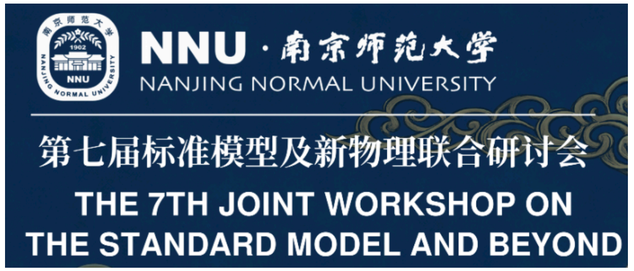


中国科学院高能物理研究所

Institute of High Energy Physics, Chinese Academy of Sciences



New QCD Experimental Studies at e^+e^- Colliders

JinFei Wu

IHEP, CAS

Based on arXiv 2609.20154 , arXiv 2607.13804, Phys.Rev.D 112 (2025) 7, 074029, Chin.Phys.C 49 (2025) 2, 023001, Phys. Rev. Lett. 135 (2025), 151804

In collaboration with Xinchou Lou, Yuzhi Che, Gang Li, Yanping Huang, Manqi Ruan

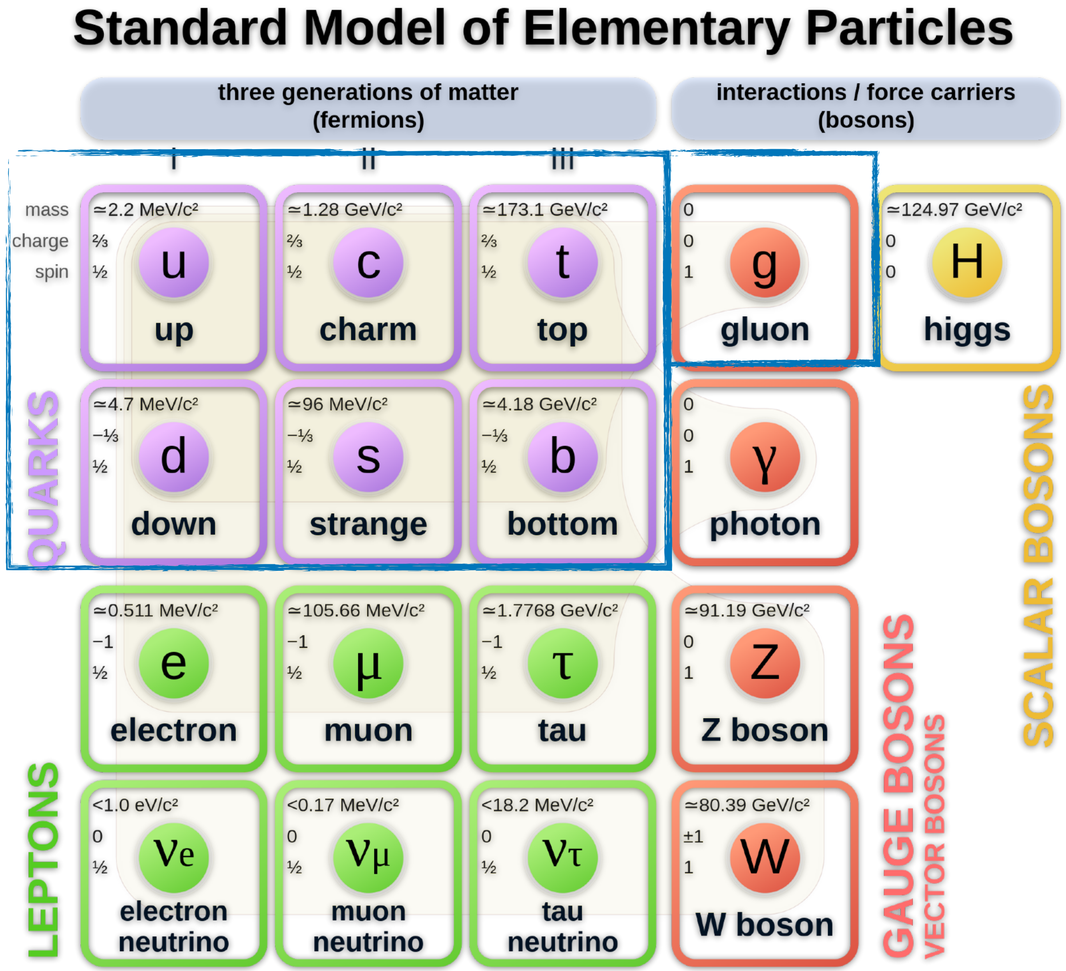
The 7th Joint Workshop on the Standard Model and Beyond

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Introduction

- The strong interaction is one of the four fundamental forces of nature, which is described by QCD.



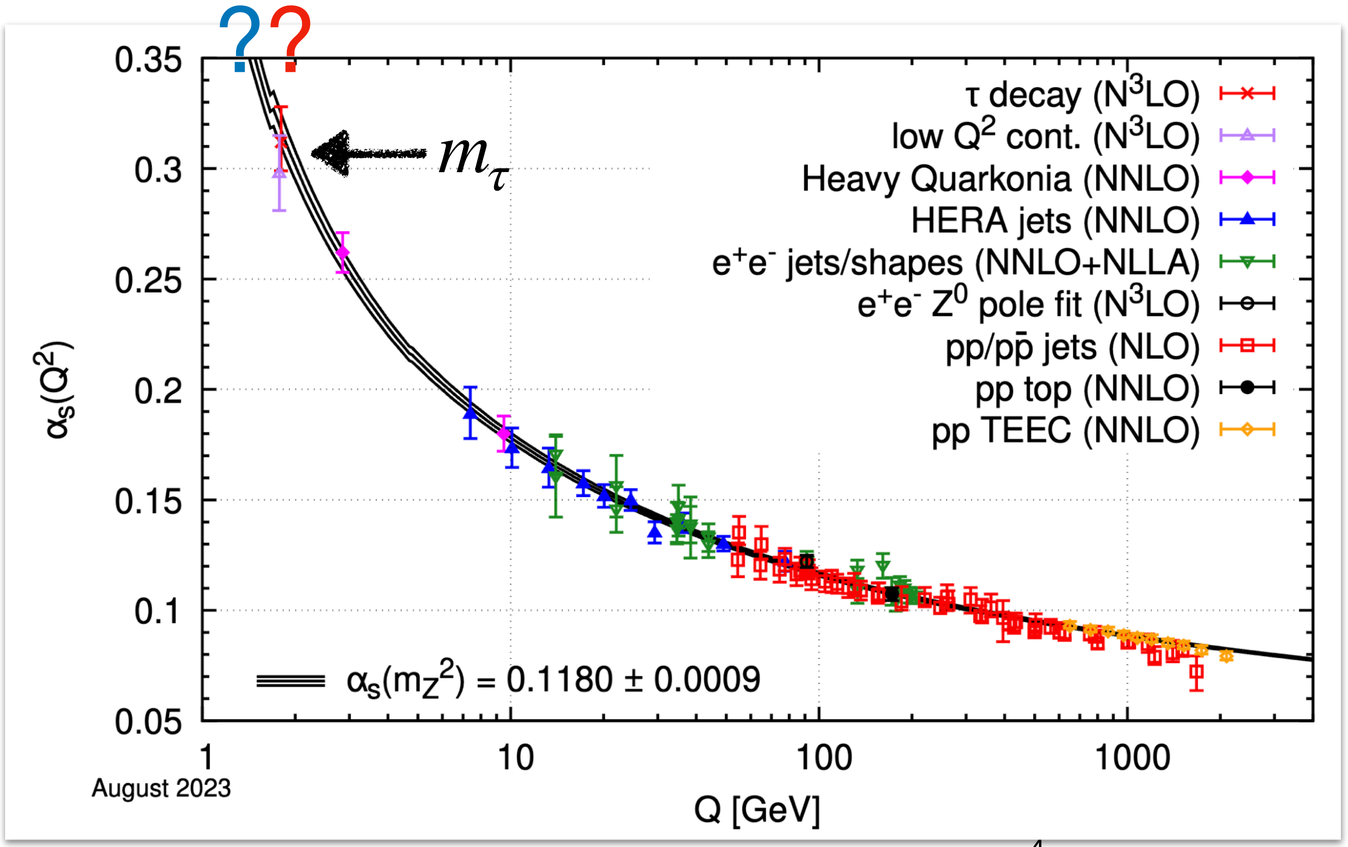
- Two important features: **asymptotic freedom** and **color confinement**

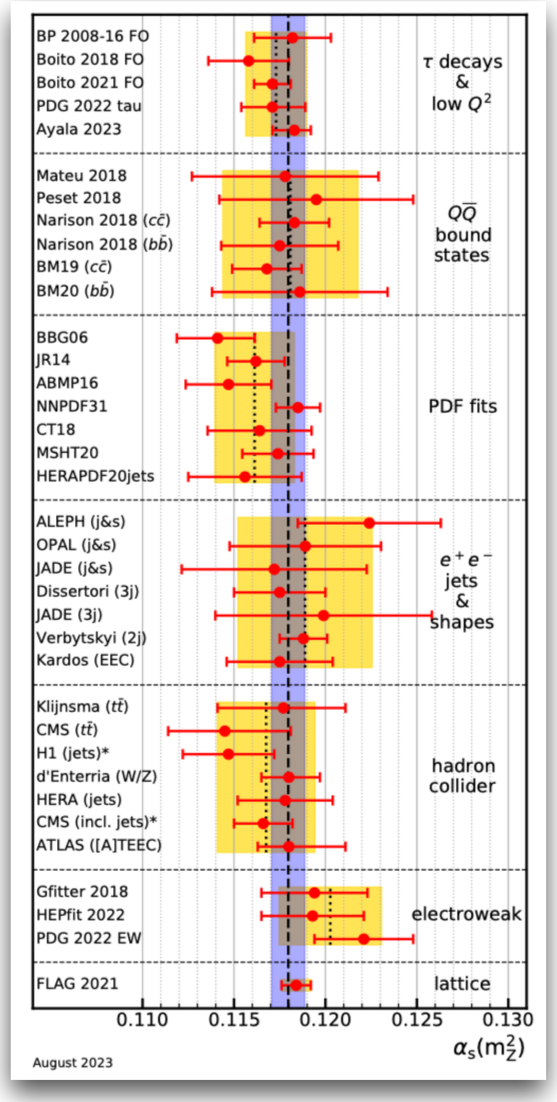
- It binds quarks and gluons into color-neutral hadrons, and also drives **hadronization**.

- It is the **least known interaction** in SM, but **important for precise measurements** and **new physics searches**.

Introduction

- The running behavior of strong coupling constant, α_s, gives rise to the **asymptotic freedom**.
  - RQ1 : **What happens to α_s below m_τ? How does α_s behave at different energy scales?**

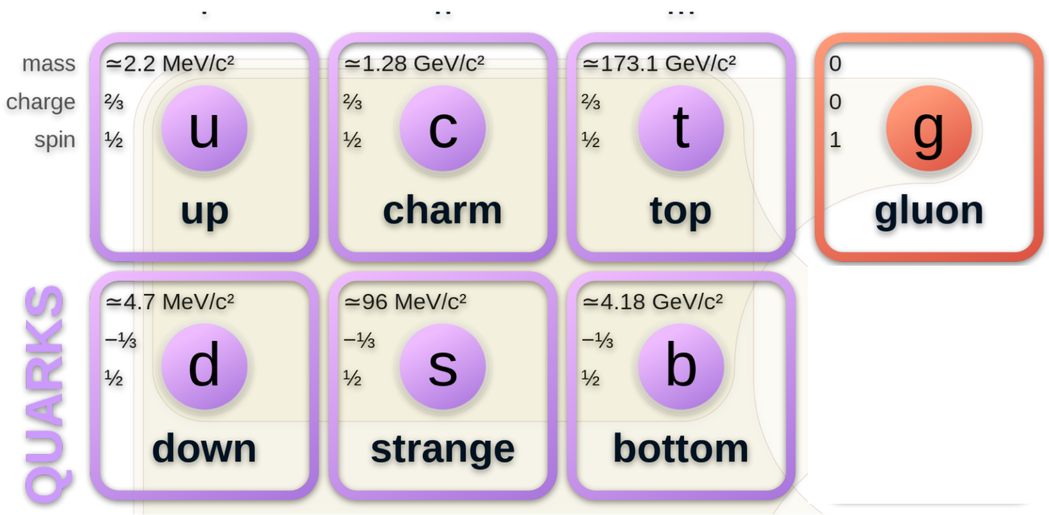




Introduction

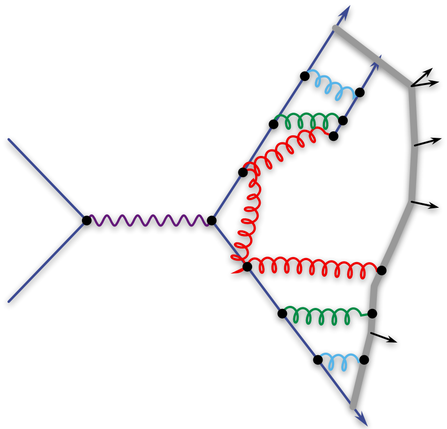
- As a consequence of **color confinement**, gluons carrying color charge have never been observed in isolation to date.

