet energy correction refinement
- Enhanced simulation study (NLO, more α_s values, other PDF sets, other generators, etc.)

OTHER ANALYSIS APPROACHES

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





+ LHCb RUN 3 AND UPGRADES

UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia Galileo Galilei

Thank you for your attention!

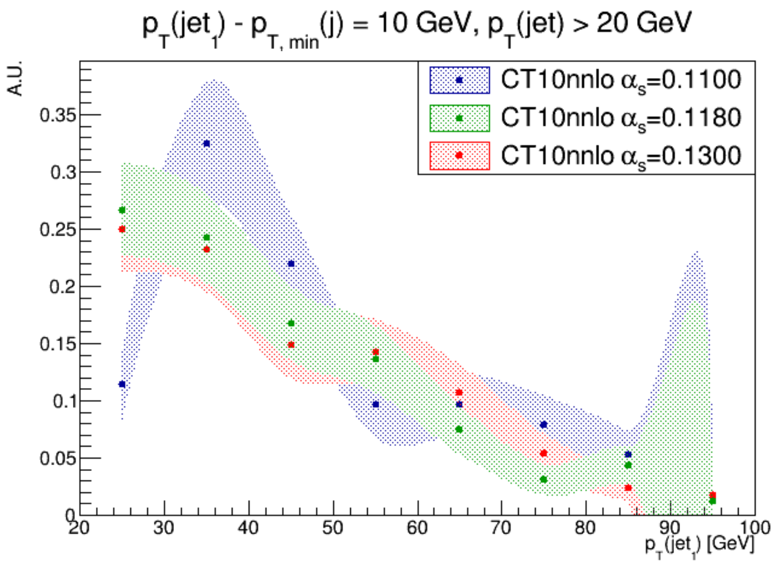
Back-up slides