  - RQ2 : **Can isolated gluons be observed experimentally? Is there any strong interaction induced invisible particles?**

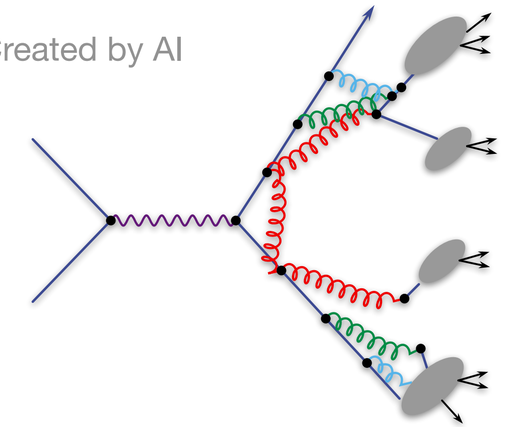


- RQ3 : **How do quarks and gluons hadronize? Is there any underlying feature in hadronization?**

Possible hadronization models



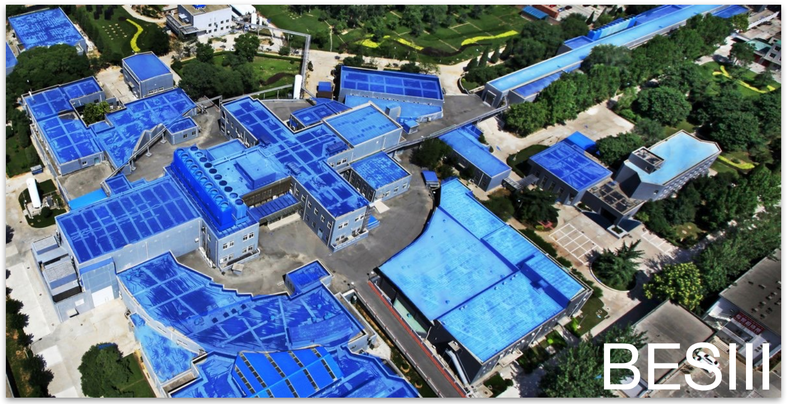
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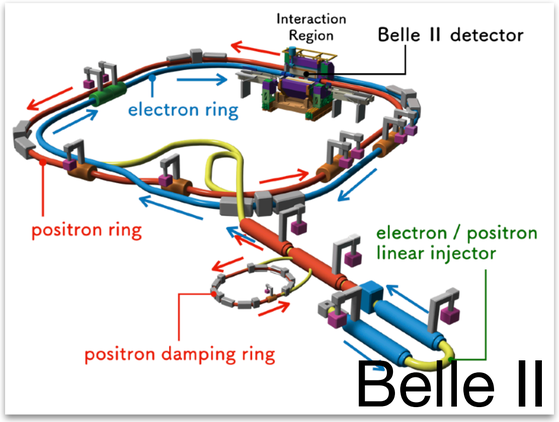


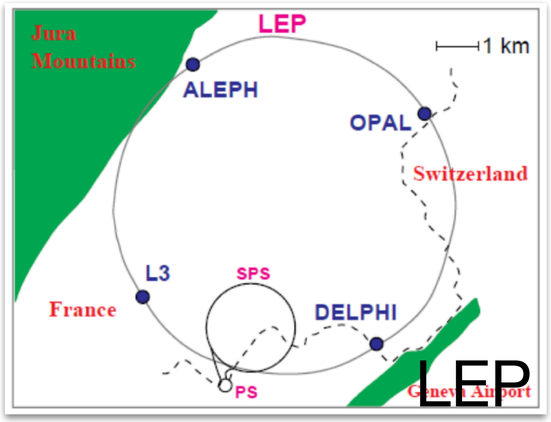
Introduction

- Why are e^+e^- colliders ideal places to address these questions?
  - Well defined initial state
  - Clean production environment

  } → easy for both theory and experiment
  - Flexible energy scale and abundant hadronization data →more aspects of QCD







+…

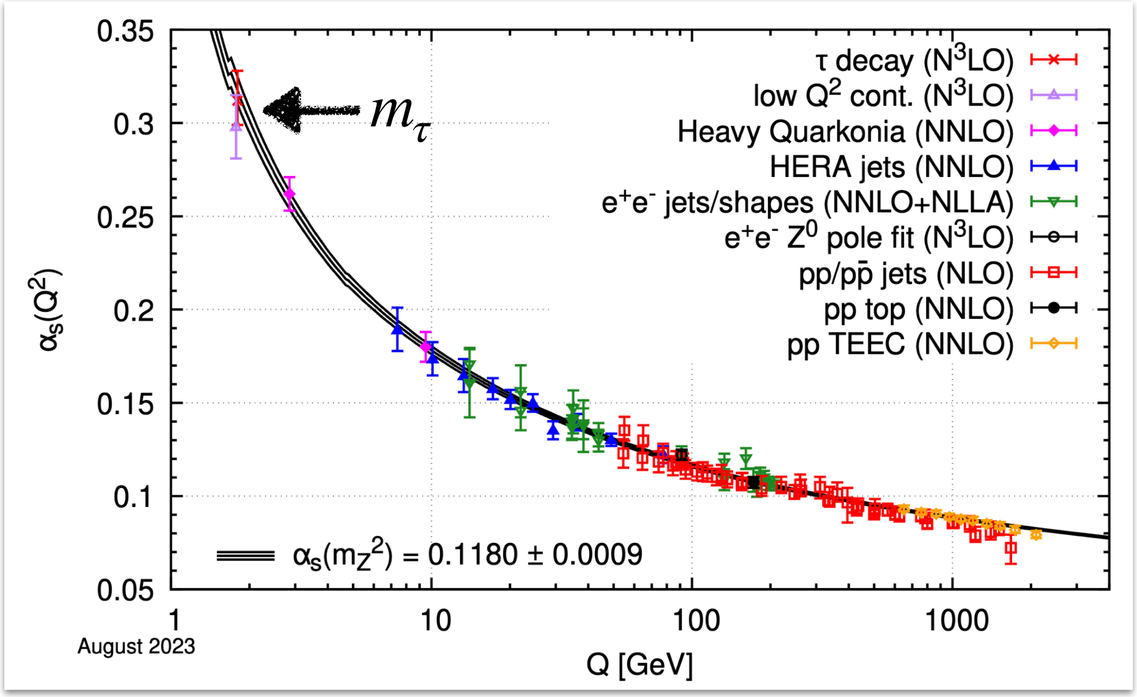
$\sqrt{s}: 2 \sim 5\ GeV$ $\sqrt{s}: 9 \sim 11\ GeV$ $\sqrt{s}: 90 \sim 209\ GeV$

- Access to **a wide range of energy scales** makes it possible to probe the **strong interaction from multiple perspectives**.

α_s from charm and beauty mesons

Phys.Rev.D 112 (2025) 7, 074029, Chin.Phys.C 49 (2025) 2, 023001

- Strong coupling constant α_s is a fundamental parameter in QCD, and characterizes the strength of strong interaction.
  - From m_τ to ~$2\ TeV$, the values of α_s have been determined at many energy scales, especially in higher energy region (> 10 GeV).



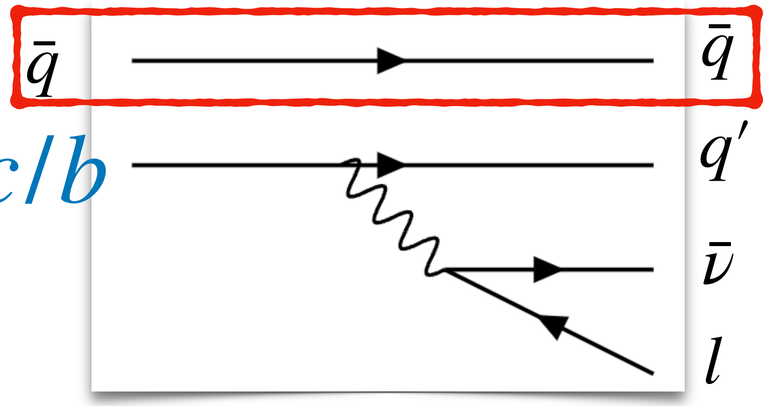
A. Can we find **alternative methods** to determine α_s and improve the global $\alpha_s(m_Z)$ determination?

B. Can we push the α_s determination to **energy scales below** m_τ?

- Maybe inclusive semi-leptonic(SL) decays of charm/beauty hadrons.

α_s from charm and beauty mesons

- The charm and beauty hadrons may be used to extract α_S, but they contain a light spectator quark except c/b quark.
  - We further check the impact of spectator quark by comparing the inclusive semi-leptonic decay width (Γ_{SL}) .



Mesons	$\mathcal{B}_{SL}$ [%]	τ [10^{-13}s]	Γ_{SL} [10^{-15}GeV]
D^0	$6.46 \pm 0.09 \pm 0.11$	4.10 ± 0.01	104 ± 2
D^+	$16.13 \pm 0.10 \pm 0.29$	10.33 ± 0.05	103 ± 2
B^+	10.8 ± 0.4	16.38 ± 0.04	44 ± 2
B^0	10.1 ± 0.4	15.17 ± 0.04	44 ± 2

- The Γ_{SL} is nearly the same for mesons sharing the same heavy quark, despite different spectators.
  - It indicates the **impact of spectator quarks** is similar, and may be **negligible** in SL.

α_s from charm and beauty mesons

- In the Heavy Quark Expansion (HQE) framework, the Γ_{SL} can be expressed as double expansions in α_s and quark masses (m_b, m_c):

$$\Gamma\left(B \to X_c \ell \bar{\nu}_\ell\right) = \frac{G_F^2 |V_{cb}|^2 m_b^5 A_{\text{ew}}}{192\pi^3}\Big[\mathbf{c}_0 + \mathbf{c}_1\frac{\alpha_s}{\pi} + \mathbf{c}_2(\frac{\alpha_s}{\pi})^2 + \mathbf{c}_3(\frac{\alpha_s}{\pi})^3 + \mathcal{O}(\alpha_s^4) + C_{\mu_\pi}\frac{\mu_\pi^2}{2m_b^2} + C_{\mu_G}\frac{\mu_G^2}{2m_b^2} + C_{\rho_D}\frac{\rho_D^3}{2m_b^3} + C_{\rho_{LS}}\frac{\rho_{LS}^3}{2m_b^3} + \cdots\Big]$$

$$\Gamma\left(D \to X_s \ell \bar{\nu}_\ell\right) = \frac{G_F^2 |V_{cs}|^2 m_c^5 A_{\text{ew}}}{192\pi^3}\Big[f_0 + f_1\frac{\alpha_s}{\pi} + f_2(\frac{\alpha_s}{\pi})^2 + \mathcal{O}(\alpha_s^3) + f_{\mu_\pi}\frac{\mu_\pi^2}{2m_c^2} + f_{\mu_G}\frac{\mu_G^2}{2m_c^2} + f_{\rho_D}\frac{\rho_D^3}{2m_c^3} + f_{\rho_{LS}}\frac{\rho_{LS}^3}{2m_c^3} + \frac{32\pi^2}{m_c^3}B_{\text{WA}} + \cdots\Big]$$

····· leading-order power correction

····· 2nd-order power correction

····· 3rd-order power correction

····· higher-order power corrections

HQE parameters: μ_π^2: the kinetic term; μ_G^2: the chromomagnetic term; ρ_D^3: Darwin terms; ρ_{LS}^3: spin-orbital terms; B_{WA}: weak annihilation (WA).

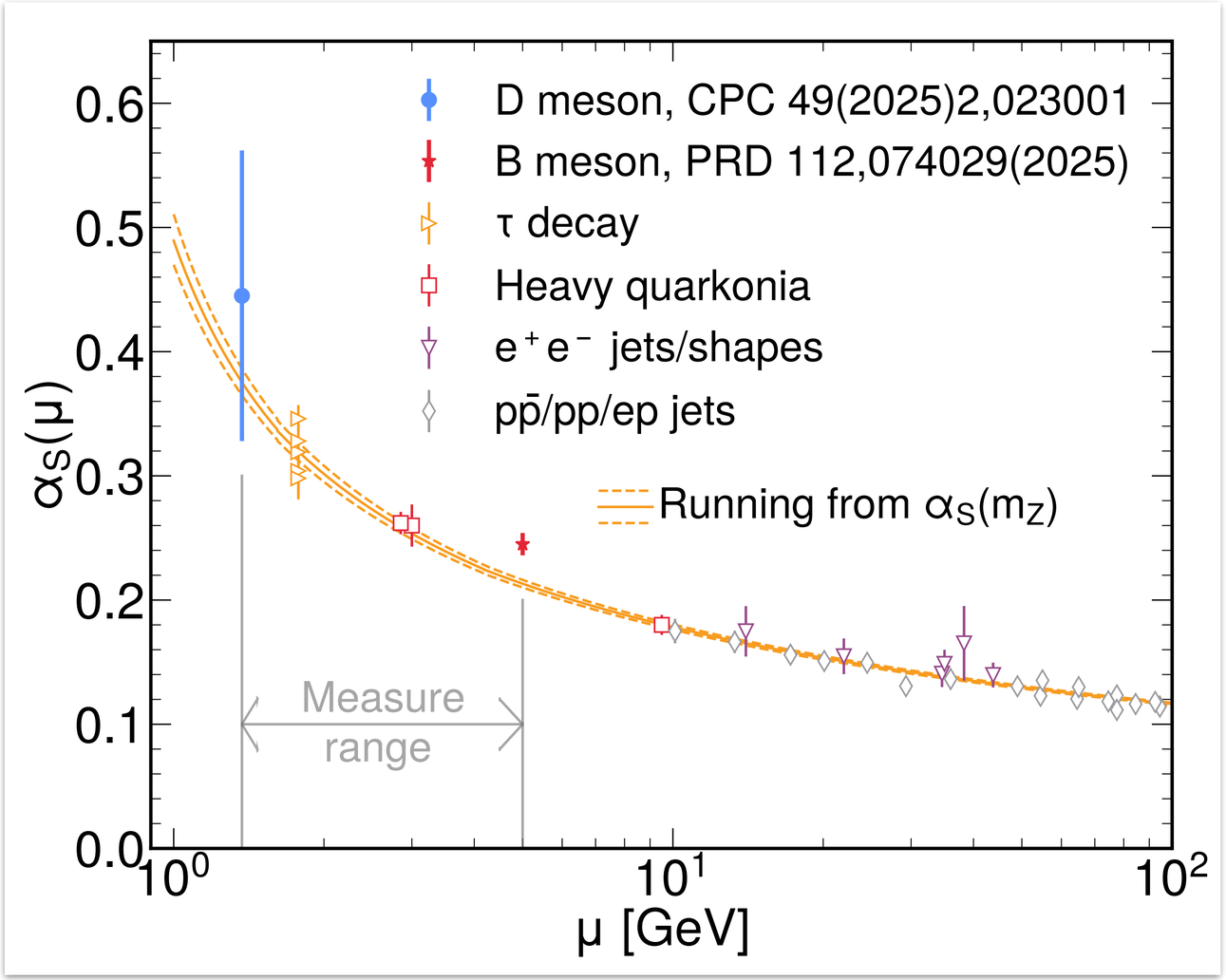
α_s from charm and beauty mesons

- A χ^2 minimization method is employed to determine α_S from the Γ_{SL},

$$\chi^2(\alpha_S, \theta_j) = \sum_i \frac{[\Gamma_{SL,D_i} - \hat{\Gamma}_{SL}(\alpha_S, \theta_j)]^2}{\sigma^2_{\Gamma_{SL,D_i}}} + \sum_j \frac{(\theta_j - \theta'_j)^2}{\sigma^2_{\theta'_j}}$$

- The D meson result **indicates that asymptotic freedom still holds at 1.37 GeV (less than m_τ).**

- For the B meson, it is possible to determine α_s **with a precision comparable to that achieved in other approaches.**



α_s from charm and beauty mesons

- The main challenge of the α_s determination using $\Gamma\left(B \to X_c \ell \bar{\nu}_\ell\right)$ lies in the precise determination of $|V_{cb}|$.

- More precise determinations of the key input parameter, $|V_{cb}|$, will further improve the studies using Belle II and future e^+e^- colliders.

- The dominant uncertainties in the D-meson study originate from m_c and theoretical calculation.

- More investigation from both experimental **measurements** and theoretical **calculations** will help to **reduce the systematic uncertainties** of $\alpha_s(m_c^2)$.

Search for sub-GeV invisible particles in J/ψ hadronic decays

- The existence of gluons was established through the observation of three-jet events, a cornerstone in confirming QCD.

Phys. Rev. Lett. 135 (2025), 151804

g (gluon) $I(J^P) = 0(1^-)$

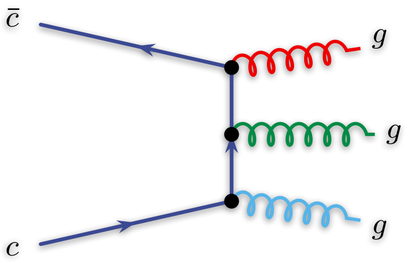
SU(3) color octet

Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 1995.

gluon spin

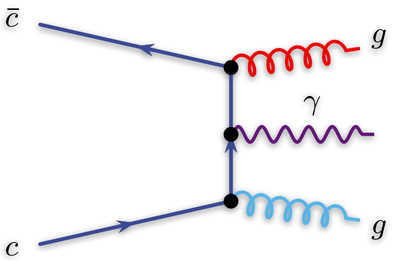
VALUE	DOCUMENT ID		TECN	COMMENT
	• • We do not use the following data for averages, fits, limits, etc. • •			
	ABREU	1992E	DLPH	Spin 1, not 0
	ALEXANDER	1991H	OPAL	Spin 1, not 0
	BEHREND	1982D	CELL	Spin 1, not 0
	BERGER	1980D	PLUT	Spin 1, not 0
	BRANDELIK	1980C	TASS	Spin 1, not 0

$J/\psi \to 3g$



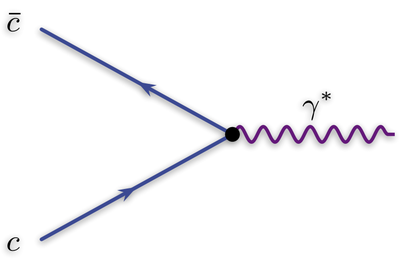
~65%

$J/\psi \to \gamma\, gg$



~8%

$J/\psi \to \gamma^*$



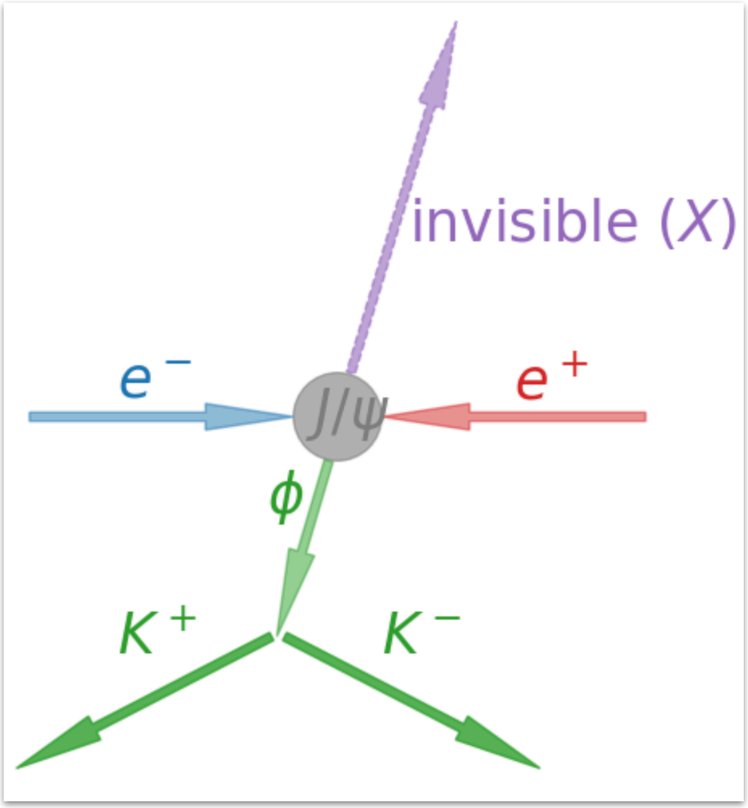
~25%

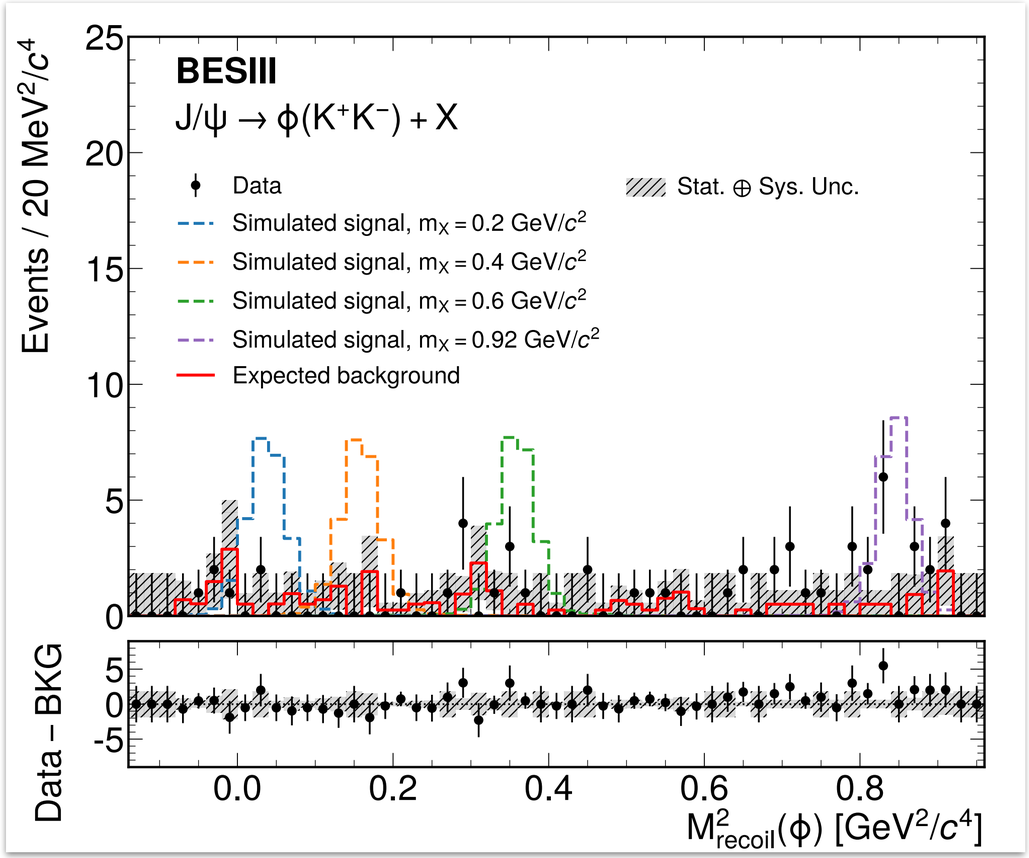
- The **search for free gluons is a direct test of color confinement** and can be carried out in the hadronic decays of J/ψ, owing to the large fraction of gluon-rich final states.
- We also **search for strong-interaction-induced invisible particles** in the J/ψ hadronic decays.

Search for sub-GeV invisible particles in J/ψ hadronic decays

- We search for sub-GeV invisible particles in the process $J/\psi \to \phi +$ invisible.

- The targeted signals are **free gluons** and **other strong-interaction-induced invisible particles.**





$$M^2_{\text{recoil}}(\phi) = (p_{e^+e^-} - p_\phi)^2$$

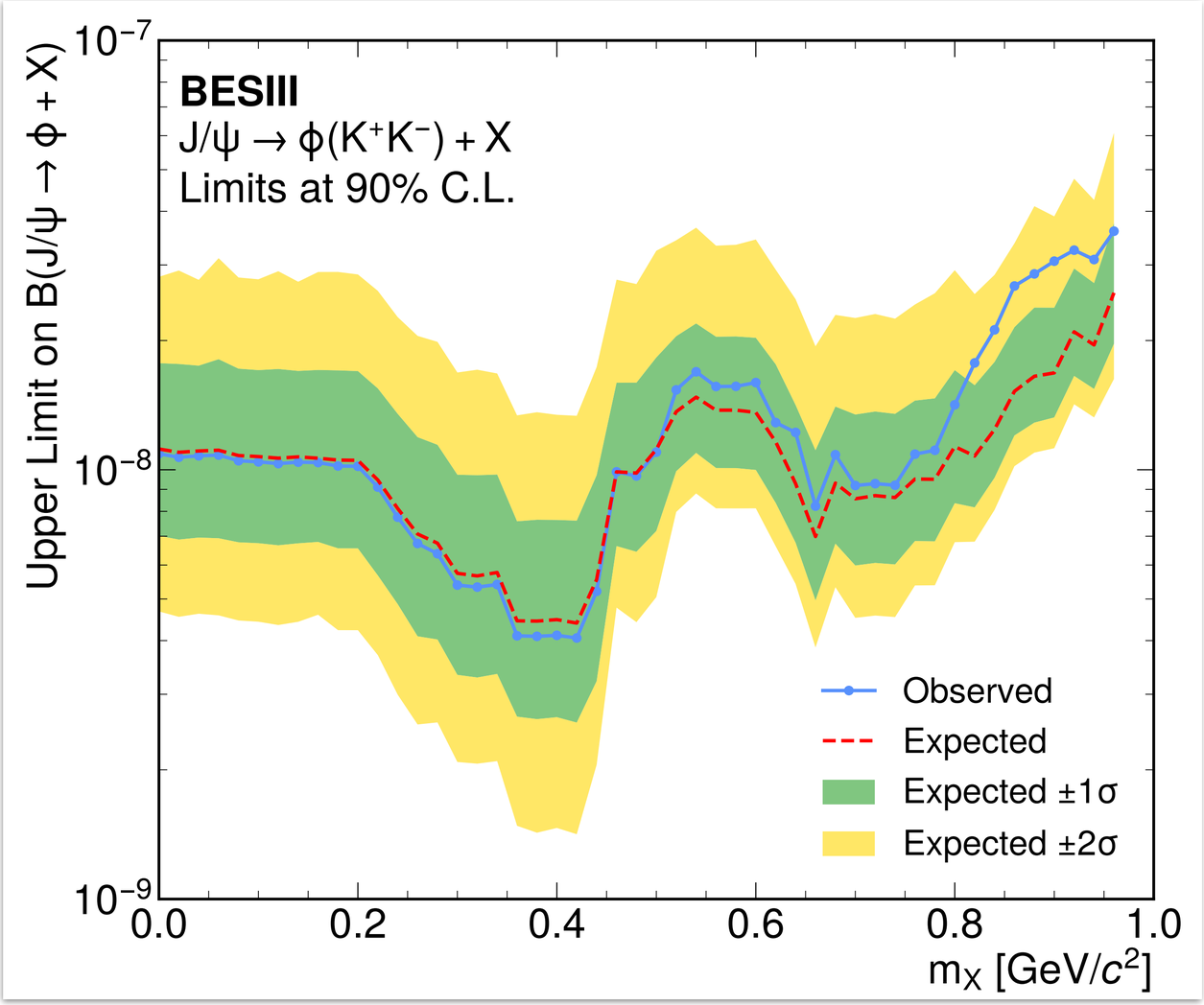
$$p_\phi = p_{K^+} + p_{K^-}$$

- The data and expected backgrounds agree well.