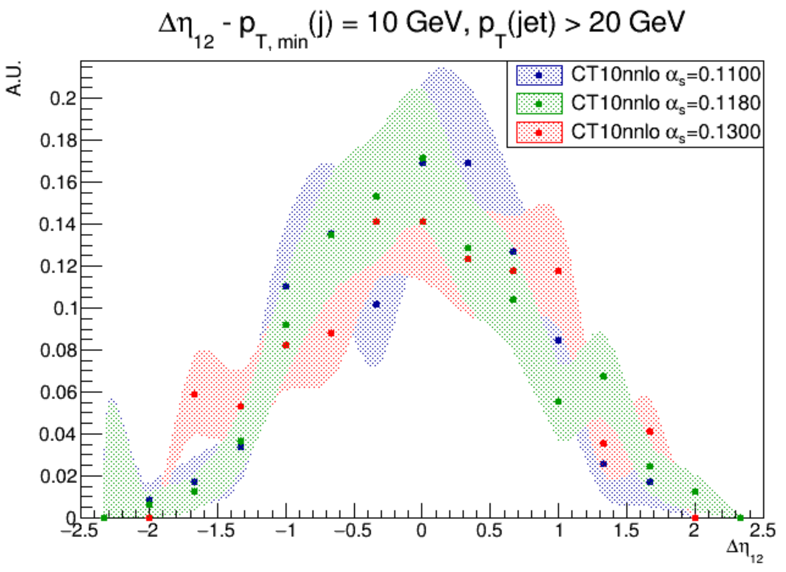
Back up

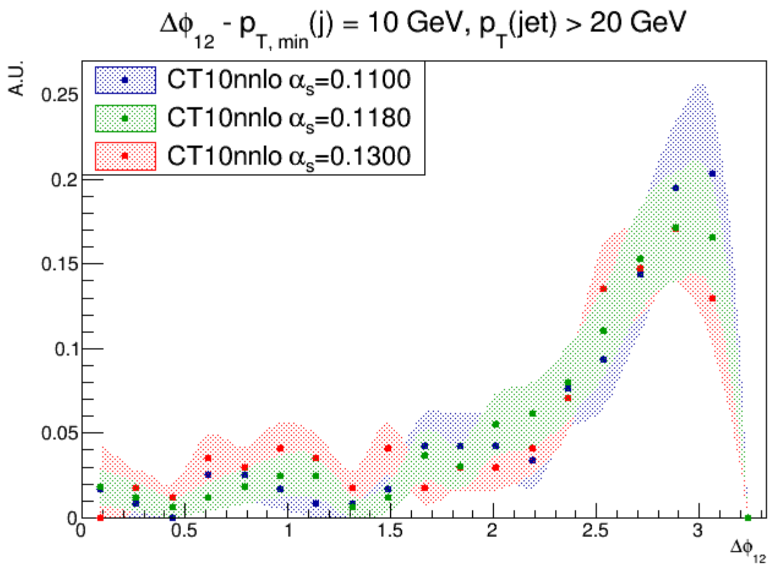
JETS SELECTION AND DISTRIBUTIONS

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

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



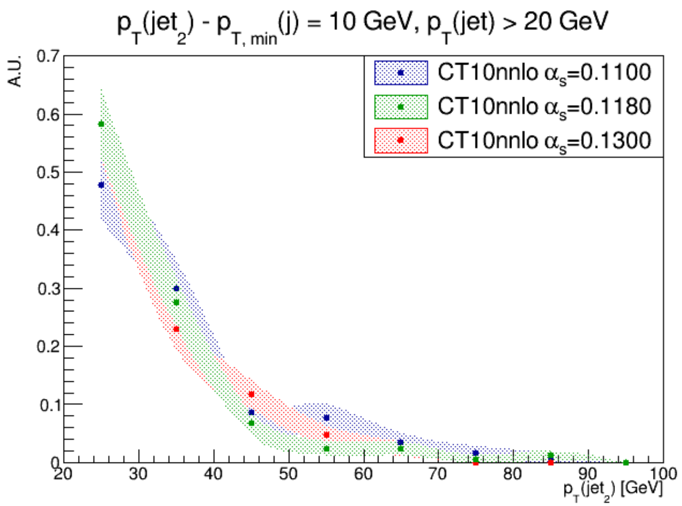


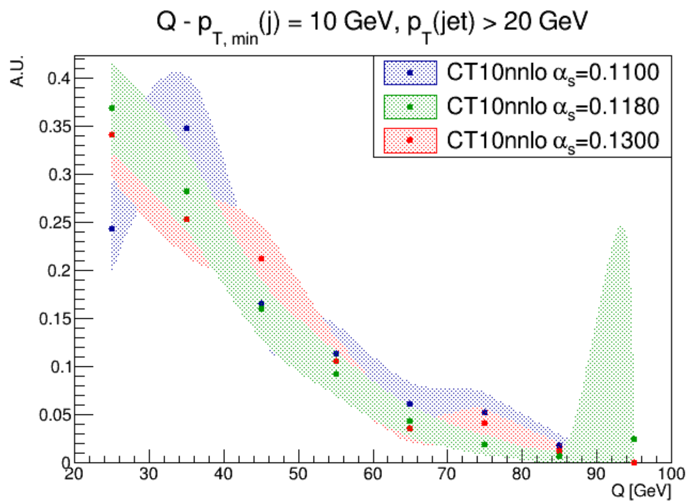


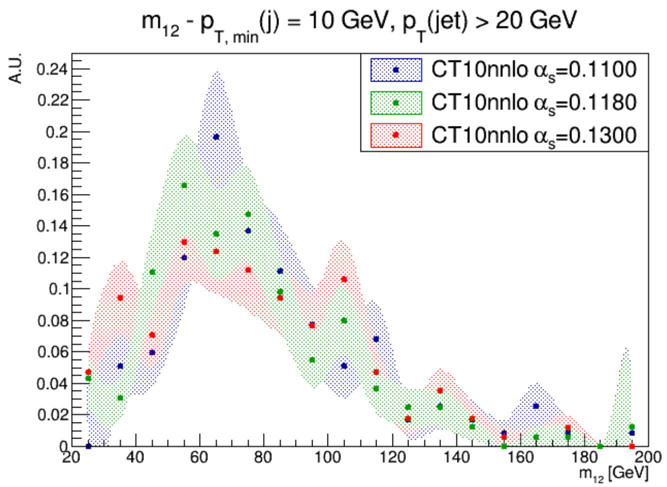
Compatibility within error bars!