- No excess over expected background is observed, and stringent upper limits are set.

Search for sub-GeV invisible particles in J/ψ hadronic decays

- The upper limits on the branching fraction of $J/\psi \to \phi +$ invisible are extracted using a profile likelihood method.



- Upper limits are also determined to be $4 \times 10^{-9}$to 4×10^{-8} below 1 GeV, which are related to the breaking of color confinement.

- Using a naive framework, this study has **comparable sensitivity to the existing sub-GeV DM searches** in the sub-GeV DM mass range.

- Notably, **a dedicated framework is needed** to translate these upper limits into constraints on the breaking of color confinement.

Double $s\bar{s}$ production in e^+e^- collisions

arxiv 2609.20154

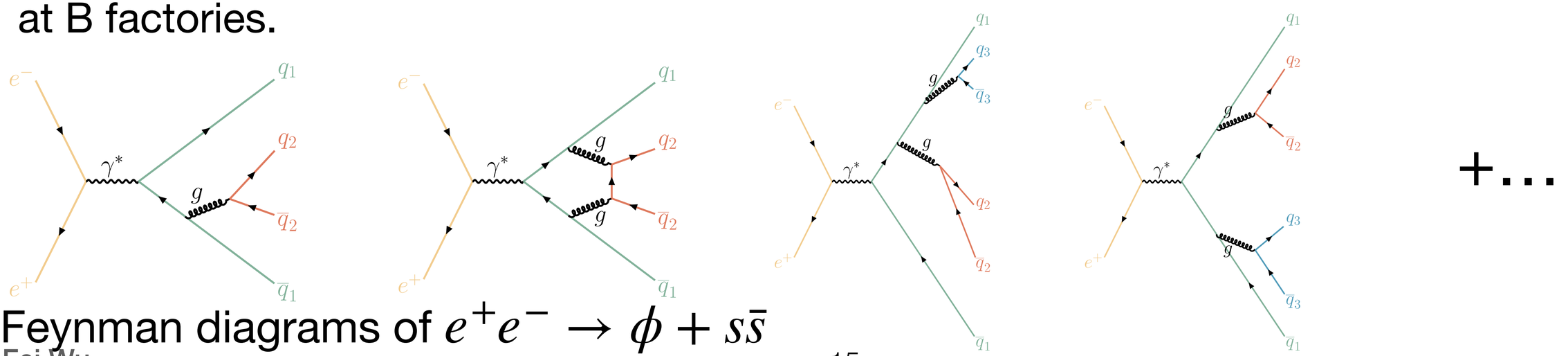
- The formation of hadrons from partons is governed by QCD and remains challenging to predict from first principles.

- Are there **any underlying features in hadronization?**

- If underlying features exist, more measurements are needed to explore them.

- We study the **double $s\bar{s}$ production processes** in e^+e^- collision at 3.08 GeV.

- Double $s\bar{s}$ production refers to processes such as $e^+e^- \to \phi + s\bar{s}$, similar to the double $c\bar{c}$ at B factories.



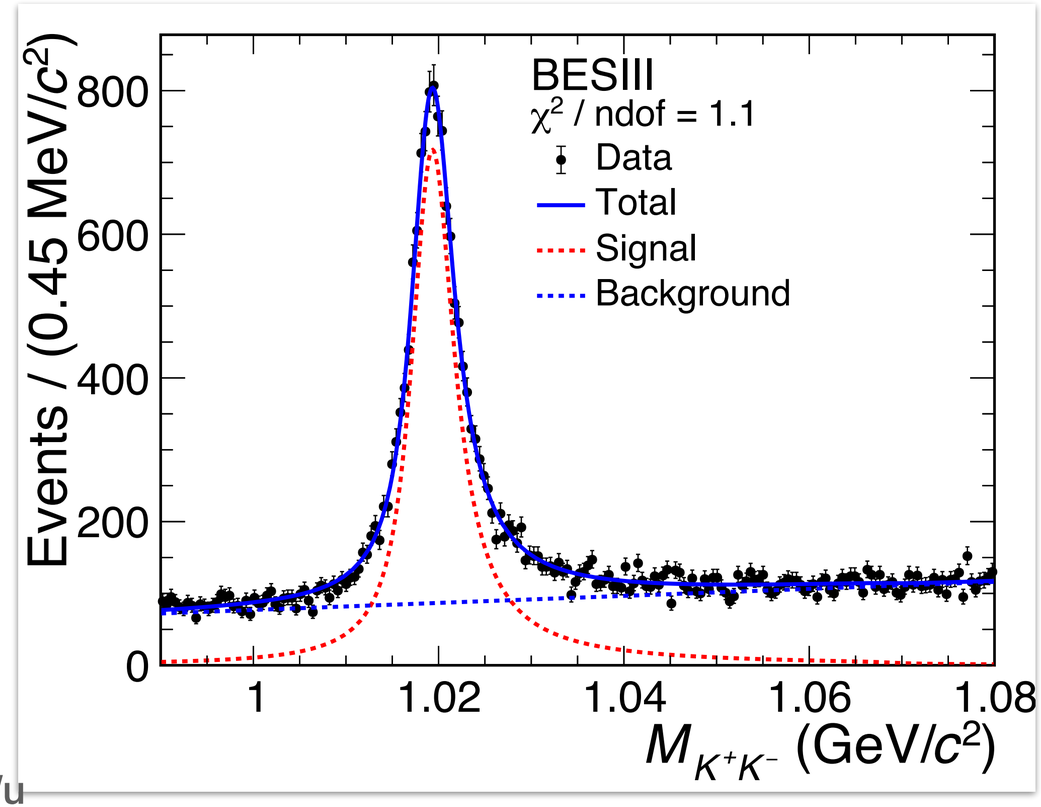
Feynman diagrams of $e^+e^- \to \phi + s\bar{s}$

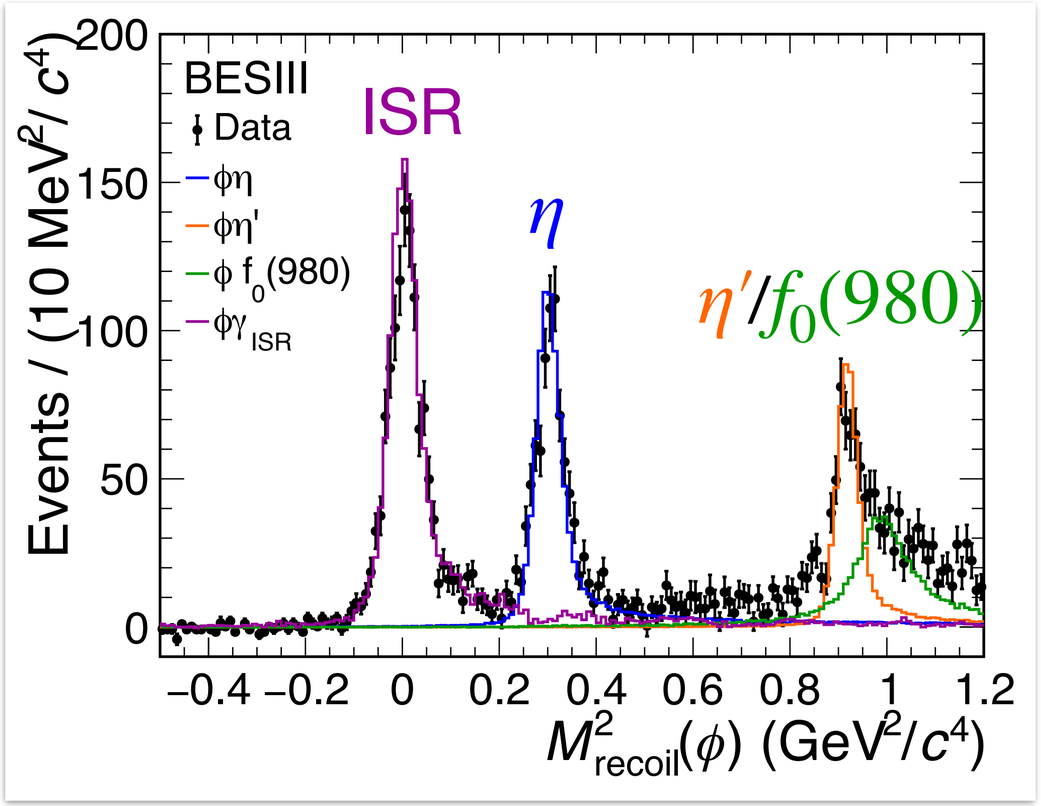
Double $s\bar{s}$ production in e^+e^- collisions

- A significant ϕ peak is observed in the distribution of $M_{K^+K^-}$; then the recoil-mass distribution against ϕ is calculated as

$$M^2_{\text{recoil}}(\phi) = (p_{e^+e^-} - p_\phi)^2,\ p_\phi = p_{K^+} + p_{K^-}$$

- Only the processes with 2 or 3 bodies are taken into account, such as $e^+e^- \to \phi\eta/K^+K^-$.



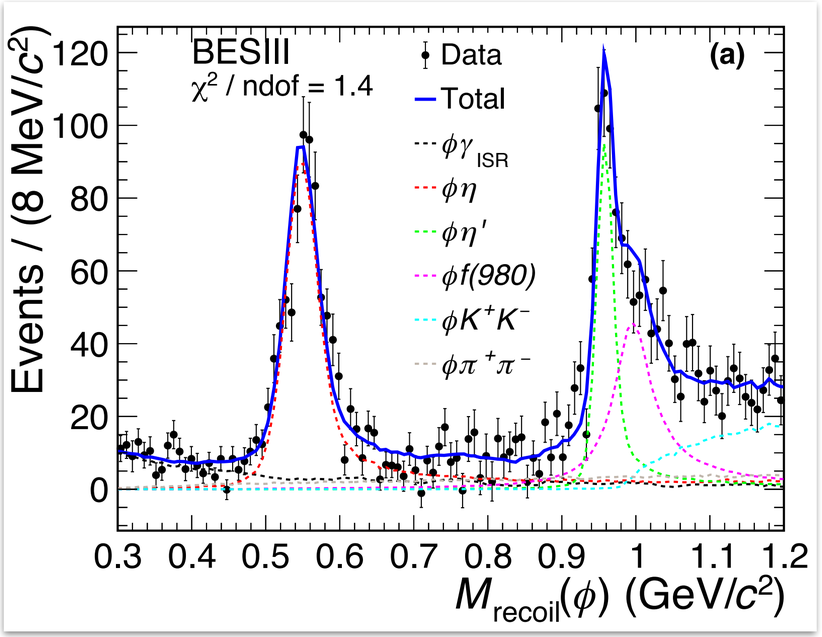


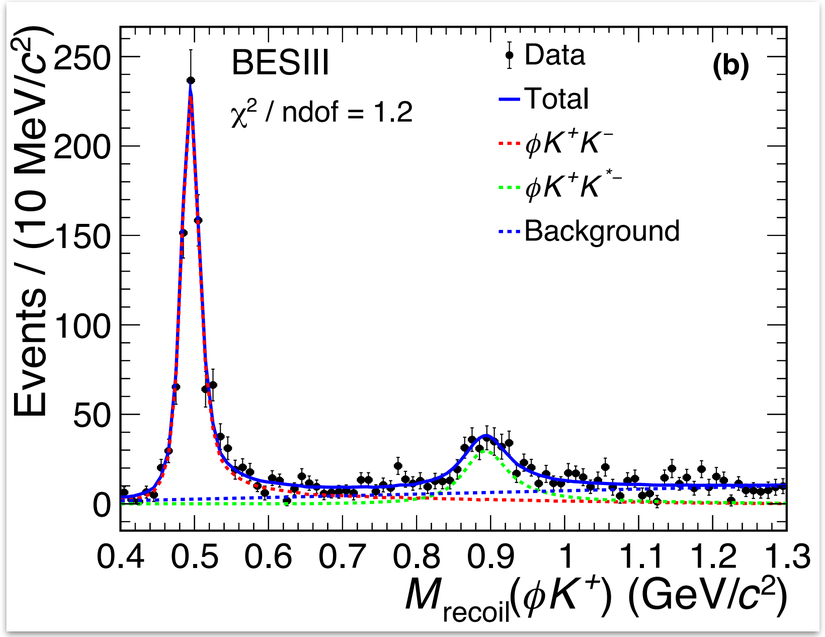
Double $s\bar{s}$ production in e^+e^- collisions

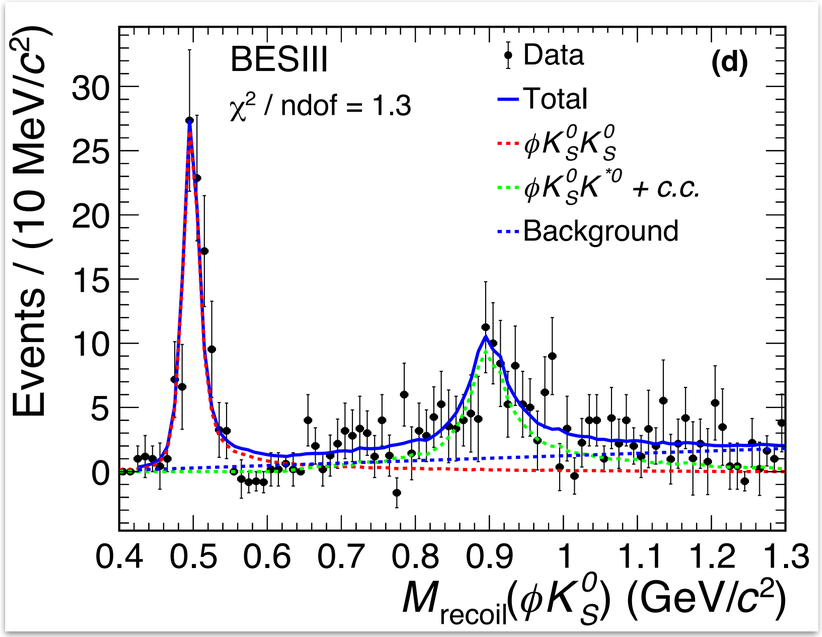
- Several fits to the mass spectra are performed to determine the observed numbers of double $s\bar{s}$ production processes.

- All fits describe the data well, and the corresponding cross sections are calculated using the fit results.

$$\sigma_i = \frac{n_i}{\mathcal{L} \times \epsilon_i \times \mathcal{B}(\phi \to K^+K^-)},$$







Double $s\bar{s}$ production in e^+e^- collisions

- The ratio of double $s\bar{s}$, $R_{s\bar{s}}$, is extracted from the cross section measurements.

Process	$\epsilon_i(\%)$	n_i	σ_i(pb)
ϕ + anything	27.5 ± 0.4	11618 ± 158	506.3±6.9±19.7
$\phi\eta$	28.5 ± 0.1	924 ± 39	38.9±1.6±1.6
$\phi\eta'$	29.2 ± 0.1	457 ± 33	18.8±1.4±2.1
$\phi K^0\bar{K}^0$	6.2 ± 0.02	108 ± 11	21.0±2.1±2.3
$\phi K^0\bar{K}^{*0}$ + c.c.	4.0 ± 0.03	115 ± 17	34.6±5.1±2.1
ϕK^+K^-	25.2 ± 0.06	1067 ± 41	50.8±2.0±4.3
ϕK^+K^{*-}	17.7 ± 0.05	322 ± 27	21.8±1.8±1.4
ϕK^-K^{*+}	17.9 ± 0.05	333 ± 27	22.3±1.8±1.5

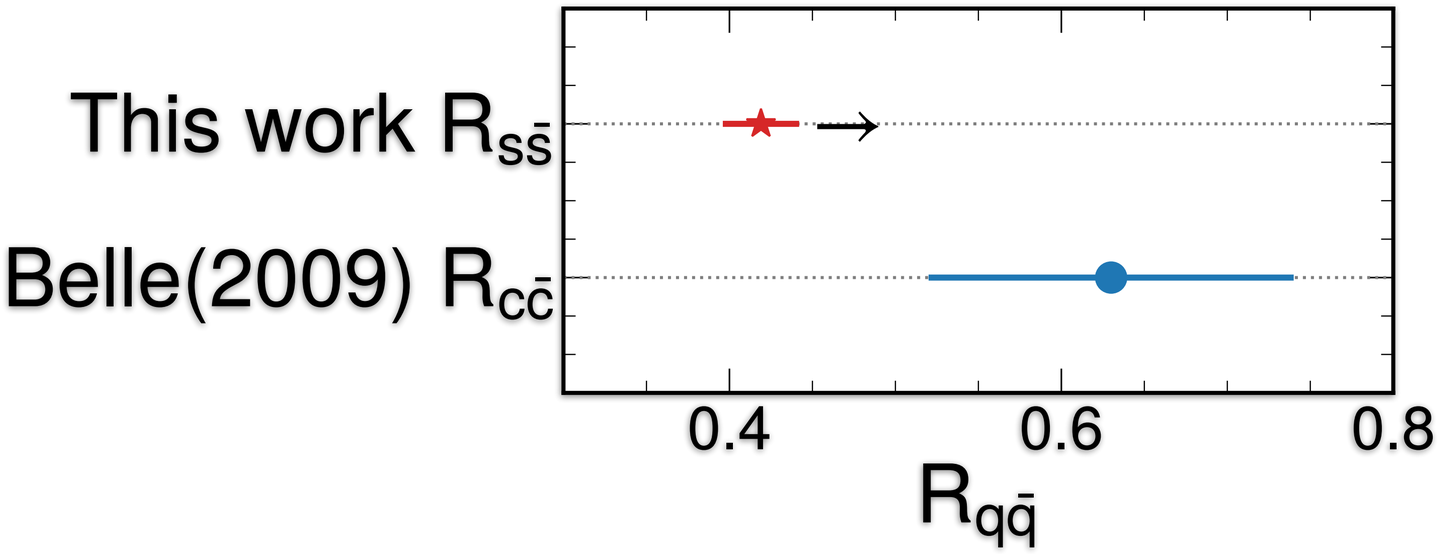
$$R_{s\bar{s}} = \frac{\sum \sigma(e^+e^- \to \phi + X(s\bar{s}))f_{s\bar{s}}}{\sigma(e^+e^- \to \phi + \text{anything})}, \quad (1)$$

where $X(s\bar{s})$ represents the η, η', K^+K^-, K^+K^{*-}, K^-K^{*+}, $K^0\bar{K}^0$, and $K^0\bar{K}^{*0}$ + c.c. states, and $f_{s\bar{s}}$ is the fraction of the $s\bar{s}$ component in $X(s\bar{s})$.

- Compared to the definition of double $c\bar{c}$ production ratio, the measured $R_{s\bar{s}}$ in this work is a lower limit due to the missed high multiplicity process.
  - If we take all possible double $s\bar{s}$ processes, the $R_{s\bar{s}}$ would be larger than the value reported here.

Double $s\bar{s}$ production in e^+e^- collisions

- The $R_{s\bar{s}}$ is measured to be $(40.4 \pm 2.3)\,\%$ for the first time, which is comparable to $R_{c\bar{c}}$ within 2σ.



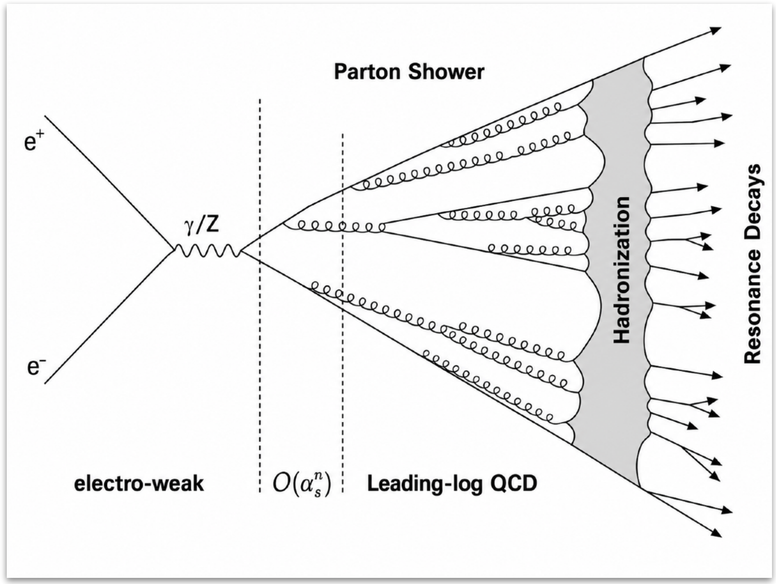
- The large value of $R_{s\bar{s}}$ confirms the phenomena observed in double $c\bar{c}$ production at B factories.

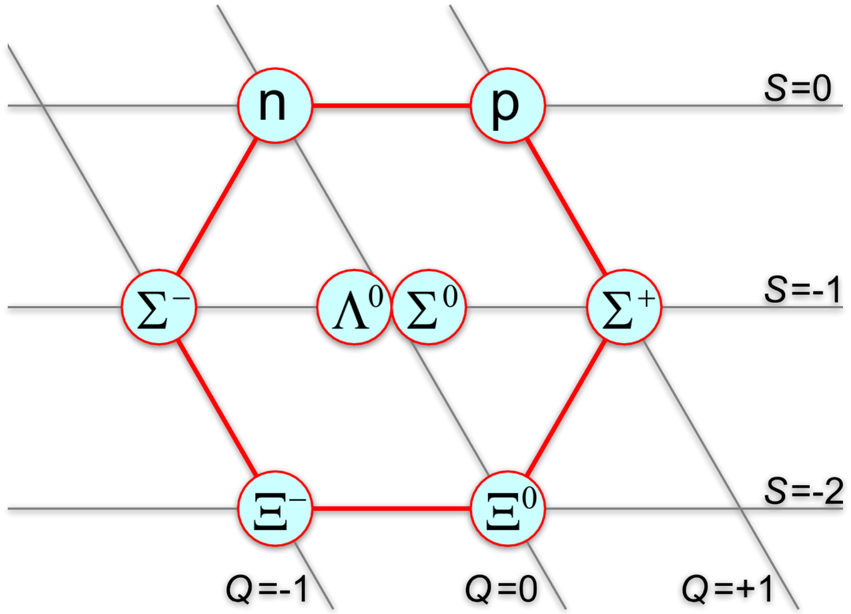
- A **new theoretical framework is necessary to calculate** $R_{s\bar{s}}$ due to the larger non-perturbative effects in the strange sector. **induced**
- The observed $R_{s\bar{s}}$, in combination with $R_{c\bar{c}}$, offers **a unique probe of underlying QCD features and flavor-dependent correlations in hadronization**.

$\Xi^{\pm}$ production in jets

arXiv 2607.13804

- Gluon jets are expected to exhibit stronger color radiation in the perturbative parton cascade and to contain larger particle multiplicities.



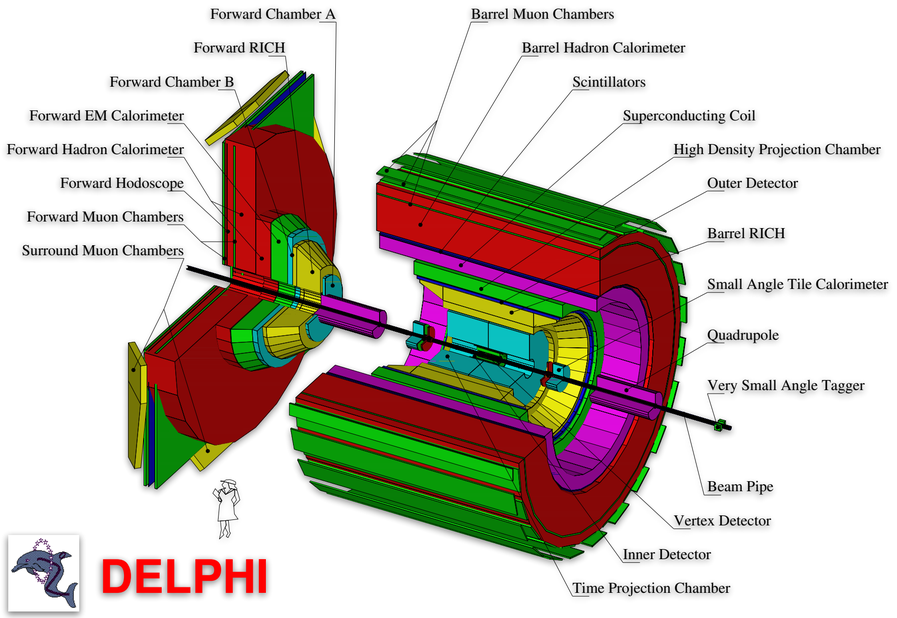


- The $\Xi^{\pm}$ baryon contains two $s(\bar{s})$ quarks.

- The **production of Ξ^{-} baryons in jets** intrinsically involves the local compensation of strangeness and baryon number, making it **a sensitive probe of double $s\bar{s}$ production and QCD**.

$\Xi^{\pm}$ production in jets

- The DELPHI collaboration opened its data and software at 2024. (See DELPHI data preservation, re-use, and open access policy)
  - Original DELPHI analysis framework, simulation & reconstruction, event display and documentation.