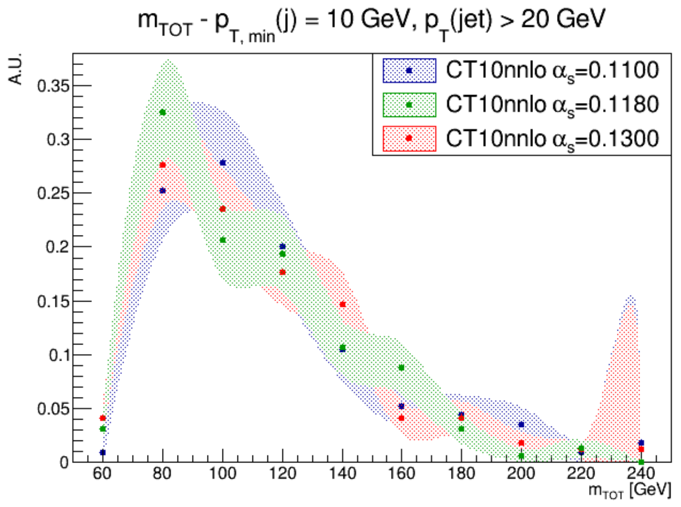
Back up

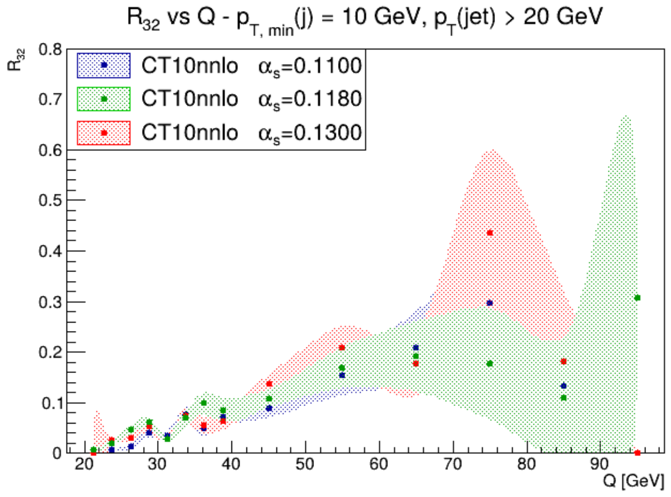
JETS SELECTION AND DISTRIBUTIONS

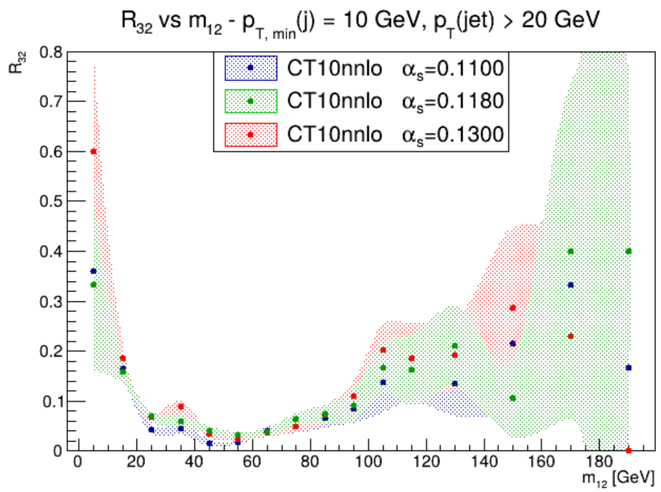












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K* AND F* VALUES

p_T(jet) [GeV] bin	K*
[20,25]	0.91 ± 0.02
[25,30]	0.94 ± 0.02
[30,35]	0.93 ± 0.02
[35,40]	0.94 ± 0.01
[40,45]	0.94 ± 0.02
[45,50]	0.98 ± 0.02
[50,55]	0.96 ± 0.02
[55,60]	1.01 ± 0.02
[60,65]	1.02 ± 0.02
[65,70]	1.08 ± 0.03
[70,75]	1.03 ± 0.02
[75,80]	1.16 ± 0.05
[80,85]	1.14 ± 0.05
[85,90]	1.17 ± 0.03
[90,95]	1.24 ± 0.05
[95,100]	1.26 ± 0.05

p_T(jet) [GeV] bin	F*
[20,30]	0.028 ± 0.007
[30,40]	0.022 ± 0.005
[40,50]	0.005 ± 0.004
[50,60]	0.013 ± 0.005
[60,70]	0.019 ± 0.006
[70,80]	0.005 ± 0.007
[80,90]	0.01 ± 0.01
[90,100]	0.017 ± 0.007