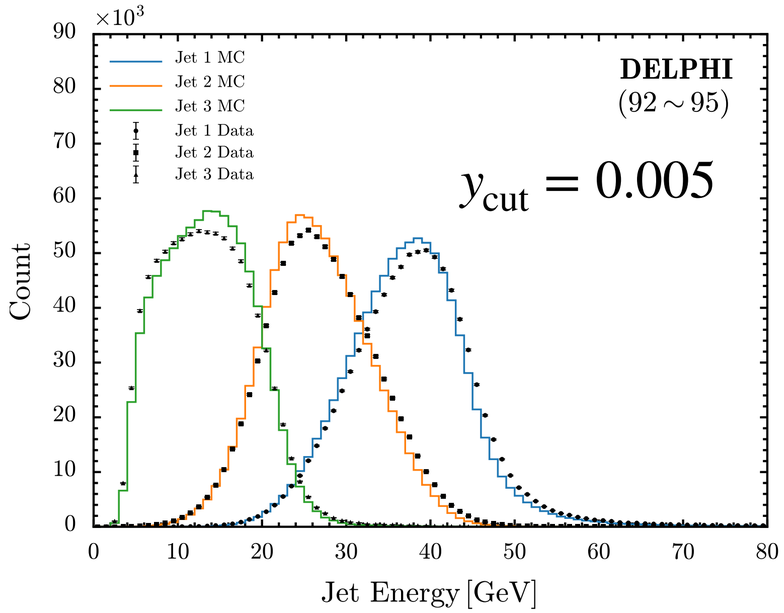
Year	$\int \mathcal{L}dt$ (pb^{-1})	E_{b} $(\mathrm{GeV/c^2})$	k_{b}	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

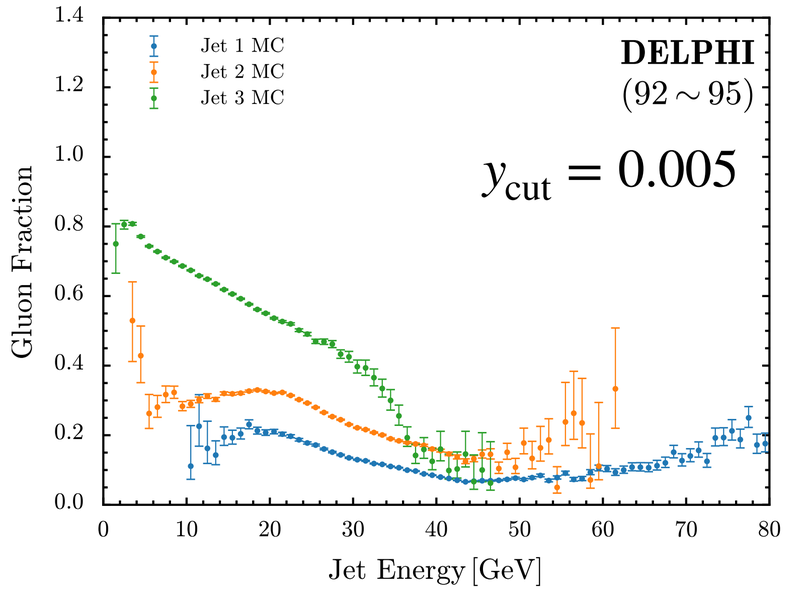
A unique opportunity to explore related physics.

In this work, the data is used to investigate hadronization and QCD.

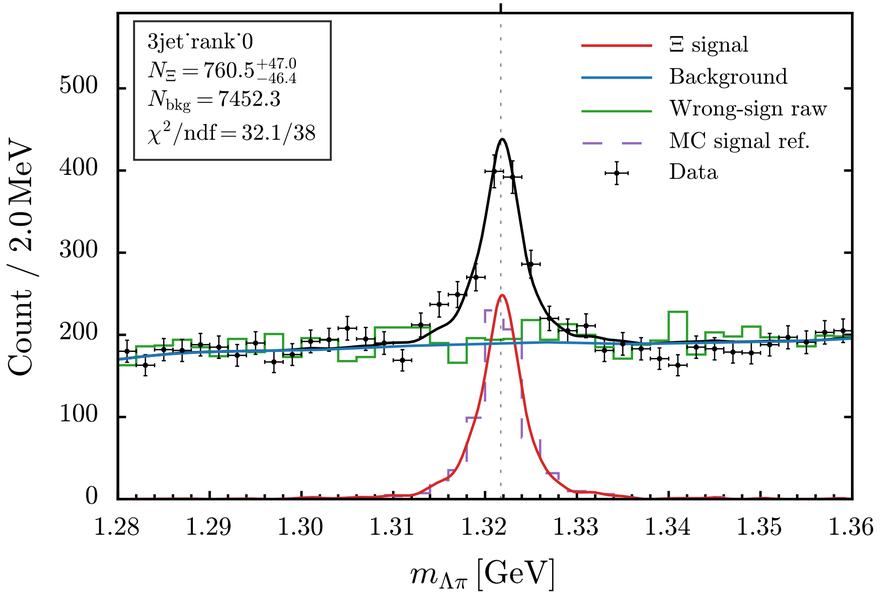
$\Xi^{\pm}$ production in jets

- Two/Three-jet events have been selected from the DELPHI legacy data by applying a $k_{\perp}$ cluster algorithm (Durham).





Clear Ξ^- peak

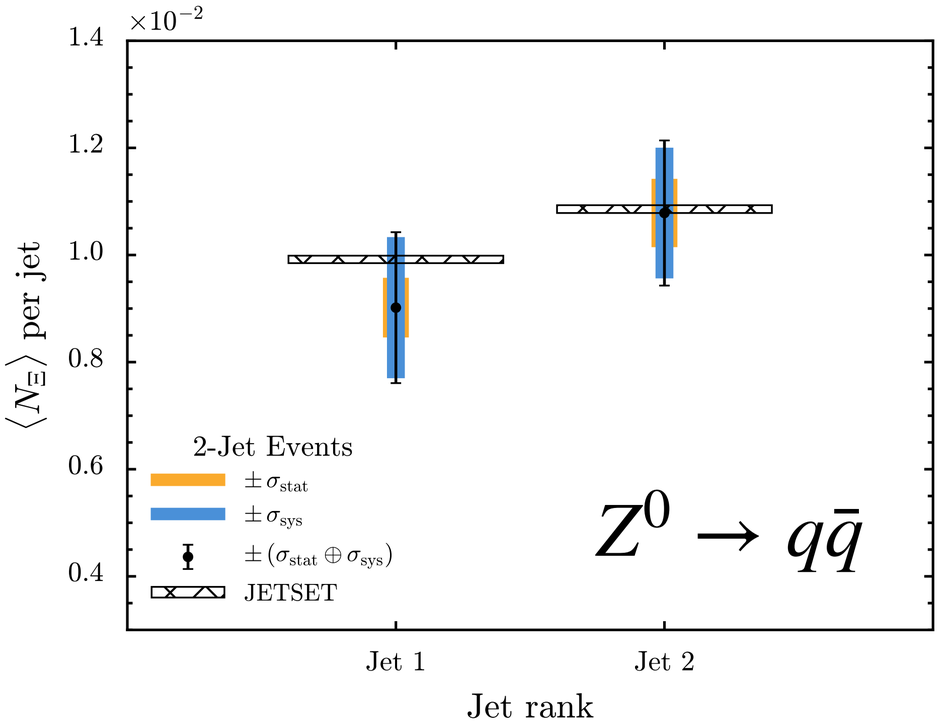


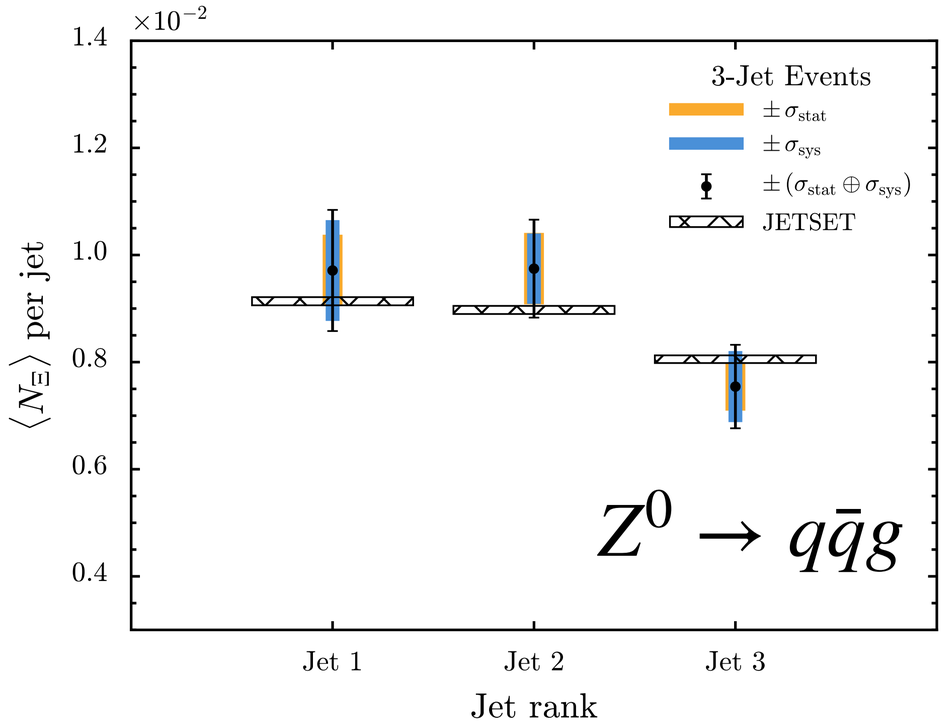
- Since the softest jet in $Z^0 \to q\bar{q}g$ events is predominantly a gluon jet, we can investigate the $\Xi^{\pm}$ production in quark and gluon jets, as well as the corresponding difference.

$\Xi^{\pm}$ production in jets

- The average Ξ production is calculated in energy-ranked jets,

$$\langle N_{\Xi} \rangle = \frac{1}{N_{\text{jet}}} \frac{N_{\text{obs}}}{\epsilon f_{\text{acc}}}$$





- The result is compatible with the prediction from the JETSET predictions.
- Despite the large uncertainty, the gluon jet appears to have a lower Ξ production rate.

$\Xi^{\pm}$ production in jets

- The fraction of Ξ production in charged tracks is calculated as below,

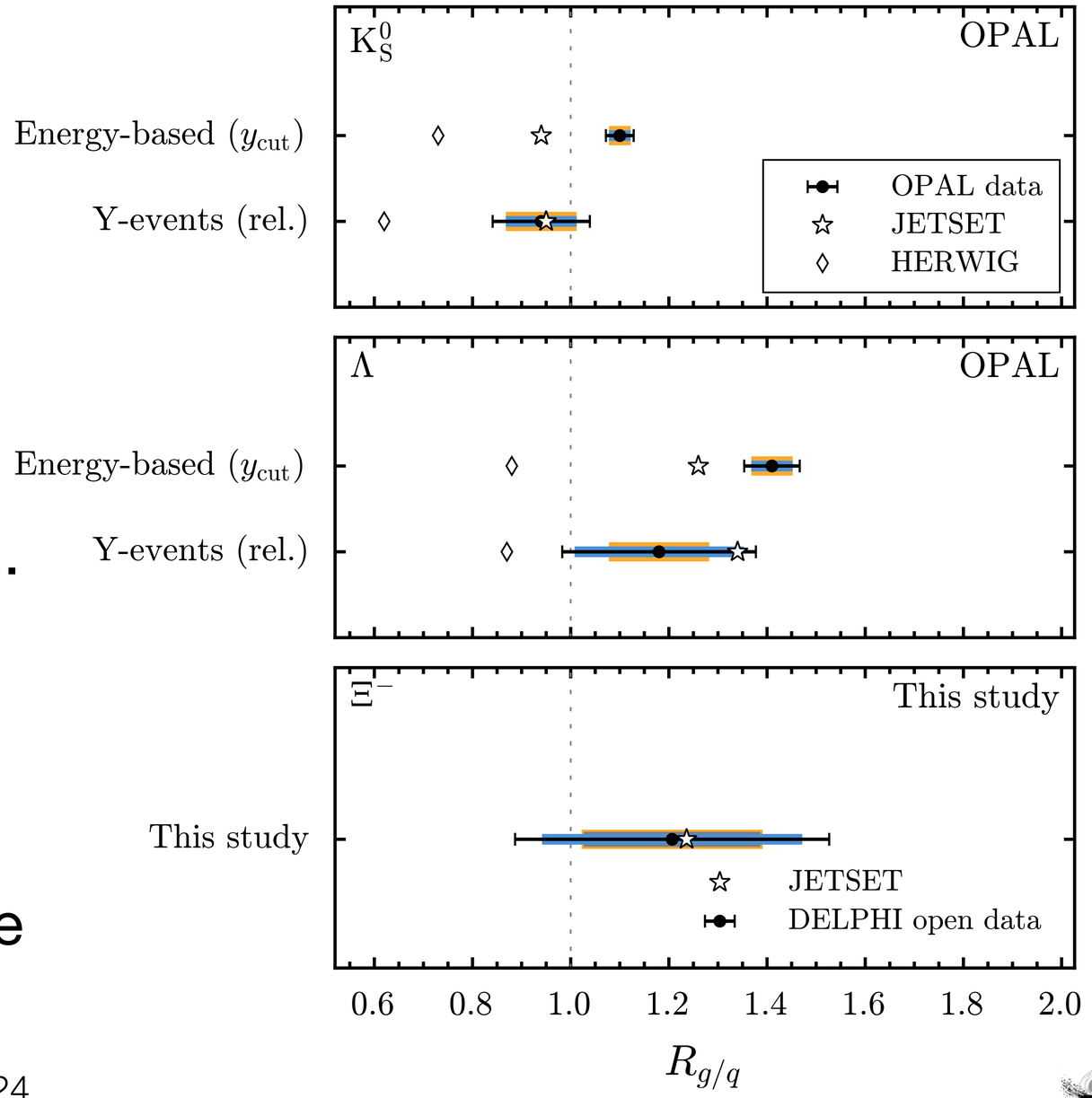
$$R^{\Xi}_{\text{jet},\,k} = \left\langle N_{\Xi} \right\rangle_{\text{jet},\,k} \Big/ \left\langle N_{\text{ch}} \right\rangle_{\text{jet},\,k}$$

- With these fractions, the ratio

$$R^{h}_{g/q} \equiv \frac{\langle N_h \rangle_g}{\langle N_{\text{ch}} \rangle_g} \Big/ \frac{\langle N_h \rangle_q}{\langle N_{\text{ch}} \rangle_q}$$ can be derived.

$$R^{\Xi}_{g/q} = 1.21 \pm 0.18(\text{stat.}) \pm 0.26(\text{sys.})$$

- The measurement is compatible with the JETSET predictions.



Summary

- RQ1 : **What happens to α_s below m_τ? How does α_s behave at different energy scales?**

  - α_s is extracted from inclusive semileptonic charm and beauty decays within HQE.

  - The D-meson result reaches 1.37 GeV, below m_τ, confirming asymptotic freedom still holds, while B mesons achieve a precision comparable to established methods.

- RQ2 : **Can isolated gluons be observed experimentally? Is there any strong interaction induced invisible particles?**

  - The first search for free gluons and strong-interaction-induced invisible particles in $J/\psi \to \phi + X$ observes no excess and sets upper limits of 4×10^{-9} to 4×10^{-8} below 1 GeV.
  - The limits can be translated into constraints on the breaking of color confinement or sub-GeV DM once a dedicated framework is available.

Summary

- RQ3 : **How do quarks and gluons hadronize? Is there any underlying feature in hadronization?**
  - The first measurement of double $s\bar{s}$ production in e^+e^- collisions at 3.08 GeV yields a lower limit of $R_{s\bar{s}} = (40.4 \pm 2.3)\,\%$, , which is comparable to $R_{c\bar{c}}$ within 2σ and confirms the large double-pair production observed at B factories.
  - Using the DELPHI open data, we measured $\Xi^{\pm}$ production in quark and gluon jets and obtained $R_{g/q}^{\Xi} = 1.21 \pm 0.18(\text{stat.}) \pm 0.26(\text{sys.})$, compatible with the JETSET prediction.

- In summary, these studies probe the strong interaction from three complementary perspectives — the precision of its coupling, the confinement of its gluons, and the dynamics of its hadronization.



Thanks!



Backup

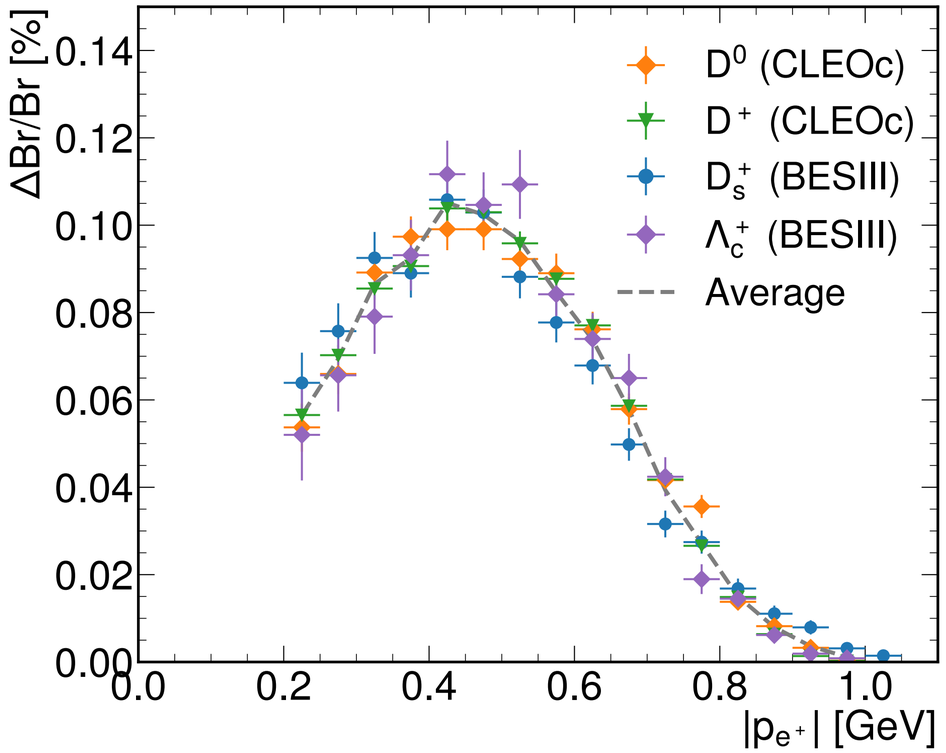
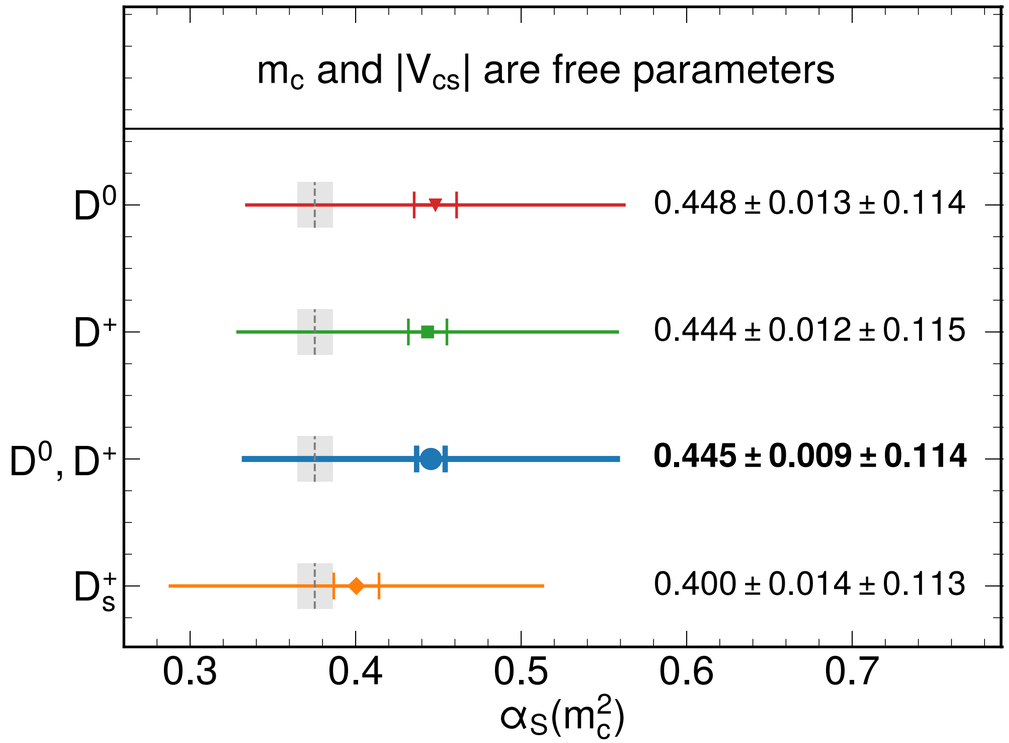


FIG. II. The lepton momentum distributions in the inclusive semi-leptonic decays of D^0, $D^{\pm}$ and $D_s^{\pm}$ in laboratory frame [arXiv:0912.4232 & arXiv:2104.07311].



$$\alpha_s(m_c) = 0.445 \pm 0.009_{\text{exp}} \pm 0.081_{m_c} \pm 0.056_{\text{trun}} \pm 0.057_{\text{others}}$$

Backup

The χ^2 fit, defined as $\chi^2(\alpha_s) = \dfrac{[\Gamma_B - \hat{\Gamma}_B(\alpha_s)]^2}{\sigma^2_{\Gamma_{B,\text{exp}}} + \sigma^2_{\Gamma_{B,\text{theo}}}}$, yields

$$\alpha_s(5\,\text{GeV}) = 0.246 \pm 0.013$$

Combining the two fits gives $\alpha_s(5\,\text{GeV}) = 0.246 \pm 0.009$, corresponding to $\alpha_s(m_Z) = 0.1266 \pm 0.0023$.

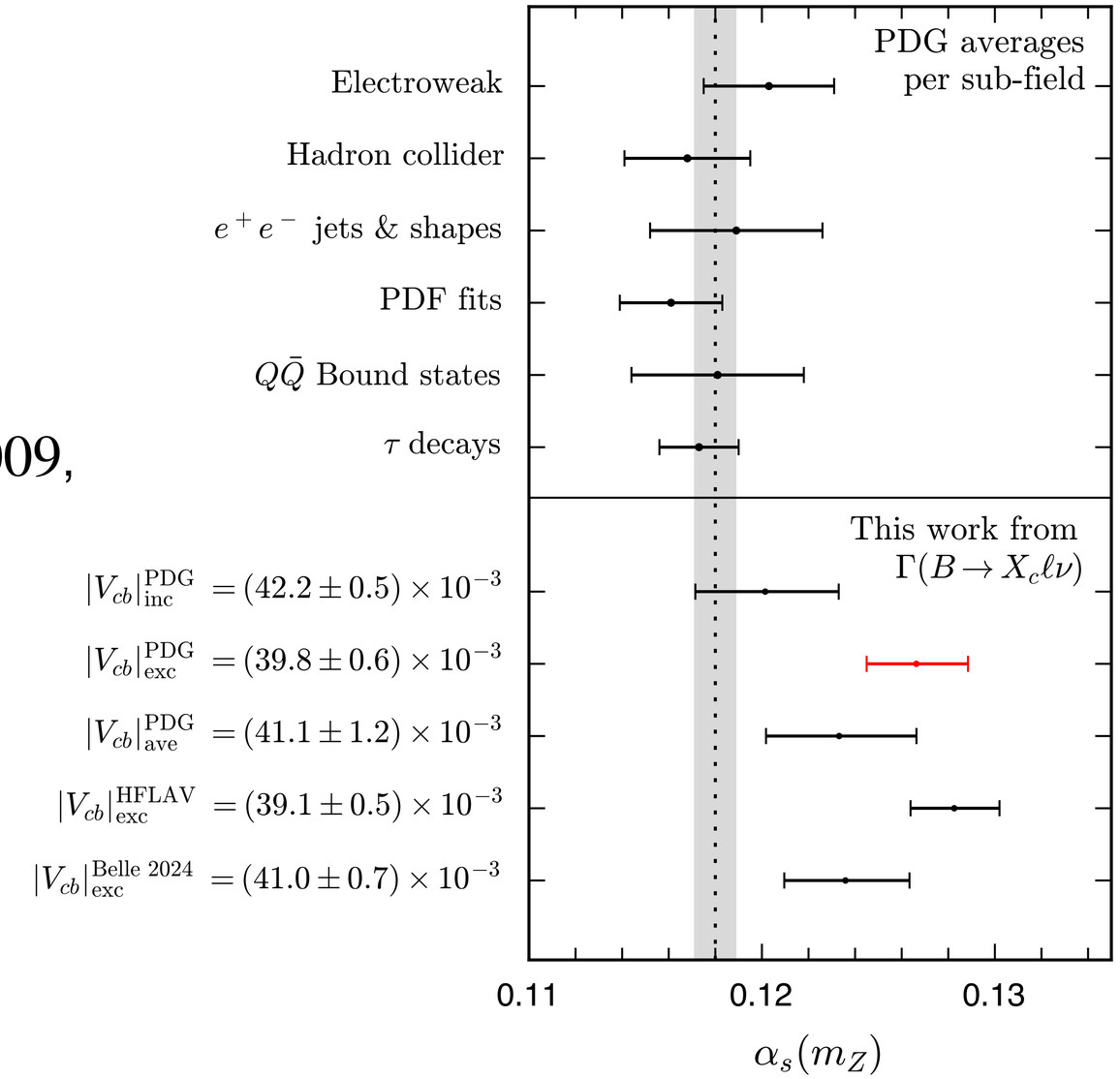


FIG. The comparison of the $\alpha_s(m_Z)$ pre-averages from six experimental subfields in PDG and the extrapolated values obtained in this work. The running of α_s along the energy scale is conducted using the RunDec package [arXiv:hep-ph/0004189]

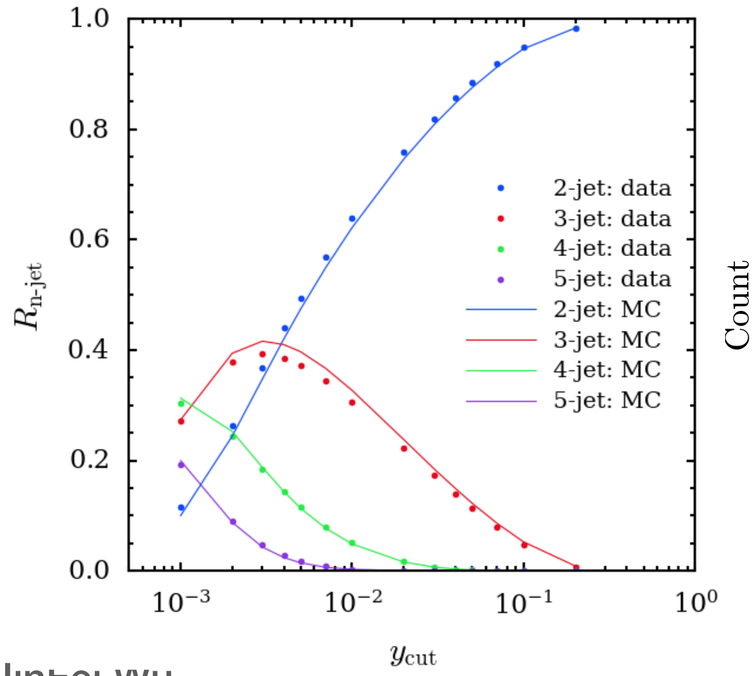
Backup

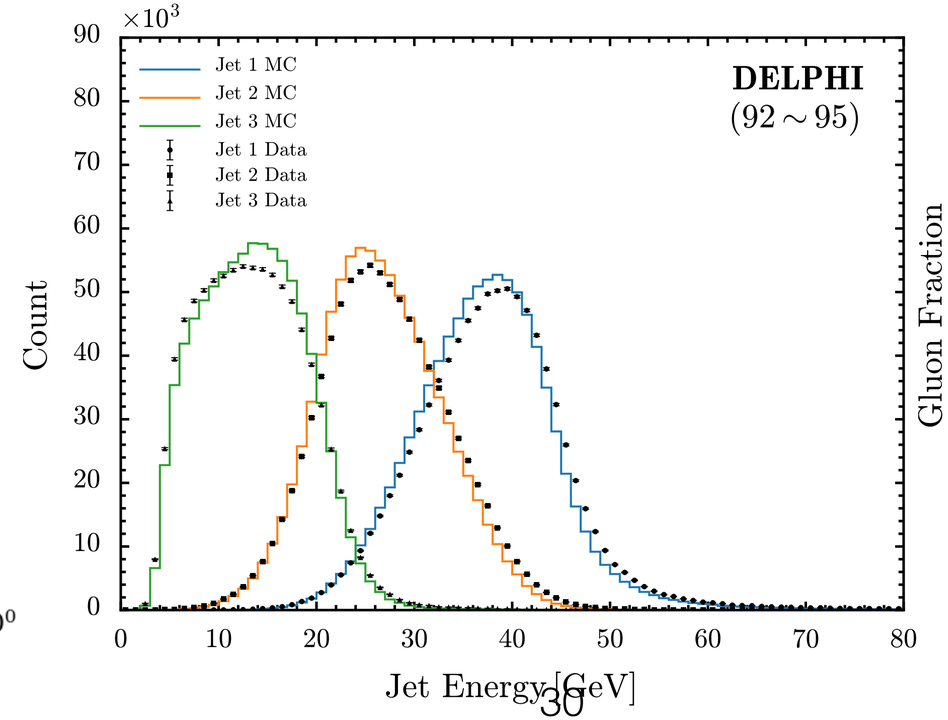
Repeat energy ranking method implemented in L3 (Phys.Lett.B 407 (1997) 389-401)/OPAL (Eur.Phys.J.C 8 (1999) 241-254).

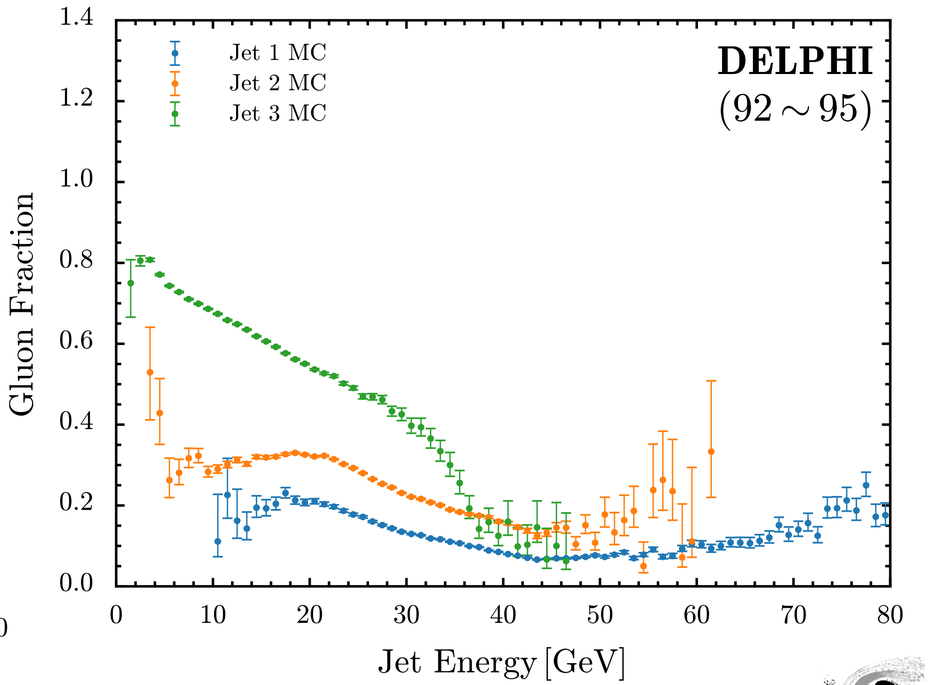
Three/Two-jet events have been selected by official cuts for **track quality** and for the **hadronic event type** as well as applying a $k_\perp$ cluster algorithm (Durham).

Durham ($k_\perp$) algorithm via FastJet: iterative pairwise clustering of all accepted charged and neutral objects.

Distance: $y_{ij} = \dfrac{2\ \min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{Q^2}$, where $Q = \sqrt{s} = 91.2\,\mathrm{GeV}$; Jet resolution parameter: $y_{\mathrm{cut}} = 0.005$

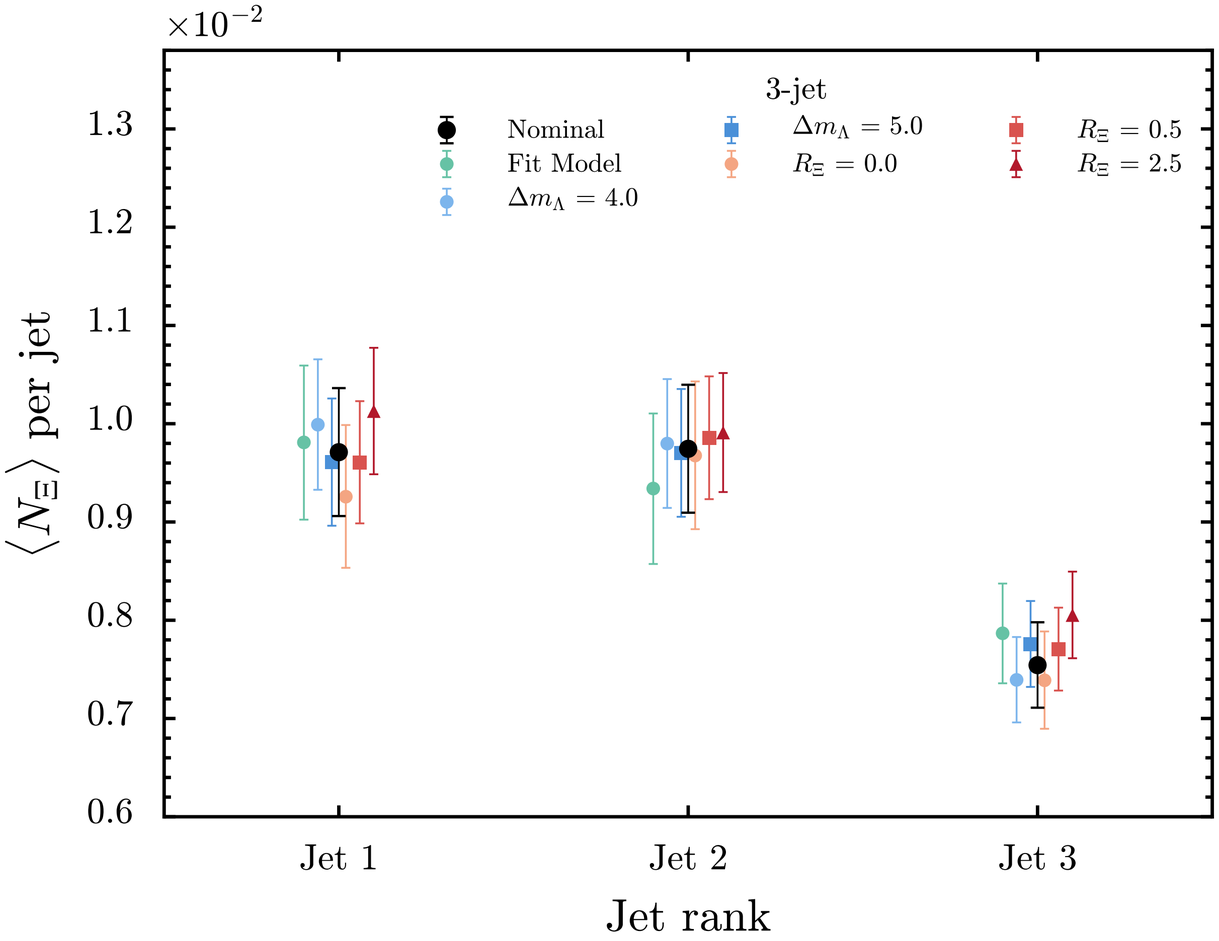






Backup

- Ξ Selection:
  - m_{Λ} window: varied from $4.5\,\mathrm{MeV}$ to $4.0\,\mathrm{MeV}$ and $5.0\,\mathrm{MeV}$.
  - minimum signed decay radius of Ξ in $R\phi$-plane: varied from $0.4\,\mathrm{cm}$ to 0, 0.5 and $2.5\,\mathrm{cm}$.
  - Largest variations are considered as the systematic uncertainties.
- Fit method:
  - Fit the sideband m_{Ξ} distribution using histogram PDF of wrong signed control sample, then subtract the background from data in the signal region ($m_{\Xi} \pm 10\,\mathrm{MeV}$).
  - Half-difference between nominal & alternative fit method is assigned as systematic uncertainty.
- Acceptance:
  - an uncertainty of $50\,\%$ on the correction factor is assigned.



Backup

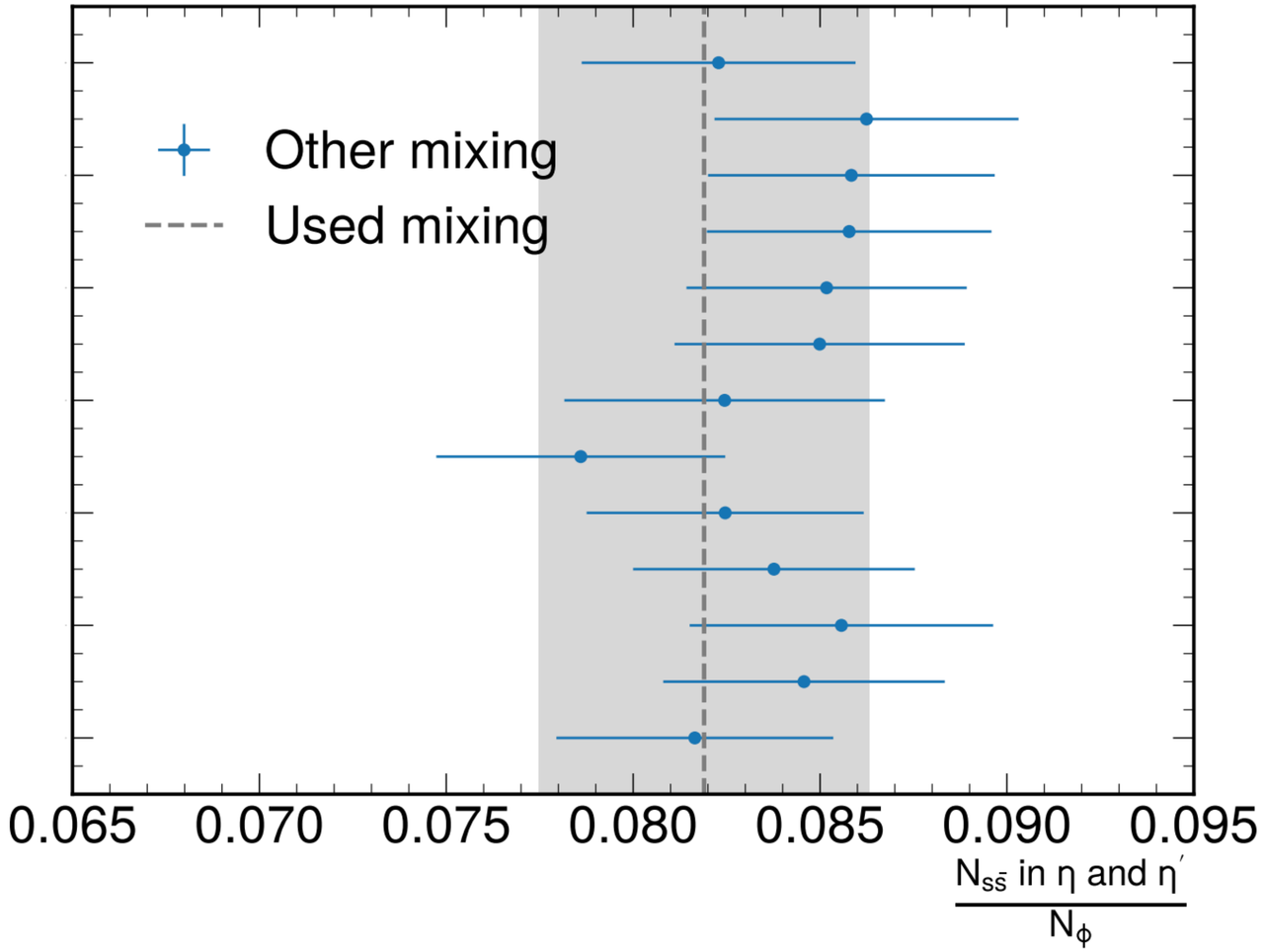


Figure 1: $N_{s\bar{s}}/N_\phi$ result based on each mixing angle result.